MEGA SCIENCE VISION-2035

ACCELERATOR S&T AND APPLICATIONS

A ROADMAP PREPARED BY THE INDIAN ACCELERATOR S&T COMMUNITY

The front cover page shows the photograph of 30 MeV Medical Cyclotron at VECC, Kolkata (top left), 2.5 GeV Indus-2 Storage Ring tunnel at RRCAT, Indore (top right), High Current Injector (HCI) at IUAC, New Delhi (bottom left) and Low Energy High Intensity Proton Accelerator (LEHIPA) at BARC, Mumbai (bottom right)

Mega Science Vision-2035
Accelerator S&T and Applications

A roadmap prepared by
the Indian Accelerator S&T Community
with RRCAT, Indore
as the Nodal Scientific Institution

and

submitted to
The Office of the Principal Scientific Advisor to the
Government of India

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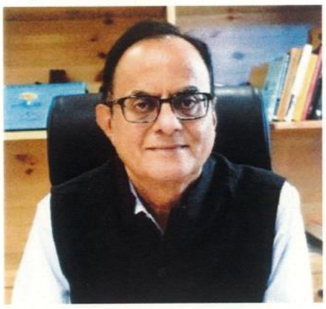
अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

सत्यमेव जयते

विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली–110011
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi - 110011
Tel. : +91-11-23022112
Fax: +91-11-23022113
E-mail : sood.ajay@gov.in
office-psa@nic.in
Website : www.psa.gov.in



MESSAGE

It is with pleasure that I receive this Mega Science Vision-2035-Accelerator S&T and Applications Report. Accelerators are the most self-evident examples of Mega Science Projects. They were invented in the 1930's for looking at the structure of matter, and have considerably grown in size, sophistication and particle energy with time. Some of the most outstanding discoveries in nuclear and particle physics have been either made or verified at accelerators. Around 25 Nobel Prizes in Physics have been awarded so far based on accelerator-related work. But for the accelerators, the entire edifice of the Standard Model of Particle Physics would not have been built.

Over a period of time, however, accelerator technology has been customized for a variety of applications. The most notable is the Synchrotron Radiation Source. It was realized that a dedicated accelerator-based source could produce high-brilliance beams of highly energetic and tunable X-rays, so crucial for research in physics, chemistry, life sciences, materials science and engineering, drugs and pharma industry, manufacturing industry and so on. This started the era of custom-built synchrotron radiation sources. Around half a dozen Nobel Prizes in Physics, Chemistry and Life Sciences have been facilitated by experiments at synchrotron radiation sources. The Spallation Neutron Sources, which produce high-flux pulsed neutron beams, have their own specific and important applications ranging from materials research to nuclear energy.

An accelerator need not always be large in size for it to be useful. We now have accelerators of all sizes and energies, delivering beams of a wide variety of particles for use in industrial and non-research settings as wide as semiconductor industry, materials modification and characterization to food preservation, medical radioisotopes and radiotherapy. Accelerator projects also involve a whole range of different technologies; in fact they push the very frontiers of technology with valuable spin-offs at times. Let us not forget that the World Wide Web, which revolutionized the way we interact and transact on the Internet today, was invented at CERN.

Accelerator-related activities in India started early, with the pioneering effort by Meghnad Saha in 1940. Owing to the resource-intensive nature of such projects, accelerator facilities of relatively modest sizes and energies have been set up over time including some low-energy accelerators for nuclear physics research and the 3rd Generation 2.5 GeV Synchrotron Radiation Source (Indus-2). Based on the valuable experience gained through these projects, as well as through our participation in important accelerator-building projects abroad, we are now moving towards building more ambitious accelerator projects in the country, like the High Brilliance Synchrotron Radiation Source, Indus-3.

I congratulate the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, the Drafting and Working Groups, and the large number of other national and international experts involved in the exercise, for producing such a comprehensive Report after widespread national consultations. It is a goldmine of information, not only for planners and policy-makers, but for scientists and technologists as well. Scientists have to now join hands and translate some of the ideas contained in this Report into reality. My best wishes to them!

Ajay K

(Ajay K. Sood)

Dated: 16th August, 2024

सत्यमेव जयते

डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव

Dr. (Mrs) Parvinder Maini
Scientific Secretary

भारत सरकार के
प्रमुख वैज्ञानिक सलाहकार के कार्यालय
विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली - 110011

Office of the Principal Scientific Adviser
to the Government of India
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi-110011

Dated 16th August, 2024

Foreword

A particle accelerator is a quintessential symbol of a Mega Science Project (MSP). Whenever we talk of an MSP today, images of the Large Hadron Collider in Geneva flash through our minds. Today, accelerators of different kinds, shapes and sizes find wide variety of applications. Accelerator Science & Technology and Applications (ASTA), thus, was an important area for the Mega Science Vision-2035 (MSV-2035) Exercise facilitated by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI). This MSV-2035-ASTA Report is the outcome of this massive national and international consultative exercise. This is the third Report to come out, after Nuclear Physics and Astronomy & Astrophysics.

Starting with basic principles of particle acceleration, the Report goes on to survey the relevance of particle accelerators from the point of view of applications. It then surveys the international and national status of Accelerator R&D. After carefully matching the national capabilities in this technologically-complex area with the requirements and desires of the Indian accelerator-user community, it puts forward a prioritized list of projects to be pursued or undertaken during 2020-35. Arriving at a nation-wide consensus on prioritization of projects is not an easy task, but the Report has achieved this goal too, along with estimates of financial and human resources that would be required. The Report puts forward some concrete suggestions regarding eco-system building activities and management aspects of accelerator-projects. This includes a discussion on enhancing the level of participation of Indian industry in such projects.

This Report brings in two special features that need special mention. First, it tries to highlight the positive impact of accelerator projects on industry and the society at large, given their wide-ranging applications. Second, a first-of-its-kind attempt has also been made to estimate Return on Investment for some typical accelerator projects undertaken by the country. Needless to say, there are a number of inherent assumptions and uncertainties in the estimations, but an honest attempt has been made to carry out this analysis.

This Report has been made possible only by the enormous effort put in by the Drafting and Working Groups (DG and WG) set up by the O/o PSA. They need our deepest appreciation. We had the benefit of advice from three successive Directors of the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore as Chair of the WG (Shri Debashis Das, Dr. SV Nakhe and Shri UD Malshe), and the exemplary pivotal support by Shri Purushottam Shrivastava of RRCAT as the Member-Secretary of WG.

From the O/o PSA, Dr. Praveer Asthana, PSA Fellow, and Dr. Arun Bhardwaj, Scientist-F (now back with ISRO), anchored this activity and provided valuable inputs. They deserve our special thanks.

I am positive that this Report will be of great value to researchers as well as funding agencies in supporting accelerator-related activities in the country.

PMaini
(Parvinder Maini)

Tel: +91-11-23022090 Fax : +91-11-23022116 E-mail: parvinder.maini@gov.in Web: http://www.psa.gov.in

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ABOUT THE MEGA SCIENCE VISION-2035 EXERCISE

Mega Science Projects (MSPs) are scientifically and technologically complex projects, requiring collaboration among scientists, engineers, technicians, project managers, funding organizations, industry, etc. on a large scale – occasionally from institutions and organizations in different nations across the world. MSPs, quite often, are also large in physical size and require large monetary, capital, human and intellectual resources. MSPs are also very long-term engagements – typically taking ten years for planning, another ten years for construction and, finally, remaining in operation anywhere from 20-50 years. It follows as a corollary that, at any given time, only a few such projects can be taken up nationally, or even globally.[1]

It is natural that the decision regarding which projects to launch nationally, or which projects to participate in internationally, is always taken through wide national consultations among the concerned scientific communities. This is the way it is done the world over. And, this is the way it has been done in India, at least over the past three decades. Such structured and periodic national consultations in India have been known by several names in the past. From some point of time, they have come to be known as "Vision Exercises". Since the disciplines of nuclear physics, high energy physics and accelerator science and technology and applications were the first to experience the need for MSPs, the Vision Exercises in India in the past were facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST). In the case of Astronomy & Astrophysics, the Astronomical Society of India has been periodically organizing such exercises.

In the Indian context, by 2020, a number of MSPs that had been identified in the earlier Vision Exercises had moved further towards funding and implementation. It was, therefore, felt that a time had come to carry out the next Mega Science Vision (MSV) Exercise. It was also realized that the country had travelled a long-way from the days of India-CERN Collaboration, which could aptly be called the turning point for India's engagement with MSPs. There were a number of national as well as international projects which India had nationally launched, or in which India was participating internationally. The concerned scientific communities in India had also grown more confident and ambitious about getting involved in more such projects. Also, large collaborations had become necessary in a number of other science disciplines too. It was, therefore, decided to make the MSV Exercise more structured, inclusive and comprehensive.

In consultation with DAE and DST, which had been facilitating such exercises earlier in a few disciplines, it was decided that it would be better if the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) facilitated the Exercise this time – given its pre-eminent S&T policy-making and coordination role in the GoI. The centre of activities thus got shifted to the O/o PSA to GoI. The O/o PSA to GoI decided that the Exercise this time would be carried out not only in Nuclear Physics, High Energy Physics, Astronomy & Astrophysics and Accelerator Science & Technology and Applications, but also in two additional areas, viz. Climate Research and Ecology & Environmental Science. Both these areas also require large-scale experimentation, data-gathering and analyses, and in many ways have been involved in MSPs without calling it by that name or realizing the same. The outcome of the MSV Exercise was expected to be comprehensive Roadmap Reports, one in each of the six areas. Given the typical time frame of MSPs, 2020-35 was decided as the period of focus for this MSV Exercise. Hence was born the Mega Science Vision-2035 (MSV-2035) Exercise in the six areas mentioned above.

For carrying out the MSV-2035 Exercise in Accelerator Science & Technology and Applications (ASTA), the O/o PSA to GoI requested the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, to act as the Nodal Institution, to which it readily agreed. RRCAT also nominated Shri Purushottam Shrivastava as the Nodal Scientist. In consultation with RRCAT, a Working Group (WG) was constituted with Director-RRCAT as the Chair, and Shri Purushottam Shrivastava as the Member-Secretary. A smaller sub-group of the WG acted as the Drafting Group (DG). The O/o PSA to GoI also laid down the goals of the Exercise and the methodology for national as well as international consultations during the Exercise.

The DG made exemplary effort in putting together several drafts of the document by reaching a large number of leading researchers in ASTA in the country, and after consulting similar roadmap documents from elsewhere in the world. The WG also met several times to look at the evolving drafts and offered valuable suggestions. A discussion was also organized among all the six WGs **to exchange ideas about several issues that were common to all the six disciplines — for example, management structures for MSPs, aspects of fund flow, human resource development, outreach efforts, etc.** Finally, a draft of the MSV-2035-ASTA Report got evolved which was approved by the WG for wider national consultations. Comments on the Draft Report were electronically invited from about 6800 researchers working in ASTA and other proximate areas in the country. Comments from about 50 researchers were received and the draft was further modified in view of those comments. This draft was sent to 30 eminent national experts for their comments, and 8 of them sent their written comments. The draft was again revised in view of those comments. In the final leg of the consultative process, this draft was sent to 23 eminent international experts approved by the Chair of the WG for their comments. 5 of them sent their comments, based on which the draft was again revised. The draft so developed was presented before the PSA to GoI and the Scientific Secretary in the O/o PSA to GoI, prior to its submission, and their comments and suggestions were also incorporated to the maximum possible extent. After all these steps, this final MSV-2035-ASTA Report has emerged.

This MSV-2035-ASTA Report is a "Roadmap" prepared by the national ASTA community outlining their hopes and aspirations for mega science activities till 2035, as best as they can foresee today. Needless to say, if there are some momentous changes in the field in this period, it might change some of the projections contained in this Report. And, a similar Exercise will again take place after another 5-6 years where this Report will get updated.

It must be emphasized that this is an 'ASTA community document', the preparation of which has been facilitated by the O/o PSA to GoI. Apart from putting the Report on the PSA Office website, it is planned to circulate the Report to various Ministries/Departments and Funding Agencies. It is sincerely hoped that the Report will be found useful by everyone associated with MSPs in the country in any manner. It is also hoped that the Report will be found useful by the international ASTA community as well.

(PRAVEER ASTHANA)
PSA Fellow, O/o PSA to GoI

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Mega Science Vision – 2035
(Accelerator S&T and Applications)

The Report

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The Drafting and Working Groups

Director, RRCAT, Indore Mr. Debashis Das / Dr. S.V. Nakhe/ Mr. U. D. Malshe	Chairperson
Members from the Drafting Group	
Ms. Sudeshna Seth, VECC, Kolkata	Member
Dr. Puneet Jain, IIT Roorkee	Member
Mr. Abhishek Rai, IUAC, New Delhi	Member
Other Expert Members	
Dr. Vinit Kumar, RRCAT, Indore	Member
Dr. S. M. Yusuf, BARC, Mumbai	Member
Dr. Malay Kanti Dey, VECC, Kolkata	Member
Dr. Tanuja Dixit, SAMEER, Mumbai	Member
Dr. Jaydeep Basu, IISc, Bengaluru	Member
Dr. Subhendu Ghosh, IUAC, New Delhi	Member
Agency Representatives	
Dr. Srinivas Krishnagopal, Nominee of Secretary, DAE	Member
Dr. M. C. Ramadevi, Nominee of Secretary, DoS	Member
Mr. S. K. Varshney/ Dr. Praveen Kumar S, Nominee of Secretary, DST	Member
Representatives of the Office of PSA	
Dr. Praveer Asthana, National Coordinator and PSA Fellow	Member
Dr. Arun Bhardwaj, Scientist–F	Member
Nodal Scientist –Mr. Purushottam Shrivastava, RRCAT, Indore	Member-Secretary

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LIST OF ACRONYMS

ACTREC	Advanced Centre for Treatment Research and Education in Cancer
AD	Antiproton Decelerator
ADS	Accelerator Driven Systems
AEC	Atomic Energy Commission
AMS	Accelerator Mass Spectroscopy
ANURIB	Applied and Nuclear physics with Rare Isotope Beams
APCC	Apollo Proton Cancer Centre
APS	Advanced Photon Source
AR	Accumulator Ring
ARPES	Angle Resolved Photo-electron Spectroscopy
ARPF	Agricultural Radiation Processing Facility
AVF	Azimuthally Varying Field
BARC	Bhabha Atomic Research Centre
BELLA	Berkeley Lab Laser Accelerator
BLIP	Brookhaven LINAC Isotope Producer
BNCT	Boron Neutron Capture Therapy
BNL	Brookhaven National Laboratory
BSM	Beyond the Standard Model
CADS	Chinese ADS program
CARIBU	Californium Rare Isotope Breeder Upgrade
CDP	Conceptual Design Plan
CEPC	Circular Electron Positron Collider
CERN	Conseil Européen pour la Recherche Nucléaire
CLIC	Compact LInear Collider
CNO	Carbon Nitrogen Oxygen
CPA	Chirped Pulse Amplification
CPE	Community Planning Exercise
CPHS	Compact Pulsed Hadron Source
CW	Continuous Wave
DAE	Department of Atomic Energy
DAEδALUS	Decay At rest Experiment for δ studies At the Laboratory for Underground Science
DAR	Decay At Rest
DC	Direct Current
DESY	Deutsches Elektronen-Synchrotron
DLA	Dielectric Laser Accelerator
DPR	Detailed Project Report
DRIBs	Dubna Radioactive Ion Beams
DST	Department of Science and Technology
DTL	Drift Tube LINAC
EBAM	Electron Beam-based Additive Manufacturing
EBS	Extremely Brilliant Source
EIC	Electron Ion Collider
EIR	Swiss Federal Institute for Reactor Research

ELI	Extreme Light Infrastructure
EM	Electromagnetic
ERL	Energy Recovery LINAC
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EXAFS	Extended X-ray Absorption Fine Structure
FAIR	Facility for Antiproton and Ion Research
FCC	Future Circular Collider
FDG	Fluoro-Deoxy-Glucose
FEL	Free Electron Laser
FLASH	Free electron LASer at Hamburg
FOTIA	Folded Tandem Ion Accelerator
FRENA	Facility for Research in Experimental Nuclear Astrophysics
fs	femto second
GeV	Giga electron Volt
GNRs	Graphene Nano Ribbons
GPCR	G-Protein-Coupled receptors
GSI	Gesellschaft für Schwerionenforschung
GW	Giga Watt
HBSRS	High Brilliance Synchrotron Radiation Source
HCI	High Current Injector
HEBT	High Energy Beam Transport
HEHIPA	High Energy High Intensity Proton Accelerator
HE-LHC	High Energy LHC
HEP	High Energy Physics
HEPS	High Energy Photon Source
HESR	High Energy Storage Ring
HGHG	High Gain Harmonic Generation
HISPA	High Intensity Superconducting Proton Accelerator
HL-LHC	High Luminosity LHC
HR	Human Resource
HTS	Horizontal Test Stand
HWR	Half Wave Resonator
IAC	IDAHO Accelerator Centre
IBC	Ion Beam Centres
IFEL	Inverse Free Electron Laser
IFSR	Indian Facility for Spallation Research
IIFC	Indian Institutions Fermilab Collaboration
IH	Inter-digital H-mode
IIHNO	Indian Institute of Head and Neck Oncology
IISER	Indian Institute of Science Education and Research
IIT	Indian Institute of Technology
ILC	International Linear Collider
IMRT	Intensity Modulated Radio Therapy
IPF	Isotope Production Facility
IPNS	Intense Pulsed Neutron Source

ISOL	Isotope Separation On-Line
IT	Information Technology
IUAC	Inter-University Accelerator Centre
IXS	Inelastic X-ray scattering
JLab	Jefferson Laboratory
J-PARC	Japan Proton Accelerator Research Complex
KALI	Kilo Ampere Linear Injector
KEK	Ko Enerugi-kasokuki Kenkyukiko
KENS	KEK Neutron Source
LAMF	Los Alamos Meson Factory
LASER	Light Amplification by Stimulated Emission of Radiation
LBE	Lead-Bismuth Eutectic
LCLS	Linac Coherent Light Source
LEAF	Low-Energy Accelerator Facility
LEBT	Low Energy Beam Transport
LE-FCC	The Low Energy FCC
LEHIPA	Low Energy High Intensity Proton Accelerator
LHC	Large Hadron Collider
LHeC	Large Hadron-electron Collider
LIA	Linear Induction Accelerator
LINAC	Linear Accelerator
LLRF	Low-Level RF
LPA	Laser Plasma Acceleration
MBA	Multi-Bend Achromat
MEHIPA	Medium Energy High Intensity Proton Accelerator
MeitY	Ministry of Electronics and Information Technology
MeV	Mega electron Volt
MoES	Ministry of Earth Sciences
MoU	Memorandum of Understanding
MOSFET	Metal Oxide Silicon Field Effect Transistor
M-RAM	Magneto-resistive Random-Access Memories
MR-LINAC	Magnetic Resonance Linear Accelerator
MSNU	Mega Science Nodal Unit
MSPs	Mega Science Projects
MW	Mega Watt
MYRRHA	Multipurpose Hybrid Research Reactor for High-tech Applications
NC	Normal Conducting
NCCCM	National Centre Compositional Characterisation of Material
NDT	Non-Destructive Testing
NICA	Nuclotron-based Ion Collider fAcility
NIMMS	New Ion Medical Machine Study
NRF	Nuclear Resonance Fluorescence
OER	Oxygen Enhancement Ratio
OFHC	Oxygen Free High Conductivity
OMP	Operations and Maintenance Plan
PDP	Preliminary Design Plan

PEC	Photo-Electro-Chemical
PET	Positron Emission Tomography
PF	Projectile Fragmentation
PIG	Penning Ion Generator
PIMS	Positive Ion Mass Specrometry
PIP-II	Proton Improvement Plan – II
PIP-II IT	PIP-II Injector Test
PPP	Public Private Partnership
PPP	Purchase Power Parity
PSA	Principal Scientific Advisor
PSI	Paul Scherrer Institute
PSLV	Polar Satellite Launch Vehicle
PSR	Proton Storage Ring
PW	Peta Watt
PWT	Plane Wave Transformer
QA	Quality Assurance
QC	Quality Control
QGP	Quark Gluon Plasma
QWR	Quarter Wave Resonator
R&D	Research & Development
RAL	Rutherford Appleton Laboratory
RBE	Radio-Biological Effectiveness
RCS	Rapid Cycling Synchrotron
REXS	Resonant Elastic X-ray Scattering
RF	Radio Frequency
RFP	Request for Proposal
RFPI	RF Protection Interface
RFQ	Radio-Frequency Quadrupole
RIB	Rare Isotope Beam
RIBF	RI Beam Factory
RIXS	Resonant Inelastic X-ray Scattering
RMC	Radiation Medicine Centre
RoI	Return on Investment
RRC	RIKEN Ring Cyclotron
RRCAT	Raja Ramanna Centre for Advanced Technology
S&T	Science and Technology
SAMEER	Society for Applied Microwave Electronics Engineering and Research
SASE	Self-Amplified Spontaneous Emission
SC	Superconducting
SCC	SC Cyclotron
SEE	Single Event Effects
SHE	Super Heavy Elements
SIB	Stable Isotope Beams
SIN	Swiss Institute of nuclear resaerch
SIOM	Shanghai Institute of Optics and Fine Mechanics
SLB	Superconducting Linac Booster

SLSF	Shanghai Light Source Facility
SLV	Satellite Launch Vehicle
SNICS	Source of Negative Ions by Cesium Sputtering
SNS	Spallation Neutron Source
SPECT	Single Photon Emission Computed Tomography
SppC	Super Proton-Proton Collider
SR	Synchrotron Radiation
SRC	Standing Review Committee
SRF	Superconducting RF
SSPAs	Solid State Power Amplifiers
SSR	Superconducting Spoke Resonator
STH	Solar-to-Hydrogen
SW	Standing Wave
SLV	Satellite Launch Vehicle
SWOT	Strengths, Weaknesses, Opportunities and Threats
TDP	Technical Design Plan
TeV	Tera electron Volt
TMC	Tata Memorial Centre
ToT	Transfer of Technology
TPS	Treatment Planning System
TRIUMF	TRI-University Meson Facility
TW	Tera Watt
TW	Traveling Wave
UGC	University Grants Commission
VECC	Variable Energy Cyclotron Centre
VMAT	Volumetric Modulated Arc Therapy
VTS	Vertical Test Stand
VUV	Vacuum Ultra-Violet
XANES	X-ray Absorption Near Edge Structure
XFEL	X-ray Free Electron Laser
XFELO	X-ray Free Electron Laser Oscillator
XPCS	X-ray Photon Correlation Spectroscopy
XRD	X-ray Diffraction
ZING-P	Zero gradient synchrotron Intense Neutron Generator – Prototype

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PREFACE

For any scientific community, it is important to periodically take up the exercise of assessing the progress made, and then developing a clear vision for the future activities, in the light of existing and projected future needs and capabilities. In the area of Accelerator Science & Technology (S&T) and Applications, this is particularly important since it involves taking up large-size, high-cost and long-term projects that are based on ever-evolving advanced technologies, and also because many of these projects have important societal applications. Due to limitations in availability of resources, it is particularly important that we develop a prioritized vision. The last such vision exercise in the area of Nuclear and High Energy Physics was conducted in 2014, jointly by DAE and DST, where recommendations were made specifically for Accelerator S&T also. Notable progress has been made since then on all the recommendations - on the ongoing projects at that time; and also on the proposed future projects, by doing the base work for taking up those projects. In December 2020, the Office of the Principal Scientific Advisor (PSA) to the Government of India formed six working groups for preparing the Mega Science Vision (MSV) reports for the country in six areas, with Accelerator S&T and Applications being one of them. The mandate, in brief, was: (a) to report the state-of-the-art in the field, and make a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis for India in the time window of 2020–2035, (b) to enunciate the need for continuing, and also undertaking new Mega Science projects, (c) to examine the relevance of such Mega Science programs for India's scientific and technological goals, and (d) to suggest appropriate evaluation, funding and management structures for such programs. This report was prepared by the Drafting Group and the Working Group members, in consultation with various active scientists and engineers engaged in Accelerator R&D. A draft of this Report also underwent community-wide consultation exercise, followed by consultation with national and international experts, through which a large number of scientists and engineers also contributed to the preparation of the Report.

It may be in order, to first take a brief look at the historical perspective and current status of this field in India. In India, R&D on accelerators started in 1940, when development of a 38 inch cyclotron was taken up by the Saha Institute of Nuclear Physics (known as Institute of Nuclear Physics at that time) immediately after a series of cyclotrons were developed at Berkeley, USA during 1932-1939 for nuclear physics studies. After facing several challenges, the 38 inch cyclotron was successfully built in 1960 in Kolkata, and a 4 MeV proton beam was extracted. Interest in use of accelerators for performing useful research spread to several universities and institutes, where low-energy DC accelerators, mainly Cockcroft-Walton accelerator and Van-de-Graff accelerator, were set up for studies with neutrons and on interaction of charged particle with matter. In 1961, a 5.5 MeV Van de Graff accelerator was purchased and installed at BARC, Mumbai. All these accelerators were used fruitfully by the Indian scientific community; and looking at the future prospects of such accelerators in the country, AEC approved construction of a 224 cm diameter Azimuthally Varying Field (AVF) cyclotron at VECC, Kolkata. Regular operation of this cyclotron started in 1981; and the light ion, medium energy beams produced by this cyclotron are being extensively used since then for research in a variety of fields. This was a large-scale project at that time, and it generated a large number of trained human resource and PhDs in the area of Accelerator S&T. During the 1980s, a 4 MeV Standing Wave (SW) electron linac was developed by TIFR, Mumbai for radiography applications. Also, during that period, an 8 MeV race-track microtron was built and installed at Savitribai Phule Pune University. It is important to note that during this early period of induction of accelerators in India, accelerators were mainly used for research, and low-energy accelerators started penetrating into the universities also, where they were used for neutron generation and ion implantation. Initially, the thrust was not so much on societal applications, but later electron accelerators were procured for radiotherapy.

During the late 1980s and 1990s, a significant leap occurred in terms of growth of Accelerator R&D in India, when relatively large-size accelerator projects were undertaken at multiple R&D institutes and centres. A 14 MV Pelletron accelerator was procured and commissioned at TIFR complex in 1989, jointly by BARC and TIFR, which produced medium energy heavy ion beams for nuclear physics research. A similar machine with a terminal voltage of 15 MV was procured and commissioned at IUAC in 1991. Later, IUAC and BARC-TIFR worked independently to successfully develop superconducting booster linacs to further accelerate the beam from their pelletrons to higher energies. This was the first time that work was carried out on Superconducting Radiofrequency (SRF) accelerator technology in India, and it generated trained human resource and knowhow in this field in the country. On the front of electron accelerators, a project for development of two Synchrotron Radiation Sources (SRS) – Indus-1 and Indus-2 - was taken up at RRCAT, Indore, in the late 1980s. Indus-1, which is a 450 MeV machine, became operational in 1999, and Indus-2, which is a 2.5 GeV machine, became operational in 2010. Both these accelerators are operated in round-the-clock mode, and provide intense x-ray beam for conducting state-of-the-art materials science research, and also for important industrial and engineering applications. All these accelerators at TIFR, IUAC and RRCAT are operated as user facilities. For Indus-1 and Indus-2, a 20 MeV injector microtron was developed indigenously, and a similar microtron was developed and given to Mangalore University by RRCAT, which still continues to serve as a workhorse there for conducting irradiation experiments for materials science research. A project was undertaken at BARC during the 1990s, to convert the then existing Van-de-Graff accelerator to a Folded Tandem Ion Accelerator (FOTIA), to increase the beam energy. FOTIA was completed and commissioned in 2000, and since then it is being used for nuclear physics experiments. During the late 1990s, a project on development of superconducting cyclotron was taken up at VECC, to accelerate heavier nuclei to higher energies, compared to the existing room temperature cyclotron. The superconducting cyclotron is now operational. Also, during this period, initial R&D on development of Rare Isotope Beam (RIB) accelerator was started at VECC with a long-term plan for developing a full-fledged RIB facility. Over the last two decades, notable progress has been made in the development of initial section of the accelerator and demonstration of low energy RIBs and materials science research using RIBs. During this period, useful international collaborations were forged between DAE and CERN, through which Indian scientists and engineers contributed towards the development of LHC and Linac-4 projects at CERN.

During the first two decades of this century, accelerator R&D in the country got a further boost by taking up projects on advanced accelerators such as IR Free-Electron Laser (FEL) at RRCAT, and Low Energy High Intensity Proton Accelerator (LEHIPA) at BARC, both of which are now operational. At IUAC, work is in advanced stage towards developing a High Current Injector (HCI) for the superconducting booster linac, to further increase the beam current; and also on developing a compact terahertz FEL, utilizing the advanced photocathode electron gun technology. At SINP, a project on setting up of a Facility for Research in Nuclear Astrophysics (FRENA), that utilises 3 MV Tandetron and 500 kV single-ended high current accelerator, has been successfully completed recently. Significant progress was made during the last two decades on developing accelerators for societal applications. Electron accelerators have been developed for industrial applications at BARC and RRCAT, and are being used for their intended applications. At IUAC, a dedicated accelerator facility has been set up for Accelerator Mass Spectroscopy, which has useful applications in the area of geochronology and archaeology. A 16.5 MeV medical cyclotron was set up at RMC, BARC in 2002, and later a 30 MeV medical cyclotron was set up at VECC in 2018, for production of medical isotopes for imaging applications. Electron linacs have been developed at SAMEER, which are installed in various hospitals for radiotherapy applications. Proton cyclotrons have been procured by few hospitals in the country for cancer therapy. RRCAT embarked on a new and promising area of Accelerator R&D on novel acceleration schemes, namely laser plasma acceleration, which is expected to make the future accelerators significantly compact. An R&D project was taken up to demonstrate acceleration of electrons and protons to high energies over a very short length, which has been successfully completed. In addition to all this, R&D activities started at RRCAT, BARC, VECC and IUAC to develop the required expertise in the area of SRF technology and other enabling technologies, in order to be ready to take up the projects on High Intensity Superconducting Proton Accelerator (HISPA) for developing Spallation Neutron Source (SNS) for state-of-the-art research on condensed matter systems and engineering applications, and also for developing Accelerator Driven System for production of nuclear energy. Collaboration has been established between Indian Institutions and Fermilab to work together on the R&D phase of HISPA for the PIP-II project at Fermilab. Indian institutions are also making important contributions towards developing accelerator components for the FAIR project in Germany as part of an international collaboration. For development of superconducting linac for RIB, VECC has collaboration with TRIUMF, Canada.

While working on a number of domestic projects, and also contributing to international projects over the last few decades, which has been described in the above paragraphs, good capability has been developed in the country in some of the areas of this field. Accelerators are primarily built for targeted user applications. Keeping in mind the existing capabilities in Accelerator S&T in the country, and the future demands of state-of-the-art accelerators for various important applications, this MSV-2035-Accelerator S&T and Applications Report presents a vision for the future course of developments that should be supported in the country. Six areas of Accelerator R&D have been identified, and in each area, we have prepared a prioritised list of projects that should be supported. In order to support these projects, an increase in funding compared to the previous decades will be needed. It is the considered view of the national Accelerator R&D community that this increased funding support is justified since this field has now picked up reasonable momentum in India, and it will be prudent to provide the necessary financial resources so that these modern advancements can be effectively leveraged for national development.

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EXECUTIVE SUMMARY

Particle accelerators are machines that are used to accelerate charged particles like electrons, protons and ions to higher energies. Ever since coming into existence in the early twentieth century, these machines have been rapidly evolving with the advancement of technology. Early particle accelerators were developed mostly for unravelling the mysteries of nuclear and particle physics. It was, however, soon realised that they have a large number of useful applications in a variety of areas, including materials research, healthcare, industry, national security and space science. Although the largest and most expensive particle accelerators are still built for particle physics applications, most accelerators are nowadays built for commercial, industrial and medical applications.

During the last few decades, rapid progress has been made in our country in each area of Accelerator S&T by building our own accelerators for a wide variety of applications, as well as by contributing to various large-scale accelerator projects worldwide for particle physics applications. We have reached a stage, where large-scale projects in Accelerator S&T can now be taken up in the country for important and useful applications. In this vision document, we bring forward the important applications for which future accelerators should be built in the country, along with discussions of national status vs. state-of-the-art in this field, followed by recommendations for the future mega science projects. A summary of these discussions and recommendations is presented below.

❖ IMPORTANT ACCELERATOR APPLICATIONS OF INTEREST

Some of the important applications of interest, for which accelerators should be built in the country, are:

- To study nuclear reactions and spectroscopy, extending the ongoing research in these areas for heavier ions and higher energies, using *high energy, heavy ion superconducting accelerator* and *cyclotron*. To create and study rare isotope nuclei, using *Rare Isotope Beam (RIB) accelerator*. Nuclear Astrophysics and Accelerator Mass Spectrometry (for geochronology and archaeology), using *low energy high current ion accelerator*.
- To study soft matter systems and materials with atomic and sub-atomic spatial and temporal resolution, using *High Brilliance Synchrotron Radiation Source (HBSRS), X-ray Free Electron Laser (XFEL)* and *Spallation Neutron Source (SNS)*. This has high-impact application in healthcare, industry, energy storage and harvesting, quantum information technology, quantum materials and devices *etc*.
- To produce medical isotopes for imaging/targeted therapy, using *cyclotrons* and other accelerators. Cancer therapy, using *electron accelerators*, and *proton/ion accelerators*.
- To irradiate medical, industrial and food products for enhanced safety and quality. Water purification, waste treatment, cargo scanning, radiography, *etc.*, using *electron accelerators*. Ion implantation, material modification, using tabletop Penning Ion Generators (PIGs).
- Nuclear power generation by utilising vast reserve of thorium in the country, and incineration of nuclear waste through Accelerator Driven System (ADS), based on *high-energy, high-power, superconducting proton accelerator*.
- To know the spectral response of payloads, to test their electronics in radiation environment and for Non-destructive Testing (NDT) of components and materials for space missions, using *SRS and electron/proton accelerators*.

❖ STATE-OF-THE-ART IN ACCELERATOR S&T

Having identified the particular areas of accelerator applications that should be pursued in the country, a brief summary of international status of Accelerator R&D in these areas is described next:

- State-of-the-art in SRSs is the HBSRS with electron beam energy typically in 3 – 6 GeV range, which utilizes Multi-Bend Achromat (MBA) lattice with insertion devices to achieve electron beam emittance less than the radiation wavelength, typically as low as 40 – 200 pm-rad, to generate a brightness of ~ 10^{22} photons/s/mm^2/mrad^2/0.1% bandwidth, or higher, for emitted x-ray.
- State-of-the-art in FELs is (i) high average power terahertz/infrared FEL, and (ii) short (femtosecond) pulse, high brightness XFEL, based on few GeV normal/superconducting linac, and having photon wavelength as low as 0.5 Å, with peak brightness of ~ 10^{33} photons/s/mm^2/mrad^2/0.1% bandwidth with a repetition rate as high as ~ 100 MHz.
- State-of-the-art SNS is based on MW-class, pulsed proton accelerator. The accelerator consists of a full energy (~ GeV) superconducting injector H^- linac, followed by a proton accumulator ring; or a relatively low energy (~ few hundred MeV) normal conducting H^- linac, followed by a rapid cycling synchrotron that accelerates the beam to few GeV. Neutrons are emitted in short (~ 100 μs) pulses that enable Time of Flight (ToF) experiments, and typical neutron flux is 10^{16} n/cm^2/s. In Europe, a European Spallation Source (ESS), based on 2 GeV, 5 MW linac (without accumulator ring) is in advance stage of development, which will give a neutron flux of ~ 10^{18} n/cm^2/s.
- For high energy, heavy ion accelerator for nuclear physics research, the state-of-the-art is to go to high current (1 μpA[1]), and compact accelerator. Majority of the machines, such as the one at GSI, Germany are now using an Electron Cyclotron Resonance (ECR) source followed by a Radio Frequency Quadrupole (RFQ) and a Drift Tube Linac (DTL) or superconducting cavities for very low velocity ions as the alternate injector to main linac.
- Cyclotron is one of the oldest accelerators, which still remains attractive as a compact accelerator, especially after the advent of superconducting cyclotron. Due to its compactness, it is attractive for medical applications. A State-of-the-art cyclotron can produce energy up to ~ 200 MeV/A[2], or even higher, which makes it attractive for nuclear physics studies, especially for RIB facility.
- Industrial accelerator programs have been strongly supported in many countries by publicly-funded R&D institutions, and have reached a level, where rugged accelerators are commercially available. Typically, 10 MeV, RF electron linacs with beam power up to few tens of kW are commercially available. Especially designed RF electron linacs with fast tuning of beam energy for cargo scanning and radiography are also commercially available. Electron accelerators with beam energy ~1 MeV and beam power ~ few 100 kW have been developed in several countries for treatment of flue gases (SO_x and NO_x) and for wastewater treatment. For ion implantation applications, low and medium energy accelerators ($\leq$ 400 keV) with modest current (up to 500 μA) are available commercially.
- For medical isotopes, 3-70 MeV, light ion cyclotrons with beam intensity of several hundreds of μA are commercially available. Some of the laboratories utilize the spare beam time of injector H^-/H^+ linacs with beam energy ~ 200 MeV for isotope production; and there are dedicated electron linacs with energy ~ 40 MeV and few tens of kW beam power for medical isotope production. For cancer therapy, 70-230 MeV proton cyclotrons, and even 400 MeV/A carbon therapy synchrotrons are commercially available. Current trend in particle therapy is integration of imaging devices (including MRI) for image-guided radiation therapy and new dose delivery techniques (like FLASH).
- Several countries are strongly pursuing the program to develop CW superconducting proton accelerator, with typical energy of ~ GeV and beam power of few tens of MW, to be coupled to sub-critical nuclear reactor, to make ADS for power production.
- R&D on novel acceleration schemes, such as Laser Plasma Acceleration (LPA), which is expected to shrink the ever-expanding size of particle accelerators in future (due to large acceleration gradient of ~GV/cm in plasma), is very strongly pursued by several countries. Using PW Ti:Sapphire lasers, generation of 8 GeV electron beams in a plasma length of 20

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[1] μpA stands for micro particle Ampere.
[2] MeV/A stands for MeV per nucleon. Here, A is the mass number, which is the total number of protons and neutrons in the nucleus of the ion.

cm, and acceleration of protons to >70 MeV energy in few microns of solid target plasma has been achieved.

❖ RECOMMENDATIONS ON MEGA SCIENCE PROJECTS (MSPs)

Based on the recommended accelerator applications for which accelerator development should be pursued, followed by an assessment of national status vs. international status of development of such accelerators, after detailed deliberations, we make the following prioritized recommendations of MSPs and Programmes in six identified application areas. Prioritization has been done after due deliberation, including factors such as, demand of the user community and expected benefits, impact on the national development, technological preparedness to undertake the project, project cost *etc.*

A. Accelerators for Photon Science Applications

Currently at RRCAT, there are two SRSs that routinely provide photon beams to users – one is the 450 MeV Indus-1, which is a VUV source with critical wavelength 61 Å, and the other one is the 2.5 GeV Indus-2, which is a soft x-ray source with critical wavelength 2 Å. For Indus-2, the beam emittance is 45 nm-rad and brightness is up to 10^{17} photons/s/mm^2/mrad^2/0.1% bandwidth. With the growth of the SRS user community in India, and due to the need to pursue high-end useful applications in this field, it is recommended to go for the next-generation HBSRS, for which preparatory exercise has been going on at RRCAT for a few years.

There is a tunable IR FEL at RRCAT, operating in the wavelength range 12.5 – 50 μm, with an average power of > 30 mW. Development of a compact THz FEL is in advanced stageat IUAC, New Delhi. With the experience gained on the S&T of FELs, it is time that preparations should be started for a future XFEL in the country.

With this background, we recommend the following MSPs:

1. Hybrid Multi Bend Achromat (HMBA) lattice-based fourth-generation HBSRS with beam emittance $\leq$ 150 pm-rad, and peak photon brightness > 10^{21} photons/s/mm^2/mrad^2/0.1% BW.
2. VUV/Soft X-ray FEL with peak brightness ~ 10^{30} photons/s/mm^2/mrad^2/0.1% BW, pulse width ~few 10's fs, rep. rate ~ few Hz, with a possibility of upgrade to hard X-ray.

B. Accelerators for Neutron Science Applications

High-current superconducting proton accelerators can produce copious flux of neutrons through spallation reaction, when they strike a suitable target. Accelerator-based pulsed spallation neutron sources are complementary to synchrotron radiation sources, and have been developed worldwide over the last several decades. There is no such source in India. Another application that makes use of controlled production of copious neutrons is ADS, which typically needs GeV proton accelerator with beam power ~ few tens of MW. Such an accelerator *does not* exist in the world, but few countries are working on it. In India, some experience has been gained on development of superconducting proton linac, through the ongoing collaboration with Fermilab for development of PIP-II accelerator. Backed with this experience, where Indian institutions have successfully demonstrated their strength to develop many of the critical components, we recommend the following two MSPs:

1. 200 MeV, 10 mA CW superconducting proton linac, as the first phase of ADS.
2. 1 GeV, 10 mA pulsed superconducting linac and accumulator ring for a spallation research facility

C. Accelerators for Industrial Applications

Industrial electron accelerators are needed for a wide variety of applications, and they have a huge commercial market. BARC, RRCAT and SAMEER have prior experience in this area, and have already built some of the industrial accelerators that are in use. It is recommended that R&D should be strengthened towards production of rugged, field-deployable industrial accelerators. Tabletop ion sources have lot of applications with great market demand, and R&D should be done to develop them. Similarly, applications like electron beam welding machine and electron microscope are also important, and R&D should be pursued for developing such machines. After detailed deliberations, we recommend the following projects:

1. Field-deployable 7.5/10 MeV, 10 kW and 7.5/10 MeV, 30 kW industrial electron LINACs
2. Field-deployable multi-energy, say, 3-6 MeV, tens of kW electron LINACs for X-ray radiography as well as neutron radiography, cargo scanning *etc.*
3. Low-energy (1 MeV), high average power (several 100s of kW) electron accelerators for flue gas treatment and wastewater treatment.
4. Low-energy (5-70 keV), moderate to high current (≥ 500 of μA), cost-effective, tabletop PIG ion sources for ion implantation in semiconductor industry, making portable neutron generators, and R&D on generating green hydrogen via water splitting, *etc*.

D. Accelerators for Medical Applications

Currently, there are more than 20 imported medical cyclotrons in the country that are used for producing medical isotopes. VECC, Kolkata is working on developing an indigenous 18 MeV, 50 μA H^- cyclotron for medical isotope production. For radiotherapy, electron linacs have been developed by SAMEER, Mumbai, which are used in hospitals. A large number of such machines are however still imported in the country. Based on the existing experience on cyclotron for isotope production and electron linac for radiotherapy, it is recommended that more such machines, with advanced features, should be developed in the country. Few proton cyclotrons have been imported in the country for cancer therapy. With the existing experience in the country on cyclotrons and synchrotrons, a strong R&D program should be initiated, to develop such machines with priority. We therefore recommend the following MSPs:

1. 10-70 MeV H^- cyclotron with beam current ~ 0.1 – 1 mA for medical isotope production
2. Electron Linac for Intensity Modulated RadioTherapy (IMRT) applications
3. 6 MeV X-band medical linac for Cyberknife/Radiotherapy applications
4. 70-230 MeV proton accelerator and 400 MeV/A carbon ion accelerator for therapy

E. Accelerators for Nuclear Physics Applications

For the nuclear physics community in the country, currently there are three large accelerators – two medium energy, heavy ion accelerators with superconducting booster linacs - one at TIFR, Mumbai and the other at IUAC, New Delhi; and a room temperature cyclotron at VECC. The new superconducting cyclotron at VECC is also available to users. There is a low energy, high current accelerator named FRENA at SINP, Kolkata for nuclear astrophysics studies. In addition, there are several small accelerators in universities and other institutes/centres for nuclear/atomic physics and materials science studies. Due to ever-growing number of users, we recommend that a new heavy ion accelerator be built with higher current and higher energy for heavier ions. The RIB accelerator program, for which ground-work has already been done, should be strengthened and a full-fledged project should be undertaken. We therefore recommend two MSPs:

1. Radioactive Ion Beam (RIB) Accelerator with beam energy up to 100 MeV/A, and upgrade of existing heavy ion accelerators.
2. Future heavy ion accelerator with beam energy around 10-20 MeV/A, *i.e.*, beyond Coulomb barrier, covering a wide range of heavy ions, with beam current up to few hundreds of pnA.

F. R&D on Laser Plasma Accelerator and Applications

Laser Plasma Accelerator (LPA) has lot of potential since they can shrink the size of future accelerators. In addition, it is also seen as a compact source of ultra-short x-ray/γ-ray pulse. It is, therefore, timely that we vigorously pursue this area of R&D. RRCAT has made good progress in this area in the last decade. It is therefore recommended to take up the following projects:

1. Basic R&D on LPA and its applications
2. LPA based electron accelerator with energy ~ GeV, and proton/ion accelerator with energy ~ 30-70 MeV; and R&D on LPA based intense ultra-short (femtosecond) X-ray/γ-ray source.

For execution of each of the projects, the gap between the existing and required level of technology has been broadly identified in the document, and the gap needs to be closed during R&D phase of the project. Special emphasis needs to be given to R&D activities to ensure the availability of materials like high purity niobium, high purity copper, high quality permanent magnets that are needed for various accelerator projects. In order to achieve self-reliance, emphasis also needs to be given to indigenous development of crucial component required for accelerators, for which we are currently dependent on imports.

❖ RECOMMENDATIONS ON THE FUNDING AND PHASED DEVELOPMENT OF MSPs, AND HRD ASPECTS

Most of the future accelerator projects discussed in this document can be broadly divided into two categories – (i) projects that are much larger in size and cost compared to past projects, and (ii) projects that aim towards development of a large number of accelerators for societal applications. Taking up of such large-scale projects requires a paradigm shift in the funding and execution methodology, and project management, which has been highlighted in the document. In particular, in these projects, local industry will have a much bigger role compared to what they had in the past projects. The industry, therefore, needs to be strengthened so that the development work can be taken up under Private Public Partnership (PPP). We recommend a strong drive to be undertaken for this, treating industry as our partner, and in many case, also as user of our projects. Also, we strongly recommend that administrative and procurement procedures need to be reviewed and reformulated, if necessary, for speedy progress in large projects. MSPs require a large pool of trained human resource, and such projects will also be multi-institutional, across various government departments. More importantly, they need to be taken up, funded and executed in a phased manner, for which suitable mechanisms for funding and monitoring needs to be evolved. In this context, we recommend the following:

- For each MSP, a conceptual plan, along with Conceptual Design Report (CDR) should be prepared with identification of a lead institute. The MSP should be divided into three phases – (i) R&D phase, (ii) construction phase and (iii) commissioning phase.
- A centralized project submission forum should be created, which could be a cell in the Office of PSA, or a dedicated mega science forum at a national level. Each MSP's technical approval should be given by a high-level apex committee, comprising of heads of funding agencies, scientific experts and financial authorities.
- A Standing Review Committee (SRC) should be formed for approved MSPs, for periodic review and scientific approval for continuing the funding. Before giving the approval for the construction phase, SRC should ensure that the R&D phase is successfully completed, and Reference Design Report (RDR) is completed, along with production-ready design for all critical components.

On the front of training human resources, an Indian Particle Accelerator School, along the lines of US Particle Accelerator School could be started, targeted specifically towards the planned MSPs. Creation of job opportunities with increased industry participation should be explored.

We would like to emphasize that in this document, we have come up with a prioritised list of projects that should be taken up in each of the application areas of Accelerator S&T, and given tentative details of timeline, along with budgetary and human resource requirements. We believe that for each MSP and Programme, the relevant groups in the community will prepare a detailed proposal, after due deliberations, where more concrete details will be provided.

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1. Particle Accelerators: An Introduction

In this chapter, a general introduction to particle accelerators and its constituent subsystems and components has been given.

1.1 Accelerator Basics

Accelerators are devices that increase the energy of charged particles. They can be classified on the basis of the nature of particles being accelerated: electron, proton and ion accelerators. They can also be classified on the basis of the topology of the accelerator itself: linear and circular accelerators. Finally, they can also be classified on the basis of the principle of acceleration: DC and RF accelerators[3].

These classifications gain significance because the science and technology of accelerators depend on, and vary with, the nature of the accelerator under consideration, *e.g.*, linear DC proton accelerator, or circular RF electron accelerator, or linear RF ion accelerator. These differences arise from three fundamental physics facts:

(1) DC electric fields are conservative, which means that one cannot accelerate particles repeatedly in these fields (therefore circular DC accelerators do not exist);

(2) heavier particles are more difficult to accelerate to relativistic energies than lighter ones (*e.g.*, electrons become relativistic at a kinetic energy of around 0.5 MeV, while protons become relativistic at an energy of around 1 GeV);

(3) light particles that are accelerated in a circle emit energy as synchrotron radiation (SR) much more copiously than heavy particles (*e.g.*, at any given energy, an electron will emit 10 trillion (1×10^{13}) times as much SR as a proton).

Figure 1.1.1 schematically shows different types of possible configurations of an accelerator. The first statement above limits DC accelerators (electron or proton) to energies of few tens of MeV, because of the maximum electric field that can be sustained; the second makes linear RF proton and ion accelerators considerably more complex than linear RF electron accelerators, because of the constantly changing (non-relativistic) speed of the particles; the third practically limits circular RF electron accelerators to energies of a few hundred GeV, because beyond this limit, a very large fraction of the particle's energy is lost as SR.

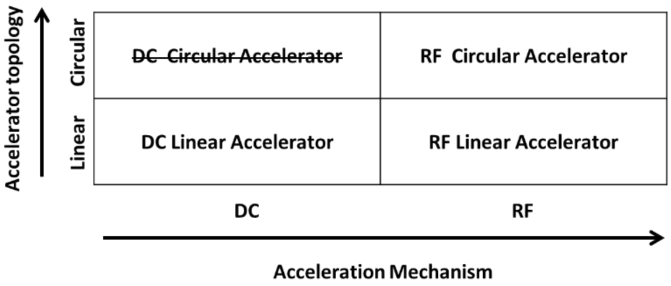

Fig. 1.1.1: A schematic showing different possible configurations of an accelerator.

Charged particles in circular accelerators need to be bent in a circle, and this is achieved using a constant magnetic field – a dipole field. Charged particles in all accelerators need to be kept focused as they traverse through the accelerator. This is typically achieved using focusing magnets. Thus, the design of magnets is an important aspect of accelerator technology.

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[3] In addition to DC and RF accelerators, there exists plasma accelerator, as discussed later in the document.

Of course, accelerators do not accelerate single particles, but a set or *bunch* of charged particles. Since a moving charge constitutes a current, the intensity of a particle beam is measured in terms of its current. For ion accelerators with higher charge state, intensity of particle beam is often quoted in terms of number of particles crossing per unit time, *e.g.*, typically in units of particle nanoampere (pnA). When the beam current (or intensity) is high, the mutual Coulomb repulsion between the particles in the beam can significantly affect the motion or dynamics of the particles. Clearly, this is bigger issue for non-relativistic speeds, which means that this is typically an issue for electrons only up to a few tens of MeV, but for protons it can be an issue up to many GeV. Since this Coulomb force, or *space-charge force*, may become highly nonlinear, it can and does lead to nonlinear dynamics of the particles, including chaotic motion that can result in loss of beam from the accelerator. This is an important area of research in accelerators.

In the next section of this chapter, we give a brief introduction to the various sub-systems and components of an accelerator.

1.2 Accelerator Subsystems and Components

Particle Source:

The first element in any accelerator is the source of the charged particles that are to be accelerated: an electron source or a proton source or an ion source. Electrons and protons are relatively easier to produce: electrons can be produced just by heating a filament, or by shining a laser on a metallic or semiconductor photocathode, and protons by ionizing hydrogen gas or electrolyzing water. For ions, the source needs to be a material that contains the particular element (say carbon) ion that needs to be accelerated. An added complication is that there may be different isotopes of that element, and, for a given isotope, there may be different charge states that one is interested in. Additionally, the ions desired may be positive or negative. The ion source has to cater to all these requirements. Some accelerators accelerate anti-particles, such as positrons and antiprotons. Positrons are naturally produced during β^+ decay, and typically in accelerators, they are produced when γ-photons (produced by bremsstrahlung) decay into e-e^+ pairs in a target. Antiprotons are produced by proton beams bombarding a proton-rich target.

The particle source should also be able to produce particles with the required current (intensity). In addition, physics considerations also impose requirements on the quality of the particle beam, in terms of the size and divergence of the beam, or more specifically their product (called the *emittance*, which is just the area occupied by the beam in phase space): this requirement on the emittance has to be met by the particle source for most accelerators.

For several research applications, one needs to produce polarized beams of electrons, protons and ions. Specific techniques are needed in each case to produce a particular species of polarized beams.

Accelerating RF cavity:

The heart of a radiofrequency (RF) accelerator is the RF cavity, in which the particles are actually accelerated. The RF cavity is essentially a resonator, which contains electromagnetic waves (similar in principle to a microwave oven). Particles entering this resonator or RF cavity pick up energy from the electromagnetic wave and are hence accelerated. Many RF cavities will be needed to accelerate particles to the required energy, if that energy is greater than a few MeV. The electromagnetic design of the RF cavity depends on the type of particle being accelerated and its speed when it reaches the particular cavity. In addition, technologically, the cavity can either be made out of a high-conductivity metal like copper, and run at room temperature, or it can be made out of niobium and run at 4K or even lower temperatures (using liquid helium to cool the cavity). The advantage of the latter is that niobium becomes superconducting (SC) at 4K, and therefore there is only a minimal heat loss[4] on the surface of the cavity. This is an important advantage in many cases, *e.g.*, when one wants to operate at higher acceleration gradients, and especially, when one wants to operate accelerators at high duty-cycles. Therefore, many future accelerators are being designed to be SC. Overall, there are significant challenges in the science and technology of RF cavities, and a lot of research and effort are devoted to designing and building them.

RF system:

The electromagnetic waves that fill the RF cavities have to be produced using RF sources. These RF sources actually incorporate RF amplifiers, which can vary enormously, depending on the frequency of the waves, their power level, the desired stability of the source, and other factors such as size and cost. Typically, very high-power sources (of hundreds of kW and more) are based on klystrons, magnetrons, travelling-wave tubes, tetrodes, Inductive Output Tubes (IOTs) *etc.* With recent advances in solid-state devices like high power transistors and MOSFETS, the solid-state RF sources are competing with the tubes from several hundreds of kW of output power up to MW in various frequency bands. The solid-state RF amplifiers have additional advantages of higher reliability, longer life and elimination of high voltage power supplies. These amplifiers need a seed RF signal to amplify, which is given from an RF generator. In addition, it is typically necessary to condition these RF signals, such as to control and vary their amplitude and phase in specific ways related to the coupling of the RF power to the RF cavity, and this is achieved using a Low-Level RF (LLRF) system.

Magnets and magnet power supplies

Circular particle accelerators use dipole magnets to bend the particle beam around the accelerator, and all accelerators use quadrupole magnets[5] to focus them. However, all magnets necessarily have fringe fields (to satisfy Maxwell's equations). These fringe fields contain higher-order multipoles (beyond the dipole and quadrupole) that are non-linear[6] and can have a deleterious effect on the dynamics of the beam in the accelerator. Therefore, in design and construction of all magnets, particularly in the large dipole magnets used to bend the beam, great effort has to be made to ensure that the contribution of the higher-order multipoles is within the limit specified by the beam dynamics analysis. Electromagnets are more commonly used, but due to several advantages, permanent magnets are also used in several cases. In addition, magnets can also be constructed to be SC, the advantage here being that SC magnets can produce much higher magnetic fields, allowing tighter bends and therefore compact (circular) accelerators. One also needs specialised, output-current-controlled, high-stability power supplies of various types (*e.g.,* DC or slow-ramped, fast-ramped, *etc.*) to energize and operate various magnets such as dipole, quadrupole, *etc.*, with

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[4] Although there is no heat loss in a superconductor in case of DC, there is a small, but finite heat loss even in a superconductor, in case of RF. This necessitates a cryo-plant with adequate capacity for a SC accelerator.

[5] In addition to quadrupoles, other focusing elements such as solenoid magnets, Einzel lenses, dipole magnets *etc*. are also sometimes used to provide the necessary focusing.

[6] Quite often, nonlinear magnets such as sextupoles and octupoles, which have inherent nonlinearity, are used in an accelerator to take care of specific beam dynamics issues, and it needs to be ensured that ill effects of nonlinearity are within acceptable limits.

stringent requirement on output current stability (few 10s to few 100s of ppm) in case of DC or slow-ramped power supplies and tight tracking accuracies in case of fast-ramped power supplies. Pulsed power supplies providing current pulses of very large amplitude (in kA) with very stringent amplitude stability and time jitter requirements are used for pulsed magnets.

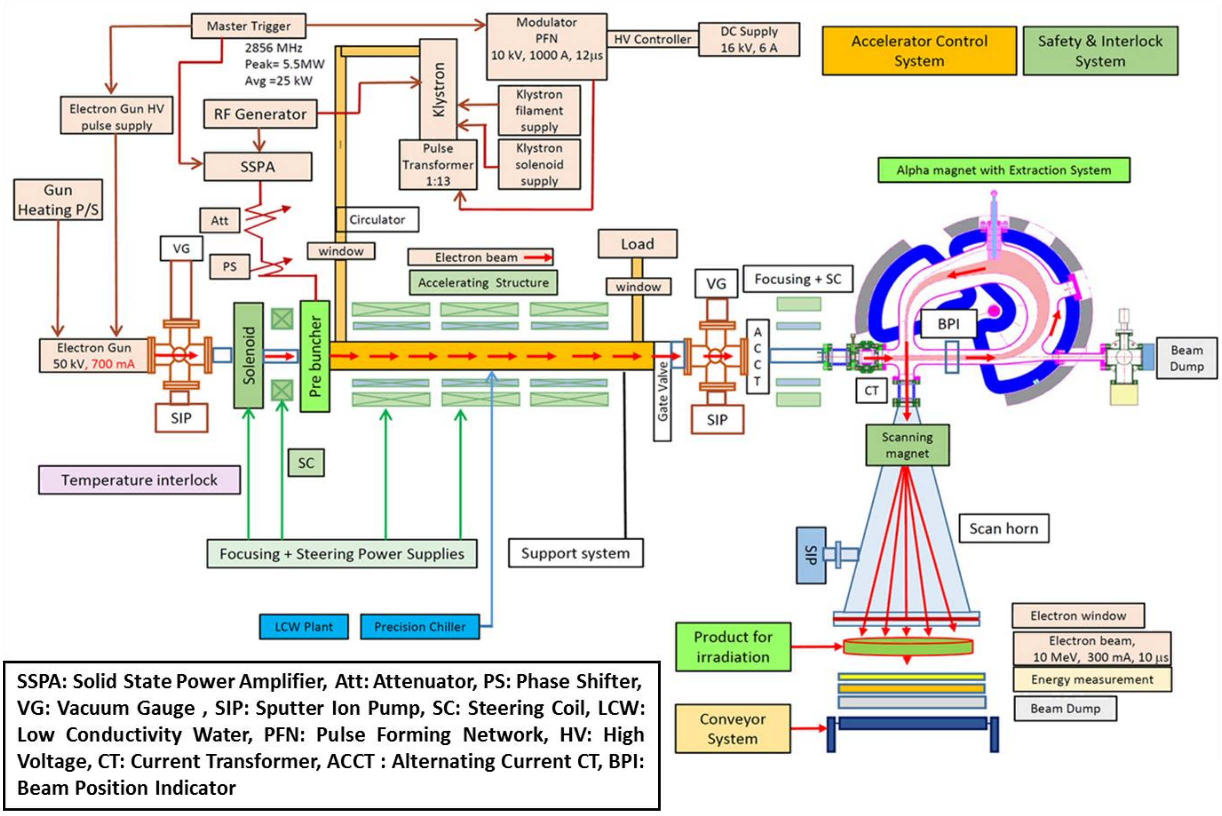

Fig. 1.2.1: Block diagram showing various sub-systems and components of an industrial RF linac developed at RRCAT.

Beam instrumentation and diagnostics:

Since the charged particles being accelerated are microscopic and invisible, it is essential to have diagnostic instruments that can probe the properties of the beam so that one is kept informed of how the beam is evolving in the accelerator. Beam properties that need to be measured include its energy, current, position, size, structure, emittance, *etc*. Specific beam diagnostics instruments have to be designed and developed to make these measurements. These instruments also involve substantial electronics, some of which must be very fast, in the pico second or even femto second time scale. It is worth mentioning that in modern times, with the use of polarized beams, polarization is also an important beam property that is measured, for which one requires a polarimeter.

Cryogenic Infrastructure:

If superconducting RF (SRF) cavities or magnets are being used, then one must have a *cryogenic system* that produces the cryogen (liquid helium), transports it to the SC element, and recovers it back in case of helium. For a high average power SRF accelerator, large scale 2 K system is needed. Cryoplant is often one of the most expensive components of a SRF accelerator complex. More recently, Nb_3Sn-based SRF cavities have been proposed, which can be cooled by even commercial cryocoolers.

Other systems:

Charged particles cannot be accelerated in air because they would scatter from the air molecules and get dispersed. Therefore, particle beams in accelerators are always accelerated and transported in evacuated chambers, where ultra-high vacuum of the order of 10^{-9} to 10^{-7} mbar is maintained. The *vacuum system* that maintains and monitors this vacuum is a crucial part of any accelerator. If, due to mal-operation of the RF system, vacuum system, magnets, *etc*., the beam is not controlled, it can hit the vacuum chamber, causing production of harmful radiation such as gamma rays, neutrons, *etc*. It is therefore essential to have a robust *control and interlock system* that controls all the elements in the accelerator, and also shuts off the beam automatically in case of malfunction of any element. This requires extensive and often fast electronics. If the elements are at room temperature, then one often needs a *low conductivity water system* to cool these elements. Finally, in order to ensure radiation safety, one needs an extensive *radiation monitoring system* that monitors the radiation not only in the accelerator vault, where in any case personnel access is denied while the accelerator is being operated, but also in the areas outside, which are expected to be occupied, to ensure that all persons and areas in the vicinity of the accelerator are safe from radiation. Beam Loss Monitors also help in minimizing beam losses, to improve the radiation safety. For cryogenic accelerator, Oxygen Deficiency Hazard (ODH) system is typically required. *Access control system* is also an important system to provide safe access to accelerator tunnels. It is important to note that for safety considerations, approval from the regulatory authority is required before the construction of an accelerator vault where the accelerator is planned to be installed, and also before each stage of operation of an accelerator.

Figure 1.2.1 shows a block diagram of a typical accelerator, in this case the industrial RF electron linac developed at RRCAT, to illustrate various sub-systems and components that we have described in this sub-section.

Accelerators are often used to produce intense beams of photons, as in Synchrotron Radiation Sources (SRSs) and Free Electron Lasers (FELs), and also intense beams of neutrons, as in a Spallation Neutron Source (SNS). In an SRS, photon beam is produced through synchrotron radiation by passing an energetic (~ GeV) electron beam in a storage ring through bending magnets, where they have a circular trajectory, and through undulators/wigglers, where they have a sinusoidal trajectory. In an FEL, a still brighter photon beam is produced through beam-wave interaction by passing an energetic electron beam through undulator. Neutron beam is produced in an SNS by striking an energetic proton beam on a target with high atomic number, through the spallation process. Dedicated beamlines are needed to carefully transport the photon/neutron beam to the target or experimental station. Design and development of various beamline elements and the complete beamline are also an important part of the development of the accelerator.

In the next chapter, we discuss the important and relevant application of particle accelerators, which make them an indispensable tool for basic science, as well as societal applications.

2. Accelerators Applications: Relevance in the Indian Context

Particle accelerators have an important role to play in national development. They are no more seen as merely the tools to do curiosity-driven research. Research in areas such as nuclear physics, condensed matter science, materials science and biological science enhance our understanding of important natural phenomena, which are often put to use for industrial and medical applications. Particle accelerators are often built for direct industrial, medical and security applications. In the field of atomic energy, there has been worldwide interest in using particle accelerators for harnessing energy by way of driving a nuclear reactor by means of neutrons, which are produced when the beam from proton accelerator hits a dedicated target in the reactor. In this chapter, we identify the unique role of particle accelerators in several important applications, particularly in the Indian context.

2.1 Nuclear Physics Applications

Particle accelerators are important tools to investigate the structure, properties and interactions of nuclei and nuclear matter, some of which lie at the core of a wide range of applications of nuclear physics in area such as energy production, medicine, national security, *etc*. Low energy nuclear physics deals with studies on structure and stability of nuclei, and nuclear reactions; and high energy nuclear physics deals with studies on behaviour of nuclear matter. Accelerator requirement is different for low and high energy nuclear physics.

Low Energy Nuclear Physics Applications

Van-de-Graff, Pelletron, Cyclotron and Heavy ion linac are used for studies on nuclear structure, nuclear spectroscopy, nuclear fission, nuclear fusion and other nuclear reactions, which have been of interest to the Indian nuclear physics community. Typical requirement from the accelerator is to get a beam of light as well as heavy ion, stable as well as unstable ion, with energy in the range of few MeV/A to as high as 100 MeV/A, and beam current in the range of few pnA to as high as few pμA. The trend is to push towards heavier ions that can be accelerated, and to increase the beam energy and beam current. Two areas, which are pursued worldwide, and where Indian nuclear physics community also has interest, for which the development of accelerators should be continued, are:

Generation and investigation of unstable nuclei, using heavy ion beam above Coulomb barrier energy, to cover a broader region of nuclei

In order to have a better understanding of the fundamental nuclear interaction, facilities have been created to generate unstable nuclei, also known as rare isotopes, and investigate them. Such rare isotopes are generated in Rare Isotope Beam (RIB) accelerators [Chakrabarti 2021]. There are two ways to produce RIBs – (i) Projectile Fragmentation (PF) method, where primary, energetic heavy ion beams of projectiles are fragmented into a variety of isotopes while passing through thin targets, and rare-isotopes of interest are selected in-flight with an isotope separator, and (ii) Isotope Separation On-Line (ISOL) method, where a primary beam hits a thick target, and the target undergoes fragmentation and fission, after which the rare isotopes are separated online, when they are made to pass through the downstream accelerator. PF method is well developed, and suitable for short lived radioisotopes. The beam power and the number of fissions per second are good metrics for comparing the PF type and ISOL type facilities. Primary goal of an RIB facility is to create a variety of RIBs , and study the limits of nuclear stability. Facility for Rare Isotope Beams (FRIB) at MSU, USA is a large RIB related user facility, which has been recently commissioned [Ostroumov 2024]. Such an RIB accelerator is of interest to the Indian nuclear physics community, to strengthen and widen the scope of ongoing research in experimental nuclear physics.

Currently, all the Super Heavy Elements (SHE) of the seventh row of periodic table have been discovered, and there is a quest to discover the heavier elements in the eighth row, which is being done in the SHE factories at JINR, Russia; GSI, Germany and RIKEN, Japan [Roberto 2023]. The requirements are - primary beam of medium mass ions with ~7 MeV/A energy, and a few 100’s of μg of actinide targets with proper cooling. Since the cross section of desired nuclear reaction is very low, a very high beam current is needed.

Cross-sections for stellar nucleosynthesis

Stellar nucleosynthesis [Schatzh 2016] happens around a temperature of 10^7 K. It seems to be high but the corresponding energy is not enough to overcome the Coulomb repulsion between the nuclei. For example, the hydrogen burning of the second-generation stars mainly takes place via the proton-proton chain and the CNO cycle. These are nuclear reaction networks, which finally set up the fusion of protons into helium, and hence produce energy in these stars. The exact knowledge of the reaction rate (*e.g.*, in the reaction $^{16}O(p,\gamma)^{17}F$) is necessary for modelling the nucleosynthesis in hydrogen-burning stars. A tabletop ion source generating ~10 to 50 keV proton beam and >100 μA beam current is needed to measure such reaction rates, since the uncertainty in this data is large till date. The proton capture reactions with light nuclei such as ^{11}B, ^{12}C, ^{16}O need to be studied with precise measurement of cross section, which is of great relevance in nuclear astrophysics. Typically for reactions relevant to astrophysics, along with low cross-sections at Gamow energies, one has to deal with the problem of a cosmic-ray induced background. Unlike a terrestrial laboratory, this background can be six orders of magnitude less in underground laboratories.

High Energy Nuclear Physics Applications

Studies on fundamental properties of nuclear matter, and its behaviour at extreme conditions, which forms a part of high energy nuclear physics, require much more energetic and powerful accelerators. Indian nuclear physics community has been working in some of these areas through international collaboration, which is described below. In some of the facilities, Indian accelerator community has contributed towards building the accelerator, which is continuing.

Investigations on new form of nuclear matter, using heavy ion beams with high energy

Studies on new form of nuclear matter, known as zero net baryon density state and high baryon density state of Quark Gluon Plasma (QGP) can be performed in collider experiments with heavy ion beam having energy >100 GeV/A or fixed target experiments with beam energy ~10 TeV/A [Mustafa 2021]. At RHIC, USA or LHC, CERN, where the beam energy is high and beam current is low, the high-temperature region above the transition temperature $T_c = 160$ MeV[7] is studied. The high baryon density region studies are being carried out at the accelerator facilities FAIR, GSI, Germany; NICA, JINR, Russia and J-PARC, KEK, Japan; with accelerators in the energy range 10-50 GeV/A[8] and relatively high current on fixed targets.

Indian scientists have been participating in these international collaborations.

Generation of secondary particles, such as neutrino, pions, kaons, muons and anti-protons, using high power, GeV proton beams, and use of these secondary particles as beams

Secondary beams [Galambos 2013] are widely used in nuclear, hadron and particle physics, such as, neutrino and anti-neutrino beams to measure CP violation; low energy anti-proton to test CPT invariance; and to investigate effect of gravity on matter and anti-matter, *etc*.

Proton accelerator facilities at TRIUMF, LAMF, SIN (later merged with EIR to form PSI) and RAL have been providing intense muon beams since the 1980's, and JPARC has also joined this group since 2008. An intense muon beam circulating in a storage ring can be a source of clean and intense neutrinos, called a "neutrino factory". In FAIR project in Germany, the SIS100 ring will be used to produce 30 GeV proton beam with intensity 5×10^{12} protons s^{-1}. The beam will be accumulated and cooled down, if necessary, in an antiproton ring called High Energy Storage Ring (HESR). Low energy (ultra-cold) antiprotons are used to test CPT invariance, and also to investigate the effect of gravity on matter and antimatter.

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[7] Here, T_C is the transition temperature from hadronic matter to QGP, and T_C =160 MeV corresponds to baryon chemical potential $\mu_B = 0$.

[8] T_C is lower for higher value of μ_B corresponding to high baryon density state.

At CERN, the antiprotons produced in the 26 GeV proton synchrotron were cooled down to 5.3 MeV in an antiproton decelerator (AD) to improve the precision of gravitational measurements of anti-hydrogen.

The Indian accelerator community has been participating in international collaborations at CERN and FAIR.

Electron-Nuclei Interaction

An Electron Ion Collider (EIC) is under development at BNL for further investigations on quarks and gluons and their interaction within the nuclei [Feder 2020].

Specifically, the design meets the following key requirements:

- Center-of-mass energy range from ~ 20 to 100 GeV, upgradable to ~ 140 GeV,
- Ion beams from deuterons to the heaviest stable nuclei,
- High luminosity[9], up to 10^{34} cm^{-2} s^{-1} for electron-proton collisions,
- Highly spin-polarized electron, proton, and light-ion beams, and
- An interaction region and integrated detector capable of nearly 100% kinematic coverage, with the capability of incorporating a second such interaction region, if needed.

The EIC allows probing of the substructure of protons and neutrons via a high-energy electron. The EIC can uniquely address three profound questions about nucleons - neutrons and protons, and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Indian nuclear physics community is participating in this international collaboration.

Experimental hadron spectroscopy, using γ photons produced through Inverse Compton Scattering

When a laser beam is made to collide with an energetic electron beam in an accelerator, such as electron storage ring, it undergoes frequency up-conversion. This is known as Inverse Compton Scattering (ICS), and is a very useful source of generation of tunable γ *photons,* which is of great interest to nuclear physics community [Fujiwara 2014], both from the point of view of studying the fundamental process of ICS itself that is of relevance in astrophysics environments, and also for experimental hadron spectroscopy studies and photonuclear reaction studies that are of interest to nuclear physics community.

2.2 Condensed Matter Physics Applications

Condensed Matter Physics deals with the macroscopic and microscopic physical properties of matter, where behaviour of the condensed phases of solids, liquids, glasses and crystals are characterized by hierarchical length and time scale dependent behaviour. Study of condensed phases is essential, since it also provides a new horizon for designing novel materials, *e.g.*, the spin nature of electron transport lies at the heart of modern magnetic data storage technologies, such as computer hard drives and magneto-resistive random-access memories

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[9] Luminosity of a collider is defined as the number of particle collisions per unit area per unit time.

(MRAMs). The neutron and X-ray probes, through the well-established scattering and spectroscopic techniques, are used for investigating microscopic/mesoscopic structures and the sub-milli/micro second dynamics of these condensed phases [Narayanan 2017]. These probes find applications in various analyses (such as residual stress analysis) of engineering materials, and also in the disciplines of environmental science and agricultural science.[10]

Accelerator-based research has led to many fundamental discoveries in condensed matter physics in the past. The 2nd generation[11] synchrotrons (HASYLAB, NSLS, CHESS, SRS, *etc.*) have been mostly used to determine structural aspects. The 3rd generation synchrotrons (ESRF, APS, SPRing-8, PETRA-III, *etc.*) have, in addition, provided valuable information on slow dynamics (millisecond and above) at mesoscopic length scales through X-ray photon correlation spectroscopy (XPCS) and inelastic X-ray scattering (IXS) that are highly dependent on flux and coherence. However, the landscape of SR-based research will be completely altered with the advent of 4th generation High Brilliance Synchrotron Radiation Source (HBSRS).

Neutrons are neutral sub-atomic particles; their high penetrating ability allows property measurements and non-destructive evaluation, deep within a specimen that is otherwise difficult to obtain with X-rays or charged particles. Neutron scattering, although lacking in flux and beam dimensions compared to X-ray scattering, provides information on multiple length and time scales. Their wavelength is commensurate with inter-atomic distances and their energy is comparable to both lattice and magnetic excitations (phonons and magnons), making them an ideal probe for both structure and dynamics. Besides, they have magnetic moment and are thus uniquely sensitive probes of magnetic interactions. While atomic resolution in condensed matter systems can be achieved, the temporal resolution is limited to few picoseconds or longer, using explicit Fourier transforms (FT) of dynamical structure factor obtained from back scattering or inelastic scattering spectroscopy or through implicit FT from neutron spin echo (NSE) spectroscopy. This suggests the possibility to probe dynamics only at the scale of several groups of atoms. On the other hand, the unique properties of X-rays and relatively higher achievable intensity make them an efficient complementary probe. The HBSRS based SR sources and X-ray Free Electron Lasers (XFELs) can complement these high intensity spallation sources by providing atomic and sub-atomic spatial and temporal resolution; the latter can provide molecular and atomic scale movies of soft matter systems like polymers, nanoparticles, glassy materials and biological systems. Furthermore, these high-resolution accelerator-based sources, having high spatio-temporal coherence would pave the way for obtaining imaging and molecular movies spanning length scales from few nm to μm, and more along with simultaneous unprecedented temporal resolution.

In our country, the Dhruva reactor at BARC, Mumbai provides the platform for neutron-based activities, while Indus-1 and Indus-2 synchrotrons at RRCAT, Indore provide the infrastructure for X-ray based research. Unlike a steady state reactor, in a spallation neutron source, the high energy (~ GeV) pulsed proton beam is allowed to collide with heavy nuclei, splitting off a large number of neutrons. Such spallation sources, with much higher

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[10] Biogeochemical cycling of different elements including nutrients and toxic metals and metalloids in different components of the environment is largely regulated by the redox and molecular speciation of the element, *i.e.*, the distribution of the element amongst chemical species in a system. The use of the synchrotron-based X-ray absorption spectroscopy (both bulk- and μ-XANES and EXAFS) for determination of in-situ speciation of elements in environmental samples is a standard practice now. The use of μ-XRF and μ-XRD is also invaluable for determination of spatial association of elements and mineralogy at the micron scale in an environmental sample.

[11] This nomenclature is explained later in Section 3.2.

instantaneous neutron flux as compared to steady state reactors, provide a lot of useful information accessible by no other means. A spallation neutron source also possesses inherent time structure, which can be utilized for many applications involving time dependence. For comparison, the Dhruva reactor gives limited neutron flux (core flux ~ 1.8×10^{14} n cm^{-2} s^{-1}) as compared to the upcoming European Spallation Source (ESS) at Lund, Sweden (peak flux ~ 40×10^{15} n cm^{-2} s^{-1}). Yet another advantage of spallation source for condensed matter studies would be availability of muon beam. Muons are sub-atomic particles, similar to electrons but around 200 times heavier. They implant themselves into materials and then decay, releasing information about the environment they were embedded in, thereby proving to be an excellent probe of internal magnetic fields. These gains will bring a paradigm shift in neutron science done in the country, and expand the use of neutron methods, providing the wider research community with a smart new set of experimental options. Regarding the synchrotrons in our country, the brightness of Indus-2 is 10^{17} photons s^{-1} $mm^{-2}mrad^{-2}$ per 0.1%BW[12], as compared to ~ 10^{20} photons s^{-1} $mm^{-2}mrad^{-2}$ per 0.1%BW in ESRF, France and 5×10^{33} photons s^{-1} $mm^{-2}mrad^{-2}$ $0.1\%BW^{-1}$ in European XFEL at Hamburg, Germany; and the associated limitations have so far allowed choosing only those kinds of condensed matter research problems, which suit to be probed by the national synchrotron facilities. The experiments with these facilities have been mostly ex-situ. The in-operando experiments and sub-millisecond in-situ experiments, which are the state-of-the-art from today's global perspective, are yet to be realized.

In the roadmap of Indian technologies, it has become the need of hour to have more advanced neutron and X-ray sources with significantly higher intensity and associated improved characteristics, to cope with the pace of advancement in condensed matter physics studies, particularly in the area of emerging materials.

In addition to X-ray and neutron beams, particle beams (electrons and ions) also find application in basic studies of condensed matter, particularly for modification and probing. Condensed matters are modified by well-controlled ion implantation and defect creation. Also, low and medium energy ions and electrons are used to probe the material structures and properties using accelerator-based techniques, such as low/medium/high energy ion scattering, ion induced X ray emission, secondary ion mass spectroscopy *etc*. Highly focused accelerated electron beam is used for powerful microscopy and spectroscopy (Transmission Electron Microscope, Electron Energy Loss spectroscopy, Energy Dispersive X ray emission and Scanning Electron Microscope *etc*.). Also, nano size beams of ions and electrons are relatively easy to obtain, as compared to X ray and neutron probes, for local modification and investigation of nanomaterials.

2.3 Materials Science Applications

Materials Science, including chemical sciences, has benefited enormously due to the availability of 2nd and 3rd generation synchrotrons. However, the availability of advanced 4th generation synchrotron sources and XFELs, along with advanced X-ray imaging techniques that have emerged due to advancement in semiconductor material growth and device processing techniques, will fundamentally alter the nature of information that can be obtained from various materials, including energy and storage materials, electronic and thermo-electric materials, biological materials, materials for catalysis, phase change materials, new

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[12] This is the brightness from insertion devices in Indus-2. The brightness from bending magnets in Indus-2 is 10^{14} photons/s/mm^2/$mrad^2$/0.1% BW. Most of the 3rd generation synchrotron sources already have a brightness in the 10^{20} photons/s/mm^2/$mrad^2$/0.1%BW. MBAs will reach 10^{22} photons/s/mm^2/$mrad^2$/0.1% BW.

superconductors, *etc.* The outcome of ground-breaking research from the Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Centre (SLAC), USA has significantly enhanced our understanding of processes like photosynthesis [Bhowmick 2023], catalysis *etc.* It is important to note that such information can now be obtained from in-operando systems, so that such understanding can provide greater impetus to the relevant technologies. Batteries and other energy materials can now be studied in operating conditions with unprecedented spatial and temporal resolution [Tang 2021]. Traditional synchrotron-based techniques like XRD, EXAFS, ARPES[13] and RIXS can now be performed on various novel materials with temporal resolution and with imaging capabilities, which provide crucial information on kinetics of phase transitions in these materials under extreme conditions of pressure or temperature. In several condensed matter systems, the phase transitions - both structural and electronic - occur on a local scale, and not throughout the volume. The nano-sized beams that are possible with the 4th generation synchrotron sources would enable probing phase behaviour of such systems with high spatial and temporal resolution, which is necessary to track the evolution of structural dynamics. Such studies are particularly important for structural materials such as steel and zirconium alloys, which are ubiquitously used in nuclear reactors. The exploitation of high energy X-ray at large synchrotron sources such as SPring-8, APS and ESRF has led to the development of 3D/4D Materials Science. The modelling of microstructure generated from such studies provides a great leap into the understanding of the mechanics and failure of load bearing materials used in nuclear industry. These materials, are, however, highly absorbent for X-rays. Hence the development of beams combining high photon energy (typically in the range 80 - 120 keV), high brilliance and monochromaticity is essential for such endeavours.

Accelerator-based neutron beams also find lot of applications in materials science. Particular mention should be made of the material damage studies that are of relevance to fusion reactors. Typical requirement is a neutron source with 10^{18} n/s in CW mode for material damage studies (50-100 dpa/year) for fusion reactor components. For the fusion research program, fusion neutronics is another area of research that can be pursued with an accelerator based neutron source.

Ion beam irradiation of solids gives rise to the formation of atomic defects in the target, and modifies the material properties. It finds application in surface modification, nanopatterning, quantum structure (dot, wire, well) formation, buried layer formation, silicon on insulator (SOI) buried oxide layer formation *etc.* One of the most trending applications of ion beams is in the field of sustainable, efficient and clean energy technologies. Photo-Electro-Chemical (PEC) energy storage and conversion technology by water splitting is one such aspect [Lu 2010, Bora 2013]. The artificial PEC water splitting is one of the most promising abundant sunlight-to-storable-energy-conversion processes, which is capable of directly producing hydrogen. Around the world, there has been interest in production of hydrogen, as green fuel, through this approach, and R&D is being pursued on materials research, using SRS, to make the cost of production competitive. Several metal-oxide semiconductors, viz., TiO_2, α-Fe_2O_3, $BiVO_4$, ZnO, WO_3, *etc.* have been in use as PEC devices; however, due to their poor solar-to-hydrogen (STH) conversion efficiency and inability to split water with visible light irradiation (comprising of 54% of whole solar spectrum), their use has been severely limited. Recent experimental results have demonstrated that micro/nanostructure modified PEC materials by using low-energy (few tens of keV) ion beams of high-fluence (~ 10^{11} to 10^{17} ions cm^{-2}) can significantly enhance their STH conversion efficiency [Joy 2018]. The table top ion sources in the energy range 10-70 keV are compact, and cost-effective machines; their

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[13] ARPES is best implemented on low and medium energy synchrotrons.

indigenous development can play an important role in the contribution towards PEC technology by Indian researchers. Further, these machines also find applications in synthesizing advanced materials, *e.g.*, in graphene milling with 25-30 keV He^+ and/or Ne^+ ions, the high-resolution probe size enables the direct-write of GNRs (Graphene Nano Ribbons) for device applications.

2.4 Biological Science Applications

Accelerator-based research has led to many fundamental discoveries in biological sciences in the past, including determination of structure of biomolecules, leading to several Nobel prizes [ATP (1997), Ribosome (2009), GPCR (2012)]. The major contributions have come mainly in the area of structural biology [Cohen 2012]. However, the structure of many proteins, including intrinsically disordered proteins, membrane proteins and other biomolecules, which are of great significance in functioning of cellular machinery, have been hindered due to the inability to obtain these materials in crystal form, or by the small sizes of crystals produced[14]. Moreover, all such studies have invariably been done at cryogenic temperatures to avoid radiation damage, and not under physiologically relevant conditions. These limitations can be overcome with the 4th generation HBSRS based synchrotrons and the XFELs. Multimodality, *i.e.*, using different probes to solve a scientific question is an essential feature of synchrotron facilities in biology (and also in physical sciences). Serial crystallography, which is implemented nowadays at synchrotrons and also at FELs, allows obtaining structure of biological molecules under physiological conditions, using very small (~ 0.1 Å) crystals, or even without the need for their crystals (using high brilliance synchrotron sources and XFEL) [Hough 2021]. X-ray FEL LCLS at SLAC, and VUV FEL FLASH at DESY, have already revolutionized this area by providing high resolution crystal structures of proteins and biomolecules, which are of critical importance in understanding various biological functions, diseases and disorders. Moreover, these accelerators also open up possibilities of imaging biological materials like virus, bacteria and cells, with unprecedented spatial and temporal resolution. Finally, challenging processes involved in real time tracking of biomolecule and pathogen interaction with cells could become possible. Visualization of such processes in-vivo would not only enhance our fundamental understanding of these crucial micro and cell biological process, but also provide pathways for eradicating acute and infectious diseases through development of effective strategies for therapy, including discovery of new drug molecules. High resolution crystal structure(s) of protein and biomolecules will help in synthesis and discovery of new biological and molecular entities with better targeting and tailor-made properties. It is important to note that diffraction methods would be increasingly used for measurements involving ligand/inhibitor design by using chemical fragments (fragment-based drug discovery). These are also likely to be in serial crystallography setups. Structural biology is increasingly moving into fluorescence techniques (even tomography is likely to be a routine technique over the next few years). Phase resolved X-Ray tomography needs to be incorporated [Walsh 2021]. Two partner communities who need to be involved here are medicinal chemistry/chemical biology and imaging.

Synchrotron radiation also finds application in study of bone mineral density of small animals with utmost precision, which can be standardized for applications. Radioisotope study with

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[14] Biomolecules have a particular function and mechanism of action. Study of the mechanism of action of biomolecules needs structural characterization. Crystallization is one of the best methods to find out structure and mechanism of action of a biomolecule. Synchrotron radiation is the most powerful tool for solving the structure of biomolecules.

animal models can be explored to its maximum for the benefit of human diagnosis and treatment.

During the Covid-19 pandemic, synchrotron radiation was effectively used for analysis of SARS-CoV-2 [Michalska 2020, Kozielski 2022].

In addition, IR radiation from FEL can be used very efficiently in photodynamic therapy, and surgery (by ablation) in neuroscience and ophthalmology. IR radiation from FEL is also used very effectively in bio-imaging. THz radiation from FEL can be used in dentistry, dermatology (skin cancer), THz spectroscopy and bio-imaging of biomolecules, DNA/RNA, amino acids/peptides, proteins, carbohydrates, cells and tissues.

2.5 Medical/Pharmaceutical Applications

A very important societal application of particle accelerators is in the medical field [Eickhoff 2008], particularly for therapy, and also for production of radioisotopes for medical imaging. Medical isotopes used for imaging applications are of two types - PET (Positron Emission Tomography) isotopes, and SPECT (Single Photon Emission Computed Tomography) isotopes. Apart from diagnostics, radioisotopes are also used for radiation therapy (Brachy Therapy and Targeted Radionuclide Therapy) for treatment of cancer.

Pharmaceutical Applications

During the last few decades, the use of radioisotopes in nuclear medicine has shown a significant growth. One of the major factors contributing towards this has been the availability of cyclotrons, which are exclusively dedicated to the production of radioisotopes for SPECT and PET imaging. Most of the medical cyclotrons in our country are in the energy range up to 18 MeV for protons, and they are dedicated for the production of PET isotopes, specifically ^{18}F and ^{18}F labelled Fluoro-Deoxy-Glucose (FDG). However, there are many other isotopes, which are very useful in nuclear medicine, such as ^{68}Ga, ^{124}I, ^{64}Cu, ^{99m}Tc *etc*., which require 18 MeV – 70 MeV protons for their production. At present, there is only one such facility in our country - a 30 MeV medical cyclotron [Debnath 2019]. Isotope production using 18 MeV – 70 MeV protons can also be realized with room temperature/ SC LINACs. As will be elaborated later in this document, proton LINACs for various R&D applications are planned to be developed in the country, and medical isotope production can be one very useful spin-off application of the proton beam tapped at suitable energy from such LINACs. A list of isotopes, along with their uses, is mentioned in Table 2.5.1.

Currently, there are around 20 medical cyclotrons operational in Indian metros- all procured from international commercial companies. This small number of facilities is inadequate to cater to the demand of the large population of India. Besides, due to high cost of these imported facilities, treatment is too expensive to be afforded by the vast rural and semi-urban population of the country.

Apart from medical applications of radioisotopes, its role in structural characterization of pharmaceuticals is also of interest, which is being explored. Currently the trend of pharmaceutical therapies is moving from traditional dosage forms to more complex drug delivery systems like targeted nanoparticles, liposomes, antibody-drug conjugates, microspheres *etc*. to name a few. Such complex drug delivery systems rely on loading the active constituents, *i.e.,* small drug molecules or large complex protein based molecules into the preformed empty vesicles. These drug delivery systems are however more tedious to characterize, both in-vitro and in-vivo. Suitable radioisotopes can be incorporated into these vesicles so that the structure and physio-chemical characteristics can be characterized through high-resolution imaging. Moreover, the drug loaded into the vesicles can be tracked for pharmacokinetic and pharmacodynamic effects, when administered in suitable animal models. Such applications of radioisotopes can accelerate the development of complex generic pharmaceuticals as well as new drug discovery programs.

Table 2.5.1: List of medical isotopes and their applications

Medical Isotope	**Half-life $T_{1/2}$**	**Use**	**Applications / Comments**
^{18}F	109.8 m	PET	FDG – Oncology, cardiology and neurology NaF – Whole Body bone scan F-MISO – Hypoxia imaging FLT – Tumour proliferation FET – Amino acid transporter marker
^{225}Ac	9.92 days	Therapy	Prostate cancer therapy, alpha particle emitter, most potent-grade radioisotope currently available
^{11}C	20.4 m	PET	Brain physiology and pathology, in particular for locating epileptic focus, and in dementia, psychiatry, and neuropharmacology studies, and significant role in cardiology
^{13}N	9.96 m	PET	
^{15}O	2 m	PET	
^{64}Cu	12.7 h	SPECT	Genetic diseases affecting copper metabolism, such as Wilson's and Menke's diseases, for PET imaging of tumours, and also cancer therapy Tracer for blood flow, hypoxia and cell binding studies as PTSMa
^{99m}Tc (^{99}Mo/^{99m}Tc generator)	6 h (66 h/6 h)	SPECT	Most commonly used radionuclide in the field of diagnostic imaging, **Annually, the use of ^{99m}Tc covers about 85% of nuclear medicine applications.** Used to image the skeleton and heart muscle, brain, thyroid, lungs (perfusion and ventilation), liver, spleen, kidneys (structure and filtration rate), gall bladder, bone marrow, salivary and lachrymal glands, heart blood pool, infections and numerous specialized medical studies
^{103}Pd	17.5 d	Therapy	Prostate cancer diagnostic and therapy
^{67}Cu	61.83 h	SPECT	A high uptake of ^{67}Cu was observed in the tumour as well as in the liver and kidney, which are the major organs for copper metabolism. The longer-lived ^{67}Cu decays exclusively by β^- emission, and has been used to label monoclonal antibodies and antibody fragments for radio-immunotherapy
^{67}Ga	78.3 h	SPECT	Specific types of cancer, such as Hodgkin's disease, lymphoma, or lung cancer, also used for acute swollen lesions

Medical Isotope	**Half-life $T_{1/2}$**	**Use**	**Applications / Comments**
^{82}Sr/^{82m}Rb generator	25 d/5 m	PET	Myocardial perfusion imaging, diagnosis of myocardial ischemia
^{68}Ge/ ^{68}Ga generator	271 d/ 68 m	PET	Neuro-endocrine tumour imaging, prostate cancer diagnosis.
^{201}Tl	73.5 h	SPECT	Myocardial perfusion imaging (MPI) and localization of myocardial infarction
^{123}I	13.2 h	SPECT	Diagnostic study of thyroid disease
^{124}I	4.1d	PET	^{124}I decays simultaneously by positron emission and by electron capture. Therefore, it should be a prospective labelling radionuclide for both approaches: diagnostic PET investigations, *e.g*. of tumours, and experimental radiotherapy by means of short-range high-LET Auger electrons
^{211}At	7.2 h	Therapy	Targeted alpha therapy

Medical / Radiotherapy Applications

Apart from the production of radioisotopes, another important application of a particle accelerator is in cancer therapy. Electron accelerators are used to generate highly penetrating X-rays, when energetic electrons, in the range of 6-20 MeV, are bombarded on a high atomic number material like tungsten. These X-rays, when collimated and directed towards the cancerous tissue, kills cancerous cells and stops its further multiplication. Currently, there are 15,130 radio therapy systems operational in the world, out of which 1007 units are in India, which include photons and electrons (689), brachytherapy (318) and proton therapy (1) [IAEA]. Most of the radiotherapy machines available for treatment in India are imported. The research reactors Dhruva and Apsara-U at BARC produce limited radioisotopes for their applications in cancer treatments. Radiation Medicine Centre (RMC), BARC, Mumbai and Tata Memorial Centre (TMC), Mumbai play a significant role in this regard. At SAMEER, Mumbai, 6 MeV radiation oncology systems have been developed, and commissioned at various government hospitals for treatment [Dixit 2020]. The technology of this therapy system has been transferred to industry for mass production. As per ICMR data, the projected number of cancer cases both in males and females till 2020 was 13.9 lakhs, and will rise to 15.7 lakhs by 2025 [ICMR-NCDIR]. To cater to the growing needs of our country, and to treat cancer patients, approximately 4000 more radiotherapy units with advanced Intensity Modulated Radio Therapy (IMRT) techniques will be required [Munshi 2019].

A fraction of the cancer cases, which are difficult to treat using radiotherapy, require hadron therapy-based treatment. Protons of 230 MeV or carbon ions of 400 MeV/A are required for hadron therapy. For proton acceleration, the cyclotrons are generally popular. In a cyclotron, suitable energy degraders are used to vary the energy from 250 to 70 MeV during therapy, leading to large radioactivity near the degrader. In a synchrotron, the charged particle moves in a fixed path, where it gets accelerated through RF cavities, and the magnetic field is suitably ramped, keeping up with the particle energy, which ensures that it keeps moving on the fixed path, till the desired energy is reached, after which it is extracted. Although for energy variation, the synchrotron has an advantage over the cyclotron due to ease in varying the energy and no requirement of energy degraders, the compactness and low cost of cyclotrons have made them a worldwide preferred choice for proton therapy. For carbon ion acceleration, the synchrotrons are used. Hadron or heavy ion therapy has still remained a niche area in the Indian scenario. Therapies using heavy ion beams have demonstrated promising results in dealing with difficult-to-treat tumours, *e.g.*, paediatric cancer, tumour in spine, eye, brain *etc*. These kinds of tumours are difficult to treat with photon therapy because of the risk of damaging the neighbouring sensitive tissues. Single proton of given energy deposits most dose in the Bragg peak at a specific depth, which is determined by the beam energy. This has led to the most accurate beam delivery methods, using spot scanning technique developed at PSI, Switzerland. The principal advantage of Intensity Modulated Proton Therapy (IMPT) over X-rays is that less dose is deposited in surrounding critical structures. Some treatments may benefit from the use of particles that deliver doses with a greater radiobiological effectiveness (RBE), notably carbon ions almost three times that of protons. Other ions such as helium, oxygen and argon have also shown good results for therapy purpose.

In hadron therapy facilities, along with accelerators, gantries are required for delivering the beam precisely to the patient from any direction. Normally, gantry for hadron machine is a huge mechanical structure, which consumes a major fraction of the cost of such a facility. Therefore, a multi-ion therapy machine with real time imaging is an ideal technology for future hadron therapy. Of course, efforts should be made to reduce the cost, and to make the machine compact.

2.6 Industrial Applications

Particle accelerators (electron accelerators as well as ion accelerators) have a wide variety of industrial applications. In fact, a largest fraction of the total number of accelerators built around the world is for industrial applications, and manufacturing of such accelerators represents an industry with large investment [Sessler 2014]. Ion accelerators (5 keV to 1.5 MeV) with moderate beam currents (few hundreds of μA) are used for ion implantation during manufacturing of semiconductor, *e.g.*, the ion beam generated surface defects enhances charge-transfer property in hydrogen titanate (H_4O_4Ti), an n-type semiconductor, used for super capacitors. Electron accelerators are used for various applications, such as industrial processing and industrial process monitoring, where they use the energetic electron beam directly or the X-ray/ γ-ray produced through bremsstrahlung by hitting the electron beam on a metal target, or, even the neutron beam produced using the γ-ray.

For industrial processing with electron accelerators, energetic electrons (few hundreds of keV to a few MeV) are required to penetrate to tens of cm from the surface of the material. Such electron accelerators have applications in sterilization of medical products, preservation of agricultural and food products, radiography *etc*., and are also used in various industries, such as rubber, plastics/polymer, petrochemical, electrical, coating, adhesive industry, *etc*. Cross linking of polymers using electron beam treatment is the most widespread application, which makes the material hard, and more heat resistant. Low-energy and high-power electron beams are also used for X-ray systems for scanning and spectroscopy, electron beam welding, electron beam drilling, electron beam curing, chemical modification of materials, 2D and 3D printing, purifying drinking water, treatment of solid wastes and toxic gases, *etc*. Details of some of the important applications are described in the following paragraphs.

For medical sterilization and processing of agricultural and food products, electron LINACs with energy around 10 MeV and average power around few tens of kW are required. Electron beam is used to destroy microorganisms, bacteria or insects. For agricultural products, it is also used to inhibit sprouting and delay ripening.

Electron Beam-based Additive Manufacturing (EBAM) is another application of low energy high power electron beam, which is emerging in a major way across the world. The main application of additive manufacturing is in bio-medical and aerospace applications. Very complex design of metallic components can be made using this technique. In EBAM technique, sharply focused and high-power electron beam is used to melt high atomic number metals in powder form to build very intricate design in a layered manner.

Low-energy and high-power electron accelerators are also used for treatment of wastewater from sewage sludge [Han 2006, Siwek 2020], textile dying units, pesticide industry *etc*., and toxic gases, such as marine diesel exhaust gases, by breaking down the pollutants in forms that can be removed easily by other processes. A high power 1 MeV, 400 kW accelerator is typically needed to treat up to 10,000 cubic meters of waste water every day.

In the Indian context, for the next fifteen years, it will be prudent to develop electron accelerators and tabletop ion sources for several of the above applications. Electron accelerators have several advantages over the cobalt-based radioactive sources. A large number of 7.5/10 MeV, few tens of kW; 0.5/1 MeV, few tens to few hundreds of kW electron accelerators, and, 5-50 keV tabletop ion sources of varying fluence (~$10^{11}$to 10^{17} ions cm^{-2}) of H^+, He^+, N^+, Ar^+, *etc*. will be required for several industrial applications.

In addition to the accelerators described above, Synchrotron Radiation Sources also have significant applications in various industries, such as in pharmaceutical industry for drug discovery, in electronic industry for lithography, battery research *etc*.

2.7 Security Applications

Accelerators play an important role in national security. In early days of development of nuclear weapons, important data related to cross sections of nuclear reactions were obtained using low energy ion accelerators. In recent times, particle accelerators are used in scanning devices for security applications, and also for generating giant electromagnetic (EM) pulses for defense applications. High power accelerators also have the potential for military applications.

Electron accelerators are used for cargo scanning, where the X-rays/γ-rays, produced by electrons through bremsstrahlung, are used for detection of contraband material to prevent any illegal activities or terrorist threats [Kutsaev 2017]. X-ray imaging using transmission radiography is an established technique. Usually X-rays of two different energies are utilized to differentiate materials because each material will alternate the X-ray dose at different energies in a different manner. By comparing the alternation at two different energies, it is possible to calculate the appropriate atomic number of the material. γ–rays are used to determine the isotopic composition of the target material that is of interest, from the nuclear security point of view through Nuclear Resonance Fluorescence (NRF). The isotope, which has been stimulated, releases γ–rays with a very sharp energy that is characteristic of that isotope. Neutrons, produced by striking the γ-rays on suitable target, are also used for imaging. Neutron radiography uses neutrons transmitted through an object for scanning. It is used to detect any nuclear material present by triggering fission reaction, which in turn produces X-rays that can be detected, and will have a characteristic spectrum of the fission process. Typically, 6-15 MeV electron accelerators with 10-20 kW average beam power, are required for such applications.

An important requirement for developing a cargo scanning system is to develop the 3D imaging capability. To obtain images, multiple X-ray sources are placed at different angles and provide a CT type scan. For such a system, short pulses with higher repetition rates are required. Currently, LINACs up to 3 MeV energy are available with the CT arrangement. The multiple energy contrast imaging, using CT technology, will be in high demand in the near future. The base technology needs to be modified to accommodate pulse to pulse variation of energy, or having a set of systems to enable contrast imaging.

Besides electron beams, the THz radiation with average power around μW are useful for security related scanning applications. THz radiation can be generated in FEL, using an electron accelerator. Although THz radiation can be produced by other means, the advantage with FEL is that it can produce intense, tunable and narrow bandwidth THz radiation. There are three prime advantages of THz. First, unlike X-ray, THz radiation poses no health risk for scanning the humans. This implies that at the airports, humans can also be subjected to scanning. Second, THz radiation can detect concealed weapons since many non-metallic, non-polar materials are transparent to THz radiation. Third, target compounds such as explosives and illicit drugs have characteristic THz spectra that can be used to identify these compounds.

Accelerators are used to generate giant EM pulses to simulate the effect of nuclear weapons on electronics and control systems, and, also for high-speed X-ray imaging. Such applications require ~ 1 MeV, several kA class accelerators.

2.8 Atomic Energy Applications

One of the important applications of high-power, GeV class proton LINACs, which is envisaged in modern times, is, as drivers of ADS for transmutation and energy production. High-energy proton LINACs with different power levels are also used as driver for spallation neutron sources, neutrino factories, muons colliders and production of rare isotope beams for nuclear physics, *etc*. These LINACs are required to deliver several MW to few tens of MW proton beams and operate with continuous wave (CW) or pulsed high intensity beams.

In particular, ADS has evoked considerable interest in the nuclear community world over, because of their capability to produce power, to incinerate the Minor Actinides and Long-Lived Fission Product components of radiotoxic waste, and, for utilization of Thorium as an alternative nuclear fuel. In the Indian context, due to our vast thorium resources, ADS is particularly important as one of the potential routes for accelerated thorium utilization and the closure of the fuel cycle [Degwekar 2017]. It has been projected that the existing thorium reserve of India has the potential to quench the energy need of Indian population for few hundred years.

In ADS, a high-intensity proton accelerator is used to produce 1 GeV protons, which strike a target (such as lead or tungsten) to produce spallation neutrons. These neutrons enter a sub-critical core and induce nuclear reactions, including fission. Such a system is intrinsically safe, because if the accelerator is turned off, the fission chains are self-terminating. Spallation neutrons in ADS can also be used to produce enriched plutonium, and also for producing nuclear material for fusion.

An important parameter in the ADS design is the "spallation ratio", i.e., the number of neutrons per incident proton on the target, per GeV. The spallation ratio increases with the proton energy above 100 MeV and saturates at around 1 GeV. Hence the optimum energy of the accelerator is 1 GeV because beyond that there is very little increase in the number of neutrons per unit beam power. To increase the neutron flux, one can then increase the intensity of protons, *i.e.*, the current of the accelerator. A primary concern in building such high-power LINACs is the beam loss, which could limit the availability and maintainability of the LINAC and various subsystems due to excessive activation of the machine. A careful beam dynamics design is therefore needed to avoid the formation of halo that would finally be lost in the LINAC or in transfer lines.

In addition to ADS, where accelerator can be used to harness nuclear energy through controlled nuclear fission, accelerators can also be used for harnessing nuclear energy through controlled fusion [Hofmann 2018]. This requires heavy ion accelerator for achieving inertial fusion. Here, a high energy heavy ion beam is used to rapidly heat and compress a small pellet to achieve fusion. Typical requirement is to generate 8 GeV lead ion beam. Lot of R&D has been going on the design and development of heavy ion fusion accelerators. Current interest in fusion is through inertial confinement route that utilizes high energy lasers. It is however believed that over several decades, the scenario employing heavy ion beams should be a solution.

2.9 Space Applications

Particle accelerators have important applications in the space program too [Virtanen 2006], mainly as a diagnostic tool for testing various components in satellite and space mission projects, *e.g.*, for characterizing the spectral response of payloads for astrophysics mission, testing the electronic and electromechanical components for their radiation hardening, as well as for their degradation in the radiation environment. Beamlines of SR sources are often used for evaluating the spectral responses of X-ray/ γ-ray instruments that are launched on board a satellite. Also, accelerator beamlines are used to simulate the space environment in terms of particle and radiation flux; the components such as semiconductor detectors, solar cells, and, the electrical, electronic, and electromechanical components of spacecraft's satellites are tested in that environment using electron, proton and ion beams. In India, synchrotron beamlines of Indus-2, and charged particle beamlines of IUAC and the BARC-TIFR LINACs have been used for this purpose.

Electron beams available at RRCAT can also be used for calibration of charge particle monitor and also for testing of semiconductor devices in radiation environment, which will be particularly useful for human space program associated missions.

In order to better understand the effect of exposure of cosmic radiation, NASA and Brookhaven National Lab (BNL) have established a joint lab - the NASA Space Radiation Laboratory (NSRL) on the Brookhaven campus to study the possible effects of this exposure [Miller 2016]. BNL uses beam from tandem (~15 MeV) and rapid cycling synchrotron (up to GeV, proton and ions) to test electronics and effect on bio cells for spaceflights. At NSRL, there is R&D for simulating cosmic radiation damage of electronics and biological cell for spaceflights, for which protons and ions are used from 100s of MeV/A to couple of GeV/A. Proton beamlines at BARC-TIFR LINAC facility have also been used for testing and calibrating the charged-particle radiation monitors in vacuum for space applications. Effect of radiation dosage on semiconductor devices for space applications are studied by exposing controlled particle fluxes on the devices at this facility. Mono-energetic beams of select energies are used for the experiments to calibrate the instruments. However, the energy range for proton beams is limited. Similarly, there are select energy proton beamlines at IUAC for specific energy ranges.

The Pelletron Facility of IUAC has been used by ISRO for addressing the Single Event Effects (SEE) response of the microelectronic components for their space program. Use of heavy ion beams has resulted into a few specific contributions to the Indian Space Program, *e.g.*, indigenization of devices being used in the spaceship.

Another very important application of accelerators in space projects is doing high energy radiography as a part of Non-Destructive Testing (NDT) of components and materials. The 8 MeV and 15 MeV electron LINACs have been used for inspecting rocket motors of SLV and boosters of PSLV. Both X-ray radiography as well as neutron radiography are used for NDT, which can be done using electron accelerators also. Dual energy LINACs (9 MeV/ 15 MeV) are typically used for radiography. Development of such electron LINACs will be useful for the Indian space program. In general, linear induction accelerators can be used as intense x-ray source, and also for proton radiography.

2.10 Other Applications

Being an important tool, particle accelerators have applications in other important areas also, which are not covered in previous sections. For example, atomic collisions using particle accelerators, the studies performed with highly charged ions that are produced using ion accelerators, or by using the bright photon beams from synchrotron radiation source or free electron laser, and photon induced interactions help us in understanding various phenomenon in atomic and molecular physics that are of relevance in atmospheric science, astrophysics and plasma physics [Vane 1995].

Electron accelerators and free electron lasers are useful for performing important studies in chemistry. For example, in pulse radiolysis, short pulse [few μs to tens of ns] of energetic electron beam (~ 10 MeV) is used to produce free radicals in a solution [Yadav 2007], which is of interest in the field of radiation biology. Similarly, light from FEL and SRS can be used to perform photon induced chemical reactions that is of interest from the point of view of its applications in different areas.

3. International Scenario in the field of Accelerator R&D

After having discussed the important applications of accelerators in the previous chapter, here we discuss the international scenario of R&D on different types of accelerators for such applications.

3.1 Linear and Circular Colliders for High Energy Physics Research

For many decades now, progress in high-energy physics (HEP) has been driven by colliders – both electron and proton [Gourlay 2022]. The focus has been mainly on discovering all the particles predicted by the Standard Model: this endeavour ended successfully in 2012, with the discovery of the Higgs boson at the LHC at CERN. Beyond Standard Model (BSM) physics includes finding answers to open questions such as: the hierarchy problem[15] and the masses of the fundamental particles; unification of the four fundamental forces especially through a quantum description of gravity; the nature of dark matter; the origin of matter-antimatter asymmetry in the universe (CP violation), *etc*. One of the theoretical models developed over many decades to address some of these issues was Supersymmetry (a new symmetry that predicts bosonic partners for all fermions and fermionic partners for all bosons). Most Supersymmetry models predicted the existence of new particles that would be seen at the energy scale of the LHC (13 TeV). The lack of any signals of supersymmetry at the LHC came as a serious setback for Supersymmetry, and at the same time gave impetus to proposals for the next collider(s).

The only approved and ongoing collider project is the HL-LHC (High Luminosity LHC). This is essentially an upgrade of the existing accelerator, the key goals being to increase the energy from 13 TeV to 14 TeV, and increase the luminosity by a factor of five to seven. HL-LHC is expected to start operating in 2027. In the following paragraphs, we discuss briefly the future lepton colliders and hadron colliders for HEP.

Future Lepton Colliders

An important and natural road forward is to build an electron-positron collider as a Higgs factory that will explore the luminosity frontier and do precision physics at energies lower than that of the LHC. The two competing linear collider projects proposed in this direction are the International Linear Collider (ILC), to be hosted in Japan, and the Compact Linear Collider (CLIC) at CERN. Both projects have been discussed for many decades now. CLIC will use normal conducting (NC) technology at 12 GHz, powered not by conventional RF sources but by a second, low-energy, high-current, electron beam (the Two Beam Accelerator concept), which can deliver very high gradients of 70-100 MV m^{-1}. CLIC will be commissioned in stages with centre-of-mass energy ranging from 380 GeV (in a 11 km tunnel) to 3 TeV (50 km tunnel). A technical design exists, and the projected roadmap is for commissioning around 2034 for the 380 GeV stage, and 2055 for the 3 TeV stage. The ILC will use SC technology at 1.3 GHz, with a gradient of around 30 MV m^{-1}. It will be commissioned in stages, with centre-of-mass energy ranging from 250 GeV (in a 20 km tunnel) to 1 TeV (40 km tunnel). The projected roadmap is for commissioning around 2034 for the 250 GeV stage and extending to around 2057 for the 1 TeV stage.

There are also two competing circular electron-positron collider proposals: the Circular Electron Positron Collider (CEPC) in China, and the Future Circular Collider (FCC)-ee, at CERN. Both have been in discussion since 2011. Both proposals involve building a new 100 km underground tunnel – almost four times the size of the LHC tunnel. The CEPC envisages running at different centre-of-mass energies, between 91 and 240 GeV, while the FCC-ee will operate between 91 and 365 GeV. The two projects have different luminosity optimization

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[15] Hierarchy problem is related to large discrepancy in the relative strength of weak force and gravitational force.

strategies and peak luminosity, with SR and beamstrahlung being important limiting considerations. The CEPC is projected to start around 2030 (at the lowest energy), running into the early 2040s. The FCC-ee is projected to start around 2038 (at the lowest energy) and extend to the 2050s.

Future Hadron Colliders

The outlook for hadron colliders (besides the HL-LHC already discussed) is even further into the future, and beyond the 2035 horizon. There are two competing proposals, both predicated on using the 100 km tunnels proposed to be built for the circular electron-positron colliders, CEPC and FCC-ee, after the completion of the lepton collider programs, and will extend the energy frontier. A critical technology requirement is developing SC dipole magnets with a field strength of 12-20 T (compared to 8.7 T at the LHC), which will require substantial R&D, especially in the use of Nb_3Sn to handle the higher magnetic fluxes.

The Future Circular Collier (FCC)-hh, proposed at CERN, would have a 100 TeV centre-of-mass energy, would be built in the FCC-ee tunnel, and would use the LHC or HL-LHC as the injector. The FCC-hh is projected to start operating around 2045, and extend into the 2070s, with a potential 150 TeV version extending all the way to 2090. The Super Proton-Proton Collier (SppC), proposed in China, would be built in the CEPC tunnel, and have a centre-of-mass energy of 100 TeV. The SppC is projected to be commissioned around 2045 and extend up to around 2065.

At CERN, there are also discussions on intermediate energy hadron colliders. The High Energy LHC (HE-LHC) would be sited in the LHC tunnel but use 16 T dipole magnets to reach an energy of 27 TeV; it is projected to operate from 2045 to 2065. The Low Energy FCC (LE-FCC) would be sited in the new 100 km tunnel, but use 6 T magnets to reach 37.5 TeV.

Other Colliders

There are also discussions at CERN for a Large Hadron-electron Collider (LHeC), that will collide electrons with 1.2 TeV protons in the LHC; this is projected to operate from the early 2030s. There is also a proposal for an FCC-eh, which will collide 3.5 TeV protons and electrons in the 100 km FCC-hh tunnel.

The discussion so far has focussed on colliders and leaves out the neutrino sector. However, much interesting particle physics can be done by studying neutrinos. To produce a high flux of neutrinos, one typically needs a high flux of high-energy protons that can bombard a dense target to produce neutrinos. These are then detected in large, typically underground, detectors placed far away from the source. The Proton Improvement Plan – II (PIP-II) accelerator, being developed at Fermilab, is a 800 MeV, 2 mA, CW, SC LINAC. This LINAC will inject into the Main Injector and produce a 1.2 MW proton beam at energies between 60-120 GeV that will strike a target to produce neutrinos, which will be detected 1300 km away, in South Dakota. India is already collaborating in the PIP-II project.

The benefits to the Indian accelerator community, through mega science collaborations in ILC, CLIC or HE-LHC (the three projects most likely to come up in the time-frame of 2035) are not clear and needs greater scrutiny. There are also discussions on muon colliders, which are far from the project stage and are therefore not addressed. Plasma-based electron accelerators have the potential, in the long term, to be viable options for high energy accelerators.

3.2 Synchrotron Radiation Sources

A synchrotron radiation source has been a versatile and important tool for performing contemporary research on materials and biological systems for various applications [Kim K.-J 2017]. There are over 50 light sources worldwide that are either operational or under construction [IAEA SRS]. Facilities around the world have constantly evolved and are classified as the first, second, third and fourth generation light sources, each stage marking significant development in the design of SR source by improving the photon brightness of the source, and reducing the electron beam emittance. First generation sources were not specifically designed as light sources, and it used the parasitic synchrotron radiation from the storage ring designed for high energy physics experiments. Second generation light sources were specifically designed to optimize the synchrotron radiation from bending magnets in the storage ring. This was followed by third generation light sources, where specially designed magnetic insertion devices were used to enhance the photon brightness. More recently, fourth generation light sources have become popular, which produce diffraction limited photon beam by reducing the electron beam emittance through innovations in the magnetic lattice of the storage ring. Indus-2, in India, is a nearly 3rd generation SR source, which operates with insertion devices. There are several operational 3rd generation machines worldwide, such as APS in USA, ESRF in Europe and Spring-8 in Japan that provide SR with much lower emittance (ε_n~few nm-rad) and a much higher brightness (upto ~10^{20} photons s^{-1} $mm^{-2}mrad^{-2}$ 0.1%BW^{-1}) as compared to Indus-2 (ε_n~135 nm-rad; brightness of SR from dipoles: ~10^{14} photons s^{-1} $mm^{-2}mrad^{-2}$ 0.1%BW^{-1}, brightness of SR from insertion devices: ~10^{17} photons s^{-1} $mm^{-2}mrad^{-2}$ 0.1%BW^{-1}). These parameters are well-known markers to assess the suitability of machine for performing contemporary R&D.

There has been a worldwide effort to design and build storage rings for generating SR with much lower emittances, *i.e.*, further down to the “diffraction limit”. There has been a great interest in constructing new SR facilities or upgrading the existing ones, to achieve significantly reduced emittance based on Multi-Bend Achromat (MBA) lattices. Storage rings use a lattice based on achromats having a certain number (say M) of bending magnets with suitably designed quadrupoles. Third generation light sources have typically used double or triple bend achromats. In an MBA lattice, one uses achromats with $M \gg 3$, which results in reduction of horizontal emittance since the emittance scales as ~ M^{-3} for a fixed circumference [Kim K.-J 2017]. Use of MBA was first proposed in 1995; however, its implementation posed several challenges and required significant R&D to be done.

The MBA lattice with its special dispersion function distribution helps in reducing the horizontal beam emittance in electron storage rings with larger numbers of dipole magnets. Currently, development of such sources is being actively pursued in other parts of the world, namely, Europe, USA, Japan, China, *etc*. The first MBA lattice-based SR source is MAX IV in Lund, Sweden, a 528 m circumference, 3 GeV, 500 mA storage ring, providing horizontal emittance of ~ 200-330 pm-rad, that started operation in mid-2016. Another such SR source is SIRIUS in Brazil, a 3 GeV storage ring with a circumference of 518 m, providing horizontal emittance around 280 pm-rad. The planned upgrade projects in the lower electron energy range include ALS-U at LBNL, USA; DIAMOND-II in the UK; SLS-2.0 in Switzerland; CLS-2.0 based on MBA lattice in Canada; Elettra-2.0 in Italy and SOLEIL-U in France.

The European Synchrotron Radiation Facility (ESRF) in France has upgraded the existing 6 GeV, 200 mA storage ring of nearly 844 m circumference to ESRF-EBS (Extremely Brilliant

Source) by adapting hybrid MBA design that has enabled reduction of emittance from 4000 pm-rad to about150 pm-rad. The facility has been opened for users in August, 2020.

The Advanced Photon Source (APS) at Argonne National Laboratory, USA has also recently upgraded its 7 GeV, 100 mA, 1100 m circumference storage ring to APS-U (upgrade) facility. It is a 6 GeV, 200 mA electron storage ring based on MBA lattice, designed to reduce the horizontal emittance to 41 pm-rad.

Since 2016, DESY in Germany has been pursuing R&D towards upgrading its PETRA III synchrotron light source (6 GeV, 100 mA, nearly 2300 m circumference storage ring) to a 4th generation light source (6 GeV, 200 mA) based on hybrid MBA lattice aiming for reduction in horizontal emittance from 1300 pm-rad to less than 20 pm-rad. The PETRA IV facility is expected to be operational by 2027.

The High Energy Photon Source (HEPS), being built in Beijing, China, is a 6 GeV, 200 mA, 1.3 km, ultra-low emittance (~ 50 pm-rad) storage ring light source that follows MBA design. The project is expected to be completed by 2025.

It is planned to upgrade SPring-8 synchrotron light source at RIKEN, Japan (8 GeV, 100 mA, storage ring of nearly 1400 m circumference) to a diffraction-limited X-ray source with an ultra-low emittance storage ring (6 GeV, 100 mA) with a target emittance value of ~100 pm-rad.

3.3 Free Electron Lasers

Free-Electron Lasers (FELs) are versatile, widely tunable, sources of coherent Electromagnetic (EM) radiation, which can be designed for operation around a desired wavelength, anywhere from the THz to X-rays [Kim K.-J 2017]. They utilize the interaction of a high-quality, short-pulse, relativistic electron beam with a transverse magnetic field, varying sinusoidally along the direction of electron beam, to produce ultra-short pulses of coherent EM radiation. There are two broad wavelength regions, where FELs have significant advantages over conventional radiation: (i) THz/IR wavelengths, where the conventional sources are not as easily tunable, or as powerful as FELs, and (ii) X-ray wavelengths, where conventional lasers do not exist and SR sources have peak brightness ten orders of magnitude smaller, and pulse widths two-three orders of magnitude broader, compared to FELs. We provide a brief summary of international status of R&D on FELs in these two broad areas.

There are around forty long-wavelength FELs around the world that are operating/ planned in THz/IR/Visible region [Neyman 2017]. Attached to many of the IR/THz FELs are user facilities that are being used for a variety of research in different areas of science and technology. On the frontier of high average power FELs, two FEL projects are notable. The Novosibirsk FEL in Russia, which has been operational since 2001, lases in the wavelength range 90-340 μm (FEL1) and 40-80 μm (FEL2) with an average power of 0.5 kW, and is the world's highest average power source of coherent narrow-band (less than 1%) radiation in this wavelength range. This FEL is based on an 8.5-13.4 MeV, 30 mA (FEL1) and 21-22.8 MeV, 10 mA (FEL2) NC Energy Recovery LINAC (ERL). The high average power FEL at the Jefferson Laboratory (JLab) is based on a 200 MeV, 10 mA SC ERL, which became operational in 2003. It lased at 1.6 μm with an average power of 14.2 kW, and is the highest average power FEL at this wavelength. Efforts at JLab later shifted more towards high average power operation in the UV.

X-ray FELs are based on the principle of Self Amplified Spontaneous Emission (SASE), which was proposed independently in Russia (in 1980) and in the USA (in 1983). Proof of principle experiments were demonstrated in different projects, first at longer wavelength (mm wave) and then subsequently at shorter wavelengths (IR, visible and UV) over the next decades. A soft X-ray FEL, the Free electron LASer at Hamburg (FLASH) was made operational in 2005 in Germany, which utilized a 1.25 GeV SC LINAC to achieve lasing up to the water window wavelength of 40 Å. The world's first hard X-ray FEL, the LINAC Coherent Light Source (LCLS), which became operational at SLAC, in 2009, is based on a 14.3 GeV NC electron LINAC and operated at 1 Å. Owing to the unique characteristics of radiation from an XFEL, groundbreaking experiments have been performed at ultrafast time scales to understand the fundamental processes of chemistry, materials and energy science, biology and technology. It required several breakthroughs, such as the photocathode gun technology, preserving the beam quality by controlling its emittance growth and implementing a laser heater to add a small energy spread to the beam to control the longitudinal instability. SLAC has recently developed LCLS-II, which is based on a 4 GeV SC LINAC such that it can be operated at a much higher repetition rate (1 MHz compared to the present 120 Hz). The SACLA X-ray FEL, based on a 400 m long, 8.5 GeV, NC C-band LINAC, and a compact undulator, became operational at the Spring-8 facility in Japan in 2011. The European XFEL Facility, based on a 17.5 GeV SC LINAC, became operational in 2017, and operates down to 0.5 Å. PAL-XFEL in Korea and Swiss FEL in Switzerland, both based on NC LINAC have also started operating since 2016 and 2017, respectively. Shanghai High repetition rate XFEL and Extreme light facility (SHINE), based on SC LINAC is under construction in China, and is expected to be commissioned by 2025.

The peak brightness of the XFEL is typically 10^{33} photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% BW^{-1}, which is around ten orders of magnitude higher than that of an SR source. Also, the pulse width of the radiation is around a femtosecond, which is two to three orders of magnitude smaller than that in an SR source, and allows us to investigate molecular dynamics, which is not possible in an SR source. In addition, radiation from an XFEL has good transverse coherence and spectral purity. In order to further improve the spectral purity, R&D efforts are going on towards different ways of seeding, such as external seeding by a laser at a sub-harmonic wavelength, and self-seeding by first lasing at a longer wavelength, then filtering the radiation using a monochromator and using the long wavelength monochromatic radiation to seed the SASE FEL at the next stage. FERMI FEL (FEL-1 operating at wavelength 20-100 nm and FEL-2 operating at 4-20 nm) is the first soft X-ray FEL in the world, which successfully demonstrated lasing with external seeding in 2010 to obtain stable pulses with reduced spectral width. Self-seeding was demonstrated in the hard X-ray LCLS FEL in 2012. An X-ray FEL oscillator (XFELO) [Kim 2017], which could provide bandwidth as narrow as a few meV is also under development at SLAC and DESY, using diamond crystals as Bragg reflectors for the optical cavity. Owing to these enhanced characteristics, XFEL is very attractive as a next generation light source. However, unlike an SR source, it will have smaller number of beamlines and thus can cater to highly specialized users (requiring either ultrashort pulse or ultra-high peak brightness), but fewer in number.

3.4 Spallation Neutron Sources

Neutrons are commonly produced either through a fission reaction in a nuclear reactor, or through a spallation reaction by bombarding a heavy metal target with energetic proton beam, after which the emitted neutrons are slowed down to meV energies, using a moderator [Lander 1986]. Typically, the nuclear reactors produce a continuous beam of neutrons, having a flux up to ~ 10^{14} n cm^{-2} s^{-1}. A spallation-based source has an advantage that it can give pulsed neutrons with high peak flux, which enables time-of-flight experiments, thus opening up a whole new range of possibilities for detailed investigations on novel materials for important applications. Spallation neutron sources are therefore, the principal way to produce pulsed neutron beam with high peak flux of ~10^{16} n cm^{-2} s^{-1}. In addition, unlike nuclear reactors, spallation-based neutron sources have no issues regarding proliferation or inventory of long-lived radioactive isotopes.

The first spallation neutron source, named ZING-P, was built at ANL, USA in 1974 using a 200 MeV, 20 W average power accelerator and generated a peak thermal neutron flux of ~ 10^{11} n cm^{-2} s^{-1}. ZING-P was forerunner of the next project named Intense Pulsed Neutron Source (IPNS), in the same laboratory in early 1980s, using a 450 MeV accelerator with an average beam power of 6.4 kW. During the same period, KEK Neutron Source (KENS) was built at KEK, Japan using a 500 MeV, 3.5 kW accelerator. Both IPNS and KENS generated a peak thermal neutron flux of ~ 10^{14} n cm^{-2} s^{-1} and pioneering research with neutron scattering was done at these places; it shows that cutting-edge science could be done with moderate intensities and moderate beam power. KENS and IPNS got decommissioned in 2005 and 2008, respectively. Subsequent to the commissioning of IPNS and KENS, an important milestone was reached in RAL, UK in 1985, where the ISIS[16] source was developed based on 800 MeV accelerator with an average beam power of 160 kW. In all these projects, the accelerator comprised an H^- injector LINAC, followed by a Rapid Cycling Synchrotron (RCS), where the injected beam was further accelerated and compressed to < 1 µs. LANL, USA commissioned its LANSCE source in 1986, based on 800 MeV, 80 kW injector LINAC, followed by a Proton Storage Ring (PSR) to compress the injected beam from the LINAC, without accelerating it further. Such compressor rings are known as Accumulator Ring (AR). A CW spallation neutron source, called SINQ, was commissioned at PSI, Switzerland in 1996, which is based on 590 MeV, 1.4 MW accelerator. This accelerator comprised 870 keV Cockcroft-Walton accelerating column, followed by a 72 MeV, 4-sector cyclotron and 590 MeV, 8-sector cyclotron. Since this is a CW machine, the peak neutron flux is ~10^{14} n cm^{-2} s^{-1}. In the last two decades, remarkable advancements in this technology have been realized through the demonstration of MW-class pulsed accelerator driven SNS at ORNL, USA in 2006 [Mason 2006, Kim S.-H 2017], and also at J-PARC, Japan in 2008 [Futakawa 2011]. The SNS at ORNL uses an accumulator ring after the 1 GeV, 1.4 MW, SC LINAC, whereas the J-PARC machine uses a 3 GeV, 1 MW RCS after the 400 MeV, NC injector LINAC. One of the major challenges in developing a MW-class SNS is to ensure a small beam loss (<1 W m^{-1}) in the accelerator, to keep the induced radioactivity acceptable. Another challenge is to take care of the thermal shock, as this beam strikes the spallation target. Both the machines are indeed milestones, being the world's first MW-class machines, where the aim of high peak neutron flux of ~ 10^{16} n cm^{-2} s^{-1} has finally been achieved. The accelerator for SNS at ORNL is going to get upgraded to 1.3 GeV, 2.8 MW by 2025.

More recently, CSNS in China, which is based on a 1.6 GeV, 100 kW accelerator and having neutron flux similar to ISIS, has been commissioned in 2017 and an upgrade to 500 kW is planned in the next phase. China is also working on a Compact Pulsed Hadron Source (CPHS), which will be based on a modest 13 MeV, 16 kW pulsed proton LINAC to establish a medium flux, university-based neutron source for multidisciplinary research and neutronics/device development [Loong 2010]. A new SNS project, the European Spallation

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[16] Interestingly, ISIS is not an acronym, it is the name of an ancient Egyptian goddess who could restore life to dead!

Source (ESS) at Lund, Sweden is at a very advanced stage. The ESS will be based on a 2 GeV, 5 MW LINAC. It will not have an accumulator ring[17], and neutron pulse length will be ~2-3 ms, unlike ~100 μs for the case of accumulator ring or RCS based machines. This will, however, generate a high peak flux of ~ 10^{18} n cm^{-2} s^{-1} due to the high average power of the accelerator.

3.5 Heavy Ion Linear Accelerators

A nucleus with mass number greater than 4 is typically referred to as heavy ion. Electrostatic accelerators such as the Van de Graff accelerator and the Pelletron provide excellent beam quality for precision nuclear physics experiments with heavy ions. The maximum energy of such accelerators is, however, limited to a few hundreds of MeV and is governed by the maximum terminal voltage that can be sustained. In order to increase the beam energy further, heavy ion booster linacs are added. These boosters use resonant cavities operating at radio frequencies in the range of few tens to few hundreds of MHz to accelerate heavy ions. The cavities can be either normal conducting copper cavities operating at room temperature or superconducting structures operating at liquid helium temperatures, the latter being the preferred choice in the present day linacs. The use of superconducting technology for heavy ion acceleration started in the late 1960s and early 1970s, stimulated by the development of the helix accelerating structure, using niobium as the superconductor, at Karlsruhe (Germany) and Argonne National Lab (ANL),USA; and lead plated on copper at California Institute of Technology(CalTech), USA. The helix was soon replaced with the Split Ring Resonator (SRR), which provided better mechanical stability, and hence improved phase control during operation. The ANL superconducting linac, and the booster linac at Stony Brook, USA were the first heavy ion machines, which got commissioned in the late 1970's and early 1980's [Delayen 1989, Nolen 1994]. Both machines used superconducting SRRs as the accelerating structures. While bulk niobium was the material of choice for the ANL linac, the accelerator at Stony Brook used lead plated on copper as the superconducting material for the resonators. A large number of laboratories have since then successfully built superconducting linacs for heavy ions. Noteworthy among them are, the ALPI facility at LNL, Italy; the ISAC and ISAC II facilities at TRIUMF, Canada; the SC linac facility at JAERI, Japan; the FRIB heavy ion linac at MSU, USA and the boosters at Australian National University and the University of Sao Paulo, Brazil. Majority of these machines that initially served as boosters to the tandem accelerators, are now using an Electron Cyclotron Resonance (ECR) source followed by a normal conducting/superconducting Radio Frequency Quadrupole (RFQ) and a normal conducting Drift Tube Linac (DTL), or a RFQ followed by superconducting cavities for very low velocity ions as the alternate injector. This has resulted in manyfold increase in the beam intensities (typical beam currents ranging from few hundreds of pnA to few pμA) available for the experiments. A wide variety of accelerating structures have been developed and used in these accelerators viz. the Quarter Wave Resonator (QWR), which were used for the first time for the development of superconducting booster linac in Weizmann Institute, Israel; the Interdigital Resonator for very low velocity ions; Half Wave Resonator (HWR); the Single Spoke Resonator (SSR) and MultiSpoke or Crossbar H mode (CH) cavities, *etc*.

In the early stages of development of the superconducting RF technology for accelerators, both niobium and lead were used as the superconducting materials in the fabrication of the accelerating cavities. However, owing to its better superconducting properties (resulting in

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[17] It is however planned to have an accumulator ring, following ESS, to compress the beam for ESS neutrino Super-Beam (ESSnuSB) facility.

higher accelerating gradients) and relative ease of handling the accelerating cavities, bulk niobium has become the material of choice for all the present day accelerators. An alternative in the form of niobium thin films sputtered on copper has also been used in cavity fabrication at CERN and at LNL, and QWRs built using the sputtering technique are being used for beam acceleration in both the laboratories. Although these cavities achieve very high quality factors at lower gradients (even higher than the bulk niobium cavities with identical geometry), their Q value degrades sharply with increasing field levels, and they are not able to match the performances at higher operational gradients. The sputtering technology thus still needs to mature before its full-fledged use in accelerators. A lot of R & D is also going on in using materials with better superconducting properties than niobium, as the material for cavity fabrication. One of the foremost contenders in this field is Nb_3Sn, which, owing to its higher critical temperature T_c and critical magnetic field H_c values, can fundamentally generate higher accelerating voltages. The technology of building Nb_3Sn cavities by diffusion of tin vapours in niobium however still needs to be perfected before its use in large accelerator facilities.

The R&D on superconducting heavy ion booster linac, using bulk niobium cavities, is focussed on increasing the real estate gradient in accelerators, in order to make the machines compact. In this direction, at GSI, Germany, a multi-gap Crossbar H-mode (CH mode) linac has been successfully demonstrated, where a high beam intensity (~1.5 pμA) has been achieved [Barth 2018]. Design optimizations of the existing accelerating structures for heavy ions have been carried out to reduce the peak fields on the RF surface vis-à-vis improving the mechanical stability of the structure. This has allowed the new cavities to operate at a significantly higher gradient than the older designs, for example the $\beta = 0.077$ QWRs in the ATLAS accelerator at ANL, installed and commissioned in 2013, have operated at an average gradient of 7-8 MV/m as opposed to 3-4 MV/m, achieved with the older split ring cavities. The surface treatment and handling techniques of the heavy ion superconducting cavities have also witnessed significant advancements over the past two decades, taking clue from similar developments for electron cavities. Separation of the cavity vacuum from that of the cryomodule, use of electropolishing for a better surface finish, high pressure rinsing, heat treatment and use of class 10/100 clean rooms for assembly of the cavity strings have resulted in improved average gradients over the years.

3.6 Room Temperature and Superconducting Cyclotrons

Since its invention by Lawrence and Livingston in 1931, the cyclotron has evolved in various forms with added features to improve in terms of energy and beam intensity. With the incorporation of new technology such as superconductivity to utilize higher magnetic field in the range of 5-7 Tesla, cyclotrons could produce even higher energy beams (~200 MeV/A) covering the entire periodic table. Cyclotrons have been the most widely used accelerators in their various forms, such as, classical cyclotrons, synchrocyclotrons (frequency modulated cyclotron), Azimuthally Varying Field (AVF) cyclotrons, separated sector cyclotron, SC cyclotrons, *etc*.

Some of the landmark developments in cyclotron R&D include [Pandit 2019]:

- 184-inch[18] 200 MeV synchrocyclotron at Berkeley was built in 1946.
- Highest beam energy from a synchrocyclotron at Gatchina, Russia reaching 1 GeV.

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[18] This indicates the pole diameter of the magnet

- In 1958, the first AVF proton cyclotron was built at Delft, Netherlands and by 1970, forty AVF cyclotrons were already in operation worldwide.
- 520 MeV AVF cyclotron at TRIUMF, Canada (Spiral poles, H^- acceleration, Meson Factory) and it is a 56-ft cyclotron with the largest diameter of its kind.
- 2.5 m diameter AVF cyclotron at PSI Switzerland, 590 MeV High Intensity Ring cyclotron at PSI Switzerland (Meson Factory).
- *K*-500, the world's first SC cyclotron at NSCL, Michigan State University, USA; the extraction of first beam of particles in 1982, and *K*-1200, the second SC cyclotron produced stable ion beams in 1989.
- Subsequently, SC cyclotrons were built at Texas, USA (*K*-800); Catania, Italy (*K*-800); AGOR SC cyclotron facility at University of Groningen, NL (*K*-600); Chalk River SC cyclotron, Canada (*K*-520).
- A 4-m SC cyclotron with separated orbit channels (TRITRON) for acceleration of heavy ions up to 21 MeV/A, commissioned in 1997 at Munich, Germany.

Cyclotron based Radioactive Ion beam facilities:

Cyclotrons have been in use in Radioactive Ion Beam facilities, some of which are mentioned below [Chakrabarti 2021]:

- SPIRAL-2 of the GANIL, France accelerator complex is the newest RIB facility.
- At MSU, USA, the *K*-500 and *K*-1200 coupled cyclotrons-based RIB facility (projectile-fragment).
- Dubna Radioactive Ion Beams (DRIBs) at the JINR accelerator facility at Dubna, Russia. The cyclotrons used in this facility produce and accelerate neutron-rich exotic isotopes of light elements such as ^{6}He and ^{8}He.
- *K*-540 RIKEN Ring Cyclotron (RRC) at the RI Beam Factory (RIBF), an old RIKEN accelerator facility in Japan, operational since 1986, provides the world's most intense low atomic mass (<60) RI beams.
- *K*-570 fixed-frequency, *K*-980 intermediate-stage ring and *K*-2500 SC separated-sector ring cyclotrons are the three new RIBF facilities that can boost energies of the output beams from the RRC up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions.
- TRIUMF-ISAC Radioactive Ion Beam Facility, where short-lived isotopes are produced by the ISOL method, using a beam of up to 100 µA of 500 MeV protons from the TRIUMF H^- cyclotron, which bombards thick production targets.

It is worth mentioning that Linac based RIB facility is also of interest. One example is the envisaged BISOL project in China.

High power cyclotron for neutrino physics research:

Cyclotrons have been used for neutrino physics research too. Two high-power cyclotrons exist for DAEδALUS (Decay At rest Experiment for δ studies At the Laboratory for Underground Science) program in USA, to produce 60 MeV/A and 800 MeV/A beams. The former provides the injector to the latter, which can then produce pion/muon DAR (Decay At Rest) neutrino fluxes. The injector can also be used by itself to produce isotope DAR beams.

3.7 Industrial Accelerators

For ion implantation, low and medium energy accelerators ($\leq$ 400 keV) with modest current (up to 500 μA) are available commercially, and a large number of these accelerators are used worldwide for semiconductor device manufacturing, particularly for doping of CMOS channels, and also for improvement of surface properties of metals, ceramics and polymers. For processes requiring higher dose (up to 10^{18} ions cm^{-2}) and higher depth, ion accelerators based on RF LINAC have also been developed with higher energy (few MeV) and higher current (few mA) [Sessler 2014].

Development of electron beam irradiation accelerators in Europe, USA, Canada, Russia, Japan, China, *etc*., has reached an advanced stage to meet the required performance levels for various applications. On the basis of strong support from publicly funded R&D institutions for large accelerator programs and high-quality performance level achieved by these machines, the industry in these countries is able to manufacture and export their machines to meet worldwide demand for applications. For electron beam irradiation applications, RF LINACs with beam energy of 10 MeV and beam power up to few tens of kW are commercially available. High power Rhodotron accelerators were developed in 1980s by a group of researchers from CEA, France, which are based on accelerating the electrons repeatedly through a single coaxial resonant cavity [Sessler 2014]. The patented design of Rhodotron is licensed to IBA, Belgium, for its commercial production. The US postal service uses a 130 kW Rhodotron to sanitize the mails.

Cargo scanning and radiography are other important applications for which although electron accelerators are available commercially, R&D is ongoing on to meet new requirements of performance enhancement. For Cargo scanner, in order to perform elemental analysis, it is required to have a LINAC with fast energy tuning, operating in the mode of interlacing pulses, alternately with low- and high-energy. Such RF LINACs have been developed during the last decade in ScanTech Sciences, LLC, Russia and Radiabeam Technology, LLC, USA [Kutsaev 2017].

Development of electron accelerator for treatment of flue gases (SO_x and NO_x), which are produced when we burn fossil fuels, has been of great interest in several countries, such as Japan, Germany, USA, Poland and China [Torims 2020]. Typical beam energy is 0.7-0.8 MeV, beam power 40-160 kW, for flue gas flow rate of 20,000-30,000 N m^3 hr^{-1}.

For wastewater treatment, electron accelerators have been developed and installed in several countries [Han 2006]. In Korea, a wastewater treatment plant was commissioned in 2005, utilizing a 1 MeV, 400 kW DC accelerator. The plant has a capacity to treat 1000 m^3 per day of industrial wastewater. With technology transfer from the IAEA, China has installed and commissioned a wastewater treatment plant in 2020, utilizing electron beam technology, with 30,000 m^3 per day capacity, which is the largest wastewater treatment facility using electron beam technology in the world.

In modern times, giant cluster ions such as C-60 or Si-100 and fine metal particles also have lot of applications. Accelerators that can accelerate those particles are limited. Electrostatic accelerator and Linear/Circular Induction accelerator only can work for this purpose. Induction synchrotron and induction microtron are unique solutions to obtain high energy giant cluster ion beams. In Japan, the slow and fast cycling induction synchrotrons have been operated at KEK from 2003 to 2019. In China, an induction synchrotron is considered at Institute of Fluid Physics, an induction storage ring is under design for the THz FEL at Tsinghua University. In India, a compact fast cycling induction synchrotron is under design at

SAMEER. Laser Ablation Ion Source (LAIS) is becoming attractive as a heavy ion source from low charge-state to high charge-state. In Japan, the development of LAIS using frozen gas targets or liquid metal targets that ensure effectively infinite life of heavy ion sources is quite active. Their entry into heavy ion accelerators is expected to take place within 5 years.

3.8 Medical Accelerators

One of the earliest applications of particle accelerators that was visualized, was the medical application, particularly cancer treatment. Later, the usefulness of radioisotopes in medical diagnostics, and targeted therapy, was also recognised, where accelerators play an important role, along with nuclear reactors. We describe below the international scenario of utilization of particle accelerators for such applications.

Medical Cyclotrons for isotope production

Cyclotrons for production of biomedical radionuclide are generally compact, use light ions, viz., H^+, H^{2+}, He^{2+}, and accelerate them in the energy range of 3-70 MeV with a beam intensity up to a few hundreds of μA. They are used to produce short-lived PET isotopes, and also the long-lived PET generators and SPECT isotopes.

At present, the global manufacturers of medical cyclotrons are IBA, SIEMENS, GE, SUMITOMO, *etc.* Some of the well-known commercial companies that produce radioisotopes using cyclotrons are listed in Table 3.8.1.

Table 3.8.1: International companies manufacturing cyclotrons for radioisotopes

Company name	Particle	Beam Energy (MeV)	Beam current (μA)
ACSI	H^- /(D^-)	14, 24, 19 (9) / 30/ (15)	>100, >300
ABT	H^+	7.5	5
BEST	H^-	7.5, 14, 15-35,70	5, 100, 1500, 800
CIAE	H^-	14, 70	400, 750
NIIEFA	H^-/ D^-	18/9	100/50
EUROMEV	H^-	12	100
GE	H^-, H^- /D^-	9.6, 16.5/8.6	50, 100/65
IBA	D^+, H^-/D^-, H^+ H^-/D^- H_2^+/He^{2+}	3.8, 10/5, 11, 18/ (9), 30/ (15), 30-70 / (15-35) 17.5 /70	60, 100/ (35) 120 150, 500 50/ (35)
KIRAMS	H^-	15-30	500
SIEMENS	H^-	11	40
SUMITOMO	H^-/ D^-	7.5/3.8, 9.6/4.8, 12/6, 18/10	60 / (30)

LINACs for radioisotopes production

Apart from the commercial medical cyclotrons, electron and proton LINACs are also used for production of radioisotopes. LINACs can deliver higher beam current compared to cyclotrons.

Some examples are given below:

- *Isotope Production Facility (IPF)*

IPF uses 100 MeV H^- LINAC at Los Alamos Neutron Science Centre, which was a precursor to SNS, to produce radioisotopes $^{68}_{32}Ge/^{68}_{31}Ga$, $^{225}_{89}Ac$ and $^{82}_{38}Sr/^{82}_{27}Rb$. The beam current in the LINAC is 225 µA, and there is a plan to upgrade it to 300 µA.

- *Brookhaven LINAC Isotope Producer (BLIP)*

BLIP uses the excess beam capacity of their 200 MeV proton LINAC injector for the synchrotron to produce isotopes, which are crucial for nuclear medicine for both research and routine clinical use, and which are generally unavailable elsewhere. The radionuclides presently producible at BLIP are ^{7}Be, ^{28}Mg, ^{52}Fe, ^{65}Zn, ^{67}Cu, ^{68}Ge, ^{82}Sr, ^{83}Rb, $^{95m,96}Tc$, ^{97}Ru. and ^{225}Ac. The average LINAC beam current has increased from 30 µA in 1982 to 200 µA in 2019. There is a plan to upgrade beam current to 250 µA. There is also a proposal for Centre for Linac Isotope Production (CLIP), which will include proton energy upgrade to 600 MeV with an average beam current to 200 µA, and a light ion linac with 60 MeV/A with an average beam current 200 µA.

- *Argonne's Low-Energy Accelerator Facility (LEAF)*

This facility consists of 50 MeV, 20 kW electron LINAC and a 3 MeV Van de Graff electron accelerator. It produces ^{99}Mo through sub-critical fission of low enriched Uranium and also through (γ, n) reaction on ^{100}Mo target. In addition, it produces ^{67}Cu and ^{47}Sc.

- *IDAHO Accelerator Centre (IAC)*

This facility has 40 MeV electron LINAC for medical isotope (^{67}Cu) production.

In addition to the above, mention must be made of 50 MeV, MW-class superconducting electron linacs, which have been envisaged in few of the projects for ^{99}Mo production. There is a project at TRIUMF, Canada, and also a plan for such a project using the technology of conduction cooled Nb_3Sn cavity at Fermilab, USA.

Medical accelerators for therapy

Some of the commercially available accelerators for cancer therapy are the proton cyclotrons from IBA, SUMITOMO, VARIAN *etc.*, and carbon therapy synchrotrons from TOSHIBA, HITACHI *etc*. Out of the 123 functional hadron therapy machines worldwide, 109 are proton therapy machines, mostly based on cyclotrons delivering 230 MeV fixed energy [PTCOG]. Only 14 facilities deliver around 400 MeV/A energy carbon ions based on synchrotrons. Some treatments benefit from the use of particles that deliver doses with a greater radiobiological effectiveness (RBE), notably carbon ions, almost three times that of protons. A lot of research is going on in exploring other ions for therapy such as those of helium, oxygen and argon to maximize on RBE and Oxygen Enhancement Ratio (OER). The gantry in a therapy machine is a rotating arm, which delivers the beam precisely to the patient from any direction. Normally, gantry for hadron machine is a huge mechanical structure, which is very expensive. Out of the above-mentioned 14 carbon ion therapy machines, few are commercially available from TOSHIBA, Japan. They have developed a SC gantry which is much more compact than the Heidelberg Ion Therapy machine in Germany. Proton cyclotrons are available from IBA, Belgium, and they are the leaders in providing proton therapy machines in the world. The main research as of now in particle therapy is integration of imaging devices for image-guided radiation therapy (including MRI). The integration of measuring devices for dose reconstruction (for example, transit dosimetry, prompt gamma, acoustic signals) is the area which is being given maximum focus as of now. New dose delivery techniques, like FLASH, using protons are also under study [Lin 2021, Patriarca

2020]. In FLASH radiotherapy, irradiation at dose rates far exceeding those currently used in clinical contexts is given in bursts, and due to "FLASH" effect, this reduces radiation-induced toxicities while maintaining an equivalent tumour response. First human patient was given this therapy in 2018 in Switzerland. The international research is now focussing to make the footprint small, and to reduce the cost of particle therapy machines. Likewise, at CERN, with vast experience of designing LHC SC magnets, efforts are focussed to see if SC magnets can reduce the footprint of the machine, and in this regard, they have recently worked on the design of a non-rotating toroidal gantry GaToroid. Provision for multi-ions for treatment is also being made at the design stage. With these criteria, synchrotron design with fast and slow extraction possibility, upgraded injector section, multi-ion delivery beamlines and compact gantry are under design. Recently, design study was initiated at CERN to study implementation either of i) a NC synchrotron, ii) a SC synchrotron, or iii) a LINAC based system. The designs are under review as a part of the New Ion Medical Machine Study (NIMMS) and projected timeline is 2035 for completion of the studies.

Commercially available, advanced radiotherapy machines offer state-of-the-art technology in radiotherapy, but at a very high cost. These machines are capable of delivering Intensity Modulated Radiotherapy (IMRT) or Volumetric Arc Therapy (VMAT). These techniques use the information of the tumour from CT/MRI so that doctors can decide accurate dose delivery. As of now, much of the cost goes in control and delivery of the dose to achieve the complex IMRT techniques. A new and emerging area is Magnetic Resonance Linear Accelerator (MR-LINAC), a combination of an MRI scanner and a LINAC, in which in-situ images will benefit in Image Guided Radiotherapy.

3.9 Accelerators for Accelerator Driven Systems

There are a number of countries that have interest in ADS. Of these, the most active (besides India) are the following:

China:

The Chinese ADS program (CADS) was launched in 2011. It envisaged three steps: (i) a 50 MeV, 10 mA, proton accelerator driving a 5 MWth[19] sub-critical reactor; (ii) extending the beam energy to 600 MeV, to an ADS Experimental Facility of 80-100 MWth, through a liquid metal target; (iii) a full-scale 100 MWth ADS Demonstration Facility, with a 1.5 GeV, 10 mA proton beam. After this stage, the technology will be transferred to industry. Quite recently, commissioning of China ADS Demo Linac was completed, demonstrating 0.2 mA 25 MeV CW proton beam and the 12 mA, 26.2 MeV pulse beam [Liu 2020]. In order to increase the power in CW mode, in February 2021, after encountering many difficulties and set-backs, including damage to the accelerating cavities that necessitated replacing them, the goal of 20 MeV, 10 mA has been achieved . The accelerator has been operated at 93-96% duty factor, for a period of 108 hours at 7.3 mA (126 kW) and 12 hours at 10 mA (174 kW). This is the first CW SC proton LINAC in the world to approach the 200-kW level.

Europe (Belgium):

The Multipurpose Hybrid Research Reactor for High-tech Applications (MYRRHA) project in Belgium plans to demonstrate the ADS concept with a 600 MeV SC proton LINAC coupled through a liquid Pb-Bi spallation target to a 57 MWth sub-critical reactor with a Pb-Bi cooled subcritical fast core. In 2020, MYRRHA has successfully accelerated a 4 mA (peak) pulsed

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[19] MWth stands for Mega Watt - thermal

(200 ms, 0.5 Hz) beam through its 1.5 MeV radio-frequency Quadrupole (RFQ). The next step is to install CH cavities to accelerate beam up to 5.9 MeV. Construction of the MYRRHA reactor is expected to begin in 2026, with full operation from 2034.

Japan:

In Japan, the ADS program is centered around a 1.5 GeV, 20 mA proton LINAC driving 800 MWth sub-critical reactor, cooled using a lead-bismuth eutectic (LBE). This ADS system can transmute around 250 kg of Minor Actinides per year.

In addition to building accelerators for producing energy through controlled fission, there has been interest in building accelerators for supporting the research and development for fusion reactors too. One example is IFMIF, which is a multi-national project, based on two 5 MW CW deuteron accelerators.

3.10 Laser Plasma Acceleration

Laser Plasma Acceleration (LPA) is a new acceleration technique that can provide accelerating gradients three orders of magnitude greater than those available in conventional RF accelerators. Such large acceleration gradients (~ GV cm^{-1}) can be produced in a plasma medium by an intense ultra-short (femtosecond regime) laser pulse generated by high peak power (~100 TW to 1 PW) Ti:Sapphire laser systems, developed using the Nobel Prize (2018) [Mourou 2019] winning technique of Chirped Pulse Amplification (CPA). An intense, focused laser pulse leads to rapid ionization and plasma formation in a variety of materials (solid, gas, gas-clusters and liquid) and subsequent particle acceleration in the created plasma medium. For proton/ion acceleration, the high-power laser is focused on a high-density, thin (sub-µm to few µm thickness) metallic foil plasma, and proton/ion acceleration occurs at the rear surface of the metal foil due to huge sheath field (~TV m^{-1}) set up by the escaping high-energy (several MeV) electrons. For electron acceleration, the high-power laser is focused inside a low-density gas plasma (of length few mm to several cm). The electron beams generated by LPA possess a number of unique properties, such as ultra-short pulse duration of the order of the laser pulse (few femtosecond), and high peak currents. This makes them attractive for the development of compact, tunable (sub-keV to several MeV photon energy) X-ray/γ-ray sources, *i.e.*, so called Laser Synchrotrons. R& D is also going on towards using Laser plasma accelerators for radiation therapy, production of medical isotopes, and also as an injector to a conventional accelerator.

Impressive progress has been made in this vital area of research and development of advanced particle accelerators in the last two decades [Tajima 2020]. Generation of 8 GeV electron beams in a plasma length of 20 cm has been demonstrated using a PW Ti:Sapphire laser at LBNL, USA. LPA driven X-ray/γ-ray sources using betatron radiation and inverse Compton scattering process have been developed, and, possible applications have been demonstrated. Suitability of laser plasma electron accelerator for development of a compact FEL has also been demonstrated. At GIST, Korea, acceleration of protons to > 70 MeV energy in few microns of solid target plasma has been achieved, implying an acceleration gradient of ~TV m^{-1}. Still, several challenges remain. Reducing the energy spread to that demonstrated by RF accelerators is important, as is beam pointing and stability. Precise control of laser and plasma parameters is needed for the generation of high-quality, high current beams. Operation at high repetition rate would depend on the development of high-power laser technology for these repetition rates. The main challenge towards developing high-energy laser plasma accelerators is to sustain the acceleration over longer plasma length, which necessitates multi-stage acceleration, a technique also being investigated and proposed for development of future particle colliders based on plasma acceleration technique. Lastly, future development on laser systems providing ultra-short-duration pulses with several joules of energy at high repetition rate (100 Hz to kHz) would significantly impact the field of Laser Plasma Acceleration and its potential for various applications. Worldwide, efforts are also being made for developing suitable laser technology in this regard.

Globally, considerable R&D is being performed, through experiments, theory and simulations, to obtain a deeper understanding of the associated high-field laser and plasma physics and underlying acceleration mechanisms, and to address the issues listed here. On the electron acceleration front, suitable conditions for generation of high-energy (> GeV), low-divergence (few mrad), quasi-mono energetic (of energy spread 1-10%) electron beam have been identified. Similarly, efforts are underway for generation of high-energy (50-250MeV), proton beams with low divergence and energy spread, which has not been possible till date. Generation of high-quality (comparable to RF accelerators) beams is important for several applications. In this regard, suitable beam transport systems for LPA generated electron/proton beams are also being considered, investigated and developed.

Several countries, such as USA, Canada, U.K., France, Germany, Italy, Japan, Russia, China, Korea *etc*., have extensive programs on the development and utilization of LPA for X-ray/γ-ray sources (Laser Synchrotrons). Tremendous progress has taken place on the development of CPA-based high-power laser systems. Around the world, today nearly a hundred 100 TW systems are operating, and around twenty PW lasers are existing or under construction. In USA, several national labs and universities are engaged in this field. At LBNL, USA, under the Berkeley Lab Laser Accelerator (BELLA) project, it is aimed to develop 10 GeV electron and proton/ion accelerators. In Europe, Rutherford Appleton Laboratory (RAL), UK, and Ecole Polytechnique, France, have played crucial role in taking this technique forward to the level where it is today. Based on the expertise gained by various European countries, an ambitious collaborative project named ELI (Extreme Light Infrastructure) is underway. In this project 1-10 PW laser systems are being set up at three locations, namely, The Czech Republic, Romania and Hungary, and shall be used for high-field R&D of laser-plasma particle accelerators. In Asia, in addition to Japan and Korea, China is following this vital area of research and has demonstrated significant technological development during the last two to three decades. Shanghai Institute of Optics and Fine Mechanics (SIOM) has developed and demonstrated technological capabilities in the field of ultra-short, high-power lasers towards development of several PW to 100 PW class laser systems. At several institutes/ universities in China, high-power laser facilities have been set-up or are under installation for investigations on laser plasma particle acceleration and associated medical applications.

In addition to the Laser Plasma Acceleration (LPA), many other schemes under advanced acceleration techniques are also being explored and investigated worldwide. Among these, Inverse Free Electron Laser (IFEL) and Dielectric Laser Accelerator (DLA) are worth mentioning. In IFEL, an intense, ultra-short duration laser electric field is used to accelerate co-propagating electron beam through a suitable magnetic undulator. R&D on this scheme has shown to have potential for development of future compact accelerators of several MeV to 100 MeV energy through intensive investigations, particularly performed at Accelerator Test Facility, Brookhaven National Laboratory (BNL), USA. DLA scheme uses ultra-short duration laser pulses and dielectric microstructure, and R&D on this scheme has also progressed well during the last decade, although it is suitable for acceleration of electrons to comparatively lower energy (100s of keV to MeV) range.

4. National Scenario in the field of Accelerator R&D

After having discussed the international status of R&D in important areas of accelerator science and technology, we discuss the national scenario in this area of R&D.

4.1 Accelerators for Nuclear Physics Studies

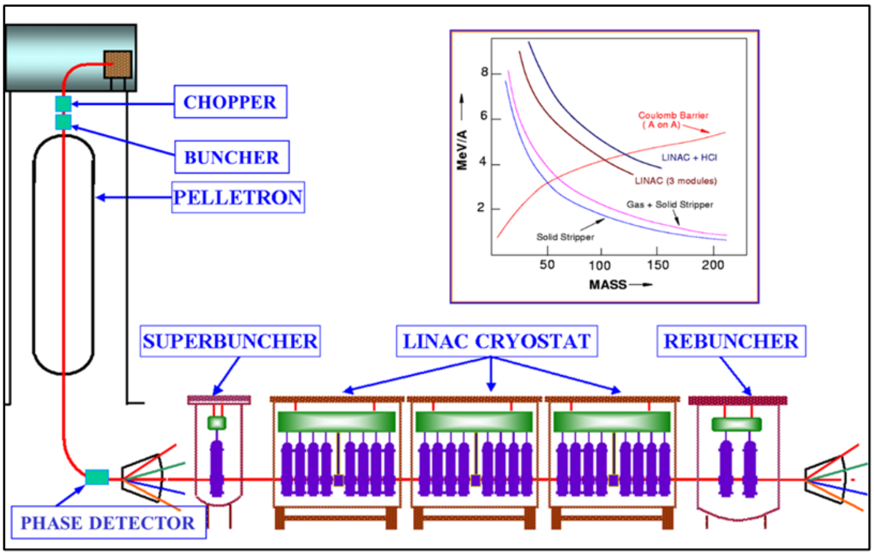

Fig. 4.1.1: Schematic of the 16 MV Pelletron along with the Superconducting Linac of IUAC as energy booster. The inside figure shows the energy per nucleon required to overcome the Coulomb barrier, along with the energy available from accelerators and their combinations e.g. Pelletron (for Solid stripper, and for Gas+Solid Stripper), Pelletron + Linac and High Current Injector + Linac.

In India, the accelerator facilities for pursuing experimental nuclear physics research using stable ions now exist at three accelerator centres, viz., two medium-energy (few tens of MeV) heavy ion Pelletron accelerators - one at IUAC, New Delhi (see Fig. 4.1.1) and the other at BARC-TIFR, Mumbai (see Fig. 4.1.2) [Nanal 2018]; and a room temperature variable energy cyclotron (*K*-130) at VECC, Kolkata (see Fig. 4.1.3). In the past few decades, SC LINACs have been added to the pelletrons of IUAC [Ghosh 2009] and BARC-TIFR [Nanal 2018], in order to boost the beam energies. A high-current injector (HCI) based on a high-temperature superconductor ECR source[20], capable of producing metal and inert gas ions with higher beam current, is in the final stage of commissioning at IUAC (see Fig. 4.1.4). The design goal of HCI has been successfully validated [Hariwal 2022] and its integration with the SCLINAC will be initiated soon. The Pelletron facilities provide heavy ion stable beams at energies of 5-6 MeV/A for projectiles up to A ~ 50. *K*-130 cyclotron provides 7-15 MeV proton beam, 28-60 MeV alpha beam and 8-10 MeV/A heavy ion beams. All three facilities provide heavy ion beams with energies in the region of the Coulomb barrier. In addition to all these, there are small accelerators in universities, such as the 3 MV Pelletron accelerator at Guru Ghasidas University and Institute of Physics, 1.7 MV Tandetron at IIT Kanpur, and an old variable energy cyclotron at Panjab University, which have also contributed to nuclear physics research in the country. The nuclear physics experiments performed using accelerators can be classified broadly into two groups: nuclear reactions such as fission, fusion, scattering, *etc.* around the Coulomb barrier, and nuclear spectroscopy.

A SC *K-500* cyclotron has been built at VECC, Kolkata (see Fig. 4.1.5), which provides beams of still higher energies in the range 10-40 MeV/A [Debnath 2021]. An ISOL type facility for RIB research is developed at VECC, Kolkata using *K*-130 cyclotron as the driver

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[20] High-temperature superconductor ECR source utilizes coils of high T_c superconductor to produce higher magnetic field for electron cyclotron resonance, to produce high currents of highly charged ions.

accelerator (see Fig. 4.1.6) [Naik 2023]. It has a charge breeder and separator, followed by an RFQ and Inter-digital H-mode (IH) heavy ion linacs – LINACs 1-3, which have been commissioned that gives RIBs having energy upto 415 keV/A. LINAC 4 has been installed after that, which will increase the energy to 1 MeV/A. There is a plan to add superconducting Quarter Wave Resonators (QWRs) to further accelerate the RIB. A SC electron LINAC is being added as driver accelerator to the RIB facility at VECC. In years to come, the Indian nuclear physics community is considering further large-scale accelerator facilities for research with RIBs, studies towards SHE, nuclear astrophysics, *etc*.

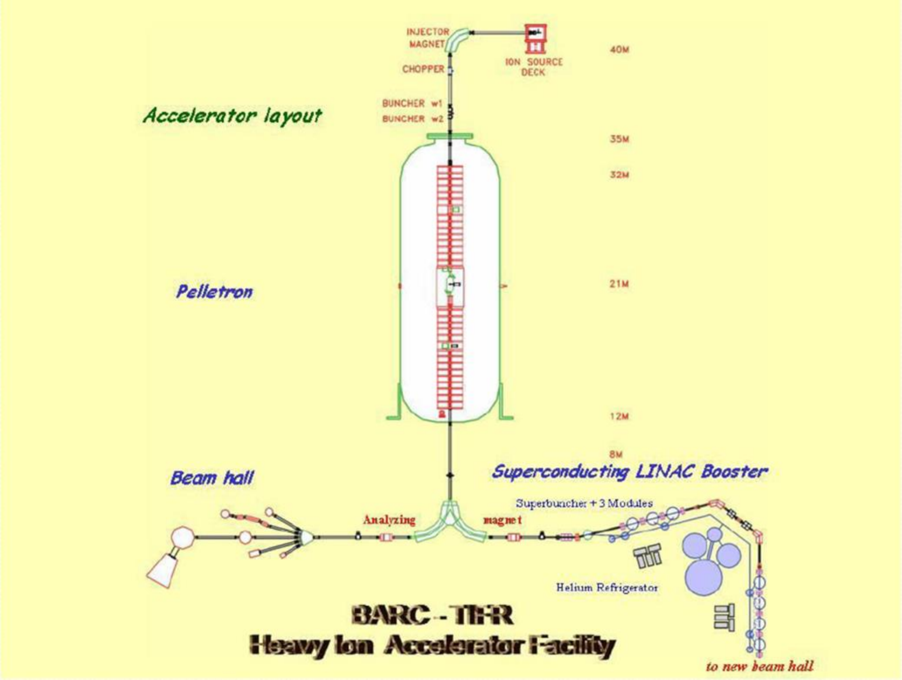

Fig. 4.1.2: Schematic showing the BARC-TIFR heavy ion accelerator facility.

Fig. 4.1.3: Photograph of K130 Room Temperature Cyclotron at VECC, Kolkata.

A 6 MV Folded Tandem Ion Accelerator (FOTIA) was commissioned in 2000 at BARC for basic and applied research [Singh 2002]. The negative ions, extracted from a SNICS-II ion source at 150 keV, subsequently accelerated up to 6 MeV in a low energy accelerating tube, are stripped off their electrons to become positive ions (n^+). These energetic ions are sent into the second accelerating tube mounted in the same column section leading to total energy of (n+1) × 6 MeV.

All these accelerators have been used to perform high impact research in our country in areas such as nuclear fission [Ramamurthy 1990], nuclear fusion [Tripathi 2002], cluster structure of light nuclei [Datar 2013], nuclear level density [Rout 2013] nuclear spectroscopy [Matta 2015], and Atomic and condensed matter physics [Misra 2004].

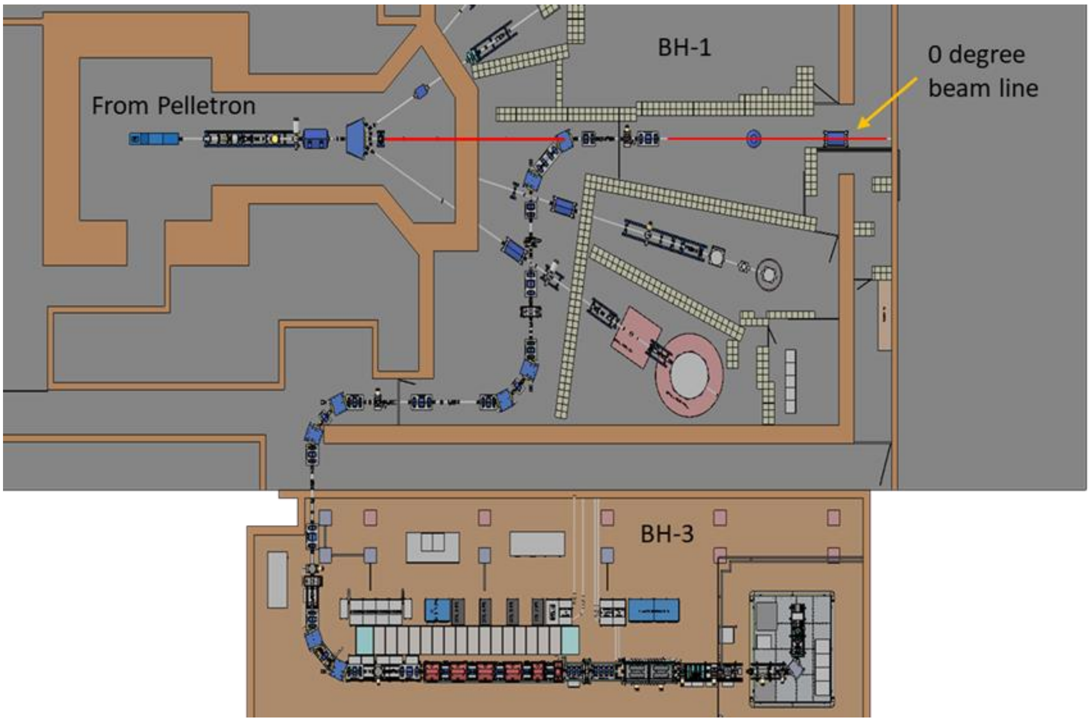

Fig. 4.1.4: The schematic of High Current Injector of IUAC, the future injector accelerator of the SC Linac of IUAC.

Fig. 4.1.5: Photograph of K500 superconducting cyclotron built at VECC, Kolkata

A 30 mA, Low Energy High Intensity Proton Accelerator (LEHIPA) is being built at BARC, Mumbai. It consists of a 50 keV ECR ion source, a 3 MeV CW RFQ and a Drift Tube LINAC (DTL). The ion source and the RFQ are already developed, and 3 MeV proton beam has been extracted from RFQ, to do some material irradiation experiments. More recently, the beam from RFQ has been accelerated to 20 MeV through the four tanks of DTL [Mathew 2023]. A 3 MV Tandem accelerator at NCCCM, BARC, in Hyderabad, is being used for chemical analysis and characterization of materials at the surface and depth profile measurements.

Fig. 4.1.6: RIB facility installed in one of the experimental caves of the K130 Cyclotron

A Facility for Research in Experimental Nuclear Astrophysics (FRENA) at SINP, Kolkata, has recently been commissioned and will provide opportunities for research in the field of low-energy nuclear astrophysics for the first time in India [Basu 2023]. Centered around high current, 3 MV Tandetron and a 500-kV single-ended accelerator that would be installed in the second phase, FRENA will help address important queries related to different astrophysical scenarios, especially those related to the fusion of heavy-ions like ^{12}C, ^{16}O and ^{20}Ne. With the development of a neutron facility at a later stage, neutron-induced reactions would be studied for investigating the s-process nucleosynthesis. It would also provide scope for studying specific reactions in the H and He-burning phases of stars and the p-process reactions.

4.2 Development of Synchrotron Radiation Sources

The SR sources, namely, Indus-1, commissioned in 1999 and Indus-2, commissioned in 2005, are the only two SR sources in India, which have been operational in round the clock mode since February 2010 at RRCAT, Indore [Deb 2013]. Figure 4.2.1 shows a schematic of the Indus accelerator complex, and photograph of Indus-1 SRS, along with a view of Indus-2 tunnel is shown in Fig. 4.2.2. While Indus-1 is a 450 MeV, 125 mA storage ring; the Indus-2, a 2.5 GeV, 200 mA, with a circumference of 172.47 m, is presently the largest and the highest energy SR source in the country. Both Indus-1 and Indus-2 have been designed and developed with mostly indigenous efforts. Various state-of-the-art technologies, such as magnet technology, beam diagnostic systems, ultra-high vacuum technology, RF systems, *etc*. and several innovative concepts have evolved in realizing such complex machines. Indus-2 has three insertion devices[21] installed in its straight section. During the last few years, several important upgrades have been made, which have resulted in its performance enhancement.

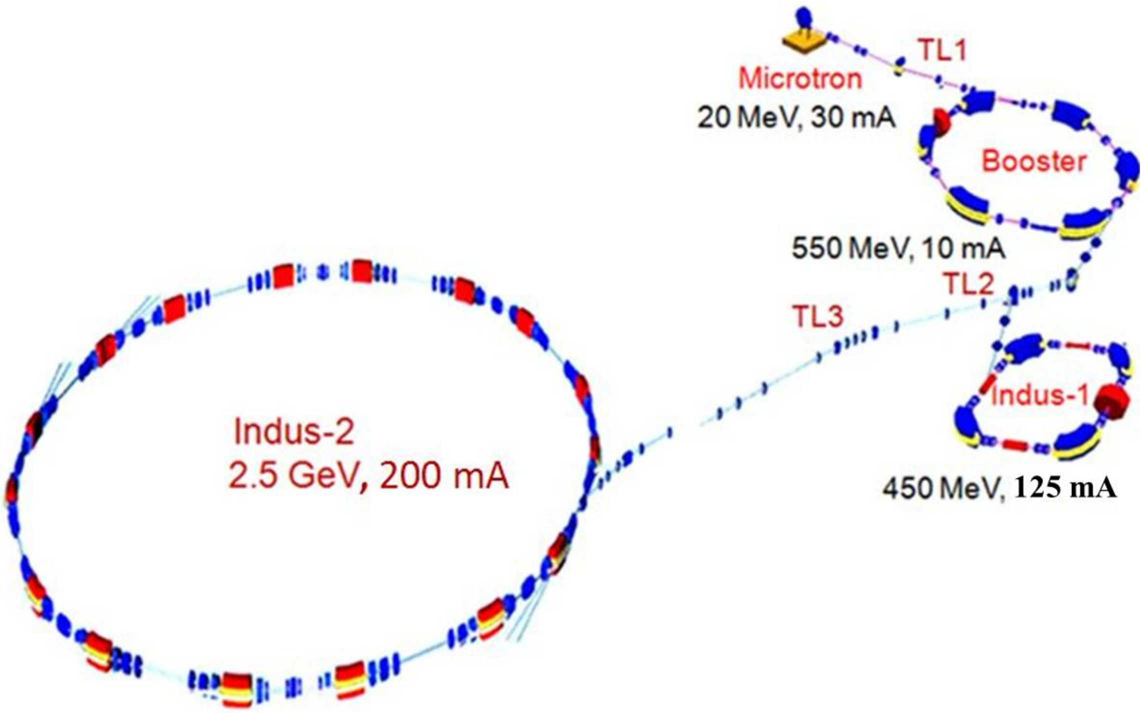

Fig. 4.2.1: Schematic showing different accelerators in Indus accelerator complex

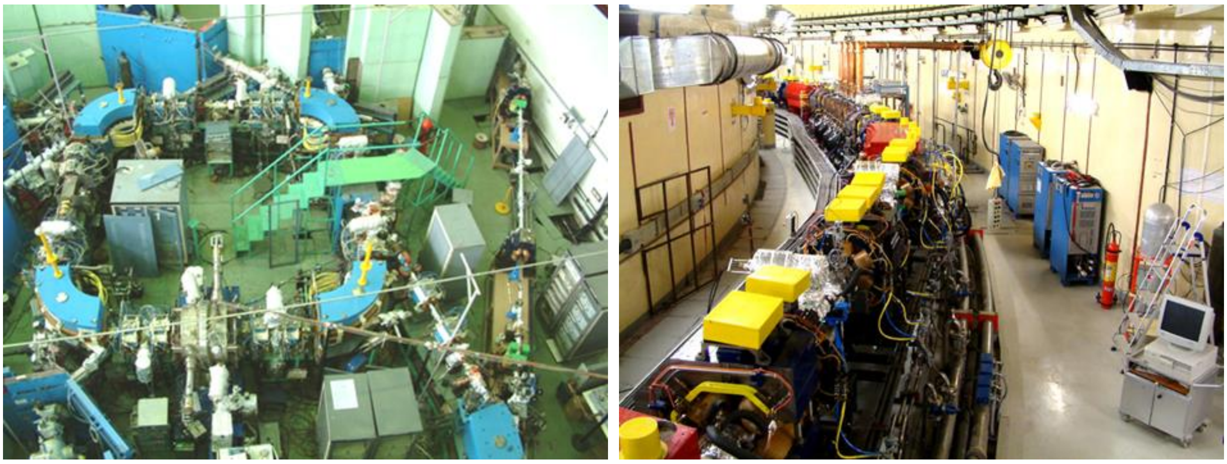

Fig. 4.2.2: Photograph of Indus-1 SRS (left), and Indus-2 tunnel (right).

The Indus accelerators offer excellent research facilities to users and researchers from academia and industry from all over the country for variety of experiments in areas of basic and applied sciences and other applications of national importance. For utilization of Indus-1 and Indus-2, several beamlines have been developed by RRCAT, BARC, SINP and UGC-DAE CSR. Currently, there are 7 operational beamlines on Indus-1, and 19 operational

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[21] Insertion Device is a special magnetic device installed in the straight section of SRS that produces a suitably tailored magnetic field profile to enhance the spectral characteristics and flux/brightness of the emitted radiation.

beamlines on Indus-2, and a few more are expected to be available for users shortly. Figure 4.2.3 shows a view of Indus-2 experimental hall with beamlines. The user-base and the research outcome from the Indus accelerators have shown a steady growth over the years. In the year 2023, nearly 1078 user experiments were carried out and 180 publications came out in peer reviewed international journals. High quality research has been done in Protein crystallography, Energy materials, Catalysis, Battery materials, Materials research, nuclear materials, *etc.*, using Indus beamlines [Singh 2019, Panda 2020, Pedireddy 2021, Chakraborty 2021, Pradeep 2020]. In the last few years, research establishments from some Indian industries have also been using the Indus beamlines.

Fig. 4.2.3: A view of Indus-2 experimental hall with beamlines.

Indian institutions have also designed and developed beamlines for international synchrotron facilities. For example, SINP has designed and developed an Indian beamline in the Photon Factory Synchrotron in KEK, Japan. This project was supported by DST and is being used over the last ten years by scientists from various institutions of our country. Another such beamline has been developed with DST support in the Elettra synchrotron in Italy. Two more DST supported activities have led to the access of Indian scientists to international beamlines – to PETRA-III, DESY, Germany; and to RAL, UK for synchrotron X-ray and neutron scattering experiments, respectively. In both Germany and UK, the two India-motivated beamlines were developed by the respective laboratories in which Indian scientists were also involved.

A synchrotron beamline of Indus-2 has been used for characterizing the space mission payloads for astrophysics research. Recording of accurate spectral response, however needs calibration for flux levels. Using a transfer standard detector or instrument for flux calibration will be very useful to carry out the calibration experiments. A monoenergetic beam with well-controlled and calibrated intensity/ flux level is required to calibrate various instruments. Also, the experiments with low energy radiation need to be carried out with the instruments in vacuum chambers.

The modest values of emittance and brilliance of Indus-2 put a limit on the smallest spot sizes that can be achieved at the experimental stations. Some examples are as follows: the smallest spot size of $4.5 \times 7.5\ \mu m^2$ that has been achieved in Indus-2, is at the XRF microfocus beamline, which has a typical photon flux of 10^7 photons/sec and is used for X-ray fluorescence measurements. Other measurements like micro-diffraction, and micro-absorption using similar spot sizes, which have a huge impact on our understanding of materials and systems at the micron level, require much higher photon flux (typically $> 10^{10}$

photons/s) at the sample, and are not possible at any of the Indus-2 beamlines because of the large emittance of the Indus-2 source. Limitations in reducing the spot size also limit the maximum pressure that one can achieve for high pressure diffraction measurements, and, high-pressure experiments in excess of 100 GPa are nearly impossible at Indus-2. Similarly, the non-availability of high energy photons (~100 keV) limits the q-range for making diffraction measurements at extreme conditions of high pressure and/or high temperature. Limitations are also observed in imaging the specimens, which contain high atomic number elements due to the limited penetration depth of the relatively low energy photons (currently max up to 40 keV) available from Indus-2. Study of crack and its propagation under load in end-cap weld of fuel pins is an extremely relevant problem for Department of Atomic Energy (DAE). This, however, could also not be studied suitably due to limitations of the Indus-2 source. The large emittance of Indus-2 SR beam, which results in poor coherence and small photon flux at the sample, results in reduced resolution of images, specifically when analysing composite materials having similar electron densities. Unavailability of high flux monochromatic beams of sizes of ~10 μm^2 also limits the range of protein crystals that can be currently probed using the facilities at Indus-2. Currently, only relatively large sized protein crystal (typically larger than 200 μm dimension) can be studied at the Indus-2 protein crystallography beamline. Flux limitations also put a lower limit on the solute concentration in dilute solutions for carrying out X-ray diffraction and X-ray absorption measurements. Although in-situ/in-operando studies are carried out at Indus beamlines, these measurements are limited to a time resolution of several seconds/minutes. Acquisition of data at shorter time intervals of less than a second is not possible due to the reduced flux and consequently the requirement of longer time required for acquiring a single frame data. In order to overcome these limitations, it is highly desirable to build a next generation synchrotron radiation source, as will be discussed in Section 6.3. This will enable us to perform useful materials research of immediate interest, and also useful research for societal applications, such as necessary spectroscopy for hydrogen generation by water splitting, research on batteries for enhancing their performance, pharmaceutical applications, *etc.*

4.3 Development of Free Electron Lasers

In India, work on long-wavelength FELs is being actively pursued at RRCAT, Indore, and IUAC, New Delhi. In the past, some experimental activities took place at University of Pune and Institute for Plasma Research, Gandhinagar. In the following paragraphs, we describe the activities being carried out at RRCAT and IUAC.

The RRCAT FEL project is aimed towards developing an Infra-red Free-electron Laser (IR-FEL)-based user facility. An IR-FEL has been designed and developed for potential use in IR/ THz spectroscopy of materials. This is an oscillator-based FEL, utilizing a 15-25 MeV NC electron LINAC with a peak micro-pulse current of 50 A, and designed to operate in the wavelength range of 12.5-50 μm, with an expected out-coupled CW average power of 30 mW at 10 Hz operation. Construction of the facility was completed in 2016, and first lasing was observed in November, 2016. Saturation of the IR-FEL was achieved in 2021, with a maximum CW average power of 34 mW at 23 μm (for 2 Hz operation), and wavelength tunability from 12-40 μm was demonstrated [Chandran 2021]. Recently, the operation of IRFEL has been established in the wavelength range 12.5 – 50 μm. Figure 4.3.1 shows a photograph of the RRCAT IRFEL facility. Detailed characterization of the electron and optical beam has been done and the IR beam has been transported to a user area through an optical beam line over a distance of ~ 50 m. The IRFEL-based user facility has been set up for IR-THz spectroscopy of materials in low temperature (down to 5 K) and high magnetic field (up to 7 T) environments.

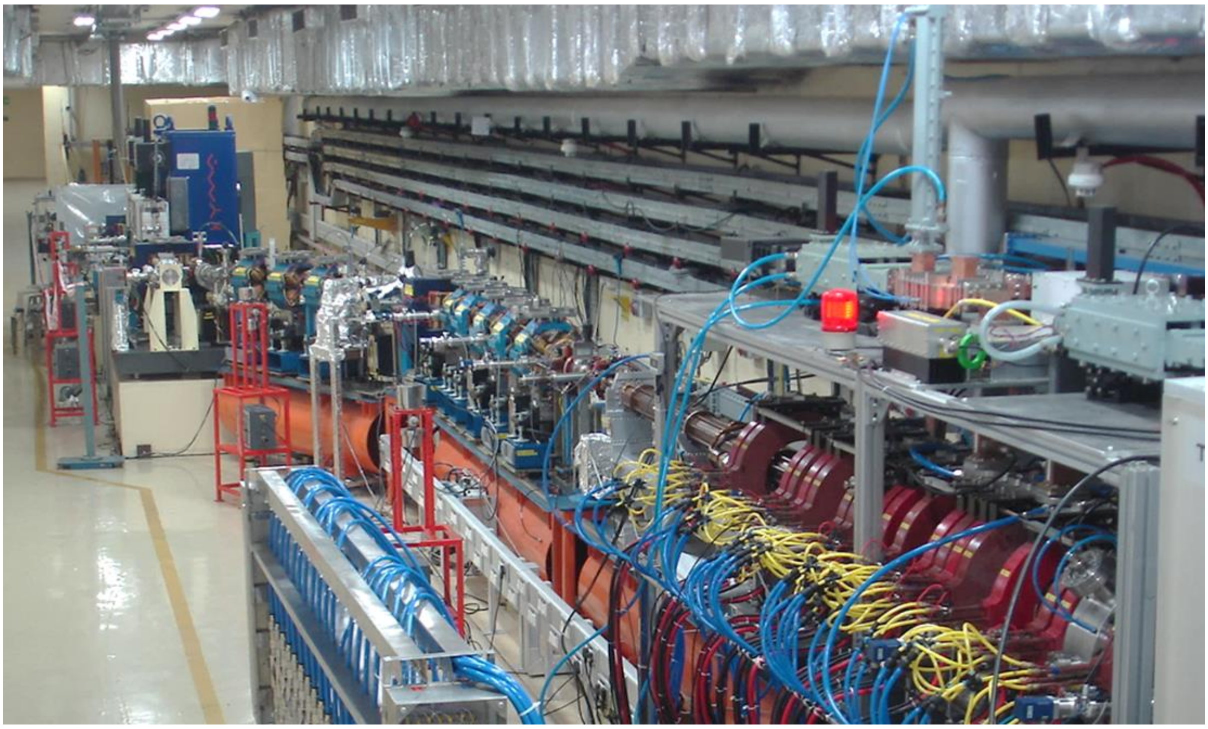


Fig. 4.3.1: Photograph of the IRFEL set-up at RRCAT

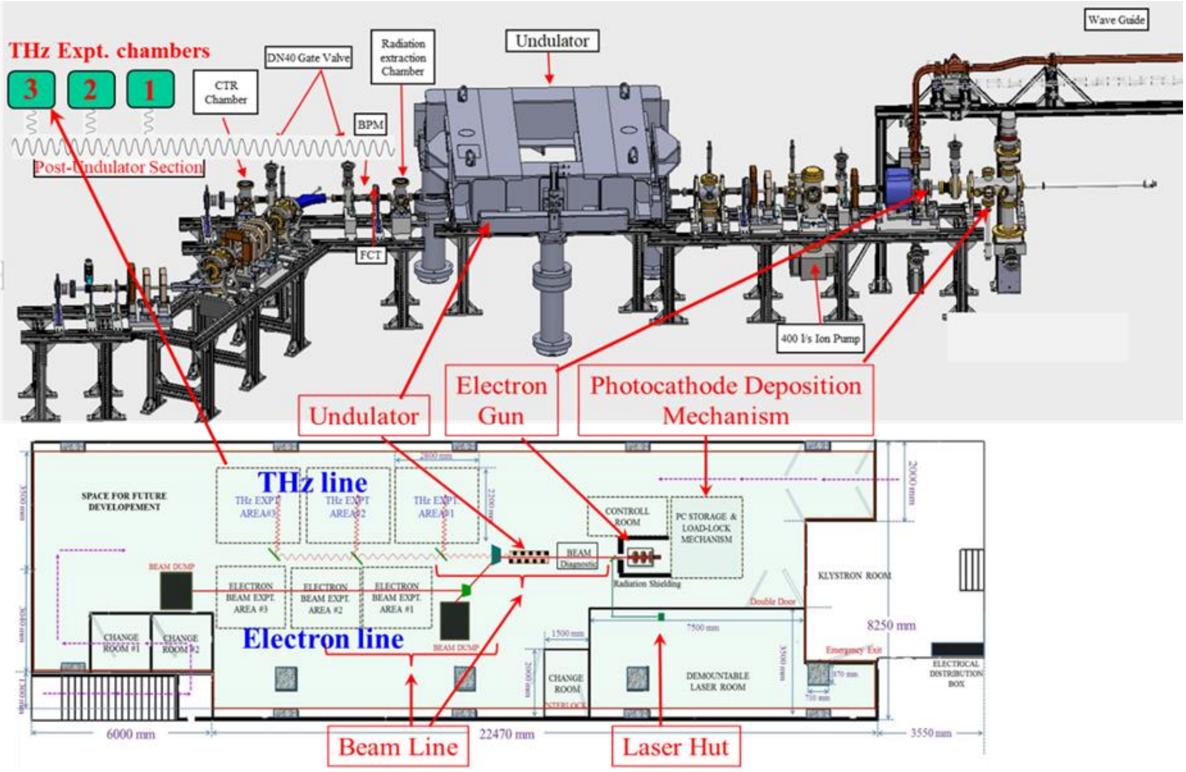


Fig. 4.3.2: Schematic and the 3-D beam line design of the compact THz-FEL facility which is at the final stage of commissioning at IUAC.

At IUAC, a compact THz-FEL facility, based on RF photocathode electron gun, is under the initial commissioning stage (see Fig. 4.3.2) [Ghosh 2017]. Once operational, it will be the first pre-bunched FEL facility based on RF photocathode in India and will be among the few in the world. The complete accelerator facility is ~ 5 m long and will deliver intense THz radiation as well as an electron beam for doing experiments in multidisciplinary fields. The photocathode electron gun, powered by a klystron, is expected to generate a maximum accelerating field of ~120 MV m^{-1}, which will produce an 8 MeV electron beam. The electron beam, after being focused by solenoid and quadrupole magnets, will be injected into a compact undulator to produce THz radiation in the frequency range of 0.18 to 3.0 THz. In preliminary experiments, dark current has been observed in the set-up, which originated from the copper photocathode, when high accelerating fields were generated inside the cavity. More recently, laser has been coupled to the photocathode electron gun, and first beam from the copper photocathode, as generated by the laser has been observed and analyzed. The compact undulator has already been installed in the beamline along with beam line components. It is expected that the first signature of THz radiation will be demonstrated within a couple of years.

4.4 R&D for Spallation Neutron Source

In India, R&D efforts have been going on towards development of Indian Facility for Spallation Research (IFSR) for more than a decade. Three important components of IFSR are – (i) accelerator system, (ii) spallation target and moderator system, and (iii) neutron beamlines and experimental facilities. Efforts have so far been mainly concentrated on developing the design and technology of the accelerator system. For the accelerator system, choice of having a full energy SC H^- injector LINAC, followed by a proton accumulator ring has been adopted, instead of a low energy injector LINAC and RCS. This design strategy has been chosen, keeping in mind that the experience obtained in development of 1 GeV, 1 mA H^- SC LINAC will be useful for 1 GeV, 10 mA H^+ SC LINAC, the Indian ADS accelerator. RRCAT has worked out the baseline physics design of the 1 GeV H^- pulsed injector LINAC and 1 GeV proton accumulator ring [Jana 2019]. The injector LINAC will have a front-end, comprising an H^- ion source and an RFQ - both operating at room temperature, the SC LINACs comprising of spoke resonators and elliptic cavities, along with the associated transport lines. During the last decade, RRCAT has worked on the development of the front-end of the accelerator. A 50 keV RF discharge-based H^- ion source (pulse current: 11 mA, duty factor: 10%), coupled to a 1.8 m long Low Energy Beam Transport (LEBT) line, has been developed there, and initial experiments have been performed, based on which LEBT is being upgraded. A 3.5 m long, 325 MHz RFQ is under fabrication using in-house machining facility. In addition, a 150 kW, 325 MHz, solid state power amplifier has been developed, which will be used for powering the RFQ. Four such amplifiers will be required to power the RFQ. Figure 4.4.1 shows photographs of the ion source and solid-state RF amplifier developed at RRCAT.

During the last decade, IUAC, RRCAT and VECC have worked with Fermilab under the Indian Institutions Fermilab Collaboration (IIFC) to successfully develop SC spoke resonator and elliptic cavities for the R&D for PIP-II project [Shrivastava 2021]. More recently, complete infrastructure facility for fabrication, processing, dressing and testing of superconducting cavities has been developed at RRCAT, using which 650 MHz, five-cell SRF cavities have been developed in India for the R&D phase of PIP-II project at Fermilab. This experience and expertise will be useful for the indigenous program on development of SC injector LINAC for IFSR. Further details on this are elaborated in Section 4.5, where we describe the national status of SC accelerator technology. Some initial studies on spallation targets have been done at RRCAT. BARC has vast experience in the area of neutron beamline development, and also on development of experimental facilities for the beamlines tapped from research reactors, which will be useful for setting up of beamlines for IFSR.

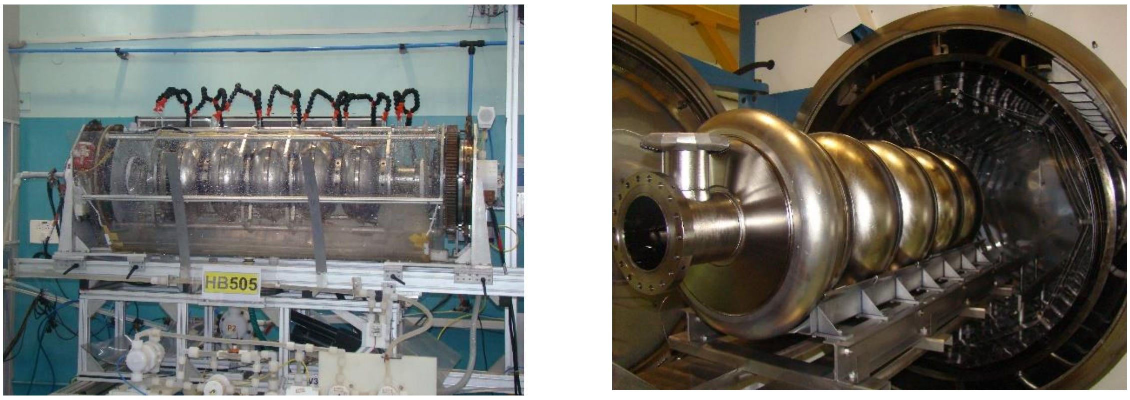
Fig. 4.4.1: RF discharge based H- ion source (left) and 325 MHz, 150 kW Solid State Amplifier (right) developed at RRCAT.

4.5 Superconducting RF Accelerator Technology

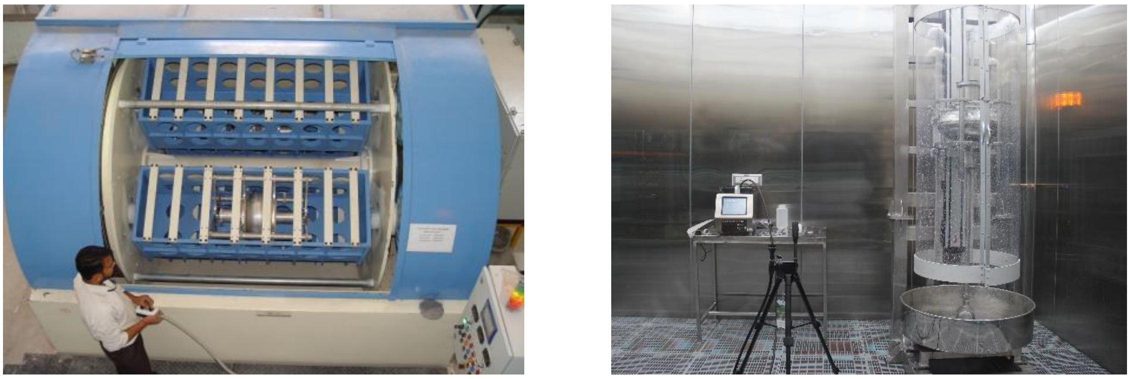
The use of SC technology for accelerators in India started in mid-eighties at TIFR, Mumbai, with the development of the SC heavy ion booster LINAC using lead plated on copper quarter wave resonators (QWRs) in collaboration with SUNY, Stony Brook, USA. In the early nineties, a similar collaboration between IUAC, New Delhi (then NSC) and Argonne National Lab, USA led to the development of niobium QWR-based heavy ion LINAC at IUAC. Both the SC LINAC facilities are operational and are being used to provide energized ion beams for scheduled experiments. During late nineties and early 2000's, the design and development of SC cyclotron had been started at VECC, Kolkata and, very recently, the energized beam from the cyclotron has been demonstrated. The proposed facilities that will employ SC accelerator technology are – (i) accelerator for ANURIB facility, (ii) injector LINAC for IFSR, (iii) injector LINAC for IADS, and (iv) injector LINAC for XFEL.

Development of SC accelerator requires setting up of various auxiliary facilities for fabrication, surface processing and testing of SC cavities. Two such facilities for developing niobium resonators are operational- one at RRCAT, and other one at IUAC. RRCAT has successfully established various SRF infrastructure facilities for the development and tests of 650 MHz SRF cavities under the Indian Institutions Fermilab Collaboration [Shrivastava 2021]. A complete chain of facilities for fabrication and RF characterization at various stages, including the infrastructure facilities for processing, High Pressure Rinsing (HPR), Vertical Test Stand (VTS) and Horizontal Test Stand (HTS) has been established. Figure 4.5.1 shows the important infrastructure that has been built for SRF cavity fabrication, processing and dressing at RRCAT. Several cavities have been successfully tested in the VTS. The HTS has been commissioned, and has been used to test the cavities at RRCAT. Fig. 4.5.2 shows photographs of the HTS and VTS at RRCAT.

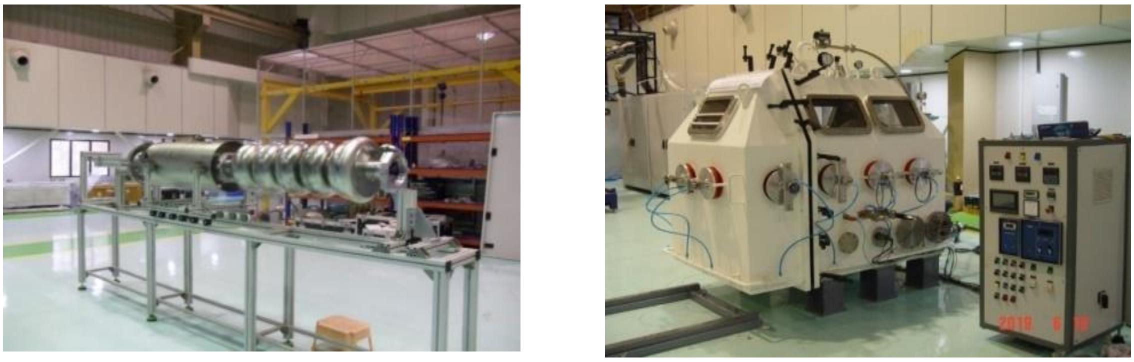
The resonator fabrication facility at IUAC is primarily used for fabrication of QWRs for the SC LINAC, and includes an electron beam welding machine, a surface processing laboratory, a high vacuum furnace and a 4K test facility. IUAC has also developed the capability to design low-β QWRs. One such $\beta = 0.05$ QWR has been designed and prototyped for use with the high current injector (HCI) to match the velocity of the heavy ions with the acceptance of the SC LINAC. The resonator achieved a Q_0 of 7×10^8@ 6 MV/m gradient, which far exceeded the design value of 3×10^8.



Electropolishing Setup *High Vacuum Annealing Furnace*



Barrel Polishing Machine *HPR Setup in ISO-4 Class Cleanroom*



Insertion Bench for Cavity Dressing *Welding Glove-box for Cavity Dressing*

Fig. 4.5.1: Various facilities for SRF cavity fabrication, processing and dressing at RRCAT, along with the components developed at RRCAT.

The RRCAT facility is presently being used for developing elliptical cavities (650 MHz and 1.3 GHz) and includes arrangements for cold forming of niobium sheets, an electron beam welding machine, a surface processing laboratory, a high vacuum furnace, tuning facility for elliptical cavities, optical inspection of the RF surface, glove box for welding in a controlled environment, centrifugal barrel polishing facility and 2K vertical and horizontal test stands. Few numbers of 5-cell 650 MHz $\beta_g = 0.92$ cavities have been fabricated, processed, dressed and tested successfully using the developed infrastructure, and a high Q-value (4×10^{10}) along with high acceleration gradient (29 MV m^{-1}) have been demonstrated. Three prototype cavities have been tested and qualified for PIP-II prototype cryomodule. RRCAT has also developed a single-cell elliptical cavity, using laser welding technique. This cavity was processed and tested at Fermilab, USA and its performance was at par with the cavities fabricated through the conventional method, *i.e.*, using electron beam welding. Two more identical facilities for niobium resonator fabrication, processing and testing are coming up – one at BARC, and the other one at VECC. VECC has developed some local vendors, who are capable of developing die punch assemblies and forming of elliptical niobium half cells, using hydraulic press, followed by machining of niobium. The VECC workshop has procured a hydraulic press and the elliptical half cells of SRF cavities can also be formed in-house. Procurement of an electron beam welding machine is in the process, and so is the setting up of a class-100 clean room facility. Cavity processing facility including electro-polishing, high pressure rinsing, facility for optical inspection and vertical test will also be set up as part of the SRF infrastructure development project.

Fig. 4.5.2: Photograph of VTS facility (left) and HTS facility (right) at RRCAT.

BARC, RRCAT and VECC have also developed capability for design of elliptic cavities and spoke resonators. BARC and RRCAT have successfully demonstrated the technology to build solid state power amplifiers to power the elliptic cavities and SC spoke cavities. BARC and RRCAT are also working on development of cryomodules, low-level RF (LLRF) system and RF Protection Interface (RFPI) for accelerator in collaboration with Fermilab, USA.

Several collaborations, in the past as well as presently ongoing, at national and international level, have provided a major thrust to the development of SC accelerator technology in the country. Noteworthy among these are:

- RRCAT and IUAC: Four numbers of single-cell, and one number of five-cell, 1.3 GHz elliptic cavities were developed under this collaboration. These were processed and tested at Fermilab. While the third single-cell cavity achieved $Q_0 = 2\times10^{10}$ at 35 MV m^{-1} @ 2K (40 MV m^{-1} @ 1.8K), the fourth cavity achieved 37.6 MV m^{-1} @ 2K and the 5-cell cavity had $Q_0 = 2\times10^{10}$ at 20 MV m^{-1} @ 2K (42 MV m^{-1} @ 1.5-1.7K). A prototype 650 MHz, $\beta = 0.9$, single-cell SRF cavity was fabricated in collaboration with IUAC .The cavity achieved the accelerating gradient (E_{acc}) of 19.3 MV/m with excellent quality factor Q_0 of 7×10^{10} at 2.1 K during VTS testing at Fermilab.
- BARC, IUAC and Fermilab: Two bare 325 MHz $\beta_g = 0.22$ single spoke cavity were developed at IUAC under this collaboration. Both these cavities were processed and tested at Fermilab, and their performance during RF tests exceeded the design goal for the PIP-II LINAC. They were later jacketed at BARC under the IIFC collaboration, and one of the cavities was installed in PIP-II Injector Test (PIP-II IT) facility accelerator for beam acceleration.
- IUAC and VECC: This is an ongoing collaboration for the development of single-cell and five-cell, 650 MHz, $\beta_g = 0.61$ elliptical cavities. Two single-cell cavities have already been fabricated, and the work on the five-cell cavity is underway. The first single cell

cavity achieved an acceleration gradient of 34.5 MV m^{-1} without quench, which is a world record for this class of cavity, operating at this frequency. Recently, the second single-cell cavity was tested at Fermilab, and it has achieved 25 MV m^{-1} at $Q_0 = 1.57\times10^{10}$ @ 2K, and exceeded the design requirements for the PIP-II LINAC.

- Indian Institutions and Fermilab Collaboration (IIFC): The IIFC was established in 2009 between Fermilab and four Indian laboratories, viz., BARC, RRCAT, VECC and IUAC. The MoU targets collaborative R&D on SRF technologies, as applied to high-intensity proton LINACs. The scope of the collaboration includes development of the accelerator physics designs for SC LINACs, cavities and cryomodules at various frequencies, SRF infrastructure, RF power sources, instrumentation, controls and cryogenics.
- VECC AND TRIUMF: VECC in collaboration with TRIUMF, Canada is developing a 50 MeV, 100 kW SC electron LINAC, as the photo-fission driver for the upcoming ANURIB facility at Kolkata.

4.6 Cryogenic Technology for Accelerators

At present, cryogenic technologies serve as the backbone of all the superconducting accelerator programs, everywhere in the world. Unlike Europe and the USA and other industrially developed nations, cryogenic technology in India, with the apparent exception of Liquefied Nitrogen Gas (LNG) and steel industry, is in a very nascent stage till today. Even the LNG and steel industry depend heavily on imported cryogenic technologies, and thus do not really contribute to indigenous industry development for cryogenic applications, and only contribute towards cryogenic infrastructure development and augmentation activity. However, only a well-developed cryogenic industry can support the large accelerator programs of the future. Hence, opportunity exists to catapult the development of cryogenic technologies, infrastructure and industry in the country to world-class levels and beyond, using the Indian accelerator program as a catalyst. The state of cryogenic technology in the country is mostly a story of successes with one-off laboratory prototypes with the last mile surge to convert the same into saleable and scalable industrial machines, which is still lacking for various reasons, the major one being a lack of industrial ecosystem for these products. What is gratifying to note is the presence of serious research groups in various domains of cryogenic refrigerators. Notable progress took place during the last decade on indigenous development of Helium Liquefier/Refrigerator to produce ~ 45 L/Hr. of Liquid helium [Kush 2011, Ansari 2017]. In the field of low capacity (mW class) refrigeration systems involving different types of cryocoolers, significant work has been done in reputed DAE and other national laboratories as well in premier academic institutes like the IITs. However, cryocooler manufacturing industries have not bloomed in the country.

4.7 Development of Industrial Accelerators

Work on development of industrial electron accelerators is being carried out in India at BARC, Mumbai [Sharma 2023]; RRCAT, Indore [Dwivedi 2019] and SAMEER, Mumbai [Upadhyay 2022].

BARC has set up a 500 keV, 20 mA DC accelerator at BRIT complex in Vashi, Navi Mumbai. The accelerator is in use for surface modification studies by textile industry. Apart from that, industries such as Reliance India Limited are using it for cross linking of plastic sheets and granules. Hindustan Lever Limited is planning to irradiate its brand of wheat flour by utilizing this facility. BARC and IIT-Madras are pursuing radiation damage studies of materials, including electrical and electronic circuits. BARC has set up a facility- ‘Electron

Beam Centre' at Navi Mumbai for various industrial applications. This facility has 3 MeV and 10 MeV electron accelerators, which were developed indigenously for industrial processing applications. BARC and ECIL have jointly developed 9 MeV electron LINACs for cargo scanning. R&D is also being pursued in BARC on DC accelerators and RF LINACs for wastewater treatment and flue gas treatment. In this context, initial studies are being carried out on design and development of 1 MeV, 100 kW electron accelerators, for which, more recently, round-the-clock operation at 850 keV, 50 kW has been demonstrated. BARC is also working on developing 30 MeV, 10 kW LINAC for neutron generation. Single and Dual energy LINAC for NDT/radiography with material discrimination has also been demonstrated.

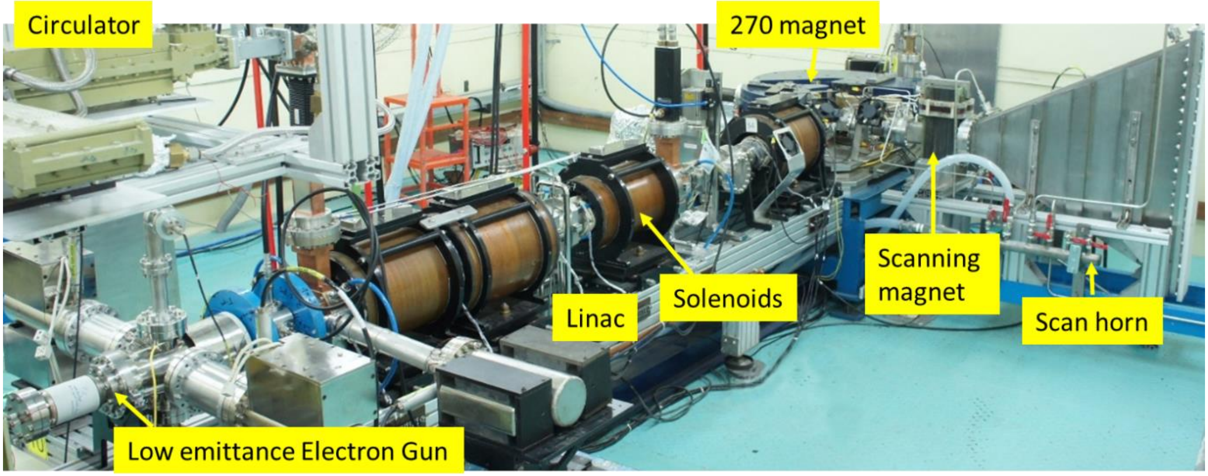


Fig. 4.7.1: Photograph of the 9.5 MeV, 10 kW industrial electron linac developed at RRCAT.

BARC has worked on development of several versions of Kilo Ampere Linear Injector (KALI) accelerator and Linear Induction Accelerator (LIA), having electron beams in the energy range from 50 keV to 1 MeV, current in the range 0.1 to 30 kA with few tens of ns pulse width and repetition rates up to 100 Hz, to generate giant EM pulse for various applications.

Considerable progress has been made at RRCAT in development of 10 MeV RF LINACs during the last ten years. Two 10 MeV, 6 kW RF electron LINACs, indigenously designed and developed, are installed at Agricultural Radiation Processing Facility (ARPF) in Indore. License has been obtained for operating these LINACs for sterilization of medical products. Both the LINACs are regularly used for medical sterilization, material irradiation studies and seed irradiation studies. An upgraded version of these LINACs with 9.5 MeV, 10 kW beams, and with an energy filtering system to filter out >10 MeV electrons has also been developed. Figure 4.7.1 shows a photograph of this linac at RRCAT. This LINAC will be used for irradiation of agricultural and food products. More recently, a further upgraded version of this linac has been developed, demonstrating 15 kW of beam power. The technologies developed so far in the country need considerable improvement both in terms of reliability and high power to reach competitive performance levels required for self-sustaining installations in the industry. Presently, there are no 7 MeV/10 MeV installations for bulk radiation processing in the country, but many industries are trying to establish the 10 MeV, 20 kW facilities with imported accelerators.

At SAMEER, Mumbai, 15 MeV, 1 kW electron LINACs have been developed for R&D purposes, and, also for possible non-destructive testing applications (see Fig. 4.7.2).

VECC, Kolkata had developed a Penning Ion Generator (PIG)-based tabletop ion source as an injector for its cyclotron. Several indigenous ECR ion sources, operating at 2.45 GHz, 6.4 GHz and 14.4 GHz developed by VECC are being used for materials applications, the latter two are high charge state ion sources, while the former is a high-current ion source. IUAC has developed two tabletop ion sources operating at 30 kV and 60 kV. They have two-electrodes extraction system and deliver few μA beam current for H, He and Ar species, and are mainly used for ion beam irradiation for materials/industrial applications. IIT Roorkee, in collaboration with IUAC, is developing a three-electrode extraction system, which will provide ≥ 500 μA and better beam optics. BARC has initiated a PIG ion source-based neutron generator in collaboration with IIT Roorkee. It is aimed to generate 200 kV and few μA deuteron beam; the neutrons will be generated through D-T reaction. It will be used for defense applications.

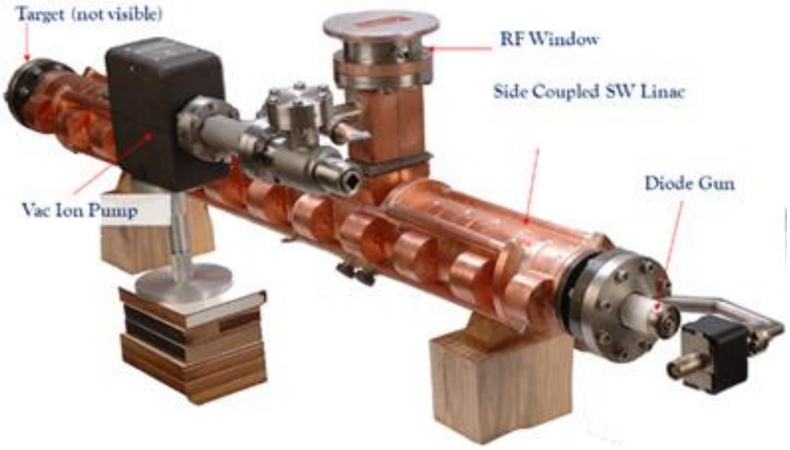


Fig. 4.7.2: SAMEER’s side coupled standing wave 15 MeV accelerator.

4.8 Development of Medical Accelerators

Efforts are being made to develop medical accelerators for producing isotopes for medical diagnostics, as well as for therapy.

Medical Cyclotrons for isotope production

In India, reactor produced radio-pharmaceuticals have been routinely used by the nuclear medicine centres for a long time. Few numbers of low-energy cyclotrons have also been running in cities like Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Bangalore, Trivandrum, Chandigarh, *etc*., producing PET radioisotope and ^{18}F labelled FDG. At present, more than 20 medical cyclotrons are operational in India. All of these machines are procured from commercial companies like GE (16.5 MeV), Siemens (11 MeV), IBA (18 MeV) *etc*. However, there is an increasing demand for SPECT isotopes such as ^{201}Tl, ^{123}I, ^{111}In, ^{67}Ga *etc*. These isotopes have longer half-life, which is an advantage, since their activity does not reduce significantly during transportation from the production facilities to the diagnostic centres. All these radioisotopes require higher beam energy and intensity for their profitable production. For this reason, a 30 MeV, 500 μA proton cyclotron facility has been set up by VECC (see Fig. 4.8.1) [Debnath 2019]. This high-current cyclotron is being used to produce PET and SPECT isotopes for medical diagnostics purposes. At the same time, there is provision for front-line research experiments in the fields of materials science, radiochemistry, liquid metal target development *etc*. The facility is based on a high-current cyclotron (Cyclone-30) and five beam lines, procured from IBA, Belgium. Two proton beams can be simultaneously extracted from the cyclotron. The beams can be of different energy and intensity. There will be several beamlines for utilization of the beam. Two beamlines are being dedicated for SPECT and one for PET isotope production. In addition, there is one dedicated beamline for materials science and chemistry research. A fifth beamline, which bends the beam vertically down into a basement cave, will be utilized for dedicated experiments for R&D on windows for high power beams.

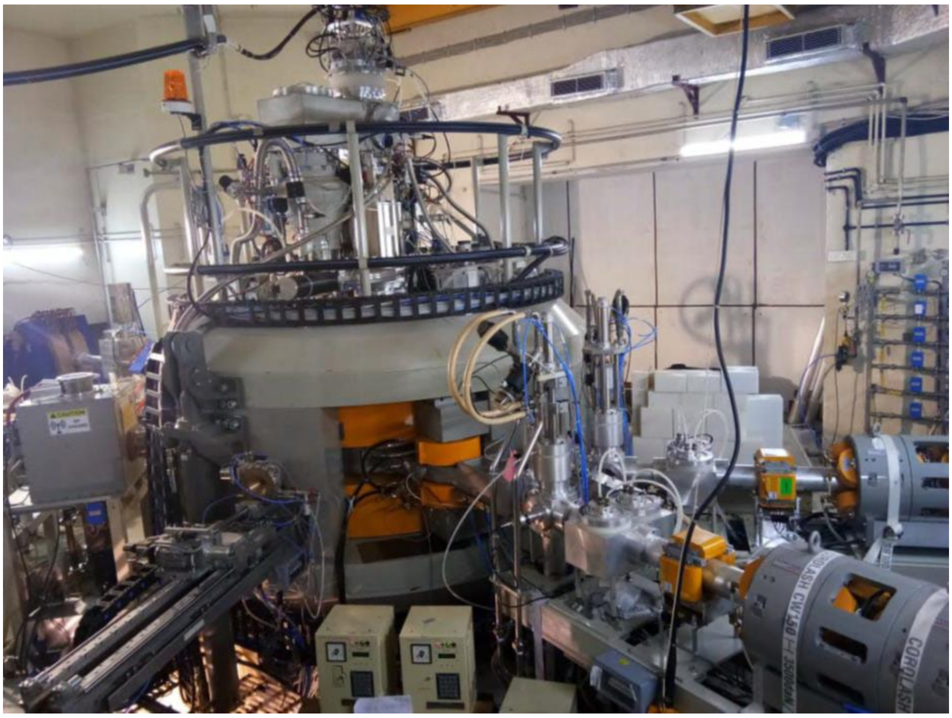


Fig. 4.8.1: Photograph of 30 MeV medical cyclotron at VECC, Kolkata.

Even before the commissioning of the medical cyclotron, the *K*-130 room temperature cyclotron of VECC was being used for development of few medical isotopes. The experience gathered during the process development for generation of radioisotopes with the *K*-130 cyclotron facility was very useful, while developing the process for generation of some of the medical isotopes in the medical cyclotron facility.

At present, medical cyclotrons are procured from companies like IBA, GE, Siemens *etc*. VECC has taken up a project for developing the cyclotron and associated technologies for production of medical radioisotopes, and to transfer the technology of 18 MeV, 50 μA H^- cyclotron and target irradiation systems for production of medical radioisotope (^{18}F) to Indian industries. The objective is to enhance the availability and export of radioisotopes, patient care and medical research. In addition, there is an indigenous effort to develop a NC LINAC at SAMEER for ^{99}Mo production.

Radio Therapy Machine

SAMEER's first medical LINAC was commissioned at PGI, Chandigarh in the year 1991. Later, on the recommendation of oncologists, the electron energy was enhanced to 6 MeV, and a machine was commissioned at the Mahatma Gandhi Institute of Medical Sciences (MGIMS), Wardha, Maharashtra, where over 90,000 patient exposures were delivered. The second machine was operational for more than 10 years at Cancer Institute, Adyar, Chennai, and more than 1,80,000 exposures were delivered to 73,000 distinct patients. These machines, named as "Siddharth" (see Fig. 4.8.2), were developed under the Jai Vigyan program of Government of India through the Ministry of Electronics and Information Technology (MeitY), formerly known as DoE [Dixit 2020].

Fig. 4.8.2: SAMEER's 6 MeV Oncology machine -"Siddharth".

In the second phase of Jai-Vigyan programme, four more machines have been developed, and are being deployed in various hospitals across India. The first machine under Phase-II has been installed, and commissioned at IIHNO, Rau, Indore and more than 90,000 exposures have been delivered to patients, the second machine has been installed at Amravati Cancer Foundation, Amravati, using which, more than 60,000 exposures have been delivered to patients, third machine is installed at Cancer Institute Adyar (replacing old SAMEER machine), and more than 200 exposures were given till date, using this machine. In all more than 3,75,000 exposures have been given by SAMEER's radiotherapy machine. These three machines are still treating patients in the hospitals. These machines were basic machines to demonstrate the energy and beam quality required for therapy purposes. All the medical parameters like flatness, symmetry, dose stability and energy uniformity were measured for these machines, and were found to be at par with any imported machine from Varian, Elekta, Accuray, etc. These machines were also TYPE approved by AERB. The Transfer of Technology (ToT) of this machine was done to Panacea Technologies.

Later, after successful demonstration of parameters and patient treatment at various locations, it was decided to enhance the technology and introduce the possibility to achieve dual electron energies of 6 and 15 MeV from the same LINAC and multiple electron energies from 6 to 18 MeV for treatment. The prototype of this novel dual-energy LINAC has already been developed, and tested at SAMEER. This LINAC is an advanced version of the basic 6 MeV technology, and because of multi energy delivery, it is equipped with asymmetric jaw collimator, multi-leaf collimator and 3D treatment planning system (TPS). This LINAC will suffice for the need of oncologists to have multiple energies, as well as both photons and electrons at the same location. A Request for Proposal (RFP) is under progress for transfer of technology for mass production of this indigenous dual energy LINAC.

Particle Therapy

India has only one hadron therapy, viz., proton therapy, machine operational at the Apollo Proton Therapy Centre, Chennai since January 2019. With the launch of Apollo Proton Cancer Centre (APCC), India has become the 16th nation in the world to offer proton therapy for cancer. Particle therapy machine at APCC is an IBA cyclotron. One more particle therapy installations is under commissioning at ACTREC (The Advanced Centre for Treatment Research and Education in Cancer), Kharghar's Tata Memorial Centre. These machines are equipped with gantries, which are huge mechanical structures to support the guiding magnets. As of now, imported proton therapy machine costs around ₹ 450 Crore, whereas carbon therapy machine may cost around ₹ 1200 crore. Size of the machine is another criterion, because of which, huge infrastructure is required. High cost of machine and infrastructure increases the treatment cost, which can be 20 times or even higher, as compared to the conventional radiotherapy treatment.

4.9 R&D on ADS Accelerators

The accelerator for the Indian ADS has to produce 1 GeV, tens of mA, proton beam with minimum (<1 nA m^{-1}) beam loss for hands-on maintenance of the accelerator. This makes the development of accelerators for ADS very challenging.

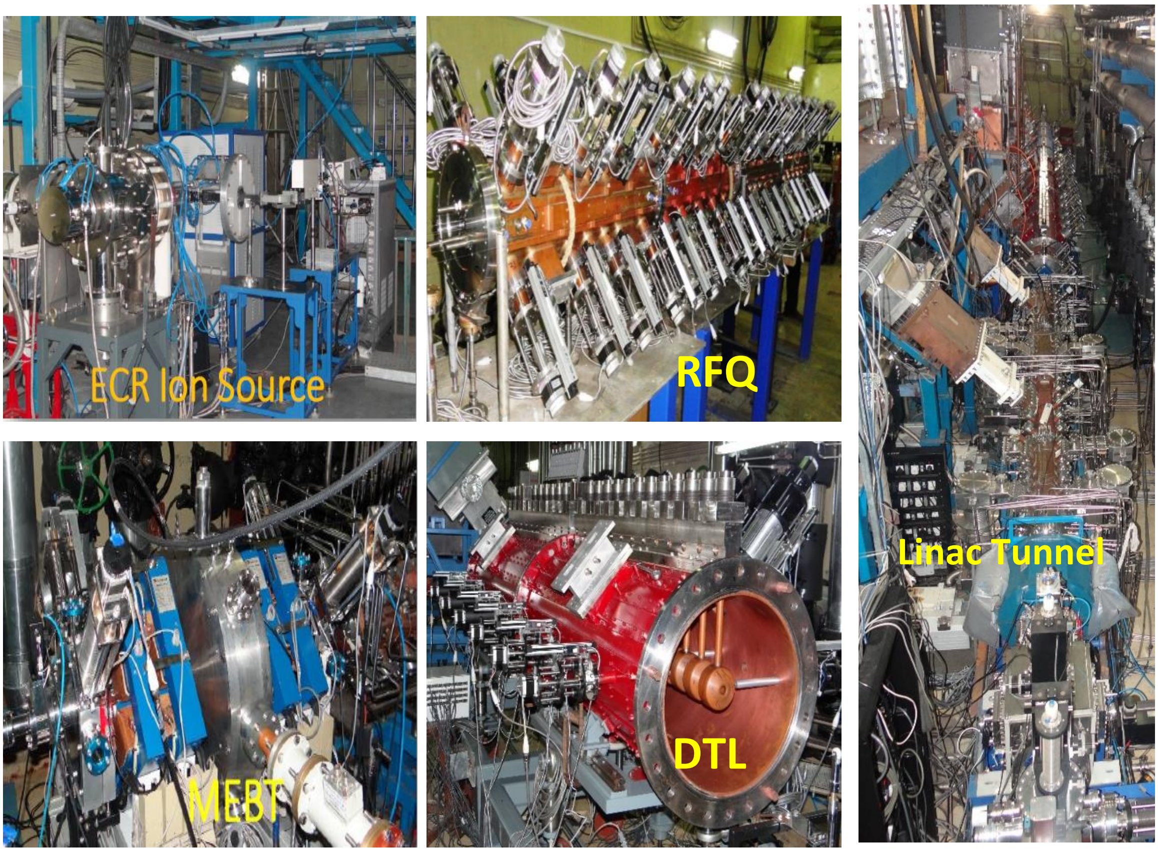


Fig. 4.9.1: Pictures of different components of LEHIPA, along with LEHIPA tunnel at BARC.

Since the low energy part of any proton accelerator is quite critical, at BARC, it was decided to develop a Low Energy High Intensity Proton Accelerator (LEHIPA), with an energy of 20 MeV and a current of 10 mA. After ascending a steep learning and technological curve, beam acceleration to 3 MeV through the RFQ was demonstrated in 2019, and with all the hardware in place (see Fig. 4.9.1), the beam has been accelerated to 20 MeV in 2023 in pulsed mode (100 μs, 1 Hz) in the four tanks of the DTL [Mathew 2023].

The key accelerator areas where R&D is needed are:

- reliability limitations of the front-end system,
- critical accelerator physics and beam halo formation studies for high current beams,
- cost reduction of the cavity and cryomodule with higher gradient and quality factor,
- RF coupler development for high-current CW SC cavities,
- improvement in cryomodule design for lower cryogenic loss,
- operation of LINAC with failed and/or tripped cavity, and,
- efficient power source to reduce the cost of AC to RF power conversion

4.10 R&D on Laser Plasma-based Compact Accelerators

In India, since the early days of evolution of the field, both experimental and theoretical studies on laser plasma interaction have been performed at various national labs and universities viz., BARC, Mumbai, IIT Kanpur, IIT Delhi, TIFR, Mumbai and IPR, Gandhinagar. High-power Nd:Glass laser systems were developed at RRCAT, Indore. In 2006, a CPA-based 10 TW Ti:Sapphire laser system was set up at RRCAT, for laser plasma interaction studies in the ultrashort, ultra-intense regime, and particularly to start initial investigations on Laser Plasma Acceleration. This was followed with a 150 TW laser system, and currently procurement and installation of a 1 PW Ti:Sapphire laser system has been completed (see Fig. 4.10.1). At the same time, CPA-based Ti:Sapphire laser systems have also been set up/planned at TIFR and BARC for basic research in intense laser plasma interaction.

Fig. 4.10.1: Photographs of 1PW and 150TW, 25fs Ti:Sapphire laser systems at RRCAT, Indore.

RRCAT, Indore, being a center working on lasers, as well as on accelerators, is involved in extensive investigations on LPA. In initial experiments, using high-power (10-150 TW), ultra-fast (25-50 fs) Ti: sapphire lasers, interacting with 1.2 mm of plasma length, acceleration of electrons from 25 MeV to over 100 MeV was achieved. Recently, using longer gas-jet plasma of 4 mm length, acceleration of electron beams in the energy range of ~200 MeV to over 500 MeV has been demonstrated [Hazra 2020]. Generation of ultra-short duration x-rays (sub-keV to 10s of keV photon energy) through betatron oscillation of electrons in the laser plasma channel and its application for radiography and phase contrast imaging have been demonstrated [Mishra 2022]. Experimental investigations on acceleration of protons/ions have also been done, and generation of >10 MeV proton beam has been demonstrated, using a 150 TW laser. Suitability of proton beams for PET isotope production, and nuclear reaction has also been explored [Tayyab 2019]. From the long-term view, a research and development program on high-repetition-rate ultra-short duration lasers suitable for driving Laser Plasma Accelerators and other advanced acceleration schemes is also the need of the hour. Finally, enhancing industry capability for development of variety of large size optics of desired quality for use in development and use of high-power ultra-short duration laser systems would also be essential.

4.11 Accelerators for Earth Science and Geology

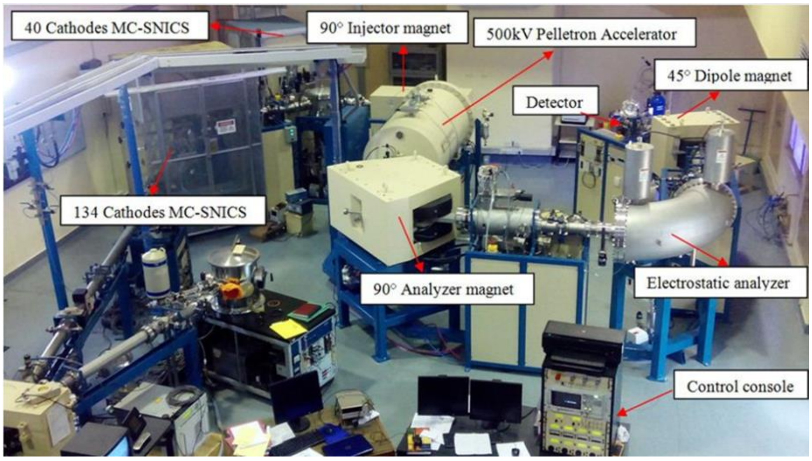


Fig. 4.11.1: Accelerator Mass Spectrometry Facility at IUAC.

In India, the first development of an Accelerator Mass Spectrometry (AMS) facility for ^{10}Be and ^{26}Al measurements took place at IUAC, New Delhi [Sharma 2019]. This was achieved through suitable augmentation of the existing 15UD Pelletron accelerator with a dedicated beam line. A separate dedicated facility for AMS studies of ^{14}C, ^{10}Be and ^{26}Al based on 500 kV Pelletron accelerator (XCAMS: the compact ^{14}C accelerator mass spectrometry eXtended for ^{10}Be and ^{26}Al) was established with sample preparation laboratories in 2015. Studies related to quaternary lakes and fluvial sediments, tectonics, paleoclimates, erosion and denudation, paleoseismology, historic and prehistoric archaeological sites have been performed, using this facility. IUAC has generated valuable human resource by providing training in this field, and also helped other institutes to establish AMS and allied facilities in India. Views of the AMS facility for Earth Science and Geology at IUAC are shown in Figs. 4.11.1 and 4.11.2.

A Geochronology facility is being established at IUAC with financial support from the Ministry of Earth Sciences (MoES), Government of India. The objective of the geochronology project is to provide state-of-the-art analytical facilities for characterizing and dating of geological samples that inform on the time scales (chronology) of earth processes – ranging from the early earth to modern events. When completed, the facility will have a nest of all the equipment that a geologist would need to perform contemporary cutting-edge research in the field of isotope geochemistry, and geochronology pertaining to earth, atmospheric, oceanic and planetary sciences at the international level.

Fig. 4.11.2: High Resolution Secondary Ion Mass Spectrometer at IUAC (HRSIMS).

5. Requirements of the User Community, Existing Capabilities, Gap Areas and the Path Ahead

The user community of accelerators comprises users who perform their R&D using the accelerators, as well the users who use the accelerators for various industrial, medical and other applications. Based on the need of accelerators for India's future, as can be extracted from the discussions in Chapter 2, and keeping in mind the international status and national status of accelerator development, as described in Chapters 3 and 4 respectively, in this chapter, we first discuss the requirements of the Indian user community in Section 5.1. We then make an attempt to assess the preparedness of the accelerator community in India to take up the projects for meeting these requirements. In this regard, we discuss the existing capabilities in the country in the field of accelerator science and technology, at the sub-systems and components level in Section 5.2, and this discussion is further carried out in Section 5.3, to assess the available technology and gap areas for developing different types of accelerators. Finally, in Section 5.4, we put forward our views about the path ahead, to meet the future needs.

5.1 Requirements of the Indian user community

The accelerator requirements of the Indian User Community are broadly as follows.

For Research in condensed matter physics/materials science/biological science

- High Brilliance Synchrotron Radiation Source (bright X-ray pulses)
- X-ray Free Electron Lasers (ultrashort and bright X-ray pulses)
- Spallation Neutron Source (short and intense neutron pulses)
- Low energy (a few keV – several tens of keV) and high-fluence ion accelerators for materials science research

For Research in nuclear physics

- Future heavy ion accelerator with beam energy 10-20 MeV/A and beam intensity of few pμA for nuclear physics research
- Accelerator for Rare Isotope Beam
- Low Energy (0.01 – 5 MeV), high current (few hundred pμA) accelerator for nuclear astrophysics research
- Accelerator for Accelerator Mass Spectrometry (AMS)

For Industrial applications

- Industrial electron LINACs, having energy of few MeV and beam power of few kW – few tens of kW
- Low energy (few keV – 100's of keV), high current (few 100's of μA) ion accelerators
- Compact accelerator driven neutron generator

For Medical applications

- Medical electron LINACs, like IMRT, having advanced features for therapy
- High current (~ few mA) cyclotron for production of medical isotopes
- Medical cyclotrons for cancer therapy
- 70-230 MeV proton synchrotron for medical therapy
- 450 MeV/A Carbon/ All Ion accelerator for hadron therapy

For Harnessing Nuclear Energy

- High average power proton accelerator for ADS

While analyzing this list of user requirements, we notice that some of the user needs require a common accelerator technology to be developed. We thus come up with a consolidated common list of accelerators that need to be developed, in order to fulfil the above user requirements:

- Industrial and medical electron LINACs, having energy of few MeV and beam power of few kW – few 10's of kW
- Injector electron LINACs with beam energy ~ few hundreds of MeV to few GeV, as injector for SR source and FELs; and with beam energy ~ 50 MeV for pre-accelerator for RIB production
- 1 GeV SC proton injector LINACs with beam power ~ 1 MW for SNS; and, with beam power ~ 10 MW for ADS; with several other applications at intermediate

energies, such as 50 MeV proton LINAC as pre-accelerator for RIB production, 200 MeV proton LINAC for medical isotope production, 70-230 MeV proton LINAC for research in cancer therapy *etc*.

- 70-230 MeV proton synchrotron for medical therapy
- ~ few GeV electron storage ring, based on MBA lattice for HBSRS
- High current (~ few mA) cyclotron for production of medical isotopes, and high energy, high current cyclotrons for RIB production and acceleration
- Future heavy ion accelerator with beam energy 10-20 MeV/A and beam intensity of few pμA for nuclear physics research
- Low energy (a few keV – several 10's of keV) and high-fluence ion accelerators for materials science research
- Low energy (0.01 – 5 MeV), high current (few hundreds of μA) accelerator for nuclear astrophysics research
- Compact accelerator driven neutron source

In the next sub-section, in order to explore the possibility of building such machines, we assess the existing capabilities in the country in the area of accelerator science and technology at the sub-systems and components level.

5.2 Accelerator Science and Technology at Subsystems and Components Level

In this section, we take a look at the current status of accelerator science and technology in the country at the sub-systems and components level for the variety of accelerators of our interest, as described in the previous section. Each sub-section talks about one particular type of accelerator, and elaborates on different major components of that type of accelerator.

Electron Linear Accelerators

- *Electron gun – thermionic and photocathode gun*
  Thermionic electron guns have been developed at RRCAT and BARC for indigenously developed industrial electron LINACs, and also at SAMEER for indigenously developed medical electron LINACs. Recently, high rep rate (650 MHz) electron gun is being developed at VECC for electron LINAC for RIB. At RRCAT and IUAC, technology has been developed for laser photocathode electron gun, using copper surface as the photocathode. R&D is being pursued at IUAC on semiconductor-based photocathode gun.

- *DC electron accelerator*
  DC electron accelerators have been developed at BARC for industrial applications.

- *RF accelerating structures*
  RRCAT has developed Plane Wave Transformer (PWT) RF accelerating structures, as well as Traveling Wave (TW) structures for RF electron LINAC. BARC has developed bi-periodic Standing Wave (SW) accelerating structures, and SAMEER has developed side-coupled SW structures. Thus, expertise exists in developing a variety of RF accelerating structures for electron LINAC. TW structures can be used for developing high energy (~ 100 MeV - few GeV) electron LINACs for various applications.

- *RF power sources – Klystrons*
  Program has been initiated for indigenous development of Klystrons at CEERI, Pilani.

- *Klystron modulators*
  Klystron modulators have been developed at RRCAT, BARC and SAMEER for their in-house developed electron LINACs.

- *Microwave and waveguide components*
  Several of the waveguide components have been developed by RRCAT, BARC and SAMEER for their in-house developed electron LINACs.

- *Control System*
  RRCAT, BARC and SAMEER have built the control system for their in-house developed electron LINACs.

Electron Synchrotrons and Storage Rings

- *Injector microtron*
  RRCAT has expertise in developing microtron, as an injector for the booster synchrotron, and also for several other applications. Capability now exists to design and develop injector linacs too.

- *Booster Synchrotrons*
  RRCAT has designed, developed, erected and commissioned the 550 MeV booster synchrotron. Expertise exists in the area of physics design, magnet technology, RF technology, beam diagnostics and vacuum technology.

- *Storage Rings as Light Sources*
  RRCAT has designed, development, erected and commissioned a 450 MeV electron storage ring Indus-1, and 2.5 GeV electron storage ring Indus-2. Here also, full in-house expertise exists in the area of physics design, magnet technology, RF technology (including Solid State Amplifiers), beam diagnostics, vacuum technology, and also on development of solid-state RF power source.

- *Synchrotron Radiation Utilization Beamlines*
  RRCAT, BARC, SINP and UGC-DAE CSR have expertise in design of beamline for synchrotron radiation sources. Optical components are mostly needed to be procured. Although on various aspects of optics development, R&D is being pursued.

Proton Linear Accelerators

- *Ion Source*
  BARC and VECC have developed ECR ion sources. IUAC has developed two two-electrodes tabletop ion sources of 30 keV and 60 keV energies respectively. RRCAT is in the process of development of H^- ion source. VECC has developed H^- ion source for the medical cyclotron project.

- *Radio Frequency Quadrupole*
  BARC has developed and commissioned 3 MeV proton RFQ. RRCAT is in the process of developing 3 MeV H^- RFQ.

- *Drift Tube LINAC*
  BARC has developed 20 MeV DTL, which is currently being commissioned. Beam has been successfully accelerated through the four tanks of DTL.

- *Superconducting Spoke Resonators and Elliptic Cavities*
  Superconducting Spoke Resonator (SSR) for $\beta_{opt} = 0.11$ has been developed at IUAC, and tested at Fermilab. SSR for $\beta_{opt} = 0.22$ and Superconducting Elliptic Cavities for $\beta_{opt} = 0.92$ have been developed at BARC and RRCAT, respectively for the PIP-II project at Fermilab. Here, β_{opt} is the speed of the charge particle in unit of speed of light that can be accelerated with optimum efficiency in the SSR structure.

- *Vertical Test Stand and Horizontal Test Stand*
  Vertical Test Stand (VTS) for test of bare SC cavities and Horizontal Test Stand (HTS) for the test of dressed SC cavities have been developed at RRCAT. Both VTS and HTS have been commissioned at RRCAT, and are routinely used.

- *Helium Liquefier/Refrigerator*
  Indigenous Helium Liquefier/Refrigerator has been developed at RRCAT to produce 45 L/Hr. of Liquid helium or 120 Watts of refrigeration at 4.5 K. Aluminium plate fin heat exchangers have been developed that can be used, down to liquid helium temperatures. Similar capability has been developed at BARC too.

- *Cryomodules*
  Design capability is being developed at RRCAT and BARC for the development of cryomodules, under IIFC.

- *RF power sources*
  Solid State Power Amplifiers have been developed at BARC and RRCAT, which are to be utilized for the PIP-II project at Fermilab.

- *RF power couplers*
  RF power couplers have been developed at BARC for the RFQ and DTL accelerators, and are under development for SC cavities. Brazing of ceramic window is a challenging task, and for coupler development, it is crucial to develop expertise in this area.

- *Tuners*
  Tuners for SC elliptic cavities have been developed at RRCAT, which will be utilized for PIP-II project at Fermilab.

- *Low level RF (LLRF) control*
  BARC is participating in the development of LLRF control and RF Protection Interface (RFPI) for PIP-II project at Fermilab.

- *Control System*
  BARC is participating in the development of control system for the PIP-II accelerator at Fermilab.

Proton Synchrotrons and Accumulator Ring

- *Beam injection*
  Design studies have been done at RRCAT for High Energy Beam Transport (HEBT) from injector LINAC, and then beam injection into 1 GeV proton accumulator ring.

- *Lattice Design*
  Extensive lattice design studies have been done at RRCAT for the 1 GeV proton accumulator ring. Lattice error studies, correction schemes, beam collimation schemes and electron-proton instability have also been studied.

- *Beam Extraction*
  Design studies have been done at RRCAT for the beam extraction system for the 1 GeV proton accumulator ring, and also the transport of the extracted beam to beam target.

Light and Heavy Ion Accelerators

- *Ion Sources*
  These have mostly been procured. Some expertise exists at VECC on indigenous development of ion sources for cyclotron project.

- *Van de Graff and Pelletrons*
  These have been procured at BARC, TIFR, IUAC and few universities.

- *RFQ for High Current Injector*
  This has been developed and commissioned at IUAC.

- *SC Quarter Wave Resonators for booster linac*
  Expertise exists at TIFR on Pb-coated cavity development, and at IUAC on Nb cavity development, through their in-house development projects.

- *Inter Digital (IH) mode Drift Tube LINAC*
  Expertise exists at VECC through their in-house development of several of them for the ongoing RIB project.

Cyclotrons

- *Ion Source*
  Some expertise exists at VECC on indigenous development of ion sources for cyclotron project.

- *Normal Conducting Cyclotrons*
  Expertise exists on all aspects, viz., RF, magnets, beam dynamics, beam diagnostics and beam extraction of NC cyclotron, through the in-house project on development of *K-130* cyclotron, which is operating successfully.

- *Superconducting Cyclotrons*
  Here also, expertise exists on all aspects, viz., RF, magnets, beam dynamics, beam diagnostics and beam extraction, through the in-house project on development of *K-500* cyclotron, which is operating successfully.

- *Separated Sector Cyclotrons*
  Design studies have been done at VECC on separated sector cyclotron.

Beam Targets

- *Spallation Targets for Neutron Source*
  Initial design studies done at BARC for ADS targets.

- *Targets for RIB*
  Design studies done at VECC for the RIB project

Radiation Detectors

- This is common to all accelerators. Knowledge base exists in this area at BARC. RRCAT and BARC are pursuing development of some of the radiation detectors, and RRCAT is specially working on semiconductor-based radiation detectors.

Cryogenic Facility

- *Helium liquefier*
  Both RRCAT and BARC have developed indigenous helium liquefiers, although of smaller capacity (~ 30-45 l/h)

- *Cryogenic Transfer lines*
  Expertise exists in the county on the technology of cryogenic transfer lines that are needed for accelerators.

- *Cryoplants*
  This often needs to be bought. Expertise exists in the country on procurement of cryoplants.

- *Cryomodules and other sub-systems*
  BARC and RRCAT are gaining experience in this area through collaboration with Fermilab on PIP-II project.

Accelerator Physics

- *Electromagnetic Design*
  Expertise exists on the electromagnetic design of various RF accelerating structures, NC as well as SC, addressing a wide range of relevant issues, such as higher order modes, beam induced effects, various instabilities, RF power coupling, *etc*.

- *Beam Dynamics*
  Good expertise exists in the area of beam dynamics in RF LINACs, cyclotrons, DC accelerators, synchrotrons, storage rings through a wide variety of accelerator projects in the country.

- *Computer Codes*
  Few of the computer codes for beam dynamics have been developed for performing part of the beam dynamics calculations. This needs to be strengthened. Facility needs to be developed for grid computing and large-scale data management for extensive computer calculations.

5.3 Available Technologies and Gap Areas

In this section, we talk about technologies that are available for the accelerator requirements, as a whole, and the gap areas that need to be filled in for meeting the projected requirements of future accelerators.

Electron Linear Accelerators

Capability exists for building all the sub-systems of industrial electron LINACs, except the high frequency RF power sources, and some of the microwave components. Future effort needs to be channeled towards making the developed electron linacs robust for industrial and medical applications. Also, expertise needs to be augmented to build high energy electron LINACs by addressing the issues related to vacuum brazing of large accelerating structures, and also the RF and controls issues, while adding large number of accelerating sections to go to higher energies.

Electron Synchrotrons and Storage Rings

In the field of SR sources, experience exists in the country in design and development of 3rd generation sources, but that needs to be augmented and gap areas need to be filled in, in order to extend our expertise to design and development of High Brilliance Synchrotron Radiation Source (HBSRS) based on MBA lattice. Meeting the stringent requirements on ultra-precision magnet systems and RF systems, and having expertise on estimation and control on the impedance of various components for storage ring based on MBA lattice is a gap area, on which work needs to be done. Similarly, another gap area is the design and development of suitable insertion devices with high accuracy. An important gap area that needs attention is beamline components like monochromators, X-ray mirrors and lenses, beam instrumentation and X-ray detectors.

Free-Electron Lasers

In the field of free electron lasers, experience exists in the country on development and commissioning of long wavelength FELs. However, in order to venture into short wavelength and high average power FELs, the expertise needs to be generated in gap areas such as generation and manipulation of low emittance and ultra-short pulses of electron beam, high stability RF and microwave systems, design of SASE FELs and seeding schemes, undulator development and accurate magnet calibration facilities, *etc*.

Proton Linear Accelerators

Capability exists for development of SC cavities. Experience exists in the country on developing ion sources and RFQ and DTL accelerator for various projects. However, several gap areas exist, such as beam acceleration in large number of independently phased SC cavities of proton accelerator, resonance control of SC cavities, LLRF, control system *etc.*, which have been partially addressed through the ongoing international collaborations. Experience exists in the country in design and development of very low beta SC accelerator for heavy ions. However, expertise needs to be built in the country on design and development of SC proton and electron accelerators, taking care of the inter-related design issues in a holistic manner. The gap areas, which limit the beam quality and beam current, need to be addressed for the future projects.

Proton Synchrotrons and Accumulator Ring

Design capability exists, and some practical experience exists in development of similar systems for electron synchrotron and storage ring.

Medical accelerators for hadron therapy

For the indigenous development of Hadron Therapy facility, proton and heavy ion accelerator technologies already developed in the country may be exploited. However, a huge technological milestone has to be achieved to develop the beam delivery system of these machines by designing an efficient gantry system. Also, there is no experience in the country on development of proton synchrotron. A team consisting of accelerator personnel and medical professionals from the field of ion-based radiation therapy needs to be developed in order to work together towards the development and production of Hadron therapy facilities in India.

Ion Accelerators

Expertise exists at BARC/TIFR, IUAC and VECC to take up future projects in this area through the successful development of superconducting booster linacs at BARC/TIFR and IUAC and room temperature accelerating structures at VECC.

Cyclotrons

Expertise exists at VECC for *K-130* NC and *K-500* SC cyclotron. Expertise needs to be extended to design and development of high-energy and high-current separated sector cyclotrons, particularly addressing the space charge issues.

Induction Accelerators

Some experience exists in the country in this area through the development of induction linac at BARC. Induction accelerator technology is nowadays used in synchrotrons and microtrons also due to certain advantages. In particular, induction synchrotrons are becoming popular for hadron therapy machine. Expertise needs to be developed in this area.

Detector Systems

Detection system development for scattered driving particles or secondary particles *etc.,* are inseparable from the accelerator development. Especially, in order to capture signals from the body generated during and after dose irradiation, such as prompt gammas, positron annihilation gammas, or acoustic waves, novel detector systems and quick DAC systems would be demanded for on-line monitoring of the ion beam irradiation. Expertise needs to be built in the country in this area.

Beam Targets

Need to develop expertise in this area for SNS, ADS, RIB.

Cryogenic Technology

The superconducting accelerator technologies align well with the turbo-expander based cryogenic systems. However, this technology is typically difficult to scale for low refrigeration capacity applications due to the need of special technologies, particularly the ultra-high-speed turbo-expanders. The key challenges in this direction would involve the following:

i) Development of large throughput high speed cryogenic turbo-expanders.
ii) Development/adaptation of large capacity high pressure screw compressors for closed loop cryogenic processes.
iii) Vendor development for large capacity compact cryogenic heat exchangers.

In addition to developing the technology of cryogenic refrigeration system, we also need to develop the technology of long cryomodules that are typically needed in SRF accelerators. A long-term plan is needed to bridge the gap between the existing technology and the required technology in this area.

There are some common gap areas that are common to many of the accelerators discussed in this section, which needs to be addressed. For example, the high purity niobium that is required for superconducting cavities, OFHC copper that is required for normal conducting cavities, high quality rare earth magnets that are needed for insertion devices in SRS and FEL are mostly needed to be procured from very limited foreign sources, and there is inherent uncertainty associated with the procurement. Hence, emphasis should be given to R&D for indigenous development of these materials, meeting the stringent quality requirement. Similarly, for superconducting cavities and magnets, procurement of helium from limited foreign sources also suffers from similar issue.

In all the areas listed above, expertise needs to be built in accelerator physics and engineering design, particularly in the development of computer codes, and also in beam dynamics with space charge and several beam instabilities, to move on the intensity frontier. In the following subsection, we describe the technology advances that have been made to bridge some of the gap areas, both as a result of ongoing international collaborations, as well as infrastructure development in the country.

5.4 Path Ahead

In order to be able to make the desired progress towards developing the required technologies in a timely manner in future, so that the expectations of the user community can be met, we need to work on the gap areas, which we discussed in the previous section. This needs to be achieved through indigenous efforts, as well as through goal-oriented international collaborations. Current status of technology advancement achieved through indigenous efforts and international collaborations are described below one-by-one, which need to be further strengthened.

Capacity Building as a result of National Programs

Over the last several decades, good capacity building exercise has taken place in the development of accelerator science and technology. Some of those are described in this sub-section.

In the area of SC accelerator development, good infrastructure has been created at RRCAT, IUAC and BARC, partly indigenously and partly with international collaboration, which will be useful for taking up the projected mega science projects. Infrastructure has been developed for fabrication, processing, dressing and qualification of superconducting cavities. Similarly, infrastructure has been built for development and testing of superconducting as well as normal conducting magnets and Solid State Power Amplifiers (SSPAs). Currently, infrastructure is being developed for cryomodule development. With the recent commissioning trials of Low Energy High Intensity Accelerator (LEHIPA) at BARC, some experience in the area of normal conducting proton LINAC commissioning has also been gained.

In the area of superconducting heavy ion LINAC, good capacity building exercise took place in the country while developing superconducting LINAC boosters for Pelletrons at TIFR and IUAC.

On the front of electron LINAC development, good infrastructure has been created at RRCAT, BARC and SAMEER for machining, brazing and testing of accelerating structures. A variety of electron LINACs have been developed with this infrastructure.

Since the existing synchrotron radiation sources Indus-1 and Indus-2 at RRCAT have been built mostly with indigenous components, a good capacity has been built during the last several decades in the area of in-house design, development and commissioning of booster synchrotron and storage ring. Infrastructure has been created in other crucial areas of development, such as synchrotron magnet technology, ultrahigh vacuum technology, beam diagnostics, RF and microwave technology, accelerator controls, RF cavity *etc*.

In the field of Free Electron Laser (FEL), RRCAT has gathered rich experience after being involved in the development of an IR FEL machine over the last two decades. A similar capacity building exercise is going on at IUAC in connection with the development of a compact FEL THz facility based on a RF photocathode electron gun.

Similarly, due to the program of *K-130* and *K-500* cyclotron development and commissioning at VECC, good infrastructure has been developed for normal conducting as well as superconducting cyclotron.

Technology Advances in the light of ongoing international collaborations

In the area of development of SC accelerator technology, ongoing international collaborations with Fermilab, TRIUMF, CERN and FAIR have been useful.

The ongoing collaboration with Fermilab on design and development of PIP-II SC H^- LINAC is providing us the opportunity of learning the intricacies of different aspects of the technology, particularly the superconducting elliptic cavities, superconducting spoke cavities, cryomodules, accelerator controls and commissioning *etc*. The experience on superconducting cavity processing, dressing and qualification has been particularly useful. This collaboration will thus help us in filling up of the gap areas in superconducting proton accelerator technology.

Similarly, the collaboration with TRIUMF, Canada on development of SC electron accelerator as the primary accelerator for neutron rich RIB has given us very useful experience on superconducting accelerator technology. This collaboration will thus help us in filling up of the gap areas in superconducting electron accelerator technology.

The collaboration with CERN has given us experience with several state-of-the-art technologies such as superconducting magnet technology, modulators for RF and microwave systems, and also some RF and microwave components. This collaboration has thus helped us in filling some important gap areas in superconducting magnet technology.

The existing collaboration on FAIR project has given us good experience in development of state-of-the-art power converters for accelerators.

The technical collaborations with KEK, Japan; BNL, USA; DESY and HZDR, Germany, have been extremely useful in developing the compact FEL facility at IUAC.

The path ahead is, therefore, to invest effort and financial resources on filling up the gap areas and strengthening the existing capabilities further, and take up the planned mega science projects, as will be described in the next chapter. In order that we succeed on this path ahead, in addition to developing the required technologies through indigenous programs, as well as international collaborations, we need to create a conducive ecosystem, by way of developing industry partnership, human resource development, *etc*., which we describe later in Chapter 7.

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6. Proposed Directions to be pursued during 2020-2035

Research and Development work in accelerator science and technology is primarily driven by the intended applications in different areas, which are of interest to the user community. In the previous chapter, we discussed about the requirements of accelerators from the user community, and also the existing scientific and technological capabilities to build the required accelerators, along with the gap areas that need to be bridged for successful development of machines to meet the user requirements. In this chapter, keeping this scenario in mind, we describe the proposed directions to be pursued over the next 15 years, in the area of accelerator science and technology. Some of the proposals have been discussed for quite some time now, but have not yet reached the stage of funding approval. Various design goals for the machines that are described in the proposal are open for further fine tuning, based on the feedback from the vast user community and experts. At the end of this chapter, we also provide a prioritized list of projects in the six categorized areas, namely, Nuclear Physics Applications, Photon Science Applications, Neutron Science Applications, Medical Applications, Industrial Applications and New Acceleration Techniques.

6.1 Accelerators for Rare Isotope Beams

Radioactive Ion Beams (RIBs) – also called rare isotope beams, with their promise of making accessible hitherto unexplored regions of the nuclear chart, and also with their enhanced intensity for already synthesized nuclei, have clearly emerged as the frontier of low energy nuclear physics. Apart from nuclear physics and astrophysics, RIBs open up new areas in materials research and biology, and provide an alternative route for medical isotope production. Further, the accelerator technology needed for producing these beams has led to the development of particle therapy machines for treatment of cancer, and also led to ion beam applications in industry. Two proposed directions for RIB facilities are given below.

Applied and Nuclear physics with Rare Isotope Beams

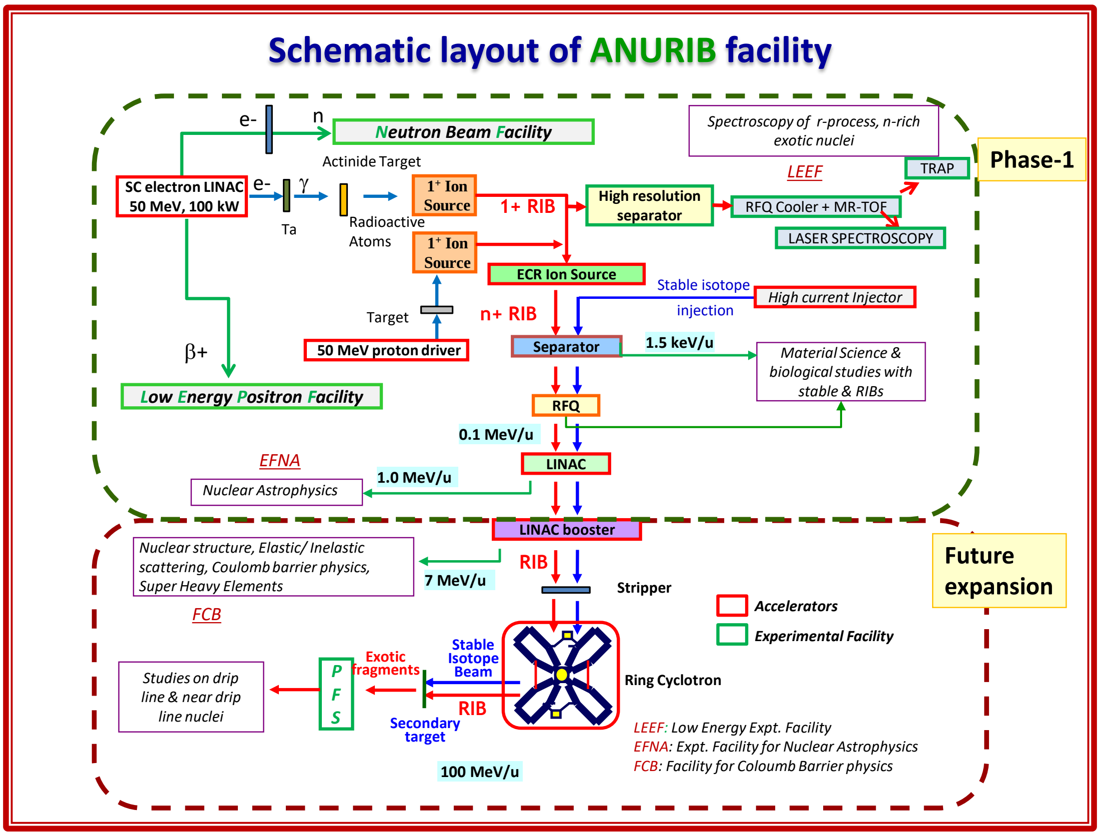

Fig. 6.1.1: Schematic of ANURIB – the proposed facility for **A**pplied and **NU**clear physics with **R**are **I**sotope **B**eams

VECC had made a beginning a decade ago, albeit on a modest scale, and constructed a low-energy RIB facility around the existing *K*-130 cyclotron. A few RIBs with an intensity of around few thousand particles per second have been produced, and several building blocks, namely, the country's first RFQ LINAC, online ECR ion-source and a heavy-ion LINAC [Bandyopadhyay 2006] have been indigenously developed. The next generation RIB facility, named ANURIB (Advanced National facility for Unstable and Rare Isotope Beams) [Bandyopadhyay 2015], is being planned for applied and nuclear physics with rare isotope beams, a schematic of which is shown in Fig. 6.1.1. It has been funded by the DAE for technical design and R&D on gap areas towards construction of the facility.

In this proposal, a 50 MeV, 100 kW CW SC electron accelerator will be the main driver accelerator for the ANURIB. The electron accelerator will produce neutron rich rare isotopes through gamma-induced fission of actinides. The development of actinide target for optimum production is a very challenging task. A high-current 50 MeV proton cyclotron will be the second driver accelerator to be used for the production of proton-rich isotopes. A dedicated ECR ion-source and high-current injector will produce intense beams of beta-stable isotopes that will be mass-separated and accelerated using the same set of accelerators. Thus, RIB as well as stable isotope beams (SIB) will be available from ANURIB. This scheme will open up the physics opportunities at various intermediate stages. After initial acceleration in RFQ and room temperature LINACs, SC LINAC boosters (SLBs) based on Niobium QWR will be used to increase the beam energy to around 7 MeV/A, opening up the regime of Coulomb barrier physics and production of SHE using RIBs as well as SIBs. This beam can be injected in to a Ring Cyclotron to further boost the energy to around 100 MeV/A, opening up the regime of physics of near-drip line nuclei. Apart from SIB, fragmentation of RIB will become accessible, thus giving ANURIB a unique edge in exotic nuclei physics. The electron accelerator can also be used for producing beams of neutrons and low energy pulsed positrons. These beams have applications in materials research and other multi-disciplinary areas. For this purpose, provision has been kept in ANURIB for a dedicated neutron beam facility and a low energy positron beam facility.

In the following paragraph, we present a SWOT analysis of the ANURIB project:

Strengths:

- Prior experience exists on development and operation of majority of the sub-systems.

- A good user base exists to utilize this accelerator for research in nuclear physics and multidisciplinary applied fields.

Weaknesses:

- Limited industrial support due to highly specialized nature of jobs.

Opportunities:

- Spin-off technologies are of use for several societal benefits of interest.

Threats:

- The accelerator developed may become outdated if the project execution is delayed.
- Project execution may get severely affected in a likely scenario, where sufficient number of trained scientists and engineers throughout the long project period is not ensured.

RIB based on spontaneous fission source

There is another attractive scheme to produce exotic neutron rich radioactive ion beams away from stability, and this type of facility can be set-up as a complimentary facility of ANURIB. The proposed facility can be an exciting up-gradation of the upcoming facilities like the High Current Injector at IUAC.

Such a facility has recently become operational at Argonne National Laboratory, USA. Its basic principle of operation is as follows:

It uses ^{252}Cf, which is generated in high flux nuclear reactors, and is commercially available. Typically, 1 Curie source of ^{252}Cf is taken, which undergoes spontaneous fission, and the fission fragments supply ion beams of ^{252}Cf fission fragments, which are thermalized in a gas catcher. Handling of the ^{252}Cf source with such a high activity is a challenge. The singly and doubly-charged ions extracted from the gas catcher are mass-separated and delivered either to a low-energy experimental area, or charge bred with the existing ECR source and subsequently reaccelerated by the existing High Current Injector, which is RFQ, followed by NC LINAC, and finally SC LINAC. In this process, a large variety of exotic radioactive ion beams from the fission fragments of Californium can be produced, and accelerated up to energies of few tens of MeV/nucleon**.** This type of facility, if planned for future, can be taken up as an augmentation project. The basic framework of the accelerator will be similar to the existing accelerators in India, comprising RFQ, NC/SC LINAC, *etc*. The procurement of the strong Californium source may not pose a serious threat, as this is commercially available in sufficient quantities.

In the following paragraph, we present a SWOT analysis of this project:

Strengths:

•IUAC already has a good accelerator infrastructure for this project.

Weaknesses:

•Lack of trained human resource for project execution.

•Limited technical support from the Indian industry.

Opportunities:

•Will generate trained human resource in accelerator technology and nuclear physics.

•Possibility to become one of the prominent laboratories in the world in this new field.

Threats:

•Very limited job opportunity in the field may distract researchers to join this project. .

6.2 Other Accelerators for Nuclear Physics Studies

The accelerators that are being used for nuclear physics studies in India include low energy accelerators, cyclotrons and superconducting booster linacs. Low energy accelerators are of particular interest for nuclear astrophysics experiments to study rare processes, because of which we need higher beam currents. Such accelerators need to be built deep underground so that there is negligible cosmic background. In order to extend the facility to Indian users beyond FRENA, low energy accelerators can be planned in the tunnel for India-based Neutrino Observatory. In the remaining part of this section, we describe proposals for new accelerators, and also future upgrades of the existing accelerators, to keep pace with the progress in this area of research.

Future Heavy Ion Accelerator Facility

Though it is important to have new accelerators, which require large funds and dedicated expert human resource, augmenting the capabilities of the existing ageing heavy ion accelerators with relatively modest funds is equally important to fully exploit their potential. This will help us in getting due returns from the investments already made, and also to utilize the human resource already invested in the associated area of R&D. The high current injector project of IUAC also needs priority in resource allocation, and in human resource mobilization, as the same would provide rare isotope beam species with higher intensity.

The waiting period to get beam time at the existing accelerator facilities at IUAC is currently 2-3 years. At the BARC-TIFR Facility, there are demands for more beam time from the users, partly because the user community has grown over the years, and also because there are more studies being performed on rare processes. Hence, there is a strong need to arrange for additional beam time for the research community. Considering the inadequate number of existing accelerator facilities for nuclear research in India, it is strongly felt that more accelerators in the low energy range (around Coulomb barrier) with reasonable intensity (tens of particle nanoampere (pnA)) are needed in India. To perform nuclear physics experiments with stable beams, either new heavy ion accelerator facilities can be built, or the existing ones can be used with up-gradation, if necessary. Greater variety of beams, especially stable beams of less abundant isotopes and heavier neutron rich beams like ^{54}Cr, ^{62}Ni, ^{70}Zn etc., are expected to be delivered by such machines. Beam energy up to ~10 MeV/A and beam current in the range of tens to hundreds of pnA will enable the research community to explore rare channels in nuclear reactions, and help in studying exotic phenomena in nuclear structure. Currently, two upcoming facilities- the high-current injector at IUAC, and the SCC at VECC can deliver some of these ion species mentioned above.

As far as a low energy accelerator facility is concerned, as discussed in the beginning of this sub-section, it will be useful to extend the existing facilities for nuclear astrophysics experiments. In this regard, as suggested by the nuclear physics community, a low energy accelerator facility based on a single ended 5 MV Van de Graaff accelerator, with high current positive ion ECR source may be developed. In the first phase, a C-14 dating facility based on Positive Ion Mass Spectroscopy (PIMS) technique may be set up. Such a facility will cater to archaeological research in the country, along with Accelerator Mass Spectrometry (AMS) technique - based facility, which is already being used in the country, and is based on negative ion source, and with relatively lower value of beam current. In the second phase, the Van de Graff accelerator may be setup along with a recoil mass separator, which can be used for (i) measuring nuclear cross sections at around Gamow energy which are crucial for understanding stellar core "burning", including measurements with rare gas beams in inverse kinematics, and (ii) generate intense neutron beams, which will be used both for measuring neutron cross sections relevant for fission and fusion reactors, and also for accelerator driven Boron Neutron Capture Therapy[22] (BNCT).

We present below a SWOT analysis for Future Heavy Ion Facility project:

Strengths:

- Prior experience exists on proven and robust technology needed for this project.
- Strong user base exists, who will use the new facility for research in multi-disciplinary fields *e.g.*, chemical science, biological science, geo-chronology, *etc*.

Weaknesses:

- Lack of trained human resource, who can take up and complete the project.
- Limited industry support and limited collaboration between Indian laboratories.

Opportunities:

- Opportunity to utilize the potential of Indian industry and strengthen it.

Threats:

- Project execution may get delayed due to extant administrative processes for procurement.
- Very limited job opportunity in the field may distract young researchers to join this project.

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[22] In BNCT, suitable tumour-localizing drug containing ^{10}B is injected into the patient's body, and the patient is irradiated with epithermal neutrons, which are absorbed by ^{10}B to produce α particles that kill the cancer cells.

6.3 High Brilliance Synchrotron Radiation Source

With Indus-2 operating successfully for the last two decades, the need for a High Brilliance Synchrotron Radiation Source (HBSRS) based on MBA lattice design, has been strongly felt by the Indian scientific community, which will also serve as a key enabler to place India on the world horizon of the state-of-the-art SR sources, and the associated science and technologies.

The proposed HBSRS will have an emittance of $\leq$ 150 pm-rad, with the emitted X-ray radiation photon energy higher than 150 keV and a peak photon brightness greater than 10^{21} photons/s/mm^2/mrad^2/0.1% BW. A schematic view of the proposed HBSRS is shown in Fig. 6.3.1. It will tentatively have a 200 MeV injector LINAC. The beam from the LINAC will be injected to booster ring via a transport line. The electron beam energy will be increased from 200 MeV to 6 GeV in the booster synchrotron. The 6 GeV electrons will be extracted from the booster and injected into the storage ring through a transport line to fill a beam current of 200 mA. The circumference of the booster will be kept lower than storage ring so that the complete booster ring is accommodated inside the storage ring tunnel. The basic design parameters however need to be debated based on extensive user feedback. For example, possibility of having full energy injection to the storage ring should also be explored, keeping in mind that the option of using the full energy linac could be useful possibly for XFEL in future[23].

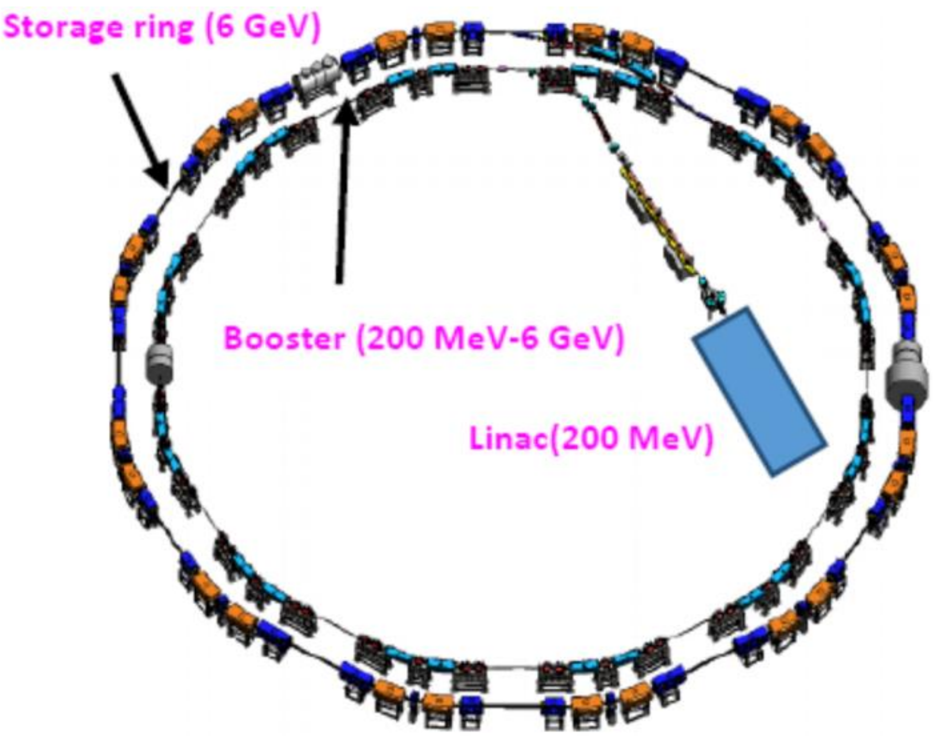

Fig. 6.3.1: A schematic view of the proposed accelerator configuration for HBSRS.

It is proposed to take up the design, development and construction of HBSRS, in two broad phases:

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[23] Although the crucial design requirements of injector linac for XFEL and full energy injector linac for SRS are not the same, a possibility of meeting both the requirements in the same linac may be explored.

Phase-1 (Preparatory and Prototyping Phase, 2 years) : This would essentially consist of generation of user requirements, evolving/refining machine parameters, prepare the machine layout, prepare the conceptual design of the machine and specifications of beamlines, design review, sub-system level design and initiation of prototyping, evolving detailed documentation for series manufacturing, identifying Indian industries for necessary capability building, evolving procedures for fast-track procurement, detailed planning for the facility, site preparation, *etc*.

Phase-2 (Construction and Commissioning Phase, 6 years): It will essentially mark the construction and commissioning of the HBSRS facility. In this phase, civil construction of the facility, completion of prototyping and series manufacturing, testing, qualification of sub-systems and machine components, system integration, installation, phase-wise machine commissioning and work on front-ends and initial beamlines *etc*. will be carried out. By the end of this phase, the machine will be commissioned and beamlines will be available to users.

In the following paragraph, we present a SWOT analysis of the HBSRS project:

Strengths:

- A pool of trained human resource exists with experience on Indus accelerators.
- Some amount of basic industry support exists, which was created for Indus accelerators.
- Strong user base exists to utilise the beamlines of HBSRS.

Weaknesses:

- Limited support of local industry for supply of major systems on turn key basis.
- Excessive dependence on international suppliers for critical beamline components.

Opportunities:

- There exist many societal applications, for which there is a demand for such a source in the country. Also, it will provide the required facility to Indian users within the country.
- A very effective means to develop and sustain human resource and industry in the field of accelerator science, technology and utilization in the long run.
- A capability demonstrator, placing India in a leadership role in the field of particle accelerator science, technology and utilization.

Threats:

- The pool of trained human resource is depleting.
- Lack of job opportunity in this field may distract young researchers to join this project.
- Sanctions on proprietary international manufacturers of some critical machine and beamline components can delay the completion of the project.

6.4 Free Electron Lasers

There exists significant expertise and experience in the country in the areas of long wavelength FELs - its design, development, installation and commissioning. These projects have generated qualified and trained human resource for building FELs, who have successfully commissioned them. This group can serve as a nucleus for building larger groups of trained human resource for future activities in the field.

There is a strong growing interest over the last decade in the field of THz, which finds lot of societal applications in security, high altitude communication, food industry, *etc*. The present source of THz radiation has got some limitation as it is broad band and the power is relatively low, if one needs to concentrate on a narrow frequency range. The FEL-based THz source will overcome this problem, as it is tunable with a narrow bandwidth. The knowledge and expertise being gained to develop a compact normal conducting FEL-based THz facility can be made useful in future to develop a superconducting photoinjector based THz facility, which will provide tunable THz radiation with much greater average power unlike the Tabletop THz source.

With the current worldwide interest focused on X-ray FELs, and novel schemes like seeding, high gain harmonic generation, *etc*., to ultimately achieve stable FEL performance at hard X-ray wavelengths with fs pulses of GW peak power, there is a need for the present expertise in the country to be scaled up in order to take up such challenging projects in future. There are certain areas of science and technology, which are common to all the areas of current interest in FELs, which need to be mastered in order to build a state-of-the-art machine in future. Generation and manipulation of low emittance electron beams, development and qualification of semiconductor photocathodes, bunch compression to achieve fs bunch lengths, diagnostics for ultra-short electron bunches, high stability RF and microwave systems, design of SASE FELs and seeding schemes, undulator development and characterization facilities, *etc.* are some of the areas that need to be addressed, in order to ultimately plan for X-ray FELs. This can be accomplished by identifying multiple young research groups from different laboratories in the country, who can be tasked with the demonstration of one or more of these in a 3-5 years' time frame.

An intermediate goal could be the development of a 1 – 1.3 GeV electron LINAC delivering high brightness electron beam of a few hundred pC charge with a pulse length of few 10's of fs. This would serve as a test-bed for qualification of technology for future X-ray FELs, and could also serve as an injector for a VUV/soft X-ray FEL to produce radiation with a wavelength of few nm (4-100 nm), and a peak brightness up to 10^{30} photons/s/mm^2/mrad^2/0.1% BW. Different schemes like seeding, harmonic generation, *etc.* could also be tested on this FEL. The LINAC could be NC or SC, depending upon the user case for the VUV/soft X-ray FEL, or on the state-of-art in FELs at the time of taking up the project. Undulator development for this FEL would also be an important technology development. Following the superconducting route would make the injector common for scaling up to build a high average power hard X-ray FEL in the future, and to build a high average power IR FEL for security applications. Another pilot project that needs to be taken up expeditiously is to build and demonstrate a SC LINAC system with a suitable photoinjector to accelerate an electron beam up to say 100 MeV.

Once demonstrated, the 1 – 1.3 GeV accelerator can be scaled up to the desired energy of 8 – 14 GeV to build a hard X-ray FEL in the long term. It may be noted here that most X-ray FELs have been built at accelerator facilities that already had high energy linear accelerators operating for other applications. Also, there has been a vibrant exchange of scientific ideas and technologies between different research groups within these countries, and even internationally, to ultimately build a state-of-the-art facility. Ascending the learning curve in all the concerned science and technology fields would take a long time, and make progress very slow, which would defeat the idea of building a state-of-the-art facility. Hence, multiple research groups will have to work synergistically within the country to address the existing gap areas, and vibrant collaboration(s) will have to be established with other international XFEL facilities in order to ultimately build the facility in a time frame that would serve the interests of the user community. The user community will have a very important role to play in driving the design specifications for the machine since the basic choice of a NC versus SC LINAC system, the pulse structure, the wavelength region of interest, *etc.* will depend upon the envisaged usage of the machine.

On the front of high average power IR FEL for possible applications in national security, it will be useful to work on the development of a 10 kW IR FEL based on a 100 MeV SC LINAC in the energy recovery mode. Design and R&D on demonstration of the ERL concept may be taken up as phase-I of this activity, before taking up its construction in phase – II. Although it may be possible in future to build a solid-state IR laser with the desired characteristics for security applications, it may be prudent to work on high average power IR FEL until a suitable tunable high average power solid state laser is developed.

In the following paragraph, we present a SWOT analysis of different proposed projects on FELs. Let us first present a SWOT analysis for the proposed FEL-2 project, i.e., the second FEL project at IUAC, New Delhi, which will extend the operating wavelength to Infra-Red (IR), and also produce THz radiation with higher intensity, compared to the existing THZ FEL project, namely FEL-1 project.

Strengths:

•Strong user base is expected in multidisciplinary fields of physical, biological, medicinal science, and also in areas such as security, pharmaceuticals, atmospheric sciences, *etc*.,

Weaknesses:

•Lack of additional trained human resource, industrial infrastructure.

•Inadequate collaboration amongst Indian laboratories on this project.

Opportunities:

• There is a desire to develop X-ray FEL in the country, for which development experience of IR/THz FEL will be of help.

Threats:

•Lack of sustainable business opportunities for the industry will affect the interest of industry in taking up the jobs related to such a project.

Next, we carry out a SWOT analysis for the IR/THz FEL project at RRCAT, and also the future short wavelength FEL projects in the following paragraphs:

Strengths:

•Trained human resource exists with experience on development of IR FEL.

•RRCAT has enough space to house such a facility.

•It is based on a technology that is well proven by now, which can be studied to evolve the best suited stage-wise approach for an Indian X-ray FEL project.

Weaknesses:

•Lack of focused effort on beam dynamics studies, which is needed for the design/technology development for high-end components and sub-systems of XFEL.

•Very limited industrial support for development and characterization of full systems on turn-key basis.

•Lack of Indian sources of important raw material (viz. rare earth magnets for undulators, OFE copper for RF structures, *etc*.). There are problems in procuring from established international suppliers.

•Poor participation in international conferences, leading to very little one-on-one interaction of Indian scientists with international experts and resource persons in the associated fields.

•No clear-cut science case dictating the desired specifications of a machine in India. Often machine builders have to look for users to justify building the machine.

•Lack of experience in the design and development of high energy LINACs.

•Lack of collaboration with international partners in the field.

•Limited awareness about this field in universities and academic institutes.

Opportunities:

•Since there is a need for trained human resource for XFEL project in future, the long wavelength FEL projects can use this as opportunity to hire human resource, which will get trained in due course of its execution, and will be ready to take up XFEL project.

•As the SRF accelerator technology gets matured in the country, it will be looking for its users. This opens up a possible direction towards a high average power FEL both for long wavelength and short wavelength.

•With two FEL-based user facilities to be established in the next 2-3 years, research students can be attracted to pursue a career in advanced topics related to machine design/development or applications. Efforts can also be made to retain this trained human resource to contribute to the development of an X-ray FEL/user facility.

•Common targets can be fixed for building X-ray FELs and next generation SR source in the country, which will be mutually beneficial for both the activities.

•With clear short- and medium-term goals, synergy can be established between the different accelerator science and technology institutes in the country to develop prototypes of gap area technologies, with clear acceptance conditions and input/output plug compatibilities. Such a multi-institute effort would help promote collaboration for the future machine.

•Many reputed international labs have facilitated many start-ups based on the technologies developed for their high energy accelerators and accelerator-driven light sources. If the Indian industry is able to participate and deliver turn-key systems for an X-FEL project, they will have an opportunity to enter the global market for such systems. A mega light source project requires a large number of high-tech systems for which there may be a possibility for a reputed Indian industry to establish collaboration with a known foreign company or research lab, which would promote the ‘Make in India’ concept.

Threats:

•There is already a wide gap between technologies developed in the country for accelerator-driven light sources projects, and the state-of-art systems developed worldwide for X-FELs and SRSs. Delay in initiating a coherent activity towards building a state-of-the-art X-ray FEL in the country will further widen this gap.

•The average age of the present generation of trained human resource who have designed the FELs and light sources in the country is high, with many being in the > 50 years age bracket. Without the initiation of a new project and the timely induction of young scientists and engineers, many cumulative years of expertise may be lost.

•Worldwide, X-ray FELs have involved technologies developed in different laboratories of the world with very strong collaboration and information exchange. Restricted scientific and technological interactions (through conferences, visits, and MOUs) have the associated risk of ascending steep learning curves for all technologies, which can cause very long delays or even failures.

- The quality of workmanship required for most of the systems for high energy accelerator-driven light sources is very high. Hence, attempts at involving local industry on L1 basis, without pre-qualification through multiple single-party tenders on some shortlisted industries can lead to failures or very long delays. (For example, the Swiss X-FEL development required a large number of klystron pulse modulators. Prototype modulators were ordered on multiple established companies after bringing them on a common price footing. After the successful development and qualification of the modulators, orders were placed on multiple companies for the large numbers with shorter delivery time scales.)
- Some high-end systems should be identified and procured. Putting efforts at developing such systems, many of which will be one-off requirements, will take up precious time and resources.
- Any stage-wise plan should be made with the final stage target also clearly defined such that buildings and facilities are ready to accept the intermediate and final configurations as progress is made. Starting with only the first few stages, without considering the longer-term goals, can lead to gross incompatibilities at a later stage resulting in time and cost over-runs. This also holds true for all regulatory clearances required for the activity, since such clearances will be given, based on the final configuration and parameters.

6.5 Spallation Neutron Source

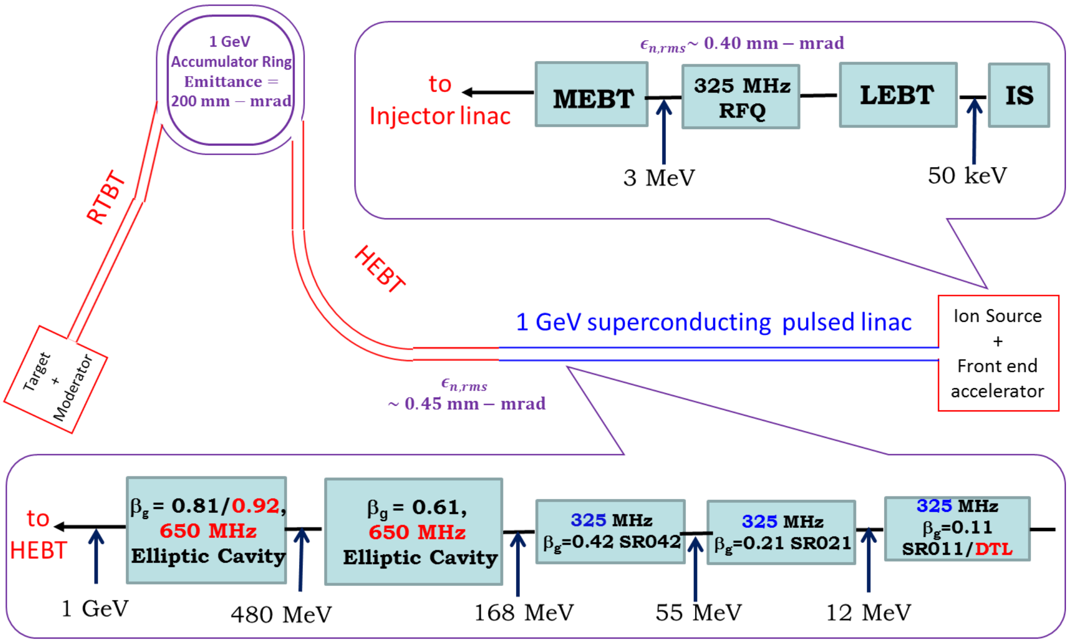

Fig. 6.5.1: A schematic layout of the proposed accelerator for IFSR.

There is a long history of neutron physics in India and there is a large user base. Therefore, development of a spallation neutron source should be assigned a high priority. It is proposed that an Indian Facility for Spallation Research (IFSR) should be built for experimental studies in condensed matter physics and various engineering applications [Jana 2019]. It may be based on a 1 GeV pulsed accelerator with an average power of 1 MW. Schematic layout of a suggested configuration of the accelerator is shown in Fig. 6.5.1. Choice of 1 GeV injector LINAC, similar to that of the SNS, Oak Ridge, has an advantage compared to the 2 GeV LINAC of the ESS because the construction cost of the latter will be double the cost of the former. The ESS will not use an accumulator ring (AR)[24]; as a result, the proton pulses will not get compressed to µs, and in order to compensate for that effect, the beam power has been increased to 5 MW in ESS. The possibility of upgrade to higher energy and higher power should be kept in the design.

Developing the IFSR will also be linked to the future project on ADS for utilization of thorium for energy production because both these projects require an expertise in building high average power SC LINAC. IFSR can thus be seen as a precursor to ADS program in India.

High power proton beam has several applications. Provision should be kept to tap the proton beam at different energies for useful applications, such as medical isotope production at 200 MeV, experiments on clinical radiotherapy at 250 MeV and also nuclear physics experiments at 1 GeV. In the initial stage of development, after commissioning the first SC spoke cavity module at an energy of ~12 MeV, a medium flux pulsed neutron facility may be developed to gain useful experience in the field. Also, provision should be kept for a beam dump to collect 3-5% beam all the time for isotope production. Also, RTBT should have a target to produce muons for high energy physics experiments. This will take only 1-2 % beam intensity.

Developing a spallation neutron source is a long-term project. Looking at the benefits of such a state-of-the-art machine, it will be prudent for India to venture into this activity. There exists experience in different areas of design and development of various systems of the injector, especially in the light of work done in different laboratories during the last decade. Working on the AR will be a new experience. RRCAT has complete know-how on development of Indus-1 and Indus-2 electron storage rings; it will be quite helpful in taking up the work on AR. Also, designing the 1 MW target-moderator system will be challenging, and R&D effort in this area needs to be pursued.

A Detailed Project Report (DPR) should be written for taking up the project in a phased manner, where in the first phase, all the R&D issues should be addressed, after which the construction phase can start. The progress of the first phase should be reviewed critically before embarking on the construction phase. Such a megaproject will be a long-term project (15 years), requiring a large number of people from different institutions to work together. A suitable strategy needs to be developed for this. Also, the possibility of future upgrade should be kept in mind while finalizing the project at the end of the R&D phase. It will be important to make use of the ongoing international collaborations in this area, to speed up the progress.

In the following paragraph, we present a SWOT analysis for the IFSR project:

Strengths:

•A pool of trained human resource exists in the country with experience on developing the front-end of the accelerator, and also on developing the SC cavities for the LINAC.

•A good level of infrastructure facilities exists in the country for all the stages of development of SC cavities.

•There exists experience in the country in building electron synchrotrons and storage rings. The experience gained and pool of trained human resource in the area of synchrotron development will be useful for taking up a project on building the proton accumulator ring.

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[24] It is however planned to have an accumulator ring, following ESS, to compress the beam for ESS neutrino Super-Beam (ESSnuSB) facility.

- User base in the area of neutron science exists in the country through utilization of research reactors; and also dedicated user teams, which have been using the accelerator-driven pulsed neutron sources abroad.

Weaknesses:

- Although trained human resource exists for the small-scale projects that have been taken up so far in this area, it is simply not adequate to complete such a large-scale project. Also, the existing human resource is ageing, and sufficient number of younger staff has not been hired in the past in this area.
- There are several areas, where we do not have prior experience, such as beam target development, running an accelerator with large number (~100s) of cavities, *etc*. Target development is one of the challenging areas.
- Industries have not been adequately developed to work in this area. Good industrial support is needed for such large-scale projects.
- In-depth R&D is needed for succeeding in the endeavour to build such a state-of-the-art machine. Accelerator community in India has so far worked in the project mode. Emphasis on R&D needs to be stronger, else it will turn out as our weakness, hampering our progress in such projects.

Opportunities:

- The ongoing international collaboration for building high power CW SC proton LINAC PIP-II at Fermilab is a good opportunity that we can utilize to speed up our learning process. During the ongoing R&D phase, some of the crucial components of this LINAC have already been successfully built by India, and supplied to Fermilab. A pool of trained human resource has been generated through this project. Our international collaborators have always expressed their keenness on collaborating with us, based on our past performance while working with them. We can utilize this as an opportunity, and speed up our progress through collaboration.
- We have an existing system of human resource training such as the BARC Training School, which can be utilized to generate a pool of trained human resource in few years for such projects.
- The accelerator that will be developed will have immense potential for generation of medical radioisotopes. This will be a spin-off of this project for societal applications.
- The Indian Industry can be developed in a big way in this area of R&D, catering to the requirements of this project; and once developed, they can supply such state-of–the-art components to the international community, generating employment in this R&D area.

Threats:

- Unavailability of niobium material with required purity level in the country may turn out to be a threat since sourcing of this material from foreign suppliers is becoming challenging. Similar is true for helium. If these issues are not addressed, they may pose a threat.
- Since this project requires the development of a large number of components, such as SC cavities, magnets *etc,* there is an associated risk of failure in fabricating them; and hence, project planning is to be done, keeping various options in mind. Such risk and mitigation analyses are done by our international partners in collaborative projects, but have so far not been integrated in the project planning for accelerator projects in India. If we do not take care of this issue, this could be a potential threat.

•There have to be well-defined intermediate goals, and markers for deciding whether to move ahead in the project. "Not having a thorough, foolproof and realistic long-term plan till the final goal" is one threat that can jeopardise us. If the projects take much longer to fructify, there is a threat that the developed accelerator may turn out to be way behind the existing machines.

•For such large-scale projects, even in the advanced countries, multi-institutional national and/or international collaborations are forged. In India, inter-institutional collaborations have been resorted to, but at a (relatively) smaller scale. There is a need for bringing paradigm shift in this approach; otherwise, this can be a threat in taking up such large-scale projects.

6.6 High Power Industrial Accelerators

Design and development of following types of electron/ ion accelerators should be taken up:

- Field deployable 10 MeV, 10 kW and 10 MeV, 30 kW electron LINACs for various applications, *e.g.*, bulk irradiation of medical and food products. For irradiation of food products, the energy needs to be limited to 7.5 MeV. Use of SC technology for ≥ 30 kW average beam power electron LINACs should also be explored.
- Field deployable multi energy, say, 3-6 MeV, tens of kW electron LINACs for X-ray radiography as well as neutron radiography, cargo scanning and other specific applications.
- Low energy (1 MeV), high average power (several 100's of kW) electron accelerators for flue gas treatment and wastewater treatment.
- Low-energy (5-70 keV), moderate to high current (≥ 500 μA), cost-effective (~ ₹ 1 crore) tabletop ion sources for various applications, *e.g*., ion implantation in semiconductor industry, energy storage devices, portable neutron generators, materials R&D for clean and green energy via water splitting, *etc*. These tabletop ion sources have long life operation, low power consumption and these sources possess no radiation hazard. They are in high demand, not only in the Indian industries, but also the academic institutions.
- R&D on (i) low energy (~ 20 keV – 1 MeV) electron accelerator with extremely focussed beam intended towards indigenous development of Transmission Electron Microscope and Electron Beam Welding Machine, and (ii) low energy focussed ion beam accelerator for ion lithography, quantum pattern writing and local probing.

Emphasis should be laid on developing rugged and field deployable accelerators, keeping in mind the nature of industrial applications. Successful technology translation/ productisation should be a key goal. Development of these accelerators along with their sub-systems, *e.g.*, klystrons, magnetrons, RF window, circulators, directional couplers, accelerating tubes, vacuum pumps, detector systems along with dosimeter development for Gy to kGy range and their acquisition systems *etc*., will help in achieving complete self-reliance, which is particularly important while developing systems for security applications.

In the following paragraph, we present a SWOT analysis of the high-power industrial accelerator projects:

Strengths:

- Successful experience exists in the country by way of design, development, fault correction, licensing and operation of several electron beam facilities and ion accelerators.
- Established program and expertise exists in the country in various domains of accelerators and radiation applications.

Weaknesses:

- Some of the crucial components, *e.g.*, klystron can be sourced from only few manufacturers. Indian efforts on developing klystron have suffered from lack of in-depth engineering design, and high-quality manufacturing set-ups.
- In some areas, only imported components are available, *e.g.*, in dosimetry. Indian sources need to be developed.
- Focus on full-power, long-duration testing of full chain of devices is missing.
- Not enough stress on prototyping and experimental validation of the physics designs.

Opportunities:

- These are new emerging technology areas, and will help in making forays in high gain-high tech areas, thereby helping improve the overall technology scenario and economy.

Threat:

- Indian Industry has started preparing their proposals for importing High Power Linacs from developed countries. If such relatively low-cost proposals materialize, and there is a delay in demonstrating the indigenous technology in the country, then indigenous development for wider societal benefits may get affected.

6.7 Accelerators for Medical Isotopes and Therapy

This is a very important area of societal application of accelerators. Considering the high demand for medical isotopes, we recommend that indigenously developed cyclotrons with energies ~ 20 MeV may be set up in different states of India, through technology transfer to the industry. Cyclotrons with energies higher than 35 MeV require higher level of infrastructure and trained human resource for operation, and it may not be commercially viable to be set up such machines in each state. It can be instead set up in research institutes. Any medical isotope with longer half-life may be transported to different states after production in the research institute /regional plants. Higher energy cyclotrons and linacs are needed for specific isotopes, and accelerators are also needed for radiotherapy and hadron therapy. We would like to make recommendations as given below:

Accelerators for Medical Isotope Production

- Compact medical cyclotron for radioisotope production (10-70 MeV H^-, 100 µA to 1 mA):

Design and development of compact room temperature medical cyclotrons in the energy range 10 MeV to 70 MeV (with beam current ~ a few 100’s of µA), and associated technologies for the production of a variety of medically-useful radioisotopes, like ^{18}F, ^{68}Ga, ^{124}I, ^{64}Cu, ^{99m}Tc, *etc*.

- Compact medical cyclotron for radioisotope production (60 MeV, H_2^+, 1-5 mA):

This will be a compact room temperature H_2^+ cyclotron, having extraction with stripper foil, and splitting of extracted beam to four extraction ports, 5 mA H_2^+ beam will produce 2.5 mA proton beam at four numbers of separate targets simultaneously. This feature perfectly suits the requirements of a radioisotope production facility. Four numbers of separate targets can be irradiated simultaneously at this facility. Increase of cyclotron beam current intensity will improve commercial and clinical viability of difficult-to-produce radioisotopes, such as ^{225}Ac (half-life 9.92 days) and the long-lived ^{68}Ge/^{68}Ga (270d/68min) PET generator. Objective of the machine will be towards economically-viable production of imaging PET and therapeutic radioisotopes to cater to the needs of the country. With such an accelerator, it is expected that the production rates of, say, around 50 Ci of the ^{68}Ge parent isotope per week for PET, and 200 mCi of ^{225}Ac isotope per hour for α-therapy, can be reached.

- 50 MeV, 100 kW superconducting electron LINAC for radioisotope production:

Electron LINACs are used for production of ^{99}Mo through photo fission by γ-radiation, which is created by bremsstrahlung. This can be a spin-off application of the 50 MeV, 100 kW SC LINAC, being developed for the ANURIB facility at VECC. High power electron LINACs can create both proton- and neutron-rich isotopes by generating high energy X-rays that knock out protons or neutrons from stable atoms, or by fission of uranium. Photonuclear reactions, using bremsstrahlung photon beams from less-expensive electron LINACs, can generate isotopes of critical interest. This also allows for production of isotopes not possible in nuclear reactors. Recent advances in SC electron LINACs have decreased the size and complexity of these systems such that they are economically competitive with nuclear reactor. Also, India is developing infrastructure for SRF technology in different R&D institutes, in Ministry of Education and DAE. Production facility of medical isotopes based on a SC electron LINAC, will be a societal application in the medical field, of this SRF infrastructure. Using Uranium target, this facility can produce ^{99}Mo, which decays into ^{99m}Tc. ^{99m}Tc is the most widely used SPECT isotope, used in 80% of all nuclear medicine procedures and decays away soon after imaging is completed.

(*For SWOT analysis, human resource and funding requirements of 50 MeV, 100 kW electron linac for radioisotope production, refer to the ANURIB Project*.)

- 200 MeV, 1-10 mA proton LINAC for radioisotope production:

Proton LINAC has an advantage that the beam current can be higher compared to typical beam currents achievable in cyclotrons. The proton accelerator being developed for ADS/SNS application can have a spin-off application for this purpose.

In the following paragraph, we present a SWOT analysis of the compact medical cyclotrons for isotope production.

Strengths:

•50 years of experience exists in construction and operation of complex cyclotrons (*K130* room temperature cyclotron, *K500* SCC), and also on assembly, testing and operation of a 30 MeV medical cyclotron.

•Trained human resource exists for complex accelerator projects and expertise exists in development of accelerators and related technologies.

Weaknesses:

•Limited industrial support for design and manufacturing of accelerator components.

•Lack of collaboration with international partners, needed for speedy progress.

Opportunities:

•Radioisotopes are in great demand for disease diagnosis, and demand is increasing.

Threat:

•Overall, it is an emerging and evolving technology. Any new medical imaging technology may replace the existing technology, which is based on diagnosis with radioisotope. Also, requirement of a particular radioisotope may also get changed to a new one, since requirement for new kinds of radioisotopes may emerge, which may require higher proton energy for production.

Accelerators for medical treatment

There have been lot of advances in the radiotherapy machines, especially in dose delivery techniques using X-rays. It is the need of the hour to enhance the current indigenous basic radiotherapy technology to deliver intensity modulated radiotherapy, with image guiding capabilities. As discussed in Section 2.5, such machines are required in large numbers to cater to the growing number of patients in the country, and at a reasonable cost. Therefore, development of indigenous radiotherapy machines with advanced features should be taken up on priority.

A proposal for multi-ion particle therapy machine is being pursued at SAMEER in collaboration with Tata Memorial Centre (TMC), Mumbai and KEK, Japan [Dixit 2021]. The assumed synchrotron is characterized by two notable properties: (1) fast cycling at 10 Hz and (2) barrier bucket acceleration. Those characteristics are not found in the existing RF synchrotrons that are common in the current hadron therapies. The former suggests that the driver can work as a flash therapy driver. The latter provides a large flexibility of dose handling, which may make great benefits for patients. Extensive discussion with oncologists is required to take them on board. The proposed Multi Ion Accelerator is injector free[25] and capable of accelerating any type of ions from helium to argon. The design is focussed to achieve carbon ions with energy of 400 MeV/A. One of the key features is that being a fast-cycling synchrotron, the total time for dose deposition is just 50 ms[26], which ensures faster dose delivery. This will help in reducing the error due to motion of tumour inside the patient's body. For this to happen, the system is equipped with fast extraction mechanism and continuous energy variation scheme. The proposal has undergone technical feasibility examination by experts in the country. The main design effort in SAMEER's proposal will be to reduce the cost of the machine by making it injector free, and also providing other ions in the same machine. The multi-ion accelerator proposal consolidated by SAMEER and TMC in collaboration with KEK for hadron therapy has been developed in consultation with leading oncologists, experts from DAE, and it is at par with the international scenario. Therefore, we propose a consortium to come up around this proposal, wherein experts from major national and international laboratories contribute to develop various sub-systems for the Indian Hadron Therapy machine. It is proposed that in the first phase, a less expensive prototype machine with beam energy ~ 20 MeV/A be developed with a footprint of 7 m × 7 m, and then in the second phase, a full-fledged machine with 400 MeV/A may be developed.

A 70-230 MeV proton synchrotron may also be of interest, which can be built by RRCAT as it has experience in design and construction of electron synchrotrons, which will be useful here.

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[25] The accelerator will be injector free in the sense that unlike a conventional synchrotron, it does not need a pre-accelerator like RFQ and DTL to inject the beam into synchrotron.

[26] This is faster than the typical dose delivery time of 1-4 s in the case of cyclotron-based machine.

In the following paragraph, we perform a SWOT analysis of development of All Ion Accelerator (prototype as well as full version with beam energy ~ 400 MeV/A) for Therapy and Radiobiology.

Strengths:

•This ion accelerator is based on proven but a new technology of induction synchrotron without injector. This will make the accelerator compact and also reduce the construction cost, since we do not need to develop the injector linac.

•Most of the components developed during the prototyping stage will be used in the proposed full-energy hadron therapy machine. In fact, the prototype developed will be used as an injector for the Main Ring of the full-energy machine.

•All ions (light gaseous ions and heavy metal ions) desired by the oncologists for therapy will be available with this accelerator.

•Building this prototype will pave the way for the full-energy hadron therapy machine in comparatively less time.

•An additional pool of researchers will emerge who will do experiments in various fields of medical physics and radiobiology using this facility.

•This will provide job opportunities to many skilled personnel in India in the field of Accelerator Science and Technology.

Weaknesses:

•Lack of trained human resource.

•Lack of experience of Indian industry in development of required accelerator components.

Opportunities:

•No ion synchrotron exists in the country, although an ion synchrotron has lot of applications. This can thus be taken as an opportunity to develop an ion synchrotron indigenously. This will pave the way for even higher energy ion accelerator development in India. Also, it will help us in carrying out cutting-edge research in multi-disciplinary fields. This will promote research in basic and applied sciences.

•There is an international market of such accelerators. This can be used as an opportunity to establish this technology in the country and transfer it to Indian industry.

Threats:

• Delay in the development of this facility will have the consequence that we will lag behind in the science that one could explore with this machine.

•It may be difficult to attract young researchers to this field due to lack of job opportunities in India after they complete their doctoral and post-doctoral work using this facility.

•Time-consuming administrative process may act as a threat in timely execution, if there is no adequate planning.

In the following paragraph, we present a SWOT analysis of the new generation medical electron accelerator project.

Strengths:

•We have the technology of electron medical LINAC, which has given beam suitable for patient treatment. Trained staff and facility to build such machines also exist with us.

•Treatment cost will reduce with indigenously developed machines.

•Wide vendor base in industry, who will contribute to the machine development.

Weaknesses:

•Lack of sophistication, as required by the medical doctors to treat the patients with ease, with advanced add-on features.

• Lack of experience of Indian industry to deliver advanced add-on components.

•Lack of constant and consistent support to run such projects in a program mode, to ensure that medical LINACs will be available in large numbers to cater to larger population.

Opportunities:

•It is one of the best opportunities to design and develop a state-of-the-art radiotherapy machine, with all the advanced features available in any imported machine. This will pave the way for indigenously development of very advanced technology machines.

•State-of-the-art radiation oncology system made in India will be available for mass production. This will further promote research in medical sciences.

•PPP mode of implementation will attract more industrial partners.

Threats:

•Delay in initiating such an activity will lead to further delay in providing advanced treatment to many needy patients in the country.

•Delay in providing less costly treatment to patients.

6.8 Accelerator for ADS

ADS is important for the energy security of the country, and since the core technology of High Intensity Superconducting Proton Accelerator (HISPA) is common with other applications such as Spallation Neutron Source, Radioactive Ion Beams, Radioisotope Production, *etc.*, high priority should be given to this program, in the following two stages:

Medium Energy High Intensity Proton Accelerator (MEHIPA)

This should be a 200 MeV, 10 mA SC accelerator, conceived as a green field project [Pathak 2021]. It will consist of a 3 MeV NC RFQ, and SC spoke cavities up to 200 MeV. Taken up in mission mode, this project can be executed in ten years. This accelerator can be coupled to a Demo ADS system, comprising a sub-critical reactor in the vicinity of ~ 100 MWth.

High Energy High Intensity Proton Accelerator (HEHIPA)

This should be a 1 GeV, 10 mA SC accelerator, taking forward MEHIPA by adding on SC elliptic cavities. This project can be executed in another 10 years. This accelerator can be coupled to a full-fledged ADS reactor system.

In addition, attention needs to be paid on following two important areas:

Studies on Target Material and Material Damage

Setting up of ADS will require extensive studies on target material and material damage (> 50 dpa) studies, especially in a radiation environment. This needs to be taken up.

Cryogenic Technology to be developed

Suitable infrastructure in terms of a cryoplant with an estimated capacity of ~ 3 kW at 2K, and associated cryogenic systems will be needed.

SWOT analysis for the proposed project on accelerator for ADS is similar to the one mentioned for the IFSR project, except that there the challenges are enhanced to a significantly higher level in terms of (i) higher average power of the accelerator, at least by an order of magnitude, (ii) enhanced reliability of accelerator since it will be coupled to a power reactor, and (iii) higher average power to be handled by the target for neutron production.

6.9 Laser Plasma Accelerators

Since Laser Plasma Acceleration (LPA) is a very promising area of R&D that may play a key role in development of compact and low-cost accelerators for a variety of applications, it is important that experimental, as well as theoretical and simulation research, are pursued vigorously in this area in India. Availability of compact and low-cost laser plasma electron/proton/ion accelerators will have profound impact on basic science as well as societal applications of accelerators, *e.g.*, medical applications (radiation therapy, PET isotope production), irradiation applications (food product irradiation, sterilization of medical equipment) *etc*. The above applications along with imaging applications would get further boost with the development of compact laser synchrotrons, providing intense, ultra-short (fs regime) tunable X-ray/γ-ray radiations.

Based on the available expertise and availability of high-power (150 TW and 1 PW) Ti:Sapphire lasers at RRCAT, the following goals should be pursued over the next 15 years: acceleration of electron beams to GeV or higher energies; acceleration of proton/ion beams to several tens of MeV (30-70 MeV); and development of laser plasma accelerator based intense ultra-short (fs regime pulse duration) X-ray/γ-ray source (photon energy: sub-keV to several MeV) through betatron oscillation and inverse Compton Scattering scheme. Suitability of laser plasma accelerated particle (electron/proton/ion) beams for radiation therapy, medical isotope production and radiography applications will also be demonstrated. In this regard, investigations towards development of suitable beam transport systems will also be carried out. A suitable electron beam transport system will also facilitate initial investigations/planning towards exploring suitability of laser plasma accelerator of GeV energy for development of compact FEL radiation source in future.

In the following paragraph, we present a SWOT analysis of the LPA project:

Strengths:

- RRCAT has good experience in R&D on intense laser plasma interaction, and some expertise has also been generated in the field of LPA through the experimental and simulation studies undertaken during the last two decades. This could be used for making further advancements in this field, to be at par with the international community.
- Expertise in the field of laser plasma interaction is also available at other national labs and universities viz., BARC, Mumbai, IIT Kanpur, IIT Delhi, IPR, Ahmedabad and particularly TIFR, Mumbai, where ultra-short laser plasma interaction has been investigated for various associated basic physical process.

Weaknesses:

- Adequate R&D has not been pursued to enhance the capability in two important supporting fields, *i.e.*, (i) development of ultra-fast (femtosecond) lasers, having high-power and high-repetition rate, and (ii) diagnostics for characterization of ultra-short laser pulses, which are used in LPA.

- There is a lack of adequate human resource in this field in the country. It is particularly important to address this issue since simultaneous efforts are required on various associated fronts, to ensure rapid understanding, and growth of technology through intense investigations, to ensure timely development of compact low-cost particle accelerators and synchrotron sources for various applications. It is important to maintain long term sustainability of this vital area of R&D in the country, in order to remain in pace with international community, for which adequate human resource is needed. Existing human resource is ageing, and younger staff have not been hired in sufficient numbers in the past.
- Desired industrial support is not available for development of high-power, ultra-short lasers and also for development of associated technologies for development of laser crystals and other large size optics.
- Although simulation support has been set up to support understanding and planning of LPA in a limited manner at RRCAT (and also at few other places in the country), the desired level of activity and capability is still lacking. We need to have larger number of trained people in this vital area of research on LPA.

Opportunities:

- Through on-going activities on basic physics aspects of LPA at RRCAT and other institutes in the country, right opportunity exists to accelerate progress in this vital area of R&D, where we have not been very late in initiating the activities in the country.
- It is a good opportunity to perform R&D on development of a compact and relatively less expensive accelerator for societal applications, such as generation of medical radioisotopes and radiation therapy.
- There exists good possibility for international collaborations on the required research aspects, and also on various associated technologies in the area of high-power, ultra-short lasers and optics development. If Indian industry is involved in the technology developed through international collaboration, industry will also benefit.
- Existing system of BARC Training School offers an opportunity to generate trained human resource in this area, over the next several years for the project.

Threats:

- Since the state-of-the-art high-power, ultra-short duration laser systems required for LPA projects are procured from abroad, troubleshooting during operation and maintenance of such systems may pose challenge and there is a threat that it can become a show stopper in case of long downtime of the laser. This becomes more severe due to lack of adequate number of trained staff.

In addition to the Mega Science for satisfying the user needs, which we described in this chapter, there is a strong need to take up projects to enhance the level of research on fundament accelerator science in the country, which will be driving force to look forward in the distant future. R&D areas like new acceleration techniques have already been discussed. New areas of light source research, *e.g.*, generation of coherent synchrotron radiation, inverse Compton scattering based γ-ray source, *etc.*, new acceleration techniques such as inverse free electron laser, surface wave accelerators, *etc.*, computer code development and development of experimental accelerator facilities for accelerator research are some such topics, to which we need to pay attention. So far, there has not been adequate emphasis on indigenous development of elaborate codes for beam simulation as well as for design and operation of various accelerator systems. It is very important that this scenario is changed, for which we should put considerably greater emphasis on code development and documentation. This is necessary to achieve self-reliance in R&D on particle accelerators.

6.10 Applications-oriented Priority List for the Proposed MSPs

In this section, we bring out a priority list for the proposed Mega Science Projects and Programmes. We have categorised the projects on the basis of their intended applications. In this way, there are six categories, under which the projects have been characterized – (i) Accelerators for photon science applications, (ii) Accelerators for neutron science applications, (iii) Accelerators for industrial applications, (iv) Accelerators for medical applications, (v) Accelerators for nuclear physics applications, and (vi) R&D on new acceleration techniques. Although each of the categories has equal priority, we have tried to make a priority list within each category.

A. **Accelerators for Photon Science Applications**
   1. Multi Bend Achromat (MBA) lattice-based fourth generation high brilliance synchrotron radiation source with beam emittance $\leq$ 150 pm-rad and peak photon brightness greater than 10^{21} photons/s/mm^2/mrad^2/0.1% BW.
   2. VUV/Soft X-ray Free-Electron Laser with peak brightness up 10^{30} photons/s/mm^2/mrad^2/0.1% BW, with a possibility of upgrade to hard X-ray FEL.

B. **Accelerators for Neutron Science Applications**
   1. 200 MeV, 10 mA CW superconducting proton linac for ADS.
   2. 1 GeV, 10 mA pulsed superconducting linac and accumulator ring for IFSR.

C. **Accelerators for Industrial Applications**
   1. Field deployable 7.5/10 MeV, 10 kW and 7.5/10 MeV, 30 kW industrial electron LINACs for irradiation applications.
   2. Field deployable multi energy, say, 3-6 MeV, tens of kW electron LINACs for X-ray radiography as well as neutron radiography, cargo scanning and other specific applications.
   3. Low energy (1 MeV), high average power (several 100’s of kW) electron accelerators for flue gas treatment and wastewater treatment.
   4. Low-energy (5-70 keV), moderate to high current ($\geq$ 500 of μA), cost-effective (~ ₹ 1 Crore) tabletop ion sources for various applications, viz., ion implantation in semiconductor industry, energy storage devices, portable neutron generators, clean and green energy via water splitting, etc.

D. **Accelerators for Medical Applications**
   1. 10-70 MeV H^- Cyclotron with beam current ~ 0.1 – 1 mA for medical isotope production.
   2. Electron LINAC for intensity modulated radiotherapy applications.
   3. 6 MeV X-band medical linac for Cyberknife/Radiotherapy applications
   4. 70 – 230 MeV proton accelerator and 400 MeV/A carbon ion accelerator for cancer therapy.

E. Accelerators for Nuclear Physics Applications

1. Radioactive Ion Beam (RIB) Accelerator with beam energy up to 100 MeV/A, and upgrade of existing heavy ion accelerators.
2. Future heavy ion accelerators with beam energy around 10-20 MeV/A, i.e., beyond the Coulomb barrier, covering a wide range of heavy ions, with beam current up to few hundreds of pnA.

F. R&D on New Acceleration Techniques

1. Basic R&D on LPA and its applications
2. LPA based electron accelerator with an energy ~ GeV, and proton/ion accelerator with an energy ~30-70 MeV; and R&D on LPA based intense ultra-short (femtosecond) x-ray/γ-ray source.

Annexures A.1 and A.2 give estimated timeline and budget for these proposed MSPs. Note that the budget estimates are indicative and approximate, although attempt has been made to be as realistic as possible, for which the building and technical infrastructure costs have also been included in most of the cases. A more realistic budget estimate will emerge, when the DPRs for various proposals are prepared by the relevant agencies for seeking the approval.

We would like to emphasize that the above is a suggested priority list. During the process of proposal and approval of an MSP, out of the suggested list, the users' community has to make a detailed case for the particular MSP, including the readiness to utilize the frontline facility fruitfully for discovery science and/or societal/industrial/medical applications, when ready. In addition, the readiness of the users' community to develop the experimental facility simultaneously with the accelerator construction also needs to be established. In the case of medical and industrial accelerators, involvement of the end users, right from the beginning is a must. They should be encouraged to start developing relevant techniques so that the accelerators are utilized to the fullest extent.

Even if all the suggested MSPs are not taken up, R&D for design and development of accelerator systems (RF, magnets, vacuum, diagnostics, controls etc.) involving very high-level technological complexities, including development of real good industrial partners, should be carried out as preparatory exercise.

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7. Building the Ecosystem for Accelerator Science & Technology and Applications

In this chapter, we discuss the steps needed for building the ecosystem for growth of accelerator science and technology in India in the current scenario. There are specifically four elements that need to be discussed in this regard – (i) taking the local industry on board in accelerator development work, (ii) developing high quality human resource for carrying out state-of-the-art R&D in this area, (iii) setting up a strategy for outreach, which is needed to bring awareness about the importance, necessity, usefulness and challenges of accelerator science & technology and its applications among common people, particularly among the student community, to attract them to work in this area, and finally (iv) setting up a structure for project management and financing. In the following sections, we take up these issues one by one; and end this chapter by an overall SWOT analysis.

Before we start the discussions in this chapter, it may useful to have a look at the present details about the Accelerator S&T community in India, in terms of the number of scientific and technical staff involved, typical investment and productivity in Table 7.1.

Table 7.1: Present details on Indian Accelerator S&T community size, funding and productivity[27]

No. of scientific personnel (Scientists and Engineers)	700
No. of technical persons (Scientific Assistants and Technicians)	600
Number of patents so far	22
PhDs produced during last ten years (excluding the Ph Ds produced from machine utilization)	50
Investment per year in accelerator projects	₹ 150 crores
Foreign Exchange (FE) component of investment per year in accelerator projects	₹ 30 crores

7.1 Industry Participation: Bringing the Industry as a Partner

In this section, we describe the important role of industry in large-scale development work that is required for accelerator projects. We cite some examples based on past experience, and then emphasize the need to further strengthen the industry participation, especially in the light of projects envisaged in the future.

Current status

In several indigenous projects on accelerator development at BARC, RRCAT, VECC and IUAC, there has been a strong involvement of industry, and in some cases, development work has been done by industry through MoUs. Also, several technologies developed in labs have been transferred to the industry. Some of the details in this regard are given in Annexure A.3[28]. As already discussed in the SWOT analysis for various proposed projects in Chapter 6, a common weakness in all the proposals is the lack of adequate industrial support, particularly the inability of Indian industry to deliver the required components and sub-systems for large accelerator projects on turnkey basis. There is considerable scope to enhance the role of Indian industry here, and this will also enable the Indian industry to enter the international market for manufacturing and supply of such high-tech components and sub-

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[27] Information presented in this Table in based on the inputs received from various Indian institutes engaged in R& D on Accelerator S&T.

[28] Note that the list presented in Table A.3.1 in Appendix A.3 is indicative, and not exhaustive.

systems. Indian Accelerator S&T community and Govt. of India have an important role in enhancing the industry participation in accelerator projects.

It is important to realise that industry is not only our partner in building the accelerator, but it is also a user of these machines, as elaborated in Table A.3.2 of Annexure A.3. Some effort has already started in the country in this direction, as elaborated in Annexure A.4. Working hand-in-hand with industry is therefore essential.

Future recommendations

Since the industry involvement is particularly important for taking up mega science projects in the area of accelerators, *it is recommended that some investments be made to support and strengthen the industry, to prepare it for this role*. *Bringing the industry on board through the technology transfer and incubation route needs to be further strengthened*. Once the industry is well-developed to take up the required development effort on a larger scale, it will help expedite the development work under various projects. It should be ensured that the industrial partners are on board right from the design stage. Industry will also get benefited in several ways through this process. A good example can be set by developing industrial and medical accelerators in the Public Private Partnership (PPP) mode, and by getting the important components of accelerators for international projects developed by the Indian industry. Such an approach will also help address the issues regarding delay in execution of projects that results due to complex administrative procedures in national laboratories, as also mentioned earlier during the SWOT analysis of various projects. This way, the Indian industry will also advance and a pool of useful human resource will also get generated. Also, the industry will be able to employ PhDs, which will not only create job opportunities but also help advance the R&D portfolio of the industry further. *Creation of an Accelerator Corporation will be extremely helpful in meeting some of the above objectives*. It could start under the guidance of, and support from institutions like ECIL, to be intellectually powered by accelerator specialists.

It is also important to mention here that collaborative partnership with industrial institutions, funded by Government, such as CMERI, Durgapur, ECIL, Hyderabad, and also government funded R&D Centres with expertise in highly specialized areas should be actively explored.

7.2 Training and Retaining Human Resources

A very important component, which plays a crucial role in executing projects on development of state-of-the-art accelerators, is the availability of adequate number of high-quality, motivated and trained human resource. Before taking up a mega science project in accelerator S&T, it is essential to ensure that adequate human resource exists, or will be generated to complete the project successfully. Due to the long-term nature of the projects, it is especially important to ensure this, keeping in mind the ageing human resource.

Existing programs

In the national labs under DAE, one of the sources of trained scientists and engineers for R&D in the field of accelerator S&T is through the BARC Training School, where fresh engineering graduates and science postgraduates are recruited and imparted basic as well as advanced training in some aspects relevant to accelerator S&T. The BARC training school and other programmes are excellent sources of trained human resource. However, keeping in mind that large number of trained personnel are required, who cannot be trained/sourced via the BARC Training School alone, one could spread the training programs across the country through dedicated M. Sc. and M. Tech. courses in IITs and universities. The programmes can have some visiting faculty from accelerator centres. A hands-on lab training (~ 6 months) at various accelerator centres can be embedded into the course work. Another source of generating trained personnel is through Ph.D. programs in Accelerator S&T in national labs and academic institutes/ universities.

Future recommendations

Some countries like France have developed very successful master's programs around large-scale facilities. They go beyond accelerators (*i.e.*, include lasers, neutrons) and train young scientists, whose skills are in high demand [Lascala 2024]. Regarding smaller infrastructures, Europe in particular has developed the concept of "distributed infrastructures", where smaller size infrastructures are coordinated and shared during development and user operation. In India, in consultation with the Chairman-AEC/Secretary-DAE, Secretary-DST requested Chairman of University Grants Commission (UGC) to set up a committee under his chairmanship for taking the lead in establishment and subsequent operation and maintenance of smaller accelerator facilities on the campuses of higher educational institutions like various universities, IITs, IISERs, etc. for the purposes of human resource development as well as research in materials science *etc*. Chairman, UGC had formed a committee under the chairmanship of Late Prof. S. K. Joshi to consider this matter and the gist of their recommendations is given below [Joshi 2020]:

- Three Ion Beam Centres (IBC) may be formed at three universities e.g. Mumbai, Allahabad and Panjab, and the existing accelerators at these places may be used as national facilities. They may be kept under routine operation and may periodically be maintained by receiving help from IUAC, Delhi. It should however be noted that for running these centres, adequate technical staff will be required apart from faculty and students.
- In this process, the University could also enrich its teaching programs by offering special papers/modules on Accelerator S&T in various courses, which could be taught by the scientific/technical staff of the IBCs. New post-graduate courses on Medical Physics, Radiation Biology *etc*. could be started by the scientific/technical staff of the IBC working in that university. This mechanism will provide trained human resource for the existing accelerator-based healthcare system and also for the new upcoming mega accelerator projects of the country. In addition, short training programs could be run by the scientific/technical staff of the IBCs for the technicians who would operate accelerators in hospitals for cancer therapy.
- These IBCs could further augment their Ph.D. programmes in their own universities or in the other user universities. Once successful, this model can be implemented in some other universities also to supply the huge pool of human resource required for large accelerator projects in India.

However, in order to attract bright students towards the field of accelerator S&T from the university and other non-DAE system, additional job opportunities have to be created. In this context, if the Indian industry evolves adequately in accelerator S&T, it could become an important source of employment generation, as is the case in many other countries, which are advanced in this area of R&D. Also, we can attract scientists and engineers who have done their Ph.D. abroad to return and contribute to our national mega science program, but this also requires creating adequate job opportunities. The issue of trained human resource and their job security can be partially resolved through offering post-doctoral positions to brilliant and enthusiastic doctoral scholars from life sciences and pharmaceutical sciences, who can be later accommodated in healthcare and pharmaceutical sectors as they can use applied knowledge to diagnose challenging diseases, develop medicines and therapies for India and global markets. Likewise, post-doctoral fellows can be accommodated in institutions like IITs, NITs, NIPERs, CDRI *etc.* to develop research programmes in collaboration with the BARC, RRCAT *etc*. This would create a pool of scientists with cross-functional and diverse knowledge to engage them in applied science fields like pharmaceuticals. A similar engagement already exists across the world in many pharmaceutical departments and top universities.

In addition to all these, the role of national level schools and workshops in accelerator S&T is important in imparting training in specialized areas. An Indian Particle Accelerator School, along the lines of US Particle Accelerator School [USPAS] and CERN Accelerator School [CAS], could be started in a regular manner, which could be tuned specifically for the suggested mega science projects, and could be useful for both lecturers and students. Under the New Education Policy, attempt may be made to include Accelerator Science and Technology in UG and PG courses. Internship programmes should be created for college students in the area of Accelerator S&T.

Short-term courses for the user community of accelerators should also be organised, to spread awareness among the new users of accelerators. A good idea could be to organize such training courses during the Indian Particle Accelerator Conferences.

It should also be noted that MSPs are high-budget, long-duration projects with large collaborations and contain huge number of technically complex systems and sub-systems. A team of project management personnel trained in management of such R&D projects is also a key need. In addition to S&T, the skill set should encompass project management, finance, HR management, legal issues, contract handling, *etc*., using contemporary tools and IT. We should also realize that successful execution of MSPs will be a collaborative work between national labs, academic institutions, PSUs and private industries. We therefore need to create a working mechanism that addresses the issue of movement of personnel between such organisations. Successful technology transfer and market penetration would need a system which incentivizes such mobility.

7.3 Outreach

The accelerator labs in India as well as several Indian universities are having important orientation programs related to particle accelerators. RRCAT used to run an Orientation Course on Accelerator and Laser Science and Technology [OCAL] and their applications for post-graduate students, and Young Scientist Research Program for B. Tech and M. Sc. Students, which got interrupted during the Covid-19 pandemic. Many such students who were trained at RRCAT, BARC, IUAC and VECC through different outreach programs have joined various accelerator labs in the country and abroad. It is important to engage universities and colleges to inform students and faculty members about the excitement and opportunities in Accelerator S&T and its numerous applications to create awareness as well as interest in them to take up challenges in this advanced area. It will be useful to multiply the number of outreach programmes with activities like lab visits, internship programmes, lecture series in teaching institutions *etc*. to sensitize larger number of people about this field.

7.4 Suggested Funding, Approval and Monitoring Procedures

Mega Science Projects (MSPs) in the field of accelerator science and technology are user-driven. It should be ensured that each MSP is a multi-institutional project, with clarity in the role of each institute; has an identified Lead Institute, and the proposal for MSP should start with an extensive Community Planning Exercise (CPE). Looking into the complex nature of MSPs, it is also recommended that a common consultative group composed of experienced members of community should be formed for accelerator science and technology, to provide some level of guidance while formulating a proposal. Consultative Group may be reconstituted every two years at a national-level meeting.

MSPs are typically long-term projects, which need special planning, funding and monitoring mechanisms, since they involve multiple institutes and experts from different fields. Particularly for particle accelerators, an MSP often requires venturing into altogether new R&D, and it typically takes more than 15 years to fructify. This has been so in the advanced countries too, which have vast and long experience in the field. This poses a challenging situation while planning any project, especially keeping its long-term nature. The following methodology can be broadly followed for planning and managing such projects.

There should be a full picture of the mega project, with a clear plan of all the infrastructure to be developed, along with the necessary government approvals for the site, for which an in-principle approval from the government should be sought, with the necessary financial support to complete the feasibility study in a reasonably short time. The execution of the mega project should be planned in stages, with important and tangible deliverables after each stage. For example, a 1 GeV proton accelerator for ADS can have radioisotope production as a deliverable, using the 200 MeV proton linac that will be developed in the first stage, and so on. Also, since such projects involve large investments, thorough financial planning, keeping in mind the existing government procedures, will also be important.

The establishment of a secure, state-of-the-art IT infrastructure, which promotes workflow automation of all aspects of project execution, including scheduling, finance, HR, design, engineering, procurement, reviews, QA/QC *etc.* should be a key component of any MSP. Information dissemination with accuracy and speed, version management[29], transparency, building and maintenance of knowledge-base, *etc.* is vital for the collaborative execution of such large projects running over decades. We need to considerably improve such systems for MSPs in the country. This infrastructure should be adequately funded, manned and easily accessible. The funding agencies and higher management should treat this process as an essential and high-priority element of project management.

Before taking up any long-term project, it will be extremely important to visualize the long-term human resource scenario and ensure that adequate number of quality human resource become available to run the project. This becomes especially important in the context of our country since we have a rather limited workforce in this area of R&D. Also, the leaders for the project should be chosen at a relatively younger age, to ensure that they have long-enough tenure to execute a substantial part of the project with some important deliverables.

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[29] Version management means keeping track of changes made in different versions of the documents.

The role of review is also extremely important for a long-term project, since if a mistake is made at some stage, its implication could be drastic and would affect the outcome of the project for a long time. A mechanism of goal-oriented and technically-thorough review by top domain experts in the concerned area is a must. If unavailable in the country, we should not shy away from seeking help from international experts.

Such projects will typically have the following phases:

- R&D Phase, where design reports are prepared, reviewed and finalized after building necessary prototypes
- Construction Phase, where the machine is constructed with an approved and reviewed design
- Commissioning Phase, where the machine is commissioned, and experimental facilities around the machine are also completed

A successful mega science project would need sustained funding over a long-term period. Each MSP's technical approval should be done by a high-level apex committee, called Inter-Agency Committee (IAC), which should be co-chaired by the heads of all the funding agencies involved, with scientific experts, financial authorities and other concerned officials of the funding agencies as the members. Following this, the extant financial approval processes of the Government of India should be followed. Each MSP should have a Lead Agency, and it should have a scientific expert committee for overseeing the scientific and technical aspects of the project, recommendations of which should be considered by the apex committee. Involvement of international experts in various expert committees may become necessary if national experts are not available, and their help should be ensured. We recommend the following procedure:

Submission of proposals:

The funding for mega science projects could come from multiple agencies and participating scientists may typically be affiliated to institutes supported by a number of different agencies. Hence, it will need a centralized proposal submission forum. We propose that the project proposals be submitted to a dedicated cell in the Principal Scientific Advisor (PSA) Office – Mega Science Nodal Unit at PSA (MSNU-PSA), or to a dedicated mega science submission forum at the national level. This initial central point of contact should be able to identify the Lead and Partner Funding Agencies and forward the proposal to the Lead Agency for joint technical evaluation and funding. The status of the proposal should be communicated to the nodal person of the project. The Lead Funding Agency may also consider the possibility to host calls for proposals for participation in a MSP, if necessary.

Periodic Reviews by Standing Review Committee (SRC):

We propose that the Lead Funding Agency should set up a Standing Review Committee (SRC) for each mega science project, consisting of national, international experts and funding agency representatives. This scientific committee would review the proposals at various stages (as mentioned below) within a timeline of 3-6 months from the submission of the project report. It will give recommendations for funding, and advice on course corrections, if needed. The SRC will be expected to monitor the project at least every year, and give its feedback to the project proponents. The projects will be designated as belonging to the following three stages. The recommendation of the SRC for the future of a project may be made based on the yearly reports on the progress towards achieving the goals. The report of the SRC in the penultimate year of the project should have special significance.

I. Fresh/Early stage: Fresh mega science projects should typically complete the Community Planning Exercise, and start with a Conceptual Design Plan (CDP) prepared by a consortium of scientists, which is submitted to the Principal Scientific Advisor (PSA) Office or a dedicated mega science submission forum at the national level. The CDP should, among other aspects, include the science goals of the project, a tentative list of potential contributions, a timeline, and funding required for R&D and prototyping of crucial components, statutory clearances (wherever needed) leading to establishing the feasibility of the project. It is like a letter of intent to have the mega project, with seed money to demonstrate the feasibility of the proposal. The CDP will be reviewed by the SRC. All successful Early Stage proposals are also expected to go through the process as listed below.

II. Design, Construction and Commissioning stage: Mega science projects could be in various stages of development, like in the research and development stage or in the stage of construction and commissioning. Projects in such stages can submit their Preliminary Design Plan (PDP) if in the R&D stage, or Technical Design Plan (TDP) if in Construction and Commissioning stage, to SRC for review and recommendation. These stages would typically include proposals for funding of infrastructure facilities, large-scale production of components, and/or funding required for construction of the buildings and other conventional services, and for development of different systems and their integration, along with stage-wise commissioning.

III. Operation, Maintenance and Upgrade Stage: Mega science projects will eventually enter a phase where the machine utilization will run for a long period to realize the science goals. In due course of time, upgrades are required to keep pace with ever-evolving users' wish list. This stage is normally referred to as operation and maintenance stage. The nodal scientist could submit an appropriate Operations and Maintenance Plan (OMP), containing details like science goals, milestones and funding required for continuing the project/utilization, including upgrades, to SRC for recommendation. For mega science facilities, it will cater to running the facility successfully with maximum up-time and utilizing it for achieving the desired scientific and technological goals of the project.

Figure 7.4.1 shows the flowchart of the proposed stages in funding, management and evaluation structures for fresh/early-stage MSPs.

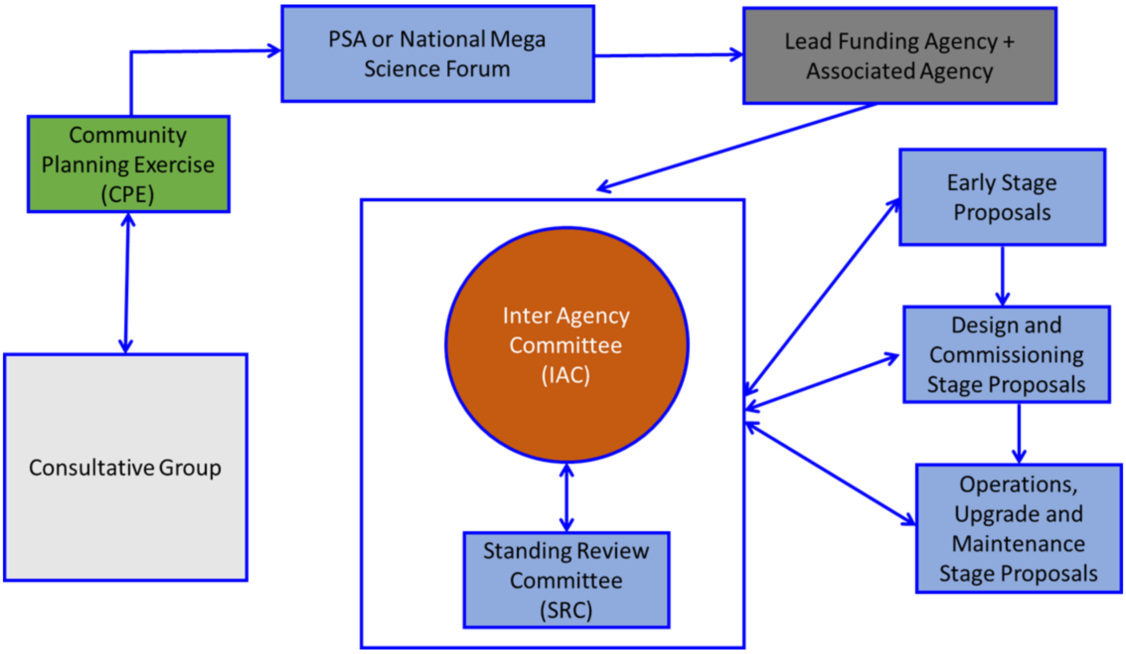

Fig. 7.4.1: The proposed stages in funding, management and evaluation structures for fresh/early-stage MSPs.

7.5 SWOT Analysis

Although in Chapter 6, we have done a SWOT analysis for each proposed project, here we present a brief SWOT analysis for the Mega Science Projects in the area of Accelerator Science & Technology and Applications, as a whole.

Strengths

- There exists in the country some prior experience related to each of the projects that have been proposed. A good seed infrastructure and pool of expert human resource has been created, while working on the past projects. Most of the accelerator projects taken up in the country have been successfully completed, even when it has taken more than the stipulated time in some cases. For some of the projects, good industry support exists to some extent, which needs to be further strengthened.
- Our international collaborators have always expressed their keenness on collaborating with us based on this strength.
- For most of the proposed accelerator projects, a strong user base exists in the country, and they have important societal applications.

Weaknesses

- Most of the projects that have been proposed in Chapter 6, have been under discussion and/or consideration for quite some time now. They have, however, not yet reached the stage of formal approval. This has been partly because of our weakness in not being able to put forward the projects with adequate planning and confidence. We need to improve on this.
- Ageing and insufficient number of human resource could turn out to be another weakness for future projects, and warrants planned remedial action.
- Inadequate industrial support for many of the proposed projects is also an important issue, which needs to be addressed with measures to strengthen the industry.
- Inadequate participation of accelerator scientists and engineers in international conferences is also one of the major weaknesses. Our representation in international accelerator conferences is weaker even compared to the countries that are relatively less active in this field.
- Complex administrative processes involved in the procurements can also turn out to be a major weakness if it is not addressed suitably.
- Another important weakness is that S&T personnel are not trained in the management of large, complex projects. Lack of experienced project managers for managing large S&T projects is an important weakness. HR, finance and purchase functions are not under the effective control of project management. This leads to diffused responsibilities and accountabilities, when projects suffer cost and time overruns.

Opportunities

- The ongoing international collaborations in the area of accelerators are good opportunities for us and we can utilize these to speed up our learning process for the benefit of the proposed projects.
- We have an existing system of training human resource such as the BARC Training School, which can be utilized to generate a pool of trained human resource in a few years for such projects.

- Indian industry has lot of potential, and if adequately supported by government and R&D institutions, it can turn out to be an opportunity for both the industry and accelerator R&D to grow together.

Threats

- “Not having a thoroughly foolproof and realistic long-term plan till the final goal” is a serious threat that can jeopardise our plans.
- If the projects take much longer to fructify, there is every possibility that the developed accelerator may turn out to be way behind the state-of-the-art machines elsewhere in the world.
- Delays due to administrative procedures can become a threat, which need to be suitably addressed. Delay in execution of a project may occur if there is a lack of clarity about the final goal, for example, whether the final goal for a particular project is to develop the indigenous expertise for building the machine (since we need to build many such machines), or whether the final goal is developing a one-of-its-kind machine for several outstanding applications.
- Embargoes and import restrictions, human resource attrition and poaching of skilled personnel may also become real threats.
- The possibility of short-sighted views against MSPs should not be discounted.

From the SWOT analysis of different projects, we observe that a common pattern emerges. There exists expertise in many areas in the country; however, the number of such experts in each area is quite small and suffers from the threat of extinction due to ageing of existing experts and lack of fresh recruitments. There is not enough support from local industry (partly due to inadequate efforts made in the past) for most of the proposed projects, which leads to expensive imports and higher costs and no transfer of technology to local industry. On top of this, complicated administrative procedures lead to additional delays in the projects. It is extremely important that all these threats be addressed properly for success of various accelerator projects and their utilization.

8. Synergies with other Mega Science Areas

In this chapter, we discuss the synergy of the proposed mega science projects in Accelerator Science & Technology and Applications with two other mega science areas with which there is considerable overlap – namely nuclear physics, and high energy physics.

8.1 Nuclear Physics

Particle accelerators are workhorses for doing research in experimental nuclear physics. Level of R&D activities in experimental nuclear physics is very much dependent on the availability of state-of-the-art particle accelerators in the country. The MSPs in Accelerator Science & Technology have been proposed keeping the user needs in mind, as elaborated in detail in Chapter 2. The proposal on RIB accelerator is clearly with the aim to enable the nuclear physicists in the country to do frontline research on exotic nuclei. Also, the proposed proton accelerators for IFSR and ADS will provide proton beams up to 1 GeV energy, which can also be very relevant for nuclear reaction studies. Emphasis has also been laid on increasing the number of low energy accelerators for nuclear physics to enhance their availability for ever increasing number of users, along with upgrade of existing heavy ion accelerators and taking up project for future heavy ion accelerator.

8.2 High Energy Physics

As in experimental nuclear physics, experimental high energy physics research is also heavily dependent on state-of-the-art high energy particle accelerators, like particle colliders. These machines are very expensive, and nowadays, even globally, such machines are not built by a single country, but through international collaborations involving many countries. There is no plan currently to build such a machine in India, although India is participating in some such international projects, such as the PIP-II project at Fermilab, where a high energy, high average power proton linac is being built for research in neutrino physics. This will give the HEP community of India an opportunity to participate in a frontline research area. Similar involvement is there in the HEP projects at CERN and at FAIR. It may be noted that if a 1 GeV proton accelerator is built in India for the spallation source, or ADS, there will be a possibility to generate muons, which will be of interest to HEP community in India.

Annexure A.1 – Timeline for Major Projects – Tentative[30]

<table>
<tr><th></th><th>Year
Project</th><th>2020-21</th><th>2021-22</th><th>2022-23</th><th>2023-24</th><th>2024-25</th><th>2025-26</th><th>2026-27</th><th>2027-28</th><th>2028-29</th><th>2029-30</th><th>2030-31</th><th>2031-32</th><th>2032-33</th><th>2033-34</th><th>2034-35</th></tr>
<tr><td rowspan="3">Photon Science Applications</td><td>HBSRS</td><td colspan="5">Capacity Building</td><td colspan="2">Design and prototyping phase</td><td colspan="6">Construction and commissioning phase with few beamlines</td><td colspan="2">Utilization</td></tr>
<tr><td rowspan="2">FEL</td><td colspan="5">Utilization phase of IR FEL</td><td colspan="5">Utilization phase of THz FEL</td><td colspan="5" rowspan="2">Construction and beam commissioning phase for full energy accelerator for future XFEL</td></tr>
<tr><td colspan="5">Construction phase of THZ FEL</td><td colspan="5">Construction phase for intermediate energy accelerator for future XFEL</td></tr>
<tr><td rowspan="2">Neutron Science Applications</td><td>ADS</td><td colspan="10">Construction of MEHIPA and coupling with an ADS Demo Reactor</td><td colspan="5">Construction of HIPA and coupling with the ADS Reactor (by 2040)</td></tr>
<tr><td>IFSR</td><td colspan="5">Infrastructure development and Prototyping phase</td><td colspan="5">Construction phase with1 GeV SC LINAC and Accumulator Ring</td><td colspan="5">Construction phase for target stations and user Facility</td></tr>
<tr><td rowspan="3">Industrial Applications</td><td>Irradiation</td><td colspan="5">Field deployment of 5/7/10 MeV, 10-20 kW industrial e^- linac</td><td colspan="5" rowspan="3">Construction phase for enabling the manufacturing of higher power industrial accelerators through PPP mode. Design and development of low-energy (5-70 keV), moderate to high current (≥ 500 of μA), table-top ion sources.</td><td colspan="5" rowspan="3">Field deployment phase for industrial version of rugged high power industrial accelerators</td></tr>
<tr><td>Radiography & Cargo Scanning</td><td colspan="5">Field deployment phase of 3-6 MeV e^- linac for radiography and cargo scanning</td></tr>
<tr><td>Waste Water Treatment</td><td colspan="5">Field deployment of DC accelerator and e^- linac for wastewater treatment</td></tr>
<tr><td rowspan="2">Medical Applications</td><td>Isotope Production & Radiotherapy</td><td colspan="5" rowspan="2">R&D phase for (i) medical cyclotrons for isotope production, and e^- linac for Intensity Modulated Radiotherapy and cyberknife applications, and (ii) proton accelerator and All ion hadron accelerator for therapy applications</td><td colspan="5" rowspan="2">Construction phase for medical accelerators for isotope production and therapy applications.</td><td colspan="5" rowspan="2">Preparations for field deployment phase through medical qualification and technology transfer.</td></tr>
<tr><td>Hadron Therapy</td></tr>
<tr><td rowspan="2">Nuclear Physics Applications</td><td>RIB, Upgrade of existing Heavy Ion Accelerator</td><td colspan="5" rowspan="2">R&D phase for RIB and new Heavy Ion Accelerator. Upgrade of existing accelerators – HCI, Cyclotron etc.</td><td colspan="5" rowspan="2">Construction phase for RIB and new Heavy Ion accelerator, and Design phase for beamlines. Upgrade of existing accelerators and its beam commissioning.</td><td colspan="5" rowspan="2">Commissioning and initial operation phase of new heavy ion and RIB accelerator.</td></tr>
<tr><td>New Heavy Ion Accelerator</td></tr>
<tr><td rowspan="2">LPA and Applications</td><td>Basic R&D on LPA and its applications</td><td colspan="5" rowspan="2">R&D phase for LPA for electron/proton/ion, and intense X-ray source based on LPA</td><td colspan="5" rowspan="2">Construction phase for LPA based electron accelerators (energy: several tens of MeV to few GeV), proton accelerators (energy: 10-50 MeV) and ultra-short duration x-ray/γ-ray source.</td><td colspan="5" rowspan="2">Construction phase for LPA based 100-250 MeV proton accelerators for radiation therapy applications, and compact FEL.</td></tr>
<tr><td>Construction of LPA for various applications</td></tr>
</table>

HBSRS – **H**igh **B**rilliance **S**ynchrotron **R**adiation **S**ource
MEHIPA – **M**edium **E**nergy **H**igh **I**ntensity **P**roton **A**ccelerator
HEHIPA - **H**igh **E**nergy **H**igh **I**ntensity **P**roton **A**ccelerator
ADS – **A**ccelerator **D**riven **S**ystem
IFSR – **I**ndian **F**acility for **S**pallation **R**esearch
FEL – **F**ree **E**lectron **L**aser
RIB – **R**are **I**sotope **B**eam
LPA – **L**aser **P**lasma **A**ccelerator

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[30] Colour coding: Blue stands for design and prototyping phase, Gold stands for construction and commissioning phase and Green stands for utilization phase

Annexure A.2 – Funding Requirements – a Tentative Estimate (Required funding in ₹ cr per annum (p.a.) is for the respective block of five years)

Applications Area		Current/Last Project Sanctioned Budget in ₹ cr	2020-25		2025-30		2030-35	
			FTE (Scientists/ Engineers)	Funding in ₹ cr (p.a)	FTE (Scientists/ Engineers)	Funding in ₹ cr (p.a)	FTE (Scientists/ Engineers)	Funding in ₹cr (p.a)
	Projects							
Photon Science Applications	HBSRS	--	--	40	35	1000	85	200
	FEL	58	68	40	104	191	110	164
Neutron Science Applications	ADS	200	50	200	50	200	200	1600
	IFSR	51	10	60	50	600	20	600
Industrial Applications	Irradiation	--	12	19.2	8	25.2	8	40.2
	Radiography & Cargo scanning							
	Wastewater Treatment							
Medical Applications	Isotope production and radiotherapy	23	116	143.2	52	210.8	65	161
	Hadron therapy							
Nuclear Physics Applications	RIB, Upgrade of existing Heavy Ion Accelerator	390	38	61.6	25	131.6	23	150
	New Heavy Ion Accelerator							
LPA and Applications	Basic R&D on LPA and its applications	105	30	20	60	150	60	300
	Construction of LPA for various applications							
Ecosystem Building Activities	Maintenance of existing accelerators, establishing common grid computing facility and data center, Training and outreach	--	--	50	--	50	--	50
	Grand Total	827	324	634	384	2558.6	571	3265.2

(The monetary estimates are based on 2020 as the Base Year. The figures quoted above have the inherent inflationary and FE rate uncertainties. FTE requirements is only for scientists and engineers, it does not include technicians.)

A PRIORITIZED ROAD MAP for 2020-2025

Applications Area	Modest Growth Scenario	₹ cr (p.a.)	Aspirational Growth Scenario	₹ cr (p.a.)
	Total Required Funding	421.8	Total Required Funding	634
	Projects			
Photon Science Applications	HBSRS – CDR and Prototyping	40	HBSRS – CDR and Prototyping	40
	FEL – IR FEL utilization, Construction of THz FEL	10	FEL – IR FEL utilization, Construction of THz FEL	10
			R&D for XFEL	30
Neutron Science Applications	ADS – 40 MeV, 10 mA CW proton linac	200	ADS – 40 MeV 10 mA CW proton linac	200
	IFSR – Infrastructure development, prototype cryomodule development	60	IFSR - Infrastructure development, prototype cryomodule development	60
Industrial Applications	Industrial Accelerator – Field deployment of electron accelerator for (i) irradiation, (ii) radiography and cargo scanning and (iii) wastewater treatment	19.2	Industrial Accelerator – Field deployment of electron accelerator for (i) irradiation, (ii) radiography and cargo scanning and (iii) wastewater treatment	19.2
Medical Applications	Medical Accelerator - Design and R&D on (i) medical cylotrons for isotope production, (ii) e$^-$ linac for intensity modulated radiotherapy and cyberknife applications.	28	Medical Accelerator - Design and R&D on (i) medical cylotrons for isotope production, (ii) e$^-$ linac for intensity modulated radiotherapy and cyberknife applications.	28
			Hadron Therapy Accelerator - Design and R&D on proton accelerator and All ion accelerator for hadron therapy	115.2
Nuclear Physics Applications	Heavy Ion and RIB Accelerator – HCI, RT Cyclotron, RIB (CARIBU)	29.6	Heavy Ion and RIB Accelerator – HCI, RT Cyclotron, RIB (CARIBU)	29.6
			Design and R&D phase for future Heavy Ion accelerator	32
LPA and Applications	Basic R&D on LPA and its Applications	10	Basic R&D on LPA and its Applications	10
			Construction of LPA for applications	10
Ecosystem Building Activities	Maintenance of existing accelerators, Training and outreach	25	Maintenance of existing accelerators, Training and outreach activities	25
			Establishing common grid computing facility and data centre	25
	Projects mentioned above are initiations of mega science projects for which a good base has been created through R&D activities during the last decade, and are natural extensions of ongoing activities. Details about the preparatory work can be found in Chapter 4, and details about the proposed projects can be found in Chapter 6. In the Modest Growth Scenario in this specified period, work on design and R&D on variable energy multi-ion accelerator for therapy will not be taken up, and design and R&D phase for future heavy ion accelerator will not be taken up.		In the Aspirational Growth Scenario in this specified period, it is aimed that through Design and R&D on variable energy multi-ion accelerator for therapy, India will become one of the few countries to develop state-of-the-art accelerators for cancer therapy; and (i) R&D for XFEL, (ii) design and R&D phase for future heavy ion accelerator, (iii) initiation of construction of LPA accelerator, and (iv) establishing common grid computing facility and data structure will pave the way to develop state-of-the-art accelerators for front-line research and societal applications.	

A PRIORITIZED ROAD MAP for 2025-2030

Applications Area	Modest Growth Scenario	₹ cr (p.a)	Aspirational Growth Scenario	₹ cr (p.a.)
	Total Required Funding	1336.6	Total Required Funding	2558.6
	Projects			
Photon Science Applications	HBSRS – Construction of HBSRS	1000	HBSRS – Construction of HBSRS	1000
	FEL – O&M and utilization of THz and IR FEL	31	FEL – O&M and utilization of THz and IR FEL	31
			Construction of intermediate energy electron linac for XFEL	160
Neutron Science Applications	ADS – Utilization of 40 MeV proton accelerator for isotope production and R& D for 200 MeV proton accelerator	50	ADS – Utilization of 40 MeV proton accelerator for isotope production and R& D for 200 MeV proton accelerator	50
			ADS – construction of 200 MeV proton accelerator	150
	IFSR – Construction of 10 MeV pre-injector pulsed H^- linac	50	IFSR – Construction of 10 MeV pre-injector pulsed H^- linac	50
			IFSR – Construction of 500 MeV H^- pulsed linac	550
Industrial Applications	Industrial Accelerator - Construction of industrial accelerators with higher power and enabling its manufacturing through PPP mode.	25.2	Industrial Accelerator - Construction of industrial accelerators with higher power and enabling its manufacturing through PPP mode.	25.2
Medical Applications	Medical Accelerator - Construction and commissioning of medical accelerators for radiotherapy and isotope production.	53.8	Medical Accelerator - Construction and commissioning of medical accelerators for radiotherapy and isotope production.	53.8
			Construction and commissioning of medical accelerators for hadron therapy	157
Nuclear Physics Applications	Heavy Ion and RIB Accelerator - HCI, RT Cyclotron, RIB	91.6	Heavy Ion and RIB Accelerator - HCI, RT Cyclotron, RIB (CARIBU)	91.6
			Construction of Future Heavy Ion Accelerator	40
LPA and Applications	Basic R&D on LPA and Applications	10	Basic R&D on LPA and Applications	10
			Construction of LPA for applications	140
Ecosystem Building Activities	Maintenance of existing accelerators, Training and outreach activities	25	Maintenance of existing accelerators, Training and outreach activities	25
			Establishing common grid computing facility and Data Centre,	25
	Projects mentioned above are initiations of mega science projects for which a good base has been created through R&D activities during the last decade, and are natural extensions of ongoing activities. Details about the preparatory work can be found in Chapter 4, and details about the proposed projects can be found in Chapter 6. In the Modest Growth Scenario in the specified period, work on construction of (i) 200 MeV proton accelerator for ADS, (ii) 500 MeV H^- pulsed linac for IFSR, (iii) intermediate energy electron linac for XFEL, (iv) medical accelerator for therapy, (v) future heavy ion accelerator, (v) electron/proton accelerators based on LPA and (vi) common grid computing facility and data centre will not be taken up.		In the Aspirational Growth Scenario in the specified period, it is aimed that through construction of (i) 200 MeV proton accelerator for ADS, (ii) 500 MeV H^- pulsed linac for IFSR, (iii) intermediate energy electron linac for XFEL, (iv) medical accelerator for therapy, (v) future heavy ion accelerator, (v) electron/proton accelerators based on LPA and (vi) common grid computing facility and data centre, India will be able to come at the forefront in advanced accelerator technology that has a variety of research as well as societal applications.	

A PRIORITIZED ROAD MAP for 2030-2035

Applications Area	Modest Growth Scenario	₹ cr (p.a)	Aspirational Growth Scenario	₹ cr (p.a)
	Total Required Funding	589.2	Total Required Funding	3265.2
	Projects			
Photon Science Applications	Construction of beamlines for HBSRS, its commissioning and operation	200	Construction of beamlines for HBSRS, its commissioning and operation	200
	Utilization and upgrade of FELs	24	Utilization and upgrade of FELs	24
			Construction of full energy injector linac for XFEL	140
Neutron Science Applications	ADS - Utilization of 200 MeV proton accelerator for isotope production and R& D for 1 GeV proton accelerator	50	ADS - Utilization of 200 MeV proton accelerator for isotope production and R& D for 1 GeV proton accelerator	50
			ADS – Construction of 1 GeV linac	1550
	IFSR – R& D for 1 GeV pulsed H$^-$ linac	50	IFSR–R& D for 1 GeV pulsed H$^-$ linac	50
			Construction of 1 GeV pulsed H$^-$ linac and proton accumulator ring	550
Industrial Applications	Validation and deployment of industry version of rugged industrial accelerators	40.2	Industrial Accelerator - Validation and deployment of industry version of rugged industrial accelerators	40.2
Medical Applications	Field deployment, medical qualification and technology transfer of proton accelerator for isotope production and electron linac for radiotherapy application	80	Field-deployment, medical qualification and technology transfer of proton accelerator for isotope production, and e$^-$ linac for radiotherapy	80
			Field-deployment, medical qualification and technology transfer of proton accelerator for therapy	81
Nuclear Physics Applications	Heavy Ion and RIB Accelerator - HCI, RT Cyclotron, RIB	110	Heavy Ion and RIB Accelerator - HCI, RT Cyclotron, RIB	110
			Utilization of future Heavy Ion accelerator	40
LPA and Applications	Basic R&D on LPA and Applications	10	Basic R&D on LPA and Applications	20
			Construction of LPA for applications	280
Ecosystem Building Activities	Maintenance of existing accelerators, Training and outreach	25	Maintenance of existing accelerators, Training and outreach activities	25
			Establishing common grid computing facility and Data Centre	25
	In the Modest Growth Scenario in the specified period, work on construction of (i) 1 GeV injector proton linac for ADS, (ii) 1 GeV pulsed H- linac for and proton linac for IFSR, (iii) full energy electron linac for XFEL, (iv) field deployment, medical qualification and technology transfer of proton accelerator for therapy application, utilization of future heavy ion accelerator, (v) electron/proton accelerators based on LPA, and (vi) common grid computing facility and data centre will not be taken up.		In the Aspirational Growth Scenario, through the work on construction of ((i) 1 GeV injector proton linac for ADS, (ii) 1 GeV pulsed H- linac for and proton linac for IFSR, (iii) full energy electron linac for XFEL, (iv) field deployment, medical qualification and technology transfer of proton accelerator for therapy application, utilization of future heavy ion accelerator, (v) electron/proton accelerators based on LPA, and (vi) common grid computing facility and data centre, India will be at the forefront in advanced accelerator technology and applications.	

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Annexure A.3 – Participation of Indian Industry

During the early periods of accelerator development in India, required components were developed mostly in-house in the R&D Centres/Institutes. This situation however changed during the later years, when large-size accelerator projects were undertaken. This could happen due to the growth of Indian industries. Currently, several industries are involved in design, development, fabrication and commissioning of various subsystems and components of accelerators. An indicative list of few industries, having significant participation in accelerator-related activities in India, is given below.

Table A.3.1: Indian Industry participation in Accelerator Science & Technology Projects

Sr. No.	Industry	Name of the project/s	Project carried out at	Remarks
1	Aarti Engineering Company, Mumbai	Development of photon absorber for Indus-2	RRCAT, Indore	Has a good facility for precision machining
2	Active Devices Inc., Mumbai	Development of RF power sensors	RRCAT, Indore	Technology transferred from RRCAT to this company
3	Apollo Heat Exchangers Pvt. Ltd., Mumbai	Development of Aluminum plate fin heat exchangers for cryogenic applications	RRCAT, Indore	Developed the heat exchangers for Indigenous Helium Liquefier/Refrigerator
4	Asaco Pvt. Ltd., Hyderabad	Fabrication of Niobium (Nb) half cells and dumb-bells	RRCAT, Indore	Long experience with this company in fabrication of Nb half cells and dumb-bells
5	Aseem Electronics, Delhi	Nuclear electronics development, RF power amplifier development and production	IUAC, Delhi	Electronics Components supplier
6	Avasarala Technologies Ltd., Bengaluru	Precision Positioning System Jacks for superconducting dipole for LHC	RRCAT, Indore	Successfully developed this item for the LHC project
7	Berryline Labs Pvt. Ltd, Kolkata	PCB fabrication for Solid State RF amplifiers	VECC, Kolkata	PCB manufacturer
8	BrahMos Aerospace Thiruvananthapuram Ltd., Thiruvananthapuram	Development of vane-type RFQ	BARC, Mumbai	Specializes in precision machining and brazing
9	Bright Engineering Works Pvt. Ltd., Mumbai	Development of electron gun for industrial electron accelerator	BARC, Mumbai	Technology Transferred from BARC to this company
10	Central Manufacturing Technology Institute (CMTI), Bengaluru	Development of sextupole magnets for Indus-2 accelerator	RRCAT, Indore	An autonomous R&D institute under the Ministry of Heavy Industries, Govt. of India, specializing in manufacturing technology.
11	Central Tool Room and Training Centre, Kolkata	Fabrication of Niobium half-cells for superconducting elliptic cavity	VECC, Kolkata	A Govt. of India society under MSME Ministry. Specialized in die punch assemblies, forming and precision machining
12	CSIR-Central Electrochemical Research Institute, Tamilnadu.	Copper plating of SS vacuum chamber for the spiral buncher, for the HCI project	IUAC, Delhi	A premier R&D institute in Electrochemistry

Sr. No.	Industry	Name of the project/s	Project carried out at	Remarks
13	D&S Electrical Works, Indore	Coil windings for different types of magnets and pulsed transformers for various accelerator projects	RRCAT, Indore BARC, Mumbai	Specializes in making coil windings for accelerator magnets.
14	Don-Bosco Technical Institute, New Delhi	Several components for accelerator, such as Nb cavities, Cryostats, RFQ, Drift Tube LINAC, Phase Detector, Harmonic Buncher, UHV chambers, and various experimental facilities, such as Neutron Detector Array and Gamma Detector Array	IUAC, Delhi	A teaching-cum-technical institute, which intends to take up jobs that are challenging from the perspective of mechanical engineering
15	Dynaspede Integrated Systems Pvt. Ltd., Bengaluru	Development of components for industrial electron linac	BARC, Mumbai	A manufacturing company with good facility for precision manufacturing
16	ECIL, Hyderabad	Solid State RF Amplifier	BARC, Mumbai IUAC, Delhi	High quality amplifiers, meeting international standards
		Quench Heater Protection Systems for LHC at CERN, Local Protection units for LHC at CERN. High stability magnet power supplies for the FEL project.	BARC, Mumbai RRCAT, Indore	Electronics of international quality and standards
17	Erawat Engineering Pvt. Ltd., Indore	Prototype of undulator for synchrotron radiation source	RRCAT, Indore	It is a manufacturing company, and has recently worked with RRCAT towards development of a prototype undulator
18	Fast Tech Engineers Pvt. Ltd., Mumbai	Development of Titanium end caps for superconducting cavities	RRCAT, Indore	End caps of titanium were developed by this company in collaboration with RRCAT
19	Femto Logic Design Pvt. Ltd., Chennai	Development of tuners for superconducting cavities	RRCAT, Indore	Developed the tuners for PIP-II accelerator in Fermilab
20	Fluidyne Engineers India Pvt. Ltd., Mysore	Bellows for superconducting cavities	RRCAT, Indore	Bellows were developed by this company in collaboration with RRCAT
21	Fore Vac. Industries, Pune	Various vacuum components for accelerators, beam line, experimental facilities, *etc*.	IUAC, Delhi	Internationally competitive vacuum products

Sr. No.	Industry	Name of the project/s	Project carried out at	Remarks
22	Gala Precision Engineering Pvt. Ltd., Thane	Centrifugal Barrel Polishing Machine	RRCAT, Indore	Centrifugal Barrel Polishing Machine is used for cavity processing at RRCAT
23	Godrej Industries Ltd., Mumbai	Large size dipole magnets for Indus-2 and Microtron	RRCAT, Indore	Specializes in high precision machining of large size components.
24	Goodwill Engineering Works, Ghaziabad	Small machining works related to RFQ, DTL, 50 keV Table Top Accelerator, *etc*.	IUAC, Delhi	Good for small fabrication works
25	Govt. Tool Room and Training Centre, Mysore	CNC machining of vanes, posts *etc*., for RFQ	IUAC, Delhi	A Karnataka Government Undertaking. Specializes in high accuracy machining work.
26	Graftec-India, Noida	Development and production of nuclear electronics and RF power amplifiers	IUAC, Delhi	Electronics Components supplier
27	Heavy Engineering Corporation Ltd., Ranchi	Fabrication of 80 ton Iron structure of main magnet for superconducting cyclotron	VECC, Kolkata	A Government of India Enterprise, which is a leading suppliers of capital equipment in India for steel, mining, railways, power, defense, space research, nuclear and strategic sectors.
28	Hind High Vacuum Company Pvt. Ltd., Bengaluru	General Purpose Scattering Chamber. High vacuum Furnace. Miscellaneous vacuum components.	IUAC, Delhi	Internationally competitive vacuum products
29	Hindustan Aeronautics Ltd., Nasik	Aluminum vacuum chambers for bending magnets for Indus-2	RRCAT, Indore	Its expertise in precision machining of large size aluminum components is useful for accelerator community.
30	IIE Semiconductors Pvt. Ltd., Faridabad	Development and production of nuclear electronics and RF power amplifier	IUAC, Delhi	Electronics Components supplier
31	Indo Danish Tool Room, Jamshedpur	Fabrication of Dee of RF cavity for superconducting cyclotron	VECC, Kolkata	A Govt. of India society under Min. of MSME. Specialized in development of die punch assemblies, forming and high accuracy machining work
32	Indo-German Tool Room, Ahmedabad	CNC machining of vanes, posts, *etc*., of RFQ	IUAC, Delhi	A Govt. of India society under Min. of MSME. Specializes in high accuracy machining work

Sr. No.	Industry	Name of the project/s	Project carried out at	Remarks
33	Indo-German Tool Room, Indore	CNC machining of (i) prototype of power extraction and transfer structures for CTF3 project at CERN, and (ii) RFQ vanes for IUAC. Precision positioning systems jacks for superconducting dipole for LHC project at CERN. Precision machining work for (i) dipole magnets vacuum chambers for CTF3 project at CERN, and (ii) Quadrupole magnets for beamline of VECC K500 SC Cyclotron	RRCAT, Indore IUAC, Delhi VECC, Kolkata	A Govt. of India society under Min. of MSME. Specializes in high accuracy machining work within reasonable price
34	Inox India Ltd., Vadodara	Cryostat for Horizontal Test	RRCAT, Indore	Has facility for development of long cryomodules for superconducting accelerator
35	Institute for Design of Electrical Measuring Instruments (IDEMI), Mumbai	Development of Drift Tube Linac for LEHIPA	BARC, Mumbai	A Govt. of India society under Min. of MSME. Specializes in product development, tool engineering and allied fields.
36	Jindal Aluminum Ltd., Bengaluru	Extruded aluminum vacuum chambers for straight sections for Indus-2	RRCAT, Indore	India's largest aluminum extrusion company.
37	Kamal Engineering Works, Mumbai	Ion pumps and accessories	RRCAT, Indore	Technology transferred from RRCAT to this company
38	M/S Dutta & Dasgupta, Kolkata	Fabrication of Niobium half-cells of superconducting elliptic cavity	VECC, Kolkata	Specializes in development of die punch assemblies, forming and high accuracy machining work
39	M/S Element14 India Pvt. Ltd., Bengaluru	Development and production of nuclear electronics and RF power amplifiers	IUAC, Delhi	Electronics Components supplier
40	Mansha Vacuum Technologies Pvt. Ltd., Bengaluru	Welding Glove-Box	RRCAT, Indore	Developed welding glove-box for dressing of superconducting cavities
41	Matrix Tooling Systems, New Delhi	Tuning plates for RFQ	IUAC, Delhi	Specializes in high precision CNC wire cutting
42	Nonferrous Materials Technology Development Centre, Hyderabad	Developed the OFHC copper material for Indus-2 project.	RRCAT, Indore	It is an autonomous R & D institution under the aegis of Ministry of Mines, and specializes in the development of advanced materials, and innovative processes.

Sr. No.	Industry	Name of the project/s	Project carried out at	Remarks
43	Paras defense and Space Technologies Pvt. Ltd., Mumbai	Development of components of industrial electron linac	BARC, Mumbai	Specializes in precision manufacturing of components
44	PCB Power India, Ahmedabad	Development of Piezo driver for tuner for superconducting cavity	RRCAT, Indore	Good quality work with custom design support
45	Radiant Safeway Pvt. Ltd., New Delhi	Tuning plates, coupler *etc.* for RFQ	IUAC, Delhi	Specializes in laser welding of small components
46	Raut Uni-Tech Pvt. Ltd., Mumbai	Coupler for superconducting cavity, waveguide components	BARC, Mumbai	Specializes in making microwave components
47	Scientific Mes-Technik Pvt. Ltd., Indore	High current magnet power supplied for the FEL project	RRCAT, Indore	Manufacturer of Test and measuring instruments, along with DC Power Supplies.
48	Shiva Electronics, New Delhi	Development of nuclear electronics and RF power amplifiers	IUAC, Delhi	Electronics Components supplier
49	SMP Enterprises, Pune	Various Vacuum components for accelerators, beam line, experimental facilities, *etc.*	IUAC, Delhi	Internationally competitive vacuum product
50	Snowcool Systems India Pvt. Ltd., Thane	Precision water chillers for the FEL project	RRCAT, Indore	Manufacturer of industrial chillers for various applications
51	Ti Anode Fabricators Pvt. Ltd. (Tiaano), Chennai	Helium Vessel	RRCAT, Indore	Developed Titanium components for Helium vessel for superconducting accelerator
52	Titanium Equipment and Anode Manufacturing Co Limited, Chennai	Components for superconducting cavities	RRCAT, Indore	Specializes in rolling, welding, machining and testing of helium vessel
53	Vacuum Techniques Pvt. Ltd, Bengaluru	Various vacuum components, such as RFQ vacuum chambers, spiral buncher *etc.* Machining and brazing of DTL components	IUAC, Delhi BARC, Mumbai	Internationally competitive vacuum products
54	Yash Enterprises, Pune	Development of Solid-State RF Power Amplifier modules	RRCAT, Indore	Technology transferred from RRCAT to this company

In the light of large-scale accelerator projects to be undertaken in future, there is a strong need to further enhance the involvement of Indian industry in a big way.

The Indian Industry will also benefit by the MSPs and Programmes, as indicated in Table A.3.2.

Table A.3.2: List of Indian Industrial Sectors that will derive major benefit from the proposed accelerator projects, as users of the accelerators

Sr. No.	Proposed accelerator project	Indian Industry that will derive benefit from the proposed accelerator project
1	High Brilliance Synchrotron Radiation Source (HBSRS)	Pharmaceutical and healthcare industry, Materials and manufacturing industry, Semiconductor industry, Chemical and petrochemical industry
2	Radioactive Ion Beam (RIB) accelerator	Pharmaceutical and healthcare industry, Materials and manufacturing industry
3	Heavy ion accelerator	Pharmaceutical and healthcare industry
4	230 MeV proton accelerator	Healthcare industry
5	10-70 MeV H^- Cyclotron with ~ 0.1 – 1 mA beam current	Healthcare industry
6	Electron Linac and ion sources	Healthcare industry, Agricultural and food products industry, Security sector, Materials and manufacturing industry, semiconductor industry
7	Indian Facility for Spallation Research	Materials and manufacturing industry, Chemical industry
8	Accelerator for ADS	Power sector, Nuclear industry

Annexure A.4 Impact of Accelerator Projects on Indian Industry and Society

The field of accelerator science and technology has grown in the country at a slow but steady pace during the last several decades. It has now grown to a stage where it has started to show visible impact on Indian industry and society. We briefly describe below the impact of some of the major accelerator projects on Indian industry and society.

Industrial Electron Accelerators

Using its indigenously built electron accelerator facility with required process control capability, which has FDA license as well as quality management certification (ISO 13485), RRCAT is providing electron beam irradiation services for sterilization of medical devices. This facility is being used by medical device and gem industry. During the financial year 2022-23, RRCAT earned ₹ 3.79 lacs, from payment towards use of this facility. This facility is also being provided to other industries, including semiconductor switching devices industry. RRCAT is also working with industry to test the indigenously developed 10 MeV, 10 kW industrial electron linac in industrial environment for process operations. This is being done under an incubation agreement, for which an incubation fee of ₹ 1 lakh has been paid to RRCAT. The linac is presently under installation and commissioning at an industry site in Bengaluru. In addition, RRCAT has also developed a 10 MeV, 10 kW linac for food irradiation applications. There are plans to develop more food irradiation linacs through Indian industries, and also to develop high throughput food irradiation facility.

The 10 MeV electron accelerator developed by BARC is being used for gemstone irradiation; and during the FY 2022-23, BARC earned ₹ 1.5 lacs through this. The electron accelerators developed by BARC are also being used by industry for R&D related to cables, food preservation, seed mutation, chitosan (bio stimulator) irradiation, waste water treatment, materials science studies etc.

It should be emphasized that at this stage, commercialization of indigenously built industrial accelerators has just begun, and the focus so far has been on demonstrating the use of industrial accelerators and winning the public confidence that irradiated products are not harmful. As a result, only a notional minimal amount has been charged for product irradiation at this stage. Many of the companies who were going abroad for getting their products irradiated are now confident that they can get it done in India.

Synchrotron Radiation Sources

Recently, commercial utilization of the beamlines of the Indus-2 Synchrotron Radiation Source at RRCAT has started. About ten Indian pharmaceutical companies have been regularly coming to Indus beamlines for experiments. For this, RRCAT has earned an amount of ₹ 19 lakhs during the FY 2022-23. Pharmaceutical companies have been able to obtain necessary clearances for public sale of some of their medicines on the basis of investigations performed at Indus-2. With such demonstrated successes, and due to the more focused efforts being made for popularizing the utility of Indus-2 for Indian industry, it is expected that there will be many-fold growth in commercial use of Indus-2 and the planned SRSs in India.

Medical Isotope Production Accelerators

Medical radio-isotopes are produced by VECC using their 30 MeV Medical Cyclotron Facility, in collaboration with BRIT in Kolkata. VECC is responsible for operation and beam delivery, whereas BRIT is responsible for the chemistry, quality control and supply of the radioisotopes to different hospitals in Kolkata. Several isotopes are being produced and supplied to meet the requirements. This has led to earnings of ₹ 1.7 crore during 2022-23. These isotopes used to be imported earlier. With the development of such accelerators within the country, import of such isotopes will further reduce. This will go a long way in ensuring the health security of our citizens. VECC is working on development of an indigenous 18 MeV medical cyclotron for isotope production, and technology will be transferred to industry after its successful completion.

Electron Accelerators for Radiotherapy

SAMEER has indigenously built electron linacs for radiotherapy, which have been installed and commissioned by them in various hospitals across India, and a large number (3-4 lakhs) of patients have been treated using these accelerators. SAMEER-made 6 MeV oncology machines are treating patients at the Indian Institute of Head and Neck Oncology, Rau, Indore; Amaravati Cancer Foundation, Amravati; and the Adyar Cancer Institute, Chennai. This machine has been type approved by AERB, and the technology has been transferred to Panacea Technologies. Many of the sub-systems of this accelerator, e.g., gantry, klystron modulator, control systems, accelerating structure components, *etc.* have been developed by the Indian industry. SAMEER has no mechanism for raising invoice for selling these machines to hospitals. Efforts need to be made to make such machines available in large numbers in India through technology transfer to the Indian industry.

Accelerators used for Nuclear Physics Applications

Heavy ion accelerators based on Pelletrons and superconducting booster linacs at BARC-TIFR and IUAC; room temperature cyclotrons and superconducting cyclotrons at VECC; FOTIA at BARC are operated round-the-clock, and extensively used by researchers from universities and R&D organisations. Some industries have also approached in the past to use the beam time at some of these accelerators on payment basis. However, in the absence of any mechanism to raise invoice for the beam time, this could not materialize. Steps are now being taken towards formalization of a suitable mechanism for this purpose.

FAIR Collaboration

India is the third largest contributor in the construction of the upcoming international project, the Facility for Antiproton and Ion Research (FAIR), after Germany and Russia. Indian contributions include in-kind components for FAIR accelerator as well as experimental detector systems. The accelerator components include: (a) ultra-stable power converters (382 already delivered out of a total of 520), designed and developed jointly by BARC, RRCAT, VECC and ECIL, and fabricated at ECIL, Hyderabad; (b) ultra-high thin-walled vacuum chambers (58 delivered), fabricated by Vacuum Technique, Bangalore; (c) beam stopper (three devices with proper cooling arrangements placed in three separate vacuum chambers to stop high intensity primary and secondary beams), designed by CSIR-CMERI, Durgapur, being produced by Trident-Kanpur jointly with Hans-machinery, Howrah and Flyvac-Bangalore; (d) power cables (184 km co-axial cables), design and fabrication being done by Siechem-Pondicherry; (e) IT-cables of different types, being produced by Siechem–Pondicherry; (f) design of superconducting magnets for the superconducting fragment separator at FAIR, done by VECC-Kolkata. Apart from the in-kind items mentioned above, Indian industries are now also able to bid directly for FAIR equipment, and some of the items where Indian companies have been found technically suitable include - (a) UHV chambers, (b) platform for the beam-stopper, (c) cryogenics components (current leads etc). One Indian company (INOX-India, Ahmedabad) has received orders for about ₹ 20 cr for supplying cryogenic equipment for FAIR. Several such proposals are at various stages of evaluation.

CERN Collaboration

As a result of India's long-time collaboration with CERN programmes, and its well-recognized and valuable contributions to the construction of LHC as well as the CMS and ALICE detectors, India first acquired an Observer status, and then an Associate Member status, on the CERN Council. After India became an Associate Member, Indian industry could bid directly for CERN's tenders for supplying items to CERN outside the ambit of the project-specific in-kind contributions. The process is slowly picking up, with Indian industry getting into the CERN supply-chain system and competing with their European and global counterparts.

Since 2019, nearly 60 companies have participated in the CERN tendering process, out of which 15 have received offers/contracts. As of January 2023, about 90 companies have registered themselves with the CERN e-procurement website. Indian companies have mainly contributed in the areas of electrical engineering, information technology, electronics, cryogenic and vacuum equipment, mechanical engineering, raw materials and other industrial facilities. The products range from surgical masks during Covid times to complex PCBs and large argon storage tanks. The overall value of offers/contracts received from CERN by Indian companies during 2019-2022 is nearly ₹ 60 crores.

Indian Institutions-Fermilab Collaboration

Indian Institutions (BARC, RRCAT, VECC and IUAC) and Fermilab signed an agreement in 2011 to jointly contribute to the development of world's highest power cw proton accelerator – with a beam energy of 800 MeV and cw beam current of 2 mA – under the project PIP-II at Fermilab. This project is envisaged to be executed in two phases – R&D Phase and Construction Phase. Indian Institutions are making in-kind contributions to this project by delivering multi-cell superconducting cavities, normal and superconducting magnets, solid-state RF Amplifiers, and low-level RF Systems. The R&D Phase of the project will be completed soon after which the construction phase will commence. This collaboration was highlighted in the Joint Statement from the United States and India on 22nd June, 2023, where it was mentioned that "President Biden and Prime Minister Modi hailed our deepening bilateral cooperation on cutting-edge scientific infrastructure, including a $140 million in-kind contribution from the Indian Department of Atomic Energy (DAE) to the U.S. Department of Energy's (DOE's) Fermi National Laboratory toward collaborative development of the Proton Improvement Plan-II Accelerator, for the Long Baseline Neutrino Facility — the first and largest international research facility on U.S. soil". It is expected that the Indian industry will participate in the development and production of these components in a big way, and this will open another pathway for the Indian Industry to enter the global market in cutting-edge technology areas, like what happened in the case of CERN and FAIR collaborations.

The above examples go on to show that accelerator technologies have achieved certain level of maturity in India. The impact of accelerators has also started being felt by the Indian industry and society at large, especially in the healthcare sector. There is considerable scope for even wider use of accelerators in the country. Accordingly, considerably greater efforts are required to promote development and use of accelerators and accelerator technologies in the country.

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Annexure A.5: Return on Investment (RoI) for Accelerator Projects

During the course of evolution of this Report, a suggestion was made to the Working Group (WG) to attempt estimating the Returns on Investment (RoIs) on some typical accelerator projects in the country. Given that large financial investments are typically needed to be made in such projects, such an exercise will help the concerned scientific communities to introspect more deeply about the quantitative benefits that would accrue from such projects, during their planning and construction, and would also motivate and encourage them to maximize their utilization when operational. Despite the importance and novelty of this suggestion, the WG soon realized its limitations in carrying out this exercise – first, such an attempt had not been made earlier in the country; second, there were thus no well-established principles to follow; and third, the scientific community including the WG was not accustomed to converting non-monetary returns like number of research papers, number of doctorates produced *etc.* into monetary terms. While it was clear to the WG that such a task was best accomplished by economists, it decided to make an honest attempt to carry out the RoI-exercise with necessary caveats regarding all the approximations made.

Before the numerical estimates are presented in the Table below, it will be useful to briefly mention the methodology adopted for this RoI-analysis. We first classify the accelerator projects into three categories – (i) the accelerator projects that create user facilities; (ii) the accelerator projects that are intended to develop accelerators in R&D institutes for societal applications; and after successful development, the technology for which can be transferred to local industry through Technology Transfer (TT) mode or incubation mode, where they can develop these accelerators as import substitutes; and (iii) the large-scale accelerator projects that are currently in their R&D phase, and their construction phase will commence after the closure of the R&D phase. In this Appendix, we carry out the RoI-analysis only for the first two categories of projects. For projects like the ADS accelerator and the IFSR accelerator that fall in the third category, it will be too speculative to project the RoI at this stage, and we have therefore excluded these projects from RoI-analysis here. Table A.5 shows the RoI-analysis for some of the important operational accelerator projects in India, and also for one major proposed accelerator project (namely, Indus-3/HBSRS).

We have also devised two sets of parameters which will help us estimate the RoI – the first set will help us quantitatively (though obviously approximately) calculate the Economic Returns in Rupee terms; and the second, which tell us about the Societal Returns by way of enhanced knowledge or strengthening of scientific and technological ecosystem of the country. As mentioned above, the WG found itself ill-equipped to convert the second set of parameters into Rupee terms; and thus decided to present these outputs in terms of their usual units/numbers.

Focusing on the parameters for Economic Returns, the WG has devised a method to estimate the RoI. For the first category of accelerator projects that are already operational as user facilities, an important return is by way of saving that is made by not incurring the travel cost and machine utilization cost that Indian scientists would have ended up paying for utilizing similar facilities abroad in the absence of these national facilities. In order to estimate the machine utilization cost in other advanced economies abroad, we have employed either of the following two methods – (i) using the rate at which it is charged for similar machines abroad, or (ii) multiplying the total investment made towards construction, operation and maintenance of the machine in India till 31 December 2023 by the PPP Dollar-Rupee ratio in 2023 (PPP stands for Purchase Power Parity) [PPP]. The investments made during different years are all escalated to 31 December 2023, by considering 5% price escalation per year due to inflation (without any compounding), and then added. This ensures that the Investment as well as the Return refer to the same year (2023) for correct comparison. While calculating the investment, the O&M as well as upgrade costs have also been added to the machine construction cost, and the total investment is noted down in column 2 of Table A.5. It may be noted that the saving described in column 6 of Table A.5 is in a sense notional saving, which is obtained by subtracting notional earning from the total investment. For some of the machines, there has been direct earning as well, which is described in column 7 of Table A.5.

For calculating the RoI in terms of saving for the second category of accelerator projects that we described above (para 2 above), we have subtracted the cost of imported machine from the total investment made for indigenously developing those machines. It may be noted that when the technology for developing these accelerators for societal applications is transferred to the local industry and they develop and market these accelerators as import substitute, the RoI made by the R&D lab for developing that particular accelerator will be many times larger.

Column 3 of the Table describes the total amount of purchase order that is placed on Indian industry for the particular project. This also brings in indirect economic returns to the nation by way of boosting industrial production, employment, tax earnings, foreign exchange savings due to import substitution, *etc*. However, we have no means of estimating the net earnings on these counts and hence, we have just mentioned the amount that went to the Indian industry by way of purchase orders.

There is another important facet of mega science projects that needs to be flagged. The expenditure made on such projects is mostly in the nature of capital expenditure made by the government and it helps build a national high-tech capital asset. All economic advantages that accrue to a nation's economy through capital expenditure also accrue by virtue of these projects.

Columns 4 and 5 describe the number of industries, where additional technological capabilities got developed, and number of technologies that got transferred to the industry due to the particular accelerator project. Column 7 describes the direct earning by way of technology transfer to industry or services to society etc.

We then describe different societal benefits for each of the accelerator projects in remaining columns of the Table, like research output, human resource development, *etc*.

Given the uncertainties inherent in the calculations given below, we would not like to draw very strong conclusions. However, it appears that a national accelerator facility, in the long run, does make up for the investments made in construction, operation and maintenance even in monetary terms, apart from making substantial contributions to the research and high-tech industrial eco-system of the country.

Table A.5: Estimation of Return on Investment (RoI) till 31. 12. 2023 for selected accelerator projects in the country

Projects (1)	Total Investment till 2023 (₹ crores) (Establishment / Construction of facility, Operation & Maintenance, *etc.*) [Original Cost escalated to Dec 2023, @ 5% /year] (2)	Economic Returns					Societal Returns				
		Orders placed (₹ crores) on Indian industry for capital items → boosting industry, employment, *etc.* (3)	Number of industries, where additional technological capabilities built (4)	Number of Technologies transferred so far (5)	Notional Savings (₹ crores) by way of import substitution, or by way of avoiding additional costs in utilizing the accelerator facilities abroad, *etc.* (6)	Direct earnings (₹ crores) by way of technology transfer, services, *etc.* (7)	Number of research papers published (8)	Number of PhDs produced (9)	Number of technical personnel trained (10)	Direct beneficiaries of the technology/ product (number of patients treated, amount of agricultural produce treated, *etc.*) (11)	Number of unique S&T opportunities opened up for the Nation (for international collaborations, world-class sites for facilities, *etc.*) (12)
Indus-1 and Indus-2 Synchrotron Radiation Sources at RRCAT	[Indus-1 (1999) + Indus-2 (2005, Round the Clock Operation -2010)] – 500 O& M - 125[1] **Total - 625**	250	30	7	Travel: 140[2] Beam-time:[3] 840 **Saving: 140 + 840 – 625 = 365**	0.40	~1500	~ 150	Scientists/ Engineers - 900 Technical Staff – 200 Interns / Project Trainees - 350	NIL	Attracting Indian Industry to SRS → 16 industry users at Indus beamlines, most of them are pharmaceutical industries.
Construction of proposed HBSRS (Indus-3)	Indus-3 - 9700 Estimated time for completion: 8 years from financial sanction **Total - 9700**	6000	~ 100[4]	~ 15[4]	Travel: 1000[5] Beam-time[6] (12 beamlines × 25 years × 200 days/year): 4800 **Projected Savings[7]:1000 + 4800 – 9700 = -3900**	~ 600[8]	~22,000[4]	~750[4]	Scientists/ Engineers – 3800 Tech. – 450		Expected industries/sectors to benefit from Indus-3: Pharmaceuticals, chemical, Energy, FMCG, Metallurgy, Mining, Heavy Engg., agriculture *etc.*

Note:

[1] The maintenance cost includes only the cost of spares and replacement of ageing components.

[2] This estimate has been made by taking the cost of one visit to international SRS facility as ~ ₹ 2 lakh, and the total number of users experiments carried out at Indus beamlines since 2011 as ~ 7000. The travel cost for carrying out the experiments at international SRS facility is taken as notional saving due to this facility in India.

[3] For PETRA-III, the reported cost charged to India is 1.736 M€ per year (for 152 days of beam time) for 1.3 beamline-equivalent, implying around ₹ 8 lakhs per beamline per day. The total number of users experiments carried out at Indus beamlines since 2011 is approximately 7,000. Taking 3 days per user experiment, the number of beamline-days comes out to be 21,000. Unlike PETRA-III, Indus-1 and Indus-2 are not operated in top-up mode that results in relatively reduced beam availability. In addition to this, specifications of Indus-1 and Indus-2 are on the lower side of PERTA-III in terms of beam energy and emittance. In order to account for these two factors, the cost of beam time usage has been scaled down by a factor of 50%. Thus the notional savings can be calculated as below: 7,000 experiments × 3 days/experiment × 0.5 scaling factor × ₹ 8 lakhs / day = ₹ 840 crores.

[4] These are projections over a period of next 25 years, based on the data from ESRF experience.

[5] This estimate has been made by anticipating ~2000 annual user experiments on 12 beamlines on Indus-3 for 25 years @ 2023 rates of 2 lakh per visit per person.

[6] Since Indus-3 will be operated in top-up mode, instead of using the reduced rate as done for Indus-1 and Indus-2, the same rate as charged by PETRA-III, *i.e.*, ₹ 8 lakhs per beamline per day has been used for calculation of saving due to 12 beamlines for 25 years.

[7] The user numbers are expected to increase progressively as the number of beamlines on the same machine increases. The notional earning due to beam time will be proportionally higher with more number of beamlines (approx. 38 more) in future on the same machine. Also, the O&M cost for Indus-3, and construction cost of additional 38 beamlines is not added here.

[8] Assuming about 10% of the user experiments, *i.e.* ~200 experiments per year are from the industry, and each industry user uses the beam for about 24 hours on an average, then with the cost of use per hour being ₹ 50,000/-, the earning from industry is expected to be about: ₹ 600 cr. The number of industrial users is expected to increase progressively, as the number of beamlines on the same machine increase - the earnings will proportionally be higher.

		Economic Returns					Societal Returns				
Projects (1)	Total Investment till 2023 (₹ crores) (Establishment / Construction of facility, Operation & Maintenance, *etc.*) [Original Cost escalated to Dec 2023, @ 5% /year] (2)	Orders placed (₹ crores) on Indian industry for capital items→boosting industry, employment, *etc.* (3)	Number of industries where additional technological capabilities built (4)	Number of Technologies transferred so far (5)	Notional Savings by way of import substitution, or by way of avoiding additional costs in utilizing the accelerator facilities abroad, etc. (6)	Direct earnings (₹ crores) by way of technology transfer, services, *etc.* (7)	Number of research papers published (8)	Number of PhDs produced (9)	Number of technical personnel trained (10)	Direct beneficiaries of the technology/ product (number of patients treated, amount of agricultural produce treated, *etc.*) (11)	Number of unique S&T opportunities opened up for the Nation (for international collaborations, world-class sites for facilities, *etc.*) (12)
Pelletron + Superconducting Booster Linac + High Current Injector at IUAC	Pelletron (1989) – 220 SC Linac (2008) – 130 O&M – 250 **Total – 600** HCI – 80 (recently operational)	117	48	05	Beam time[1]: 2202 Saving = 2202 – 680 = 1522	NIL	~ 6000	1150	Scientists/ Engineers – 136 Technical staff – 78 Intern/ Project trainees – 840	NIL	27 MoUs with national institutes and 12 MoUs with international institutes. Collaboration with important accelerator Centers in Japan, Germany, UK, USA, Australia, France, Italy, Russia, Israel, Switzerland, Canada, etc.
AMS + IBA at IUAC AMS: Accelerator Mass Spectrometry, IBA: Ion Beam Accelerator	IBA (2015) - 22 AMS (2010) - 02 **Total - 24**	NIL	NIL	NIL	Beam time[2]: 93 Saving = 93– 24 = 69	NIL					
LEIBF + NIBF + TTA at IUAC LEIBF: Low Energy Ion Beam Facility, NIBF: Negative Ion Beam Facility, TTA: Table Top Accelerator	LEIBF (2008): 14 NIBF (2003): 3 TTA (2008):1 **Total - 18**	NIL	25	03	Beam time[3]: 66 Saving = 66 – 18 = 48	NA					

Note:

[1] The per shift (8 hours) O&M cost of Pelletron + Superconducting Linac + HCI at IUAC is ~ ₹ 3.3 lakhs. It has been informally learnt from GANIL that their O&M Cost is an order of magnitude higher. GANIL, however, is a much more advanced facility, and a direct comparison is therefore difficult. The cost of analysis/sample on comparable AMS facilities in advanced economies is ~ 4 times that of IUAC-cost. As a very conservative estimate, we have multiplied the Indian Investment by the PPP dollar-rupee ratio (3.67 in 2023) and treated this as the cost that our scientists would have incurred if they had carried out the investigations elsewhere in advanced economies. The difference between this and the total investment in col. 2 gives us the notional saving in col. 6.

[2] From the calculation of the cost/sample being characterized in foreign laboratories –
IBA: ₹ 10 cr/year × 8 years = ₹ 80 cr, AMS: ₹ 1 cr/year × 13 years = ₹ 13 cr, so total cost that would have been spent = ₹ (80+13) cr = ₹ 93 cr.

[3] Once again, estimated based on PPP dollar-rupee ratio (3.67 in 2023) in the absence of user-charge-rates for realistic equivalent facilities abroad.

Projects (1)	Total Investment till 2023 (₹ crores) (Establishment / Construction of facility, Operation & Maintenance, *etc.*) [Original Cost escalated to Dec 2023, @ 5% /year] (2)	Economic Returns: Orders placed (₹ crores) on Indian industry for capital items → boosting industry, employment, *etc.* (3)	Economic Returns: Number of industries where additional technological capabilities built (4)	Economic Returns: Number of Technologies transferred so far (5)	Economic Returns: Notional Savings (₹ crores) by way of import substitution, or by way of avoiding additional costs in utilizing the accelerator facilities abroad, *etc.* (6)	Economic Returns: Direct earnings (₹ crores) by way of technology transfer, services, *etc.* (7)	Societal Returns: Number of research papers published (8)	Societal Returns: Number of PhDs produced (9)	Societal Returns: Number of technical personnel trained (10)	Societal Returns: Direct beneficiaries of the technology/ product (number of patients treated, amount of agricultural produce treated, etc.) (11)	Societal Returns: Number of unique S&T opportunities opened up for the Nation (for international collaborations, world-class sites for facilities, *etc.*) (12)
Heavy Ion Accelerator at BARC-TIFR	Pelletron (1988) – 35 Linac (2002, 2007) - 48 O&M – 140 **Total - 223**	80	10	4	Beam time (35 years): 818[1] **Saving = 818 - 223 = 595**	NIL	830 (35 high impact papers)	~160	~500	NIL	International collaborations with important accelerator Centers in USA, Japan, France, Germany and Brazil

Note:
[1]Following the methodology described on the previous page for IUAC Heavy Ion Accelerator, we have multiplied the Indian Investment by the PPP dollar-rupee ratio (3.67 in 2023) and treated this as the cost that our scientists would have incurred if they had carried out the investigations elsewhere in advanced economies.

Projects (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Normal Conducting (K=130) Cyclotron at VECC	NC Cyclotron (1977) - 377 Upgrade (2010) - 38 O&M - 170 **Total - 585**	190	10	4	Travel (46years)[1]: 138 Beam time (46years)[2]: 759 **Saving: 138 + 759 – 585 = 312**	-	~ 350	~ 60	Scientists/ Engineers ~ 600 Technical staff ~ 800 Trainee/Student ~ 100 (for all three projects)	NIL	International collaborations with CERN, BNL, MSU, Texas-AMU, GANIL, REIKEN *etc.*
Superconducting Cyclotron at VECC	SC Cyclotron (2019) - 120 O&M - 61 **Total - 181**	101	13	NIL	Travel (5years)[1]: 5 Beam time[2] (5 years): 15 Saving: 5 + 15 – 181 = -161[3]	-	~100	~ 15		NIL	
Medical Cyclotron at VECC	Med. Cyclotron (2018) - 311 O&M – 24 **Total - 335**	124	5	NIL	Market value of med. isotopes produced [4]: 45 Saving: 45 – 335 = -290[3]	1.7 (for 2023)	~20	NIL		~ 30,000 patients	National capacity for constructing and running medical cyclotrons built.

Savings calculations
[1] Travel cost is taken as ₹ 20 lakhs per experiment (for 5 scientists) × 15 experiments per year = ₹ 3 cr per year for NC cyclotron. Utilization of SC cyclotron is in its initial stage, where ~ 5 experiments per year are being performed. Travel cost of ₹ 1 cr per year is taken for this case.
[2]Beam time cost is calculated per year as ₹ 7500 per hour × 6000 hours/year × 3.67 (PPP factor) = ₹16.5 cr per year for NC cyclotron. Since utilization of SC cyclotron is in its initial stage, where experiments have been performed @ 1200 hours/year. Beam time cost is therefore taken as ₹ 3 cr per year for SC cyclotron
[3]Saving will slowly build-up with time, as the utilization is expected to remarkably improve in near future.
[4]For medical cyclotron, the medical isotope cost is calculated, taking the cost of FDG dose as € 175 per dose ×10000 doses per year × 3 years.

<table>
<tr><th rowspan="2">Projects
(1)</th><th rowspan="2">Total Investment till 2023 (₹ crores)
(Establishment / Construction of facility, Operation & Maintenance, *etc.*)
[Original Cost escalated to Dec 2023, @ 5% /year]
(2)</th><th colspan="5">Economic Returns</th><th colspan="5">Societal Returns</th></tr>
<tr><th>Orders placed (₹ crores) on Indian industry for capital items, boosting industry, employment, *etc.*
(3)</th><th>Number of industries where additional technological capabilities built
(4)</th><th>Number of Technologies transferred so far
(5)</th><th>Notional Savings (₹ crores) by way of import substitution, or by way of avoiding additional costs in utilizing the accelerator facilities abroad, *etc.*
(6)</th><th>Direct earnings (₹ crores) by way of Technology Transfer (TT), services, *etc.*
(7)</th><th>Number of research papers published
(8)</th><th>Number of PhDs produced
(9)</th><th>Number of technical personnel trained
(10)</th><th>Direct beneficiaries of the technology/ product (number of patients treated, amount of agricultural produce treated, *etc.*)
(11)</th><th>Number of unique S&T opportunities opened up for the Nation (for international collaborations, world-class sites for facilities, *etc.*)
(12)</th></tr>
<tr><td>6 MeV Medical Linac at SAMEER (6 machines)</td><td>Medical linacs – 6 nos. (2008, 2014, 2017, 2023) – 22.5
Total = 22.5</td><td>9.41</td><td>10</td><td>1</td><td>Import cost (6 machines) = 36[1]
Saving = 36-22.5 = 13.5</td><td>1</td><td>10</td><td>2</td><td>Scientists/ Engineers – 38,
Technical staff – 32
Interns - 60</td><td>~ 80000[2] patients treated</td><td>CSIR/CSIO was involved in optics development. Capacity to build cancer therapy machine built in country.</td></tr>
<tr><td colspan="12">Note:
[1] Average import cost of a machine with features similar to that of the machine developed by SAMEER is ~ ₹ 6 cr each.
[2] This is calculated based on 4 lakhs exposure given cumulatively by these machines over a period of time and minimum 5 exposures to each patient.</td></tr>
<tr><td>Industrial Accelerator at RRCAT</td><td>10 MeV industrial linacs – 2 nos. (2021) – 22
O&M – 1.2
Total = 23.2</td><td>12</td><td>5</td><td>1</td><td>Import cost (2 machines): 35[1]
Saving = 35 -22 = 13</td><td>0.05</td><td>30</td><td>NIL</td><td>Scientists/ Engineers – 30
Technical staff - 10</td><td>> 30 lakhs Class-B Risk medical devices sterilized using electron beam</td><td>World class electron beam radiation processing facility for sterilization of medical devices</td></tr>
<tr><td colspan="12">Note:
[1] Import cost of a machine with similar features is about ₹ 17.5 cr each.</td></tr>
<tr><td>Free Electron Laser at RRCAT</td><td>Machine Cost (2021) - 51
O& M = 0.6
Total = 51.6</td><td>16</td><td>02</td><td>NIL</td><td>Travel[1]: 0.2
Beam time[2]: 2
Saving = 2.2 – 51.6 = - 49.4[3]</td><td>NIL</td><td>25</td><td>5</td><td>Scientists/ Engineers – 10
Technical staff - 10</td><td>NIL</td><td>Unique FEL based user facility, which is the only one of its kind in the country</td></tr>
<tr><td colspan="12">Note:
[1] This is the expected savings on travel cost for foreign visit @ ₹ 2 lakhs per experiment cycle, for 10 experiment cycles so far, each one week long.
[2] Cost that user would have paid for a similar facility abroad @ ₹ 20 lakhs per experiment cycle, for 10 experiment cycles so far, each one week long.
[3] Being newly commissioned machines, RoI will slowly build up. 30 user experiment cycles expected per year when full utilization commences.</td></tr>
<tr><td>RRCAT developed Microtron at Mangalore University</td><td>Machine cost (1995): 4
O&M: 0.1/year
Total = 6.8</td><td>0.05</td><td>1</td><td>NIL</td><td>Travel (28 years):16.8
Beam time (28 years): 42
Saving = 58.8 – 6.8 = 52</td><td>0.85</td><td>378</td><td>~135</td><td>15</td><td>NIL</td><td>Unique facility catering to university researchers in India</td></tr>
<tr><td colspan="12">Note:
[1] Travel cost: ₹ 2 lakhs per week experiment cycle, Beam time cost @5 lakhs per week experiment cycle. 30 experiment cycles /year is assumed.</td></tr>
</table>

Acknowledgements

A large number of accelerator scientists and technologists in the country, outside the Working Group, have contributed towards preparation of this document by giving their inputs and also through valuable discussions held with them. We would like to particularly thank Shri T. A. Puntambekar, Director, Electron Accelerator Group, RRCAT, Shri Jishnu Dwivedi, Associate Director, Technology Development and Support Group, RRCAT, Dr. Archana Sharma, Director, Beam Technology Development Group, BARC, Dr. K. K. Pant, Head, FEL Utilization Section, RRCAT, Dr. Anand Moorti, Head, Advanced Plasma Acceleration Section, RRCAT, Dr. Sumit Som, Director, VECC, Dr. Arup Bandyopadhyay, Head, Accelerator Physics Group, VECC, Dr. Vaishali Naik, Head, Radioactive Ion Beam Facilities Group, VECC, Dr. Anjan Dutta Gupta, Head, Mechanical Engineering Group, VECC, Shri Aditya Mandal, Head, RF Section, VECC, Dr. Subhasis Chattopadhyay, Former Head, Experimental High Energy Physics & Applications Group, Prof. A. C. Pandey, Director, IUAC, Dr. S. Chopra, Former Program Leader, Pelletron, RBS, AMS and Geochronology, IUAC, Dr. P. N. Prakash, Program Leader, Linac SRF and Cryogenics, IUAC, Dr. S. Muralithar, Program Leader, GDA/INGA, IUAC, Dr. N. Madhavan, Program Leader, HIRA/HYRA, IUAC, Dr. P. Sugathan, Program Leader, GPSC/NAND, IUAC, Dr. Ambuj Tripathi, Program Leader, Materials Science, IUAC, Mr. Rajeev Mehta, Program Leader, High Current Injector, IUAC, Dr. Vandana Nanal, TIFR, Mumbai and Dr. Ganesh Sanjeev, Mangalore University. We would also like to thank a large number of people from the scientific community for their useful feedback and suggestions. In particular, very useful and important suggestions from Dr. R. K. Bhandari, Dr. P. D. Gupta, Dr. Amit Roy, Dr. Milan Sanyal, Sh. Gurnam Singh, Dr. R. G. Pillay, Sh. Y. S. Mayya, Dr. B. Gopal, Dr. Deepak Raparia, Dr. G. K. Sahoo, Dr. Jean Dailant, Dr. Ken Takayama, Dr. K. J. S. Sawhney and Dr. Maurizio Vretenar are duly acknowledged. We would like to thank Dr. Arabinda Mitra, former Scientific Secretary, and Dr. Parvinder Maini, the Scientific Secretary in the Office of the PSA to the Govt. of India. We would also like to acknowledge the efforts of Computer Division, RRCAT for hosting the webpage for getting online feedback/suggestion from the members of the scientific community on this document. Finally, and most importantly, we express our appreciation for Prof. K. VijayRaghavan, Former PSA to the Govt. of India, for initiating the MSV-2035 Exercise, and Prof. Ajay K. Sood, PSA to the Govt. of India, for his continued support.

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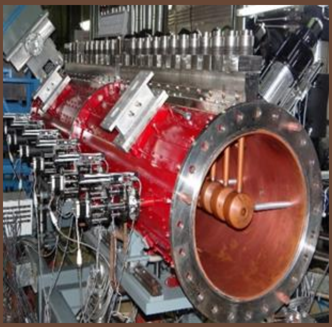
The back cover page shows the photograph of beamline of BARC-TIFR Pelletron Linac Facility at TIFR, Mumbai (1st row, left), RFQ (1st row, middle) and DTL (1st row, right) at LEHIPA Facility, BARC Mumbai, Niobium QWRs in linac cryostat at IUAC, New Delhi (2nd row, left), Superconducting Cyclotron and beamline at VECC, Kolkata (2nd row, middle), RIB Linac at VECC, Kolkata (2nd row, right), SAMEER's 6 MeV oncology machine -"Siddharth" (3rd row, left), SRF cavities developed at RRCAT and installed in PIP-II prototype cryomodule (3rd row, right), Experimental results on laser plasma acceleration at RRCAT, Indore, (4th row, left) and Infra-red Free-electron Laser at RRCAT, Indore (4th row, right)



Layout of PIP-II HB650 pCM having three β=0.92 RRCAT cavities and three β=0.9 FNAL cavities