Next-generation particle accelerators for frontline research and wide-ranging applications in India – how to realize them?

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Several modern accelerator facilities have been set up in India for basic and applied research during the past 5 decades. Indian scientists have been able to carry out excellent accelerator-based research at these as well as international facilities. Applications of accelerators in healthcare and industry have also grown in recent years. There is a strong realization now, at all levels, that a quantum jump needs to be given to the field of accelerator science and technology in India to fulfil the aspirations of the research community to be at par internationally in our areas of strength. Applications in industry and healthcare also have to grow substantially to benefit the common man. In this article an analysis of the methodology and logic behind the evolution of our accelerator programme has been presented. More importantly, recommendations have been given for gainfully implementing a rather ambitious programme that is proposed to be taken up in the next few decades.

Keywords: Accelerators, basic and applied research, industrial and health care applications, international collaborations.

THE history of accelerators in India goes back to the development of a 38 inch cyclotron at the Calcutta-based Institute of Nuclear Physics (now called Saha Institute of Nuclear Physics) in 1940 by Meghnad Saha. However, construction of the 224 cm Variable Energy Cyclotron (VEC) at Kolkata by the Department of Atomic Energy (DAE) during 1970–77 ushered in the era of building large and modern accelerators in India[1,2]. Raja Ramanna was the main motivating force behind this bold initiative aimed at creating a frontline accelerator facility for nuclear physics research by the Indian scientists. Prior to that, a few low-energy machines, including a 2 MV Van de Graaff at Indian Institute of Technology, Kanpur (IIT-K), small cyclotron at Panjab University and a 5.5 MV Van de Graaff at BARC were available for this purpose. The design of the VEC was adopted from similar machines operating at Berkeley and College Station (Texas) in USA. But the important fact is that it was constructed in India by an Indian team. This machine has been providing ion beams for over 35 years and it is still in operation at the VEC Centre (VECC) at Kolkata. It accelerates beams of protons, deuterons, alphas and heavy ions with maximum energy of about 25 MeV per nucleon. A large number of VEC users also belong to other areas such as materials science, radiochemistry, analytical chemistry, isotope production, radiation physics, biology, etc. It is a national facility available to the experimentalists from various R&D institutions and universities of the country.

Development of the tandem Van de Graaff-type accelerators for medium-energy ion acceleration for nuclear physics research was emphasized in the mid-sixties when the Atomic Energy Commission (AEC) took the decision to construct the VEC. Therefore, Bhabha Atomic Research Centre (BARC), Mumbai took up a project to indigenously design and construct a 2 MV tandem accelerator[3]. It was operated in 1982 to deliver the beam. A similar machine was also constructed at the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam.

Construction of the VEC generated enormous confidence among both accelerator builders as well as industry in the field of accelerator technology. Equally important was the creation of a competent group of experts in this field who could take up still bigger challenges. After intense deliberations involving a large community of scientists at the national level, DAE took a bigger step in the mid-80s to start design and construction, once again indigenously, of a complex of electron storage rings Indus-1 (450 MeV)[4] and Indus-2 (2.5 GeV)[4,5] along with the injectors of various types at the Raja Ramanna Centre for Advanced Technology (RRCAT); formerly Centre for Advanced Technology, at Indore. The motivation in this

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case was to utilize the synchrotron radiation for basic and applied research in condensed matter physics, materials science, biology, etc. Several Indian industries were also involved in the construction of these accelerators. The accelerators at RRCAT are operational and are being utilized by a large number of experimental groups for research. The Centre also developed a variety of smaller accelerators for medical and industrial applications. A microtron accelerator (8 MeV) was built at the Centre[6] and gifted to Mangalore University for radiation physics research in 1995. The facility is still operational with vibrant interdisciplinary research programmes being carried out by groups from several universities and academic institutions.

VEC provided light ion beams with medium energy to the experimentalists during the 1980s. During this period interest was growing internationally in the use of heavy-ion beams for nuclear physics research. The Indian nuclear physicists too had intense discussions and, to remain at the forefront of the field, recommended to procure a state-of-the-art tandem accelerator with about 15 MV terminal potential. It was decided to be set up and operated jointly by BARC and Tata Institute of Fundamental Research (TIFR), Mumbai with funds from DAE. The Pelletron Facility was set up at the Colaba campus of TIFR[7]. Several components of the beam transport system were fabricated in India. The facility has been widely used by experimental groups of the country since its commissioning in 1989 and continues to produce excellent research output.

The University Grants Commission (UGC), New Delhi took a historic decision to set up an advanced accelerator facility, within its own system, that would be available freely to research students and faculty members in the universities. The underlying idea of promoting the accelerator-based research culture in the universities with facilities of their own was very much appreciated. It was decided to install a tandem accelerator, like the one at TIFR, but with higher terminal voltage (16 MV) along with several elaborate experimental facilities. The Inter University Accelerator Centre (IUAC), formerly the Nuclear Science Centre (NSC), housing this accelerator facility[8], has been actively engaged in high-quality research in nuclear physics, materials science, radiation biology, etc. for the past 25 years. This gave a big boost to the efforts aimed at promoting accelerators and accelerator-based research in universities and other academic institutions.

The importance of accelerators and accelerator-based research, mainly nuclear physics at that time, was realized by Meghnad Saha over 75 years ago. As a result of relentless efforts, he managed to get initial funding to set up a small cyclotron[9] at his Institute in Calcutta in 1940. His far sight was remarkable because the cyclotron itself was invented only a few years prior to that in USA by E. O. Lawrence (1938 Nobel Prize winner). Lawrence had significantly helped Saha in his cyclotron project. However, due to turbulent times in those days all over the world, the Calcutta cyclotron could be commissioned only in 1953 with an internal beam of 4 MeV protons. Several components of this cyclotron were fabricated in India. A small cyclotron (5 MeV) was also brought from the University of Rochester, USA and installed at Panjab University, Chandigarh after renovation almost 5 decades ago[10]. It is still in operation for materials analysis and research. Several other small accelerators were developed or installed and utilized for research at BARC, TIFR, IUAC, Indian Institute of Science (IISc), IIT-K, Bose Institute, Banaras Hindu University (BHU), University of Calicut, University of Poona, Andhra University, Aligarh Muslim University, Punjabi University, Institute of Physics (IOP) and some more by dedicated scientists and students. See Divatia and Ambasankaran[2] for more historical details.

Second phase of accelerator development in India

Basic and applied research

Planners of all the major accelerator centres had made provision for the next phase/s of accelerator development in order to provide substantially more advanced facilities to the user community. Implementation of those phases of development has also been completed. In the case of RRCAT, phase-II, i.e. the Indus-2 facility started almost simultaneously with the first phase. VECC took up the construction of the superconducting cyclotron over a decade after the commissioning of the room-temperature cyclotron. BARC/TIFR and IUAC took up the projects of development and construction of superconducting linac booster as post accelerator, virtually, overlapping with the installation of their tandem machines. Some details of these accelerator facilities are given in the following paragraphs.

Indus-2 is a highly advanced storage ring which requires excellent accelerator design and development capabilities of the accelerator system[11]. Its stable operation requires highly precise magnetic field and acceleration system. All other systems also required technologies, driven virtually to cutting edge, for the accelerators to operate reliably so that good experiments may be carried out. It is quite appropriate to mention that Indus-2 is a real quantum jump over Indus-1. The machine has been in operation for experiments for the past three years. Several beam lines are operational for simultaneous use for experiments, while more are being added.

The second phase at VECC is a compact superconducting cyclotron capable of producing heavy-ion beams with energy significantly higher than VEC[12]. The heart of the cyclotron is a 100 tonne superconducting magnet operating with over 5 T field. Cryogenics technology at liquid helium temperature got a big boost in the country by building and operating this magnet. The radiofrequency system too is highly complex and advanced in nature. Internal beam of heavy ions was accelerated to full radius at the end of 2009. Further, intense R&D activities on a Radioactive Ion Beam (RIB) facility led to acquiring technological knowhow on complex, low-β radiofrequency quadruple (RFQ) and IH-type linac accelerating modules[13].

The BARC/TIFR and IUAC Pelletron Facilities decided to develop superconducting linacs as post accelerators to boost the energy of heavy-ion beam[14,15]. Crucial superconducting radiofrequency (SRF) technology was developed in this process for the first time in the country. Knowhow on large-scale cryogenics and related technologies was strengthened further. While TIFR adopted Pb-plated Cu as the superconductor for its linac, IUAC decided to adopt Nb as the superconductor. This played a significant role in developing SRF technology in India utilizing niobium as superconductor. IUAC set up a complete facility for Nb cavity design, fabrication and testing facility in-house[16]. It is important to note that all the SRF-based accelerators in the world use niobium. The 5.5 MV Van de Graaff machine at BARC was successfully converted into a folded tandem accelerator. This facility, called FOlded Tandem Ion Accelerator (FOTIA)[17], is regularly operated for a variety of experiments. Accelerator development activities in India have also been reviewed from time to time by other authors[18,19].

A slight but necessary digression in the discussion: the Institute for Plasma Research (IPR), Gandhinagar developed several advanced technologies in the course of implementing its nuclear fusion-related projects over the past two decades. These technologies are also applicable for the accelerators to a significant extent. They include cryogenics, RF, high vacuum, power supplies, control and instrumentation, etc. Further expansion and advancement of these key technologies is going on in connection with the ambitious ITER-India programme currently under implementation at IPR.

Industrial and healthcare applications

BARC embarked on the design and construction of the formidable front end of a high-power proton linac – the next-generation accelerator. This was a significant step taken by DAE towards development of driver accelerator for an Accelerator Driven (Subcritical) System, generally, referred to as ADS. The ultimate objective is thorium breeding and 'green' nuclear power generation. The front end, LEHIPA – Low Energy High Intensity Proton Accelerator[20], is a complex linac that would accelerate proton beams to 20 MeV energy, but with unusually high intensity, i.e. 30 mA.

Applications of accelerators in the industry have been steadily on the rise during the past few decades in several countries. BARC and RRCAT developed low-energy, high-beam power electron accelerators (irradiators). While BARC developed electron linacs[21], RRCAT has been working on both linacs as well as microtrons[22]. A few irradiators were also procured and installed in the industrial establishments. Applications of these irradiators include quality enhancement by material modification, food and spices preservation, sterilization of medical products, etc. The Society for Applied Microwave Electronics Engineering and Research (SAMEER), which originated at TIFR and is presently operating under the Department of Electronics and Information Technology, Government of India has been working on the development of low-energy electron linacs (<15 MeV) for cancer therapy[23,24]. Such accelerators are of coupled cavity linac-type, but involve complex technologies for their fabrication. VECC is installing a 30 MeV, 500 μA proton cyclotron facility for production of Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) isotopes for powerful medical diagnostics applications using imaging techniques[25]. This facility will also be used for certain unique materials science and ADS-related experiments.

International collaborations

International collaborations on the development of accelerator science and technology also helped us to strengthen our capabilities in several advanced areas. The RRCAT fabricated and delivered, under strict quality control, a large number of superconducting corrector magnets for the Large Hadron Collider (LHC)[26]. VECC is collaborating with TRIUMF, a premier accelerator laboratory in Canada, to develop a 50 MeV, 2 mA superconducting linac for electrons to be used for production of neutron-rich RIBs by photo-fission route[27]. IUAC and RRCAT are working jointly with Fermilab, USA on the development of SRF cavities and resonators suitable for high-power proton accelerators[28]. VECC and BARC are also part of this collaboration for large-scale cryogenics and instrumentation development. India will contribute to the construction of the Facility for Antiproton and Ion Research (FAIR) in Germany. The contributions include large superconducting magnets[29], power converters, beam stoppers, vacuum chambers and sophisticated detectors for experiments. The coordinating agency is Indo-FAIR Coordination Centre (IFCC) at the Bose Institute, Kolkata, with VECC playing important technological role.

Accelerators at academic institutions

In the recent years several universities and academic institutions are either installing or actively considering installation of small accelerators in their departments to revive or initiate the culture of accelerator-based research. These include IIT-Kanpur, Kurukshetra University, University of Allahabad, University of Mumbai, Guru Ghasidas Vishwavidalaya (Bilaspur), Panjab University and BHU. The stress is on multidisciplinary research and materials analysis. An Accelerator Mass Spectroscopy (AMS) facility, supported by the Ministry of Earth Sciences, will be operational soon at IUAC[30].

To summarize, India has developed substantial capability in terms of technology and expertise in the field of accelerators over the past 5 decades. The expertise is available on several types of accelerators, both circular as well as linear. We have a small core of experts on accelerator as well as accelerator systems design, fabrication, assembly, testing, installation, integration and commissioning. The accelerator systems include a variety of magnets, RF systems, power supplies, vacuum systems, ion sources, beam diagnostics, controls and instrumentation, advanced technical services, cryogenics, radiological shielding, etc. Moreover, execution of several large projects has also resulted in the generation of construction and management expertise. Indian industry has also contributed to the development of the field in the country to an extent, but much more could be and needs to be done. The present worth of the accelerator installations constructed for R&D as well as applications would run into several thousand crores of rupees.

Future plans and outlook

So far, the major motivation for the development of accelerator facilities in our country has been basic research, although some efforts have gone hand in hand for applications as well. It will continue to be the same in the future too, but now some important motivations have arisen on the applications side. One of them is the ADS, where the high-beam power accelerators will play a key role for fuel breeding and waste incineration. In this role they fit quite well in India's three-stage nuclear power programme. However, accelerator technologies have to be driven to real cutting edge in order to meet the critical requirement of precision and reliability during operation. There would be a number of stages of this development before commercial operations begin. At each stage of the development, however, the accelerators would be utilized for fruitful research and applications. The full-scale ADS driver accelerator needed is of relatively higher energy, say ~1 GeV. On the other hand, much smaller but operationally fully streamlined accelerators are playing a crucial role in the industry for producing a large number of value-added products such as electronic components, biocompatible materials, polymers, disposable medical products, sterilized food products, etc. Small accelerators are also being increasingly employed for precise materials testing, inspection and mechanical fabrication. Further, accelerators, primarily cyclotrons, are being extensively used for producing radioisotopes for powerful medical diagnostics for dreaded diseases like cancer. Accelerator-based techniques such as Rutherford Back Scattering (RBS), Proton Induced X-ray Emission (PIXE), Activation Analysis, Elastic Recoil Detection Analysis (ERDA), Nuclear Reaction Analysis (NRA), Accelerator Mass Spectrometry (AMS), etc. are highly accurate and sensitive for materials analysis. A large number of accelerators are being employed for this purpose in research and industry. The world market of accelerator-based products in the industry has been estimated to be US$ 500 billion annually[31,32]. Large proton/hadron accelerators, usually cyclotrons or synchrotrons, have proved to be invaluable tools for cancer treatment, particularly for tumours located in the sensitive parts of the body. There are close to 50 such therapy facilities already operational or in the planning stage in the world. At present, there is no such facility operational, in India, but a few are likely to come up in the near future. Several hospitals are using modern electron accelerators for cancer therapy, but they are mostly imported. These accelerators are excellent substitutes for radioisotope-based facilities.

Development and planning for advanced or new accelerator facilities for research has been going on for the past several years at various institutions in the country. While this 'phenomenon' is more natural at the established accelerator centres, an interest in starting accelerator-based research is growing in several teaching institutions. Additionally, substantial increase in participation in the collaborative research programmes, in an organized manner, at large international accelerator facilities such as CERN, Fermilab, BNL, GANIL, KEK, RIKEN, Spring8, etc. has generated strong user groups in the country – many of them also in the universities and other academic institutions. These user groups are advocating the setting up of large accelerator facilities in India. As a result, several well-formulated project proposals are now under active consideration of various government funding authorities. Some of them are briefly described in the next section.

Emerging accelerator programmes in India

While the DAE institutions have been more active, several academic institutions are also taking initiatives on advanced accelerators. Some major emerging activities are briefly described below, where, in some cases, the cost of a single project may run into several thousands of crores of rupees:

1. RRCAT: A spallation neutron source facility is proposed to be eventually constructed at this Centre. The accelerator would be a superconducting linac to accelerate protons to over 1 GeV energy. It will be a pulsed machine but with high average beam power (~1 MW). In the next five years or so, the related R&D activities

would be carried out primarily on the superconducting RF cavities and related instrumentation. Large-scale production of such cavities with high yield will have to be ensured for cost optimization. Construction of the accelerator would be taken up in the next phase, which is projected to start possibly in the 13th Plan. The facility may take three Plan periods for completion and has been named as the Indian Spallation Neutron Source (ISNS)[33,34]. The other major activities at this Centre include development of free electron laser (FEL) facility, upgradation of the Indus accelerators, accelerator-based irradiation facilities, etc.[34].

2. VECC: An advanced Rare Ion Beam (RIB) facility is proposed to be constructed over the next three Plan periods in a phased manner. In the first phase, the accelerators will be constructed to produce RIBs, up to about 10 MeV per nucleon energy, for nuclear physics and allied research. In this phase the accelerators involved would be RFQ and linacs. Both neutron-rich as well as neutron-deficient RIBs would be accelerated for experiments. Initially, the ISotope On-Line (ISOL) method is planned to be used for RIB generation. In the subsequent phase of the project, the RIB energy would be boosted to over 100 MeV per nucleon using a superconducting separated sector cyclotron. The RIBs will then also be produced by fragmentation method. A small storage ring may also be added to the accelerator complex. This facility has been named as Advanced National facility for Unstable and Rare Isotope Beams (ANURIB)[35].

3. BARC: The ADS driver accelerator, a high-power superconducting linac, and associated systems would be developed[36]. In the first phase, the accelerator segment delivering 200–300 MeV beam energy with several mA beam current has been planned. Technologically, there is a significant overlap with the RRCAT accelerator programme for the spallation neutron source. The Centre also has a strong programme for developing a variety of electron linacs with final energy ranging from several to few tens of MeV[37]. The electron beam would be used for a variety of applications and for production of neutrons for specific experiments.

4. TMC: A proton/hadron therapy facility for cancer therapy is planned to be set up at the Tata Memorial Centre, Mumbai. The main accelerator would be either a cyclotron or a synchrotron.

5. IUAC: Phase-wise development and construction of photon sources to produce terahertz, infrared and X-ray radiation has been initiated at this Centre. Advanced accelerator systems such as FEL, laser-driven photocathodes, sophisticated undulator magnets, etc. are involved in this programme[38].

6. IISc and SINP: Intense discussions and planning activities to install third generation or better synchrotron radiation sources have been going on at these institutes. Electron storage rings between 3 and 6 GeV energy are being debated over by the user community.

Discussion

It is quite evident that India has made substantial progress in the field of modern accelerators during the past four decades – both on the expertise and manpower as well as technology fronts. It is primarily on the basis of this strength that initiatives have been taken for constructing large and challenging facilities described above. If the planning is thoughtfully done, some next-generation accelerators can be made operational in the next 5–10 years in the country. India would then become a powerful hub of accelerator-based research in the subcontinent. In order to achieve this, however, a lot more needs to be done on the manpower and technological fronts to further strengthen the indigenous capabilities. This is imperative for the country's progress, given the highly beneficial potential of accelerators in industry and healthcare, apart from the requirements of basic research. These aspects will be further elaborated later in the text.

Accelerator development

The Indian accelerator teams now have the design capability for different types of accelerators. At present they are mostly using the codes developed elsewhere through some international collaboration or commercial codes for the simulations. This is done to eliminate or minimize the possibility of serious lapses in the design, installation and operational stages, particularly when the accelerator complex involves several machines in tandem to achieve the ultimate performance. It is most desirable to develop our own codes to get deeper insight of the particle acceleration and beam handling processes which are getting more and more complex for the new generation of accelerators. This applies both to the accelerator design as well as accelerator systems design. Optimum design also leads to huge cost savings.

The field of accelerators would have made substantially more progress had the country's industry been more actively involved in the design, development and construction of the machines. Moreover, implementation of the projects would have been faster. The requirements of extreme precision and quality control in the core systems demand, apart from expertise, the flexibility to utilize high-quality components at each stage. The industry is possibly better equipped to implement this criterion. As we now embark on constructing very large accelerators, the involvement of the hi-tech industry is all the more necessary in the entire process at each stage. This would also automatically ensure beneficial utilization of the technological fallouts. Advances in the technologies related to magnets, microwave, RF, vacuum, power supplies, cryogenics, etc. have particularly benefitted the society in many ways.

Industry and healthcare

According to a recent survey, almost 35,000 big and small accelerators have been built all over the world during the past 6 decades. Of these, about 11,000 are used directly for cancer treatment while majority of the rest is used is industry, barring a small fraction (<3%) only for basic research. The value of the industrial products employing accelerators for production, in some way or the other, may soon reach a trillion dollars annually. The industrial accelerators may either accelerate ions or electrons, but in a few cases may be used to produce secondary radiations for utilization. The ion accelerators are generally used as implanters to produce semiconductor devices, display screens, solar cells, biocompatible devices, etc. Presently, this accounts for about 60% of the accelerator-based industrial products market. The electron accelerators are used as irradiators for applications such as product sterilization, food preservation, material modification, precision mechanical fabrication, metallurgical processes, cargo inspection, etc. The other general applications of industrial accelerators include radioisotope production for medical diagnostics and therapy, highly precise analysis of materials, fault detection in fabrication, industrial water purification, etc. In India, over 15 small cyclotrons, all imported, are operational at various establishments for the production of radiopharmaceuticals, mainly, ^{18}F-based fluorodeoxyglucose (FDG) for cancer diagnostics. Many more such facilities are coming up in view of the superb efficacy of the PET-CT technique for imaging. In order to operate these facilities efficiently and with mandatory radiation safety protocols, trained accelerator manpower is required. The hadron therapy facilities mentioned above will require much bigger accelerator complexes.

It would be quite appropriate to state that accelerators can contribute substantially to a country's economy. They are playing an important role in enhancing the quality of our lives and have the potential for further improvement. China has over a thousand accelerators, may be more, operating in several spheres of industry and healthcare.

Involvement of industry in accelerator construction

With enhanced participation of the industry in accelerator development and construction, the R&D institutions can concentrate more on the advanced and critical aspects of the field. Eventually, the specialized industry should be able to design and build industrial accelerators or smaller accelerators for the academic institutions utilizing their own expertise and intellectual resources. In several countries the accelerator experts working in the research laboratories are allowed to interact with the industry and help them develop the capabilities. So, there is an undeniable need for availability of skilled accelerator manpower in the industry.

India has a large number of scientists who carry out accelerator-based research at facilities in the country and abroad. They are located in various R&D as well as academic institutions. Their number is steadily growing with several accelerator facilities coming up or being planned. However, in order to exploit the potential of the accelerators in the industry, efforts on applied research need to be stepped up. Persistent efforts would be required by some researchers to develop processes and techniques which would be economically viable for production or processing on an industrial scale. For example, in the production of semiconductor devices using ion implantation technique, one requires to have precise control of depth and dose, appropriate masking material and configuration, uniformity of dose, temperature control, defect annealing procedure, etc. The parameters vary for different kinds of semiconductor devices. Similarly, appropriate parameterization is required to achieve a particular objective of material modification while utilizing an electron irradiator. A huge data bank on the reactions taking place during the irradiation process or during interaction of energetic particles with the target material is available. This information would be useful for developing the production processes. Considerable scientific expertise is also required for mandatory characterization and quality control.

Manpower for accelerator programmes

It is evident that the manpower for accelerators and accelerator-based applied research needs to be considerably strengthened in our country. The accelerator expertise is mostly acquired while implementing the R&D or construction projects. Virtually, no academic institution in India imparts formal training and education in these multidisciplinary areas. Even if it is done, it would be difficult to find students for such courses for the want of a good job market. It is for the same reason that the students, barring some rare exceptions, are not interested in carrying out doctoral research in these areas. However, regular scientists of the established accelerator centres are increasingly doing Ph D on accelerator science and technology topics. It would no doubt be quite advantageous if fresh graduates or postgraduates become available with some level of formal accelerator education. Accelerator-related industry should be particularly interested in employing them. To start with, the universities and engineering institutes that have small accelerator facilities operating in their departments or planning to install some may be asked to run regular accelerator courses.

Organizing accelerator schools or workshops at regular intervals on various topics would also be essential. It can easily be done, but the experts from established accelerator centres should be able to spare some time for these specialized training programmes. Needless to say that the experts would also be academically benefited by imparting such training and interacting with the students. Participation from the industry related to accelerator and accelerator-based R&D activities should be particularly encouraged in such programmes.

As we now embark upon implementing large and complex accelerator projects, the science and technology of these machines need to be mastered at a much advanced level. In several cases we need to resort to innovations to incorporate indigenously developed systems and products. This obviously calls for laying considerable emphasis on dedicated, accelerator-related R&D in the country. It is also desirable to involve scientists and engineers from the industry in the development of certain complex and crucial systems, so that they may take up the actual fabrication with much deeper insight. The number of students carrying out advanced research in the accelerator-related topics needs to undergo a quantum jump in order to achieve the targets in a reasonable time-frame. This will also strengthen our design capabilities and facilitate development of reliable and cost-effective accelerators for industry and healthcare. Joint Ph D programmes between accelerator centres and academic institutions would be highly beneficial in achieving the goals. As an intellectual investment for the future, we need to attract students to take up research on advanced accelerator concepts such as laser and plasma wakefield acceleration, beam-driven acceleration, muon collider related acceleration, etc.[39]. The scientific and technological challenges in these areas are immense, but the fallout would be highly beneficial in future.

Conclusion

In order to gainfully implement the ambitious but well-conceived accelerator programme in India and to take advantage of accelerators in industrial development and healthcare, the related R&D and manpower generation need to undergo a quantum jump. It is highly desirable to introduce the culture of imparting formal education and research in accelerator science and technology in the academic institutions. They should be encouraged to install and operate small accelerator facilities for basic and applied research. These institutions would then be in a position to play a much larger role in both national and international accelerator projects. Joint programmes on accelerator R&D between accelerator laboratories and the teaching institutions should be set up. It is expected that advanced research related to science and technology of new acceleration concepts will attract good research students to the field. Participation of industry, right from the design and R&D stages of large accelerator projects, would be highly beneficial to reduce costs and save time. This would also ensure reaping the benefits of technological fallout for several spheres of science, technology, industry and healthcare in the country.

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