

India's potential to develop particle accelerators for societal, industrial and environmental applications

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During the past over 50 years, India has been constructing and setting up several particle accelerator facilities for scientists to carry out frontline basic and applied research. Significant amount of investment has been made and the trend, fortunately, continues. Our scientists and technologists have acquired excellent expertise to design and build challenging accelerators and related systems. The expertise is now being utilized to carry out R&D on particle accelerators for accelerator-driven systems for nuclear power-related applications. In this article, a strong case has been made to intensify as well as diversify our efforts to develop small accelerators and systems for societal, industrial and environmental applications. Justifications for the availability of expertise and the strong need for the proposed developments in the country have also been provided.

Keywords: Ion implantation, isotope production, particle accelerators, physics research, wastewater treatment.

It is almost 50 years since India began construction of large and modern accelerators, primarily for basic and applied research¹. The first large accelerator to be constructed was the 224 cm variable energy cyclotron (VEC) at Calcutta (now Kolkata) during 1970–77. Subsequently, the construction of large electron storage rings, Indus-1 and Indus-2, and their injector synchrotron at Indore gave a big push to accelerator technology in the country. Our accelerators were dominated by room-temperature magnet technology until that time. Setting up of modern pelletron accelerator facilities at Mumbai and Delhi, and construction of superconducting linacs as post accelerators introduced new technologies, namely very high voltage and superconducting radiofrequency (SRF) in our accelerator programmes. Thus, four major accelerators centres evolved in the country by the end of 1980s. These are the Variable Energy Cyclotron Centre (VECC), Kolkata, Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, Inter-University Accelerator Centre (IUAC), New Delhi and BARC–TIFR Pelletron Facility (at TIFR), Mumbai. In the meantime, development of small electron accelerators utilizing high voltage as well as room temperature radiofrequency (RF) technologies was under way at the Bhabha Atomic Research Centre (BARC), Mumbai and the Society for Applied Microwave Electronics Engineering and Research (SAMEER), Mumbai for application purposes.

Further advancements in accelerators in the country continued with the construction of the K500 superconducting cyclotron at VECC and low energy high intensity proton accelerator (LEHIPA) at BARC in the late 1990s and early 2000s (ref. 1). Moreover, activities related to the setting up of a radioactive ion beam (RIB) facility at VECC also added to our knowhow for advanced accelerators during that period. The 5.5 MV Van de Graaff accelerator at BARC was converted into a folded tandem machine resulting in creation of the Folded Tandem Ion Accelerator (FOTIA) facility.

More recently, the focus has shifted to the development of further advanced precision and 'futuristic' technologies. All the major accelerator centres are engaged in developing SRF technology in the country² for building high current proton linac that would be used as a spallation neutron source (ISNS)³ for basic and applied research, and as driver accelerator for the accelerator-driven subcritical system (ADS)⁴. Project proposals for such accelerator-based facilities are evolving at RRCAT and BARC, and some R&D activities are in progress. VECC is constructing a superconducting linac for high-power (~100 kW) electron beam to produce RIBs through photo-fission route for its advanced facility – advanced national facility for unstable and rare isotope beams (ANURIB)⁵, under development for basic research.

Collaborations with international accelerator laboratories such as Fermilab (USA), TRIUMF (Canada), GSI Darmstadt (Germany), RIKEN (Japan), KEK (Japan), etc. are proving to be highly fruitful. Significant amount of knowhow regarding SRF and related cryogenics,

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superconducting magnets, solid-state RF, high-power beam targets, beam diagnostics and specialized accelerator systems, in general, has been generated by our scientists and engineers. More recently, development of highly precise and complex free electron laser (FEL) systems to produce terahertz (THz) and infrared radiation (IR) is in progress at RRCAT⁶ and IUAC⁷. These will be used for frontline contemporary scientific research in several areas.

Several types of electron accelerator systems have been developed for applications at BARC⁸, RRCAT⁹ and SAMEER¹⁰. The planned applications include food irradiation, sterilization of products, cargo scanning, cancer therapy, etc. However, over 200 electron accelerators operating in different hospitals and institutions for cancer treatment are all imported systems. A number of cyclotron-based medical facilities have been set-up or are coming up in the country in both public as well as private sectors. They include a 30 MeV proton cyclotron for medical isotope production as well as R&D studies at VECC¹¹, several smaller cyclotrons in different cities to produce fluorine-18 for cancer diagnosis using positron emission tomography (PET), and 230 MeV proton cyclotrons for cancer therapy at Apollo Hospital, Chennai and Tata Memorial Centre (TMC), Mumbai. All these cyclotron systems are imported.

Thus, the field of accelerators in India has taken deep roots. Substantial expertise – scientific, engineering and technological – has been generated in diverse areas related to this field. As mentioned above, the emphasis, however, has been on their utilization, primarily, for research. The present-day value of investment in the existing accelerator facilities would easily reach about Rs 5000 crores. Further, the cost of the facilities that are being planned would be much bigger. This does not include, however, accelerators that are being used or installed for medical diagnostics or therapy.

To summarize, substantial investment – technological, financial and human resources – has been made over the past five decades to set-up accelerator facilities for research in the country. Impressive expertise has been generated in a variety of fields related to accelerator science and technology. However, little attention has been paid to utilize this expertise and the acquired know-how for societal applications and industrial development. To be more explicit, the accelerators are being utilized on a large scale the world over for cancer treatment, diagnosis of deadly diseases, food preservation, product sterilization, product quality enhancement, industrial processes, production of electronic components, safety and security, highly precise analysis, etc.¹². They are also emerging as effective machines/devices for environmental cleaning – water as well as air. The above-mentioned applications have evolved over a long period of time by the efforts of dedicated scientists, technologists and engineers at various research laboratories as well as in the industry. We

too have the potential to achieve that in India now. We can begin with only in some key priority areas. Incidentally, majority of the accelerator-based set-ups for the applications mentioned above are not expensive. It is important to keep in mind that along with the accelerators, suitable for a particular application, other equipment/systems for eventual utilization also have to be developed. For example, to produce radiopharmaceuticals for medical diagnostics, the appropriate target irradiated with cyclotron beam needs to be transported quickly to the hot cells. Here, automatic process control modules operate sequentially to produce and separate the compound or radiopharmaceutical that can be safely injected into the patient's body.

Accelerator expertise at various laboratories in the country

In a later section, some specific accelerator applications that India should seriously consider to develop through well-coordinated efforts will be discussed. Prior to that, let us have a look at the special expertise and knowhow that our accelerator centres have developed. The information given here may not be complete but is relevant to the specific suggestions. Names of the accelerator centres, where the expertise and infrastructure for design, construction and operation exists, are given in brackets.

- Low- and medium-energy ion accelerators, e.g. cyclotrons, linacs, radiofrequency quadrupoles (RFQ), high voltage/electrostatic accelerators (VECC, IUAC, BARC, TIFR).
- Low- and high-energy electron accelerators, e.g. synchrotrons, linacs, microtrons (RRCAT, BARC, SAMEER).
- Large and precision electromagnets (weighing tens of tonnes) and their highly stable power supplies (RRCAT, VECC, BARC, IUAC).
- High-power RF systems for ion accelerators and related instrumentation (VECC, BARC, SAMEER, IUAC).
- High-power RF systems for electron accelerators and related instrumentation (RRCAT, BARC, SAMEER).
- High-power microwave systems for pulsed and continuous mode operation (RRCAT, SAMEER).
- Precision high-voltage power supplies (VECC, RRCAT, BARC, IUAC, TIFR, SAMEER).
- High and ultrahigh vacuum systems with large volumes (RRCAT, VECC, BARC, IUAC, TIFR).
- Beam transport and transfer systems, and related components such as focusing magnets, beam steerers, beam scanners, beam diagnostics, etc. (RRCAT, VECC, IUAC, BARC, TIFR).
- Ion sources for high charge state and intense ion beam production (VECC, IUAC, BARC, RRCAT).

- Electron guns for intense beam production (RRCAT, BARC, SAMEER, VECC).
- Superconducting magnets for accelerators, associated power supplies and quench detection systems (VECC, RRCAT).
- Superconducting RF components: cavities, resonators, etc. (RRCAT, IUAC, VECC, TIFR).
- Large-scale cryogenic systems for liquid helium (4K, 2K) and liquid nitrogen temperatures, including cryostats, transfer lines and instrumentation (VECC, RRCAT, BARC, IUAC, TIFR).
- Computer control systems for accelerators and beam instrumentation (RRCAT, VECC, BARC, IUAC, TIFR, SAMEER).
- Radiation shielding design and materials for intense ion and electron beams (VECC, RRCAT, BARC).
- Safety issues related to high power accelerator installations (Atomic Energy Regulatory Board and major accelerator centres in the country).

The scientists and engineers at various accelerator centres in the country have done enormous amount of R&D on each system/component/device/technique mentioned above. Very large number of references are available in international journals and conference proceedings. Major reporting on the work done appears in the proceedings of the Indian Particle Accelerator Conferences (InPAC series). The Institute for Plasma Research (IPR), Gandhinagar has also developed advanced expertise on many of the technologies mentioned above. They have seemingly better interface with the industry for R&D.

Some important applications of particle accelerators in the Indian context

It is thus obvious that Indian accelerator centres already have excellent expertise and infrastructure to develop accelerator-based systems for crucial applications. As mentioned earlier, such applications are wide-ranging and numerous¹²⁻¹⁴. SAMEER has made impressive developments on electron accelerators and associated equipment for cancer therapy using photons¹⁰. Moreover, BARC⁸ and RRCAT⁹ have developed electron accelerator systems for irradiation of food products for enhanced shelf life and for quality enhancement of industrial products apart from product sterilization. The commercialization of these systems needs substantially more efforts. Looking at the global trends and the need in the Indian context, accelerator systems for the following applications require immediate attention: (i) Production of short-lived radioisotopes for inexpensive diagnosis of serious diseases and disorders such as cancer. (ii) Ion implantation for digital electronics components/devices production with good control and precision. (iii) Environmental cleaning: specifically, industrial and municipal wastewater as well sludge and flue gas.

The first two applications require ion beams with up to a few megaelectron volts (MeV) energy, but with high intensity. The third one requires low-energy (1–10 MeV), electrons with rather high-power beams – several hundreds of kilowatts. The following subsections give details of each of these applications.

Production of short-lived radioisotopes

Injectable radiopharmaceuticals labelled with certain short-lived radioisotopes, produced using accelerators, facilitate powerful diagnostics for several disorders and diseases in the human body. Cyclotrons delivering ~10–30 MeV proton beams have evolved as the most suitable accelerators for this purpose¹⁵. Almost 1000 cyclotrons are operating all over the world as dedicated machines for radioisotope production. More than half of such cyclotrons deliver ~10–20 MeV energy and about 75% of them are used for the production of the radioisotope fluorine-18 for cancer diagnostics. It has a half-life of 109.8 min. About 20 cyclotrons are operational or being installed in India solely for this purpose. Virtually all these centres produce the fluorodeoxyglucose (FDG) molecule labelled with fluorine-18. This radiopharmaceutical is injected into the patient's body for scanning with a PET camera. The scans help medical specialists to accurately diagnose the cancerous parts and, additionally, provide important metabolic information. Cyclotrons delivering relatively higher energy beams, say ~30 MeV or more, are utilized to produce other useful radioisotopes such as gallium-67, indium-111, iodine-123, thallium-201, etc. They are relatively longer-lived, few tens of hours, and are also useful for medical diagnostics. There are no accelerators to produce them in India, and so they are routinely imported from abroad by our hospitals at high costs.

The demand for cancer diagnostics using fluorine-18 via PET scans is rapidly growing in the country. The rise has been, in fact, exponential during the past decade or so. In order to make such scans more affordable for the people, it is important to design, develop and manufacture the FDG production systems in the country itself. A 10–20 MeV proton cyclotron is the central part of such a system. Developing such an accelerator is well within the capability of the experts in India – particularly, complete expertise exists at VECC with decades of experience in the construction and operation of cyclotrons. Further, expertise on the design and fabrication of high-beam current target systems also exists at this Centre. As mentioned earlier, the irradiated target needs to be transported quickly to the hot cell where necessary chemical processes are carried out in radiation-shielded environment to extract the radioisotope (fluorine-18) from the target and produce FDG. The unused target material, usually isotopically enriched and expensive, is recovered for reuse to save production costs. All the steps and

processes, subsequent to the irradiation of the target, need to be fully automatic. They all take place in the hot cells. The necessary equipment, including the chemistry modules, require careful development for reliability and patient safety reasons. This expertise is available at BARC and Board of Radiation and Isotope Technology (BRIT), Mumbai. Such availability will be further strengthened once the 30 MeV medical cyclotron facility, recently commissioned at VECC, starts regular production of radiopharmaceuticals¹⁶.

Thus, by constituting an appropriate team of experts, cyclotron-based facility for FDG production can be developed in a short period at a low cost. Commercial production of such facilities will then be required to make cancer diagnosis, particularly the PET-oriented, affordable and accessible to large population. The affordability will further increase if PET cameras are also designed and manufactured in the country. Specially positioned array of gamma detectors is the central part of this camera. This knowhow also exists abundantly in India where we have a strong community of nuclear physicists and radiochemists who routinely use the gamma detectors, the scintillation crystals with associated electronics, in their experiments. The other parts of the camera are conventional.

Ion implantation for digital electronics components/devices production

Low-energy ions produced by accelerators are used to dope the semiconductor material for precise and large-scale production of integrated circuits (ICs). This method of production is much superior to the conventional diffusion methods because it is efficient, precisely controlled and less polluting. This is the most important and largest industrial application of accelerators. These ICs, employing CMOS, MOSFET, etc. are used extensively in the production of computers, communication equipment, display screens and other digital devices. The world market of semiconductors produced using accelerators is estimated to be several lakh crores of rupees, annually¹³. There are a large number of manufacturers of accelerator-based systems, called ion implanters, for this purpose in the international market. There were an estimated of about 10,000 ion implanters as estimated in 2012, with a projected increase of 250–400 every year. India has few such units that have been purchased from international suppliers¹⁷. However, in view of the increased emphasis on manufacturing the computational and communication devices in the country, large-scale indigenous production of ICs for this purpose is foreseen in not so far a future. A large number of ion implanters would be required. Depending on the application, the accelerators should be able to deliver heavy ions with energy ranging from a few hundreds of kiloelectron volts to ~10 MeV. The beam current requirements are moderate.

IUAC has excellent expertise to design, develop and operate such accelerators. The R&D centres like, IGCAR, Kalpakkam, TIFR and VECC too have the relevant accelerator expertise. Further, Kurukshetra University¹⁸, Allahabad University¹⁹ and Guru Ghasidas Vishwavidyalaya²⁰, Bilaspur have set-up small but modern accelerator facilities to produce low-energy beams for ion implantation and other scientific experiments. However, for the commercial production of ICs, one requires to develop sophisticated equipment, infrastructure and knowhow in other relevant areas apart from the accelerators²¹. These areas involve expertise on beam manipulation, masking techniques to generate the desired concentration profile of the dopants, simulation of the dopant ions' interaction with the substrate (e.g. silicon), wafer holders and their movement mechanisms, dosimetry, characterization of the doped layers, etc. Such expertise is also available at various laboratories and institutions. The objectives of developing commercially viable ion implanter systems can be conveniently achieved as the required technological 'ingredients' are all available in India. Such systems, if produced in the country, would be less expensive and easily maintainable.

Environmental cleaning: treatment of conventional waste

Here, by conventional waste we mean wastewater as well as sludge from industries and municipalities, and flue gases emanating from sources such as thermal power plants, waste incinerators, etc. Several groups in the world have successfully demonstrated the effectiveness of electron beams for treating conventional waste before disposal and/or reuse^{22–27}. There are industrial establishments in several countries that are commercially utilizing this technique in full-scale plants. The electron beam when incident on water produces highly reactive radicals. These radicals are short-lived but they efficiently drive the oxidation and reducing reactions²⁸. Thus, highly complex molecules present in the 'waste' are 'destroyed' and the simpler by-products are easily removed by non-polluting techniques. These radicals also convert into sharply reacting chemicals that destroy the DNA and, eventually, the cells of harmful bacteria, viruses and parasites present in the waste. Moreover, cell destruction also occurs when the radiation interacts directly with the DNA molecules²². Both processes lead to disinfection of the waste for safe handling and utilization. Textile and pharmaceutical industries consume large quantities of water during operation. The wastewater is highly polluted with complex chemicals and has strong odour. The municipal wastewater, additionally, has harmful organisms. Electron beams simultaneously remove chemicals, odours and organisms^{22,24}. Polluted sludge from municipalities and industries such as metal processing, cosmetics, personal care, etc. is similarly treated using electron

beams before safe disposal²⁶. In the case of flue gases, the hazardous chemicals are mostly oxides of sulphur and nitrogen. Reactive radicals produced by electron beams in the presence of water and ammonia convert these harmful oxides into useful fertilizers, namely nitrates and sulphates of ammonia²⁹.

It is clear that the volumes of waste under discussion are extremely large^{30,31}. Experts have estimated that if the operation of an industrial plant has to be made commercially viable, the electron beam power should be in the range 0.8–1 MW. The beam energy ranges from ~1 to 10 MeV depending on the application²⁶. This is the case if only electron beams are used for complete treatment, and no chemical and biological treatments are involved. This would be the most desirable case. However, presently, the maximum electron beam power available is <0.5 MW. In such a case, the treatment is first done with electron beams followed by chemical treatment. It is still advantageous because the required quantity of chemicals reduces by a factor of more than two and so does the undesirable chemical pollution²⁴. Flue gas treatment, however, requires lesser electron beam power for treatment²⁹.

Although waste treatment using electron beams is clean and effective, it has to compete well with the incumbent conventional methods that use large quantities of chemicals and bio-products. In order to achieve economically the required beam power levels, accelerator experts are working on newer technologies²⁶. This includes the use of SRF cavities for acceleration. Further, interesting challenges include the powerful electron gun, space charge-dominated beam dynamics, convenient radiation shielding solutions, etc. Moreover, it should be possible to operate the plant in relatively remote places as well. Incidentally, in India, the major waste-generating sources are close to the metros or big cities^{30,31}. Electron beam production efficiency of ~80%, vis-à-vis the electrical power, is achievable²⁶. This is a big advantage over the conventional treatment methods.

As mentioned earlier, electron accelerator development is fairly well advanced in India. BARC, RRCAT and SAMEER have designed and constructed electron accelerators that are capable of delivering several tens of kilowatts of beam power for industrial applications. R&D projects are ongoing at those centres to further increase the beam power using conventional technologies. At the same time, highly advanced expertise is available at BARC, RRCAT, VECC, IUAC and TIFR to fabricate and operate SRF cavities usable for electron beam acceleration. Mention has already been made earlier about a 100 kW beam power superconducting electron accelerator under construction at VECC. In short, with the expertise that already exists in the country, high beam power electron accelerators can be developed in not too long a time for environmental cleaning purposes. This is true for the accelerators employing conventional as well as SRF technologies.

Handling such a high beam power is not a trivial problem. However, by extrapolating the expertise already available at BARC, RRCAT, VECC and some other national laboratories, it should be possible to design appropriate systems. Handling large amount of waste (solid, liquid or gas) is another challenge. Good amount of expertise has been developed while the Department of Atomic Energy set-up radiation treatment plants at Vadodara and Ahmedabad³². An industrial level treatment plant (~10,000 m³/day) based on the electron accelerator would consume 1–2 MW of electrical power³³. This may be a problem at relatively remote places. A possible solution could be to operate with a captive solar power plant. However, for municipal waste and flue gas treatment, the required power levels should be lower. Nevertheless, development and large-scale use of electron beam treatment of conventional waste is a must for our country due to the enormity of the problem. Utilizing the expertise already available and with well-coordinated efforts, this is eminently achievable. Incidentally, the cost of such a set-up would not be too high and the investment should quickly pay-off.

Conclusion

India has invested significant amount of resources for the development and construction of particle accelerators over the past five decades. The motivation has mainly been to carry out frontline basic and applied research by our scientists. The purpose has been and is being served extremely well. In the process, however, highly advanced and precision technologies have been developed in several specialized areas. The available knowhow in the country has now crossed the threshold where it is conveniently possible to develop small accelerator-based systems that will be of immense use in social, industrial and environmental domains. Cyclotrons along with the associated radiochemistry systems for the production of radiopharmaceuticals for medical diagnostics are presently being imported. In view of the sharply rising demand, e.g. of fluorine-18 for powerful diagnosis of cancer, it would be worthwhile to develop and produce them in the country. We should also manufacture ion implanter systems for large-scale and efficient production of ICs employing semiconductor systems. This would be an important step forward for reducing our dependence on the import of computational and communication devices. They are crucial for the quick implementation of digital revolution to benefit the common person in the country. Environmental cleaning (water and air) using accelerated electron beams may look a bit futuristic. Several advanced countries do not think so. With the serious pollution problems that India is facing, development of some innovative systems may become more urgent. Electron accelerator-based systems powered by captive solar plants or windmill system

would be able to operate even in remote areas. We should intensify our efforts to reap the benefits that small particle accelerators offer for national development. Formation of an autonomous accelerator corporation would facilitate the much-needed involvement of industry in this field.

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