Published Online: 10 July 2018

Proc Indian Natn Sci Acad **89** No. 1 March 2019 pp. 3-11

DOI: 10.16943/ptinsa/2018/49412

Review Article

Accelerators for Science and Society

S KAILAS and R CHIDAMBARAM
Bhabha Atomic Research Centre, Mumbai 400 085, India

(Received on 04 April 2018; Revised on 10 May 2018; Accepted on 17 May 2018)

The charged particle accelerators were originally developed for pursuing research in frontier areas of physics. They are now being used not only for basic research in science, but also in a variety of applications of great relevance to the society. The charged particle accelerators are employed in health care, industry, agriculture, national security, environment, archaeology and cultural heritage related programmes. An overview of the charged particle accelerators, the ion and the electron types, the national and international scenario and the application potential of these accelerators in various programmes is provided in this article.

Keywords: **Charged Particle Accelerators; Linear Accelerator; Cyclotron; Pelletron; Synchrotron; Superconductivity**

Introduction

The accelerator related activity got started in India (Divatia and Ambasankaran, 1985) very soon after the first accelerators were commissioned in the west more than 80 years back. Prof. Meghnad Saha took a keen interest to build an accelerator in Kolkata in the early 40's. The first major accelerator for research was a 1 MV cascade generator, which was commissioned at TIFR in the early 50's. In the 60's and 70's, a number of accelerators were installed at BARC, IIT Kanpur and other universities like Panjab university, Aligarh Muslim University, Banaras Hindu University and Andhra university (Divatia and Ambasankaran, 1985; Chidambaram and Kailas, 1995; Kapoor 1998; Mehta 2002; Bhandari and Roy, 2015; Lalremruata *et al*., 2017). The indigenous development of a major accelerator in India was the variable energy cyclotron at Kolkata in the late 70's (VECC, 2018). This was a great achievement and this accelerator, after refurbishment, is working very well even today. Next important step was the commissioning of two pelletrons at Mumbai (located at the Tata Institute of Fundamental Research (TIFR)) and Delhi, to which and mainly through indigenous efforts, super-conducting Linear Accelerators (LINAC) have been added (BARC, 2018; TIFR, 2018; IUAC, 2018). Both the pelletrons are operating successfully for the past 25 years delivering beams to a large number of users. The largest accelerator complex in India is at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore (RRCAT, 2018). This houses the indigenously developed Synchrotron Radiation Sources, Indus-1 and Indus-2. A large number of user beam lines have been developed around Indus. In the last 5 years or so, performance of Indus 2, the 2.5 GeV accelerator has been outstanding and high quality research work has been carried out using the facility and the list of users is growing rapidly. Along with the big accelerators used primarily for research, a number of small accelerators; both ion and electrons are available in the country for mainly applications. Total number of all the accelerators in the country will be of the order of 100 or so.

However, the number of accelerators around the world has grown continuously and at a significant pace since the time they were commissioned more than 80 years ago. Presently, this number, including both the ion and the electron types, both big and small, exceeds 30,000 (Accelerator for society, 2018; Hamm

**Author for Correspondence: E-mail: kailas@cbs.ac.in*

and Hamm, 2012; Hamm, 2013; PTCOG, 2018). More than 60% of these are for industrial use. Nearly 30% of the accelerators are in the healthcare sector. There are other applications in agriculture, environment and national security, and even for helping authenticate paintings. Interestingly the number of accelerators employed in basic research programmes is only 1% of the total, though it includes all the big accelerators.

In this review, we will, after a briefintroduction, discuss the Indian accelerator scenario – the ongoing and planned programmes. Next, we summarise the International large size accelerators, mainly the ones recently commissioned and the ones which will be operational in the next few years. We also mention some of the mega accelerator projects which are in the planning stage. Then, we take up the large usage of charged particle accelerators not only in basic research in science but also in a wide variety of applications of great relevance to the society. We end the review with concluding remarks.

The Indian Accelerator Programme

As mentioned earlier, India has four major accelerator centres in the country – Delhi, Indore, Kolkatta and Mumbai. All the accelerators in these centres are running successfully, catering to a large number of users from the Department of Atomic Energy and teaching institutions. There are also smaller size accelerators at BARC (Mumbai and Hyderabad), Institute for Plasma Research, Gandhinagar, IUAC, IIT, Kanpur, Physical Research Lab (PRL), Ahmedabad, Guru Ghasidas Vishwavidyalaya, Bilaspur, Institute of Physics, Bhubaneswar, Indira Gandhi Centre for Atomic Research, Kalpakkam, Kurukshetra, Mangalore, Mumbai, Pune and Panjab Universities. There are also accelerators operated by hospitals for healthcare. It is clear that the number of accelerators in India both for basic research and applications is very small compared to most developed countries. In Asia, Japan and China are way ahead of the number of accelerators and also the related technology to build these accelerators. Let us discuss some of the recent developments in the national accelerator programme. At RRCAT Synchrotron facility, to enhance the beam quality, in terms of spectral range and brightness, a number of insertion devices have been placed in the synchrotron ring. Three undulators are already inplace and commissioned. One superconducting wavelength shifter and one superconducting multipole wiggler are under installation. In Indus-2, there are 13 beam lines operational on bending magnets. Another 7 beam lines for different measurements are under construction. Active discussions are also conducted amongst the synchrotron users and the accelerator experts about the next generation synchrotron source in India, which could be based on 3 to 8 GeV electron accelerator. RRCAT is incidentally a partner in the LIGO project, because of the high technical competences developed during the work with accelerators (RRCAT, 2018).

We should also mention the indigenous development of a K^*-500 superconducting cyclotron at VECC. The internal beam was seen quite some time back. The external beam has not yet been taken out for experiments. Some remedial measures are being undertaken and we are eagerly looking forward to the superconducting cyclotron being available to the users in near future (VECC, 2018).

Major accelerator facilities operational in the country are listed in Table 1. There are some mega accelerator programmes that have been taken up in recent times, which will be completed in the next 10 to 15 years in a phased manner: Development of a 1 GeV proton spallation source at RRCAT (RRCAT, 2018), and the radioactive ion beam facility, ANURIB at VECC (VECC, 2018). And there are other programmes like the high current ECR injector project at IUAC (IUAC, 2018), Low Energy High Intensity Proton Accelerator (LEHIPA) at BARC (BARC, 2018) and a 230 MeV proton machine for cancer therapy at Tata Memorial Centre, Mumbai. These are all expected to be available to the users in next few years. Many of the emerging accelerator programmes in India have been described very well by Bhandari and Roy (Bhandari and Roy, 2015). The upcoming mega accelerators in the country are also summarised in Table 1.

For some of our mega-scale accelerator programmes, we are also leveraging International collaboration. For example, for the radioactive ion beam programme, we have collaboration with Canada (TRIUMF). For the spallation neutron source we are collaborating with Fermi Lab in Chicago. But the major efforts in building these facilities will be our own. The creation of infrastructure and availability of trained

Table 1: Accelerators in India – Present and Future

Place	Accelerator	Remarks
Inter University Accelerator Centre (IUAC), New Delhi	15 MV Pelletron coupled to Nb based SC LINAC	Ion Accelerator, Operational
	High Current ECR Injector to the SC LINAC	Under construction
Raja Ramanna Centre for Advanced Technology (RRCAT), Indore	INDUS I (450 MeV) and INDUS II (2.5 GeV) Synchrotron Radiation Source	Electron accelerator, Operational
	Spallation Neutron SourceBased on 1 GeV protons	Under design approvalstatus
Variable Energy Cyclotron Centre (VECC), Kolkatta	K* = 130 Room temperature cyclotron	Ion Accelerator, Operational
	K* = 500 Superconducting cyclotron	Not operational
	Advanced National Facility for Unstable Rare Isotope Beams (ANURIB)	Under construction
BARC – TIFR Pelletron – LINAC facility at TIFR, Mumbai	14 MV Pelletron coupled to Pb based SC LINAC	Ion accelerator, Operational
BARC	Low Energy High Intensity Proton Accelerator (LEHIPA)-20 MeV Protons	Under construction
BARC	Medium Energy (100 to 200 MeV) High Current Proton Accelerator	Under planning

Note: The maximum energy for a given ion of mass number A and charge q (charge state of the ion) from a cyclotron is given as. $E = K^*q^2/A$. The K* is related to the maximum magnetic field and radius of the cyclotron magnet

manpower will be the key elements in pushing these programmes on a faster time scale. India has successfully contributed to International programmes not only in building accelerators/sub-systems but also to the development of beam lines and detector facilities. The Department of Atomic Energy contributed 40 million dollars worth of super-conducting corrector magnets (sextupole, octupole and decapole) (Leader: RRCAT, Indore) and advanced grid software (BARC) to the Large Hadron Collider (LHC) in CERN Geneva, experiments with which a few years back gave the first signatures of the Higgs Boson, the missing particle in Standard Model or the so-called God Particle! The above contribution was estimated at European costs; our actual cost was a little over half of this. The balance went into an Indian Fund, which supported our scientists' travel and stay, when they went to work in CERN.

The introduction of hi-tech Indian equipment into this multi-billion dollar facility is a tribute to Indian technology. India is also contributing to and participating in experiments with two detectors – CMS (Leader: TIFR, Mumbai) and ALICE (Leader: VECC, (Kolkata) – and analysis of data from them. The first signatures of the Higgs Boson came from the CMS detector. CMS and ALICE are the acronyms for the two major detector facilities operational at CERN and Indian scientists and engineers from the national labs and universities have contributed to the construction of these world class detector set-ups.

As a part of the MOU between the Fermi lab and Indian institutes, India is expected to fabricate and supply components for the accelerator Fermilab is building. In return, Fermi is making available to us the technical know-how to make critical accelerator components and help to build the infrastructure required to fabricate them. RRCAT and IUAC developed sometime back a 1.3 GHZ single cell Nb SC RF cavity. Recently, the group has developed a 5 cell cavity. This was for a future Superconducting Proton Linac based Spallation Neutron Source. India is also committed to supply power supplies and beam line components for the upcoming Facility for Antiproton and Ion Research (FAIR) in Germany. India is collaborating with GANIL, France in their upcoming accelerator programme SPIRAL2.

International Scenario

The 125 GeV Higgs particle could be produced/observed only when the collision energy from the LHC was a few TeV. Building higher energy accelerators with higher intensity continues to be the motivating factor in many upcoming accelerators. Some of the recent developments were reported in the recent International Particle Accelerator Conference (PIPAC, 2017) in Denmark. The commissioning of the European XFEL (X-ray Free Electron Laser) in Germany based on 6 to 17.5GeV electrons, providing x-rays in the energy range of 0.25 to 25 keV, is noteworthy. The facility is expected to be fully functional with all the user facilities in 2019. The Linac Coherent Light Source, attached to the Stanford University Linear Accelerator is, of course, the world's first and most powerful Free Electron Laser, and it will be a versatile tool for multidisciplinary research. Using the XFEL we can not only look at atom size objects but also study ultra - fast reactions involving atoms, molecules and clusters. It is also expected to create and investigate warm dense matter (which exists in the cores of large planets) using XFEL.

LHC has now been operated with 6.5 TeV protons with luminosity higher than the design value. There are plans to increase the energy to the ultimately design energy of 7 TeV in a progressive manner after two years. CERN also plans to develop High Luminosity LHC as the next step in improvement to the machine. This will be followed by High Energy LHC after 20 years or so. For this, some plans are underway about the next generation circular colliders. In USA, the Facility for Radioactive Ion beams (FRIB) is the next major facility that will be commissioned in the next 5 years. The European spallation source based on high current 2 GeV proton is expected to come on stream in 2023. The FAIR facility is another major one to come up in the next few years. China has just commissioned its proton spallation neutron source facility based on 1.6 GeV protons.

Dr. Fabiola Gianotti, CERN's Director General said recently that they have begun design studies for a new circular super-collider (100 TeV) that would be about 90 to100 km in circumference. China is thinking of building a p–p colliderof 50 to 90 TeV as its "long term" programme. But there is a feeling in the global accelerator community that the strategy should be to concentrate on one powerful machine, without duplication. The status of recent/upcoming international accelerator facilities is summarised in Table 2.

The proposed International Linear Collider(ILC) is likely to be built in Japan. The International Committee for Future Accelerators (ICFA), in a recent meeting, has suggested that ILC, originally designed with an electron-positron collision energy of 500 GeV can be operated at 250 GeV, and still be a good 'Higgs Boson Factory', which will deliver a wealth of data to study the various properties of the Higgs Boson, and will be less costly and could be realized in a shorter time frame. It is needless to say that the accelerator technology has to make a "quantum jump" to

Table 2: Status of Recent/upcoming international accelerator facilities

Place	Facility	Remarks
CERN,Europe	LHC 13 TeV CM energy	Operational. The energy is likely to be increased to 14 TeVafter two years
Germany	European XFEL based on 15 to 17.5 GeV electrons	Commissioned. Full operation with users in 2019
China	1.6 GeV proton based Neutron Spallation source	First neutron beam seen in 2017
USA	FRIB – Facility for Rare Ion Beams	Expected completion in 2022
Sweden	European Neutron Spallation Source based on 2 GeV protons	Expected completion in 2023
CERN,Europe	HL – LHC High Luminosity LHCFuture Circular Collider FCC based on protons and/or electrons	Beyond 2025Expected after 2035 100 TeV planned for p-p collisions
Belgium accelerator	MYRRHA- based on 600 MeV – 4 mA proton transmutation feasibility	Being developed for demonstration of nuclear waste
Japan ?	International Linear ColliderILC based on electron – positron collision 250 to 500 GeV cm energy	Site for the facility to be announced soon
Germany	FAIR Facility for Antiproton and Ion Research	Construction underway. To be ready in the next few years

accomplish the futuristic accelerators. The superconducting magnets and superconducting RF technologies are very crucial in these developments. The superconducting technology of today is based on research on superconductivity which is nearly 100 years old. Bulk Nb continues to be the material of choice in making SC cavities in building RF structures. Accelerating field gradients of 20 to 30 MV/m are now routinely achieved. Research and technology development is ongoing to reach higher gradients of the order of 100 MV/m using the normal conducting resonators. Fields, as high as, 70 MV/m have been demonstrated in the Compact Linear Collider(CLIC) test facility at CERN. Research is underway to develop Superconducting material Nb_3Sn (T_c=18.3°K) as the next generation alternative to bulk Nb (T_c=9.2°K). It is proposed to utilize Nb_3Sn in the development superconducting magnets required for High Luminosity LHC programme to achieve higher magnetic fields above 10 T or so. In addition to the development of new materials, powerful Klystrons/ solid state amplifiers, beam diagnostics, beam dynamics, etc. will all have to be upgraded to suit the requirement of the future accelerators. These are exciting challenges in a broader area of accelerator science and technology. For more information on the International accelerator programme, interested readers may see (PIPAC, 2017) and the various articles covered in this conference.

Accelerator Applications

Even though charged particle accelerators got developed for basic research, they are widely used in many different areas of great relevance to society (Fig. 1). As mentioned earlier, the accelerators are employed in healthcare and industry in a big way. Even in the field of energy- energy generation, fertile to fissile breeding and nuclear waste transmutation, high energy high intensity accelerators are very much needed in addition to the nuclear reactors. There is a Multipurpose Hybrid Research Reactor for High- tech Applications (MYRRHA) project of the Belgian Nuclear Research Centre, which is an Accelerator Driven Sub-Critical Reactor System (ADS). The facility, in some sense a coupled operation of an accelerator and a reactor, is being built for demonstrating the nuclear waste transmutation feasibility (PIPAC, 2017; MYRRHA, 2018). India has a major interest in ADS, both as an energy-producing

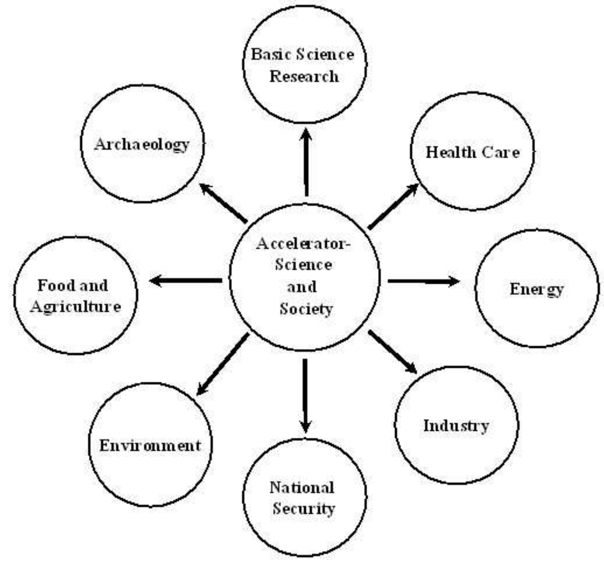

Fig. 1: Accelerators for Science and Society

system, as a fissile material breeder and as a nuclear waste burner. India has embarked on a long-term programme of identifying and developing various technologies and sub-systems required for building an ADS. The indigenous development of LEHIPA is in this direction, as it can serve as an injector to the high energy high intensity proton accelerator required for the ADS project. The accelerator driven system in the nuclear power programme has been reviewed some years ago (Jagatap and Kailas, 2009).

Both ion and electron accelerators are employed in healthcare. In the entire world, there are around 70 accelerators dedicated to accelerator based cancer therapy. Another 40 odd accelerator facilities are in different stages of development for hadron therapy (PTCOG, 2018; NuPECC10, 2010; NuPECC17, 2017). Tata Memorial Centre will develop a proton therapy centre, based on 230 MeV protons, for cancer therapy. We understand that Appollo Hospital in Chennai will also be getting a similar machine from IBA, Belgium who are the world leaders in supply of accelerators for healthcare. In the world, besides protons, only high energy carbon ions have been employed for cancer therapy. Interestingly, there is no hadron therapy facility which used alpha particles. The alpha particles have less lateral scattering as compared to that of protons and hence offer a sharper dose fall off which is desirable for cancer therapy. Keeping these options in mind, Tata Memorial Centre (TMC), Mumbai is proposing development of a multiion cancer therapy machine for future. Involvement of expert groups in India in this project will be important. The radio-isotopes which are required for healthcare are traditionally produced using the nuclear reactors and neutron irradiation. They are the neutron rich radio-isotopes. However, there are a number of neutron deficient radioisotopes like; ^{18}F, ^{201}Tl, ^{123}I, ^{67}Ga-needed for PET/SPECT diagnostics, which can be produced only using accelerators. VECC is installing a 30MeV, 500 μA proton cyclotron facility (VECC, 2108) for production of Positron Emission Tomography (PET) and Single Proton Emission Computed Tomography (SPECT) isotopes. The TMC has been operating a 16.5 MeV proton cyclotron for PET programme for nearly 20 years. Currently in India we have more than 10 small sized cyclotrons operational for radioisotope application (Shinto, 2017).

Industrial use of accelerators is the most dominant application (Hamm and Hamm, 2012; Hamm, 2013; Mehta, 2000). The semiconductor industry uses ion implantation facility in a big way. Use of electron beams for irradiation and welding is another application. Internationally electron beams have been also used for treating municipal waste and flue gas from power plants to make it free from N and S. A number of technologies have been developed at BARC over the last two decades in use of low energy industrial electron accelerators (BARC, 2018). Curing paint, cross linking of polymers, changing colour of diamonds, sterilization of medical products, treatment of flue gas (Basfar, 2010), radiation hardness of electronics components are some of the programmes where electron accelerators have been employed in India. Municipal waste hygenisation is currently being handled by use of gamma sources. The gamma sources can be easily changed to electron accelerators, once the required radiation dose level requirements increase. However, the Indian Industry is still not fully geared to employ accelerators for various applications and also has not made substantial investment in this advanced technology. Similar programme for the industrial use of electron accelerators is also an important ongoing activity at RRCAT. Society for AppliedMicrowave Electronics Engineering Research (SAMEER), (SMAEER, 2018) is another organization in India engaged in indigenous development of electron accelerators for applications. Both the Mumbai and Delhi pelletrons and ion beams are used for testing the longevity of electronics components involved in space flights.

Another major area where accelerators are widely used is under national security. Electron accelerator having dual energy option, e.g. 3 and 6 MeV, has been developed by BARC (BARC, 2018). The system is undergoing trials before being deployed in the port for cargo scanning. Using mini or portable neutron generators and neutron induced reactions, explosives can be detected easily using (n,γ) and (n,n′γ) reactions on the constituents (C,N and O) of the explosives. BARC has demonstrated one such facility (BARC, 2018). Both, the neutron and X-ray imaging of objects are complementary techniques and they are used in many applications including security.

Traditionally, gamma rays have been used for irradiation of vegetables, fruits and spices etc for extending the shelf life and delay in ripening/inhibition of sprouting. Electron accelerators (directly or using the photons generated by the electrons hitting a high Z target) are slowly replacing gamma sources for these applications. Electron accelerators have the advantage that the machine can be switched on and off, as per the need, which is not possible when we employ gamma source for this purpose. RRCAT has developed a 10 MeV LINAC for agricultural radiation processing programmes and installed the same in the Devi Ahilya Bhai Holkar Mandi at Indore.

Gamma radiation has been used by BARC for accelerated but controlled mutation of plants.to produce seeds which are high yielding, drought resistant, tolerate extremes of temperature, grow even in salty lands and take less time to mature. Again agriculture is an area where more electron accelerators can be deployed (to replace gamma sources) to enhance the shelf life of agricultural produce and reduce their wastage due to inadequate storage facilities.

Archaeology is another area where accelerators are used for dating of old samples available in small quantities. India, with its rich cultural heritage and having unique samples could exploit this route to know more about our rich history. It is like knowing the past reliably to predict the future with confidence. The Accelerator based Mass Spectrometry (AMS) technique is a highly sensitive one for dating radioactive samples, having long half-lives but available in small amounts (Kutschera, 2016; Fifield, 1999). In the whole world, there are nearly 100 accelerator facilities dedicated to this programme. The AMS technique based on cosmogenic nuclei like; ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{129} I etc. has been employed to understand the climate change, increase of ocean temperature, rock erosion,age of ice cores, deposition rates of sediments in ocean, dating old ground water etc. over the years. Using ^{14}C based carbon dating, using the AMS technique, we can determine the age of the sample as old as 50 thousand years. Solar activity and climate change are related and the above studies are very important to know the pattern of the past, in terms of climate change so that we can make more reliable prediction about the future. The AMS technique has been also employed to date very old paintings without significant damage to the art pieces. With funding from the Ministry of Earth Sciences IUAC (IUAC, 2018) has recently commissioned a world class AMS facility based on 500 kV accelerator. A large number of users are already carrying out experiments based on ^{14}C. More recently, the MoES has sanctioned a project to IUAC(IUAC, 2018) to develop a world class centre for Geochronology. Ion beam analysis of samples is another important activity which employs nuclear physics techniques for characterisation of samples (Mackova *et al*., 2017) in general and after electron or ion beam processing in particular. The well-known techniques are Rutherford Back Scattering (RBS), Particle induced gamma or X-ray emission (PIGE, PIXE), Nuclear Reaction Analysis (NRA) etc. A large number of small and low energy accelerators are being employed in this programme. Since 1988, the accelerator AGLAÉ (NuPECC10, 2010; NuPECC17, 2017) has been installed at Louvre museum, France for studying in a non-destructive manner heritage objects. Also, the LABEC (NuPECC10, 2010;NuPECC17, 2017) Tandem laboratory in Florence is dedicated to this kind of activity. Both these facilities have external PIXE and PIGE instrumentation and associated detectors. The confocal PIXE method has been employed at AGLAE facility, to determine the elemental composition of paintings as a function of depth. The differential PIXE technique is used at the Florence facility for a similar purpose. The nature, concentration and location of the various elements reveal not only the heritage object's history/age, but enable the authentication of rare old art pieces. Synchrotron radiation has been used to characterize and develop materials in a number of areas. Interested readers may refer to the international conference series -Conference on Application of Accelerators for Research and Industry (CAARI)(CAARI, 2018) to have more information regarding the use of accelerators in research and industry.

There are also attempts to build small or compact Linear accelerators. The plan is to build accelerators which are a few feet long, instead of a few hundred feet length but still do most of the things accomplished using the longer machine. Both CERN and Fermi lab (USA) are involved in this kind of development with societal applications, like healthcare, in main focus. ADAM is a research company inspired by CERN and is a spin off company of CERN which is concentrating on developing compact accelerators for treatment of cancer (ADAM, 2018). According to Vretner, CERN also has a vision of building 1m size accelerator weighing 100 kg which could be used for analysis of paints and jewellery. A project called Accelerator Application Development and Demonstration (A2D2) at Fermilab (A2D2, 2018) is planning to develop compact electron LINACs for treatment of tumours. It augurs well that the two giants of the world in advanced accelerator technologies are extending this knowledge and expertise to develop mini accelerators for applications. There are other developments in the techniques and technologies to build compact accelerators. Some years ago, SLAC physicist Joel England and colleagues demonstrated electron acceleration in a laser driven dielectric microstructure (Perelta *et al*., 2013). Progress made in the area of laser based acceleration of charged particles (Laser wakefield acceleration experiments) using intense, ultra-short lasers has been reviewed recently by Mangles (Mangles, 2017). The table-top, compact accelerators can be perhaps realised in future, following this technique. In India, both at TIFR (TIFR, 2018) and RRCAT (RRCAT, 2018), R and D work towards acceleration of electrons and ions using the laser wakefield technique has been going on for more than a decade. Compact size neutron generators are already developed and are in use for a variety of applications (Vainionpaa *et al*., 2014; Burkhart, 2006). One of the applications is in well logging to explore the presence of oil, gas and coal, making use of fast/slow neutron induced reactions (Burkhart, 2006)]. In India we have been organising the Indian Particle Accelerator Conference (InPAC) for the past 15 years, fully supported by the Board of Research in Nuclear Sciences, DAE to review the progress made in the various accelerator programmes in the country. As we build/commission more accelerators (big and small) in the country, the usage of these machines for societal applications will also grow many-fold.

Conclusion

Continuity in technology is essential to preserve knowledge in any field, and in a field like Accelerators, where the demand, both from Science and from Society/Industry is high and increasing continuously, the knowledge momentum must be kept up.

The Office of Principal Scientific Advisor (PSA) has brought together three major entities with high complementary competences – IGCAR, BHEL and NTPC – to carry out R&D towards an 800 MWe Advanced Ultra super-critical coal-based thermal plant, where the steam temperature is above 700°C, and therefore for the same amount of power produced, there is less emission of carbon-di-oxide. This is not a zero carbon technology but a relatively lower carbon technology. Nobody in the world has built such a power plant, and that is why R&D on this is so exciting. The Govt. has sanctioned the project last year and work has begun on it in a mission mode. While waiting for the sanction, for several years, the PSAOffice had supported several small 'pre-project R&D activities', like design of boiler tube materials, turbine blade design and so on to keep the momentum going and the groups synergised and active. That was very important to quickly start up the main project when the sanction finally came. As we are planning several major accelerator-based projects in the country, we should adopt a similar approach of pre-project activities in major component technologies. This will also strengthen the infrastructure for accelerator development here and train manpower for component technologies in this field. Involvement of IITs, NITs and universities is essential in what should be a major national effort.

International collaboration is also essential, both for bringing in the latest technology into our own accelerators and to participate in international accelerator projects, of which there may be only one-of-a-kind of any type because of high cost. The Indian accelerator programmes and the related developments were discussed in the recently concluded Indian Particle Accelerator Conference (InPAC18) held at RRCAT, Indore. It is clear that considerable activity is going on in India in this field of complex technologies. It is essential that such activity should be strengthened and sustained by active collaboration amongst the national labs, teaching institutions and industry. One of the reasons for the success of the Indian nuclear power programme has been a strong support from the industry. As India progresses to become a developed country in the not too distant future, it is needless to say that development and usage of charged particle accelerators in the country has to grow many- fold, as has been the case in many developed countries.

Acknowledgements

The authors acknowledge colleagues from BARC, IUAC, RRCAT, TIFR, TMC and VECC for helpful discussions and for their inputs in preparing this review article. We also thank the referees for their useful suggestions.

References

A2D2- Accelerator Applications and Development and Demonstration center (2017); http://news.fnal.gov/ September 21, 2017 by Leah Poffenberger, Fermi National Accelerator Laboratory

Accelerators for society (2018) www.accelerators-for-society.org

ADAM - a research company inspired by CERN (2018) www.adam-geneva.com

BARC (Bhabha Atomic Research Centre) (2018) www.barc.gov.in

Basfar A A (2010) A review of electron beam flue gas treatment (EBFGT) as a multicomponent air pollution control technology *Nukleonika* **55** 271-77

Bhandari R K and Roy A (2015) Next generation particle accelerators for frontline research and wide ranging applications *Curr Sci* **108** 1608-1615

Burkhart R (2006) Neutron generator and well logging www.osti.gov. Sandia National Lab

CAARI (Conference on Application of Accelerators for Research and Industry) (2018) www.caari.com

Chidambaram R and Kailas S (1995) Accelerators – Achievements and future projections *Curr Sci* **69** 572-577

Divatia A S andAmbasankaran C (1985) Accelerator developments in India Pramana *J Phys* **24** 227-244

Fifield L K (1999) *Rep Prog Phys* **62** 1223-1274

Hamm R W and Hamm M E (2012) Industrial Electron Accelerators and Applications, World Scientific Publishing Company

Hamm R W (2013) Industrial Accelerators, Proceedings of International Particle Accelerator Conference, China 2013

InPAC18 (Indian Particle Accelerator Conference series, 2018) (2018) – Recent one held at RRCAT in January, 2018

IUAC (Inter University Accelerator Centre) (2018) www.iuac.res.in

Jagatap B N and Kailas S (2009) Accelerator Driven System in the nuclear power programme, Indian Nuclear Society News, 2009, **6** Editor B N Jagatap Guest Editor S Kailas

Kapoor S S (1998) Accelerator based activities in India, In proceedings of the Asian Particle Accelerator Conference (PAC98 conference) 8-11

Kutschera W (2016) Accelerator Mass Spetrometry: State of the art and perspectives *Advances in Physics* **1** 570-575

Lalremruata B, Kailas S Bhoraskar V N Ganesan S Saxena A Nayak B K Tyagi A Musthafa M M Mukherjee S Mukherjee G Naik H Dhole S D (2017) International Atomic Energy Agency, Nuclear data Section, International Nuclear Data Committee (INDC) Report – 0050

Mackova A, Kucera J, Kamenik J, Havranek V and Kranda K (2017) *Nuclear physics news* **27** 12-17

Mangles S P D (2017) arXiv:1705.10588v1 [physics.acc-ph] 30 May, 2017

Mehta G K (2000) High energy accelerators and material science *PINSA* **66** 653-674

Mehta G K (2002) High energy accelerators and associated developments in India Pramana *J Phys* **59** 703-712

MYRRHA (2018) http://sckcen.be/en/Technology_future/MYRRHA

NuPECC10 (Nuclear Physics European Collaboration Committee – Long Range Plan 2010) (2010) Perspectives in Nuclear Physics Research- www.nupecc.org

NuPECC17 (Nuclear Physics European Collaboration Committee – Long Range Plan 2017) (2017) Perspectives in Nuclear Physics Research- www.nupecc.org

Perelta E A *et al.* (2013) Development of electron accelerator in a laser driven dielectric microstructure *Nature* **503** 91-94

PIPAC (Proceedings of the 8th International Particle Accelerator Conference, 2017) (2017) http://www.jacow.org/

PTCOG (Particle therapy cooperative group) (2018) www.ptcog.ch

RRCAT (Raja Ramanna Centre for Advanced Technology) (2018) www.rrcat.gov.in

SAMEER (Society for Applied Microwave Electronics Engineering and Research) (2018) www.sameer.gov.in

Shinto A (2017) Current trends in clinical and medical imaging **1** 1-4 Juniper publications

TIFR (Tata Institute of Fundamental Research) (2018) www.tifr.res.in

Vainionpaa J H, Gary C K, Harris J L, Piestrup M A, Pentall R H and Jones G (2014) Technology and applications of neutron generators developed by Adelphi Tech, *IncPhysica Procedia* **60** 203-211

VECC (Variable Energy Cyclotron Centre) (2018) www.vecc.gov.in.