Indian Accelerator Program-An overview

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Preamble

Accelerators are playing an important role both in basic research and beneficial applications in the fields of healthcare, national security, environmental science, food preservation, etc. In India, very significant progress has been made, during last few decades, towards design and construction of accelerators. A large number of small and big accelerators have been built and being regularly used. Funding agencies are also supportive for the new projects particularly for societal and industrial applications. In this article, an overview of the Indian accelerator development program is given.

1. Introduction

A particle accelerator is an instrument used to increase the kinetic energy of charged particles such as electrons, protons and heavy ions. For an experimental nuclear scientist, the particle accelerator is similar to that of a microscope to a biologist and chemist or a telescope to an astronomer where the resolution/resolving power of the instrument depends on the wavelength of the probe/particles. In accelerators, higher the energy smaller will be the wavelength so resolving will be better and one can investigate the smaller size objects. Accelerators are part of our daily life and we are using them every day. In general, we are regularly watching television (TV), where the electron beam is accelerated, focused, deflected and scanned.

Accelerators were initially developed for fundamental research with primary aim to understand the structure of the nuclei, the nature of the nuclear forces and the properties of the nuclei not found in nature. Currently, accelerators play very important role both in basic and applied research. They are now used very extensively, in addition to basic research, for medical science, industry, national security, environmental science, production and study of new particles and super-heavy elements, etc. The radioisotopes produced using accelerators are used for medical diagnostics and treatment, particularly for cancer therapy. Electron accelerators are used for food preservation, and as Synchrotron Radiation Sources for material science research. Recently, it is proposed to use accelerators for nuclear energy generation using Thorium (^{232}Th) as fuel [1] which is abundantly available in India. These thorium-based systems are expected to be inherently safe. Today, accelerators in the energy range of keV to TeV have been designed and built. The large accelerators are used in research on the fundamental interactions of the elementary subatomic particles.

In 1919, Rutherford discovered proton through following reaction between a nitrogen nucleus and alpha particles [2]:

$^{14}N + ^{4}He \rightarrow p + ^{17}O$

Discovering proton was a landmark experiment and he was given Nobel Prize in 1908 for disintegration of elements using alpha particles from radioactive sources. Till 1932, most of the nuclear physics studies were done using energetic alpha particles released by the decay of radioactive elements. The maximum kinetic energy of these naturally emitted alpha particles was 6-8 MeV, which was not enough to disintegrate heavy elements and hence it was felt that in order to disintegrate heavier nuclei by alpha particles, it would be necessary to accelerate alpha particles to higher energies. Although, at that time it looked difficult to generate, in laboratory, voltages sufficient to accelerate particles suitable for nuclear research, the calculations of Gamow [3] indicated that considerably less-energy ions would be sufficient for the purpose. This was known to happen due to the tunneling effect. This inspired scientists and engineers to build accelerators that could provide ions with sufficient energy for nuclear physics research.

Charged particle accelerator development in the world started in the late 1920s. In the next 40 to 50 years, the growth towards development of technology and a variety of accelerators all over the world was phenomenal for fundamental research as well as beneficial applications.

The first successful experiments with artificially accelerated ions (protons) were performed by Cockcroft and Walton in 1932 [4]. Using a voltage multiplier, they accelerated protons to more than 700 keV and bombarded them onto the lithium nucleus to produce two alpha particles:

$p + ^{7}Li \rightarrow ^{4}He + ^{4}He$

This was the first nuclear physics experiment where a nucleus was transmuted using artificially accelerated proton beam. They received Nobel Prize in 1951 for this work.

2. Brief History of Accelerator Development

By 1931, R J Van de Graaff had constructed the first belt-charged electrostatic high voltage generator [5]. In a Van de Graaff generator, the voltage is generated by transferring charge to high voltage terminal using a belt made up of an insulating material like nylon or rubber. The high voltage terminal along with pressure vessel forms a capacitor and develops a voltage V (= Q/C) when charge Q is transferred to the capacitor. Here C is the capacitance of the capacitor. The structure of Van de Graaff accelerator was modified by adding one more high voltage column section and putting the ion source outside at ground potential (tandem accelerator). In a tandem accelerator [6], negative ions are injected into the low energy accelerating tube. They are converted into positive ions in the stripper system located in the high voltage terminal before their acceleration in the second accelerating tube. This allows acceleration of heavy ions also and to higher energies. Charging was further improved by replacing the belt by pellet chain and the accelerators are called pelletrons [7]. Tandem accelerators up to 35 MV terminal potential [8] have been designed and built. The SF_6 is used as insulating gas in these accelerators.

In 1928, the principle of the linear accelerator was demonstrated by Wideroe [9]. He used alternating high voltage to accelerate sodium and potassium ions to energies twice as high as those imparted by one application of the peak voltage. In 1931, E O Lawrence and David H Sloan at Berkeley, USA, employed high-frequency fields to accelerate mercury ions to 1.2 MeV energy. The cyclotron was conceived by Lawrence as a modification of linear accelerator. The particles in a cyclotron follow circular orbits under the influence of a magnetic field making it a compact accelerator. Lawrence and Livingston demonstrated the principle of the cyclotron in 1931 [10], accelerating ions to 80 keV and protons to more than 1 MeV energy. In 1940, Kerst constructed the first betatron [11], a magnetic-induction accelerator for electrons. During the period of 1930s, the accelerator physics and technology developed very rapidly all over the world. Accelerators even in TeV energy range have been designed and built. Some of big accelerator laboratories where high energy accelerators are developed are CERN, Geneva, Switzerland; Fermi National Accelerator Laboratory, USA; Brookhaven National Laboratory, USA; DESY, Hamburg, Germany; KEK, Tsukuba, Japan; Nuclear Physics Laboratory, Dubna, Russia to name a few.

3. Indian Accelerator Programme

In India, accelerator development started in the 1940s, when Meghnad Saha decided to build a 38" cyclotron, based on the Lawrence's cyclotron at Berkeley, at the Saha Institute of Nuclear Physics (SINP), Calcutta (now Kolkata). He sent his student (B D Nagchaudhuri) to Berkeley to learn the technology. It delivered an internal proton beam current of 50-70 μA at 4 MeV in 1960 and later an external beam for experiments. Although it took time to complete the project it gave lot of confidence and encouragement to the Indian scientists to take up the accelerator developmental work. At the Tata Institute of Fundamental Research (TIFR), Mumbai, a 300 keV open air Van de Graaff accelerator was built and operated and also development work on a 1 MeV electron linear accelerator was carried out. Simultaneously, Cockcroft-Walton accelerators were built at the SINP and the Bose Institute, Calcutta (Kolkata), a 1 MV Cockcroft-Walton accelerator (Cascade generator) was bought and installed at TIFR, Mumbai and a 150 kV neutron generator was built at the Aligarh Muslim University (AMU), Aligarh [12].

For the first time a large accelerator, a 5.5 MV Van de Graaff accelerator, purchased from the High Voltage Engineering Corporation (HVEC), USA, was setup in 1962 [13] at the Bhabha Atomic Research Centre (BARC), Mumbai. Though the accelerator was purchased, the switching magnet, beam lines and experimental setups were built indigenously. It provided μA beam currents of protons and alpha particles. The facility was used extensively for nuclear physics and atomic physics experiments. Fig. 1 shows Homi Bhabha, Raja Ramanna and other senior scientists during inauguration of the Van de Graaff accelerator at BARC, Trombay, Mumbai.

Sometime later, a 2 MV Van de Graaff accelerator, also purchased from the HVEC, was installed at the Indian Institute of Technology (IIT), Kanpur, and a 2 MeV electron accelerator was built indigenously at the Indian Institute of Science (IISc), Bangalore. Using these accelerators for research, stimulated the scientists and a need for bigger accelerators was strongly felt. Homi Bhabha, the then Chairman, AEC, addressed the issue and convened a meeting in 1964 at the IISc. In the meeting, it was decided to have two large accelerators for the nuclear physics experiments for the Indian scientists. It was decided to buy a heavy ion tandem accelerator and build an AVF cyclotron, indigenously. With this decision we entered into a new field of building large accelerators. Later, the University Grant Commission (UGC) also decided to set up an

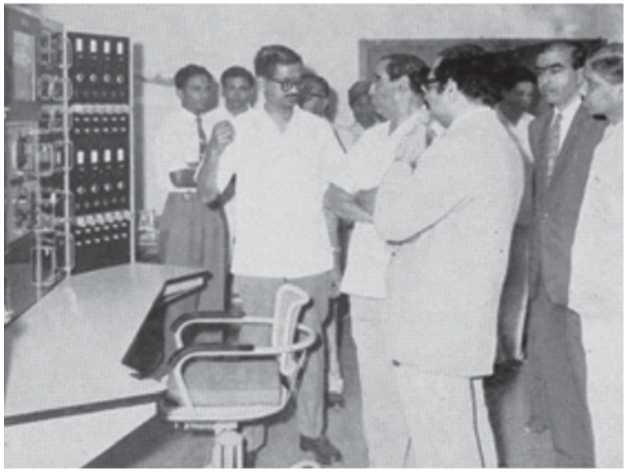

Fig. 1: Raja Ramanna, Homi J Bhabha, H N Sethna and other senior scientists at the time of commissioning of the 5.5 MV VandeGraaff at Trombay, BARC in February 1962.

accelerator centre at New Delhi mainly for the university users. It was called the Nuclear Science Centre (NSC) and later renamed as the Inter-University Accelerator Centre (IUAC).

India has presently a large number of small and big accelerators [14]. Most of them are used in hospitals and industry. Only few accelerators are used for nuclear physics and allied sciences studies. Presently, there are 4 major accelerator centres for research in India. They are: Bhabha Atomic Research Centre (BARC)/Tata Institute of Fundamental Research (TIFR), Mumbai; Variable Energy Cyclotron Centre (VECC), Kolkata; Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and Inter-University Accelerator Centre (IUAC), New Delhi.

A 14 UD Pelletron accelerator facility was set up in Mumbai [15]. Scientists and engineers of BARC and TIFR steered the project to its conclusion. Though accelerator components were purchased from M/s NEC, USA, the pressure vessel, beam lines and experimental systems were developed indigenously. The accelerator was commissioned in 1989. Since then, it has been in use for basic and applied research in nuclear and allied fields. It has been delivering light and heavy ion beams (up to ^{127}I) to users for advanced scientific experiments. In order to increase the particle energy further, it has been augmented with a superconducting linac booster, which consists of 28 lead-plated Quarter Wave Resonators [16]. The output energy can be boosted by about 3 MeV/q for heavy ions.

The 5.5 MV Van de Graaff accelerator at BARC was converted into a 6 MV Folded Tandem Ion Accelerator (FOTIA) [17], which was commissioned in the year 2000 and has been in continuous operation since then delivering both light and heavy ion beams. As part of the Accelerator Driven subcritical Systems (ADS) program, BARC has also taken up a project to design and develop a 1 GeV, 30 mA proton linear accelerator [18]. In order to understand accelerator physics issues at low particle energies, where space charge phenomenon dominates, BARC is building a Low Energy High Intensity Proton Accelerator (LEHIPA) [19, 20]. It consists of a 3 MeV four vane type Radio Frequency Quadrupole (RFQ) [19] and a Drift Tube Linac (DTL) [20] to accelerate proton beam energy to 20 MeV. The LEHIPA is presently in the process of commissioning. A 11 MeV proton beam has been obtained recently at the end of the second DTL tank. High energy part of the ADS accelerator will be built at Vizag, BARC and will have superconducting accelerating structures.

BARC initiated development on electron accelerators (3 MeV, 30 kW DC; 10 MeV, 10 kW RF accelerator;10 MeV, 5 kW; 6/4 MeV dual energy accelerator) at the Electron Beam Centre (EBC), BARC for industrial applications [21]. Broad range of applications are concluded with these accelerators such as biological waste management; Flue gas treatment; seed mutations to develop new varieties of beans, rice, moringa etc.; mass scale irradiation of onion and other food commodities; exotic coloration of various types of gemstones and many research applications for different divisions of BARC. In addition to S-band RF linac, a 6 MeV X-band linac has also been designed and developed for medical applications and it is under trials.

Going back in time, construction of the first large accelerator in India was carried out in Calcutta, indigenously, by a dedicated team of scientists and engineers during 1970-77 [22]. It is an Azimuthally Varying Field (AVF) cyclotron based on the design of the 88" cyclotrons at Berkeley and Texas, USA. It is a room temperature cyclotron capable of delivering variety of light and heavy ion beams up to energy 130(q^2/A) MeV. This cyclotron is called Variable Energy Cyclotron (VEC). The Variable Energy Cyclotron Centre (VECC) at Kolkata started around this accelerator. The cyclotron is in use for nuclear physics and allied research by experimentalists from all over the country. In 1998, an indigenously developed 6.4 GHz Electron Cyclotron Resonance (ECR) heavy ion source was installed to accelerate heavy ion beams. Beams of neon and oxygen ions were routinely accelerated.

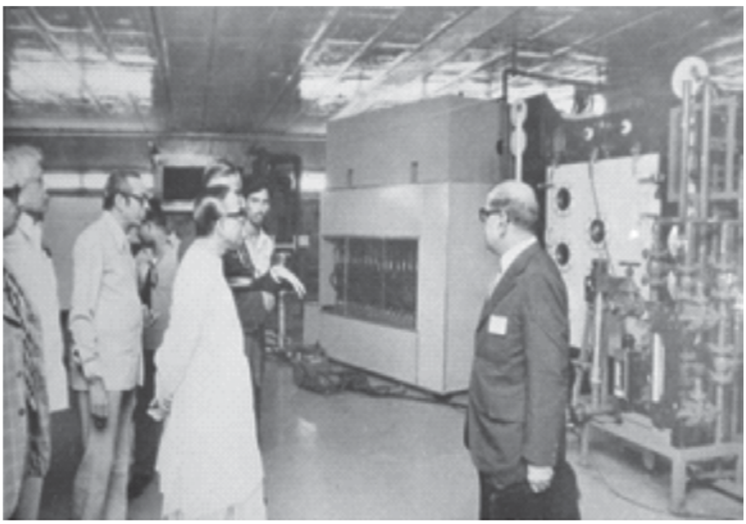

Fig. 2: Former chief minister of West Bengal Jyoti Basu visiting the Variable Energy Cyclotron in 1976 when it was nearing completion. Senior scientists like Raja Ramanna, C Ambasankaran, A S Divatia, Santimay Chatterjee, A K Ganguly and B B Bhattacharjee can also be seen in the picture.

With the users demanding higher ion energies, VECC has also built, indigenously, a superconducting cyclotron with K= 520 [23]. This cyclotron can accelerate light ions to 80 MeV/nucleon and heavy ions to 10 MeV/nucleon energy. The pole diameter of the superconducting main magnet is 142 cm. The superconductor is niobium-tin strands embedded in copper. The magnet is designed to produce maximum hill field of 5.5 Tesla and maximum valley field of 4.5 Tesla. It is the largest iron-core superconducting magnet operational in the country. A 14.5 GHz ECR source is used to produce heavy ions for acceleration in the cyclotron.

In trial runs, nitrogen beam was accelerated to 252 MeV. More beams will soon be available for experiments.

It is always a desire of the nuclear physics community to study elements far away from the β-stability line as it can provide highly interesting new physics. Several phenomena occurring in the outer space and stars can be simulated in the laboratory. An ISOL- post accelerator type of Rare (Radioactive) Ion Beam (RIB) facility has been developed at VECC [24]. In the present system, nuclei are produced inside a thick target using high intensity proton and alpha beams from the VEC. The radioactive atoms diffusing out from the thick target are ionized to charge state $q=1^+$ in the integrated target-cum-source and then transported to an on-line ECR ion source where $q=n^+$ radioactive ions are produced in a two-ion-source mode. These ions are then accelerated to high energies using a four-rod type RFQ and IH linac structures to about 1MeV/nucleon energy. In the next phase, the RIBs will be produced through photo-fission process using a 50 MeV, 2 mA superconducting electron linac (CW) and actinide targets [25]. The electron linac is being developed in collaboration with an advanced accelerator laboratory TRUMF in Canada. In the subsequent phase, radioactive ion beams can be accelerated to 100 MeV/nucleon energy using a cyclotron. The most difficult front-end part of the RIB accelerator facility has already been designed, built and commissioned at VECC.

More than 1500 cyclotrons are operating all over the world as dedicated machines for radioisotope production for medical applications. More than half of such cyclotrons deliver 10–20 MeV energy protons and about 75% of them are dedicated for the production of the radioisotope ^{18}F ($T_{1/2}$ = 109.8 min) for cancer diagnostics. The Fluorodeoxyglucose (FDG) molecules labelled with ^{18}F radioisotope are produced through radiochemistry processes. FDG is injected into the patient's body for scanning with a PET camera. These scans help doctors to effectively diagnose the cancerous parts. In India, over 40 cyclotrons are operating solely for the production of FDG in hospitals and commercial organizations. All these machines are purchased from international manufacturers. Cyclotrons delivering beams of 30 MeV protons or more, can also produce other useful radioisotopes such as ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl, etc. They are relatively long-lived isotope, and are also useful for medical diagnostics. A 30 MeV medical cyclotron facility has been set up by VECC at Kolkata [26]. Some radioisotopes are routinely produced and supplied to hospitals.

The Raja Ramanna Centre for Advanced Technology (RRCAT), Indore is the largest accelerator and laser technology centre of the Department of Atomic Energy (DAE). It houses two indigenously designed and constructed synchrotron radiation sources [27], namely, INDUS1(450 MeV) and INDUS-2 (2.5 GeV). An electron beam extracted from the source is first accelerated to 20 MeV using a microtron accelerator and injected into a 550 MeV (maximum) booster synchrotron. The electron beam is then injected either into INDUS-1 or INDUS-2, where it is accelerated and stored for several hours/days. During bending in the dipole magnets of the storage ring, the beam emits synchrotron radiation having critical wavelength 61 Å for INDUS-1 and 2 Å for INDUS-2. Both storage rings are operational and being used for experiments. The INDUS-2 was commissioned for experiments in December 2005. The Fig 3 shows the then Prime Minister of India Dr. Man Mohan Singh inaugurating the facility and dedicating it to the nation. The Centre was also renamed as Raja Ramanna Centre for Advanced Technology (RRCAT) from the earlier Centre for Advanced Technology (CAT). Both INDUS-1 and INDUS2 have several beam lines as well as advanced research facilities for experiments in material science, condensed matter physics, biological science, etc. A very large research community from various research and academic institutions are carrying out experiments.

Fig. 3: Former Prime Minister of India Dr. Man Mohan Singh inaugurated the INDUS-2 and dedicated the SRS facilities to the nation in Dec 2005. The Centre was also renamed as Raja Ramanna Centre for Advanced Technology

The Centre has been instrumental in indigenous development of very large number of hi-tech accelerator systems and components as well as technologies. To increase the shelf life of the agriculture products by irradiating them with radiation, RRCAT has also set up an Agriculture Radiation Processing Facility (ARPF) at Indore [28]. It uses an indigenously developed, state-of-the-art electron linac (10 MeV) as the main radiation source.

As mentioned earlier, in order to meet the growing accelerator-based research needs of our universities and academic institutions, the University Grant Commission (UGC), Government of India has set up the Inter-University Accelerator Centre (IUAC)) in New Delhi. It houses several accelerator facilities. A 15 UD Pelletron machine, purchased from M/s NEC, USA is the main accelerator at the Centre [29]. It was later augmented with an indigenously designed and developed superconducting linac utilising niobium-based accelerating structures [30]. Beams from the Pelletron accelerator are injected into this linac booster. The facility can accelerate a variety of heavy ion beams to 5-10 MeV/nucleon energy. The Pelletron can also be used as a stand-alone accelerator for advanced experiments. A High Current Injector (HCI) facility has also been built at the Centre [31]. It consists of an ECR ion source, an RFQ and a DTL. The indigenously designed and developed HCI facility can accelerate beams to about 1.8 MeV/nucleon energy. It has recently been commissioned. The beam from HCI would be transported and injected into the superconducting linac booster for further acceleration to higher energy. More intense and higher energy beams would then be available for experiments to the users. In addition to the above, the Centre has several other low energy accelerator-based facilities. They include 1) Negative ion beam facility; 2) Accelerator Mass Spectroscopy (AMS) facility; 3) Rutherford Back Scattering (RBS) facility; 4) Table-top Accelerator; 5) Free Electron Laser facility (called DLS) (under development); 6) Positive ion beam facility. A new National Geochronology Centre is also being set up at IUAC for advanced studies in the fields of geology, oceanography, climate change, environment sciences, archaeology etc. Main scientific activities will be based on utilization of AMS techniques using a 6 MV Pelletron accelerator. The setting up of this Centre has been entrusted to the IUAC by the Ministry of Earth Sciences (MoES), Government of India.

The Indira Gandhi Centre for Atomic Research (IGCAR) has set up two accelerators (400 kV and a 1.7 MV Tandem for heavy ions) to simulate the radiation damage and its analysis in the fast breeder reactor components [32]. Several small accelerator facilities have also been set up by various research and academic institutions all over the country. Some of them are 3 MV Pelletron at Institute of Physics (IOP), Bhubaneshwar, 3 MV Pelletron at Guru Ghasidas Vishwavidyalaya, Bilaspur, 3 MV Tandetron at NCCCM, Hyderabad, 3 MV Tandetron at SINP and 1.7 MV accelerator at IIT Kanpur. An 8 MeV electron accelerator at ECIL, Hyderabad is being used to test electronic components. An indigenously developed 8 MeV microtron (by RRCAT) has been operational at the Mangalore University for applied research by several institutions for over 2 decades now. In 1960s, Prof H S Hans brought an 8 MeV proton cyclotron from Rochester University as a gift. It was set up at the Punjab University, Chandigarh and is still in use for experiments. SAMEER, Ministry of Electronics and Information Technology, Government of India has developed 4/6 MeV electron accelerators for cancer therapy. They are also in the process of mastering the technology for 30 MeV electron accelerators. The Apollo Hospital in Chennai is using 230 MeV cyclotron for proton therapy for cancer. The Tata Medical Centre (TMC), Mumbai is also setting up a 230 MeV cyclotron at the Advanced Centre for Treatment and Education in Cancer (ACTREC), Kharghar for cancer therapy using protons. TMC is also planning for a heavy ion accelerator for cancer therapy. With all these design and developments activities, India has now matured enough to take up bigger challenges in the field of accelerators.

4. International Collaboration

Accelerating gradients in the room temperature structures are restricted, due to breakdowns, to about 1-2 MV/m in DC accelerators and less than 10 MV/m for RF accelerators.

In order to build the modern, state-of-the-art high energy, high intensity accelerators, it is necessary to master the superconducting RF technology where gradients of upto 100 MV/m are possible to achieve. Even higher gradients (100-300 GV/m) can be achieved, in principle, in the Laser Plasma accelerators. Some development work has been done at RRCAT and TIFR. However, this is still in R&D stage and will take considerable time to mature for utilization. All these are highly complex technologies and, therefore, it has been decided to collaborate with the advanced international accelerator laboratories who have enough experience and expertise in the field and are willing to share the technologies with Indian institutions on mutual benefit basis.

The DAE and several Indian universities/institutions were already participating, both in accelerator components building and experiments, at many international laboratories particularly CERN, the European Council for Nuclear Research, Geneva towards construction of the Large Hadron Collider (LHC). India has supplied nearly 2000 superconducting sextupole and decapole corrector magnets, nearly 3000 quench protection system power supplies, nearly 7000 precision magnet positioning jacks as well as design/control software. The RRCAT played a major role in this collaborative program. Also, the Indian scientists and engineers participated in extensive magnet measurements for the LHC project. After successful collaboration with CERN, India has established collaboration with the Facility for Antiproton and Ion Research

(FAIR), GSI, Germany and Fermilab, USA. The Fermilab is building a high beam power accelerator using superconducting accelerating cavities. This collaboration will help us in development of high intensity proton linear accelerators for our ADS and Spallation Neutron Source (SNS) programs. Superconducting cavities, precision magnets and RF power amplifiers designed and developed in India (in collaboration with Fermilab) have met the stringent specifications. The VECC is also participating in FAIR project and making in-kind contributions by supplying, among others, large gap superconducting magnets and several hundreds of power supplies for various systems. The components supplied to FAIR have met the demanding specifications.

All this gives us strong confidence for taking up the challenges towards building bigger accelerators for our own frontline research and applications programs.

5. Mega Science Accelerator Programmes

Following accelerator projects have been envisaged:

1) 1 GeV, high intensity, CW proton accelerator as ADS driver for thorium breeding and nuclear power generation in the near future.
2) 1 GeV, high current, pulsed proton accelerator for SNS benefitting frontline research in material sciences and applications.
3) Fourth generation synchrotron radiation source for discovery science experiments.

5.1 Accelerators for ADS Programme

In 1985, Carlo Rubia at CERN proposed an Accelerator Driven sub-critical reactor System (he called it Fast Energy Amplifier) [33] which can 1) generate electricity using thorium as fuel, 2) manage the nuclear waste (incineration of long-lived minor actinides) and 3) transmute the long half-life fission products. In an ADS, about 1 GeV proton beam from an accelerator falls on a heavy target, such as lead, and produces 25-30 neutrons/incident proton through spallation reaction. These neutrons then interact with ^{232}Th to convert it into ^{233}U which is fissionable. In the ADS, the `reactor' is sub-critical and the required extra neutrons are provided by the accelerator, thereby making the ADS an inherently safe system. This is because the accelerator beam can be withdrawn very quickly in case the reactor tends to became supercritical for any reason. The ADS is very important for India as we have large deposits of ^{232}Th. In view of this, the DAE has initiated a program to develop ADS. Once successful, our `green' nuclear power program can be sustained for centuries to come.

One of the most important components of ADS is a high intensity proton accelerator. For the Indian ADS program, physics design of a 1 GeV, 30 mA proton accelerator has been done

at BARC [18]. It consists of a 50 keV ion source, 3 MeV RFQ, 20 MeV DTL and superconducting accelerating structures to accelerate beam up to 1 GeV energy. Due to extremely high beam currents, space charge effects are highly dominant at low energies. In order to understand and resolve these issues, a 20 MeV, low energy high intensity proton accelerator (LEHIPA) has been designed and built [20]. As mentioned earlier, the installation and commissioning of LEHIPA is in progress at BARC.A 10 MeV cyclotron-based system to study ADS related issues at low energies was also planned at VECC [34]. A high current ECR ion source was built and several experiments related to space charge effects were done [35]. In order to gain experience in designing and building the superconducting RF cavities, etc.,

Fig. 4: Signing of MOU for collaboration between Indian Institutions and Fermilab, USA (IIFC) for development of high intensity systems on Feb 10, 2010

an MoU to jointly develop accelerator sub-systems was signed between Indian Institutions (BARC, RRCAT, VECC, IUAC) and Fermilab on February 10, 2000 to formalize the collaboration [Fig. 4].

Excellent progress has been made in developing various components and sub-systems under this collaboration. Superconducting RF cavities at operating frequency of 1.3 GHz and 650 MHz were designed and fabricated in India. They were processed and tested at the Fermilab. The accelerating gradients exceeding 37.5 MV/m, $Q > 10^{10}$ for 1.3 GHz cavity and 19.3 MV/m, $Q> 10^{11}$ for single-cell cavities at 650 MHz was obtained. This performance is very satisfactory and of international standards. IUAC also designed and fabricated the spoke resonators, complex superconducting accelerating structures at the low energy end of the accelerator, and supplied to the Fermilab. They were also found to be of international standards. Excellent infrastructure for state-of-the-art technologies have thus been created at various Centres, namely, BARC, RRCAT, VECC and IUAC.

5.2 Spallation Neutron Source

There is a high demand for intense beams of high energy neutrons for condensed matter research. For neutron-based research, a Spallation Neutron Source (SNS) is planned at the Raja Ramanna Centre (RRCAT), Indore. It consists of a high current ion source, RFQ, DTL/SDTL up to 100 MeV and superconducting RF cavities for acceleration from 100 MeV to 1-2 GeV [36]. It will be a pulsed accelerator with repetition rate of 20 Hz. Presently, R&D is going on to develop the accelerator subsystems.

5.3 Fourth Generation Synchrotron Radiation Source

In order to meet the growing requirement of modern facilities for condensed matter research, a need is felt to set up a 4^{th} generation Synchrotron Radiation Source in the country [37]. Several discussions have been held in the scientific community to decide on its parameters and location. The general consensus is to build a 6 GeV electron storage ring to meet the requirements of the research community.

Conclusions and General Remarks

Particle accelerators are invaluable machines that are used to do fundamental and applied research in several branches of science. They are, at the same time, extremely useful for diagnosis and treatment of dreaded diseases/disorders like cancer. Their applications in industry have reached to the levels, elsewhere in world, where they are contributing, directly and indirectly, to the national economy. India has made significant progress in the field of designing and building accelerators. However, most of the accelerators have been built in national R&D institutions and there is a strong need to proliferate them to universities/academic institutions. We should also involve industry in these developments. Strong emphasis needs to be given in India to exploit the immense potential of accelerators for societal applications and industrial development.

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