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Heavy ion accelerator and associated developments in India

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Abstract. Developments of ion accelerator and associated facilities in India are presented. Various types of accelerator facilities which are systematically built in the country through sustained development and research programs at various research centres and institutions are highlighted. Impact of accelerator in different interdisciplinary fields of research are highlighted.

Keywords. Accelerator; tandem Van de Graaff; cyclotron; resonator.

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1. Introduction

The particle accelerator was a planned development started with an objective to split the atom. It was achieved through Cockcroft–Walton particle accelerator in 1932 when lithium atom was split with 400 keV protons. At about the same time Van de Graaff invented the electrostatic generator which provided an excellent tool for probing the nucleus. This led to the inevitable need for higher energy and associated advances in accelerator development. Low energy accelerators started finding applications in many disciplines as nuclear physics moved to higher energy. Nuclear physics exploration needs gradually shifted to heavy-ion accelerators. These opened up new vistas in other disciplines. The impacts of accelerator developments have been felt in astrophysics, materials science, radiobiology, medical diagonosis and therapies and industry besides atomic, nuclear and particle physics. Nuclear physics continues to move to higher energies to explore quark-gluon plasma. Elementary particle physics needs much higher energy, which has now become the driving force for the development of very high-energy accelerators.

I will concentrate on the history of heavy ion accelerators in India. The developments in scientific and allied areas connected with these accelerators will be mentioned.

2. Chronology of early accelerators in India

The accelerator development in India started in the forties but picked up momentum in the fifties. A 37 inch Cyclotron was installed in Saha Institute of Nuclear Physics (SINP), Kolkata and a 1 MeV Cockroft–Walton accelerator was commissioned in Tata Institute of

Fundamental Research (TIFR), Bombay in 1953. In addition, 400 keV neutron generators were installed at the Saha Institute of Nuclear Physics, Kolkata, Bose Institute, Kolkata, Aligarh Muslim University, Aligarh and Andhra University, Waltair. A 66 cm variable energy cyclotron, built at University of Rochester, USA was made operational after some modification in Panjab University, Chandigarh.

In early sixties one 5.5 MV Van de Graaff accelerator of High Voltage Engineering Corporation (HVEC), was installed at the Bhabha Atomic Research Centre (BARC), Bombay which provided much needed filip in accelerator based research in the country. A decision was taken in 1964 that a 224 cm variable energy cyclotron should be built indigenously in Kolkata and one tandem Van de Graaff accelerator should be acquired.

Unfortunately the decision to acquire Tandem Van de Graaff accelerator could not materialize due to foreign exchange constraints and attempts to get it through Indo–US programme in the Indian Institute of Technology, Kanpur as a National facility failed. Establishment of a large tandem accelerator in late sixtees would have made a significant impact to nuclear physics community in the country. The challenge taken to build all components of the variable energy cyclotron indigenously produced delays and the cyclotron became operational only in the late seventees. During this period small Van de Graaff accelerators (400 kV) were installed in the Universities at Varanasi and Patiala, and a 2 MV Van de Graaff accelerator at Indian Institute of Technology, Kanpur. The variable energy cyclotron at Kolkata (VECC) was providing proton beams and was functioning as a user facility.

The accelerator development programme got some boost in early eightees through the indigenous development of a 2 MV tandem Van de Graaff accelerator in BARC, Bombay and establishment of the Centre for Advanced Technology (CAT) at Indore, for the development of technologies associated with accelerators, lasers and related systems.

The 14 MV pelletron, joint BARC–TIFR facility located at the Tata Institute of Fundamental Research Campus in Mumbai started operating in 1988 leading to considerable research work in the field of heavy-ion nuclear reactions, spectroscopy, nuclear fission, atomic physics etc.

Efforts of the academic community to have a front ranking accelerator based research facility within the family of teaching institution finally succeeded in December 1984 with the establishment of the Nuclear Science Centre (NSC) as an Inter-University-Centre under the aegis of the University Grants Commission (UGC). A 15 MV pelletron accelerator was made operational in 1989, and started operating as a user facility in 1990 with experimental facilities such as a recoil mass spectrometer called heavy ion reaction analyzer (HIRA), gamma detector array (GDA), facilities for on-line/in-situ materials science with swift heavy ion beams, dedicated beam lines for atomic physics and radiobiology.

3. Accelerators for allied areas

Synchrotron radiation facility, INDUS-1 is commissioned in June 1999 in the Centre of Advance Technology (CAT), Indore. It is a 450 MeV synchrotron with a 20 MeV microtron as an injector. The next phase INDUS-2 will have 2.5 GeV synchrotron booster which is expected to be commissioned in 2003. It will be possible to operate INDUS-2 at an energy between 700 MeV to 2.5 GeV and is designed to have more than 15 beam lines.

Commissioning of a 3 MV pelletron in Institute of Physics, Bhubaneshwar provided support for increasing demand for materials science and characterization with ion beams, and initiation of accelerator mass spectroscopy (AMS) programme.

ECR development project in NSC has resulted in a low energy ion beam facility (LEIBF) to provide high flux of highly charged ions. There are plans to create a soft landing facility for materials modification.

Successful conversion of the 5.5 MV single ended Van de Graaff accelerator in BARC, Bombay into a 6 MV folded tandem accelerator (FOTIA) has resulted in generation of expertise for accelerator development, besides strengthening the programmes of application of nuclear techniques to other disciplines. Electron accelerators and accelerator dedicated for materials characterization in several institutions, and medical accelerators are not covered here. Possibility of starting some development towards the innovative approach of accelerator-driven-sub-critical reactor system (ADS) is being looked into.

4. Tandem accelerators and boosters

A list of pelletron (with terminal potential lower than 12 MV) is provided in table 1. Also many of the HVEC mechines have been upgraded to achieve higher terminal potentials. These are listed in the second part of the table.

5. Superconducting LINAC boosters

Heavy ion superconducting linear accelerators as boosters to tandem electrostatic accelerators have been operating for more than two decades, and employ a variety of superconducting structures. The development of superconducting structures began in 1960s, and the first demonstration of useful performance was given at Stanford in 1965 in tests on superconducting lead cylindrical X-band cavities, both in single cell and multi-cell configuration. This work laid the foundation for the superconducting accelerator project at Stanford for an electron LINAC based on multi-cell 1.3 GHz niobium cavities. This was the first application of r.f. superconductivity to particle acceleration. Although the project was not successful it addressed all the major problems of the technology, including resonator design, fabrication and operation. Soon after, a project to build a superconducting proton

Table 1. Pelletrons.

ANU, Canberra, Australia	1974	15.5 MV
Tsukuba, Japan	1975	12 MV
Weizmann, Israel	1976	14 MV
Oak Ridge National Lab, USA	1982	25.5 MV
JAERI, Japan	1982	18 MV
CNEA, Argentina	1985	20 MV
TIFR-BARC, Bombay	1989	14 MV
Nuclear Science Centre, New Delhi	1990	15 MV
LNL, Legnaro, Italy		15 MV
CIAE, Beijing, China		13 MV
Max Planck, Heidelberg		14 MV
Munich, Germany		15 MV
Yale University, USA		21 MV
Davesbury, UK		20 MV
Vivitron, Strasburg France		20 MV

LINAC was initiated at Karlsruhe. This project focused on the development of slow-wave structures for protons and heavy ions, and both multi-cell helically loaded cavities and Alvarez-type drift-tube structures were fabricated from niobium and tested. Although the helically loaded structure performed at high field levels it suffered due to poor mechanical stability and posed difficulty in controlling the r.f. phase at high fields. During the same period (1969–71) groups at Argonne and California Institute of Technology also began developing helically loaded slow-wave accelerating structures.

At the California Institute of Technology (Caltech) development started with a helically loaded cavity made of lead plated on copper. Soon variants seeking better mechanical stability were created and initially spiral loaded, and subsequently split-ring cavities were developed. Argonne group switched to develop a niobium split-ring cavity. Phase stable operation of a split-ring cavity above 3 MV/m was achieved in 1977 and this type of cavity formed the basis for the booster LINAC at Argonne, the first superconducting heavy ion LINAC, which began operating in 1978. The lead plated on copper split-ring cavities developed at Caltech were used for the superconducting booster accelerator at the State University of New York at Stony Brook, which began operating in 1983. Another LINAC based on lead plated on copper cavities was built at Oxford and since moved, initially to Daresbury, and later to the Australian National University, Canberra, where it is presently located. The success of the split ring resonator prompted other laboratories to build booster LINACs, which began operation at Florida State University in 1987 and Kansas State University in 1990, and at University of Sao Paulo, Brazil, where the LINAC is presently under construction.

University of Washington, Seattle, Japan Atomic Energy Research Institute (JAERI), and INFN, Italy started programs to build superconducting linear accelerators in the 80s. The Washington group joined an ongoing collaboration between Weizmann Institute and SUNY, Stony Brook to develop the coaxial line quarter wave resonator (QWR). The QWR structure is characterized by excellent mechanical stability and very broad velocity acceptance, making it particularly well suited for a booster required to accelerate ions of a wide range of mass. The LINAC at University of Washington, based on lead plated on copper QWR, started operating in 1988. The group at JAERI collaborated with Argonne and designed a niobium (bonded to copper) QWR for their LINAC, which started operating in 1994. The group at INFN began their program with lead plated on copper QWR, but has since developed bulk niobium, and niobium sputtered on copper cavities successfully. The LINAC at INFN also started operating in the mid 90s.

6. Indian scene

In the early 80s two large tandem accelerators were planned in India. The first, a collaboration between the Tata Institute of Fundamental Research (TIFR) and Bhabha Atomic Research Centre (BARC), for a 14 UD tandem pelletron accelerator located at TIFR, Mumbai, and a 15 UD tandem pelletron accelerator at the newly created inter-university research center – Nuclear Science Centre, New Delhi. Both projects envisaged adding a booster accelerator at the outset of their respective tandem accelerator projects. In the early and mid 80s the TIFR–BARC group collaborated with SUNY, Stony Brook group to learn and develop a superconducting lead plated on copper QWR for their LINAC. This group also thrived in establishing facilities to construct the cavities indigenously using the wellequipped workshops at both TIFR and BARC. At NSC work on setting up a superconducting LINAC started in the early 90s. A collaboration to develop a suitable superconducting structure started at Argonne in early ’92, with the design and fabrication of a niobium QWR. Several novel features, as described briefly in the following, were incorporated in the new design.

1. A niobium QWR jacketed in a stainless steel outer vessel – rather than niobium bonded to copper, as had been done on the split-ring resonator at Argonne and several other labs, and the JAERI QWR – was designed to avoid cracks from developing (from thermal cycling). This design feature has been incorporated in a superconducting radio frequency quadrupole as well as resonant cavities being designed for the proposed RIA project at Argonne.
2. A niobium pneumatic slow tuner bellows was incorporated at the open end of the QWR to provide several kHz of tuning range. This design feature is also being incorporated in the cavities designed for the proposed RIA project at Argonne.

NSC prototype resonator has been installed in the LINAC beamline as a superbuncher and pulsed beam from the 15UD pelletron (FWHM 1.3 ns) has been bunched to 150 ps at the entrance of the LINAC. Work on completing the commissioning of the first LINAC cryostat is nearing completion. A superconducting resonator fabrication facility (SuRFF) is also being set up at NSC to fabricate niobium cavities indigenously. Major facilities include an electron beam welding machine, a high vacuum furnace, and a surface preparation laboratory including a high pressure rinsing facility (DI water at 80 bar).

To enhance the heavy-ion energies from two pelletron accelerators in Mumbai and New Delhi, superconducting LINAC boosters based on quarter wave resonators (QWR) are being developed. The QWR’s for TIFR–BARC booster are being made of OFHC copper with lead plating. LINAC modules with 12 QWR’s has been beam tested. The booster will have seven modules. The booster in New Delhi is based on niobium-based RF technology. The QWR’s for NSC pelletron energy booster was designed and developed in collaboration with the Argonne National Laboratory. The resonator of NSC booster is designed to operate at 97 MHz with better than 3 MV/m acceleration at 4 W of RF input. One booster module with 8 QWR’s is being assembled and will be beam tested by July 2002.

7. Heavy ion cyclotron

7.1 *Variable energy cyclotron*

The $K = 130$ room temperature cyclotron (VEC) operating in Kolkata for the past two decades for light ions is now coupled to an indigenously developed, 6.4 GHz ECR source. It is being used for experiments with 6 to 9 MeV/nucleon oxygen and neon beams.

In order to extend the heavy ion accelerator capability of the VEC, a more powerful and versatile ECR source operating at 14.4 GHz frequency supplied by M/S Pantechnik has been commissioned to produce highly stripped solid ions. All components of the new injection line between this source and the cyclotron are fabricated. Installation and commissioning of this line to inject variety of heavy ions into the cyclotron will begin next month. This will provide a medium-energy heavy ion facility to the experimentalists.

7.2 *Superconducting cyclotron*

In order to extend the scope of heavy ion beams at VECC, it was decided to construct a superconducting cyclotron to provide ions upto 80 MeV/A energy. The project has been making steady progress. Fabrication of the 100 ton main magnet frame was completed. Final inspection of accuracy of machining and assembly is going on. All parts are expected to be delivered at VECC before April 2002. Several test windings, including a 1/5th scale model coil using actual superconducting cable, were made using the sophisticated superconducting coil winding set up. Fabrication of the parts of the RF cavity and associated vendor development has been proceeding satisfactorily. Majority of the fabrication drawings for the complex cryostat assembly are completed. Actual fabrication will begin within the current financial year. Entire scheme of the cryogenic delivery system was finalized and technical discussions with the possible fabricators were carried out. Several precision electronic units for various systems of the cyclotron such as power supplies, RF electronics, controls, magnetic field measurements etc. were fabricated in house. Several meetings were organized at national level to finalize the schemes for experimental facilities of effective utilization of the superconducting cyclotron in the X plan. Majority of the work on the superstructure for the building has been completed. Civil part will be completed by the end of March this year. Beam commissioning trials are expected to be in 2005.

8. Development of experimental facilities

8.1 *Radioactive ion beam facilities*

Beams of unstable ions called radioactive ion beams (RIB) are produced using nuclear reactions. Depending upon the method of extracting the RIB species, they are divided into two kind of facilities: Isotope separator online (ISOL) facility and in-flight facility.

ISOL facility: RIB ions are produced in a thick target, and released through the thermal diffusion. These species are then ionized, pre-accelerated and then further accelerated using post-accelerators.

The major difficulty encountered in this process is in chemical release of the species and the ones most effectively extracted are neutral ions like He, Ar etc. The main technical challenge in accelerating is in the pre-acceleration where efficiency of transmission has to be maximized. The most suitable technology is found to be: ECR ion-source in $1^+/N^+$ mode followed by a mass separator and RFQ/low beta LINAC with post acceleration using high beta LINAC. First such facility to be operational was Louven cyclotron facility in Belgium.

VECC in India has also undertaken an ISOL-based project for producing RIBs using cyclotron as primary accelerator. Major progress has been made in two key areas: the two-stage ECR-based ion source is being tested and fabrication of RFQ is to start soon.

The basic limitation of ISOL-based RIB facility emanates from the slow diffusion process of the ions, which put a limit on the life-time of ions which can be extracted to be upward of 100 ms or so. ISOL facilities for RIB's provide precise energy definitions and good optical qualities. The main limitations of such facilities come from the fact that the life-times of the extracted species are of the order of seconds. A part from this, most of the present generation ISOL facilities with positive ion injectors (Louven-Belgium, GANIL-France) will be delivering only inert gas beam in near future. Those with negative ion injectors (ORNL-USA, LNS-Catania, Italy) will not be able to deliver many species due to negative electron affinity.

In-flight RIB facility: In this type of facility, RIBs are produced using fragmentation or direct reaction. The RIB ions are separated from primary beams in-flight using spectrometers before they decay and are refocused to experimental target for secondary reactions. This type of facility has been operating in NSCL, USA and RIEKEN, Japan using many stages of spectrometers for separating the primary beams.

These facilities have the advantage of getting down to a few nano-second life-time and provide variety of species but at high energies. Light RIB's such as ^{8}Li, ^{8}B (life-time $<$ s), ^{7}Be (negative electron affinity) etc. required for many nuclear reaction studies of astrophysical interests cannot be produced with such facilities. The in-flight RIB facilities like Notre Dame-Michigan facility, USA and CIAE, China have produced a few of these beams.

The facility built up at NSC utilizes in-flight technique where RIB's are produced using direct reactions in inverse kinematics mode. Here the existing pelletron facility acts as primary accelerator and RMS HIRA as rejecter of primary beams and refocusing of RIB's. Use of inverse kinematics eliminates the need of post acceleration as enough energy is imparted to the RIBs by inverse kinematics (e.g. 21MeV ^{7}Be beam is extracted from 25MeV ^{7}Li beam). New optics and hardware has been developed in-house for efficient primary beam rejection in inverse kinematics. ^{7}Be beam extracted is finely focused and pure making it ideal for low energy nuclear reaction studies.

9. Cryogenics for accelerators

Cryogenics at 4.5 K was, until 1990, limited to a few low temperature laboratories for research in basic physics. There were a dozen plants of capacity from 5–20 l/h, most of them based on expansion engines. National Physical Laboratory, New Delhi has a project to develop superconducting magnets and have fabricated magnets of bore diameter of 100 mm with strength upto 7 Tesla. Cryogenics took a quantum jump with the heavy ion accelerator development projects. A large 150 l/h (600 W at 4.5 K) CCI make liquefier was installed at Nuclear Science Centre, New Delhi in 1997 to cool the superconducting cavities of the booster. This is based on expansion engine and has operated well with annual production of 40,000 l. TIFR, Bombay installed a Linde machine of capacity 100 l/h (380 W at 4.5 K in 2000) for their booster. In the same year VECC, Calcutta commissioned Air-Liquide plant with a production rate of 100 l/h to cool the magnet of the superconducting magnet with a bore diameter of 140 cm along with the cryopanel for pumping the cyclotron. A large Air-Liquide liquifier of capacity 400 W at 4.5 K plus 200 l/h liquid to cool the magnet and current leads of a steady state superconducting Tokomak is commissioned at the Institute of Plasma Physics, Ahmedabad. Other than the helium refrigerators there have been development of large size cryostats and distribution networks. An indigenously developed liquid helium distribution network with a total length of 40 m was commissioned in NSC last year.

10. Accelerator mass spectroscopy

Heavy ion accelerators provide an ultra-sensitive technique for counting trace elements resulting in accelerator mass spectroscopy (AMS) for dating. It has been used widely for radiocarbon dating. The ratio of ^{14}C to ^{12}C in a sample provide information about the date when an organism died upto 5000 years (half-life of ^{14}C is 5730 years). AMS can be used for detection of long lived radio-isotopes, e.g., ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{129}I etc. More than 50 accelerator laboratories in the world are used for AMS. Although cyclotrons are used for AMS because of the high current, tandem accelerators are preferred. This is because tandems use negative ions which avoids interference of stable isobars ^{14}N (for ^{14}C), ^{26}Mg (for ^{26}Al), and ^{129}Xe (for ^{129}I) as they do not form negative ions.

Tandem accelerators of lower potentials are good for ^{14}C measurements. The big machines are used for the measurements of ^{36}Cl, ^{41}Ca and ^{59}Ni where because of higher energies the techniques available for nuclear detection make it possible to determine both charge and mass of rare isotope precisely and competition from neighboring stable isobars ^{36}S, ^{59}Co are eliminated.

The Institute of Physics, Bhubaneshwar commissioned the first AMS facility in India with a 3 MV tandem accelerator focussing on ^{14}C measurements and planning some ^{10}Be measurement for the future. Extensive modification to the machine has been done by installation of a 40 sample multi-cathode source allowing quick throughput in sample measurement, a fast switching method by modification of the injector magnet chamber by putting in a bouncer tube and a pulsing system along with offset cups. The analyzer magnet chamber has also been modified to include an offset cup where ^{13}C is measured while ^{14}C is counted in a detector. An electrostatic analyzer has also been put to eliminate effects of ^{13}C contamination with ^{14}C due to charge-changing collisions in the high energy end of the machine.

The Nuclear Science Centre is trying to supplement such measurements by utilizing part of the beam time available to measure ^{36}Cl and other isotopes which IOP facility cannot measure. A multi-cathode source will be installed later this year. A velocity selector (Wien filter) is designed and ordered. A multi-anode detection system and an off-axis Faraday cup has been indigenously fabricated, installed and tested with beam. A recirculating terminal turbo gas stripper system is also installed to achieve stability of transmission. Modifications to the injector magnet and analyzer magnet are contemplated for future. In the second phase a gas-filled magnet is planned for better separation of ^{36}Cl and ^{36}S. The Wadia Institute of Himalayan Geology, Dehradun, University of Pondicherry, JNU, New Delhi, Physical Research Laboratory (PRL), Ahmedabad are some of the institutes providing support in sample procurement and analysis. When the high current injector and the LINAC are fully commissioned a major portion of pelletron beam time will be used for AMS studies.

11. Developments in material science due to heavy ion accelerators

Heavy ion accelerators of high energies, providing swift heavy ions (SHI) upto several GeV, and choice of ion species have created a new area of intense activity called ‘swift heavy ions in materials engineering and characterization (SHIMEC)’. Compared to sparsely ionizing radiation SHI (energy $>$ 1 MeV/nucleon) moving inside the target exhibit different physical interaction with material. They predominantly interact through inelastic scattering with the electrons producing trail of excited/ionized atoms and electrons along the path of the primary ion. This is known as electronic energy loss (Se). Its effects on materials are in contrast to familiar elastic scattering of low energy ions causing direct damage (defects) in the lattice. It is found that SHI can also affect the lattice, as evident from the well-known phenomena of tracks produced in insulators, if the electronic energy Se exceeds a certain threshold. It is our ability to control and produce defects that provide possibility of engineering new materials. In other words, we can modify materials so that they can acquire desired optical, electrical and mechanical properties. Electronic energy loss in the materials can be varied from the level of eV/A upto a very high value, say 10 keV/A by choosing appropriate ions and their energies. This remarkable flexibility provides unique opportunities to engineer properties of the materials.

High Tc superconductors: It has been demonstrated that columnar defects in high Tc superconductors provide the pinning of vortices that improves the critical current and associated properties of materials. In superconducting microwave devices subject to magnetic field, the columnar defects help to control dissipation due to the motion of vortices.

Electronic devices: Heavy ions can anneal existing defects in the materials under certain conditions and, of course, produce defects after the threshold in electronic energy loss is exceeded. This has applications in deep implantation associated devices. It is observed that strains in the crystal lattice can be relived by the electronic energy loss. The characteristics of the devices can be profitably modified.

Magnetic materials: The precipitation of amorphous latent track by SHI is also observed in crystalline metallic targets, but need large Se. This opens up applications in the field of magnetism, where most of the materials are metallic.

Nanostructures: SHI modify material in columns of 50–100 Å diameter. These columns when etched give controllable size pores and are used as micro-filters. These columns can be filled with desired materials to form diode arrays etc. These can lead to synthesizing nanostructures.

12. Concluding remarks

Accelerator development programme in India has always been very seriously affected by the resource crunch. Projects formulated usually take enormous time and efforts to materialize. This has hampered the natural growth. Perseverance of the community is mainly responsible for whatever progress or continuity in the accelerator development programme. Impact of accelerators in various disciplines, particularly materials science has been constantly increasing which is perhaps the main reason that the nuclear physics community manages to get financial support for accelerators. Technological developments associated with the accelerators and experimental facilities required for experiments continue to provide very significant input to new technologies. Emerging possibilities of use of accelerators in generating clean power is expected to provide significant impetus for future developments.

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