DEVELOPMENT OF HEAVY ION ACCELERATOR AND ASSOCIATED SYSTEMS

D. Kanjilal, Inter University Accelerator Centre, New Delhi 110067, India

Abstract

A 15 UD Pelletron electrostatic accelerator is in regular operation at Inter-University Accelerator Center (IUAC). It has been providing various ion beams in the energy range from a few tens of MeV to 270MeV for scheduled experiments. A superconducting linac booster module having eight niobium quarter wave resonators has been made operational for boosting the energy of the heavy ion beams from the Pelletron for experiments at higher energies. A new type of high temperature superconducting electron cyclotron resonance ion source (HTS-ECRIS) was designed, fabricated and installed. It is in regular operation as a part of an alternate high current injector (HCI) system being developed for injection of highly charged ions having higher beam current in to the superconducting linac. A radio frequency quadrupole (RFQ) accelerator is being developed to accelerate highly charged particles (A/Q ~ 6) to an energy of 180 keV/A. The beam will then be accelerated further by drift tube linacs (DTLs) to the required velocity for injection of the beams to the linac booster. Details of various developmental activities related to the heavy ion accelerators and associated systems are reported.

ACCELERTOR AND RELATED SYSTEMS

Pelletron

The 15UD Pelletron electrostatic accelerator [1, 2] having compressed geometry tubes for 16MV terminal potential, is in regular operation at IUAC since 1990. It has been upgraded by using resistor grading of accelerating columns and support posts, two turbo molecular pumps based re-circulating gas stripper along with a foil stripper system at high voltage terminal, multi harmonic buncher, multi-cathode sputtered negative ion source, external chiller for cooling the re-circulating SF_6 gas and accelerator mass spectrometry beam line having off-set Faraday cup and Wien filter. One of the unique features of the Pelletron at IUAC is the incorporation of the off-set quadrupole triplet (see Fig. 1) after the Gas/Foil Stripper system for selection of ions having desired positive charge state inside the terminal before acceleration by high energy section after the terminal. A matching quadrupole triplet after the off-set quadrupoles is used to match the selected ions to the high energy section of the Pelletron. This helps in decrease in loading of the charging system by reducing the number of charge states to be accelerated after the terminal to one charge state selected by the off-set quadrupole triplet followed by matching quadupoles triplet inside the high voltage terminal. It also makes the analysis of the charge states of ions stripped of electrons again at higher energy by the next foil stripper in the high energy dead section located after six of the fifteen units from the terminal simpler. The 15 UD Pelletron has been operational round the clock seven days a week maintaining high uptime and delivering a variety of beams to users from all over India and abroad. All types of problems faced during its operation since 1990 are solved successfully by the accelerator personnel of IUAC. The integrated beam pulsing systems have been in regular use for various experiments and for accelerating beams through LINAC. The AMS facility has been tested successfully and user experiments have been carried out regularly.

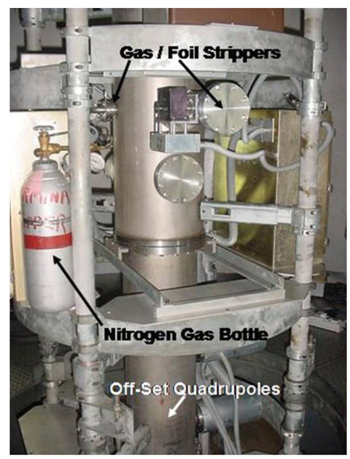

Figure 1: Off-set quadrupoles after strippers in terminal.

Supeconducting Linac Booster

The basic design and development of the superconducting linear accelerator (linac) which started in early ninties at IUAC is based on niobium technology. Later a collaboration to design and fabricate a suitable superconducting linac structure was developed in early 1992 with Argonne National Laboratory (ANL) [3]. Quite a few novel features were incorporated in the new design. Instead of niobium bonded to copper which was used in ANL's split-ring resonator, a niobium quarter wave resonator (QWR) jacketed in a stainless steel outer vessel was developed [4]. The linac system at IUAC consists of one superbuncher cryostat having one QWR, three linac modules and one rebuncher cryostat containing two QWRs. Each linac module consists of a cryostat holding eight QWRs and one superconducting solenoid magnet (see Fig. 2). Twelve resonators were fabricated in collaboration with ANL [5]. Another three resonators have been fabricated indigenously and tested. Two of them are used in the first linac module and rebuncher.

dk@iuac.ernet.in

Bulk production of fifteen more QWRs for second and third linac modules are nearing completion.

All the problems observed during acceleration of beam through the first linac module have been analyzed systematically and rectified successfully. Some of the major problems encountered during earlier beam tests were: 1) inadequate cooling of the niobium resonators by liquid helium for attaining higher accelerating fields, 2) requirements of high RF power (150-300 W) to operate the resonators leading to cable melting, metal coating on the niobium surface and increased cryogenic losses, 3) cold leak in the tuner bellows from the vacuum seal and/or from the electron beam welded joints of the niobium bellows convolutions of the tuner, and 4) exposure of brass rack and pinion mechanism of the drive coupler causing zinc coating on the inside surface of the RF power port of the niobium resonator. These problems were systematically analyzed and solved for further beam tests and regular operation of linac (see Fig. 2) for scheduled experiments.

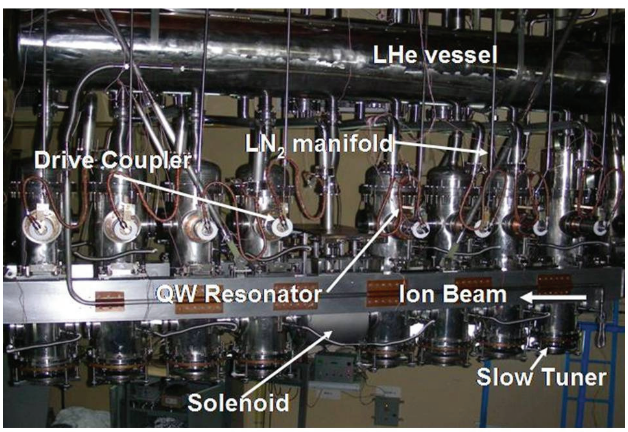

Figure 2: First linac having eight QWRs and super-coducting solenoid.

Hemispherical dome structure on each of the eight Nb QWRs was incorporated to avoid accumulation of bubbles below the top flat flange. In addition to the stoppage of formation of bubbles near the top Nb surface by moving them upward, the dome structure provided a buffer volume for liquid helium near the top Nb surface where current is maximum. After this, all resonators performed very well and an average field of about 4 MV/m could be achieved regularly. The requirements of forward RF power was reduced by a factor of about half by using a novel technique of damping the mechanical modes of the resonator [6]. For this purpose eighty polished stainless steel balls of 4 mm diameter were inserted in the central conductor. With the new damping mechanism, a forward power of less than 100 W was found to be sufficient for each of the resonators to lock it at maximum achievable fields (up to 5 MV/m) at ~ 6 W of power going into liquid helium (LHe). An improved slow tuner fixture was designed to avoid entry of helium gas inside niobium bellows for controlling the capacitance. The slow tuner is controlled by flexing stainless steel (SS) bellows which pulls or pushes Nb bellows by a SS-shaft. The problem of helium leakage from slow tuner disappeared after incorporation of this new design. Modified drive couplers are designed and fabricated to avoid exposure of brass made rack and pinion mechanism. The problem of coating on the niobium surface near RF power port is eliminated. The superconducting niobium resonator fabrication facility was commissioned at IUAC. The facility consists of an electron beam welding machine, surface preparation laboratory for ultrasound cleaning, electropolishing, high vacuum furnace for heat treatment/annealing, high pressure rinsing and a test cryostat. Initially a single QWR was fabricated and tested successfully. It is being used in the rebuncher cryostat of the linac. Later two completely indigenous QWRs were fabricated. One of them is installed in the first linac module for regular operation of linac. Production of fifteen more QWRs for the 2nd and 3rd linac modules is at the final stage of completion. In addition to the in-house programs of indigenous fabrication of resonators and associated components, IUAC has taken up a project to construct two niobium single spoke resonators for Project-X at Fermi National Accelerator Laboratory (FNAL), USA. Raja Ramanna Centre for Advanced Technology (RRCAT), India has started fabrication of a Tesla-type single cell niobium cavity in collaboration with IUAC.

For acceleration through linac the ion beam from negative ion source is bunched by multiharmonic buncher placed before entrance to the 15UD Pelletron accelerator. The high energy sweeper after the analyzer magnet is used to remove the background of the pulsed beam pre-accelerated by the 15 UD Pelletron. The typical pulse width available is about 1 ns. The beam is further bunched to 150 to 200 ns by adjusting amplitude and phase of the superbuncher (one QWR) before the entrance of the first linac module. Each of the linac modules consists of total eight QWR resonators with a superconducting solenoid placed at the centre of the module as shown in Fig. 2. After optimizing the phase and amplitude of every resonator the beam is accelerated to the required energy to conduct scheduled experiments. The energy focus or time focus at the target in the experimental chamber is optimized by adjusting the superconducting rebuncher having two QWRs [7]. Time focus of about 400 ps is achieved.

During various beam acceleration experiments through linac, the transmission of more than 90% was achieved through the niobium QWR resonators. A series of tests were conducted systematically before regular operation of SC-LINAC booster for scheduled experiments started. All the resonators in the linac cryostat have been performing satisfactorily. An average accelerating field of ~4 MV/m is obtained at 6 W of input power. All the cavities were phase locked with ~100 W of forward power from the amplifier. The average locking field was ~3.8 MV/m.

Beams of carbon, oxygen (isotopes A=16 and A=18), fluorine, silicon, titanium and silver have been accelerated by the linac.

High current Injector

A high current injector (HCI) system is being developed for injection of highly charged ions having higher beam current in to the superconducting linac. A high temperature superconducting ECR ion source (HTS-ECRIS) PKDELIS[8] requiring simpler single-stage cryostat and air-cooled cryo-cooler has been designed, developed and installed successfully (see Fig. 3). The performance of the source is as per the design goal. Analysed beam current of more than one milli-Ampere for nitrogen, neon, argon are obtained from this source. The HTS coils have been operational for more than 27000 hours without any problem. A radio frequency quadrupole (RFQ) accelerator is being developed to accelerate highly charged particles (A/Q ~ 6) to an energy of 180 keV/A. The beam will then be accelerated further by drift tube linacs (DTLs) to the required velocity for injection of the beams to the linac booster.

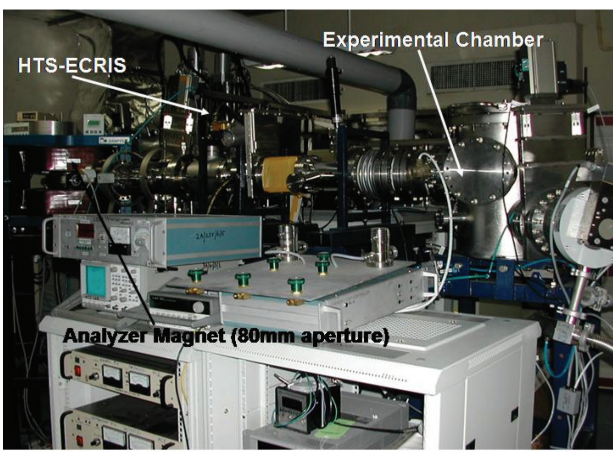

Figure 3: The HTS-ECRIS with analyzing magnet.

The cryogen-free HTS-ECRIS is very suitable for operation on a high voltage platform as required for our HCI program. The two axial coils are cooled by single-stage Gifford McMahon type refrigerators to 23K for optimum operation. The performance of HTS-ECRIS is found to be excellent. The power and cooling requirements of this type of ECRIS is decreased by a factor of 10 compared to conventional ECRIS using copper coils.

To reduce the loading of the high voltage power supply biasing the high voltage platform and the accelerating tubes across the platform and ground due to space charge of multi-charged ions from ECR, a large acceptance analysing magnet having 80 mm pole gap is placed on the high voltage platform to pre-select ions from the ECR source befor acceleration from the high voltage platform. The main design goals for the analysing magnet are large acceptance, minimum weight, air-cooling and reasonable mass resolution. The geometrical aberrations due to higher order terms are minimized by incorporating multipole field components. The vertical focussing is obtained by incorporating increasing sextupole field components at the entrance and exit of the magnet. This is achieved by having cylindrical pole shape at entrance and exit with negative radius of curvature. The horizontal focussing is achieved by introducing decreasing sextuple field component in the radial plane at the middle of the magnet.

A prototype unmodulated 48.5 MHz radio frequency quadrupole (RFQ) was developed initially to have a detailed understanding of the various issues involved in the mechanical design, beam optical design and tests. The electrodes are in the form of four-rod structure. The bore radius and length of the electrodes are 4 mm and 1.17 meters respectively. A fully automated bead puller system is used to test the performance of the prototype RFQ. The prototype is a full scale model of the final design. The design parameters like RF frequencies, shunt impedance, water cooling, tunability, mechanical vibrations and stability are being investigated with this prototype. After successful bead pull tests of unmodulated prototype RFQ, modulated vanes are fabricated (see Fig. 4).

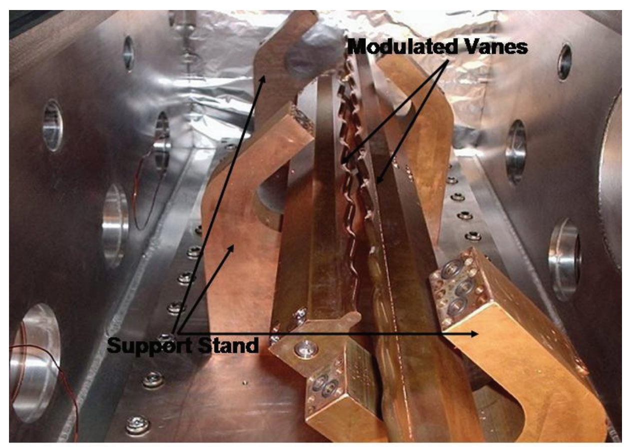

Figure 4: Modulated vanes of RFQ in the chamber.

Six Inter-digital H type RF resonators operating at 97 MHz are being designed and developed to accelerate ions from 180 keV/u to 1.8 MeV/u. A bead pull test was carried out to measure the voltage profile across the gaps of the first prototype cavity (see Fig. 5). The voltage profile is found to be reasonably good. The prototype cavity having an inner diameter of 85 cm and length of 38 cm is fabricated using SS304 material. The vacuum test is completed successfully. The machining of the ridges, stems and drift tubes has been carried out at IUAC using the in-house vertical machining centre (VMC) and associated facilities. Water cooling channels have been made in each of the stems as well as the end walls of the cavity.

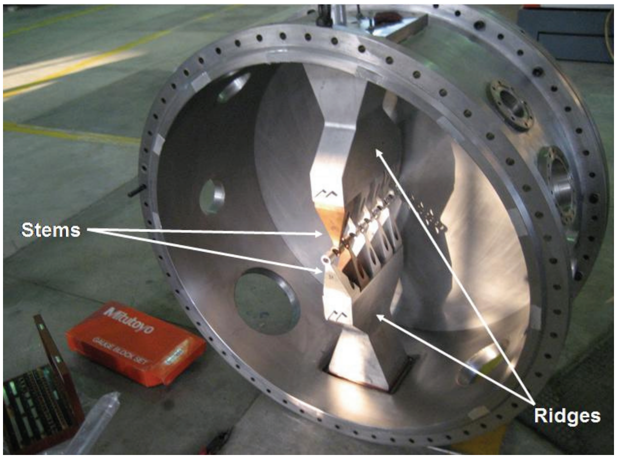

Figure 5: Prototype DTL cavity with stems and ridges.

CONCLUSION

The 15 UD Pelletron has been in regular operation round the clock seven days a week. It has been upgraded at various stages for improved performance. It has been delivering various beams from proton to gold in a wide range of energy from tens of MeV to hundreds of MeV. The first module of the superconducting linac booster is fully operational. Various beams have been accelerated using this linac module. Average accelerating field achieved was more than 3.5 MV/m. A cryogen free high temperature superconducting ECR ion source (HTS-ECRIS) PKDELIS for alternate high current injector for the superconducting linac has been developed for production of various ion beams at higher charge states. Its superconductiong axial coils have been under regular operation at 23K for more than 27000 hours. This high performance HTS-ECRIS requires much less power and cooling water making it ideal ion source for operation on a high voltage platform for future high current alternate injector. The RFQ and DTL are being developed as a part of the high current injector program. Development of other superconducting resonators as collaborative projects are taken up.

ACKNOWLEDGEMENTS

The author is grateful to A. Roy, Director, IUAC for planning and executing the futuristic programs in development of accelerators and associated systems. The contributions of the colleagues at IUAC involved in these developmental projects are highly appreciated.

REFERENCES

[1] D.Kanjilal et al, Nucl. Instr. Meth. A 328 (1993) 97.
[2] S. Chopra et al, Nucl. Instr. and Meth A 550, 70 (2005) 70.
[3] D. Kanjilal, DAE-BRNS Symp on Nucl. Phys., 47A (2004) 21.
[4] A. Roy, Current Science 76 (1999) 149.
[5] P. N. Prakash et al, Pramana 59 (2002) 849.
[6] S. Ghosh et al, Phys. Rev. ST Accel. Beams 10 (2007) 42002.
[7] S. Ghosh et al, Phys. Rev. ST Accel. Beams,12,Phys. Rev. ST Accel. Beams 12, (2009) 40101.
[8] D. Kanjilal et al, Rev. Sci. Instr. 77 (2005)1.