SUPERCONDUCTING CYCLOTRON PROJECT AT VECC

R.K. Bhandari and Bikash Sinha

Variable Energy Cyclotron Centre, Department of Atomic Energy
I/AF, Bidhan Nagar, Calcutta 700 064, India

Abstract

Construction of the superconducting cyclotron has been making steady progress at this Centre. Several major components of the accelerator are already on order. In house fabrication of some special systems and components is also going on. Fabrication problems related to certain cryogenic parts of the accelerator have been largely overcome. Efforts are being made to fabricate the components, as far as possible, within the country to generate enough indigenous expertise for efficient development and operation of the cyclotron. It is scheduled to be commissioned in early 2002. In this paper, the progress made on various aspects of the machine will be described.

1 INTRODUCTION

A room temperature Variable Energy Cyclotron (VEC) with K value 130 has been operating at our Centre since 1981 as a national facility for the Indian universities and research institutions. It has recently been upgraded by adding a 6.4 GHz ECR source to meet the users' demand for heavy ion beams. Towards the end of 80s we had submitted a proposal to our Department for constructing a superconducting cyclotron to further expand the scope of heavy ion research at the Centre. The proposal was approved and funding became available in early 1993. Design of the Calcutta superconducting cyclotron[1] is similar to the machines operating at the National Superconducting Cyclotron Laboratory (NSCL)[2], MSU and Texas A&M University (TAMU)[3], College Station, both in USA. The bending and focussing limits are 520 and 160, respectively. Therefore, light and medium mass heavy ion beams with energy between 80 MeV/A to ~10 MeV/A are expected to be available (Figure 1). A new building will be constructed within the campus for the new accelerator. In the first phase, two experimental areas for heavy ion research and one for medical applications will be available. For future expansion of the accelerator facility, provision has been kept in the building and beamlines design to bend the beam by 180^o and transport it for injection into the VEC. Status of fabrication of various system and components is described in the following sections.

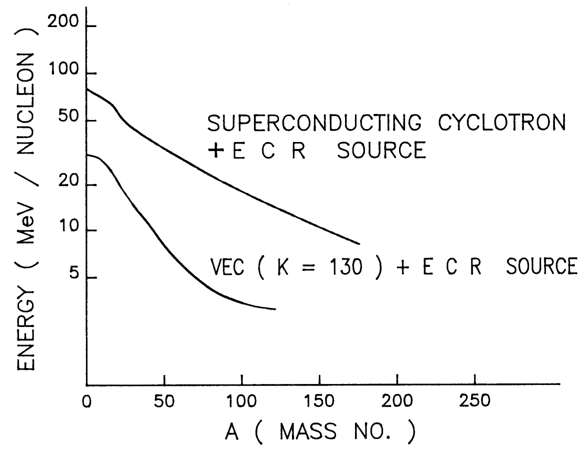

Figure 1: Energy /nucleon vs. mass for heavy ion beams to be available with VEC and superconducting cyclotron

2 CYCLOTRON SYSTEMS AND COMPONENTS

The cyclotron magnet has a pole diameter of 142 cm and the beam would be extracted at 67 cm radius. Maximum hill and valley fields are expected to be 5.8 T (hill gap: 6.35 cm) and 4.3 T (valley gap: 91.4 cm), respectively, resulting in a maximum average field of 4.9 T. There will be three spiral-shaped 53^o dees and the normal operating frequency for the RF system will range between 9 to 27 MHz. Maximum dee voltage is 80 kV. The acceleration chamber is evacuated, primarily, with the help of turbomolecular pumps and cryopanels.

2.1 Main Magnet Frame

The main magnet frame which provides return path for the magnetic flux will be made from low carbon steel forgings. This pill box type structure, enclosing the cryostat and superconducting coil assembly, is made of five major parts i.e. upper and lower pole caps, upper and lower return path rings and centre return path ring. There are three pairs of spiral sectors bolted to the upper and lower pole caps with appropriate fixtures. Maximum allowable carbon content is 0.25%. However, it is important to control the chemical composition and heat treatment for the upper and lower symmetric parts. Variation of carbon percentage between upper and lower pole caps over 0.07% is not allowed. This requires rather

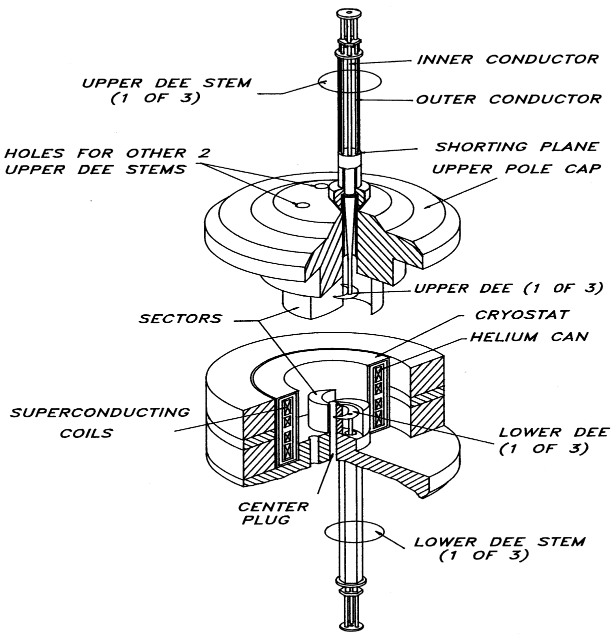

Figure 2 : Cross sectional view of the superconducting cyclotron at VECC

stringent quality control in preparing the forgings. All the forgings will be subjected to ultrasonic tests for voids etc. Another important issue is the uniformity of magnetic properties over the surface of each pole cap. Samples taken from the pole caps will be subjected to magnetic tests at about 4 T field. Three fold symmetry is of particular importance.

Contract for fabrication of the forgings as well as complete machining of this 100 tonne magnet frame has been awarded to M/s. Heavy Engineering Corporation Limited, a public sector company who had earlier fabricated the magnet frame for the VEC. All parts of the frame are expected to be available on site in about two years' time from now.

2.2 Superconducting Coil

A bunch of 500 NbTi filaments, each of 40 μm diameter, in copper matrix, forms the superconductor for the coil. The bunch, overall diameter 1.2 mm, is embedded in a slot along the length on the broader face of copper wire with 2.794 mm x 4.978 mm cross section. Copper to superconductor ratio for each filament is 1.3:1 while its overall value is 20:1. A division of the Bhabha Atomic Research Centre, Mumbai, is developing the cable for our cyclotron. Minimum continuous length of 3 km is expected to be available.

The coil is split into two parts, namely, α-coil and β-coil for proper shaping of the magnetic field radial profile. It is wound on a stainless steel bobbin as shown in figure 2. The bobbin forms part of the cryostat. The coil will operate in cryostable mode. In order to provide passage for liquid helium to come in direct contact with the superconductor in each turn, vertical spacers are used between each two layers of the coil. These spacers are made of fibre glass laminates (NEMA G-10) and are azimuthally distributed at 2^o interval. Turn to turn insulation will be provided by using 0.1 mm thick mylar sheets. Glass epoxy laminates are used to make spacers between the α-coil and β-coil. The winding is done at high tension of 2,000 psi to prevent the conductor movement. Further, after winding, ten layers of aluminium banding will be wound at 20,000 psi around the coil. The bobbin is welded shut to form the liquid helium can.

An elaborate set up to wind the superconducting coil is under fabrication and is expected to be delivered on site later this year. The set up incorporates mechanisms for straightening of the conductor, tensioning, cleaning, soldering, ultrasonic checking, dimension checking, insulation application etc. A full scale steel bobbin is under fabrication for simulating the actual winding conditions to test the set up. It is also planned to wind a 1/5 scale coil with actual superconducting cable.

2.3 Cryostat and Cryogenic Transfer Lines

The vessel, referred to as liquid helium can above, is one major part of the cryostat. It will be made from special stainless steel with 12-14% Ni contents for better welding properties. This assembly, including the coil, is wrapped with several layers of super insulation and placed inside an annular space between two concentric cylindrical vessels made of magnetic steel. This annular chamber is called the coil tank. It is evacuated to a pressure ~$2x10^{-5}$ under normal operating conditions. The inner cylinder encloses the magnet pole piece. The outer cylinder encloses the liquid helium chamber and is in turn enclosed by the magnet frame as shown in the figure 2. Surfaces of the coil tank which face the vacuum are electroless nickle plated in order to minimize outgassing. Thin copper cylinder cooled by liquid nitrogen, called radiation shield, is placed between the coil tank walls and the liquid helium chamber. The radiation shield is wrapped with multilayer insulation. This shield along with the super insulation and coil tank vacuum serve to minimize the heat load.

The components mentioned in the above paragraph are all in two halves - one above and the other below the median plane. They are, however, interconnected through thick stainless steel plate having vertical penetrations for flow of liquid helium, in the liquid helium chamber region, between upper and lower half. There are several horizontal penetrations which provide access to drive the parts of deflector and diagnostic probes in the acceleration region. The actuators for these drives are located outside the magnet frame. The superconducting coil is held in position with the help of nine support links of which six are horizontal and three vertical. Scotch ply is used for making these links which are fitted with strain gauges for proper alignment of the coil when energized. Special care is taken to minimize the heat load through the support links.

The cryostat assembly is a very complex part of the cyclotron in view of special welding standards, several interfaces with the other parts and the need to minimize heat loads on liquid helium chamber. We have consulted with several manufacturers for its fabrication and assembly. It is very difficult to make one agree to do this job. However, the problem will soon be overcome as a couple of them have agreed to take it up as an R&D job. But it may cost us more. Some welding skills to fabricate the cryogenic components are being developed in house in our workshop.

The network of cryogenic transfer lines delivers liquid helium and liquid nitrogen to the cryostat and the cryopanels in acceleration region of the cyclotron. They have a special role to play during cooldown of these components from room temperature to the operating temperatures. The dewars containing these cryogens are to be located in the high bay area above the cyclotron vault. About 50 to 60 meters of transfer lines will be required as per our building plan. There are two types of transfer lines, namely, liquid jacketed lines and vacuum jacketed lines. In the liquid jacketed lines there are four thin walled stainless steel tubes inside a vacuum pipe. Two tubes carry liquid and gaseous helium and the other two carry liquid and gaseous nitrogen. All these four tubes are enclosed by radiation shield at 100K and multilayer insulation. The vacuum jacketed lines comprise of single thin walled stainless steel tube wrapped with multilayer insulation inside a vacuum pipe. The cryopanels are installed in lower dees of the cyclotron. For this reason the cryogens are first transported to the basement below the machine and then pumped up. The pump cryostat, housing both liquid helium and liquid nitrogen pumps, is located in the basement. It has been decided, at present, to fabricate the transfer lines in the laboratory. A special facility is being set up for this purpose. Some prototypes have already been fabricated and are under tests.

2.4 Cryogenic Plants

Heat loads for the liquid helium plant add up to about 120 W at 4.5K. They include cryopanels (60 W), cryostat/coil assembly (38 W), median plane penetrations (8 W), current leads (6 W) and miscellaneous loads (8 W). A liquid helium plant with refrigeration capacity over 200 W at 4.5K is being procured. In the liquid helium production mode, it will generate over 70 litres per hour with liquid nitrogen pre-cooling. A 90 litres per hour capacity liquid nitrogen plant is already in operation at the Centre. It will be augmented to generate about 175 litres per hour in different stages as the project progresses. Two 1000 litre dewars -one each for liquid helium and liquid nitrogen, will be located in the high bay area as buffer storage for the cyclotron.

2.5 Radiofrequency System

The accelerating system comprises of three dees placed in the valleys. Each dee is made up of two halves which are installed in the corresponding upper and lower valleys. The two halves are connected somewhere near the extraction region. A unique aspect of this system is maintaining phase difference of 120^o between two successive dees, in order to accelerate particles in fundamental mode, as far as possible. The dees are fed separately from three chains of amplifiers.

Three $\lambda/2$ resonators are inserted vertically, 120^o apart, through the magnet pole caps as shown in the figure 2. Each of these ~20 m long resonators consists of two $\lambda/4$ cylindrical cavities tied together at the centre. They are symmetrically placed above and below the median plane. These cavities are short-circuited transmission lines terminated by the upper and lower dee halves. Each cavity has two portions. The portion nearer to a dee half comprises of coaxial inner and outer conductors made of OFHC copper. While the outer conductor is cylindrical with uniform diameter, the inner conductor has tapered diameter. This portion is thus a tapered transmission line. It extends slightly above and below the respective pole caps. The other portion is made up of hexagonal outer conductor and cylindrical inner conductor. Frequency tuning is carried out with the help of movable sliding short in this portion. Silver graphite buttons attached to Be-Cu contact fingers on the sliding short provide contact between the inner and outer conductors. Cooling is done using low conductivity water (LCW).

We plan to use Eimac 4CW 150,000E tetrode tube for each of the 3 main amplification stages. Two solid state amplifiers, each providing 300 W power output, will drive the main amplifier. Tuning of the amplifiers is carried out by movable sliding shorts similar to those in the resonators. Trimmer capacitor will do the fine tuning. RF energy is coupled to the resonators in the lower half through coupling the capacitor.

The resonator assemblies are under fabrication at the Central Workshops of the Bhabha Atomic Research Centre, Mumbai. Prototype cavities will be ready by the end of the 1998 for experimental studies. Extensive computer simulations using SUPERFISH code are being pursued. The electronic part of the system is being done by the RF group at the Centre.

2.6 Trim Coils

There are 13 sets of trim coils wound around the pole tips (sectors). These conventional coils will be fabricated using 6.35 mm square cross section copper conductor with central hole for water cooling. Insulation is provided on each turn during winding. A spare pole tip has been ordered with the company fabricating the magnet frame. It will be used to wind the trim coils at the Centre.

2.7 Injection

Heavy ions will be injected externally along the magnet axis through the upper pole cap. A spiral inflector will be used at the cyclotron centre for inflection. At present our planning is to install two 14 GHz ECR sources in the high bay area. Both of them will be room temperature sources. First design of the external injection line has been worked out, primarily, for finalizing the building design. Magnetic elements will be used on the line.

2.8 Extraction

The extraction system consists of two electrostatic deflectors followed by nine magnetic channels. The electrostatic deflectors are placed in two successive hills and are of angular width 55^o and 43^o, respectively. The electrodes are made of stainless steel 304. The septum material is titanium while the spark anodes are made of tungsten. The electrostatic deflectors introduce enough turn separation so that the magnetic channels take over the rest of the extraction process. Magnetic channels are far more effective as compared to electrostatic deflectors. They are made of low carbon steel and each channel is a triplet of three bars shaped to match the beam orbit. Extraction takes place almost over one full turn. All parts of the extraction system are movable with the help of actuators. In order to compensate for the asymmetry harmonics introduced by the movable magnetic channels, compensating bars have been provided. These bars also can be positioned as desired. Prototypes of the magnetic channels have been fabricated for field distribution studies.

2.9 Vacuum System

Clean high vacuum is required in the cyclotron not only for the survival of heavy ions during acceleration but also for holding high voltages for acceleration and extraction systems. The acceleration chamber will be evacuated to a normal operating pressure of about 10^{-7} torr. Due to the compact design of the cyclotron, pumping is severely conductance limited. Three 75 mm diameter pumping conduits have been provided through the upper pole cap where 3 turbomolecular pumps will be installed. These pumps are expected to evacuate the chamber to about 10^{-5} torr in ~4 hours. Subsequently, liquid helium cooled cryopanels will take over the main pumping. These panels are mounted in the three lower dee halves and are surrounded by liquid nitrogen baffles. A total of about 4,000 l/s pumping speed will be offered by the cryopanels. Narrow space between the copper RF liner and the untreated pole surfaces will be differentially pumped to maintain cleanliness and level of vacuum obtained by the cryopanels.

2.10 Power Supplies

The α and β superconducting coils are energized by two independent power supplies, each rated for 20 V, 1000 A (max) with 10 ppm long term stability. In order to protect the coil in case of a quench or a catastrophic situation, the stored energy (up to 22 MJ) is diverted on to a fast dump resistor. The rate of current decay in such a situation is limited to maximum 5.3 A/s in order to avoid excessive mechanical stresses on the radiation shield in the cryostat. On the other hand, a slow dump system is used to discharge the current in normal and controlled operation. In this case the current decay rate is 0.241 A/s. There will be 18 trim coil power supplies with rating 30 V, 400 A (max) with 30 ppm long term stability. A large number of power supplies with similar ratings will be required for the beam line magnets, ECR source and low energy injection line magnets.

The radiofrequency system, operating with three identical amplifiers uses one 20 kV, 22.5 A anode power supply with fast crowbar protection mechanism. Moreover, 3 each of screen grid, control grid and filament power supplies will also be required to operate this system. Two deflector power supplies are rated for 120 kV, 2 mA operation. Our experience with VEC shows that it is rather advantageous to build the power supplies in house provided, of course, sufficient manpower is available. Major design and development work has been taken up for all types of power supplies. Several prototypes have also been fabricated and successfully tested.

2.11 Computer Control

The need for stringent control and monitoring of various systems' parameters calls for a computer-based control system. The actual strategy to be adopted is still in the stage of evolution. However, it is tentatively planned to provide high-end graphics workstations as operator consoles. In the front-end/equipment layer of control, several PCs may be connected. The hardware interfaces may be add-on cards for PC, PLCs and/or microcontrollers in view of their easy availability and in-house experience in their use. Operating system at the operator interface level will be UNIX, while LYNXOS or QNX is preferred for the front-end/equipment layer computers. It is also proposed to build up data bases for different cyclotron systems and parameters for effective on-line development. Several prototype computer control projects have been started at the Centre.

2.12 Beam Lines

The use of movable magnetic channels in the extraction system makes the beam exiting from the cyclotron with angular variation of $\pm 3^{o}$ in direction and with wide variation in the phase space properties. Therefore, powerful steering magnets need to be placed near the exit point to align the beam. The magnet/s must operate effectively in the high stray field environment. After aligning the beam, four quadruple magnets will be used to match the transverse phase space. Dispersion matching is also very important. Rigidity of the beams to be handled ranges between 2.6 T-m to 3.34 T-m.

Figure 3 shows the layout of the beam lines proposed to be installed. Rather unusual bending stations are as a result of the building constraints. There will be three experimental areas in the first phase. The cave no. 1 will have two beam lines while caves 2 and 3 have one beam line each. Further extension of the experimental areas is possible through either of the beam lines leading to the cave 1 depending on the building and land constraints. Provision has also been made in the building and the beam lines to turn the extracted around and bring it to the experimental areas of VEC located in another building across the road.

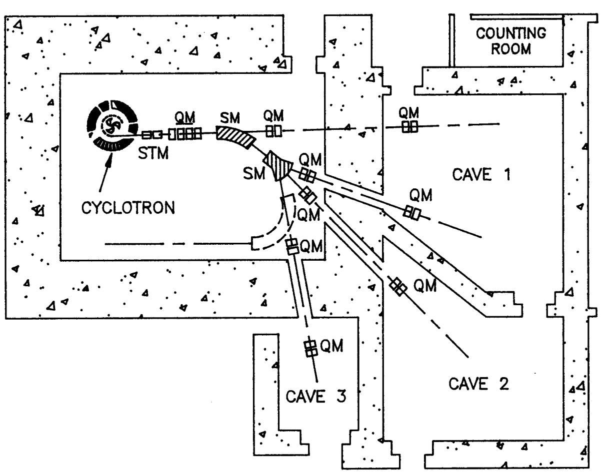

Figure 3:Layout of the beam lines for the superconducting cyclotron planned in the first phase at VECC

2.13 Building and Services

Detailed design of the new building which will house the superconducting cyclotron facility has been completed and the construction will begin shortly. Cyclotron vault is enclosed by 3.5 m thick concrete walls for radiation protection as per new and stricter international regulations. Detailed planning of the airconditioning and other services has also been completed.

3 ACKNOWLEDGMENT

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