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Superconducting Cyclotron and its Vacuum System

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Abstract. A large superconducting cyclotron is under construction at this Centre and will be used to accelerate heavy ion beams to energy up to 80 MeV/A for light heavy ions and about 10 MeV/A for medium mass heavy ions. The vacuum system for this accelerator has several different aspects. The main acceleration chamber will be evacuated to a level of about $10^{-7}$ torr using both turbo molecular pumps and specially designed cryopanels. The surfaces exposed to this ‘vacuum’ are mostly made of OFE copper. The cryogenic transfer lines, to cool the cryopanels, are of several meters in length and they pass through RF resonators extending below the magnet. The cryostat that will house the superconducting coils has an annular vacuum chamber, which is evacuated to a level of approximately $10^{-5}$ torr using a turbo molecular pump. Cryopumping action starts once the coils are cooled to low temperatures. A differential pumping is provided below the RF liner that encloses the pole tip of the main magnet. The space that is pumped in this case contains epoxy-potted trim coils wound around the pole tips. Crucial interlocks are provided between the differential vacuum and the acceleration chamber vacuum to avoid distortion of the RF liner, which is made of thin copper sheets. The other important vacuum system provides thermal insulation for the liquid helium transfer lines. In this paper a brief description of the superconducting cyclotron will be given. Details of various vacuum aspects of the accelerator and the logistics of their operation will be presented. Introduction of some of the improved equipment now available and improved techniques are also discussed.

1. Introduction

A large superconducting cyclotron is under commissioning at this Centre [1, 2]. The cross-sectional view of the cyclotron is shown in figure 1. The cyclotron will be used to accelerate heavy ion beams to energy up to 80 MeV/A for fully stripped light heavy ions and about 10 MeV/A for heavy ions as shown in figure 2.

The main component of the cyclotron is a warm bore iron core magnet with coils made of Nb-Ti superconducting cable operating at 4.5 K temperature. The vacuum system of this accelerator has several different aspects. The main acceleration chamber (also called Beam Chamber) is evacuated using three turbo molecular pumps to a pressure of about $10^{-5}$ mbar. Further reduction in pressure to lower than $10^{-7}$ mbar is achieved by three cryopanels intricately shaped to locate in the lower Dee cavities.

Cryogenic transfer lines pass from below, through the lower resonators (projecting about 5 metres below the magnet) and are terminated as cold fingers to which the thermal shield with chevrons and pump respectively are securely and firmly fastened. The volume of the acceleration chamber is approximately 1.0 cubic meter. The surfaces exposed to this high vacuum are mostly OFE copper to minimize the outgassing. These components are part of RF acceleration system. The overall aim is to attain a goal of high reliability and availability of the system with minimum manpower for operation and maintenance.
2. Cyclotron Subsystems

2.1 Main Magnet Frame
All parts of the frame are made of low carbon steel forgings. Rigorous chemical and ultrasonic test were carried out on the forgings before the machining was done. Azimuthally variation of all the pole tips (figure 3) both inner and outer has been maintained within the specified limit of 127 micron. The mass of the main magnet iron frame (figure 4) is about 80 Tons.

2.2 Superconducting coil
The winding of superconducting coil (figure 5) made of Nb-Ti cable was done in house. It consists of two independent coils of 1082 turns and 2234 turns respectively. These are designed to carry maximum current of 800 A. Dump resistors and quench protection circuit have been installed to protect the coils during any quench or any other abnormalities.

2.3 Cryostat
The cryostat (figure 6) that houses the superconducting coils has an annular vacuum chamber also called cryostat outer vacuum chamber (OVC). It is a single space between the inner liquid helium container (the stainless steel bobbin) and the outermost container, called the coil tank. A liquid nitrogen cooled OFE copper annulus, thermal shield, ensures there is no direct line of sight between the inner liquid helium container and coil tank. Several layers of double aluminised mylar sheets are
wrapped around the inner liquid helium container and thirty layers are wrapped on the thermal shield to reduce heat in-leak. The pressure in the vacuum space is less than $10^{-5}$ mbar during operating state.

2.4 Cryogenic delivery system and helium plant
The cryogenic delivery system has already been commissioned. Apart from supplying LHe to the cryostat, a major function of the delivery system is to cool the cryopanels to evacuate the acceleration chamber to high vacuum. The cryogens must be pumped up from below the cyclotron to the cryopanels through the RF resonators. Figure 7 shows the superconducting magnet with cryogenic transfer lines for the cryostat.

Both LN$_2$ jacketted as well as vacuum jacketted transfer lines will be used in the system. The HELIAL 50 liquefier has been coupled to the cyclotron cryostat as well as to the cryopanels. The liquefaction capacity with LN$_2$ pre-cooling is 100 l/h while without LN$_2$ pre-cooling it is 50 l/h. Refrigeration capacity with LN$_2$ cooling is about 250 W at 4.5K. The helium plant operates in mixed mode in our system (i.e. both as liquefier and refrigerator).
2.5 RF system
The 3-phase RF system of the cyclotron will operate in the frequency range 9 – 27 MHz with amplitude and phase stability of 10 ppm and 0.5 degree, respectively. Each Dee along with half-wave coaxial cavity develops peak voltage of 100 kV having fed with RF power (100 kW max.) from each of the 3 high power RF amplifiers. Like main dee-cavity, each amplifier is tuned by moveable sliding short. A PC-based stepper motor controlled sliding-short movement system is used for tuning the cavities at different frequencies. The material for fabrication is OFHC copper for most of the RF resonator parts. A large number of the resonator components are exposed to high vacuum.

2.6 Trim coils
There are 13 sets of trim coils (3 x 13) wound around the pole tips. OFHC copper conductor with 6.35 mm square cross section and central hole for water-cooling has been used. Coils are epoxy impregnated. The trim coil set 1st and 13th are used to correct the first harmonic field and the rest are used to correct the average magnetic field for isochronism.

2.7 ECR source
In addition to the already operational PANTECHNIK’s 14 GHz ECR source, an indigenously designed source is being constructed. This source will also operate at 14 GHz microwave frequency. The axial mirror peak field on the injection side is 12 kG and on extraction side it is 10.75 kG. A ‘halbach’ type sextupole geometry with 11.24 kG field at the inside plasma wall will be used.

3. Various vacuum spaces and their design considerations
The superconducting cyclotron has following major vacuum spaces serving different functions - acceleration chamber, liner vacuum, beam line, cryostat outer vacuum chamber (OVC) and transfer lines. Design of vacuum system for the cyclotron, needs the following considerations in addition to a good estimate of the vacuum level required in different spaces.
   a) Selection of suitable combination of pumps considering severe limitation of space and accessibility.
   b) Presence of strong magnetic field restricts the location of the pumps.
   c) Net conductance thus obtained is limited and hence the real leaks into the system must be nonexistent, and virtual leaks arising out of permeation, trapped volumes and outgassing from the surfaces exposed to the vacuum space, shall be minimized as much as possible.
   d) Cryopumps have much larger net pumping speed. Since they are capture pumps, any leak into system results in their faster saturation and require regeneration at shorter intervals, which will interfere with the cyclotron operation. In view of this, the vacuum spaces with cryopumps also need to have low virtual leaks and non-existent real leaks as much as possible.
   e) Most of the cyclotron vacuum system and it’s components are not bakable because of the complexity of the system and the materials used in them.

3.1 Acceleration chamber
In the acceleration chamber, charge particles are accelerated in cyclic orbits of progressively increasing diameters under the influence of electric and magnetic fields. They stay in the chamber for a considerable amount of time and also traverse about a kilometre distance. Some of the charged particles, which either pick up one or more electrons or get stripped of one or more electrons, are considered lost, since they go out of resonance with the applied electric field. The transmission (T) of a beam of particle in traversing a distance dl in a vacuum chamber having Ni atoms/cm³, where i denotes the specific background species, is the following [3]:

\[ T = (1 - \sum_i N_i \sum_m \sigma_i(q, q + m) dl) \times 100 \]
Where, $q$ is the ion charge and $m$ can be both positive and negative integer. In the acceleration process $\sigma(q, q + m)$ is charge exchange cross-section and is a function of velocity.

Results of calculation with $^{40}\text{Ar}^{8+}$, which is considered representative of the vacuum requirements, is presented in Figure 8. A clean, oil free vacuum at a pressure less than $10^{-7}$ mbar enables to limit the transmission losses to less than 5% during the acceleration of the charged particles.

There are three turbo molecular pumps for the acceleration chamber. The net pumping speed for all three pumps together is about 150 litres/sec. Roughing ports of the chamber is connected to the backing pump for the turbo pump for each module through an electro-pneumatic isolation valve, as shown in figure 9. Due to permeation and outgassing loads, the turbo pumping modules alone are not expected to reduce the pressure in the acceleration chamber below $10^{-6}$ mbar.

For achieving lower pressure, three cryopanels are placed in each of the lower dee in the valley gap as shown in figure 10. Each cryopanel is made of OFE C10100 copper and the liquid helium cooled
Cryopanel is surrounded by liquid nitrogen cooled chevron baffles. A 3D view of various surfaces of cryopanel is shown as in figure 11.

The inside surface of the liquid nitrogen panel is blackened to reduce radiation heat in-leak to the liquid helium cooled panel. All other surfaces of OFE copper are silver-plated. The material of screws to connect the two panels to their respective cold fingers is Be-Cu with a central hole. Be-Cu is chosen for its favourable coefficient of thermal expansion with respect to OFE copper that will ensure that the screws will not be loosened during/after cool down. Central hole is provided to remove trapped gases in blind holes in the cold fingers, effectively. During pumping, the maximum temperature of the chevron baffles is expected to be within 120K, and that of the liquid helium cooled panel below 20K. The three cryopanels together provide a pumping speed of 6000 litres/sec for air. The lower surface of liquid helium cooled panels is coated with activated charcoal, which helps in cryo-adsorption of hydrogen, helium, and neon gases. The heat load of each liquid helium cooled panel is 2.5 W. But the net heat load on cryogenic distribution system arising out of each panel is 20 W, primarily because of the space constraints leading to larger heat in-leak in the distribution system. While liquid nitrogen flow rate required to maintain steady state temperature of the chevron baffles is 90 litres/hour, consumption of liquid nitrogen is expected to be quite low, ~15 litres/hour for all three panels. The temperature measured in the cold head, where the LHe panel is mounted, is shown in figure 12 for various heater powers in a test run. Cryopanels will require regeneration as indicated by rise in pressure in the acceleration chamber.

![Figure 12. Helium-cooled cold head temperature for various heater wattages.](image)

![Figure 13. Schematic of the controlled vacuum breaking and pressure release.](image)

Due to the constraints of RF system and complexities in the cryogenic delivery system phase II (supplying cryogens to cryopanels), it was not possible to incorporate devices for monitoring and control of heating during regeneration. Instead, following philosophy has been incorporated.

a) Usually, individual liquid helium panels only will be regenerated up to 120K, as and when required by isolating the liquid helium flow to the chosen panel. There will be occasions when only two cryopanels are pumping the chamber while the third is under regeneration.

b) For regenerating both liquid helium and liquid nitrogen cooled panels, all the three cryopanels will be regenerated together. During this period liquid helium panel will always be kept warmer than liquid nitrogen panel above 120K by circulation of 300K helium gas in the liquid helium cold finger. The vacuum in the acceleration chamber can be broken in a controlled manner by introducing dry nitrogen gas through mass flow controllers as shown in figure 13. Any inadvertent pressure increase above atmospheric pressure is avoided using a pop off valve, which releases any excess gas above 100 mbar (g) directly to atmosphere.
3.2 Liner vacuum

The liner is made of OFHC copper of low thickness and of highly intricate shape closely following the contour of the magnet iron hills and valleys as shown in figure 14. A low quality vacuum is adequate in the liner vacuum space. The space between the upper liner and the upper magnet iron elements within the cryostat inside diameter forms the upper liner vacuum space. Similarly, the space between the lower liner and the lower magnet iron elements within the cryostat inside diameter forms the lower liner vacuum space. Epoxy impregnated trim coil assemblies on the magnet pole tips lie within the liner ‘vacuum’ spaces. A set of two oil sealed rotary pumps with interlocked valves, one of them as hot stand-by, assures the availability of pumping. There are three vacuum ports available for each of the two vacuum spaces. Two ports each of the two spaces are connected to a common header as shown in the figure 15. During routine operation, the liner is first evacuated. The beam chamber evacuation is begun only after attaining < 0.10 mbar in the liner. Two pumps are provided in tandem for the liner to reduce the possibility of pumping system failure.

In case of power failure, the pumps are automatically isolated to maintain vacuum in the liner. A rupture disc is provided for interconnecting the vacuum space of liner and beam chamber at the ports located over the top pole cap. This rupture disc can sustain about 1.5 bar pressure in case the beam chamber pressure is higher.

3.2.1 Safety feature for protection of the liner

The liner can sustain a differential pressure of 1 bar in one direction only, i.e., beam chamber at atmospheric pressure while the magnet iron side is under full vacuum. A differential pressure in the other direction > 200 mbar will cause permanent deformation/damage of the liner. Therefore following protections are incorporated.

The vacuum level required is low. But due to the constraints on the differential pressure across the liner, two rotary pumps, each capable of maintaining adequate vacuum are used in tandem. Both pumps are not expected to fail at the same time. If any of the two pumps fails, it is automatically isolated and the control room is warned of this event. The defective pump shall be repaired/replaced at the earliest possible opportunity (whenever the vault needs to be opened) without affecting vacuum system availability.

3.3 Beam line vacuum

Beam lines carry energetic particle beams after their extraction from the cyclotron to the designated destinations in the caves for experiments.
There are a variety of intricate elements for beam diagnostics, beam viewing, bending and focusing along the lines. Figure 16 shows a schematic diagram of external beam lines. The path length of a beam line is 20-25 metres. Beam optics has been designed for a transport efficiency of over 95%. The ultimate vacuum, theoretically, attainable for various surface conditions between two pumping modules (~3.5 m apart) is shown in figure 17.

Distributed pumping is provided between any two major elements/ on a diagnostic element along the beam line. Also, at least one pumping station is available between two isolation valves. As a measure of abundant precaution to avoid any possible ingress of particulate elements at the turbo pump inlet, evacuation after installation or any major maintenance is first done in the beam line segments through roughing port. Subsequent pumping, including roughing, is done directly through turbo pump port. The same pump is used for roughing as well as backing the turbo pump with interlocked valve. To prevent any possible oil ingress in the beam lines, scroll pumps are used for the purpose. All the demountable ports are CF flanges with OFE copper gaskets.

3.4 Cryostat outer vacuum chamber

The cryostat is primarily, a vessel that houses the superconducting coil, along with the support systems, well insulated with mylar insulation, liquid nitrogen shield and vacuum. Several inserts providing access for movable components inside the acceleration chamber are welded to this vessel. The magnet iron surrounds it from all sides. Since, the superconducting coils must remain immersed in liquid helium for energisation the governing criterion for vacuum level is low and acceptable helium boil-off rate. Conduction heat in-leak is minimized by appropriate selection of materials and design details. Radiation heat in-leak is reduced by the use of double aluminized multilayer insulation. Real leaks are minimized. Clean vacuum of about $10^{-5}$ mbar or better is required (which in turn, reduces heat load due to molecular conduction and convection to a significant level) to ensure acceptable helium boil off rate equivalent to about 20W @ 4.5K. The experimental heat flux [4] to a liquid helium system from surrounding liquid nitrogen radiation shield at 77 K is shown in figure 18. The turbo pump inlet is located about 3700 mm below the median plane. Measured magnetic field at the turbo pump inlet is 55 G at the main coil current of 550 A in both coils. Suitable magnetic shield will be provided around the turbo pump and vacuum gauges. If necessary, the turbo pump will be water-cooled. A dry pump (scroll pump) is used to back the turbo pump. The backing pump is also used for roughing through a bypass roughing line. A blank flange with a manual isolation valve is provided at the backing pump inlet. This port can be used for mass spectrometer leak detection whenever required. The net pumping speed is about 40 litres/sec. The pumping system is configured for automatic operation with fail-safe interlocks (figure 19). It is possible to isolate the pumping system using the manual isolation valve, if the vacuum level is sustained as indicated by low and reasonable liquid helium boil-off rates from the cryostat. The pumping system is capable of continuous operation with the manual isolation valve kept open.
3.5 Transfer lines
Transfer lines are of two categories, liquid helium and liquid nitrogen. The basic feature of both the transfer lines in the superconducting cyclotron is same, i.e., vacuum jacketted and double aluminized super insulation. Lower pressure in vacuum space is desirable for the liquid helium transfer lines since its latent heat of vaporization is very small.

The superconducting magnet and three cryopanels in the acceleration chamber need liquid nitrogen and liquid helium supply and the gaseous returns. In order to minimize the transfer losses of these cryogens, vacuum jacketted transfer lines with double aluminized multilayer insulation are used. The vacuum spaces in transfer lines are segmented and each segment is independently made fully vacuum tight with a pumping port. In the operating condition, clean vacuum of about $10^{-5}$ mbar is required to ensure acceptable transfer loss.

Some other features, which are also same for the two categories of transfer lines, are: a) inside surfaces are electro-polished to minimize outgassing and molecular sieve adsorber is placed in each segment to retain desired vacuum level for long duration, b) clean practices during manufacture to reduce outgassing, c) 100% radiography and no detectable leak at room temperature with helium mass
spectrometer at sensitivity of $1.0 \times 10^{-8}$ mbar l/sec after three cryoshock to 77K, d) distributed pumping at room temperature and with controlled baking and e) vacuum retention test at room temperature in each segment for 7 days after vacuum seal off valve closed indicating a pressure less than $10^{-3}$ mbar. The cross-sectional view of the transfer line of VECC is shown in figure 20.

4. Special features of the pumping modules

The pumping modules have component level and module level interchangeability with a provision for in-situ helium leak test. This will help minimize spare part inventory, ease of in-situ trouble-shooting, off-line maintenance while reducing the requirement of maintenance manpower and simultaneously, improving quality of maintenance.

The automatic operation is configured for taking over the control from roughing stage or any other stage. The vacuum system will always be kept under vacuum and isolated under all conditions, except during maintenance within the system. If the pressure in the system is $> 1.0$ mbar, the roughing valve remains open. The backing pump of the module starts roughing the system. When the system pressure reaches $< 0.1$ mbar, the roughing valve automatically closes. After the roughing valve is closed, the turbo pump isolation valve opens when the pressure in the turbo pump inlet is less than the system pressure. In case of power failure, the isolation valve closes automatically. Initially, the system will be inhibited for automatic re-start after resumption of power. After having trouble free vacuum system control continuously for a few months, the system will be permitted to re-start automatically after resumption of power supply.

Technically dry scroll pumps, compound turbo pump capable of working under higher backing pressure and occasional air in-rush for short duration, conflat seals, provision for in-situ helium leak test, modular pumping units with component level and module level interchangeability, PLC control with RS 485 communication, screws with central hole for the cryopanels to reduce outgassing and trapped volume, best possible cryopanel regeneration philosophy within the constraints of the cyclotron are adopted in the system.

5. Conclusions

Based on new insights in the vacuum science and availability of improved equipment, our attempt has been to improvise the vacuum system of the superconducting cyclotron at VECC Kolkata, with regard to the system in the similar machines of Michigan State University and Texas A&M University. Field performance due to these improvements will provide encouragement.

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