

Vacuum System of the Large Cyclotrons at VECC

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Abstract: Variable Energy Cyclotron Centre (VECC) has two large cyclotrons, K-130 cyclotron and K-500 cyclotron. The first beam in the room temperature K-130 cyclotron (RTC) was accelerated in June 1977. The cyclotron accelerated and delivered alpha and proton beams consistently to the cyclotron users for several years. Heavy ion beams were available in this cyclotron from 1997 to 2007. Presently, the cyclotron is working as a primary source for RIB production. The cyclotron has an acceleration chamber volume of about 28 m³. The total length of beam line is about 65 m. Vacuum of the order of 1×10^{-6} mbar is presently maintained in the cyclotron and beam line using diffusion pumps. It is one of the largest vacuum systems operating in India. It is consistently being operated 24 x 7 round the year giving beam to the cyclotron users. A K-500 superconducting cyclotron (SCC) with K=520 has been constructed at Kolkata. SCC will be used to accelerate beams to 80 MeV/A for light heavy ions and about 10 MeV/A for medium mass heavy ions. Three turbo molecular pumps are connected to the acceleration chamber. Three cryopanel placed inside the lower dees in the valley gap of the superconducting magnet are available in the accelerating chamber for achieving high vacuum. The acceleration chamber having a volume of about 1.0 m³ was operated using turbomolecular pumps, liquid nitrogen cooled panels and liquid helium cooled cryopanel at different stages during beam commissioning. Differential pumping is provided across the RF liner to avoid distortion. The first beam line of about 21 m has been installed in the cyclotron. The outer vacuum chamber of the cyclotron magnet cryostat has active pumping. The vacuum system of the superconducting cyclotron is also operating reliably round the clock throughout the year. The paper describes the details of the vacuum systems of the large cyclotrons at VEC Centre Kolkata India, its commissioning and operating experience.

1. Introduction

A K-130 cyclotron [1] and a K-500 cyclotron [2] are being operated at VEC Centre. RTC has a 224 cm water cooled magnet of about 262 Ton. The magnetic field is 2.12 T at the hill and 1.65 T at the valley. The radio frequency system operates at a frequency from 5.5 to 16.5 MHz with Dee voltage of about 70 KV. The beam chamber has a volume of about 28 m³. It presently uses an internal PIG ion source and uses an electrostatic deflector for extraction of beam from the cyclotron. It is one of the largest vacuum systems operating in India. It is consistently being operated 24 x 7 round the year giving alpha and proton beams to the cyclotron users.

SCC has a superconducting magnet. The magnet uses NbTi wire immersed in a pool of liquid helium. The cold mass is about 7 Ton. The 80 Ton magnet iron is kept at room temperature. The radio frequency system operates at a frequency of 9 to 27 MHz. SCC will be used to accelerate heavy ion

beams to energy of upto 80 MeV/A for light heavy ions and about 10 MeV/A for medium mass heavy ions. SCC is also operating reliably round the clock throughout the year with internal beam for commissioning trials

2. K-500 superconducting cyclotron

The major components in the vacuum system of SCC [3] are beam chamber, liner, injection line, external beam line, magnet cryostat and cryogenic system.

2.1 Beam chamber

The beam chamber is enclosed by the radio frequency liner at the top and bottom and the inner wall of the main magnet cryostat at the sides. An o-ring of diameter 1.3 m seals the interface of the liner and cryostat. The beam chamber has a volume of about 1.0 m³. Figure 1 shows part of the beam chamber. The material for liner is copper CDA 101, the inner wall of the main magnet cryostat is made of iron, which has been elctroless nickel plated. The median plane of the cryostat forms part of the beam chamber. It is made of SS 316. The dee and the extraction elements are major components in the beam chamber. The dee is made of copper CDA 101, the magnetic channels from iron, the electrostatic deflectors from titanium. Table -1 gives the surface area of different components

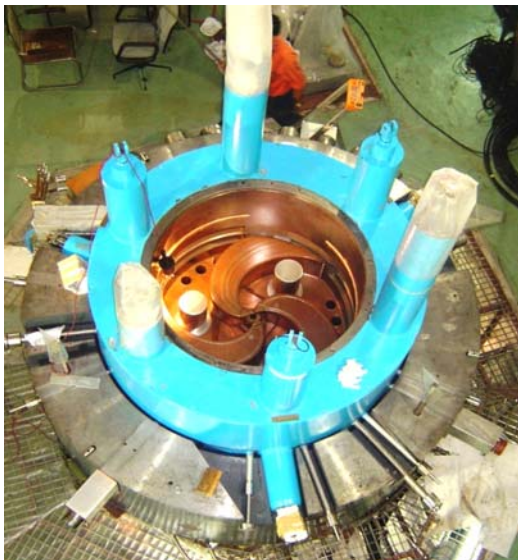


Fig. 1. Main magnet cryostat assembled on the lower radio frequency liner

Table 1. Components of SCC Beam Chamber

Name of component	Material	Surface area m ²
Inner wall of main magnet cryostat	AISI 1010 Nickel plated	5.6 approx
Radio frequency liner	CDA 102 and CDA 110 copper	20.7 approx
Dee	CDA 101 copper	6.4 approx
Dee Stem	CDA 101 copper	6.0 approx

The median plane of the beam chamber (Fig. 1) has twenty penetrations having complex geometries. Two probes move in the beam chamber. They are equipped with maintenance chambers, isolation valves and independent pumping modules for connecting them to the high vacuum beam chamber. The radial probe has a drive of about 2.1 m and the bore probe has a drive of about 1.8 m [4]. The probes are connected to edge welded bellows to ensure leak tightness during movement and reliable operation of the probe. The maintenance chamber of the radial probe was modified to place a DN 63 pump below the maintenance chamber. It is equipped with a glass view port for viewing the probe.

There are three ports of 75 mm diameter in the magnet for connecting the beam chamber to positive displacement pumps. Three 550 litre/sec DN 160 turbo-molecular pump backed by scroll pumps have been connected to the beam chamber. The turbomolecular can tolerate an axial magnetic field of a 10 mT and a transverse magnetic field of 5 mT. During the magnetic field mapping of the superconducting cyclotron the axial magnetic field was also measured. Based on the results of the magnetic field measurement, it was decided to place the pumps at a elevation difference of 2.85 m

from the magnet with piping of length 3.5 m so that the pump is placed in an acceptable magnetic field.

The cyclotron vacuum was initially operated with turbo molecular pumps. Considerable time of taken to achieve high vacuum for operation of the radio frequency system. The ultimate of 1×10^{-7} was achieved after about a month of operation and baking using the radio frequency system. The ceramic insulator of the radio frequency system had frequent failures. After achieving good vacuum in the beam chamber, internal beam was viewed in the cyclotron (Fig. 2) on the scintillation screen of the bore probe [4] (Fig. 3).



Fig. 2. Accelerated Neon beam spot on beam viewer

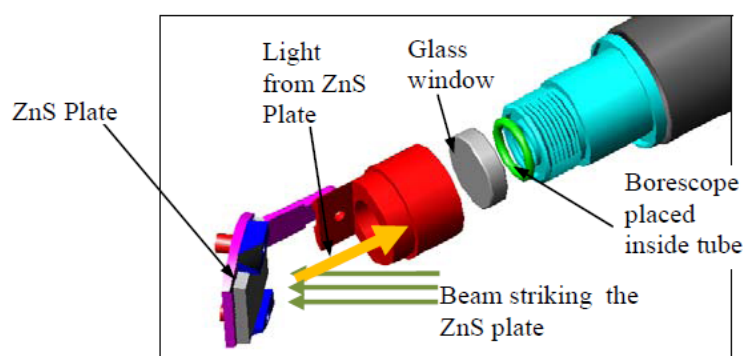


Fig. 3. Beam scintillation probe

Dee voltage, however, could not be raised because the beam chamber vacuum deteriorated as rf power to the cavity was increased. The chevron baffles (Fig. 4) were then cooled with liquid nitrogen. A pressure of 5×10^{-7} mbar could be achieved (Fig. 5) with the flow of liquid nitrogen in the chevron baffles [5] and the radiation shield having a projected surface area of about 0.27 m^2 per cryopanel. The operation of the cyclotron improved with the improvement in the vacuum of the cyclotron. The failures of the ceramic insulators of the cyclotron was reduced. The radio frequency system could be raised to higher voltages easily and beam was first extracted to the outer radius of the cyclotron.



Fig. 4. Baffled of cryopanel placed in the dee

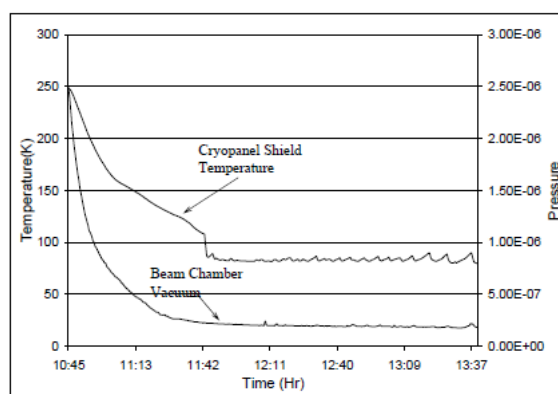


Fig. 5. Liquid nitrogen cooling of cryopanel

Commissioning trials were carried out in the cyclotron. But, it was observed that there was considerable beam loss in the outer radius. Due to conductance limitation, the effective pumping speed of the turbo-molecular pumps is about 135 l/sec. Although cooling the baffles and thermal shield of the cryopanel with liquid nitrogen gave a addition pumping speed of 30,000 l/sec, only moisture could be pumped using the surfaces cooled to about 90K. Liquid helium was then used to cool the cryopanel. There are three cryopanel of area 0.15 m^2 placed inside the lower dees (Fig. 6). Beam loss

in the beam chamber of the cyclotron was considerably reduced (Fig. 7) [6]. The improvement of vacuum was considerable after cooling the cryopanel with liquid helium (Fig. 8). The vacuum in the cyclotron improved from about 5×10^{-7} to 5×10^{-8} mbar after initiating flow of liquid helium through the cryopanel.

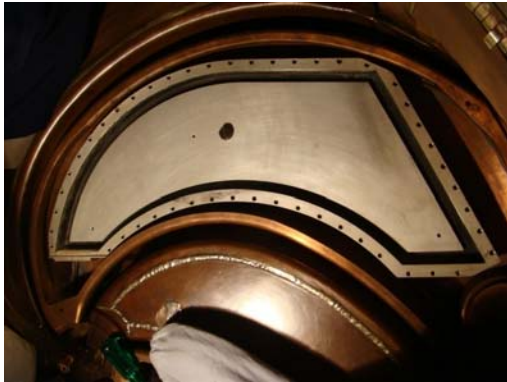


Fig. 6. Cryopanel placed inside the radiation shield

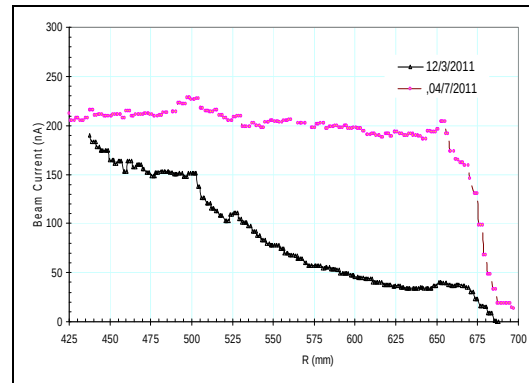


Fig. 7. Beam profile after operation of the cryopanel

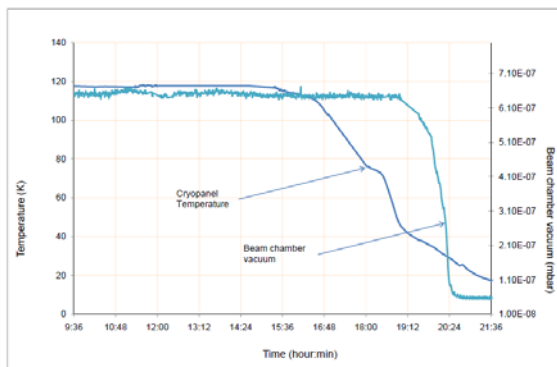


Fig. 8: Improvement of vacuum after liquid helium cooling of the cryopanel

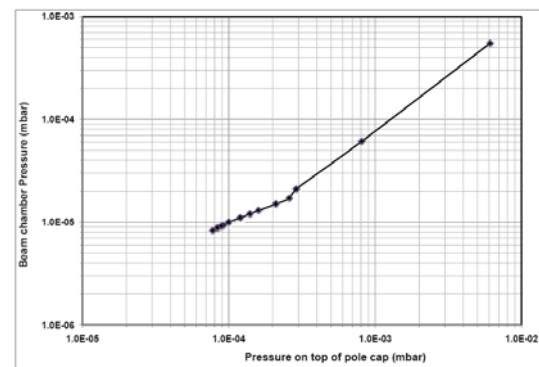


Fig. 9: Calibration of vacuum gauge

Measurement of vacuum in the cyclotron and its interpretation have some uncertainties. The vacuum gauge has to operate in the presence of high magnetic field. The gauge cannot also be mounted close to the beam chamber as the beam chamber is surrounded by the cryostat and the magnet yoke in the sides and the magnet yoke at the top. In order to eliminate the effect of magnetic field the gage was placed away from the magnet. In order to calibrate the gauge, a set-up was fabricated with a high vacuum pump and two gauges were placed away from each other with equivalent conductance between them. The calibration curve was generated by plotting the values observed by the gauges (Fig. 9)

2.2 Cryogenic system for cooling the cryopanel

The cryopanel is placed inside the dees. They are cooled by liquid helium. The chevron baffles and the thermal shield of the cryopanel is cooled by liquid nitrogen. The cold head for the liquid helium cooled cryopanel and the cold head for liquid nitrogen cooled baffle is placed at the end of a 6 m long 50 mm diameter compact transfer line. This transfer line is connected to co-axial bayonets for liquid helium and liquid nitrogen at the other end for easy dismantling. Due to the complex configuration of liquid helium flow, a liquid helium pump was used for circulating liquid helium in the circuit. Fig. 10 gives the pump characteristics of the liquid helium pump tested under ideal conditions and the calculated system characteristics. After complete installation and commissioning of the liquid helium

pump in the cryogenic system, the desired head of the pump was not observed. Modifications were carried in the circuit to also use the head of the liquefier during operation of the system. The cooling power of the cold head for liquid helium cryopanel was tested and found to be about 10 watt at 10 K [7] (Fig. 11).

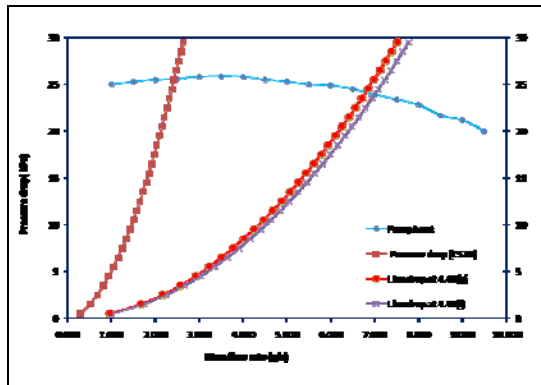


Fig. 10. operating point of the liquid helium pump

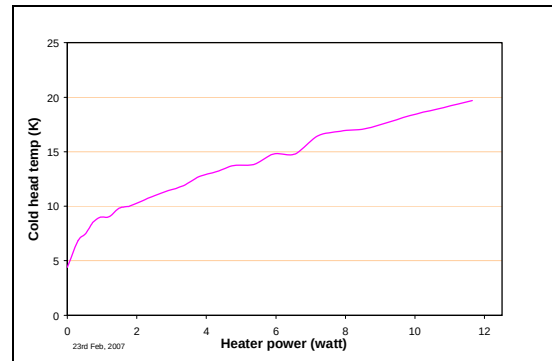


Fig. 11. Cooling capacity of liquid helium cold head

Different cyclotron laboratories have used different schemes for circulation of liquid helium through the cryopanel. The NSCL MSU cryogenic system [8] uses a sub-cooler and a pressurised liquid helium system. The cryogenic system at Texas A & M university, USA [9] has a reciprocating pump for liquid helium circulation through the cryopanel. The TRIUMF cyclotron used a cryogenerator initially and later used a helium refrigerator [10]. The AGOR cyclotron uses a cryocooler and heat pipes for cooling the cryopanel [11]. In VEC K-500 cyclotron, the cryogenic system was initially using a helial 50 for cooling the main cyclotron magnet. The cryogenic system for cryopanel was designed with the operating parameters of the helial 50 [12]. A liquid helium pump was added in the helium circuit to circulate liquid helium through the cryopanel [7]. In order to add to the redundancy of the system, later a helial 2000 was added [13]. The liquid helium system was also modified to operate the delivery dewar at a higher pressure. A sub-cooler was also added to the liquid helium system. These additions in the liquid helium system have made the liquid helium pump redundant.



Fig. 12. Copper rf liner



Fig. 13. Lower magnet iron

2.3 Liner vacuum

A thin copper sheet covers the contour of the hill and valley of the iron magnet. The space between the copper sheet (Fig. 12) and iron magnet (Fig. 13) is evacuated and a low quality vacuum is maintained in that region. It contains the iron pole tips, the copper liner, epoxy of the trim coils and insulation of the trim coils. It acts as a guard vacuum for the beam chamber and is required to ensure structural

stability to the thin copper sheet forming the liner. At the beam chamber end, it is isolated using a 1.3 m o-ring placed below the cryostat. At the magnet end, there are 148 feed throughs which carry about 300 amperes to each trim coil. The upper and lower liner are connected together and evacuated using a 5 m³/hr rotary pump.

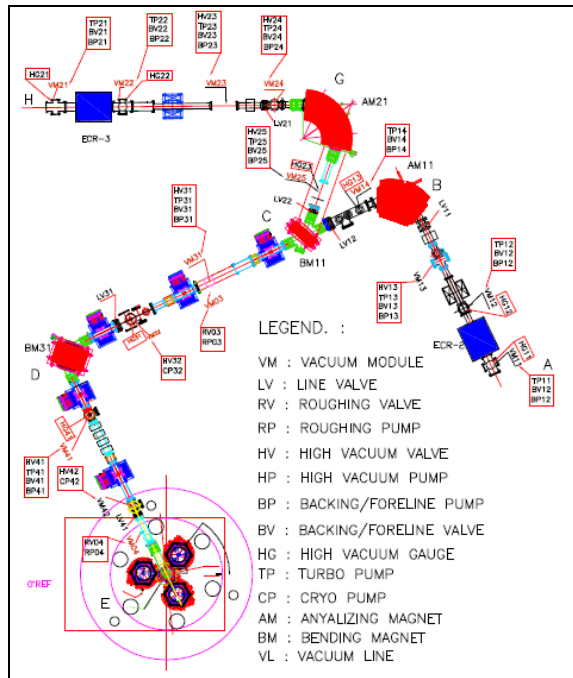


Fig. 14: Horizontal section of injection line

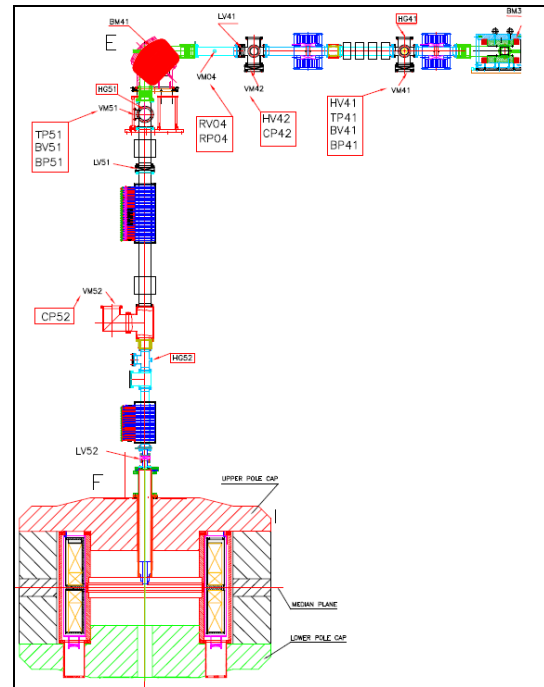


Fig. 15: Vertical section of injection line

2.4 Injection line vacuum

VEC K-500 superconducting cyclotron uses an ECR ion source located at Highbay above the cyclotron. The heavy ion beam from the ion source passes through an analysing magnet for charge state separation. Thereafter, the beam is transported through the horizontal section having a bending magnet (Fig. 14). At the end of the horizontal section, a vertical bending magnet bends it to the vertical section (Fig. 15) terminating at the inflector placed in the median plane of the cyclotron. Solenoid lenses are used in the horizontal and vertical beam line for focussing. Uncooled faraday cup, slits and collimators are placed in the beam line for diagnostics. The components have edge welded bellows for movement and are of welded construction. The length of the beam line is about 19 m. It is made of Stainless Steel SS 304, consists of vacuum chambers with copper gasket in all joints other than the ion source, where some viton o-rings have been used. It has a volume of about 0.2 m³ and a surface area of about 8.4 m². A vacuum of 5×10^{-7} mbar is achieved by a combination of three DN 160 turbo molecular pumps and two DN 160 and one DN 200 cryopumps.

2.5 External beam line

Fig. 16 shows the beam line layout for the superconducting cyclotron, The quadrupole magnets for all the beam lines have been fabricated. The large switching magnets have been designed and fabrication is in progress. The vacuum chamber for the switching magnets have been designed and procurement is in progress [14]. The components for the first beam line have been assembled (Fig. 17). Turbomolecular pumps backed by scroll pumps have been used in the first beam line. The length of the first beam line is about 20 m with metal gasket joints. Faraday cup, beam viewer and water cooled slits have been used. The movement of these diagnostic equipments use edge welded bellows to eliminate any air leak in the system during their movement.

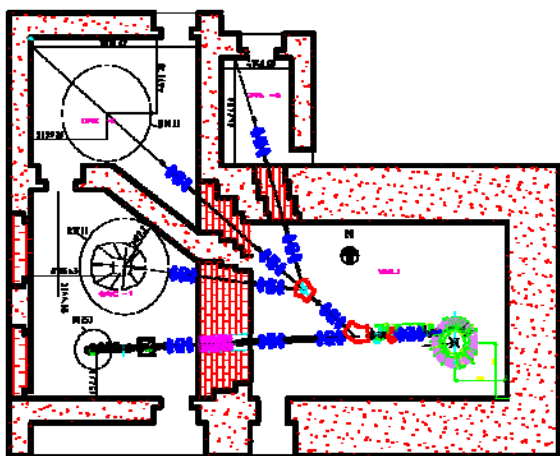


Fig. 16. Layout of beam line in SCC

The beam line from the vault extends to the experimental cave (Fig. 18) with a large scattering chamber placed at the end. Shielding is placed in between the vault and the experimental cave and the beam line has a shield wall plug (Fig. 19) to bring the radiation at the experimental cave within allowable limits, when beam is accelerated in the vault and the experimental cave is occupied for preparation of experiments.



Fig. 18. Beam line in experimental cave

2.6 Magnet cryostat

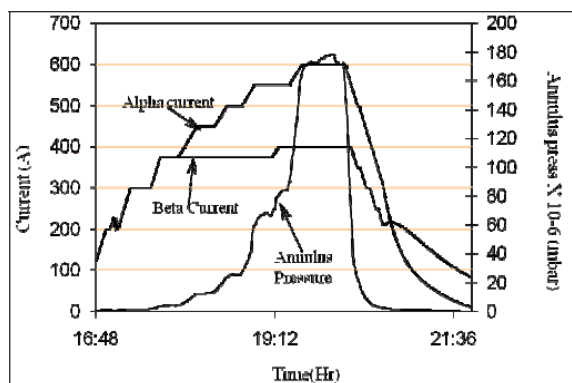


Fig. 20. Pressure variation during energisation

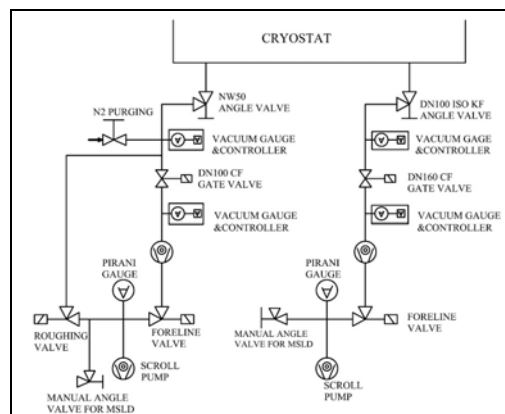


Fig. 21. Vacuum pumping for cryostat

2.7 Cryogenic system

The cold box for helium refrigerator (Fig. 22), cryogenic manifolds and the piping for transfer of liquid helium and liquid nitrogen to the magnet cryostat and the cryopanel form a large vacuum system. The cold box has a pump connected to the vacuum chamber of the cold box [16]. This pump is continuously operated. The dewars, cryogenic manifolds and the piping have about forty five independent volumes, a volume of 0.4 m^3 , line length of 61.3 m and surface area of $3.5 \times 10^5 \text{ m}^2$. The cold surfaces have activated charcoal for pumping the annular space during operation.



Fig. 22. Helial 50 cold box

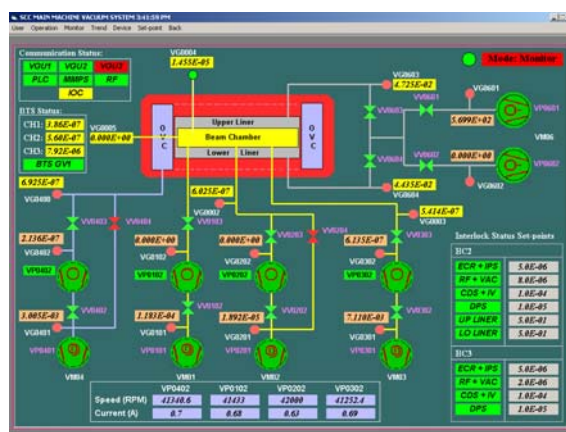


Fig. 23. OPI for K-520 vacuum

2.8 Supervisory control system :

The Experimental Physics & Industrial Control System (EPICS), a standard open-source dual layer software tool for designing distributed control system, was adopted to implement the supervisory control software for the vacuum system for superconducting cyclotron [17]. The indigenously developed Input Output Controller (IOC), which communicates with PLC, was in the lowest layer. The Operator Interface (OPI) sitting on top of IOC, communicates with the IOC for monitoring and supervisory control. The OPIs (Fig. 23) were developed in-house incorporating the features for system 'mimic' for ease of operation, on-line trending of selected parameters, audio-visual alarm, user authenticated secure mode for control of various components and modification of set-points, etc. These provide a diagnostic view of control hardware to the user.

3. K-130 cyclotron

The vacuum system of the K-130 cyclotron is operated by a fractionating oil diffusion pump having a speed of 42000 l/s for air. This is one of the largest vacuum pumps in India. It has a 2.5 ton electro-pneumatically operated main gate valve and a refrigerated Chevron baffle at the top. A pair of above

three assemblies is suspended from the two large opening in the resonator tank. Chevron baffles over the diffusion pumps are cooled to -60°C with the help of Freon refrigeration units. The cyclotron has been operating for over thirty years. The cooling coil of the diffusion pumps had lost contact with the body, cracks had developed in the backing line and the valves were not sealing properly. The vacuum system for K-130 cyclotron was refurbished [18] by changing these components. The vacuum chamber of analysing magnet formed by the pole pieces and side plates had leaks while energisation of the magnet. A new separate vacuum chamber was design, fabricated and replaced [19] to improve the beam line vacuum.



Fig. 24. K-130 cyclotron and beam line

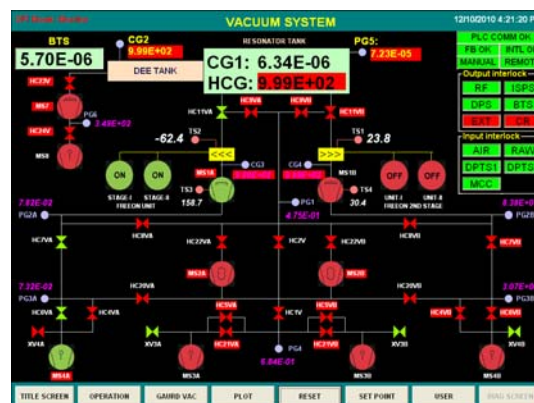


Fig. 25. OPI of K-130 cyclotron

3.1 Control system for K-130 cyclotron vacuum system

The control systems were implemented using Schneider make PLC with integrated Modbus-TCP connectivity [17]. The field components were distributed judiciously among the PLC input/output modules to overcome the single field component or PLC hardware failure. The system was designed to incorporate 'auto', 'manual' and 'maintenance' mode of operations. A hardware local panel was provided at each node for in-situ operation in manual mode and maintenance mode. The PC based remote terminal facilitates the user to monitor and operate the system in manual and auto mode. Fig. 25 shows the OPI of K-130 cyclotron vacuum system.

4. Conclusions

The vacuum systems for the large cyclotron at VEC Centre have been operating reliably. The vacuum in the beam chamber of K-520 cyclotron was considerably improved by cooling the cryopanel with liquid helium. The addition of charcoal to the helium cooled panels is likely to further improve the performance of the vacuum system of K-520 cyclotron. The vacuum system of the K-130 cyclotron was improved substantially with new components.

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