Vacuum System of the Ion Source and Injection Line of a High Current Compact Cyclotron

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Abstract. A 2.45 GHz microwave ion source and the transport system of high current proton beam for injection study in a compact cyclotron have been designed, fabricated indigenously, installed and commissioned. Presently it is under testing for beam characterization and inflection study. The vacuum system consists of a plasma chamber with 8mm slit in the plasma electrode, two-segment ceramic insulators (Al2O3) column, which supports the beam extraction electrodes and isolates the high voltage deck from the beam line and a 3m long low energy beam transport line (LEBT) equipped with several diagnostic elements such as faraday cup, slits, beam viewer etc. There is a provision to connect a needle valve to feed gas into the chamber for beam space charge neutralization studies. An online vacuum data logging software has been developed for continuous monitoring of the vacuum near the extraction zone. Monitoring system being very sensitive to the high voltage breakdown, is designed with a spark protection circuit which provides an isolation of 10kV using an optical isolation technique. In this paper we present design philosophy, operating experience and some experimental results. We have studied the behaviour of vacuum system near the extraction zone under various operating conditions of the high current ion source.

1. Description of Ion source

The 2.45GHz microwave ion sources are now a days widely used to produce several mA of proton beam for various applications. These sources are based on the principle of off resonance microwave discharge. The main features of such sources are high yield, high proton fraction and long term stability and reliability which meet the requirement of a driver for an ADS system. At the Variable Energy Cyclotron Centre, Kolkata a 2.45 GHz microwave ion source and the injection line to transport high current proton beam have been designed, fabricated indigenously, installed and commissioned (shown in Fig. 1) which produces protons beam at 80 keV. The main objective of this development is to carry out detailed injection study of high beam current in a compact cyclotron. The ion source consists of a plasma chamber, two solenoids and a triode ion extraction system. The diameter of the apertures in the plasma electrode, accelerating electrode and de-accelerating electrode are 6mm, 8mm and 8mm (new one) respectively. The plasma chamber is a double walled water-cooled cylindrical stainless steel chamber of 100 mm length and 90 mm diameter. The microwave power from the 2.45 GHz, 1.2 kW magnetron is coupled to the chamber through a three stubs tuning unit, an auto tuner and water cooled ridged wave-guide. Ion source with adjustable solenoid, its power supplies, microwave generator (2.45 GHz, 1.2 kW), a high precision gas...
flow system etc., all are kept at a high voltage deck ~100 kV. High voltage deck is separated from the ground through polypropylene insulators. A two-segment ceramic insulators (Al₂O₃) column, which supports the beam extraction electrodes, separates the high voltage deck and the beam line at the ground potential. Power to the various subsystems on the deck is supplied using a 150kV, 30kW isolation transformer. Since all subsystems of the ion source are placed on the high voltage deck, an isolated control system is used for remote monitoring and operation of various sub-systems e.g. microwave generator, microwave tuner, solenoid magnet power supplies and gas feeding system. The system architecture is modular with dedicated control nodes for individual sub system. The PC based supervisory console is connected with the control nodes in RS485 multi-drop fashion through an indigenously developed optical fibre based serial link for electrical isolation. A protection circuit is also implemented to reduce communication failure due to frequent spark.

The injection beam line consists of two magnetic solenoids (SOL1: 40 cm, 3.6 kG) (SOL2: 40 cm, 3.3 kG), with some diagnostic elements slits, faraday cup and emittance monitoring box. The beam from the ion source is expected to contain a substantial fraction (~10 to 20 %) of molecular hydrogen ion. Two motor controlled independent slits, one set for the x-plane and other set for the y-plane is used to control the size of the beam and to reject the molecular hydrogen beam. We have also provided another water cooled fix slit of 4 cm dia after the first solenoid and before the waist position of proton. Beam current measuring equipments used in the beam line are; a water-cooled faraday cup (up to 10 mA only) with secondary electron suppresser and a DCCT. Three turbo pumps having pumping speed of 520 l/s are used to evacuate the entire system. We have achieved vacuum of the order of 1.5 x 10⁻⁷ Torr near the extraction zone and in the beam line. Control units for adjusting current in the solenoids, movement of solenoids, tuning of microwave power, adjustment of gas flow etc. is placed on the high voltage deck and control and monitoring of the various voltages and current is done with a PC at ground potential through optic fibre.

![Image](image-url)

**Fig. 1.** Ion source on high voltage deck and LEBT with two solenoid magnets. At the end of beam line we see locally made water-cooled beam dump cum faraday cup.

We have obtained 6.4 mA beam current on FC and 8.5 mA on DCCT at 400 watt of microwave power and extraction voltage of 80 kV. We transported this beam up to the last beam dump near the diagnostic chamber. We observed increase in the beam current ($I > 10 \text{ mA}$) at the DCCT with increase in microwave power. Beam spot of 80 keV, 5 mA proton beam on water cooled alumina plate is shown in Fig. 2. Most of the ring type shadow around the hot spot is due to other beams and neutrals generated in the extraction region. At present we are testing the source for long term stability and beam quality improvement.
A spiral inflector will be used to inflect the beam in the median plane of the 10 MeV cyclotron and to place the beam on the proper orbit. We have designed and studied the various optical properties of the inflector in the presence of space charge effects. We observed that the influence of space charge is drastic on emittance growth with upright ellipse as initial conditions. However, with optimized tilted ellipse the emittance growth is minimal. Thus the beam optimization for matching is very much important and necessary to avoid the beam loss. This inflector has already been fabricated and tested with high voltage upto 25kV. In order to study the inflection and transmission of high beam current through the spiral inflector, we have designed and fabricated a small magnet (shown in Fig. 3) having a similar characteristics as the central region of 10 MeV cyclotron. Magnet has already been assembled with a vacuum chamber with inflector inside and is connected in the beam line. The preliminary testing of beam transmission at low beam current ~ 1 mA is going on. A beam transmission of 50% has been achieved and efforts are on to improve the transmission efficiency. We would like to point out here that we need first to optimize the beam transmission at low current to avoid any damage to the inflector. The fabrication of a sinusoidal beam buncher together with a fast faraday cup is near completion. These components will be installed very soon after the second solenoid magnet to study the behavior of beam bunching at high current.

Fig. 2. Beam spot of 80 keV, 5 mA on water cooled alumina plate. Most of the ring type shadow around the hot spot is due to other beams and neutrals generated in the extraction region.

Fig. 3. Magnet assembly with vacuum chamber to house the spiral inflector and the spiral inflector on based plate of the chamber.
2. Estimation of vacuum requirement

Low conductance has been utilized to achieve steady state pressure differential among inter-connected spaces and also to control the pressure differential as per the process requirement. Ion source is one of such application where the plasma chamber pressure needs to be controlled at different set values as per the ion production requirement while extraction chamber pressure is to be maintained regularly at pressure lower than $1 \times 10^{-5}$ mbar to avoid sparks and discharge against the high extraction voltage. Schematic diagram of ion source and beam line components are shown in Fig. 4 highlighting the main vacuum parts. Plasma and extraction chambers are connected through 8 mm aperture for the extraction of ion beam. Upstream pressure controller has been connected to the plasma chamber to control hydrogen gas flow rate in the plasma chamber to reach the set pressure. Pumping modules have been designed for ion source and installed at extraction chamber. The pumping modules have been designed in view of achieving plasma chamber vacuum in the range of $1 \times 10^{-5}$ mbar for gas flow rate settable in the range of 2-5 sccm, keeping the extraction chamber vacuum better than $1 \times 10^{-7}$ mbar. After extraction the ions move through a beam transport line of 3.2 meter long and diameter 100 mm. The beam line consists of two magnetic solenoids with some diagnostic elements slits, faraday cup and emittance monitoring box. The Vacuum system has been divided in two parts to estimate the pumping requirement, the ion source and extraction part and beam transport line.

![Fig. 4 Schematic of vacuum system of ion source and beam transport line.](image)

The pumping system has been designed to get pressure in the plasma chamber in range of $\sim 10^{-3}$ mbar with a load of gas flow rate $\sim 2$ sccm of hydrogen and maintaining the pressure better than $1.5 \times 10^{-5}$ mbar in the extraction chamber. The total estimated outgassing load from plasma chamber and extraction system is $\sim 2 \times 10^{-5}$ mbar l/s. The plasma and extraction chambers are pumped by two 500 l/s turbo molecular pump having high compression ratio for hydrogen. These are electrically isolated by ceramic of low out-gassing rate. The base pressure of $1 \times 10^{-6}$ mbar in the plasma chamber and $\sim 2 \times 10^{-7}$ mbar in extraction zone have been routinely obtained without any gas load.

A uniform vacuum of $1 \times 10^{-6}$ mbar is needed to be maintained from the extraction chamber to end of beam line which is 3.2 m long. Major portions of the beam line consist of tubes of diameter 100 mm except at two locations where 152 mm crosses are connected for assembly of pump and diagnostic components. This offers an overall volume of approximately 37.4 liter and a surface area of $\sim 1.45$ m². The total estimated gas load from line is $1 \times 10^4$ mbar l/s. We have used metal gaskets at demountable joints and same have been considered at the time of estimating the load. A 500 l/s turbo molecular pump backed by scroll pump has been used to evacuate the beam line at distance of 1.5 meter from extraction chamber. At the end of the beam line we have installed a vacuum chamber to in-house the spiral inflector. The total estimated gas load from this chamber is approximately $\sim 7 \times 10^6$ mbar l/s. This chamber is pumped by a turbo pump of speed 60 l/s and partly pumped by the beam line turbo pump.
3. Online Vacuum Monitoring
The online vacuum data logging software have been developed with a spark protection hardware circuit for continuous monitoring of the vacuum near the extraction electrode and in the backing line of the pump for 2.45 GHz microwave ion source. The monitoring system which we put initially was found very sensitive to voltage breakdown at high voltage deck and used to hang even with a minor spark. Once, the entire circuit as well as the serial port of the pc was damaged by the induced voltages due to sparks. In order to make the system reliable in such kind of environment we have carried out detailed study and some modifications in the circuit. Now we have added a spark protection circuit which provides an isolation of 10kV using an optical isolation technique. It uses 6N137 digital opto isolator IC, along with max232 which is basically used for isolating the low voltage electronics with the high voltage system without affecting the communication speed. The spark protection system uses two symmetrical circuits. One circuit convert max232 voltages coming from PC to TTL level, so that opto-isolator can work in TTL voltages and provide an isolation of 10kV. The other circuit again transforms the TTL voltage level into max232 voltage level. In this way the data are transmitted through a RS232 cable to the vacuum gauge with isolation. This circuit has been tested for continuous operation and found to be very satisfactory. The peak in the Fig. 5 shows the increase in the vacuum due to spark produced near the extraction electrode whereas second plot in Fig. 5 indicates the reduction in the pressure when the ion source was operating. Pressure resumed the almost same value after switching off the source. We have also provided facility to log the reading in the Microsoft excel sheet for further analysis of the data. The temperature of the vacuum gauge is also monitored to detect any malfunctioning of the vacuum gauge.

Fig. 5. Online display of the pressure near the extraction zone. Bump indicates the pressure rise due to spark of high voltage. The second plot shows the duration of reduced pressure zone in which ion source was operating.

4. Operational experience
The key issue during the designing and commissioning of the ion source was to get a satisfactory working regime. In this kind of source two positions of ECR points are very important. One ECR point should be located very near to the microwave window which is very vital for microwave power coupling into the source plasma. The other ECR point is required to be present at the extraction hole of the plasma electrode to create dense plasma for better ion extraction. The magnetic field at the middle of chamber helps the plasma in radial confinement and axial diffusion. The optimization of the required field values were set up by adjusting the locations of the solenoid coils and currents.

During the initial operations of the source, we faced few problems and taken appropriate actions:
- Initial promising operations were halted several times due to failure of the electronic components at the high voltage deck induced by HV sparking. To solve these problems we have grounded...
most of the floating conductors inside the deck and also done some modification by connecting a high resistance between isolation transformer and the deck. We placed appropriate filters and tested the system up to 90 kV with negligible leakage current (200 \( \mu \)A).

- There was a serious problem in microwave coupling to the plasma. We observed very high reflected power and lots of heating in the ridged wave-guide. Locally made control of manual tuner did not work properly. We inserted an auto tuner in the system. We designed and fabricated a new water-cooled ridged wave-guide and replaced it with the existing one.

- The thermal fracture of microwave window from the back streaming electrons and source plasma heating was another problem. We have now placed a 5 mm thick boron nitride plate behind the water-cooled plasma chamber. A RF quartz window is now placed for vacuum sealing just before the 90 deg bent in the waveguide. This will save the system in case of fracture of boron nitride microwave window.

- We faced lots of glow discharge and internal arcing during initial operation in the extraction region. Earlier our extraction slits were supported by cylindrical electrodes without any holes for the pumping. The main cause of the above problem was suspected to be the back streaming electrons that are produced by the proton impact ionization of neutrals in the extraction system. The electrons thus produced are then accelerated by electric field back towards the plasma chamber where they are focused on the axis by the magnetic field cause the discharge. In order to improve the vacuum in this region we machined several holes in both biased and ground electrodes. This process reduced the frequency of discharge by a considerable amount and improved the performance of the source.

The outlined strategy and improvement in the subsystems improved the reliability and performance of the source in terms of the long term stability. We have operated the source continuously for 8 hours with current more than 5mA on the Faraday cup. There were only 3-4 sparks which stopped the beam which was recovered within 2 minutes after the tripping of the high voltage.

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