Distributed UHV System for the Folded Tandem Ion Accelerator Facility at BARC

S K Gupta, A Agarwal, S K Singh, A Basu, Sapna P, S P Sarode, V P Singh, N B V Subrahmanyam, J P Bhatt, S S Pol, P J Raut, S V Ware, P Singh, R K Choudhury and S Kailas

Nuclear Physics Division, Bhabha Atomic Research Center, Mumbai 400 085, India.

sgupta@barc.gov.in

Abstract. The 6 MV Folded Tandem Ion Accelerator (FOTIA) Facility at the Nuclear Physics Division, BARC is operational and accelerated beams of both light and heavy ions are being used extensively for basic and applied research. An average vacuum of the order of $10^{-8}$-$10^{-9}$ Torr is maintained for maximum beam transmission and minimum beam energy spreads. The FOTIA vacuum system comprises of about 55 meter long, 100 mm diameter beam lines including various diagnostic devices, two accelerating tubes and four narrow vacuum chambers. The cross sections of the vacuum chambers are 14mm x 24mm for 180°, 38mm x 60mm and 19 x 44 mm for the and 70° & 90° bending magnets and Switching chambers respectively. All the beam line components are UHV compatible, fabricated from stainless steel 304L grade material fitted with metal gaskets. The total volume ~5.8 x 10^5 cm³ and surface area of 4.6 x 10^4 cm², interspersed with total 18 pumping stations. The accelerating tubes are subjected to very high voltage gradient, 20.4 kV/cm, which requires a hydrocarbon free and clean vacuum for smooth operation of the accelerator. Vacuum interlocks are provided to various devices for safe operation of the accelerator. Specially designed sputter ion pumps for higher environmental pressure of 8 atmospheres are used to pump the accelerating tubes and the vacuum chamber for the 180° bending magnet. Fast acting valves are provided for isolating main accelerator against accidental air rush from rest of the beam lines. All the vacuum readings are displayed locally and are also available remotely through computer interface to the Control Room. Vacuum system details are described in this paper.

1. Introduction
The FOTIA [1] is a medium energy heavy/light ion accelerator; ions are accelerated through the accelerating tubes by electrostatic potentials and finally transported to the experimental beam lines covering a long path of about 37 meters. A distributed pumping system [2] having eighteen pumping stations has been designed to maintain UHV in the entire accelerator, the total volume of ~5.8 x 10^5 cm³ and surface area of 4.6 x 10^4 cm² for the whole accelerator including three experimental beam lines and 2 scattering chambers. Since the charge exchange cross sections for heavy ions are very large, it is necessary to minimise the residual gas pressure and maintain ultra high vacuum in the accelerating tubes and rest of the beam transport system of such accelerators. This is also required to reduce the loss of intensity and spread in energy of the ion beams. The FOTIA vacuum system (figure 1) comprises of about 55 meter long, 100 mm diameter beam lines including various diagnostic devices, two accelerating tubes and four narrow dipole magnet chambers. Turbo Molecular Pump
(TMP), combination of Titanium Sublimation Pump (TSP) and Sputter Ion Pumps (SIP) or only SIP’s are employed for the main accelerator. However, Diffusion Pumps (DP) and TMP’s with proper isolation devices and protection against back streaming are used for experimental ports.

**2. System Design**

The design criteria for conductance and pumping speed is based on the feature that at every point in the space between the pumping stations both adjacent pumps contributes to the pumping. This helps in achieving uniform pumping speed at all the points in the beam tube. The beam tube diameter is chosen such that the pipe conductance for a length of the tube is equal to or more than the combined pumping speed of each pumping station. This ensures no loss of pumping speed. The length of beam tube is decided mainly by beam optics parameters i.e. object and image distances of focusing elements, dipole magnets etc. All the beam line components are UHV compatible, fabricated from stainless steel 304L grade material fitted with metal gaskets. This enables baking of the beam lines at elevated temperature and ensures better ultimate vacuum.

### 2.1. Calculation of effective pumping speed and sizing of pumps

Let $U_1, U_2$ are conductance of pipe on both side of the tee (figure 2)

$p_1, p_2$ are pressures

$q_1, q_2$ are throughputs

$S_1, S_2$ are pumping speed

$p$ is pressure

$q$ is throughput

$S$ is pumping speed

$S_{e1}, S_{e2}$ are the effective pumping speed at either side of the tee.
By definition -

\[ q_1 = p_1 S_1 \]
\[ q_2 = p_2 S_2 \]
\[ q = p S \]

Also

\[ \frac{1}{S_1} = \frac{1}{U_1} + \frac{1}{S_{e1}} \] \hspace{1cm} \text{(1)}

\[ q_1 = (p_1 - p) U_1 \]
\[ q_1 = (q_1 / S_1 - q / S) U_1 \]

\[ \therefore \frac{1}{U_1} = \frac{1}{S_1} - \frac{q}{q_1} \frac{1}{S} \]

or

\[ \frac{1}{S_1} = \frac{1}{U_1} + (q / q_1) \frac{1}{S} \Rightarrow \frac{1}{U_1} + 1 / [(q_1 / q)_S] \] \hspace{1cm} \text{(2)}

By comparing equations 1 & 2, effective pumping speed at mouth of the tee

\[ S_{e1} = (q_1 / q) S \]

So the space between the pumps is maintained such that \( q_1 = q_2 = 0.5q \) and hence half of the pumping speed is available at farthest point i.e. at the start of next pumping station. This way one can maintain uniform pumping speed at all the points in the beam tube. The beam tube diameter is chosen such that the pipe conductance for a length of the tube is equal to or more than the combined pumping speed of each pumping station. This ensures no loss of pumping speed. The length of beam tube is decided mainly by beam optics parameters i.e. object and image distances of focusing elements, dipole magnets etc.
2.2. Layout of Beam Lines and Selection of Pumps

In order to optimise the dimensions of various element along the beam path, it is essential to work out the beam optics of the entire system. There are various computer codes in use for such calculations. All these codes use matrix formulation, where each ion optical element is characterised in terms of transport matrix. The location and aperture size of diagnostic components such as beam profile monitors, faraday cups, beam defining slits and steerers are decided by the beam sizes at various points in the beam path and thus it is necessary that for maximum beam transmission the “acceptance” of all the element should be more than the emittance of the beam at that point. The type of the pumps installed in a particular section is based on the gas load in that section. As indicated in Table 1, the ion source section has a large gas load which increases substantially whenever samples are changed in the ion source. A turbo molecular pump with the speed of 1600 l/s maintains ultra high vacuum in this region. The other sections which are thoroughly degassed and have very small out gassing loads from metal surfaces, are pumped by a combination of TSP and SIP or only by SIP. TSP’s and SIP’s are always preferred for accelerators as they produce most clean and hydrocarbon free vacuum, moreover, these pumps do not need attention for normal operation and the gas pumped remains deposited in the pump body as solid Titanium compound / flakes of the gas pumped. In case of power failure it does not spoil the vacuum immediately. These pumps can be reconditioned by removing deposited material by chemical cleaning or glass bead blasting. Other choices are Cryo

| Sec. No. | Name of the section | Main components | Volume (cm³) & surface area (cm²) | Gas load (Torr-lit/sec) | Pumping speed (lit/s) |
|----------|---------------------|----------------|----------------------------------|------------------------|----------------------|
| 1.       | Ion source          | Ion source, Acc. Tube, E.S. steerer | 47713 10822                   | 1.44 x 10⁻⁵           | 1600                 |
| 2.       | Injection line      | 70° Magnet Chamber, 20° Deflector, E.S. Steerer | 51616 19287                  | 6.3 x 10⁻⁶           | 840                  |
| 3.       | Low energy accelerating tube | Einzel lens, Acc. Tube, E.S. Steerer, valve | 22407 17194                  | 1.08 X 10⁻⁶          | 140                  |
| 4.       | Terminal            | Stripper and 180° Magnet Chambers, Pumping unit | 9628 4473                    | 9.34 X 10⁻⁷          | 140                  |
| 5.       | High energy accelerating tube | Acc. Tube, Mag. Quad.Triplet, Pumping unit | 31455 20812                  | 7.5 X 10⁻⁶           | 140                  |
| 6.       | Analysing magnet    | 90°Magnet chamber, BPM,FC, Slits, Pumping unit | 40834 18393                  | 1.0 X 10⁻⁶           | 980                  |
| 7.       | Main Beam line      | Scatt.chamber, S/W magnet, Mag. Steerer, M.Q.T. | 106306 50198                 | 9.5 X 10⁻⁶           | 3000                 |
| 8.       | Additional Beam lines (Four Number) | Scatt.chamber, Mag. Steerer, M.Q.T., BPM, FC | 270312 317317                 | 7.0 X 10⁻⁵           | 2560 (500 x 4+ 70 x 8) |

Table 1: Gas load Estimates
pumps and Diffusion pumps with proper isolation devices and protection against back streaming. While using oil based pumps for high gradient insulating assemblies care must be taken to avoiding accidental back streaming of pump fluid by using cryo arrays / traps. Oil free sorption mumps and diaphragm pumps are also available.

2.3. Gas Load Estimates

The FOTIA vacuum system has been divided into seven sections. As it is clearly shown in figure 1, a section is a length of beam line between two valves with drift tube, diagnostic, corrective and the beam optical components, and has at least one pumping station.

In molecular flow region for calculation of gas load, volume of the system is not very important it affects only initial pump down time up to the pressure of 1x 10⁻³ torr. Total gas load from a system is the summation of gas loads contributed due to presence of impurities having high vapour pressure, leakage from weld joints, outgassing and permeation from the surface and the pump down time can be evaluated in the following manner.

\[ Q_{\text{g}} = Q_{l} + Q_{d} + Q_{v} + Q_{p} \]

Where

- \( Q_{l} \) = Gas load due to leakage.
- \( Q_{d} \) = Gas load due to outgassing
- \( Q_{v} \) = Gas load due to volatile impurities of high vapour pressure
- \( Q_{p} \) = Gas load due to leakage

In steady state condition

\[ P_{u} = \frac{Q_{g}}{S_{\text{eff}}} \]

The details of the individual sections with main components, volumes and surface areas, gas loads, and the capacity of the pumps used, are given in Table 1.

2.4. Details of Vacuum System Components

The 180º Folding Magnet Chamber made of SS304L has internal dimension of 21 x 18 mm and wall thickness of 1.5 mm. The Distance between view ports is 610±0.4 mm. Concentricity of viewing ports w.r.t. entry/exit port is 1.6 mm over the length of 485 mm. Weld joints tested with MSLD, leak rate less than 1X10⁻¹¹ std-cc/sec and absolutely no pressure to vacuum leak.
A general purpose scattering chamber [3] of 800 mm diameter has seven identical ports of internal diameter 160 mm at 55°, 90°, 145°, 180°, 235°, 270° and 325° in the horizontal plane. The two ports have provision for viewing window using toughened glass. The interface flange has provision to hold a pair of apertures for beam collimation. The two apertures decide the maximum beam spot size (or beam wandering) on the target. The chamber has provision for mounting multiple targets mounted on a ladder, movable detector arms with detectors mounted on it and a close circuit video camera to monitor the beam spot on the target etc.

A eight port 400 mm diameter scattering chamber has ports at 45°, 90°, 135°, 180°, 225°, 270° and 315° in the horizontal plane and two 100 mm port on top and a 150 CFF port for pumping at bottom. The 90° port is used to accommodate a Si(Li) detector with Mylar window and 0° port has provision for extracting beam in air for radiation damage studies of live cells and external PIXE Studies. A load lock mechanism facilitates transfer of multiple targets mounted on a target ladder in scattering chamber. This chamber is being extensively used for PIXE, External PIXE, RBS and Radiation of live cells studies.

A 5-port switching magnet located in the beam hall is used to inject beam in to either of the 0°, ±25° or ±50° beam line. The picture shows a view of the beam lines showing scattering chamber, magnetic quadrupole, steerer and other diagnostic components.
2.5. Safety Interlocks and Monitoring

Safety of the pumps and other devices like high voltage charging system, beam handling components etc., is ensured by interlocking their operation with the safe vacuum level in the respective sections by using changeover contacts available from ion gauge controller. The accelerating tubes are very crucial components of the accelerator and need to be maintained under ultra high vacuum at all the time. To protect these accelerating tubes from accidental air rush, three fast closing valves (closing time < 70 msec) have been provided at the end of both the tubes and near switching magnet. A residual gas analyser is also used to monitor the traces of SF6 gas in the accelerating tubes and beam lines. The Programmable Logic Controller (PLC) based safety interlock system [4] is employed for monitoring and control of sputter ion pumps, compressor and rotary pump. All crucial interlocks are hard wired for fail safe operation. Three specially designed ion pumps to withstand an external pressure of 100 psig and vacuum of 10^{-10} Torr inside the system are used in the Accelerator Tank and are also protected against high voltage spark flashovers near feedthroughs at sub-atmospheric pressures. To avoid damages, the operation of roughing pump, which is used to evacuate the accelerator tank, has been interlocked with the SIP power supply. The vacuum readings are monitored both locally and remotely using CAMAC based control system.

3. PERFORMANCE

The performance of the UHV system has been quite satisfactory. An average vacuum of 2x10^{-8} Torr has been achieved in the entire transport system including accelerating tubes. The Pressure to vacuum leaks in the accelerator are thoroughly checked by observing RGA and vacuum readings at each accelerator tank closing. In order to achieve mild and uniform degassing of accelerating tubes, infrared lamps were used for baking. The pump down characteristics for accelerating tube is shown in Figure 7.

![Figure 7: Pump down Characteristics of Accelerating tubes](image_url)

4. References

P. Singh, Ind. J. Pure & Appl. Phys., 35, 172 (1997)
S.K.Gupta et al, Bulletin of Indian Vacuum Society, 3, 31 (2000)
Suresh Kumar et al, Proc. IVSNS-2003 (2003) pg.170
Rajesh Kumar et al, Proc. Ind. Part. Acc. Conf. (InPAC2003), (2003) page 658

Acknowledgement

We thank Dr. V.C. Sahni for his keen interest in the development of the facility.