Vacuum System of the 3MeV Industrial Electron Beam Accelerator

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Abstract. One DC Accelerator, for electron beam of 3 MeV energy and 10 mA beam current, to derive 30 KW beam power for Industrial applications is nearing completion at Electron Beam Centre, Kharghar, Navi Mumbai. Beam-line of the accelerator is six meters long, consists of electron gun at top, followed by the accelerating column and finally the scan horn. Electron gun and the accelerating column is exposed to SF6 gas at six atmospheres. Area exposed to the vacuum is 65,000 sq.cm, and includes a volume of 200 litres. Vacuum of the order of 1x10^-7 mbar is desired. To ensure a good vacuum gradient, distributive pumping is implemented. Electron beam is scanned to a size of 5cm X 120cm, to get a useful beam coverage, for industrial radiation applications. The beam is extracted through a window of Titanium foil of 50µm thickness. A safety interlock, to protect the electron gun, accelerating column and sputter ion pumps, in case of a foil rupture, is incorporated. Foil change can be done without disturbing the vacuum in the other zones. System will be integrated to a master control system to take care of the various safety aspects, and to make it operator friendly.

1. Introduction

Utility of the accelerators is getting more recognized in recent times for its widening arena of applications. They are widely used for the enhancement of material properties, preservation of food, sterilization of the surgical equipments and waste treatment. Accelerators provide variable level of processing intensities as its parameters can be well manipulated to suit the requirements. They do not pose any inherent environmental threat when not in operation and better operational safety is ensured. Improvisation of the insulation properties of the cable sheathing, and imparting fascinating colors to the precious stones are some of the proposed applications of this accelerator apart from the R & D activities.

2. Functional requirement of high vacuum

Vacuum plays an important role in the performance of the accelerator. The beam quality is better, if the vacuum is better. The electron beam has to travel a distance of approximately six meters before it is scanned and taken out through the Titanium window. Poor vacuum can adversely affect the beam parameters. Hence, it is essential that the beam – line and the scan horn have to be maintained at a vacuum of 1 X 10^-7 mbar or better. Considering the length of the accelerator and the impedance due to constrictions, distributive pumping is implemented to maintain the desired vacuum gradient.
The electron beam interacts with the molecules in the path of transmission, resulting losses due to scattering. On colliding with the residual gas molecules, the beam loses its energy due to inelastic collisions with the atomic electrons and nucleus. Ionisation leads to ionisation loss and yields secondary electrons. Interaction of the beam with the nucleus too leads to energy loss and emission of bremsstrahlung. Beam loss is occurred due to both the elastic and non-elastic collisions. The total beam loss due to these two effects is given by the following formula.

\[
\frac{dT}{ds}_{\text{total}} = \frac{dT}{ds}_{\text{ion}} + \frac{dT}{ds}_{\text{rad}}
\]

Where,

\[
\frac{dT}{ds}_{\text{ion}} = 4\pi r_0^2 \frac{m_e c^2}{\beta} N Z \left\{ \ln \left[ \frac{\beta \left( \frac{T + m_e c^2}{l} \right)}{l} \right] - \frac{1}{2} \beta^2 \right\}
\]

\[
4\pi r_0^2 = 1.0 \times 10^{-24} \text{ cm}^2 \text{ where } r_0 \text{ is the classical electron radius,}
\]

\[
m_0 c^2 = \text{ rest mass of the electron } = 0.511 \text{ MeV}
\]
\[ \sigma = 0.580 \times 10^{-21} \text{ cm}^2 / \text{nucleus and } \beta = \frac{v}{c} \]

\[ \left[ \frac{dT}{ds} \right]_{\text{rad}} = N \left( T + m_e c^2 \right) \rho Z^2 \left[ 4 \ln \left( \frac{T + m_e c^2}{m c^2} \right) \frac{1}{3} \right] \]

\( \text{NZ} = \text{number of electrons / cm}^3, \text{N} = \text{total number of atoms / cm}^3, \text{Z} = \text{atomic number of the target.} \)

\( I = Z^*, \text{average ionisation potential of the atoms ( MeV )} \)

\begin{center}
\text{LAYOUT OF THE VACUUM SYSTEM COMPONENTS}
\end{center}

|   |   |   |   |
|---|---|---|---|
| 1. Electron Gun | 5. Gate valve (CF-100) | 9. RP (300l/min) | 13. Bellows |
| 2. SIP (40l/s) | 6. Gate valve (CF-150) | 10. SIP (500l/s) | 14. Beam sensor |
| 3. Accelerator column | 7. Magnetron gauge | 11. Focusing coil | 15. Scan magnet |
| 4. Focusing coil | 8. TMP (550l/s) | 12. Steering magnet | 16. SIP (70l/s) |

3. Design of the vacuum system

The total surface area exposed to the vacuum is about 65,000 cm\(^2\). An average out gassing rate of \( 1 \times 10^{-9} \text{ mbar liters / sec / cm}^2 \) is considered. Then the throughput is \( 6.5 \times 10^{-5} \text{ mbar liters / sec} \). The required vacuum is \( 1 \times 10^{-7} \text{ mbar} \). The pumping speed available at the top of the gun is \( C_g S / (C_g + C_c) \), where ‘\( C_g \)’ and ‘\( C_c \)’ are the conductance of the gun and the accelerator column respectively and ‘\( S \)’ is the speed of the pump. Similarly pumping speed available at the Titanium window is \( C_h S / (C_t + C_h) \), where ‘\( C_h \)’ and ‘\( C_t \)’ are the conductance of the horn and the transition tube respectively. Employing a sputter ion pump of 500 l / s, an effective pumping speed of 25 l / s and 40 l / s are obtained at the top and the bottom ends of the accelerator. The corresponding values of the ultimate vacuum are 2 X 10\(^{-6}\) mbar and 2.5 X 10\(^{-7}\) mbar respectively. To improve the vacuum at the top, a sputter ion pump of speed 40 l / s is introduced in the electron gun. This pump is of special design, as it has to withstand SF6 gas at a pressure of six atmospheres. Another sputter ion pump of 70 l / s speed, is employed in the scan-horn to improve the vacuum there, as the opening of the beam sensing aperture along with the scan magnet chamber opening, restricts the conductance to the main pump. The main pump employed is a sputter ion pump of 500 l / s speed. For evacuation at the initial stage, and
on cycling of the system to atmospheric pressure for maintenance, to bring the vacuum to a comfortable level (10^{-6} mbar range), before switching on the sputter ion pump – to improve the life of the sputter ion pump – one turbomolecular pump of speed 550 l/s is also employed. Rotary pump of speed 300 l/min is employed for the backing of the turbomolecular pump.

4. Methods and Techniques adopted to achieve the desired vacuum

The surfaces exposed to high vacuum, desorbs gases during the evacuation. There are number of techniques and methods, to deal with the surface outgassing. Some of these methods are followed during the fabrication. The chief objective of this practice is to improve the quality of the surface by providing a high degree of surface finish. By this means we can reduce the effective surface area and hence the gas load from the outgassing. Machining of the SS without the use of lubricating oil, one can achieve a surface finish of 30-60 microns, and with oil, a better finish of 20-40 microns can be achieved. By grinding, a finish of 30 microns can be achieved, while honing provides a finish of 2 microns. The vacuum pipeline, electron gun, scan-horn and foil holder assembly are fabricated out of SS304. Care is taken at the time of the fabrication to see that the surface finish conforms to the high vacuum practice as mentioned above. Additionally, the internal surfaces of the vacuum pipeline are electro-polished, since it provides a very good surface finish and helps in achieving low out gassing rates. OFHC copper gaskets are used for the conflat flanges. Viton gaskets are used in the foil holder assembly. Foil holder assembly is leak-tested separately, prior to the installation in the scan-horn.

5. General description of the HV system

For extracting the electron beam, out of the scan-horn, a Titanium foil of 50 µm is used. This foil is vulnerable to puncture and can cause an air rush in to the accelerator, spoiling the electron gun, accelerator column, sputter ion pumps. Ideally, a fast acting valve is to be located above the scan-horn. But the fast acting valve will be effective when the valve is considerably away (5 meters minimum) from the rupture sensing point, and is not effective in our case as the length is less than a meter. Sufficient numbers of gate valves are provided to attend to the services of various sections without affecting the vacuum in the other regions. Pirani and Magnetron (Cold cathode) gauges are used to monitor the vacuum in various regions. Gauge is provided ahead of the turbomolecular pump to monitor it’s performance, separately. All the valves are accommodated in the safe area to protect it from radiation. Measuring the ion current in the sputter ion pump in the gun the degree of vacuum there can be ascertained.

6. Interlocks

The operation of the accelerator in general and the vacuum system in particular are computer controlled. The vacuum system is interlocked to a nitrogen gas pressure switch and a water flow switch, so that in the absence of the nitrogen pressure and the water, the system cannot be switched on. The Pirani gauge mounted on the four-way cross is interlocked with the TMP so that the TMP should not be switched on till the vacuum read by the Pirani gauge is better than 1 X 10^{-5} mbar. Valves to isolate the sputter ion pump at the scan-horn and that to isolate the scan-horn from the top region are interlocked to the Magnetron gauge at the scan-horn, in such a way that, when the vacuum deteriorates to 1 X 10^{-5} mbar, these valves will close. This gauge is further interlocked to the high voltage power supply and the gun power supply.
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