PHYS719P REPORT NO.2: ACCELERATOR VACUUM TECHNOLOGY AND AN EXERCISE ON VACUUM ASSEMBLY

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Abstract

Maintaining a desirable vacuum condition is important for securing the beam performance, in terms of keeping the mean free path of accelerating particles long enough and minimizing the impact of radiation on the interior side of the wall. This report presents a brief introduction to the general concepts of vacuum and a hands-on exercise on the assembly of vacuum components.

I. INTRODUCTION

Vacuum environment for accelerators

Particle accelerators require ultra-high vacuum (UHV, 10^{-7} – 10^{-10} Pa) to ensure optimal beam performance. If residual gas molecules remain in the beam path, the interaction of beam and gas causes ionization, leading to the unwanted scattering of accelerating particles. This degrades the efficiency and luminosity of the accelerator.

Maintaining a clean vacuum is also important in data collection and prevention of surface contamination. Interactions between the beam and residual gas contribute to unwanted noise in detectors, reducing the signal-to-noise ratio (SNR) and interrupting the analysis of physics phenomena of interest. Especially in high-energy physics experiments, small random fluctuations in acquired data can lead to inconsistencies of results. Also, surface contamination can occur due to accumulation of residual gas molecules, and their interaction with synchrotron radiation can modify chemical properties of interior surfaces.

Synchrotron radiation and its effect on accelerators

Charged particles undergoing circular motion emit synchrotron radiation (SR). Especially when the particle velocity is close to the speed of light, the direction of radiation aligns with the tangential direction of circular trajectory. Interaction of SR with vacuum chamber walls leads to photodesorption of gas molecules, which in turn increases the pressure and introduces additional *gas load* into the vacuum system. The gas load directly affects the beam lifetime (τ), which is given as following [1]:

$$\begin{aligned} I_e &= I_{e0}\exp(-t/\tau), \\ \tau^{-1} &= \sum_i \left(\sigma_B(Z_i) + Z_i\sigma_M + \sigma_R(Z_i)\right) p_i, \end{aligned} \tag{1}$$

since the increase of pressure (p_i) by gas load reduces τ. The heat generated by SR also lead to an increase of local temperature, affecting the thermal stability of accelerator

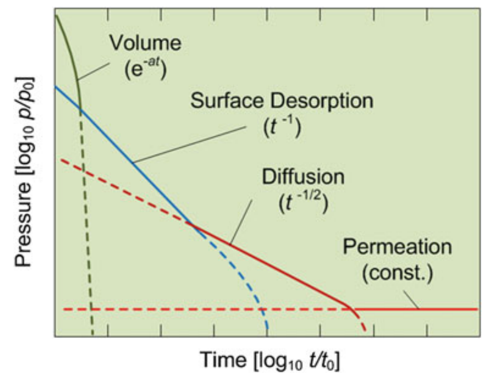

Figure 1: (Adopted from ref. [2]). Decrease rate of vacuum pressure limited by various factors. The dominant factor change as the pressure decrease.

components (i.e. *heat load*). The average power density of SR is as follows [1]:

$$\left\langle P_{\mathrm{Ie,line}} \right\rangle \ [\mathrm{W/m}] = 88.4{\times}10^3 E_e[GeV]^4{\times}I_e[A]/\rho C, \tag{2}$$

where ρ and C are radius and circumference of a circular storage ring in meters. Given that $E_e = 4\,\mathrm{GeV}$, $I_e = 3.6\,\mathrm{A}$, $\rho = 74\,\mathrm{m}$, and $C = 2\,\mathrm{km}$,

$$\left\langle P_{\mathrm{Ie,line}} \right\rangle \ = 88.4\times 10^3 4^4 \times 2.6/74/2000 = 550\,\mathrm{W/m}. \tag{3}$$

This is high enough to melt down the interior surface of vacuum components.

Heat(or thermal) load and gas load needs to be carefully managed, especially from the design phase of vacuum system. Photon stops equipped with cooling systems are designed to absorb high-energy photons before they can interact with chamber walls. The photon stop should have high thermal conductivity and be resistant to radiation, so materials such as copper and tungsten are often utilized. In order to deal with gas load, pumping systems such as ion pump and cryopumps are placed where photons are irradiated.

II. BRIEF INTRODUCTION ON VACUUM TECHNOLOGY

In order to establish ultra-high vacuum (UHV) state required for accelerator, one needs to understand the distinct stages of vacuum evacuation characterized by different mechanism of gas removal. As shown in figure 1, the process can be summarized as following 4 steps:

(1) Volume gas removal: dominated by molecular flow, free gas molecules are pumped out. In this stage, pressure decreases exponentially: $P(t) = P_0 e^{-kt}$, where k and P_0 are constants.

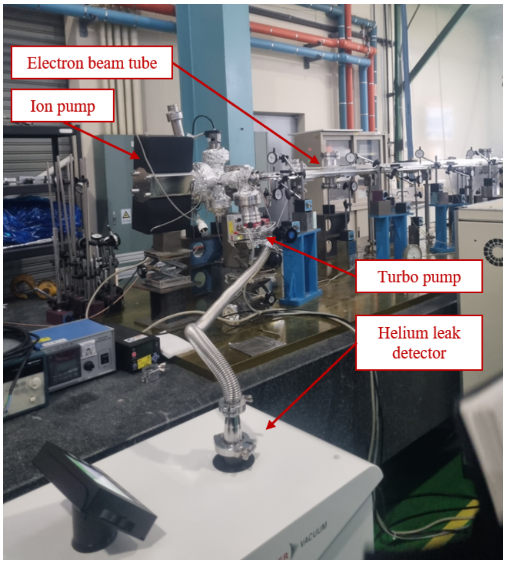

Figure 2: Prototype of electron beam tube and vacuum system.

(2) Surface desorption: as the bulk gas is removed, gases and vapors previously adsorbed at chamber surface are desorbed, and the pressure varies slowly: $P(t) \sim t^{-1}$.

(3) Diffusion: gas trapped in the metals are diffused to the vacuum, following a pressure behavior of $P(t) \sim t^{-1/2}$.

(4) Permeation: outside gas pass through chamber walls and pressure remain constant. This stage highly depends on choice of wall or shielding materials.

Understanding these steps is crucial for establishing and managing vacuum environment, including selection of proper pumps and gauges.

Figure 2 shows a prototype of vacuum system for accelerator beam tube. In order to test the tightness of vacuum chamber, helium leak detector can be used by sputtering helium gas nearby the vacuum flange. If the sputtered helium permeates into the vacuum system due to the imperfections of the vacuum assembly, then the helium leak detector will capture the leaked helium using the principle of mass spectroscopy.

Measurement of vacuum pressure

Various types of gauges are employed to measure the vacuum pressure. Widely used vacuum gauges include thermal conductivity gauge (or Pirani gauge) and ionization gauges. In the Pirani gauge, a heated filament loses heat through conduction to surrounding gas molecules. Here the thermal conductivity depends on the pressure, so this type of gauge is ineffective in UHV, since the gas density becomes very low and the change in filament temperature becomes not measurable. Ionization gauges can measure UHV conditions and operate by ionizing residual gas and measuring the resulting current by the displacement of ions. Especially, hot cathode ionization gauges consist of a hot filament that emits electrons which ionize the gas molecules through collision, and the generated ions are collected by an electrode.

III. ASSEMBLY OF VACUUM CHAMBER AND MEASUREMENT OF PRESSURE

(a) (b)

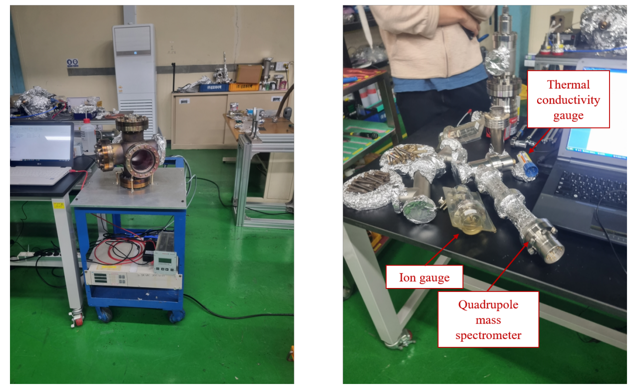

Figure 3: (a) Picture of vacuum chamber before disassembly. (b) Gauges prepared for integration onto the vacuum system.

Assembly and performance validation of a vacuum system is conducted as a hands-on practice. The practice is carried out in the following steps:

(1) Disassembly of the existing vacuum chamber, shown in figure 3(a)

(2) Assembly of the vacuum chamber (including flanges and adapters for gauge installation)

(3) Installation of the gauge and connection of electronics

(4) Vacuum evacuation and leak test

In the disassemble and reassemble steps (1-3), one needs to make sure that gaskets and the interior side of vacuum flanges are clean. Any contamination can lead to degradation of the vacuum environment. Gaskets are important in creating a reliable seal between different components. When the flange screws are tightened, gaskets can prevent leaks by filling the gaps between mating surfaces. Gasket material should differ from other vacuum components such as the chamber body and the flange, because the same materials tend to stick after a vacuum evacuation. The picture after the chamber is assembled is shown in figure 4(a).

After the start of vacuum evacuation, leaks due to imperfectness of vacuum assembly is tested using helium leak detector. Helium gas is sprayed around suspected leak points, and the leakage is searched by checking the increase of leak rate in the detector. The identified leaks are sealed by tightening bolts, followed by repeated checks to confirm if the leak is solved. The interior of vacuum chamber is shown in figure 4(c), where the red luminous filaments are components of quadrupole mass spectrometer (QMS) which analyzes the residual gas in the vacuum system.

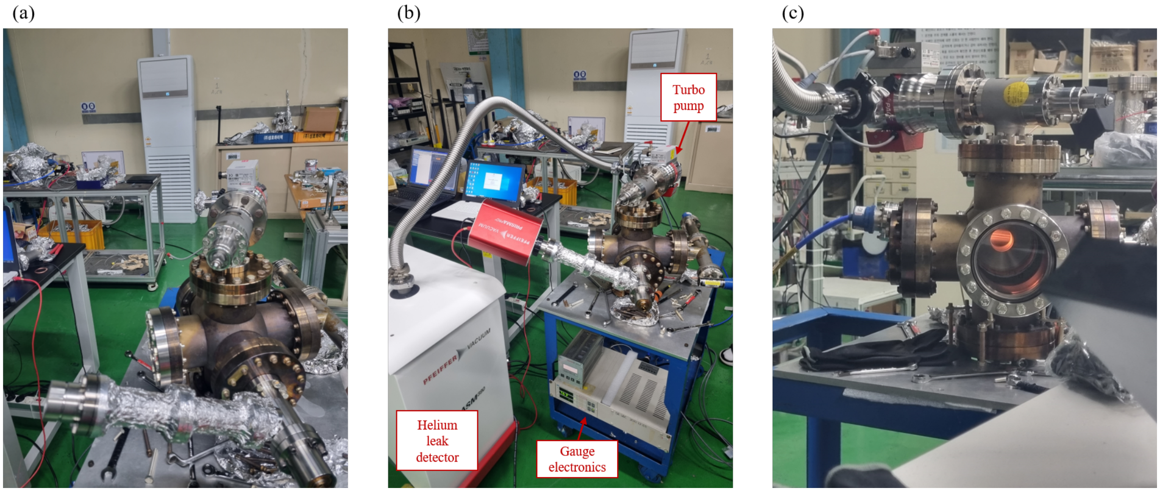

Figure 4: (a) Vacuum chamber after the installation of gauges. (b) Connection of helium leak detector and gauge electronics which measure and display the pressure inside the chamber. (c) Another view of vacuum chamber showing the interior through a window.

IV. SUMMARY

Particle accelerators reqire high vacuum to maintain beam quality, by minimizing interactions with residual gas molecules. Especially, one needs to manage the heat and gas load by synchrotron radiation, since their interaction with vacuum walls leads to desorption of gas molecules and damage accelerator components.

Through assembly of a vacuum system and its performance validation, insight onto the procedure of establishing vacuum system is gained. Proper selection of pumps and materials based on deep understanding of vacuum are not only important , skills on cleaning and assembling vacuum components are very important in the establishment of vacuum system. Even if the assemble procedure is not perfect, one can complement the vacuum tightness through helium leak detection.

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