FUNDAMENTAL STUDIES ON ACCELERATOR VACUUM SYSTEMS*

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Abstract

Vacuum quality is a critical factor in accelerator operation. Insufficient vacuum levels lead to increased interactions between the beam and residual gas particles, resulting in beam loss and reduced operational stability. This paper outlines the fundamental principles of vacuum systems required for accelerators and experimental studies conducted to achieve and maintain high vacuum conditions necessary for reliable beam performance.

INTRODUCTION

In accelerator systems, maintaining an ultra high vacuum environment is essential for stable beam operation. Residual gas molecules inside the vacuum chamber can interact with the particle beam, leading to scattering, beam loss, and degradation of beam quality. As accelerators aim for higher beam intensities and longer operation times, achieving and maintaining better vacuum conditions becomes even more critical.

The vacuum system in an accelerator is designed to minimize beam-gas interactions by reducing the number of gas molecules present in the beam path. To achieve this, a combination of vacuum pumps, careful material selection, and optimized chamber designs are employed. Key parameters such as base pressure, outgassing rates, and mean free paths must be carefully considered.

In this study, we review the basic principles behind vacuum generation, vacuum pump, and gauge. Next we describe experimental approaches to achieving the required vacuum levels. Through this work, our aim is to build a foundation for understanding vacuum systems in accelerator.

BASIC PRINCIPLES OF VACUUM SYSTEM

To design a vacuum system, several fundamental factors must be considered. These include the size (volume) of the system, the initial pressure, the target operating pressure, temperature, flow rate, and the type of target gas. Based on these specifications, the primary selection of vessel materials, machining, piping, valves, and gauges must be made.

Subsequently, depending on the required vacuum level, the type of vacuum pump and its pumping speed are determined.

In order to properly design and operate such a system, it is essential to understand the dominant gas sources at each vacuum level and to select appropriate pumps and gauges. In the following sections, we first examine the sources affecting vacuum performance.

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Gas Sources During Evacuation

During the evacuation process, the dominant gas source changes depending on the pressure and time. Initially, the volume gas inside the vacuum chamber is removed, leading to a rapid decrease in pressure. The pressure drop follows an exponential decay behavior, typically expressed as e^{-kt}.

As the volume gas is sufficiently removed, surface-adsorbed gases, mainly water vapor (H_2O), become the dominant source. In this stage, the pressure decreases inversely with time, following a $\frac{1}{t}$ relationship.

Over longer timescales, gas molecules such as hydrogen (H_2) diffuse from the bulk material to the surface. This diffusion-limited regime shows a pressure decrease proportional to $\frac{1}{\sqrt{t}}$.

Finally, at very long times, permeation of external gases through the chamber walls becomes the limiting factor, causing the pressure to reach a stable asymptotic value.

All of these processes are illustrated in Fig. 1.

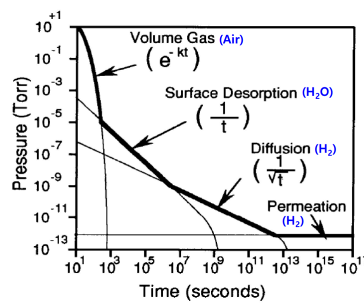

Figure 1: Pressure evolution during evacuation, indicating changes in dominant gas sources [1].

Vacuum pump

The choice of vacuum pump depends on the required vacuum level. In the low vacuum region, **Rotary Vane Pumps** and **Scroll Pumps** are commonly used. These pumps operate by trapping gas between rotating structures, and then sequentially performing suction, isolation, compression, and exhaust processes. Using such dry pumps, it is generally possible to reach pressures down to approximately 1 Torr.

However, at higher vacuum levels, these pumps become ineffective, as they cannot efficiently compress the remaining gas molecules.

To achieve high vacuum, a secondary pump is employed after the primary pump. One such secondary pump is the **Diffusion Pump**. In a diffusion pump, oil is filled at the bottom of the barrel and heated by an internal heater. As the oil evaporates, vapor flows upward along a chimney equipped with nozzles. The oil vapor exits through the nozzles and collides with gas molecules in the chamber, transferring momentum and directing the gas molecules toward the bottom.

Since the bottom region maintains a relatively higher pressure, the connected primary pump can efficiently remove these gas molecules. Oil vapor that contacts the barrel walls condenses and returns to the bottom reservoir.

Diffusion pumps are capable of operating effectively from 10^{-3} Torr down to 10^{-8} Torr. Except for the risk of oil backstreaming, diffusion pumps can reliably achieve high vacuum conditions.

The **Turbo Molecular Pump (TMP)** is also a secondary pump used to achieve high vacuum. It operates by transferring momentum to gas molecules through rapidly rotating blades.

The pump consists of alternating rotor and stator stages. The rotor is a set of blades mounted on a high-speed shaft, rotating typically between 20,000 and 90,000 rpm. As gas molecules collide with the angled rotor blades, they are given downward momentum toward the exhaust. Between each rotor stage, a stator is positioned. The stator blades are stationary and guide the gas molecules toward the next rotor, maintaining the molecular flow in the pumping direction.

Through repeated acceleration and redirection by the rotor and stator stages, gas molecules are efficiently transported toward the backing port.

TMP operate effectively from 10^{-3} Torr down to 10^{-10} Torr. If the vacuum level is not sufficiently low before operation, a large number of gas molecules can collide with the rotor blades, potentially causing mechanical damage. Therefore, a primary pump must be used to achieve an adequate vacuum before starting the TMP.

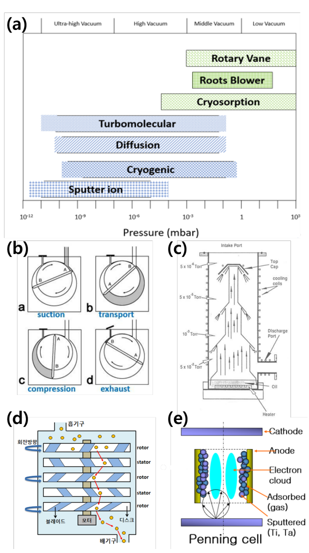

Figure 2: (a) Operational pressure ranges and structures of vacuum pumps, such as (b) Rotary Vane Pump, (c) Diffusion Pump, (d) TMP, (e) SIP.

Another type of vacuum pump used for ultra-high vacuum is the **Sputter Ion Pump(SIP)**. SIP operate by ionizing residual gas molecules and embedding them into solid surfaces. In a sputter ion pump, residual gas molecules are removed through a two-step process involving ionization and surface interactions.

First, electrons emitted from the cathode are trapped by a magnetic field and spiral through the vacuum, increasing the probability of colliding with and ionizing gas molecules. The resulting positive ions are accelerated toward the cathode under the influence of an electric field. When these ions collide with the cathode surface, they are either embedded directly into the material or chemically react with it, effectively removing them from the vacuum environment.

At the same time, the ion impact causes atoms (Ti) from the cathode material, typically titanium, to be sputtered onto nearby surfaces. This deposited titanium actively captures additional gas molecules by chemical bonding, providing another mechanism for removing gases from the system.

Through these processes, sputter ion pumps can achieve and maintain pressures in the range off 10^{-5} Torr to 10^{-10} Torr. The operating pressure ranges and typical structures of each pump are illustrated in Fig. 2.

Vacuum gauge

The selection of appropriate gauges also depends on the vacuum level, similar to the choice of pumps.

Thermal conductivity gauges, such as **Pirani gauges**, measure vacuum by detecting changes in heat loss from a heated filament as the pressure varies. They are effective from atmospheric pressure down to approximately 10^{-3} Torr.

Convection gauges operate on a similar principle as Pirani gauges, but are designed to improve sensitivity at higher pressures. In these gauges, the filament is mounted horizontally to promote stronger convection effects. For accurate pressure measurements, the gauge must be installed horizontally within the vacuum system.

At higher vacuum levels, ionization gauges are used to measure pressure by detecting the ion current.

In the case of **Hot Filament Ionization Gauges**, a filament is heated to emit electrons. These electrons collide with gas molecules, ionizing them, and the resulting positive ions are collected at an ion collector. The measured ion current is proportional to the pressure of the residual gases. Hot filament ionization gauges typically provide accurate pressure measurements from about 10^{-3} Torr down to 10^{-10} Torr.

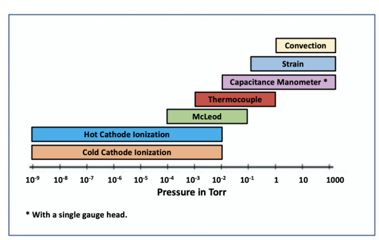

Figure 3: Operational pressure ranges for each vacuum gauge [2].

However, a major drawback of hot filament gauges is that the filament can burn out. To address this limitation,

Cold Cathode Ionization Gauges were developed. In cold cathode gauges, no filament heating is required, but a high voltage is applied to create a gas discharge, which ionizes the gas molecules.

For residual gas analysis, **Quadrupole Mass Spectrometers(QMS)** are used. They separate ions based on their mass-to-charge ratio and provide both pressure measurements and gas composition analysis.

The operating pressure ranges for each gauge are illustrated in Fig. 3

EXPERIMENTS WITH VACUUM CHAMBER AND CLAMP

To deepen our understanding of vacuum systems, we conducted experiments using a vacuum chamber and a 6-axis clamp.

Vacuum chamber

The experimental setup for the vacuum chamber is shown in Fig. 4. One side of the chamber was connected to a turbo-molecular pump, followed by a helium leak detector. Due to concerns about vibration from the turbo pump, it was used only during the initial evacuation phase, while an ion pump was employed to maintain the vacuum during steady-state operation.

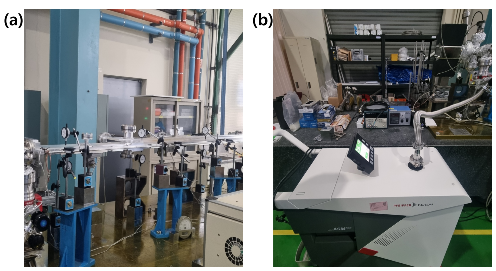

Figure 4: (a) Vacuum chamber with the turbo-molecular pump connected on the left side, and (b) helium leak detector connected downstream of the turbo-molecular pump.

To test for potential leaks in the vacuum chamber, helium gas was sprayed around suspected leak points. Helium is preferred for leak detection because gases like nitrogen, oxygen, and argon are abundant in the atmosphere, making it difficult to distinguish leak signals. Although neon and other inert gases are also suitable, their higher cost makes helium the standard choice.

The presence of helium inside the chamber was detected using a mass filter, such as a quadrupole mass spectrometer (QMS), previously described. If a leak is present, helium molecules diffuse into the chamber, leading to an increase in the helium signal detected by the leak detector.

6-axis Clamp

An assembly process using a 6-axis clamp was also carried out. Since any physical contact or contamination can act as a source of vacuum degradation, latex gloves were always worn during handling. Gloves were replaced whenever contact with non-clean components occurred. If contamination was suspected, parts were cleaned with ethanol, and separated components were wrapped in aluminum foil to prevent further exposure.

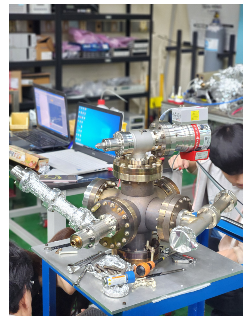

Figure 5: Installed vacuum clamp with connected components including the pump, view port, and gauges.

Vacuum components were typically connected using flanges. A flange usually has a circular shape with bolt holes around the periphery, allowing components to be tightly fastened using bolts and nuts. A gasket was placed between flange surfaces to achieve sealing through cold welding under applied pressure.

During assembly, a torque wrench was used to tighten the bolts. Instead of sequential tightening around the circumference, the bolts were tightened in a star pattern to ensure uniform pressure distribution across the flange surface.

On the 6-axis clamp, a view port was attached to one side, while a vacuum pump was installed on the top side. Additionally, an ion gauge and a convection gauge were mounted on different ports to monitor vacuum conditions (see Fig. 5).

Helium leak testing was performed after assembly. Due to insufficient tightening of the clamp, the system could only achieve a vacuum level of approximately 10^{-5} Torr.

CONCLUSION

Vacuum systems were studied through a review of fundamental principles and the classification of pumps and gauges based on pressure ranges. Experimental work was carried out using a vacuum chamber and a 6-axis clamp. The experiments focused on basic evacuation procedures, leak testing, and component assembly. Through these activities, a deeper understanding of vacuum system and operational considerations was obtained.

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