ACCELERATOR VACUUM SYSTEM

Jang Won
20252116

THE IMPORTANCE AND MAINTENANCE OF VACUUM

Vacuum system plays a critical role in the operation of accelerators. Achieving and maintaining an ultra-high vacuum environment is essential for stable beam transport but also for protecting sensitive equipment from radiation, heat and contamination. Beam-gas interactions contribute to beam degradation, reducing beam lifetime, increasing background noise and causing beam losses. So, vacuum pumps must be installed at appropriate locations with sufficient pumping speed, following the photon stops scheme.

Synchrotron radiation(SR) should be considered in order to maintain a vacuum. There are several effect of SR on vacuum system. When the SR hit the surface, it deposits the power on it and heat up and damage beam pipes. Also, SR impact leads photoemission effects, causing desorption of gas molecules from surfaces. To manage these issues, two strategies are employed: distributed photon stops and localized photon stops. Distributed photon stops are protective structures along the vacuum chamber to make short shadow that protect small photons. Localized photon stops make long shadow regions that shield more sensitive parts of the chamber from large photon.

VACUUM PROCESSING STAGES

The process of achieving high vacuum in an accelerator typically proceeds through several stages. When a vacuum system is initially pumped down, the pressure decreases exponentially over time. This stage corresponds to the evacuation of free gas molecules filling the chamber. As the volume gas is largely removed, the process transitions to surface desorption, where gas molecules absorbed on the chamber walls dominate the out gassing. Due to the distribution of desorption energies across the surface, the pressure decay approximates a 1/t, creating a characteristic envelope profile. To enhance the vacuum quality during the surface desorption phase, a baking process is often applied. By heating the vacuum chamber to elevated temperatures, the surface-bound gas molecules especially water desorb more rapidly, thereby significantly accelerating the reduction of residual gas and improving the ultimate achievable vacuum. Following surface desorption, diffusion from the bulk material becomes the primary source of gas. Hydrogen and other small molecules migrate from within the material towards the surface, initially providing a substantial outgassing rate that gradually diminishes as the internal source depletes. Over time, the system approaches a steady-state equilibrium where the rate of diffusion matches the pumping rate at the surface.

In the long-term regime, permeation becomes the dominant process. External gases, particularly hydrogen from the atmosphere, slowly penetrate through the chamber walls, ultimately setting a fundamental limit on the achievable vacuum level.

TYPES OF VACUUM PUMPS

A. Mechanical Pumps

Mechanical pumps operate by physically moving a confined volume of gas from the vacuum chamber to the exhaust side, effectively reducing the internal pressure. There are various types of mechanical pumps, such as rotary vane pump, scroll pump. These pumps can achieve a low level of vacuum.

B. Turbo Molecular Pump

Turbo molecular pump(TMP) work by imparting momentum to gas molecules. In a TMP, rotating blades are tilted at a specific angle and spin at very high speeds to impart directional momentum to incoming gas molecules.(TMP is generally not used during accelerator operation due to vibrations.) This design allows gas molecules to be preferentially deflected toward the exhaust direction, effectively pumping them out of the vacuum chamber. A turbo-molecular pump consists of several stages. Each stage is composed of a rotating blade set(rotator) followed by a stationary blade set (stator). After passing through the first rotor, gas molecules acquire a net momentum in a particular direction. The stator blades, fixed between each rotor, are introduced to randomize the molecular momentum and reorient the molecules, allowing the next rotor to efficiently impart additional momentum. By repeating this process over multiple stages, the pump can progressively lower the pressure, enabling the achievement of much higher vacuum levels than would be possible with a single stage alone. Each rotor-stator stage pair is optimized with specific blade tilt angles according to the local pressure conditions to maximize pumping efficiency. For effective momentum transfer, the peripheral speed of the rotor blades must exceed the average thermal speed of the gas molecules, typically reaching several kilometers per second. This ensures that gas molecules are effectively captured and directed toward the exhaust, even at extremely low pressures.

C. Ion Pump

An ion pump is a capture-type vacuum pump that removes residual gases by ionizing them and embedding the resulting ions into solid surfaces. It operates by applying a high voltage, across a set of anodes and cathodes arranged in the presence of a strong magnetic field. Electrons emitted from the cathodes spiral along the magnetic field lines, greatly increasing their path length and enhancing the probability of ionizing gas molecules through collision. Once ionized, the positively charged gas ions are accelerated toward the negatively charged cathode surfaces. Upon impact, these ions either become implanted into the cathode material or sputter cathode atoms onto nearby surfaces. The sputtered atoms, typically titanium, further act as getters, chemically binding residual gas and enhancing the overall pumping efficiency.

Table 1: Vacuum Pump Pressure Ranges

Pump Type	**Pressure Range [mbar]**
Mechanical Pump	10^{-3}
Turbo Molecular Pump	10^{-1} to 10^{-10}
Ion Pump	10^{-6} to 10^{-11}

TYPES OF GAUGE

A. Direct pressure measurement gauge

A direct pressure measurement gauge determines pressure by measuring the mechanical force exerted by gas molecules. Direct gauges are based on the fundamental definition of pressure.

B. Convection Gauge

A convection gauge is an enhanced type of thermal conductivity gauge that takes advantage of gas convection to improve pressure measurement in the slightly higher pressure range. A heated filament loses heat to surrounding gas molecules, and the rate of heat loss is related to the gas pressure. A convection gauge also accounts for natural convection currents that occur at higher pressures. So, the convection gauge must be installed horizontally to ensure that natural convection currents form correctly under the influence of gravity

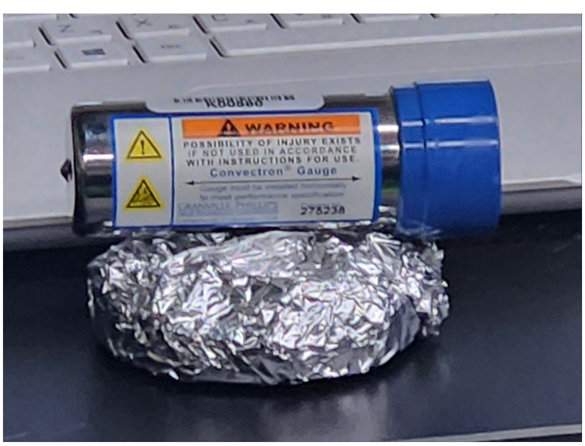

Figure 1: Convection gauge

C. Ion gauge

An ion gauge operates based on the principle of electron-impact ionization, where thermionically emitted electrons from a hot filament ionize residual gas molecules. Typically, the filament is made of tungsten or iridium coated with thorium (Th) to lower the work function and facilitate electron emission at relatively lower temperatures. A positive voltage is applied to a surrounding grid (anode), which serves to accelerate and focus the emitted electrons toward the central region of the gauge, increasing the likelihood of collisions with incoming gas molecules. When a gas molecule is ionized, the resulting positive ion is collected by a thin central electrode, known as the ion collector.

To minimize background noise and false signals, particularly from x-ray-induced electron emission, the ion collector must be extremely thin. If the collector is too thick, high-energy electrons colliding with nearby metal surfaces can generate x-rays, which may in turn release electrons from the collector surface. These unintended electrons can be misinterpreted as ion current by the detection circuitry, leading to a systematic underestimation of pressure.

Another critical operational consideration is the vulnerability of the filament to oxidation. During atmospheric exposure or venting, oxygen can readily react with and damage the hot filament, shortening its lifespan or rendering it inoperable. To prevent this, ion gauges must be vented only under controlled conditions, often with dry nitrogen or inert gas to avoid introducing reactive species like O. Additionally, because elevated filament temperatures can increase outgassing from nearby surfaces, materials with high work functions are used to maintain efficient electron emission at lower filament temperatures, thus reducing local outgassing and improving vacuum quality.

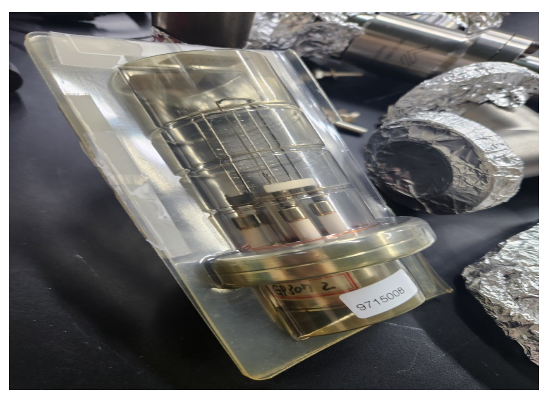

Figure 2: Ion gauge

Table 2: Gauge Pressure Ranges

Pump Type	**Pressure Range [mbar]**
Direct Pressure Measurement Gauge	10^{-1}
Convection Gauge	10^{2} to 10^{-4}
Ion Gauge	10^{-3} to 10^{-7}

Qaudrupole mass spectrometer and leak test

A quadrupole mass spectrometer (QMS) is a key diagnostic tool used to analyze the composition of gases within a vacuum system. It functions by ionizing neutral gas molecules and filtering the resulting ions based on their mass-to-charge ratio (m/z) using a quadrupole electric field. The system consists of three main components: an ion source, a quadrupole mass filter, and a detector. In the ion source, energetic electrons emitted from a filament collide with neutral gas molecules, producing positively charged ions. These ions then pass through a quadrupole formed by four precisely aligned rods to which a combination of radio frequency (RF) and direct current (DC) voltages is applied. Only ions with a specific m/z value have stable trajectories and reach the detector, while others are destabilized and filtered out. As the RF and DC voltages are scanned, ions of different masses are sequentially transmitted, generating an m/z spectrum where the x-axis represents the mass-to-charge ratio and the y-axis indicates the ion current intensity, proportional to the partial pressure of each gas species. Each gas has a unique spectral signature; for example, hydrogen appears at m/z = 2, helium at 4, water vapor at 18, nitrogen at 28, and carbon dioxide at 44, allowing precise identification of residual gas components.

One of the applications of the QMS is helium leak detection. Helium is used as a tracer gas due to its inert nature, low atomic mass, and extremely low background concentration in air. During a leak test, helium is locally sprayed around the suspected regions of the vacuum system, and if a leak exists, helium penetrates the system and is quickly detected by the QMS as a sharp increase in the ion current at m/z = 4. This method enables high-sensitivity detection of leaks that would otherwise go unnoticed, and its non-destructive nature makes it ideal for critical components such as accelerator beamlines.

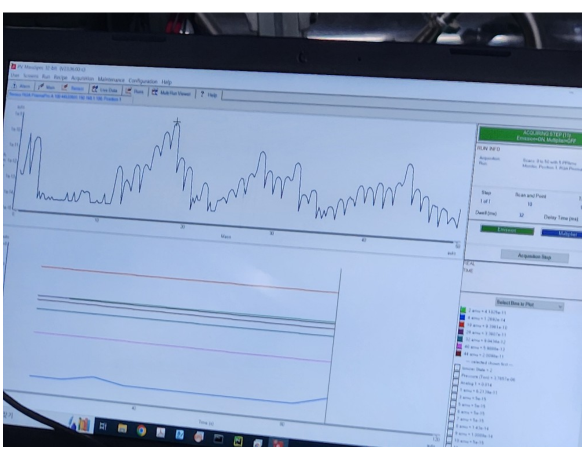

Figure 3: MZ spectrum of QMS

CONCLUSION

Maintaining ultra-high vacuum conditions is critical for stable beam operation in accelerator systems. In this report, we examined the principles, challenges, and technologies related to accelerator vacuum environments. From the initial pump-down process using mechanical and turbo pumps to the long-term maintenance via ion, getter, and cryopumps, each component plays a vital role. Photon-stimulated desorption caused by synchrotron radiation must be managed through appropriate shielding and pump placement strategies. Diagnostic tools such as ion gauges and residual gas analyzers provide essential monitoring capabilities to ensure system integrity over time. Ultimately, establishing and maintaining a high-quality vacuum requires a comprehensive understanding of both the physical processes and the engineering practices behind them.

REFERENCES

[1] Taegyun Ha, *Lecture Notes on NUCE719P*, DIVISION OF ADVANCED NUCLEAR ENGINEERING, POSTECH, PowerPoint presentation, 2025.