ULTRA-HIGH VACUUM PRACTICES AND LEAK TESTING FOR ACCELERATOR APPLICATIONS

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Abstract

This paper presents a practical approach to understanding ultra-high vacuum (UHV) systems in particle accelerators, focusing on vacuum leak testing techniques. We highlight the necessity of maintaining pressures below 10^{-9} mbar to mitigate beam-gas interactions that degrade beam lifetime and increase background noise. Particular attention is given to synchrotron radiation effects in electron accelerators, especially photon-stimulated desorption (PSD) that elevates gas loads. The four-stage evacuation process and diagnostic methods employing thermal-conductivity and ionization gauges are described. Hands-on training with vacuum component assembly and helium leak detection—both for single-port and multi-port chambers—is detailed. Through these exercises, students gain critical skills for achieving and verifying vacuum integrity, offering valuable preparation for early-career work in accelerator technology and vacuum engineering.

INTRODUCTION

Particle accelerators propel subatomic particles to high energies for scientific research and various applications. To preserve beam properties over long distances—often several kilometers—the beamline must remain free from unwanted interactions. Residual gas molecules in the beam pipe cause scattering and particle loss, which shorten beam lifetime and increase background noise in measurements.

To minimize these effects, beamlines are maintained in ultra-high vacuum (UHV) conditions—pressures below 10^{-9} mbar—where collisions become negligible. Constructing and sustaining robust UHV systems is fundamental to accelerator performance.

In high-energy electron accelerators, synchrotron radiation poses an additional challenge. Photons emitted during electron deflection strike chamber walls and induce photon-stimulated desorption (PSD) of adsorbed gases, significantly increasing gas loads. This requires special vacuum engineering designs. To deepen our understanding and develop practical maintenance skills, we conducted training in vacuum leak testing.

THEORY

In synchrotron light sources, high-energy electrons traveling along circular orbits emit intense electromagnetic radiation known as synchrotron radiation (SR). When SR is absorbed by the inner walls of the vacuum chamber, it generates a significant local heat load and simultaneously induces photon-stimulated desorption (PSD), which rapidly increases the gas load. (Eq. 1, [1]) These effects directly contribute to beam loss (τ): if the vacuum system cannot efficiently handle both the heat and gas loads, the pressure rises, leading to increased beam-residual gas collisions, reduced beam lifetime, and elevated background noise in detectors.

$$\begin{aligned} I &= I_0 e^{t/\tau} \\ \frac{1}{\tau} &= \Sigma_i(\sigma_B(Z_i) + Z_i\sigma_M + \sigma_R(Z_i))p_i \end{aligned} \tag{1}$$

where I_e is beam current, τ is life time, and σ_B, σ_M, and σ_R are the cross sections of major three interation processes with gas molecules. The lifetime is in proportion to the pressure, p_i, i.e., gas load.

Synchrotron radiation in circular accelerator

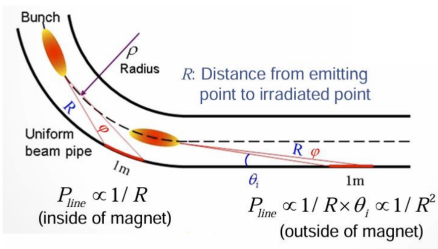

Figure 1: Synchrotron radiation effects from inside magnet and outside of magnet.

To account for the heat load caused by the SR effect, it is necessary to consider the average power density, as shown in Eq. 2 [1].

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

The area power density, P_{area}, is a value further derived from P_{line} to specifically account for the power density generated only in the vicinity of the magnet, as shown in Eq. 3. Through this, the maximum power density can be evaluated. For example, the peak power line density in SuperKEKB reaches approximately 9 kW/m [1]. Copper can typically withstand a power density of about 10 to 20 kW/m, and considering a safety margin, the vacuum system must adequately suppress the gas load to prevent damage to the vacuum chamber and ensure stable accelerator operation, as demonstrated in Eq. 3 and Fig. 1.

$$\begin{cases} P_{area} \propto \frac{P_{line}\gamma}{R} \\ P_{area} \propto 1/R & \text{where inside of magnet} \\ P_{area} \propto 1/R^2 & \text{where outside of magnet} \end{cases} \tag{3}$$

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Vacuum evacuation process

In this subsection, we discuss the vacuum evacuation process. The vacuum evacuation process can be divided into four main stages: (1) Volume Gas, (2) Surface Desorption, (3) Diffusion, and (4) Permeation. We briefly introduce each stage and explain how vacuum evacuation is achieved.

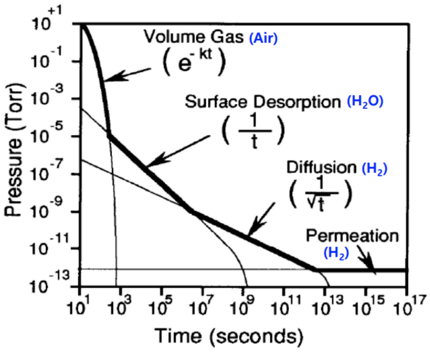

Figure 2: Vacuum evacuation process pressure-time curve.

Fig. 2 shows the pressure variation as a function of time. Since the proportion of particles in the air changes with pressure, the vacuum evacuation process is divided into four stages.

(1) Volume gas removal: The pump removes free gas molecules in the chamber, rapidly lowering the pressure from atmospheric levels to about 10^{-3}–10^{-4} Torr within seconds to minutes. This stage is most efficient due to the high gas density.

(2) Surface desorption: Gas molecules adsorbed on the chamber walls are released by thermal energy or vibration and then pumped away. This lowers the pressure further to the 10^{-6}–10^{-7} Torr range over several to tens of minutes.

(3) Diffusion: Gas trapped within the chamber wall material slowly diffuses to the surface and is released, reducing pressure to 10^{-6}–10^{-8} Torr over hours to days. The rate depends on temperature and material properties.

(4) Permeation: External gas molecules slowly penetrate the chamber wall or seal and are removed by the pump. This slow process is dominated by small molecules like hydrogen and can take days to months.

Vacuum concentration diagnostics devices

Vacuum diagnostics in beamline systems typically employ a combination of thermal-conductivity and ionization gauges to cover the full pressure range. A Pirani gauge measures pressure by detecting the change in thermal conductivity of a heated filament as gas density varies, making it ideal for rough to medium vacuum ($\sim 10^{-3}$ to 10^{-1} mbar). For high and ultra-high vacuum ($\sim 10^{-9}$ to 10^{-3} mbar), an ionization gauge (i.e.,convection gauge) is used: electrons emitted from a hot cathode ionize residual gas molecules, and the resulting ion current—proportional to pressure—is measured. By combining these gauges under a unified controller (such as the PRISMA PRO), one achieves continuous, accurate vacuum monitoring across several decades of pressure.

HELIUM LEAK TEST

In this section, we present the assembly process of the vacuum components and the subsequent helium leak test, with the primary goal of gaining experience in and understanding of the vacuum testing procedure.

One-port vacuum chamber

The assembly process began by carefully disassembling the flange and the vacuum chamber (Fig. 3). Both the flange and the mating surfaces of the chamber were thoroughly cleaned using alcohol to remove any particulate contaminants, residues, or oils that could compromise the vacuum seal integrity.

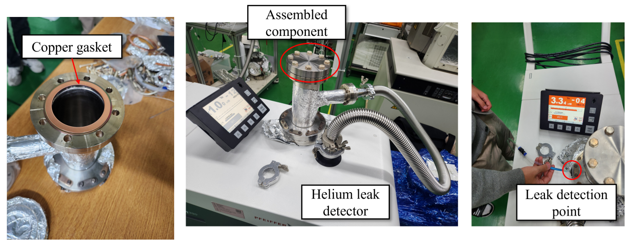

Figure 3: (Left) Copper gasket mounted on the CF cross flange, (Center) Assembled component connected to the helium leak detector, (Right) Leak detection point identified after helium injection

After cleaning, a new copper gasket was placed between the flange and the chamber to serve as the sealing interface. The flange was then mounted onto the chamber, and the flange bolts were inserted and loosely tightened by hand.

To ensure a uniform compression of the copper gasket and to prevent potential vacuum leaks, torque was applied to the bolts in a sequential, crisscross pattern. Multiple iterations of torque verification were performed to achieve an even distribution of force across all bolts, maintaining consistent torque values as specified for the assembly.

This careful and methodical bolting process is critical to establish a reliable ultra-high vacuum (UHV) seal between the chamber and the flange.

Following the assembly, a helium leak test was conducted to verify the vacuum integrity of the system.

The assembled chamber was connected to a helium leak detector via a flexible metal hose. Once the vacuum inside the chamber reached the appropriate pressure level for testing, helium gas was gently sprayed around the external surfaces of the flange, the bolt connections, and other potential leak points.

The helium leak detector continuously monitored for any helium ingress into the vacuum system. Any degradation in

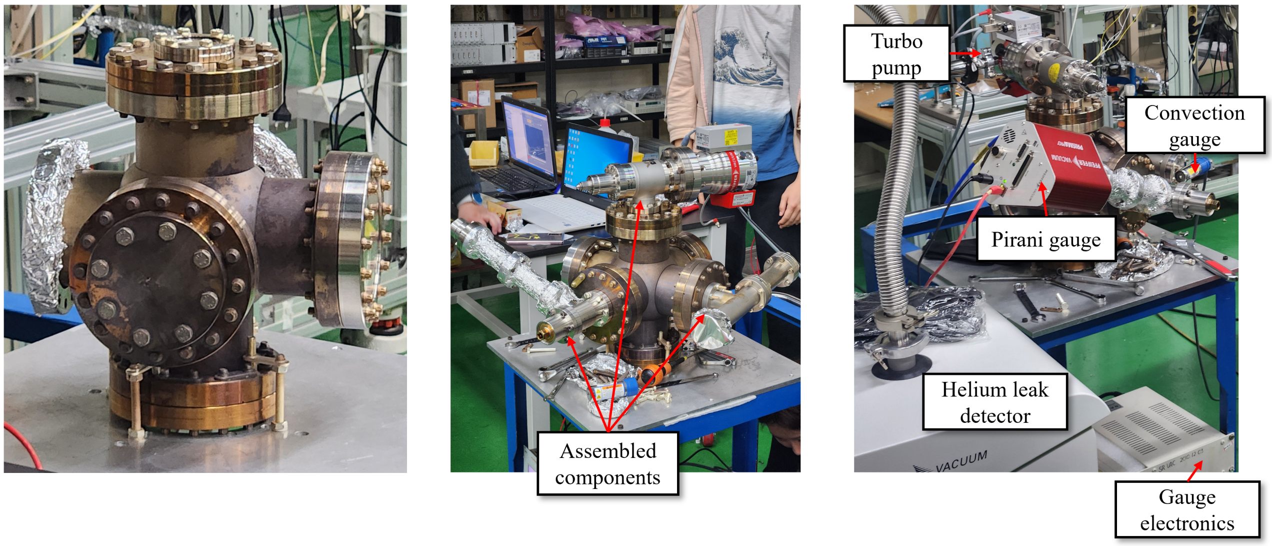

Figure 4: Vacuum test configuration. (Left) Bare cross-shaped vacuum chamber with multiple CF feedthroughs. (Center) Assembled device mounted on the chamber. (Right) Complete test bench including turbomolecular pump, convection (Pirani) gauge, helium leak detector and gauge electronics.

the vacuum level or a rise in detected helium concentration would indicate the presence of a leak at the corresponding sprayed location.

During the testing, no helium leakage was detected from the part we assembled, confirming the integrity of our assembly. However, a helium leak was identified at a different location outside of the assembled section, necessitating further inspection and repair.

Multiport vacuum chamber

The disassembly and reassembly procedures for the six-port vacuum chamber were similar to those for the one-port chamber, but involved four flanges, requiring more careful handling. During assembly, gaskets and flange surfaces were cleaned thoroughly to avoid contamination that could degrade vacuum quality. Gaskets, made from different material than the chamber body, ensured proper sealing by filling microscopic gaps when flanges were tightened.

After assembly, the chamber was evacuated and tested for leaks using a helium leak detector. Helium gas was sprayed around flange interfaces and bolts, and any detected leaks were addressed by retightening bolts, followed by repeated confirmation tests.

SUMMARY

We presented an integrated overview of ultra-high vacuum systems in particle accelerators, combining theoretical principles and practical training. Maintaining UHV conditions (below 10^{-9} mbar) is critical to minimizing beam-gas interactions and preserving beam quality. We discussed synchrotron radiation effects, including heat load management and photon-stimulated desorption (PSD), and outlined the four-stage evacuation protocol essential for UHV attainment.

The practical exercises covered vacuum component assembly and helium leak detection, with emphasis on proper cleaning, gasket installation, and bolt-tightening procedures. Leak testing validated the integrity of both single-port and multi-port chambers. This comprehensive training framework equips future accelerator personnel with essential technical skills, thereby enhancing operational reliability and beam performance.

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REFERENCES

[1] T. Ha, "Accelerator vacuum system I," Lecture Notes, NUCE719P-01, Pohang, Republic of Korea, May 2025.