HOW VACUUM WORKS IN THE ACCELERATOR*

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Abstract

In this experiment, a vacuum chamber was assembled and the vacuum performance was evaluated by analyzing the residual gas inside. The chamber was sealed using a copper ring, and the sealing condition was checked through a helium leak test after being evacuated using a turbo pump. The results of the residual gas analysis showed that water vapor (H_2O) was detected at the highest rate. This is because the H_2O adsorbed on the surface was not removed due to insufficient vacuum baking and pumping out processes. This confirms the importance of surface cleanliness, material handling, and H_2O removal during the vacuum formation process. Appropriate baking and careful assembly processes are essential to achieve and maintain a high vacuum state. Through this experiment, we obtained a practical understanding of vacuum dynamics, residual gas behavior, and leak detection techniques, which can be directly applied to the design and operation of beamline vacuum systems for particle accelerators.

INTRODUCTION

The vacuum condition is of importance when it comes to the beam accelerating in the beamline chamber. In the ideal state, there should not be any residual gas molecule which interrupts the generation, acceleration, transportation, and manipulation of the beam [1]. Additionally, if the gas adheres to the inner surface of the beam chamber, it can give rise to the detriment of the facilities, even shortening its lifespan. The vacuum system is essential for these reasons and a variety of techniques and tools are mobilized.

In this study, we built up a sample vacuum chamber and tested whether it successfully achieved the vacuum condition by monitoring the gas concentration inside. The chamber has to be depressurized by a vacuum pump after obstructing all the exposed parts, and how much a helium gas is inflowed inside the chamber can indicate the extent of the vacuum chamber blocking state. The residual gas is acquired by measuring the mass of each gas, which allows us to figure out where parts are not sheltered and how much the external gas exists in the chamber. Since there are a lot of assembly components, we make sure to check all of them by injecting the helium gas that detects the deficiency of the vacuum shielding. The state of vacuum is finally accomplished when the chamber pressure does not drop anymore and no leakage is detected by helium sensor.

Through this experiment, we are able to understand the factor affecting the vacuum and design our own vacuum chamber that can be adopted in the beamline. The removal of contamination on the surface of the chamber and intensive sealing allowed the chamber to maintain vacuum. Although most of the gas is exhausted in the experiment, there are several residual gases such as Hydrogen(H_2), Nitrogen(N_2), and Carbon monoxide(CO) that are released from the chamber surface. Collectively, this research shows the overall process of setting the vacuum parts in the beamline and the method of examining the vacuum state.

VACUUM THEORY

A vacuum simply means the state in which the pressure we are interested is lower than that of the atmosphere. Here, the pressure is the force exerted on the unit area and can be written as Eq. (1)

$$Pressure = \frac{Force}{Area} \tag{1}$$

where the unit is usually *Pascal*. As the pressure is lower, the vacuum state is higher and the state is divided into many steps according to the measured pressure. An entire vacuum requires to remove not only all visible matters but also all electromagnetic radiation, which is an empty space [2].

A tendency of air pumping follows the exponential function with respect to time. It proceeds quickly in the early stage where the spatial gas comprises the major part, and gets slower as the release of the gas from the chamber surface becomes remarkable. Since it is easy to remove the spatial gas, the initial depressurization is operated is carried out at a fast pace. When the exhaust of the space gas is completed, the pressure decrease begins to slow down as the continuous release of gaseous particles adsorbed on the surface becomes prominent. Afterwards, when the exhaust continues and the surface particles are depleted, the pressure enters the diffusion region where the pressure decreases inversely proportional to the square root of time due to the diffusion of particles contained in the vacuum vessel itself.

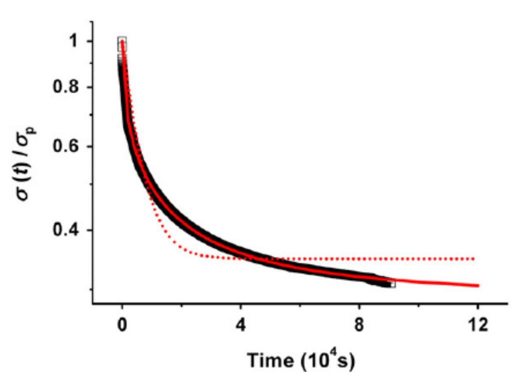

Figure 1: Representative curve indicating the vacuum-pumping tendency. [3]

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Even if the gas inside the chamber is removed using a vacuum pump, it is impossible to achieve a complete vacuum state. Generally, residual gases such as H_2, N_2, and CO remain because the gases that have permeated the surface and interior of the material are slowly released, or the molecules adsorbed on the wall are desorbed [4]. In particular, hydrogen is difficult to remove because it penetrates deeply into the metal, and sufficient removal is not achieved with only a general vacuum pump such as a turbo molecular pump. For this reason, when a high vacuum or ultra-high vacuum environment is required, an ion pump or cryogenic pump is additionally used to more effectively remove the residual gases. Since residual gases affect particle acceleration performance, beam quality, and equipment life, they are a major consideration when designing a vacuum system.

EXPERIMENT PROCESS

We assembled a 6-way stainless steel chamber and used a leak detector to check which part has pressure leakage. By conducting a series of process building vacuum chamber with a variety of equipment, we acquired skills to maintain vacuum facilities such as beamline and learned how to diagnose the vacuum state. We prepared a turbo pump to remove the air inside, helium leak detector to identify assembly tolerance, mass spectrometer to check residual gas, and vacuum chamber which can be used on the beamline.

Vacuum Chamber

First, we covered a total of six opened flanges with the viewport-mounted lid. Each lid is adhered to the main chamber's flange by a linkage of a copper ring. The copper ring helps the metal to stick each other as if they were welded. When the high assembly load is exerted on the copper ring, it deforms according to the shape of the docking flange. After that, we tighten screws along the edge of the lid drawing the cross-direction. It is very important to tighten the screws in alternating cross directions to ensure an even force exerted. This is because if we tighten the screws sequentially in one direction, the flange and lid may not be aligned properly. Additionally, a torque wrench is actively used to tighten every screws.

Most of all, any kinds of contamination is not allowed during this process. If there is a pollutant inside the chamber which would be a beamline in a real accelerator, it emits the external gas like vapor or even other molecules. Thus, we used clean gloves and aluminium foils when we are supposed to contact the chamber parts, especially the surface and binding sites.

Decompression

The revomal of the air in the chamber is operated by means of a turbo pump that is powered by a power supply until the leakage is not significantly detected. The leakage can be found whenever the concentration of helium gas increases because we inject helium through the crack that gives rise to a vacuum defect and the pump turns on again after the crack has been repaired. However, there are cases where the helium concentration rises high as helium in the air is come into the chamber.

When detecting gas, a heat conductivity gauge is used, and the heat of the gauge changes depending on the concentration of air, which can be used to determine whether there is a vacuum. As more gas escapes from the chamber, the detector temperature drops as the inner part of the chamber approaches a vacuum. Power is consumed to maintain the temperature, and by measuring this increase in power consumption, we can determine how much gas is moving out. The reason for using helium is that an inert gas must be used to prevent the reaction with the material of the chamber, and nitrogen is not suitable because nitrogen already exists in the air which could confuse the precise measurement. Neon(Ne) can also be used, but it is expensive and not easy to obtain, so helium was selected because it is relatively cheap and easy to access. Therefore, we injected helium gas throughout the depressurization process to be enable that the inside of the chamber successfully reached a vacuum state.

RESULT AND ANALYSIS

This research showed that it is possible to create a vacuum environment that is so well sealed that there are no areas where the helium concentration spikes. We can also see the composition of the residual gas after the vacuum process. A mass spectrometer analyzed the residual gas in the chamber and displayed the ratio of each gas as shown in the following graph. Major residual gases include water vapor (H_2O), hydrogen (H_2), carbon monoxide (CO), nitrogen (N_2), and carbon dioxide (CO_2). Even if the atmospheric components are removed through pumping inside the vacuum chamber, various residual gases remain. At the same time, it can point out which one is insufficient among the vacuum process by measuring the specific gas.

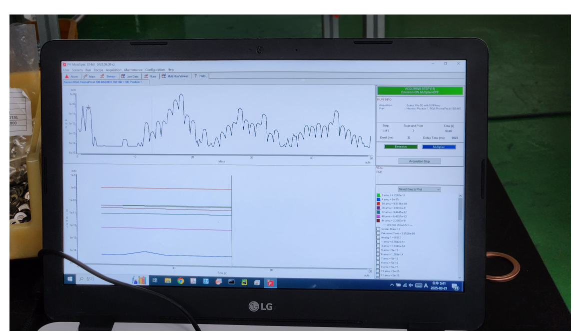

Figure 2: The constituent molecules of the residual gases with respect to the molecular mass.

As we discussed earlier, N_2, H_2, and CO are detected by the spectrometer. However, contrary to expectations, water vapor was detected as the dominant residual gas inside the chamber. Water vapor is not easily removed by normal pumping alone. This result is attributed to insufficient baking or pump-down processes, which failed to remove H_2O adsorbed on the surface. In addition, there is a high possibil-

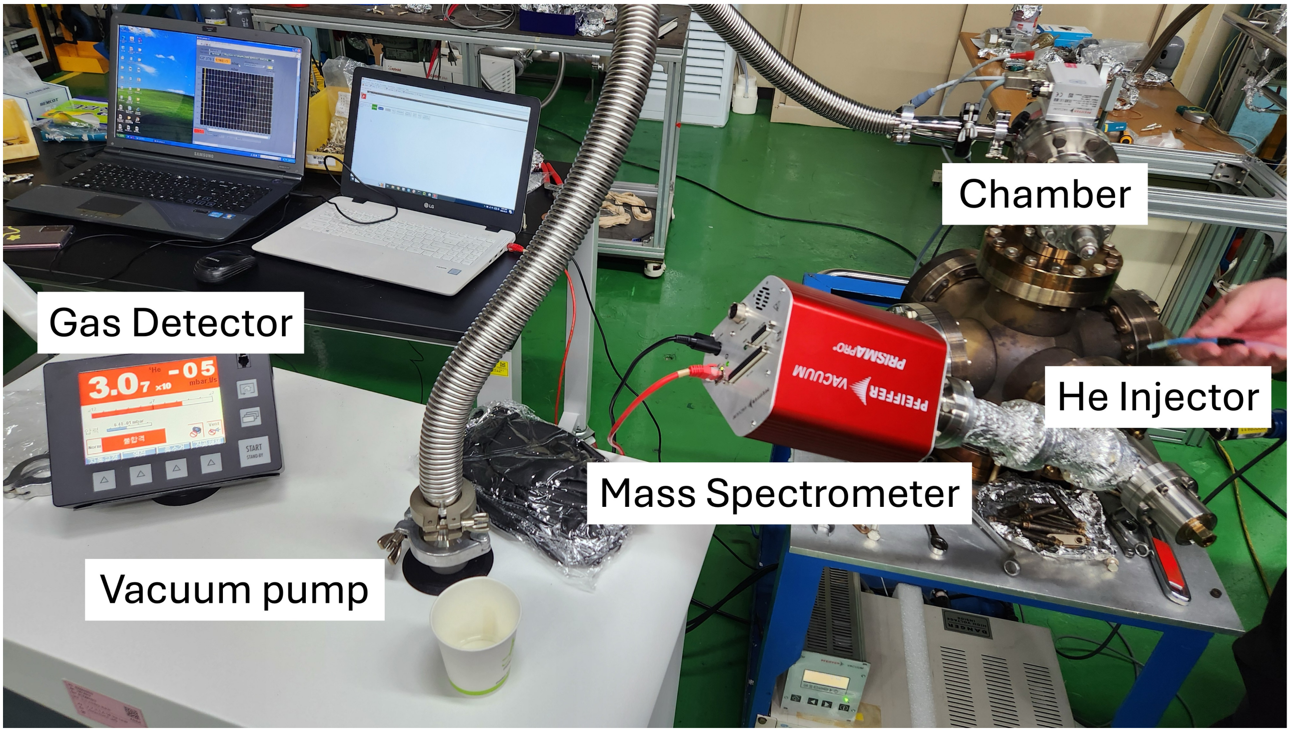

Figure 3: The experimental apparatus in a nutshell.

ity that the gloves were contaminated and moisture on the hands entered the chamber during assembly work. Therefore, it was confirmed that appropriate vacuum baking and thorough removal of water vapor are essential for achieving high vacuum conditions.

Table 1: Overall composition of the residual gas

Molecule	Molecular mass	Amplitude
H_2	2	6e-11
H_2O	18	1e-9
CO and N_2	28	5e-11
CO_2	44	4e-11

Collectively, we found that the assembly of the chamber is of importance when it comes to establishing the basic vacuum condition. The baking and pumping also determine the residual gas, an we can use the residual gas to track back how much level the vacuum has progressed.

CONCLUSION

This experiment verified that the basic assembly quality and the vacuum treatment process of the vacuum chamber are very important in the formation of a high-vacuum state. The results of the helium leak test showed that the chamber's sealing condition was acceptable, but the residual gas analysis showed that the proportion of water vapor (H_2O) was the highest. This showed incomplete vacuum baking and pumping, and the possibility of contamination through gloves or the external environment during the assembly process cannot be ruled out. The limitation of this experiment is that the proper baking procedure was not performed, and in the future, a process to remove surface-adsorbed gases in advance through baking at an appropriate temperature is necessary. In addition, the possibility of contamination should be minimized by improving the clean environment and material handling procedures during assembly. This experiment empirically demonstrated that the management of residual gas in the vacuum chamber directly affects the beam quality and the lifespan of the particle accelerator, and provided useful experience for the design and operation of high-vacuum systems.

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