Mechanical design of experimental apparatus for FIREX cryo-target cooling

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Abstract. Mechanical design of an experimental apparatus for FIREX cryo-target cooling is described. Gaseous helium (GHe) sealing system at a cryogenic environment is an important issue for laser fusion experiments. The dedicated loading system was designed for a metal gasket. We take U-TIGHTSEAL® (Usui Kokusai Sangyo Kaisha, Ltd.) with an indium plated copper jacket as an example. According to its specification, a linear load of 110 N/m along its circumference is the optimum compression; however a lower load would still maintain helium (He) leak below the required level. Its sealing performance was investigated systematically. Our system demanded 27 N/mm of the load to keep He leak tightness in a cryogenic environment. Once leak tightness was obtained, it could be reduced to 9.5 N/mm.

1. Introduction

Cryogenic target layering of First Ignition Realization Experiment (FIREX) has been studied. A target is cooled by ambient GHe at low pressure with precise temperature control. To make sure of He leak tightness, mass-produced metal gaskets, such as Helicoflex delta® (Garlock) and U-TIGHTSEAL® (Usui Kokusai Sangyo Kaisha, Ltd.), have been applied for vacuum sealing in a dedicated apparatus [1], and their validity has been confirmed in a cryogenic environment. According to their instructions, the optimum linear loads to metal gaskets are more than a hundred and several tens N/mm along its circumference. Therefore, mechanical structures must be rigid for their applications. To date, we have employed a standard configuration with a pair of flanges tightened by bolts.

For laser fusion experiments, 10’s of ms before laser irradiation, a cryogenic target must be exposed to target chamber space. Based on the ILE cryogenic target system which was produced for central ignition experiments [2], its target container is separated to the upper and bottom parts. It must be He leak tight for target cooling. Instead of the above-mentioned standard configuration, rigid structures sustain pushing a pair of flanges against each other, and indium, which is good at a cryogenic seal [3], is used as a sealing material. Its disadvantage is that expertise on indium sealing is required. For the routine of laser experiments, stable sealing performance is demanded.

One solution would be metal gasket seal. To incorporate its stable sealing performance within a cryogenic system for laser fusion experiments, not the optimum but a required load to keep He leak tightness is substantial for system design. We designed and constructed a preliminary seal and loading system for cryogenic use. Onset compression loads of GHe leak are researched systematically. The required load on a metal gasket and related system design are discussed.
2. Mechanical design of apparatus

2.1. Design of cryogenic seal with metal gasket

Metal gaskets possess stable seal performance when an industrial product is manufactured to high tolerances. Figure 1 represents an example of a metal gasket. It consists of a spring and jacket. The elasticity of the spring and the plasticity of the jacket make the metal gasket a high performance seal. Figure 2 shows a characteristic curve. There is a hysteresis effect because of permanent deformation of the spring and jacket. The leak rate will have dropped below the required level when a load reaches \( F_0 \) on the compression curve. Applications of the optimum compression load \( F_2 \) are recommended according to instructions. Decompressing the load below \( F_1 \) results in the leak rate exceeding the required level again. The compression load between \( F_0 \) and \( F_2 \) is the design point of our cryogenic sealing system.

A metal gasket loading system and target holder with a flange is shown in Figure 3. A screw type loading mechanism with a load cell can control the load to a metal gasket precisely. A spring section makes the stress to a metal gasket uniform. To reduce heat in-leak to cryogenic parts, Glass Fiber Reinforced Plastic (GFRP) is used in the bottom part of the loading system. The target holder is inserted into a target can as shown in figure 4. The counterpart of a pair of flanges is equipped on the target can with a groove. A metal gasket U-TIGHTSEAL® with an inner diameter of 81 mm and a height of 3.1 mm (see figure 1) is employed. We select an indium plated copper jacket gasket for cryogenic use. The indium coating must ensure He leak tightness. The announced optimum linear compression load is 110 N/mm along its circumference; requiring a total compression of 29.0 kN on the gasket. Highly rigid structures would be required to be proof against a load of this magnitude. To combine structural design with high cooling performance, a metal gasket should be used at a low compression load range. Its possibility is investigated in the next chapter.

![Figure 1. An example of metal gasket, U-TIGHTSEAL®. It is a gasket with an indium plated copper jacket.](image1)

![Figure 2. A characteristic curve of metal gasket. After a cycle of compression and decompression, permanent deformation of a spring and jacket remains.](image2)

2.2. Cooling system with reduced vibration

For system cooling, a 4 K Gifford-McMahon (GM) cryocooler (Sumitomo Heavy Industries, Ltd.) is employed. It becomes a vibration source. For target observations, a vibration free system is ideal. The target can is connected to the cryocooler using flexible thermal conductive links and is supported by a different structure with vibration control from the cryocooler. Vibration reduction has been demonstrated, and cooling performance has been reported [4].
3. Experiments

A required compression load on the metal gasket is researched. Figure 5 shows the diagram of He leak tests. The gasket was compressed in the range of 8.6 N/mm to 27 N/mm. GHe was filled in the target can at ~1 kPa. Its sealing performance was evaluated using a He leak detector (HELEN A-221M-LD, Anelva Corporation) which can measure a leak in the range of $10^{-15}$ to $10^{-12}$ Pa m$^3$/s. The threshold intrinsic He leak rate was decided to be $1.0 \times 10^{-11}$ Pa m$^3$/s. The measurements were systematically conducted at room temperature and in a cryogenic environment.

Initial compression loads of 14 N/mm and 27 N/mm were tested. At first, a He leak rate with a load of 13.7 N/mm was measured at room temperature. As filling the target can with GHe at 1.07 kPa, no leak was detected under the condition with $3.0 \times 10^{-11}$ Pa m$^3$/s of a background leak rate. Then the system was cooled down to ~10 K. The GHe pressure was decreased to 49 Pa and the load was settled down to 14.3 N/mm. At this point, a leak rate was $2.9 \times 10^{-11}$ Pa m$^3$/s. As GHe was added into the target can up to 1.00 kPa, the leak rate increased to $7.6 \times 10^{-11}$ Pa m$^3$/s. A load of 14.3 N/mm is not large enough to reach the allowable leak rate level. In spite of the leak, a 200 L/s class turbo molecular pump could keep an insulation vacuum. After the measurements, the system was warmed to room temperature and the used metal gasket was replaced with a new one. A He leak rate with a 26.7 N/mm load was measured at pressure of 1.03 kPa in the target can. No leak was detected under the condition with $1.5 \times 10^{-12}$ Pa m$^3$/s of a background leak rate. Then the system was cooled down to 7.4 K. The GHe pressure was decreased to 48 Pa and the load was settled down to 26.9 N/mm. While the pressure added to 1.02 kPa, the leak rate was constant at $1.2 \times 10^{-12}$ Pa m$^3$/s. Eventually, no leak was detected. While decompressing the gasket by ~0.96 N/mm, leak rates were measured. The system could keep He leak tightness down to 9.46 N/mm, and then an intrinsic He leak of $8.1 \times 10^{-11}$ Pa m$^3$/s was detected at 8.61 N/mm. When it was recompressed to 14.5 N/mm, He leak tightness was recovered. After the successful first cool down, the system was warmed up to room temperature and the load was released. Using the same metal gasket, the second cycle was started. A load of 26.6 N/mm could keep He leak tightness against 1.13 kPa GHe pressure at room temperature again. A back ground leak rate was $6.9 \times 10^{-11}$ Pa m$^3$/s. The system was cooled down to 7.4 K. While the GHe pressure was increased from 49 Pa to 1.02 kPa, the leak rate was stable at $5.6 \times 10^{-11}$ Pa m$^3$/s. While decompressing the gasket by ~1.9 N/mm, leak rates were measured. When the loads were decreased to 17.3 N/mm and then 15.3 N/mm, measured rates monotonically increased to $1.0 \times 10^{-10}$ Pa m$^3$/s and $2.1 \times 10^{-10}$ Pa m$^3$/s, respectively. When the gasket was recompressed again to 24.0 N/mm, He leak tightness was recovered.
After the second cool down, the system was warmed to room temperature and the compression was unloaded. In the third cycle, a load of 26.5 N/mm could keep He leak tightness against 1.27 kPa GHe pressure at room temperature. After cooling down to 7.3 K, no leak was detected. A back ground leak rate was $1.9 \times 10^{-11}$ Pa m$^3$/s. Decompression to 19.2 N/mm allowed an intrinsic He leak of $1.1 \times 10^{-9}$ Pa m$^3$/s, and then recompression to 26.9 N/mm could keep He leak tightness again. Figure 6 shows intrinsic He leak rate versus linear compression load in a cryogenic environment. Because of the hysteresis effect of metal gasket, the onset load of He leak in the decompressing process becomes high by cooling cycles. Judging from the experimental results, a compression load of 27 N/mm was large enough to keep He leak tightness, and furthermore the metal gasket has the potential for multi-time use. We would combine high cooling performance with metal gasket sealing for a cryogenic system.

4. Summary
For the mechanical design of a cryo-target apparatus, the sealing performance of U-TIGHTSEAL® with an indium plated copper jacket was systematically tested. Despite the optimum compression linear load of 110 N/mm, the required load is found to be 27 N/mm for our system, and therefore high rigid structure is not demanded. Furthermore it possesses the potential for multi time use. High cooling performance would be combined with a metal gasket sealing system.

References
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