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Helium guard system design for HIAF iLinac cryogenic distribution system

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Abstract

2 K superfluid helium cryogenic system is the crucial component of many large accelerators. When the cryogenic system is operating at 2K@3129Pa, many room-temperature parts are connected to superfluid helium via tubes. Air Leakage in these connections may lead to air contamination of the cryogenic system. Air contamination may cause equipment failure in cryogenic systems and, in extreme cases, render the entire accelerator system inoperable. Helium guard is a technique that guards against air contamination of these sub-atmospheric pressure connections in 2 K superfluid helium cryogenic system. This paper introduces a typical 2 K cryogenic distribution design for large accelerators, and make risk analysis of air contamination. Finally, the analysis of specific leakage points and detailed engineering design are presented, which may be used as a reference when designing of a 2 K superfluid helium cryogenic distribution system.

Keywords: superfluid helium, cryogenic system, air contamination, helium guard, leakage hole

1. INTRODUCTION

High Intensity heavy-ion Accelerator Facility (HIAF) will be built by Institute of Modern Physics (IMP) of Chinese Academy of Sciences (CAS), which is located in Huizhou, Guangdong Province, China. It is one of the crucial construction components for China National Major Scientific and Technological Infrastructure Construction (2012-2030). As shown in Fig. 1, the ion beam is generated by a superconducting ECR ion source (SECR) and then accelerated by a superconducting proton linac (iLinac), a booster synchrotron (BRing), a high-energy fragment separator (HFRS) and a high-precision spectrometer ring (SRing) [1]. Experimental terminals are available for several energy segments. After construction and commissioning, the project will serve as an advanced experimental platform for research on heavy ion beam applications, nuclear safety applications, and nuclear technology applications.

The main objective of the superconducting proton linac（iLinac）is to generate high-power proton beams for secondary accelerator and experimental terminals. These beams are accelerated to their ultimate energy mainly by niobium superconducting radio frequency (SRF) cavities and superconducting magnets in cryomodules. A total of 96 SRF cavities will be installed in 17 cryomodules. The cavities are cooled with 2 K superfluid helium because it provides better heat transfer characteristics at the solid-liquid interface and less pressure fluctuation than liquid helium. Furthermore, while operating at 2.0 K, large accelerators based on high-frequency superconducting cavities and superconducting magnets have the lowest refrigeration costs and overall power usage [2]. Most large superconducting accelerators around the world have been using superfluid helium cooling, including the Large Hadron Collider (LHC) [3, 4], the European Spallation Source (ESS) [5], and the Shanghai High repetition rate XFEL and Extreme light facility (SHINE) [6].

2 K superfluid helium has a saturated pressure of 3129 Pa, which is much lower than atmospheric pressure. Many room-temperature components are indirectly connected to superfluid helium when the cryogenic system is operating at 2 K. All of these parts have a certain leakage rate, which could result in air contamination. Air contamination will cause equipment failure in cryogenic systems, and in the

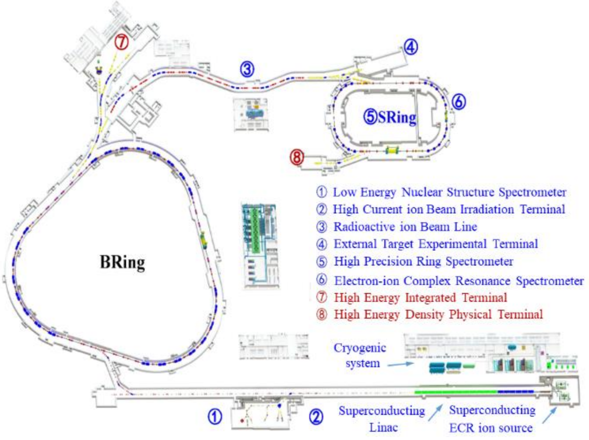

Fig. 1. The schematic layout of the HIAF accelerator.

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worst situations, it will make the entire accelerator system unable to work. Helium guard is a technical method that using pure helium instead of air to cover the potential leak spots, and the air contamination of 2 K superfluid helium cryogenic system could be avoided. However, detailed analysis and design of helium guard in 2 K cryogenic system have not been studied in detail [2]. The main work of this paper is to introduce HIAF cryogenic distribution design and make risk analysis of air contamination. Finally, the practical engineering design of the HIAF iLinac cryogenic distribution system is elaborately described. This paper introduces the HIAF cryogenic distribution design and make a risk assessment of air contamination. Finally, the practical engineering design of helium guard for the HIAF iLinac cryogenic distribution system is elaborately described and analysed.

2. HIAF ILINAC CRYOGENIC DISTRIBUTION SYSTEM

In practical cryogenic systems, superfluid helium is obtained based on Joule-Thomson effect. Saturated superfluid helium can be obtained by throttling of liquid helium or supercritical helium. Fig. 2 shows the schematic for the HIAF iLinac cryogenic system. The cryogenic system mainly consists of a helium refrigerator, cryogenic transfer lines and valve boxes, warm distribution lines, recovery and purification system, and cryomodules. The cryogenic transfer lines, valve boxes and an end box comprise the cryogenic distribution system. Supercritical helium at 4.5K@3bara and gas helium at 50K@14bara are available from the helium refrigerator. The 50 K cold gas is used to cool the thermal shield and the current leads with a return temperature of 75 K at 13.5 bara. Supercritical helium is used to cool the cavities and couplers. The heated gas returns to a 2 K very low pressure(VLP) return line at 27 mbara and a 75 K coupler system(CS) return line at 1.3 bara, respectively. The VLP gas is compressed to about 1.05 bara by a cold compressor unit and a vacuum pump unit. The HIAF cryogenic system has a maximum flow rate of 100 g/s and a corresponding cooling power of 2 kW at 2 K.

The valve box process is shown in Fig. 3. The valve box contains cryogenic valves, warm valves, pressure transmitters, safety valves, temperature sensors and others.

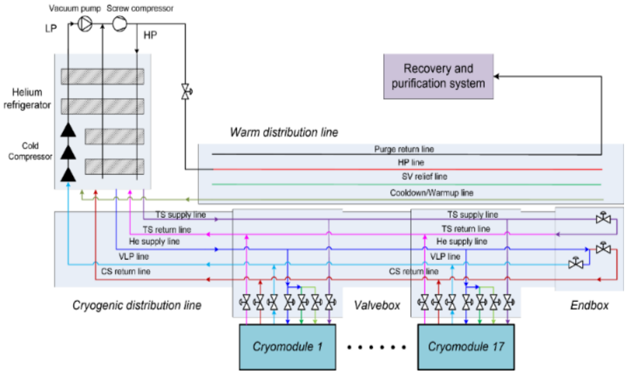

Fig. 2. The schematic of HIAF iLinac cryogenic system.

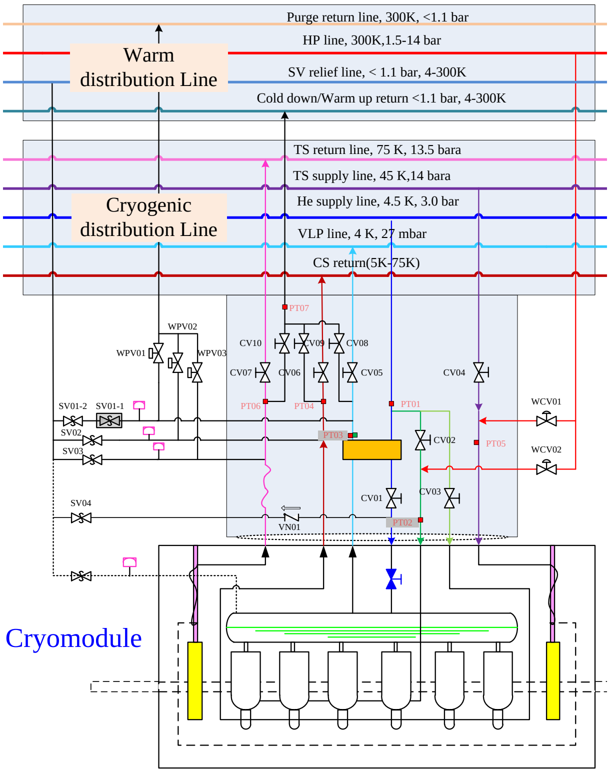

Fig. 3. The process of valve box for HIAF iLinac.

In the 2 K operating model, the saturation pressure is 3129 Pa. The supercritical helium enters the helium vessel through a 2 K heat exchanger, cryogenic valve CV01, and a JT valve, and the return gas enters the VLP line through cryogenic valve CV05. The VLP gas is then compressed by cold compressors and vacuum pumps to atmospheric pressure(1.0 bara). There are numerous flexible connectors in this cooling loop, including pressure transmitters, cryogenic valves, safety relief valves, cold compressors and vacuum pumps. It is important to thoroughly investigate air contamination and to apply the helium guard for engineering design.

3. RISK ANALYSIS OF AIR CONTAMINATION

3.1. Relationship between helium and air leakage rate

Before the cryogenic system is put into operation, each flexible connector must typically have its leakage detection using a helium mass spectrometer leak detector. As seen in Fig. 4, during the leakage detection procedure, positive pressure helium (> 1.0 bara) is sprayed at possible leaking spots with an internal vacuum in VLP gas-occupied area. The internal leakage rate of helium for relief valves and cryogenic valves ranges from 10^{-5} to 10^{-6} Pa·m^3/s, while the external leakage rate of the valves ranges from 10^{-7} to 10^{-9} Pa·m^3/s. The external leakage rate of the pressure transmitters is around 10^{-8} Pa·m^3/s. Helium leakage rate is supplied by the equipment supplier and actual test, and must be converted to the air leakage rate.

Air enters the VLP loop using flexible connectors in the 2 K operation model, reviving the helium tank or pipelines

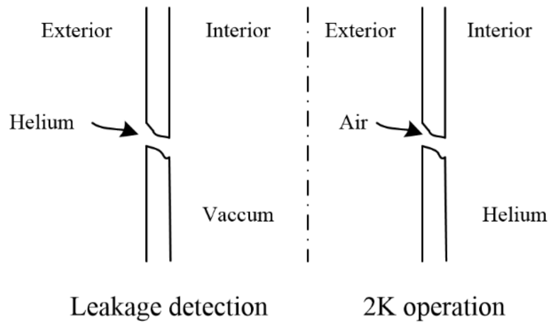

Fig. 4. The schematic of leakage detection and 2 K operation for leakage hole

air pollution. In our work, we need evaluate whether air pollution affects the cryogenic distribution system. In a practical cryogenic system, the structure of the leakage point is diverse and extremely complex. The leaking hole is typically seen as a narrow, round tube for qualitative analysis. Through the leakage hole, gas flows from the high pressure end to the low pressure side.

For uniform circular section tube type leakage, the leakage rate is [7]:

$$Q = \left\{ \frac{\pi d^4 \bar{p}}{128 \eta L} + \frac{1}{6}\left(\frac{2\pi RT}{M}\right)^{1/2} \frac{d^3}{L} \left[\frac{1+\left(\frac{M}{RT}\right)^{1/2} d\,\bar{p}/\eta}{1+1.24\left(\frac{M}{RT}\right)^{1/2} dp/\eta} \right] \right\} (p_1 - p_2)$$
(1)

Where d, L is the tube diameter[m], M is relative molecular weight[kg/mol], η is viscosity[Pa·s], $\bar{p}$ is mean pressure of p_1 and p_2[Pa], p_1 is inlet pressure and p_2 is outlet pressure[Pa], R is molar gas constant, T is ambient temperature[K]. It's not hard to see from eq.(1) that the leakage rate is related to the geometric size, gas properties, end pressure and ambient temperature. When $p_1 >> p_2$, $p_1 = 100$ kPa, and $T = 293$ K, the air leakage rate through a leakage hole is:

$$Q_A = \frac{1.33\times10^{-7}}{L}\left[5.4d^4 + 7.4d^3 + 0.074d^2 \ln(1+25d)\right]$$
(2)

According to eq.(2), when the equivalent tube diameter is around 1μm, the leakage rate is about 10^{-8} Pa·m^3/s for $L = 0.1$ cm,and about 10^{-9} Pa·m^3/s for $L = 1$ cm. The above size covers common leakage hole sizes for welding joints or flange connections. Whether in leak detection or 2 K operation, p_1 is much larger than p_2. According to eq.(1) and (2), the influence of pressure to leakage of both gas could be ignored.

The characteristics of gas leakage are closely related to the flow regime of the leakage hole. Viscous, transition and molecular flow may be present when the air passes through the leaking hole from the high pressure end to the low pressure end. The product of the average pressure and the tube diameter can be used to determine the flow regime. The flow regime is viscous flow when $\bar{p}d$ is larger than 0.67 Pa·m, and molecular flow when $\bar{p}d$ is less than 0.02 Pa·m. Under the identical leaking hole, pressure, and viscous flow conditions, the relationship between the leakage rates of air and helium is as follows:

$$Q_{He} = \frac{\eta_{Air}}{\eta_{He}} Q_{Air}$$
(3)

The different gas leakage proportion of the molecular flow leakage hole should be equal to the inverse ratio of the square root of the molecular weight:

$$Q_{He} = \sqrt{\frac{M_{Air}}{M_{He}}} Q_{Air}$$
(4)

According to engineering experience, the flow regime is transition flow when the leakage rate is between 10^{-6} Pa·m^3/s and 10^{-9} Pa·m^3/s. However, there is no appropriate theoretical formula for accurately calculating the leakage rate of transition flow. The transition flow leakage is theoretically between viscous flow and molecular flow. As a result, the air-to-helium leakage rate is as follows:

$$Q_{Air} = (0.38 \sim 1.12) Q_{He}$$
(5)

3.2. Risk analysis

According to the ideal-gas equation, the leakage rate is:

$$Q = \frac{PV}{t} = \frac{mR_g T}{t} = \dot{m} R_g T$$
(6)

Where P is the pressure, V is the volume, t is time, m is the mass, R_g is the gas constant. For air,

$$R_g = \frac{8.314\, J/mol \cdot K}{0.029\, kg/mol} = 287\, J/kg \cdot K$$
(7)

In the valve box, pressure transmitters, cryogenic valves and safety relief valves and warm valves in the VLP cooling loop will have air contamination if there aren't any guard method. For pressure transmitters, air leakage mainly comes from manual valves and external connections (G1/4 or NPT). For all the valves, internal leakage through the valve seat when the valve is closed and external leakage through joint parts such as flanges maybe all taken into consideration. The safety valves and cryogenic valves in the valve box are where leaking occur with maximum quantity. The tightness of the valve seats is always less than 1.0×10^{-5} Pa·m^3/s. A valve box leaks roughly 10^{-5} Pa·m^3/s overall for helium, and the flow through the valve core may be considered viscous flow. Air leakage rates are almost equivalent to helium leakage rates. 1.16×10^{-7} g/s is the corresponding leakage mass flow. There are 18 valve boxes and the highest VLP flowrate of the HIAF iLinac distribution system is 100 g/s. So the partial pressure of air is 1.2×10^{-3} Pa for the VLP flow.

When the safety valves, cryogenic valves and other critical leakage points, are well guarded with helium, the

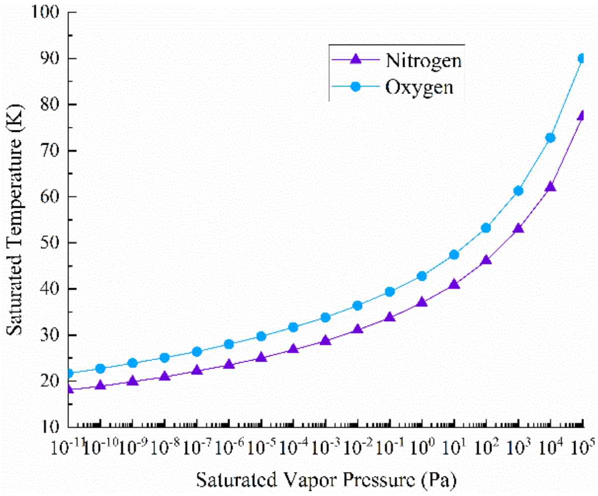

Fig. 5. Saturated vapor pressure of nitrogen and oxygen.

overall leakage rate in a valve box is estimated to be 10^{-9} Pa·m^3/s. It is reasonable to consider molecular flow passing via each leaking hole. Helium leaks at a rate that is 0.38 times of air. The comparable leakage mass flow in a valve box is 4.4×10^{-12} g/s. The partial pressure of air is 4.5×10^{-8} Pa in the VLP helium gas.

According to Fig. 5, the saturation vapor pressure of nitrogen and oxygen varies with temperature. The saturation vapor pressure of both is lower than 10^{-11} Pa at a temperature of about 20 K. Experimental data are few below 20 K, primarily due to the lack of an effective vacuum gauge. It can deduce that oxygen and nitrogen will condense at 2 K temperature based on the decreasing trend of saturation vapor pressure with temperature.

The average annual operating time for the helium cryogenic system is 8000 hours. The relationship of leakage rate, mass flow rate and overall mass is shown in Fig. 6. The quality of the total pollutant varies from 4.1×10^{-2} g to 108 g per year when the cumulative effect of pollution is taken into account and the ice plug phenomenon may happen. The equivalent spherical radius of solid ranges from 4.4 mm to 130 mm. Cold compressors and 2 K plate-fin heat exchangers in the VLP loop have narrow flow channels that are only a few millimeters wide. Equipment damage or decreased efficiency may result from the ice plug phenomena. The impact of air leakage must be considered when the overall leakage of a valve box reaches 10^{-9} Pa·m^3/s.

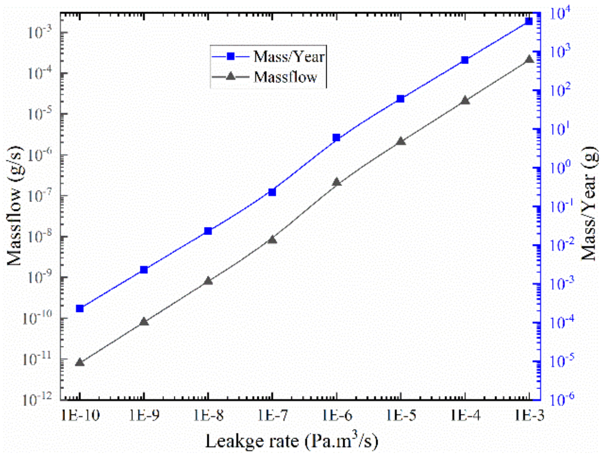

Fig. 6. The relationship between leakage rate, mass flow rate and total mass.

4. ENGINEERING DESIGN

The schematic structure of helium guard for valves is shown in Fig. 7. The outlet pressure of cryogenic valves CV02, JT valve and CV05 is about 3100 Pa (VLP). Helium guard is provided by pure helium through a tube and a hand valve to the rod top of cryogenic valves with a sub-atmospheric pressure outlet. Pure helium replaces air and leaks into valves without affecting the purity of the VLP loop. For warm valve WCV02, the inlet and outlet of the warm valve are installed in reverse. Air leakage from the flange and other sealing faces is avoided by using pure helium at the actual inlet. This method is simple to implement and does not necessitate any additional design. These methods solve the air pollution caused by external leakage. To prevent internal leakage, we adopt a simple design. When these valves operate at VLP pressure at one connection tube, the other side is connected with pure helium at atmospheric pressure, as shown in Fig. 3.

Helium guard vessels are used to protect pressure transmitters and relief valve components that may cause air contamination. Fig. 8 illustrates the schematic structure of the helium guard for pressure transmitters and relief valves. With a pure helium supply tube and a manual valve, the vessel has pressure transmitters with a corresponding manual valve, and the first-stage relief valve. Pressure transmitter signal lines are led out via a feedthrough. As pointed out above, the internal and external leakage of the safety valve is significant. Because exhaust function of the safety valve will be affected, it is not practicable to install a pure helium supply at the outlet of a single safety valve. Otherwise, a substantial circulation flow occurs once pure gas is introduced directly into the recovery and purification system, resulting in significant energy waste. Two-stage

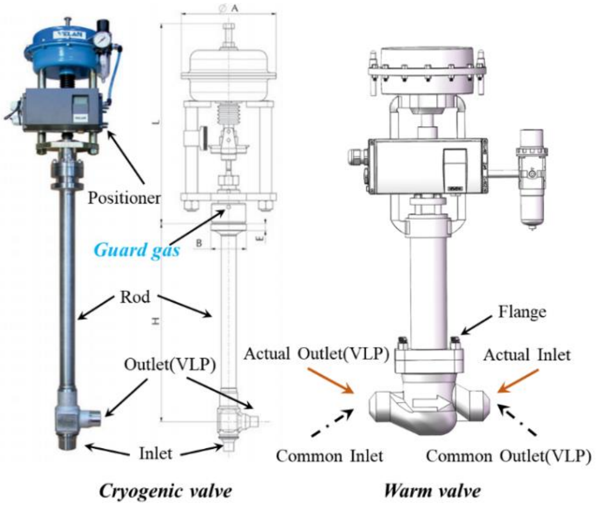

Fig. 7. Schematic structure of helium guard for valves.

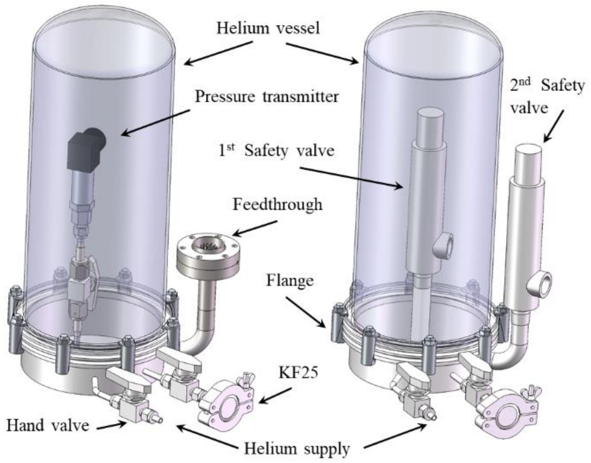

Fig. 8. Schematic structure of helium guard for pressure transmitters and relief valves.

safety valves are the most practical design (SV01 and SV02 in Fig. 3). The first stage safety valve is installed in a helium vessel with a pure helium supply and a manual valve. The external leakage of the safety valves is avoided. The second-stage safety valve is installed outside the vessel. Considering the pressure drop of pure helium gas along the long tube, the maximum pressure of helium supply is about 1.2 bara. The exhaust pressure for the first stage safety valve is 2.0 bara and that for the second stage safety valve is 1.5 bara. To prevent unexpected exhaust and guard gas overpressure, we have a check valve for each helium supply line of the helium guard line of safety valve for one valve box. An additional manual valve with a KF25 connector is installed outside the vessel for helium displacement while the internal components need to be overhauled separately.

5. CONCLUSIONS

The main purpose of this study is to demonstrate a typical 2 K cryogenic distribution system, risk analysis of air contamination, and practical engineering design. The helium leakage detection rate could be used to directly determine the air leakage rate into the VLP helium loop with reasonable accuracy. When the cumulative pollution effect is taken into account, the maximum possible quality of the total pollutant is 1080 g per year for HIAF cryogenic distribution system without helium guard. In order to avoid the ice block phenomena and equipment damage, air leakage must be considered when the overall leakage of a valve box approaches 10^{-9} Pa·m^3/s. This approach and technical method have been used in HIAF iLinac cryogenic distribution system.

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