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Cryogenic system design for HIAF iLinac

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Abstract A helium cryogenic system is designed by the Institute of Modern Physics, Chinese Academy of Sciences, to supply different cooling powers to the cryomodules of ion-Linac (iLinac) accelerator, which serves as the injector of the High Intensity Heavy-Ion Accelerator Facility project. The iLinac is a superconducting heavy-ion accelerator approximately 100 m long and contains 13 cryomodules cooled by superfluid helium. This article describes the cryogenic system design of the iLinac accelerator. The requirements of the cryogenic system, such as cooling mode, refrigeration temperature, operating pressure and pressure stability, are introduced and described in detail. In addition, heat loads from different sources are analyzed and calculated quantitatively. An equivalent cooling capacity of 10 kW at 4.5 K was determined for the cryogenic system according to the total heat load. Furthermore, a system process design was conducted and analyzed in detail. Further, the system layout and the main equipment are presented.

Keywords Ion-Linac (iLinac) accelerator · Superfluid liquid helium · Cryogenic system · Cryomodule

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1 Introduction

As one of the 16 priority national projects for science and technology for the 12th 5-year plan in China [1], the High Intensity Heavy-Ion Accelerator Facility (HIAF) [2] was commissioned in early 2019 in Guangdong Province by the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS). The first experiment is expected to be conducted around 2024 [3]. The HIAF will provide intense primary and radioactive ion beams for nuclear physics, atomic physics and application research sciences [4]. The proposed experimental stations include a nuclear structure spectrometer, low- and high-energy irradiation target caves, an electron–ion recombination precision spectrometer, a high-energy external target station and a precision spectrometer ring. A schematic of the HIAF project is shown in Fig. 1. The facility consists of a superconducting electron cyclotron resonance (SECR) ion source, ion-Linac (iLinac), booster ring (BRing), fragment separator (FRS) to produce radioactive beams, spectrometer ring (SRing), beam merge ring (MRing), several experimental terminals at the low- and high-energy ends and setups for in-ring experiments. The SECR provides highly charged ion beams. The iLinac is designed to accelerate ions with a charge–mass ratio of $Z/A = 1/7$ (e.g., $^{238}U^{35+}$) to an energy of 17 MeV/u. The ions provided by the iLinac are injected into and accelerated in the BRing to reach the required intensity and energy (i.e., up to 2×10^{11} particles per pulse (ppp) and 800 MeV/u for $^{238}U^{35+}$). They are then either fast-extracted and transferred to the external targets or the SRing or slowly extracted to the terminals for a wide range of studies in applied science, including biology and material sciences. The highly charged ions injected into the SRing reach 10^{11-12} ppp.

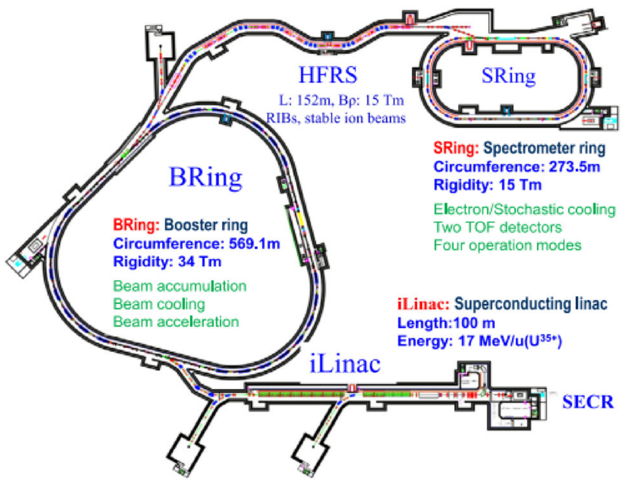

Fig. 1 (Color online) Schematic of the HIAF project

Further, both the BRing and SRing are equipped with electron coolers [5–7].

The purpose of the cryogenic system is to ensure the required superconducting operating conditions for the iLinac. The iLinac is a superconducting heavy-ion accelerator with an operating temperature of 2 K. It comprises a low-energy beam transport (LEBT) line, radio frequency quadruple (RFQ) system, medium-energy beam transport (MEBT) line and superconducting section [8]. The beams are accelerated to their final energy by niobium superconducting radio frequency (SRF) cavities operating at 2 K. A total of 86 SRF cavities, 43 superconducting solenoids in the superconducting section, 13 cryomodules that contain two quarter-wave resonator (QWR) cryomodules, five half-wave resonator (HWR) 010 cryomodules and six HWR 015 cryomodules are present. Each cryomodule must refrigerate all the superconducting solenoids and cavities, current leads and the inside section of couplers in cryomodule. The cavities and solenoids exhibit better performance when bath-cooled with 2 K superfluid helium than when cooled with 4 K helium. Superfluid helium is widely used in superconducting cavity cooling because of its unique characteristics such as high thermal conductivity, good pressure stability, low viscosity and high specific heat.

A detailed schematic of the helium refrigeration system is shown in Fig. 2. The cryogenic system contains a cryoplant with cold compressors that compress cold helium gas [9, 10], a distribution system to deliver helium to cryomodules, a helium recovery and purification system, a control system and a gas tank system to store helium and liquid nitrogen. The helium gas is cooled and liquefied in the cryoplant to provide cooling power to the superconducting objects of the accelerator. The cryogenic distribution line is installed along the entire superconducting section of the accelerator to deliver and distribute the low-temperature helium to the cryomodules; it is a multichannel transfer line containing both helium and nitrogen pipes and is connected to the cryomodules via a connecting box. In addition, an end box is placed at the bends of the pipes at the end of the distribution line to conduct different operations such as cooldown and warm-up. The end box contains connectors through which the helium supply pipe connects to the low-pressure vapor pipe, and the thermal shield supply pipe connects to the thermal shield return pipe. The liquid helium produced by the cryoplant is transferred by the distribution system to the cryomodules. Each cryomodule comprises a *J–T* valve and a heat exchanger. The 2 K superfluid helium is generated in the cryomodules driven by the cold compressors and the room temperature compressors.

The huge cooling power requirement and complex helium distribution network of the project make the design of the cryogenic system very challenging. Heat loads, equivalent refrigeration capacity and cooldown time are the most critical design parameters and must be accurately derived from the iLinac design. This paper presents the preliminary process design for the HIAF iLinac cryogenic system and describes the key requirements of the accelerator. The expected cooling capacity, temperature levels and operating modes are calculated, and the transient processes of the system, such as cooldown, warm-up, liquid filling and pump-down to 2 K, are studied in detail.

2 Cooling requirements and heat load calculation

Accelerator cooling requirement and heat load estimation are the primary input parameters for cryogenic system design. These parameters determine whether to use a liquefier or a refrigerator, the size and cooling capacity of the refrigeration equipment, the complete system process and the construction and operation cost of the whole cryogenic system. Table 1 lists the main requirements of the cryogenic system for the HIAF iLinac. As shown in the table, the running temperature of SRF cavities and solenoids is 2 K with bath cooling. The operating pressure of the cavity is set at the saturation pressure of superfluid helium with a small fluctuation of $\pm$ 0.1 mbar [11], and the maximum allowable pressure for the SRF cavities is set at 3 bar. In addition, the liquid helium level is controlled within $\pm$ 0.5% of the set point [12]. Cavity cooling is provided by liquid helium filled in the helium jacket around the cavity. During the cooldown process of the cavities, the cooling rates are set at 2 K per hour and 4 K per hour for the cooldowns from 300 to 100 K and 100 to 4.5 K, respectively. This is because the superconducting cavity performance is significantly affected by the temperature gradient across the cavity wall during cooldown. The temperature

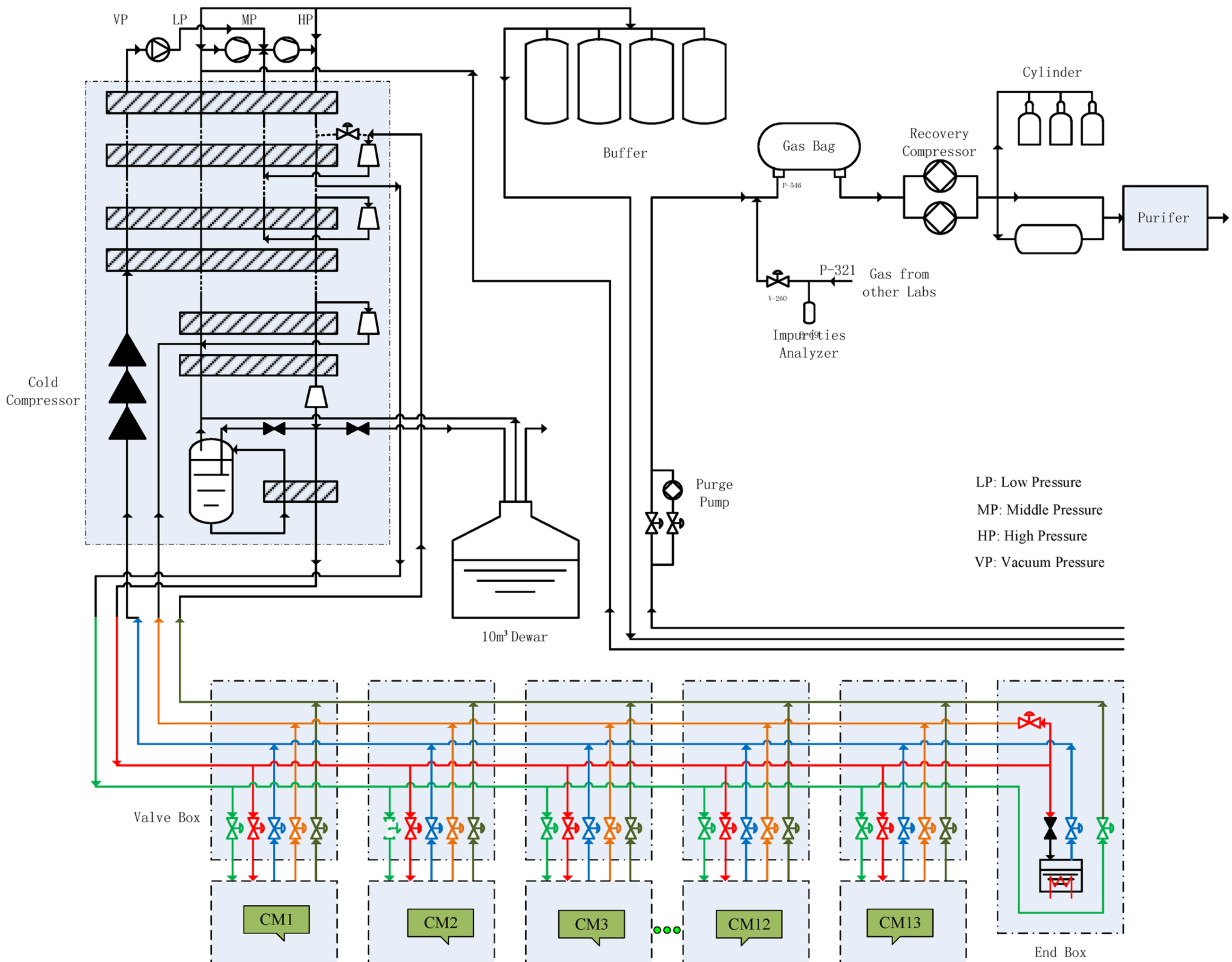

Fig. 2 (Color online) Schematic of the HIAF iLinac cryogenic system

Table 1 Main requirements of the cryogenic system for HIAF iLinac

Cooling time	300 K–100 K: 2 K/h, 100 K–4.5 K: 4 K/h
Cooling mode	Bath-cooled
Operating temperature	2 K
Operating pressure	31.3 mbar
Maximum pressure	3 bar
Pressure stability	± 0.1 mbar
Liquid-level stability	± 0.5%

gradient originates during cooldown, when liquid helium accumulates very quickly at the bottom of the helium jacket in the beginning, resulting in rapid cooling of the cavity bottom. On the contrary, the middle and top parts of the cavity are located far from the accumulated liquid and are thus cooled much more slowly. This difference in the cooling rates gives rise to a remarkable temperature gradient that influences the cavity performance [13].

The heat load of the cryogenic system mainly originates from three sources: cryomodules, transfer line and the refrigerator itself. In Fig. 3, Q_1, Q_2 and Q_3 represent the heat loads from the refrigerator, transfer line and cryomodules, respectively. All forms of heat transfer, namely, convection, thermal radiation and heat conduction, contribute to the total heat load of the system. Among these sources, the heat load caused by convection is believed to contribute only a very small percentage in the cryogenic system because of the high vacuum insulation measures. For the HIAF iLinac cryomodules, the heat load from heat conduction is the most important heat source for the SRF cavities, which are connected to numerous equipment at higher temperatures, such as pipes, posters, liquid-level meters, power couplers, tuners and current fuses. In addition, the heat load from thermal radiation from wall surface at high temperatures, such as vacuum shell and thermal

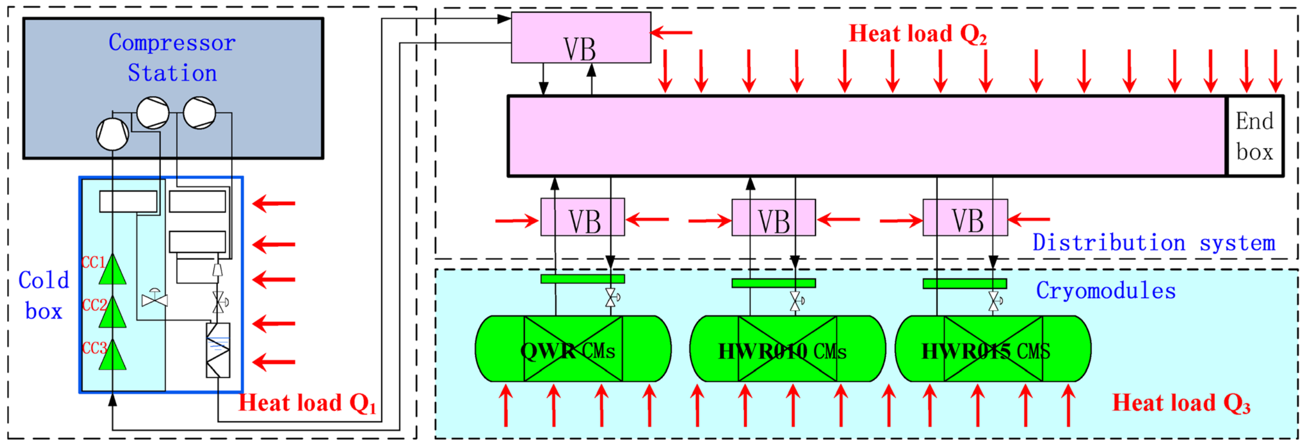

Fig. 3 (Color online) Main sources of heat loads in the cryogenic system

shield, and convective heat transfer of residual gas in the vacuum cavity contribute to the total heat load on the SRF cavities. A layer of thermal shield cooled to 50–75 K by forced cryogenic helium gas is employed in the cryomodules of the HIAF iLinac to reduce the heat load caused by radiation; further, the thermal shield is coated by multilayer insulation (MLI) blankets. In addition, 4.5 K forced cooling helium is required to provide cooling power to minimize heat leak from the power couplers to the cavities. For the distribution system, the heat load originates from sources including cryogenic valves in valve boxes, transfer line and bayonets. Clearly, controlling the heat load of the distribution system is more important because the heat load increases the helium enthalpy at the end of the transfer line, affects the *J–T* valve inlet temperature and decreases the ultimate superfluid helium yield. To avoid disadvantageous instabilities, all fluids must be ideally transported over sufficiently long distances in the mono-phase state. The local two-phase circulation of saturated liquid can be tolerated within limited lengths and a controlled range of vapor quantity. Therefore, multichannel transfer lines with thermal shields of 50–75 K are utilized in the HIAF iLinac cryogenic system to reduce thermal radiation to inner helium pipes. The heat load on the refrigerator must be minimized during the design and the manufacturing stages by the equipment supplier.

Each HIAF iLinac cryomodule has three heat load levels: 2 K heat loads for operation of cavities, 4.5–8 K heat loads for power coupler operation and 50–75 K heat loads for the thermal shield and heat intercepts. The heat loads include static heat loads and dynamic heat loads, as listed in Table 2. The main contributors to the static heat loads at various temperature levels are the RF power couplers, cryogenic valves, multilayer insulation, solid supports, cold tuners and instrument cables [14]. The dynamic heat loads at various temperature levels mainly originate from RF power dissipated in the 2 K helium bath

Table 2 Heat loads of the cryogenic system for HIAF iLinac

Equipment	2 K (W)	4.5–8 K (W)	50–75 K (W)
Cryostat	1206	1508	4784
Valve box	80	80	200
Transfer line	131.5	131.5	394.5
Sum	1417.5	1719.5	5378.5
Safety factor	1.5	1.2	1.1
Design refrigeration capacity	2125.5	2063.4	5916.35
Equivalent heat load/4.5 K	7439	2063	650.7
Sum of heat load/4.5 K	10 kW/4.5 K		

by the cavity and power coupler, and the rest originate from accelerator beam loss. The beam loss accounts for a large proportion of the total heat load. In heat load estimation of the cryogenic system, 1 W/m for the beam loss at 2 K is considered in this study [9].

The heat load of the cryogenic system determines the refrigeration capacity and size of the helium refrigerator and contributes significantly toward the construction and operation cost of the whole cryogenic system. Investment for the cryogenic system accounts for a great proportion of the whole investment for the accelerator; therefore, heat load assessment becomes particularly important. However, estimating the dynamic heat load of the accelerator is frequently difficult, and an inevitable difference between the design and the actual product is present for different processing and installation technology [15]. Therefore, the actual refrigerating capacity is normally larger than the designed value. Half of the heat loads of the cryomodules originate from the cavity dynamic loads. An uncertainty factor must be added to this estimation based on previous facility construction and operation. In engineering design, the solution for the uncertainties of heat load estimation is to multiply the calculated heat loads by a safety factor. Based on engineering experience, safety factors of 1.5, 1.2 and 1.1 are chosen for the heat loads of 2 K, 4.5–8 K and 50–75 K, respectively. In addition, the 4.5 K equivalent refrigeration capacity is a very important value to understand the size and the capital costs of the cryoplant. Thus, these three heat loads of the HIAF iLinac cryogenic system are converted to 4.5 K heat load according to the coefficient of performance (COP) of the system. The COPs for converting the 2 K and 50–85 K heat loads to 4.5–8 K heat load are 3.5 and 0.11, respectively. Therefore, the resulting 4.5 K equivalent heat capacities of each temperature with the safety factors are 2.1 kW, 2.0 kW and 5.9 kW for 2 K, 4.5–8 K and 50–75 K loads, respectively. The total 4.5 K equivalent capacity of the cryoplant is 10 kW.

3 Process design

Cryogenic system process design is conducted based on the cooling requirements of the accelerator, which uses a fully segmented cryomodule configuration. The cryomodules can be operated individually or together. As mentioned above, the cryoplant supplies cooling power to three cooling levels in each individual cryomodule with the help of the distribution system. According to the requirements, the cryogenic group of IMP carried out the process design by considering the cooling time, cooling mode, operating temperature, maximum pressure, pressure stability and liquid-level stability. Further, helium supply, helium recovery, purification and system cleaning are necessary processes for the cryogenic system. Three main processes of the cryogenic system, namely, cooling circuit, cleaning circuit and external circuit, were designed to meet the accelerator requirements for long-time stable operation, according to its corresponding function.

3.1 Cooling circuit

To allow the SRF cavities to benefit from their superconductivity, the cavities must be cooled down to the working temperature by cold helium. The working temperature of the HIAF iLinac is 2 K. In a 2 K cryogenic system, helium circulates among regions with distinct pressures and temperatures. The conversion between different pressures and temperatures occurs in cold boxes and cryomodules; each region corresponds to a helium sub-circuit. Helium gas and liquid helium are then transferred by the distribution system to the cryomodules and cryoplant via different circuits. A flow diagram of the cooling circuits is shown in Fig. 4. Four main sub-circuits are elaborated in this paper.

The primary sub-circuit, which belongs to the refrigerator itself, allows helium to circulate between the cold box and the compressors. Helium at ambient pressure and room temperature is compressed up to 20 bar by a three-stage compressor in the compressor station, which then flows to the cold box through the high-pressure pipeline. The compressed gas helium, precooled by liquid nitrogen and multistage heat exchangers, is then expanded by turbo-expanders and throttled by a throttle valve in the cold box, where liquid helium is produced.

The function of the second sub-circuit is to cool the thermal shield of cryomodules, transfer lines and current leads of superconducting solenoids. All these parts are designed to function between 50 and 77 K. Helium gas at 18 bar and 50 K is extracted from the high-pressure pipe after the second heat exchanger in cold box; it is then transferred to cryomodules via the distribution system, where it cools the thermal shield and solenoid current leads. After exchanging heat with the thermal shields and current leads, the helium gas returns to the inlet of the first stage turbine of the cold box at approximately 16.5 bar and 75 K.

The third sub-circuit, with helium in the supercritical state, is used for RF power coupler cooling. Helium at 3 bar and 4.5 K is extracted from supercritical helium interface in front of the *J–T* valve in the cold box. After being subcooled by liquid helium in the cold box, the helium is transferred to the top portions of the power couplers to minimize heat conduction to the cavities. Helium is warmed from 4.5 to 8 K at the end of the power coupler, which then returns back to the cold box via a cryogenic return line.

The last and most delicate sub-circuit is used to produce 2 K superfluid helium. Helium in this sub-circuit has to undergo a mixed compression cycle before it can reach 2 K. Before the production of 2 K helium, the cryomodules must be partially filled with 4.5 K liquid helium generated from supercritical helium by the throttling of JT valve. When the liquid helium reaches a certain level, the cryoplant starts the cold compressors to reduce the helium pressure in cryomodules to the saturation pressure, i.e., 30 mbar, of superfluid helium. The cold compressors rise the helium pressure in the downstream pipeline from 30 mbar to 0.5 bar. Then, a sub-atmospheric pressure compressor pressurizes the helium gas to 4 bar to complete a helium cycle. Simultaneously, supercritical helium at 3 bar and 4.5 K is continuously transferred to the connect box (see Fig. 4), where cryogenic valves, sub-atmospheric pressure heat exchanger and *J–T* valve are installed. In the connect box, the supercritical helium is precooled to 2.2 K by counter-flow helium via a sub-atmospheric pressure heat exchanger, which minimizes helium-flashing losses. Then, the helium is throttled from 3 bar to 3 mbar by a *J–T* valve,

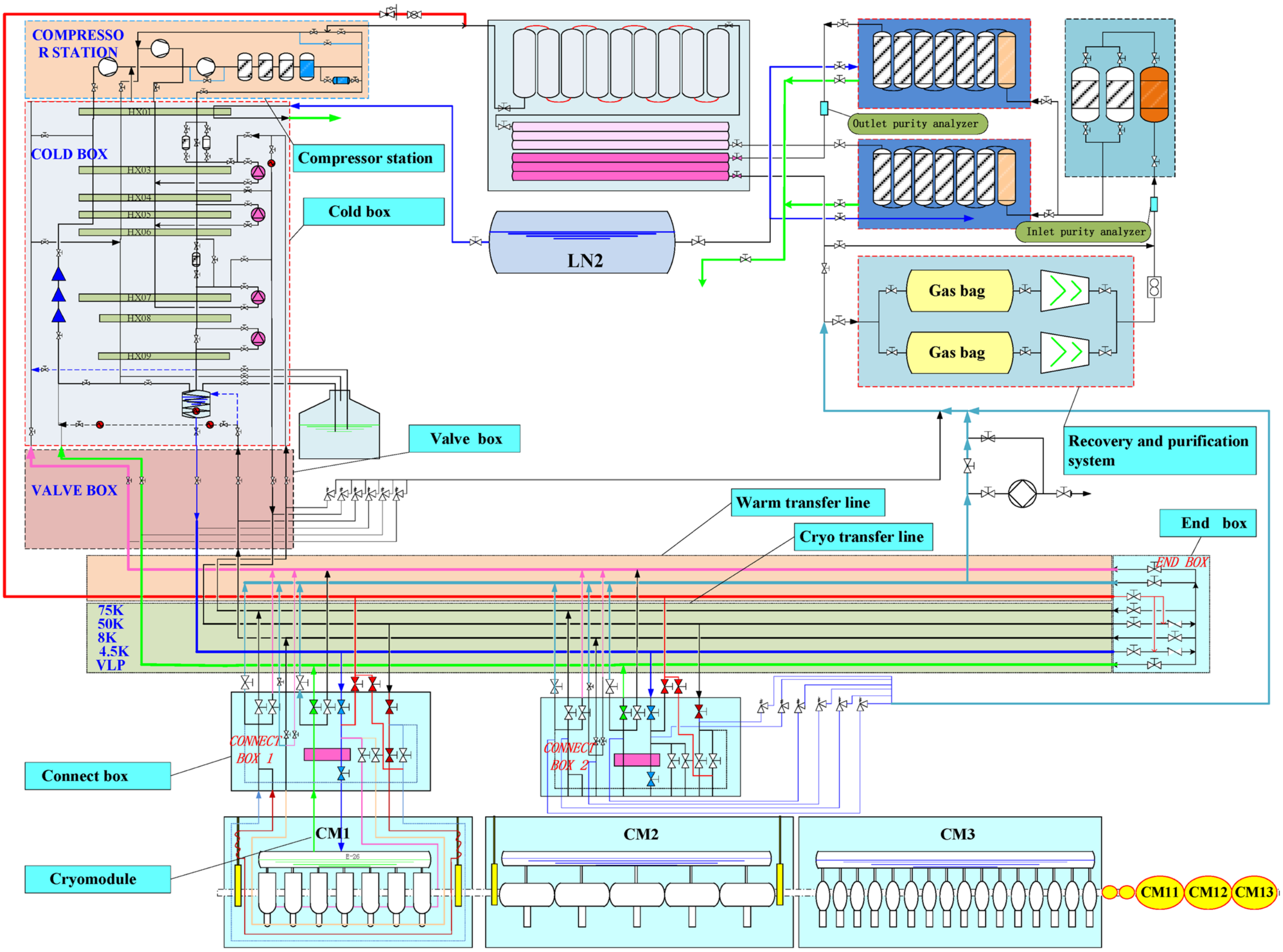

Fig. 4 (Color online) Flow diagram of the HIAF iLinac cryogenic system

producing 2 K superfluid helium. A continuous and stable superfluid helium supply can be obtained by simultaneous filling of helium and mixed pump decompression.

3.2 Purging circuit

Another important circuit is present for purging the whole cryogenic system before the system is started. Helium purity must be higher than 99.999% in the HIAF iLinac cryogenic system, so the entire cryogenic system can be thoroughly cleaned. The cold box, transfer line, buffer and cryomodules must be vacuumed and purged using ultra-high purity helium several times until the residual gas absorbed by the metal surfaces is released. The cold box and buffers can be pumped and purged separately using pump interfaces. However, the cryomodules can only be cleaned online using process pipes of the distribution system. The process pipes are installed in multichannel pipes and are usually used to recover helium gas. When purging the cryomodules before cooling down, it is used for pumping gas out of the cryomodules with the help of valve boxes and the end box (see Fig. 4). After all the pipelines inside the cryomodules are vacuumed, pure helium is filled in the cryomodules via warm helium gas pipes that are connected to the buffer. To minimize the operational costs, all purging helium gas is recovered using a recovery and purification system [16]. After purification, helium is returned to clean helium tanks, which are connected to the buffer tanks for replenishing helium to the system.

3.3 External circuit

In addition to the aforementioned circuits, an external circuit for helium supplementary and recovery is present. Because helium atoms are small, they easily leak into the ambient environment through tiny molecular size holes on pipelines. Therefore, pure helium must be replenished to the system. Moreover, helium could be polluted by air inhalation, particularly in a sub-atmospheric pressure system, which is dangerous for the cryogenics system and must be avoided. Gases other than helium can cause freezing or clog in the heat exchangers of the cold box or capillary tubing. Once clogging or freezing occurs, the whole cryogenic system must be stopped and no solution exists other than warming up and purging the entire system, which is extremely time-consuming in a large cryogenic system.

To address the two above-mentioned tasks, an external circuit of cryogenic system that can supply and recover helium both online and off-line is designed carefully in the HIAF iLinac. As shown in Fig. 4, two types of helium storage tanks are present in the system, namely, purified helium tank and contaminated helium tank. The purified helium tank is connected to the buffers, which directly supplies helium to the cryogenic system. When the pressure of the high-pressure pipe is lower than the set point, i.e., 20 bar in the HIAF iLinac cryogenic system, the purified helium is filled into system from the buffer to maintain system pressure. On the contrary, when the pressure of the high-pressure pipe is higher than the set point, pure helium flows out of the system into the buffer tank. It is a very complicated process and is always relative to system dynamic heat loads. Small and slow heat load fluctuations can be handled by buffer adjustment and compressor frequency control. However, large and quick changes in system heat load such as cavity quench cannot be managed only by the cryogenic system, in which case, the helium recovery and purification system plays an important role. To avoid damages to pipes, valves and other parts, more than one safety valve is typically installed in line with different threshold values. Rapid increase in pressure above a certain threshold opens the lower safety valve; then, helium discharges into the relief system through the valve, avoiding helium losses to the environment. In worst case, if a large amount of helium is vaporized and helium pressure surges beyond the second threshold, the safety valve leading to a gasbag is opened. With the inflation of gasbag, the helium pressure decreases to nearly ambient pressure. Helium in the gasbag is then recovered and stored in the contaminated helium storage tank and pressurized using a recovery compressor. Nevertheless, some helium gas cannot be recovered because of the enormous dynamic heat load. In other words, very large amounts of cryogenic helium are vaporized to gas with higher temperature, which exceeds the running capacity of the recovery compressors.

The recovery and purification system of the HIAF iLinac is designed for both online and off-line modes according to system operation condition. If a small amount of impure helium enters the recovery and purify system, the system temporarily stores this helium in a contaminated helium tank without purification. On the contrary, if a large amount of impure helium gushes into the recovery and purification system from the running cryogenic pipes, the system switches to the mode that simultaneously recovers and purifies the impure helium. The online mode functions as follows. First, helium gas coming from the running system of other experimental terminal temporarily enters the gasbag, where the gas pressure is at atmospheric pressure, which is the allowable pressure at the inlet of the recovery compressor. Second, helium is pressurized to 150 bar using recovery compressors and then transferred to the purifier. The purifier runs at liquid nitrogen temperature at a working pressure of 150 bar and employs the adsorption principle of activated carbon at high pressure and low temperature to adsorb impurities in helium such as nitrogen, oxygen, hydrocarbons and water. The helium purity at the outlet of the purifier can reach up to 99.999% and can meet the purity requirement of the cryogenic system. Finally, pure helium is stored in the pure helium storage tank or is filled into the buffer. The working of the off-line mode is similar to the previous mode; specifically, the purification process is the same as that in the online mode. A significant difference is that the off-line mode functions independently without requiring the running of helium cryogenic system. Helium transferred to the purifier comes from the impure helium tank and not from the running system. Another difference is that helium is stored at normal scenarios, i.e., if the pressure of the storage tank reaches the set point, all helium is purified at once.

4 Operation modes

The HIAF iLinac cryogenic system is designed to operate under different modes and can perform regular warm-up and cooldown processes and maintain the cold mass at an arbitrary temperature of 4.5–300 K. Moreover, a 2 K working environment can be obtained by reducing the helium pressure when excessive helium is filled in the helium jackets. The cryogenic system must precisely control the helium pressure and the liquid helium level. The fluctuations in helium pressure and helium level must be ± 10 Pa and ± 5%, respectively. Each cryomodule requires three temperature and pressure levels of cryogenic process cooling. In addition, the cryogenic system is equipped with a fail-safe mechanism, which enables restart of the whole cryoplant and cryomodules from any fault condition such as power outage and cavity quench.

4.1 Regular cooldown and warm-up processes

The cryogenics system achieves cooldown and warm-up of the entire cold mass of the HIAF iLinac using liquid helium circulating through its distribution system. Each cryomodule is connected to the main transfer line via a connection box. Every connect box can independently adjust the cooling power transferred to the cryomodule attached to it, which allows temperature control of each cryomodule. Therefore, in some rare cases [17], the cryogenic system can cooldown or warm-up a single cryomodule and maintain others at running temperatures. Before cooling down a cryomodule, the thermal shield and the current leads are first cooled by cold helium gas of temperature 50 K and pressure 18 bar. At this point, the returning helium gas is directed to the room temperature compressor inlet and where it is pressurized. However, as the temperature of the thermal shield decreases, the returning helium gas becomes increasingly colder and is collected by different sections of the cold box according to the gas temperature. After the thermal shield is cooled, 4.5 K supercritical helium from cold box is continuously injected into the cryomodules by pro-cooling pipe to cool the cold mass until its temperature reaches 4.5 K. During this process, the returning helium gas is collected by either the compressor or the cold box, based on the gas temperature. The cooling rates of cavities must be 2 K per hour during 300–100 K and 4 K per hour during 100–4.5 K. The cooling rate is controlled by letting a part of the room temperature gas flow out from the high-pressure pipe and mix with 50 K helium gas or 4.5 K superfluid helium gas in the valve box. Therefore, the injecting liquid temperature and cooling speed are maintained under control. In the warming-up process, all the cryomodules can be warmed up naturally by their static heat load, rapidly using resistive heaters installed in the cryomodules or by blowing warm helium gas from the high-pressure pipe of the cryogenic system into the cryomodules. Warm-up by static heat load has the least impact on the cryogenic system, and the evaporated helium gas can be instantly recovered. In case of accelerated warm-up, liquid helium is quickly vaporized and stored in the buffers for further recovery.

4.2 Obtaining 2 K environment

The 2 K operation environment is realized by filling the helium vessel and the cavity jacket in the cryomodules with 4.5 K liquid helium, followed by depressurizing. First, excess 4.5 K liquid helium is injected into the helium vessels and cavity helium jackets inside the cryomodules until the liquid level reaches a required value. Subsequently, the cold compressors and the sub-atmospheric pressure compressor in the cryoplant start decompressing the helium in the cryomodules. Helium evaporates and carries heat along, as its vapor pressure decreases. When the helium vapor pressure is finally pumped to 30 mbar, which is the saturation vapor pressure at 2 K, superfluid 2 K helium is obtained. To improve the liquid helium content in the gas–liquid flow, a *J–T* valve and a sub-atmospheric heat exchanger are used [18]. However, when the superconducting cavities and superconducting magnets are in operation, the 2 K liquid helium is quickly consumed and must be replenished. The replenishment is achieved by continuously supplying 4.5 K helium through the powerful pumping system of the distribution system, which maintains the vapor pressure at 30 mbar.

4.3 Fail-safe mechanism

The cryogenic system can recover from fault conditions and automatically restore the functions of the cryoplant, distribution line and cryomodules. The recovery time from system trips is pushed to a minimum because a static heat load always exists, which continuously increases the helium pressure in the cryomodule. If the system recovery time is too long, the helium vapor accumulates in the system and leaks through safety valves or bursting films, causing system contamination. The acceptable recovery period is less than few hours. Two typical scenarios to restart from power or system failure are presented below. First, in case of a rapid power outage, the system starts a backup diesel power generator and maintains its functions at a low power mode. After electricity is restored, the compressor power supply must switch to the original state. Second, if a rapid and overwhelming heat load occurs, such as due to multiple cavity quench or heavy beam losses, the helium pressure surges rapidly. In this case, the system uses the pressure relief valves to quickly reduce the helium pressure to recover the system [19].

5 Main equipment and system layout

Cooling requirements, cold mass and the total volume of liquid helium decide the capacity and size of the main equipment of the cryogenic system. The overall equivalent cryoplant capacity for the HIAF iLinac is 10 kW at 4.5 K. To reach this cooling capacity, the system required an electric power of 3.5 MW from the grid, 280 m^3/h cooling water and instrument air of 120 m^3/h. The entire cryogenic system covers a land area of 60 m × 30 m. All equipments are placed in a cryogenic hall in the HIAF iLinac campus. The cryogenic hall is mainly divided into seven functional areas: refrigeration machine room, cryogenic warehouse, compressor room, recycling room, control room, power distribution room and water supply room, as shown in Fig. 5. A 10 kW/4.5 K refrigerator, liquid helium Dewar, distribution valve box, transfer lines and other experimental equipment are placed in the refrigerator room. A cryogenic warehouse stores low-temperature equipment, such as vacuum pump, infusion tube, cryogenic valves, bayonet joints and bellows. The recycling room is mainly equipped with the recovery and purification system,

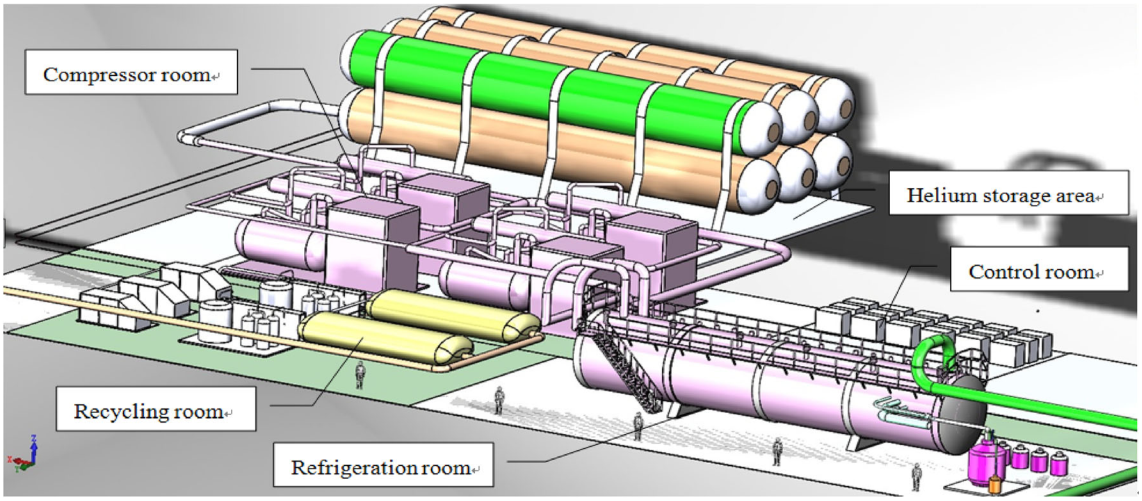

Fig. 5 (Color online) Equipment layout of the HIAF iLinac cryogenic system

including gasbags, recovery compressors, purifiers and other ancillary equipment. The compressor room houses large and heavy compressors. Vibration, noise, maintenance, foundation and other related factors must be fully considered in determining the location of the compressor room. In addition, the loading and installation of compressors require the compressor room to be equipped with hoisting units, such as bridge cranes or forklifts. In addition, the door of this room must lead to an open-space allowing for the entry and exit of heavy equipment and vehicles. The control room hosts all cabinets, UPS power supply unit and relevant secondary instruments, such as thermometers, vacuum gauges, helium level gauges and pressure transmitter. Due to the compact displacement and continuous running of a large number of control instruments, forced ventilation and air conditioning of the control room must be considered. The cryogenic control room is the control center for the entire cryogenic system, which must be located beside the refrigerator to enable close observation of the refrigerator status. Outside the cryogenic hall lies the tank farm, covering an area of 20 m $\times$ 15 m, where the helium storage tank and liquid nitrogen tank are placed.

The main components of the HIAF iLinac cryogenic system are the compressors system, oil removal system (ORS), cold box, transfer line and the helium recovery and purification system. The compressor system consists of the compressors stations, oil removal system and gas managing devices. Three compressors are present in a warm compressor system with working pressures of 1.05 bar, 4 bar and 20 bar, respectively. The oil removal system comprises three stages of coalescing filters, which remove oil from the compressed helium downstream of the high-pressure compressor. After filtering, the remaining oil content in helium at the outlet of the ORS is less than 10 ppb, which meets the purity requirement of the cryogenic system. The cold box comprises turbines, plate-fin-type aluminum heat exchangers, double-bed 80 K absorber, single-bed 20 K absorber, cryogenic valves and associated instrumentations. The 2 K cold box is integrated with the 4 K cold box to become a single unit. A series of cold compressors are installed in the cold box to increase the helium pressure at cryogenic temperature and recover the cooling power. In addition, a 2000 l liquid helium storage Dewar is present to subcool supercritical helium. The transfer line is connected to the cold box and the cryomodules to supply and distribute helium from the cryogenic helium. In addition to each cryomodule, a connection box that distributes and regulates the helium pressure and liquid helium level in cryomodules is present. Further, a vacuum separator device is essential in transfer line. With vacuum separated, the faulty cryomodule can be cut off from other cryomodules and devices in cryogenic state in the iLinac. The transfer line is designed as a multichannel pipe with a thermal shield at 50–75 K to prevent thermal radiation originating from room temperature from entering the inner helium pipe. The cryogenic section of the HIAF iLinac is 100 m long and has 150 cryogenic valves installed in it. The helium recovery and purification system mainly include a purifier, two types of storage tank, recovery compressors and a gasbag. The purifier has a purification ability of 200 m^3/h, and functions at a working pressure of 15 MPa and temperature of 77 K. Activated carbon is employed in the purifier to remove contaminants because of its ability to absorb impurities gases in helium at high pressure and low temperature. Liquid nitrogen is supplied to the purifier to maintain consistent low temperature. The storage tank can store about 10000 m^3 of helium gas at ambient pressure and temperature, of which 4000 m^3 is stored in the pure helium tank and the rest in impure helium tank. The recovery compressors having a compressing capacity of 200 m^3/h at 15 MPa are used for helium recovery.

6 Conclusion

In this study, we reported a cryogenic system design based on superfluid liquid helium for the HIAF iLinac. The cooling requirements and heat load estimation were discussed in detail. A refrigerator of capacity 10 kW at 4.5 K, including one of 2.1 kW at 2 K, was specified to provide the cooling power for the accelerator. Further, the preliminary process design of the cryogenic system was summarized. Several operation modes such as cooldown, warm-up, pump-down, system purification and acquisition of 2 K helium were described and analyzed. Furthermore, the main equipment and system layout were discussed.

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