Study on cooling process of cryogenic system for superconducting magnets of BEPCⅡ *

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Abstract In the upgrade project of the Beijing Electron Positron Collider (BEPCⅡ), three superconducting magnets are employed to realize the goal of two orders of magnitude higher luminosity. A cryogenic system with a total capacity of 0.5 kW at 4.5 K was built at the Institute of High Energy Physics (IHEP) to support the operations of these superconducting devices. For preparing the commissioning of the system, the refrigeration process was simulated and analyzed numerically. The numerical model was based on the latest engineering progress and focused on the normal operation mode. The pressure and temperature profiles of the cryogenic system are achieved with the simulation. The influence of the helium mass flow rates to cool superconducting magnets on the thermodynamic parameters of their normal operation is also studied and discussed in this paper.

Key words BEPCⅡ, superconducting magnets, cryogenic system

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1 Introduction

BEPCⅡ is an upgrade project of BEPC and the design luminosity of 1×10^{33} $cm^{-2}\cdot s^{-1}$ at 1.89 GeV is two orders of magnitude higher than its predecessor[1]. The strategy to realize this goal involves the micro-β_y scheme and the multi-bunch collision, which is implemented by two superconducting RF (SRF) cavities[2] and a pair of superconducting quadrupole (SCQ) magnets[3] in the double-ring of BEPCⅡ. For the BESIII (Beijing Spectrometer III) detector the superconducting solenoid magnet (SSM) is adopted to produce an axial magnetic field of about 1.0 T with good field uniformity over the tracking volume[4]. Dedicated for cooling the three kinds of superconducting devices, which have respectively distinct requirements in the cooling principles, a cryogenic system with a total capacity of 2×0.5 kW at 4.5 K has been built at IHEP in the framework of the collaboration between the Technical Institute of Physics and Chemistry (TIPC) and IHEP, Chinese Academy of Sciences (CAS). Fig. 1 is the layout of the cryogenic system of BEPCⅡ relative to the storage ring[5]. The cryogenic system is composed of two separate refrigeration plants of 0.5 kW each, Plant A for two SCQ magnets together with SSM in the first interaction region and Plant B for cavities in the second colliding hall. The refrigeration power for each plant is provided by Linde TCF50S refrigeration system with few adaptations. Five distribution Valve Boxes (VB) with two dewars take charge of realizing respective cooling principles and operation modes of different customers. Single and multiple channel vacuum-jacked transfer lines with multi-layer insulation are employed efficiently and safely to transport the cold gas or liquid helium.

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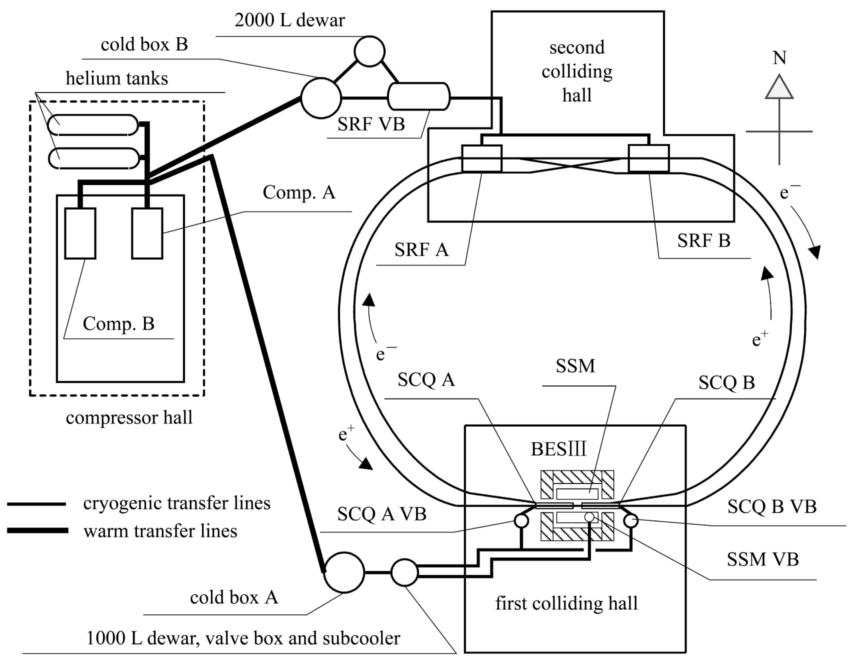

Fig. 1. Layout of the cryogenic system of BEPCⅡ.

In order to prepare the commissioning of cryogenic system for the superconducting magnets, the refrigeration process was simulated and analyzed numerically. Based on the latest engineering progress the simulation focused on the normal operation mode. The helium mass flow rate, pressure drops over the flow channels and thermodynamic parameters of these superconducting devices are determined with the simulation. The mutual influence of the helium mass flow rates cooling three superconducting magnets on the thermodynamic parameters under their normal operation is also analyzed and discussed.

2 Cryogenic system for magnets

The normal operation of SCQ magnets is supported by the supercritical single-phase helium to eliminate the possible vapor bubble in the helium flow around the coil winding and avoid the flow instabilities in the constrained cooling channels[6]. The single-phase helium flow has to be sub-cooled with boiling saturated helium[7]. The SSM is designed to run at about 4.5 K and cooled by the pressurized two-phase flow in the serpentine pipes welded to the outer surface of the support cylinder[8].

The three magnets share a cryogen production and distribution system. Fig. 2 is the simplified schematic illustration of refrigeration process for magnets in normal mode[9]. In the steady state, the compressed helium gas of 1.3 MPa flows into Cold Box A and comes out from J-T valve at about 5.0 K and 0.27 MPa. Passing through the cryogenic transfer lines and the heat exchanger immersed in the bath of the liquid helium of 1000 L dewar, the helium flow is sub-cooled to the supercritical condition.

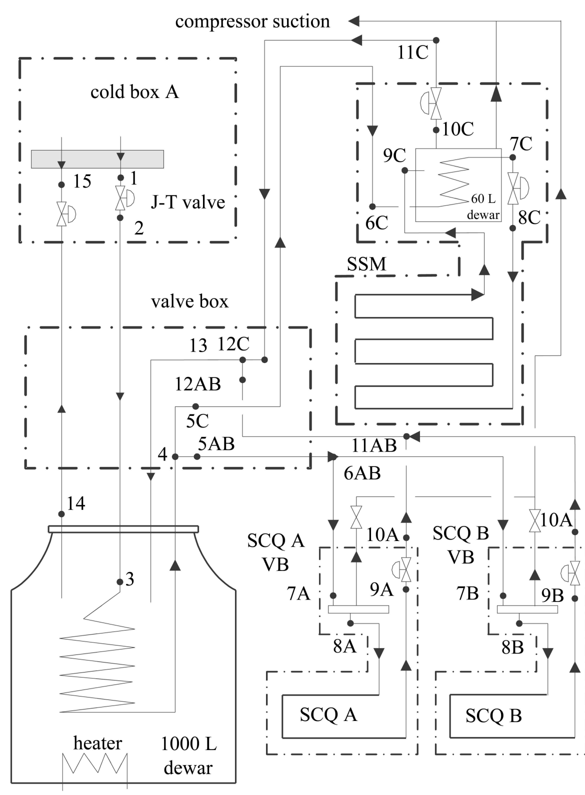

Fig. 2. Simplified schematic illustration of refrigeration process for magnets in normal mode.

The supercritical helium cooling the SCQ magnet convenes into a small container, which is located at the bottom of the current leads in the valve box, with a part of boil-off helium gas going up to cool the leads. Then the flow goes through the outer and inner cooling channel of the magnet in turn to carry off the leaking heat. Before returning to the 1000 L dewar, a control valve is responsible for the adjustment of the pressure below the critical point.

In order to acquire a buffer time in case of the refrigerator suspension and decrease the quality of the helium flow cooling SSM, a 60 L dewar is equipped in which a heat exchanger is immersed to pre-cool the helium flow. The pressure of pressurized two-phase flow of helium cooling the magnet is 0.135 MPa. The flow goes back to 60 L dewar with a branch to the cooling current leads.

The backward flows from different branches converge in the distribution Valve Box and then go back to 1000 L dewar. The dewar serves as a phase separator in which the liquid helium is vaporized by the heat from the heat exchanger, the intrinsic heat leaks and the power heater. The cool helium gas returns to the low-pressure side of Cold Box A to maintain the refrigerating capacity.

3 Heat loads and main assumptions

Table 1 lists the heat loads of cryogenic system used for the simulation. The rigid transfer lines, single-channel or multi-channel, have a heat leak of 1 W/m to cold helium and the flexible lines have 2 W/m. The bayonets, which are detachable for the connection of the cryogenic transfer lines, and valves, have each the heat leak of 1 W. The heat loads and leaks are entirely absorbed to increase the entropy of helium flow.

Table 1. Heat loads for the simulation.

items	heat loads	unit
SCQ magnet (A/B)	15	W
SSM	27	W
1000 L dewar	20	W
60 L dewar	2	W
current leads of SSM	0.4	g/s
current leads of SCQ	0.32	g/s
multi-channel(4 tubes)	1	W/m
flexible tube	2	W/m
cryogenic valve	1	W/each
bayonet	1	W/each

Single-phase (the vapor quality: $x < 0.01$ or $x > 0.9$) pressure drops along the cryogenic transfer lines is calculated according to the Darcy friction factor. This factor (as represented on a Moody chart[10]) is as a function of Reynolds numbers (Re) for laminar flow, and as a function of both Reynolds number and wall roughness ratio (roughness over diameter, e/D) for turbulent flow.

The pressure drops in two phase (i. e., vapor-liquid) flow can be dramatically higher than the pure liquid flow at the same overall mass flux, easily one or two orders of magnitude higher. Two-phase multipliers have been used to account for this and provide a simple means of estimating the relative increase in pressure drop due to the presence of the vapor phase. In this study the two-phase multipliers for the two phase helium flows are predicted by the simplest homogeneous model, where both phases are assumed to flow with the same average velocity[11]. The equations proposed by McAdams et al.[12] in 1942 are used to evaluate the mixture dynamic viscosity (μ) and density (ρ) of two-phase helium flow.

For the full open ball valves, the equivalent length is 340 times of their diameters[13]. Pressure drops in the cooling channels of superconducting magnets are neglected. For the performance of heat exchangers in the 1000 L and 60 L dewars, the calculation is conducted by Ref. [14]. The refrigerator is assumed to provide the helium of setting conditions in the stable and automatic operation. The thermo physical data of helium are taken from the standard helium property code HEPAK[15].

The quasi-Newton iterative and downhill methods[16] are adopted in the computing process in which the mass flow rates and the pressure or pressure drop over the control valves are chosen as the independent variables to construct the functions in accordance with the mass balances of the liquid containers and the equal pressures at the point of pipes' inter-junctions.

4 Simulation results and discussion

Figure 3 provides the pressure (a) and temperature (b) profiles of the cryogenic system for the magnets. The total mass flow rate for three magnets is 31.58 g/s and is sub-cooled to 4.507 K at 0.262 MPa by the heat exchanger in the 1000 L dewar. Under the flow rate of 11.997 g/s for the SCQ-A and 13.8 g/s for the SCQ-B, they can both operate at the average temperature of 4.75 K and the temperature rise of helium flow through magnets is around 0.2 K. The pressures and temperatures of two branches for the SCQ magnets have slight difference due to different lengths of the cryogenic transfer lines but both can meet the normal operation requirements. Just out of the SCQ magnets, the helium is further throttled to release the pressure by a control valve.

As the SSM is situated far away from the refrigerator, the flow rate of 6.1 g/s has a temperature rise along its long cryogenic transfer lines. The pre-cooler in the 60 L dewar is effective to eliminate the rise with releasing a heat quantity. As two control valves take charge of the adjustment of the pressure, SSM can normally work at 0.135 MPa and correspondingly the temperature of 4.54 K. The helium flow quality out of the magnet is 0.379, which is less than its upper limitation of 0.5, and 0.46 out of 60 L dewar.

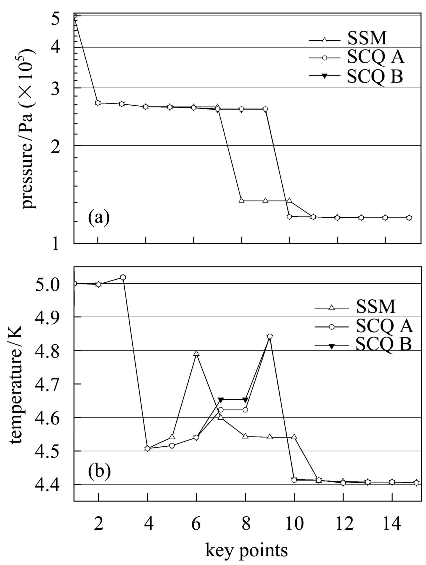

Fig. 3. Pressure (a) and temperature (b) profiles of the cryogenic system for superconducting magnets.

After cooling the magnets, the branches come together in Valve Box and go back to 1000 L dewar. To keep the mass balance of the dewar and vaporize the liquid helium, a heat power of more than 200 W should be added necessarily although the intrinsic heat loads of dewar and heat from exchanger have adequately been considered.

The vapor quality of the helium flow for the SSM exercises a strong influence on the heat transfer between the fluid and the magnet. The relation of the helium mass flow rate cooling the SSM and the flow quality out of the magnet has been investigated as indicated in Fig. 4. The mass flow rate should be more than 4.5 g/s to keep the vapor quality of the flow lower than 0.5. As the system is shared by two other customers, the impact of increasing the flow rate for the SSM on the states of two SCQ magnets has also be taken into consideration as revealed by Fig. 5. In the above two figures, the mass flow rates of 11.997 g/s for the SCQ-A and 13.8 g/s for the SCQ-B is fixed. The increasing in the total mass flow rate entirely contributes to the flow cooling the SSM. As shown in Fig. 5, though the input temperature (Point: 3) of the sub-cooler is almost not varying with the increasing of the total flow rate, the output temperature (Point: 4) rises. The flows for SCQ magnets both have the same climbing tendency. For the helium supply of the SSM, the pre-cooler in the 60 L dewar can serve as an oscillation dumper, as its output temperature (7C) is stable with further quantity helium to cool the SSM.

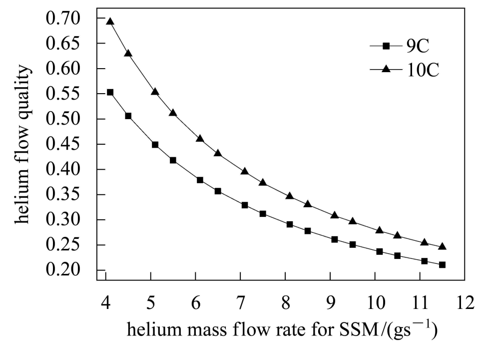

Fig. 4. Relation of the helium mass flow rate for the SSM and the flow quality out of the magnet and 60 L dewar.

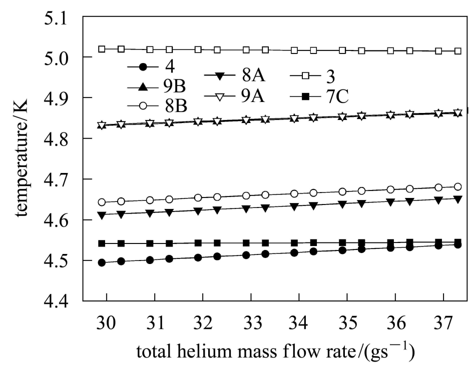

Fig. 5. Impact of increasing the flow rate for the SSM on the states of SCQ magnets.

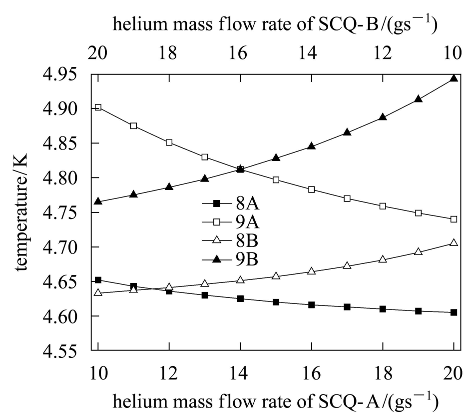

Fig. 6. Changes of two SCQ magnets' temperatures with the respective various mass flow rates.

Above the critical pressure (0.2275 MPa) supercritical liquid helium behaves just in a single phase and the heat is absorbed by the sensible heat of the helium with a corresponding increase in temperature (0.5 J/g, ΔT=0.1 K). The higher the mass flow rates, the lower the temperature rises. To investigate the temperature changes of SCQ magnets only impacted by the helium mass flow rates, we assume that the total mass flow rates of 35 g/s for three magnets and

5 g/s for SSM is invariable and the rest of 30 g/s is distributed to the SCQ magnets in a mutually complementary way. Fig. 6 indicates the changes of two magnets' temperatures with the respective various distributions of mass flow rates. In this situation, the outlet temperatures lower than 4.85 K out of SCQ magnets are obtainable only when the flow rates for the magnets range from 12 g/s to 17 g/s.

5 Conclusion

The mathematical models for the normal operation of cryogenic system for superconducting magnets of BEPCⅡ have been developed based on the latest engineering progress and the flow chart. The numerical simulation was conducted with the method of quasi-Newton iterative and downhill. According to this analysis, the normal working conditions of these superconducting magnets have been figured out under the total mass flow rates of 31.58 g/s. It can be afforded by the refrigerators. The distributions of the heat loads in the entire system are concluded, which will benefit the oncoming commissioning of the completely cryogenic and superconducting system of BEPCⅡ. The operating margins and parameters of three superconducting magnets, which are accommodated in the same cryo-plant and cooled in different cooling principals, have also been analyzed and discussed.

Preliminary commissioning of the cryogenic system has successfully been carried out when the SSM was at its offline position. The operation conditions of the superconducting magnets were met by the adjustment of the head loads and pressure by the heaters in the dewars and the opening of the control valves. The deviations between the preliminary commissioning and the numerical simulation in this paper are within estimates.

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