The cryogenic system of BESIII in preliminary design

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The cryogenic system of the superconducting (SC) solenoid magnet consists of a refrigerator, compressor, buffer tank, recovery tank, liquid nitrogen storage tank, control dewar and SC solenoid magnet, where the refrigerator, compressor, buffer tank and recovery tank are shared with another superconduting user of Beijing Electron Positron Collider II (BEPC II), a pair of superconducting interaction region quadrupole magnets (SCQ). The solenoid magnet is indirectly cooled by forced, two-phase, helium flow during steady state operation and switched to a thermo-syphon mode in case of emergency stop of the refrigerator. This paper describes the preliminary design of this cryogenic system, including the heat load estimation, the cooling flow scheme, the operation modes, the structural design of the pipes, control dewar and cryostat of this SC solenoid magnet.

INTRODUCTION

The cryogenic system of the SC solenoid magnet for the Beijing Spectrometer III (BESIII) detector system will be constructed at the Institute of High Energy Physics (IHEP) in Beijing. In order to realize the goal of increasing the luminosity of BEPC by two orders of magnitude, three superconducting hardware systems, which are a pair of SCQ, a pair of superconducting radio frequency cavities, and the superconducting detector (SCD) solenoid magnet, need to be developed in BEPCII. The SCD solenoid magnet which is inside the BESIII detector is designed to produce axial steady magnetic field of 1.0 Tesla over the tracking volume and to meet the requirement of particle momentum resolution to particle detectors.

This paper describes the preliminary design of the BESIII cryogenic system including the heat load estimation, the cooling flow scheme, thermodynamic design, the configuration of the control dewar and cryostat, and the operation modes of this SC solenoid magnet.

BASIC PARAMETERS OF THE BESIII MAGNET

We adopt a design featuring single layer of coil, indirect cooling by forced flow of LHe, pure aluminium based stabilizer and NbTi/Cu superconductor for the magnet. A serpentine tube with a bore diameter of 25 mm is welded on the outer surface of the support cylinder. One of main reasons that the pool boiling method is unfavorable is possibility of an explosive boiling off resulting in the rapid loss of cryogen in a quench. The force cooling method also has the advantage that a smaller quantity of cryogen is required.

The overall dimension of the magnet is 3.89 m in length, 2.65 m in inner diameter, and 3.4 m in outer diameter. The coil itself is 3.5 m in length and 2.9 m in effective diameter. The general parameters of the magnetic solenoid of the BESIII detector are summarized in TABLE 1.

Table 1 Basic parameters of the BESIII magnet

Items		Parameter
Cryostat		
	Inner radius	1.325 m
	Outer radius	1.700 m
	Length	3.890 m
Coil		
	Effective radius	1.450 m
	Length	3.500 m
	Conductor dimension	3.70 mm × 20.0 mm
Electrical parameters		
	Central field	1.0 T
	Nominal current	3150 A
	Inductance	2.0 H
	Stored energy	9.2 MJ
Cold mass		3.5 ton

CRYOGENIC SYSTEM OVERVIEW

The system consists of a helium compressor, a cold box, transfer lines, a control dewar, a magnet cryostat, a buffer tank, a recovery tank, and a liquid nitrogen storage tank, where the helium compressor, cold box, buffer tank, recovery tank, and liquid nitrogen storage tank are shared with a pair of SCQs. Therefore, a flow diagram of the cryogenic system only including the control dewar, magnet cryostat, and transfer lines is shown in Figure 1.

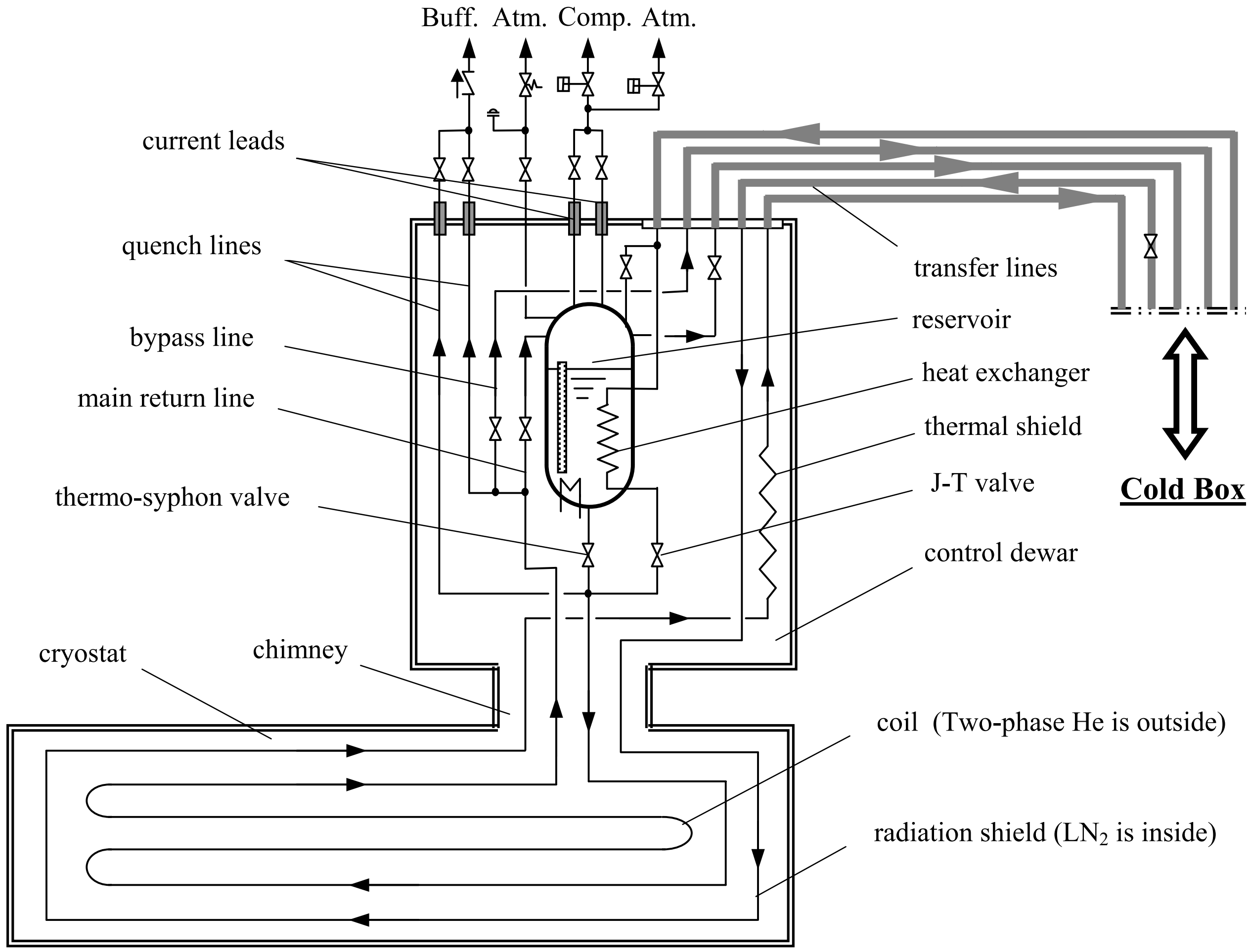

Figure 1 Flow diagram of the cryogenic system

The compressed helium gas at 1.65 MPa from the compressure flows into the cold box and comes out at 5.4 K and 0.3 MPa after the J-T valve in the cold box. Passing through the transfer line and the heat exchanger inside the control dewar at the top of the magnet, the helium gas is sub-cooled to 4.52 K at a pressure of 0.285 MPa. At this point, the helium condition is supercritical. After the J-T valve inside the control dewar, the helium is in the two-phase state at 4.46 K and 0.125 MPa and flows into the magnet through the chimney port. In the steady state, the magnet is indirectly cooled by forced, two-phase flow at a mass flow rate of 10 g/s. After cooling the magnet, two-phase helium returns to the control dewar. The boil-off helium gas from the control dewar flows into the cold box via transfer line. The returning cold gas comes back to the compressor, cooling the input helium line. Part of the helium returning from the magnet is used to cool the current leads. The returning route of the helium can take one of two possible paths. One path is the usual route, to compressor suction, and the other is to the atmosphere.

OPERATION MODES

There are eight operation modes designed for BESIII cryogenic system, which are gas charging mode, cooldown mode, normal operation mode, quench mode, quench recover mode, refrigerator failure mode, warmup mode and shut down mode.

In the case of a quench, the magnet is separated automatically from the control dewar and the boil-off helium gas from the magnet flows to the buffer tank directly through the quench lines.

In the case of the refrigerator suspension, the thermo-syphon valve will be opened to make the Lhe in the reservoir circulate through the coil pipe gravitationally. This thermo-syphon cooling mode may be possible for the coil to be kept at a sufficiently low temperature until the discharge is completed.

In the case of cooldown, warmup and quench recovery, if the temperature of the return helium gas is higher than 20 K, the return gas will flow back through the bypass line instead of the main return line to meet the demand of the cold box.

HEAT LOAD

The upper thermodynamic parameters are decided on the basis of the estimation on the heat load shown in Table 2. What should be mentioned here is the dynamic heat load listed in this table. Except the steady head load, during the excitation or discharge, the heat caused by the electromagnetic induction in support cylinder should also be taken into accounted. If we set the discharge ramping rate dI/dt is 3300 / 1800 = 1.833 A/s, we can obtain the dynamic heat load $Q_{dy} = E^2 / R = 3.39$ W, where E is the induced voltage and R is the electricity resistance of the support cylinder.

Table 2 Heat load estimation

Items of Heat Load	**77 K**	**4.5 K**
Support rods in cryostat	26.527 W	1.038 W
Radiation in cryostat	73.801 W	3.236 W
Current leads	——	7.920 W + 0.421 g/s
Radiation in chimney & control dewar	10.025 W	0.407 W
Support rods in chimney & control dewar	3.900 W	0.022 W
Byonet and valves in control dewar	46.000 W	13.000 W
Measuring wires	5.311 W	0.831 W
Dynamic heat load	——	3.390 W
Total	165.5 W	29.85 W + 0.421g/s
Heat load used（× safety factor of 1.5）	**248 W**	**44.8 W + 0.63 g/s**

HELIUM AND NITROGEN PIPES

According to the estimation on heat load and using the safety factor 1.5， the mass flow rates of nitrogen and helium have been determined, which is 1.89 g/s (that is 8.42 L/h) for nitrogen and 10g/s for helium whose inlet pressure is 0.285MPa and temperature is lower than 5.5K.

Based on the mass flow, the inner diameters of nitrogen and helium pipes have also been decided, which are 14 mm for nitrogen and 16mm for helium. Considering the quench mode, the inner diameter of helium pipe in the coil cryostat has been increased to 25 mm. Under this design, the maximal pressure drop in nitrogen pipe is expected to 0.113 MPa and the pressure drop will be 3000 Pa during the normal operation. Concerning the helium pipe, the maximal pressure drop is 0.216 MPa, the normal pressure drop is 2500 Pa, and the quench pressure drop is 4100 Pa.

CONTROL DEWAR AND CHIMNEY

The following principle is used to determine the volume of the control dewar: the system should operate still normally for four times the discharge time (the discharge time of 0.5 hour is assumed) in the case of the refrigerator suspension. The volume of the dewar we decided to use is 200 L, whose main dimension parameters are: diameter and height of the reservoir: $\phi_o 722 \times 794$ mm, thickness of the reservoir: 9 mm, diameter and height of the vaccum vessel: $\phi_o 1500 \times 2100$ mm, thickness of the vaccum vessel cylinder: 8 mm, thickness of the end plates: 40 mm. The superconducting bus lines from the coil enter the reservoir through insulated feedthroughs and are connected with helium-gas-cooled Cu current leads.

With respect to the heat exchanger inside the reservoir, where the super-critical helium flow is cooled inside the pipe and the saturated liquid helium boils outside the pipe. Through the thermodynamic analysis, the general heat resistance R = 0.0301 m•K/W was obtained. Hence the calculated length of the pipe *L* is 8.14 m.

The chimney containing all the cryogenic and electrical lines from the coil crosses the barrel yoke, where the superconducting current leads are indirectly cooled through thermal conduction from the helium return line.

CRYOSTAT

The BESIII superconducting solenoid consists of the coils in a cryostat. The outer high-strength aluminum hoop restrains the conductor and the coolant is supplied through the aluminum tubes axially attached to the outer surface of this support cylinder. Two coaxial aluminum cylinders, with close end plates cooled by LN_2, act as the radiation heat shield.

Having set up a simplified thermodynamic model of the cooling tube and support cylinder, through the thermal analysis, we found if the heat load of 45 W is distributed evenly on the support cylinder and the number of the axial turns of the helium cooling pipe is 24, the maximal temperature difference on the outer surface is about 0.002 K. Considering the unevenly distributed head load can not be avoided, the safety factor 10 has been introduced. In this case, the maximal temperature difference will be 0.02 K, which is still safe enough. Therefore, we finally adopt the following helium cooling pipe: the diameter is ϕ31/25 mm, the length of per turn is 3.5 m, the number of turns is 24.

CONCLUSIONS

The design of the cryogenic system of the superconducting solenoid magnet of BESIII has been done. In this design, the heat load of the whole system has been estimated, the cooling flow scheme and the operation modes determined, and the structural design of the pipes, control dewar and cryostat accomplished