Conceptual design of a 2kW cryogenic system for the neutrino superconducting beam line magnet system in the J-PARC 50GeV proton accelerator.

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An intense neutrino beam generated by the J-PARC 50 GeV proton accelerator is planned as a second generation long-baseline neutrino-oscillation experiment to study neutrino oscillation. A superconducting magnet system is required for the arc section of the beam line to bend the beam within the available space. One string of 14 cryostats containing two magnets is cooled by supercritical helium (SHE) flow re-cooled by two-phase helium (2PHe) counter flow. The string with a length of 150 m is set in the neutrino beam line tunnel 12m bellow the ground. Cooling flow is supplied by a helium cryogenic system with a capacity of 2 kW at 4.5K. The conceptual design of the cryogenic system is described.

INTRODUCTION

A second generation long-baseline neutrino-oscillation experiment has been proposed as one of the main research projects by using the J-PARC 50 GeV proton accelerator that is a JAERI-KEK joint facility constructed in the Tokai-campus by 2007 [1], [2]. The neutrino-oscillation experiment needs artificial neutrino beam being injected into the Super-Kamiokande detector located 295km west of J-PARC. To produce such neutrino beam, the primary proton beam is transported from the main synchrotron to an aluminum target (see Figure 1). This beam line has a bending section with a radius of 105 m, where a superconducting magnet system with a dipole field of 2.6 T and quadrapole filed of 19T/m is required.

A helium refrigerator is constructed to keep these magnets in the superconducting stage. Not only thermal load estimation but also cooling characteristics depending on flow condition should be considered to make specifications of the refrigerator. This paper describes a conceptual consideration about the magnet cooling scheme and the refrigerator system.

THERMAL LOAD AT MAGNETS AND TRANSFER LINES

Superconducting combined function magnets & cryostats.

The magnets system consists of 14 pairs of single layer left/right asymmetric coils with same dipole function in combination with focus/defocus quadrapole function [3, 4]. The main parameters of the magnet are summarized in Table 1.

Each pair of coils is set in one cryostat with a unit length of 10.5m including an inter-connections (see Figure 2), and 14 cryostats are strung along the 150 m arc region (see Figure 1). The cryostat design is based on the LHC arc dipole magnets, so that some parts, support posts and shield trays etc., are purchased from common mass products to reduce the cost. The radiation trays are set onto the suitable anchor point of the posts and are kept at 50-80 K by cold He gas flow. The estimated heat leakage into the cold mass are listed in Table 2. Several beam monitors and collector coils will be inserted into some suitable interconnections, where the additional

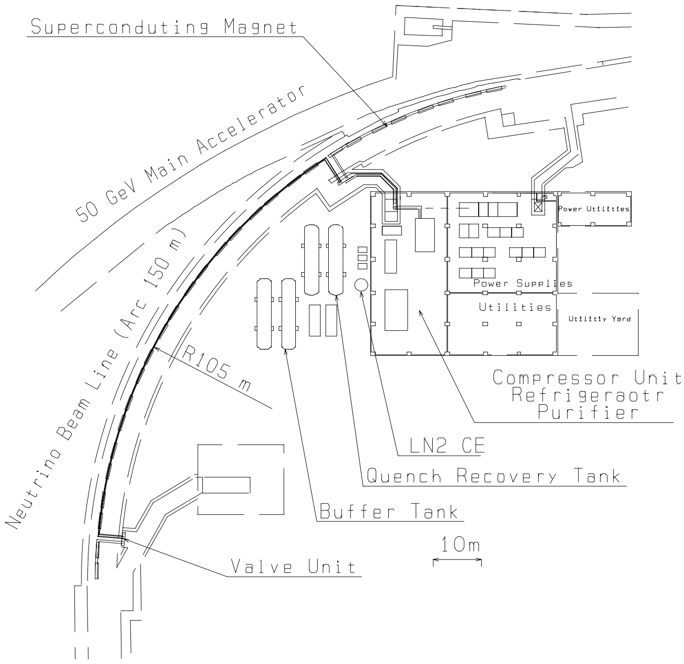

Figure 1 Arc section of the neutrino beam line and layout of the magnets and cryogenic components.

Table 1 Main design parameters of the superconducting combined function magnet

Physical length	3609 mm	Cold vessel diameter	570 mm
Magnetic length	3300 mm	Cold vessel length	4150 mm ×2
Coil inner & outer diameter	173.4 & 204.0 mm	Vacuum vessel diameter	914.4 mm
Yoke inner & outer diameter	244 & 550 mm	Vacuum vessel length	8438 mm
Shell (Vessel) outer diameter	570 mm	Interconnect length	2062 mm
Weight	6.2 ton	Fluid capacity (in cold vessel)	70 ℓ
Operating current	7345 A		
Dipole field	2.59 T	Cooling type	SHE forced flow w/ 2PHE recooler
Quadrupole filed	18.7 T/m		
Stored energy	285 kJ		
Inductance	12.9 mH		

Table 2 Thermal load at the magnet cryostat

		300 K to 50-80 K (radiation shield)	50-80 K(radiation shield) to 4.5 K
Cryostat	Radiation	24.8 W	0.26 W
	Conduction	28.1 W	3.0 W
	Sub total	52.9 W	3.26 W
Interconnect	Radiation	20.0 W	0.024 W
	Conduction		0.80 W
	Sub total	20.0 W	0.824 W
Beam loss			150 W (1.0 W/m (maximum))
Total (14 cryo.+ 13 Inter. + beam loss)		1001 W	206 W
In future design, heat leakage through beam monitors and collector magnets (3-5 W/equipment) will be added.			

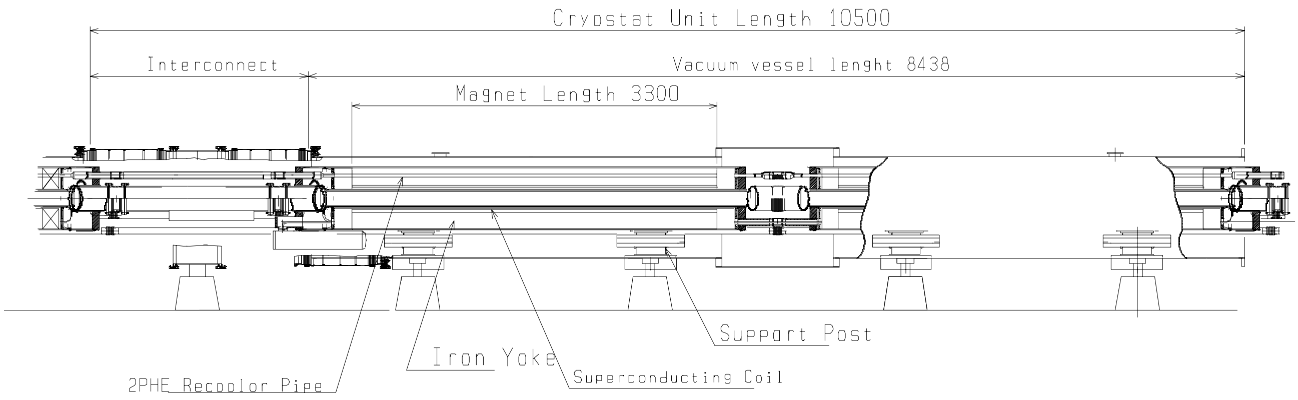

Figure 2 Magnet cryostat

heat-leakage of 3-5 W/component is estimated.

Dynamic heat dissipation due to the high intensity beam is predicted as beam halos of 1W/m in maximum along the beam line continuously during the accelerator running.

The total heat load at the magnet string is estimated up to about 206 W at this moment, and predicted additional loads due to beam monitors, collector magnets and beam pipes would not exceed 100 W in total.

Magnet cooling circuit

A superconductive critical temperature of the coil at the operational current of 7345 A is 6.4 K, consequently the cryogenic system must keep the coils below 5.0 K with stability margin. The cold mass is cooled by supercritical helium (SHE) flow directly. Saturated helium gas flow (2 phase helium, 2PHE) is not chosen as coil coolant because of its low dielectric strength and low heat transfer in the vapor stagnation. But utilizing the latent heat in 2PHE is essential to improve thermodynamic efficiency of the cryogenic system. Otherwise several times larger flow rate is required in case of single SHE flow. Figure 3 shows the conceptual flow diagram. Supplied SHE flow enters one end of the string, goes through the magnets in sequence, and then reaches a valve unit at the opposite end of the string. SHE expands into 2PHE at the JT valve there. 2PHE counter flow re-cools SHE in the cryostat, finally returns to the refrigerator. ϕ 34 mm copper tube for 2PHE flow is inserted in a ϕ 50 mm bore through iron yoke and a part of SHE flow can be re-cooled with 2PHE (see Figure 2, 3). If whole SHE flow is heat-exchanged with 2PHE, lower SHE temperature is realized. But the string doesn't have a space for installation of usual heat exchangers.

Transfer line

Main components of the cryogenic system, a compressor, a cold box and buffer tanks etc., are located on the surface area. 40 m sub-tunnel is constructed to make a way from this surface site to the main beam line at -12 m under the ground. The 4.5K cold helium (SHE supply, 2PHe return) and 50-80K shield cooling gas are transferred through pipes arranged within a common vacuum jacket laid in the sub-tunnel (see Figure 1). Between a main-sub tunnel junction and one end of the magnet string, SHE supply, 2PHE return and shield supply pipes in the common jacket are lined along the magnets. Between opposite string end and the JT valve box another multi-pipe transfer line is trained. One bypass line for pre-cooling magnets and one shield return line are laid along the magnets between the valve unit and the main-sub junction individually. The average heat leaks are specified as follows [5]:

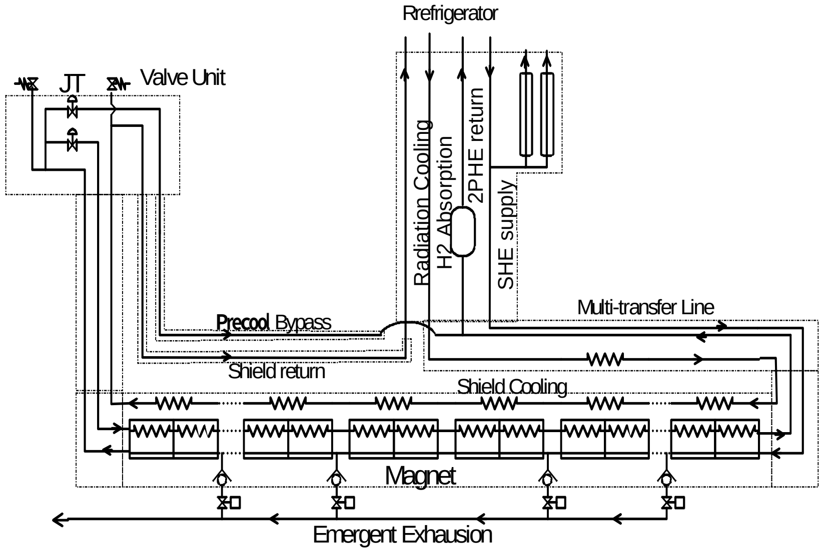

Figure 3 Conceptual flow diagram of the cryogenic system

4.5 K supply and return surround by 80K radiation shield	<0.5 W/m (0.1W/m possible)
50 K supply – 80 K return	<1.3 W/m
Bypass without radiation shield	<1.0 W/m

By using these parameters, heat loads at transfer lines are estimated as shown in Table 3.

Total thermal load

Other thermal loads in the valve unit of 9W, current leads of 1g/sec/pair have to be taken into account. The total thermal loads are 410 W on the cold mass and 1339 W on the shield (see Table 4).

Table 3 Thermal load at the transfer lines

Location	Transfer	Length	Fluid	Load
Sub tunnel	Main-sub tunnel junction ↔ Cold box	40 m	SHE supply & 2PHE return	40 W
			Shield gas supply & return	104 W
Main tunnel (1)	Upper end of the string ↔ Main-sub junction	50 m	SHE supply & 2PHE return	50W
			Shield gas supply	65 W
Main tunnel (2)	Down end of the string ↔ Main-sub junction	100 m	Pre-cool bypass	50 W
			Shield return	130 W
Main tunnel (3)	Down end of the string ↔Valve unit	15 m	SHE supply & 2PHE return	15 W
			Shield gas supply	39 W
Total thermal load			Cold mass (4.5K)	105 W
(Pre-cool bypass is not taken into account)			Shield	338 W

MAGNET COOLING CONDITON

It is important for the refrigerate specification to estimate magnet cooling characteristics depending on cold helium flow behavior. Obviously the larger heat transfer into 2PHE from SHE flow removing thermal loads results in the lower SHE and coil temperature. But, according to the present cryostat design, a part of SHE beside the 2PHE copper pipe is re-cooled. So, the rest SHE, that is, the coil rise up to higher temperature expected by whole SHE/PHE flow. The cooling characteristics depending on SHE/2PHE flowing pattern is analyzed to find a proper flow condition. The analysis boundaries are as follows:

Table 4 Summary of thermal load

	Cold mass	Shield
Magnet	206 W	1001 W
Transfer line	105 W	338 W
Current leads	90 W (1g/s)	
Valve unit	9 W	
Total	410 W	1339 W

- Supplied SHE pressure and temperature are fixed at 400 kPa and 4.5 K respectively.
- The maximum coil temperature must be lower than 5.0K for superconductive margin.
- The return 2PHE pressure must be larger than 120 kPa for return to the compressor.

Some features of the calculating method are as follows:
- The heat transfer coefficient at 2PHE is calculated by Klimenko's functions.
- The 2PHE pressure drop is calculated on homogeneous model.

Figure 4 shows that the coil temperature cooled by 100 g/sec flow rises up to 4.8 K under the predicted thermal load of 15 W/cryostat (heat leak of 3.26W + beam halo 150 W/14 cryostats). The expansion pressure at the JT valve needs 140 kPa for return pressure of 120 kPa. Optimum flow ratio χ of 0.5 is also found by this analysis.

SPECIFICATION OF CRYOGENIC SYSTEM

The parameters of the cryogenics system are specified by referring the thermal analysis described in the former section. As primary performance, this cryogenic system has to supply 100g/sec, 4.5K, 400kPa SHE to the magnet string, which means about 2.0 kW at 4.5 K. For radiation shield cooling of 1500 W, the cryogenic system also supply 100 g/s, 50 K helium gas to the magnet string. Corresponding to the refrigeration power, a compressor should have capacities of 600 – 700 kW, 1800 kPa and 200 g/sec.

Two considerable phenomena induced by irradiation are predicted in the magnet cryostats. One is that hydrogen is emitted from the organic material, for example, insulation sheets and plastic spacers. According to recent experimental study about molecular emission from irradiated polymers, hydrogen is major component and may be stored up to 0.2 g during a half year beam run. This value is low enough to be adsorbed in the system.

The other phenomenon is that helium is transformed into tritium because of nuclear transmutation. The transmutation into tritium has an average of 54 Bq/cc in helium volume at 1 W/m beam loss. And tritium also is stocked up to 95 μg in the string after half year beam run. Though the tritium quantity is negligible from view point of refrigerator operation, the value of 54 Bq/cc is beyond a HTO criterion of < 5mBq/cc in the tritium control regulation. This means that the whole cryogenic system must be inside of a restrained radioactive area once tritium diffuses into the cold box or the compressor. In the revised design work, the tritium treatment must be solved.

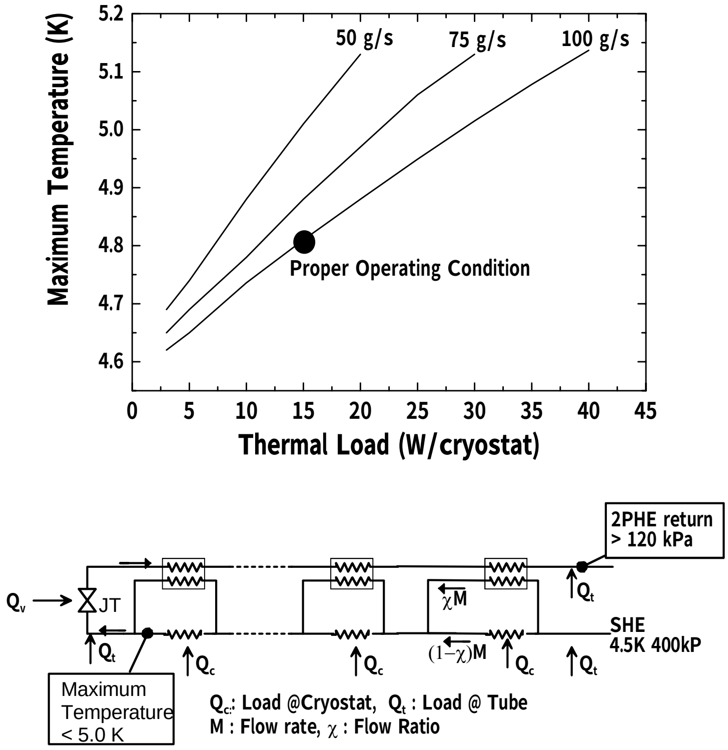

Figure 4 Cooling characteristic depending on flow condition.

SUMMARY

A 2 kW helium cryogenic system at 4.5 K is to be built to cool the superconducting magnet system for the neutrino beam experiment in J-PARC. 100 g/s SHE/2PHE circulation is required to keep the magnets below 5.0 K.

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