DEVELOPMENT OF CURRENT LEADS FOR THE SUPERCONDUCTING CORRECTORS IN THE SUPER-KEKB INTERACTION REGION

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Abstract

To supply the electrical power for the superconducting (SC) correctors in the interaction region (IR) of the proposed Super-KEKB, an assembly of vapour cooled current leads (VCCL) is designed, which consists of 8 brass leads and can transport currents to 4 correctors simultaneously. The design current of the leads is about 50 A. The thermal and electrical behaviours have been studied by the finite elements method (FEM) and the cryogenic experiment is carried out to validate the performance. In this paper the design will be presented and the experimental results will be compared with the FEM simulation.

INTRODUCTION

The KEKB has achieved the world record luminosity of 2.1×10^{34} cm^{-2}s^{-1} with the crab cavities. The upgrade project to the KEKB, Super-KEKB, has been proposed with Nano-beam scheme and the target luminosity is 80×10^{34} cm^{-2}s^{-1} with beam energies of 4 and 7 GeV [1]. The design of the magnets in the IR is one of the technological hardships to be overcome and the configuration of the IR magnets system includes 5 SC main quadrupoles, 3 permanent quadrupoles, 2 SC compensation solenoids and 35 SC correction coils [2]. This R&D is dedicated to designing a compact current lead assembly for the SC correctors.

The current lead has to span the temperature interval between room and liquid helium temperature to energize the SC magnets and inevitably induces some extraneous heat leaking to the magnet cryostat which largely determines the running cost and the refrigeration capacity of cryogenic system. The conduction-cooled current lead even with optimized structure conducts 47 W/kA of heat leak to the helium bath. The heat leak could be reduced to 1.1 W/kA by the VCCL which can fully use the enthalpy change of the vaporized helium as it warms up. High temperature superconducting (HTS) current lead can reduce the heat load to the 0.1 W/kA level but the disadvantage is the complex structure and strict operation requirements on the cryogenic system. The VCCL is widely adopted for the SC magnets with the acceptable heat load for the refrigeration system.

The powering of the Super-KEKB IR SC correction magnets will be made via 35 electrical circuits for a current of about 50 A. A total number of 70 leads will transport the current. A compact assembly of VCCL was designed and simulated by FEM. The leads have been fabricated and assembled for cryogenic test. This paper presents their features and the preliminary measurement results.

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MATERIAL FOR THE CURRENT LEADS

The heat leak of the current lead comes from the thermal conduction down the lead from room temperature and ohmic Joule heating generated within the lead. As most metals and alloys obey the Wiedemann-Franz Law fairly well, which shows that heat conductivity and electrical resistivity are inversely related, the coexistence of their minimization is impossible. It results in the independence of the minimum heat leak associated with the transmission of a given current on the lead materials. But the use of the high-purity material makes the leads unstable and liable to burn-out at currents only slightly above the optimum current and also increases the heat leak of the standby mode.

Leads made from impure copper are much less sensitive to excess current and are preferable for most applications. Phosphorus deoxidized copper is adopted in some projects but some special care should be taken during the manufacturing process, such as annealing and hydrogen furnace welding [4]. Brass is a good compromise between poor thermal and good electrical conduction [5] with the stable chemical and mechanical properties. In this research brass (Cu90Zn10) was chosen. After the leads were fabricated the brass electrical resistivity was evaluated by measuring the lead resistance at room, liquid nitrogen and liquid helium temperature. Its thermal conductivity was calculated by the Wiedemann-Franz Law. The FEM simulation was upgraded with these measured properties.

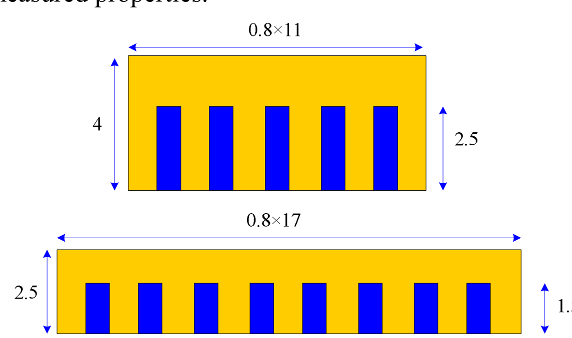

Figure 1: Two structures (Up: A and Bottom: B) of current lead for the Super-KEKB IR SC correction magnets.

STRUCTURES OF THE CURRENT LEADS

Two structures for the Super-KEKB SC correctors were designed as shown in Figure 1 referred to the present KEKB SC corrector lead structure. The brass fins of the structures between the gaseous helium channels can greatly enhance their heat transfer. Table 1 lists the design parameters of the two structures with the present KEKB

Table 1: Design parameters of the VCCL for the Super-KEKB IR correction magnets.

Item	Structure A	Structure B	Present KEKB lead
Operation current (A)	50	50	100
Cross-section area of helium (mm^2)	10	9.6	15
Cross-section area of brass (mm^2)	25.2	24.4	40
Ratio of the areas of helium to brass	0.397	0.393	0.375
Heat exchanging length (mm)	690	690	690
Heat exchanging area (m^2)	0.02	0.021	0.02415

current lead as a reference. The two have the very similar structure parameters so that pressure drop, voltage drop, and temperature profile along the lead length and heat leak to the cold end simulated by FEM are almost the same, which will benefit the thermal and fluid balance distribution.

By increasing the mass flow rate of the cooling helium, the temperature gradient near the cold end along the lead turns smaller. Correspondingly the heat leak to the cold end is reduced. However the cryogenic cold box has to consume some additional refrigeration or liquefaction capacity to circulate the gaseous helium. In a closed-circuit system the running cost of the leads should be evaluated in terms of the total refrigeration capacity consumption and there is an optimized helium flow rate for a given current. For the lead with a small current the optimized flow rate is too small to control effectively and the hardware and software for the individual controlling will increase the cost of both the construction and operation.

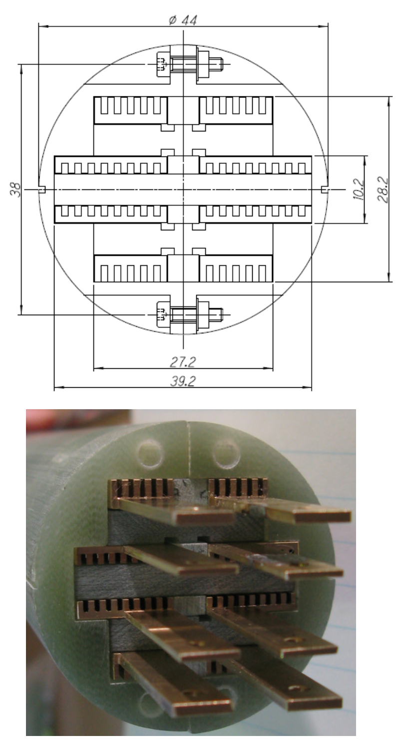

Figure 2: Cross section picture and drawing with dimensions of the compact 8-lead assembly.

To reduce the complexity and cost of the cryogenic system a compact assembly is proposed in which 8 individual leads of 50 A (two different structures) are integrated on a common insulating flange. Figure 2 shows the G10 support to accommodate the 8 leads and its cross section. Each lead was covered with two layers of Kapton film for the electrical insulation. Between two leads copper blocks are placed for the thermal interception to compensate the possible unbalanced distribution of the helium flow for each lead and G10 blocks for the electrical insulation. The heat transfer effect of the intermediate copper blocks has been verified by the FEM model of two leads with Ansys simulation [6]. The combination of the leads is encompassed between two slices of G10 and the assembly is inserted into a tube with vacuum layer to eliminate the external influence on the lead temperature distribution.

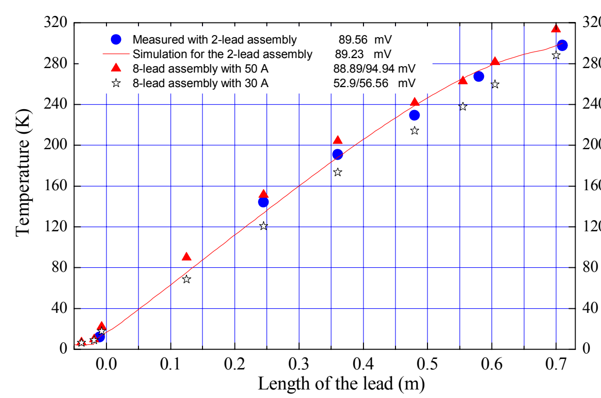

Figure 3: Temperature profile of the lead with the different currents and helium flow rates measured and simulated.

TESTING ON THE 2-LEAD ASSEMBLY

As the first step an assembly of two individual leads of the structure A in Figure 1 was assembled for the cryogenic test. Just like the 8-lead assembly design the two leads were spaced out by G10 and copper blocks and linked by LTS cable at the cold end. The total helium vapour flow rate through the two leads was controlled by a manual value and measured by thermal and volumetric flow meters. Some thermocouple temperature sensors were placed along the lead length and on the top of the leads to test the temperatures. The cold end temperature was measured by the carbon resistance sensors and the voltage drops was also measured by the instrumentation wires soldered at the top and bottom of each lead.

In the Figure 3 the circles shows the measured temperatures along the leads with 50 A current and 2.0 standard litres per minute (SLPM) helium flow (about 2.29 mg/s for each lead). As the lead cold end was about 60 mm above the liquid helium (LHe) level the temperature was higher.

In order to estimate the heat leak to the cold end the lead with 50 A current and 2.29 mg/s helium was simulated by the FEM model with Ansys software. The mutual influence of the temperature distribution and material properties was considered in the way of the iterative processes. The boundary conditions were the 300 K temperature of the brass at the warm end as measured and the 4.5 K inlet temperature of the helium at the cold end. The temperature profile and voltage drops are shown by the solid line in Figure 3 and are matched with the measured points. In the simulation the heat leak of each 50 A lead was calculated and is about 0.08 W.

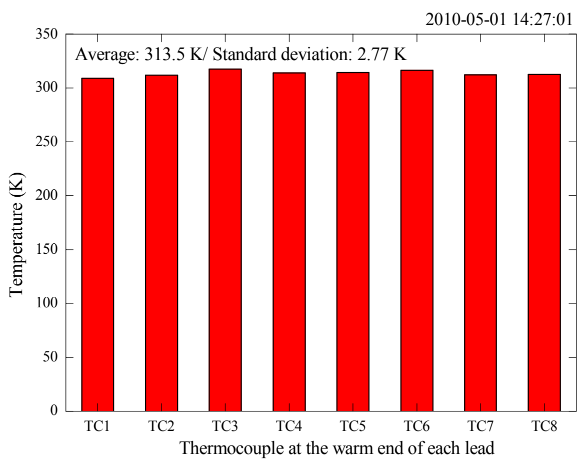

Figure 4: Temperature of the lead warm ends.

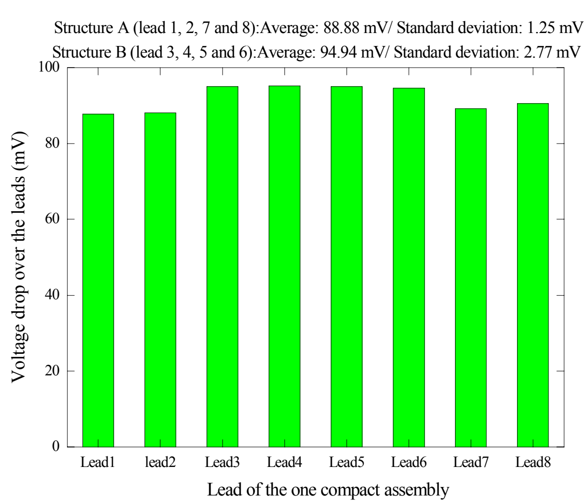

Figure 5: Voltage drops of each lead.

TESTING ON THE 8-LEAD ASSEMBLY

The assembly of 8 individual leads with two structures was assembled mainly to check the thermal and electrical uniform of the 8 leads. Two modes were measured: 50 A +7 SLPM (2.42 mg/s for each lead) and 30 A + 6 SLPM (2.079 mg/s for each lead). The temperature profiles were indicated in Figure 3 with triangles and pentagrams respectively. Unfortunately the connection cable at the warm end was too thin so that it heated the lead and the temperatures were higher than those of the 2-lead assembly.

The distribution histograms of the temperatures at the warm end and voltage drops of each lead are shown in Figure 4 and Figure 5. At the warm end the average temperature is 313.5 K and the standard deviation is 2.77 K. As there are two structures with some slight difference such as the cross-section area of the brass and the lead extension parts, the voltage drops of the two structures have a distinction of about 7 mV. However for each structure the standard deviation is less than 3 mV.

The heat leak was estimated by two Cernox temperature sensors with a certain distance at the cold end of a lead of the 8-lead assembly. For 50 A current and 2.42 mg/s helium vapour mode each lead has a heat leak of about 0.106 W, which is higher than the 2-lead assembly simulation, because the cold end of the 8-lead assembly was 120 mm above the LHe level and the temperature was higher.

CONCLUSION

For the Super-KEKB IR SC correction magnets we proposed a compact assembly of vapour cooled current lead of 50 A. The structures have been studied with FEM simulation and the fabrication has been completed. The material properties were evaluated by the measurement of the lead resistance. The cryogenic test has been carried out. The temperature profiles and voltage drops were measured and compared with the Ansys simulation. The heat leak to the cold end was concluded. Some improvements and further experiments will be taken in the near future.

ACKNOWLEDGMENTS

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REFERENCES

[1] The 15th KEKB Accelerator Review Committee Report, kekb.jp, March 2010.
[2] N. Ohuchi et al., 15th KEKB Accelerator Review, http://www-kekb.kek.jp/MAC/2010/.
[3] A. Ballarino, Physics C, 468(2008): 2143-2148.
[4] Q. J. Xu et al., Cryogenics 49(2009): 21-26.
[5] Guy K. White et al., Experimental techniques in low temperature physics, 4th ed. Oxford: Clarendon Press; 2002. P: 192-193.
[6] Ansys, Inc. Theory Reference, 1998.