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Development of a compact HTS lead unit for the SC correction coils of the SuperKEKB final focusing magnet system

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ABSTRACT

Forty-three superconducting (SC) correction coils with maximum currents of about 60 A are installed in the SuperKEKB final focusing magnet system. Current leads to energize the SC correction coils should have an affordable heat load and fit the spatial constraints in the service cryostat where the current leads are installed. To address the requirements, design optimization of individual lead was performed with vapor cooled current lead made of a brass material, and a compact unit was designed to accommodate eight current leads together in order to be installed with one port in the service cryostat. The 2nd generation high temperature SC (HTS) tape was adopted and soldered at the cold end of the brass current lead to form a hybrid HTS lead structure. A prototype of the compact lead unit with HTS tape was constructed and tested with liquid helium (LHe) environment. This paper presents a cryogenic measurement system to simulate the real operation conditions in the service cryostat, and analysis of the experimental results. The measured results showed excellent agreement with the theoretical analysis and numerical simulation. In total, 11 sets of the compact HTS lead units were constructed for the 43 SC correction coils at KEK. One set from the mass production was tested in cryogenic conditions, and exhibited the same performance as the prototype. The compact HTS lead unit can feed currents to four SC correction coils simultaneously with the simple requirement of controlling and monitoring helium vapor flow, and has a heat load of about 0.762 L/h in terms of LHe consumption.

1. Introduction

The SuperKEKB, the upgraded project of the KEKB, is an asymmetric-energy, double ring collider of 7 GeV electrons and 4 GeV positrons and is currently under construction at KEK [1]. Its target luminosity is $8\times10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is 40 times higher than that of the KEKB. The accelerator design is based on the nano-beam scheme, and the final focusing magnet system at the interaction region (IR) is a key component in achieving the target [2]. The IR optics has been designed with the superconducting (SC) quadrupole doublets for each beam and the magnet system consists of eight main SC quadrupole magnets (QCS), four compensation SC solenoids (ES), and 43 SC correction coils (35 correction coils and eight cancel coils) [3,4]. The SC magnets are assembled into two cryostats, located at the left and right sides of the accelerator interaction point (IP), respectively. The two cryostats are cooled with sub-cooled liquid helium (LHe) at 0.16 MPa and 4.5 K by two independent refrigerators of about 250 W cooling capacity, which have served for the TRISTAN and KEKB projects at KEK [5–7].

Among the 43 SC correction coils, 20 coils are installed in the left cryostat and the remaining 23 coils are in the right cryostat [8]. Their operation currents are chosen in order to correct misalignment of the main quadrupoles, and the maximum currents are about 60 A. The SC correction coils are energized by power supplies at room temperature (~300 K). Eighty-six current leads (40 for the left side and 46 for the right) are needed to feed the total current of approximately 5 kA over the temperature interval from room temperature to LHe temperature environments. Metallic conductors of current leads also thermally link the environments and cause a considerable heat load on the LHe cryogenic system. The large total current of the SC correction coils requires an optimum design of current leads, and the large number needs a compact structure to save the occupied space in the service cryostat which serves as an interface between the SC magnet cryostat and cryogenic multi-channel transfer line.

The development of current leads for SC magnets has proceeded for many years, motivated by the wide range of applications of SC magnets in the science and engineering fields. The basic principles of the lead design optimization have been understood and are described in [9]. There are a few types of current leads, which are widely used, such as the conduction cooled current lead (CCCL), the vapor cooled current lead (VCCL), and the

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Table 1
Different types of current leads and the heat leaks of their optimum design.

Lead type	Item	Value	Unit
CCCL	Heat leak	47	W/kA
VCCL	Heat leak	1.04	W/kA
	Mass flow rate of helium vapor	50.27	$\times 10^{-6}$ kg/s-kA
		16.9	SLPM/kA
	LHe consumption	1.45	L/h-kA
HTS lead	Heat leak	<0.1	W/kA

high temperature SC (HTS) lead. By fully utilizing the cooling capacity of cryogens or eliminating resistance at the cold end of the current lead, the heat leaks sequentially decrease, as listed in Table 1 [10–12]. Heat leak is a key parameter when choosing a current lead type for SC magnets, and should be considered first. The heat load of the current lead is a combination of heat leak and consumption of cold helium vapor or gas, and is usually dominant in cryogenic systems for SC magnets. The decision to adopt the VCCL type for the SC correction coils was primarily based on the acceptable heat load and simple operation requirement of the cryogenic system.

The VCCL design optimization of a brass material was carried out with theoretical analysis and numerical simulation. To address the large number of current leads, eight current leads were integrated into one compact unit with one common flange to host eight electrical insulation feedthroughs and one cylinder to collect their helium vapor flows. The 2nd generation (2G) HTS tape was soldered at the cold end of the brass current lead with a simple soldering procedure. The adoption of HTS tape was expected to further reduce the heat load of the brass current lead and to raise the current-carrying capability, which had been demonstrated with numerical simulation and cryogenic experiments. In this paper, the development of the compact HTS lead unit for the SC correction coils is presented in detail.

2. Vapor cooled current lead with HTS tape for the SC correction coils

2.1. Optimum design of the brass vapor cooled current lead

The optimum VCCL has a minimum heat leak of 1.04 W/kA to its cold end in LHe and is cooled by the vaporized helium vapor flow of 50.27 mg/s-kA or 16.9 SLPM/kA (SLPM: standard liter per minute) over a temperature range of about 300 K. The minimum heat load is independent of chosen materials because of the Wiedemann–Franz Law. However, changes in materials can bring some variations of the geometrical parameters of metallic conductors and correspondingly influence heat transfer with helium vapor or gas. For mechanical strength and thermal stability, brass material was chosen for the VCCL of the SC correction coils. Brass is considered as a good compromise between poor thermal and good electrical conduction [13] and current leads made of brass may be operated stably in overcurrent modes [14].

For a given current and material, design optimization is mainly concerned with the geometrical parameters (area of cross-section and length) of metallic conductors, which are determined by the electrical and thermal properties of the material. The electrical resistivity (ρ) of the chosen brass material was obtained by measuring sample resistances at room, liquid nitrogen (LN_2), and LHe temperatures. As shown in Fig. 1(a), some values are interpolated between the measured points to obtain the whole curve from 4 K to 300 K by referring to the temperature-dependent tendency of the electrical resistivity of standard brass, which contains about 90% copper and 10% zinc in weight [15]. The thermal conductivity (k) was calculated with a constant Lorenz number of 2.45×10^{-8} W Ω/K^2 by the Wiedemann–Franz Law. In Fig. 1(b), thermal conductivity curves of two samples of copper with residual resistance ratios (RRR) of about 50 and 3, respectively [16], are also plotted for reference.

As the first step of the VCCL design described in [9], the optimum lead geometry is quantized by a shape factor and can be calculated according to the following formula

$$\frac{I_D\times L_o}{A_o}=\int_{z_1}^{z_{2o}} k(\theta)dz \tag{1}$$

where I_D is the design current, L is the effective length for heat transfer between the metallic conductor and helium vapor, A is the area of the conductor cross-section, θ is the temperature of the element length dx at the position x, and the subscript 'o' denotes an optimum quality. The variable z is used as a substitution to eliminate the nonlinear item in the differential equation of thermal equilibrium and is expressed as follows:

$$dz=\frac{Idx}{k(\theta)A} \tag{2}$$

where x is the physical distance from the cold end of the lead. With the thermal boundary conditions of the warm and cold ends of the current lead and by minimizing heat leak to the cold end, the solution of the differential equation results in a temperature profile of the optimum lead, as shown in Fig. 2. The temperature variation with the parameter z applies to all the optimum leads regardless of current and material, so the variation curves of the three materials coincide very well in Fig. 2.

The key point in calculating the optimum shape factor of a given material is that the corresponding relevance between $k(\theta)$ and z is established by the intermediate variable of temperature. Variations of thermal conductivity of the three materials with the parameter z are plotted in Fig. 3. The integration of the right term in Eq. (1) can be obtained by a numerical method and is the area between its own curve and the horizontal axis. Table 2 lists the calculated optimum shape factors for the three materials and their areas of conductor cross-section for a current of 50 A and a length of 690 mm. Material changes can bring variations in the optimum shape factors and correspondingly in the geometrical structures. Because of its lower thermal conductivity, the shape factor of the brass material is much less than that of phosphorus deoxidized copper (RRR$\sim$3), which is widely adopted for VCCL applications. Small cross sectional areas of copper materials cause difficulties in maintaining mechanical stability and also limit helium vapor channel dimensions for heat transfer.

With the optimum shape factor of 1.42×10^6 A/m for the brass material, the individual VCCL structure was designed. The cross sectional area of the brass conductor is 25.2 mm^2 and the effective length for heat transfer is 690 mm, as shown in Fig. 4(a) and (b). Its optimum current is 51.8 A and is very close to 50 A. More details about the lead structure can be found in [17] and [18]. The lead structure design has been studied numerically with the ANSYS/FLOTRAN™ module and details about the simulation method can be found in [19].

Fig. 5 presents the temperature profiles along the effective length of the lead with the optimum operation conditions of 51.8 A current and 2.5 mg/s helium vapor flow, and the theoretical analysis curve agrees with the result of numerical simulation very well. The curves have zero gradients at the top of the lead and their voltage drops are about 80 mV, which are in accordance with the criteria of the optimum VCCL design.