Design Study of a Superconducting Quadrupole Magnet System Sustainable Under Dark Current Heating in ILC Main Linac

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***Abstract*—The International Linear Collider (ILC) main linac comprises a series of 12 m-long cryomodules. The cryomodule contains eight 9-cell superconducting (SC) RF (SRF) cavities and an SC quadrupole magnet combined with dipole correctors to focus and steer electron and positron beams. The magnets are installed between the SRF cavity string and at the longitudinal center of a common cryomodule/cryostat. These magnets are conductively cooled by pure aluminum channels thermally connected to a 2 K two-phase helium pipe for cooling the SRF cavities. A recent study shows that field-emitted electrons, so-called "dark current" initiated in the SRF cavities, are transmitted through the SRF cavity string and reach the SC magnet. The energy is inevitably absorbed in the SC coil due to the magnetic field, resulting in risks of a quench caused by the coil heating. We are investigating alternate magnet designs by using Nb_3Sn or MgB_2 SC and by adding the dark current absorber surrounding the beam-pipe to realize sustainable magnet operation under the dark current heating. We report the design study of the magnet system and interfaces to the cryomodule accommodating it with the SRF cavities.**

***Index Terms*—Conduction cooling, superconducting, accelerator magnet.**

I. Introduction

THE international linear collider (ILC) is a proposed next generation e^+/e^- linear collider.

One of the critical components of ILC is two main linacs which accelerate the electron and the positron to final beam energy. The main linacs accelerate the electrons and positrons to 125 GeV (ILC250) in the first stage and 250 GeV in the second stage (ILC500). Each main linac consists of approximately 8,000 L-band (1.3 GHz) nine-cell niobium superconducting (SC) cavities. They are integrated into a 12 m-long cryomodule (CM). The ILC will have two types of modules, one integrating nine cavities (Type-A) and one integrating eight cavities, with an SC quadrupole (SCQ) package (Type-B). Fig. 1 shows the SCQ package assembled in the CM type-B. The length of both modules is 12.652 m [1]. The SCQ package is a superferric quadrupole magnet combined with two dipole correctors. The spacing of each SCQ package is 37.96 m, and the quadrupole magnets form a FODO lattice. Two dipole correctors steer beams to the correct orbit. The vertical corrector also bends the beam to follow the Earth's curvature. The SCQ package is accompanied by the beam position monitor (BPM).

The SCQ packages consist of two types of magnets depending on the beam energy at the position of the magnets. Table I shows the main parameters of these SCQ packages. The L.E. type will locate at beam energies below 25 GeV, while the H.E. type will be at higher points. The L.E. type will have a smaller GL than

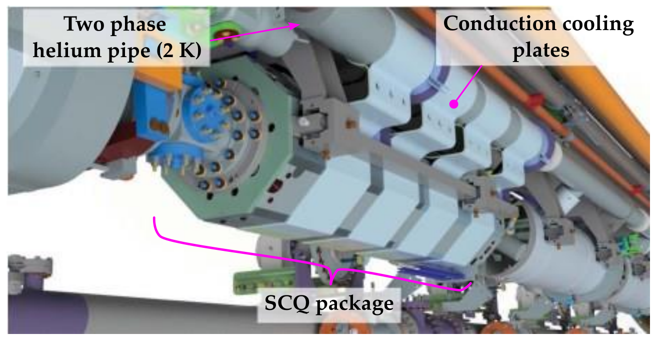

Fig. 1. The SCQ package in the CM type-B.

TABLE I
Specifications of the SCQ Magnet Packages

Parameters	L.E. type	H.E. type
Beam energy	$\leq$ 25 GeV	$\geq$ 25 GeV
Physical length	0.25 m	1 m
Magnetic length	0.20 m	0.95 m
Radius of inner pole	0.045 m	
Field gradient (G)	19 T/m	40 T/m
G integral	3.8 T	38 T
B_0	0.05 T	0.11 T
B_0 integral	0.01 T m	0.10 T m
Max. field in quad. coil	~1.5 T	~3 T
Operation temperature	2 K	

Manuscript received 13 November 2022; revised 30 January 2023 and 11 February 2023; accepted 19 February 2023. Date of publication 6 March 2023; date of current version 16 March 2023. This work is supported by Innovation Center for Applied Superconducting Accelerators (iCASA) at KEK. *(Corresponding author: Y. Arimoto.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2023.3252484.

Digital Object Identifier 10.1109/TASC.2023.3252484

TABLE II
PARAMETERS OF SC WIRES

	Unit	NbTi	Nb_3Sn	MgB_2
Bare wire diameter	mm	0.50	0.65	0.55
Insulated diameter	mm	0.55	0.8	0.7
Filament diameter	μm	3–10	2–3	<~150
Cu to SC ratio		2	1	0.8
$T_c{}^*$	K	9	18	39
$T_c{}^\dagger$	K	7	13	15

$T_c{}^*$: Critical temperature at $B = 0$ T, and $I = 0$ A
$T_c{}^\dagger$: Critical temperature at $B = 3$ T, and $I = 100$ A

H.E. one; the length of the L.E. type of magnet is shorter than the H.E. one. In Table I B_0 is the strength of the dipole field generated by dipole corrector magnets. G and B_0 integral are values which are integrated G and B_0 along axial direction of magnet, respectively.

A full-scale model magnet has been designed and developed at Fermilab in cooperation with KEK [2], [3], and cold tests with a liquid helium bath and with a pulse-tube cryocooler in conduction cooling configuration were performed [2], [4], [5]. A shorter model magnet has been installed into a CM at Superconducting Test Facility (STF) of KEK, moreover, cold tests have been carried out. The magnet was conductively cooled from the liquid helium line for the SC cavity at 2 K via pure aluminum plates. They succeeded in energizing the magnet with 25.6 A. Although the SC coils showed a higher temperature than expected, the cause of the problem is understood and it is shown that improvement is possible [6].

The SC coils, which have been used for the SCQ magnets developed so far, are made of NbTi cable. However, an issue with a risk of quench for the NbTi coil arose. The problem is the dark current heating on the coils. A local high electric field at the surface of the SRF cavity will emit the electrons as a dark current, and the cavity will accelerate the dark current with the main beam. Since the dark current will have lower energy than the main beam, a quadrupole field of the SCQ will bend it and the dark current deposits a certain amount of energy on the superconducting coils. It is about 5 W, including a safety factor of 3. This dark current heating will increase the temperature of the coils by 5 K within 1 sec. The temperature rise will reach the critical temperature of NbTi at three Tesla (Table II). This issue will be overcome by using the coils made of Nb_2Sn or MgB_2 which have a higher critical temperature than NbTi. We started studying the possibility of applying these SC cables for the SCQ package. The points of this study are the production cost, the efficiency of conduction cooling, magnetic field quality (magnetic hysteresis), the operation margin, and unknown technical problems.

II. THE DESIGN STUDY OF THE SUPERCONDUCTING COIL FOR THE SCQ MAGNET

We will make three types of test coils which made of NbTi (Furukawa Electric Co.), Nb_2Sn (Furukawa Electric Co.), and MgB_2 (Hitachi Co.), and will experimentally evaluate thermal balance. The appropriate SC material will be selected for the coils. After that, a model magnet will be produced by using

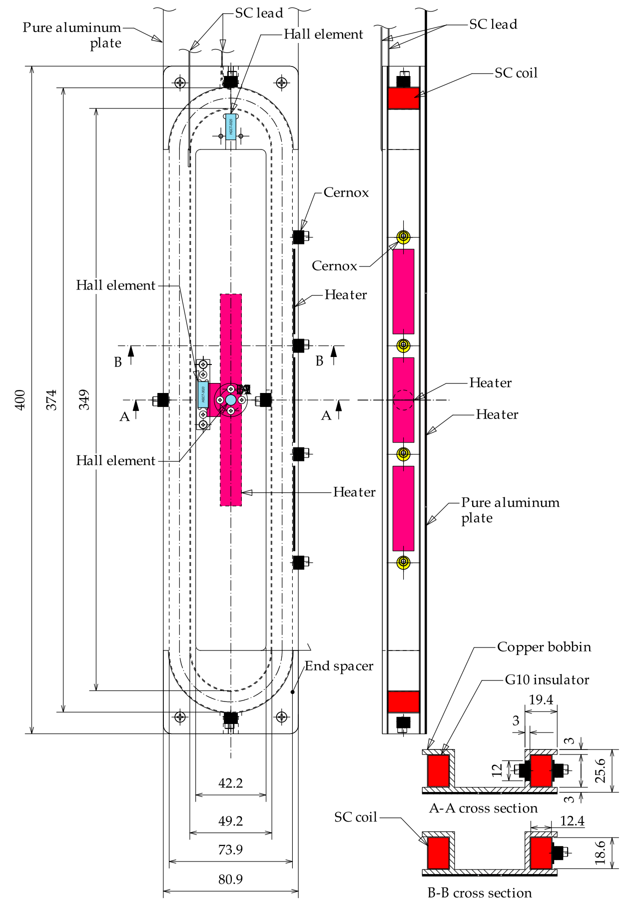

Fig. 2. The drawing of the test coil with NbTi cable.

the coils and the magnetic measurement and a total test will be performed. The following describes the apparatus for the test coil measurement now in preparation.

The test coils are a race-track form and have a bobbin made of copper, which has a higher melting point than the reaction temperature for Nb_2Sn and MgB_2. The length is about 300 mm, and is 1/3 of the practical coil, while the cross-section is the same as the practical one. On the coil surface, they have three polyimide thermofoil heaters (Minco Co.) which provides heat to simulate energy deposited by the dark current. To warm up the entire volume of the bobbin, it has a polyimide heater (Sakaguchi E.H Voc Co.). We measure the temperature profile of the coil with Cernox temperature sensors (CU type: Lake shore Co.). Fig. 2 shows the drawing of the test coil for NbTi cable. The NbTi cable has a diameter of 0.55 mm, including insulation, and the number of turns is 744. The bobbin has three hall elements for monitoring the magnetic field around the coil.

Fig. 3 shows a schematic setup for a cold test of the test coil. The cryostat has a 12-liter liquid helium pot, and the test coil is below the pot. A pure aluminum conduction plate connects the test coil and the bottom of the pot to cool the coil. The radiation shield made of copper covers these devices and evaporated helium gas from the pot cools down the radiation shield. This cryostat equips the power cable, which energizes the coil to 100 A and by attaching a window frame iron yoke,

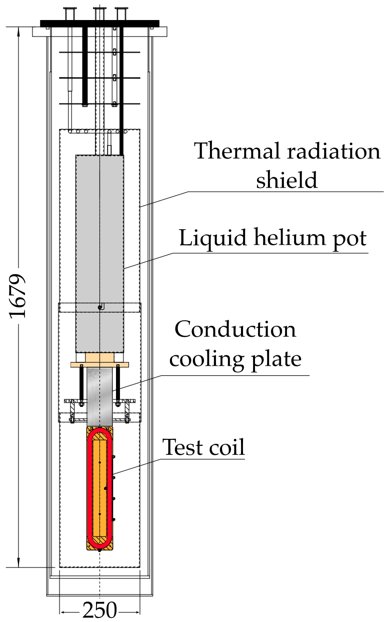

Fig. 3. The schematic view of the test cryostat.

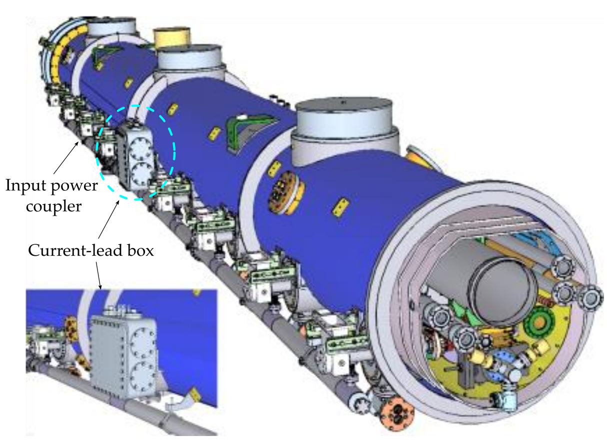

Fig. 4. The CL box on the cryomodule type-B.

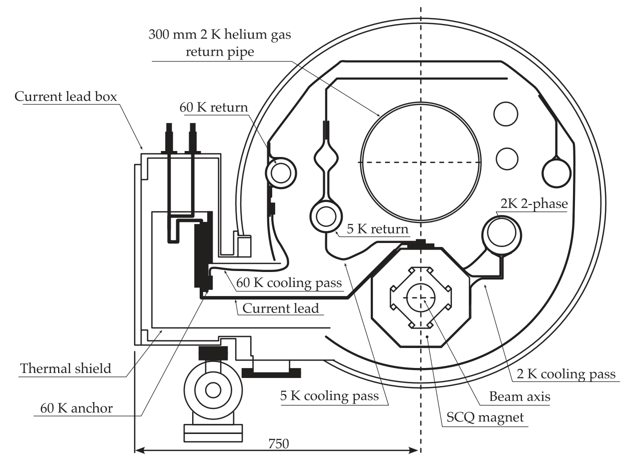

Fig. 5. The schematic view of the CL box and the CM at the SCQ package.

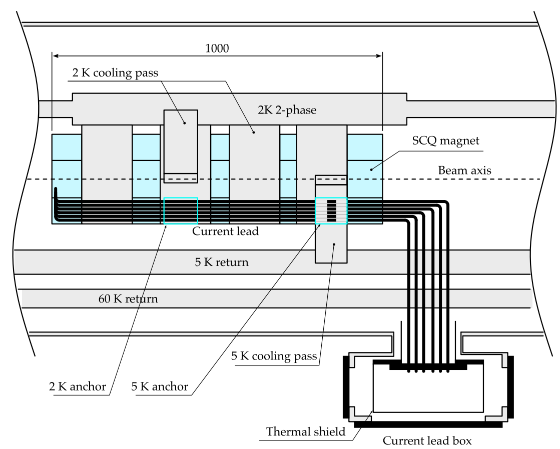

Fig. 6. The schematic top view of the CL, CL box in the CM in vicinity of the SCQ package.

the maximum field at the test coil will reach the maximum field of the H.E type of the SCQ package (see Table I). With this system, the thermal balance of the conduction cooling of the coils will be evaluated.

III. Interfaces to the Cryomodule

A. Current-Lead Box

As previously mentioned, the SCQ package consists of three types of magnets: the main quadrupole magnet, the vertical bending dipole magnet, and the horizontal one; the package has six current leads (CLs). The CL box is a service port that will supply the SCQ magnets' current from the CM outside to the inside. So far, it locates at the opposite side of the input power coupler for the SRF cavity; we proposed that we put the CL box on the same side as the input couplers as shown in Fig. 4 [7].

This configuration makes larger space for the installation work of the CM into the main linac tunnel. Fig. 5 shows a schematic cross-sectional view of the CL box and the CM.

B. Current Lead

We are investigating the CL configuration from the magnet to the CL box. The CLs also are cooled by conduction cooling; this makes them free from High-Pressure Gas Safety Act. The CLs will be routed from the lead end of the magnet to the opposite end through the surface of the magnet yoke and led to the current lead box (Fig. 6). There are two thermal anchors for the CL on the surface of the magnet yoke; one is a 2-K anchor, the other one is a 5-K anchor. In addition, the CL box has a 60 K anchor which connects to the CLs (Fig. 5). The 60 K anchor also cools the thermal shield in the CL box.

Fig. 7 shows schematic diagrams of the material configurations for the CLs, and Table III shows the calculated heat loads for the CLs. The columns labeled "cond." indicate the heat loads from a high-temperature area to low temperature one, and "heat." is Joule heating in the six current lead, where the currents of 100 A is applied for the six CLs. The value below the heat leak

TABLE III
THE HEAT LOADS ON THE CL OF THE SCQ PACKAGE

Material Component Unit	**(ILC-TDR)** Static (W)	Dynamic	**Cu** Cond. (W)	Heat.	**Cu+NbTi** Cond. (W)	Heat.	**Cu+MgB$_2$** Cond. (W)	Heat.	**Cu+HTS** Cond. (W)	Heat.	**Efficiency** W/W
RT → 60 K	3×4.13	3×4.13	15.3	9.0	15.3	9.0	15.3	9.0	15.3	9.0	16.5
	24.8		24.3		24.3		24.3		24.3		
60→5 K	3×0.47	3×0.47	0.9	1.5	0.9	1.3	0.9	0.8	0.1	0	198
	2.82		2.4		2.1		1.7		0.1		
5→2 K	3×0.28	3×0.28	0.6	0.2	0.01	0	0.01	0	0.01	0	703
	1.68		0.8		0.01		0.01		0.01		
Integrated to RT	2100		1400		820		750		430		

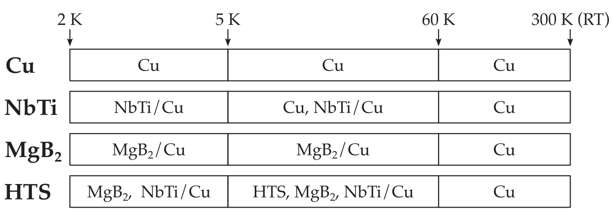

Fig. 7. Several configurations of the CL material. The left label is the name of the CL we call here; the top label is the temperature at the thermal anchor. Here, RT is room temperature. The material names in the squares are the CL material in each temperature region.

and the Joule heating is a sum of the above two values. The ILC-TDR value in this table refers the Table 3.9 in [1]. Since the TDR value is averaged values of a CM string which consist of three CMs (two type-A and a type-B), Type-A has no QCS package, to obtain the heat load on the one type-B CM, we multiply this value by three, in Table III. The integrated to RT is total heat load, obtained by multiplying efficiency to heat load at each region and summing these values over all three region. It can be seen that the addition of the superconducting leads will reduce the heat load 1/2 or 1/3 compared with the Cu type CL. The HTS type is about two times smaller than the NbTi type or the MgB_2 type of CL.

IV. SUMMARY

The ILC main linac has the SCQ magnet package, which is conductively cooled, in the CM type-B. The superconducting-coil of the SCQ magnet gets dark current heating and causes a risk of quench. We are investigating the SCQ magnet package that is sustainable against dark current heating. For this purpose, we have been investigating Nb_2Sn or MgB_2 as the superconducting coil. We will make test coils made of NbTi, Nb_2Sn, and MgB_2. We are preparing the test bench to evaluate the thermal balance for these test coils. We proposed the new CL box location. It will benefit from minimizing the CM horizontal width (envelope) for easier installation into the ML tunnel, provide a more flexible space between the CM and tunnel wall. The SCQ-CLs will also be conduction-cooled and further optimization study is in progress, to establish the best CL configuration with a combination of Cu and LTS/HTS to minimize power consumption.

ACKNOWLEDGMENT

The authors are grateful to S. Belomestnykh and Y. Orlov, Fermilab for their kindest cooperation for the CM design drawings and for the SCQ magnet design and development. We appreciate Toshiba Corp. for their professional cooperation for the new SCQ CL and CL-box engineering design work.

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