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STUDY OF CONDUCTION-COOLED SUPERCONDUCTING QUADRUPOLE MAGNETS COMBINED WITH DIPOLE CORRECTORS FOR THE ILC MAIN LINAC

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Abstract

A superconducting rf (SRF) cryomodule for International Linear Collider(ILC) main linac equips superconducting quadrupole magnet combined with dipole correctors. The magnets are superferric magnets with four superconducting (SC) race track coils conductively cooled from a two phase helium pipe of the cryomodule. The quadrupole field gradient and dipole field are 40 T/m and 0.1 T, respectively. The magnet length and iron-pole radius are 1 m and 0.045 m, respectively. It is known that dark current is generated at SRF cavities and accelerated through the following linac string. An orbit of the dark current of electrons is bent by the quadrupole field and the electrons hit the SC coils. An estimated power deposition on the coils may reach more than a few watts and the SC coil temperature may locally reach to critical temperature within a few second, in case of NbTi superconductor. We aim to realize the SC magnet which can be stably operated without quench under a such thermal condition. We plan to develop test coils made of three types of SC materials, NbTi, Nb_3Sn, and MgB_2 which have different critical temperature. We will develop a short model magnet, based on the test coil results. Here, we will present the magnet design study and the R&D plan.

INTRODUCTION

A cryomodule (CM) of the ILC main-linac contains eight or nine SRF cavities. A superconducting quadrupole (SCQ) magnet package is installed into every three CMs, and the quadrupole magnet configures FODO lattice structure in the main linacs. The quadrupole magnet package is combined with two dipole magnets for horizontal/vertical beam steering; the distance between two SCQ magnet packages is 38 m. The required parameters of this magnets are summarized in Table 1.

The magnet package has unique features that it should have splittable structure at a vertical plane so that it can be installed after an assembly of the SRF-cavity-string in a clean room (Fig. 1), and it should be conductively cooled from a two-phase-helium pipe without liquid-helium pressure vessel. A full-scale model magnet has been designed and developed at Fermilab [1, 2], and cold tests with liquid helium bath and with a pulse-tube cryocooler in conduction cooling configuration was performed [1, 3, 4]. A shorter model magnet has been installed into a CM at Superconducting test facility (STF) of KEK and cold tests have been carried out. The cold test with these model and prototype magnets demonstrated expected performances with the conduction cooling mode, however, heat load by a dark current heating was not considered in design.

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Table 1: Specifications of SCQ Magnet Package. L.E. type and H.E. type are SCQ packages used at less than beam energy of 25 GeV and more than 25 GeV, respectively. B_0 is a strength of 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.

Parameters	L.E. type	H.E. type
Beam energy	≤ 25 GeV	≥ 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	

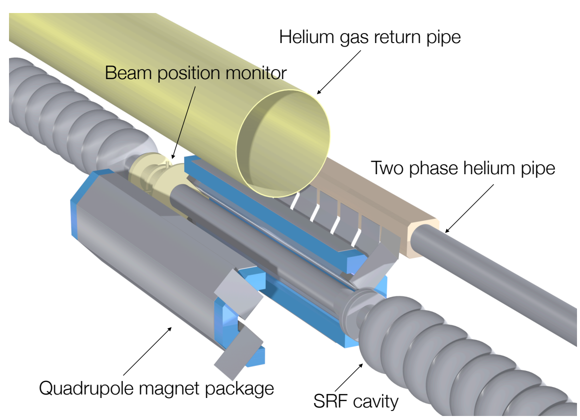

Figure 1: Splittable quadrupole package in CM.

DARK CURRENT EFFECT

In SRF cavities, electrons can be emitted from surfaces of the SRF cavities via field emission [5]. The emitted electrons are accelerated and contribute to a dark current. The dark current electrons hit the quadrupole magnet packages and deposit its energy on the magnet. The simulation by Sukhanov et al. shows that the equilibrium loss in the quadrupole pack-

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age is 1.35 W at beam-energy of 125 GeV and 1.7 W at 250 GeV, where they assumed that all cavities of the linac contribute equally 50 nA into the dark current [5].

It is planned that ILC will be upgraded to beam energy of 500 GeV in the future stage. The magnet package will not be replaced and the lattice configuration of the SCQ magnets will be changed to FFODDO configuration at 500 GeV.

The temperature rise (ΔT) by the dark current at the magnet was estimated with assuming that power deposition (P) is 5 W including some safety factor for the future upgrades [6]. A repetition rate (f) of the dark current is 5 Hz [7], energy deposit per pulse (E) is $P/f = 1$ J; a mass of the cold mass (part of beam pipe and magnet) for energy deposition (m) is assumed to be 4 kg, and specific heat of copper (C_{cu}) is 0.05 J kg^{-1} K^{-1} at 3 K. Using these values, ΔT per one beam pulse is given by,

$$\Delta T = E/(m \cdot C_{cu}) = 1/(4 \times 0.05) \sim 5\,\mathrm{K}. \quad (1)$$

This indicates that in case of NbTi, a few pulses (within 1 second) of the dark current rise a temperature of the SCQ coils higher than critical temperature of the SCQ coils. Therefore, we will consider Nb_3Sn or MgB_2 as a candidate of superconducting material for coils of the SCQ magnet package; they have much higher critical temperature than NbTi (Table 2).

In this study, we aim at developing the SCQ magnet package which is sustainable against the dark current heating with conduction cooling.

Table 2: Parameters of SC Wire. $T_c{}^*$: Critical temperature at $B = 0$ T, and $I = 0$ A. $T_c{}^\dagger$:Critical temperature at $B = 3$ T, and $I = 100$ A.

	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

PLAN FOR DEVELOPMENT OF SCQ MAGNET PACKAGE

In this development, we will develop test coils made of NbTi, Nb_3Sn, and MgB_2 and perform cold test to study thermal behaviours which cause quench; the coils will be cooled by a cryocooler with a conduction cooling. On each coil, heater will be attached to simulate the dark current heating. Based on the test, we choose suitable superconducting material and construct a short model magnet (the length of the model magnet is ~300 mm). We will perform magnetic measurement for the model magnet, and measure thermal property. Through this study, we will obtain data to develop the practical magnet. In Table 2, properties of the superconducting wire under consideration are summarized.

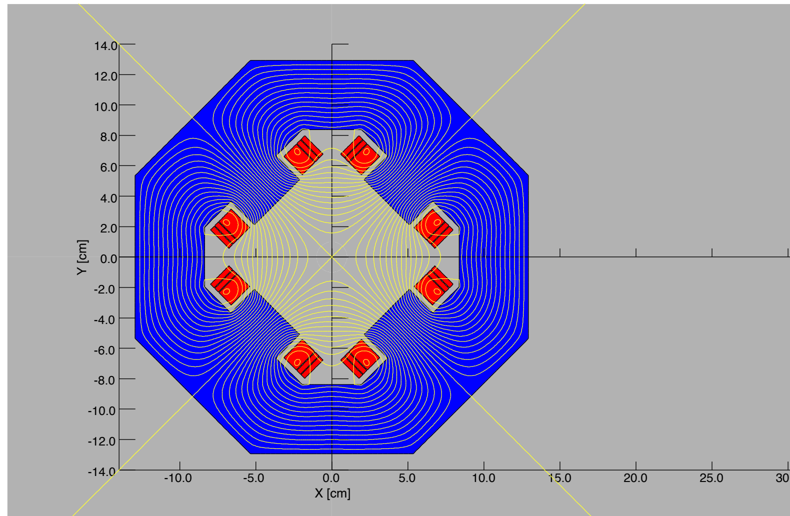

Figure 2: 2D calculation model and flux line at $I_q = 82$ A.

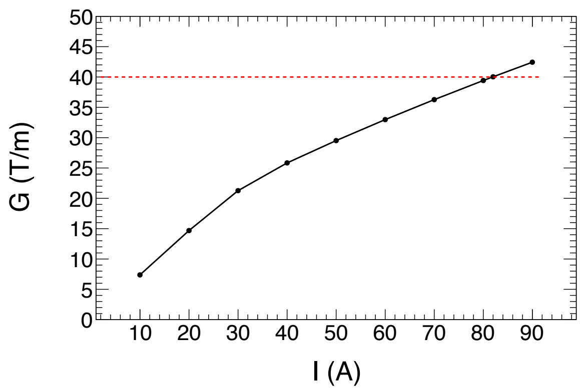

Figure 3: Magnetic field gradient as a function of quadrupole coil current. Horizontal broken line is specification value of the field gradient.

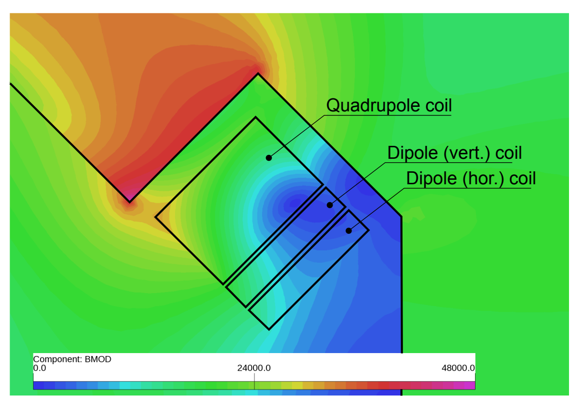

Figure 4: The color contour of the B-field strength around the coils. The current of the quadrupole coil is $I_q = 82$ A, and the current of the both dipole coil is $I_d = 35$ A.

CALCULATION OF LOAD LINE

To obtain a load line, 2D magnetic field analysis was performed with Opera2D. The yoke design is based on Ref. [1]. A coil cross section is determined from the insulated diameter of the NbTi wire as listed in Table 2; a SC coil for

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quadrupole has the number of turns of 744 and a cross section of 17.1x11.5 mm=196 mm^2. Both two dipole coils have 217 turns and a cross section of 17.1x3.4 mm=58 mm^2. A calculation model is shown with *B*-field flux in Fig. 2. A yoke is made of iron and an octagonal shape is adopted as the yoke shape. This shape is convenient to a precise alignment compared with a cylindrical shape.

To obtain a current of a quadrupole magnet where the magnet generates the field gradient (G) given in Table 1 for H.E. type, G was calculated as a function of the current, I_q (Fig. 3). The gradient linearly increases as a function of current, and an iron saturation effect appears beyond 30 A. This plot shows that the specification value of G is achieved at I_q =82 A.

A color contour plot of a *B*-field strength around coils is shown in Fig. 4. In this calculation, I_q is set to 82 A and a current of the both dipole magnets, I_d is set to 35 A; at this I_d skew and normal dipole components of 0.11 T are generated with the dipole magnets. This plot shows that the maximum *B*-field at the quadrupole coil is 3.1 T.

The obtained load line and critical current as a function of critical *B*-field for NbTi, Nb_3Sn, and MgB_2 is shown in Fig. 5. The load line is shown with solid line (blue) and inverse triangles, and an extrapolation of the calculation are shown with a broken line (blue). The curves of $I_c(B_c)$ are plotted in several temperatures (refer to legend in Fig. 5 for detail). The operation current of 82 A is on 47% of the load line for NbTi, 59% for MgB_2 and 30% for Nb_3Sn at T_c = 4.2 K.

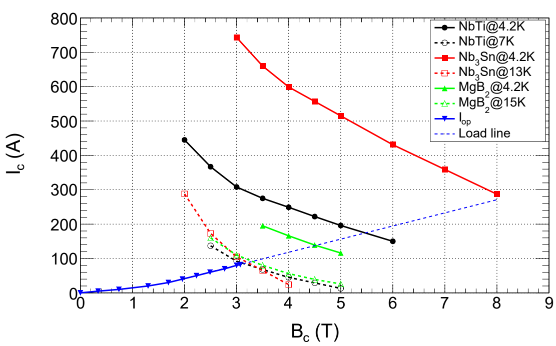

Figure 5: Critical current as a function of critical *B*-field for NbTi, Nb_3Sn, and MgB_2 and load line of the quadrupole magnet package. Refer to legend for detail.

SUMMARY

The SCQ magnet packages will be installed into the main linacs of ILC. The packages consist of the SCQ magnet combined with the two SC dipole correctors. The dark current will be lost in the SC magnet and deposit its energy (less than 10 W with a safety margin). It will rise temperature of the magnet by >~ 5 K.

It is shown that the operation current of 82 A is 59% for MgB_2 and 30% for Nb_3Sn at T = 4.2 K. These materials have enough operational margin at temperature of 4.2 K.

Operational temperature margin is under investigation and to be combined with magnetic design. The superconductor material, Nb_3Sn or MgB_2 enables to absorb the SC coil temperature rise up to 12 K or higher. To seek for optimum superconducting material for the coil, we will make test coils using three types of superconductor, NbTi, Nb_3Sn, and MgB_2 and investigate thermal behaviour with conduction cooling. Then, we will construct a model magnet with the selected SC material and measure thermal property with conduction cooling and magnetic field quality.

ACKNOWLEDGEMENTS

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