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Study on Conduction Cooling of Superconducting Magnets for the ILC Main Linac

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***Abstract*—In the main linac of the International Linear Collider (ILC), superconducting magnets for beam focusing and steering will be located periodically in superconducting RF (SRF) cavity string for beam acceleration in common cryomodules. A concept of conduction cooling of the combined-functioned, splittable superconducting magnets has been proposed and investigated to adapt much different features and to meet different requirements for the superconducting magnet and SRF cavity in fabrication, assembly, and operation. It is required to integrate the superconducting magnet after the SRF cavity string assembly is completed under an ultra-clean environment, and to isolate and the magnet operation by using conduction cooling through thermal links to a liquid helium supply pipe. According to this concept, a model magnet development was carried out in cooperation with Fermilab and KEK, and has been demonstrated in KEK superconducting RF test facility (STF). In addition, an important issue has been recently identified. High gradient SRF cavities naturally emit field emission electron flux from the inner surface, so-called dark current. It may pass through the subsequent SRF cavity string and penetrate into the superconducting magnets placed downstream. It may heat up the superconducting coils, and may cause a quench. Therefore, further study on reliable conduction cooling and to secure the superconducting magnet operation with a keeping sufficient safety margin is quite essential. In this paper, we report the installation, the improvement achieved in STF, and the R&D progress in the study on the conduction cooling of the superconducting magnet for the ILC main linac.**

***Index Terms*—liear accelerator, superconducting magnet, conduction cooling, field emission, dark current.**

I. Introduction

THE ILC main linac consists of two types of cryomodule (CM). Type-A cryomodules include 9 SRF cavities. On the other hand, Type-B cryomodules contain 8 SRF cavities and one superconducting quadrupole (SCQ) magnet package. In Fig. 1, a schematic of the Type-B cryomodule is shown. At the middle part of the module, an SCQ magnet is drawn. The SCQ magnet package is combined with two dipole magnets as horizontal and vertical beam steering [1]. Because of a long linac structure, there are two energy stages and the required features of magnets for each stage are different. Specifications of the SCQ magnet package are summarized in Table 1.

An emphasized feature of the ILC SCQ is its splittable structure. This structure is designed by a requirement from the SRF cavity to prevent from contaminating inner surface of cavities during string assembly operation in ultra-clean environment. Adopting the splittable structure, the SCQ magnet does not need to be brought into the clean room, and is able to be attached to the beam line after all cavity assembly is done. However, the SCQ magnets are forbidden to have their own helium vessel to store liquid. As a result, the SCQ magnets are cooled down with conduction cooling through high-efficiency conductors of heat. As such conductors, highly purified aluminum sheets are usually used for this purpose [2]. So far, in collaboration with FNAL and KEK, long length model mag-

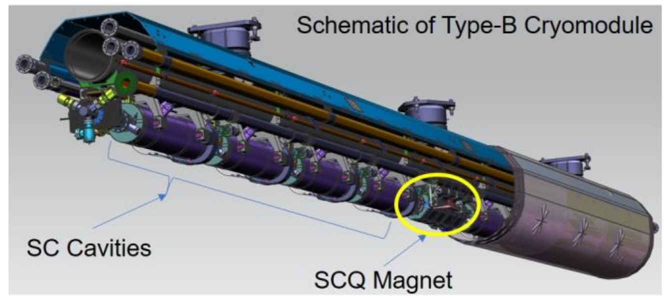

Fig. 1. Schematic of Type-B cryomodule of ILC. The Type-B cryomodule consists of 8 superconducting RF cavities, and a superconducting magnet package.

TABLE I
Specification of SCQ Magnet for ILC

Parameters	Low Energy Type	High Energy Type
Beam Energy	5～25 GeV	25～250 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	19 T/m	40 T/m
Maximum Field of Q-coil	～ 1.5 T	～ 3 T
Operation Temperature	2 K	

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nets are fabricated and investigated performances applying cold tests at the testbench [3-6]. Adding that, a short model magnet is also constructed and has been installed into a CM of STF accelerator. Following this paper, test results and several improvements in the accelerator environment demonstrations will be described. In addition to those above, authors recognize that a heating issue driven by the dark current would be a major problem for the high gradient linac machine such as ILC. To avoid unexpected quench risks occurred by the dark current, several improvement studies are done. We report some results of FEM calculations.

II. Model Magnet R&D in KEK STF

TABLE II
PARAMETERS OF AN INSTALLED MODEL MAGNET PACKAGE

Parameter	Unit	Value
Physical Magnet Length	mm	340
Magnet Width	mm	322
Magnet Height	mm	220
Effective Length	mm	230
Magnet Pole Aperture	mm	90
Beam Pipe Bore Aperture	mm	78
Integrate Peak Gradient	T	2.0
Peak Quadrupole Gradient	T/m	8.7
Quadrupole Magnet Inductance	H	0.66
Operation Current	A	30
Superconductor		NbTi
Superconductor Diameter	mm	0.5

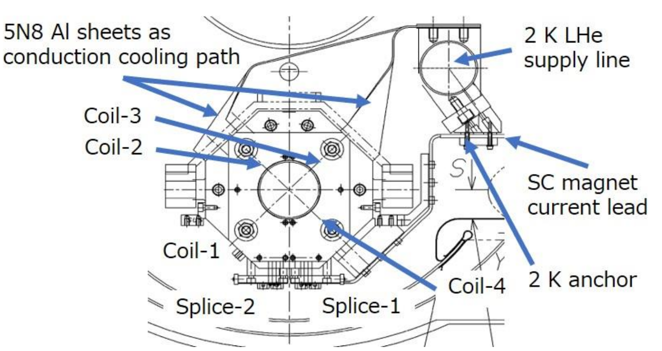

Fig. 2. Cross section drawing of installed SCQ magnet.

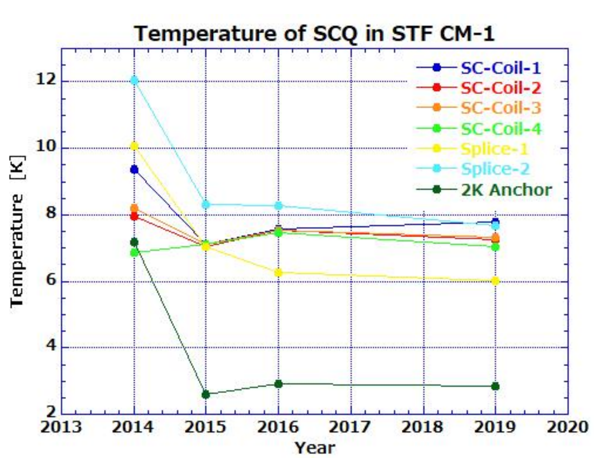

Fig. 3. Installed SCQ temperature transition plot.

Fabrication of the short type model magnet was started at FNAL in 2013, and the magnet was installed into KEK STF in the same year. Some of primary parameters are listed in Table II. From 2014, the STF accelerator was operated several times, and the SCQ magnet underwent cold tests. Fig.2 shows a cross section drawing of the SCQ, which also includes other important components of the magnet system like 2 K LHe supply line, 2 K anchor point, and highly purified aluminum strips which connects between the magnet body and the 2 K supply line. According to Fig.3, almost all part of the magnet showed above NbTi critical temperature, because of not enough thermal anchoring of current leads. To improve this situation, HTS current lead plates were inserted on the 5 K region of the Cu current leads. This improvement drastically changed thermal profiles, and the quadrupole could be excited with 25.6 A. However, all 4 coils still showed rather higher temperatures even though the thermal anchor was attached on the 2 K heat bath. In 2019, all current leads were removed from just before point of the 2 K anchor. However, even after the removal operation, thermal profiles of the magnet had never changed. From this experimental trial, it was argued that incoming conduction heat component through the current leads were not the source of the reason why the magnet was kept rather higher temperature.

To investigate the source which kept the whole magnet system hotter, the amount of carried heat flux was evaluated by using following Fourier's law

$$Q = \lambda \times \Delta T \times S \ / \ L \tag{1}$$

where λ corresponds to thermal conductivity, ΔT is temperature difference, S is cross sectional area, and L is distance. Because the temperature distribution of the magnet system was known, and also all dimensions could be picked up from design drawings. As a result, Q could be calculated, and the evaluated value was about 1 W. To confirm the above simple analytical calculation, FEM method was used to reproduce the measured temperature profiles. An obtained result is shown as Fig.4. Assuming 1 W heat load comes from top of the anchor support, then, measured thermal distributions are reproduced. Large thermal gradients are concentrated on stainless steel wall.

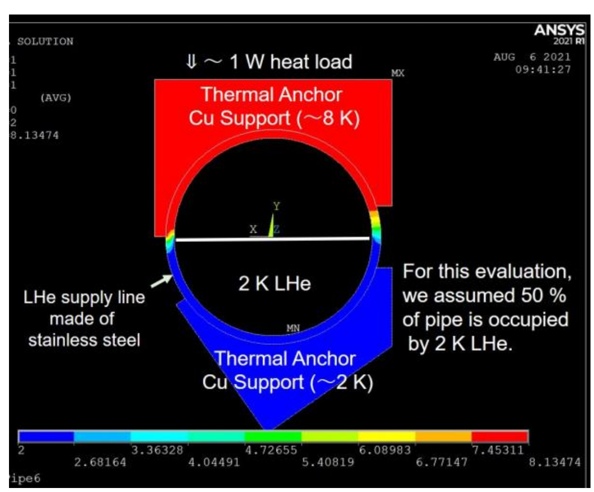

Fig. 4. Numerical calculation results of thermal profile confirmation.

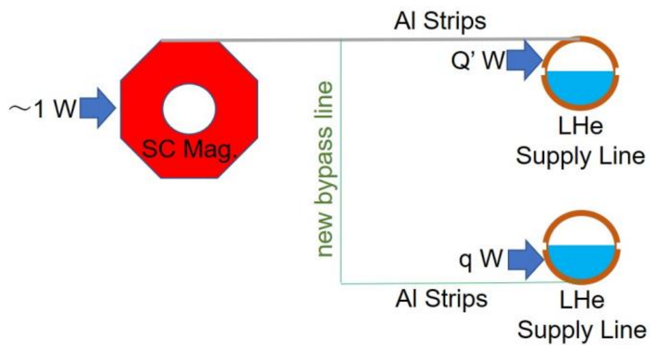

Fig. 5. Improved thermal pass with a new bypass line.

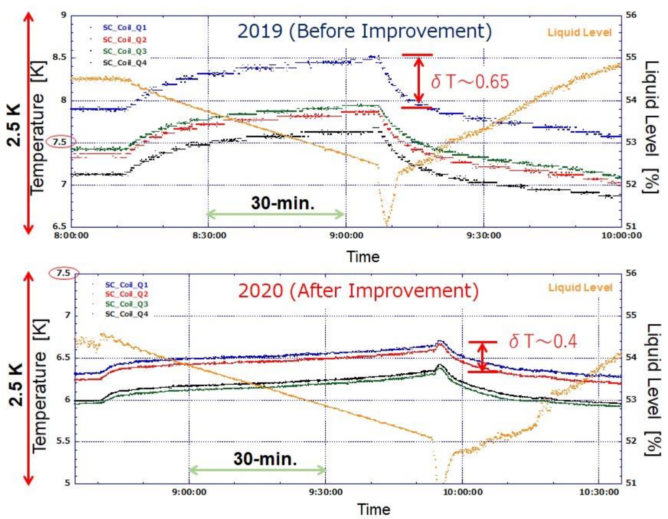

Fig. 6. Liquid level study before improvement (above), and after improvement (below).

Through the evaluation study of carried heat amount and thermal profile of the system, it is revealed that an anchoring position of the SCQ was not appropriate and convection contribution from 2 K He vapor was not sufficient to provide an enough cooling capability. The CM-1 cryomodule is a part of the STF accelerator and is quite difficult to decompose to repair the SCQ thermal anchor position. The only remaining way is to use a magnet service port for current leads connecting operations locating a side wall of the cryomodule. In Fig.5, an outline of the improvement is shown. A new bypass line of Aluminum (Al) strip was attached at the bottom of the 2 K supply pipe (2 K anchor point). The other side of the bypass line was attached at the nearest position to the SCQ as far as hands reached from the service port. Two trend plots of the thermometric of the SCQ are shown in Fig.6. Both plots have the same range of vertical axis (2.5 K), however, the represented region is different. The below one (after improvement) shows a lower temperature region, and it is possible to understand that after the improvement, all coils of the SCQ have become about 1.5 K colder. Studies of liquid He level were also done. When JT-valve of the 2 K system was closed, 2 K supply pipe would be dry out about one hour later. Fig.6 also includes these results. Before improvement, the SCQ temperature depends on the liquid level height because of the anchoring position. However, the dependency on the level was relaxed after the improvement.

As a result, it is possible to conclude that the new bypass line works well to stabilize the SCQ thermal profile. The SCQ installed CM-1 was operated with rated current 30 A in 2021 machine operation of STF. We also have confirmed that two steering magnets control beam position successfully by using downstream BPM signals.

III. Dark Current heating and improvement idea

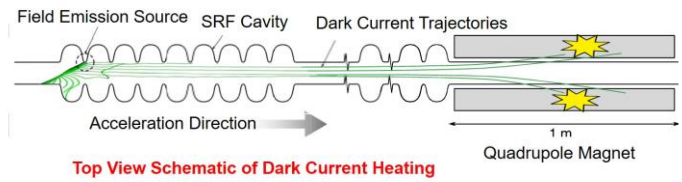

Fig. 7. Schematic of field emissions from cavity and heating at SCQ.

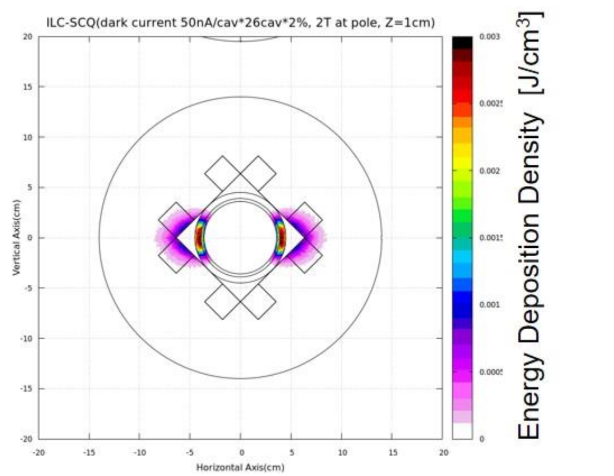

Fig. 8. Numerical simulation result of energy deposition density at the SCQ.

As a last part of the paper, a new issue for quadrupoles of the ILC main linac would be discussed. Recent outstanding progress of cavity fabrication scheme makes it possible to reach higher accelerating gradient. However, at the same time, it brings about a new potential problem of additional heating and quench risk for SCQ [7-9]. Field emissions are not possible to avoid in such a high gradient cavity. Some of those emitted electrons are captured by accelerating phase of RF, and propagate to downstream as so-called dark current. Emitted dark currents are accumulated in between an interval of SCQ packages. In ILC case, it is 38 m long. Each charged particles have almost the speed of light, however, their energy is not uniform. So, the energy matching with appropriately aligned SCQ would not be achieved, and focus/defocus magnetic forces would bend the injected dark current. Finally, those bent currents are absorbed by SCQ coil and iron yoke. As results of recent simulations, evaluated dark current is about 50 nA from one 1.3 GHz cavity, and energy deposition to the SCQ could reach about 1.7 W in ILC 500 GeV option case. Taking into account the safety factor of 3, 5 W heat load is assumed. ILC adopts 1-ms beam with 5 Hz repetition rate. It leads that 1 joule energy will be deposited within 1-ms onto the SCQ, and turned off in following 200-ms [10].

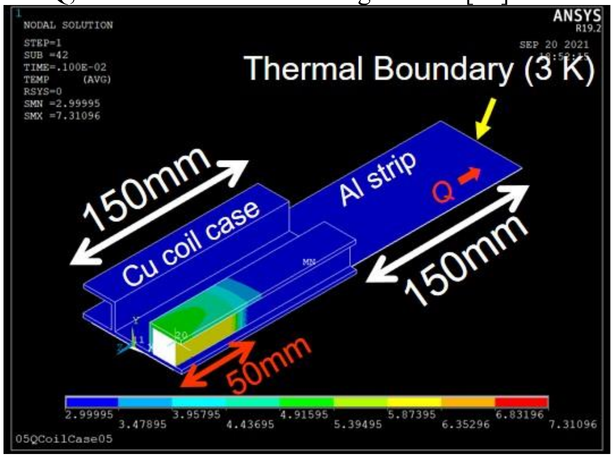

Fig. 9. FEM simulation setups to investigate thermal profiles of model coil.

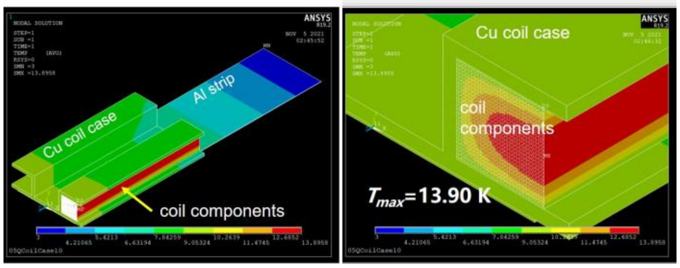

Fig. 10. Numerical simulation results of steady state with dark current heating.

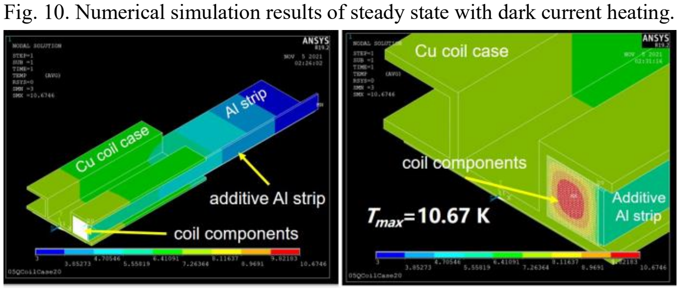

Fig. 11. Numerical simulation results with an additive aluminum strip.

To investigate the dark current heating effects, FEM simulations are conducted. Fig.9 shows simulation setups. Assuming a 30 cm coil with 30 cm Al strip attached without arc section, and calculate half part of it. Only central cubic part of 50 mm length will be heated up. The heat distribution must be imitating the effect from dark current, however for this time, adopted uniform heating for simplicity. Obtained results are shown in Fig.10 and Fig.11. If any additive support is not included (original coil style), the maximum temperature reaches about 14 K as a steady state. It almost reaches magnesium bromide critical temperature in 3 T. To reduce the attainment temperature, it is necessary to reinforce the thermal conductors. Considering the energy deposition profiles depicted in Fig.8, attaching an additive Al strip on the open side of coil case seems effective. The open side is surrounded by feeble magnetic field, and this is good advantage to avoid thermal conductivity reduction through magnetoresistance effect. This configuration is calculated and the results are shown in Fig.11.

An additive Al strip is attached to the coil side wall directly, and the attainment temperature is less than the critical temperature of niobium tin. From those study results, it is possible to argue that the auxiliary Al strip sufficiently works to reduce the temperature rise of the coil. Niobium tin and magnesium bromide are wire candidates for ILC with dark current heating.

IV. Conclusion

As a demonstration of conduction cooling R&D, we have developed a short model magnet superconducting magnet in collaboration with FNAL, and installed it into KEK STF. After some improvements, the SCQ package is successfully operated in CM1 cryomodule. Making use of lessons learned in STF and also SuperKEKB QCS experiences, we have started a new R&D program with a new model magnet to be sustainable against the dark current heating which was recently recognized to be a major issue for the high gradient linac machine such as ILC. To avoid unexpected quench risks, we evaluate thermal profile evolutions in the new SCQ using FEM method, and propose a new conduction cooling scheme of a thermal link from the SCQ coils and 2 K LHe supply pipe. Appling our improved anchoring scheme, FEM calculation shows the model coil and magnet steady state temperature is less than the critical temperature of niobium tin even with dark current heating of 5 W. This effectivity will be tested with similar dark current heat load imitated with heaters experimentally in near future.

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References

[1] C. Adolphsen *et al*., “The International Linear Collider Technical Design Report Volume 3. II: Accelerator Baseline Design”.

[2] H. Hoshikawa *et al*., “Magnetoresistance of 5N, 6N, and 6N8 high purity aluminum”, AIP Conf. Proc., vol.1435, no.140, 2012.

[3] V. Kashikhin *et al*., “Superconducting Splittable Quadrupole Magnet for Linear Accelerators”, IEEE Trans. Appl. Supercond., vol. 22, no.3, 2012.

[4] V. Kashikhin *et al*., “Performance of conduction cooled splittable superconducting magnet package for linear accelerators”, IEEE Trans. Appl. Supercond., vol.26, no.4, 2016.

[5] N. Andreev *et al*., “Conduction cooling test of a splittable quadrupole for ILC cryomodules”, IEEE Trans. Appl. Supercond., vol.23, no.3, 2013.

[6] N. Kimura *et al*., “Cryogenic performance of a conduction cooling splittable quadrupole magnet for ILC cryomodules”, AIP Conf. Proc., vol.1573, no.1, 2014.

[7] A. Sukhanov *et al*., “Model of Dark Current in SRF Linac”, Proc. 6th Int. Particle Accelerator Conf. (IPAC’15), Richmond, Virginia, USA, 2015, 1834-1836, TUPJE081.

[8] A. Sukhanov *et al*., “Dark current studies in ILC main linac”, Proc. 28th Linac Accelerator Conf. (LINAC16), East Lansing, Michigan, USA, September 25-30, 2016, THPLR007.

[9] A. Yamamoto *et al*., “Dark current electrons and irradiation heating of superconducting magnets for high-gradient SRF linacs”, in TTC 2021, TESLA Technology Collaboration, DESY, 2021.

[10] Y. Arimoto *et al*., “Study of conduction-cooled superconducting quadrupole magnets combined with dipole correctors for the ILC mail linac”, Proceedings of the 12th International Particle Accelerator Conference (IPAC2021), Campinas, SP, Brazil,1375-1377, TUPAB017.