Conduction Cooling Test of a Splittable Quadrupole for ILC Cryomodules

Nikolai Andreev, Vladimir S. Kashikhin, James Kerby, Nobuhiro Kimura, Masahiko Takahashi, Michael A. Tartaglia, Taizo Tosaka, Akira Yamamoto

***Abstract*—A superconducting splittable quadrupole magnet was designed at Fermilab for use in ILC-style cryomodules, in which the magnet is to be assembled around the beam tube to avoid contaminating the ultraclean SRF beam volume. This quadrupole was built and first tested in a liquid helium bath environment at Fermilab, where its quench and magnetic performance were characterized. The device is intended to be cooled by conduction when installed in cryomodules, so a separate test was made at KEK where an appropriate conduction cooling test facility exists. We present results of the thermal performance of the magnet in the conduction cooling mode, and discuss its excitation characteristics in this operating mode.**

***Index Terms*—Superconducting Magnet, Cryogenic Test Facility**

I. Introduction

THE development of a focusing element that meets all requirements for ILC [1] Main Linac cryomodules has challenged the superconducting magnet community for a number of years [2]-[6]. Of those requirements, shown in Table I, keeping the magnetic axis position stable to within 5 microns during a 20% field strength variation is perhaps the most difficult. One design, made at Fermilab, is based upon superconducting racetrack coils supported within a laminated iron yoke structure; the design concept and test results for the first model magnet of this type (RTQ01) have been previously reported [2]-[3]. Subsequently this design has evolved in two important ways: first, the steering dipole coils were removed to a separate corrector element, to eliminate magnetization effects that complicate the center position dependence on coil excitation history. Second, to simplify cryomodule assembly and decouple magnet fabrication, testing and installation from superconducting RF (SRF) cavity preparation (in super-clean environment), the magnet has been split into two halves that can be clamped around the beam tube and not risk contamination within the clean SRF beam tube. In such a design, it is natural to consider a conduction cooled configuration, which offers further simplification and cost reduction by eliminating a 4 K liquid helium vessel, and takes advantage of nearby 2 K helium supply pipes needed for SRF.

A second racetrack quadrupole with this split yoke design (RTQ02) was fabricated and tested at Fermilab using a test stand with 4.4 K liquid helium bath cooling [7]. The quench performance was studied up to 110 A, limited by the test stand venting capacity, across several thermal cycles (TC). As with RTQ01 the training was somewhat slow but reasonably well remembered after each TC. An exhaustive magnetic measurement program was carried out, which showed the quadrupole meets field quality specifications up to the maximum operating gradient, 54 T/m at 100 A. The center stability was within specifications at some currents, but varied by as much as 8 microns in the mid-current range, in the direction across the yoke gap; the requirement was easily met in the orthogonal direction parallel to the yoke gap. Furthermore the upper and lower halves showed slightly different current dependence of the center shifts.

Measurements of the split yoke faces indicated a non-uniform gap along the length, which could account for non-linear behavior of the center position; this is likely caused by some warping when welding together the laminations. To test this hypothesis, the yoke faces have been machined flat by Toshiba Corporation, and thin (0.5 mm) iron shims were introduced on each face to maintain the quadrupole geometry.

TABLE I QUADRUPOLE SPECIFICATION

Parameter	Unit	Value
Integrated peak gradient	T	36
Aperture	mm	78
Effective length	mm	660
Peak gradient	T/m	54
Field non-linearity at 5 mm radius	%	0.05
Dipole trim coils integrated strength	T-m	0.075
Quadrupole strength adjustment for BBA*	%	-20
Magnetic center stability at BBA*	μm	5
Magnetic center offset in cryomodule	mm	0.3
Quadrupole azimuthal offset in cryomodule	mrad	0.3
Liquid helium temperature	K	2.2
Quantity required		560

*BBA refers to a 20% variation in field strength for Beam-Based Alignment

Manuscript received October 9, 2012. This work was supported in part by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, and in part by the Japan-U.S. cooperative program in High Energy Physics.

N. Andreev, V.S.Kashikhin, and M. Tartaglia are with the Fermi National Accelerator Laboratory, Batavia IL 60510 USA (corresponding author phone: 630-840-3890; fax: 630-840-8079; e-mail: tartaglia@fnal.gov).

J. Kerby was with Fermlab, Batavia IL 60510 USA. He is now with the Argonne National Laboratory, Argonne IL 60439 USA (e-mail: jkerby@aps.anl.gov).

N. Kimura and A. Yamamoto are with the KEK laboratory, Tsukuba, Japan (e-mail: nobuhiro.kimura@kek.jp).

M. Takahashi and T. Tosaka are with Toshiba Corporation in Tokyo, Japan (email: masahico.takahashi@toshiba.co.jp, taizo.tosaka@toshiba.co.jp).

II. Cryo-Cooler Test Assembly Design

Tests made in the liquid helium bath at Fermilab were important to qualify the basic performance characteristics of the quadrupole. However, it was desirable to further explore the behavior in a conduction cooling configuration. In this way one can measure the available thermal margin of the superconductor, study the effects of AC losses on the coil temperature and quench performance, measure the recovery time after a quench, and make other tests. Furthermore, a conduction cooled test facility is valuable as a way to decouple testing from the need for a supply of liquid helium for cool down and continuous operation.

The Cryogenic Science Center at KEK took responsibility for building a new conduction cooling test stand dedicated for this purpose. The design is based upon the use of a Sumitomo Heavy Industries Pulse-Tube Cryo Cooler (PTCC) which has a 1 Watt cooling capacity at 4 K, and about 40 W at 50 K. The detailed design and assembly of the vacuum vessel, shields, power leads and magnet were completed with the collaboration of Toshiba Corporation engineers and technicians in Tokyo, and the assembly was shipped to KEK in July 2012. Fig. 1 shows a cross sectional view of the test stand and magnet assembly, and Fig. 2 shows a detailed schematic of the power lead construction. The design includes 5 HTS power leads to reduce the 4 K heat load, which connect to the magnet leads and to each of the internal coil-to-coil splices; this allows the possibility to power the magnet up to 150 A in either dipole or quadrupole configurations, depending upon how power supply connections are made to the leads. A warm bore tube extends completely through the vessel, to allow rotating coil magnetic measurements.

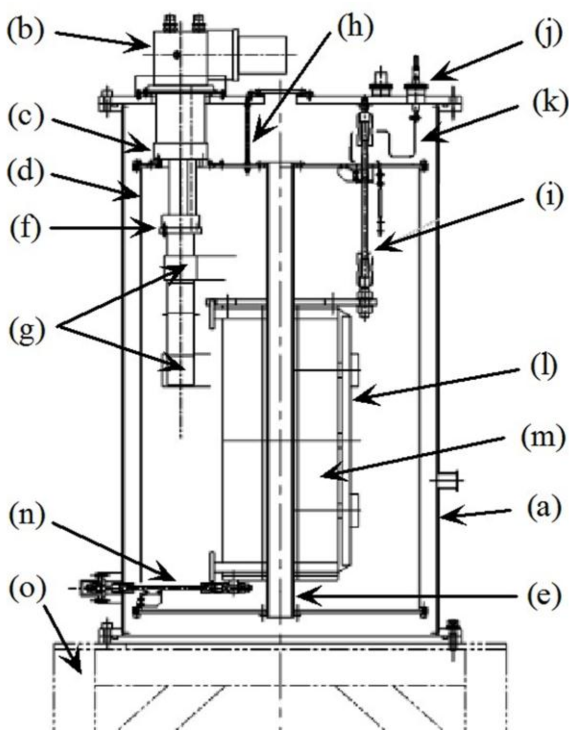

Fig. 1. Conduction cooling test stand assembly: a) vacuum vessel, b) pulse-tube cryo cooler, c) PTCC 1st stage, d) radiation shield, e) warm bore tube, f) PTCC 2nd stage, g) Pure Al, Cu connection bars, h) shield support, i) magnet support, j) hermetic feed through, k) copper lead, l) conduction cooling block, m) splittable quadrupole magnet, n) horizontal support, o) stand.

The major challenge is to design and construct the apparatus such that the heat load is less than 1 W to the 4 K region. The shield temperature is affected by heat conducted through 4 horizontal and 4 vertical supports and 5 copper leads, which are thermally anchored to the shield, and by the room temperature radiation load from top, bottom, sides, and warm bore tube. In addition to these static loads, Joule and eddy current heating arise during powered operation. The temperature distribution is then a function of the thermal resistances across heat conduction paths in the circuit from PTCC stages to each component, and the PTCC cooling power behavior versus temperature of each stage (its "load diagram"). Supports are designed to handle up to 1.5 g forces that may arise during shipping or from earthquakes; they were optimized using low conductivity Fiber Reinforced Plastic (FRP) materials. Thermal and electrical resistances were minimized with high purity aluminum and copper components and with Indium gaskets at shield joints.

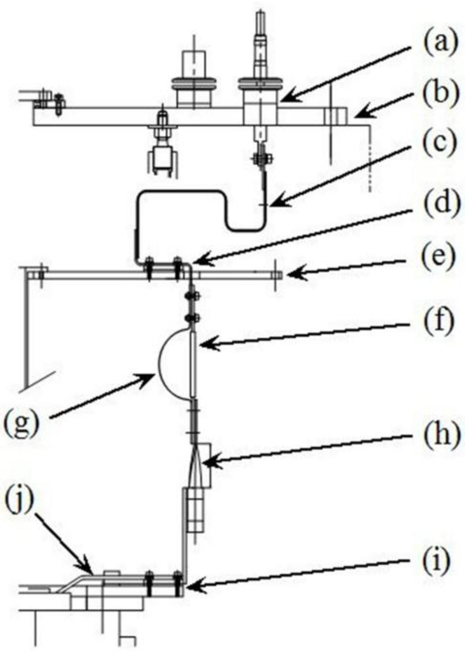

Fig. 2. Current Lead Construction: a) ceramic power feed-through, b) Vacuum vessel top plate, c) Copper lead, d) 50 K thermal anchor, e) radiation shield, f) HTS lead, g) Stainless Steel bypass lead, h) Flexible Copper lead, i) Copper Lead 4K thermal anchor, j) Copper-stabilized NbTi lead.

The temperature distribution in the 4 K region is affected by conduction through the FRP supports, and radiation from the thermal shield which is reduced by using multilayer superinsulation. Leads of HTS nearly eliminate that source of heat conduction, but a small contribution remains from the Stainless Steel bypass (to carry current if the HTS material quenches). Instrumentation wiring for temperature and voltage monitoring also conduct a small amount of heat. During powered operation Joule and eddy current heating affect the 4 K region.

To ensure low thermal resistances at 4 K, large channels of high purity ("5-nine", or 99.999%) aluminum and copper are used to connect clamps around the magnet yoke to the PTCC 2nd stage cold head. In a parallel connection to the cold head, similar large area channels are connected to a set of thin pure aluminum strips that were glued over the exposed faces of the coil packages (made from structural aluminum to resist distortion at high field). Fig. 3 shows a photograph of the PTCC, conduction cooling channels, magnet and leads during test stand assembly. Table II summarizes the estimated static heat loads to each stage of the system for the final design.

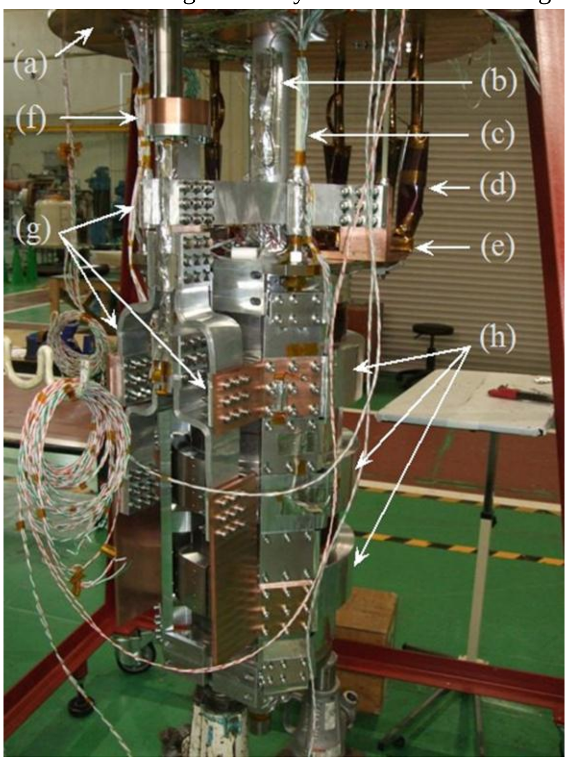

Fig. 3. Conduction cooling test stand during construction: a) top radiation shield, b) warm bore shield, c) vertical magnet support, d) Cu lead below HTS, e) Cu/SC lead thermal anchor, f) PTCC stage 2 cold head, g) pure Al and Cu conduction channels, h) stainless steel clamps around magnet yoke.

TABLE II STATIC HEAT LOAD ESTIMATES

Component/Location	Temp [K]	Est. Heat Load [W]
Assumed 1st Stage Temperature	45	
Current Lead conduction to shield		29.5
300 K Radiation at shield		7.10
Shield Support conduction to shield		3.49
H+V magnet support cond. to shield		1.03
Assumed 2nd Stage Cold Head Temp.	3.5	
Current Lead conduction to anchor		0.4550
Shield radiation (@45 K) to 4 K		0.0463
H+V Support cond. to 4 K magnet		0.0350
Instr. Wires conduction to 4 K		0.0114

III. Conduction Cooling Performance

The total mass to cool to 4 K is assumed to be 400 kg of iron. The PTCC performance load diagram of the cooling power as a function of 1st and 2nd stage temperatures has been previously measured at KEK [8]; the expected cooling power is about 40 W at 50 K and 1 W at 4 K, consistent with vendor data. From Table II we expect heat loads of 41.1 W and 0.548 W at the 1st and 2nd cold stages, respectively. Based upon these estimated heat loads, initial assumption of PTCC temperatures, and calculated thermal resistances, a cool down time of 300 hours (12.5 days) was predicted.

To monitor thermal performance during the test, a total of 19 temperature sensors were mounted in strategic locations: 5 platinum sensors to measure cryo-cooler 1st stage and shield temperatures near the leads, bottom, and warm bore; 14 Cernox® sensors on the cryo-cooler 2nd stage, cooling channels, 4 K thermal anchor near the leads, on the magnet yoke clamps, magnet bottom, and on each of the coils. Voltage taps were also applied across each of the coils, and to each segment of the current leads, for quench protection and study.

After achieving a good insulating vacuum level of 4.5·10-5 Pa, the PTCC compressor was started and cool down began on August 1; the actual cool down to 4 K took only 190 hours (8 days). Fig. 4 shows the temperature trend of selected (shield and coil) temperatures during this period. The measured heat loads, calculated from the PTCC load diagram as well as calorimetrically from the rate of temperature rise with PTCC turned off, were 32 W and 0.6 W to the 1st and 2nd stages, respectively. Further analysis of the static temperature values in different locations is under way to assess the heat sources and thermal resistances in more detail.

During the cool down, and again during warm up after the test, the coil resistances were measured using a very small current through the magnet. The residual resistivity ratio (RRR) was determined to be about 140 in both measurements.

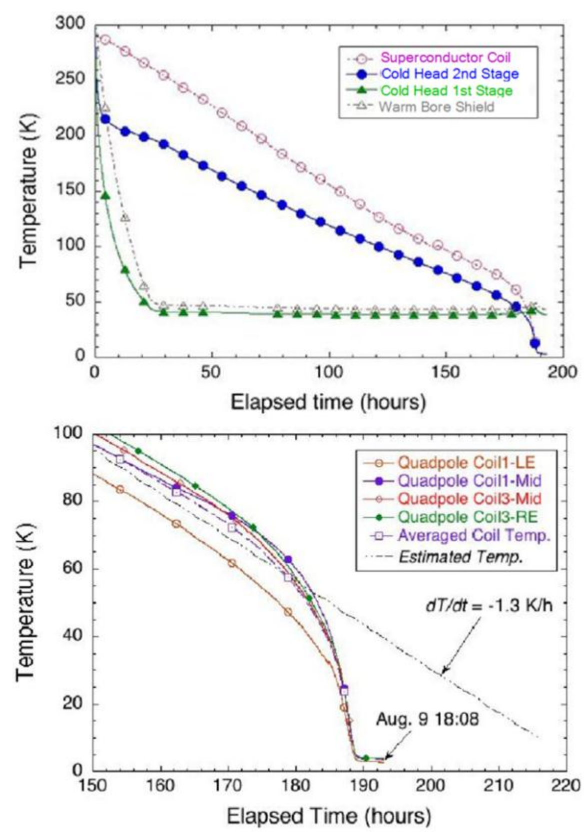

Fig. 4. Cool down from 300 K to 4 K (top), detail of final cooling phase from 40 K to 4 K (bottom).

IV. Excitation Characteristics

Following the successful cool down to 4 K, initial studies were made of the system and magnet characteristics during AC and DC powered operation. First was a measurement of heating from AC losses while ramping up and down between 0 and 5 A at 0.1 A/s (about 10 times the maximum ramp rate required for ILC operation). To convert the measured equilibrium increase of coil temperatures into a heat load, a calibration was performed by introducing known amounts of power to the quench protection heaters, ranging from 0.05 to 0.26 W. The resulting AC loss at 0.1 A/s was found to be 0.057 W.

For higher current operation, the magnet was protected using an energy extraction resistor and diode in parallel to the power supply, with a “dump switch” to disengage the power supply following quench detection. Based upon quench development studies and earlier test results at Fermilab, the maximum operating current in this power test was limited to 30 A due to unavailability of a protection heater power supply. Operating up to this current allowed the study of many important performance characteristics. At the equilibrium conduction cooling temperature of about 4.2 K, the quadrupole did not spontaneously quench in many ramps, several up to 30 A. Therefore it remembered its earlier training despite thermal cycle, shipping, machining and other handling.

A study of the thermal margin was made, to compare the actual superconductor performance with expectations from the intersection of magnet load line with critical surface. Strip heaters within the epoxy-impregnated coils can be used to raise the coil temperature for this purpose; however temperature sensors located on the outer surface of the coils do not directly measure the coil temperature and there is a large uncertainty on the thermal resistance. Instead, turning the cryo-cooler off creates a very slow and uniform rise in the cold mass temperatures. Fig. 5 shows an example of this test, in which the quadrupole was first ramped to a high current, then the PTCC compressor was stopped. The temperature climbed until the critical surface was reached and a coil quenched. Fig. 6 shows the measured points and critical current predictions based upon sample strand measurements, standard NbTi parametrization [9] and calculated peak field.

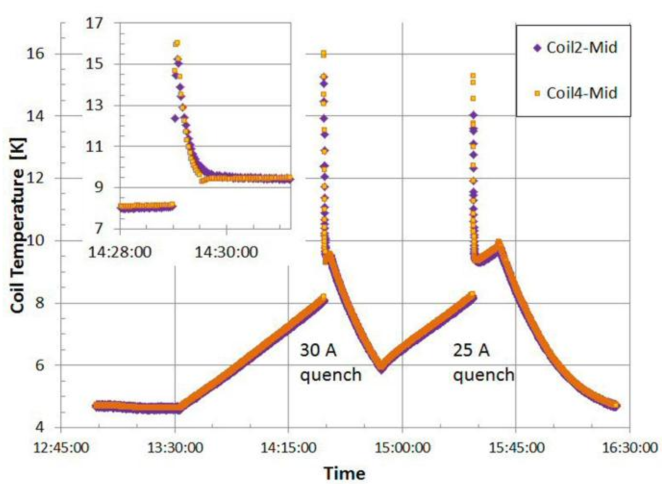

Fig. 5. Coil temperature rise due to background heat load when PTCC is turned off with magnet powered at fixed currents; rapid temperature rise and recovery (insert) from eddy current heating due to fast current discharge into dump resistor.

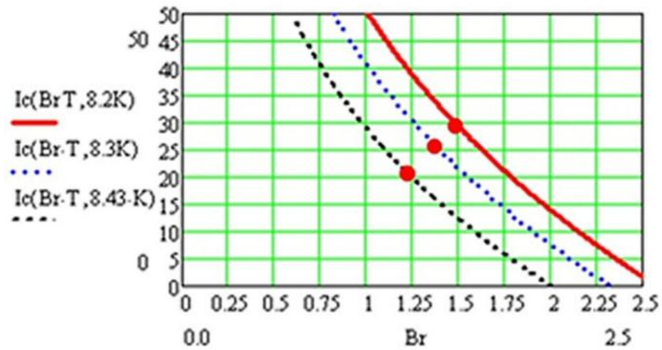

Fig. 6. The superconductor critical current as a function of coil peak field. Dots represent the quench currents (20 A, 25 A, 30 A) at elevated coil temperatures (8.43 K, 8.3 K, 8.2 K).

The rapid current discharge through the dump results in a very fast temperature rise due to eddy currents generated in the Aluminum cooling strips and in the iron shim in the split yoke gap, which quickly decays (see Fig. 5 insert). Subsequent current ramps to 30 A, made at up to 0.4 A/s, demonstrate that eddy current heating at high ramp rates (40 times the rate needed for ILC beam-based alignment) did not result in a quench.

The magnet cooled by conduction with only a single cryo-cooler has a large temperature margin (at 30 A current, and 1.5 T, 8.2 K - 4.2 K = 4 K). In the cryomodule, the quadrupole will be cooled to 2 K by a superfluid LHe supply pipe, resulting in a temperature margin more than 6 K at 30 A.

V. Conclusion

The splittable quadrupole for ILC-type cryomodules was successfully tested in the conduction cooling mode at KEK using a cryostat built by Toshiba, in which the heat load at 4 K was only 0.6 W. The test demonstrated good performance in the conduction cooling mode of the splittable quadrupole magnet, which showed no re-training and large (4 K) thermal margin consistent with short sample prediction, at currents up to 30 A. Fast ramping at 0.4 A/s did not cause a quench.

The magnet with the cryostat will be shipped to FNAL to continue the test to high current (>100 A) and perform high precision magnetic measurements [6] starting in the fall of 2012. In the farther future this facility will be valuable for performance testing of other small magnet styles that require a conduction cooling environment, suitable for cryomodules.

Acknowledgment

The authors thank M. Harrison, R. Kephart, M. Ross, R. Stanek, C. Adolphsen for the financial support of this program, and J. Tompkins, M. Lamm, A. Zlobin for labor resources. Many thanks to the Toshiba team for building such an advanced cryostat and for the final magnet assembly to operate in the conduction cooling mode.

REFERENCES

[1] "International Linear Collider Reference Design Report," http://www.linearcollider.org/cms/?pid=1000025.

[2] V.S. Kashikhin *et al*., "Design and Manufacturing Main Linac Superconducting Quadrupole for ILC at FERMILAB," *IEEE Transactions on Applied Superconductivity*, vol. 18, No. 2, June 2008, pp. 155-158.

[3] V.S. Kashikhin, *et al.,* "Test results of a superconducting quadrupole model designed for linear accelerator applications," *IEEE Transactions on Applied Superconductivity*, vol. 19, Issue 3, Part 2, June 2009, pp. 1176-1182.

[4] F. Toral, *et al*., "Magnetization Effects on the Superconducting Combined Magnet Prototype for XFEL"", *IEEE Transactions on Applied Superconductivity*, vol. 19. No. 3, June 2009, pp. 1136-1140.

[5] C.M. Spencer, *et al.*, "Measuring the Magnetic Center Behavior and Field Quality of an ILC Superconducting Combined Quadrupole-Dipole Prototype," *IEEE Transactions on Applied Superconductivity*, vol. 20, Issue 3, May 2010, pp. 1964-1968.

[6] G.V. Velev *et al.*, "A Fast Continuous Magnetic Field Measurement System Based on Digital Signal Processors," *IEEE Transactions on Applied Superconductivity*, Vol. 16, No. 2, June 2006, pp. 1374-1377.

[7] V. S. Kashikhin, *et al*., "Superconducting Splittable Quadrupole Magnet for Linear Accelerators," *IEEE Transactions on Applied Superconductivity*, vol. 22, No. 3, June 2012, p. 4002904.

[8] N. Kimura, et al., "Development of Cryogenic System for Large-scale Cryogenic Gravitational Wave Telescope," Proceedings of Cryogenic Society of Japan, vol. 85, 2011, p.218.

[9] L. Bottura, "A practical fit for the critical surface of NbTi," *IEEE Trans. Appl. Supercon.,* Vol. 10, No. 1, pp.1054-1057, 2000.