High Temperature Superconducting Quadrupole Magnets With Circular Coils

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***Abstract*—Particle accelerators use a variety of low field magnets. This paper describes a recently proposed, novel concept of using circular superconducting coils for multipole iron-dominated magnets. This type of magnet design is most suitable for the use in high temperature superconductors (HTS), as well as in react and wind magnet technology. The HTS quadrupole magnet with 45-mm aperture and 100-mm diameter coils was designed, fabricated, and tested. The magnet design includes the choice of superconductor, three-dimensional (3-D) magnetic field optimization, and mechanical design. The magnet models were tested at the liquid nitrogen temperature. This paper presents and discusses the test results.**

***Index Terms*—High temperature superconducting magnet, design, fabrication, test.**

I. Introduction

THE main goal of the proposed research and development project was to design, build, and test a high temperature superconducting (HTS) magnet with a novel configuration that is most suitable for HTS and that can work in the temperature range of 50 K–77 K. The intention is to implement recent advances in the field of HTS wire technology for multipole accelerator magnets. This activity is supported by the Fermilab LDRD Program. The first phase of the project is to build and test the novel HTS magnet [1] in FY2018–FY2019.

This is a novel important step in the field of magnet technology. Many room temperature and low temperature superconducting magnets could be replaced by HTS magnets. Doing so will result in energy and cost savings. The energy saving comes from the magnet's superconductivity and its ability to operate at an elevated cryogenic temperature. The cost savings comes from the reduced volume of the superconductor, the number of fabricated coils/magnets used, the configuration of the simple coils, and the substantially reduced number of power supplies for magnet strings, as shown in [2].

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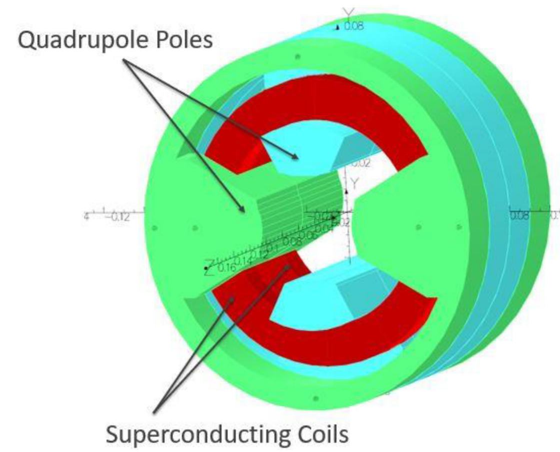

Fig. 1. Quadrupole magnet with two coils.

Three circular HTS coils were fabricated and assembled with an iron yoke forming a quadrupole magnetic field. Initially, the double coil magnet and the single coil magnets were tested at liquid nitrogen temperature to prove the design and magnet parameters. Linear accelerators based on superconducting magnet technology use a large number of relatively weak superconducting quadrupoles. In this case, an iron dominated quadrupole is the most cost-efficient solution. The field quality in this magnet is defined by iron poles; the magnet air gap is minimal as are the coil ampere-turns. Nevertheless, it contains long, racetrack type coils, which must be rigid and fixed by a mechanical structure to provide the needed mechanical stability [3]. The novel concept of using circular superconducting coils in such a quadrupole type (Fig. 1) was described, with a discussion of quadrupole parameters and the results of the three-dimensional (3D) magnetic designs. Variations of the short and long sectional quadrupoles and multipoles were presented in [1].

In the future, International Linear Collider (ILC) 4182 room temperature quadrupoles and 1050 sextupoles could be replaced by HTS magnets. The FNAL PIP-II CDR used room temperature quadrupoles between cryomodules. Using HTS magnets will make the project more attractive, which will promote this novel HTS magnet technology. In Italy, INFN initiated research and development (R&D) based on the concept proposed in [1] to fabricate a sextupole corrector magnet for future accelerators [3], [4].

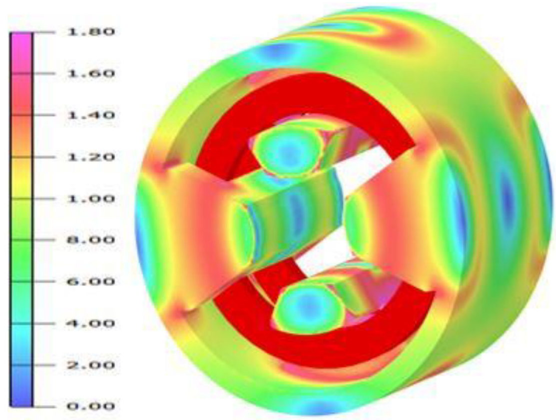

Fig. 2. Double coil quadrupole geometry and flux density distribution in the iron yoke for 3.7 kA coil ampere-turns.

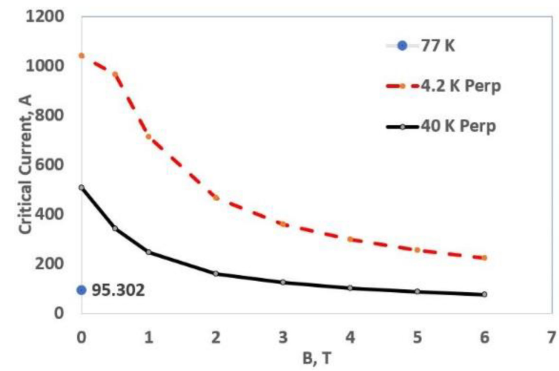

Fig. 3. Short sample superconductor SCS4050 test results. Data at B = 0 T related to the superconductor self-field. The field was perpendicular to the HTS tape surface or parallel the c-axis (H//c).

TABLE I
QUADRUPOLE PARAMETERS

Parameter	Unit	Single coil	Double coil
Magnet aperture	mm	45	45
Coil number of turns		20	94
Superconductor		BTG*	SCS4050**
Coil peak current***	A	185	10
Coil ampere-turns***	kA	3.7	0.94
Peak field in the coil	T	0.25	0.07
Field gradient	T/m	8.7	2.4
Magnet length	mm	50	100
Outer yoke diameter	mm	170	170

* Brookhaven Technology Group (BTG) superconductor.
** SuperPower superconductor.
*** Current reached at 77 K test.

II. Quadrupole Magnet Design

The main idea of the proposed magnet is to use a single circular coil instead of several coils to generate a multipole field. The magnetic flux in this case should be directed around the coil to the magnet poles constituting, for example, a quadrupole field configuration, as shown in Fig. 1. This geometry was proposed in [1] for superconducting coils. This configuration was also extended to superconducting short and long multipole magnets with different apertures.

In many cases, for a single coil quadrupole there is not enough quadrupole integrated field to generate a specified strength. Moreover, the single coil magnet produces a relatively low solenoidal longitudinal field component. This could be compensated for by adding a second magnet with the same configuration but reflected (symmetrical) relatively to the first magnet in the X-Y plane, as shown in Fig. 2. In this second magnet, the current should have a direction opposite to the current in the first magnet. This double coil quadrupole is shown in Fig. 2; its parameters are presented in Table I.

One can see that the double coil quadrupole is capable of generating 2 T–3 T of integrated field gradient in a length of 240 mm. These parameters meet, for example, the LCLS-II cryomodule magnet specification. The $<$0.5 T field on the coils and the large superconductor bending radius allows for the efficient implementation of HTS.

One of the most advanced HTS wires suitable for magnet applications is the 2G HTS wire (coated conductors), based on (RE)BCO (rare earth barium copper oxide elements).

III. Superconductor Parameters

To fabricate the double quadrupole coils, we used a SuperPower SCS4050 superconductor with the following dimensions: 4 mm $\times$ 0.1 mm. Its composition was 1% HTS, 40% Cu, 4% Ag, and 50% Hastelloy. The short samples were tested at various temperatures and different external fields (Fig. 3).

Thus, at 77 K and a peak coil field B = 0.25 T, the critical current reduction Ic[B]/Ic[self-field] = 0.5, and the current will be 48 A.

The single coil quadrupole was fabricated from the BTG superconductor. The cable was comprised of eight exfoliated YBCO filaments supported by a 50 μm thick copper stabilizer. A wide, 10 mm, YBCO filament was exfoliated from the metal substrate using a procedure described in [6]. The 10 mm wide tape was sliced into 2.4 mm wide filaments with a 200 W CO_2 laser slicing system operating in a reel-to-reel mode. Prior to the cable assembly, the filaments were coated with 40 μm of Sn62Pb36Ag02 solder by dip-coating. The coated filaments were arranged in a stacked array and sandwiched between two, 2.38 mm wide, 0.16 mm thick Nichrome ribbons (Hyndman Industries, standard Kanthal A1 ribbon), and then wrapped with 40 AWG Nichrome wire with 2 mm pitch. The total cable thickness was approximately 1.2 mm.

IV. Magnets Fabrication

Two quadrupole magnets were fabricated at Fermilab. The pre-assembled low carbon steel yoke parts are shown in Fig. 4. The simple winder (Fig. 5) was used to wind two, double pancake coils. Each coil has 94 turns. We did not use the coil vacuum impregnation with an epoxy in order to have the possibility of working out the coil leads, which was expected to create some issues because of the rather sharp bending from the tangential

Fig. 4. Pre-assembled two quadrupole yoke rings.

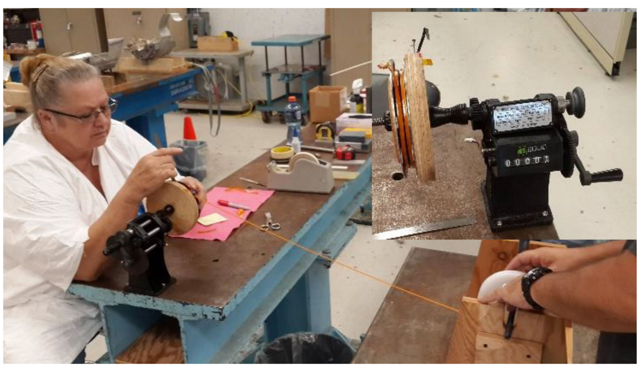

Fig. 5. Double pancake coil winding, and the winder in the top right corner.

to the radial direction. Yoke rings have slots to accommodate these leads.

Both coils were mounted onto the iron yoke rings, and their outer surfaces were radially compressed by aluminum rings to avoid conductor motion under Lorentz forces.

The BTG coil was wound around a 160 mm aluminum former with 10 N tension. The current leads were made by soldering the YBCO filament stack to a 200 mm thick, 30 mm long copper foil tap. Then, 3 mm braided copper wires were soldered to the tap, thus finishing the current lead. We did not use any insulation. Instead, the layer separation provided by the Nichrome wire wrap provided partial insulation. The voltage leads were 32 AWG polytetrafluoroethylene-insulated wires (Alpha wire) directly soldered to the edge of the superconducting filament stack. After the winding, the coil assembly was placed in a furnace for the re-flow step, which took 10 min at 182 °C. During the re-flow-step, the solder partially melted thus fusing the filaments into an electrically-connected solid. After characterization of the *as-wound* coil at 77 K, the same set of measurements was repeated after the re-flow and epoxy impregnation steps. The transport current was provided by Sorensen 10/1200 power supply, and the coil voltage was measured using a Keithley 182 nano-voltmeter.

We used Stycast 1266, low-viscocity epoxies for the winding impregnation. The coils were wrapped with six layers of 5 mil fiberglass and placed in a tight-fitting mold filled with epoxy. The mold was evacuated in a vacuum chamber for 20 min, after which the epoxy was cured following the manufacturer's recommended curing profile.

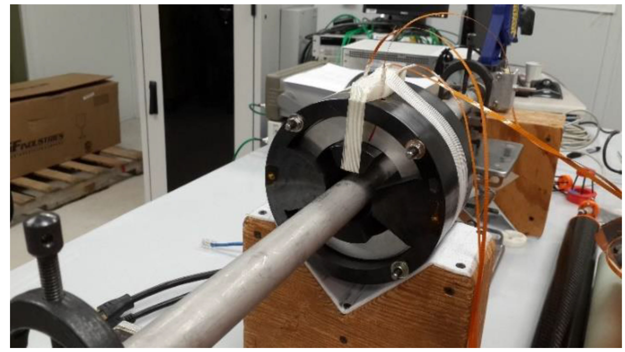

Fig. 6. Field measurements using a rotational coil system.

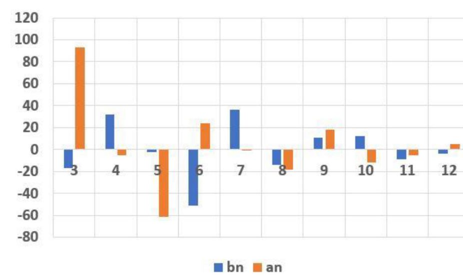

Fig. 7. Normal **bn** and skew **an** field harmonics at the 15 mm reference radius.

V. Two Coils Magnet Tests

Initially, the quadrupole magnet field was measured at room temperature using the rotational coil system shown in Fig. 6. The field harmonics were measured at a very low current (0.5 A) to avoid overheating the conductor.

Fig. 7 shows the measured harmonics in units (10^{-4}), which, in general, are in agreement with the design.

It should be noted that, during measurements at such a low current, about 40 units of harmonics fluctuations were observed for various rotations.

After obtaining the room temperature measurements, the magnet was mounted to the support structure (Fig. 8) and tested in the liquid nitrogen bath.

Fig. 9. Shows how coil resistive voltages increase with the current.

Because voltages typically increase in the same way, it was suggested that this causes issues with the leads and splice. This suggestion was confirmed by the magnet disassembly when we observed very sharp bends in the conductor leads. The conductor leads were damaged during the coil final assembly with the iron yoke when the conductors were directed in the lead slots in the yoke. Both coils have been rewound now, and they provide a lower curvature pass for the leads through the yoke. Soon, the magnet will be retested.

VI. Single Coil Magnet Test

The single coil magnet was assembled with the superconducting coil fabricated by BTG* and two, low carbon steel rings

Fig. 8. Quadrupole magnet after the cold test at 77 K.

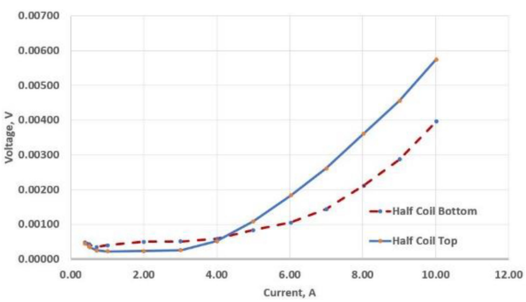

Fig. 9. Quadrupole coil voltages vs. currents for the 77 K test.

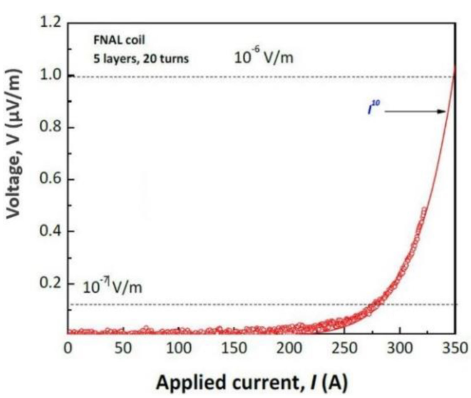

Fig. 10. The BTG coil test in the self-field at 77 K.

(Fig. 4). Initially, the coil without the iron yoke was tested in the liquid nitrogen without an external field. Test results are shown in Fig. 10. The coil has 20 turns wound from the HTS cable [6]. The coil current reached 275 A when the resistive voltage increased to 0.1 mV.

After assembling the coil in the quadrupole yoke, the magnet was tested at the Fermilab test facility in the liquid nitrogen bath. The magnet reached the 185 A current without a substantial increase in voltage. Figure 11 shows the test results for the magnet 1 A/s ramps up and down. The inductive voltage was at the level of 0.4 mV. At higher currents, this voltage decreases because of the iron saturation effects and the substantial

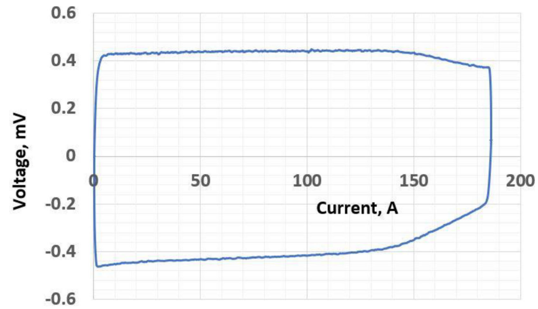

Fig. 11. Single coil quadrupole test at 77 K.

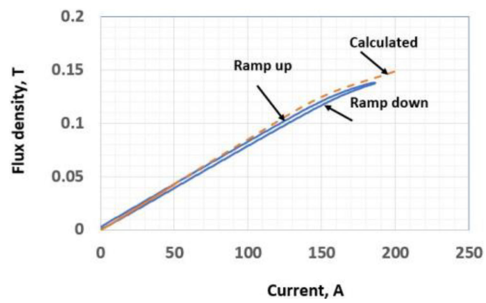

Fig. 12. Single coil quadrupole Hall probe field at 77 K.

inductance decrease. The current ramp was stopped when the coil resistive voltage reached 10 μA.

During the tests, the magnetic field was monitored by a Hall probe, which was mounted 5 mm from the pole. There was good agreement between the measured and calculated data, as shown in Fig. 12. After 150 A, the magnet yoke started to show some saturation effects.

VII. Conclusion

Two quadrupole magnets with different coils were designed, fabricated, and tested. We identified current limiting issues for the first magnet, and leads repair is in progress. The second HTS cable-based magnet achieved design parameters, and we confirmed the feasibility of using HTS cables. During the tests, no magnet quenches were observed. The work will continue to upgrade magnets for a cryogen-free operation with a cryocooler.

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