HTS Dipole Magnet Model for the Persistent Current Operation

Vladimir Kashikhin, Daniele Turrioni

Abstract—**Recent advances in the fabrication of high-temperature superconducting (HTS) coils allow the design of superconducting accelerator magnets that work in a persistent current mode. Many various, rather low-field magnets in particle accelerators operate in the DC current mode. Fermilab designed, fabricated, and tested an HTS dipole magnet model that has 20-mm air gap and a magnetic field up to 0.5 T. The magnet has a primary copper coil that for a short period pumps the energy in the short-circuited secondary HTS coil. The current paper presents the design, fabrication, and testing of this magnet at liquid-nitrogen temperature.**

Index Terms— **High Temperature Superconducting, Persistent Current, Accelerator Magnet, Magnet Test.**

I. Introduction

HIGH temperature superconducting (HTS) magnets are of great interest in the future applications. This paper describes activity conducted at Fermilab for the development of an HTS accelerator dipole magnet that works in a persistent current mode. Previously, quadrupole magnets with circular HTS coils were used as a test bench for novel HTS coil configurations [1] – [6]. The stable current induced in HTS short-circuited loops generate a highly stable magnetic field in the quadrupole aperture [7] – [9]. These successful tests made visible the design, fabrication, and testing of HTS dipole magnets.

II. Short-Circuited HTS Coils

Most high temperature superconductors are manufactured in the form of a thin tape. For HTS coils, several issues have been found difficult to resolve:

- It is difficult to fabricate superconducting splices between HTS conductors.
- The quench propagation velocity in the multi-turn HTS coils is very slow, which could easily overheat and damage the superconductor. Additionally, the quench detection and HTS coil protection systems are complicated.
- The HTS multi-turn coil performance is limited by the lowest superconductor property along the superconductor tape length. Even small defects or errors while winding this brittle conductor could completely damage the coil.

The main idea of the proposed HTS coil is to use a stack of HTS tapes and cut them in a longitudinal direction without cutting at the ends. Coil ends should have enough length to transport the circulation in the loop current. After cutting, the stack of loops is formed in a round configuration as shown in Fig. 1.

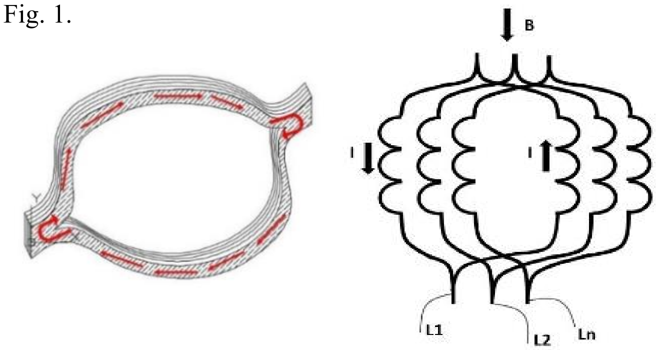

Fig. 1. HTS coil assembled from parallel loops. Arrows show the circulating current ***I*** directions. ***L1 – Ln*** conductor loops, ***B*** – flux density.

Several HTS coils were successfully tested in various magnet configurations [9]. Inducing a continuously circulating current in the HTS coil involved using the current transformer schematic shown in Fig. 2. The primary and secondary coils need to be strongly inductively coupled. Initially, the main power supply (MPS) ramps up to the maximum current, inducing the opposite current (Lentz's law) in the HTS secondary. If both coils are 100% coupled, then the current induced in HTS is equal to the total primary winding ampere-turns. In the next step of the

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operation, the HTS coil current was reduced to zero by heating from the heater power supply (HPS). Then, the HPS was turned off and the HTS coil returned to its superconducting state.

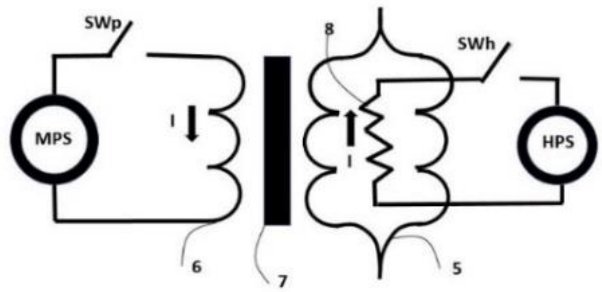

Fig. 2. Magnet system schematic. MPS and HPS – main and heater power supplies, 6 – primary winding, 5 – secondary HTS coil, 7 – magnet core, 8 – heater, SW – switches.

Finally, the MPS current ramped down to zero inducts the continuously circulating current into the HTS coil. The test in liquid nitrogen (LN_2) showed fast HTS coil heating and cooling, which defined the short time cycle of the current transformer.

III. HTS Dipole Magnet Design

The HTS dipole magnet has a conventional iron-dominated accelerator magnet configuration having a gap of 20 mm. The OPERA3D magnet model is shown in Fig. 3.

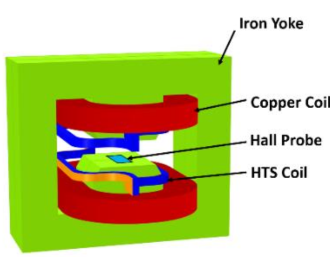

Fig. 3. Magnet model with copper and HTS coils.

It is useful to simulate the current induced in HTS coils by primary copper coils. For the simulation OPERA3D ELEKTRA transient analysis code was used [10]. To avoid singularities HTS coil superconducting loops were modeled by conductors with very high conductivity. The total current in the primary copper coils was ramped down exponentially with the time constant of 1 s from 4 kA to zero, inducing about the same current in HTS coils as shown in Fig. 4.

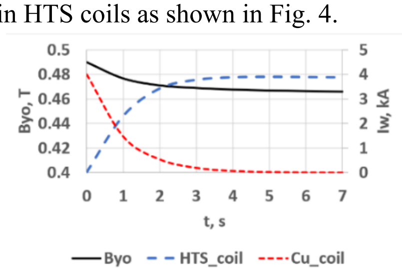

Fig. 4. Flux density in the gap and total currents (Iw) in HTS and Cu coils.

The current induced in HTS coils supports the "frozen" flux in the coils, which generates a slightly lower magnetic field in the magnet gap. This difference is explained by a smaller HTS coil geometry which generates ~6 % lower field than the copper coil as shown in Table 1. The total HTS coil current was obtained by a current-density integration of the coil cross-section. It was rather difficult to model HTS coil loops having just 2-µm thickness of the HTS from 100 µm of the total thickness. It is almost impossible to generate the reasonable mesh for this multi-loop HTS coil. The HTS coil was modeled by six short-circuited loops having 1 mm thickness. The magnetic field penetration in HTS coils was provided by a slow current down ramp in the primary coil. Fig. 5 shows equal current density distribution in all HTS loops. A more accurate analysis of current density distribution would include the superconductor properties combined with the critical current density.

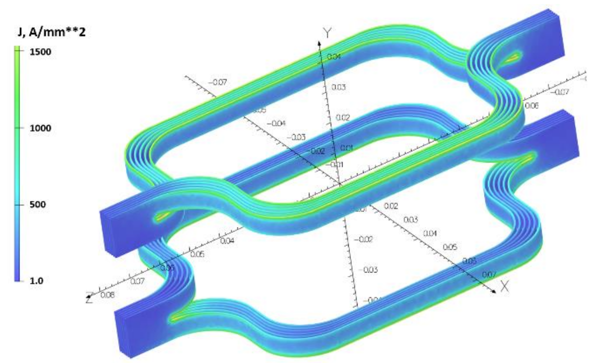

Fig. 5. HTS coil model and induced current density.

Because the primary coils spend only a short time pumping energy in the secondary HTS coils, they could be wound from a copper wire, which extremely reduces the cost of magnet. Copper coils were cooled to the LN_2 level of 77 K.

Experiments with the quadrupole magnet immersed in LN_2 provided good results because of the direct copper coil cooling [9]. The maximum copper coil temperature was only 80 K, even for 70 s ramp time; the maximum current was 350 A. At the same time, the HTS coil stayed at 77 K, but the induced current was efficiently zeroed by the coil heater. This promising result revealed approaches to combining the copper primary coils with the secondary HTS coils. It also substantially reduced the magnet cost because of the inexpensive primary coil and the simple secondary HTS without current leads.

IV. Dipole Magnet Fabrication

The dipole magnet consists of three major elements: (a) two copper primary coils, (b) two HTS coils, and (c) an iron yoke split in the middle. The copper coil has 20 turns, and the HTS coil has 112 loops of REBCO superconductor. The HTS coil has Kapton insulation, and heater wire wound around all loops forms a toroidal coil. On the top of the heater wire was wound a layer of Kapton insulation. The dipole magnet's main parameters are shown in Table 1.

TABLE I
DIPOLE MAGNET DESIGN PARAMETERS

Parameter	Unit	Primary coil	Secondary coil
Magnet gap	mm	20	20
Coil number of turns/loops		20	112
Conductor		Copper	HTS
Conductor dimensions	mm	2x2	0.1x12*
Coil total current	A	4000	4000
Peak field in the gap	T	0.49	0.46
Inductance (single loop coil)	μH	1.8	1.1
Magnet length	mm	50	
Outer yoke dimensions	mm	171.5x147.2	

*12 mm superconductor from SuperPower split to form 6 mm wide loops.

The iron yoke was assembled from 0.35 mm thick laminations. Laminations were taken from an EI 225 industrial transformer and modified by EDM cutting to form the magnet pole as shown in Fig. 6.

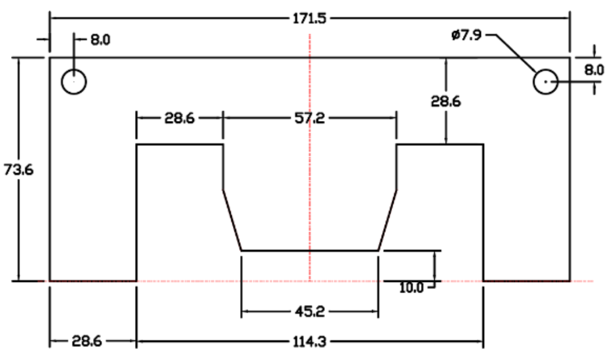

Fig. 6. Upper dipole magnet lamination. Dimensions in mm.

Copper and HTS coils were clamped to the top and bottom of the iron yoke. The nichrome heater wire leads were connected to a 10 A x 30 V DC regulated power supply.

The magnet was also instrumented with voltage taps and thermal sensors connected to the LabView based data acquisition system. Two Hall probes were mounted on the magnet poles to monitor the total magnetic field generated in the magnet gap by all coils. Fig. 7 shows the assembled magnet model.

Fig. 7. HTS dipole magnet view.

V. HTS DIPOLE MAGNET TEST

The magnet was tested in the LN_2 bath. Fig 8 shows the magnet test setup when the magnet had just been removed from the LN_2 bath.

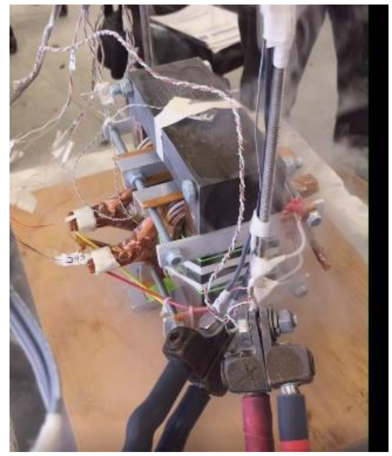

Fig. 8. The magnet test setup when the magnet had just been removed from the LN_2 bath but HTS currents continued to circulate for about 10 s.

The magnet test cycle included a cooling down to the LN_2 (77 K) temperature. Then the primary coil was energized from the computer-regulated 2 kA x 5 V power supply. The primary coil's magnetic field induced in the secondary HTS coil's currents circulated in the opposite direction relative to the primary coil current to suppress the flux rise. Initially, the primary coil currents were tested in the range of 100 A–300 A. The HPS was energized to eliminate these currents in HTS coils, but because the coils were immersed in the LN_2, it was not enough heater power to transfer the superconductor in a normal (non-superconducting) condition. Only when starting the primary currents from 400 A were heaters capable of clearing induced currents in HTS coils. After that, the primary current was reduced to zero, inducing the final operational current in HTS coils. At this moment, the primary power supply was disconnected but HTS coils continued to generate the magnetic field working in a persistent current mode. Fig. 9 shows the magnet test results at 500 A primary coil peak current.

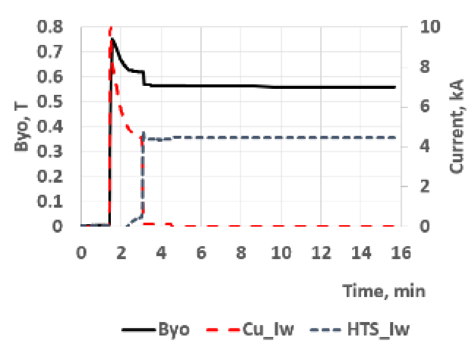

Fig. 9. The magnet test for 500 A in the primary copper coils.

Fig. 9 shows a fast primary coil decay current caused by the copper material heating and the limited 5 V power supply peak voltage. The peak stable induced current in HTS coil was 4.47 kA, which corresponds to 40 A an average current in the HTS loops. The HTS coil current was calculated from the magnetic field measured by Hall probes. Fig. 10 shows the test monitoring system at 500 A peak primary current when the continuously circulating current generated 0.5 T in the magnet gap.

Fig. 10. The HTS magnet test monitoring system.

The long-term magnet performance was verified during a 14-hour overnight test until all LN_2 was evaporated from the bath and the magnet was quenched at 90 K of HTS coil temperature (see Fig. 11). The magnetic field was stable during this period, and the primary power supply was disconnected.

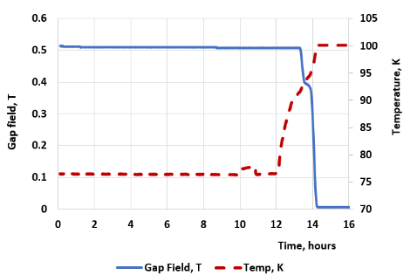

Fig. 11. Long term magnet test in a persistent current mode.

The magnet temperature was also stable, but when the boiling liquid level reached the temperature sensor after 10 hours of operation, there were some ~3 K temperature fluctuations, which in 1 hour returned to the 77 K value. Superconductor resistivity increased with the rise in the temperature, which slowly reduced HTS coil current and the magnetic field, as shown in Fig. 11, meaning the magnet HTS coil is self-protected against the dangers of fast superconductor quenches. Nevertheless, Fig. 12 (scaled up Fig. 11) shows small, less than a single loop, average current of 40 A HTS current and corresponding field jumps.

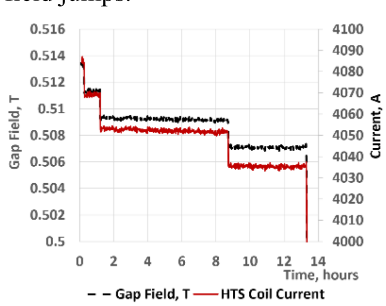

Fig. 12. HTS coil current jumps.

The result means some loop areas reached the critical parameters and a small fraction of energy was dissipated in this loop resistivity, reducing the total current in the coil. In this situation, as was shown in [9], the short pulse of the heater could stabilize the HTS coil current and field to the level better than 0.05 % which is enough for accelerator magnets.

Conclusion

The HTS dipole magnet was designed, fabricated, and successfully tested. The magnet's ability to work in a persistent current mode was confirmed by a 14-hour test in an LN_2 bath. The stable 0.5 T field was generated in the magnet gap. The peak field was limited by the voltage (5V) of the primary power supply, the heater's low efficiency, and the iron yoke saturation.

This type of HTS coil is very stable against quenches because it consists of large number of parallel superconducting loops having low thermal resistance between them. When resistance grows in one loop the current in other loops increases to compensate the possible flux variation. From this point of view the HTS coil is self-protected. In this parallel system possible defects in one loop just reduces the current in this loop without disturbing magnet performance like in multi turns coils.

We are planning to redesign the magnet to generate higher magnetic field. It should be noted that these magnets could work at a lower temperature in the range of 20 K–40 K provided by cryocoolers. In this case, HTS superconductors will be capable of carrying several times higher currents and generating proportionally higher magnetic fields.

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