HTS Quadrupole Magnet for the Persistent Current Mode Operation

Vladimir Kashikhin, Daniele Turrioni

Abstract— **In this study, a new high-temperature superconducting (HTS) quadrupole magnet with circular coils was designed and built at Fermilab. Several HTS coils were also investigated at the temperature of liquid nitrogen. The main goal of this activity was to investigate the coils and magnet operation in a persistent current mode to reduce accelerator magnets' capital and operational expenses. To accomplish this, HTS short-circuit coils were used. In the paper, HTS coils and magnet design, fabrication, and tests were discussed. The magnetic field in the magnet aperture and the field decay when the magnet operated in the "frozen flux" mode were measured. The test and simulation results were compared, confirming the advantages of the proposed approach.**

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

I. INTRODUCTION

THIS paper describes experimentation initiated at Fermilab related to the design, fabrication, and testing of high-temperature superconducting (HTS) coils and quadrupole magnets. Previous papers presented novel configurations of multipole iron-dominated magnets with circular superconducting coils [1–6]. This magnet configuration is most suitable for fabrication of round coils wound from high-temperature tape-type superconductors, which are sensitive to sharp bends and deformations.

There is currently substantial interest in designing magnet systems capable of operating in a persistent current mode like MRI NbTi-based solenoids. However, in these solenoids, a large inductance combined with nano-ohms splice resistances provides a large time constant of trapped current decay. For HTS-based magnet systems with much lower inductances and larger splice resistances, the operation in this mode is an issue.

One of the options for resolving the issue described above is using HTS coils without splicing, and longitudinal cuts of HTS tape without the ends cut have been explored [7]. This approach has been used for solenoids, but it has a complicated coil winding technology [8]. We explored another novel technology where the HTS coil is assembled from parallel superconducting loops. In this case, the magnet system consists of a primary coil used as a magnetic field source and a secondary one where the induced current circulates. In the initial stage, we used a permanent magnet assembly to generate the current in a secondary short-circuit coil. This test allows verification of whether the large fraction of flux in agreement with Lentz's low transferred into the secondary HTS coil. Following this, we tested the quadrupole magnet assembly as in [6], but the system was combined with an HTS closed-loop-type coil (see Fig. 1).

II. CLOSED LOOPS HTS COILS

The main idea of the proposed HTS coils is using a stack of HTS tapes and cutting 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 the cut, the stack of loops is formed in a round or other configuration as shown in Fig. 1.

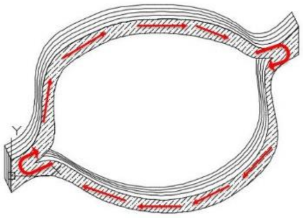

Fig. 1. HTS coil assembled from parallel loops. Arrows show the circulating current directions.

Two types of coils were tested with outer and inner current return ends (see Fig. 2).

Fig. 2. Tested HTS coils with outer ends (left) and inner ends (right).

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The HTS coils had external Kapton electrical insulation with wound on the top toroidal Rogowski coil to measure total current. Coils also had heaters and voltage taps wires.

III. HTS Coil and Permanent Magnet Test Setup

A. Cold Test Setup

For the initial coil tests, a permanent magnet setup was used. Eight $SmCo_5$ permanent magnet bricks were assembled on the ferromagnetic plate for generating the primary magnetic field in the vicinity of the HTS coil (see Fig. 3).

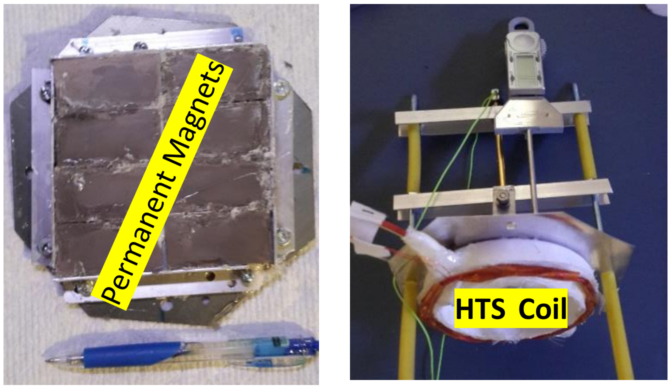

Fig. 3. Permanent magnets assembly (left) and HTS coil (right).

The sets shown in Fig. 3 were assembled in the test setup shown in Fig. 4.

Fig. 4. Permanent magnet test setup to test HTS coils.

The HTS coil assembly could move up or down in the vertical direction. The coil position was controlled by a digital dial indicator. Tests were performed in liquid nitrogen at a temperature of 77 K. Initially, the coil was fixed in the uppermost position, and after cooling, it slid down under the coil weight. Induced in the coil current provided their levitation. When loaded with extra iron block weight, the induced current increased until the gap between the permanent magnet and coil closed. In this case, the maximum possible current circulated in the coil, defined by the strength of the permanent magnets and the superconductor's critical current.

B. Field Simulation

The magnetic field of this assembly was simulated by OPERA3D to verify the parameters that could be achieved in the "frozen flux" mode of operation. The simulated model and results are shown in Fig. 5 and Table 1.

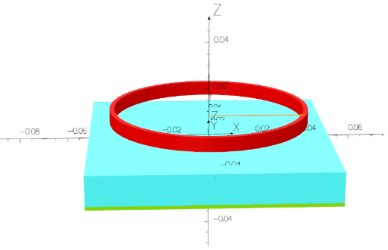

Fig. 5. Model of HTS coil with the permanent magnet.

TABLE I
Calculated Parameters

Coil Iw, kA	Coil Fz, N	*Coil Bz, T	Coil flux, Wb
0	0	0.1	0.00057
2	35.5	0.064	0.00026
4	***70***	***0.027***	***-0.000061***
6	103	-0.01	-0.00038
8	134.7	-0.048	-0.0007
10	164.9	-0.085	-0.006

*z=10 mm from the permanent magnet surface to the Hall probe on the coil outer surface.

The "frozen flux" condition for the coil fulfilled at 4 kA induced the current with a vertical load of 70 N or 7 kg applied to the coil (See Table 1).

C. Cold Tests

The test setup was placed in a can, and this was filled with liquid nitrogen. The coil was in the uppermost vertical position. After several minutes of assembly cooling, the coil was released and dropped to the self-supporting (levitated) position.

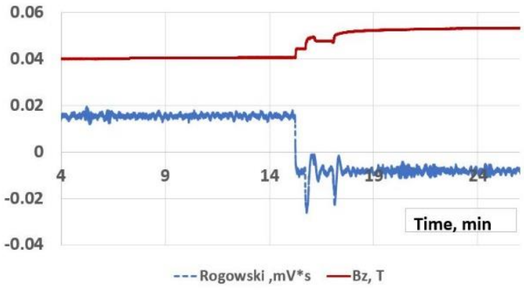

Fig. 6. Coil field and Rogowski coil integrated voltage.

Following this, the coil was loaded with a weight of 1.2 kg. The coil stably levitated during 10 min (see Fig. 6), with a field of 0.04 T on the surface where the Hall probe was positioned. After 15 min of testing, the weight was doubled to 2.4 kg. The gap between the coil and permanent magnet block was closed with the corresponding field increase to 0.053 T. The induced HTS coil currents measured by the Rogowski coil were 655 A and 1017 A correspondingly. It is a promising result that the magnetic field was highly stable (better than 0.5 Gauss; see Fig. 7) for the fixed coil and Hall probe positions.

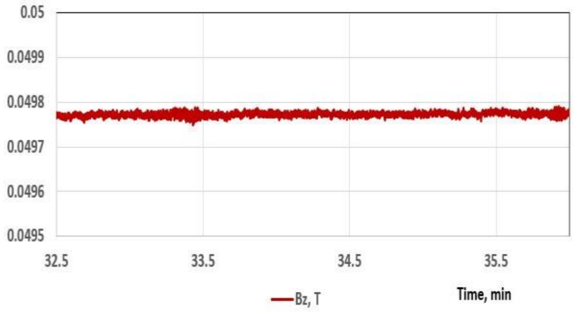

Fig. 7. Magnetic field stability in the persistent current mode.

Several coils were tested, and none of them were damaged during warming up. It was almost impossible to quench the coil in the liquid nitrogen via mounting on the coil surface heater. When the assembly with the trapped current was lifted from the bath, the HTS resistance slowly grew and the current slowly dissipated.

IV. QUADRUPOLE MAGNET

A. *Quadrupole Magnet Parameters*

For the quadrupole magnet, the iron yoke and primary HTS coil from previously tested magnets were used [6]. In the space between the yoke and coil, the secondary HTS coil, assembled from 50 HTS closed loops, was mounted (see Table 2). Around the coil was wound a nichrome heater wire of 3.3 Ω resistance. Finally, on the coil were wound 200 turns of Rogowski toroidal coil to measure the current.

Fig. 8. Quadrupole magnet with two round HTS coils.

TABLE II
QUADRUPOLE PARAMETERS

Parameter	Unit	Primary coil	Secondary coil
Magnet aperture	mm	45	45
Coil number of turns		20	50
Superconductor		BTG*	SCS12050**
Coil peak current***	A	185	5 (estimated)
Coil ampere-turns***	kA	3.7	-
Peak field in the coil	T	0.25	
Field gradient	T/m	8.7	
Magnet length	mm	50	
Outer yoke diameter	mm	170	

* Brookhaven Technology Group (BTG) HTS coil [6].
** SuperPower superconductor 12 mm wide.
*** Current reached in the self-field at 77 K test.

The secondary coil was assembled from 50 loops of 12-mm-wide HTS wire cut in the middle as shown in Fig. 1. The magnet was instrumented with voltage taps and three Hall probes mounted on the magnet poles to monitor the total magnetic field generated by both HTS coils.

B. *Magnet Cold Tests*

The magnet was tested several times in the liquid nitrogen bath. Initially, it was tested with 50 A in the primary coil, which has 20 turns, and correspondingly, a total current of 1000 A (see Fig. 9).

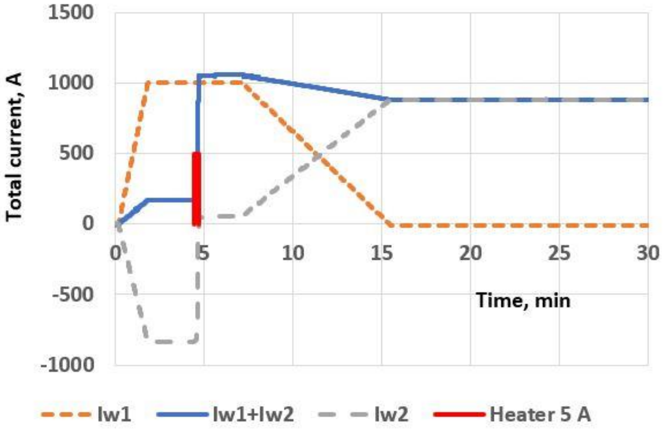

Fig. 9. Magnet test with the 1000 A peak total current in the primary coil.

When the total current in the primary reached 1000 A, a negative current of 833 A was induced in the secondary, which could be explained by the lack of 100% coupling between the two coils. After 4.5 min, the heater was energized by a 5 A current pulse, which transferred the secondary coil in the normal condition with a corresponding current jump to zero. Later, the primary total current was ramped down to zero at 2 A/s. The positive 883 A current was induced in the secondary circulating without decay, generating the stable magnetic field in the magnet aperture (see Fig. 10).

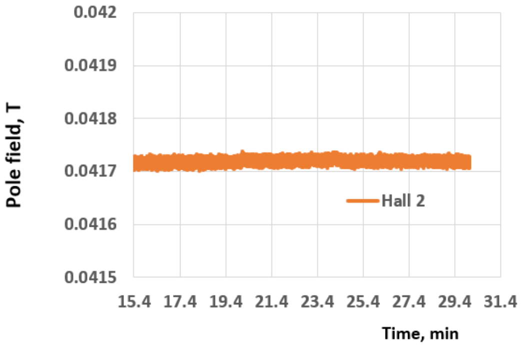

Fig. 10. Magnet field in the aperture on the pole surface.

It could be observed that the magnetic field was stable in the range of 0.2 Gauss, representing the Hall probe resolution. This was a promising result for accelerator magnet designers. The primary coil ramp to 2000 A is shown in Fig. 11.

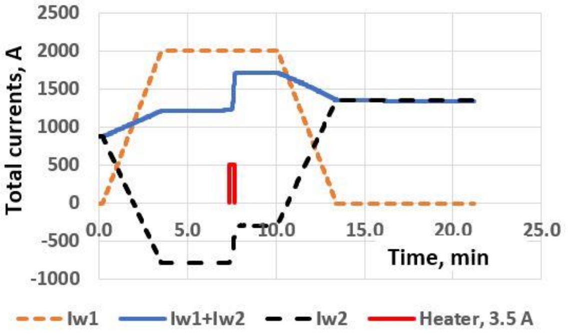

Fig. 11. The primary coil current ramp to 2000 A.

Measured using the Hall probe, the magnetic field stability was again in the range of 0.2 Gauss. The secondary coil current reached only 1344 A because a ramp down occurred due to not being fully cleared secondary current by the heater. The 3000 A primary coil total current ramp is shown in Fig. 12.

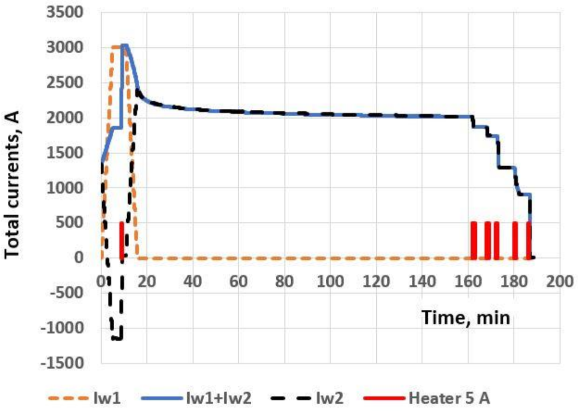

Fig. 12. The primary coil current ramp to 3000 A.

The peak secondary current was 2283 A, which initially had a fast decay and became much slower later, with a rate of 0.78 A/min. This means that the secondary coil at this current had a residual resistivity with some areas in a not fully superconducting condition. After 160 min of stable secondary current circulation, five short heater pulses were initiated to check for the possibility of the secondary current's controlled ramp down regulation. The coil was not quenched and showed stable performance. The maximum stable secondary coil performance was found to be close to 1900 A at 2400 A in the primary current (see Fig. 13).

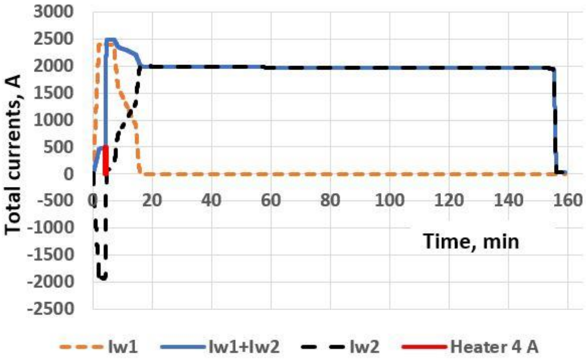

Fig. 13. The primary coil current ramp to 2400 A.

The current in the secondary circulated for more than 2 hours without decay, continuously generating the magnetic field in the magnet aperture without an external power source.

V. CONCLUSION

Several HTS coils with a closed-loop configuration were successfully tested with the permanent magnet and quadrupole setup. During the tests, no magnet quenches were observed. The HTS coils and quadrupole magnet operations were successfully demonstrated in a persistent current mode without an external power source.

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