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TESTING OF A SINGLE 11 T Nb_3Sn DIPOLE COIL USING A DIPOLE MIRROR STRUCTURE*

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Abstract

FNAL and CERN are developing an 11 T Nb_3Sn dipole suitable for installation in the LHC. To optimize coil design parameters and fabrication process and study coil performance, a series of 1 m long dipole coils is being fabricated. One of the short coils has been tested using a dipole mirror structure. This paper describes the dipole mirror magnetic and mechanical designs, and reports coil parameters and test results.

INTRODUCTION

A 5.5 m long twin-aperture 11 T Nb_3Sn dipole magnet is being developed by FNAL and CERN for the LHC collimation system upgrade [1]. Two of these dipoles with a collimator in between will replace one 14.3 m long 8.33 T NbTi LHC main dipole. The 2 m long dipole demonstrator tested at FNAL in 2012 reached 10.4 T [2] and the 1 m long dipole model tested in 2013 achieved 11.7 T at the LHC operating temperature of 1.9 K [3]. Both magnets demonstrated extensive training and substantial conductor degradation. To better understand and improve the magnet quench performance, a 1 m long dipole coil was fabricated and tested using a dipole mirror structure. This approach allowed testing a standard 11 T dipole coil in a different mechanical structure, but at operating conditions similar to those seen by a real dipole.

This paper describes the magnetic and mechanical designs of the dipole mirror for testing 11 T dipole coils. The coil parameters, fabrication details, instrumentation and test results are also presented and discussed. Quench protections studies are reported elsewhere [4].

DIPOLE MIRROR DESIGN

To provide an efficient way to test and optimize Nb_3Sn dipole and quadrupole coils, appropriate magnetic mirror configurations were developed and successfully used at FNAL [5, 6]. The design of the dipole mirror for testing 11 T dipole coils is based on the mechanical structure of the dipole mirror HFDM developed and used at FNAL to test smaller aperture Nb_3Sn dipole coils [5]. The cross-section of the 11 T dipole mirror MBHSM01 is shown in Fig. 1. The coil covered by ground insulation and thin stainless steel protection shell is placed inside a horizontally split iron yoke and pre-compressed by two Aluminum clamps and a bolt-on stainless steel skin.

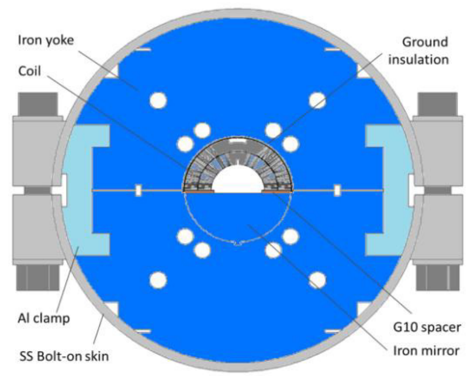

Figure 1: MBHSM01 dipole mirror cross-section.

High magnetic permeability of the mirror at low fields ensures dipole-like field and Lorentz force distributions in the coil. At high fields, due to the iron saturation, the field and Lorentz force distributions change in the coil mid-plane turns. Fig. 2 shows the 2D magnetic flux diagrams in the dipole mirror yoke (left) and coil (right) at 17 kA calculated using ROXIE [7] with non-linear iron magnetic properties. The plot in Fig. 3 shows that the field (and the Lorentz force) in the coil pole turns in both the 1 m long 11 T dipole and the corresponding mirror configuration is practically the same at all currents.

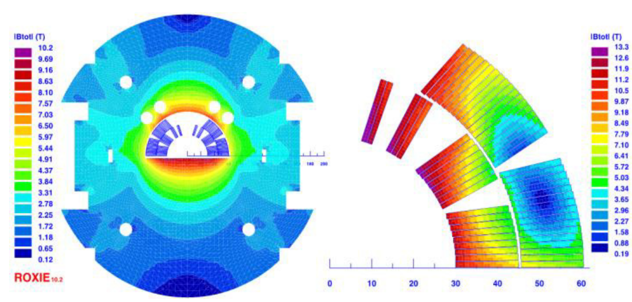

Figure 2: Magnetic flux distribution in the mirror magnet yoke (left) and the coil (right) at I=17 kA.

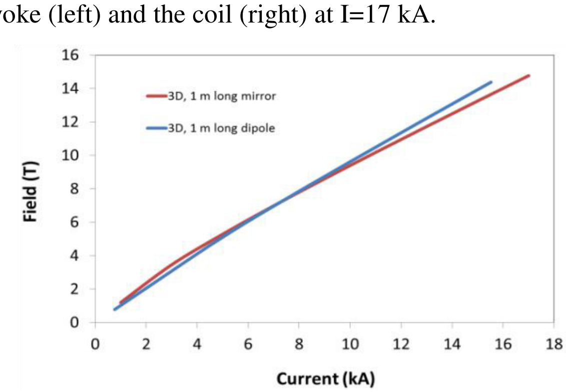

Figure 3: Magnetic field vs. current in coil pole turns.

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COIL AND MIRROR FABRICATION

The MBH coil design and baseline fabrication process are described in [2, 3]. The two-layer coil consists of 56 turns wound from a single piece of cable insulated with 0.075 mm thick and 12.7 mm wide E-glass tape with ~50% overlap. The coil poles are made of Titanium alloy whereas wedges, end spacers and saddles are made of stainless steel. The MBH08 coil uses a 40-strand Rutherford cable with 0.7 mm RRP-108/127 strand and a 0.025 mm thick and 11.5 mm wide stainless steel core. End parts used in coil MBH08 have the same design as in previous coils. During winding each coil layer was impregnated with CTD-1202X liquid ceramic binder and cured under a small pressure at 150ºC for 0.5 hr. During curing, the MBH08 inner and outer layers were shimmed in the mid-plane to a size smaller than the nominal coil size by 0.8 mm and 1.3 mm respectively to provide room for the Nb_3Sn cable expansion during reaction. The MBH08 coil was reacted in Argon using a 3-step cycle with T_{max}=640°C for 48 hrs. Then the coil was impregnated with CTD101K epoxy and cured at 125°C for 21 hrs.

To study quench development and propagation in 11 T dipole coils, protection heater efficiency and coil heating during a quench, MBH08 was equipped with protection and spot heaters. Two standard protection heaters, made of 0.025 mm thick stainless steel strips, were placed on each side of the coil between the 1st and 2nd layer of the ground insulation. The spot heaters were installed in the coil straight section under the inner and outer-layer midplane turns. The coil was also instrumented with voltage taps and a quench antenna (QA) to detect and localize quenches during magnet quench performance and protection heater studies. The voltage tap scheme and relative position of QA pick-up coils are shown in Fig. 4.

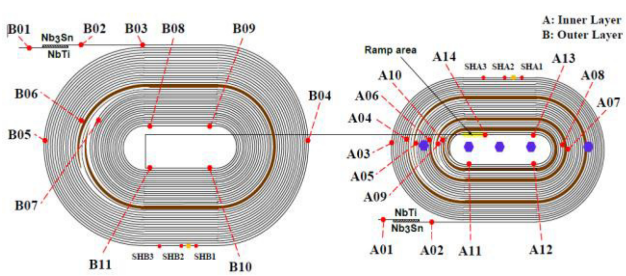

Figure 4: Voltage tap scheme in MBH08 coil.

The MBH08 coil and the mirror blocks were placed inside a horizontally split 400 mm iron yoke which covers the entire coil length including the Nb_3Sn/NbTi lead splices. A small initial pre-load was applied to the coil and fixed with Aluminum clamps. Then the yoked coil was installed inside the 12 mm thick bolt-on skin and compressed in the press to the target coil pre-stress which was secured with stainless steel bolts. A small axial load to each coil end was applied and controlled by two instrumented bolts (bullets) on each end through 50 mm thick stainless steel end plates. The MBHSM01 dipole mirror inside the bolt-on half-skin is shown in Fig. 5.

Figure 5: MBHSM01 mirror inside the bolt-on half-skin.

Due to the smaller azimuthal Lorentz force produced in mirror configurations, the maximum coil pre-stress of ~130 MPa after cooling down allows keeping the coil under compression up to its short sample limit.

TEST RESULTS

MBHSM01 was tested at FNAL in December 2013 – January 2014. The goal of this test was to understand the role of coil design and pre-stress on its quench performance. The quench current limit for dipole mirror MBHSM01 was estimated using measured data from witness samples and the magnet load line (Fig. 3). The estimated magnet short sample limits (SSL) are 13.0 kA at 4.5 K and 14.5 kA at 1.9 K, which correspond to coil maximum fields of 11.73 T and 12.89 T respectively.

The mirror training quenches at 4.5 and 1.9 K are shown in Fig. 6. Quench currents normalized to the magnet SSL at the corresponding temperatures are shown in Fig. 7. MBHSM01 quench training started at 4.5 K with a standard current ramp rate of 20 A/s. The current plateau of 12.9 kA or almost 100% of SSL was reached in 25 quenches.

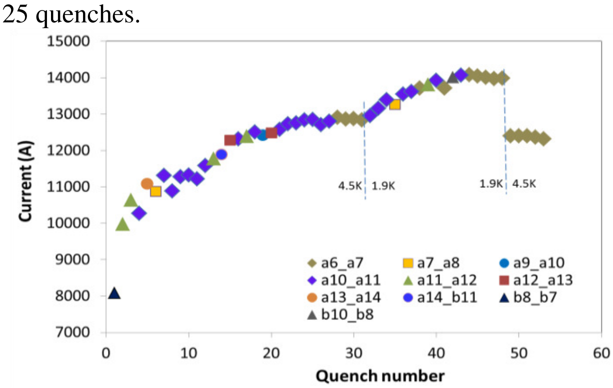

Figure 6: Mirror training at 4.5 and 1.9 K.

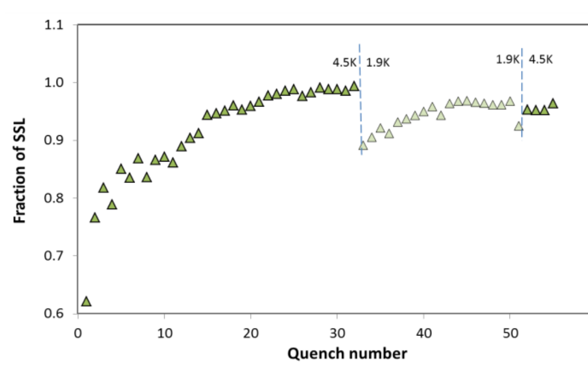

Figure 7: Fraction of SSL during training.

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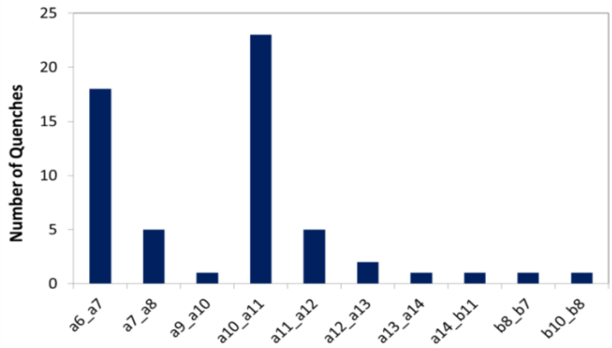

Figure 8: Quench origin during magnet training.

Then training continued at 1.9 K in superfluid helium and the current plateau of 14.1 kA or 97% of SSL was reached in 15 quenches. After training at 1.9 K, a ~4% degradation of the magnet quench current was observed at 4.5 K.

Quench multiplicity in different coil segments is shown in Fig. 8. All training quenches started in the high field area of the coil inner layer, with only two quenches in the coil outer layer. Plateau quenches both at 1.9 K and 4.5 K developed in the A6_A7 segment (Fig. 4), with the first QA signal in coil #2 in the non-lead end. The A6_A7 is a half-turn segment, next to the 2nd wedge on the non-transition side. Unlike in MBHSP01 [2] and MBHSP02 [3], no quenches were observed in MBHSM01 after "holding" a 13 kA current at 1.9 K and 12 kA at 4.5 K for ~25 min.

The ramp rate dependences of MBHSM01 quench current at 4.5 K and 1.9 K are shown in Fig. 9. At 4.5 K, they are low as expected for a coil made of cored cable. However, at 1.9 K the ramp rate sensitivity becomes stronger at current ramp rates above 50 A/s, with a minimum around 200 A/s. At 4.5 K the ramp rate quenches developed in A6_A7 at dI/dt=5-50 A/s and in A7_A8 at dI/dt> 50 A/s. At 1.9 K the quenches occur in A6_A7 at dI/dt=10-50 A/s and in A11_A12 at dI/dt>50 A/s. No quenches were observed at 1.9 K when ramping the current down from 14 kA at 200 A/s.

Temperature dependence of MBHSM01 quench current in the temperature range from 1.9 to 4.5 K is shown in Fig. 10. The sharp reduction of magnet quench current above the lambda-point points to the strong effect of coil cooling conditions on magnet quench performance.

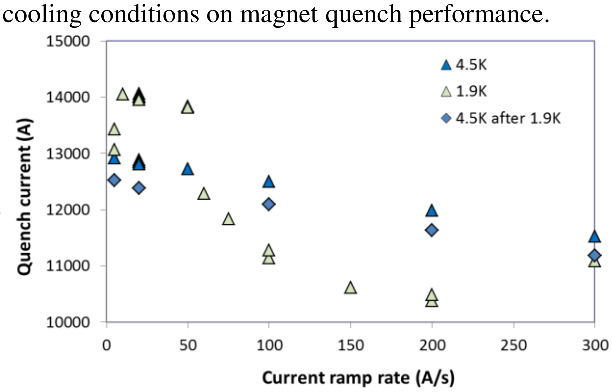

Figure 9: Ramp rate dependence of coil quench current.

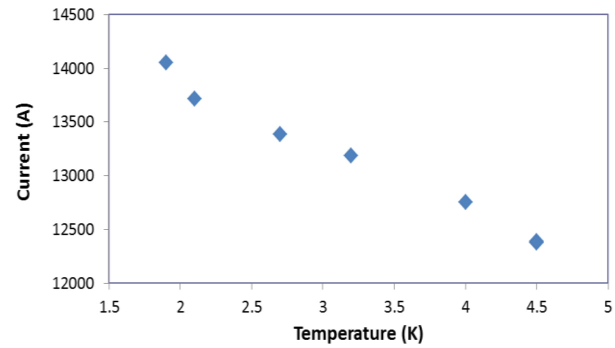

Figure 10: Temperature dependence of quench current.

CONCLUSION

A dipole mirror structure to test single coils up to 2-m long for the 11 T dipole program has been developed at FNAL. A new 1 m long coil MBH08 was assembled and tested using this structure at 4.5 K and 1.9 K.

Dipole mirror MBHSM01 reached ~100% of its SSL at 4.5 K, and ~97% of its SSL at 1.9 K. Some small quench current degradation was observed at 4.5 K after magnet training at 1.9 K. The magnet exhibited stable performance, no spontaneous quenches were observed at constant current of 12 kA at 4.5 K and of 13 kA at 1.9 K for ~25 minutes. This result was also reproduced in the recently tested 11 T dipole model MBHSP03 [8].

The cored cable used in this coil significantly reduced the magnet ramp rate sensitivity at 4.5 K. Some irregular ramp rate behaviour was observed at 1.9 K at current ramp rates above 50 A/s.

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