

# QUENCH PERFORMANCE OF THE FIRST TWIN-APERTURE 11 T DIPOLE FOR LHC UPGRADES\*

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## Abstract

FNAL and CERN are developing a twin-aperture 11 T Nb<sub>3</sub>Sn dipole suitable for installation in the LHC. A single-aperture 2-m long dipole demonstrator and two 1-m long dipole models have been fabricated and tested at FNAL in 2012-2014. The two 1 m long collared coils were then assembled into the first twin-aperture Nb<sub>3</sub>Sn demonstrator dipole and tested. Test results of this twin-aperture Nb<sub>3</sub>Sn dipole model are reported and discussed.

## INTRODUCTION

The planned upgrades of the Large Hadron Collider (LHC) call for additional collimators in the dispersion suppressor (DS) areas around points 2, 3, 7, and CMS and ATLAS detectors [1]. The work on the development of the 11 T Nb<sub>3</sub>Sn dipole for the LHC collimation system upgrade, started in 2011 [2], continues at FNAL [3] and at CERN [4]. Seven 1 m long coils were fabricated at FNAL since 2012. Four coils were assembled in two collared coil blocks and tested in a single-aperture configuration [5]-[7]. Both collared coils were trained above the LHC nominal operation current of 11.85 kA to a field in the magnet aperture of ~11.6 T at 1.9 K, or 97% of the dipole design field of 12 T. During the tests important information on the magnet quench performance and field quality, including geometrical harmonics, coil magnetization, iron saturation and dynamic effects in 11 T dipole models, was obtained [5]. These collared coils have been assembled in a first twin-aperture dipole model MBHDP01 and tested in February-March 2015. This paper summarizes the twin-aperture magnet design and construction, and reports test results of this Nb<sub>3</sub>Sn dipole model focusing on magnet quench performance including training, ramp rate sensitivity and temperature dependence of the magnet quench current. The twin-aperture dipole quench performance is compared with the data for the single-aperture models MBHSP02 and MBHSP03.

## MAGNET DESIGN AND CONSTRUCTION

The design concepts of the 11 T Nb<sub>3</sub>Sn dipole in single-aperture and twin-aperture configurations, developed at FNAL and at CERN, are described in [2]-[8]. The calculated 2D design parameters for single- and twin-

aperture dipoles (FNAL design) at I<sub>nom</sub> of 11.85 kA, T<sub>op</sub> of 1.9 K, nominal strand J<sub>c</sub>(12T,4.2K) of 2750 A/mm<sup>2</sup> and cable I<sub>c</sub> degradation of 10% are reported in Table 1.

Table 1: 11 T Dipole Design Parameters.

Parameter	Single-aperture	Twin-aperture
Yoke outer diameter, mm	400	550
Nominal bore field at I <sub>nom</sub> , T	10.88	11.23
Short sample field B <sub>SSL</sub> at T <sub>op</sub> , T	13.4	13.9
Margin B <sub>nom</sub> /B <sub>SSL</sub> at T <sub>op</sub> , %	81	83
Stored energy at I <sub>nom</sub> , kJ/m	424	969
F <sub>x</sub> /quadrant at I <sub>nom</sub> , MN/m	2.89	3.16
F <sub>y</sub> /quadrant at I <sub>nom</sub> , MN/m	-1.58	-1.59

In a twin-aperture configuration, two collared coils are placed inside a vertically split iron yoke with an iron spacer in between, and are surrounded by a thick welded stainless steel skin. Two thick stainless steel end plates, welded to the skin, restrict the axial motion of both collared coils.

MBHDP01 uses two collared coils: one, tested in MBHSP02, consists of coils 05 and 07 and the other one, tested in MBHSP03, consists of coils 09 and 10. Based on the test results in a single-aperture configuration, the collared coil with coils 09 and 10, was re-collared with a slightly larger radial shim of 0.075 mm installed in between coil and collar to increase the coil pre-stress. The midplane collar-yoke shims, the same for both collared coils, were reduced to the minimum size necessary to compensate for the difference in collar and yoke thermal contraction. These midplane shims, the same as in MBHSP03, provide some small collared coil bending at room temperature to keep contact between the collar and the yoke after cooling down. All the coils are electrically connected in series as shown in Fig. 1 (left). The assembled twin-aperture dipole model MBHDP01 before end plate welding and coil splicing is shown in Fig.1 (right).



Figure 1: The coil electrical connection (left) and the assembled MBHDP01 cold mass before end plate welding and coil splicing (right).

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To detect and localize quenches all four coils were instrumented with voltage taps. The typical coil voltage tap scheme in a two-layer 11 T dipole is shown in Fig. 2.

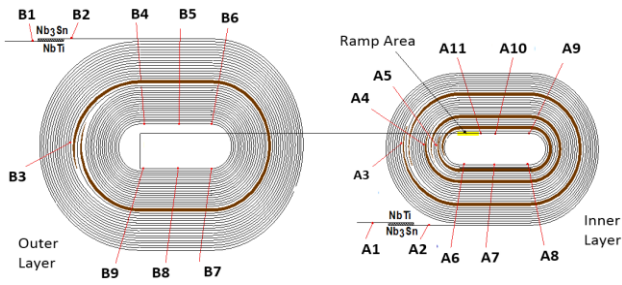


Figure 2: Voltage tap scheme in an 11 T dipole coil.

## MBHDP01 QUENCH PERFORMANCE

Twin-aperture dipole model MBHDP01 was tested at FNAL Vertical Magnet Test Facility in February-March 2015. Test results for both collared coils in a single-aperture configuration were reported in [3], [5], [6]. In a single-aperture configuration both collared coils were trained to the same magnetic field in the aperture of 11.6 T at 1.9 K. In MBHSP02 this field level was reached at 12.58 kA and in MBHSP03 at 12.12 kA. It was also found that due to large degradation, MBHSP02 reached its conductor limit whereas MBHSP03 did not. Since the two collared coils are connected in series in a twin-aperture configuration, it was expected that MBHDP01 would be limited by MBHSP02 collared coil with coils 05 and 07.

Thus the main objectives of this test were: a) observation and comparison of collared coil performance in single- and twin-aperture configurations; b) observation of the effect of coils 09 and 10 disassembly and re-collaring with higher pre-stress and the effect of smaller bending of coils 05 and 07 on magnet training and conductor degradation.

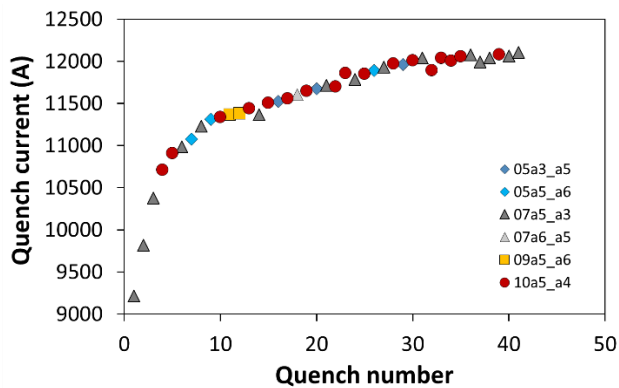


Figure 3: Quench current training of twin-aperture MBHDP01.

MBHDP01 training was performed at 1.9 K in superfluid helium with a current ramp rate of 20 A/s. The magnet quench currents vs. quench number are plotted in Fig. 3. The quenches were detected practically in all four coils which is not surprising due to implemented change of the mechanical stress in both collared coils. The first low-

current quenches and the quenches at the current plateau occurred in the inner-layer blocks next to pole of coil 07 (the same coil and location as in single-aperture MBHSP02). Half of all quenches was detected in the inner-layer pole blocks of coil 10 and only two in the inner-layer pole blocks of coil 09.

The training curve has two regions one with fast and one with slow training rate. Slow training at currents above 11 kA is likely due to epoxy cracking between the inner-layer pole blocks and coil pole turns caused by high Lorentz force and the conservative coil pre-stress in this model. As a result of slow training MBHDP01 reached its current plateau after ~30 quenches.

The values of the maximum bore field in MBHDP01 during magnet training are shown in Fig. 4. For comparison MBHSP02 and MBHSP03 bore field training data at 4.5 and 1.9 K are also plotted in Fig. 4. The data at 4.5 K are represented with dark markers and the data at 1.9 K with light markers. The magnet bore field for twin-aperture MBHDP01 was calculated using the values of quench current and calculated 3D transfer function. The magnet bore field for single-aperture MBHSP02 and MBHSP03 was calculated using the values of quench current and measured magnet transfer functions [5]. The first quench in twin-aperture MBHDP01 occurred practically at the same level of ~9 T bore field as in single-aperture MBHSP02 and MBHSP03. MBHDP01 reached the maximum bore field of 11.5 T at the current of 12.1 kA which is only 0.1 T lower than in the single-aperture models. This difference may slightly change when using the measured MBHDP01 transfer function as in the case of MBHSP02 and MBHSP03 [3], [5].

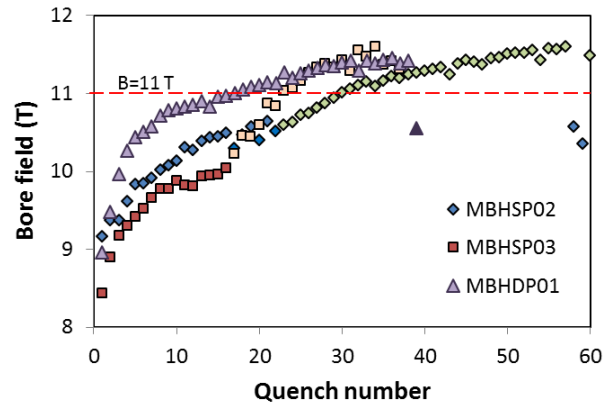


Figure 4: Magnet training comparison for twin-aperture MBHDP01 and single-aperture MBHSP02 and MBHSP03.

Fig. 5 shows the holding time to quench vs. current measured in MBHDP01 at 1.9 K and 4.5 K after magnet training. This effect was observed in MBHSP02 [6]; no spontaneous quenches were detected in MBHSP03 after ~30 minutes at steady current. As can be seen, there is a good correlation between single-aperture MBHSP02 and twin-aperture MBHDP01 at both temperatures. At 4.5 K one can even notice some improvement of magnet stability

at the current plateau. All the spontaneous quenches developed in the outer-layer mid-plane block b2\_b3 of coil 07 in both magnets.

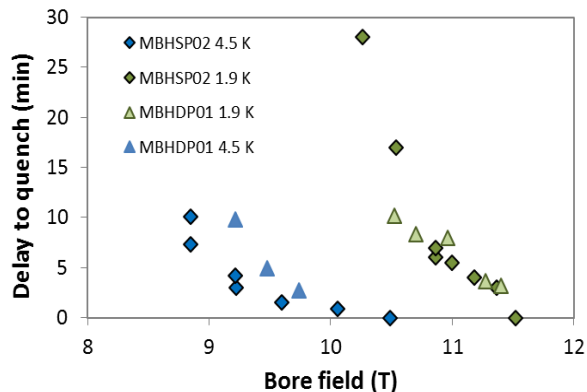


Figure 5: Holding time to quench vs. bore field at current plateau of twin-aperture MBHDP01 and single-aperture MBHSP02.

The dependence of the MBHDP01 and MBHSP02 bore field on the current ramp rate at 1.9 and 4.5 K is shown in Fig. 6. There is a very good correlation of the data at both temperatures. All ramp rate quenches in MBHSP02 and MBHDP01 started in the inner-layer central blocks of coil 07. Since all four coils use a cable with a stainless steel core, eddy currents in the inner-layer mid-plane turns are effectively suppressed leading to a relatively low ramp rate sensitivity of the magnet quench current.

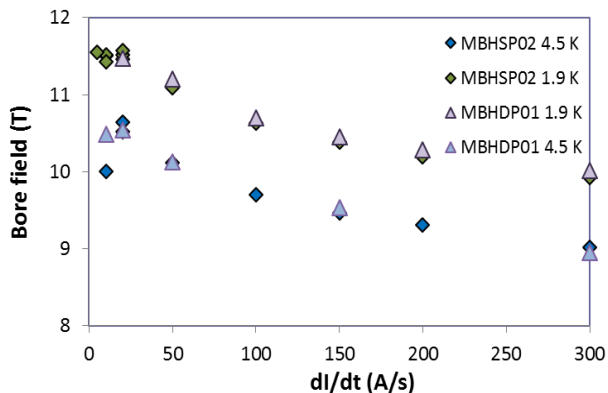


Figure 6: Ramp rate dependence of quench bore field in twin-aperture MBHDP01 and single-aperture MBHSP02 at 1.9 and 4.5 K.

Temperature dependences of the bore field at quench in twin-aperture MBHDP01 and single-aperture MBHSP02, measured in the temperature range of 1.9-4.6 K, are shown in Fig. 7. As above there is a very good correlation between the data for single-aperture MBHSP02 and for twin-aperture MBHDP01 at all measured temperatures. In MBHSP02 quenches started in the inner-layer blocks a4\_a5 of coil 05 and 07, and outer-layer mid-plane block b2\_b3 of coil 07. In MBHDP01 all quenches occurred in inner-layer blocks a5\_a4 and a4\_a3 of coil 07. It is consistent with the large permanent conductor degradation in coils 07 observed during MBHSP02 test [5], [6].

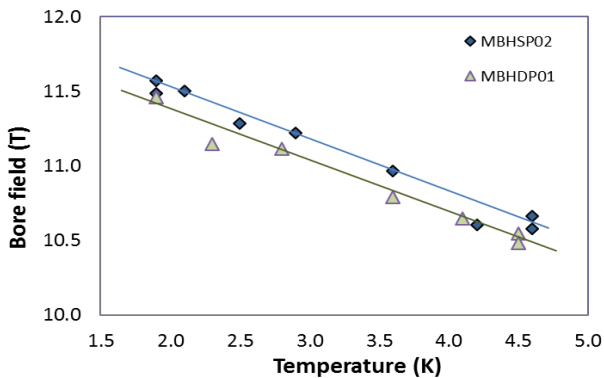


Figure 7: Temperature dependence of the quench bore field in twin-aperture MBHDP01 and single-aperture MBHSP02.

## CONCLUSION

The first 1 m long twin-aperture Nb<sub>3</sub>Sn dipole model MBHDP01 has been built and tested at FNAL. The magnet reached a bore field of 11.5 T at 1.9 K, which is 97% of its design field. It is less than 1% lower than the maximum bore field obtained in the single-aperture models. As expected, the magnet demonstrated similar quench performance which was limited by large conductor degradation in the collared coil used in MBHSP02. No additional coil degradation was introduced during re-assembly of one of the collared coils and twin-aperture dipole assembly process. Magnetic measurements in one of the two apertures will be performed in the next test run.

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