TEST RESULTS FOR INITIAL PRODUCTION OF LHC INSERTION REGION DIPOLE MAGNETS*

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Abstract

The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) is making and testing 20 insertion region dipoles for the Large Hadron Collider (LHC) at CERN. These 9.45 m-long, 8 cm aperture magnets have the same coil design as the arc dipoles now operating in the Relativistic Heavy Ion Collider (RHIC) at BNL and will be of single and twin aperture cold mass configurations. They will produce fields up to 4.14 T for operation at 7.56 TeV. The magnets will be tested at 4.5 K using either forced flow supercritical helium or liquid helium. This paper reports the results of tests of four D1 magnets, including spontaneous quench performance, verification of quench protection heater operation, and magnetic field quality.

1 INTRODUCTION

The dipoles required in the Intersection Regions (IRs) of the LHC have field and aperture requirements close to those of the RHIC arc dipole magnets [1],[2]. Thus, the superconducting coils developed for those magnets can be used in a cost-effective dipole design that satisfies CERN's requirements. Under the auspices of the US/CERN LHC Collaboration, the magnets are being built at BNL using as much of the tooling constructed for the RHIC program as possible.

2 MAGNET CONSTRUCTION

The complete LHC program at BNL includes 20 dipoles for four lattice locations (D1, D2, D3, D4) [3-5]. In this paper, we report cold test results and field quality measurements in four of the five D1 magnets. The D1 magnets help bring the two beams of the LHC into collision at IRs 2 and 8. Four magnets will be installed; one is a spare. The LHC magnet code for the D1 is MBX; the cryogenic assembly code is LBX. The D1 magnets are single aperture, straight magnets. A cross section is shown in Fig. 1. The NbTi superconducting cable was left over from the RHIC magnet production. The nominal magnet length is 9.45 m. The nominal coil inner diameter is 80 mm. As for RHIC, the cold iron yoke is separated from the single layer coil by injection-molded phenolic spacers.

Because both beams pass through the D1 magnets, the aperture is as large as possible. The outer diameter (OD) of the beam tube has been increased from 73 mm (for RHIC) to 78 mm (for LHC). This change reduces the radial space for the helium coolant from a nominal 2.5 mm to 1 mm. Some of the remaining space is filled by the beam tube's Kapton wrap. The reduced cooling has important consequences for magnet operation in the test stand. The D1 magnets have quench heaters for protection at 1.9 K. They are mounted outside the coils, further reducing the space available for the coil.

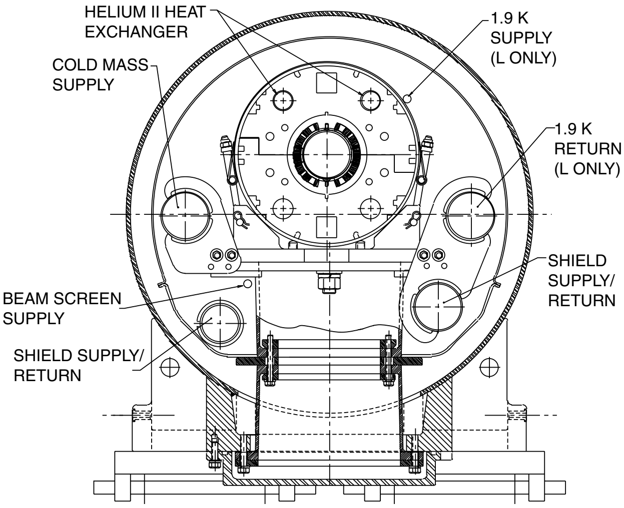

Figure 1: Cross section of the D1 dipole.

3 QUENCH PERFORMANCE

All magnets were tested horizontally in their cryostats using forced flow supercritical helium at 4.5 K and 12 atm. As mentioned earlier, the D1 design results in a reduced flow of helium to cool the conductor, especially when heat is introduced in a quench or through conduction and radiation. The warm bore tube (WBT) used in testing is double-walled and vacuum-jacketed but internally open to the outside to allow the use of magnetic field measuring coils, making it a source of heat from the outside. It was expected that this might lower the quench performance of the magnet from that of the original RHIC dipoles. The WBT that was installed inside the magnet beam tube went through several reconfigurations to reduce the heat leaking from the outside before quench currents were high enough to perform magnetic field measurements above the ultimate operating field of 4.14 T (7.56 TeV operation). Furthermore, the WBT had to be removed entirely before quench currents could reach the conductor limit.

Fig. 2 shows quenches for all four magnets with either no WBT or with an improved, centered WBT (D1L103). D1L101 and D1L105 trained quickly to the conductor limit, nominally 7300 A (16% margin), after the WBT was removed. D1L103 had the WBT throughout testing since

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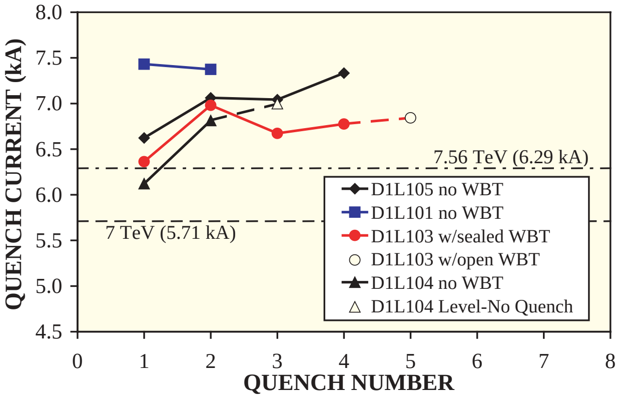

Figure 2: Quench plots of D1 magnets.

the performance was improved enough that field measurements could be done. The highest quench current reached with the WBT open to room temperature was 6844 A (9% margin). For the fourth D1, D1L104, the WBT was not installed, and the magnet quickly trained to 7000 A (11% margin), at which current the magnet was operated for 20 min, and then cycled again to 7000 A with no quench.

4 QUENCH PROTECTION

RHIC dipoles are self-protecting, and so are the D1 dipoles at 4.5K [6]. However, for 1.9 K operation in the LHC, active quench protection is necessary in D1 dipoles to prevent possible conductor damage at some quench currents. A quench heater design developed for RHIC insertion dipoles was used. Each heater is a copper-plated stainless steel strip 25.4 µm thick, 44.45 mm wide and 10.16 m long, wrapped in Kapton/b-stage epoxy on both sides. There are thirteen 127 mm long sections that have the copper plating etched off and that are spaced at 0.75 m intervals along the length of each strip. The magnet coil is equipped with four of these strip heaters, attached by heat-bonding them axially along the length of the coil halfway between the midplane and the pole. The heaters are fired in pairs by a trigger pulse from the quench detector at a preset delay after detection of the quench. A series of manually triggered strip heater quenches were performed at 4000 A to determine minimum heater currents to cause each half coil to quench no longer than 200 ms after heater firing. The time constant of the exponentially decaying heater pulse was nominally 46 ms. The results showed that the minimum parameters needed were about 75 A, 166 V, and 286 J per strip heater pair. Since we would expect maximum hot spot temperature at about 4000 A [6], these results show that parameters used in these tests result in proper operation of the heaters to protect the magnet during a quench at any current in 4.5 K operation. For protection at 1.9 K, more energy into the heaters will be necessary.

5 MAGNETIC MEASUREMENTS

The field quality is measured using a 1 m long rotating coil system. The integral harmonics are obtained by summing measurements made at 10 axial locations in 1 m steps. The integrated dipole field is obtained using a 10 m long non-rotating coil with two orthogonal dipole windings. All the dipoles will be measured at room temperature. One dipole has been measured in the superconducting state.

5.1 Warm Measurement Results

Four single aperture dipoles (3 cryostated) have been warm measured so far. The mean and standard deviation of integral harmonics in these four magnets are given in Table 1. The values are in “units” of 10^{-4} of the dipole field at a reference radius of 17 mm. All the harmonics, except the normal sextupole, are consistent with expectations based on data in the RHIC dipoles. The normal sextupole has a systematic offset from the RHIC data, but is consistent with the results in two twin aperture D4b dipole prototypes built at BNL [7].

Table 1 Summary of integral harmonics measured warm in four D1 dipoles (in units at 17 mm)

Harmonic	Mean (units)		Std. Dev. (units)	
	Normal	Skew	Normal	Skew
Quadrupole	-0.18	-0.53	0.38	1.90
Sextupole	-1.48	-0.39	0.49	0.05
Octupole	0.017	-0.068	0.030	0.214
Decapole	0.095	0.052	0.016	0.005

The integral transfer function (ITF) is obtained by ramping the magnet from 0.5 A to 30 A at 60 A/s. The ITF in the three cryostated magnets has a mean of 6.6592 T·m/kA and a standard deviation of 0.02%.

5.2 Cold “DC” Measurement Results

Harmonic measurements in the superconducting state have been carried out in one D1 dipole, D1L103. The harmonics were measured as a function of current on the upward ramp at each of the 10 axial positions of the measuring coil. For these “DC” measurements, the current was held fixed during the measurements. At one of the axial positions, measurements were also done on the down ramp to characterize the superconductor magnetization effects. The dipole field is 0.2 T at 282 A and 4 T at 6020 A.

Figs. 3 and 4 show the skew quadrupole and the normal sextupole harmonics as a function of current at the eight locations (2 thru 9) in the straight section. For position 5, the down ramp data are also shown. The skew quadrupole shows a small amount of hysteresis, which may be a result of feed down. It also has a noticeable saturation, which is a result of an off-centered cold mass in the cryostat. There is some axial variation (±1 unit) in the geometric value. The normal sextupole is relatively uniform along the magnet length and has negligible saturation.

5.3 Dynamic Effects

Dynamic effects, such as sextupole time decay and ramp rate effects, were studied using a 1 m long rotating coil mounted on an external drive system and positioned. in the straight section, close to the non-lead end. The coil was rotated at 1.32 s/rev instead of the usual 3.5 s/rev for better time resolution. The coil signal was acquired

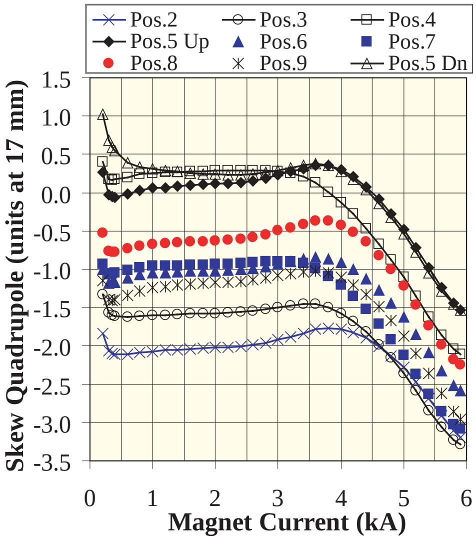

Figure 3: Skew quadrupole at the eight 1 meter segments in the straight section of D1L103.

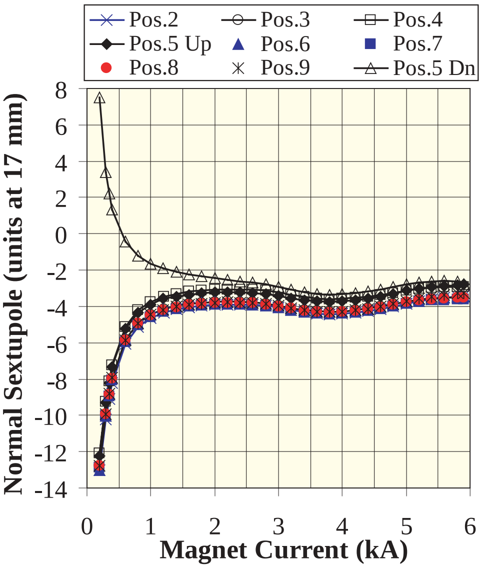

Figure 4: Normal sextupole at the eight 1 meter segments in the straight section of D1L103.

continuously and the data analysis accounted for any variation of current during one revolution of the coil [8].

The dynamic effects were studied as a function of the maximum cycle current and ramp rate. The time decay and snapback behavior were measured at 350 A, close to the expected injection field in the LHC. The sextupole was found to decay by ~0.8 unit (at 17 mm) over a period of 2000 s. The amount of decay varied by ±0.2 unit depending on the ramp rate (5 A/s to 40 A/s) used for the cycle.

The difference in the normal sextupole harmonic measured during the up and the down ramps is a sensitive indicator of superconductor magnetization and eddy current effects. The hysteresis in the absolute value of the sextupole (in mT) is shown in Fig. 5 as a function of current for several values of the ramp rate. A DC measurement with the fast rotating coil system, as well as a similar measurement with the regular "mole" system are also shown for comparison. The hysteresis increases with ramp rate and the effect is ~0.035 mT at 40 A/s. For an injection field of 0.2 T, this translates into a ramp rate induced sextupole of less than 1 unit at 40 A/s.

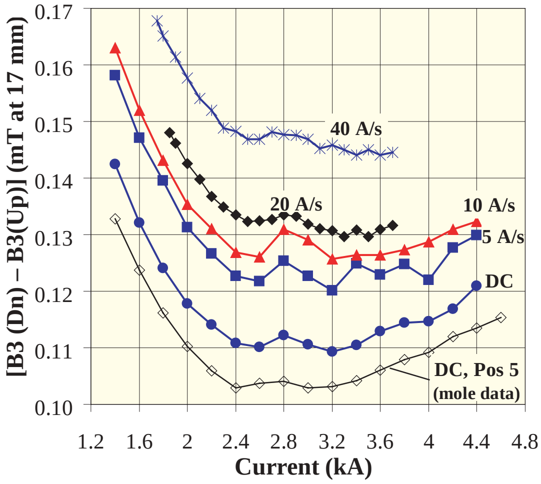

Figure 5: Hysteresis in the normal sextupole harmonic as a function of current and ramp rate in D1L103.

6 CONCLUSIONS

The single aperture dipoles built by BNL for the LHC insertion region have been shown to perform adequately after issues related to heat load from the warm bore tube have been addressed. The field quality in these dipoles is as expected.

7 REFERENCES

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