TEST RESULTS FOR LHC INSERTION REGION DIPOLE MAGNETS*

Joseph Muratore#, Animesh Jain, Michael Anerella, John Cozzolino, George Ganetis, Arup Ghosh, Ramesh Gupta, Michael Harrison, Andrew Marone, Stephen Plate, Jesse Schmalzle, Richard Thomas, Peter Wanderer, Erich Willen, Kuo-Chen Wu,
BNL, Upton, NY 11973, U.S.A.

Abstract

The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) has made 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 are of single aperture, twin aperture, and double cold mass configurations. They are required to produce fields up to 4.14 T for operation at 7.56 TeV. Eighteen of these magnets have been tested at 4.5 K using either forced flow supercritical helium or liquid helium. The testing was especially important for the twin aperture models, whose construction was very different from the RHIC dipoles, except for the coil design. This paper reports on the results of these tests, including spontaneous quench performance, verification of quench protection heater operation, and magnetic field quality.

INTRODUCTION

The Superconducting Magnet Division at BNL has built 20 dipole magnets for five Interaction Regions (IRs) at LHC as part of the US/CERN LHC collaboration. The field and aperture requirements at these locations are such that these magnets can use the same coil design developed for the arc dipoles presently operating in RHIC [1]. This was a cost effective way of manufacturing these magnets by using existing RHIC tooling and parts. So far, 18 magnets have been tested at BNL at 4.5K, and 2 spares are awaiting test.

MAGNET DESIGN FEATURES

All 20 magnets have 9.45m magnetic length and 80mm aperture and use the RHIC coil design, but these are straight with no sagitta. There are four types designated as D1, D2, D3, and D4, depending on the number of apertures and the separation between apertures [2]. D1 has a single aperture in one cold mass and is essentially a RHIC dipole and has been described in a previous paper [3]. The D2 and D4 dipoles are dual apertures in one cold mass and differ only in separation between the bores: 188 mm and 194 mm, respectively. The D3 dipole, with aperture spacing of 414 mm, consists of two single aperture RHIC cold masses in a single cryostat. The dipole fields in the two apertures of the D2, D3 and D4 magnets point in the same direction, unlike the twin aperture dipoles in the LHC arc. The design features and functions of the BNL-built insertion dipoles are discussed in greater detail in [4]. The operating magnetic fields vary according to location and beam energy, and this determines the operating currents and consequently the maximum current limits used during testing. The highest field required is 4.14 T in some D1s and D2s at the maximum machine energy of 7.56 TeV, which corresponds to 6.3 kA and 6.6 kA respectively.

QUENCH PERFORMANCE

Due to the differences in construction among the types of dipoles, some test conditions (such as cooling schemes) and parameters (such as maximum quench current and quench protection) were varied. All dipoles were tested horizontally at 4.5 K in their cryostats using forced flow supercritical helium at 12 atm and 70 g/s. The D2, D3, and D4 dipoles were also tested in liquid helium at 1.4 atm to simulate the actual cooling scheme to be used in the LHC. As discussed in a previous paper [3], D1 magnets had a cooling deficiency during testing due to a wider beam tube and the presence of a warm bore tube (WBT) for field measurements. This necessitated testing without the WBT until it was improved to reduce the heat leak. The modified WBT, with added insulation, centering in the bore, and heat stationing, resulted in expected quench performance, enabling field measurements to be done to the required maximum currents. However, it still presented a head load, even in the other dipole types, that affected quench performance along with other test facility heat leaks, in an unpredictable way. For this reason and for schedule efficiency, quench tests were performed to a maximum current limit depending on each magnet type's required maximum field plus some margin. D1's, at first tested to the nominal conductor limit of 7.3 kA without the WBT, were later limited to 7 kA. The quench current limits for the D2, D3, and D4 dipoles were 6.8 kA, 6.5 kA, and 6.6 kA, respectively.

Fig. 1 shows the quench test results for all the D1 dipoles and the first of the D3's. As can be seen, when tested with no WBT or the improved WBT, the D1 and the first D3, D3L101, shown as two separate magnets on the plot, reached the conductor limit or the maximum test limit with very little training. The second D3, D3L102, is not included on the plot because there were a large number of quenches done to determine the cause of erratic

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#muratore@bnl.gov

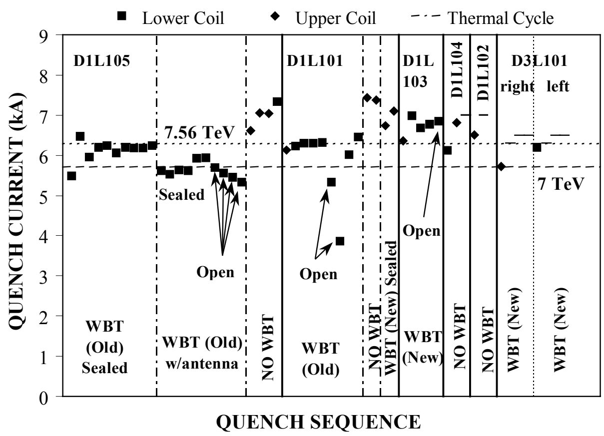

Fig. 1: Quench test results in D1L and D3L dipoles.

performance. It was found that the 70g/s flow was not adequate when split between the two cold masses. When the cold masses were operated and cooled individually each went immediately to the 6.5 kA test current limit for D3. Since the cryogenics system at that time was configured to provide 70 g/s at 12 atm, the remaining tests were done with liquid helium cooling. Quench performance was stabilized and 6.997 kA was reached after one training quench at 6.265 kA. It should be noted that this was with both warm bore tubes open to room temperature for field measurements.

Fig. 2 shows the quench performance of all nine D2 and two D4 dipoles. As can be seen, these dual aperture, single cold mass magnets had a similar heat load issue as the D1 dipoles. Here, cooling by liquid helium bath was not sufficient to overcome heat leaks due to the WBTs and other parts of the test stand, so quench performance in this cooling scheme was unpredictably erratic. However, with forced flow cooling, the magnets trained well to the test limits or higher. Most were tested to 7 kA or higher (8% margin). For all magnets after the first, training was first done with forced flow to validate quench performance and carry out field measurements, then the cooling scheme was switched to liquid helium to verify

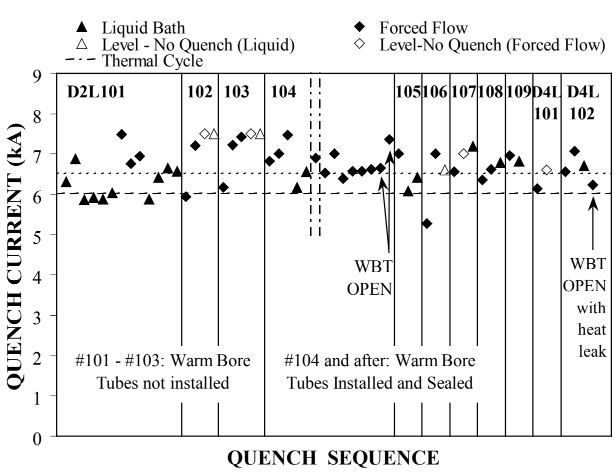

Fig. 2: Quench test results in D2L and D4L dipoles.

operation of the magnet and level probes since the magnets will be cooled this way in the LHC. In summary, when properly cooled, all magnets reached the operating current corresponding to 7 TeV with either no training (15 magnets) or one training quench (3 magnets).

QUENCH PROTECTION

Quench protection issues for the D1 dipoles were discussed in [3]. In a previous quench propagation study with a D4 prototype [5], it was shown that the dual aperture magnets were not self-protecting. Quench hot spot temperatures of 750 K (12.9 miits) could be reached at midplane locations without any active quench protection. By the use of strip heaters, described in [3], this could be reduced to safe levels below 500 K.

For the first D2 tested, it was determined by 4 kA strip heater quenches that heater nominal voltages and currents of at least 480 V and 100 A were necessary. Since miits values during spontaneous quenches were still in the 10-11 range (~400K), further adjustments were made to lower the quench temperatures. The time constant for the heater pulse was reduced by a factor of 2, to 100 ms, by decreasing the capacitance of the discharge circuit, and both the strip heater and quench detector delays were minimized to 1 ms. This had the immediate effect of reducing the miits to the 8-9 range (~300K or less). Additionally, starting with the second D2, an energy extraction resistance of 35 mΩ was added to the SCR switch circuit. All further quench tests were done with these parameters, and miits values stayed in the range 8-10 for the remainder of testing.

MAGNETIC MEASUREMENTS

The field quality is measured in all dipoles 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. During warm measurements, the integrated dipole field is also obtained using a 10 m long non-rotating coil with two orthogonal dipole windings. All the dipoles have been measured at room temperature. Two D1, six D2, two D4 and two D3 dipoles have also been measured in the superconducting state.

The transfer function in the D1 and D3 dipoles is 0.709 T/kA at low fields, and drops by 6.5% at 5.9 kA due to iron saturation. The transfer function in the D2 and D4 dipoles is somewhat lower due to stainless steel collars used between the coil and the yoke – 0.636 T/kA at low fields and drops only ~1% due to saturation at 6.4 kA.

Tables 1 and 2 give a summary of the integral field quality at room temperature in terms of selected field harmonics. All other harmonics are well below 10^{-4} of the dipole field (1 "unit") at a radius of 25 mm. The skew sextupole is almost entirely from the ends. In the case of the twin aperture D2 and D4 dipoles, there is a significant normal quadrupole term seen in the warm measurements due to cross-talk resulting from relatively poor permeability of the yoke steel at very low fields [6]. This also causes a systematic difference between the left and

Table 1 Summary of integral harmonics (in units of 10^{-4} at 25 mm) measured warm in all the D1 and D3 dipoles (11 apertures total).

Harmonic	Mean (units)		Std. Dev. (units)	
	Normal	Skew	Normal	Skew
Quadrupole	–0.62	–0.93	0.68	2.61
Sextupole	–2.94	–0.89	1.70	0.14
Octupole	0.01	0.08	0.17	0.69
Decapole	0.50	0.20	0.20	0.07
22-pole	–0.62	0.02	–0.01	0.02

Table 2 Summary of integral harmonics (in units of 10^{-4} at 25 mm) measured warm in all the D2 and D4 dipoles (24 apertures total).

Harmonic	Mean (units)		Std. Dev. (units)	
	Normal	Skew	Normal	Skew
Quadrupole	–5.34 (L) / 5.13 (R)	–0.60	0.67 (L) / 0.54 (R)	0.22
Sextupole	–3.22	0.05	1.31	1.90
Octupole	0.10	–0.98	0.16	0.38
Decapole	0.62	0.16	0.39	0.61
22-pole	–0.64	0.00	0.02	0.01

the right apertures for this term, as shown in Table 2. This systematic quadrupole term largely disappears at fields above ~0.3 T. At very high fields, there is again a very small cross-talk induced quadrupole (~0.2 unit at 6.4 kA) due to saturation of the iron yoke.

Since all the magnets have not been measured cold, warm-cold correlations derived for each magnet type will be used to extrapolate the warm measurement results wherever necessary. The D2 and D4 dipoles differ very slightly in the aperture separation, and a common warm-cold correlation can be used for these two groups of magnets. On the other hand, even though the D3 dipoles consist of two D1-like cold masses in a common cryostat, the saturation behavior of certain harmonics in these magnets is quite different from D1 due to cross-talk at high fields. These are the even normal (quadrupole, octupole, etc.) and the odd skew (sextupole, decapole, etc.) terms. This cross-talk also results in a systematic change in the dipole field angle of opposite sign in the two apertures of the D3 magnets. This shift is ±0.2 mr at 5.9 kA.

An example of the differences in the saturation behavior of the D1 and D3 magnets is shown in Fig. 3 for the integral normal quadrupole term. The D1 magnet does not exhibit any current dependence of this term due to complete left-right symmetry. The cross-talk above 4 kA is clearly evident for the D3 magnet from the current dependence, as well as the opposite saturation behavior of the left and the right apertures. The quadrupole term in the D2 and the D4 dipoles also shows a similar saturation behavior, but the amount of saturation is only about 0.2 unit. The two apertures are expected to show the same saturation behavior for the sextupole term. However, there is still a slight difference between the

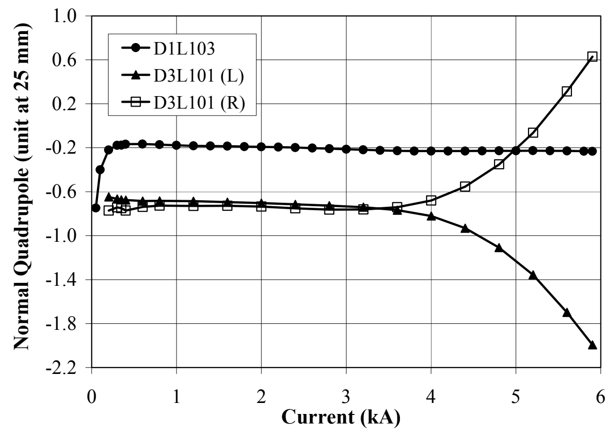

Fig. 3: Variation of the integral normal quadrupole term with excitation in a typical D1 and D3 magnet

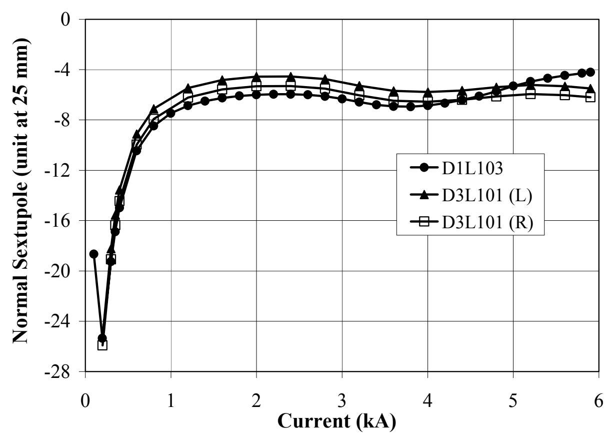

Fig. 4: Variation of the integral normal sextupole term with excitation in a typical D1 and D3 magnet

excitation curves for the D1 and the D3 magnets, as shown in Fig. 4. The normal sextupole in D1 changes by about 2 units between 4 kA and 6 kA, whereas the D3 magnets show hardly any change.

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