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Cold Test Results of the Inner Triplet Orbit Correctors for the LHC

W.Venturini Delsolaro, M. Karppinen

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The inner triplet orbit correctors for the LHC, MCBX and MCBXA, underwent acceptance tests at superfluid helium temperature at CERN, before shipping to FNAL for integration in the cold masses. A total of 27 MCBX (Horizontal-Vertical Dipole Correctors), of which 9 MCBXA (with nested Sextupole-Dodecapole insert), are needed for the LHC, including spares. The paper discusses the test protocols for series magnets, and reports the results of quench performance and cold magnetic measurements. The peculiarities of combined training and the hysteresis effects in the nested windings are presented, together with the search of the optimum setting procedure to minimize the persistent current effects on the beam dynamics.

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***Index Terms*—Nested superconducting magnets, LHC correctors**

I. Introduction

The orbit correctors in the inner triplets of the LHC are nested dipoles, to provide the vertical and horizontal orbit correction within the stringent space constraints [1]. Each triplet includes three MCBX units, one of which, called MCBXA, is equipped with sextupole and dodecapole correctors, also nested, to compensate the field errors of the low-β quadrupoles. The nested dipole coils are individually powered and can produce both a horizontal and a vertical field. The nominal field integral is 1.5 Tm in any direction at the operating temperature of 1.9 K, which gives a maximum kick angle of 64.2 μrad at 7 TeV. In the following, when speaking of inner and outer coils, we refer to the magnet layout. More details on the magnet design can be found in [2], [3]. After the prototyping phase, the series production started at the end of 2003 and was completed in summer 2005. All the acceptance tests took place at the CERN vertical test facility [4], following a tight schedule to meet the delivery terms agreed between CERN and FNAL. The testing work was successfully completed in August 2005.

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II. Test protocols

A. Power tests

The MCBX dipole pair has to generate fields at various angles, and in presence of the return flux of the b3-b6 insert for MCBXA units. Like for any corrector, the required strength of the MCBX will depend on the exact values of the imperfections to be compensated, which in this case are mainly the misalignments of the inner triplet quadrupoles. Nominal values were specified in the design and in the test protocols in a conservative way with respect to the most demanding operating conditions. To qualify a magnet, it is sufficient to power the two dipoles simultaneously with sinusoidal currents to create a rotating field at the maximum intensity, while the b3-b6 coils are set at full strength. In this way the quench performance is checked in all the operational space of current combinations. Yet magnets, unless extensively trained, invariably fail such test. In the first place, each dipole must be trained well beyond the level targeted for the rotating field. The distribution of magnetic forces in the coils depends upon the dipole angle, thus, after an individual training of the two dipoles, more quenches at other angles are to be expected before succeeding a full rotation. This so-called combined training can be done at fixed field amplitude, by slowly changing the angle (current ratio between dipoles) from 0 to 360 degrees, or, alternatively, at fixed angle by ramping up the currents. Combinations of the two methods were used at the start of the series tests. Subsequently, the following test protocol was established: a) individual training at 4.4 K up to 700 A, b) combined training by series connections of the two dipoles producing fields at 45 degrees, at 4.4 K, c) rotating dipole at nominal current (550 A) and 1.9 K, d) for MCBXA, rotating dipole at 550 A and 1.9 K with the correctors set at gradually higher currents. In order to spare time, the first part of the power test was at 4.4 K, the training being dominated by mechanical disturbances.

B. Magnetic measurements

Magnetic measurements by means of rotating coils were taken at 1.9 K and at several currents between 5 A and 550 A along the magnet load line. The standard cleansing cycle was a ramp at 10 A/s up to 550 A, then down to -550 A and back to 0 A. It was always executed before each measurement.

III. QUENCH PERFORMANCE

A. Individual training

All the individual training curves of inner and outer coils at 4.4 K are shown in Fig. 1 and in Fig. 2. It can be observed that outer coils have longer (more quenches needed to reach nominal) and less stable training than inner coils: looking at the ensemble, training curves of inner coils run almost parallel, whereas outer coils are more erratic. This was true regardless of which coil was trained first, and can be correlated with the radial stress profile, because the inner coil is always subject to the higher stress.

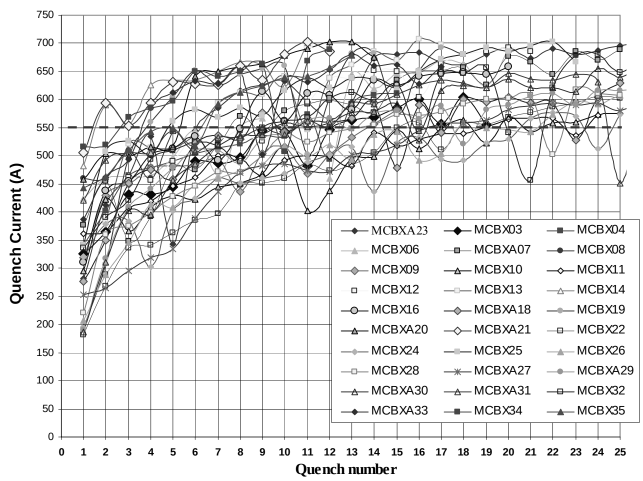

Fig. 1. Training curves of outer coils at 4.4 K

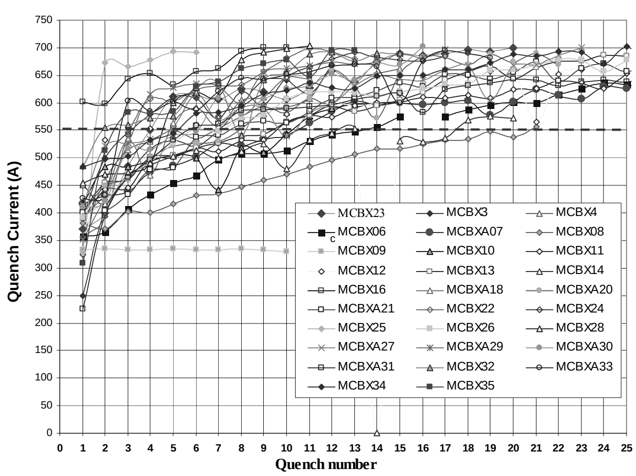

Fig. 2. Training curves of outer coils at 4.4 K

B. Combined training

As mentioned, the first part of combined training was the so-called diagonal powering, i.e. with the two dipoles in series and with different polarities (Fig. 3). The idea was to "settle" the coils by applying the magnetic forces symmetrically.

Once the nominal field was reached at all angles, the power test of MCBX units was stopped (point c of the test protocol). MCBXA units, instead, were further trained to the highest possible performance in the presence of the background fields of the corrector insert (point d of the test protocol). In this process, compromises had to be made between fully trained magnets and schedule needs.

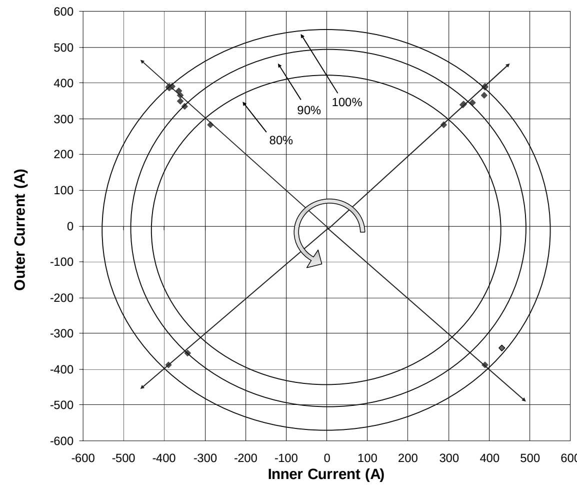

Fig. 3. Example of combined training: the points along diagonals represent quenches at fixed angle. One quench that occurred during the rotating dipole at nominal intensity is visible in the IV quadrant.

Table I summarizes the levels of performance reached by the magnets. For MCBXA units, the current for the combined training with the multipole correctors was increased from 80 A to 100 A after receiving indications of high b_3 and b_6 in some of the low-β quadrupoles [5].

TABLE I
SUMMARY OF COMBINED TRAINING RESULTS

Fraction of operational space reached at 1.9 K	Number and type of magnets
100%	11 MCBX and 2 MCBXA
90%	3 MCBX
95 %	3 MCBXA
85%	1 MCBX
80 %	3 MCBXA
75 %	1 MCBX
rejected	1 MCBX

C. Summary on quench performance

Only about half of the series magnets could be trained to the performance established in the test protocols. Yet all series magnets except one were qualified for the LHC; the weaker magnets being assigned to the less demanding locations [6].

IV. MAGNETIC MEASUREMENTS RESULTS

The magnetic field was measured at 1.9 K on a total of 21 magnets. Integrated transfer functions of inner and outer dipoles (in Tm/kA at 17 mm) are shown in Fig. 4.

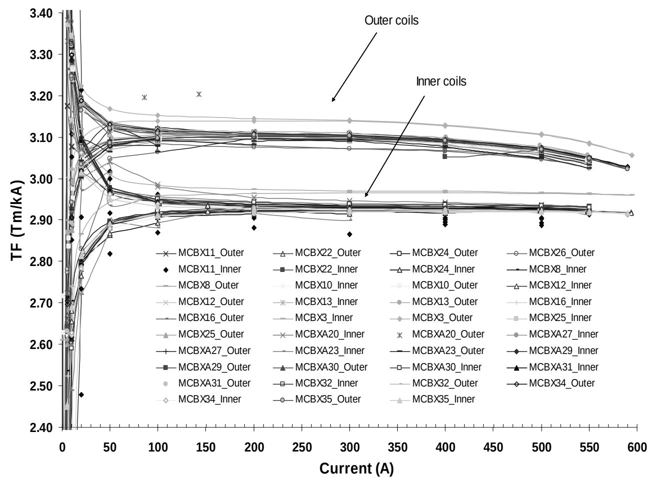

Fig. 4. Dipole transfer functions of inner and outer coils at 1.9 K

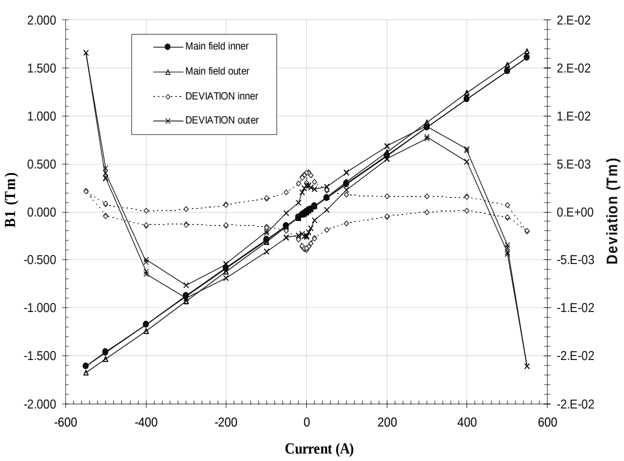

Fig. 5. Field versus current relationships of inner and outer coils, at 1.9 K. On the right hand scale, the deviation from a linear fit, highlighting the hysteresis at low field and the iron saturation at high field

The average dipole field integral measured at 550 A was $\int B_1$(inner)=1.607 Tm, the standard deviation was 0.003 Tm; whereas for the outer dipoles $\int B_1$(outer)=1.686 Tm, with 0.048 Tm standard deviation. Finite elements calculations, done with Roxie [7], give 1.678 Tm and 1.719 Tm for the inner and the outer dipole respectively. The discrepancy might be only in part explained by insufficient coverage of the magnet length by the measuring coil, and it is not yet fully understood. As visible in Fig. 4, a sizable saturation effect is present in the outer coils whereas the inner dipoles have quasi linear load lines. This is understandable as the outer dipole is closer to the iron yoke and produces a larger flux density. Both dipoles display hysteresis at low field due to the combined effect of the iron and of the superconductor magnetization. The current-field relationships are shown in Fig. 5, together with their deviation from the linear best fits. The width of the hysteresis loop was worked out in Fig. 6 as a function of current for a few magnets.

Outer coils have less hysteresis, possibly because the iron,

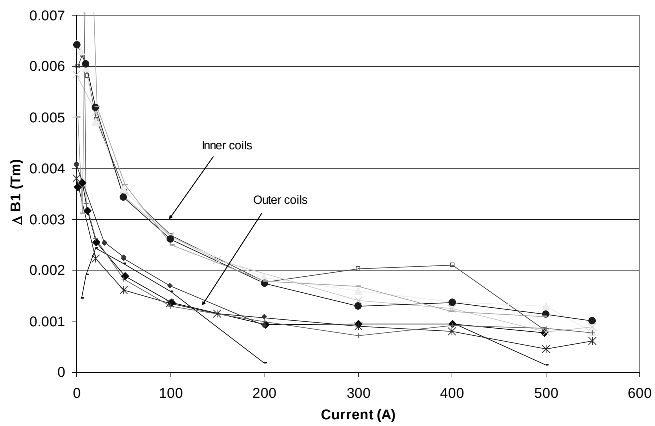

Fig. 6. Widths of the hysteresis loops of the main fields as a function of current at 1.9 K. The inset shows a magnification of the hysteresis curve

closer to the outer coils, counteracts the diamagnetism of the superconducting filaments; and because of the larger bore radius. No detailed calculation has been done to quantify the contributions of the two effects. The field quality of inner triplet correctors is not considered critical [8]. The largest harmonic is the sextupole, which is ranging around -12 units (1200 ppm of the main field at 17 mm radius). The iron saturation affects b3 for about 3 units in the outer dipole and is negligible in the inner dipole. Warm/cold offsets of geometric multipoles are negligible with respect to beam dynamic targets.

V. SEARCH FOR THE MINIMUM REMANENT FIELD

For a superconducting magnet, a drawback of nested designs is the formidable complication that they introduce in the hysteresis effects. In a single coil, the system of persistent currents, and therefore each affected multipole, is a function of the powering history. In an MCBXA it is a function of the powering histories of the four coils, i.e. an object defined on an infinite dimensional space. Thus, from a mathematical standpoint, finding an optimum setting procedure (assuring the magnetic field is a minimum when it is set to zero) is quite an impervious problem. This kind of issue can be of relevance when seeking to reproduce machine settings from run to run in superconducting accelerators [9], [10]. For the MCBX, one goal is to establish the maximum difference of magnetic field that can occur for the same current setting with different magnetic histories. To show the variability of the residual field we report the results of a simple experiment: in an MCBXA unit we have measured the residual dipole field after having cycled each of the four magnets to its nominal current. The cycles were applied to the four magnets in different sequences, indicated here by an acronym: for example OISD means that the order was: outer dipole, inner dipole, sextupole, then dodecapole.

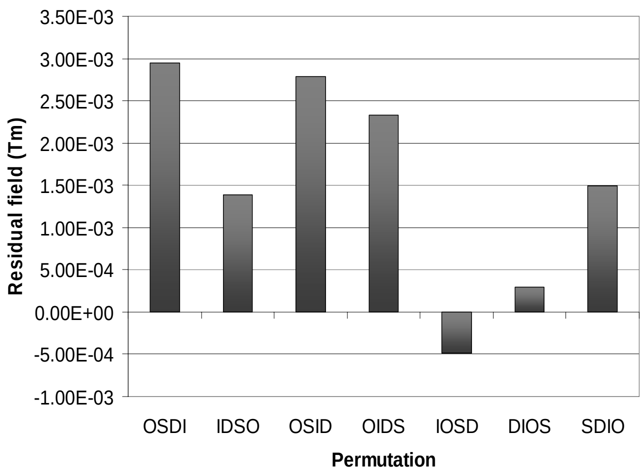

Fig. 7. Variation of the residual dipole field at 0 A with the order chosen for a cleansing cycle performed on each of the four magnets

As visible in Fig. 7 the residual field depends strongly on the permutation. Moreover, the level of remanent field at zero current is often not negligible with respect to the tolerances for machine operation [8]. Despite this complexity, a relatively simple degaussing cycle [11] applied to any of the two dipoles proved to work extremely well to suppress the residual fields. A saw tooth current cycle of decreasing amplitude, tailored on the penetration field of the superconducting filaments, reduced the remanent integrated dipole from 3.2 10^{-3} Tm down to 3 10^{-5} Tm, which is negligible for the beam [8].

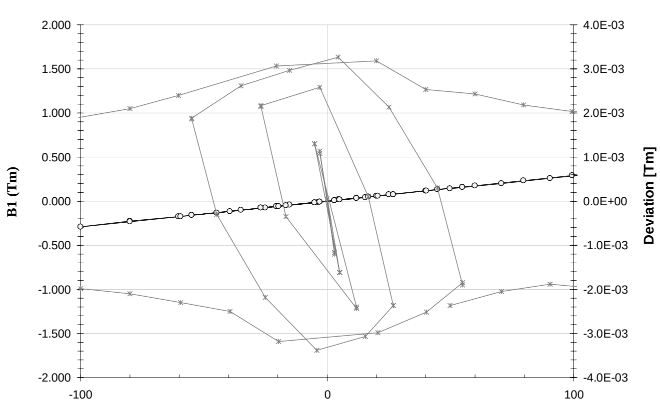

Fig. 8. Degaussing cycle of inner dipole: a saw tooth current cycle of reducing amplitude allows setting at zero the residual field in the magnet bore

VI. Conclusion

The series tests of the orbit correctors for the LHC low-β triplets were completed in August 2005. The main outcomes are the qualification of nearly all magnets for the LHC; valuable experience in the combined powering, often plagued by cross talk phenomena; and extensive knowledge of the magnetic characteristics. The latter will permit to prepare the mathematical models needed to use effectively the magnets in the LHC. The problem of searching a setting procedure reducing the remanent field was solved by the degaussing technique. Still open problems remain, notably the reproducibility of the field angle, which could have an impact on the fine tuning of the beam separation plane. The actual relevance of this fact for the LHC remains to be ascertained.

Acknowledgment

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