Quench Performance and Field Quality of the LHC Preseries Superconducting Dipoles

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***Abstract*—The preseries production of the LHC main superconducting dipoles is presently being tested at CERN. The foremost features of these magnets are: twin structure, six block two layer coils wound from 15.1 mm wide graded NbTi cables, 56 mm aperture, polyimide insulation and stainless steel collars. This paper reviews the main test results of magnets tested to day in both normal and superfluid helium. The results of the training performance, magnet protection, electrical integrity and the field quality are presented in terms of the specifications and expected performance of these magnets in the future accelerator.**

***Index Terms*—Magnetic field measurement, superconducting accelerator magnets.**

I. Introduction

The Large Hadron Collider (LHC) [1], presently under construction at CERN, requires 1232 superconducting dipole magnets, featuring a nominal field of 8.33 T inside a cold bore tube of 56 mm inner diameter and a magnetic length of 14.3 m. In November 1999, CERN has placed, with three European firms, a first order for 3 × 30 dipole cold masses. The construction of these cryo-magnets is the result of close collaboration between CERN and European Industry. The design of the LHC full-scale superconducting dipoles and status of their production in industries is described in detail in [2], [3]. At this moment (October 2003) over 100 series dipole cold masses were delivered to CERN for the assembly into cryostat closely followed by the testing at cryogenic conditions. Until now about 65 dipoles were tested at the CERN Superconducting Magnet Test Plant (SMTP). This paper presents and briefly analyzes the results of these tests in terms of field quality, electrical and cryogenic integrity and the quench performance.

II. Tests and Measurements at Cryogenic Conditions

A. Superconducting Magnet Test Plant

The LHC magnets must satisfy strict performance requirements that are controlled throughout extensive tests and measurements at cold conditions prior to their installation in the collider. The superconducting magnet test facility is being equipped with 12 test stands and the necessary cryogenic infrastructures to perform the tests of all the main ring magnets within the allocated time.

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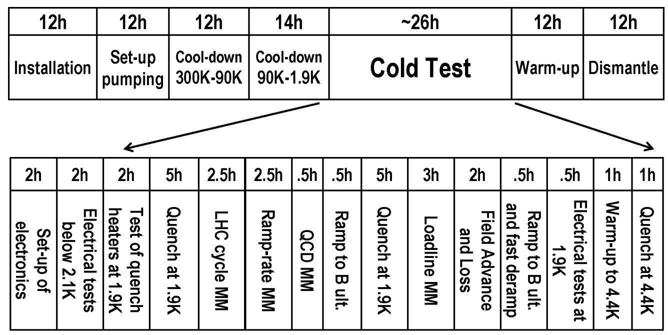

Fig. 1. Standard test cycle for the LHC preseries dipole magnets without a thermal cycle and the sequence of tests typically performed at cold conditions.

Today six series type test stands have been built, commissioned and are operational. The remainder will be ready by May 2004 when the full rate of the production is expected to be reached.

The main phases and their nominal duration of a standard test without a thermal cycle are shown in Fig. 1 together with the sequence of tests typically performed at cold conditions. The quoted durations will be reached once all these activities will run on a round the clock basis.

The essential sequence of the magnet tests at cryogenic temperature is the following. Once a cryostated magnet has undergone preliminary tests at room temperature it is prepared for the cold tests. Both apertures of the 15-m long dipole units are equipped with the “warm bore anticryostats”. These anticryostats consist of two concentric, thermally insulated pipes fitted with electrical heaters. They allow to insert the magnetic field measuring equipment, which is operated at room temperature and at atmospheric pressure, while the magnet itself is kept at cold. The preparation is completed after the upstream end of the cryostat is closed with a magnet return box (MRB). The magnet is moved by means of a dedicated transport vehicle onto the steel support girder of one of the test benches. After positioning and alignment of the magnet its downstream end is connected to the cryogenic feed box (CFB) of the stand. The magnet anticryostats are connected to the CFB anticryostats to allow room temperature access on both sides. The CFB represents the interface between the cryogenic infrastructure and the magnet to be tested. It serves to evacuate the cryostat and to check the tightness of the cold mass and the insulation vacuum enclosure. The CFB hydraulic circuits allow passing the cool down power and, at the end of the test, the warm-up power to the magnet. The electrical power is fed in via current leads for the main coils (11850 A to reach the nominal field of 8.33 T) and for the corrector magnets (600 A). In addition, helium pressurization due to provoked and natural quenches of the coils is controlled through this box.

B. Power Tests and Measurements

The power tests carried out on the LHC pre-series dipoles seek to qualify the magnets in terms of the number of training quenches necessary to reach nominal (8.33 T) and ultimate (9 T) field levels. It is required that the nominal field of 8.33 T is exceeded after the second training quench, the 9 T ultimate field after the 8th quench. All dipoles are expected to reach 8.6 T after a thermal cycle to room temperature, validating the magnet property of keeping the "memory" of quench training. To verify this more than 8 dipoles from each of the three production sites were undergoing an extended test program consisting of two to three runs separated by thermal cycles from 1.8 K to room temperature and back to 1.8 K. The technology to localize weak points where spontaneous quenches are initiated was developed during the prototyping phase of the LHC magnets. The long shafts used for the magnetic measurements were systematically used as "quench antenna" for the quench diagnostic function [4].

The quench heaters protecting the magnets against high spot temperatures and internal voltages during quenches were systematically tested. In particular their delays needed to propagate the quenches and the Miits at several current levels. During the whole test campaign of each magnet the electrical and the cryogenic integrity were carefully monitored by means of dedicated test and measurements.

C. Magnetic Measurements

The magnetic field quality of the LHC dipoles in cold conditions is measured by means of a long rotating coil system [4]. Measurements of the field are performed in all operating conditions at several current levels including in particular the injection plateau (0.54 T) and collision plateau (8.33 T). The magnetic measurement equipment has been developed and tailored to measure 100% of the superconducting dipole magnets. The main objective of the measurement is to provide the integrated field strength, the average field direction, the magnetic length and the steady-state field error components as a function of the operating current. The measured field at relevant operating conditions is used directly to compare to the beam optics requirements, and qualify the magnet for installation. In addition the measurements are used to quantify the main sources of field imperfections. These errors fall into two categories: errors which are of steady state nature (geometric errors, saturation effect, magnetization effect), and those which are of dynamic nature (ramp rate effect, decay of magnetization). The static errors are deduced from measurements at constant field along the magnet loadline, beginning at field values of 0.25 T and up to 8.5 T. The effect of the nominal ramp rate on the harmonics is obtained by cycling the magnets between the injection current and the nominal current. The effect of the decay of the magnetization at injection is quantified during the so-called machine cycle with a simulated injection plateau.

Finally, the measured field, and in particular the geometric errors deduced from static measurements, are used to establish warm-cold correlations that are of paramount importance for steering the production.

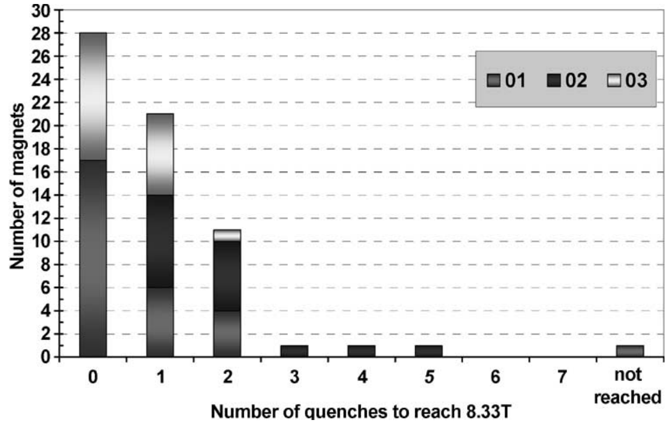

Fig. 2. Histogram of the number of quenches to reach 9 Tesla for the first 64 LHC preseries dipoles.

III. Performance of The First Preseries Dipoles

A. Quench Performance

The first pre-series dipoles display on average satisfactory quench performance. Already in the early stage of the production the three companies assembling the dipole cold masses demonstrated their capabilities for producing the dipoles reaching the ultimate field of 9 T without or with very little quench training. As it is shown in Fig. 2 only 4 dipoles did not reach the nominal field of 8.33 T after the 2nd quench. One dipole systematically quenched at field plateau of about 6 T due to cold welds in 28 out of 36 strands in one spot in the outer layer conductor.

The quench performance data for Firm 1 [Fig. 3(a)] show that the number of quenches required for reaching 9 T increased over the production of the first 27 magnets. This deterioration can be explained by magnet imperfections due to the use of new assembly lines and an increased production rate which required training of new teams and most probably affected quality of the assembly work. Recent tests of some magnets produced later indicate a recovery of the quality of the coils production. The total average of the production so far requires 2.9 quenches for reaching 9 T. Firm 2 [Fig. 3(b)] showed a similar deterioration over the production of the first 25 magnets (on average 4.4 quenches to reach 9 T). The improvements expected after the learning period have not yet been measured. Firm 3 magnets [Fig. 3(c)] required a larger number of quenches at the beginning of the production. Even though the quench performance had initially improved for part of the production the last measurement results show again increased number of required quenches and the production needs more follow up. On average Firm 3 magnets required 3.2 quenches for reaching 9 T.

B. Quench Localization

The vast majority of the training quenches for all tested preseries dipoles are located in the coil ends, with no predominance of one or the other. In the last prototype magnets the coil ends and neighboring transition regions remain the weak

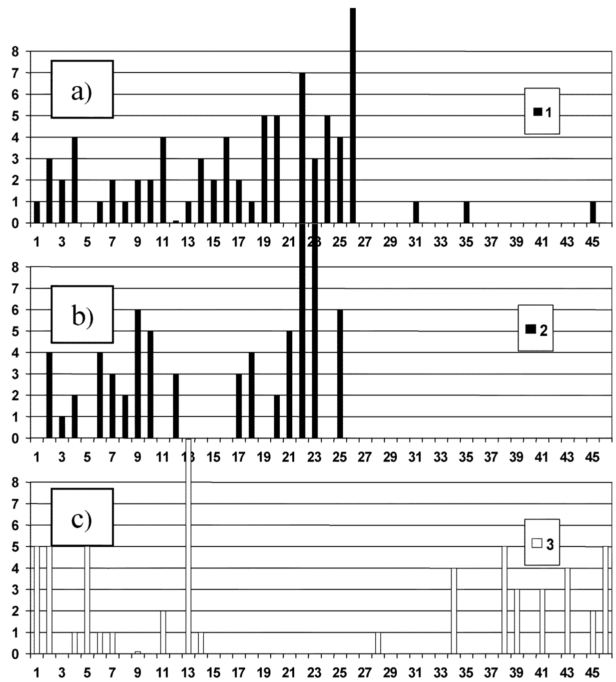

Fig. 3. The quench performance data for a) Firm 1, b) Firm 2, c) Firm 3. The number of quenches required for reaching 9 T is plotted versus the production number of magnet.

point regarding the mechanical stability of the magnet structure. A more robust design and industrialized manufacturing of the straight part and of the ends improved the training performance with respect to the prototype generations. Comparing further the pre-series magnets, it follows that the performance enhancement depends mainly on the collared coil assembly. So far particular assembly details chosen by the three manufacturers hardly influence the training performance. The same conclusion applies to the space and time distribution of the so-called "spikes" [5], the quench precursors resulting from conductor motions, proving the success of the undertaken uniformization of the key assembly operations in the three companies assembling the cold masses.

C. *Quench Sensitivity to Ramp Rate, Magnet Protection*

As already reported [3], the sensitivity of the measured dipoles to quench for high current ramp rate is in general low and not very different from magnet to magnet. This point is particularly important for the machine operation as it has an impact on the protection of the magnets connected in series. In the case of a quench of one dipole in a string of magnets, the quenching magnet is short-circuited by a by-pass diode [6]. All the other magnets of the string have to be discharged with a ramp rate up to 120 A/s. Present dipoles at nominal current exhibit a very comfortable margin in this respect.

D. *Conductor Performance, Electrical Integrity*

The quench performance of a magnet is usually referenced to the performance of its superconducting cables in operating conditions. It is practically impossible to reach the cable limit at 1.9 K for the series LHC dipoles because of training and the integrity and performance of the cables have to be evaluated

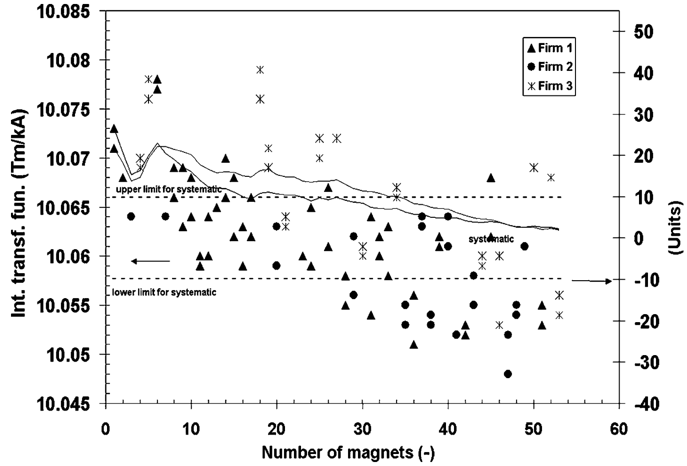

Fig. 4. The integrated transfer function of the dipole field (ratio of integrated dipole field to operating current). Right axis shows the limit of the systematic error in 10^{-4} relative units.

by means of dedicated quenches performed in normal boiling helium at 4.4 K. The results of these tests will be described in detail in a separate publication.

Although the electrical integrity of the tested dipoles is in general satisfactory, several dipoles, delivered by all three firms, exhibited deficient strength of the electrical insulation, mainly for the quench heaters circuits. Corrective actions improved significantly the active parts and instrumentation of the following magnets.

IV. Magnetic Field Quality

The integrated transfer function of the dipole field (ratio of integrated dipole field to operating current) is plotted in Fig. 4. A difference between firms appeared with the transfer function of Firm 3 being in average 7 units of above those of Firm 2, the data of Firm 1 being in between. The spread observed among all the magnets tested is about 7 units both at injection and at collision, being at the limit of the specified r.m.s. value of 8 units. The origin of this difference between manufacturers is under investigation.

The multipole components for the first measured magnets at nominal field are summarized in Figs. 5. Normal and skew field multipoles, $\mathrm{b_n}$ and $\mathrm{a_n}$ respectively, are in units of 10^{-4} relative to the main dipole field expressed at a reference radius of 17 mm. The multipoles plotted are integrated over the magnet length, including ends, and are compared to the maximum allowed bounds on the average and the spread for the LHC operation.

The first part of the preseries magnet production exhibited relatively large normal sextupole $(\mathrm{b_3})$ values measured both at injection and nominal field [Fig. 5(a)]. These values are inherent to the coil geometry of the first preseries dipoles. Also the normal decapole $(\mathrm{b_5})$, was found to be outside the target requested for the accelerator. In order to reduce these geometric field errors, corrective action consisting of a small change of the copper wedge dimensions, keeping the coil azimuthal length unchanged has been undertaken [7]. The first results of this correction obtained during the cold measurements are shown in Fig. 5(b). It can easily be noticed that both the $\mathrm{b_3}$ and $\mathrm{b_5}$ values

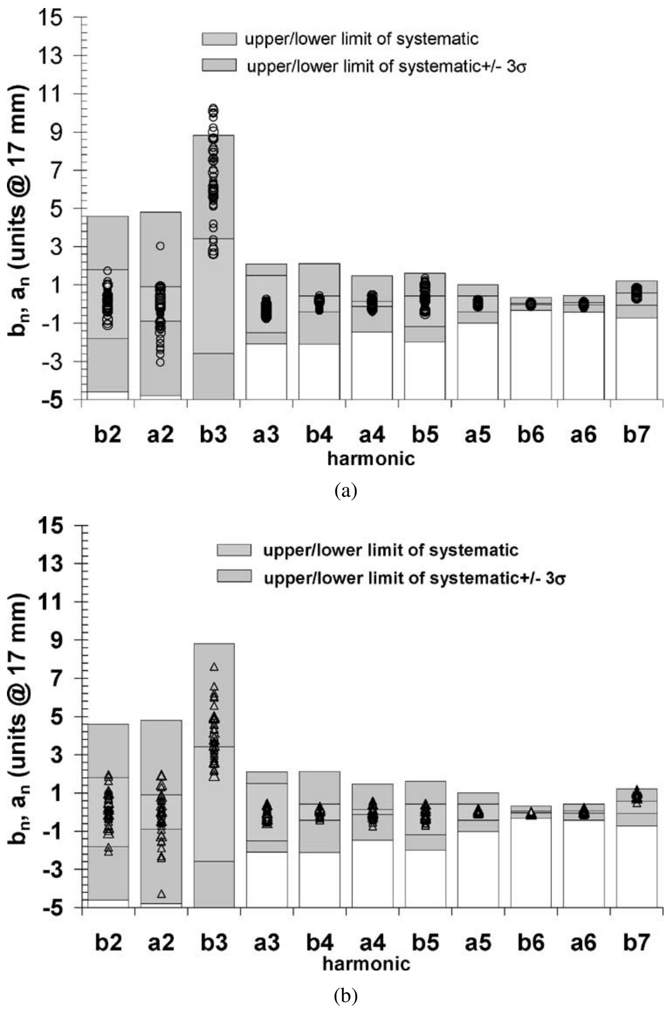

Fig. 5. (a) Normal and skew field multipoles normalized to the main dipole field measured at nominal value of 8.33 T for the first preseries dipoles before modification of the cross-section. (b) Normal and skew field multipoles normalized to the main dipole field measured at nominal value of 8.33 T for the preseries dipoles after modification of the cross-section to correct sextupole and decapole multipole components

were reduced by 4 units in b_3 and 0.8 units in b_5 but are still slightly out of the tolerance for b_3 at collision and b_5 at injection [8].

Recently a decision was taken to implement another change of the cross-section in order to better center these values on their targets. Results concerning warm measurements on magnets with the third cross-section are described in [8]. All remaining higher order multipoles at injection and nominal field, except slightly too high b_7, are in practice comfortably within the allowed limits.

V. Conclusion

In view of the LHC main dipole full rate series production, significant efforts are devoted to standardize and homogenize manufacturing processes. All these operations are controlled by strict assembly and quality assurance procedures and finally by thorough cold testing prior to installation.

An extensive test and analysis program is being pursued. Up to this point, all pre-series magnets tested to date, apart for 4 (6% of tested), passed the nominal field of 8.33 T after maximum 2nd quench. In total over 90% of tested magnets fulfilled all specified acceptance criteria. The pre-series dipoles display on average good quench performance. Satisfactory capability of keeping the "memory" of the quench training, were verified by applying a thermal cycle to the first thirty magnets. The electrical isolation has been successfully improved after some deficiency found on some of the first magnets tested.

The field quality of the pre-series twin-aperture dipoles has been measured in all accelerator conditions. The expected field effects due to the superconducting cable, yoke saturation, ramp rate inducing inter-strand current have in general been confirmed.

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