Performance of the First LHC Pre-Series Superconducting Dipoles

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***Abstract*—Within the LHC magnet program, a preseries production of final design, full-scale superconducting dipoles has presently started in industry and magnets are being tested at CERN. The main features of these magnets are: two-in-one structure, 56 mm aperture, six-block two layer coils wound from 15.1 mm wide graded NbTi cables, and all-polyimide insulation. This paper reviews the main test results of magnets tested to date in both supercritical and superfluid helium. The results of the quench training, conductor performance, magnet protection, sensitivity to ramp rate, and magnetic field quality are presented and discussed in terms of the design parameters and the aims of the LHC magnet program.**

***Index Terms*—Field quality, LHC-main dipoles, magnet protection, quench training, superconducting magnet.**

I. INTRODUCTION

THE LARGE Hadron Collider (LHC), now under construction at CERN, will provide proton-proton collision with a center-of-mass energy of 14 TeV and an unprecedented luminosity of 10^{34} cm^{-2} s^{-1} [1]. To reach 7 TeV per beam in the existing LEP tunnel presents some considerable technological challenges. The small tunnel cross-section as well as the need to minimize the cost imposes a two-in-one cryo-magnet design for the main dipoles and quadrupoles. The 8.33 T operating field of main dipoles can only be obtained at an acceptable cost by cooling the magnets down to 1.9 K, below the lambda point of helium.

The experimental program on the LHC two-in-one main cryo-dipoles started at the turn of 1989–1990. Since then seven full-scale magnets of the 1st generation and five of the 2nd generation were built in industry and tested at CERN. The design and main test results of these cryo-magnets have been described in several earlier publications [2]–[4].

In 1998, CERN launched in industry the fabrication of six dipole prototype collared coils of the 3rd generation. These collared coils were subsequently assembled into cryo-dipoles at the CERN Magnet Assembly Facility (MAF).

In 1999, a first order for three times thirty pre-series dipole cold masses was placed with three European firms. The first six pre-series cold masses have been assembled like the prototypes at the MAF starting from collared coils produced in industry. The subsequent pre-series dipole cold masses are fully produced by industry and cryostated at CERN.

In this paper, the main test results of the first eleven pre-series dipoles tested at the CERN Superconducting Magnet Test Plant (SMTP) will be reviewed. The results of quench training, conductor limit, sensitivity to ramp rate, magnet protection, and field quality will be discussed in terms of the design parameters and the aims of the LHC dipole program.

II. MAGNET DESIGN FEATURES

The design of the 3rd and final generation of the LHC full-scale superconducting dipoles is described in detail in [5]–[7]. The construction of these cryo-magnets is the result of close collaboration between CERN and European Industry. Only the main design features will be recalled here in view of the discussion of the test results.

The 3rd generation LHC dipole coils are wound with two different, 15.1 mm wide NbTi Rutherford cables. The inner layer cable consists of 28 strands of 1.065 mm diameter, while the outer layer cable is made of 36 strands of 0.825 mm diameter. In comparison to the “5-block” coil of the 2nd generation, the 3rd generation coil has the conductors of each quadrant distributed in 6 blocks. The all polyimide cable insulation is composed of two layers of 25 μm thick tapes each overlapped by 50%, and a third 70 μm thick adhesive coated layer, spaced by 2 mm to provide channels for helium penetration into the coils. The two-in-one LHC dipoles have a single racetrack type collar in austenitic steel, embracing the coils of the two dipole channels.

III. PERFORMANCE OF THE FIRST PRESERIES CRYO-DIPOLES

A. Test Procedure

The power tests carried 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. The provisional acceptance criteria require the nominal field to be exceeded after no more than the 2nd quench and the ultimate field after no more than 7th quench. The first 30 dipoles (3 times 10 from the three production sits) are undergoing an extended test program, also validating the magnet property of keeping the “memory” of quench training after a thermal cycle. For this purpose the tests are typically carried out in two to three runs separated by thermal cycles from 1.8 K to room temperature and back to 1.8 K. The results of this extended program of tests will permit the establishment of final acceptance criteria and verification of test procedures.

For the cold tests, 15-m long cryo-dipole units equipped with corrector magnets are installed on test stations at CERN SMTP.

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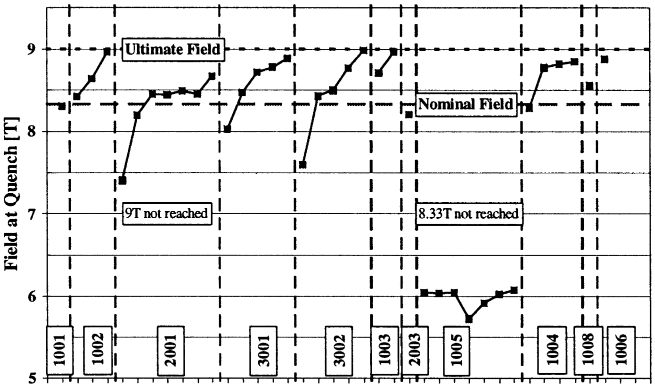

Fig. 1. Training curves in the limit of 7 quenches to reach 9 T, recorded for the first runs for first eleven pre-series dipoles (chronological order).

TABLE I
SUMMARY OF QUENCH PERFORMANCE

Dipole Name	First quench [T]	No. of quench to 8.3T	No. of quench to 9 T	1^{st} quench after ther. cycle [T]	margin ΔT_1 [K]	Acceptance Fulfilment [Yes/No]
1001	8.31	1	1	> 9T	1.65	Yes
1002	8.43	0	3	> 9T	1.54	Yes
1003	8.71	0	2	No th. cycle	1.58	Yes
1004	8.29	1	4	> 9T	1.64	Yes
1005	6.05	Not reached	Not reached	No th. cycle	-	No
1006	8.89	0	1	> 9T	1.51	Yes
1008	8.56	0	1	8.8	1.51	Yes
2001	7.4	2	Not reached	8.38	-	No
2002	Electric problem			Not tested at cold		
2003	8.21	1	1	> 9T	1.54	Yes
3001	8.03	1	5	8.86	1.39	Yes
3002	7.59	1	5	8.60	1.56	Yes

The beam screens are not mounted in the magnet apertures to permit insertion of the so-called "anticryostats," which allow the use of measuring shafts at room temperature for quench location and magnetic field measurements [8].

B. Quench Performance

For the standard quench training test, the quench current is reached with a nominal ramp rate of 10 A/s. Fig. 1 shows the quench performance recorded during the first test campaigns for all eleven pre-series magnets tested to date. A summary of the quench performance is reported in more details in Table I.

All tested dipoles except 1005 reached the nominal field of 8.33 T after at most a 2nd quench. The 1005 dipole was found to quench at field plateau of about 6 T (8.5 kA). All quenches originated at the same location. Further quench tests revealed a strong correlation between the magnet temperature and the quench current. This provided evidence that the quenches were limited by significant degradation of the conductor. The 1005 magnet was sent back to its manufacturer. After disassembly and inspection at the position indicated by the quench localization, cold welds in 28 out of 36 strands were found, explaining the degradation of the quench performance. It has to be reminded that cold welds are not allowed in the LHC cables and many cares have been taken in the cable contracts to assure their absence. Their presence in the 1005 magnet is due to a human error at fabrication, emphasizing the importance of the strict quality control and cold testing of the magnets. Immediate corrective actions have been taken.

One of the dipoles, 2002, could not be tested in cryogenic conditions due to deficient electrical insulation of several quench heaters circuits. Thorough inspection performed after disassembly of the cold mass has identified an important failure mode, which can develop during the collaring. Dedicated tests were implemented in industry to detect and correct as early as possible the defects of this type.

C. Quench Localization

All training quenches for all tested pre-series dipoles are located in coil ends, with no predominance of one or the other. In the final design magnets as in the two previous generations the coil ends and neighboring transition regions remain the weak point regarding the mechanical stability of the magnet structure. With respect to the performance of the 2nd and 3rd generation prototypes the quench training of the final magnets is significantly better. Improved quench performance of the pre-series magnets seems to originate from more robust design and industrialized manufacturing of the straight part of the magnets. Despite some minor quench training instabilities no important detraining effect [9] was observed. Reduction of this effect is particularly important for the LHC machine operation.

For the same coil design the quench performance is still influenced by the assembly details chosen by industry. This is evident comparing the results on the pre-series magnets in Fig. 1 and Table I. Note that the first digit of the magnet serial number indicates the vendor. The same conclusion applies to the space and time distribution of the so-called "spikes" [10], the quench precursors resulting from conductor motions.

D. Quench Sensitivity to Ramp Rate, Magnet Protection

As already reported [9], the sensitivity of the quench field to ramp rate of the first pre-series dipoles 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 quench level and protection of the magnets connected in series. In case of a quench of one dipole in a string of magnets connected in series, the quenching magnet is short-circuited by a by-pass diode [11], [12]. All 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. An impact of the ramp rate on the quench level was studied at 4.4 K, as at superfluid temperatures it was not observable due to too low ramp rate sensitivity. For magnets exhibiting the highest inter-stand cross-contact resistance R_c (ca. 100 $\mu\Omega$, see [13]) the first signatures of a possible current sharing mechanism contribution to the ramp rate sensitivity were observed but the overall effect on the quench level remained negligibly low.

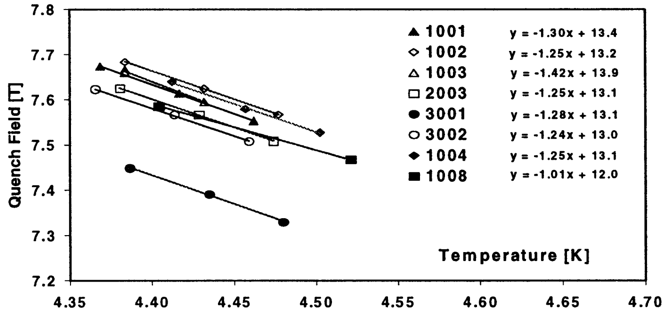

Fig. 2. Quench performance in vicinity of 4.4 K.

E. Conductor Performance and Integrity

The quench performance of a magnet can better be assessed if referenced to the performance of its superconducting cables in operating conditions. Due to the quench training effect in nominal operating conditions it is in general not possible to reach the cable limited quench level. For the LHC dipoles, the integrity and performance of the cables are evaluated by means of dedicated quenches performed at elevated temperatures in the vicinity of 4.4 K. These tests are carried out after quench training at 1.9K reaches the LHC ultimate field of 9 T. In this way the quenches at temperatures around 4.4 K are normally not affected by the mechanical behavior of the coils but are limited by the conductor performance, since these quenches occur below 8 T under much lower electromagnetic forces. The quench performance as a function of temperature in the vicinity of 4.4 K for all measured magnets is shown in Fig. 2. From these quench tests an important parameter can be deduced, namely the temperature margin ΔT, defined as the difference between the bath temperature and the sharing temperature at the nominal field and current. The cable design for the LHC magnets has been made for a margin at superfluid helium of $\Delta T_1 = 1.4$ K and $\Delta T_2 = 1.7$ K for the inner and the outer cable respectively. The choice of the margin was made to guarantee that the cables always stay in non boiling helium while cooling system is balancing the energy dissipation due to the current ramping, resistive joint losses, and the beam losses during the machine operation [1], [14].

To evaluate the temperature margin, the magnet quench current reached in the 4.4 K temperature range is compared with the critical current I_c measured on the corresponding cable. It is assumed that the magnet quench current obeys to the same relation as the cable critical current. The magnet quench current is first referred to the reference temperature and field of 4.22 K/7 T (4.22 K/6 T), which is used for the inner (outer) cable I_c measurements. In this way the reference quench current is derived at 4.22 K. Making use of this current and the shift coefficients [15] derived for each inner (outer) cable producer from 4.22 K/7 T (4.22 K/6 T) to 1.9 K/10 T (1.9 K/9 T) it is possible to calculate the critical current at nominal field and temperature of 1.9 K. The final value of the temperature margin $\Delta T_1 (\Delta T_2)$ is found applying the linear relationship for the $I_c - T$ characteristic (see Table I).

The same method, in conjunction with the quench localization allows also to detect and to evaluate a temperature increase in a splice region where excessive heat can be generated due to the non conform splice resistance or insufficient cooling.

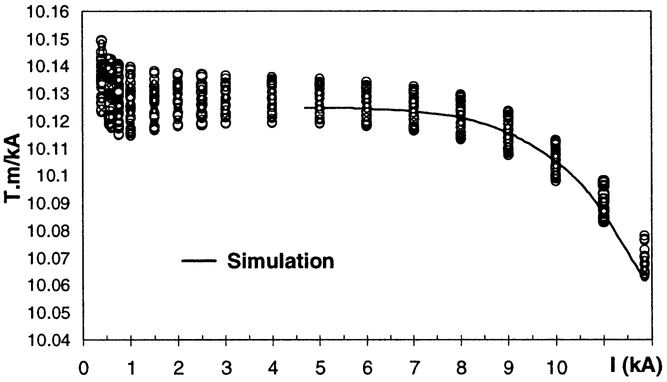

Fig. 3. Integrated transfer functions measured in the pre-series dipoles as a function of the current.

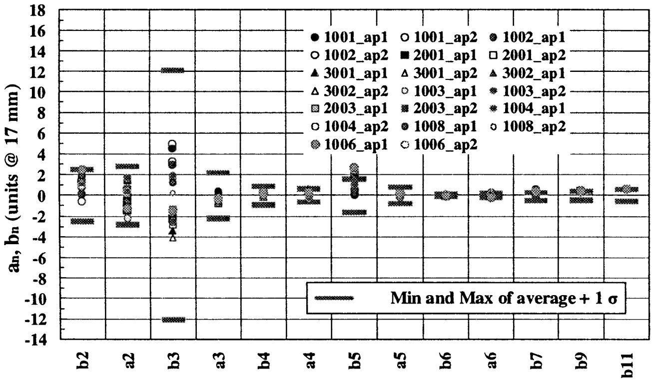

Fig. 4. Integrated harmonics measured at injection field.

The temperature margin is planned to be one of the magnet performance parameters to be used for possible sorting of the magnets prior to their installation in the tunnel.

IV. MAGNETIC FIELD QUALITY

The magnetic field quality of the LHC dipoles in cold conditions is measured by means of a long rotating coil system [8]. Measurements of the field are performed in all accelerator conditions at several current levels, in particular including the injection plateau (0.54 T) and nominal collision plateau (8.33 T). The integrated transfer function of the dipole field (ratio of integrated dipole to operating current) is plotted in Fig. 3. The spread observed among the ten magnets tested amounts to 6.55 10^{-4} at injection and 6.26 10^{-4} at collision, safely within the specified r.m.s. value of 8 10^{-4}. The field direction in each magnet aperture shows a nonzero average twist (difference from one end to the opposite one) of 1.1 mrad, while the difference between the two apertures is 0.5 mrad. Both values are within the specified bounds of 3 mrad for the twist and 0.8 mrad for the co-planarity. These effects are statistically not significant for the tested magnets because of the small number of magnets where these parameters could be measured.

The higher order multipole components for the first ten measured magnets at injection and at nominal field are summarized in Figs. 4 and 5. Normal and skew field multipoles, b_n

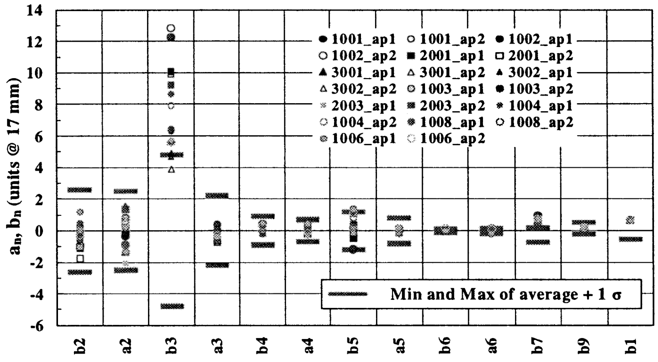

Fig. 5. Integrated harmonics measured at nominal field.

and a_n respectively, are normalized to the main dipole field, scaled by a factor 10^4 and 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. As compared to the multipoles measured on prototype dipoles the b_2 and a_2 components were successfully minimized by changing the geometry of the iron inserts in the yoke. The large normal sextupole (b_3), decapole (b_5) and b_7-multipole values measured at injection and nominal field are inherent to the coil geometry of the first pre-series dipoles, due to the difficulty to satisfy the conflicting requests of good field quality and sufficient pre-stress in the windings.

When compared to the beam dynamic constraints at injection and nominal field, the normal sextupole and the b_7–multipole are outside the specification at nominal field and the normal decapole is outside the allowable limits at injection. 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 [6]. All remaining higher order multipoles at injection and nominal field are in practice within the allowed limits. The field errors generated by the persistent and coupling currents and their decay during the injection plateau are discussed in detail in [16] whereas interpretation of the saturation and geometric effects is given in [17].

V. CONCLUSION

An extensive test and analysis program is being pursued for the LHC main cryo-dipoles. Up to this point, all eleven pre-series magnets tested to date, apart for one, passed the nominal field of 8.33 T after maximum 2nd quench. Nine magnets out of eleven exceeded the LHC ultimate field of 9 T, also after thermal cycles. First pre-series dipoles display on average better quench performance than the prototypes. This includes better quench performance, better capability of keeping the “memory” of the quench training and coil structure less sensitive to the detraining effect.

The field quality of the first ten pre-series twin-aperture superconducting dipole magnets for the LHC has been measured in all accelerator conditions. The hypotheses made on field effects due to the superconducting cable, yoke saturation, ramp rate inducing inter-strand current have in general been confirmed.

As already reported [9] the quench performance of the first pre-series dipoles still carries the signature of the manufacturers. The results of the field quality seem also to be related to the chosen pre-stress in the coils and still existing manufacturing variants.

In view of the LHC main dipole series production, significant efforts are now 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.

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