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Electrical and Magnetic Performance of the LHC Short Straight Sections

S. Sanfilippo, J. Beauquis, L. Bottura, M. Buzio, M. Coccoli, J. Garcia-Perez, P. Pugnat, N. Sammut, A. Siemko, N. Smirnov, A. Stafiniak, E. Wildner

Abstract

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***Abstract* - The Short Straight Section (SSS) for the Large Hadron Collider arcs, containing in a common cryostat the lattice quadrupoles and correction magnets, have now entered series production. The foremost features of the lattice quadrupole magnets are a two-in-one structure containing two 56 mm aperture, two-layers coils wound from 15.1 mm wide NbTi cables, enclosed by the stainless steel collars and ferromagnetic yoke, and inserted into the inertia tube. Systematic cryogenic tests are performed at CERN in order to qualify these magnets with respect to their cryogenic and electrical integrity, the quench performance and the field quality in all operating conditions. This paper reports the main results obtained during tests and measurements in superfluid helium. The electrical characteristics, the insulation measurements and the quench performance are compared to the specifications and expected performances for these magnets. The field in the main quadrupole is measured using three independent systems: 10-m long twin rotating coils, an automatic scanner, and single stretched wire. A particular emphasis is given to the integrated transfer function which has a spread of around 12 units rms in the production and is a critical issue. The do-decapole harmonic component, which required trimming through a change in coil shims, is also discussed. Finally, the magnetic axis measurements at room temperature and at 1.9 K, providing the nominal vertical shift for installation are reported.**

***Index Terms*—LHC, Quadrupole, Superconductivity, Field Quality, Quench Training.**

I. INTRODUCTION

THE Large Hadron Collider (LHC), under construction at CERN and expected to start operation in 2007 will include a total of 360 NbTi lattice quadrupoles (MQ) assembled in arc Short Straight Sections (SSS) of 61 different types [1]. These magnets will operate at 1.9 K with a nominal field gradient of 223 T/m for the quadrupole. The LHC main quadrupole project is the result of collaboration between CERN and CEA Saclay (France). CEA was in charge of the magnet design and CERN took the responsibility for the contract and for the components [2]. The 360 fully assembled cold masses needed were ordered with the German firm ACCEL Instrument in July 2000, CEA and CERN ensuring the technology transfer. The quadrupoles were manufactured at ACCEL but the corrector magnets as well as numerous other components were made by other suppliers and were delivered to ACCEL by CERN. Starting in 2003 the series-production has reached 631 collared coils and 239 cold masses in August 2005. To date we report in this paper the result of 150 short straight sections tested in operational conditions at CERN Superconducting Magnet Test Plant (SMTP). The population is made up of MQs with two coil layouts that have been used in the production. Half of the MQs are with the original base-line cross-section and the other half with a second cross-section featuring in the mid-plane an additional insulation sheet of 0.125 mm.

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II. MAGNET DESIGN FEATURES

The design of the arc short straight sections is described in detail in [2-5]. For the scope of the present paper only the main design features in view of the discussion of the test results will be recalled. The lattice quadrupole is composed of a pair of two independent apertures with 56 mm bore assembled into a common yoke separated by a distance of 194 mm at 1.9 K. Each quadrupole coil consists of four double layer windings, based on 15.1 mm wide NbTi Rutherford cables insulated using three wraps of Kapton^{TM}. The inner and outer layers are made of the same keystoned cable without a splice and consist of 36 strands of 0.825 mm diameter coming from three manufacturers. The Nb-Ti filament size is 6 μm and the Cu:Sc ratio is 1.9. The magnetization of the strands from all manufacturers is measured at CERN at a field of 0.5 T in a 1.9 K helium bath [6]. The maximum values specified for the LHC production are 23 mT with control limits of ±4.5 % around their average value. The design parameters for the quadrupole are a field gradient of 14.5 T/m at injection (0.45 TeV beam energy) and 223 T/m at nominal (7 TeV beam energy) corresponding respectively to currents of 760 A and 11850 A over an effective length of 3.11 m. The quadrupole reaches 241 T/m with a peak field in the coil of 7.5 T at ultimate machine performance (9 T dipole field).

Each coil is independently collared with 2 mm- thick non-magnetic austenitic steel collars. They are inserted together inside an iron yoke made of a single-piece low-carbon steel lamination. The cold mass consists of a 5.35 m long austenitic stainless steel inertia tube into which are aligned the twin-aperture quadrupole and two pairs of different auxiliary magnets at each end of the quadrupole. Combined dipole-sextupole corrector units are located at one end (MSCB) whilst either two small octupole (MO) or two tuning quadrupoles (MQT) are mounted in the other end [5].

III. TEST PROCEDURES

The SMTP at CERN is composed of 12 tests stands and is equipped with the necessary cryogenic infrastructure to perform the tests of all the main ring magnets within the allocated time [7]. The cold tests intend to qualify the cryogenic and vacuum integrity. Electrical tests are executed after each critical phase and power tests are carried out aiming at qualifying the magnets in terms of the number of training quenches necessary to reach the nominal (223 T/m) and the ultimate (241 T/m) field gradient levels. The correctors are tested in cold conditions up to 600 A for the MO, MS and MQT magnets and up to 55 A for the dipole orbit correctors.

The field quality of about 10% of the MQ will be measured in machine operating conditions at superfluid helium temperature. A warm-to-cold correlation based on measurements at room temperature performed on 100% of the MQs in industry is used to extrapolate the field quality of the other cold masses [8]. The beam screens are not mounted in the magnet apertures to permit the insertion of the so-called “anticryostats”, which allow the use of room-temperature magnetic systems like the automated scanner [9], the single stretched wire (SSW) [10] and the 10-m long shafts based on the 15-m long ones used for the dipoles [11]. The position of the magnetic axis of the MQ and of the correctors is determined at room temperature and 1.9 K with respect to a fiducial reference frame defined by optical targets mounted on the cryostat. Warm axis measurements are done on all units with a scanning rotating-coil probe (“AC mole”) [12]. The MQs are powered with 5 kA at 1.9 K (an intermediate current level that minimizes the effects of magnetization and saturation) and 20 A DC (or 1A AC) at room temperature, while the correctors are fed with nominal current at 1.9 K and 0.5 A AC at room temperature. The overall accuracy of the axis position is estimated about 0.2 mm for MQs and 0.3 mm for correctors, considering the best-suited instrument for each magnet type and temperature. This accuracy is adequate to compare results to tolerances.

IV. ELECTRICAL AND QUENCH PERFORMANCE

The electrical tests consist mainly in DC resistance measurements to check the integrity of the magnet instrumentation and on measurements of the insulation resistance at high voltage for the MQ and the correctors versus ground and between each other. Four SSS were not tested or partially tested at cold because of insulation faults appearing before or after the cold tests in the corrector circuits.

For the standard quench training test, the quench current of the MQ is reached with a nominal ramp rate of 10 A/s. Each corrector is powered up to their ultimate currents at 1 A/s for the dipole, at 5 A/s for the sextupole, MO and MQT magnets. The histogram in Fig. 1 shows the number of quenches to reach the nominal field gradient for all 150 SSS tested to date. The magnets display satisfactory quench performance: all MQs except one that has been rejected reached the nominal gradient of 223 T/m and 95% of them after the 2nd quench. In average each SSS requires 0.55 quench to reach the nominal current. 13 MQs were tested after a thermal cycle from 1.9 K to room temperature and back to 1.9 K and showed a good memory (except one rejected). Several correctors in SSS required training to reach the ultimate current even if each of them were trained to ultimate current before assembling.

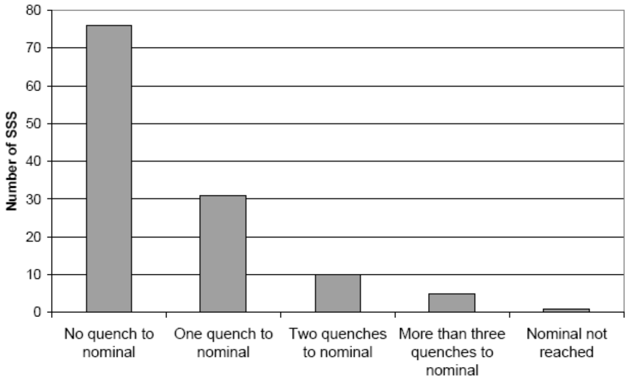

Fig. 1. Histogram of the number of quenches to reach the nominal gradient (223 T/m)

V. FIELD QUALITY

A. *Field quality at injection and nominal current.*

The field quality of 21 short straight sections (42 apertures) has been fully measured in cold conditions (field gradient and multipoles). 15 MQs are with the original base-line cross-section, 6 magnets with a second cross-section. For the first 8 MQs the automated scanner was used to qualify the field quality. For the remaining 13 MQs two complementary systems were used: the field gradient was measured using the SSW system and the multipoles with the 10-m long shafts. The field gradient was also measured for additional MQs using the SSW system. The higher-order multipole components at injection and at nominal field are summarized in Figs. 2 and 3. Normal and skew field multipoles, b_n and a_n respectively, are normalised to the main quadrupole field (n=2), 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 on the spread for the LHC operation (i.e the limits for an individual quadrupole) [13]. At injection and nominal fields most integrated multipoles are within the allowable limits. The large spread of the normal do-decapole values observed at injection and nominal fields (b_6) are due to the change in cross-sections. The first series of quadrupoles show b_6 values outside the target at injection by about + 1.5 units. The corrective action taken jointly by CEA Saclay and CERN (addition in the mid-plane an of an insulation sheet of 0.125 mm [8]) was found to be effective with a decrease of the b_6 by 1.9 units in average measured in the MQs with the cross-section 2 (see Table I).

TABLE I
MEASURED MULTIPOLES Cn AND AND STANDARD DEVIATION σCn AT 1.9 K AND INJECTION FIELD FOR MQS WITH THE TWO CROSS-SECTIONS

Multipole component	c_n (units) Cross-section I	σc_n (units) Cross-section I	c_n (units) Cross-section II	σc_n (units) Cross-section II
b_6	1.46	0.50	-0.41	0.40
b_{10}	-0.09	0.07	-0.24	0.07

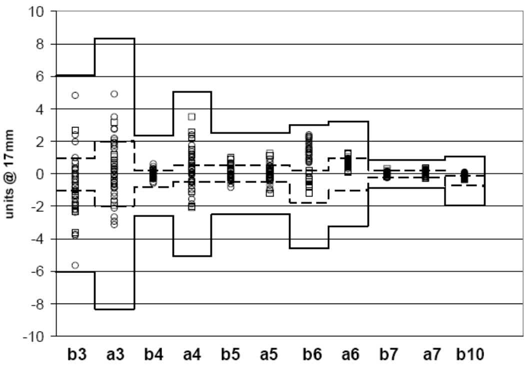

Fig. 2. Field quality at injection field (14.5 T/m). The dot lines display the upper and lower limits for the systematic value and the continuous line the limits for an individual quadrupole. Magnets feature two types of cross-section, cross section 1 (circles), cross section 2 (square).

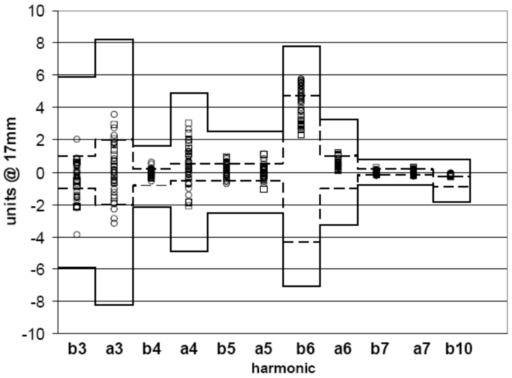

Fig. 3. Field quality at nominal field (223 T/m). The dot lines display the upper and lower limits for the systematic value and the continuous line the limits for an individual quadrupole. Magnets feature two types of cross-section, cross section 1 (circles), cross section 2 (square).

B. Integrated transfer function of the gradient

The integrated transfer function (TF) of the field gradient (ratio of integrated quadrupole to operating current) is plotted as function of the current in Fig.4. The average and the standard deviation calculated at injection, at 5 kA and at nominal current are presented in Table II.

TABLE II
INTEGRATED TRANSFER FUNCTION (AVERAGE, SPREAD) AT INJECTION AND NOMINAL CURRENT VERSUS THE SPREAD EXPECTED BY BEAM DYNAMICS

Current level.	Average measured T/kA	σ measured (units)	σ beam dynamics (units)
Injection (760 A)	58.360	12	10
Geometric(5 kA)	58.361	12	10
Nominal (11850 A)	58.288	11	10

The saturation of the ferromagnetic yoke results in a reduction of the transfer function at nominal field by approximately 13 units with respect to the geometric value evaluated at 5 kA. The spread observed amounts to 12 units and 11 units respectively at injection and collision, close to the limits of the standard deviation value of 10 units specified by the beam dynamics [13].

A systematic shift of 17 units was found for the absolute field gradient between measurements performed using the automated scanner and the SSW system. Investigation and repeated calibrations indicate that for the field gradient the calibration of the automated scanner was quite delicate and is not reliable. Details about the calibration procedure and comparison of the results between the two systems can be found in [14],[7]. Therefore the SSW system has been considered as the reference system and the transfer function measured with the automated scanner was corrected in Fig. 4 by subtracting the experimental shift of 17 units.

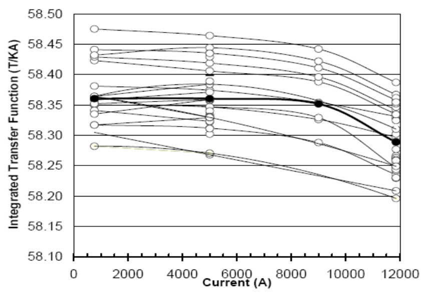

Fig. 4. Integrated transfer functions for the MQ as a function of the current. The bold continuous line displays the average transfer function. The SSW system has been used as the reference system for the field gradient.

Recently MQs with high transfer function measured at room temperature were produced [8]. The origin was traced back to magnetic permeability in the collars which are out of tolerance. The measurements at cold for few magnets with this high permeability show that this effect disappears in operational conditions. It implies nevertheless a dedicated scaling to extrapolate the room temperature measurements at nominal condition [8].

C. Magnetization effects of multipoles at injection.

The magnetization associated with persistent currents in the NbTi superconducting filaments affects the allowed harmonics (b_2, b_6 and b_{10}) especially at low fields. This contribution to the field error is defined as the difference between the multipole value measured at injection current and the geometric component. The magnetization effect on the first allowed multipoles (average Δc_n^P and standard deviation σc_n^P) is summarized in table III and compared to calculation based on strand measurements.

TABLE III
MEASURED VS. EXPECTED PERSISTENT CURRENT FIELD ERRORS IN UNITS

Multipole component	measured Δc_n^P (units)	measured σc_n^P (units)	expected Δc_n^P (units)	expected σc_n^P (units)
b_2	0.17	4	-4.39	0.6
b_6	-3.63	0.80	-3.48	1.50
b_{10}	0.05	0.06	0.1	0.18

The magnetization effect on b_6 and b_{10} was found to be in agreement with the expectations based on strand measurements. For b_2, the magnetization effect did not match with the expectations with an average change of 0.17 units as compared to the expected -4.39 units. The random component for b_2 is also larger than predicted with an r.m.s of 4 units versus the 0.6 units expected. One part of this contribution originates from the reproducibility of the measurement systems which is close to 1.5 units for b_2.

D. Decay of the multipoles at injection.

The field contribution of persistent currents decays during injection, resulting in systematic effects in the allowed multipoles [15]. The measured decay for the allowed harmonics (b_2, b_6 and b_{10}) during a simulated injection plateau of 1000 s is summarized in Table IV. All MQs were submitted to the same powering history: they were quenched and pre-cycled to a flat-top current of 11850 A for 1000 s before ramping to a minimum current of 350 A and finally to the injection current of 760 A.

TABLE IV
MEASURED AVERAGE Δc_N^D AND STANDARD DEVIATION σc_N^D OF FIELD DECAY ERRORS IN UNITS

Multipole component	Δc_n^D	σc_n^D
b_2	-1.75	2.00
b_6	0.42	0.2
b_{10}	-0.02	0.03

The multipole decay, quantified by the difference between the value at the beginning (0 s) and at the end (1000 s) of injection is small and within the allocated contingency.

VI. MAGNETIC AXIS

To date, axis test results are available for 111 SSS as reported in detail in [16]. Warm measurements show that the magnetic elements are aligned with systematic and random errors smaller than 0.1 and 0.3 mm respectively. In all cases considered so far, mechanical and magnetic tolerances are respected provided that the magnets are installed in the tunnel in such a way as to compensate the measured misalignment. In addition, a correlation between warm and cold magnetic axis has been established over a sample of 23 SSS, taking the cryostat fiducials as a reference. The amplitude of the thermal contraction in the lateral and vertical directions is presented in Fig. 5.

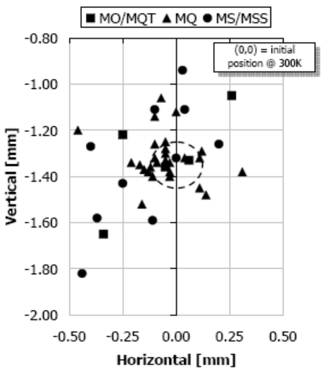

Fig. 5. Lateral and vertical movements of magnetic elements in the SSS during the cool down. The origin of the axes represents for each magnet the initial position at room temperature. The circle stands for the 1σ bounds for the MQ tolerances.

The measurements show that:

- the MQ move downwards by 1.32 mm on average with a standard deviation of 0.1 mm, in agreement with expectations.
- the lateral movement of the MQ is on average zero, as expected, with a standard deviation of 0.14 mm.
- the correctors follow the MQ within an measurement uncertainty of 0.4 mm (statistics over 11 SSS).

VII. CONCLUSIONS

The extensive cold tests and the analysis program of the arc SSS are being pursued with an increasing rate. Up to this point, only 5 magnets among the 150 tested at cold did not fulfill the requested specifications. Four MQs are kept on hold for investigation because of doubts in the insulation strength detected in the corrector circuits and one MQ was rejected because of insufficient quench performance. The training performance of the MQs is in overall excellent as 95% of the MQs passed the nominal field gradient of 223 T/m after the 2nd quench. The multipoles at cold are consistent with the beam dynamics requirements after correction of b_6 which was above the allowed range for the first MQs. The spread of the transfer function of the field gradient measured at cold is close to the allocated budget with an r.m.s. of 12 units. The magnetic elements (MQs and correctors) are aligned within acceptable limits of the machine, provided the installation is done using the measured fiducials.

VIII. ACKNOLEDGMENTS

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