EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 808

Axis Measurements, Field Quality and Quench Performance of the First LHC Short Straight Sections

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Abstract

The series testing at 1.9 K of the 360 Short Straight Sections (SSS) for the Large Hadron Collider have started at CERN in September 2003. The SSS contain the lattice quadrupoles and correction magnets in a common cryostat. The lattice quadrupoles feature two collared coils with 56 mm bore assembled in a common yoke. The coils are wound in two-layers from 15.1 mm wide NbTi cable, insulated with polyimide tape. The paper reviews the main test results performed in superfluid helium. The magnetic field and magnetic center position of the quadrupoles and associated correctors were measured with two independent systems, namely an automated scanner and a single stretched wire technique. The quench training, the field quality and the magnetic alignment measurements are presented and discussed in terms of the specifications and expected performances of these magnets in the LHC. We discuss in detail the field quality in terms of multipole errors measured at injection and nominal field and decomposed into geometric and persistent current magnetization errors. Warm/cold correlation for the geometric multipoles and the magnetic axis is also presented.

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Presented at the Applied Superconductivity Conference (ASC/04)
3-8 October 2004, Jacksonville, USA

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Geneva, 24 March 2005

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***Abstract*— The series testing at 1.9 K of the 360 Short Straight Sections (SSS) for the Large Hadron Collider have started at CERN in September 2003. The SSS contain the lattice quadrupoles and correction magnets in a common cryostat. The lattice quadrupoles feature two collared coils with 56 mm bore assembled in a common yoke. The coils are wound in two-layers from 15.1 mm wide NbTi cable, insulated with polyimide tape. The paper reviews the main test results performed in superfluid helium. The magnetic field and magnetic center position of the quadrupoles and associated correctors were measured with two independent systems, namely an automated scanner and a single stretched wire technique. The quench training, the field quality and the magnetic alignment measurements are presented and discussed in terms of the specifications and expected performances of these magnets in the LHC. We discuss in detail the field quality in terms of multipole errors measured at injection and nominal field and decomposed into geometric and persistent current magnetization errors. Warm/cold correlation for the geometric multipoles and the magnetic axis is also presented.**

***Index Terms*— Field Quality, Quench Training, Superconducting Accelerator Magnets.**

I. INTRODUCTION

THE Large Hadron Collider (LHC), now under construction at CERN will contain 360 lattice quadrupoles (MQ) assembled in arc Short Straight Sections (SSS) of 61 different types [1]. Arc SSS will operate at 1.9 K and their quadrupole at nominal field gradient of 223 T/m.

The development of the lattice quadrupole magnets started in 1989 in collaboration with the CEA-Saclay for the design of the cold mass and with the CNRS laboratory of Orsay in France for the design of the cryostat. These collaborations resulted in a successful construction and testing of 3 prototypes [2]-[4]. The 360 fully assembled cold masses needed for the LHC were ordered with the German firm ACCEL Instrument in July 2000, CEA and CERN ensuring the technology transfer and the follow up of the series fabrication [5]. The cold testing of the series SSS started in September 2003 at the CERN Superconducting Magnet Test Plant (SMTP) [6].

In this paper, the main test results of the twenty series SSS tested up to end of August 2004 will be reviewed. The results of the electrical tests, the quench training performance, field quality and magnetic axis measurements will be discussed in terms of the design parameters.

II. MAGNET DESIGN FEATURES

The design of the arc short straight sections is described in detail in [2]-[5]. Only the main design features will be recalled here in view of the discussion of the test results. The lattice quadrupole features two independent apertures with 56 mm bore assembled into a common yoke separated by a distance of 194 mm at 1.9 K. The two layers of the quadrupole coils are wound with a 15.1 mm wide NbTi Rutherford cable made of 36 strands of 0.825 mm diameter coming from three manufacturers. The magnetization of the strands is measured at CERN at a field of 0.5 T in a 1.9 K helium bath. The maximum values specified for the LHC production are 23 mT with the control limits of ±4.5 % around their average value. The main quadrupole is designed to work at an injection field gradient of 14.5 T/m (0.45 TeV beam energy) and at a nominal field gradient of 223 T/m (7 TeV beam energy) corresponding respectively to currents of 763 A and 11870 A. It reaches a gradient of 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. The two separated apertures are then assembled in a laminated yoke.

The SSS cold mass consists of a 5.3 m long inertia tube into which the MQ and correctors are precisely aligned. The correctors are an octupole MO, tuning quadrupole MQT or skew quadrupole correctors MQS on one end and a combined sextupole-dipole correctors MSCB on the other end.

III. PERFORMANCES OF THE FIRST SERIES SHORT STRAIGHT SECTION

A. *Test Procedure*

The SSS are cold tested at CERN in the SMTP, consisting of 12 tests stands and the necessary cryogenic infrastructures to perform the tests of all the main ring magnets within the allocated time [6]. The cold tests are used to qualify the cryogenic and vacuum integrity. Electrical tests are executed after each critical phase and power tests are carried out aiming at the qualification of the magnets in terms of the number of

Manuscript received October 4, 2004.

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training quenches necessary to reach the nominal (223 T/m) and the ultimate (241 T/m) field gradient levels.

The field quality is measured in machine operating conditions after the training of the MQ. The beam screens are not mounted in the magnet apertures to allow the insertion of the so-called "anticryostats" for the use of magnetic systems like the automated scanner [7], the single stretched wire (SSW) [8] and the 10-m long shafts based on the 15-m long ones used for the dipoles [9].

The position of the magnetic axis of the MQ and of the correctors with respect to an external frame are determined at 1.9 K and in warm conditions (300 K) using the SSW or the automated scanner. The MQ axis is measured with 0.1 mm accuracy at the intermediate current of 5 kA at cold and at 20 A DC current at room temperature. The stability of the magnetic axis versus current has been investigated on a few MQ's showing an acceptable deviation below 0.1 mm.

The SSW system localises the correctors with the so called "rotating wire technique", at the DC nominal current in cryogenic condition and with an AC excitation at room temperature. The reproducibility of the corrector axis measurement is with both systems in the range of, 0.1 mm and 0.2 mm, respectively at cryogenic and room temperature. The SSW uses AC excitation at room temperature of respectively 5 A and 1 A for the MQ and of the correctors. The SSW system is faster and simpler to use and will be employed for series measurement.

IV. ELECTRICAL AND TRAINING QUENCH PERFORMANCE

The electrical tests consist mainly of DC resistance measurements to check the integrity of the magnet instrumentation and of insulation measurements performed at high voltage for the MQ and the correctors versus ground and between each other. For the standard quench training test, the quench current is reached with a nominal ramp rate of 10 A/s. The histogram in Fig. 1 shows the number of quenches to reach the nominal and the ultimate field gradient for all the MQ's tested to date. The magnets display satisfactory quench performance, all quadrupoles reaching the nominal gradient of 223 T/m after at most the 2nd quench and the ultimate gradient after a maximum of 6 quenches. Four quadrupoles were tested after a thermal cycle from 1.8 K to room temperature and back to 1.8 K and showed a good memory effect with no quench recorded below 236 T/m.

Two SSS were registered as non-conforming out of the 20 cold tested. One could not be tested in cryogenic conditions due to a failure of the protection quench heaters. In the second one the insulation of the corrector MQT to ground did not pass the specified voltage of 1.5 kV.

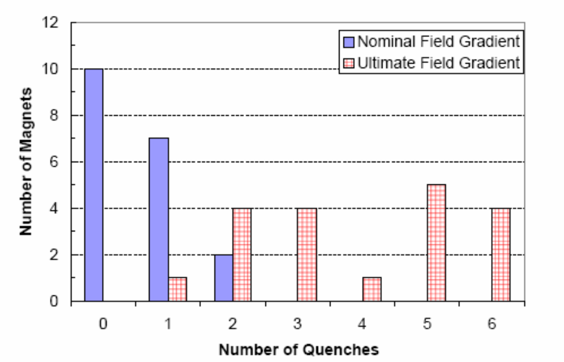

Fig. 1. Histogram of the number of quenches to reach the nominal (223 T/m) and ultimate (241 T/m) field gradient.

V. MAGNETIC FIELD QUALITY

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

So far, the field quality of seven short straight sections (fourteen apertures) has been measured in cold conditions. The higher order multipole components at injection and at nominal field of the measured MQ's 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 bounds for the average (the systematic) and for the spread allowed by the LHC operation (i.e. the latter being the limits for an individual quadrupole) [10].

At injection and nominal fields, most integrated multipoles are within the allowable limits. The large normal do-decapole, values at injection and nominal fields (b_6), are inherent to the coil geometry of the first series quadrupoles. The observed discrepancy of about +1.5 units can be explained by the consequence of an additional compression of the coils by the collars [11], not taken into account in the first definition of the coil cross-section. A corrective action has been agreed between CERN and CEA, consisting in adding in the mid-plane an additional insulation sheet of 0.125 mm.

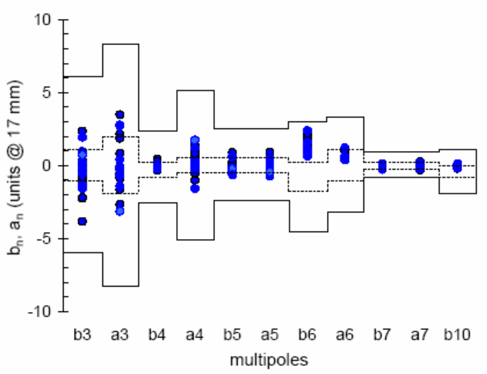

Fig. 2. Field quality at injection field. The dotted lines display the upper and lower limits for the systematic value and the continuous line the limits for an individual quadrupole.

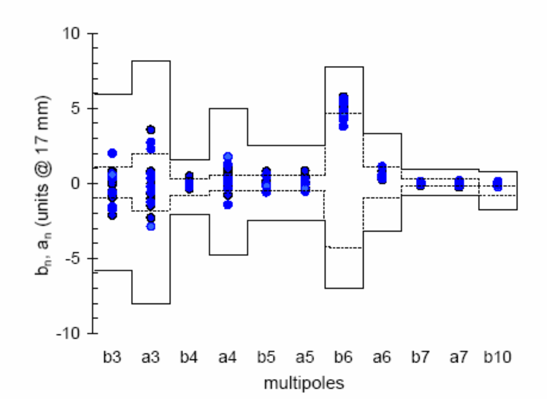

Fig. 3. Field quality at nominal field. The dotted lines display the upper and lower limits for the systematic value and the continuous line the limits for an individual quadrupole.

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.

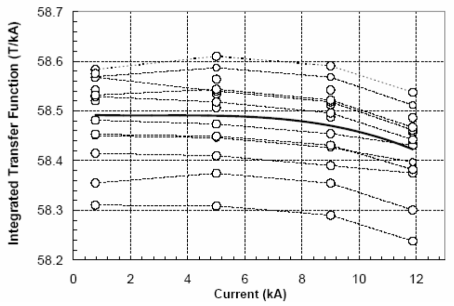

Fig. 4. Integrated transfer functions for the 14 MQ apertures as a function of the current. The bold continuous line displays the average transfer function.

The average and the standard deviation calculated at injection, at 5 kA and at nominal current are presented in Table I. These latter are compared to the specified r.m.s. imposed by the beam dynamics [10].

TABLE I

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 (763 A)	58.499	14.9	10
Geometric(5 kA)	58.496	14.9	10
Nominal (11870 A)	58.422	14.5	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 among the seven magnets tested amounts to 15 units, above the limit of the specified r.m.s. value of 10 units. This can generate a β beating out of the tolerance budget.

C. *Warm-cold correlation*

Room temperature measurements are performed at the quadrupole manufacturer to evaluate the geometric field errors. Fig. 5 shows the correlation of the transfer function of the gradient (TF) and of the geometric part of the do-decapole (b_6) between room temperature and cryogenic temperature measurements. The geometric contribution is computed as the average of the measured values on the ramp up and ramp down powering branches at 5 kA. The warm measurements are performed at a current of 12 A with positive and negative currents to eliminate the residual magnetisation. As displayed in Fig. 5, the correlation with the slope one is very good and a small offset is observed for b_6.

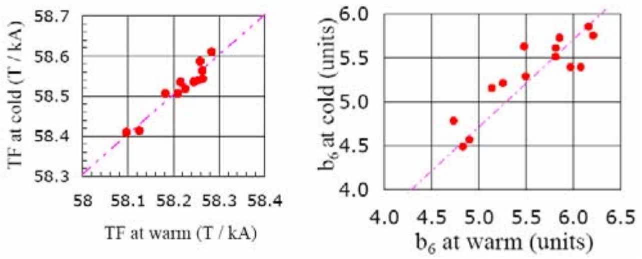

Fig. 5. Scatter plot of the transfer function of the gradient (left) and of the do-decapole (right) measured in warm and cold conditions (geometric part only). Experimental points are compared with a linear fit with a slope 1 related to the ideal correlation.

Table II shows the offset between cold and warm data (Δ_{offset}) and the standard deviation of the warm-cold correlation ($\sigma_{\text{warm-cold}}$) for the transfer function and for the most critical multipoles. The standard deviation corresponds to the spread around the ideal correlation line.

TABLE II

STANDARD DEVIATION AND OFFSET OF THE CORRELATION BETWEEN MEASUREMENTS OF GEOMETRIC FIELD QUALITY AT 300 K AND AT 1.9 K. (IN UNITS AT 17 MM)

Multipole order	Δ_{offset}	$\sigma_{\text{warm-cold}}$	$\sigma_{\text{beam dynamics}}$ injection	$\sigma_{\text{beam dynamics}}$ nominal
TF	50	6.50	10	10
b_3	0.07	0.38	1.35	1.30
a_3	0.08	0.33	1.44	1.40
b_4	-0.51	0.36	0.30	0.30
a_4	-0.1	0.60	0.90	1.30
b_6	-0.27	0.24	0.60	0.60
b_{10}	-0.04	0.04	0.35	0.35

For the critical parameters TF and b_6, the obtained offsets are in accordance with the expectations. Taking into account the change of the magnet geometry induced by thermal contraction, the computed warm-cold offsets are 49 units and –0.7 units respectively for the transfer function and the b_6 [12]. Apart from b_4, $\sigma_{\text{warm-cold}}$ is about two times lower or more than the standard deviation allowed by the beam dynamics at injection and nominal field [10]. This confirms that measurements at 300 K are an effective mean to control the geometric harmonics in operating conditions. The origin of the $\sigma_{\text{warm-cold}}$ observed for the b_4 is under investigation.

D. Magnetization effects of multipoles at injection

The magnetization associated with persistent currents in the NbTi superconducting filaments changes 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 once the injection current is reached and its geometric component. The magnetization effect on b_6 and b_{10} was found to be in agreement with the expectations. Average field changes of - 3.48 units and 0.06 units were measured in accordance with the calculated contributions of -3.48 units and 0.1 units based on strands measurements [13]. In the case of b_2, the magnetization effect did not match with the expectations with an average change of 0.38 units as compared to the -4.39 units expected [13]. The random component for b_2 was also larger than predicted with an r.m.s. of 2.6 units versus the 0.6 units expected. This discrepancy is supposed to come from a higher permeability than specified of the stainless steel collars.

VI. MAGNETIC AXIS

The first seven SSS were tested with the SSW and the automated scanner showing a typical agreement of the axis measurement of 0.2 mm. The axes of 10 SSS have been measured at both room and cryogenic temperatures. The cool down effect was estimated assuming that the SSS external fiducials are stable during the temperature change. They usually move by less than 0.1mm with respect to the reference network. The amplitude of the cold mass movements during the cool down in the lateral and vertical directions are presented in Fig. 6.

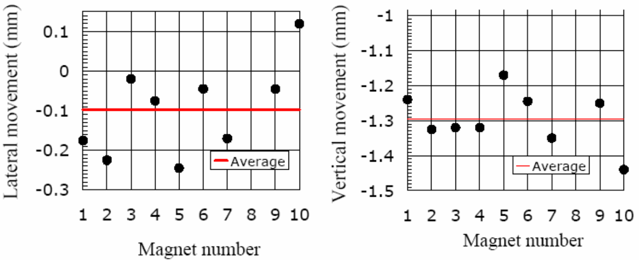

Fig. 6. Lateral (left) and vertical (right) movements of the SSS during the cool down. The magnet number 8 was incorrectly measured and the results removed. The horizontal grey straight line reflects the average in both cases.

The measurements show that:

- in vertical direction the MQ axes moves down by 1.3mm as expected (movement of the support post during the cool down), with a standard deviation of 0.1mm
- laterally the MQ moves unexpectedly toward the external side by 0.1mm with a standard deviation of 0.15mm,
- the correctors follows the MQ within 0.2mm of uncertainty, though statistics for correctors is much less.

Additional measurements will be performed as the spread of magnets movement is very close to the 0.15mm tolerance.

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, all the magnets fulfilled the requested specifications for training performance. They all passed the nominal field gradient of 223 T/m after the 2nd quench and reached the LHC ultimate field gradient of 241 T/m, after a maximum of six quenches. Warm measurements give a good evaluation of the geometric errors at cold apart from b_4 where the high spread in the warm/cold correlation is not yet understood. The multipoles at cold are consistent with the beam dynamics requirements apart from b_6, which is for the first MQ above the allowed range. Measurements performed at warm on recent collared coils with the corrected cross-section show that b_6 is now within the target [14]. The spread of the transfer function of the field gradient is above the allocated budget with an r.m.s. of 15 units. The origin could be an out of tolerance collar permeability [14]. This effect on the beam can however be reduced by appropriate pairing of the quadrupole in the accelerator lattice. The magnetic axes of the SSS (quadrupole and correctors) were measured on 10 SSS at cold and at warm. The magnet movements during the cool down are close to the tolerances, preventing to start immediately a sampling of the cold measurements axes.

ACKNOWLEDGMENT

The authors wish to thank the teams in Industry, at the CEA Saclay and at CERN involved in the construction and testing of the SSS, in particular the teams who built and maintain the test equipment, perform the cold tests operation and analyse the results.

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