EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 428

PERFORMANCE OF SERIES-DESIGN PROTOTYPE MAIN QUADRUPOLES FOR THE LHC

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After the successful construction of two first-generation prototypes of the main quadrupoles for the LHC, three series-design prototypes have been further manufactured at CEA-Saclay. Together with the sextupole-dipole corrector magnets and tuning quadrupoles, these twin-aperture main quadrupoles are assembled into the cold masses of the so-called short straight sections. Already during their fabrication, the collared coils and later the completed cold masses undergo warm magnetic measurements. Two of the main quadrupole cold masses have been mounted into their definitive machine cryostats and submitted to training and magnetic measurements. This paper presents the results of these cold tests by describing the quench behaviour, the transfer function in each of the apertures and the multipole components found at different levels of excitation. The field quality results, in cold conditions, will be compared to those measured at room temperature

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Presented at the Seventh European Particle Accelerator Conference (EPAC 2000)
26-30 June 2000, Vienna, Austria

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
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Geneva, 23 September 2000

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Abstract

After the successful construction of two first-generation prototypes of the main quadrupoles for the LHC, three series-design prototypes have been further manufactured at CEA-Saclay. Together with the sextupole-dipole corrector magnets and tuning quadrupoles, these twin-aperture main quadrupoles are assembled into the cold masses of the so-called short straight sections. Already during their fabrication, the collared coils and later the completed cold masses undergo warm magnetic measurements. Two of the main quadrupole cold masses have been mounted into their definitive machine cryostats and submitted to training and magnetic measurements. This paper presents the results of these cold tests by describing the quench behaviour, the transfer function in each of the apertures and the multipole components found at different levels of excitation. The field quality results, in cold conditions, will be compared to those measured at room temperature.

1 INTRODUCTION

The main quadrupole magnets for the arc of LHC have been described in earlier publications [1], [2]. The design and the construction of these twin aperture magnets is the result of a close collaboration between CERN and the CEA-Saclay laboratory in France. The quadrupole magnets are housed in a cold mass together with the arc corrector magnets. On one end are mounted the dipole-sextupole correctors on the other end, the connection end, the octupole, respectively the tuning or skew quadrupole correctors. The cold mass functions as the stiffening element of the assembly and at the same time as the liquid helium pressure vessel. The mounting of the quadrupoles into their cryostats was executed in a collaboration between CERN and the CNRS laboratory of Orsay in France [3]. Table 1 shows the main parameters of these magnets. Up to now three of the new magnets have been constructed in Saclay, named SSS3, SSS4 and SSS5. They were submitted to warm magnetic measurements at Saclay and the first one of them, SSS3, has undergone cold tests and magnetic measurements at CERN. SSS4 was has also undergone warm measurements at CERN and is presently prepared for cold magnetic measurements at CERN. SSS5 will be tested during the second halve of the year 2000 at the test cryogenic test station in Saclay.

Table 1: Main parameters and characteristics of the LHC quadrupole magnet and cold mass

	Value	Unit
Injection field gradient (0.45 TeV beam energy)	14.5	T/m
Nominal field gradient (7 TeV beam energy)	223	T/m
Nominal current	11’870	A
Operating temperature	1.9	K
Magnetic length at 1.9 K	3.1	m
Stored energy (both apertures) at 7 TeV	0.79	MJ
Ultimate operational field gradient	241	T/m
Gradient at short sample field limit	278	T/m
Distance between aperture axis at 1.9 K	194.00	mm
Inner coil diameter at 293 K	56.00	mm
Outer coil diameter at 293 K	118.60	mm
Number of conductor blocks / pole	4	
Electromagnetic forces / coil octant at nominal field		
Radial force (inner and outer layer)	0.54	MN/m
Azimuthal force (inner and outer layer)	-0.73	MN/m
Cold mass length at 293 K, between end covers	5355	mm
Cold mass overall length with ancillaries	6.63	m
Cold mass weight	6.5	T

2 WARM MAGNETIC MEASUREMENTS

Warm magnetic measurements were made at CEA-Saclay for the prototypes at several steps of the their fabrication. The first measurements are done once a collared coil assembly is finished. This allows to detect a faulty coil assembly and to eliminate it before it is mounted into the yoke. Once two collared coil assemblies are mounted into their common yoke and inserted into their cold mass together with the corrector magnets on each end, the warm magnetic measurements are repeated. The magnetic field is measured by the rotating coil technique.

A measuring coil of 0.75 m length placed at five positions inside each aperture. The magnet is powered with 12.5 A. The field quality is expressed in terms of relative multipole field errors with a reference radius at 17 mm. Table 1 summarises the results of the integrated multipole components for the three prototype quadrupoles after the completion of their cold masses.

Table 1: Multipole components measured under room temperature in the apertures of three quadrupole prototypes, SSS3, SSS4 and SSS5. The bn values denote the normal components, the an the skew ones.

Multipole	**SSS3** Left	**SSS3** Right	SSS4 Left	SSS4 Right	SSS5 Left	SSS5 Right
b3	**3.195**	**-0.417**	-0.440	0.039	0.431	0.364
b4	**0.182**	**-0.060**	-0.249	0.048	-0.196	-0.106
b5	**-0.757**	**-0.353**	0.101	-0.062	-0.171	-0.004
b6	**5.595**	**6.252**	5.667	5.342	5.008	4.805
b7	**0.021**	**-0.064**	-0.076	-0.050	0.044	0.168
b8	**-0.074**	**0.001**	0.010	0.011	-0.053	-0.005
b9	**-0.005**	**-0.002**	0.018	-0.004	-0.036	-0.026
b10	**-0.117**	**-0.117**	-0.160	-0.191	-0.158	-0.141
b11	**-0.021**	**-0.007**	0.001	0.004	-0.005	-0.007
b12	**-0.009**	**-0.011**	-0.007	-0.003	-0.008	-0.009
b13	**-0.008**	**-0.002**	0.005	0.002	0.003	0.007
b14	**-0.131**	**-0.132**	-0.140	-0.135	-0.136	-0.137
b15	**-0.001**	**-0.001**	0.000	0.000	-0.001	-0.001
a3	**3.204**	**-1.872**	1.629	-1.556	2.656	-1.516
a4	**-2.418**	**-0.890**	-0.110	2.153	-0.790	-2.486
a5	**0.664**	**0.436**	0.003	-0.080	0.533	-0.214
a6	**0.609**	**0.577**	0.167	0.024	0.060	-0.056
a7	**-0.002**	**-0.183**	0.067	-0.094	0.070	-0.029
a8	**-0.012**	**0.034**	-0.058	0.102	-0.038	-0.145
a9	**0.016**	**0.007**	0.003	-0.002	0.069	0.019
a10	**0.034**	**0.006**	0.077	0.063	0.049	0.079
a11	**-0.005**	**-0.018**	0.002	0.001	0.015	0.001
a12	**0.006**	**0.002**	-0.004	0.011	-0.004	0.001
a13	**0.052**	**0.046**	0.034	0.029	0.051	0.033
a14	**-0.014**	**-0.014**	0.012	0.009	0.011	0.009
a15	**-0.002**	**-0.001**	0.000	0.001	0.001	-0.002

The results of these warm measurements are in good agreement with those for the single collared apertures. A detailed analysis of the sources of the non-allowed components is given in ref. [4]. The distribution over the length of a typical aperture, here the right one of SSS5 is shown in Figure 1.

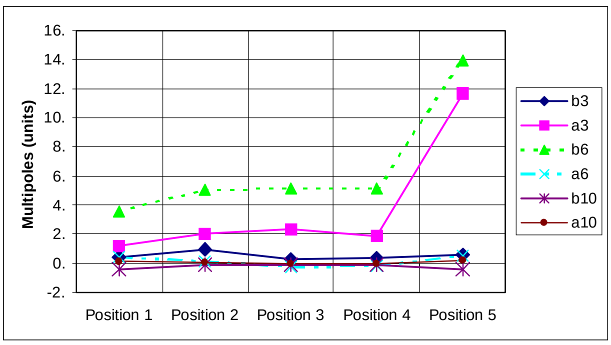

Fig. 1 Distribution of some multipole components over the length of the left SSS5 quadrupole aperture. Length of measuring coil is 0.75 m, magnetic length 3.115 m.

Once the cold masses of SSS3 and SSS4 were closed, pressure and leak tested as well as measured, they were shipped to CERN. There they were mounted into their horizontal cryostat before being attached to the cryogenic test station.

The warm magnetic measurements have been repeated at CERN for both apertures of the quadrupole in the cold mass of SSS4. The technique used for these measurements was the same as used in CEA. The equipment, however, was a separately constructed one. The multipole components found agree well with those measures at CEA which presents a reassuring confirmation of the results.

3 PREPARATION FOR COLD TESTS

For the cold magnetic measurements the fully equipped short straight sections were attached to one of the newly constructed test stations at CERN. Being prototypes, they were equipped with more instrumentation than foreseen for the series unit to go into the LHC machine. Most of this instrumentation concerns voltage taps allowing the localisation of quenches inside the coils. The powering of both apertures is made by means of one power supply which requires that both apertures are connected in series. Thus, not only the connection between the apertures had to be made, also a return connection on the second aperture was provided. This is different from the powering scheme in the machine where separate circuits exist for the focusing and de-focusing quadrupoles of the lattice. Figure 2 shows SSS3 in its cryostat together with return box, mounted to the CERN measuring station.

During the testing at the test station no beam screen as well as no Beam Position Monitor must be mounted to the cold masses, both for the prototypes and the series magnets. They would not allow the positioning of the quench antennas which permit the longitudinal location of quench origins. Further, the aperture needed for the rotating measuring coil for the multipole component measurements would not be free. The beam screen with the Beam Position Monitor monitors attached to them will be inserted in the frame of the last preparatory operations for installing the quadrupole units into the machine.

4 TRAINING

The training of the SSS3 quadrupole was short since there was only one quench registered below the nominal operational value of 11870 A or 223 T/m. This despite the fact that in this magnet the ends of the quadrupole coils were not STYCAST™ impregnated, as is done for all LHC dipoles and later for the quadrupole prototypes of SSS4 and SSS5. Figure 3 shows the training curve. After only three quenches the magnet could be powered to 13’000A (242 T/m) which was set as the upper excitation limit (corresponding to more that 9 T in the LHC main dipoles).

When stabilising the current at 13’000A, the magnet quenched, however, after a few minutes. This was traced back to the clamped high current joints between the

Figure 2: The SSS3 Short Straight Section mounted to cryogenic test station at CERN.

apertures. There about 100 nano-Ohm were measured**,** instead of the nominal 0.5 nano-Ohm. For repairing this connection by soft soldering it, the magnet had to be warmed up which provided a thermal cycling, anyway foreseen in the test programme. After the new cool-down the magnet was ramped up to 13’000A again without any quench.

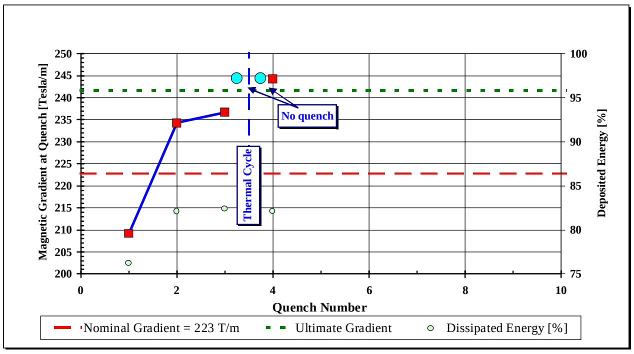

Figure 3: Training of SSS3 quadrupole including thermal cycle after which no quench occurred.

5 COLD MAGNETIC MEASUREMENTS

Table 2 shows the multipole components as measured for excitation at injection at an intermediate level and at the nominal operational level. The values at the intermediate level confirm the good correlation between warm and cold measurements. (Compare 5000A results to warm measurement results of SSS3 (bold) in Table 1.) The b6, the dodeca-pole component, is about 2.6 units above its nominal 3.9 units. This will be easily corrected for the series fabrication by reducing the coil pole shims by a few hundreds of millimetre. All the non-allowed normal and skew components can be explained by tolerance considerations, which will be difficult to improve.

Table 2: Integrated multipole components measured cold for the SSS3 quadrupole at different excitations.

	SSS3	730A	**SSS3**	**5000A**	SSS3	11750A
Multipol	Left	Right	**Left**	**Right**	Left	Right
b3	3.853	-0.580	**4.071**	**-0.926**	4.406	-1.117
b4	0.105	-0.134	**-0.026**	**-0.012**	-0.043	-0.017
b5	-0.888	-0.898	**-0.794**	**-0.975**	-0.753	-1.023
b6	3.106	4.598	**6.594**	**7.344**	6.674	7.374
b7	-0.040	-0.215	**-0.039**	**-0.096**	-0.039	-0.093
b8	-0.048	-0.013	**-0.049**	**0.018**	-0.034	0.007
b9	0.025	0.005	**-0.010**	**0.017**	-0.007	0.017
b10	-0.089	-0.151	**-0.130**	**-0.116**	-0.124	-0.112
b11	-0.022	0.016	**-0.026**	**-0.014**	-0.018	-0.010
b12	0.018	0.029	**-0.002**	**-0.006**	0.004	0.001
b13	-0.019	0.061	**-0.014**	**0.030**	-0.023	0.022
b14	-0.189	-0.212	**-0.172**	**-0.166**	-0.163	-0.163
b15	0.006	0.008	**-0.002**	**-0.003**	0.002	-0.001
a3	3.974	-2.669	**3.835**	**-2.707**	3.899	-2.604
a4	-2.917	-0.927	**-2.886**	**-1.325**	-2.920	-1.363
a5	0.609	0.729	**0.408**	**0.722**	0.319	0.751
a6	0.407	0.403	**0.335**	**0.289**	0.313	0.276
a7	0.038	-0.226	**0.042**	**-0.246**	0.041	-0.256
a8	-0.068	-0.033	**-0.031**	**0.014**	-0.023	0.017
a9	0.044	-0.031	**0.031**	**-0.017**	0.033	-0.014
a10	0.046	0.001	**0.063**	**0.029**	0.051	0.029
a11	-0.016	-0.024	**-0.001**	**-0.015**	-0.003	-0.018
a12	0.010	-0.006	**0.010**	**0.002**	0.009	0.006
a13	0.030	-0.019	**0.030**	**-0.005**	0.033	-0.001
a14	-0.016	0.000	**0.004**	**-0.001**	-0.008	-0.006
a15	0.002	-0.006	**0.001**	**-0.001**	-0.001	-0.003

REFERENCES

[1] T. Tortschanoff et al., "The Short Straight Sections for the LHC", Proc. PAC97 Conference, Vancouver, Canada. 1997.

[2] M. Peyrot, J.M. Rifflet, F. Simon, T. Tortschanoff, P. Vedrine, “Construction of the New Prototype of Main Quadrupole Cold Masses for the Arc Short Straight Sections of LHC”, Proc. MT-16, Ponte Vedra Beach, Florida, USA, 1999.

[3] L. Nielsen, V. Parma, T. Renaglia, P. Rohmig T. Tortschanoff, J.-B. Bergot, Ph. Dambre, E. Roy, D. Vincent, M. Peyrot, J.-M. Rifflet, F. Simon, “A Modular Design for the 56 Variants of the Short Straight Section in the Arcs of the Large Hadron Collider (LHC)”, Proc. EPAC-2000, Vienna, 2000.

[4] S. Redaelli, V. Remondino, W. Scandale, E. Todesco, T. Tortschanoff, M. Peyrot, F. Simon, J.M. Rifflet, “Analysis of the Warm Magnetic Measurements of the First Series-design Prototypes of the LHC Main Quadrupoles”, Proc. EPAC 2000, Vienna, 2000