PERFORMANCE OF THE FIRST LHC MAIN QUADRUPOLES MADE IN INDUSTRY

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Abstract

After the creation of a new dedicated factory and a period of technology transfer, ACCEL Instruments has constructed and delivered the first LHC main quadrupole magnets to CERN. The design of these magnets had been the subject of a close collaboration between CEA-Saclay and CERN. Thus, CEA ensures also the technology follow-up for the fabrication of 400 quadrupole magnets and their cold masses. The two quadrupoles delivered to CERN were bare magnets, i.e. magnets not integrated into their cold masses. The purpose was to verify their performance before fabricating full cold masses. The two magnets were tested at 1.9 K in a vertical cryostat at CERN. For both magnets the current could be ramped up to well above their nominal level before a quench occurred. The second powering provoked on one of the magnets a quench at the ultimate level of excitation and in the other magnet no quench, even after the ultimate current value had been well exceeded. The field quality measurements, as far as possible in the vertical cryostat, confirmed the multipole content already found during the warm field measurements made in the factory.

INTRODUCTION

The development and prototyping of the main quadrupole magnets for the LHC has been treated in earlier publications. [1], [2], [3]. It had been the subject of a close collaboration between CERN and CEA-Saclay in France. After the signature of the contract with the German Company ACCEL Instruments GmbH, CEA ensures together with CERN the technology transfer and follow up of the series fabrication in a newly created factory in Troisdorf near Bonn.

Before integrating any of the main quadrupoles into their cold masses, two bare magnets, fabricated according to the factory established procedures, were shipped to CERN for undergoing training and field quality measurements in a dedicated test facility. These measurements were thought to provide further confirmation of the soundness of design, which had already been shown by the performance of the prototypes constructed by CEA-Saclay and tested in both laboratories, CERN and CEA [4], [5]..

DESIGN FEATURES

The main parameters of the twin aperture quadrupoles are recalled in table 1.

Table 1:Main parameters of the LHC quadrupole

	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

Fig. 1: Quadrupole suspended before being inserted into its vertical test cryostat.

Contrary to the main LHC dipole magnets, the electromagnetic forces are taken only by the coil collaring system and no pre-stressing function is provided by the yoke. ACCEL has made a number of computations and mock-up tests to simplify the collar keying system from a three piece one, as used for the prototypes, to a single piece keying. ACCEL could show that with this simplified way of keying no degradation, i.e. overstressing during the keying in the press and no loss of final pre-stress has to be expected.

While ACCEL took over the concept of most of the prototype tools they developed an own highly efficient and versatile collaring press. In its final configuration the bare quadrupole magnet together with the corrector magnets on both ends of it, are assembled inside an inertia tube which functions as the helium vessel and as the stiffening and alignment element.

For transporting and testing the bare magnets, dedicated structures had to be used which ensured the solidity of the magnet, both in vertical and horizontal position and allowed to suspend it into the vertical test cryostat at CERN.

The first of the two magnets was delivered to CERN in July 2002 and was tested in August. The second one arrived in August and was tested in October 2002.

QUENCH PERFORMANCE

First quadrupole, MQ001

The first quench of the MQ001 occurred at 12631A, corresponding to a gradient of 237 T/m. Analysis of the voltage tracks showed unambiguously that the quench had been initiated in one of the external cables and not in the coils. In the light of this, it was decided to modify the test program by reducing the current ramp rate of the next training quench. That was meant to give hints on the quench mechanism, as the first quench had occurred in a very low field region, an anomalous location due to its high superconductor margin. The second current ramp was at 2 A/s and the magnet quenched at 12808 A, corresponding to 240.8 T/m. The third current ramp was at 1 A/s and the quench current was 12758 A, 239.9 T/m. All the three quenches were localized in the same spot of cable, between the outermost voltage tap and the current lead end.

In case of overheating of the bottom end of the vapour cooled current leads, a slower ramp should have lowered the quench current. On the contrary, a slight improvement of the quench current was observed. The possibility of cable degradation was put to the test by performing quenches at 4.5 K. It appeared that the critical current of the cable was not degraded, and this excluded one possible cause of the quenches at 1.9 K in the external cables. Actually, from the available evidence it was not possible to conclude whether the quench origin was in the current lead or in the cable itself. Moreover, due to the geometrical constraints the lower end of the current leads had been slightly modified. Therefore, for future tests, it was decided to add an intermediate voltage tap to the quench detection setup.

Second quadrupole MQ002

At the first current ramp to quench, at 10 A/s, there was a quench at 12476 A. It was localized in the series connection between the two apertures. The second current ramp was set at 20 A/s and the magnet reached the ultimate current of 12860 A without quenching. Then the current could be kept constant at the ultimate value for 300 s, which allowed excluding joule heating as the source of the first quench. Again the only quench had occurred outside the magnet coils. After a thermal cycle to room temperature, the magnet reached again the ultimate current without quenching, showing 100% memory effect. As in the LHC the MQ magnets will have to withstand current ramp rates up to 400 A/s, this mode of functioning was also tested on the MQ002. For both decay rates of up to 400 A/s no quench occurred between 50 and 12850 A. Finally, the quench current at 4.5 K was 11439 A, which compares well with the 11446 A at 4.43 K of the MQ001.

MAGNETIC MEASUREMENTS

The set up for magnetic measurements on MQ002 did not cover all the magnetic length of the main quadrupole. Therefore all the measurements hereafter are representative only of the 2D field quality in the straight part of the magnet.

The magnetic field was measured, after training, as a function of the magnet current between 50 A and 12500 A. As customary, geometric values are averages of the ramp up and down branches of the main hysteresis loops, evaluated at 5000 A.

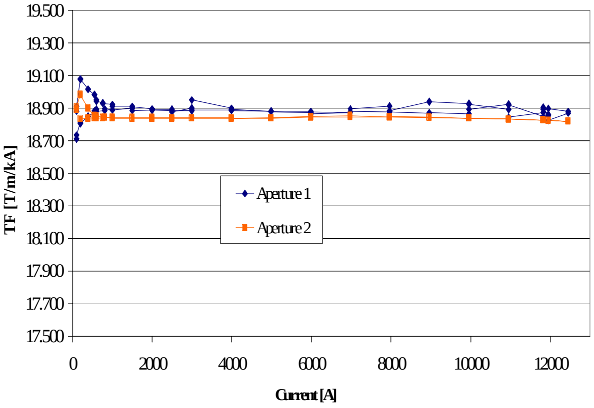

Fig. 2: Quadrupole transfer function

The values at injection current 760 A and at 12500 A are representative of the persistent currents and of the iron saturation contributions respectively. All measurements are corrected for feed-down by zeroing the dipolar component of the magnetic field.

-The measured quadrupole transfer function is shown in Fig. 2.

-The multipole components at 5000 A and at collision current are given in Tables 2 and 3.

- The variation of the normal dodeca-pole component, b6, with the current is shown in Fig.3.

CONCLUSIONS

Quench performance

The power performance of the two MQ magnets was excellent, both having reached the ultimate gradient without any training quench. The cable critical current at 4.5 K was found to be comparable to the corresponding values measured in prototypes.

After thermal cycle the current of the MQ 002 magnet could be ramped to the ultimate value without quench. The magnet withstood current ramp rates up to 400A/s at 12500 A without quenching.

Table 2: Multipole components in terms of relative field errors at 17 mm in left aperture

MQ_002	FIRST RUN		SECOND RUN	
Aperture1	**5 kA**	**11870 A**	**5 kA**	**11750 A**
b3	0.91	1.25	0.97	1.26
a3	2.50	2.42	2.70	2.49
b4	0.10	0.09	0.07	0.06
a4	-0.14	-0.02	-0.23	-0.08
b5	-0.42	-0.17	-0.62	-0.27
a5	1.16	1.07	1.14	1.08
b6	3.35	3.48	3.33	3.48
a6	0.34	0.24	0.39	0.29
b7	0.25	0.29	0.28	0.29
a7	0.14	0.13	0.11	0.13
b8	0.05	0.06	0.05	0.06
a8	-0.09	-0.04	-0.13	-0.05
b9	-0.02	0.00	-0.03	0.00
a9	0.09	0.07	0.09	0.08
b10	-0.13	-0.11	-0.13	-0.12
a10	0.01	-0.01	0.01	-0.01
b11	0.02	0.02	0.03	0.03
a11	0.02	0.02	0.02	0.02
b12	-0.01	-0.01	-0.01	-0.01
a12	-0.01	-0.01	-0.01	-0.01
b13	-0.01	-0.01	-0.02	-0.01
a13	0.01	0.01	0.01	0.00
b14	-0.18	-0.18	-0.18	-0.18
a14	-0.01	-0.01	-0.01	-0.02
b15	0.00	0.00	0.00	0.00
a15	0.00	0.00	0.00	0.00

Table 3: Multipole components in terms of relative field errors at 17 mm in right aperture

MQ_002	FIRST RUN		SECOND RUN	
Aperture 2	**5 kA**	**11870 A**	**5 kA**	**11750 A**
b3	-0.99	-1.20	0.94	1.18
a3	-1.30	-1.05	1.46	1.12
b4	1.31	0.93	1.52	1.05
a4	0.33	0.13	0.71	0.30
b5	0.20	0.36	-0.06	-0.30
a5	0.20	0.14	-0.11	-0.13
b6	3.59	3.45	3.68	3.53
a6	0.35	0.23	0.49	0.29
b7	-0.11	-0.14	0.07	0.12
a7	-0.08	-0.01	0.09	0.03
b8	-0.09	-0.12	-0.08	-0.11
a8	0.11	0.07	0.12	0.07
b9	-0.04	-0.01	0.07	0.03
a9	0.11	0.10	-0.11	-0.10
b10	-0.05	-0.06	-0.04	-0.05
a10	-0.02	-0.04	0.00	-0.03
b11	-0.01	-0.02	0.01	0.02
a11	0.01	0.02	-0.01	-0.02
b12	0.00	0.00	0.00	0.00
a12	0.01	0.00	0.01	0.00
b13	0.00	0.00	0.00	0.00
a13	0.02	0.01	-0.02	-0.02
b14	-0.17	-0.18	-0.17	-0.17
a14	-0.01	0.00	-0.01	-0.01
b15	0.00	0.00	0.00	0.00
a15	0.00	0.00	-0.01	0.00

Field quality

In general the field multipole components are small. The first allowed term, b6, the dodecapole, has a value of 3.5 units, very near to the value needed to compensate the effect of persistent currents at injection.

The results of these tests provide the confidence that the design is sound and the series fabrication in the new factory of ACCEL Instruments can be ramped up in order to fabricate all 400 main quadrupole magnets of LHC.

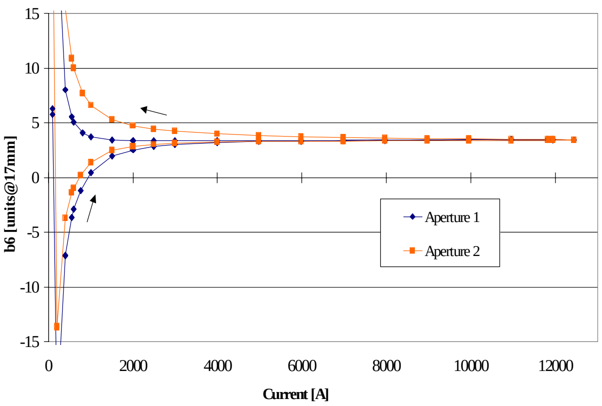

Fig. 3: Normal dodeca-pole in MQ002, b6, versus current

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