Performance of the Single and Twin-Aperture Models of the 6 kA Superconducting Quadrupole for the LHC Insertions

J. Lucas, R. Ostojic, L. Bottura, R. Bussjaeger, H. Dariol, A. Hobl, D. Krischel, G. Kirby, V. Remondino, S. Sanfilippo, M. Schillo, A. Siemko, F. Sonnemann, D. Tommasini, I. Vanenkov, W. Venturini Delsolaro

Abstract—**The LHC dispersion suppressors and matching sections will be equipped with individually powered superconducting quadrupoles with an aperture of 56 mm. In order to optimise the parameters and cost of the magnets and of their powering, the quadrupole has been designed on the basis of a 8.2 mm wide Rutherford-type cable for a nominal current of 5300 A, corresponding to a gradient of 200 T/m at 1.9 K. In order to validate the design two 1-m single-aperture quadrupoles and one twin-aperture quadrupole have been built and tested. In this report we describe the construction features of the magnets and present the results of the magnet tests.**

Index Terms— **LHC, Quadrupole, Superconducting Magnets**

I. Introduction

In order to increase the flexibility and performance of the collider and to decrease the cost of the powering infrastructure, the LHC dispersion suppressors and matching sections will be equipped with individually powered superconducting quadrupoles. The 56 mm aperture quadrupole was designed on the basis of a previously developed 8.2 mm wide Rutherford-type cable, and has a nominal gradient of 200 T/m at 1.9 K and 160 T/m at 4.5 K, for a current of respectively 5280 A and 4290 A [1].

In collaboration with ACCEL Instruments, CERN has recently completed a model program comprising two 1-m long single aperture quadrupoles and a twin-aperture quadrupole. The quench performance of the first single aperture quadrupole has been reported in [2]. In this report we recall the design features of the magnets, and present the results of the magnet tests, in particular quench training, quench protection studies and magnetic field measurements.

II. Design Features of the Magnets

The 6 kA insertion quadrupole has been designed on the basis of a 8.2 mm Rutherford-type cable wound in a double layer. Details of the design are given in [1]. In summary, the coil has two blocks in the inner and in the outer layers with a common pole angle. The parameters of the coil were optimised for the highest transfer function and operational margin, and a geometrical b_6 multipole which partially compensates the b_6 term due to persistent currents.

Five coils were wound in ACCEL Instruments using a cable with a Cu/Sc ratio of 1.7 and another five in CERN using a cable with a Cu/Sc ratio of 1.3. With these coils two single aperture quadrupoles, PB1 and PB2, were assembled. The main parameters of the quadrupoles are given in Table I.

TABLE I
Main parameters of the 1-m single aperture quadrupoles

	PB1	PB2
Cable width (mm)	8.20	
Mid-thickness (mm)	0.85	
Keystone angle (deg.)	1.05	
No of strands	34	
Strand dia. (mm)	0.480	
Cu/SC Ratio	1.7	1.3
Filament dia. (μm)	10	
I_c (A, 4.2 K and 5 T)	3270	3870
Operating temperature	1.9 K	
Nominal gradient	200 T/m	
Nominal current	5280 A	
Peak field in coil	6.16 T	
Quench field	7.3 T	7.5 T
Coil inner/outer diameter	56/90 mm	
Collar outer diameter	135 mm	
Yoke inner diameter	138 mm	
Inductance	4.55 mH/m	

The first coil of each type was used to test the winding technique. The ends of the prototype coils were impregnated in resin and several sections were made to inspect the fit of the cable to the end spacers. A detail of the coil ends is shown in Fig. 1. We found that the coil blocks fitted well to the spacer surfaces, so that no further modifications of the end spacers, nor filling of the coil ends after curing, were necessary.

The 1-m magnets are protected with two sets of strip heaters. The inner heaters are placed in between the two layers, and the outer ones on top of the coil. The position of the inner heaters requires that the second layer is wound with great care on top of the heaters, and that the coil is cured at 185°C with the inner heaters in place. Although there was considerable concern about their in-

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J. Lucas, R. Ostojic, L. Bottura, H. Dariol, G. Kirby, V. Remondino, S. Sanfilippo, A. Siemko, F. Sonnemann, D. Tommasini, I. Vanenkov and W. Venturini Delsolaro are with the LHC Division, CERN, 1211 Geneva 23, Switzerland.

R. Bussjaeger, A. Hobl, D. Krischel and M. Schillo are with ACCEL Instruments, Bergisch-Gladbach, Germany

tegrity, all inner heaters showed a high level of dielectric insulation in all phases of coil production.

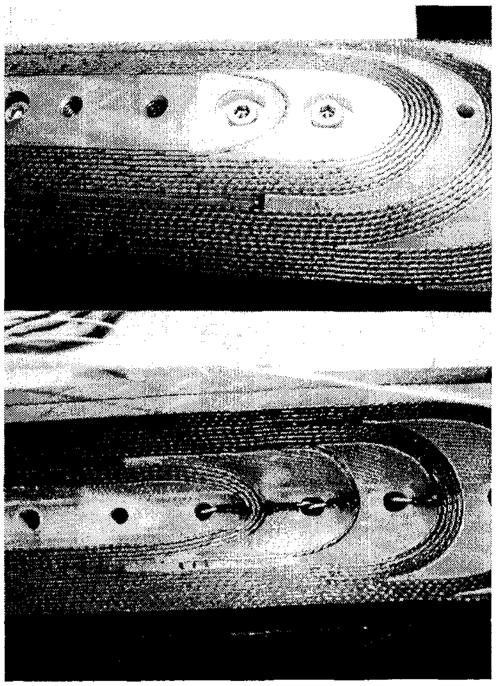

Fig. 1. Detail of the connection end of the prototype coil.

The coils were measured after curing in order to obtain their size and modulus of elasticity. The measurements were made in the straight section in steps of 100 mm, and in the coil ends. The average size of the PB1 coils was 0.33 mm larger than nominal, with an rms of 0.13 mm, while the PB2 coils were on average oversize by 17 μm, with an rms of 31 μm. As a result, the shims for the PB1 coils had to be modified for the target pre-stress of 60 MPa. The PB2 coils were assembled with the nominal shim size.

The coils were assembled using 21 mm wide collars which give the necessary pre-stress and withstand the magnetic forces. The collars were locked using four full length keys which were welded onto the coil end plates. After completion of the pole connections, the PB1 and PB2 collared coils were individually assembled in a vertically split iron yoke, Fig. 2, and tested. This arrangement is a modification of the setup normally used for testing the 1-m long single aperture models of the LHC main dipole.

After testing, the single aperture magnets were disassembled and the collared coils assembled in a two-in-one yoke structure, Fig. 3. The mechanical link between the collared coils and the laminations was made with four full-length keys which centre the collared assemblies once the laminations are in place and locked with dowel pins. The rigidity of the magnet assembly was provided by the inertia tube. This structure is similar to the LHC main quadrupole [4].

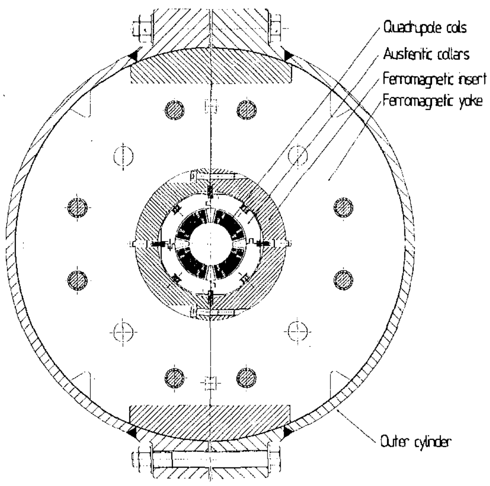

Fig. 2. Cross section of the single aperture quadrupole.

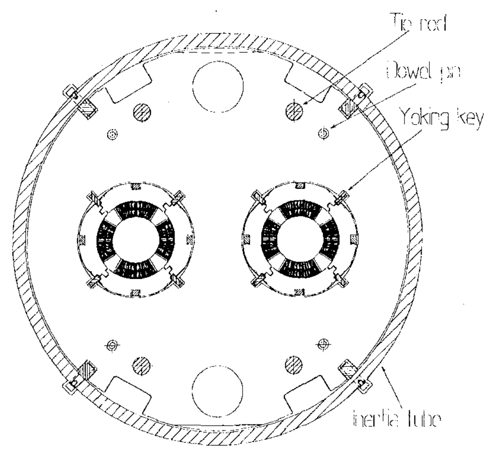

Fig. 3. Cross section of the twin-aperture quadrupole.

III. Test results

A. Single aperture quadrupoles

The single aperture quadrupoles were tested in two cycles. The tests included quench training and protection studies at 1.9 K followed by training confirmation at 4.4 K. The coils were instrumented with spot heaters and voltage taps for determining the peak temperatures, and with capacitive gauges for measurement of the azimuthal stress. The quench location was determined on the basis of the voltage tap and quench antenna signals. Due to the restrictions in the cold bore, it was not possible to measure the magnetic field with an appropriate measuring coil.

The summary of the quench training at 1.9 K of the PB1 and PB2 single aperture magnets is shown in Fig. 4. The first quench occurred for both magnets above the nominal current in the LHC, 5339 A in PB1 and 5285 A in PB2. Both magnets trained to the conductor limit in ten quenches, although the training rate was slightly lower for PB1. No training was observed at 4.4 K. After a thermal cycle, the first quench in PB1 occurred above 6000 A, showing a good memory effect, while in PB2 it occurred at 5466 A. However, the training of PB2 proceeded much faster, so that both magnets reached the conductor limit after only four quenches. The conductor limit was confirmed by varying the temperature of the helium bath. All quenches in the second cycle were performed without energy extraction from the magnets.

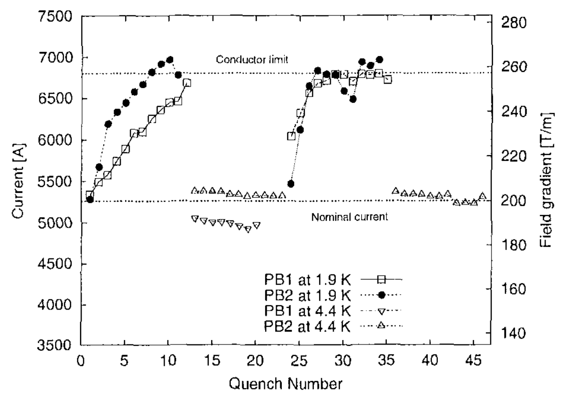

Fig. 4. Quench training of the single aperture magnets. The nominal current in the LHC is 5280 A (200 T/m) at 1.9 K, and 4300 A (160 T/m) at 4.4 K. The conductor limit of PB1 is 6800 A (1.9 K) and 5250 (4.4 K).

The majority of training quenches in both magnets were located in the region of the layer jump. This is the location of the peak field, and is in addition a mechanically delicate area. Measurements of the azimuthal stress showed that the poles are under compression of more than 10 MPa at nominal current, pointing to a possible structural weakness of the layer jump. The quenches at the conductor limit were located in the straight section and in the coil ends, indicating that the design of the end spacers was well optimised.

As part of the protection studies, the heater delay times were measured for the inner and outer heaters. The measurement results, Fig. 5, show that the delay decreases with current and is about 20 ms at 5200 A. For PB2, the two sets of heaters were measured independently, but although the inner heaters act on turns in high magnetic field, the delays are almost identical. This could be related to thickness of the polyimide insulation which is 100 μm for the inner heaters and 75 μm for the outer heaters. The inner heaters in PB1 also have a 75 μm insulation, which could explain their faster reaction.

The major difference between PB1 and PB2 is the Cu/SC ratio of the cable, respectively 1.7 and 1.3. It was therefore very important to measure the hot spot temperature in both magnets, in particular in PB2, as it would give an upper limit for the peak temperature in the full-length quadrupoles. The quench load in MIITs was measured in the case of firing of all of the inner and all of the outer heaters, as well as using half of the inner and half of the outer heaters. As expected, Fig. 6, the highest hot

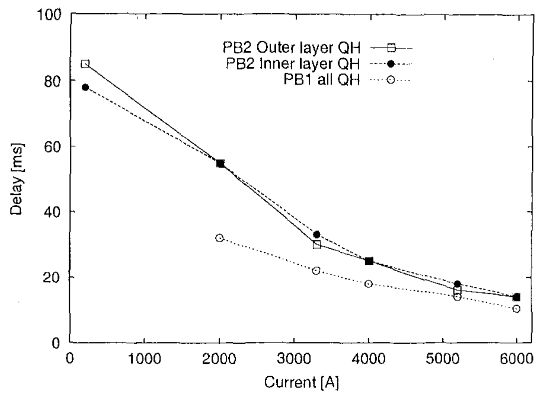

Fig. 5. Heater delays in PB1 and PB2. The initial power density in the heaters was 21 W/cm^2 and decreased with a time constant of 112 ms.

spot temperature occurs when half of the outer heaters are used, but nevertheless remains well below 300 K. At nominal current, the hot spot temperature in PB2 is reduced from 234 K to 200 K if all outer heaters are used, and by additional 20 K if the inner heaters are fired. With a higher Cu/SC ratio, the hot spot temperature in PB1 decreases by additional 20 K. The peak voltage to ground was measured to be 20 V and 27 V in the case of using the inner and outer heaters, respectively.

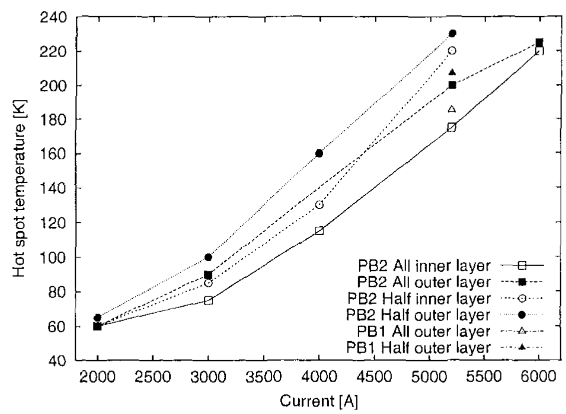

Fig. 6. Adiabatic hot spot temperature in PB1 and PB2 based on the quanch load measurements.

For magnet protection in the LHC [3], a time interval will be introduced between the detection of the quench and firing of the heaters, required for filtering spurious signals and avoiding unnecessary stops of the machine. In order to validate the effect of the additional delay, the firing of the outer heaters was gradually retarded, and the hot spot temperature was found to increase by 5 K/ms. The expected peak temperature in PB1, including a quench detection and filtering time of 20 ms, would in all cases be below 300 K. The inner heaters are therefore not necessary for magnet protection, even in the case when only half of the outer heaters are used.

B. Twin-aperture quadrupole

The quench training of the twin-aperture quadrupole is shown in Fig. 7. The first quench occurred at 5536 A, higher than in the second cycle of PB2. The majority of quenches were in the layer jumps, and the magnet trained to the conductor limit at a similar rate as the PB1 single aperture magnet.

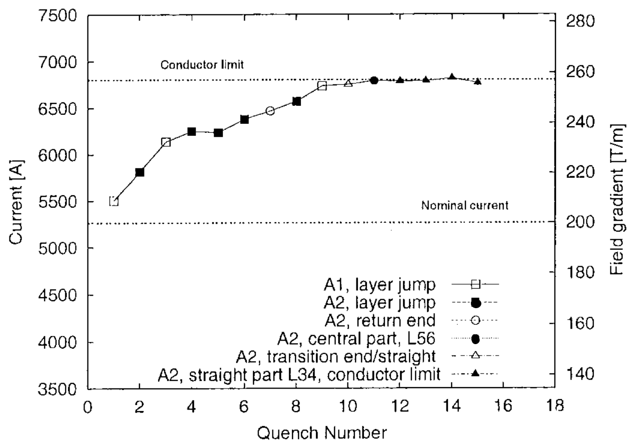

Fig. 7. Quench training of the twin-aperture magnet at 1.9 K.

The results of the warm magnetic measurements, performed with a rotating coil at the magnet current of 5 A, are given in Table II. As described above, the PB1 coils were considerably larger than nominal size, and this is clearly observed in the large allowed and non-allowed multipoles. The PB2 coils were assembled in the collaring cavity of nominal size, and the measured multipoles are a good indication of component tolerances and fabrication errors. Indeed, the measured b_6 multipole (2.7 units) closely follows the design value (2.5 units at room temperature), and similarly for b_{10} and b_{14}. The non-allowed multipoles are of the order of 0.1 of a unit with the exception of the sextupole and octupole. Further investigation is needed to determine whether this is related to a systematic feature in the coil construction.

TABLE II

Field multipoles in the twin-aperture quadrupole at 5 A. (R_{ref}=17 mm)

	PB1		PB2	
n	b_n	a_n	b_n	a_n
3	-13.61	-5.08	-2.75	1.99
4	-2.18	4.02	-0.14	-2.99
5	5.30	-1.66	0.34	-0.11
6	8.09	0.22	2.70	-1.05
7	0.82	0.41	-0.25	0.04
8	-0.18	-0.46	-0.02	-0.16
9	0.08	0.06	0.05	-0.05
10	0.32	0.01	0.49	-0.17
11	-0.01	-0.03	-0.02	0.00
12	-0.03	0.01	-0.01	0.02
13	0.00	0.03	0.01	0.00
14	-0.39	0.08	-0.46	0.00

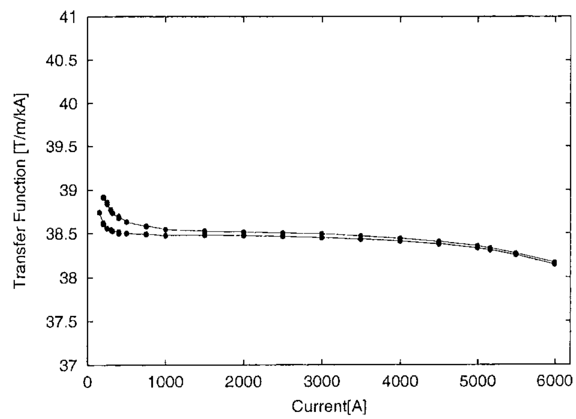

Fig. 8. Measured transfer function in the central part of the PB2 aperture in the twin-aperture quadrupole.

The transfer function in the straight section of the PB2 aperture, Fig. 8, decreases due to iron saturation by only 0.1 T/m/kA up to the nominal current (5280 A). As predicted, the apertures are therefore almost completely magnetically decoupled.

IV. Conclusions

Two 1-m long single aperture and one twin-aperture models of the 6 kA superconducting quadrupole for the LHC insertions have been built and tested. The magnets feature a two layer coil wound using a single length of 8.2 mm wide Rutherford-type cable. The first training quenches in all models were above the nominal current in the LHC, and they trained to their conductor limit at 1.9 K in a small number of quenches in all test cycles. There were no training quenches at 4.4 K. Protection studies showed that the outer heaters are sufficient for redundant protection of the magnet. Measurements of the field multipoles at room temperature and of the transfer function at 1.9 K validated the magnetic design, and showed that the required field quality can be achieved with practical coil fabrication and assembly tolerances.

V. Acknowledgments

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