Cryogenic and Mechanical Measurements of the first two LHC Lattice Quadrupole Prototypes

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Abstract

In the framework of a collaboration agreement between CERN and CEA in Saclay, France, two twin aperture quadrupole prototype magnets have been constructed at Saclay. These magnets of 3.05 m length which have a coil aperture of 56 mm and a nominal gradient of 252 T/m at 15060 A have been tested and measured at superfluid helium temperatures in a specially adapted horizontal test cryostat in Saclay. The magnets are instrumented allowing to investigate their behaviour during cool-down, operation and warming up. The paper presents a summary of the cryogenic measurement results including temperature and pressure. Further, quench data and the results of strain gauge measurements on the collars and of displacement transducers are described.

1. INTRODUCTION

The collaboration between CERN and CEA/Saclay for the work on the lattice superconducting quadrupole magnets for the LHC started end of 1989. The magnetic parameters were frozen in July 1990, followed by the detailed design [1] and fabrication of tooling and components. Two cold masses, i.e two twin quadrupoles mounted in their helium vessel, have been assembled [2] and were ready to be tested mid 1993.

Numerous tests were carried out before and during the assembly of the magnets [3]. However, the final proof of magnet performance is obtained by the cold tests. This paper describes these tests and their results for the two cold masses.

2. BRIEF DESCRIPTION OF THE MAGNETS.

2.1 Main parameters.

The main parameters, choosen in 1990, correspond to a 15 TeV collision energy for the protons of the LHC and to a field of 10 T for the superconducting dipole magnets. Table 1 lists the main parameters and figure 1 shows the cross section of the cold mass. Reference [1] gives a full description of the magnets.

Table 1
Main design parameters of the prototype quadrupole magnets

Nominal Gradient (T/m)	252
Inner coil aperture (mm)	56
Magnetic length (m)	3.05
Overall current density (A/mm^2)	530
Peak field in conductor (T)	7.76
Nominal current (A)	15060
Magnetic force Fx per octant (kN/m)	625
Magnetic force Fy per octant (kN/m)	-880
Stored energy in the cold mass (kJ)	890

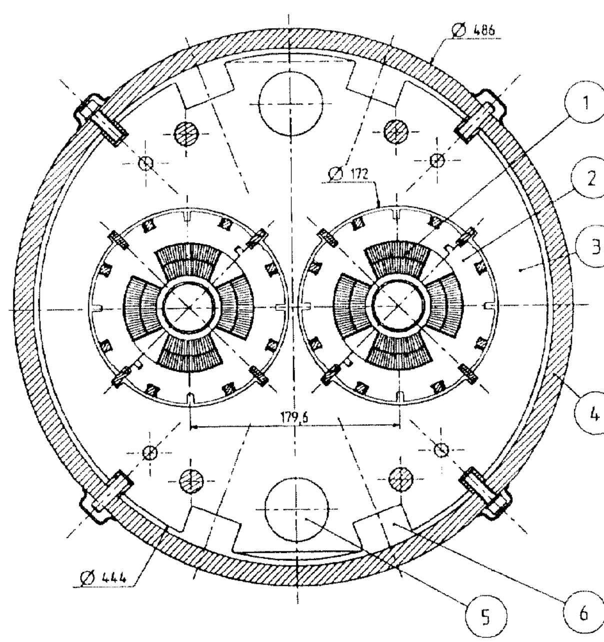

Figure 1. Cross-section of the quadrupole
1 Coils, 2 Stainless steel collars, 3 Yoke, 4 Inertia tube, 5 Holes for helium duct, 6 Passage for busbars.

2.2 Particularities of the design.

The magnet, designed on the basis of the experience gained with the quadrupoles of the HERA machine [4] [5], has, amongst others, the following particularities:
- Twin configuration

- Use of superfluid helium
- The azimuthal prestress is given by the insertion of tapered keys during the collaring process.
- The magnetic core is made of single piece laminations which are guided down along two single collared coils.

3. COLD TESTS

The cold tests [6] [7] have been performed in Saclay's test facility [8] [9], modified for this purpose. The cool down of the first magnet began at the end of June 93 and, due to liquefier troubles, the magnet was maintened at a temperature below 100 K during repair. The cold tests were made in October for the first magnet (Q1) and, for the second one (Q2), in December and January, including a thermal cycle. During these tests, the lowest temperature reached was 1.52 K.

3.1 Cryogenic measurements.

The helium bath pressure is measured at both ends of the cold mass and also in the annular space between the coils and the inner tube of the helium vessel. About 20 ms after a quench occurs or is initiated with heaters, the pressure rises first, as expected, in the channel where the quench starts. About 5 ms later, the pressure rises in the second channel and finally, it rises at both ends of the cryostat with a delay of about 50 ms. The maximum values of pressure for a quench at 15090 A were 13 bar in the annular channel and 5.5 bar at the ends of the cold mass.

The temperature measurements are made with platinum, carbon and germanium sensors mounted at several locations in the cryostat, allowing to control the cool-down by limiting the temperature difference between cryostat entry and output to 50 K. After a quench, the temperature is recorded, showing that it reaches about 20 K on the collars and 10 K on the iron core for a quench at nominal current.

Coil temperature is also evaluated via the electrical measurements: knowing the characteristics of both superconducting cable and coils, the squared integrated current (MIITs) gives the hot spot temperature while the deposited energy gives an estimation of the mean temperature reached under adiabatic conditions. During natural quenches, the maximum hot spot temperature was 82 K and the maximum mean temperature was 63 K. For magnet Q2, many quenches have been induced to study the characteristics of the protection heaters and to verify that the magnet is safe even without energy extraction. These tests will be described in detail in another publication but we just mention that during an induced quench at 14000 A without energy extraction, the hot spot temperature was 107 K and the mean temperature 68 K.

3.2 Quench performances

Figure 2 shows the quench performances of both magnets.

Q1 needed only one quench to reach and exceed the nominal current, which is at 88 % of the short sample limit on the load line. Q2 needed three quenches to reach the nominal current, the first of them being much lower than the others. After the thermal cycle, new training quenches occured with a slightly slower progression.

The last four quenches of Q2 occured at the nominal bath temperature of 1.8 K while the others occured at 1.55 K. This shows that the origin of the training is mechanical, which is not surprising if we take the low margin along the load line and the high force level into consideration.

The current corresponding to the new parameters of the LHC machine is 0.865 times the old one (In). Only Q2 magnet would have one quench before to reach this current.

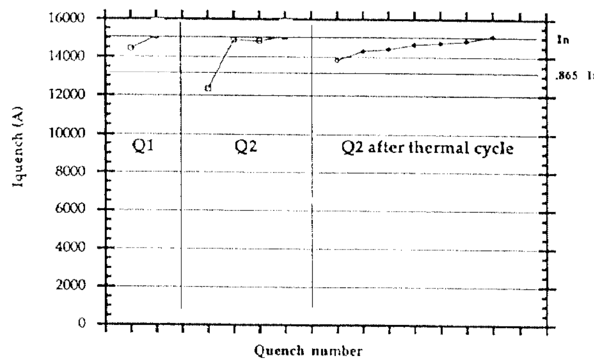

Figure 2. The quench history of both magnets

3.3 Change in prestress during cool-down and excitation.

One collared coil of magnet Q1 was equipped with specially designed strain gauge collars which measure the strain on the pole piece or "finger" of the collars [10]. In our case, 10 μm/m corresponds to 1 Mpa.

Figure 3 shows the evolution of the prestress during all the time of the tests, including the cool-down and the warm-up.

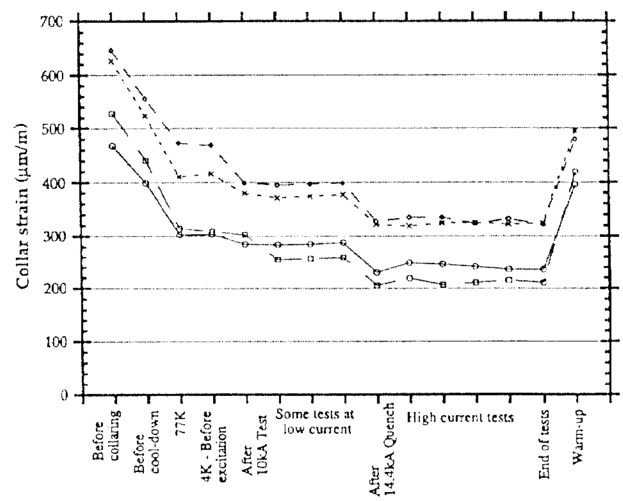

Figure 3. Change in coil prestress during magnet assembly, cool-down, excitation and warm-up.

The design prestress after collaring and at room temperature was 50 Mpa. This has been achieved and it validates the coil sizing process decribed in [3]. It is also important to see that a loss of prestress, of about 10 Mpa, occured during the 5 month elapsed between collaring and cool-down. This comes from the creep of the Kapton foils used for ground insulation. The loss of prestress during cool-down agrees with calculations and the decrease in prestress during excitation is explained by frictional forces at the collar/coil interface or within the coil itself. These effects of friction are partially balanced during warm-up by the thermal contraction changes.

Figure 4 shows the change in coil prestress during energization to nominal current. For low current, as expected, the prestress varies linearly with the square of the current, i.e. with Lorentz forces. It appears that all the coils unload at full current and that there is a significant hysteresis, and thus friction, between the collars and coils.

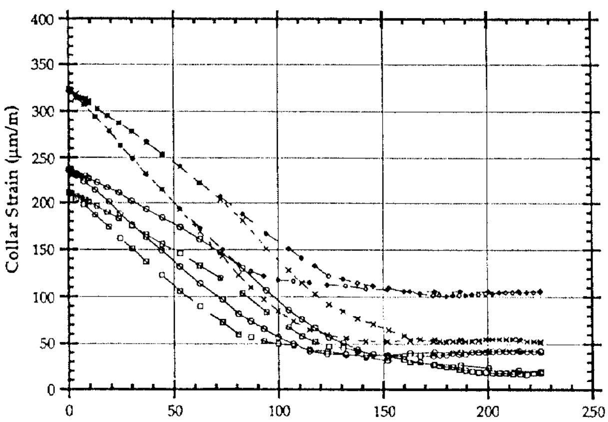

Figure 4. Change in coil prestress during powering to nominal current.

The coils unload because the dependence of the prestress with current is higher than predicted and also because there is an important creeping of the Kapton. This phenomenom was not well quantified at the design time and therefore was not considered. It is important to notice that from 12500 to 15000 A, no more prestress exists in the coils, without leading to a quench of the magnet. However, for new designs, it is recommended to correct this point and to verify that prestress always exists.

3.4 Displacement measurements.

In a particle accelerator, it is very important that the position of the quadrupole axis does not move. The centering of the collared coils in the magnetic core and of the magnetic core in the inertia tube is made with centering keys. In order to verify that the centering does not change during cool-down, energization and warm-up, displacements between elements are measured with 12 linear potentiometers calibrated to operate at liquid helium temperature. Within the limits given by the resolution of these transducers, which is 0.1 mm, no movement has been seen during the tests of both magnets.

CONCLUSION

The results of the tests described here show that the proposed design for the LHC lattice quadrupoles is correct. Each of the two tested magnets reached its nominal characteristics, which is already 15 % above those required by the new parameters of the LHC machine, after only a few quenches.

The collaboration between CERN and CEA/Saclay is continuing. The analysis of the magnetic measurements is in progress. A test of the Q2 magnet, modified to allow the superposition of a 3000 A current in one of the two quadrupole apertures is scheduled for the end of 1994.

The design of the new quadrupole adapted to the new parameters of the LHC machine is starting. It will allow to make some improvements to the design, such as control of coil prestress, and to increase the safety margin up to about 20 %.

ACKNOWLEDGMENTS

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