COMPLETION OF THE SERIES FABRICATION OF THE MAIN SUPERCONDUCTING QUADRUPOLE MAGNETS OF LHC

T. Tortschanoff, M. Modena, Y. Papaphilippou, L. Rossi, K.-M. Schirm (CERN, Geneva),
R. Burgmer, H.-U. Klein, D. Krischel, B. Schellong, P. Schmidt (ACCEL, Bergisch Gladbach),
M. Durante, A. Payn, J.-M. Rifflet, F. Simon (CEA, Gif-sur-Yvette)

Abstract

By end of November 2006, the last main superconducting quadrupole cold mass needed for the installation was delivered by ACCEL Instruments to CERN. In total, 360 cold masses for the arc regions of the machine and 32 special units dedicated to the dispersion suppressor regions are installed in the LHC ring. The latter ones contain the same main magnet but different types of correctors and are of increased length with respect to the regular arc ones. The end of the fabrication of these magnets coincided with the end of the main dipole deliveries allowing a parallel assembly into their cryostats and installation into the LHC tunnel. The positioning into the tunnel was optimized using the warm field measurements performed in the factory. On the other hand, the correct slot assignment of the quadrupoles was complicated due to the multitude of variants and to the fact that a number of units needed to be replaced by spares which were customized for other slots. The paper gives some final data about the successful fabrication at ACCEL Instruments and explains the issue of their best positions in the machine.

INTRODUCTION

The LHC contains 360 main quadrupoles in the arcs and 32 quadrupoles of the same type in the dispersion suppressor regions. In total 408 magnets were ordered with ACCEL Instruments including 16 spares which were assembled into cold masses. The series fabrication was preceded by a period of development and prototyping which was executed in the frame of a close collaboration between CERN and CEA-Saclay. CEA-Saclay took over also the technology transfer and the technical follow up during the series fabrication at ACCEL's dedicated factory in Troisdorf near Bonn, Germany.

Figure 1: Yoke assembly around quadrupole apertures

QUADRUPOLES IN THEIR COLD MASSES

The main quadrupole magnets are all of identical design. (Note that the LHC further contains quadrupoles of different design placed in the dispersion regions and matching sections of the machine as well as the low-beta quadrupoles next to the experimental insertions.) While the arc quadrupoles are placed into cold masses of identical length those for the dispersion suppressors are longer and come in two different lengths.

Figure 2: Quadrupole cold masses awaiting shipment at ACCEL

Main Quadrupole magnets

The design, prototype construction and their performance has been described in earlier papers [1],[2],[3]. Like the main LHC dipole magnets, the quadrupoles are of the two-in-one design, meaning that the apertures for the two beams are located in a common yoke (Fig. 1). The super-conducting cable is of the same dimensions as the one used for outer layer of the dipole coils. Here only the main parameters are recalled:

Injection gradient (0.45 TeV beam energy)	14.5 T/m
Nominal gradient (7 TeV beam energy)	223 T/m
Nominal current	11'870 A
Operating temperature	1.9 K
Magnetic length at 1.9 K	3.10 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 axes 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
Arc cold mass length between end covers	5.345 m

Integration into Arc Cold Masses

The quadrupole magnets are placed into their liquid helium vessel together with the corrector magnets, the bus-bars and their instrumentation. Further, the container of the protection diode assembly is attached to the vessel forming the so-called cold mass. On the connection end of the quadrupole is aligned either an octupole corrector, a tuning quadrupole or a skew quadrupole. On the other end one finds the combined sextupole-dipole correctors of which four variants exist, depending on the orientation and function of these magnets. In total, the combination of these magnets together with different interfaces of the cold mass to the helium supply line and the cryostat results in 40 variants. These variants appear in different numbers ranging between one and 30. One challenge for the fabrication consisted in anticipating the right variant for the planned installation sequence which was complicated by the fact that this planning had to be modified because of unforeseeable events in the installation of the infrastructure in the tunnel and because not all CERN supplied components were available in due time.

Dispersion Suppressor Cold Masses

The 32 cold masses for the dispersion suppressor regions feature a similar structure as the arc cold masses. However, their correctors are of different types and of different length. Thus, the 32 cold masses come in sixteen different types having quantities of one, two or six units. Contrary to the other dispersion suppressor quadrupoles which are separately powered, the 32 cold masses contain the same quadrupole magnet as in the arcs and are powered in series with the arc ones.

The assembly technique is very much the same as for the arc cold masses and took place vertically. Of these dispersion suppressor cold masses, 28 have a length, between end covers, of 6.63 m, four of them are 8.03 m long. This required the need for a dedicated vertical assembly tool, in fact, an assembly tower and the free space under the crane hook of about twice the longest cold mass length. The digging of an additional three-metre deep hole was already foreseen and executed by ACCEL during the preparation of the fabrication facility.

FABRICATION OF COLD MASSES

Main Milestones

In July 2000 the contract between CERN and ACCEL was signed. By November of the same year, ACCEL started the renovation and equipping of the two fabrication halls, having a total area of 5000 m^2. The first quadrupole magnet, not assembled into its cold mass was finished by ACCEL and successfully cold tested at CERN in a vertical cryostat facility in August 2002. In June 2004 the contract for the 32 cold masses for the dispersion suppressor regions was awarded to ACCEL. The hundredth cold mass was delivered to CERN in December 2004 [4]. The delivery of the 360 arc cold masses and 32 dispersion suppressor ones was concluded in November 2006, while the last quadrupole cold mass assembled into its cryostat and fit for installation was cold tested in mid-February 2007.

Fabrication Data

Here some total quantities of components used for the series construction of the main quadrupoles are listed:

Superconducting cable (NbTi):	540 km
Number of coil end spacers	66’000
Number of copper wedges	39’360
Number of quench heaters	3400
Polyimide tapes for cable insulation	3600 kg
Austenitic steel for collars	620 t
Number of collars	2’620’000
Low carbon steel for yoke laminations	2400 t
Number of yoke laminations	228’000
Bus-bar pairs	1230

The logistics achievement of the fabrication is illustrated by the fact that for the total quadrupole and cold mass fabrication 6’150’000 single pieces had to be procured handled and assembled. The quality assurance, based on a bar-code registration, together with thorough treatment of non-conformities was crucial for the success of the series fabrication and to the excellent performance of the magnets. It is worth mentioning that the rate of usage of critical components like the superconducting cable, the collars and quench heaters was in the order of 97 to 98 %.

Special issues

Every second quadrupole cold mass provides the connection to the cryogenic feed line (QRL) placed in parallel to the machine in the LHC tunnel. Every second of those, holding the outlet of the liquid helium, has to be equipped with flow restriction in the bus-bar connection tubes to the adjacent magnet, separating the helium circuits in the machine. These flow restrictions not only have to withstand pressure rises of up to 20 bar at cold but also to electrically insulate the main and secondary bus-bars from the surrounding steel tubes. The development of these restrictions was the subject of an intensive development at CEA-Saclay and then of an industrialization phase at CERN [5]. The fabrication and mounting of these restrictions onto about 300 pairs of bus-bars was then performed in a dedicated workplace at CERN and could be achieved just in time for the cold mass assembly.

An other critical issue was the appearance, at a late stage of the production, of collar steel with a higher permeability than specified. About 10 % of the collars had to be used with this, having an influence on the quadrupole strength and to some extent on the dodecapole component. The effect was not dramatic but it was too high to be ignored (up to 50 units for the worst cases) and required an analysis based on the measurements carried out at warm conditions at the company. However, this analysis was made more difficult by the fact that the previous cold-to-warm correlation for the field quality was lost. Once the warm-to-cold correlation for the high permeability family was re-established, the impact of this

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defect was mitigated by suitable positioning of the affected quadrupoles such that a certain cancellation was achieved (sorting).

Factory tests and quality assurance

It turned out to be necessary to introduce verifications of supplied components in addition to those initially specified in the technical specifications. This was the case for the corrector magnets for which reception tests had to be performed and for the bus-bars for which a strict verification of geometry and insulation became necessary.

Each non-conformity had to be discussed, corrected if necessary, and accepted before the component in question could be used for the next manufacturing step.

All collared quadrupole apertures underwent magnetic field measurements at room temperature which were repeated after the magnets were finished and assembled into their cold masses. The automatic on-line check of the results greatly helped the quality monitoring of the production since it avoided human misinterpretation. For only a small percentage, less than 10 %, the magnetic field measurements were made at cold conditions at CERN's test facility, mainly to establish warm-to-cold correlation or to measure the deviation of this due to the before-mentioned permeability problem of the collars.

At different stages of fabrication and assembly, the quadrupole magnets but also the circuits of the correctors and quench heaters were submitted to HV insulation tests, all documented in the individual traveller files. For the geometrical verifications of the cold mass, especially of the interfaces to adjacent magnets, to the cryostat and to the cryogenic feed line, precise measurements by means of a laser tracker system were performed.

Before delivery, each cold mass was closed and introduced into a test vessel where pressure and leak tests were performed between the different volumes, i. e., between beam tubes and cold mass volume, cold mass volume and external space, cold bore and external, as well as between heat exchanger tube and cold mass and external volume. The test reports were checked at CERN and CEA and only then the delivery could take place.

OPTIMIZED POSITIONING

The objective of optimizing the position of the quadrupoles in the ring was to obtain the smallest possible variation of the beta functions, in both planes and beams. The need for this was not only given by the normal spread of the quadrupole transfer function. This exercise became even more urgent at the time when the high permeability in collars was discovered.

The sorting of the quadrupoles consisted in placing magnets with almost identical field strength, in positions with a phase advance of almost $\pi/2$. By this a local cancellation of their influence on the beta-beating could be achieved. This procedure was however limited by the above mentioned variety of cold mass types and their mounting into cryostats. Since a certain number of bare quadrupoles where available and measured at warm conditions [6], they could be allocated to optimized positions, instructing the manufacturer in time about into which type of cold mass a given magnet had to be assembled. Thanks to the readiness and flexibility of ACCEL Instruments, the logistics of the cold mass fabrication could be adapted to this requirement. In this way, a reduction of the beating of the horizontal and vertical beta-function by a factor of 2 to 3 could be achieved in comparison to a distribution without any sorting [7].

CONCLUSIONS

On the 26th of March 2007 the last quadrupole magnet has been lowered into the tunnel, after the cryostating of its cold mass and the successful cold testing. In April one eighth of the machine was cooled down to 1.9 K and is undergoing electrical powering tests [8].

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