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The LHC Main Quadrupoles during Series Fabrication

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Abstract

By the end of August 2005 about 320 of the 400 main LHC quadrupole magnets have been fabricated and about 220 of them assembled into their cold masses, together with corrector magnets. About 130 of them have been cold tested in their cryostats and most of the quadrupoles exceeded their nominal excitation, i.e. 12,000 A, after no more than two training quenches. During this series fabrication, the quality of the magnets and cold masses was thoroughly monitored by means of warm magnetic field measurements, of strict geometrical checking, and of various electrical verifications. A number of modifications were introduced in order to improve the magnet fabrication, mainly correction of the coil geometry for achieving the specified field quality and measures for avoiding coil insulation problems. Further changes concern the electrical connectivity and insulation of instrumentation, and of the corrector magnets inside the cold masses. The contact resistances for the bus-bar connections to the quench protection diodes and the elimination of insulation problems of the main bus-bars required special attention. To this must be added actions for solving of interface problems to the neighbouring magnets in the machine and to the cryogenic feed line.

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[1]*Abstract*—**By the end of August 2005 about 320 of the 400 main LHC quadrupole magnets have been fabricated and about 220 of them assembled into their cold masses, together with corrector magnets. About 130 of them have been cold tested in their cryostats and most of the quadrupoles exceeded their nominal excitation, i.e. 12,000 A, after no more than two training quenches. During this series fabrication, the quality of the magnets and cold masses was thoroughly monitored by means of warm magnetic field measurements, of strict geometrical checking, and of various electrical verifications. A number of modifications were introduced in order to improve the magnet fabrication, mainly correction of the coil geometry for achieving the specified field quality and measures for avoiding coil insulation problems. Further changes concern the electrical connectivity and insulation of instrumentation, and of the corrector magnets inside the cold masses. The contact resistances for the bus-bar connections to the quench protection diodes and the elimination of insulation problems of the main bus-bars required special attention. To this must be added actions for solving of interface problems to the neighbouring magnets in the machine and to the cryogenic feed line.**

***Index Terms*--Large Hadron Collider, LHC, quadrupoles, series fabrication, superconducting magnets.**

I. INTRODUCTION

SINCE the middle of 2004, the fabrication of the main LHC quadrupoles [1]-[3] and their cold masses have considerably picked up momentum and reached a rate of about four cold masses per week. ACCEL Instruments has set up a dedicated new factory for this highly innovative activity in Troisdorf, near Cologne, Germany. The technology transfer and most of the follow-up was provided by CEA-Saclay, where the quadrupoles had been developed and prototyped [4]. It must be pointed out that a certain number of components for the quadrupole magnets themselves, but also for the cold masses, were CERN supplies, originating from other factories under contract with CERN and from collaborating institutes. This concerns the superconducting cables, all the insulation material (i.e., polyimide tapes and foils) the steel for the collars, the low carbon steel sheets for the yoke laminations, and the instrumentation as well as its wiring. Further, CERN supplies were the protection diodes, the main and auxiliary current carrying bus-bars, and the various corrector magnets. The latter ones are placed inside the cold masse on each end of the quadrupoles.

ACCEL Instruments established a rigorous quality assurance program used not only for maintaining the quality of their fabrication and their sub-suppliers, but also to inspect the incoming CERN supplies and to avoid integrating faulty components.

II. PERFORMANCE OF MAGNETS

Before being assembled into the magnet yoke, each collared coil is submitted to warm magnetic field measurements [5]. These are repeated once the magnet is mounted into its cold mass. From these measurements one can already judge on the field quality at cold, relying on the warm to cold correlation for the different multipole components. The most prominent ones for a quadrupole

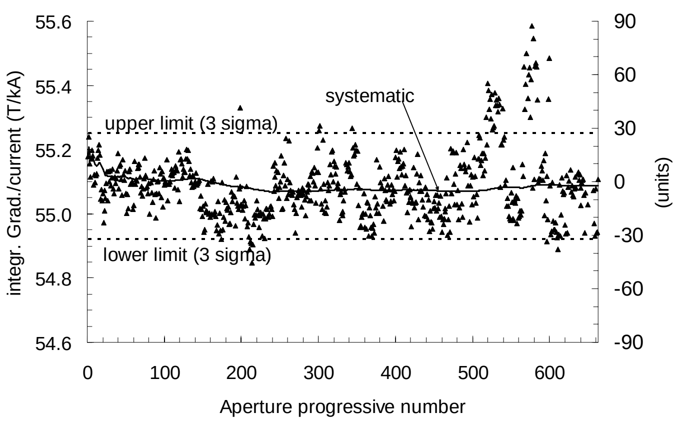

Fig. 1. Transfer function measured at warm in apertures, i.e. collared coil without iron yoke.

are the integral transfer function (i.e. the gradient times magnetic length over the current) and the dodecapole component, b_6, the evolutions of which are shown in Fig. 1 and 2. The warm magnetic measurements are made by exciting the magnet with 12.5 A and using the rotating coil technique, covering the full aperture length in five longitudinal positions.

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These measurements revealed the need for some corrections during the series fabrication. In Fig. 2 is visible that at the beginning of the fabrication, the b_6 component was higher than its upper target value. This could be corrected by inserting a 125 µm thick mid-plane shim which reduced the b_6 after the fabrication of about 200 apertures.

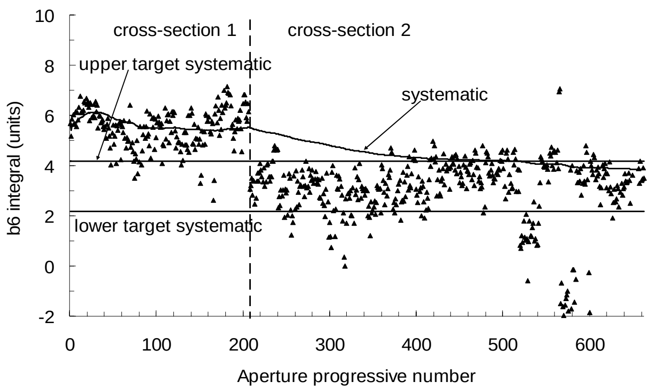

Fig. 2. Dodecapole component, b_6 measured in quadrupole apertures. The continuous line presents the running average (systematic), to be compared to the target range.

After the assembly of the collared coil apertures into their magnets and then into the cold mass vessel, the quadrupole apertures are measured again to evaluate the field quality in the final assembly. The cold masses undergo thorough electrical tests and finally extensive pressure and leak tests at 26 bars for which the factory uses two dedicated test stations. Once the results of all these tests have been documented and accepted, the cold masses are shipped to CERN where they are mounted into their cryostats. 40 variants of these cold masses exist due to the different combinations of corrector magnets [6] with the focusing and defocusing function of the main quadrupoles and the polarity of the protection diodes, combined with the four types of interfaces to the helium supply line and cryostat. In fact, together with different types of the cryostats, 61 variants of cryostated arc quadrupole units will be installed in the LHC tunnel.

Once cryostated, the quadrupole units, now called Short Straight Sections (SSS) are attached to one of the twelve magnet cold test stations. After basic cryogenic and electrical verifications, the quadrupoles undergo a training program for determining their suitability for the LHC machine. Also, all corrector magnets are powered and, if needed, trained. The result of the cold tests and training are the subject of a separate paper at this conference [7]. However, it is worth mentioning that most of the main magnets need no or up to two quenches before reaching the nominal current of 11,870 A, corresponding to a gradient of 223 T/m. Until now only one of the 130 quadrupoles tested could not be trained to this level of excitation. If a magnet needs a longer training and is pushed to higher currents, it is verified that none or very little retraining occurs after thermal cycling. At the same time, the six circuits of the corrector magnets placed at each end of the main quadrupoles are powered. Most of them can be excited to above their nominal current without quenching.

III. Experience during series fabrication

At the start and during the series fabrication, a number of issues had to be handled to correct faulty components and other quality issues. This was experienced, despite the important effort which was undertaken by ACCEL Instruments, CEA and CERN to ensure a high standard of quality assurance.

One of first problems was the coordination of the timely delivery of components which had been contractually promised as CERN provisions. Despite all efforts, the delivery of a few items, like correctors and bus-bars was late in the initial phase of the contract. Once these components arrived, numerous teething issues had to be handled.

A. Electrical issues

Most prominent was the problem of the wiring and terminal connection of the corrector magnets. It turned out that the initially foreseen conductors, called spool bus-bars, were not convenient to fulfill the function of auxiliary bus-bars for wiring the corrector magnets inside the cold mass. Only once a four-strand superconducting shielded cable became available could this problem be solved.

The contact faces of the main bus-bars, consisting of copper profiles with a superconducting cable worked in, were at the beginning not of the quality to ensure a safe transition at 12,000 A. A campaign of surface flattening and silver plating had to be launched to improve this situation. A similar problem was also detected for the connections to the pair of protection diodes and even inside the diode stack. This also required a campaign of repairs with a new procedure, both in the factory and at CERN for all cold masses already delivered. All these defaults did not have their origin in ACCEL’s factory but in the way they were prepared by the various third party suppliers or by weaknesses of the original design.

Few problems related to mistakes in the polarity of the numerous corrector magnet circuits were detected at CERN and quickly fixed. This problem originates from the complexity of the circuits and nomenclature, as well as from the lack of a polarity detector, which was not yet used during the initial phase.

Particular attention was devoted to the use of the right flux for all soldering activities. This concerns the soldering of the coil interconnections for each collared aperture, the soldering of the copper stabilizer profiles to the terminal wires of the quadrupole magnets, the connection of the main bus-bars to the stabilizers and diode bus-bars and all the interconnections of the auxiliary bus-bars, and instrumentation wires. While the safest way to avoid any corrosion problems was to use halogen-free fluxes, this type of flux fluid also turned out to be difficult to use, especially where the connections had to be done to vertically positioned contacts. For such cases, a more convenient non chlorine-free flux had to be authorized.

However, the greatest care is taken for cleaning of any remaining flux fluid stains and to avoid any contact to the stainless-steel beam tubes which are inserted later.

B. Mechanical issues

As regards the mechanical side, the interface flanges of the bus-bar tubes had to undergo some changes in order to make them compatible with their various function. These tubes have to be closed in the factory to allow the pressure and leak tests to be performed. They have also to be tightly connected to the cold test bench station as well as to the return box, and finally, in the LHC ring to the neighboring two cryo-dipole magnets.

All connection tubes, those for the main bus-bars, the beam tubes and the instrumentation wire outlets had to be protected during the transport from the factory to CERN and during their storage. In the beginning this was achieved by the same covers as used for the pressure tests. This had to be abandoned since their timely recycling could not be achieved because the rate of the cryostat mounting and cold testing could not match the cold mass production rate. The solution consisted in using cheaper dedicated, lightly mounted covers and leave the covers for the pressure tests in ACCEL's factory.

C. Material issues

As mentioned above, the field quality of all collared coils was measured in the factory. This allowed to detect symmetry defects in the assembly of the four coils, and at a certain time revealed that the material used for the collars did not meet any more the specifications for its permeability. It is well known that the permeability of the collars is strongly influencing the field quality inside the useful region. For this reason, the collars were fine blanked out of 2 mm thick austenitic steel sheets, which were ordered separately by CERN. In the Technical Specifications for this material the relative permeability was requested to be 1.003 ±0.002. When the transfer function values after aperture ~500 (see Fig. 1) appeared to be considerably higher than the upper limit, extensive investigations and computations were made. This effect was traced back to collars for which the μ_{rel} values were finally measured between 1.01 and 1.03, with a few samples showing values as high as 1.04 (at 0.1 T). This was confirmed by the b_6 value going below its lower limit (see Fig. 2). This effect is strongly reduced once the magnets are cooled down and excited to much higher currents than during the warm measurements (750 to 11,750 A in operation at cold against 12.5 A during field measurements in warm conditions). However, the good warm-to-cold correlation for the field strength and field quality is lost for these cases. This resulted in the need to increase the number of magnets beyond the initially envisaged 20 for which the time consuming magnetic measurements at cold are to be performed.

The crisis of collar permeability resulted in a certain slow down of steel fabrication and thus aperture assembly. Finally it was decided nevertheless to use almost all the collars with the higher permeability. By deciding to place these quadrupole magnets into machine positions where their strengths mutually compensate, almost no collar material or magnet apertures were wasted.

The steel producer explained the higher permeability by the appearance of δ-ferrite in the structure. By better controlling the chemical composition, the temperature at the different stages of the fabrication and rolling this could be fully avoided. All the steel produced thereafter was verified even more systematically than the spot checks in the beginning and resulted in steel sheets, which all show measured permeability values which were well inside the specified limits.

Another material issue concerns the welding between the cold mass end covers and the beam tubes. The beam pipe is made of 316 LN steel, while the interface rings for welding consist of 304 L as used for the rest of the cold mass, which functions also as the helium pressure vessel. The weld between this ring and the beam tube is critical for the beam vacuum and has been specified, unfortunately, after the start of production, to be only partially penetrating in the tube wall. Some visual defects due to full penetration triggered a more detailed investigation. X-ray verifications showed porosities, and it turned out that the material selected was not of the quality required for these demanding welds. They not only have to be vacuum tight for supercritical helium at 1.9 K, but also to resist all the stresses due to temperature differences during cool down. They also have to resist to the high pressures that may rise to 16 bar in the case of quenches. Fortunately, all warm and cold tests, as well as some special intensive aging tests carried out on two cold masses by thermal and pressure cycling did not show any degradation in the welds or any leak. Furthermore, extensive calculations and metallographic analysis indicate that the risk of crack propagation from He-vessel to beam vacuum is very unlikely [8]. Thus, it was decided to use these cold masses as they

Fig. 3. Turning tool for cold masses after assembly.

were, but to correct the material and adjust the procedure for the cold masses still to be fabricated.

IV. FACTORY PERFORMANCE

ACCEL has equipped itself with all the needed tooling for the magnet fabrication, cold mass assembly, and testing. For some of the operations more than one set of tools have been set up. This is true for the coil fabrication where the originally CEA-designed tooling was improved, and later multiplied. Also, the vertical cold mass assembly stands, and the pressure and leak test stations were doubled. Some of the tooling was purpose designed by ACCEL, like the technically sophisticated collaring press and the turning device for the cold masses from vertical position to horizontal, see Fig. 3.

Two Laser Tracker systems for all precise geometrical adjustments and verifications were provided by CERN with custom software.

Fig. 4. Finished quadrupole magnets awaiting assembly into cold masses.

The first coils and magnets were fabricated and cold tested successfully in the second half of 2002, while the first cold mass, with main quadrupole and all correctors and bus-bars inside, was delivered to CERN in February 2003. The ramping up of the production during 2003 was kept low mainly because of delays in CERN provided components and by the need to adjust and industrialize procedures in the cold mass finishing. The rate of fabrication was steadily increased during 2004, reaching and exceeding an average of four cold masses per week since the beginning of 2005. By the end of August 2005, 217 cold masses have been delivered to CERN and more than 320 quadrupole magnets (Fig. 4) have been fabricated, see Fig. 5. It is expected to complete the magnet fabrication by the end of 2005, while the fabrication and deliveries of the cold masses will continue until spring 2006.

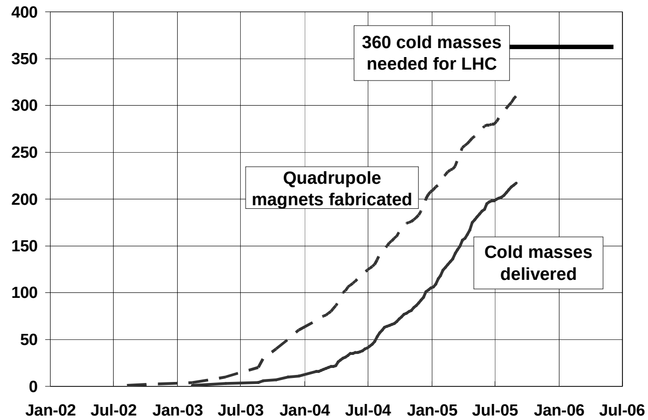

Fig. 5. Progress of quadrupole magnet fabrication and cold mass deliveries (until end of August 2005) [9].

V. ACKNOWLEDGEMENT

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