PERFORMANCE OF THE LHC ARC SUPERCONDUCTING QUADRUPOLES TOWARDS THE END OF THEIR SERIES FABRICATION

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Abstract

The fabrication of the 408 main arc quadrupole magnets and their cold masses will come to an end in summer 2006. A rich collection of measurement and test data has been accumulated and their analysis is presented in this paper. These data cover the fabrication and the efficiency in the use of the main components, the geometrical measurements and the achieved dimensional precision, the warm magnetic measurements in the factory and the performance at cold conditions, especially the training behaviour. The scrap rate of the Nb-Ti/Cu conductor as well as that of other components turned out to be acceptably low and the quench performance measured was in general very good. Most quadrupoles measured so far exceeded the operating field gradient with one or no quench. The multipole content at cold was measured for a limited number of quadrupoles in order to verify the warm-to-cold correlation. From the point of view of field quality, all quadrupoles could be accepted for the machine. The measures taken to overcome the problem of a too high permeability of a batch of collars are discussed.

INTRODUCTION

The development and prototyping of the main LHC quadrupole magnets had been the subject of a close collaboration between CERN and CEA-Saclay [1].

Figure 1: Quadrupole cold mass in cryostat, prepared for cold tests.

The fabrication of the cold masses was entrusted to one single firm, ACCEL Instruments, in Germany [2], [3]. By April 2006 all 408 main arc quadrupole magnets had been fabricated in ACCEL Instruments' factory in Troisdorf, Germany. By mid-June, about 360 bare magnets had been integrated and aligned into their rigid cold masses, which include corrector magnets and the electric and cryogenic services.

After delivery to CERN, the cold masses are assembled into their cryostats (Fig. 1) and prepared for cold tests. Due to the high number of units to be tested, the test program had to be restricted to a minimum such that all magnets undergo power tests and some training quenches but only a small percentage is submitted to field quality measurements. For their characterization one relies on the warm magnetic measurements performed in the factory and on the well controlled warm-to-cold correlation.

QUENCH PERFORMANCE

Once the running-in experience had been acquired for the cold tests, the training of the main quadrupoles was limited to 3 quenches if by this the nominal current of 11870 A was exceeded. If this was not the case and if after eight quenches the so-called ultimate current of 12’800 A was not reached, the magnet was submitted to a thermal cycle for determining if the magnet memorized sufficiently its training. Out of all 287 quadrupoles tested, only one did not reach the nominal value. A deep investigation, with position sensitive quench antennas, revealed that the quenches may have had their origin in the area of coil interconnections outside the collared coils. Fig. 2 shows the distribution of number of quenches to reach the nominal current.

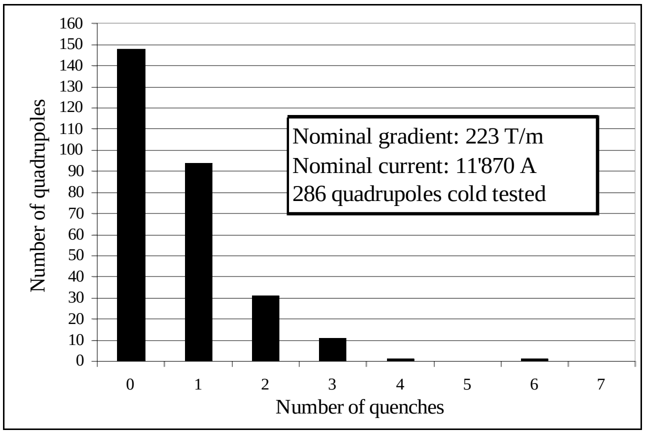

Figure 2: Distribution of quenches for reaching nominal current.

WARM MAGNETIC MEASUREMENTS

All collared coils (single aperture) and all magnets (two-in-one type) assembled into their cold masses were submitted to magnetic measurements at 12 A in the factory. In reference [4] we have given some results for the collared apertures during their series fabrication. In Fig. 3 the transfer function for all magnets is shown, while in Fig. 4 the integrated dodeca-pole component is presented.

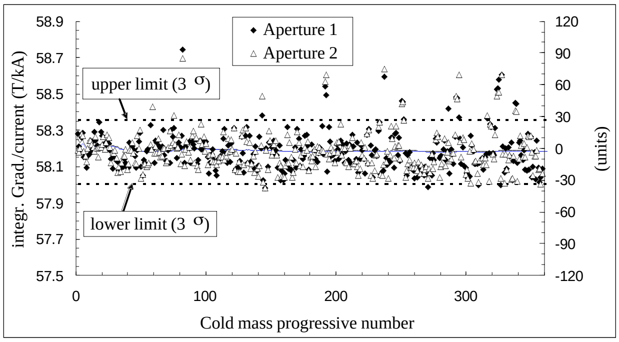

Figure 3: Transfer function at warm measured in magnets assembled into their cold masses.

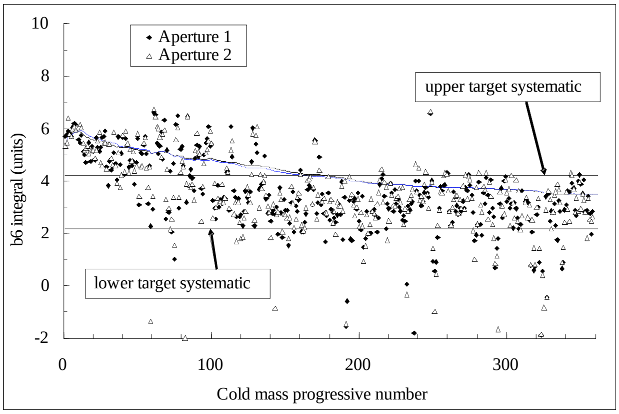

Figure 4: Integrated dodeca-pole component, b6, at warm, measured in magnets assembled into their cold masses.

Since cold mass progressive numbering does not follow exactly the aperture progressive numbering, the values beyond the upper and lower limits are spread out over the full range of cold masses. As explained in [4] and [5], these points are due either to a coil geometry that was later corrected with mid-plane shims or to a too high permeability of about 10 % of the austenitic steel used for the collars. In order to minimize the effect of the latter defect, the cold masses are positioned in the ring such that a compensation of the increased transfer function is obtained. It has been shown [5] that the effect is thereby eliminated in operational conditions.

WARM TO COLD CORRELATION

While all magnets were submitted to quench training at 1.9 K, only a small fraction has been measured at this condition for their transfer function and field quality. The purpose of this was to confirm the warm to cold correlation for these quantities. Even with the already mentioned problem of the somewhat higher permeability in some of the stainless steel collar material, this correlation could be verified. This was possible by removing the impact of permeability from the warm measurements, following the procedure described in [5].

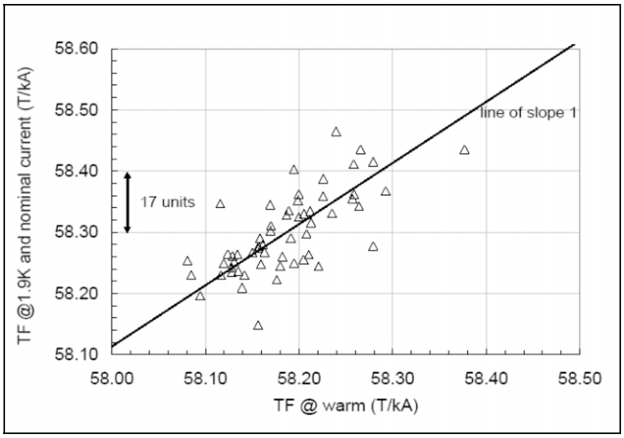

Figure 5: Warm to cold correlation of transfer function.

Fig. 5 shows the correlation diagram for the transfer function after correction for the permeability. For the higher multipole components similar behaviour of the correlation was found, see [5] for a complete analysis.

SERIES FABRICATION

ACCEL Instruments set up a dedicated factory consisting of two newly adapted, clean manufacturing halls of in total about 5000 m^2 in Troisdorf, near Bonn. At the peak of the series fabrication a staff of about 70 was employed, engineers, technicians, mechanics and electricians combined. The delivery rate of completed cold masses reached a peak value of 4.5 units per week.

CERN Supplies

CERN supplied a multitude of components for the quadrupoles and their cold masses:

- 570 km of superconducting cable
- All the polyimide tapes and foils for cable and coil-to-ground insulation
- 3’680 quench heaters
- 600 t of austenitic steel for the collars
- 2’200 t of low carbon steel for the yoke laminations
- All 360 sets of bus-bars, 80 of them equipped with flow restrictions (separating the He-II circuits in the machine)
- 720 cold bore (beam-line) tubes and 360 heat exchanger tubes
- 360 protection diode assemblies
- 168 octupole correctors, 160 tuning quadrupoles and 32 squew quadrupoles
- 360 sextupole-dipole corrector magnets (of four different types)
- 720 supports for the beam position monitors

CERN took advantage of combining the orders for quadrupole components with those for the main dipoles. This is valid for the cable which is identical with that for the outer coil layer of the dipoles, but of shorter length. In fact, the much shorter unit length for the quadrupole cable allowed substantial savings using dipole cable which during its fabrication failed to reach the unit length necessary for a dipole coil. Also the insulation material, the cold bore tubes and the heat exchanger tubes profited from combined orders. The raw steel of the yoke laminations were provided by the same steel manufacturer as for the dipoles.

While the material was provided by CERN, the execution of the cable insulation, the fine-blanking of the collars and of the yoke laminations was entrusted by ACCEL to subcontractors. For finding subcontractors for those activities, ACCEL could profit from CERN's and CEA's experience on the prototypes and on other LHC magnets.

All the remaining components (almost 15,000 single pieces are needed to produce a complete quadrupole cold mass) have been procured by ACCEL.

Cold Mass Variants

In total, there exist 40 variants of arc quadrupole cold mass, depending on the focusing or defocusing function of the main quadrupoles, on the combinations of the corrector magnets, polarity of the protection diodes, presence of the flow restrictions and cryostat vacuum barrier interface and the interfaces to the cryogenic feed line. Since these variants appear in different numbers in the machine, between one and thirty, their fabrication has to be strictly monitored. Even if it was not always possible to follow the planned sequence, due to delays in component deliveries, the fabrication was adapted to follow as closely as possible the priorities given by the installation schedule of the machine.

Flow Restrictions (Pressure Plugs)

In the machine, every second quadrupole unit is connected to the cryogenic distribution line, situated aside the magnets in the tunnel, by means of a so-called jumper. Every second jumper functions as the inlet for the helium flow while the other ones provide the outlet. In order to separate these circuits of He-II flow, hydraulic restrictions (also called pressure plugs) are used at the inter-connection tubes of the current carrying bus-bars. Two of these bus-bar pairs power the focusing and defocusing quadrupoles, one pair powers the main dipole magnets. Onto the quadrupole bus-bars are placed the so-called spool bus-bars, by-passing the currents for the corrector magnets ('spools') inside the dipole cold masses.

While the bus-bars were fabricated at the BINP in Novosibirsk, the development and prototyping of the flow restrictions had been undertaken by the CEA laboratory in Saclay. The working conditions for these flow restrictions were defined as follows:

- Temperature range between 1.8 and 300 K
- Leak tightness at operational temperature and at 20 bar <700mg/s through each of the three plugs per cold mass
- Electrical insulation to ground and between bus-bars, up to 3000 V at operation and up to 1200V at warm.
- Radiation resistance over ten years: 120 Gy and a neutron flux of $6x10^{12}n/cm^2$.

These constraints required extensive testing of different insulation materials, glues and surface treatment procedures. Furthermore, special bellows had to be introduced for taking the relative movements of the bus-bars with respect to the outer interconnection tubes. As late as 2005, CERN set up a dedicated workshop to mount these plugs onto 80 sets of the BINP-made bus-bars before shipping them to ACCEL.

Rate of Material Use

The rate of material use was especially critical for the coil fabrication and collaring where during the different stages faults can appear. The quality assurance in the factory was such that numerous tests and measurements on dimension, elastic modulus and insulation resistance were performed, allowing intercepting any defect as early as possible. For the CERN supplied components the only significant losses concerned the coils and thus the superconducting cable and its insulation. The number of coils which had to be scrapped was 90, mainly for insulation problems. This is 2.7 % of the total of 3380 coils wound. Further loss rates concern the fine-blanked collars which remained well below 2 % as well as a few of the cold bore and heat exchanger tubes.

CONCLUSIONS

The CEA-CERN based design of the main LHC quadrupoles and their cold masses has been confirmed both in its industrialization and cold performance. By mid-2006, the series fabrication in ACCEL's dedicated factory is coming to a highly successful end. By end of May 2006 more than 142 main arc quadrupole units were installed in the tunnel with a continuing nominal rate of up to seven per week.

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