STATUS OF THE LHC MAIN DIPOLE PRE-SERIES PRODUCTION

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Abstract

The procurement of a pre-series of 90 Main Dipole was decided as the first step towards the series production of 1232 Arc Main Dipoles within the LHC magnet program. The pre-series production is already completed at one Contractor's site and is approaching the completion at the other two companies. Technical aspects: manufacturing tolerances, manufacturing difficulties, first evaluation on Non-Conformities appearing during production and a short overview of magnet performance are presented.

THE LHC DIPOLE "PRESERIES" AND "SERIES" CONTRACTS

The 1232 LHC Arc Dipoles (also called Main Bending Magnets or MB) will be the "backbone" of the LHC now under construction at CERN in Geneva-Switzerland. The final design R&D phase (1996-1999) was completed in Nov 1999 and subsequently orders were placed with three European Companies: (Consortium Alstom/Jeumont-F, Ansaldo Superconduttori -I, and BNN-D) for the manufacture of 30 MB cold masses (c.m.) per contract. This initial production was called the "Pre-series". In Nov 2001 CERN placed the contracts (for the same number of MB per Company) for the remaining 1158 cold masses with the same three Companies. Today, (May 2003), the status for the 6 contracts is the following: The Consortium Alstom-Jeumont has completed the Pre-series Contract (complete delivery of the 30 c.m.) and have at their premises several Series c.m. in different phases of production up to N. 46 (16th of the "Series" Contract). 7 c.m. of Pre-series have been delivered by Ansaldo Superconduttori, and production is advancing up to c.m. 12 of the Series. BNN has delivered 13 c.m. of Pre-series and has up to c.m. 10 of the Series in progress.

Although the "steady state" production rate has not yet been achieved, the Manufacturers are coming out of the "learning phase", and it is now possible to make some conclusion about the performance of the Pre-series production during start-up, about the changes adopted during this phase and about the results obtained (see also [1]).

THE PRESERIES MANUFACTURING

Design Changes

Since the signature of the Pre-series contract and the start of manufacturing activities, the design of the C.M. (including the Technical Specification) has evolved [2]. The Pre-series c.m. manufacturing was proceeding following "on line" these changes, in order to have the changes applied ASAP limiting so the number of C.M. of "first generation".

Some changes concerned the c.m. configuration "as delivered at CERN". These changes are not relevant for the magnet final configuration (as installed in the LHC). The c.m. are delivered to CERN ready to be fully test at 1.9 K, but this configuration is later changed to prepare them for the final installation in the LHC tunnel.

The most relevant changes concerned the 2D cross section in the straight part and the geometrical configuration of the conductor blocks and end spacers in the coil ends.

Since the Final Prototype phase on, the coil-straight parts have proved to be thermally extremely stable, since no training quenches originate there. The training quenches all originate in the coil heads. In particular the first and second turn of the outer layer coil have been identified as the locations where the majority of the training quenches are triggered.

In order to optimize the field margin to quench of the coils heads, it was decided to introduce an additional end spacer after the second turn of the second layer in the coil heads in both ends (Fig.1: the additional end spacers are the two marked with digits).

Fig. 1: Complete "final configuration" set of LHC Dipole outer layer end spacers.

A 3D electromagnetic model was used to compute the peak field along the cable width (15.1 mm) in order to follow the evolution of the field value along the path of the conductor around the spacer. Graph (Fig.2) shows the peak field in the first and second turn of the second layer before and after introducing of the additional spacer, which separates the first and second turn from the third.

The computed effects of the change are clearly visible: the peak field experienced by the 1st and 2nd turn decreases as soon as the 2nd cable is separated from the 3rd, starting from 25 mm inside the head.

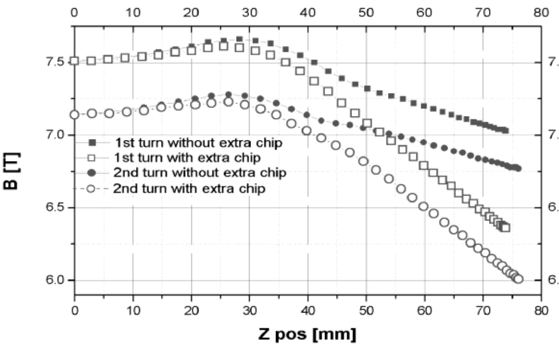

Fig. 2: The peak field in the first and second cable of the second layer with and without the extra end spacer.

The peak field reduction on the apex of the turn is about 0.6 T. With the 3D model it was possible to verify that this change in conductor position did not significantly (<0.1T) increased the field on any other conductor of the coil.

Thanks to this modification it was possible to achieve better compaction of the cable stack in the heads, resulting in a significant reduction in the number of training quenches, as will be presented below.

Corrective actions following indication from magnetic field quality measurements

At the beginning of the pre-series production, a too high value of b3 and b5 was observed [3]. A corrective action was taken based on the measurement of 9 collared coils at 300 K and 2 cryomagnets. Due to the organization of the production, where some components are assembled in parallel, the corrective action was implemented on the 30th produced magnet of the pre-series. The action consists of a small modification on the copper wedge profile (maximum 0.4 mm) of the inner layer, keeping the same overall shape of the coil to avoid any change in the adjacent collared coil components nor coil manufacturing tooling. The change was aiming at maintaining the same value of the main field, whilst reducing the b3 and b5 [3]. The effect on main field was in good agreement with simulation, and the correction on b3 and b5 was between 60% and 80% of what was expected. This cross-section correction has brought b3 and b5 to values that are now close to the optimal ones for beam dynamics.

Magnetic measurements policy and status

Magnetic measurements are carried out first of all at the Manufacturers premises at room temperature at two different moments during production: on the collared coil and on the completed cold mass. Measurements are performed with a 750 mm long rotating coil at 20 consecutive positions along the magnet axis to cover 15 m. The magnetic measurement is a contractual obligation and therefore all the magnets will be tested. Furthermore, special measurements have also been requested for critical cases (change of measuring device, analysis on anomalies in field quality, test of assembly procedures).

By early March 2003, 81 collared coils and 43 cold masses have been measured. Only one measurement of a c.m. was skipped for scheduling reasons at the initial stage of the pre-series production.

Magnets are measured later after cryostating at CERN at the normal operation condition (1.9 K). The present average delay between collared coil and cold test is one year (Fig.3) and the minimum reached so far is 7 months. This delay should be reduced to a few months during the full speed production.

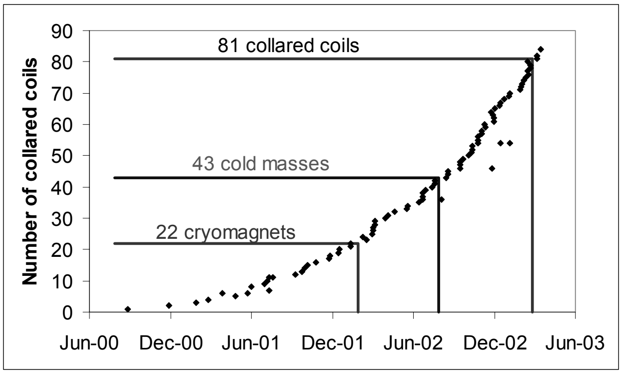

Figure 3: Measured collared coils versus time, and delay in cold mass and cryomagnet measurements.

The results of the magnetic measurements are used for two different purposes:

- the steering of the field quality towards the beam dynamics targets [4],
- the quality control of the assembly.

Their usefulness relies on the correlations between measurements at room temperature and at 1.9 K. The correlation is rather good in general and will be carefully monitored during production [5].

Assembly quality control by magnetic measurements, example of detected Non Conformities

Magnetic measurements are a powerful and economic tool to detect Non Conformities (NC) such as: assembly problems and faulty components, signatures of the tooling and trends in the production (see for instance [6] for the experience at RHIC). In over 81 collared coils, 2 cases of bad assembly procedures have been found: a double coil protection sheet (0.5 mm thick) in collared coil 2002 and a missing collaring shim in the outer layer (0.8 mm thick) in collared coil 1027. It is important to note that, in both cases the NC concerned only a short length of the magnet (1-2 meters) and therefore it would not have affected the integral field in a significant way. Nevertheless, assembly faults of this type induce discontinuities in the magnet structure that may cause performance limitations (quenches) or other serious problems. For this reason it is important to identify and correct these errors at an early stage when the correction can still be carried out in an economic and fast way. In both cases the collared coils were decollared and the defect removed. The analysis of the measurement is based on automatic filters [7] that signal alarms whenever drift of anomalies in field quality are observed.

Outline of present status for field quality and future actions

Systematic components of skew and even normal multipoles are currently within beam dynamics targets. For b3, b5 and b7 the values are close to optimal values to within a fraction of unit, being in all cases larger than the targets. If the target values would be met at the end of the production, the machine would have a good field quality. Indeed, being at the edge of the allowed ranges, trends can drive the production to values far from the optimal ones and therefore an additional corrective action should be taken. More details are given at this Conference [5].

A proposed change is to increase the midplane insulation thickness by about 0.1 mm on both layers. This would slightly increase the pre-stress within the allowed range and would push b3, b5 and b7 down towards safer values. A negligible effect is expected on the integrated main field. A test on short models has been completed [8].

Random components are within specifications with the exception of the b3, which is presently around 70% larger than the specification. This high value of the b3 spread is due to a positive trend in the first part of the production and to the correction of the cross-section. The last 50 collared coils show a much lower value of random b3.

The integrated main field [9] exhibits a systematic difference between firms of up to 20 units. This effect can be due to a variation of coil geometry of the same order of magnitude as the tolerances (some tens of microns). The magnetic length will be fine tuned through ferromagnetic laminations in the ends to reduce these differences. The final aim is to have an installation scenario where mixing between different firms is possible.

Other important design changes

An important change proposed in the last months and now under discussion with the Manufacturers concerns an eventual revision (relaxation) of the geometric tolerances of the cold masses. These tolerances were completely re-checked and revised by all specialists concerned in their definition and achievement (i.e. accelerator physics, c.m. procurement, c.m. reception and cryostating, installation in the tunnel). If confirmed, this relaxation of tolerance would significantly help the Manufacturers to speed-up and simplifying the manufacturing process.

THERMAL PERFORMANCES OF THE FIRST PRESERIES PRODUCTION

The thermal performance (also called "quench performance") is evaluated by measuring the number of quenches necessary to reach Nominal (8.33 T) and Ultimate (9 T) magnetic field level. The provisional acceptance criteria require that the Nominal field be exceeded after no more than the 2nd quench and the Ultimate field after no more than the 7th quench. To date, 28 cryodipoles have been fully tested at CERN. All cryodipoles except one reached the Nominal field of 8.33 T after at most a 2nd quench (Fig.4). The ultimate field level after thermal cycle was reached within: 0 quenches for 15 in 28 magnets, 4 quenches for 4 magnets and 2 and 4 quenches for one magnet. A detailed presentation on the performance achieved by the first 12 cold masses can be found in [10].

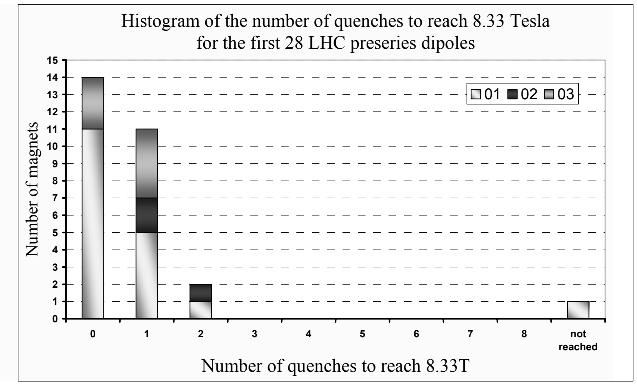

Figure 4: Thermal (quench) performance of the first 28 cryomagnets to reach Nominal field of LHC (8.33 T).

In total three c.m. have shown unrecoverable Non Conformities (appeared during tests at CERN). In one case this was due to a non conforming superconducting cable which escaped the QA controls at the cable manufacturer's premises In the other two cases the problems were affecting the electrical integrity of the c.m. In one case it was the cable insulation (a short circuit appeared during energization) and in the other case it was the integrity of the connection of the quench heaters (the element that guarantees the safe discharge of the magnet's electromagnetic energy in the case of a quench). In all three cases immediate corrective actions were taken, but these problems can be considered part of the inevitable "learning phase" of the component manufacturers (cable problem) and cold mass manufacturers (electrical problems).

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