PERFORMANCE OF LHC MAIN DIPOLES FOR BEAM OPERATION

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Abstract

At present about 90 % of the main dipoles for the LHC have been manufactured and one of the three cold mass assemblers has already completed the production. 85 % of the 1232 dipoles needed for the tunnel have been tested and accepted. In this paper we mainly deal with the performance results: the quench behaviour, the magnetic field quality, the electrical integrity quality and the geometry features will be summarized.

PRODUCTION AND QUALITY

Production has now reached over 1100 Cold Masses of the 1232 CMs to be installed and is expected to be completed by the end of October 2006 [1]. Cold tests on the remaining ~200 CMs are expected to finish by the end of 2006. During CM production the quality at the Cold Mass Assembler factories is assured by an extensive plan, which is an integral part of the technical specification. Early detection of faults during the assembly procedure is provided by a magnetic field measurement at room temperature. A total of 18 cases have been found [2], with 4 faults in the assembly, and 14 non-conform components. Magnetic measurements at room temperature have also been used to locate the position of electrical shorts for 18 cases [3]. Among them, 12 occurred in the inner layer and 4 on the outer one. In all cases the shorts were in the coil heads. After delivery to CERN, tests and measurements in operating (cryogenic) conditions are done to qualify the magnets. These tests are on the geometry, electrical integrity, quench behaviour and magnetic field quality.

MAGNETIC FIELD QUALITY

The measurements of the magnetic field at room temperature have been used to steer the production towards the beam dynamics targets, using the warm-cold correlation established at the beginning of the production and successively updated. Two changes of the coil cross-section have been implemented to steer b_3, b_5 and b_7 towards the targets (see Fig. 1 for the b_3). Today, with 90% of the magnets produced, both average and standard deviations of the transfer function and field harmonics are within targets (see Fig. 2). The spread of the transfer function has been under control for the production. The most critical parameter has been the spread of b_3, at the limit of the target (see Fig. 2). A summary of the trends during the production can be found in [4].

The magnetic field is measured in operational conditions for 15 % - 20 % of the dipoles, in particular to control the field quality at injection field level [5]. The sampling has been much higher at the beginning of the production, when the warm-cold correlations had to be established.

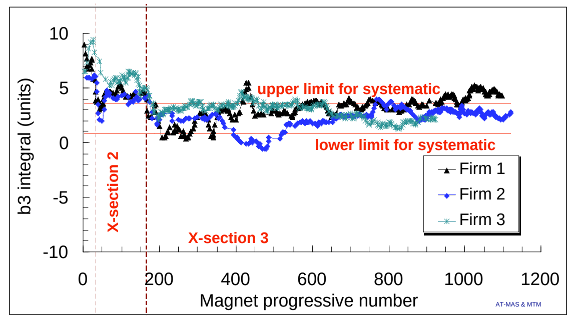

Figure 1: Running average of b_3 in the CMs, for the three CMAs, and beam dynamics targets for the average.

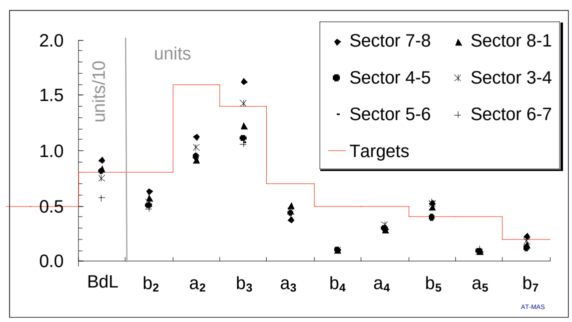

Figure 2: Standard deviation of field harmonics versus targets, for the 6 of the 8 sectors of the machine.

Correlations are stable along the production, showing a very good control of the superconducting properties of the cable, which mainly affect the field at the injection energy. A program of measurements of the dependence of the field quality on the operational settings is in progress and will allow building the field model for machine operation.

GEOMETRY

The main geometry parameters relevant for the beam are the shape of the CM along the magnetic axis and the position of the octupolar and sextupolar corrector magnets mounted at the ends of the CM. The sagitta (9.14 mm nominal value) is controlled by the shape of the welding press. Some CMs had shape excursions exceeding the 1.5 mm tolerance w.r.t. the nominal shape. At the beginning of the production the out-of-tolerance CMs, were re-shaped after welding, but this reshaping turned out to be unstable and was then abandoned. In addition, the sagitta is increasing with transport and thermal cycles, in a way that makes the individual shape unpredictable. Analysis of the shape behaviour showed nevertheless that the mean value of the sagitta change was stable. Each CM is thus adjusted by a constant amount corresponding to the mean value of the sagitta change for all CMs produced at that CMA. Thereafter, the mid support foot of the CMs is blocked inside the cryostat. Only one fiducialization is needed with this procedure [6]. CMs are classified according to aperture criteria needed for the difference positions in the half cells. (see Figure 3).

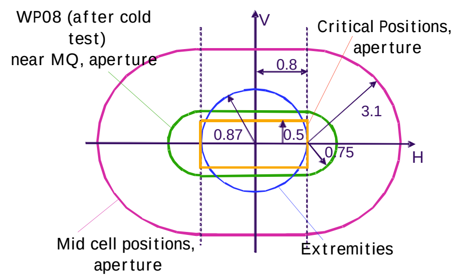

Figure 3: Geometry tolerances and classification.

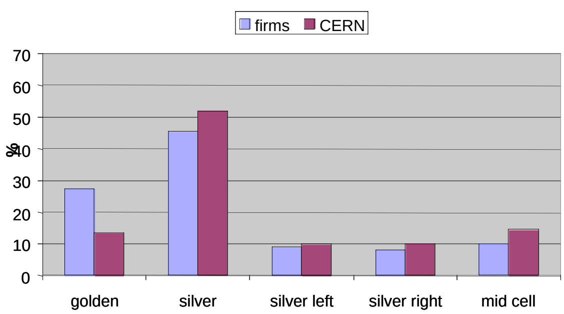

Figure 4: Geometry classes at the CMAs and at CERN.

For critical positions in the dispersion suppressor cells, CMs with very good shape are needed. Slightly more than 13 % of these "golden" CMs are needed for this. CMs within tolerance are classed "silver". Finally, 13 % of the CMs exceed the tolerances after adjustments at CERN. These CMs can be allocated in the less critical mid cell positions ("mid cell" class). The target for a good sorting margin is less than 10 % of "mid cell" CMs. CMs exceeding tolerances at one side can be allocated with the good side close to the quadrupoles. ("silver left" or "silver right"). Figure 4 shows the available classes at the CMAs and later at CERN. All magnets allocated in the machine have the required aperture. The field direction w.r.t. the mechanical mean plane has been measured on a total of 85 CMs and has been found to be on average zero with a standard deviation of about 0.8 mrad, which is well within machine requirements [7].

PERFORMANCE IN OPERATIONAL CONDITIONS

Training Quench Performance

The histogram of the dipoles cold tested so far is shown in Fig. 5. During the first test runs about 38.6% of the total number of tested magnets reached nominal field without a training quench. 11.8 % of the magnets was tested for a second time after a Thermal Cycle, mostly to further investigate weak quench performance. For these ~77.5 % reached, after the TC, the nominal field without training quench (see Fig. 6). The remaining 22.5 % required at least one training quench to reach nominal, hence the average number of quenches below nominal current were reduced after TC by about 82 %.

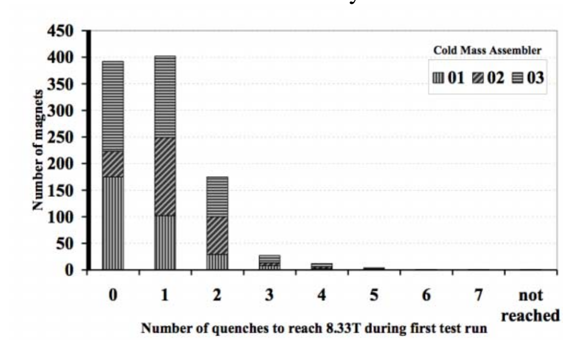

Figure 5: Training quenches to nominal current after 1 st cool-down for 1015 cold tested CMs, at the three CMAs.

From a simple extrapolation of the results of Fig. 6 with an additional assumption that magnets submitted to a TC will not quench in the tunnel, the number of quenches that may occur during the first powering cycles is estimated to be about 40 per sector. This number corresponds to a "worst case scenario" with a low probability of occurrence as it is based on a biased statistics coming from the sample of the weakest magnets.

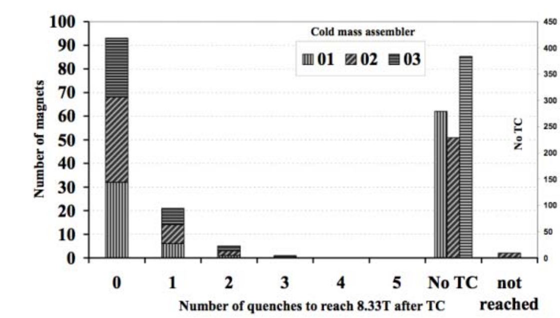

Figure 6: Training quenches to nominal current after the 2nd cool-down for 118 CMs.

A more realistic estimate, corrected in terms of the reduction of the number of training quenches for magnets not submitted to a TC gives 25 ± 6 training quenches per sector [8]. In the LHC tunnel, during the hardware commissioning, the first training quenches are expected around 11 kA (at an equivalent energy of 6.5 TeV).

The magnets that did not reach the nominal field were submitted to the second test run, executed after TC. A small fraction of them was rejected (~ 15) when the unacceptable quench performance was confirmed.

Electrical integrity

During cold tests, numerous non conformities related either to too large leakage currents or problems with the electrical continuity of the instrumentation were encountered. Most of them were traced to the final preparations at CERN and were repaired on the test stands. Around 15 magnets were rejected due to electrical problems of the CM and send back to the CMA for repair.

Vacuum and cryogenic integrity

A thorough leak search is performed during the cold tests on the CM helium enclosure and the outer cryostat vessel. The finding and repair of numerous leaks was in almost all cases related to the interconnection of magnets to the cryogenic feed boxes of the test benches. Several magnets with leaks at the foot of the cryostat were repaired directly at CERN.

SORTING STRATEGY

The geometry, magnetic and electric data collected at the CMAs, and during cold tests at CERN, is used to sort the magnets according to their quality and performance, with the aim to produce an optimal sequence of dipoles in the whole ring. To date, ring positions have been allocated for six of the eight sectors of the LHC.

The algorithm used for the allocation of slots is the one proposed in [9]. Its logic, in the present use, is based on a classification of dipoles in geometry and quench classes, according to the definition discussed above and reported in [10], and on the measured field quality vs. the specified production values. The algorithm defines pairs of magnets that compensate deviations of field errors from the average in the sector. The complete algorithm can be found in references [9] and [11].

In the beginning a concern was the deviations from the nominal geometry. In the initial production, a large fraction of magnets exceeded the production tolerance (a third in sector 8-1 and half in sector 7-8). If blindly installed, this would have led to a loss of mechanical aperture estimated to be in the range of 1.5 mm. This situation is now stabilised, but meeting the tight tolerances established for alignment, field quality and quench level remains a challenge. Table 1 reports the standard deviations of the b_1, a_2 and b_3 errors at nominal field in the four sectors, which are completely allocated. While the situation for b_1 is relatively safe, the spread of a_2 and b_3, especially in sector 7-8, required sorting to prevent a loss of dynamic aperture (estimated ~ 1 σ), scaling from the result of the tracking simulations reported in [4].

Table 1: Standard deviation of field errors at nominal current, dipoles allocated in 4 sectors, [units @ 17 mm].

	3-4	4-5	7-8	8-1
b_1	4.4	5.2	6.0	4.7
a_2	1.0	0.8	1.2	0.8
b_3	1.4	1.1	1.7	1.3

So far the sorting has been very effective. We anticipate that there will be no aperture limitation in dipole locations. At the same time, the field errors should be compensated by the pairing schemes to reduce the effective random in the installed accelerator by a factor 2 to 3, thus reducing strongly coupling and vertical dispersion (related to random a_2) as well as resonance driving term (related to the random b_3)

CONCLUSIONS

The magnetic field quality is excellent but more extended tests are essential for dynamic effects and hysteresis studies. The beam aperture appears well under control with deviations of the order of a few % of its nominal value. Quench performance is in general very good such that only a limited number (25 ± 6) of training quenches per octant is expected to occur during the LHC hardware commissioning. Magnet sorting is used to optimise average field quality and geometric aperture. The extremely good performance of the CMs as concerned vacuum tightness is to be remarked.

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