LHC DIPOLE AXIS, SPOOL PIECE ALIGNMENT AND FIELD ANGLE IN WARM AND COLD CONDITIONS

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Abstract

The installation and commissioning of LHC requires knowledge of the magnetic alignment of the spool piece correctors mounted on the dipole end plates are, as well as of the dipole main field direction. The installation is based on the use of geometric information derived from mechanical measurements performed in warm conditions, assuming that geometric and magnetic axes coincide, and that thermal contractions of the assembly are homothetic. A series of measurements has been performed at room and superfluid Helium temperature to validate these assumptions. In this paper, a statistical analysis of the correlations obtained is presented for both corrector alignment and main field direction, and the results are compared with beam optics-based specifications.

INTRODUCTION

The LHC superconducting dipole geometry is measured during manufacturing in order to control both the production quality and to check conformity to the machine requirements [1,2]. We pursue such task with tests beginning from the arrival at CERN of the cold masses until the last controls before the cryodipoles are transferred into the LHC tunnel in order to quantify further possible deformation and warm-cold correlation.

THE MEASUREMENT SYSTEM

The "AC mole" has been designed with the aim to measure in one operation the geometry of the magnetic field and the cold bore tube (CBT) with respect to an external reference system, with the aid of a LTD500® laser tracker [2].

The mole, shown in Figure 1, has a mechanically defined center where the three main sensors are precisely placed within a common cross-section plane to avoid any parallax errors. It contains:

1. A corner cube reflector centered in the mole
2. Four fixed tangential search coils
3. Four LED’s.

The mole can travel inside the CBT and be positioned at fixed points. It is oriented with respect to gravity by a motor. To know its position in space, a Laser Tracker is used. This device is a portable 3D measuring system, having a precision better than 50 microns or 10 ppm of the measured distance (at 2 σ). It sends a laser beam onto a Corner Cube Reflector placed at the point to be measured. The head of the Laser Tracker, source of the beam, is then oriented until the laser is reflected back to a detector.

To know the position with respect to the CBT the LEDs and a CCD camera installed inside the mole are used. The LEDs project light spots on to the CBT and the image of the light spots is analyzed by an image processing system.

The four tangential search coils measure the magnetic axis [3]. The magnet is powered with a small AC current and the voltages induced in the coils are synchronously detected. For a dipole, we excite the two poles in opposition instead of in series thus generating a skew quadrupole field, the so-called "Quadrupole-Configured Dipole" (QCD). See Figure 1 and 2.

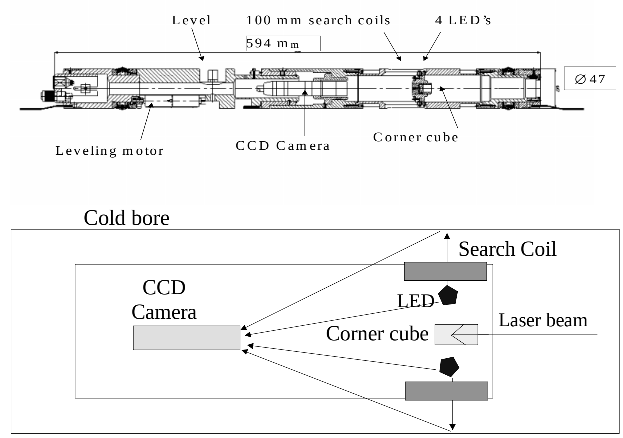

Figure 1: The design of the AC mole.

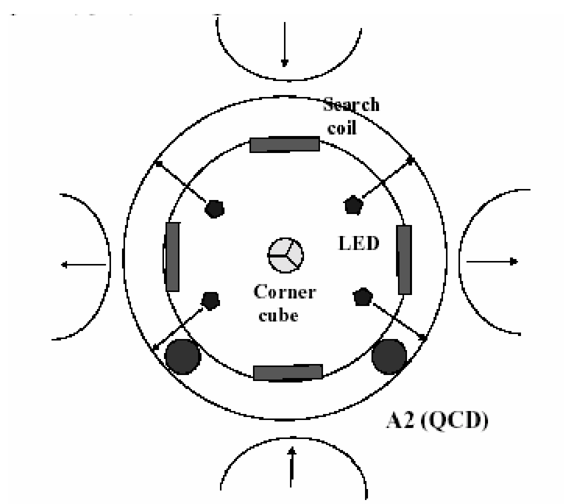

Figure 2: Cross section of the mole inside a Quadrupole Configured Dipole (QCD).

The same measurement system can locate the magnetic axis of any type of corrector magnets. This last measurement is the only method that is available after the cold mass assembly is completed to directly measure the spool pieces axis alignment with respect to the nominal geometry of the dipole.

The system can measure in two modes: the first is with the search coils in front of the magnet poles (the number of measurements depends on the number of poles under analysis); the second is with the search coils rotated at a series of 20 angles (per search coil, i.e. a total of

80 angles) such to reconstruct the magnetic sinusoidal signal around a rotation of the mole. A FFT analysis of such signal allows finding the magnetic axis as well. This harmonic based method has proven more accurate than the fixed angles one. The price to pay for it is a much longer testing time. Therefore the stationary method is used to measure the axis of the 15 m long dipoles, while the correctors are measured with the harmonic method.

The accuracy of the AC mole has proven to be of 0.04 mm for the corrector magnets and of 0.1 mm for the dipoles in QCD mode. This last value has been deduced from comparisons with other mechanical measurements systems. We assembled, a dedicated calibration bench to verify the accuracy of the harmonic method measuring the corrector axis. It is based on a naked corrector with accessible mechanical references. We proved that this measurement is insensitive to the relative position of the AC mole with respect to the corrector.

MEASUREMENT PERFORMED

The available data includes the measurements of both apertures of 48 LHC dipoles and 63 of the associated sextupole correctors (MCS) fixed to the dipole ends. These measurements were performed on cold masses before and after cryostating and after cold tests.

The data are expressed in terms of difference from the nominal sagitta in order to include in the same statistics the measurement with the dipole both at room and cryogenic temperature. A second degree polynomial fits the horizontal dipole curvature measured, such to realistically track the evolution of the sagitta.

The MCS alignment is expressed as the distance from its nominal position in the plane orthogonal to the dipole axis at the MCS longitudinal location.

DIPOLES MAGNETIC AXIS

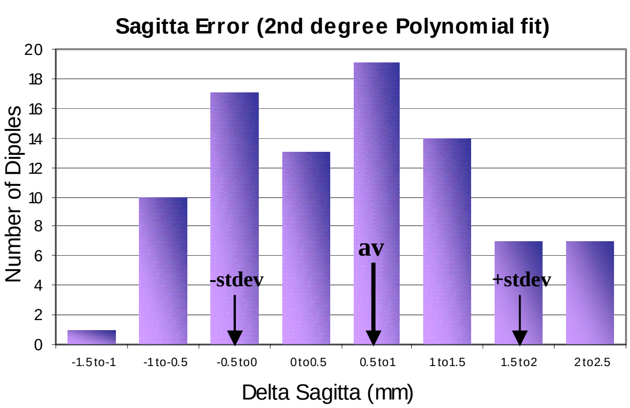

Figure 3: The distribution of differences between the measured and the nominal sagitta as measured in the middle of the dipoles. The arrows indicate the average and the standard deviation of the distribution.

The statistics for the sagitta shown in Figure 3 includes all the available measurements. This plot does not provide direct information about the deformation induced by particular steps of the cryodipole fabrication. Nevertheless its average value (av) of 0.7 mm and its standard deviation (stdev) of 0.98 mm are an indication of the difficulty to produce magnets of the dimensions of the LHC dipole with a stable geometry.

We make the assumption that the MCS position does not change with respect to the dipole ends between room and cryogenic temperatures.

Figure 4 gives the variation in sagitta measured between room and cryogenic temperature on a few dipoles. All these data are taken with the dipole installed in a bench, i.e. not moved between the two measurements. The only factor inducing a sagitta change is the variation of temperature from room temperature (warm) to liquid helium temperature (cold) or vice versa. From these few measurements the sagitta changes by at most +/- 0.8 mm. This value will be confirmed by more measurements.

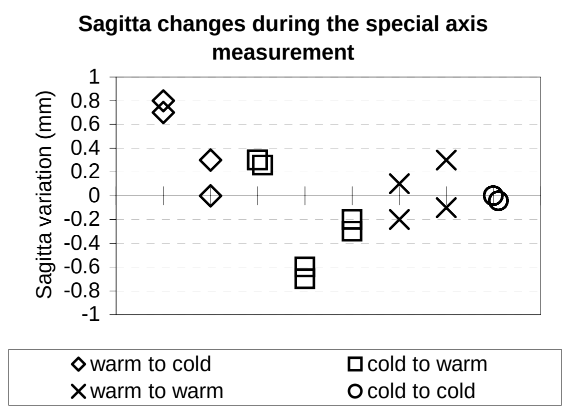

Figure 4: The changes in sagitta during cool-down and warm-up between room and liquid helium temperature, and also the stability across thermal cycles. Each of such changes is shown at each tick mark for both apertures; each marker type is relative to one magnet.

Also, in Figure 4 are shown the sagitta variation between two measurements at the same temperature and across a thermal cycle. The data available show a good stability of the dipole curvature in this case.

An exceptional case has been considered apart from the previous data. The magnet whose axis is plotted in Figure 5 suffered a very large change in sagitta, increasing in steps at each thermal cycle. The sagitta has changed always in the same direction for subsequent cool-down's and warm-up's collecting a total of ~4.5 mm. These changes did in fact correct the initial deformation with respect to the nominal sagitta as shown in Figure 5.

This last phenomenon has not been fully understood. Among the hypotheses we have supposed a change from the most natural shape due to transportation, cryostating or previous cold tests. The only certainty is that the unnatural shape has gone back to the nominal one after few thermal cycles. The mechanical behaviour of the magnets, shown in Figure 4 and 5, will be avoided by mechanically blocking the possibility of the central support post of the cold mass to slide in the horizontal plane, i.e. preventing any change in sagitta.

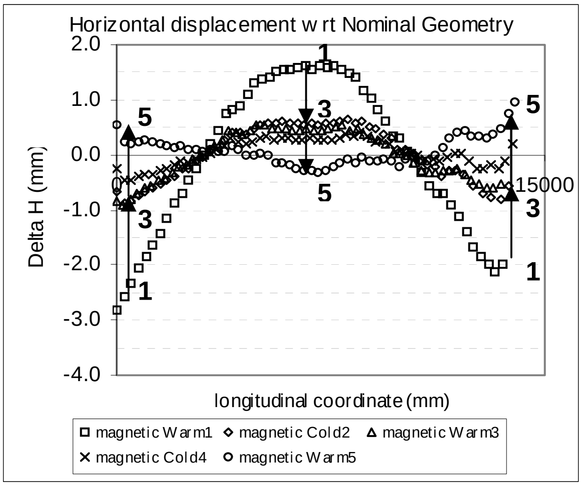

Figure 5: The changes in horizontal shape due to thermal cycles in a magnet that suffered from unexpected deformation before the cold tests.

MCS CORRECTOR MAGNETS STABILITY

The AC mole measures as well the magnetic axis of the MCS corrector magnets with respect to their theoretical position along the LHC beam trajectory. The position of the MCS with respect to the dipole geometry is linked to the sagitta of the dipole itself, confirming that the correctors do not move since assembly with respect to the ends of the dipole in both the vertical and horizontal direction.

FIELD DIRECTION

Considerable effort is spent at CERN to measure the integrated field direction of dipoles, which must be normal to the machine plane within a nominal tolerance of 1 mrad [5]. The direction is measured with a single stretched wire (SSW) system and a harmonic-coil scanning probe. The measurement is taken with reference to the cryostat fiducials and later referred to the mean plane of the cold mass, defined on the basis of mechanics.

Field direction has been measured so far in 70 dipoles. The results, taken at or extrapolated to 1.9 K, show an acceptable average and standard deviation of 0.1 and 0.8 mrad respectively, with small differences between manufacturers. A total of 16 apertures reach up to 1.5 mrad, while 3 more reach up to 2.0 mrad and 1 up to 2.7. Investigations are ongoing to understand the largest values, which are likely to be measurement artefacts. Further errors may be ascribed to mechanical instability of the cold mass inside the cryostat, which is estimated about 0.5 mrad RMS on the basis of geometrical surveys (fiducialization). Nevertheless, all out-of-tolerance magnets tested so far can be accepted, provided their allocation in the machine is suitably optimised.

Results also include the average parallelism between apertures (0.10 mrad) and the correlation between warm and cold measurements. This shows an unexpected offset of about 0.3 mrad, which however does not affect the overall conclusion.

Based on these results, the current baseline for field direction measurements includes warm measurements for all cold masses in the industry, systematically transferred to the cryostat via mechanical references on the end covers, plus spot checks at cold at CERN.

CONCLUSIONS

The "AC mole" allows to magnetically measure the sagitta of the LHC dipoles at both room and cryogenic temperatures. The measurements confirm geometric data based on the cold bore. A special campaign confirmed the accuracy of the measurement of the magnetic axis of the sextupole and decapole correctors mounted at the dipole ends.

The warm- cold correlation obtained for the field direction of the main dipoles is found acceptable to further limit the series measurements at room temperature.

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