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Warm and Cold Magnetic and Mechanical Alignment Tests of LHC Short Straight Sections

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Abstract

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***Abstract*—This paper contains a summary of the results of the magnetic and mechanical alignment tests performed at CERN on the first 111 arc Short Straight Sections. These include the mechanical axis of the Cold Bore Tube at room temperature, the magnetic axis of main quadrupoles and correctors at both room and cryogenic temperature, and the field direction of the main quadrupoles. The measurements show that the quality of the assemblies is generally within the requirements for the machine.**

***Index Terms*—Accelerator alignment, Large Hadron Collider, magnetic axis, magnetic measurements, superconducting quadrupole magnets.**

I. Introduction

THE Large Hadron Collider (LHC) being built at CERN will contain 360 so-called Short Straight Sections (SSS) in the arcs [1][2]. These assemblies of four twin-aperture Nb-Ti superconducting magnets include either an octupole (MO) or a tuning quadrupole (MQT) correctors, a main quadrupole (MQ), a normal (MS) or skew (MSS) sextupole corrector, and a dipole corrector (MCB). The cold masses work at 1.9 K and are built by Accel, like the MQs, while the assemblies are cryostated and tested at CERN.

The alignment of these magnets, defined in terms of the mechanical axis of the Cold Bore Tube (CBT) and of the magnetic axis of the multipoles (for an ideal multipole, the locus where the field **B**≡0), is a critical issue for the installation and the operation of the machine. This paper reports the results obtained on a first batch of 111 SSS measured with the techniques explained further on, which represent an extension of those already used to measure the alignment of LHC cryodipoles [3]. An example of actual measurement data is shown in Fig. 1.

Mechanical and magnetic requirements concern the offsets w.r.t. the so-called Geometric Axis (GA), i.e. the two straight lines representing the reference closed orbits of the beams as shown in Fig. 2. In particular, we should ensure that [4]:

R1) the CBT is mechanically straight within a racetrack tolerance centered on the GA and designed for compatibility with the dynamic aperture of the beam (±0.84 mm wide, ±0.31 and ±0.67 mm high at the center and ends respectively);

R2) the offset between average magnetic axis of all MQs and GA is less than 0.1 mm RMS (individual tolerance taken indicatively to be 2.5·RMS = 0.25 mm).

R3) the average magnetic axis of all multipole correctors is offset from the MQs by less than 0.2 mm RMS (indicative individual tolerance = 2.5·RMS = 0.50 mm).

R4) the average field direction in the main quadrupoles w.r.t. the mean mechanical plane of the cold mass does not exceed 0.5 mrad RMS.

Note that R1) applies to every point of the tube, whereas R2) through R4) apply to the integrated field (to which the beams are sensitive, since betatron wavelengths are large compared to magnet length). Also, the figures given are to be interpreted as desirable targets rather than contractually binding limits. Finally, items for which the tolerances are as wide as to not represent a real problem, such as the axis of the dipole correctors and the field direction of all correctors, shall not be discussed in this paper.

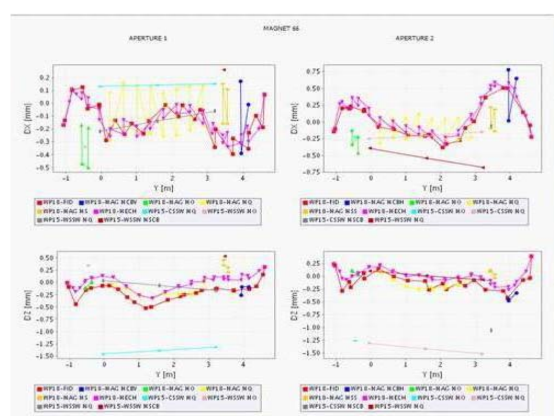

Fig. 1. Example of axis measurements results, as they appear in the on-line web database. The curves with one or three points represent integral SSW measurements; all other are obtained from mole scans. The zigzagging pattern results from the combination of scans started from both sides, and is a measure of the punctual measurement error.

II. Fiducialization

All results presented hereafter are expressed in the customary fiducialization frame (x, y, z), represented in Fig. 2, defined by a simultaneous least-squares best-fit of the GA in the (x, y) plane to the mechanical axis measurements in both apertures [5]. The x axis (transversal) points towards the

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centre of the LHC ring, while the y axis (longitudinal) originates at the end plate of the MQ and points towards the non-connection end.

In this reference system, which is materialized by three Taylor-Hobson optical targets (fiducials) placed on the cryostat, the cold GA can be found at x = ±97.00 mm. The total horizontal thermal contraction of the interaxis is 0.40 mm inside the magnets and 0.46 mm in the interconnection pieces.

An additional optimization step, consisting in a fine adjustment of the origin and orientation of the reference system, is applied before installation with the aim to ensure that requirement 1) is strictly satisfied, keeping at the same time magnetic offsets reasonably low [4].

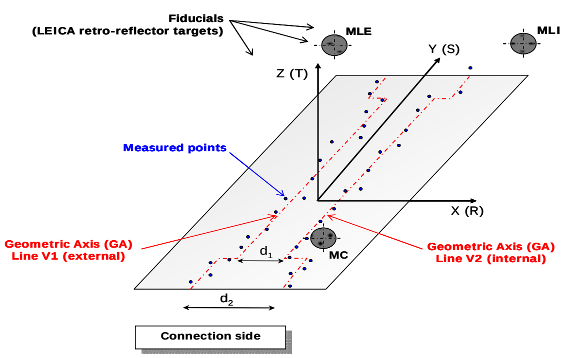

Fig. 2. Geometry for the fiducialization at 300 K.
Note that both GAs become straight parallel lines at 1.9 K.

III. Measurement Methods

In this section we describe briefly equipment and strategy for alignment tests. The overall accuracy of the quantities measured is given in Table I. All measurements are treated, validated and stored in a web-accessible database, from which they can be inspected for the final optimization and the installation stages.

A. Measurement of mechanical axis

Mechanical axis measurements are carried out at room temperature on 100% of SSS with two kinds of scanning probes (“moles”): the AC Mole [6] (so called as it is also able to measure magnetic axis with AC excitation), which provides the official results, and the Geometric Mole, which is used as a backup [5]. The AC Mole makes use of four 90°-spaced LEDs, casting projections onto the CBT, imaged by an on-board CCD camera to compute the local axis position as the center of the best-fitting circle. The Geometric Mole, on the other hand, is self-centred thanks to spring-loaded wheels. Both instruments are equipped with a retro-reflector that allows 3D position measurements with a LEICA® laser tracker, which are then related to the fiducials on the cryostat.

The two moles scan sequentially each magnet aperture twice, starting the scan from both ends. This strongly redundant scheme enables off-line detection of tracker alignment and horizontal calibration errors, avoiding the need to repeat a measurement when only one of the measurements fails (as was actually the case for 26 SSS out of 111).

The accuracy of the moles has been assessed in three different ways: by a) evaluating the difference between the two runs of each probe in the same aperture; b) comparing the interpolated difference between the results of the two probes at each point, and c) comparing the measured interaxis with the nominal value, assuming a negligible mechanical tolerance. A conservative estimate of the accuracy, giving very similar results for both instruments, has been obtained by taking the worst case among a), b) and c). The long-range precision of the laser tracker and the quality of calibration data and procedures have been found to be the main limiting factors for these instruments.

B. Measurement of magnetic axis

Magnetic axis scans are carried out on 100% of SSS at room temperature with the AC Mole, which provides official warm magnetic alignment results. Additional cold and warm tests are done with a Single Stretched Wire system (SSW), which provides integrated magnetic axis and field direction to be used as an independent basis for comparison, on about 10% of SSS [7].

The accuracy of the warm axis has been also assessed by evaluating the difference between two runs of the AC Mole in the same aperture. A cross-check with warm SSW results could be only carried out on a sample of 6 SSS and therefore the results, showing a systematic horizontal difference up to about 0.3 mm, cannot be considered conclusive. As no validated alternative for cold axis exists, the accuracy of cold SSW measurements has been taken however tentatively equal to the results of the warm cross-check. The figures obtained are similar to the standard deviation of the warm/cold correlation, which also can be considered as a measure of instrument errors assuming conservatively that thermal contractions are equal for all magnets (see §VII).

TABLE I
Estimated Accuracy of Axis Measurements (1 σ)

	Default system	Horizontal (mm)	Vertical (mm)
Mechanical axis warm (local)	AC Mole	0.20	0.17
Magnetic axis warm	AC Mole	0.26	0.10
Magnetic axis cold (MQ)	SSW	0.22	0.09
Magnetic axis cold (correctors)	SSW	0.16	0.30

Note: consistently with machine requirements, the accuracy of magnetic axes is referred to integral measurements over a whole magnet.

IV. Correlation of Magnetic and Mechanical Axis

A first indication on the quality of the assembly is given considering the relative position of mechanical and magnetic axis which, assuming symmetric coils, should coincide within the mechanical assembly tolerance. The results reported in Table II, relative to the subset of 93 SSS for which both measurements are available, show that the correlation is very good, with systematic and random errors below the estimated accuracy. However, local discrepancies up to about 1.2 mm are observed, which justifies *a posteriori* the choice of the mechanical axis as a basis for the fiducialization in order to satisfy the requirement on the physical aperture.

TABLE II
MECHANICAL ALIGNMENT OF THE CBT

Magnetic Element		Systematic (mm)	RMS (mm)	Min (mm)	Max (mm)
MO/MQT	Hor	-0.10	0.16	-0.84	0.70
	Ver	-0.02	0.17	-0.95	0.82
MQ	Hor	0.00	0.04	-0.62	0.47
	Ver	0.07	0.08	-0.31	0.57
MS/MSS	Hor	-0.03	0.19	-0.82	1.24
	Ver	0.16	0.25	-0.61	0.89

V. MECHANICAL ALIGNMENT RESULTS

The straightness of the CBT has been assessed for all 111 SSS using AC Mole results by default, except for 18 cases where results could not be validated (mostly due to calibration errors) and the Geometric Mole was used instead. A summary of the results is given in Table III, which shows shape errors about 0.2 mm RMS. While this figure is equal to the estimated accuracy for a single measurement, we believe that the instrument is capable to detect more precisely the deformation of the CBT on a length scale of a few meters. An indication in this sense comes from the interaxis, which is expected to be very close to its nominal value, and is indeed found to have a random error of only 0.12 mm.

Local measurements are found to exceed the racetrack tolerance in 52 SSS, by an amount which averages 0.11 mm and in 5 cases lies between 0.2 and 0.5 mm (further analysis is ongoing to make sure these outliers are not due to measurement errors). In the SSS installed so far, all non-conformities of this kind have been recovered with the opportune shifts and rotations at the final optimization stage.

TABLE III
MECHANICAL ALIGNMENT OF THE CBT

		Systematic (mm)	RMS (mm)	Min (mm)	Max (mm)
CBT	Hor	0.00	0.19	-0.78	0.73
	Ver	-0.01	0.21	-0.79	1.15

VI. MAGNETIC ALIGNMENT RESULTS

Average warm magnetic offsets have been computed for the 93 SSS for which magnetic scan results are available, as reported in Table IV. Considering first the MQ offset w.r.t. the GA we see that the RMS average over the whole set is close to the machine target of 0.1 mm, although the additional random effect due to the warm-cold correlation, if attributed to the magnets and not to the instrument, may aggravate the situation. We also find a small systematic offset, which can however be easily compensated by dipole correctors in the machine. The individual tolerance of 0.25 mm, which is exceeded in 6 magnets by at most 0.07 mm, can also be reduced at the final optimization stage if required.

The relative offset between correctors and MQ, on the other hand, is not affected in principle by the warm/cold correlation. The observed RMS average is well within the target of 0.2 mm, although a relatively large systematic error of 0.11 mm is found in the sextupole correctors.

TABLE IV
ALIGNMENT OF MAGNETIC ELEMENTS AT 300 K

Magnetic Element		Systematic (mm)	RMS (mm)	Min (mm)	Max (mm)
MO/MQT	Hor	-0.05	0.12	-0.62	0.58
w.r.t MQ	Ver	0.03	0.11	-1.55	0.31
MQ	Hor	-0.02	0.12	-0.69	0.45
w.r.t GA	Ver	0.02	0.10	-0.68	0.61
MS/MSS	Hor	-0.04	0.13	-0.70	0.68
w.r.t MQ	Ver	0.11	0.10	-0.49	0.90

VII. WARM-COLD CORRELATION

As the CBT is mechanically inaccessible for measurements at cryogenic temperatures, magnetic axis measurements are the only means to obtain an indication on the shape and position of the magnets at 1.9 K. Horizontal and vertical displacements have been obtained for 27 SSS and are plotted in Fig. 3, while a summary of the statistics is given in Table V. When available, the SSW has been taken as the warm magnetic reference, while the AC mole has been used in all other cases (the difference between choosing either is on average negligible).

The results indicate systematic thermal contractions very close to the expected values, i.e. zero horizontally and about 1.3 mm vertically for all magnetic elements. The random component of the correlation can be considered to be determined essentially by the uncertainty of the measurement, assuming that the contractions depend only upon the material properties of the steel structure and fibreglass posts and is therefore uniform and reproducible across the production.

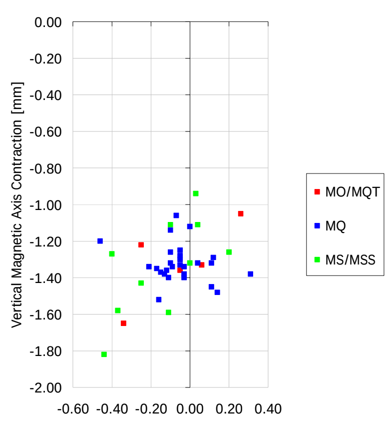

Fig. 3. Shift of the average magnetic axis of all magnetic elements in the (x,z) plane due to the thermal contractions from 300 K (represented by the origin of the axes) to 1.9 K.

TABLE V
WARM/COLD MAGNETIC AXIS CORRELATION

Magnetic Element		Systematic (mm)	RMS (mm)	N. of SSS
MO/MQT	Hor	-0.06	0.22	5
	Ver	-1.32	0.20	
MQ	Hor	-0.05	0.14	27
	Ver	-1.32	0.10	
MS/MSS	Hor	-0.14	0.21	10
	Ver	-1.34	0.25	

VIII. FIELD DIRECTION IN MAIN QUADRUPOLES

The field direction of MQs has been measured in 33 SSS with the SSW both at 1.9 and 300 K w.r.t. the mean plane of the cold mass, i.e. the plane (x,y) defined by the fiducialization. The accuracy of the measurement, estimated on the basis of theoretical analysis and repeatability tests, is about 0.2 mrad (standard deviation). The results obtained are plotted in Fig. 4, while the correlation plot is in Fig. 5 and a statistical summary is given Table VI.

The measured cold field direction has a standard deviation of 0.86 mrad, which exceeds the target of 0.5 mrad but can still be tolerated by the machine. The systematic value of 0.33 mrad, if confirmed by future measurements, can be easily compensated by skew quadrupole correctors. The average parallelism of the apertures, as expected, is of the same order of the accuracy.

The warm/cold correlation, established over a subset of 19 SSS, has an offset of -0.01 mrad and a slope of 0.98, consistently with the expected mechanical behaviour, and a standard deviation of 0.3 mm, comparable with the measurement error. This implies that warm measurements can be confidently extrapolated to 1.9 K.

TABLE VI
FIELD DIRECTION IN THE MAIN QUADRUPOLES

T (K)	Direction Average	Direction RMS	Parallelism Average	Parallelism RMS
300	0.33	0.71	0.07	0.23
1.9	0.20	0.86	-0.12	0.20

All values are given in mrad.

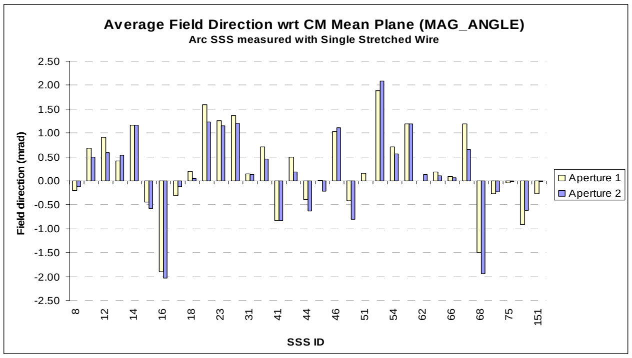

Fig. 4. Average field direction in both apertures of all 33 measured MQs at 1.9 K. Note peak values exceeding 2 mrad in some cases.

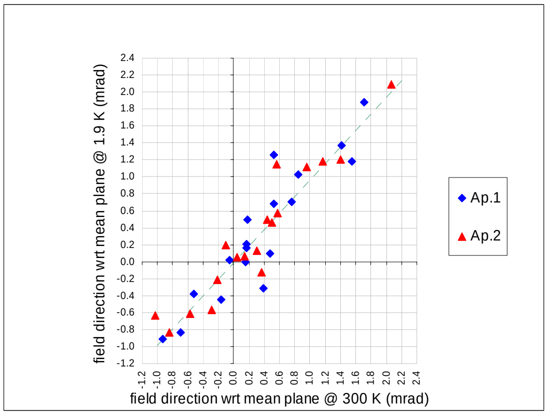

Fig. 5. Warm/cold correlation of field direction in 19 of the measured MQs. The correlation is very good also for values at the extremes of the range.

IX. CONCLUSIONS

The accuracy of the instruments used has been found to be generally adequate, although some aspects (e.g. the horizontal magnetic axis offset between AC Mole and SSW) remain to be clarified. An adequate follow-up of these measurements, including careful instrument calibration and data validation are mandatory.

The mechanical straightness of the CBTs is found to be on average very good, even if in almost 50% of cases small adjustments are necessary to avoid limiting the physical aperture for the beam.

The alignment spread of magnetic elements, on the other hand, is in some cases (field direction included) close to or beyond desirable limits. However, the possibility to: a) adjust individually the cryoassemblies with extreme deviations and b) draw on the margins built in the magnetic correction system leads to conclude that the SSS are compatible with machine requirements.

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