THE GEOMETRY OF THE MAIN DIPOLE

Elena Wildner, Jerome Beauquis, Giuseppe Gubello, Marco La China, Walter Scandale,
CERN, Geneva, Switzerland

Abstract

The main lines of discussion and analysis for the LHC dipole geometry are related to the shape of the cold mass at different stages of production and tests. The limitations in the stability of the cold mass shape induces constraints for the positioning of the spool pieces (feed down effects), for the flanges (interconnectivity) and the overall shape (aperture considerations). The geometry after acceptance in industry may change by the time of measurements at CERN. Tolerances that are needed by hardware and by beam physics will be reviewed.

GEOMETRY OF THE DIPOLE

The theoretical geometry of the dipole is shown in figure 1, and a table of some of the important parameters are given in table 1. The (x,y) plane is the plane of the accelerator. The two theoretical beam-trajectories (the two bent curves in figure 1) consist of an arc of a circle with the angle Θ and the radius ρ and of straight lines between magnets. The 3 dimensional measurements of the centre of the two cold bore tubes are fitted to the two theoretical curves. The plane obtained in this way is called the mean plane and the axes the geometrical axes.

Table 1: Dipole geometry parameters at room and operational temperature

Parameter	Symbol	Value warm	Value cold	Unit
Bending angle per dipole	Θ	5.0999988	5.099988	mrad
Magnetic length of each aperture	l_m	14.343	14.300	m
Radius of curvature	r	2812.360	2803.9281	m
Separation of tube centers	d	194.52	194	mm
Sagitta	s	9.143	9.116	mm

We are interested in the excursions of the cold bore tube relative to the theoretical shape, in the sagitta s, the positions of the spool pieces (MCS and MCDO), as well as the positions of the flanges and of the tubes at the plane C (connection side) and at the corresponding plane L at the non connection side.

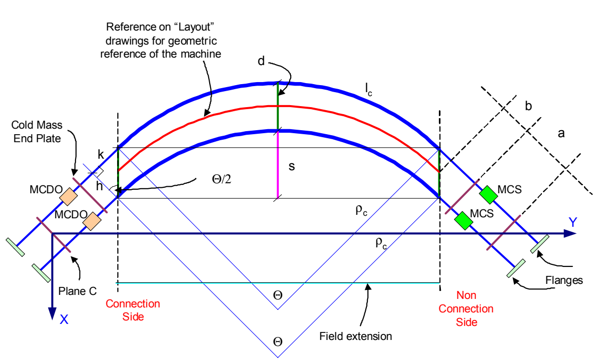

Fig. 1: Geometry of the LHC Dipole showing also the correctors at each side of the dipole

BEAM PHYSICS REQUIREMENTS

The tolerances required come from specifications on the LHC aperture, the tolerable feed-down effects from the magnetic part, the feed down from the corrector magnets at each end of the magnet in the cold mass assembly [1] and the restrictions on the interconnectivity.

The tolerances needed for the magnet to be installed are expressed in form of a race-track due to different tolerances in the horizontal and the vertical planes (figure 2) [5]. The tolerance after cold test is 0.75 mm in the vertical direction and 0.75 mm + 0.80 mm in the horizontal direction (smallest race-track). Some magnets with tighter tolerances are needed for some critical positions in the machine (rectangle). The magnets placed in mid half cell positions have relaxed tolerances (largest race-track). In figure 2 the tolerances required by beam physics and interconnectivity are shown.

The tolerance limit for the corrector position [1] is 0.3 mm, which corresponds to a standard deviation of 0.1 mm

The flanges should be within 0.87 mm at installation in the tunnel. This is estimated to correspond to 0.6 mm at the manufacturing stage.

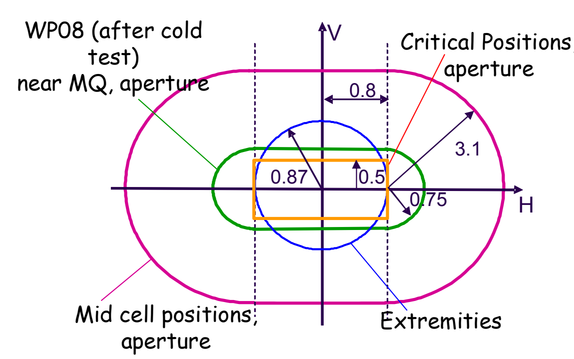

Fig. 2: Tolerances on magnets having passed cold tests (WP08). The coordinate system is defined from the best fit of the theoretical coordinate system using the measurement data.

AVAILABLE DATA

Table 2 defines the relevant measurement steps for the dipole geometry during its life cycle. There are two contractual measurements of the geometry in industry [3]: immediately after the welding of the shrinking cylinder around the yoke laminations (ITP15) and just before delivery to CERN (ITP20).

The measurements made at CERN [4] are included in Work Packages 01, 03 and 08. WP01 and WP03 do not always contain geometric measurements however at WP08 the measurement is compulsory. There may be measurements after WP08 to check stability during transport and storage at CERN. WP01 also contains magnetic axis measurements for some magnets.

Table 2: The measurement steps

Step	Test Performed
ITP15	Immediately after welding
ITP20	Before shipping
WP01	Arrival at CERN (geo and mag)
WP03	After cryostating
WP08	After cold test
WP08B	After transport and storage

EVALUATION CRITERIA

To be able to evaluate the quality of the geometry we consider the following criteria.

The position of the flanges used for interconnection of the magnets and the corrector positions are important. The corrector positions are not accessible after closing the cold mass so their position relative to the geometric mean plane is calculated using the fact that the corrector should move rigidly with the cold mass end cover since the corrector is welded to the cold mass end plate. Similarly the flange should move rigidly with the end cover. The standard deviation of the observed difference in movements of the flange and the end cover is around 0.1 mm.

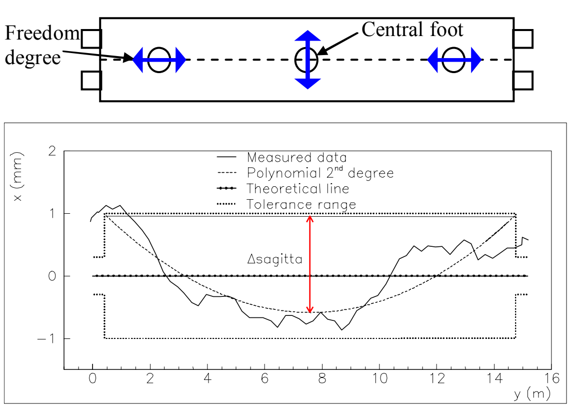

Fig. 3: Lower: calculation of the sagitta, upper: possible movements allowed by the cold mass supports in the cryostat.

We estimate the sagitta variation by using the fact that the difference between two arcs (the nominal and the measured) can be expressed as a second order polynomial. In figure 3 the nominal is the horizontal reference axis. We also look at the change in sagitta between different measurements enabled by the degree of freedom of the central foot. In this way we can estimate how the magnet shape changes with transport, cold test and storage.

Another criterion for evaluating the stability is to take the maximum of the difference between two measurements approximated by 10^{th} order polynomials and sampled every 0.1 m along the cold mass. The 10^{th} order polynomial was chosen as the lowest polynomial fitting the population within ±0.3 mm. The magnet is likely to be stable if the change in shape is less than ± 0.15mm corresponding to the Square root of the quadratic sum of the measurement errors.

RESULTS

Figure 4 shows the results of the calculation of the sagitta, using all measurements from industry, reception at CERN, cryostating and cold test. Not all magnets are measured at all these work-packages and therefore we can only show the results for a subset of the available data. These data also represent early production.

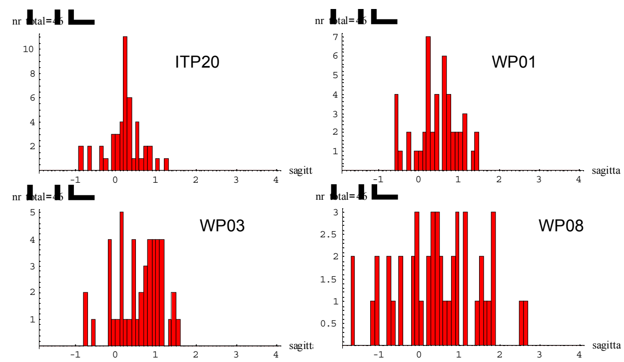

Fig. 4: The sagitta of magnets having been measured at all four work-packages, ITP20, WP01, WP03 and WP08

The same data is displayed as the mean value of the sagitta and the standard deviation in figure 5. We see here that the mean value and the spread of the sagitta increase with time.

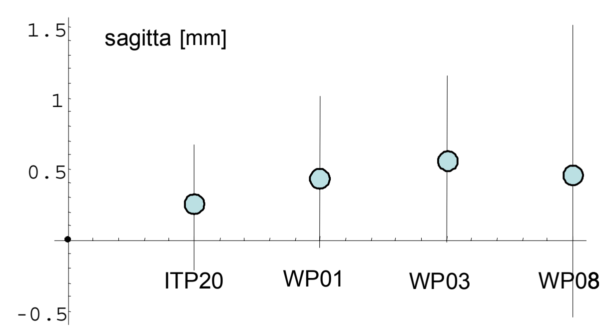

Fig. 5: The evolution of the mean value and the standard deviation of the sagitta for a population of magnets having been measured at all four packages.

If we take all measurement data from industry and after cold test, we have the largest population. Here the mean of the sagitta is –0.1 mm for industry with a standard deviation of 0.8 mm and after cold tests the data are 0.5 mm for the mean and 1.0 mm for the standard deviation.

Table 3: Measurements in industry and after cold test of the relative position w.r.t the theoretical of corrector magnet and flanges (328 magnets at ITP20 and 116 magnets at WP08)

	Measurement	Δx_{mean}	Δx_{rms}	Δz_{mean}	Δz_{rms}
Flanges	ITP20	0.01	0.10	0.03	0.11
	WP08	0.56	0.50	0.06	0.30
Sextupoles correctors	ITP20	0.0	0.01	0.01	0.20
	WP08	0.50	0.48	0.00	0.30

The corrector magnets and the flanges show a very similar behaviour due to the rigidity of the magnet end, see Table 3. We have chosen to represent the sextupole correctors as example.

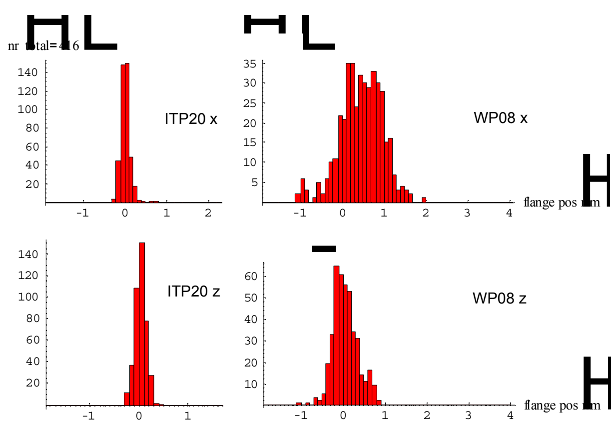

Fig 6 : The flange position, x and z for measurements at ITP20 and WP08.

If we look at each magnet individually and look at the evolution between ITP20 and WP08 we see that sagitta of most magnets increase (mean 0.7 standard deviation 0.6). This confirms the idea that each magnet tends to have an increase in sagitta.

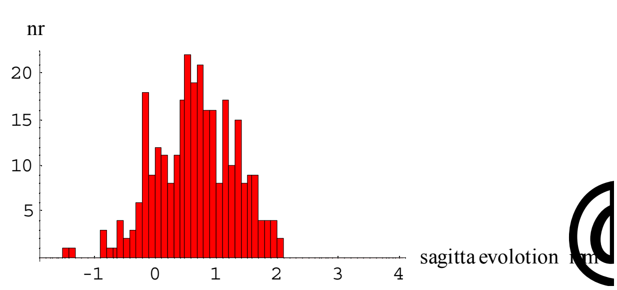

Fig 7 : Sagitta difference calculated for each magnet individually between ITP20 and WP08

Indeed the shape of the magnet changes with different operations like shipping to CERN, cryostating and cold tests. There are also examples of shape changes that are "spontaneous" or depend on transportation at the CERN site. Figure 8 shows this situation for a magnet which seemed stable up to storage. The measurements in industry and after cold test seem to confirm the stability of this magnet. However, after a check of the shape it can be seen that it has changed by more than 0.5 mm.

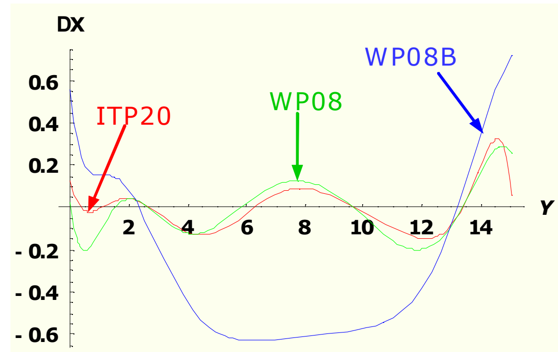

Figure 8 : "Spontaneous" change of horizontal shape during transport and storage at CERN (WP08B). The shapes are approximated using a 10^{th} order polynomial. The measurements are superposed at the horizontally fixed supports.

CONCLUSIONS

The magnets seem to have an intrinsic instability showing up as a tendency to increase their curvature (sagitta increasing) with time. The spread of the positions of the ends also increases which implies a change in the position of the correctors magnets. With the required tolerances these magnets need care to be accommodated in the LHC machine. There is also evidence that some magnets show unexpected shape changes.

Using the data collected at different stages of assembly of the cryo-magnet we cannot predict the behaviour of the magnet. Studies are on-going but there is no apparent reason in the assembly procedure that could explain this behaviour for the moment.

The magnet supports are designed toallow the cold mass to slide freely along the y-axis in the horizontal plane at the ends and horizontally in the middle (figure 3). To avoid unwanted changes of the magnet shape, it was decided to block the central foot in its position when it arrives at CERN (WP01). The trend in the sagitta that we have shown makes it necessary to carefully monitor the behaviour of all magnets after this blocking operation.

REFERENCES

[1] Field Quality Specification for the LHC Main Dipole Magnets, O. Bruning, S. Fartoukh, LHC Project report 501
[2] Geometrical Shape of the LHC Dipoles, G. Gubello, M. La China, W. Scandale, LHC Project report 673
[3] Metrology of the LHC Dipole Cold Masses, M.Bajko, A.Pardons, F.Savary, LHC Project report 538
[4] Dominique Missiaen, CERN, private communication
[5] Stephane Fartoukh, CERN, private communication