WHAT WILL THE GEOMETRY OF THE MAIN BENDS AND SHORT STRAIGHT SECTIONS (SSS) BE ?

E.Wildner

Abstract

We make a brief overview of activities related to the geometry of the main dipole and the main quadrupole. The blocking of the central support of the dipole has contributed to the stability of the cold mass in the cryostat. Work on the measurements of the spool pieces (magnetic and mechanic) has been carried out. Collection of measurements on the quad axis measurements in data bases has been made and a first report on these measurements can now be made. Work on the vertical alignment has given results for the position of the ends of the dipole.

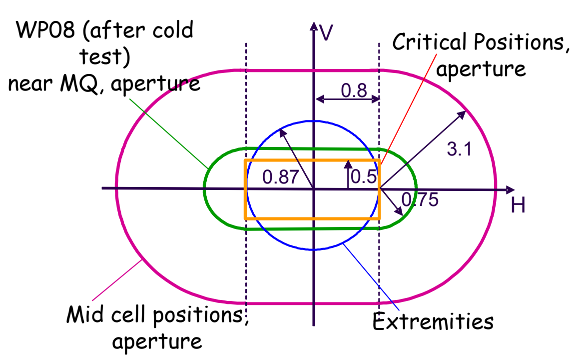
We will give a review of the results of the measurements and the analysis made so far: the shape (the axis), the interconnectivity and the spool piece positioning. We will also give some results for the cold warm relations. The effect on geometry of interconnection and the aperture and the feed-down related to shifts will be discussed. First results on the long term stability and related issues will be mentioned.

RECALL FROM "CHAMONIX XIII"

At "Chamonix XIII" we reported on the geometry of the LHC main dipole. A few important open points were addressed and we will give the status of those.

The tolerances have not changed since January 2004 and are shown in Table 1.

Table 1: Tolerances in LHC tunnel



The dipole" instability"

The instability of the shape of the magnet was one of the subjects to investigate and to remedy. In Figure 1 we se an example of a magnet (magnet number 3041) that was measured at CERN after cold test. This measurement showed that the magnet had a horizontal shape very much like the shape that was measured in industry (the red and the yellow curves in Figure 1). The magnet seemed stable. However after a measurement to check the situation [1], it was discovered that the magnet shape had changed considerably and that this shape change was confirmed by another two measurements (light and dark blue curves and light red curve in Figure 1).

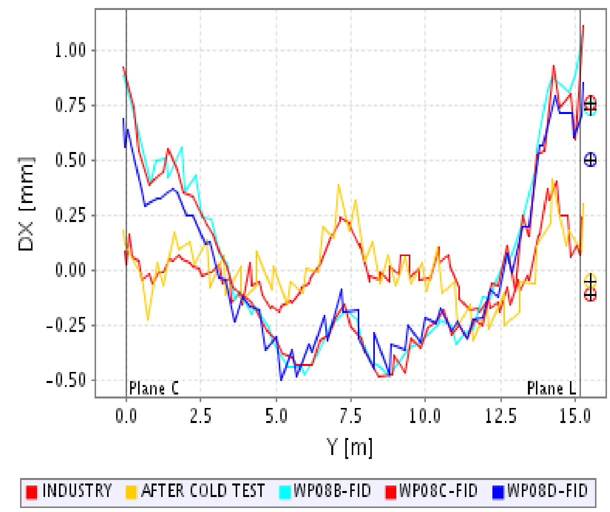


Figure 1: The shape changes of magnet 3041 The picture comes directly from a public (CERN) web tool to display all geometric measurements of a magnet.

The instability could be observed on many magnets. A workshop on the magnet stability was held in March 2004 and the outcome of this workshop was a new baseline: to block the magnet horizontally at the central support post [2] to try to avoid excursions of the magnet shape. The result is positive, see below for the results.

The position of the spool piece corrector axes

The second item that needed to be treated was the spool piece corrector positions for magnets at CERN. The mechanical axis of the spool pieces is measured at the manufacturer, when the end cover is not yet welded. No more measurement of the mechanic axis can be made. The magnetic axis of the spool pieces are only measured for a few magnets in the pre-series. To estimate the position of the spool piece axis we assume that the end part of the magnet is a rigid system and that the spool piece changes position in the same way as the reference points on the end cover of the cold mass. These estimations were compared with the limited data from the magnetic axis measurements and the correlation found was considered very poor (figure 2).

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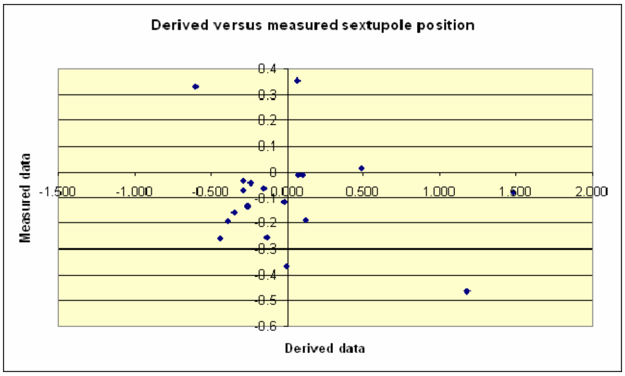

Figure 2: The relation between measured and estimated spool piece positions, horizontal plane.

A campaign was started to verify the measurements of the magnetic axis and the estimates from the mechanic measurements in industry. A test setup at CERN was used to verify the magnetic mole and the measurements of the mechanic position using a Leica. This test showed a relation between the mechanic and the magnetic postion of the test sextupolar spool piece centre not differing more than 0.15mm (two sextupolar spool pieces and two different measurement moles). The reference system is calculated from a complete mechanic measurement. With the conviction that mechanic and magnetic measurements are close, next step is to measure the magnetic sextupole axis on 5 finished cold masses and compare with the estimated values. This has to be done at the same time as the production fiducializations in SMI18 to make sure the reference system is calculated in a similar way as the one we use to estimate the sextupole positions from the measurements at the manufacturer.

Databases and software tools

A third point was to continue the work on the databases and the software tools needed for analysis and documentation. The data base for the dipole now contains all necessary information to trace measurements and important actions throughout production, like adjustments of the supports, blocking of the central support horizontally and other actions. It also contains all necessary information concerning the geometry to be used by TS/SU for the installation of the magnets in the tunnel (shifts to apply on the magnet for example). Uploads of the database are now done by the team responsible for the measurements (TS/SU) and a procedure has been introduced to make sure that the MTF and the database contain coherent information. The database for the quadrupole geometric and magnetic axis measurements (single stretched wire, magnetic and mechanical moles) is also finished. We still need the tolerances and some analysis work to be able to produce the complete documentation for the geometry of the SSS.

An important part of the documentation for the dipole has been used by the Magnet Evaluation Board. For each MEB, tables and plots are delivered to help the allocation of machine slots for the magnets. See figure 3 and 4.

Derived data - Jan 19, 2005 2:47:26 PM

MAGNET_NU	1004					
MAGNET_NAME	HCLBBR_000-CR001004					
RESHAPED	no					
STEP	ITP20-GEO		WP08-FID		WP08B-FID	
CLASS	silver right		silver left		mid cell	
APERTURE	1	2	1	2	1	2
STAGE	cold mass		cryomagnet		cryomagnet	
DSAGITTA	-0.743	-0.769	-1.979	-1.974	-0.687	-0.469
FIT_ERROR_ORDER2	0.303	0.306	0.291	0.272	0.302	0.305
MCS_DX	-0.123	-0.004	-1.357	-1.509	-0.512	-0.612
MCS_DZ	0.182	-0.064	0.476	0.302	2.066	1.668
MCDO_DX	-	-	-	-	-	-
MCDO_DZ	-	-	-	-	-	-
MAX_DX	1.002	0.744	0.977	1.003	0.89	0.73
MAX_DZ	0.519	0.413	0.631	0.606	2.13	2.18
MIN_DX	-0.791	-1.268	-1.668	-1.428	-0.77	-0.82
MIN_DZ	-0.826	-0.379	-0.455	-0.332	-1.62	-1.42
SHIFT_CFP_CONNECTION	0	0	0.255	0.099	-0.076	-0.037
SHIFT_CFP_LYRE	0	0	0.418	0.104	0.044	-0.097
DIFF_STABILITY_MAX	0	0	0.827	1.029	0.282	0.386
DIFF_STABILITY_RMS	0	0	0.533	0.538	0.06	0.098
TWIST_I0_SUM	0.045193		0.049188		0.051948	
TWIST_RMS	0.001527		0.001411		0.001519	
FLANGES CONNECTION SIDE						
DX	0.416	0.322	-0.929	-0.973	0.121	-0.034
DY	0.58	0.37	0.189	0.067	0.203	0.122
DZ	-0.065	-0.056	0.389	0.606	2.135	2.181
FLANGES LYRE SIDE						
DX	0.713	0.696	-0.521	-0.809	0.324	0.088
DY	-0.75	-1.25	-0.198	0.015	-0.162	-0.033
DZ	0.034	0.223	0.328	0.589	1.918	1.955
TWIST CONVOLUTION MAGNETIC ITP34						
APERTURE	1			2		
TWIST_INTEGRAL	-0.044186			-0.044928		

Figure 3: Plots of the shape and the classification used for aperture

Derived data - Jan 19, 2005 2:47:26 PM

MAGNET_NU	1004					
MAGNET_NAME	HCLBBR_000-CR001004					
RESHAPED	no					
STEP	ITP20-GEO		WP08-FID		WP08B-FID	
CLASS	silver right		silver left		mid cell	
APERTURE	1	2	1	2	1	2
STAGE	cold mass		cryomagnet		cryomagnet	
DSAGITTA	-0.743	-0.769	-1.979	-1.974	-0.687	-0.469
FIT_ERROR_ORDER2	0.303	0.306	0.291	0.272	0.302	0.305
MCS_DX	-0.123	-0.004	-1.357	-1.509	-0.512	-0.612
MCS_DZ	0.182	-0.064	0.476	0.302	2.066	1.668
MCDO_DX	-	-	-	-	-	-
MCDO_DZ	-	-	-	-	-	-
MAX_DX	1.002	0.744	0.977	1.003	0.89	0.73
MAX_DZ	0.519	0.413	0.631	0.606	2.13	2.18
MIN_DX	-0.791	-1.268	-1.668	-1.428	-0.77	-0.82
MIN_DZ	-0.826	-0.379	-0.455	-0.332	-1.62	-1.42
SHIFT_CFP_CONNECTION	0	0	0.255	0.099	-0.076	-0.037
SHIFT_CFP_LYRE	0	0	0.418	0.104	0.044	-0.097
DIFF_STABILITY_MAX	0	0	0.827	1.029	0.282	0.386
DIFF_STABILITY_RMS	0	0	0.533	0.538	0.06	0.098
TWIST_I0_SUM	0.045193		0.049188		0.051948	
TWIST_RMS	0.001527		0.001411		0.001519	
FLANGES CONNECTION SIDE						
DX	0.416	0.322	-0.929	-0.973	0.121	-0.034
DY	0.58	0.37	0.189	0.067	0.203	0.122
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DY	-0.75	-1.25	-0.198	0.015	-0.162	-0.033
DZ	0.034	0.223	0.328	0.589	1.918	1.955
TWIST CONVOLUTION MAGNETIC ITP34						
APERTURE	1			2		
TWIST_INTEGRAL	-0.044186			-0.044928		

Figure 4: A dynamically created .pdf file can be created at any time for any magnet in the database. Available on the web.

WORK ON THE SHAPE

The model

The difficulty to disentangle the intrinsic shape changes of the dipole from shape changes coming from positioning lead us to use a mechanical model of the dipole [3]. This model is based on an analytical approach, a mechanical beam with a flexural rigidity of 180 MPa m^4. This value is an estimated mean of the flexural rigidity, it varies slightly from magnet to magnet and this we do not take into account. The supporting does not constrain the magnet (no moments imposed).

An example of the use of the modelling programs can be seen in figures 5 and 6. In figure 5 we see two measurements made at different occasions with different supporting. We want to know if the magnet has been deformed. By simulating similar supporting for the two measurements we can check this (figure 6). For this particular case the magnet shape is the same.

Figure 5: Two measurements at different occasions of the same magnet being supported in different ways.

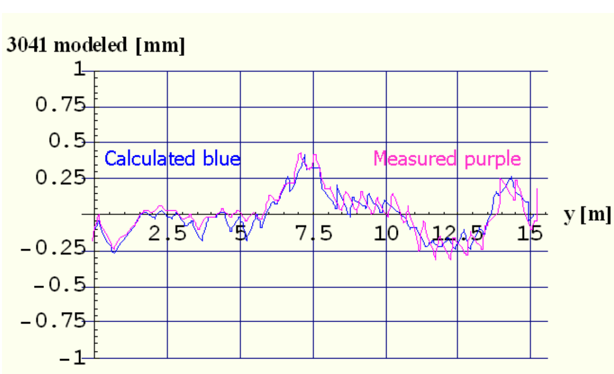

Figure 6: After simulation of similar supporting for the two measurements we can see that this magnet did not undergo significant changes of the shape.

Vertical positioning or local deformations

In figures 7 and 8 we show in one case a magnet where the ends (flanges) in the vertical plane are at a different position at the measurement in industry and at the measurement at CERN. To be able to distinguish all those magnets having local deformations, the magnets are, by simulation, supported in a similar way for the measurement in industry and for the measurements at CERN.

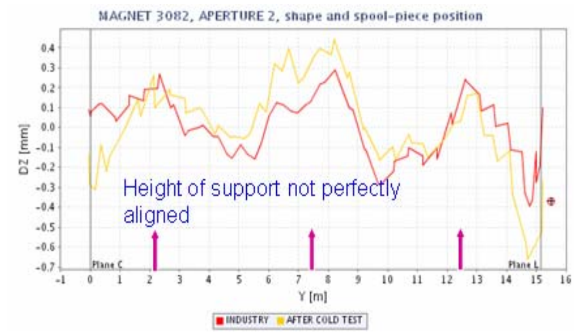

Figure 7: Example of a magnet where the flange position is different between the two measurements, industry and CERN. In this case the reason is different supporting.

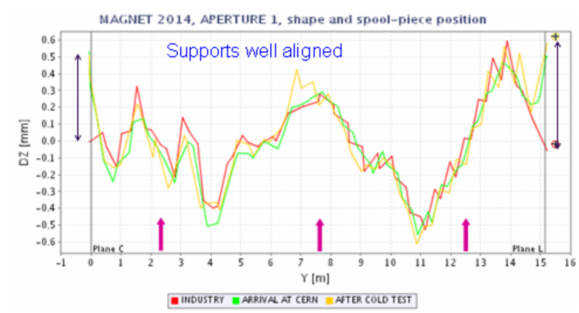

Figure 8: Example of a magnet where the flange position is different between the measurements, industry and CERN. In this case the reason is a deformation of the end or a measurement problem in industry (two measurements showing similar results are made at CERN, green and yellow curves).

Statistics from October shows that the vertical movement of the ends between measurements in industry and measurements at CERN, in particular for Firm 2, are significant. See figure 9.

If we simulate the positioning for all magnet measurements at CERN so that it corresponds to the positioning at the measurement in industry and plot a histogram of the result (see figure 10), it is clear that for Firm 2 we have two overlapping distributions. The time dependence is shown in figure 11, where a moving average of 15 magnets plotted every 5 magnets is shown. For recent production the effect is no longer present and the mean value of the difference in the flange position between measurements at CERN and in industry is now close to zero.

We still have to monitor the spread of the vertical flange position for Firm 2.

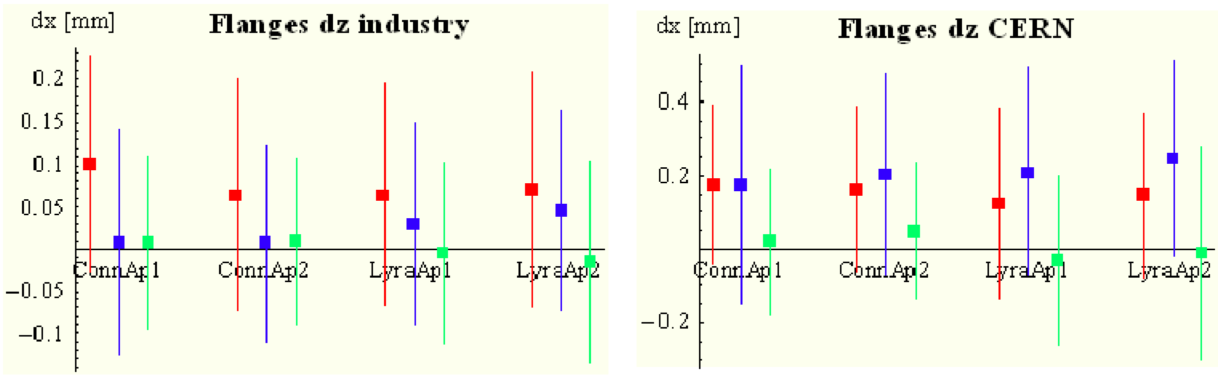

Figure 9: Statistics from October: we see that the flange position for, in particular, Firm 2 moves considerably between industry and CERN (mean 0.2 mm). Square represents mean value, line represents the standard deviation. Red, blue and green represent Firm 1, 2 and 3 respectively.

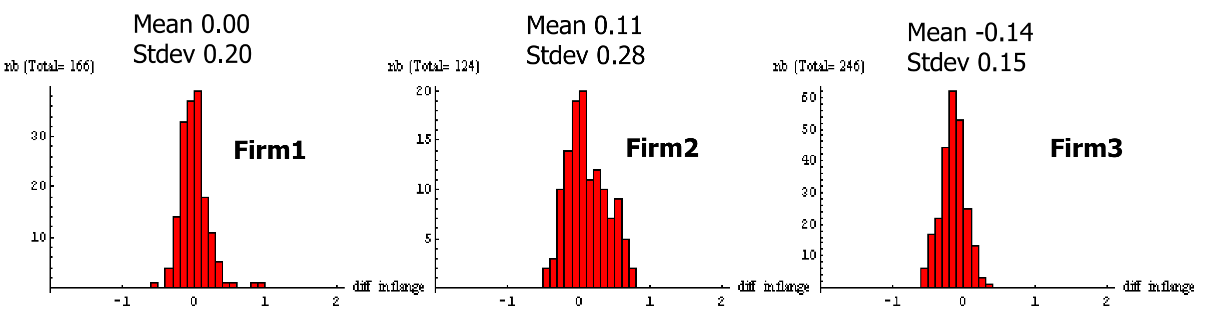

Figure 10: The difference in flange movement between industry and CERN. We can observe an overlapping distribution for Firm 2.

Figure 11: Moving average of the difference in vertical flange movement, 15 magnets plotted every 5 magnet. The flange movement for Firm2 is close to zero for recent production. Horizontal axis

Horizontal movements

In figure 12 we show statistics from October, when this study was made, where we can detect a horizontal movement of the flanges between measurements in industry and measurements at CERN after the central support has been blocked and the magnet has been adjusted towards its shape in industry. The criterion used to block the magnet horizontally is to minimize the difference in sagitta between the measurement in industry and the measurements at CERN. We first check that this adjustment procedure gives what we expect by calculating the difference in sagitta between industry and CERN measurements (figure 13). From this we conclude that the reason is not coming from the adjustment procedure; the mean value is close to zero.

The reason for the horizontal shape change is rather the fact that the sagitta change of the magnet can be detected also after the blocking of the central support (see figure 14, where the situation is shown for one typical magnet, 1046). This is explained by the fact that if the magnet changes from one circular shape to another circular shape, this difference cannot be reduced completely by applying one point force on the central support. A simple simulation of this is shown in figure 15. Correction of this effect on the flange positions is now being done at the blocking procedure (the mean value of all flange movements will be corrected at the blocking).

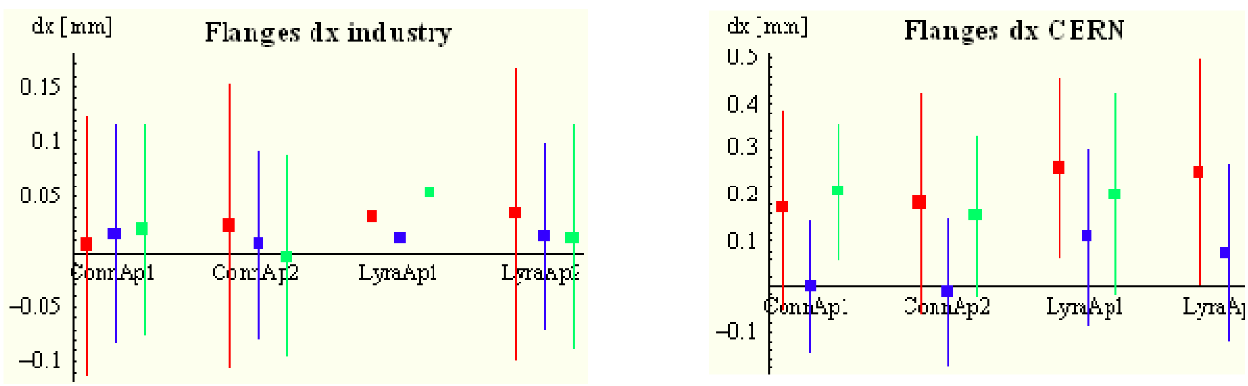

Figure 12: Statistics from October: We see that the flange position for, in particular, Firm1 and 3 move between industry and CERN (mean around 0.2 mm). Square represents mean value, line represents the standard deviation. Red, blue and green represent Firm 1, 2 and 3 respectively.

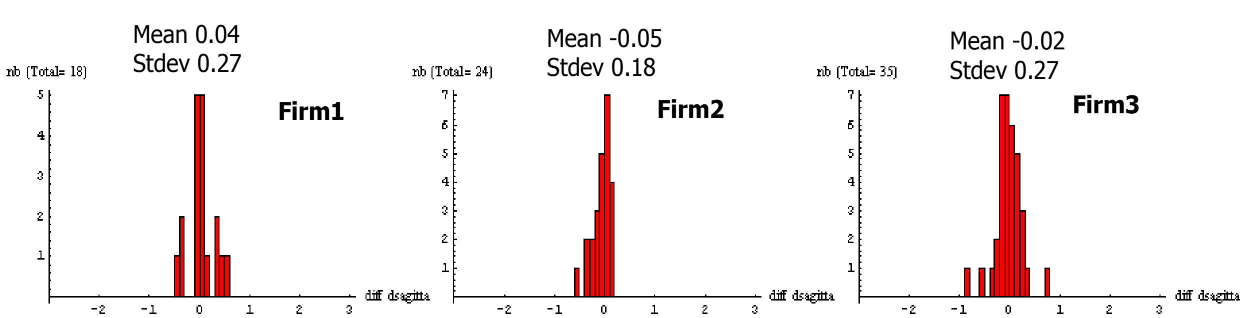

Figure 13: The difference in sagitta between industry and CERN. The mean value is close to zero.

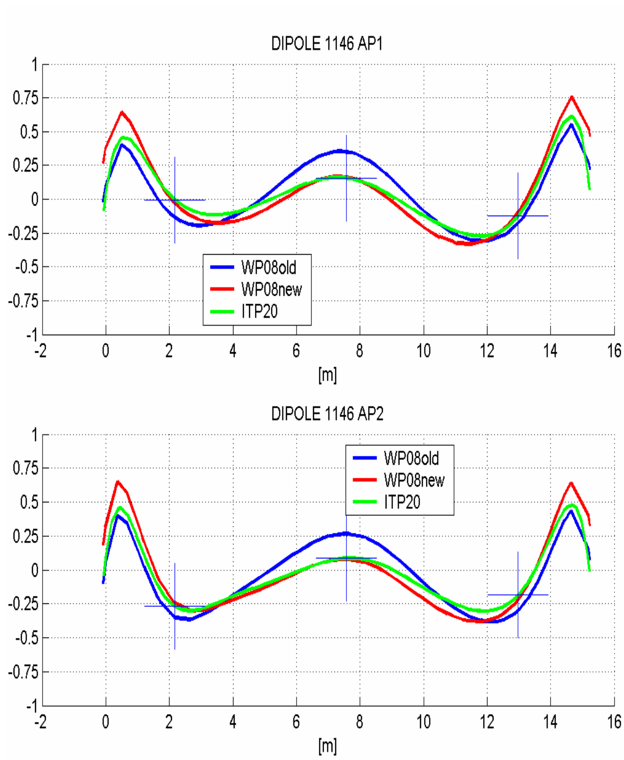

Figure 14: The effect of the sagitta increase of the magnet. The measurement at CERN (WP08old) has been adjusted to the supports at the measurement in industry (ITP20) and the result is the curve WP08new. We can detect the increase of the sagitta on the two lobes by comparing WP08new and ITP20. Abscissa along the magnet, ordinate is the horizontal position w.r.t. nominal.

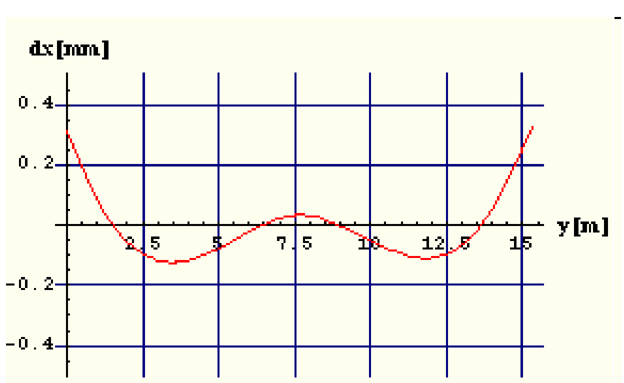

Figure 15: Simulation of a circular shape of 1mm sagitta being corrected to identical positions on the supports by a point force applied at the centre. If we arrange such that the integral of the resulting curve is zero (adjustment to the theoretical mean, or the “geometric axis”) the result can be detected as a residual at the ends of the curve. dx is the horizontal displacement and the y represents the ideal magnet axis.

RESULTS FROM STATISTICS

The shape

In figure 16 we show the situation of today for the sagitta in industry. In figure 17 we show the situation for the magnets at CERN having the central support blocked to the situation in industry. The mean values are close to zero and the spread is similar for the measurements in industry and the measurements at CERN. This means that the blocking procedure, using the sagitta as criterion, is good. For comparison the situation before the central support was blocked (March 2004) is shown in figues 18 (industry) and 19 (CERN). Here we can clearly see that the sagitta tends to increase by more than half a millimetre from industry to CERN measurements. We may in the future, due to the residue of the sagitta at the ends, need to use the criterion of putting the flange position to the same as industry instead of putting the sagitta to the same as in industry.

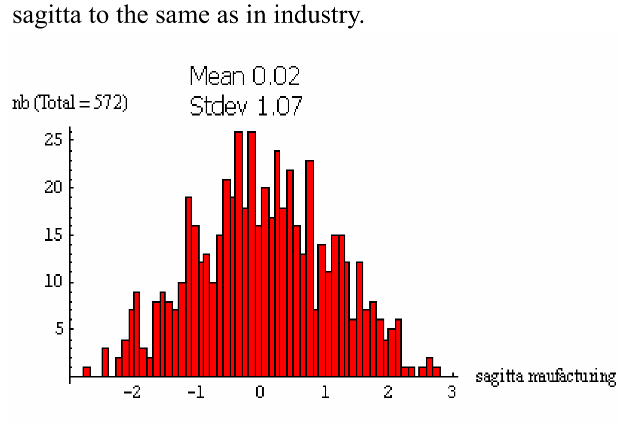

Figure 16: The sagitta in industry, January 2005

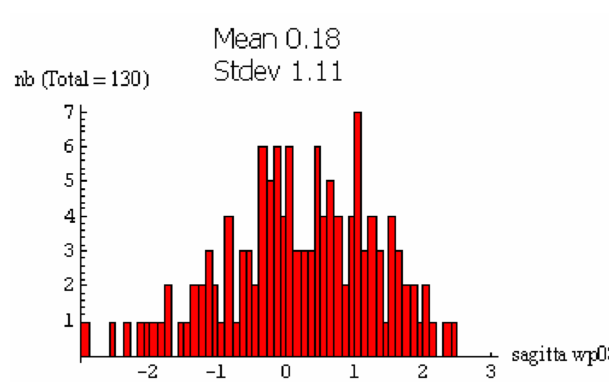

Figure 17: The sagitta at CERN, central support blocked and adjusted to give a similar sagitta as in industry, January 2005

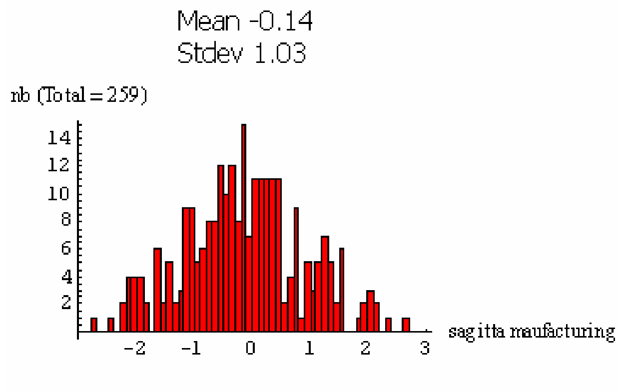

Figure 18: The sagitta in industry, March 2005

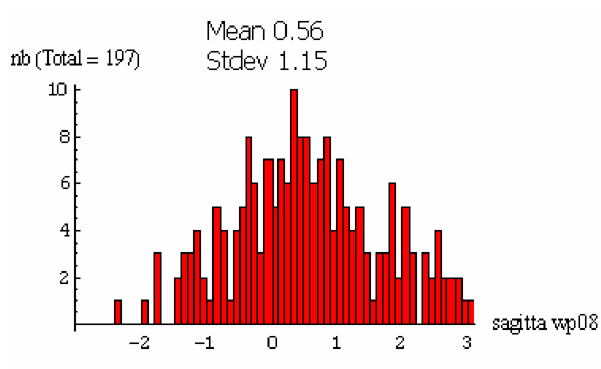

Figure 19: The sagitta at CERN, magnets not blocked, March 2005. WP08 is the work-package at CERN in which the measurement is done.

To confirm that the sagitta is similar between industry and CERN measurements, we also look at how much each magnet moves from industry to CERN. In figure 20 we can see that the mean value of the sagitta change is zero, which is the goal. The spread is due to measurement errors on the shape, the calculation of the sagitta, limits of the tolerable sagitta change and uncertainties in the blocking procedure.

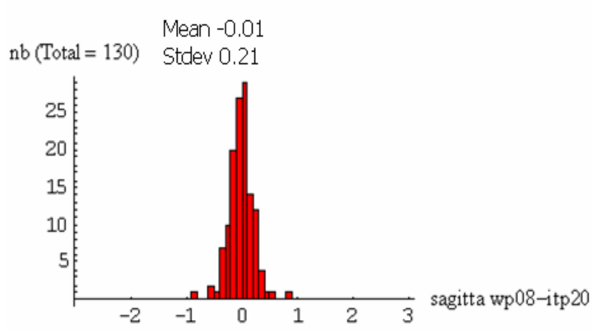

Figure 20: The sagitta is the same in industry (itp20) and at CERN (WP08).

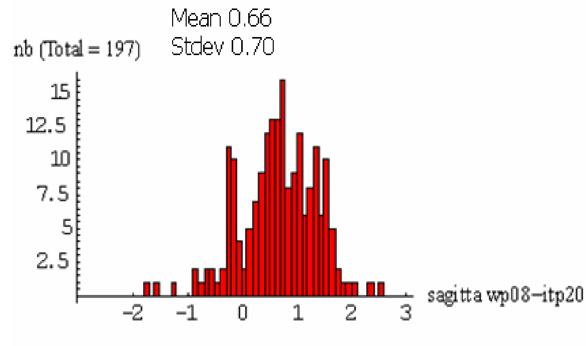

Figure 21: The sagitta change from industry to CERN before the central support was blocked.

The spool piece correctors

In figure 22 and 23 the position of the sextupolar spool pieces with respect to the ttheoretical geometric axis of the magnet. The tolerances for the correctors are 0.3 mm for the mean deviation from the theoretical axis and the spread is 0.5 mm. The bias of 0.15 mm comes from the fact that the sagitta change with respect to the nominal sagitta cannot be totally reduced by using the sagitta as blocking criterion. This residual will be compensated for in the future.

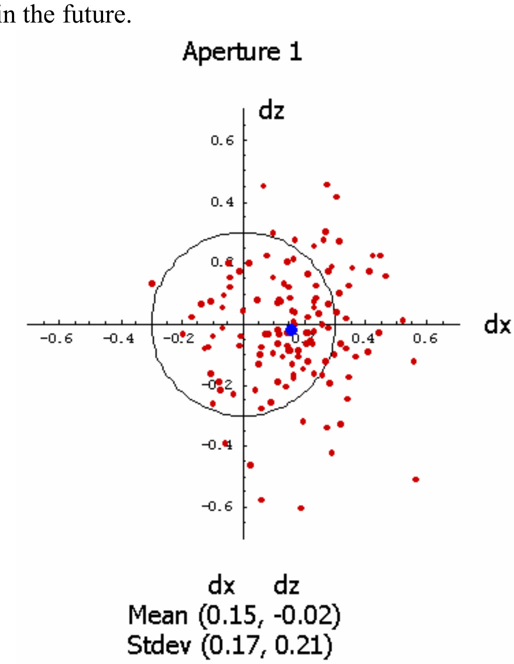

Figure 22: The sextupolar spool pice position at CERN, aperture 1.

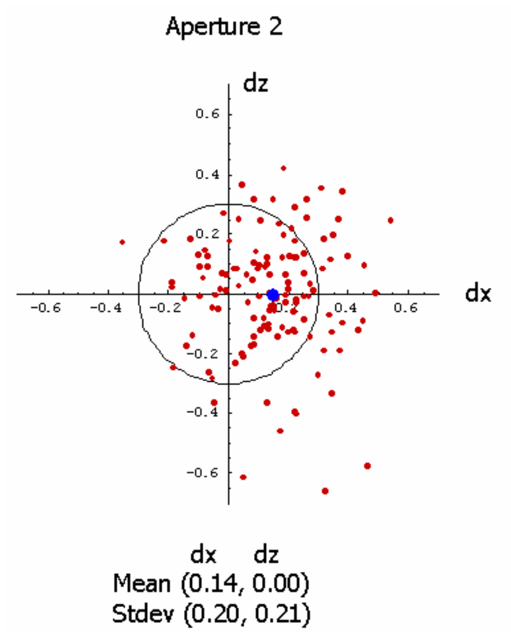

Figure 23: The sextupolar spool piece position at CERN, aperture 2.

The interconnectivity and the shifts

The positions at CERN of the flanges for the interconnection of magnets are shown in figures 24 and 25. With a few exceptions the tolerances are respected.

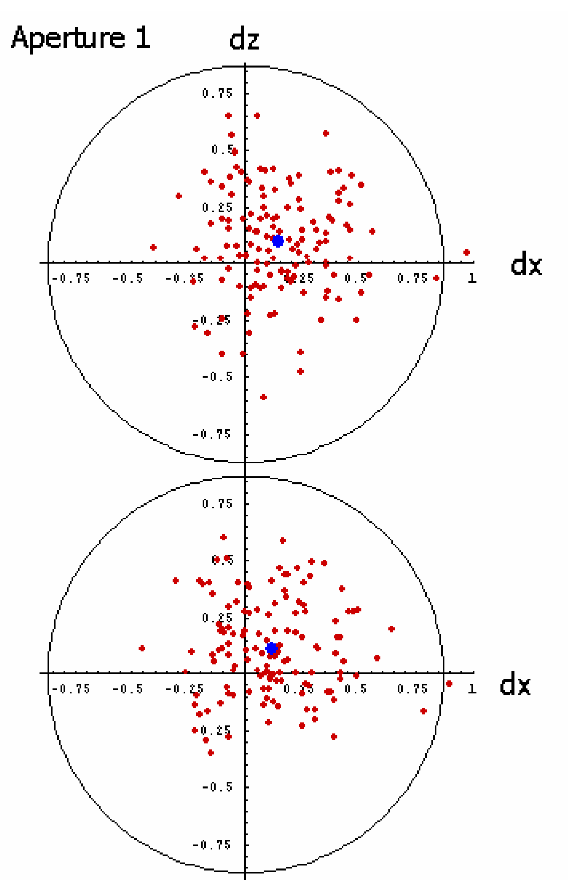

Figure 24: The effect of the sagitta increase of the magnet. The measurement at.

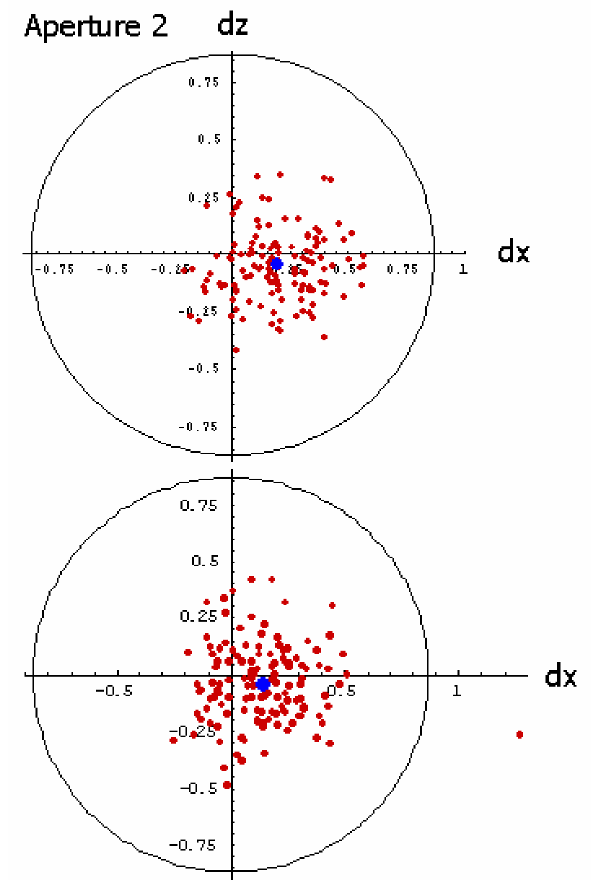

Figure 25: The effect of the sagitta increase of the magnet. The measurement at.

Magnets can be shifted a small amount without harm (feed down effects of spool piece magnetic field, aperture consideration) to allow beam tubes and service lines into tolerances. This has been done for very few magnets, see table 2. The reference measurement is the measurement that should be used for installation in the tunnel.

Table 2: magnet shifts

magnet	Reference meaurement	dx	dz
2012	WP08C	0	-0.2
2017	WP08C	0	-0.2
2018	WP08E	0	-0.1
3002	WP08E	0.45	-0.4
3009	WP08C	0	-0.2
3050	WP08C	0.2	0
1053	WP08D	-0.4	0

THE SSS

The measurements of the SSS geometry has just been loaded into the MAS geometry database and analysis of these data for use to quantify the geometry of the assembly has very recently started. Measurements have to be certified and the tolerances for the assembly have to be expressed in a way to be directly compared to the measurement data. We also need to establish tolerances for the beam to be able to adapt the software for geometry classification and certification.

The first measurements (14 SSS) show that there is an offset between the measurements using the AC mole and the stretched wire at room temperature of 0.1 mm in the horizontal plane (MQ). In the vertical plane the offset of 0.2 mm seems to be due to some outliers (figures 26 and 27). Two adjacent points in the figures correspond to the two apertures of one magnet.

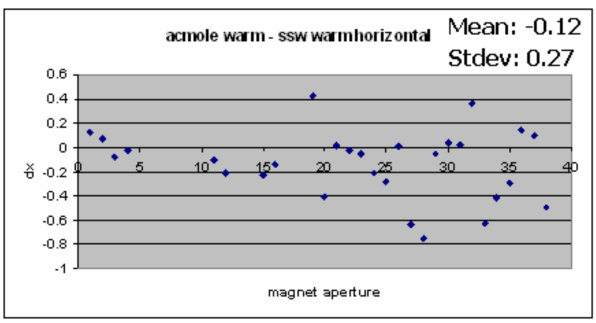

Figure 26: Comparison of measurements with AC mole and SSW at ambient temperature, horizontal plane (MQ). Units are mm.

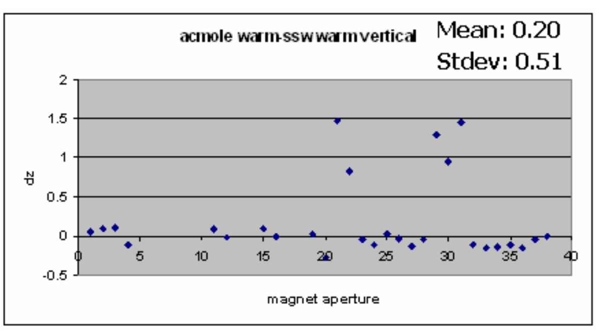

Figure 27: Comparison of measurements with AC mole and stretched wire at ambient temperature, vertical plane (MQ). Units are mm.

If we look only at the measurements of the MQ axis with respect to the geometric mean plane of the whole SSS assembly at room temperature, we find a few values which need special attention (values below -0.5 mm horizontally and more than 0.8 mm vertically). See figure 28 and 29. The geometric axis of the MQ assembly shows large variations and the position of the corrector magnets show very large value for some measurements (~10mm). A campaign is needed to disentangle measurement errors from assembly problems and to finally, after this study, give a statement on the geometry of the assembly.

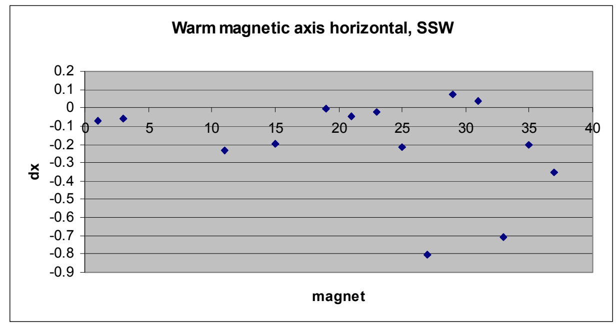

Figure 28: The magnetic axis of the MQ, measured with the stretched wire at ambient temperature. Mean between the two apertures, horizontal plane.

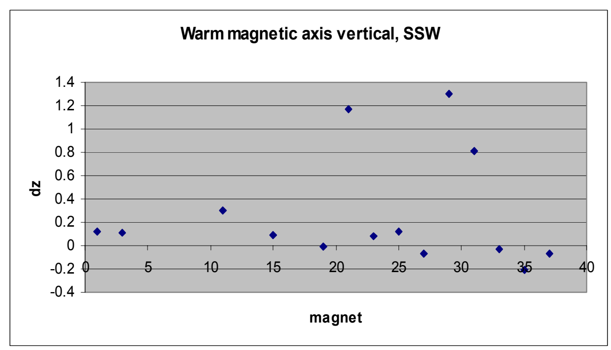

Figure 29: The magnetic axis of the MQ, measured with the stretched wire at ambient temperature. Mean between the two apertures, vertical plane. Units are mm.

COLD WARM RELATIONS

A summary of the present results is shown in table 3, where we can see that for the horizontal plane the mean value is close to zero and we also see that in the vertical plane, with respect to an external reference, the fiducials, we have a shrinkage of the assembly corresponding to an axis change of -1.34 mm if we take out probable outliers. The data is displayed in figures 30 and 31.

Table 3: Cold warm relation of MQ magnetic axis. Values without obvious outliers are shown in parenthesis.

	Cold-warm ssw dx [mm]	Cold-warm ssw dz [mm]
Mean	-0.09	-1.51 (-1.34)
Stdev	0.22	0.43 (0.12)

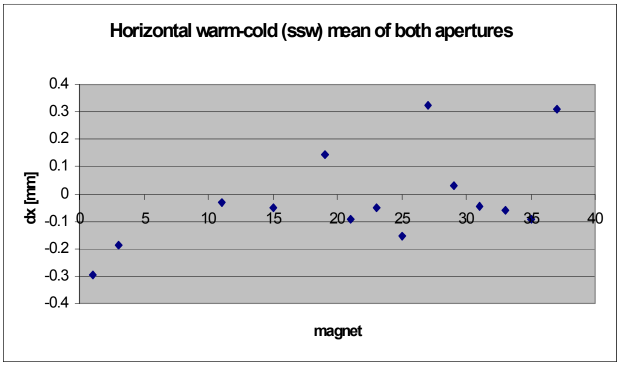

Figure 30: Warm-cold relation of the MQ axis in the horizontal plane, mean of the two apertures.

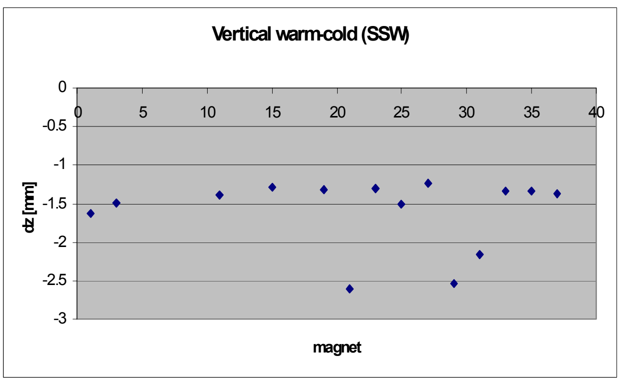

Figure 31: Warm-cold relation of the MQ axis in the vertical plane, mean of the two apertures.

THE STABILITY

The long term stability of the dipole assembly in the cryostat can only be observed on the three reference points at the ends of the cold mass. The movement of the centre of these three points between measurements made at work packages 8 and 9 at CERN are shown in figure 32 for the horizontal plane. The average movement is 0.1mm which is interpreted as an increase of the sagitta that continues along the life of the magnet. The spread is not negligible (compare for example the shifts to get the magnet into tolerances, table 2). In the vertical plane the ends show smaller movement.

These movements have to be taken into account at the geometry classification (as an additional value to the tolerance) used for allocation of magnets into different positions in the LHC. What has also to be considered is the fact that magnets may continue to move once installed in the tunnel (we do not know yet what this movement comes from and studies are ongoing). Correlation between the sagitta change (that has been imposed on the magnet with the goal adjust as close as possible to the measurements in industry) and the movement has not been detected. We know that the sagitta increases continually and we can estimate maximum values for the movement. The critical magnets are the dispersion suppressors. Those magnets have a "golden" geometry which means that they are as close as possible to the sagitta in industry and a small sagitta change and consequently they have a large potential of sagitta increase (in the very long term). We can estimate a maximum effect on this and compare to machine tolerances (ongoing work).

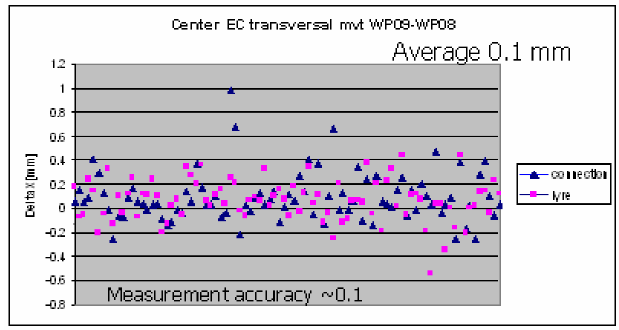

Figure 32. Movement of the reference points on the end covers of the cold mass

CONCLUSIONS

The blocking of the central support of the MB has been beneficial to control the magnet geometry and guarantee a good stability of the shape. However the sagitta change can be seen also after the blocking of the central support and gives a contribution to the movements of, in particular, the ends. This is closely monitored and can be, at least partly, corrected for by adjustments of the central support. The changes of the magnet shape at the last geometry measurement before installation (WP09) are non negligible and have to be considered in the future (contingency for tolerances and estimation of changes of the magnet shape in the tunnel). This also means that we control the interconnectivity and the position of the spool piece correctors. We however need 5 measurements of the spool piece magnetic axis with respect to the geometrical mean plane as measured by TS/SU to be able to confirm the method we use to estimate the spool piece position by calculation.

The MAS geometry databases for the MB and SSS are used in production for monitoring of the geometry and for the allocation of magnets in the LHC "slots". The measurement data for the SSS (MQ and correctors) still need to be certified. The database is being extended to all geometric measurements of all magnet assemblies. It contains all magnet geometry data necessary for installation in the tunnel. Tools for viewing of data are available. A campaign for validation of the quadrupole geometry data is needed.

Warm cold relations still have to be established for the MB and confirmed for the SSS. This point is crucial for magnet installation in the tunnel.

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