THE ALIGNMENT OF THE LHC

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Abstract

The Large Hadron Collider (LHC) has been aligned using both classical and non-standard techniques. The results of these alignments were seen on September 10th, 2008 when the beam made several turns in the machine with very few correctors activated.

This paper will present the different steps of the alignment as well the techniques used to obtain the alignment accuracy required for beam operation. The correlation of these results with the position recorded by the beam position monitors (BPM) will be presented.

THE GEODETIC NETWORK

The geodetic network is composed of about 500 points sealed in the floor. Their position was determined from the alignment of the main quadrupole magnets (MQ) of the Large Electron Positron Collider (LEP), which was in operation between 1980 and 2000 and located in the same tunnel as the LHC. The MQ position was:

- determined initially from a surface network of geodetic points using GPS, their co-ordinates being transferred to the tunnel via eight civil engineering shafts and propagated on tripods along the tunnel.
- gradually improved during the LEP shut-downs and their position in 2000, before its dismantling, was considered by the Survey team and the physicists as the best that could be achieved and therefore a good reference for the alignment of the LHC.

Levelling measurements, horizontal angles, offsets with respect to a stretched wire, gyroscopic measurements as well as mekometer range-finder were combined and compensated using the least square method in order to determine the co-ordinates of the LHC geodetic network.

The absolute 1 σ accuracy of the geodetic points in X and Y is considered to be ±2 mm for points close to the shafts and ±4.5 mm for ones located in the middle of two shafts. In the Z direction, the 1 σ accuracy is ±2 mm.

Eight deep references have been anchored in the rocks 20-25 m lower than the tunnel level and are located very close to each sector extremity. They provide stable references during levelling measurements. Their first height determination was performed during the complete levelling of the geodetic network in 2004.

THE FIRST ALIGNMENT

All components have been aligned with respect to the geodetic network in order to achieve relative accuracy of 0.25 mm [1]. It is realised in several steps:

- in the vertical plane with direct levelling done with the NA2 optical level,
- the roll angle is adjusted using a gauge equipped with an inclinometer and installed on two fiducials,
- in the horizontal plane with offsets to a stretched wire and distances measured with the tacheometer TDA5005. To avoid steps between consecutive magnets, an initial local smoothing was performed prior to performing the magnet interconnection.

THE SMOOTHING OPERATION

A second smoothing is applied to the relative component positions to minimise steps between magnets that may create perturbations to the particle beam. Further measurements are thus done directly on the fiducials located on the components without using the geodetic network since the absolute position can be considered as established at this stage. The goal is to obtain a 1 σ deviation with respect to a smooth curve of 0.15 mm in a 150 m long sliding window [2].

This operation is important particularly for the aperture, and therefore concerns all magnets.

There are three steps: a control and adjustment of the roll angle followed by a vertical and an horizontal measurement.

Roll Angle Measurement

The roll angles were measured for all the sectors under warm conditions except for sector 4-5 and 7-8. Table 1 shows the deviation from the nominal after the initial alignment and during the final smoothing. A slight degradation of the magnet roll angle between the initial and final alignment can be seen. The average deviation changes very little while the standard deviation changes from 0.045 to 0.085 mrad. Magnet deviations larger than 0.1 mrad were corrected.

Table 1: roll angle deviations from nominal

Sector	Initial alignment		During smoothing	
	Avg (mrad)	Stdev (mrad)	Avg (mrad)	Stdev (mrad)
1-2	0.00	0.04	-0.01	0.07
2-3	-0.01	0.04	0.00	0.06
3-4	0.00	0.06	-0.02	0.09
4-5	-0.01	0.04	0.03	0.09
5-6	0.00	0.04	0.01	0.08
6-7	0.00	0.04	-0.01	0.10
7-8	0.00	0.05	-0.04	0.08
8-1	0.01	0.05	0.05	0.11

Vertical Measurement

The vertical measurements are made in a double run process, using the digital level DNA03 and a CERN made illuminated staff. The sequence applied to the arcs is illustrated in Figure 1.

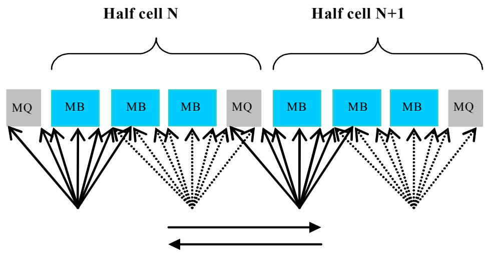

Figure 1: Vertical levelling sequence.

Sectors 4-5 and 7-8 were measured under cold conditions while the six others were measured when the magnets were at room temperature. The calculations were made with the deep references considered as fixed points.

Figure 2 shows the magnets vertical deviation from their nominal position. The 1 σ deviations are between 0.25 and 0.6 mm, the average deviation fluctuates from -0.4 mm for sector 1-2 to +0.4 mm for sector 7-8.

Horizontal Measurement

The horizontal measurements were made using a CERN-developed 'ecartometer', which measures the offsets to a straight line defined by a 120 m long stretched wire that is being protected against the wind by a duct as shown in Figure 3. All the sectors were measured under cold conditions.

Figure 3: Ecartometry measurements.

The sequence applied to the arcs is illustrated in Figure 4. Each MQ is measured at least three times, while the main bends (MB) are measured twice. The compensation was made sector by sector taking a fixed point at one extremity, an orientation point at the other extremity and a radial constraint of 2 mm, assuming the elements are close to their absolute position.

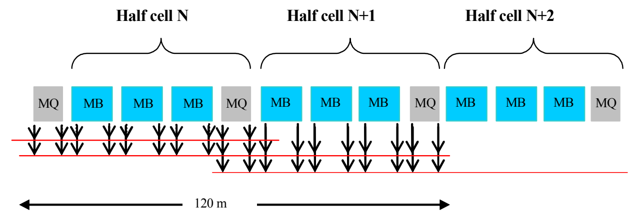

Figure 4: Horizontal offset sequence.

Figure 2 shows the magnets horizontal deviation from their nominal position. The average deviation by sector is less than 0.05 mm and very well centred.

SMOOTHING WITH 'PLANE'

The PLANE software is a CERN developed tool that calculates a "smooth" curve based on the deviation from the nominal position and identifies the magnets to be realigned [3].

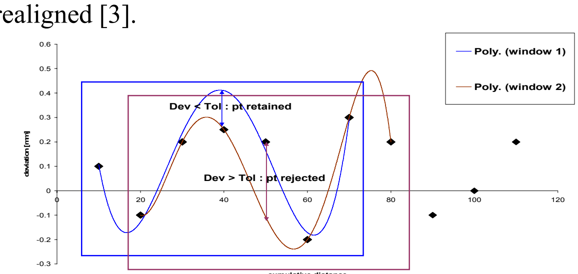

Figure 5: Windowing with PLANE.

The algorithm is based on a sliding window of variable length. Within this window all the points except the one in the window centre are fitted to a fifth order polynomial. The centre point is 'rejected' if its deviation from the polynomial exceeds a specified tolerance. The process iterates by sliding the window point-by-point as shown in Figure 5 and continues until the end of the sector is reached. Then PLANE re-iterates the whole process until no further points are rejected and recalculates the deviation to the latest 'smooth' curve for all the magnets.

A window with 63 points and a 0.25 mm tolerance was chosen to reach the specified 1 σ deviation of 0.15 mm and to minimise the number of magnets to be moved.

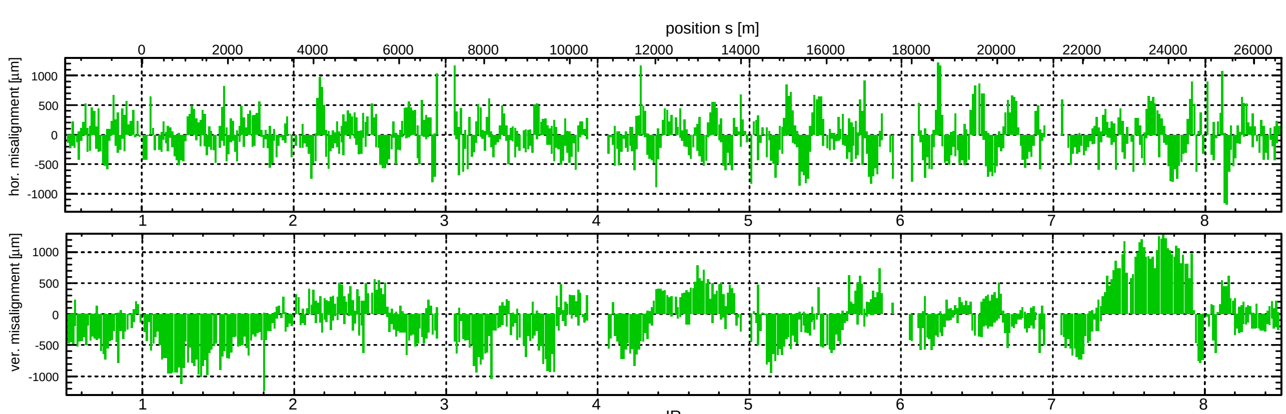

Figure 2: Horizontal and vertical magnet position deviation.

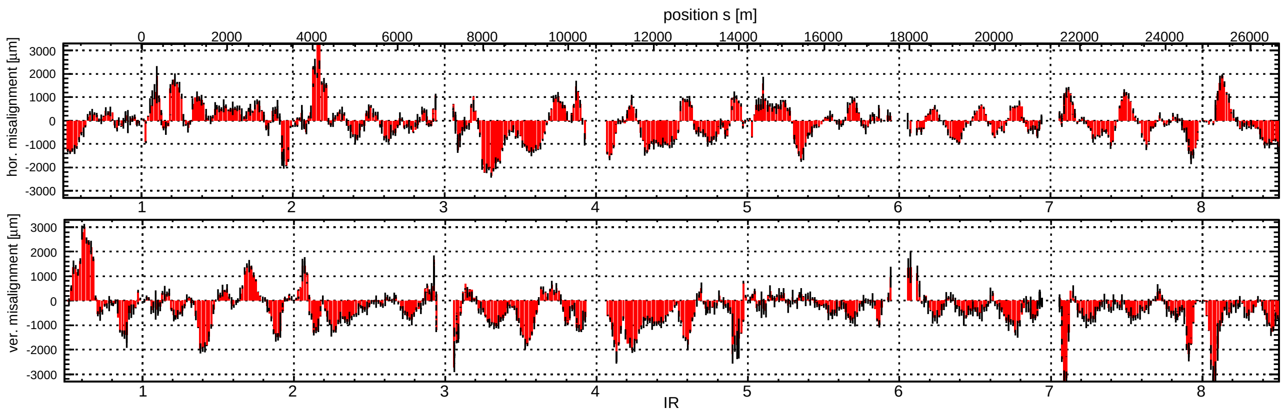

Figure 6: Beam-based quadrupole alignment estimate.

Table 2 shows the deviations with respect to the smooth curve before, after and the numbers of realigned magnets. The specification of 0.15 mm at 1 σ was reached for all sectors in both directions, with an average of 67 magnets (29%) moved per sector in H and 52 magnets (23%) in V.

Table 2: Deviations from smooth line

Sector	Vertical			Horizontal		
	Pre displ. (mm)	Post displ. (mm)	Points to move	Pre displ. (mm)	Post displ. (mm)	Points to move
1-2	0.16	0.10	41	0.19	0.11	56
2-3	0.16	0.12	63	0.20	0.11	90
3-4	0.18	0.11	84	0.21	0.11	72
4-5	0.15	0.13	45	0.19	0.11	65
5-6	0.15	0.10	49	0.22	0.11	52
6-7	0.13	0.10	20	0.20	0.11	65
7-8	0.15	0.11	46	0.17	0.10	40
8-1	0.16	0.11	65	0.30	0.10	96

BEAM-BASED ALIGNMENT ESTIMATES

Another assessment of the global machine alignment can be based on the analysis of closed orbit data, taken during the first days of LHC operation. Among the various effects compatible with the measured small betatron coupling ($|C^-|<0.07$) [4], the strongest impact on the measured closed orbit is typically due to misalignments and related dipolar feed-down effects of the MQs. As shown in [5], random MQ misalignments $\sigma_{quad.}$ propagate to the global orbit r.m.s. $\sigma_{orbit.}$ as

$$\sigma_{orbit} \approx \kappa \cdot \sigma_{quad.}$$

with scaling factors $\kappa_h = 30.5 \pm 11.5$ and $\kappa_v = 29.6 \pm 9.0$ for the nominal injection optics. The prediction error of about 30% is due to near-singularities, particularly involving magnets in the experimental insertions.

After unfolding the effects of the applied orbit corrections, the known momentum mismatch $\Delta p/p \approx 10^{-3}$ and de-selecting known erroneous BPM readings, the 1 σ bare orbits deviations can be computed to $\sigma_{orbit} = 8.5$ mm in the horizontal and $\sigma_{orbit} = 13.7$ mm in the vertical plane, and the corresponding MQ misalignment to about (0.3 ± 0.1) mm in the horizontal and (0.5 ± 0.1) mm in the vertical plane. The alignment stability over half an hour was about (0.2 ± 0.06) □m.

These results can be further refined applying an SVD-type correction to the bare orbit, using quadrupole shifts instead of dipole corrector kicks. Figure 6 shows the corresponding result. Near-singularities have been removed by enforcing condition number of less than 10^3. Error bars in Figure 6 correspond to the error propagation of electronic offset and BPM measurement noise.

The calculated cell-to-cell misalignment of about 0.1 mm is compatible and confirms the smoothing procedure. Absolute global misalignments are below 0.7 mm for the horizontal and 1.2 mm for the vertical plane on the 90 % level. A detailed analysis revealed a systematic droop of the MQ magnets ranging from IR3 to IR5, as visible in Figure 6.

CONCLUSIONS

The LHC components have been aligned with respect to an absolute geodetic network and then smoothed in order to detect some relative misalignments remaining once the interconnections of the magnets are performed. The relative 1 σ accuracy obtained after smoothing is better than 0.15 mm.

The excellent initial alignment facilitated quick threading of the beam and limited the number of corrector magnets that were necessary to establish circulating beams in 2008. In order to minimise the residual misalignments, machine re-alignments have been planned for the next two years.

REFERENCES

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