ALIGNMENT OF THE LHC EXPERIMENTAL INSERTIONS.

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1. INTRODUCTION

Luminosity and background in the experiments are strongly dependent on the quality of the survey of the machine elements. At LHC, particular care must be given to the limited aperture available in the low-β quadrupoles, to the sensitivity of these cryogenic magnets to the high flux of secondary particles produced at the crossing points and to the finite crossing angle introduced to avoid parasitic collisions. The alignment tolerances that we obtain are in the sub-millimeter scale and represent a challenge across the experimental area where direct visual survey is not possible.

2. LHC COLLISION POINTS AND EFFECTS OF QUADRUPOLE MISALIGNMENTS

2.1 The low-β set-up and its constraints

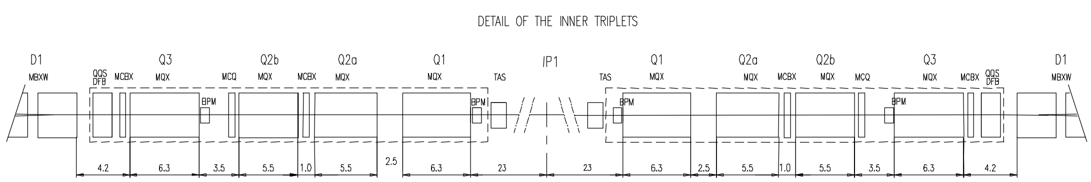

Fig. 1: Layout of the final focus in the LHC high luminosity experimental region.

Fig. 1 displays the layout of the machine elements around the high luminosity experiments. The focusing is achieved with triplets of quadrupoles, a configuration which is most efficient in the case of the round LHC proton beams [1]. The gradient of the low-β quadrupoles, their aperture and the energy flux that they can support are strong hardware limitations underlying the design of the insertions:

- the nominal LHC energy of 7 TeV and the focusing strength needed to optimize the luminosity imposes the use of supra-conducting low-β quadrupoles. The interplay between the coil structure, the gradient and the field quality one can achieve with this technology [2] puts a strong limit on the aperture of these quadrupoles.
- simulations of the cleaning system recommend a 7 σ_{beam} aperture at the primary collimators and the envelope of the halo reaches 9.8 σ_{beam} in this case [3]. This is most demanding at injection, when the transverse emittances are wider and when the counter-rotating beams must be fully separated.

- a crossing angle of 100 μrad is required during collision at top energy to separate the orbits in the section common to the two beams and to avoid parasitic crossings every 3.25 m [4]. The corresponding trajectories, viewed in the crossing plane, are shown on Fig. 2. We note that these trajectories have an excursion of 5 mm and a separation of 8 mm in the quadrupoles Q2 and Q3 where the transverse beam size of the order of 1.5 mm r.m.s..
- the energy released in inelastic proton-proton collisions represents 670 W on each side of the interaction point when LHC runs at 7 Tev with a luminosity of 10^{34} cm^2s^{-1}. A copper collimator (TAS) is located in front of the quadrupoles to intercept a large amount of this energy and to prevent resistive transition of the supra-conducting magnets [5],[6]. The distribution of secondary particles is strongly peaked along the beam axis and the efficiency of the TAS is a steep function of its aperture which should furthermore be as small as possible.

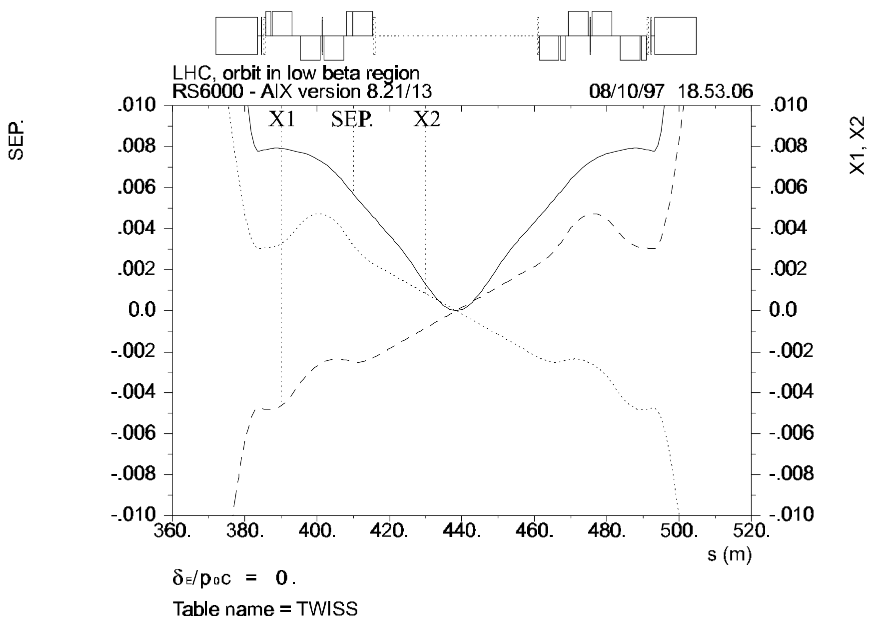

Fig. 2: Ring 1 and ring 2 closed orbit and separation for a perfect alignment of the low-β region.

The design retained for the low-β regions fulfills these requirements with an alignment tolerance of 1.0 mm for the quadrupoles and 0.5 mm for the TAS [7]. This is an upper limit and does not take account of the magnetic effects we shall study in the following section.

2.2 Effects of misalignments of the low-β quadrupoles

We first envisage a misalignment of a single low-β quadrupole within a triplet. A 50 μm lateral displacement of Q2a affects the orbits as illustrated on Fig. 3 (displacements of Q1 or Q3 give similar patterns) and we observe that:

- the separation between the 2 beams is strongly reduced in the quadrupoles Q2 and Q3.
- the beam separation at the collision point, although hardly visible on Fig. 3, is 90 μm and corresponds to $6\sigma_{beam}$.

The displacement of a single quadrupole introduces a kick which has opposite effect on both beams and mainly influence their separation.

The misalignment of a whole triplet with respect to the other has a different impact on the trajectories since the kicks corresponding to the offsets of the quadrupoles tend to compensate. Fig. 4 shows the effect of a 50μm misalignment between the left and the right low-β triplet:

- both beams are now displaced in the same direction, the trajectories still cross at the collision point, and the separation at the parasitic crossing is not modified.
- the tilt of the trajectories is modified and one of the beam gets about 1.8 mm closer to the aperture limitation in Q2.

The global offset between the low-β triplet on both sides of the collision point furthermore reduces the aperture available to the circulating beams in the quadrupoles and in the copper collimator.

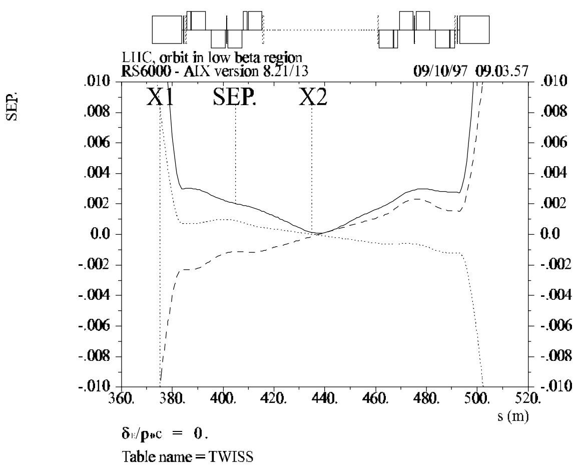

Fig. 3: Uncorrected closed orbit with a 50μm displacement of Q2a left.

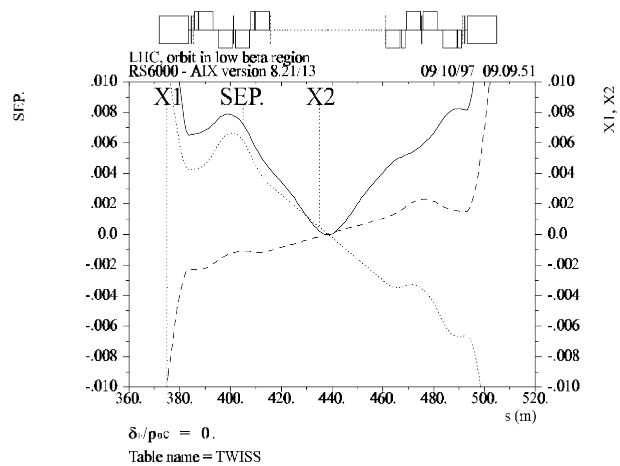

Fig. 4: Uncorrected closed orbit with a 50μm displacement of the left triplet.

Orbit correctors installed close to Q2 and Q3 will be tuned to bring the beams back in collision. However, they cannot totally restore both the separation and the aperture which is available in the low-β quadrupoles with a perfect alignment [8]. These magnetic effects lead to a more stringent alignment tolerance of 0.35 mm for a quadrupole within a triplet. A 1.0 mm relative offset between the triplets on both sides of the collision point can be corrected, provided that the experiment accepts a 0.6 mm lateral displacement of the vertex: this tolerance becomes 0.5 mm if we need to constrain the transverse position of the vertex.

3. ALIGNMENT OF THE HIGH-LUMINOSITY INSERTIONS

3.1 Stretched wire

A carbon wire [9] stretched over 120m in a gallery parallel to the LEP/LHC tunnel will provide an absolute reference for the survey of the machine elements in the collision region at point 1 (ATLAS) and point 5 (CMS). It will expand over the recombination/separation dipoles D1, the low-β quadrupoles Q1-2-3, the correctors and the copper collimators. It will also provide a reference for a network of survey monuments in the experimental cavern, in order to align the detectors relative to the machine. Fig. 5 sketches an upper view of the survey system, with intermediate reference lines on both side of the experiment and invar rods between the stretched wire and these intermediate reference lines. The system will be completed with hydraulic sensors for the altimetric survey.

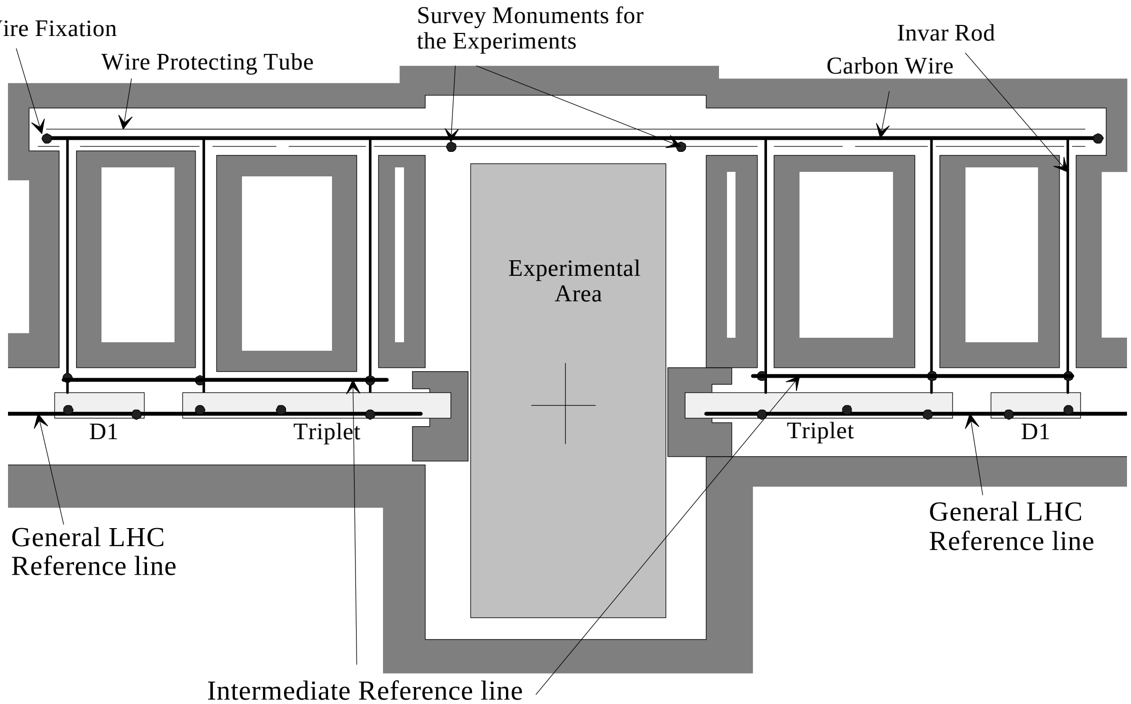

Fig. 5: Schematics of the stretched wire survey system.

The transverse alignment accuracy of the machine elements with respect to the stretched wire will be of the order of 0.2 mm r.m.s. [10]: this will insure a relative alignment of the triplets on both sides of the collision point with an accuracy of 0.3 mm r.m.s.. The vertical alignment will be even more precise since the hydrostatic levels should provide an altimetric accuracy better than 0.1 mm across the low-β region [11]. The alignment of one quadrupole within a triplet can be cross-checked with direct optical survey and the accuracy will be of the order of 0.15 mm r.m.s. in this case. These numbers perfectly match the alignment tolerances quoted before.

3.2 Beam based alignment

A good survey of the fiducial marks located on the quadrupole cryostats still does not ensure that the magnetic axis are well aligned. Beam based alignment has been used at LEP [12] and offers an alternative survey technique which eliminates alignment and tolerance problems in the magnet assembly. Beam based alignment proceeds in two steps:

1. Calibration of the beam position monitors (BPM) with respect to the magnetic axis of the low-β quadrupoles. This is achieved with the K-modulation technique [13], looking at the closed orbit displacement resulting from a small variation of the gradient of each quadrupole at a time. The closed orbit is not affected when aligned on the magnetic axis of the quadrupole and the offset of the nearby BPM is directly recorded when this situation is reached. The process is now a routine procedure at LEP [14] and we are confident that the LHC beam monitors and quadrupoles can be aligned with an accuracy better than 50 μm r.m.s..

2. Measurement of a straight trajectory to be used as an alignment reference. This requires an optical layout of the experimental insertion that ensure that the proton beams go straight in the low-β quadrupoles. The obvious solution is to switch off the low-β quadrupoles: such an optics has been developed with the version 5.0 of the LHC lattice and the corresponding β-functions are displayed in Fig. 6.

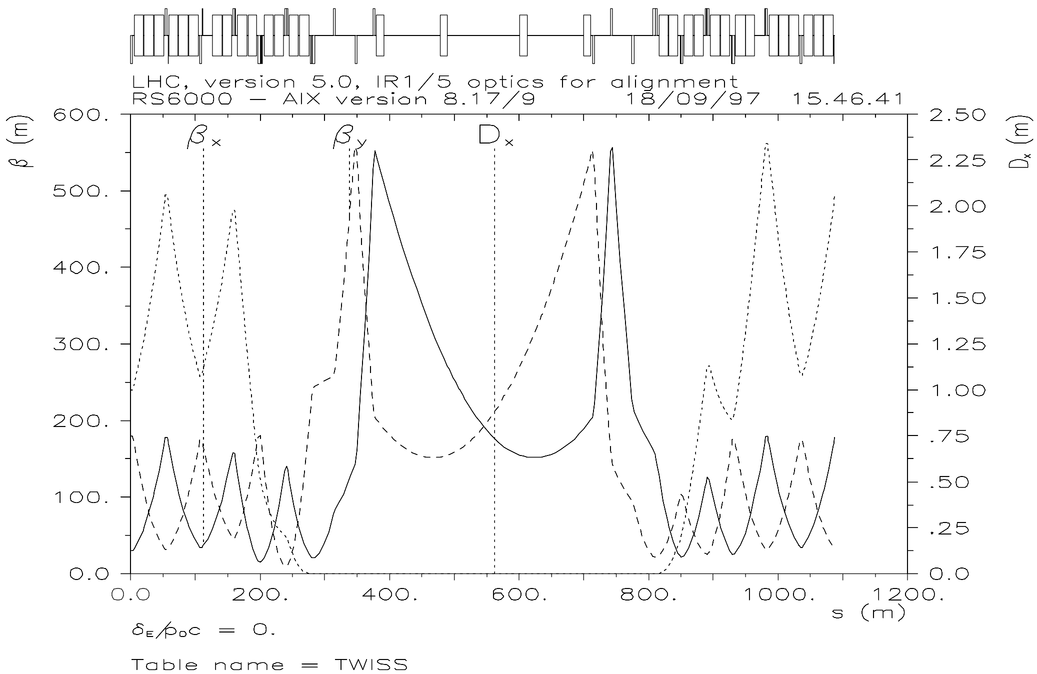

Fig. 6: Optics for beam based alignment with low-β quadrupoles switched off.

We will have 2 BPM in each low-β triplets, one close to Q1 and the other between Q2 and Q3, to record both the position and the slope of the closed orbit with respect to the quadrupoles. The alignment precision of a quadrupole within its triplet will then correspond to the measurement accuracy of the offset between a BPM and the nearby quadrupole, of the order of 50 µm r.m.s..

The relative alignment of the low-β triplets on both sides of the collision point will use a reference trajectory and will be limited by the stability of this reference trajectory against alignment and orbit corrections in the rest of the LHC. Our experience with the LEP ring is relevant here since the dimensions, the number of magnetic elements and the number of BPM are similar: tests and simulation agree [15] to indicate that the beam position in the LEP low-β region is stable within 50 µm r.m.s. once the orbits are corrected with the standard Micado [16] algorithm. An additional source of uncertainty at LHC comes from the combination/separation dipoles D1 and D2 which directly steer the beams through the low-β quadrupoles. However, the proper setting of these dipoles will be controlled with the combined information of the two counter-rotating beams, and the reference trajectory should be reproducible with a precision better than 0.1 mm r.m.s..

A beam based survey also matches the requirements for the alignment of the LHC experimental insertions. It is more accurate than the survey using the carbon wire as reference, and presents the advantage to directly measure the magnetic axis of the low-β quadrupoles.

4. CONCLUSION

We reviewed the alignment tolerances for the LHC high luminosity insertions. They are particularly stringent for the low-β quadrupoles and for the collimators which protect these quadrupoles. A thin carbon wire stretched along the experimental area is needed to provide the required positioning accuracy during the installation and commissioning of the machine. Ultimate alignment will be achieved by a beam-based technique which directly measures the magnetic centers of the low-β quadrupoles.

5. REFERENCES

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