Requirements of Beam Dynamics on the Alignment of the Low-β Insertions

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Abstract

In the collision configuration, the low-β section concentrates most of the LHC complexity: largest non-linear perturbations, the long-range (LR) interactions between beams passing the lenses off-axis and the mechanical aperture limit of the machine. A misalignments of the quadrupoles in the low-β section may therefore have more serious consequences than simple geometrical effects at the collision points. In addition to a loss of luminosity and an enhancement of the background, the LR interactions and the balance between parasitic multipoles and their non-linear correctors could be altered. The approach in this note is to identify the important beam dynamics variables that may be perturbed by misalignments and specify tolerances which should guaranty that the nominal performance can be reached.

1 Introduction

The misalignment of dipoles and quadrupoles is in general of little consequence as long as it can be locally corrected. The issue is to size correctly the corrector strengths according to the expectation of the misalignment and to assume local correction techniques will be implemented. This is the line followed to define the LHC correctors except in the low-β sections. It should be noted that local correction techniques are easy to conceive but operationally difficult. This is why experience shows that aligning a machine is always better than a correction.

Beyond this probably un-controversial statement, LHC shows the peculiarity that the low-β section is traversed by two counter-rotating beams of the same charge, experiencing two different β-functions at the same azimuth. The focusing is very strong in the low-β triplet and $\partial\beta/\partial s$ two orders of magnitude higher than in the rest of the machine. The low-β quadrupoles are two times longer than in the arcs, severely constraining the space available for the correctors.

Altogether, even-though the betatron phases advance in a negligible way in the triplets, a displacement or a tilt of a magnet cannot be locally corrected as the β-function changes too much and differently for the two beams from the magnet to the corrector. A displaced quadrupole for instance will tend to separate the beams at the collision point (at a phase shift of $\pi/2$ from the perturbation). Its correction will require at least a four-corrector bump extending over most of the low-β section to restore the beam overlap and crossing angle at the collision point. In doing so, the beam separation in the quadrupoles, the geometrical aperture and the feed-downs may be altered.

Due to these couplings, the relationship between the type of misalignment or deformation of the lenses and the beam parameters is non-trivial. We must therefore proceed in two steps:

- identify the relevant beam dynamics parameters and define their tolerances,
- consider the different types of misalignment, their correctability by various means, evaluate their consequences and bound them with the above-mentioned tolerances.

In this note, we pay attention to the first step.

2 Beam Parameters at the Collision Point at 7 TeV

2.1 Tolerance on the Loss of Luminosity

From experience in LEP [1], a 5% loss of luminosity is at the level of significance while a 10% difference between collision points is judged not acceptable. Various sources may cause a reduction of luminosity: the overlap of the beams may be altered, the beam cross-sections may be enlarged by a β-beating or by a parasitic dispersion in either of the two transverse planes. Just for local imperfections, there are 6 possible sources of luminosity loss. Assuming that the causes for a loss in luminosity are uncorrelated (may or may not be true), the luminosity loss should not exceed 2% per source. An increase of background to the detectors is equivalent to a loss of luminosity. It seems however impossible to quantify today.

2.2 Tolerance on the Beam Overlap

With a dependence of the luminosity in $Exp[-\Delta^2/4\sigma^2]$, the tolerable maximum relative displacement Δ of one beam with respect to the other is about 0.3σ to meet the 2% tolerance on luminosity.

There is a good record of experimental evidence that such small offsets cause a large increase of background or even a reduction of the beam lifetime:

- In the Sp$\bar{p}$S, the background doubles for an offset of 0.1σ and triples for an offset of 0.2σ and more [2].

- In HERA, the beam offset must be kept below 0.1σ to avoid a decrease of the proton lifetime [3].
- In LEP, though the dynamics is different due to a significant damping, an offset of 0.2σ is deemed to reduce performance [4].

A recent simulation of the LHC dynamics [6] seems to show that the offset would not be critical, or at least that it does not influence the variance of the action as observed over a long tracking run. This variance is used to define a diffusive aperture which does not appear to change for offsets between 0 and 2σ. There may not be inconsistency between the observations and the simulations as the background and lifetime are sensitive quantities so far not really predictable. Another simulation [5] shows that the crossing angle of ± 150 μrad excites the sidebands of the 13th order resonance (lowest resonance crossed by the beam in collision) as much as an offset of 0.8σ. This may be worrisome and requires further studies.

The consistency of the experimental information seems to show that the beam offset must be controlled to 0.1σ, which guarantees as well an insignificant loss of luminosity.

2.3 Tolerance on the β-beating

Assuming a simplified model where the β-function remains the same in the two rings, the tolerance on luminosity loss requires a β-beating less than 4% in each plane.

2.4 Tolerance on the Dispersion

The parasitic dispersion at the IP's causes a blow-up of the effective beam sizes, an excitation of the synchro-betatron coupling and an alteration of the beam overlap if the beam momenta and the parasitic dispersions do not vanish.

It is difficult to imagine why the beams should not be operated at $\delta = \Delta p/p = 0$. The possible transverse displacement of the beam via the RF is small (a few millimeters at most) as compared to the machine aperture and does not seem very useful. Assuming it occurs nevertheless, the tolerance on the overlap yields

$$D_1\delta_1 - D_2\delta_2 \leq 0.1\sigma_\beta \tag{1}$$

For a betatron beam size of 16μm and a momentum offset $\delta_1 = \delta_2 = 0.510^{-3}$, the parasitic dispersion must not exceed 2 mm, assuming statistical independence between Ring1 and Ring2. Such a requirement is very tight, even relaxed by an order of magnitude. It shows that the overlap will be very sensitive not only to the orbit but equally to the dispersion and that a feedback system is likely to be required.

The blow-up of the beam size by the dispersion is given by

$$\sigma = \sqrt{\sigma_\beta^2 + (D\sigma_e)^2} \tag{2}$$

When the dispersion D occurs in the plane of the crossing angle ϕ, the luminosity is given by:

$$\mathcal{L} = \mathcal{L}_0 \frac{\sigma_\beta}{\sqrt{\sigma_\beta^2 + (D\sigma_e)^2}} \frac{\sqrt{1 + (\frac{\phi\sigma_s}{\sigma_\beta}^2)}}{\sqrt{1 + \frac{\phi^2\sigma_s^2}{\sigma_\beta^2 + D^2\sigma_e^2}}} \tag{3}$$

where σ_s and σ_e are the rms bunch length and energy spread. If the dispersion arises in the other plane where there is no crossing angle, expression 3 remains valid with $\phi = 0$.

Expression 3 shows that a parasitic dispersion in the crossing plane is less harmful, as the larger overlap of the beams somewhat compensates the blow-up of the sizes. The worst case occurs in the other plane. To fulfil the tolerance on the luminosity loss, the dispersion must not exceed

$$D \leq 3\text{cm} \tag{4}$$

if we assume the same size for both beams.

Analytical and numerical studies [5] show that the synchro-betatron coupling appears negligible if the dispersion does not exceed 10 cm in the IP.

2.5 Tolerance on the Position of the Collision Point

These requirements arise from the experimental detectors.

- The absolute position of the collision point with respect to the detector should be controlled to about 1 mm transversely and about 5 cm rms longitudinally [7].
- The relative position of the collision point must be maintained throughout a fill and from fill to fill to help vertex detection. The resolution of the vertex reconstruction is about 10 μm. A first estimate of the requirement in terms of stability of the IP position is about 100μm [7]. Above this value, the experiment will require a centering of the beam, presumably done with the insertion bumps whatever the origin of the drift.

3 Beam Separation at the LR Interaction Points at 7 TeV

Here we distinguish a perturbation of the crossing angle as a whole with all LR separations scaling accordingly and a perturbation which, while not changing the crossing angle at the IP, causes the LR separation to be altered in the low-β quadrupoles.

3.1 Tolerance on the Crossing Angle

The nominal crossing angle is presently fixed to ± 150 μrad. With the new implementation of the crossing angle for version 6.1 [8], there is enough strength to double it. In fact, the available geometrical aperture in the low-β section limits the maximum angle to ± 180 μrad.

In two independent simulations [6] [9], a marked increase or modulation of the particle amplitudes is observed if the crossing angle is reduced below ± 150 μrad. This phenomenon is observed in both cases when the initial amplitude of the particles reaches about 8σ(radius in x, y plane). It turns out that the dynamic aperture by particle loss, which is significantly larger than 8σ at 10^5 turns, decreases to below this value (at least for the seed tested) when increasing the number of turns to 10^6 [9]. Since then a third simulation [11] was carried out including the beam-beam kicks, the field errors in the triplets and their correction for a large number of seeds. The onset of chaos is observed at the very small amplitude of 4σ and the dynamic aperture reduces to 5σ after 10^6 turns. An increase of the crossing angle to $\pm 200\mu$rad increases the dynamic aperture by 2σ.

These results show that the nominal crossing angle is the minimum required and that any reduction of this angle will result in a reduction of the machine performance. It further shows that the ultimate performance achievable by increasing the beam current by 1.6 to reach the beam-beam parameter achieved at the Sp$\bar{p}$S is most likely not compatible with the first generation of the insertion regions.

It remains possible to estimate a tolerance for which the change in the beam-beam LR perturbation remains small.

- A first criterion is suggested in [9]: if the dynamic aperture is given by the beam separation, the largest stable amplitude is that of the particle which approaches the core of the other beam by not more than 3σ. The wanted dynamic aperture is 6σ(the opening of the collimators). Hence the beam separation must be 9σ, corresponding to an angle of 142μrad, leaving a tolerance of -8μrad.

- Another approach is to limit the detuning due to the LR effect. Numerical experience shows that a change in amplitude detuning by 0.001 is most often associated with a significant perturbation by non-linear forces. Calculations of the tune footprints for two crossing angles (± 125 μrad and ± 150 μrad) [15] shows that the tolerance on the crossing angle is much less than 25μrad. With alternate crossings, the direct part of the LR tune shift vanishes leaving only an amplitude detuning of 0.005 at 6σ. It varies at least with the inverse fourth power of the separation [10]. Using this scaling, the tolerance on the crossing angle is 6μrad.

These figures are consistent and show that the tolerance on the nominal crossing angle is not more than 5%.

3.2 Tolerance on the Crossing Angle Bump Geometry

The aim of this section is to estimate the tolerance when a fraction of the LR encounters occurs at a smaller separation than expected.

There are about 128 LR encounters all around the machine which can be divided into three classes (figure 1):

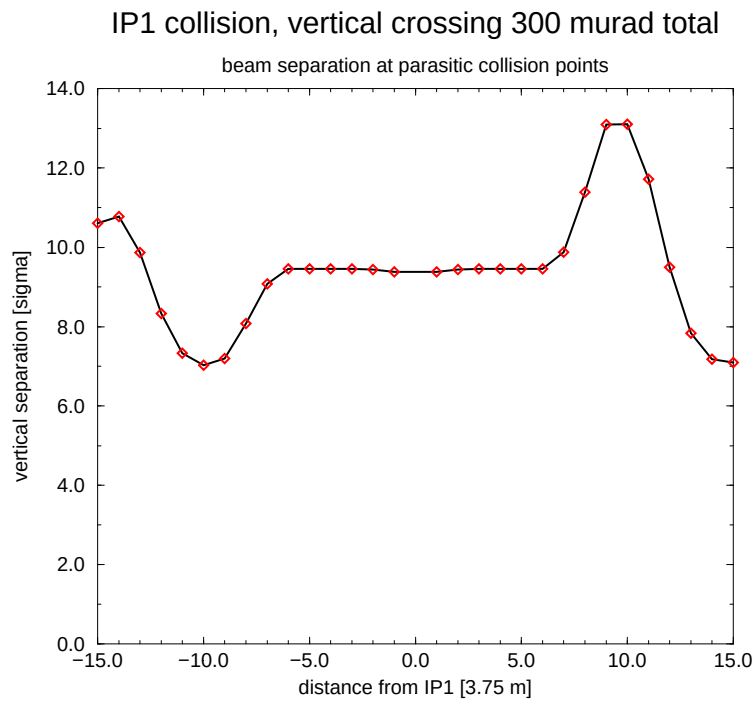

Figure 1: Beam separation in IR1 in σ's of the weak beam

- the close encounters, occurring in the low-β quadrupoles on either side of the two high-luminosity experiments in IR1 and IR5; there are about 16 such encounters occurring at a separation of about 7.5σ.
- the nominal encounters, occurring in the field-free regions and the low-β quadrupoles of IR1 and IR5, and the first encounter on either side of IR8; there are about 34 such encounters occurring at a separation of 9.5σ.
- the far encounters, occurring in the low-β quadrupoles of IR1 and IR5 and all other encounters in IR2 and IR8; there are about 78 such encounters occurring at a separation of 11σ and much more

Assuming a dependence of the detuning with the inverse fourth power of the separation [10], at least 40% of the detuning is due to the close encounters which might be perturbed if the misalignment of a quadrupole is corrected with dipole correctors. We use again the criterion that the amplitude detuning shall not be increased by more than 0.001 at $6\sigma$by a perturbation. The criterion is fulfilled if the separation of the close encounters is reduced by 1σor if 8 nominal encounters would become close encounters.

These estimates of the tolerance on the crossing angle and crossing angle geometry require dynamic aperture studies to be confirmed.

4 Global Machine Parameters at 7 TeV

The feed-downs and the non local correction of the perturbations in the low-β triplets will prevent a simple orthogonal control of the beam dynamics parameters. This is unavoidable with a common machine section where the two beams passes the lenses off-axis. To minimize the complexity of the operation, it is essential to minimize the imperfection sources, even if in theory all effects are predictable and can be controlled within tolerance.

We now consider the tolerances on the classical global beam dynamics quantities, ignoring their couplings.

4.1 Tolerance on Betatron Coupling

The LEP commissioning showed us that the usual techniques to observe and correct coupling become ineffective if the coupling is too strong. If the alignment of the low-β quadrupoles would be made to 1 mrad rms, the separation of the tunes would be 0.3 rms [13], i.e. comparable to what we encountered during the commissioning of LEP.

Two solutions are possible:

- align the quadrupoles to 0.1 mrad rms if technically possible. This would yield an rms closest tune approach of 0.03 which is a safe starting point for the minimization of the coupling (factor 30 needed),
- gradually correct one insertion at a time at several intermediate steps during squeezing. This is surely feasible but the correction may require iterations to cope with possible orbit dependent skew quadrupolar field due to feed-downs.

There is a trade-off between roll alignment quality and efficiency when commissioning the β-squeeze. Furthermore orbit coupling and higher-order couplings will not be corrected when the betatron coupling is minimized by the usual operational techniques which are global. Whatever the solution chosen, the coupling should not exceed about 0.05 before it is corrected.

4.2 Tolerance on Tune-Shifts and Chromaticities

The tolerance on the 'static' tunes of the machine is 0.001, to allow for accurate positioning of the working point with respect to resonances. The tolerance on chromaticities is not yet established. It will be small to minimize the tune modulation.

The tune modulation (e.g. due to vibrations) should not exceed 10^{-5} per source [14] from experience on other machines. The first simulation of this effect [6] is not in line with this experience and the subject will require further work.

4.3 Tolerance on Closed-Orbit Distortions

A global perturbation of the closed orbit is a typical example of unwanted consequence of the adjustment of some parameters in a low-β insertion. In order not to perturb the optimization of the other experiments and the collimation section, the 'leakage' should be well below $\sigma/10$ or corrected by orbit feedbacks.

4.4 Tolerance on Dynamic Aperture

The consequences of the static part of the misalignment should not be visible on the dynamic aperture by particle loss. The onset of chaos detected in various ways should not be modified either, as we saw they might not be sensitive enough. In practice, a reduction of $\leq \sigma/4$ at 10^5 turns is not considered significant.

5 Beam Separation at All Interactions Points at Injection

The situation at injection is contrasted:

- the effect of the low-β quadrupoles is reduced by the injection optics to that of any other quadrupole,
- the beam is less stiff and the LR encounters in IR2 and IR8 are as important as those in IR1 and IR5.

With the normalization of the beam separation and dynamic aperture by σ, the energy dependence in fact disappears [16]. There are nevertheless two times more LR encounters at 450GeV in the 'close' and 'nominal' classes. The larger beam separation (about 11σ) seems just to offset the number of kicks (assuming the scaling in d^{-4} where d is the beam separation).

The separation at injection may be critical for nominal performance but does not add constraints on the alignment of the low-β .

6 Geometrical Aperture

The aperture criterion for LHC is defined in [17]. The position n_1 of the primary collimator is calculated in such a way that the secondary halo just fit inside the available mechanical aperture. The requirement is that $n_1 \leq 7$.

The available mechanical aperture is defined as follows. The origin of the (x, y) plane is taken at the nominal orbit of beam 1, taking into account the nominal beam separation. The misalignment and mechanical assembly tolerances define a square of 1.6 mm for the possible beam positions. The envelope of circles of radius 4 mm with their centers anywhere on the periphery of the square defines all the possible positions of the beam center compatible with orbit imperfections $\sqrt{x^2 + y^2} = 4mm$ (see figure2).

In the fitting, the beam size is calculated including a β-beating of 20% and a parasitic dispersion of 55 cm.

The 1.6 mm tolerance for the transverse displacement of the cold bore with respect to its ideal position is split into 0.6 mm for the alignment of the fiducials with respect to the cold bore and 1 mm for the alignment of the fiducials with respect to the survey monuments. The latter figure assumes the deterioration of the alignment after one year of running and is based on the observation of the LEP tunnel.

With these figures, the maximum crossing angle can be increased from 150 to 180μrad, which seems highly desirable.

7 Machine Commissioning

It is clear that at commissioning time, all requirements arising from the nominal beam-beam kicks become irrelevant. The machine will be commissioned on the detuned lattice at injection. This further reduces the effect of the triplet misalignment to a small or negligible level. In this situation, the low-β does not play any specific role, except that the detectors may turn out to be more sensitive to radiation than the machine.

It is not clear at this stage whether this can be used to relax the alignment tolerances. The capability of beam-based alignment must be assessed first, including its accuracy if required in the first year or so of LHC operation, its capability of disentangling complicated effects and its cost in beam time.

8 Summary

The tolerances on the beam dynamics parameters are summarized in table 1. In many instances, the beam dynamics phenomena concerned are complex or not fully predictable, like the background. These tolerances should therefore be regarded as guidelines which will gradually be improved by beam dynamics studies. If some tolerances are difficult or expensive to fulfil, more beam dynamics studies/experiments should be carried out before

making decisions. The machine performance and efficiency will profit from all reasonably possible technical solutions which allow to reduce these tolerances. We summarized in Table 2 the tolerances on mechanical assembly and alignment used so far to assess the geometrical aperture left for the beam [17].

Parameter		Tolerance	Comment
Loss of Luminosity	per source	2%	
	all sources combined	5%	
Beam overlap at IP		0.1σ	
β-beating at IP		4%	per plane
Dispersion at IP		3 cm	per plane
Absolute position of IP	transverse	1 mm	
	longitudinal	5.5 cm	
Relative position of IP	transverse	.1 mm	stability,reproducibility
Crossing angle		7μrad	
LR beam separation		16 LR's$\times$ -1σ	
Betatron coupling	$Q_I - Q_{II}$	0.05	before correction
		0.001	after correction
Tunes	drift	0.001	
Tunes	ripple	10^{-5}	per source
Closed orbit	leakage	$< \sigma/10$	
Dynamic aperture	at 10^5 turns	$< \sigma/4$	

Table 1: Tolerance on beam parameters

Parameter	Tolerance
Transverse pos. of cold bore	0.6 mm
Alignment of fiducials	1 mm

Table 2: Tolerance on mechanical aperture

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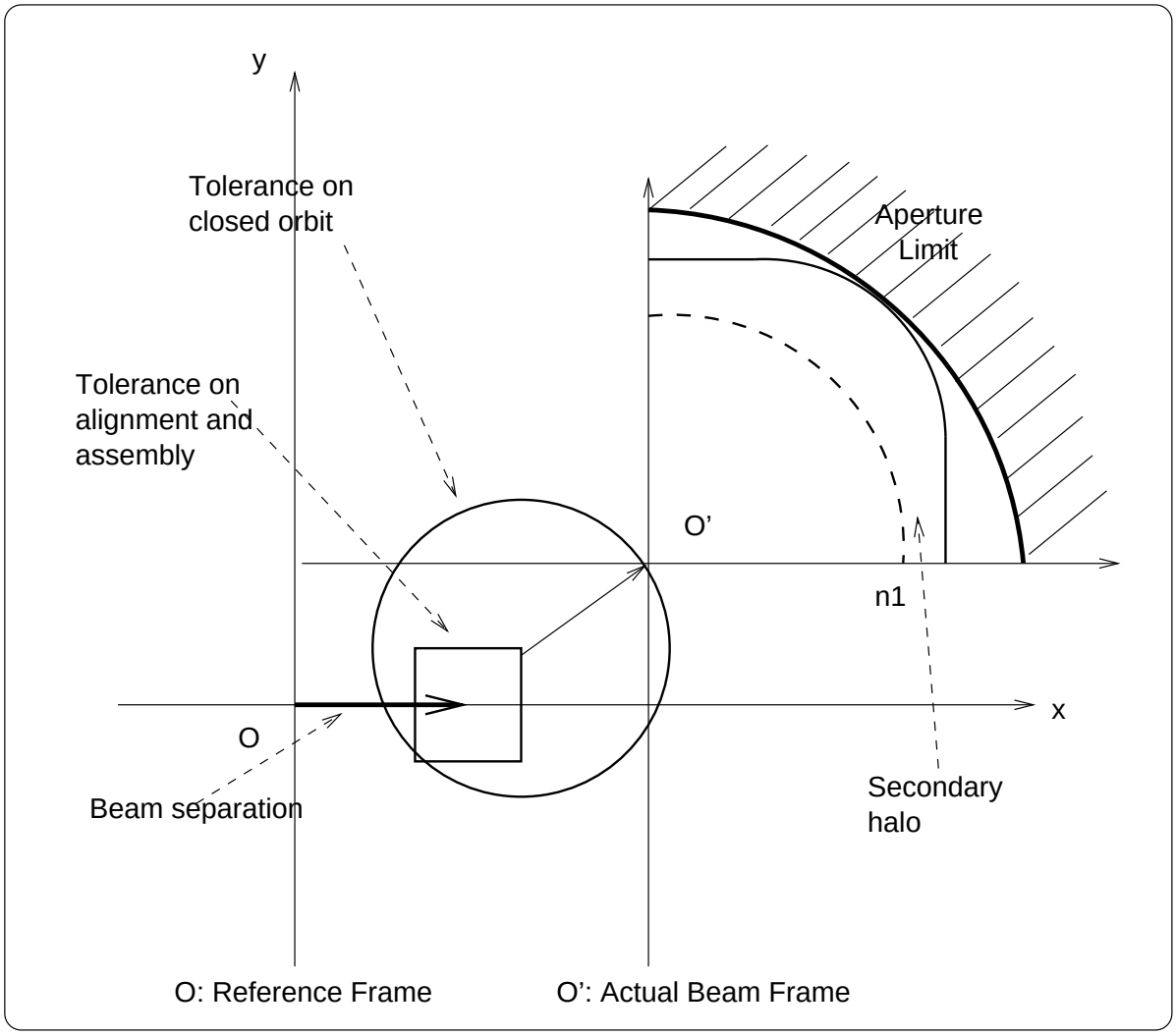

Figure 2: Definition of the LHC mechanical aperture