AN EARLY BEAM SEPARATION SCHEME FOR THE LHC LUMINOSITY UPGRADE

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Abstract

The high nominal luminosity of the LHC requires a large number of bunches spaced by about 7.5 m. To prevent more than one head-on collision in each interaction region, a crossing angle of 0.285 mrad is necessary. A side effect of this crossing angle is the increase of the effective transverse beam cross-section, thereby decreasing the luminosity by some 16%. For the LHC luminosity upgrade, depending on the focusing scenarios, this loss significantly increases and largely offsets the potential gain of a stronger focusing. In this paper we analyze a strategy to circumvent this difficulty, based on an early beam separation using small dipoles placed at a few meters from the interaction point. From the beam dynamics point of view, the essential constraint is to control the long-range beam–beam interactions in a scenario where the normalized beam separation is not constant.

INTRODUCTION

In the LHC, the beams cross at an angle to prevent more than one head-on collision inside each detector. Its value is chosen to reduce to an acceptable level the strength of the 16 long-range beam–beam interactions on either side of the IP's . This latter phenomenon sets indeed the upper limit of the LHC performance with respect to beam dynamics.

A non-vanishing crossing angle however shows several drawbacks. The most notable is the reduction of the luminosity due to the increased effective transverse beam size at the interaction point. To minimize this loss, two solutions were considered for the *LHC Upgrade Project* [1]: bunch shortening with an harmonic RF system or crossing at large angle with bunch rotation by crab cavities; these methods involve significant scientific and technical challenges.

The new concept of an 'early separation scheme' [2] offers a-priori a simpler solution with equal or larger performance. It however requires installing moderate field dipole magnets inside the experimental detectors.

As a pre-requisite to a technical feasibility study, this paper analyzes the beam dynamics issues and the magnetic field requirements. Two possible scenarios are considered: the ideal scenario has the separation dipoles before the first long-range beam–beam interaction point and no crossing angle at the IP. The second scenario is less demanding for the detectors with the separators before the 3rd interaction; a minimum crossing angle at the IP is then necessary.

PRINCIPLE OF THE EARLY SEPARATION SCHEME

The principle of the early separation scheme is to decouple two sets of contradictory requirements:

- at the IP, the crossing angle shall be as small as possible (geometric loss factor constraint)

- along the machine sections where the beams share the same chamber, the beam separation, so far parameterized by the crossing angle, shall reduce the impact of the long-range beam–beam effect on the beam lifetime to a negligible level (beam lifetime constraint).

These conflicting requirements can be satisfied by adding to the nominal separation scheme (Fig. 1a) dipoles later referred as $D0$'s 'as close as possible' from the interaction point (Fig. 1b,c). In this way, the crossing angle is re-
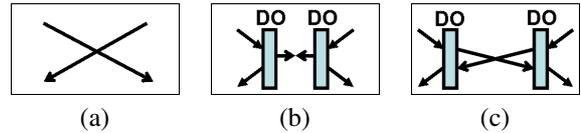

Figure 1: Crossing schemes: nominal (a), with D0 at 2 m (b) and at 9.5 m (c) from the IP.

duced while preserving the appropriate beam separation in a sense that will be defined later. This scheme is independent of the insertion layout and can be followed by either a quadrupole-first or dipole-first insertion scheme. This dipole should be feasible as the kicks involved (hundreds of μrad) are not far from the capabilities of orbit correctors.

LUMINOSITY REACH

The Luminosity Geometrical Reduction Factor

For equal round bunched beams crossing at an angle in one plane, the luminosity formula for the LHC is given by:

$$L = F \frac{n_b N_b^2 f_{rev}}{4\pi\sigma^{*2}} \quad \text{with} \quad F \approx \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}} \quad (1)$$

where n_b is the number of bunches, N_b is the number of protons inside the bunch, f_{rev} is the revolution frequency of the bunch; F is the geometrical luminosity reduction factor due to the full crossing angle θ_c, σ_z is the rms bunch length and σ^* is the transverse rms beam size assumed equal in the two planes. All quantities are evaluated in the machine reference frame. Using the nominal parameter values at IP_1 and IP_5 at collision [3], the β function at the IP is 0.55 m that gives $F \approx 0.841$.

The Luminosity Gain versus β^*

At constant beam current and insertion layout, the problem of the long-range beam–beam interactions is invariant if the transverse beam size (assumed to be the same for the two beams and planes) is taken as a scale parameter. Hence, the crossing angle shall increase like $\frac{1}{\sqrt{\beta^*}}$. The required increase of the crossing angle due to an increase in bunch charge, number of bunches and number of long-range beam–beam interactions has no theoretical expression but was estimated from numerical tracking helped by theoretical considerations [4][5]:

$$\theta_c = \theta_{c0} \sqrt{\frac{\beta_0^*}{\beta^*}} \left(6.5 + 3\sqrt{\frac{N_b n_b n_{LR}}{N_{b0} n_{b0} n_{LR0}}} \right) \qquad (2)$$

n_{LR} is the number of long-range beam-beam collisions while the 0 index denotes the nominal values. In Fig. 2 is illustrated the luminosity gain versus β^*, taking the *ultimate bunch charge* and keeping the nominal number of bunches and bunch length ($n_b = 2808$, $N_b = 1.71\ 10^{11}$, $\sigma_z = 7$ cm): the luminosity gain by about a factor of two for $\beta^* = 0.55$ m results from the higher bunch charge.

The nominal case is given by Eqs. 1 and 2. The gain in luminosity is very modest as compared to collinear crossing ('D0 at 2'). The intermediate case on Fig. 2 can be obtained in two different ways: by decreasing the bunch length by a factor of 2 with an harmonic RF system as contemplated for the upgrade [1] or by halving the crossing angle for the first few encounters with an early separation scheme installed before the third encounter ('D0 at 9.5'). The two methods give the same luminosity improvement with very different side effects: the bunch length reduction raises issues all around the machine (collective stability, electron cloud); the early separation only acts in the insertion without consequence for the machine; however a few long-range beam–beam encounters take place at a reduced separation of about 5 σ, violating the empirical law of Eq. 2: the next section will deal with this issue by numerical tracking.
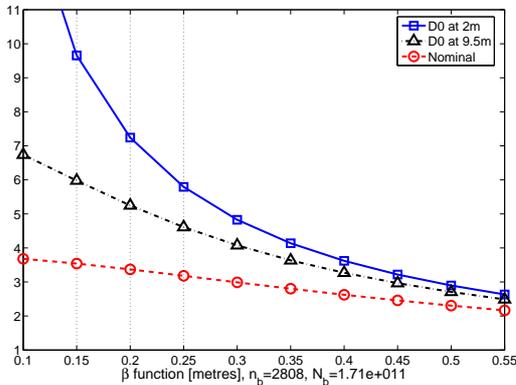

Figure 2: D0's performance with the ultimate current.

REQUIRED BEAM SEPARATION

As already mentioned, there is no established theory to predict the required beam separation in a configuration with an early separation. This knowledge is however critical to define the strength specification of the D0 dipole depending on its position with respect to the crossing point. We shall thus use qualitative arguments and verify them by tracking.

Preliminary Criterion for an Appropriate Beam Separation

The calculations of the required beam separation and tracking are all made for the baseline LHC optics version 6.5 ($\beta^* = 0.55$ m). This is primarily justified by the availability of the optics. A second justification is the large number of beam–beam tracking results available; they are essential to check out the tracking procedure that we used and that shall reproduce the existing results when D0 is at the IP. The interpretation of the tracking results relies on a sensitive criterion for the detection of the onset of strong diffusion or chaos as defined in [4].

The beam–beam tracking program used is BBTrack [6] after preparing the optics and separation system with the MAD program that is used to produce the BBTrack input.

To estimate the position of D0 and calculate its strength, we make the following conjectures: the average separation matters more than a few closer-by encounters; its value shall be the nominal 9.5 σ for the nominal beam current and scale like Eq. 2; a minimum beam separation of 5 σ shall be respected. These conjectures are based on an interpretation of former results: in the Sp$\bar{\text{p}}$S, a single encounter at a distance of 3.5 σ did not cause beam dynamics problems [7] while the average beam separation was 6 σ. Compensating in simulation the closer-by encounters at the Tevatron did not result in a significant improvement [8]. Theoretical investigations qualitatively show a threshold effect for the long-range beam–beam force [5].

D0 before the First Parasitic Encounter

In this ideal separation scheme, a zero crossing angle is allowed by putting the orbit corrector before the first parasitic encounter. We propose to put the D0 at 2 m from the IP producing an angle of 166 μrad in the nominal case. In Fig. 4 we represent the normalized distance between the two beams in this particular case. For a given beam current, we can scale the integrated field required for the D0 with $\frac{1}{\sqrt{\beta^*}}$ (Table 1).

D0 before the Third Parasitic Encounter

We explored also an other scheme less demanding for the detectors. The D0's are put at 9.48 m from the IP with a kick of 160 μrad (Table 1). Since we are not anymore before the first parasitic encounter, *we need a non-vanishing but smaller crossing angle*: we choose $\theta_c = 142.5°$, that is half the nominal, to limit the luminosity geometrical loss
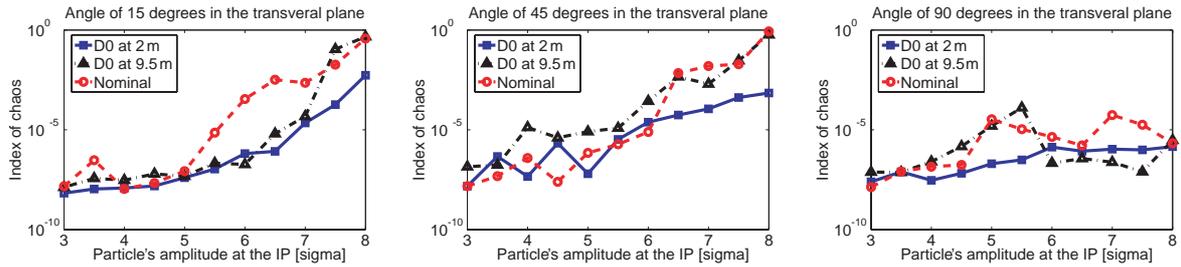
Figure 3: Analysis of the tracking results through the index of chaos, for three initial angles in the *xy* space.
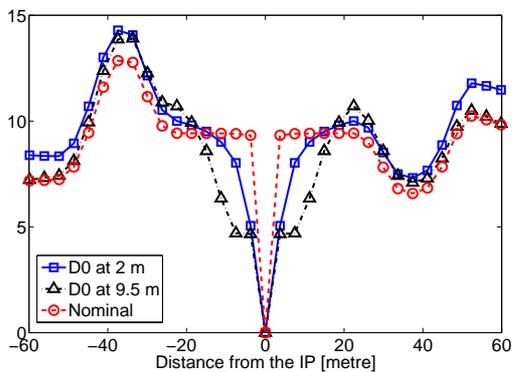

Figure 4: The separation between the two beams in the proximity of the IP$_5$.

Table 1: Minimum magnetic integrated field in the D0 at 2 m from the IP ($n_b = 2808$, $N_b = 1.71 \cdot 10^{11}$).

	$\beta^*[m]$	Integrated field $[T \cdot m]$	L/L_0
D0	0.25	6.1	5.7
at	0.20	6.8	7.2
2 m	0.15	7.9	9.5
D0	0.25	5.9 (6.8 if $n_b = 5616$)	4.6 (8.6)
at	0.20	6.6 (7.6 if $n_b = 5616$)	5.2 (9.7)
9.5 m	0.15	7.6 (8.7 if $n_b = 5616$)	5.9 (10.8)

and, on the other hand, to allow a minimum beam separation by 5 σ. To maintain the same aperture in the quadrupoles we add an other orbit corrector in front of the triplets. We obtained the separation presented in Fig. 4.

Impact of the Beam–beam Effect

The non-linear force due to the beam–beam interaction induces a chaotic motion in the large-amplitude particles. The strategy we adopted for comparing the nominal separation scheme and the new ones is based upon the detection of the chaotic regime. We use as index of chaos the variance of a particular function of the emittance [4].

The results of the tracking are shown in Fig. 3. From the comparison between the nominal and the new separation schemes as far as concerning the beam–beam interaction, the early separation schemes proposed seem to be at least as efficient as the nominal separation, confirming that the conjectures made are sufficient and possibly conservative: the encounters at 5 σ are indeed not found critical.

CONCLUSIONS

In this work we presented two new separation schemes to reduce the geometrical loss factor F, giving a much enhanced luminosity reach for low values of β^*. A salient finding is the relatively weak impact of a small number of encounters with a reduced beam separation. The positions and required integrated field of the D0 dipoles are now defined and allow the integration and implementation studies to be initiated.

ACKNOWLEDGEMENTS

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