INCREASING THE INTEGRATED LUMINOSITY OF SLHC BY LUMINOSITY LEVELLING VIA THE CROSSING ANGLE

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Abstract

With an increase of luminosity by a factor of 10, the luminosity lifetime in an upgraded LHC would decrease from 15 hours to two to four hours, depending on the upgrade strategy. If the luminosity increase is achieved primarily by a stronger and more efficient focusing rather than a beam current increase, the luminosity lifetime is in the low bound of this range. We show in this paper that the "early separation" scheme and/or a crab crossing lend itself to a very efficient luminosity levelling. It can be used to counteract the faster luminosity decay and provide a constant luminosity over hours as well as a significant increase of integrated luminosity. This is achieved by adjusting the crossing angle rather than the β^* function by means of a bump closed inside the experimental straight section, i.e. operationally simple. The initially large crossing angle reduces the beam-beam tune shift, allowing an increased beam current and higher performance with lower pile-up in the detector and lower energy deposition in the triplet. The impact of the large Piwinski angle required is first investigated.

INTRODUCTION

The ultimate goal of the LHC luminosity upgrade is to increase the integrated luminosity by a factor of 10. Several solutions are being explored [1]. In all cases, the initial luminosity lifetime is much decreased from 15 hours (nominal) to 2 to 4 hours. This very fast decay would made operations inefficient and would require a large and costly over sizing of many systems to cope with the initial large peak luminosity. Luminosity levelling by a modulation of the β^* function has often been proposed but not implemented in existing colliders due to its anticipated side-effects and significant development time. In this paper, we rather consider a modulation of the crossing angle in the framework of an upgrade based on an “early separation” scheme. Almost all side-effects are suppressed, making this procedure especially attractive for operations. The same principle can be considered if the early separation scheme is replaced by crab crossing, though with some more side-effects.

THE EARLY SEPARATION SCHEME

The principle of the Early Separation Scheme (ESS) [2] is to suppress or reduce the crossing angle at the IP while maintaining the required beam separation in the section of the machine common to the two beams, by means of small dipoles (D0) placed deep inside the detectors (Fig. 1). In this way, the geometrical luminosity loss is cancelled for an ideal scheme or significantly reduced for a practical scheme where the D0 dipole cannot be installed close enough to the collision point, with one or two long-range encounters remaining in between the crossing point and the D0 (Fig. 1). This crossing scheme opens the possibility of increasing the luminosity by reducing β^* from its nominal value of 55 cm to 15 cm [2]. Its distinct advantage is a significant gain in luminosity while avoiding hazards caused by a significant beam current increase. Its serious drawback is the interference with the detector, imposing strong restrictions on the position of the D0 magnets and integration issues.

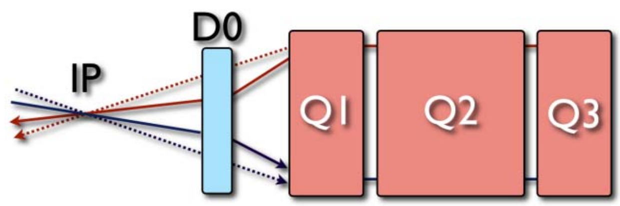

Figure 1: practical early separation with reduced crossing angle at the IP

REFERENCE SCENARIO

In the ideal ESS, the D0 dipole shall be located well before the first beam interaction point after the IP. For a 25 ns spacing (7.5 m), this position (typically 1.9 m from the IP) is inside the inner detector and hence excluded. Table 1 gives the possible positions for the two bunch spacings contemplated (25 ns and 50 ns) [2].

Table 1: Possible dipole (center) positions

		25 ns	*50 ns*
Full early separation		~~1.9 m~~	3.8 m
Partial early separation	4LRs @ 5σ	5.6 m	11.25 m
	8LRs @ 5σ	9.4 m	~~18.8 m~~

The present understanding of the long-range beam-beam effect excludes the position at 18.8 m, just at the exit of the detector, that would impose a bunch spacing of at least 50 ns. The required magnetic field integral depends on the D0 position chosen and on the strategy for the bump closure. The positions at 3.8 m and 5.6 m are favored, the first one allowing ideal early separation for a 50 ns spacing. For these positions, the required field integral is in the range 5 to 8 Tm, depending on the exact D0 position and value of the β^* function, for a bump confined in the straight section. In these two scenarios, one or two long-range encounters occur on each side of each of the two high luminosity insertions at a reduced separation of 5σ. The tolerance of the beam dynamics to these perturbing interactions is the driving criterion for the choice of the D0 position, taking into account that, from the detector point of view, the IP to D0 distance shall be maximized by all means.

This was an incentive to investigate in simulation and experimentally the consequence of long-range beam-beam interactions at reduced distance. Experiments were conducted at RHIC and in the SPS in 2007. Their results are discussed in [3], with the following outcome: Experiments have shown that a certain number of long-range encounters at a reduced distance (5σ) can be tolerated. However, their exact number is not yet clear (4 to 8?) and requires further dedicated experiments at RHIC. Another interpretation of the RHIC results is much less favourable [4], but raises consistency issues with observations on the SPS as proton-antiproton collider [5] and with former simulation results establishing the predominance of the long-range beam-beam effect over the head-on effect [6]. A simple model (2D with tune modulation) seems to show indeed (Fig. 2) that a few long-range encounters would be comparable to the SPS running conditions and acceptable. Further 6D detailed simulations are planned to further clarify this point.

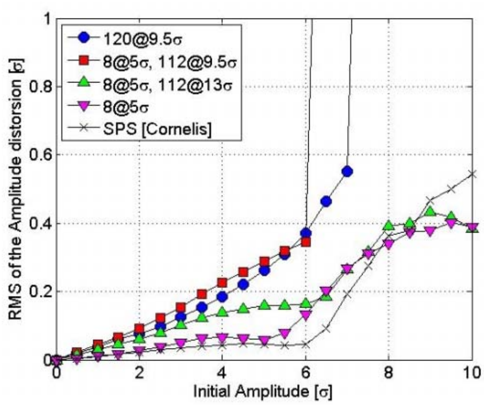

Figure 2: Amplitude distortion for several scenarios of long-range encounters: 1) nominal LHC; note the onset of chaos, 2) ESS, 3) ESS with enlarged separation in the triplet, 4) contribution of 8 encounters at a reduced separation, 5) SPS collider operating conditions.

We select for the reference scenario the D0 position at 5.6 m and β^* of 15 cm allowed by the ESS [2].

POSSIBLE SCENARIO IMPROVEMENTS

There are several methods to mitigate a perturbation by close encounters that would turn out to be excessive in the chosen reference scenario:

- the maximum separation at the long-range encounters can be increased from 9.5σ to 12 or 13σ with a significant improvement in 2D simulation. Alternatively wire compensation [7,4] can be applied to 9.5σ separation with the same result, only leaving the effect of few encounters at reduced distance,
- for the first encounters at 5σ, compensation by a physical wire so close to the beam is impossible but an electron lens becomes very attractive. Its effect on the beam is now well studied, with the demonstration of the absence of emittance blow-up [8]. A further advantage of electron-lens compensation would be the ability to further reduce the minimum beam separation below 5σ to further reduce the luminosity geometrical loss factor.
- small angle crab crossing [9] could compensate the residual crossing angle to recover head-on collision at the crossing point. The rotation angle would be of the order of 200 µrad. This scheme appears significantly simpler and less demanding than a full local crab crossing.

LUMINOSITY LEVELLING STRATEGY

The nuclear reactions dominate the luminosity decay [10]. Rearranging formulas in [10], the luminosity decay takes a simple form:

$\frac{\partial L}{\partial t} \propto -\frac{L^2}{I_b}$, where I_b is the total beam current. This shows that, for a given luminosity goal L, the ESS, that strives increasing performance with a minimum current increase, yields a lower integrated luminosity. Actually all upgrade scenarios suffer from too short lifetimes and call for luminosity levelling as an integral part of the design.

By adding an orbit corrector in front of Q1 (Fig. 1), the ESS lends itself to a natural levelling scheme: the geometrical loss factor F can be adjusted on-line by varying the crossing angle θ_c at the IP, while keeping constant trajectories outside the experimental straight sections.

$$L \propto F \quad F = 1\Big/\sqrt{1+\Phi_P^2} \quad \Phi_P = \frac{\theta_c}{2}\frac{\sigma_s}{\sigma^*}$$

$$\Delta Q_{bb} \propto F$$

where Φ_P is the Piwinski angle, a transform of the full crossing angle θ_c by the ratio of the longitudinal to transverse beam sizes σ_s and σ^*.

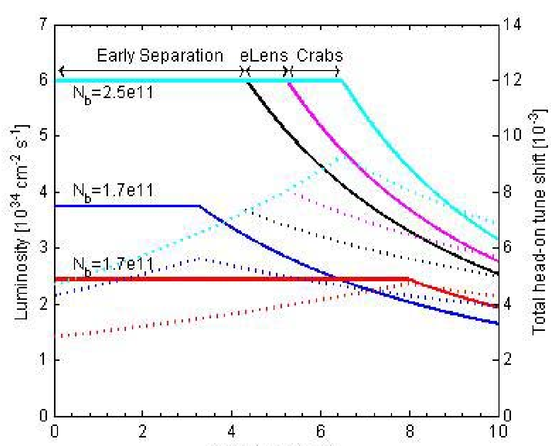

Figure 3: Luminosity with levelling and HV crossings versus time: 1) Nb=1.7 10^{11}ppb, 2) Nb=2.5 10^{11} ppb.

Assuming a bunch charge limited at its “ultimate” value Nb = 1.7 10^{11} protons per bunch, two levelling strategies are illustrated on Fig. 3 (lower curves). The luminosity can be stabilized for 4 or 8 hours at a cost of about 20% in integrated luminosity [3].

Since the beam-beam tune shift remains well below its assumed limit of 0.01, the levelling scheme opens the possibility of increasing the beam current without violating the beam-beam limit. This is shown on the upper curve where the bunch charge was increased to 2.5 10^{11} ppb, the assumed limit set by the electron cloud effect for a 25 ns bunch spacing. The luminosity is constant at 6 10^{34} $cm^{-2}s^{-1}$. The beam-beam limit is reached after at least 4 hours, when the beam current has already significantly decayed. During levelling, the beam is displaced farther away from the vacuum chamber. This should be favourable for operations. The availability of an electron lens would allow a further reduction of the beam separation (here assumed to be 3.5σ), thereby extending the period of constant luminosity. A small angle global crab crossing would allow a further improvement. It could be the test bed for a larger local crab crossing replacing the ESS for the same performance. This strategy of levelling via the crossing angle increases the integrated luminosity by a large factor (about 2) without optical side-effects.

The multiplicity is significantly reduced in the detectors to around 150 events per crossing (assuming a cross-section of 80 mbarn). The peak irradiation and heat deposition are decreased accordingly. Similar performance can be obtained with the same hardware and a bunch spacing of 50 ns if the bunch charge is increased to the level assumed in the LPA option [4].

Two issues have nevertheless to be considered: i) the modulation of the longitudinal extent of the luminous region, initially decreased by about a factor of 2; ii) the consequence of a large Piwinski angle, up to 3.5.

LARGE PIWINSKI ANGLE

Preliminary weak-strong simulations of head-on collisions alone at the maximum value of the crossing angle (794 μrad, i.e. Piwinski angle of 3.5) show no impact on luminosity for the range of bunch charges considered. These simulations shall be repeated including the long-range beam-beam effect.

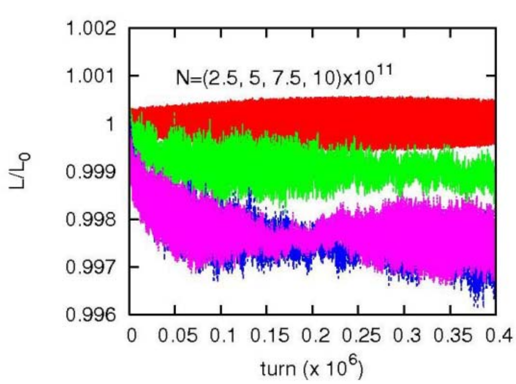

Figure 4: Luminosity evolution versus intensity for a Piwinski angle of 3.5, H-H crossing and several bunch charges

CONCLUSION

The native luminosity levelling associated to the early separation scheme alleviates a serious defect of the LHC upgrade phase 2 related to a too fast decay of the luminosity with time. Indeed the levelling applies not only to the luminosity but as well to the beam-beam tune shift. The initially lower tune shift allows for more beam current. Hence levelling through the collision angle opens the possibility of increasing significantly the integrated luminosity. It then becomes possible to propose a scenario with a constant luminosity of 6 10^{34} $cm^{-2}s^{-1}$ for 4.5 hours to 6.5 hours depending on the availability of "adds-on " (electron lens, weak crab crossing), followed by the natural decay. The multiplicity is significantly reduced to about 150. A first investigation of the large Piwinski angle required does not identify measurable perturbations. It should be noted that all advantages of the above solution can be provided by a local crab crossing scheme alone, without interference with the detectors, if its very stringent requirements can be met with sufficient reliability. On the other hand, the implementation of the early separation scheme relies on well known and predictable techniques, even though certain aspects of the magnet design are challenging [11].

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