OPTIMIZING THE LHC INTERACTION REGION TO OBTAIN THE HIGHEST POSSIBLE LUMINOSITY

W. Herr and J. Miles, CERN, Geneva, Switzerland

Abstract

The CERN Large Hadron Collider (LHC) is designed to reach the highest possible luminosities for proton-proton collisions. The maximum reachable luminosity is limited by beam-beam effects. It will be shown how the interplay of parameters such as: β^*, crossing angle, bunch spacing, energy and crossing schemes affect the beam-beam effect and therefore the luminosity. The possible side effects of the crossing geometry are evaluated and we define a set of parameters to maximize the luminosity.

1 WHAT LIMITS THE LUMINOSITY ?

1.1 Relevant parameters

The luminosity of the LHC can be written as:

$$\mathcal{L} = \frac{N^2 k_b f \gamma}{4\pi \epsilon_n \beta^*} \cdot F \tag{1}$$

where N is the number of proton per bunch, k_b the number of bunches, f the revolution frequency, γ the relativistic factor, ϵ_n the normalized emittance, β^* the betatron function at the collision point, and F a reduction factor for the crossing angle which is about 0.9 for the LHC [1, 2, 3].

1.2 LHC beam-beam effects

The most important luminosity limitation comes from beam-beam interactions which in the case of the LHC have several components. The LHC is operated with a large number of closely spaced bunches and to prevent collisions where the two beams share a common vacuum chamber, the bunches collide at a small horizontal crossing angle. However, this cannot suppress the so-called long range interactions between the separated beams in the common part. Since the bunches are closely spaced, a bunch experiences many long range interactions and their overall contribution becomes important [2, 4]. This type of interaction is non-linear and contributes to the tune spread. Experience has shown that this tune spread has to stay below certain limits [5] The contributions from both, head-on and long range interactions have to be evaluated to determine the maximum intensity for a tune spread smaller than the required value. The choice of this value is largely based on experience obtained at the SPS collider [5]. We have adopted a limit of ΔQ = 0.01 for the tune space occupied by the beam and this determines the maximum intensity.

1.3 "Normal" and PACMAN bunches

In the LHC each beam consists of a train of bunches. However, the finite rise time of the injection and extraction kickers of the injectors require small gaps without bunches in the train and a large gap is necessary for the abort system [2]. Normally, a bunch in one beam will always meet another bunch at all head-on and long range interactions. Bunches near the gaps may encounter missing bunches at parasitic collision points. These bunches have therefore an irregular collision scheme with fewer long range interactions [2] and tune shifts. The working point must be chosen such that these irregular bunches do not cross dangerous resonances. The spread of ΔQ = 0.01 has to include the nominal as well as the irregular bunches, otherwise the latter are potentially unstable if the working point is optimized for nominal bunches. Since the bunches next to the gaps are the most irregular, they would be lost first and the gaps increase leading to other bunches becoming irregular. This effect of losing bunches from the gaps is usually referred to as the PACMAN effect. The bunches are called PACMAN bunches.

2 PARAMETER DEPENDENCE

2.1 Beam separation and crossing angle

The relevant parameter for the strength of long range interactions is the separation of the two beams. In the drift space between the collision point and the focusing triplet the β-functions of the two beams are equivalent and the separation (in units of σ) can be written as [4]:

$$d_{sep} = \frac{x(s)}{\sigma(s)} = \frac{\alpha \cdot s}{\sigma(s)} \approx \frac{\alpha \cdot \beta^*}{\sigma^*} \tag{2}$$

$$= \frac{\alpha \cdot \sqrt{\beta^*}}{\sqrt{(\epsilon \beta_r \gamma)}} = \frac{\alpha \cdot \sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} = const. \tag{3}$$

where α is the full crossing angle (200 μrad), $\epsilon_n = (\epsilon \beta_r \gamma)$ the normalized emittance, β^* the betatron function and σ^* the beam size at the collision point. The parameters β_r and γ are the usual relativistic factors. This expression is valid as long as $\beta(s) \propto s^2$, i.e. in the drift space on both sides of the interaction region (IR) where $s \gg \beta^*$.

When the beams enter common quadrupoles, the betatron functions and therefore the sizes as well as the closed orbits of the two beams do not follow a simple behaviour and the correct optics parameters have to be taken into account [8].

Tune spread It can be demonstrated [4] that the tune spread from long range interactions scales approximately as $1/d_{sep}^2$ and to minimize the spread it is important to have sufficient separation. According to (3) the separation is proportional to the crossing angle α and $\sqrt{\beta^*}$. The value of α is however limited by the aperture of the focusing quadrupoles and by the excitation of synchro-betatron resonances since a finite crossing angle couples longitudinal and transverse motions [6]. This effect was simulated [2] and a value of $\alpha = 200\ \mu$rad was chosen as a compromise. A too large crossing angle would reduce the luminosity (see factor F in (1)) since the effective beam size is increased in the crossing plane. The optimization of β^* is treated in a later section.

2.2 Bunch spacing

Although the effect of one long range interaction is rather small, their large number makes this component very important. This number depends on the lengths of the common part and the bunch spacing. If the intensity is limited due to long range effects, it seems feasible to increase the luminosity by reducing the number of bunches. A reduced number of bunches would result in a reduced contribution of the long range effects to the tune spread allowing a higher intensity and may lead to a net increase of the luminosity since the luminosity is proportional to the square of the bunch intensities. This is however limited by requirements from the experiments which cannot handle a too large number of interactions per bunch crossing. The optimum spacing was found to be 25 ns [7] for the present set of parameters [3].

2.3 Tune footprints and crossing scheme

A convenient way to show the tune spread is in terms of tune footprints. Such a footprint is shown in Fig. 1 for a single interaction region. All tune shifts are normalized to the lin-

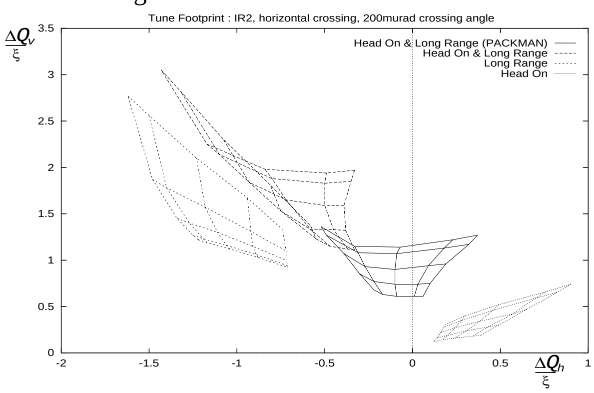

Figure 1: Tune footprint for single interaction region.

ear beam-beam tune shift ξ. The figure shows separately the head-on and long range components as well as the combined footprint for both, the nominal and the PACMAN bunches. The footprint of PACMAN bunches is displaced with respect to the nominal bunches, increasing the tune spread. With increasing long range contributions this displacement becomes larger. Additional, identical collision points simply scale the footprints. However, it is well known that for separated beams the tune shift has opposite sign in the plane of separation when the separation is sufficiently large (see long range footprint in Fig. 1). Alternating crossings, i.e.

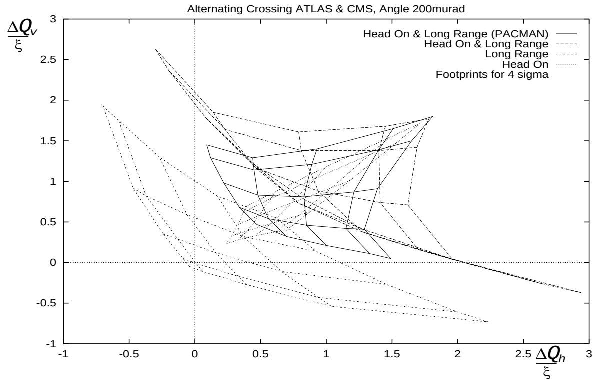

Figure 2: Tune footprint for two interaction regions with alternating crossing. Tune shifts normalized to ξ.

a horizontal and a vertical crossing can decrease substantially the overall spread [7, 8, 10] by compensation. This is shown in Fig. 2 for two IRs. A possible alternative is a

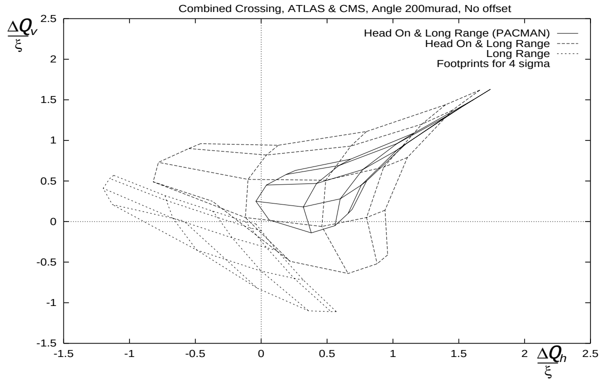

Figure 3: Tune footprint for single interaction region with crossing in both planes

crossing in two planes simultaneously (tilted crossing) since the compensation effect is always present and the asymmetry between the incoming and outgoing beam is largely decreased [9, 10]. Such a scheme is shown in Fig 3. For both cases the footprints are more symmetric and in particular the PACMAN footprint does not increase the tune space, in the latter case it is even entirely inside the nominal footprint. One should therefore choose a scheme where the PACMAN effect on the tune spread becomes negligible. For a detailed comparison of the required tune space it should be noted that for Fig. 1 only one interaction region is used while Figs. 2 and 3 are shown for two collision points: the tune space occupied by nominal and PACMAN bunches is reduced by at least 30 - 40 % for two alternating crossings and the space for two crossings in both planes is comparable to the single interaction region, i.e. the reduction factor is almost two.

2.4 Number of experiments and periodicity

Since the contributions to the tune shift add up from the different IRs the number of experiments plays an important role in the optimization [2]. Furthermore, a design with alternating crossings requires an even number of experiments for a good compensation. A further consequence of the abort gap in the bunch train is the appearance of ”SUPER PACMAN” bunches in case of more than two IR or unsymmetric layout: those bunches will have fewer head-on collisions which may lead to a further increase of the tune spread. An IR longitudinally displaced with respect to the symmetry point has the same consequences. A symmetry with two experiments exactly opposite is therefore desirable for highest luminosities.

3 LUMINOSITY OPTIMIZATION

3.1 Optimization strategy

The aim of the optimization process is to define a set of parameters which maximizes the luminosity and respects the constraints. The most important parameter, the bunch intensity, is always adjusted to get the maximum allowable tune spread in the beam and therefore maximizing the luminosity is mainly minimizing the tune spread. Due to the limited space, only the optimization of the most important parameters is discussed, other parameters such as transverse offset or orbit effects [10, 11] are not treated here.

3.2 Head-on versus long range interactions

The total current is limited and the head-on component of the beam-beam interaction cannot easily be manipulated however the long range component is sensitive to many parameters. In case of several experiments with identical crossings the tune spread is entirely dominated by the long range part [4] and PACMAN effects are important. The reduction of the long range effects is therefore the prime aim of the procedure. Alternating or tilted crossings are required for high luminosity.

3.3 Optimization of β^*

When the overall tune spread is dominated by *long range effects*, another option is a larger β^* at the collision point since it reduces the long range effects (see (2) and (3)) and allows a higher intensity. The luminosity increases with a higher power of the intensity than it decreases with β^* and one can hope to increase the luminosity by a larger β^* when the long range effects dominate. Therefore an attempt is made to find a value for β^* where the luminosity is maximum. The procedure is to increase β^* and simultaneously raise the intensity to reach the limit of $\Delta Q^{tot} = 0.01$. Fig. 4 shows the relative luminosity as a function of β^*. The dashed line in the figure corresponds to the maximum luminosity imposed by the total current limit ($4.7 \cdot 10^{14}$ particle/beam or 0.85A) showing a behaviour $1/\beta^*$. In the first, rising part of the curve, the intensity is limited by the long range tune spread and reducing β^* allows higher intensity and luminosity. An optimum for β^* around 0.5 m is clearly observed and the gain of luminosity between β^* = 0.4 m to 0.5 m is almost a factor two. It can be demonstrated [8] that the precise value of the optimum β^* depends strongly on the choice of the other parameters and values between 0.45 m and 0.80 m have been found for various scenarios.

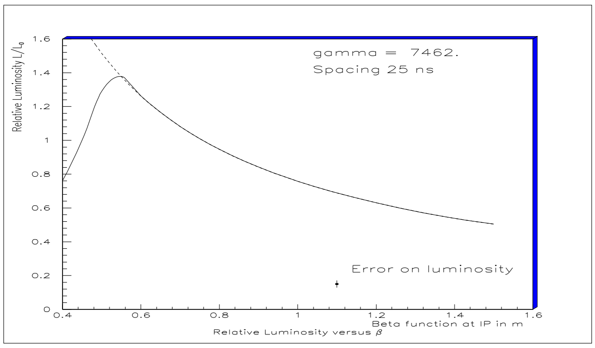

Figure 4: Relative luminosity as function of β^*

4 CONCLUSION

It has been shown that a set of parameters such as e.g. crossing scheme and angle, bunch spacing, β^* can be found to maximize luminosity. This choice is however rather sensitive to the precise scenario and a slightly modified layout (e.g. number of experiments or crossing scheme) may lead to an entirely different set of parameters and we have presented the basic considerations for such an optimization procedure. We strongly recommend that the LHC design is flexible enough to adjust these parameters as required to reach the desired luminosity.

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