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BEAM-BEAM EFFECTS IN DIFFERENT LUMINOSITY LEVELLING SCENARIOS FOR THE LHC

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Abstract

Adjusting luminosity and optimizing the luminous region in each interaction point of the LHC according to the experiments needs has become a requirement to maximize the efficiency of the different detectors. Several techniques are envisaged, most importantly by varying β^* or a transverse offset at the interaction point. Coherent and incoherent stability in the presence of beam-beam effects will be discussed in realistic luminosity levelling scenarios for the LHC.

INTRODUCTION

The two high-luminosity experiments at the Large Hadron Collider (LHC), ATLAS and CMS, were designed for a pile-up of 25 events per bunch crossing. Towards the end of the 2012 proton run, pile-up around 35 were routinely treated by the experiments. Optimistic scenarios for the operation of the LHC in 2015 leads to a pile-up around a factor 3 larger. While luminosity levelling techniques were already used for the two lower luminosity experiments, LHCb and Alice, these new conditions require the use of levelling techniques for the two high luminosity experiments as well. As beam-beam effects are strongest in these interaction regions, the dynamics of the particles may be strongly affected, depending on the method chosen. In the following, we neglect beam-beam effects in the other two interaction regions.

Levelling Techniques

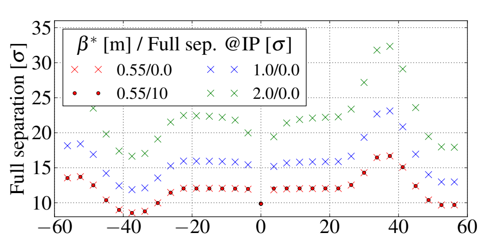

Figure 1: Normalized separation between the beams at the location of long-range beam-beam interactions, for different β^* and offset at the IP with a fixed crossing angle of 270 μrad.

Cross talk between the experiments is to be avoided. For this reason, global levelling techniques, e.g. by varying the bunch length or using RF cogging, are not considered. The remaining options to control the luminosity employ the crossing angle, the β^* or a transverse offset at the Interaction Point (IP).

The values of the crossing angle and β^* are limited both by the separation required between the beams at the locations of the long-range beam-beam interactions, which limit the dynamic aperture and by the available physical aperture in the triplet. The optimal set of crossing angle and β^*, respectively θ_0 and β_0^* would yield the maximum virtual luminosity achievable with a beam of a defined brightness. In such configuration, it is not possible to increase the crossing angle in order to reduce the luminosity, without reducing the β^*. Therefore, it is not possible to level luminosity with the crossing angle only, whereas it is possible to reduce β^* significantly without having to change the crossing angle. Comparing the β^* before and after the betatron squeeze, in the nominal case we obtain a potential reduction factor slightly above 1/20, without having to change the crossing angle.

A transverse offset at the IP of several σ, the r.m.s. transverse beam size at the IP, can easily be achieved without physical aperture constrains, consequently this techniques may provide any reduction factor.

In the following, we shall compare the limitations linked to beam-beam effects while levelling with β^* or with a transverse offset, keeping a fixed crossing angle in both cases. As illustrated by Fig. 1, only the former has a strong impact on the long-range beam-beam separation. Due to the rather small crossing angle, the effect of head-on beam-beam interactions varies weakly with β^*. The opposite is true for the transverse offset at the IP, the contribution of the beam-beam collision strongly varies during the procedure, while the normalized separation between the beams remains almost constant at the location of long-range interactions (Fig. 1). The effect on the single particle dynamics is well illustrated by the tune footprint, i.e. the tune of particles oscillating at different amplitudes in the horizontal and vertical plane plotted on a tune diagram. Figure 2 shows the tune footprint when varying the offset or the β^* in the two high luminosity experiments simultaneously. We observe that varying the offset mainly affects the tune shift of core particles, driven by the single near head-on interaction at the IP, while varying β^* has a small impact on core particles, due to the non-negligible Piwinski angle, $\phi_p = \frac{\theta\sigma_s}{2\sigma} \approx 0.8$, with σ_s the r.m.s. bunch length. Yet, there is a strong effect on the tail particles, driven by the reduction of the normalized separation at the position of the long-range interactions.

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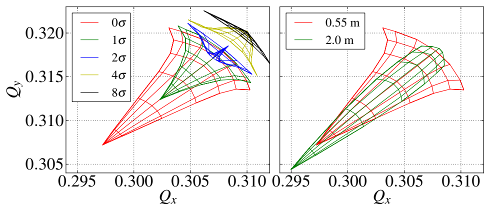

Figure 2: Tune footprint for different separations at the IP (left) and different β^* (right), with the machine and beam parameters of Tab. 1.

Table 1: Machine and Beam Parameters at the Beginning of Luminosity Production

Parameter	Value	Parameter	Value
Energy [TeV]	6.5	Intensity[10^{11}p]	1.3
Emittance [μm]	1.9	Bun. len. [cm]	7.55
β_0^* [m]	0.55	θ_0 [μrad]	270

Levelling Scenarios

With a visible cross section of $85 \cdot 10^{27}$ cm^{-2} and the parameters in Tab. 1, one obtains a pile up of 58, potentially above the experiments' acceptance. Figure 3 illustrates the evolution of the β^* or the transverse offset with the decaying intensity in order to keep the pile-up fixed to either 25 or 50 events per bunch crossing, assuming no emittance blow up during luminosity production [1].

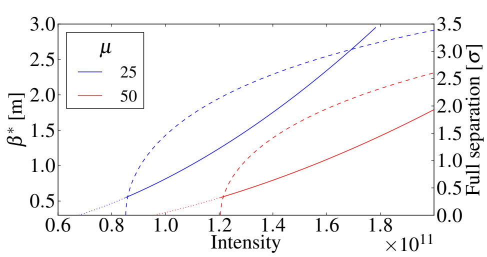

Figure 3: Levelling scenarios with fixed pile-up, with β^* (solid) or with a transverse offset (dashed), assuming the emittance remains constant during the levelling procedure. The dotted lines shows the prolongation with $\beta^* < \beta_0^*$.

DYNAMIC APERTURE

On top of the variation of the amplitude detuning, the resonance driving terms. due to near head-on collisions, as well as of the long-range interactions strongly varies during both levelling scenarios. The combination of both, leads to limitations in the dynamic aperture, it was shown that while colliding head-on with nominal LHC parameters, the dynamic aperture scales linearly with the bunch intensity and with the normalized separation between beam in the drift space around the IP, $d \approx \theta\sqrt{\frac{\beta^*}{\epsilon}}$, with ϵ the physical transverse emittance [2]. Dynamic aperture simulations with SixTrack [3], following the levelling scenarios of Fig. 3 with different crossing angles tends to validate these statements (Fig. 4). Besides, when considering β^* levelling, the reduction of the normalized separation follows the bunch intensity decay. The beam dynamics is, therefore, improved with respect to a scenario without luminosity levelling, the beneficial effect being more visible for the case with a smaller pile-up limit. As towards the end of the levelling procedure the brightness of the beams is smaller with respect to the one initially used to compute the β_0^* and θ_0. They may be adapted and therefore increase the potential levelling duration.

The head-on beam-beam forces vary strongly as a function of the transverse offset at the IP, leading to a complete flip of the footprint during the levelling procedure (Fig. 2). Nevertheless, Fig. 4 shows that the dynamic aperture remains almost constant for all separations. The slight increase of the dynamic aperture for small separations is only due to the intensity decay. This indicates that the dynamic aperture limitations are driven by long-range beam-beam interactions, as already observed with design LHC parameters [4].

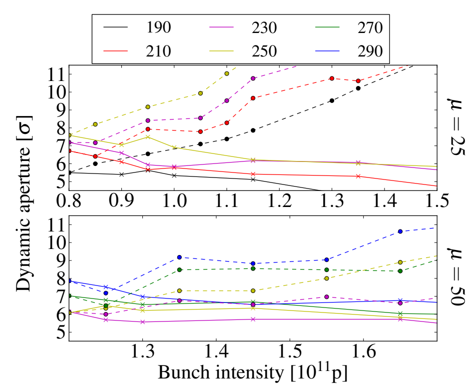

Figure 4: Comparison of the dynamic aperture while levelling with an offset (solid) or with β^* (dashed). The upper and lower plots corresponds to the levelling scenarios with a pile up limited to, respectively, 25 and 50, that are described in Fig. 3.

COHERENT STABILITY

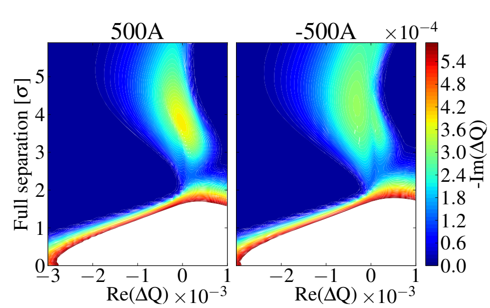

Figure 5: Stability diagram of the most critical bunch while levelling with a transverse offset at the IP, with either polarity of the octupoles at full strength.

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The variations of the tune spread due to the near head-on collision while levelling with a transverse offset at the IP has a strong impact on Landau damping of instabilities driven by the machine impedance [5]. The resulting stability diagram, using machine and beam parameters of Tab. 1 are shown in Fig. 5, for two polarities of the octupoles. As the detuning is different for each PACMAN bunch [7], we chose the one with the most critical stability diagram in both configurations. We observe that the stability is critical for separations in the order of 2 σ, which is in the levelling range of interest. Octupole magnets are used to provide detuning, i.e. Landau damping, in absence of beam-beam interactions. However, in such configurations, their impact on the stability diagram is marginal, compared to the contribution of the near head-on collision. In particular, coherent instabilities were observed during the 2012 run of the LHC, in both configurations [6, 8]. For smaller separations, the stability diagram is dominated by the detuning of core particles [5], significantly improving the stability diagram.

Levelling with β^* offers the possibility to improve the stability diagram all along the procedure. Indeed, the large tune spread for core particles is established already at the beginning (Fig. 2). The increasing strength of long-range interactions has a strong impact on the tails only and therefore does not affect significantly the stability.

Strong mode coupling instabilities of impedance and beam-beam coherent modes are also expected in configurations with offset collisions in the two IPs [9]. While these instabilities are well damped by the transverse feedback, it is important to note that, as opposed to β^* levelling, the presence of a transverse offset at the IP enforces the usage of the transverse feedback during luminosity production. Nevertheless, the LHC was routinely operated with an active transverse feedback during luminosity production, without major detrimental effect.

LUMINOUS REGION

The shape of the luminous region, in particular the longitudinal width, has an impact on the detectors' efficiency [10]. The two levelling scenarios are not equivalent in that respect. Assuming Gaussian profiles in all dimensions and neglecting hourglass effect, the r.m.s. longitudinal luminous width is given by:

$$\sigma_{\mathcal{L}} = \frac{\sigma_s}{\sqrt{2\left(1+\phi_P^2\right)}}, \tag{1}$$

the effect of the hourglass effect being neglected, as it is below 1% in the configurations considered. Because of the fixed crossing angle, the longitudinal luminous width is larger by around 10% when levelling the luminosity by a factor 2 with β^*, with respect to the minimum width, achieved with β_0^* and θ_0.

The simulations above were performed with a separation in the plane perpendicular to the crossing angle plane. A full separation Δx in the crossing angle plane leads to a longitudinal displacement of the luminous region given by:

$$\Delta s = \Delta x \frac{\theta}{2}\frac{\sigma_s^2}{\sigma^2}\frac{1}{1+\phi_p^2}, \tag{2}$$

which is in the order of 4 cm to obtain a reduction factor of 0.5, in the scenarios considered.

CONCLUSION

Levelling with β^* is more challenging from the operational point of view, yet not out of reach [11]. Nevertheless, it was shown that levelling with β^* significantly improves both the single particle dynamics and the coherent stability of the beams with respect to levelling with a transverse offset. The gain in dynamic aperture may allow to increase the β^* reach, even more in future scenarios with higher brightness beams [12]. This option also has the advantage of ensuring the coherent stability of the beams through the whole procedure, profiting from the large tune spread for small amplitude particles arising from head-on collision.

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