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STRONG-STRONG SIMULATIONS OF β^*-LEVELLING FOR FLAT AND ROUND BEAMS

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Abstract

Simulations of β^* luminosity levelling using the strong-strong beam-beam code *COMBI* are undertaken. Simulations for both flat and round beam profiles are discussed and analysed with respect to the coherent spectra. It is shown that bunches with a round beam profile will have a beam-beam parameter that is independent of β^* over the levelling steps. Flat bunches however will have a beam-beam parameter that is dependent on β^* over the levelling steps since the beam aspect ratio will change. This will change the tune of the π-mode as the β^* is levelled, which could lead to a resonance crossing.

INTRODUCTION

The High Luminosity Large Hadron Collider (HL-LHC) upgrade will allow the LHC to reach ever higher luminosities. However an increase in luminosity will lead to higher "pile up" in the machine detectors. To prevent higher "pile up" in the machine detectors luminosity levelling has been suggested, which will hold the luminosity constant over the duration of a physics run. There are a number of suggested methods of levelling the luminosity, although β^*-levelling at IP1 and IP5 (Interaction Point) in combination with offset levelling at IP8 are the baseline methods of luminosity levelling [1]. Levelling by reducing the β^* as the luminosity decays exponentially will hold the longitudinal vertex density constant throughout the process for head on collisions. This is required by the detectors.

Flat beams have been proposed as an alternate method of operation if crab cavities are not installed in the HL-LHC. Flat beams will provide a low β-function at the IP, allowing higher luminosities to be reached.

In this paper, results from luminosity levelling using a 4D strong-strong beam-beam code are discussed and analysed for the case of β^*-levelling without offset using the Soft Gaussian approximation. Here a constant bunch intensity is assumed, resulting in a luminosity increase as the β-function at the IP changes.

LEVELLING MATRIX

Since the action of changing the β-function at the IP is an adiabatic process, the emittance in both planes should be conserved before and after the levelling step. To describe this within the code, a levelling matrix is applied such that as the spatial component of the particle phase space is reduced, the momentum of the particle phase space is increased. This can be derived by considering the phase space ellipse and the particle spatial and momentum components. The initial particle position and momentum can be expressed as a function of the β^* before and after the levelling step. The beams are focused in the transverse spatial components, which is given by

$$\frac{u_1}{u_2} = \sqrt{\frac{\beta^*_{1,u}}{\beta^*_{2,u}}} \tag{1}$$

where $u = x, y$ and the subscripts $1, 2$ indicate before and after the levelling step. Likewise in the transverse momentum plane, the particles undergo a defocusing given by

$$\frac{p_{u,1}}{p_{u,2}} = \sqrt{\frac{\beta^*_{2,u}}{\beta^*_{1,u}}}. \tag{2}$$

The levelling map can be expressed as a matrix and is given by

$$\begin{pmatrix} u_2 \\ p_{u,2} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta^*_{2,u}}{\beta^*_{1,u}}} & 0 \\ 0 & \sqrt{\frac{\beta^*_{1,u}}{\beta^*_{2,u}}} \end{pmatrix} \begin{pmatrix} u_1 \\ p_{u,1} \end{pmatrix}. \tag{3}$$

This matrix is applied between the levelling steps in both the horizontal and vertical plane to ensure that the emittance is conserved.

In this article, flat and round beam profiles were investigated to determine any possible emittance growth that may arise due to the levelling process. Only head on collisions at a single IP were simulated, although multiple IP collisions are undergoing investigation. Introducing an asymmetry between planes such that $\beta^*_x \neq \beta^*_y$ allows the flat beam option to be studied for the simple case of a single head on collision per turn at one IP. The β-function at the IP was reduced every $500K$ turns (approximately 44 seconds in the machine). The β-function at the IP for the round beam was reduced in steps of,

$$\beta^*_{x,y} = 0.60\ m \rightarrow 0.40\ m \rightarrow 0.20\ m \rightarrow 0.15\ m,$$

The β^* for the flat beam profile was reduced only in the vertical plane, in steps of,

$$\beta^*_y = 0.60\ m \rightarrow 0.40\ m \rightarrow 0.20\ m \rightarrow 0.10\ m \rightarrow 0.075\ m,$$

while the β-function at the IP in the horizontal plane is held constant at $\beta^*_x = 0.3$ m. Note that in these simulations, the bunch intensity is assumed to be held constant at $n_b = 2.2 \times 10^{11}$ protons per bunch. This provides a worse case scenario in terms of the beam-beam interaction. The starting parameters for the simulations are given by the HL-LHC parameters in Table 1,

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Table 1: HL-LHC parameters.

HL-LHC Parameters		
Bunch Intensity N_p	2.20×10^{11}	2.20×10^{11}
Beam Profile	Flat	Round
$\beta^*_{x/y}$ [m]	0.3/0.075	0.15/0.15
$E_{collision}$ [TeV]	14	14
Norm. $\epsilon_{initial}$ [μm]	2.5	2.5

ROUND BEAMS

The coherent spectra for round beams in the case of zero crossing angle, do not have a dependence on β^*. The tune shift in both the vertical and horizontal planes will hence remain constant throughout the levelling process, this can be seen in Fig 1. There is a small emittance growth of approximately 0.68% per hour in the vertical plane. This emittance growth converges quickly within about 140 seconds and can be attributed to numerical noise. The horizontal plane emittance remains approximately constant, although there is again a small fluctuation, which is due to numerical noise and not from any physical process. The Yokoya factor for the round bunch can be calculated by taking the ratio of the tune shift from the unperturbed tune and the beam-beam parameter,

$$\Delta Q \approx Y \cdot \xi_{bb} \tag{4}$$

As expected the Yokoya factor is underestimated by the Soft Gaussian approximation [2], [3] and is calculated to be $Y \approx 1.1$.

FLAT BEAMS

The flat beam profile, unlike the round beam profile, will have a beam-beam parameter (ξ_{bb}) that is dependent on β^* during the levelling steps. This variation of the beam-beam parameter arises due to the asymmetry between the horizontal and vertical planes. The beam-beam parameter will increase in the horizontal plane and decrease in the vertical plane as the β^* decreases, as shown in Fig 2.

In the simple case of a single head on collision there is no observed emittance growth due to the levelling process. The maximum fluctuation in the emittance equates to approximately 0.48% per hour, which is well within numerical noise limits. However with a changing beam-beam parameter in each plane, the location of the perturbed tune will change. In the vertical plane the beam-beam parameter will reduce in size and hence the π-mode will shift closer towards the Σ-mode. In the horizontal plane the beam-beam parameter will increase in size, shifting the π-mode to lower frequencies, which may lead to a resonance crossing. A resonance crossing may lead to an emittance growth and a reduction in luminosity. Table 2 shows how the beam-beam parameter and the tune shift will change in each plane. The total Yokoya factor will remain approximately constant throughout the levelling process, agreeing closely to the round beam Yokoya factor [2]. As the beams become more flat towards

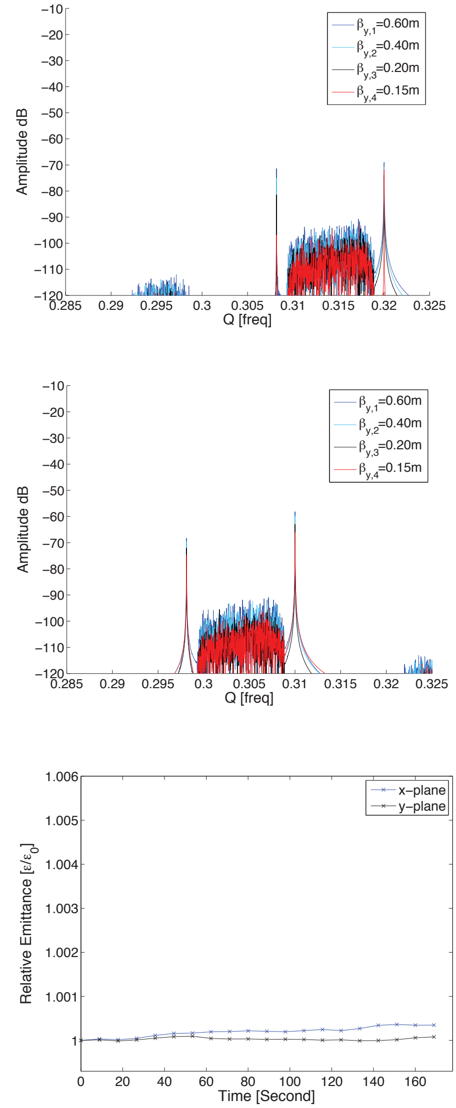

Figure 1: Figure top; shows the dipole modes in the vertical plane during the levelling steps. Figure middle; shows the dipole modes along the horizontal plane during the levelling steps. Figure bottom; shows the mean emittance throughout the levelling process. The slight emittance growth in each plane can be attributed to numerical noise with the vertical plane given by the blue line and the horizontal plane is given by the black line.

the end of the levelling process, the Yokoya factor will begin to increase. Yokoya [2] predicts for a two dimensional flat beam, the Yokoya factor to be $Y_{flat} \approx 1.148$ from the Soft Gaussian method. The Yokoya factor calculated in Table 2 agrees approximately with Yokoya [2].

DISCUSSION

From the perspective of the round beam option for the HL-LHC with crab cavities, there is no expected operational issues due to the beam-beam interaction during the levelling

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Table 2: Fractional tune of the π-mode in the horizontal and vertical planes and the beam-beam parameter and corresponding Yokoya factor for flat beam throughout the levelling process.

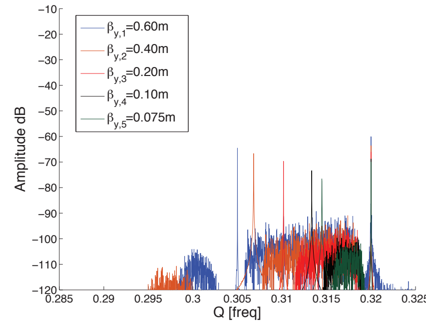
$\beta^*_{x,y}$ [m]	Q_{π_x}	Q_{π_y}	ξ_{tot}	Y_{tot}
0.3/0.6	0.301	0.305	0.0156	1.10
0.3/0.4	0.299	0.306	0.0155	1.10
0.3/0.2	0.296	0.310	0.0155	1.10
0.3/0.1	0.293	0.313	0.0159	1.13
0.3/0.075	0.292	0.314	0.0162	1.14

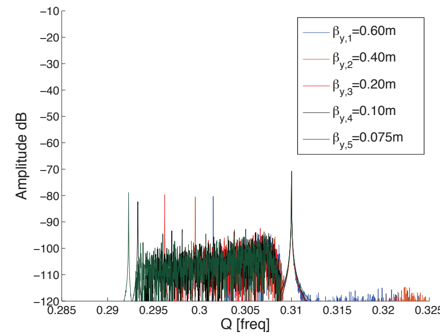
process since the beam-beam parameter is not dependent on β^*. This means that when the beams are round and without crossing angle, the frequency of the coherent spectrum will remain constant throughout the levelling process. However crab cavities may introduce noise to the beams, which may lead to an emittance growth and hence a reduction in luminosity [4].

Flat beams have been proposed as an alternative operational method for the HL-LHC when crab cavities are not included. Flat beams will allow high luminosities to be reached due to a small β-function at the IP. Flat beams will also give a large long range separation since the β^* in the crossing plane is kept constant. One possible drawback of the flat beam option is that the beam-beam parameter is dependent on β^* over the levelling steps. This will result in a change of the $\pi_{x,y}$-mode tune with every levelling step. In the horizontal plane the π-mode may shift towards a resonance. A resonance crossing will lead to an emittance growth, which in turn could lead to a reduction in luminosity.

Here only a single head on collision is considered, however with multiple head on collisions the size of the beam-beam parameter will increase as a multiple of the number of head on interactions. Multiple head on collisions at current HL-LHC tunes may lead to working point problem in which the bunch experience an emittance growth and a loss of luminosity. This may require the tunes to be shifted back to the best working point at each β^* step. Further investigation and analysis of multiple head on collisions are currently undergoing.

An additional issue that may arise at the final levelling step, which is not included in these 4D simulations, is the hourglass effect. The hourglass effect arises when the bunch length and bunch sizes are comparable in size. At the final levelling step, the flat beam profile will have a β-function at the IP given by $\beta^*_x = 0.3$ m and $\beta^*_y = 0.075$ m, where the β-function in the vertical plane is comparable to the length of bunch. This will cause a coupling between the transverse and longitudinal planes and will result in a parabolic variation of the transverse bunch sizes at the IP and hence a variation from the Gaussian bunch distribution [5]. This in turn could lead to a reduction in luminosity.





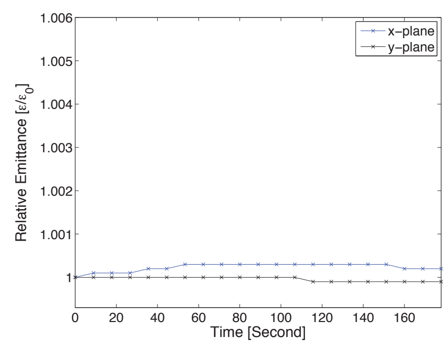


Figure 2: The top plot shows the dipole modes in the vertical plane during the levelling steps for the flat beam profile. The middle plot; shows the dipole modes along the horizontal plane during the levelling steps and the bottom plot; shows the mean emittance throughout the levelling process with the vertical plane given by the blue line and the horizontal plane is given by the black line.

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