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BEAM-BEAM STUDIES IN LHC- BEAM LOSS AND BUNCH SHORTENING

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Abstract

In Hadron colliders, luminosity degrades various mechanisms. Beam-beam related emittance growth is caused by resonances induced by crossing angle. Tune spread due to chromaticity enhances the resonances effect.

A bunch shortening phenomenon related to beam-beam interaction has been observed in LHC. The bunch length has an anti-correlation with transverse emittance. This phenomenon has been studied using a weak-strong beam-beam simulation (BBWS code).

INTRODUCTION

A bunch shortening phenomenon related to beam-beam interaction has been observed in LHC. The bunch shortening correlates with transverse emittance growth due to the beam-beam interaction. We discuss this phenomenon using a weak-strong beam-beam simulation.

Beam parameters is summarized as follows, energy E=4 TeV, bunch population $N_p=1.5\times10^{11}$, emittance of two beams, $\varepsilon_1=2.5$ μm, $\varepsilon_2=3.5$ μm, bunch length $\sigma_z=10$ cm, energy spread $\sigma_\delta=0.014\%$. Beams collides at 2 Interaction Points with horizontal and vertical crossing each with the full angle $\theta_c=290$ μrad. The beta function at IP is $\beta_x=\beta_y=0.6$ m. Tune operating point is $(\nu_x, \nu_y)=(64.31, 59.32)$. The emittance of beam 1 is smaller than beam 2. Beam 1 and 2 are treated as strong and weak beam, respectively. The beam-beam tune shift is 0.0124 for beam 2.

LHC is operated at high chromaticity $\xi_{xy}=d\nu_{xy}/d\delta=10$-15. Tune shift due to the chromaticity is 0.0028-0.0042 for energy deviation $2\sigma_\delta$. Collimators which play important role for the bunch shortening, cut transverse aperture of beam, $4\sigma_{xy}=1.4\times10^{-8}$ m.

WEAK-STRONG BEAM-BEAM SIMULATION FOR LHC

In the weak-strong simulation, macro-particles in beam 2 are tracked in the electro-magnetic field formed by the strong beam 1 represented by fixed charge distribution. Revolution is approximated by linear 6x6 matrix transformation. Two IP with H/V alternative crossing are taken into account. Chromaticity is implemented by a symplectic kick [1] using a generating function,

$$H = \frac{1}{2\pi}\left(\xi_x J_x + \xi_y J_y\right)\delta\ , \qquad (1)$$

where $J_x=(\gamma_x x^2+2\alpha_x x p_x+\beta_x p_x^2)/2$.

The simulation is performed by tracking of 131,072 macro-particles in the weak beam during 0.5-1×10^6 turns, corresponding to 44-89 sec in the real LHC. The actual bunch-shortening phenomenon occurs in several hours.

Figure 1 shows emittance growth due to the beam-beam interaction at the chromaticity $\xi_{xy}=15$. Top and bottom plots depict horizontal emittance evolution and their growth rates of horizontal and vertical, respectively. The growth rate 10^{-9}/turn, corresponds to 1 day growth time, is visible level in experiments.

Figure 2 shows the horizontal and vertical beam size evolution for the chromaticity $\xi_{xy}=15$, 0, -15. There is no remarkable difference between positive and negative chromaticity. For zero chromaticity, the growth rate is quite small, 140×10^{-9}/turn; 1/30 for $\xi_{xy}=15$.

The beam-beam tune shift is $\Delta\nu_{xy}=0.0083N_p(/10^{11})$. Any change in the bunch length is not seen in this simulation. It is natural that there is no mechanism for the shortening in this simulation.

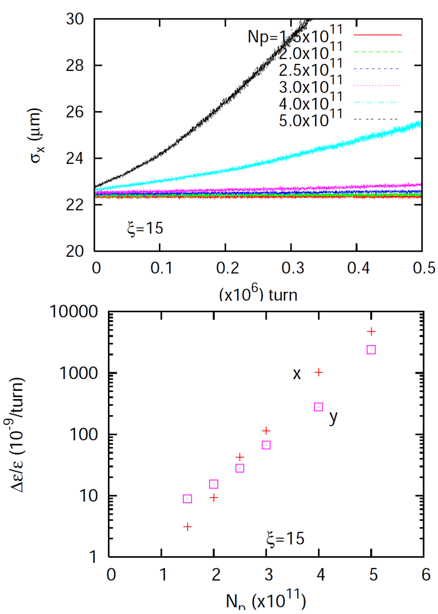

Figure 1: Horizontal emittance growth due to beam-beam interaction at the chromaticity $\xi_{xy}=15$.

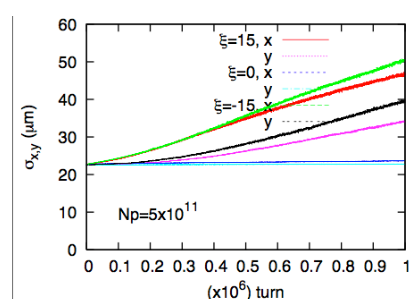

Figure 2: Chromaticity dependence of the horizontal and vertical emittance growth for $N_p=5\times10^{11}$.

BUNCH SHORTENING

We now take into account of the aperture limit of collimators $A_{xy}=1.4\times10^{-8}$ m. The bunch shortening is conjectured to be due to losses of particles with large synchrotron amplitudes [2]. Particles with large chromaticity tend to have large emittance growth as

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shown in Fig.1. It is able to conjecture the emittance growth is coupled phenomena of the large chromaticity and synchrotron amplitude (energy deviation).

Figure 3 shows beam loss at the collimator (top) and bunch length (bottom) evolution. Figure 4 summarizes the beam loss rate and bunch shortening rate as function of bunch population for the chromaticity, ξ_{xy} =15, 10 and 0. The beam loss rate is similar value as the bunch-shortening rate. The behavior does not depend on the sign of chromaticity. The correlation between emittance growth and bunch shortening is seen in Figure 5. The correlation is clear, but no unique value for $\sigma_z d\varepsilon/\varepsilon d\sigma_z$.

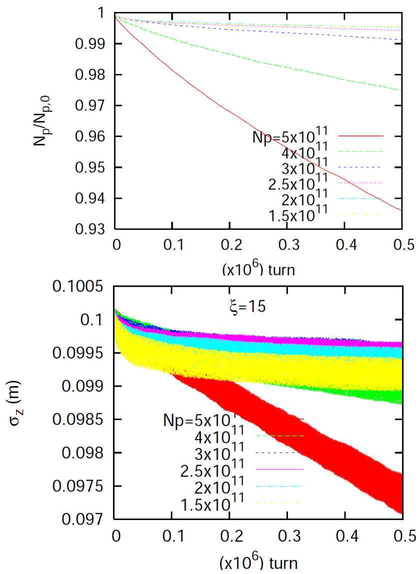

Figure 3: Evolution of beam loss (top) and bunch length (bottom) for various bunch population.

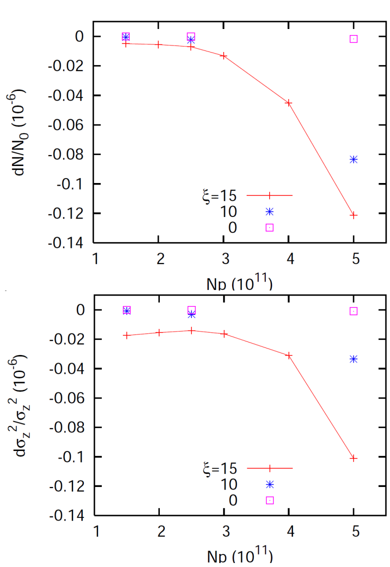

Figure 4: Beam loss rate (top) and bunch shortening rate (bottom) as function of bunch population for chromaticity ξ_{xy} =15, 10 and 0.

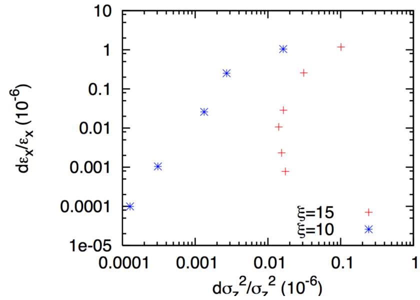

Figure 5: Correlation of bunch shortening and emittance growth rate.

Figure 6 shows beam hallo distribution for low and high bunch population. The hallo is produced mainly in vertical for low bunch population, while it is in horizontal for high population. FMA analysis had been performed for studying the beam-beam limit in LHC [3] as shown in Figure 7, where the energy deviation and chromaticity are zero. There are diffusive areas on the horizontal axis. The corresponding resonances are 7-th at $2\sigma_x$, 10-th at $4\sigma_x$ and 13-th at $7\sigma_x$. For low bunch population, 10-th and 13-th are effective [4]. Chromaticity and energy deviation, which cause modulations of tune and the diffusive area, enhances emittance growth.

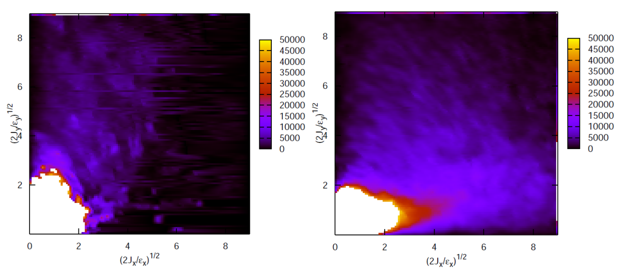

Figure 6: Beam hallo distribution for low and high bunch population. Left and right pictures depict the beam distribution after 10^6 turns for N_p=2x10^{11} and for N_p=5x10^{11}, respectively.

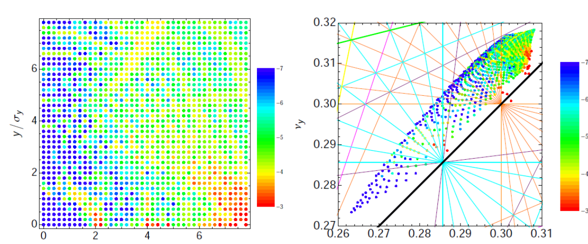

Figure 7: FMA analysis results in amplitude (left) and tune (right) spaces. The parameters in Ref [3] is used. The tune shift is similar as that of N_p=5x10^{11}.

We next investigate effects of crossing angle for the beam loss and bunch shortening. Figure 8 shows the beam loss rate and bunch-shortening rate as function of bunch population for zero crossing angle. The beam loss rate is very small for zero crossing angle even high chromaticity.

Figure 9 summarizes correlation of the beam loss and bunch shortening rates. Every case, chromaticity ξ_{xy} =15,

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10, 0 and crossing angle ϕ_c=0, 290 μrad is plotted in the figure. All points are lying down along $d\sigma_z/dN$=1. This means the bunch shortening depends only on the beam loss.

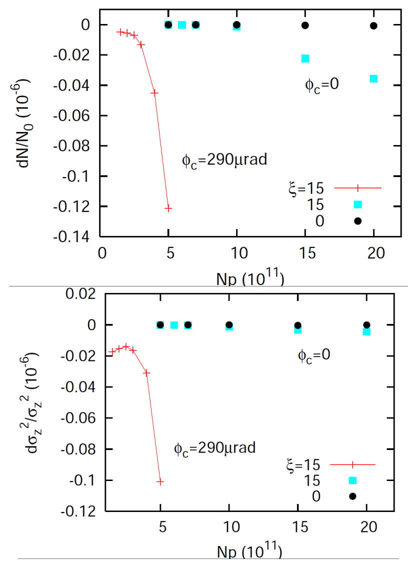

Figure 8: the beam loss rate (top) and bunch-shortening (bottom) rate as function of bunch population for zero crossing angle. Red line for finite crossing angle is plotted as a reference.

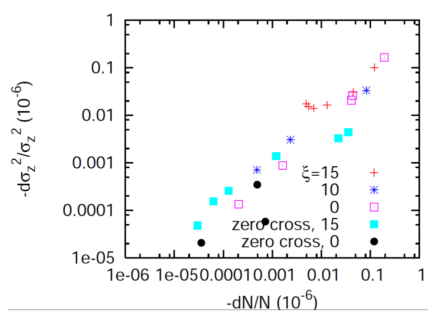

Figure 9: Correlation of the beam loss and bunch-shortening rate for every case studied here.

SUMMARY

We discuss a beam-beam effect seen in the emittance growth and bunch shortening correlating to beam loss. Large chromaticity ξ_{xy} =15 seems to be main source of the beam loss in the present parameters of LHC. It is possible to reproduce correlation of emittance and bunch length in a beam-beam simulation.

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