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STRONG-STRONG BEAM-BEAM SIMULATION OF BUNCH LENGTH SPLITTING AT THE LHC*

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Abstract

Longitudinal bunch length splitting was observed for some LHC beams. In this paper, we will report on the study of the observation using strong-strong beam-beam simulations. We explore a variety of factors including initial momentum deviation, collision crossing angle, synchrotron tune, chromaticity, working points and bunch intensity that contribute to the beam particle loss and the bunch length splitting, and try to understand the underlying mechanism of the observed phenomena.

INTRODUCTION

LHC has made important scientific discovery since its beginning of operation. In some runs of 2012, it was observed that two colliding beams starting with similar longitudinal bunch length split up after some time due to selective transverse emittance blow-up that occurs at the end of the squeeze beam mode [1]. A study based on weak-strong simulation was reported last year [2]. In this paper, we have carried out strong-strong beam-beam simulations to understand the underlying mechanism that drives the bunch length splitting given the initial unequal transverse emittances of the two colliding beams [3].

COMPUTATIONAL SETUP

All simulations presented in this study were done using a strong-strong collision model implemented in the code BeamBeam3D [4]. In order to reduce numerically induced emittance growth, and to gain computation speed, the beam-beam fields were computed assuming a Gaussian particle distribution, instead of a self-consistent approach. This assumption is justified by the fact that the initial Gaussian particle distribution does not change significantly in a short period of time under stable conditions. One million macroparticles were used for each beam. The particle distribution along the longitudinal direction was divided into 8 slices. Two collisions per turn, corresponding to the Interaction Points (IPs) 1 and 5 in the LHC, were simulated. The crossing plane was horizontal at one IP and vertical at the other IP. Linear transfer maps, calculated using the working point tunes, were employed to transfer the beams between collisions. The damper model uses a Hilbert-notch filter and two pick-ups per beam and plane, as the actual system in LHC does [5]. The actual kick is the superposition of two terms associated with different pick-ups. An artificial 4 sigma aperture is assumed in the simulation to enhance the transverse particle losses from nonlinear beam-beam effects coming from the head-on and long range encounters in the LHC real configuration. This limit in aperture seems also a good choice since it is compatible with the expected dynamical aperture in the LHC during these observations [3]. The detailed physical parameters used in the simulations are given in Table 1.

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Table 1: Physical Parameters used in the Simulations

Parameter	Value
N_p	1.5×10^{11}
$\varepsilon_{nb1}, \varepsilon_{nb2}$ / µm	2.5/3.5
β^* / m	0.6
σ / µm	18.8/22.2
σ_z / cm	9.74
Q_x	64.31
Q_y	59.32
Q_z	0.0019
θ / mrad	0.29
g_1, g_2	0.05/0.05
Damper noise	on
Collisions / turn	1 hor., 1 ver.

SIMULATION RESULTS

Using the above computational set-up, we carried out strong-strong simulations. Figure 1 shows the longitudinal rms bunch length evolution of two colliding beams with a machine chromaticity 15 and relative momentum deviation 0.0165%. The two beams starting with the same longitudinal bunch length split up after some time. Beam 1 is the beam with smaller emittance 2.5 mm, while beam 2 is the one with larger transverse emittance 3.5 mm. Due to the difference in emittance, beam 2 will experience different beam-beam effects from beam 1. The core of the beam 2 will see strong nonlinear beam-beam effects from the beam 1, while the core of the beam 1 will see mostly linear beam-beam effects from the core of the beam 2.

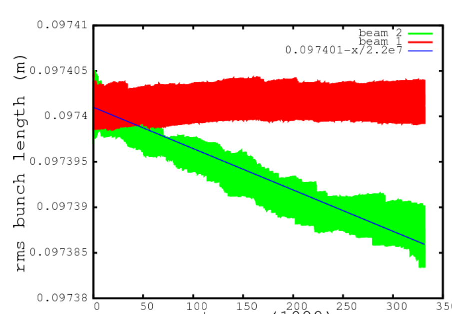

Figure 1: Longitudinal rms bunch length evolution of two colliding beams.

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The relative shortening rate of the second beam from a linear fit is about 0.02/hr. This is in consistent with the experimental observations of about 0.05/hr shorten rate. This longitudinal bunching shortening and split-up is related to the transverse particle losses. Figure 2 shows the particle survival fraction as a function of time. It is seen that the beam 2 has a larger particle loss rate than the beam 1. Such a loss could come from the particles with large longitudinal amplitude and results in the bunch length shortening and splitting. To study the effects from the longitudinal momentum deviation, we did simulations using a few different initial momentum deviations. The longitudinal rms bunch length evolution for the second beam is shown in Fig. 3. It is seen that as the momentum deviation increases, the shortening rate becomes larger. When the relative momentum deviation approaches 0.022%, a significantly fast bunch shortening is seen. This might be related to the fact that more particles fall into the 10^{th} order resonance with this larger momentum deviation.

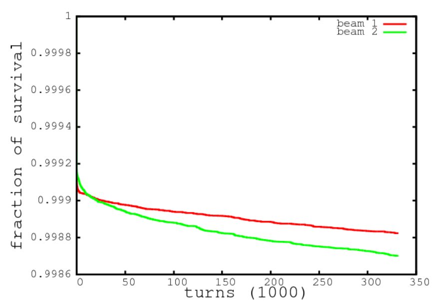

Figure 2: Evolution of the fraction of survival particles.

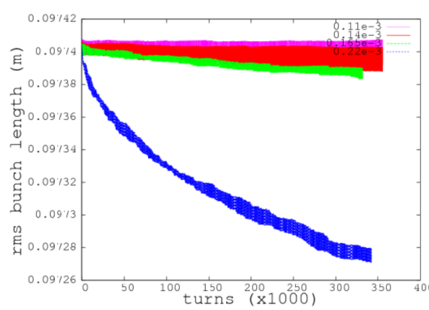

Figure 3: Longitudinal rms bunch length evolution for different initial relative momentum deviations.

Besides the effects of initial momentum deviation, we also studied the effects of chromaticity on the bunch shortening. Figure 4 shows the rms bunch length evolution of the second beam for different values of chromaticity. It is seen that with small machine chromaticity (~5 units), there is little bunch length shortening. A large chromaticity (~15 units as operationally used in the LHC) is needed to cause the significant bunch shortening. Figure 5 shows particle tune footprints for the three chromaticity values. The large machine chromaticity results in larger footprint in the tune diagram and moves more particles into the 10th order resonance.

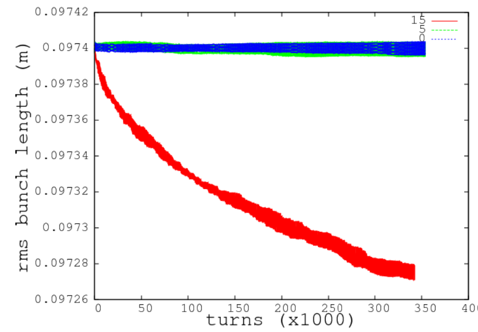

Figure 4: Longitudinal rms bunch length evolution for different machine chromaticity values.

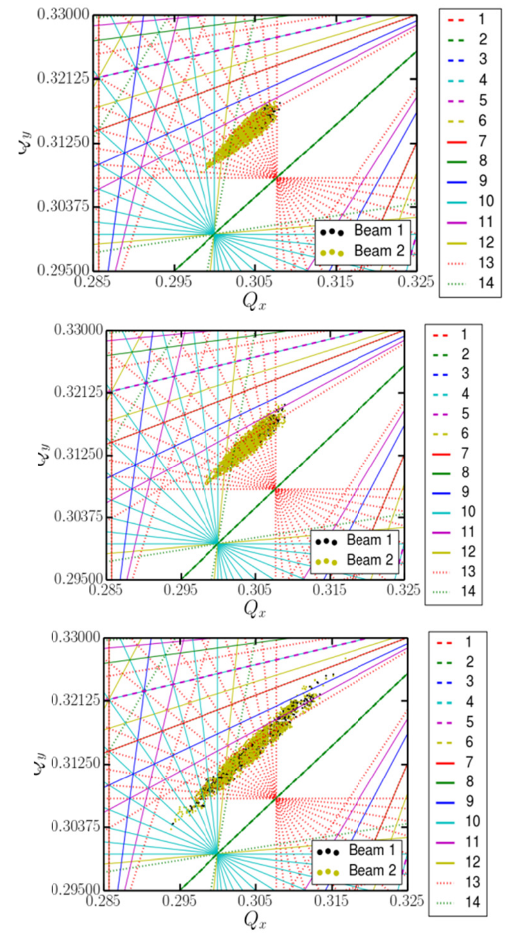

Figure 5: Particle tune footprint with machine chromaticity of 0 (top), 5 (middle), and 15 (bottom).

The longitudinal to transverse coupling is also affected by the crossing angle collision, which introduces a synchro-betatron coupling during collisions. Figure 6 shows the second beam bunch length evolution for different crossing angles at the IPs. It is seen that with zero crossing angle, there is little bunch shortening, while with too large crossing angle, the bunch shortening rate also decreases. The effect reaches a maximum for a crossing angle of 290 μrad which was the operational angle used during the 2012 run.

To check the effects from the synchrotron motion, we also varied the synchrotron tune of the machine. Figure 7

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shows the second beam bunch length evolution with different synchrotron tunes. It is seen that without synchrotron motion (i.e. zero synchrotron tune), there is little bunch length shortening. A larger synchrotron tune results in faster longitudinal motion and larger bunch length shortening rate.

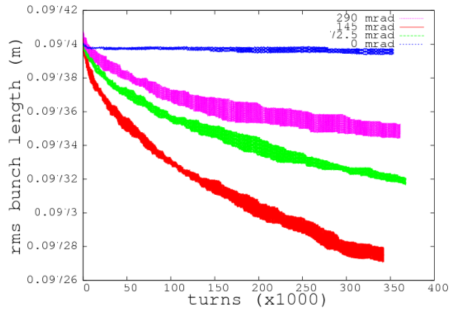

Figure 6: Longitudinal rms bunch length evolution for different crossing angles.

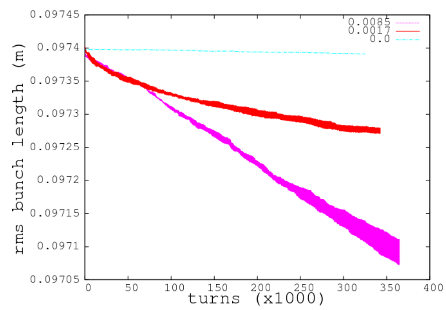

Figure 7: Longitudinal rms bunch length evolution for different synchrotron tunes.

The machine working point will affect the resonance driven particle diffusion and losses. Figure 8 shows the second beam bunch length evolution with different working points and zero chromaticity. It is seen that at a working point of (0.302,0.312), the bunch length has significantly large shortening rate.

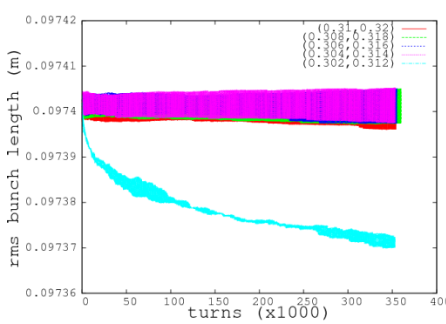

Figure 8: Longitudinal rms bunch length evolution with different machine working points.

Figure 9 shows particle tune footprints with those machine working points. It is seen when the machine working point locates at (0.302, 0.312), almost all particles are inside the 10th order resonance. This causes more particle transverse losses and larger bunch length shortening rate.

CONCLUSIONS

Using a strong-strong beam-beam simulation model, we have studied the longitudinal bunch length spliting and shortening observed at the LHC during 2012 operation. It appears that this phenomena is related to the unequal transverse particle losses that the beams have when colliding with the unequal emittances. Bunches with

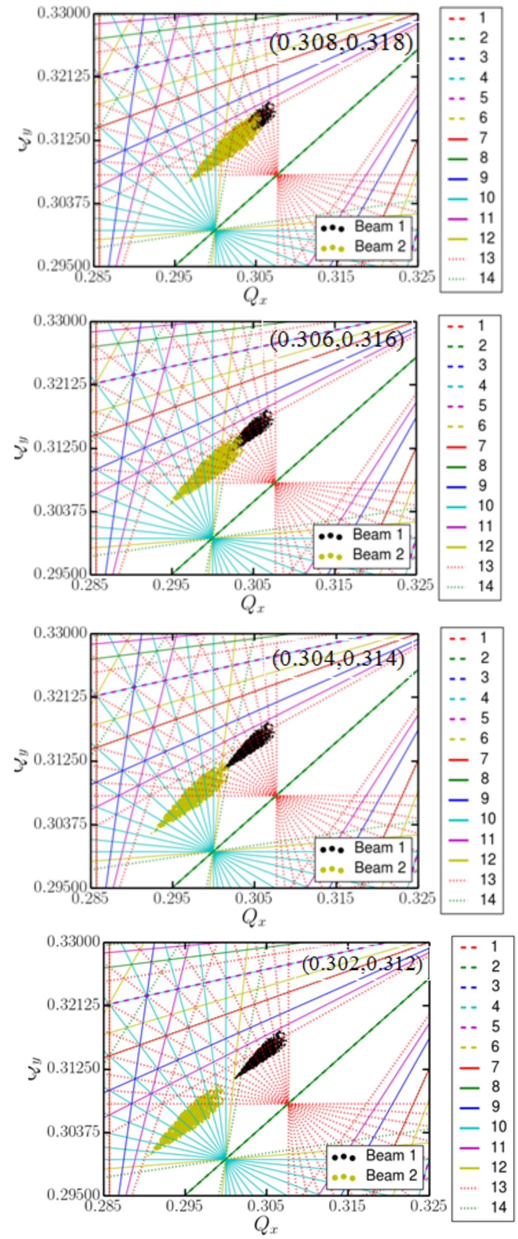

Figure 9: Particle tune footprint for different machine working points.

larger emittances show shortening and more particle losses. The significant particle loss and bunch length shortening of the second beam (the one with larger emittance) is probably due to nonlinear resonance driven particle diffusion and emittance growth coupled together with the longitudinal synchrotron motion. Such a resonance driven particle loss can be controlled with a careful choice of machine working point.

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