STUDY OF BEAM-BEAM EFFECT AT VARIOUS COLLISION SCHEMES IN LHC

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Abstract

LHC is designed as two major collision points with finite crossing angle of 140 mrad (half). The Piwinski angle is 0.4 for the design. Upgrade plans have been studied to increase the luminosity 10 times. Large Piwinski angle scheme is one of the options for the upgrade. We discuss the beam-beam effect for nominal and large Piwinski angle collision schemes in LHC.

INTRODUCTION

Proton beam in storage ring colliders does not experience any damping such as electron beam. Since there is no radiation excitation, diffusion source, which cause emittance growth, is limited to be external or dynamical. We study the emittance growth due to the nonlinear beam-beam interaction.

Following four subjects are discussed for various collision scheme in LHC.

•Beam-beam simulation in proton colliders
•Effect of crossing angle
•Large Piwinski angle
• Crossing scheme at two interaction points

BEAM-BEAM SIMULATION IN PROTON COLLIDERS

Weak-strong or strong-strong simulations are carried to study the beam-beam effects. We compare the two simulation methods at fist.

Strong-strong simulation contains statistical noise, for example the dipole position fluctuates $\sigma/N^{1/2}$. Such noise gives artificial emittance growth.

1M macro-particles have 0.1% statistical noise in offset of the collision. A strong-strong simulation [1] with 1M macro-particles was executed. We expect one day life time for luminosity. Since the beam particles circulate 10^9 turns in a day, the tolerance of the emittance growth or luminosity decrement is 0.1% for 1 M turns in the simulation. Figure 1 shows evolution of the beam size during 0.8 M turns. The strong-strong simulation gives 0.1% emittance growth in 1M revolutions in the figure. The strong-strong simulation informs that the beam-beam effect is closed to the limit of one day life time. However the weak-strong simulation does not give any growth. Figure 2 shows luminosity decrement for nominal, twice, and four times bunch populations given by the strong-strong simulation. The decrement is out of tolerance of 1 day life time. However weak-strong simulation gives little emittance growth as shown latter. Perhaps the emittance growth in the strong-strong simulation is artifact, the weak-strong simulation is reliable and simple.

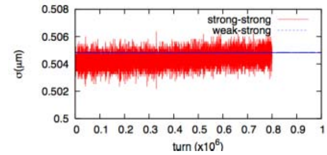

Figure 1: Emittance growth in weak-strong (blue) and strong-strong (red) simulations.

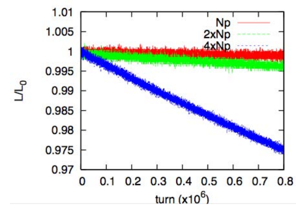

Figure 2: Luminosity decrement given by the strong-strong simulation for nominal, twice, and four times bunch populations in LHC.

COLLISION WITH CROSSING ANGLE

Lorentz boost is used to make perpendicular field for moving direction. (J. Augustin[2], K. Hirata[3]). Otherwise the treatment of the tilted field is very complex as shown in Figure 3.

Lorentz transformation seems to be not symplectic for the accelerator coordinate system $p_x=P_x/p_0$, remember adiabatic damping. No one says the adiabatic damping breaks symplecticity.

Lorentz transformation is symplectic in the physical coordinate system, therefore this treatment is symplectic.

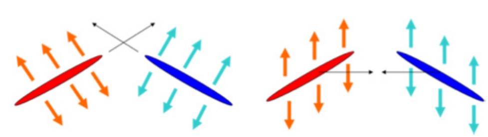

Figure 3: Schematic view of collision. Lab. frame (left) and boosted frame (right). Orange and light blue arrows are electro-magnetic field induced by the beams.

Effect of Crossing Angle

The beam-beam force is symmetric for x and y in the collision without crossing angle; Hamiltonian is even for x and y. This means that dominant resonance is $2n\nu_x+2m\nu_y=k$. Crossing angle induces odd terms in Hamiltonian. Horizontal crossing is even for y, and vertical crossing is even for x. Corresponding resonance terms depends on the crossing scheme; $n\nu_x+2m\nu_y=k$ in horizontal, or $2n\nu_x+m\nu_y=k$ in vertical. The odd terms couples to z, because Hamiltonian contains $(x\text{-}qz)^n$ terms, where q is the half crossing angle.

The odd terms with low order, 3 or 4-th, degrade luminosity performance in e^+e^- colliders. Since the tune shift in proton machines is smaller than lepton machines, higher order terms affect the luminosity decrement. Figure 4 shows 3rd order terms, xy^2z and x^3z, to demonstrate the appearance of odd order terms.

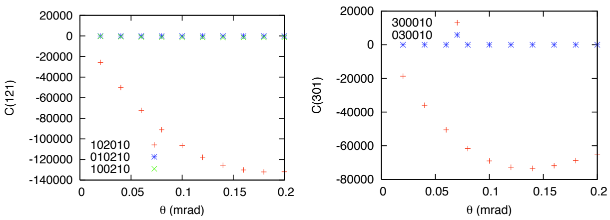

Figure 4: Coefficient of Hamiltonian. xy^2z (102010) and x^3z (300010) as a function of crossing angle q. Other terms related to p_x or p_y are very small, because of the small disruption of the beam-beam interaction.

Synchro-beta resonance terms are induced by the crossing angle. Figure 5 shows 4-th order terms and terms for their synchrotron sideband. When operating point is closed to 1/4 resonance, these terms gives several resonance overlapped.

Though these resonances are important in e+e- colliders with very high beam-beam tune shift, it may be not serious for proton colliders with low beam-beam tune shift by choosing operating point.

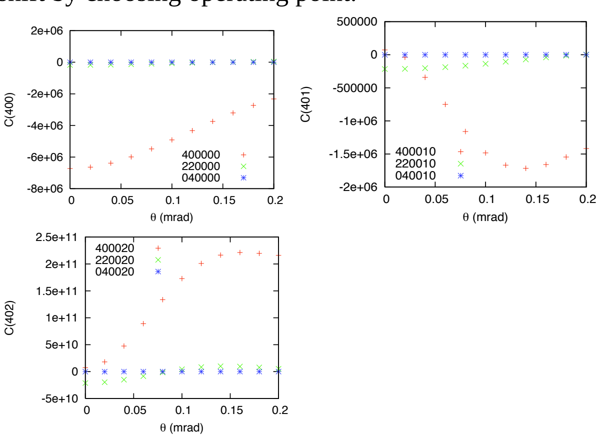

Figure 5: Synchro-beta terms as a function of Piwinski angle.

BEAM-BEAM SIMULATION FOR THE NOMINAL LHC

The weak-strong simulation was carried out for the nominal LHC. Figure 6 shows the results of the luminosity decrement for the bunch populations, N_p=1.15x10^{11} (nominal), 2xN_p, 4xN_p and 6xN_p. The crossing angle and bunch length are considered to slice a bunch longitudinally into 5 pieces. Luminosity evolutions with crossing angle 0.15 mrad and 0 mrad are plotted.

There was no visible effect in the nominal population in both cases with and without crossing angle.

The crossing angle affects the luminosity performance at much higher intensity than nominal value, 6xN_p. The luminosity decrements are much slower than those by strong-strong simulation. The luminosity for 0.15mrad crossing oscillates larger amplitude than that for 0 mrad. Perhaps a mismatch occurs due to the beam-beam force.

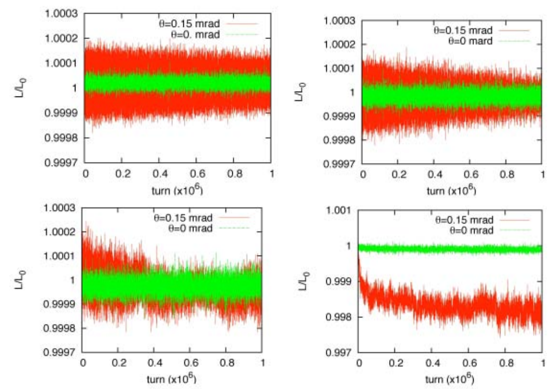

Figure 6: Luminosity decrement at the nominal LHC collision for the bunch populations, N_p=1.15x10^{11} (nominal), 2xN_p, 4xN_p and 6xN_p. Two lines plot luminosity evolution with crossing angle 0.15 mrad and 0 mrad.

LARGE PIWINSKI ANGLE OPTION-I

LHC upgrade targets 10 times higher luminosity. Large Piwinski angle scheme is one of the candidates. Piwinski angle f is the ratio of projection of tilted bunch length and horizontal beam size,

$$\phi = \frac{\theta\sigma_z}{\sigma_x}$$

We first study parameters given by F. Zimmermann [5]; Piwinski angle φ=2(0.4), bunch spacing 50(25) ns, number of bunches n_b=1401(2808), uniform longitudinal profile with σ_z=11.8(7.55) cm, L_z=41 cm, crossing angle θ(half)=190(143) μrad, N_p=4.9(1.15)x10^{11}, β*=0.25 cm, L=10(1)x10^{34} cm^{-2}s^{-1}, where values in () are nominal.

The bunch length is further shorter than Superbunch scheme [4]. There are two collision points with high beam-beam parameter in LHC. K. Takayama et al. proposed three collision schemes at the two collision points for the super-bunch. One is that both of the collision points are arranged horizontal crossing (H-H). Second is horizontal and vertical crossing each (H-V). Third is inclined crossing, in which two beams cross slantingly. In third case, x-y coupling should be studied carefully. We discuss H-H and H-V crossing here.

The characteristics of the collision scheme are summarized as,

- H-H : Tune spread is wide range, but terms only even for y exists.
- H-V : All nonlinear terms can be exist. More resonance lines are active than H-H.

The weak-strong simulations were carried out for the collision schemes. When parasitic interaction was not considered, both collision schemes were no any problem; luminosity decrement and emittance growth was negligible.

A preliminary example showed that H-V crossing is serious for Halo formation. The halo was formed by parasitic interaction. Figure 7 shows emittance growth and x-y distribution after 0.4M turns. Luminosity decrement was not seen.

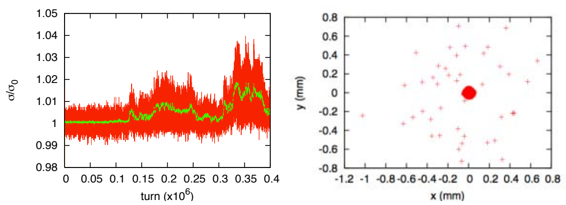

Figure 7: Evolution of emittance and beam distribution in x-y plane after 0.4M turns for H-V crossing.

For the presence of two collision points, betatron phase difference between them should affect the beam-beam performance. Systematic studies should be done [6].

LARGE PIWINSKI ANGLE OPTION-II

Another large Piwinski angle scheme is propose by J. P. Koutchouk et al.[7] The parameters are N_p=2.5x10^{11} /bunch , b*=14 cm, s_z=7.5 cm, q(half xangle)=393 mrad, Piwinski angle f= 3.5, HV or HH (or VV) crossing.

This scheme can give the luminosity, 10 times of the nominal value. Figure 8 shows evolution of the luminosity for H-H and H-V crossing. The design, twice, three and four times populations were examined. In both case no luminosity degradation was seen in the design population. H-V crossing is better for higher bunch populations in this scheme.

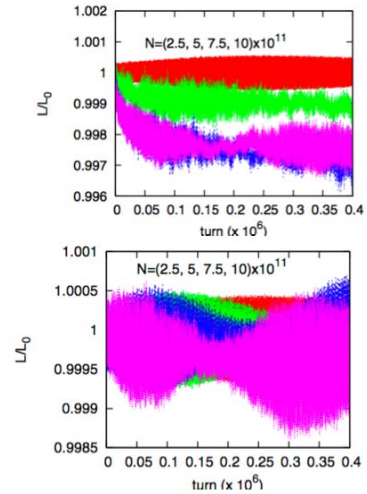

Figure 8: Evolution of luminosity for 2nd large Piwinski angle option. Top and bottom pictures are given for H-H (top) and H-V (bottom) crossings, respectively.

SUMMARY

We studied beam-beam effects for the nominal and two upgrade scheme with large Piwinski angle. In the nominal LHC scheme, degradation due to crossing angle appears in 6 times higher population. Large Piwinski angle options work well, though halo due to the parasitic interaction should be cared.

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