STRONG-STRONG BEAM-BEAM SIMULATION OF CRAB CAVITY COMPENSATION AT LHC*

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Abstract

Crab cavity is proposed to compensate the geometric luminosity loss of crossing angle collision at LHC upgrade. In this paper, we report on strong-strong beam-beam simulation of crab cavity compensation at LHC using the BeamBeam3D code. Simulation results showed that using a pair of local crab cavity compensation for each beam can significantly improve the luminosity at collision. However, this improvement could be lost due to phase errors from the rf crab cavities.

INTRODUCTION

Crossing angle in collision is used at the interaction region of high energy colliders such as LHC in order to mitigate the effects of long-range beam-beam interactions. On the other hand, using a crossing angle collision results in the loss of luminosity by a geometric factor:

$$L = L_0 \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\tan(\theta_c/2)\sigma_z}{\sigma_x} \qquad (1)$$

Here, L_0 is the nominal luminosity, θ_c is the full crossing angle, σ_z is the bunch length, σ_x is the horizontal rms beam size. In order to compensate this geometric loss, crab cavity near the interaction region was proposed to deflect the beam before colliding [1]. By appropriately choosing the location of the crab cavities and the voltage of the cavities, the two colliding beams can be brought into collision with almost zero synchrotron-betatron coupling [2]. This improves the luminosity of colliders. Crab cavities have been built and installed at the KEKB collider [3]. For the LHC upgrade, in order to attain higher luminosity, crab cavities were also proposed to compensate the geometric loss from the crossing angle collision [4]. In this paper, we present simulations of two proton beams colliding at one IP of the LHC in the presence of local crab cavity compensation using a strong-strong beam-beam model.

COMPUTATIONAL AND PHYSICAL MODELS

The computer code used in this study is the BeamBeam3D code [5]. The BeamBeam3D is a parallel three-dimensional particle-in-cell code to model beam-beam effects in high-energy ring colliders. This code includes a self-consistent calculation of the electromagnetic forces (beam-beam forces) from two colliding beams (i.e. strong-strong modeling), a linear transfer map model for beam transport between collision points, a stochastic map to treat radiation damping, quantum excitation, an arbitrary orbit separation model, and a single map to account for chromaticity effects. Here, the beam-beam forces can be from head-on collision, offset collision, and crossing angle collision. These forces are calculated by solving the Poisson equation using a shifted integrated Green function method, which can be computed very efficiently using an FFT-based algorithm on a uniform grid. For the crossing angle collision, the particles are transformed from the laboratory frame into a boosted Lorentz frame following the procedure described by Hirata [6] and by Leunissen et al. [7], where the beam-beam forces are calculated the in the same way as the head-on collision. After the collision the particles are transformed back into the laboratory frame. The BeamBeam3D code can handle multiple bunches from each beam collision at multiple interaction points (IPs). The parallel implementation is done using a particle-field decomposition method to achieve a good load balance. To model the beam transport through the crab cavity, we have assumed a thin lens approximation where the transfer map in the x-z plane is given by

$$\begin{aligned} x^{n+1} &= x^n \\ Px^{n+1} &= Px^n + \frac{qV}{E_s}\sin(\omega z^n/c) \\ z^{n+1} &= z^n \\ \delta E^{n+1} &= \delta E^n + \frac{qV}{E_s}\cos(\omega z^n/c)\,x^n \end{aligned} \qquad (2)$$

where qV/E_s is the normalized voltage of the crab cavity and ω is the angular frequency of the crab cavity.

STRONG-STRONG SIMULATION OF CRAB CAVITY COMPENSATION

Using above model, we have carried out strong-strong beam-beam simulations together with the local crab cavity compensation for the LHC. We have assumed 90 degree phase advance between the crab cavities and the interaction point. There are four crab cavities for each interaction point. The simulations were done using about 2.5 million macroparticles for each beam, 128x128 transverse grid points, and 10 longitudinal slices. To test the crab cavity model, we simulated the beam-beam interactions at LHC with a single collision point, 0.15 mrad half crossing angle, and nominal parameters used in reference 8 [8]. Figure 1 shows the peak luminosity at the LHC as a function of turns with and without local crab cavity compensation. It can be seen that by using the local

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crab cavity deflection, the luminosity has been improve by about 18%. This recovers the geometric luminosity loss due to crossing angle collision. Figure 2 shows the evolution of the square of rms sizes with and without crab cavity. Due to the deflection of the beam along the design trajectory by the crab cavity, the projected rms size along the design trajectory actually increases.

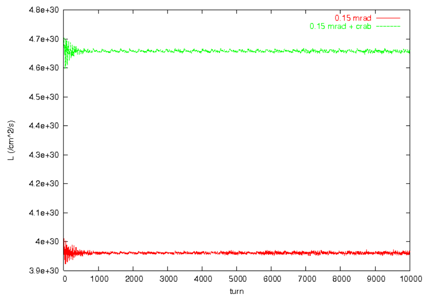

Figure 1: Luminoisty evolution with 0.15 mrad half crossing angle and with/without crab cavity.

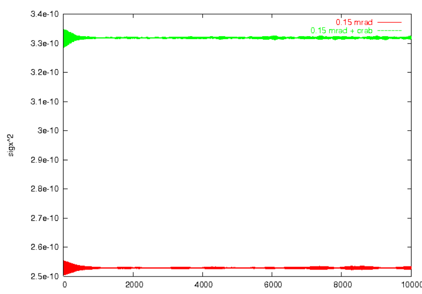

Figure 2: Square of rms size evolution with 0.15 mrad half crossing angle and with/without crab cavity.

To see how the crab cavity will help future LHC upgrade, we have run strong-strong beam-beam simulations together with the local crab cavity compensation for a variety of beta* at the collision point. The peak luminosity as a function of beta* is given in Fig. 3. For comparison, we also show the luminosity without crab cavity compensation [10]. It is seen that using the crab cavity does help improve the peak luminosity especially at lower beta*. For 0.25 m beta*, the peak luminosity increases by about 50% by using the crab cavity compensation.

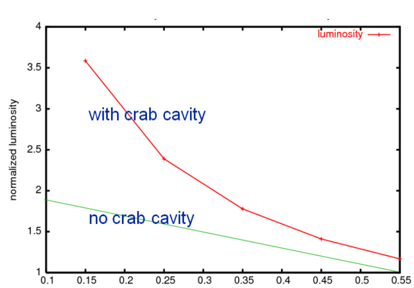

Figure3: peak luminosity as a function of beta* with/without crab cavity compensation.

EFFECTS OF PHASE ERRORS

In above studies, we have assumed an ideal situation, that is, there are no errors in the crab cavity settings. In reality, some extent of errors will always exist. Measurements at KEKB crab cavity showed rf sideband errors in the cavity [4]. This error will produce equivalent time-dependent transverse offset at the collision point. Here the offset error is given by:

$$x = A \sin(2\pi f t) \qquad (3)$$

where A is the amplitude of the offset error, f is the sideband frequency of the crab cavity, and t is the time. Fig. 4 shows the averaged emittance growth per hour as a function of the offset amplitude normalized by the beam size for the case of beta*=0.25 m and 32 kHz sideband phase error. The normalized voltage of the crab cavity is set as 7.957e-7 with 400.8 MHz rf frequency. It is seen that in order to keep emittance growth below 10% per hour, the transverse offset error from 32 kHz rf sideband should be kept below 0.1 σ.

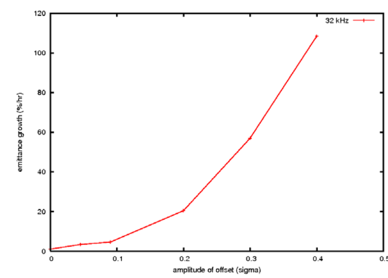

Figure 4: Emittance growth as a function of the offset error amplitude (normalized by rms beam size) for 32 KHz rf side band phase error.

Besides the rf sideband error, there could also exist some other random errors. This will results in a random transverse offset at the collision point given by:

$$x = \frac{c \tan(\theta_c / 2)}{\omega_{rf}} \delta\phi \qquad (4)$$

where $\delta\phi$ is the phase error. These phase jitters are not white noise but with some frequency spectrum as measured from the KEK-B crab cavities. To model these errors, we have used a colored Orinstein-Uhlenbeck noise with exponential dependence of correlation [8]. This fluctuation is sampled from a sequence of random numbers following the model in reference 9 [9].

$$x^0 = 0$$
$$x^{n+1} = (1 - \frac{1}{\tau}) x^n + A\sqrt{\frac{1}{\tau}} r \qquad (5)$$

where τ is the correlation time, A is the amplitude of noise and r is the a Gaussian random number with unit deviation. In this study, the correlation time of the phase jitter is assumed to be 100 turns. Figure 5 shows the growth of the averaged emittance per hour as a function of the amplitude (normalized by rms size) with above random noise. It is seen that in order to keep the emittance growth per hour below 10%, the amplitude of noise should be kept below 0.02 σ. Comparing these results with those of rf sideband errors, we can see that the random phase error is more restrictive to the operation of the crab cavity than the rf sideband error.

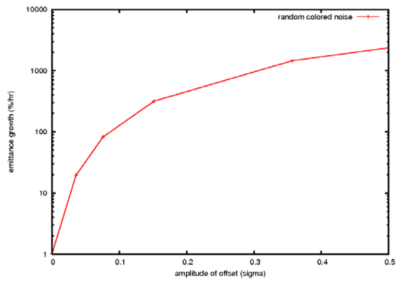

Figure 5: Emittance growth as a function of the offset error amplitude (normalized by rms beam size) for 30 KHz side band phase error.

In those simulations, we have assumed that the transverse offset caused by phase errors can be corrected through the rest of the ring. As a comparison, we also did a simulation for the above random offset error with 0.85um amplitude without including offset correction through the rest of the ring. The horizontal emittance growth evolution is given in Figure 6. It shows much larger emittance growth though 10,000 turns for the case without offset correction than the case with offset correction.

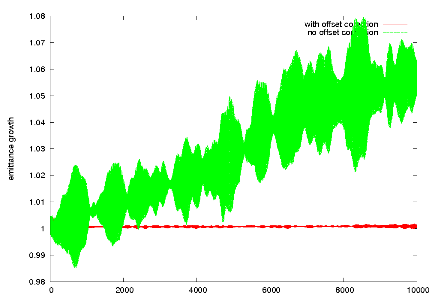

Figure 6: Emittance growth evolution with/without offset correction with 0.85 um random offset amplitude.

CONCLUSIONS

The strong-strong simulations of the beam-beam collisions with crossing angle and crab cavity compensation shows that significant luminosity improvement can be achieved at lower beta* for LHC upgrade. Including the 32 kHz rf sideband error and random colored phase error suggests that the amplitude of those errors should be kept as low as 0.1 σ and 0.02 σ respectively in order to avoid significant emittance growth (10% per hour). Further studies are needed to explore the effects of different sideband frequency errors, to explore the other crab cavity frequency, and to study the potential advantage of global compensation.

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