RECENT ADVANCES OF BEAM-BEAM SIMULATION IN BEPCII*

Y. Zhang†, IHEP, Beijing, China

Abstract

The luminosity of BEPCII (the upgrade project of Beijing electron-positron collider) have reached 3.0×10^{32} cm^{-2}s^{-1}@1.89GeV in May 2009. In this paper we'll compare the beam-beam simulation results with the real machine. In the case the single bunch current is lower than 8mA, the simulation coincides well with the real. Some phenomenon related to synchro-betatron resonances during machine tuning and simulation is shown . The tune is close to half integer help us increase luminosity, however the detector background increases at the same time. It is believed that the beam-beam dynamic effect result in the drop of the dynamic aperture. We also study the possible luminosity contribution from the crab waist scheme in BEPCII.

INTRODUCTION

BEPCII is an upgrade project from BEPC. It is a double ring machine. Following the success of KEKB, the crossing scheme was adopted in BEPCII, where two beams collide with a horizontal crossing angle 2×11mrad. The design luminosity of BEPCII is 1.0×10^{33}cm^{-2}s^{-1} at 1.89GeV, about 100 times higher than BEPC. The construction started in January 2004 and completed in June 2008 when the detector is positioned. The luminosity was only achieved 1.0×10^{32}cm^{-2}s^{-1}, since the two profile monitors in the positron ring excite very strong longitudinal instability [1]. When the two monitors were removed, 2.0×10^{32}cm^{-2}s^{-1} was achieved. In May 2009, we decided to move the horizontal tune more closer to half integer, which help us achieve 3.0×10^{32}cm^{-2}s^{-1}, and the project was reviewed by the governement in July 2009. Table 1 shows the main design and achieved parameters in BEPCII.

The beam-beam code used in our simulation is a Particle-in-Cell code [2]: (1) the transport map in the arc is linear approximation which is same as Hirta's BBC code where the synchrotron radaiation and quantum excitation is included, (2) the beam-beam force is calculated by solving Poisson equation using FFT, (3) finite bunch length effect is included by longitudinal slices, and the interpolation scheme is used to improve the convergence of slice number [3], (4) the finite horizontal crossing angle is included by Lorentz Boost [4].

In the following, we'll compare the simulated beam-beam limit with the achieved in the real machine. According to the simulation, the synchro-betatron resonances would be excited in some tune region, and similar phenomenon appears in the tune scan of real machine. We'll also show that the dynamic effect reduce the aperture in the near half-integer region. We also study the possible luminosity contribution of the crab-waist scheme in our machine. At last a summary and discussion is presented.

Table 1: Parameters of BEPCII (Design and Achieved)

	Design	Achieved
E [GeV]	1.89	1.89
C [m]	237.53	
N_b	93	70
I_b [mA]	9.8	8
$\mathcal{L}$ [$\times 10^{32} cm^{-2}s^{-1}$]	10	3.0
ξ_y	0.04	0.025
θ_c [mrad]	2×11	
β_x^*/β_y^* [m]	1 / 0.015	
ϵ_x/ϵ_y [nm]	144 / 2.2	
σ_z [cm]	1.5	
σ_e	5.16×10^{-4}	
ν_x/ν_y	6.53 / 7.58	6.51 / 5.58
ν_s	0.034	0.032
τ_x/τ_y [turn]	31553 / 31553	
τ_s [turn]	15777	

BEAM-BEAM LIMIT

The beam-beam parameter is defined as

$$\xi_u = \frac{Nr_e}{2\pi\gamma}\frac{\beta_u^0}{\sigma_u(\sigma_x+\sigma_y)} \tag{1}$$

where N is the particle number per bunch, r_e the classical electron radius, γ the relativistic factor and it should be noted that β^0 is unperturbed beta function and σ is perturbed beam size. If we do not consider the luminosity loss caused by finited bunch length and crossing angle, the bunch luminosity can be expressed as

$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y} \tag{2}$$

where f_0 is the revolution frequency, and it should be noted that σ is perturbed beam size. For flat beams $\sigma_y \ll \sigma_x$, the achieved beam-beam parameter can be expressed with bunch luminosity as

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0} \tag{3}$$

* Work supported by National Natural Sciences Foundation of China (10725525 and 10805051)

† zhangy@ihep.ac.cn

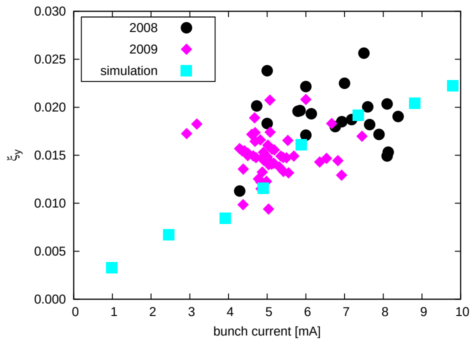

Figure 1: The achieved and simulated beam-beam parameter for $\nu_x \approx 0.53$. 2008 and 2009 refers to that before and after the removal of the profile monitors respectively.

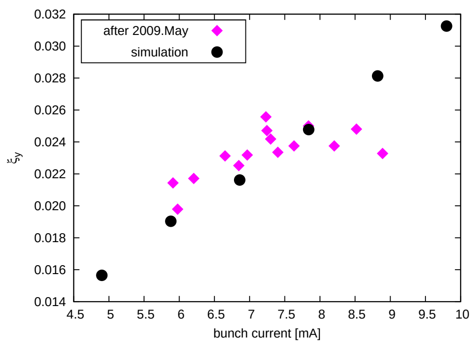

Figure 2: The achieved and simulated beam-beam parameter for $\nu_x \approx 0.51$.

Figure 1 shows the beam-beam limit for $\nu_x \approx 0.53$. There exists clear difference between 2008 and 2009, which is due to the data error. Only one bunch is used to tune the machine in 2008, and we would like to inject more bunches (5 or 10) in 2009. The latter is more credible. The maximum beam-beam parameter is close to 0.025 by simulation, and in the real machine 0.015-0.020 can be achieved stably.

Figure 2 shows the beam-beam limit for $\nu_x \approx 0.51$. The maximum beam-beam parameter is about 0.035 by simulation, and in the real machine 0.022-0.025 can be achieved stably.

In both cases, the achieved beam-beam parameter can be greater than simulation by optimization for lower bunch current. However the real is less than the simulation when $I_b > 8$mA. One possible explanation is the crosstalk between the beam-beam kick and the nonlinear map in the arc, since there is no cells in the arc and only 4-groups sextupoles are used to correct the chromaticity.

SYNCHRO-BETATRON RESONANCES

There are two kind of synchro-betatron resonances in our machine: one is caused by beam-beam kick, which can be seen in Figure 3 during machine tuning and in Figure 4 by simulation, the corresponding resonance line is $2\nu_{x,\pi} + 2\nu_s = n$.

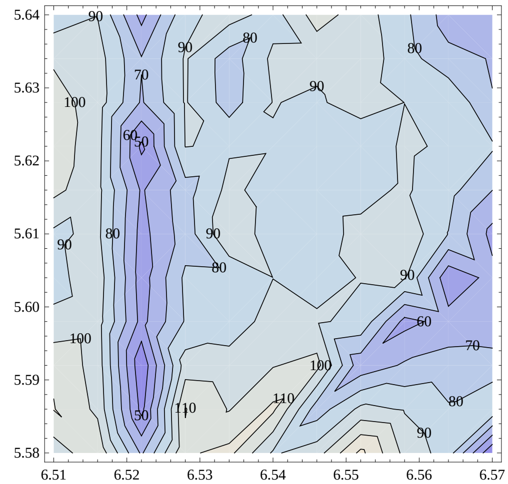

Figure 3: Luminosity versus tune of the electron ring.

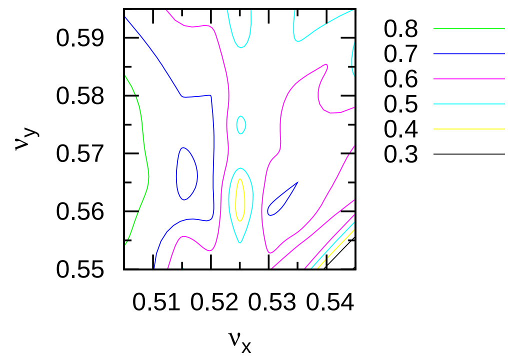

Figure 4: Luminosity versus tune by simulation.

The other is $2\nu_x + \nu_s = n$ which is more important during the lattice design near $\nu_x \sim 0.51$, since it may limit the dynamic aperture. In fact the beam-beam effect is also very effective to the resoance. In the first stage when we move the horizontal tune to 0.51, the luminosity is very sensitive to the knobs: RF voltage, tune and orbit etc. It is found that the sextupole configuration is not good, see Figure 5. After the problem is fixed, the tuning knob is normal.

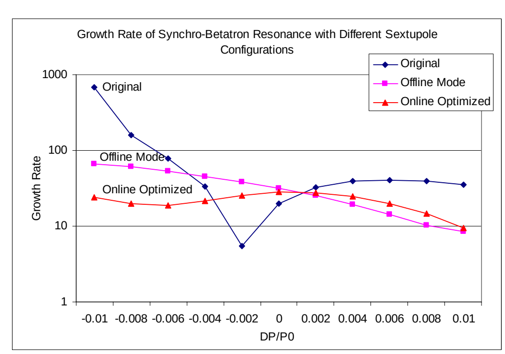

Figure 5: Growth rate of synchro-betatron resonance for different sextupole configurations.

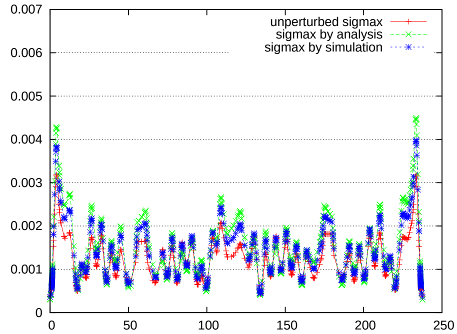

Figure 6: The perturbed horizontal beam size along the ring for $\nu_x = 0.53$ and $I_b = 8$mA

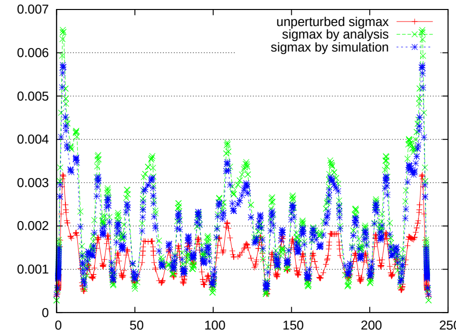

Figure 7: The perturbed horizontal beam size along the ring for $\nu_x = 0.51$ and $I_b = 8$mA

DYNAMIC EFFECT

The beam-beam interaction perturbs the twiss parameter along the ring, which is the so-called dynamic beta effect. With linear approximation, the beam-beam force is treated as linear focusing force in both transverse directions, and the perturbed beta function at IP is

$$\beta = \frac{\beta_0}{\sqrt{1 + 4\pi\xi \cot\mu_0 - 4\pi^2\xi^2}} \tag{4}$$

where β_0 is unperturbed and ξ is the achieved beam-beam parameter. The transverse emittance is also perturbed, which is the so-called dynamic emittance,

$$\epsilon = \frac{1 + 2\pi\xi \cot\mu_0}{\sqrt{1 + 4\pi\xi \cot\mu_0 - 4\pi^2\xi^2}}\epsilon_0 \tag{5}$$

The perturbed parameters can be calculated by iteration.

When our machine is running near $\nu_x \sim 0.53$, the detector's background is low enough to take data. And we can reduce the background by tuning the horizontal orbit in the IR region. When the horizontal tune is more closer to half integer, the luminosity achieves $3.0 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ but the detector cannot work due to high background. Tuning the horizontal orbit cannot improve the background.

We use two methods to study the dyanmic effect. One is the linear theory analysis, the other is making use of the simulation code: the macroparticles after multi-turn beam-beam kick is transported along the ring, and the RMS bunch size is calculated by statistics. Figure 6 and Figure 7 shows the horizontal beam size along the ring for $\nu_x = 0.53/0.51$ respectively. It is very clear that the RMS size enlarges near the horizontal final focus magnet along with the tune's close to half integer. It should be noted that the aperture is only bout 12σ without collision. It seems that we could not make full use of the high luminosity region near half integer without modification of IR.

CRAB WAIST SCHEME

There is still long way for us to achieve the design luminosity. The crab waist scheme proposed by Raimondi [6] may help us, so it's necessary to study the feasibility in our machine. There is 3 steps to implement the scheme:

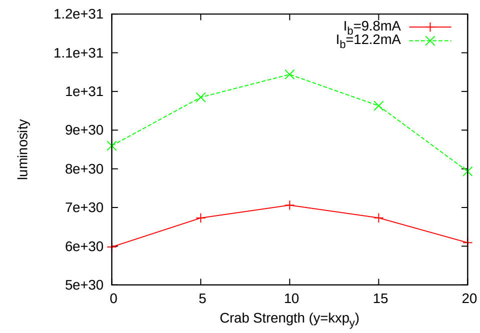

Figure 8: Luminosity versus the crab transformation strength with design parameters.

1. large Piwinski angle $\phi = \sigma_z \tan\theta/\sigma_x$, however it's only 0.43 in BEPCII
2. reduce vertical beta, which is comparable to the overlap area $\beta_y \approx \sigma_x/\theta$, and $\beta_y = 0.015 < \sigma_x/\theta = 0.034$ in BEPCII
3. crab waist transformation $H = \frac{1}{4\theta}xp_y^2$, which means $H = 22xp_y^2$ in BEPCII

It seems that we're not very lucky to use this scheme.

First we try to determine the optimum stregnth of crab waist transformation, which is shown in Figure 8. The optimum is only $\sim$ 0.2 of the full crab rotation. The beam-beam limit with crab on is shown in Figure 9 for $\nu_x = 0.53$. The achieved beam-beam parameters is increased from 0.025 to 0.030, which means the maximum luminosity is $\sim 11 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. When ν_x is more closer to half integer, the luminosity contribution is not as good as that 0.53. It can be concluded that the scheme could help us to some extent, however we still could not find a lattice solution due to dynamic aperture limitation coming from the strong sextupoles.

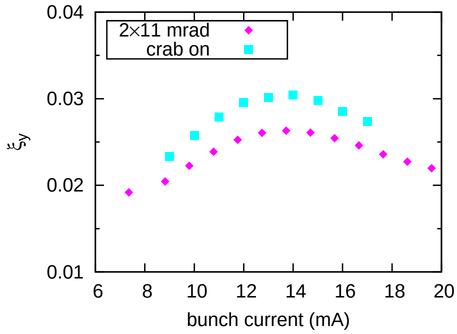

Figure 9: Beam-beam parameter versus bunch current with crab on/off.

SUMMARY

The machine has been tuning with solenoid on since June 2008. In the real machine, $\xi_y = 0.015 \sim 0.020$ is achievable near $\nu_x = 0.53$, however the simulated beam-beam limit is 0.025. Near $\nu_x = 0.51$, $\xi_y = 0.020 \sim 0.025$ is achievable, and the simulated beam-beam limit is 0.035. Not only the achieved but also the simulated is not satisfying. It is the crossing angle which reduces the beam-beam limit. We still don't know what cause the difference between the simulated and the real. It is suspected that the nonlinear map in the arc contributes to the difference. The element-by-element tracking in the arc instead of 6×6 linear map is scheduled.

By the simulation study, we notice that $2\nu_{x,\pi} + 2\nu_s = n$ could excite synchro-betatron resonances and lead luminosity loss. During tune scan of the real machine, we find similar resonance line, however it seems not very strict to conclude they prove each other. Both the dynamic aperture and beam-beam effect is sensitive to another resonance line $2\nu_x + \nu_s = n$.

The dynamic effect reduces the aperture near half integer, which makes the high luminosity region cannot be used to take data till now. On the other hand, the crab waist scheme would not increase luminosity very much. In fact lower beta at IP will help us increase luminosity with or without crab. That is to say it's a good choice to enlarge the aperture near the horizontal final focus magnet. In one words there is still long way to achieve the design luminosity.

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