Beam-Beam Effects in BEPCII

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Abstract

We first introduce the design parameters of BEPCII and simulation study of beam-beam effects during the design process of the machine. The main advances since 2007 is briefly introduced and reviewed. The longitudinal feedback system was installed to suppress the coupled bunch instability in January, 2010. The horizontal tune was moved from 6.53 to 6.508 during the course of data taking in December, 2010. The saturation of beam-beam parameter was found in 2011, and the vacuum chambers and magnets near north crossing point was moved 15cm in order to mitigate the long-range beam-beam interaction. In the megininig of 2013, the beam-beam parameter achieve 0.04 with the new lower α_p lattice and the peak luminosity achieve $7 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

INTRODUCTION

The Beijing Electron-Positron Collider (BEPC) was constructed for both high energy physics and synchrotron radiation (SR) researches. As a unique e^+e^- collider operating in the τ-charm region and the first SR source in China, the machine has been well operated for over 16 years since it was put into operation in 1989.

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 of 2 × 11mrad. The design luminosity of BEPCII is $1.0 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1.89GeV, which is about 100 times higher than BEPC [1]. The main design collision parameters are shown in Table 1. In March, 2013, the peak luminosity achieves $7.0 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 120 bunches and beam current 730mA, where a lower α_p lattice was used.

Table 1: Design Parameters of BEPCII

E	1.89 GeV	ν_s	0.034
I	910 mA	α_p	0.024
I_b	9.8 mA	σ_{z0}	0.0135 m
n_b	93	σ_z	0.015 m
V_{rf}	1.5 MV	ϵ_x	144 nmrad
β_x^*/β_y^*	1.0/0.015 m	Coupling	1.5%
ν_x/ν_y	6.53/5.58	ξ_y	0.04
θ_c	22 mrad	$\tau_x/\tau_y/\tau_z$	3.0e4/3.0e4/1.5e4

In the following, we first introduce the simulation study of beam-beam interaction during the design course of the machine. Then we'll review the performance and optimization of the real machine.

SIMULATION STUDY DURING DESIGN

Code Development

We have developed a new parallel strong-strong beam-beam code, which is used to study the effects in BEPCII [2]. The main characteristics of the code are listed below.

- Particle-in-cell. The triangular shaped cloud (TSC) method is employed for the charge assignment, where the charge of each macroparticle is assigned to its nine nearest points by weight.
- Synchrotron motion is included. The transportation throgh the arc is same as that of Hirata's BBC code[3].
- The beam-beam potential is calculated by solving the Possison equation with open boundary.
- Bunch length effect is included by longitudinal slices and the interpolation of beam-beam potentail is done when the collision between two slices is consderes, which help reduce the required slice number.
- It is assumed that a particle in one slice will not jump into not-ajacent ones the next turn. It seems that the assumption is no problem till now, especially in the ordinary collision scheme(where the required slice number is only about 5).
- Lorentz Boost is used to consider the crosing angle effect [4].

Code Check

- The geometrical factor of luminosity reduction for head-on collision. The loss in luminosity due to geometrical effect for nominal BEPCII parameters is 86%, and the code tracking result agrees well.
- The geometrical factor of luminosity reduction for collision with finite crosing angle. The loss in luminosity due to geometrical effect for design BEPCII parameters is 80%, and the code tracking result agrees well.
- The beam-beam field calculated by the code for the Gaussian beam distribiton agrees well with the Bassetti-Erskine's formula.
- The synchro-betatron mode agrees well with that the hollow beam matrix model predict [5].
- The luminosity result for BEPCII agrees well with that K. Ohmi's code [6].

Simulation Result

The achieved beam-beam parameter ξ with collision is defined as

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

where β^0 is nominal beta function without collision, and σ is disturbed beam size with collision. If we don't consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as

$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y} \quad (2)$$

where σ is disturbed beam size with collision. In the normal case, $\sigma_y \ll \sigma_x$, the achived ξ_y can be represented by lumnosity,

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

With the design parameters, the maximum ξ_y only achieves 0.025, which is shown in Fig. 1. This is bad news for the BEPCII team, since ξ_y need achieve 0.04 if we want to achieve design luminosity with design beam current. Then we did some estimation if it would be feasible to inject more bunches, and it seems no problem.

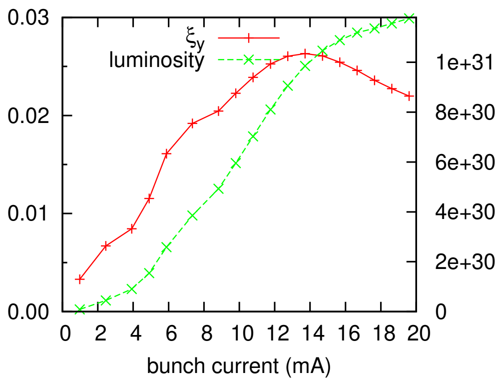


Figure 1: The acieved ξ_y and bunch luminosity versus bunch current with design parameters.

The beam-beam performance is very sensitive to the working point. The normalized luminosity versus tune is depicted in Fig. 2. The best working point is near (0.505,0.570), where the luminosity is about 80% of the design. That is to say we could achieve $8 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with design bunch current, bunch number and optimized working point.

The full horizontal crossing angle between colliding beams is 22mrad. The luminosity reduction factor is less than 10% at (0.53,0.58), however is about 30% at (0.51,0.57). It seems that the luminosity loss due to finite crossinge angle is more serious if the horizontal tune is more closer to half integer, the high luminosity working point region.

We also try to analyze the coupling contribution and did some simulation at different working point. The result is

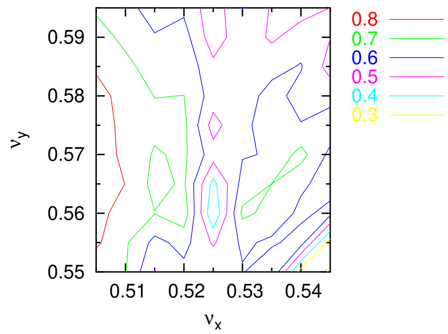


Figure 2: Tune survey of luminosity. The luminosity is normalized to the design value.

Table 2: Coupling contribution at different working point

tune	coupling	max ξ_y	Lum
(0.510, 0.575)	0.5%	0.041@11mA	12.3e30
	1.0%	0.037@12mA	12.1e30
	1.5%	0.034@13mA	12.1e30
(0.530, 0.580)	0.5%	0.026@7mA	5.0e30
	1.5%	0.026@13mA	9.2e30
(0.535, 0.575)	0.5%	0.031@9mA	7.6e30
	1.0%	0.027@9mA	6.6e30
	1.5%	0.023@9mA	5.6e30
(0.540, 0.590)	0.5%	0.025@11mA	7.6e30
	1.0%	0.024@11mA	7.2e30

summarized in Table 2. It seems that we have to move the horizontal tune more closer to half integer and control the emittance coupling less than 0.5% if ξ_y is expected to achieve 0.04.

PERFORMANCE AND OPTIMIZATION

The first electron beam was stored in the SR ring in November, 2006. Optics measurement and correction was studied at that time. The backup collision mode was first tuned in the spring of 2007. We learned the collision tuning during the course. The superconducting final focus magnet was installed in the summer of 2007. The detector was installed in June, 2008, which means the construction of the machine was finished. We'll try to review the machine tuning hisotory in chronological order.

Phase I: Autumn of 2008 - Summer of 2010

The big events in this period are listed below:

- January, 2009. Profile monitor was removed from the positron ring, which excite very strong longitudinal multibunch instability.
- May, 2009. Horizonatal tune was moved to 0.51 from 0.53. Luminosity reached $3 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is the "design goal" of the government funding agency.
- January, 2010. Longitudinal feedback system was installed and began to work.

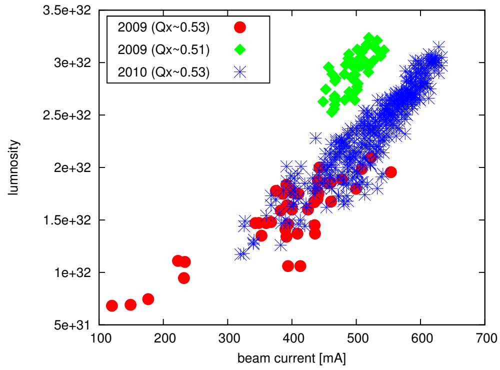
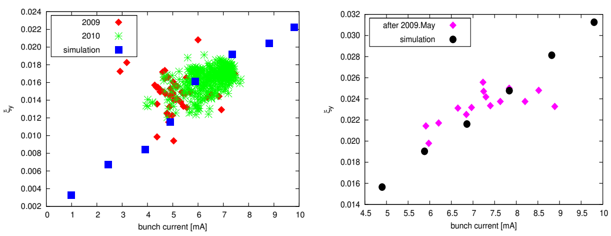


Figure 3: Luminosity versus beam current in 2009 and 2010. The difference between the red (2009) and blue dots (2010) comes from the suppression of longitudinal multi-bunch instability.



(a) (b)

Figure 4: Beam-beam parameter versus bunch current. The left figure shows that $Q_x \sim 0.53$ and the right shows that $Q_x \sim 0.51$. The longitudinal feedback system begins to work in 2010.

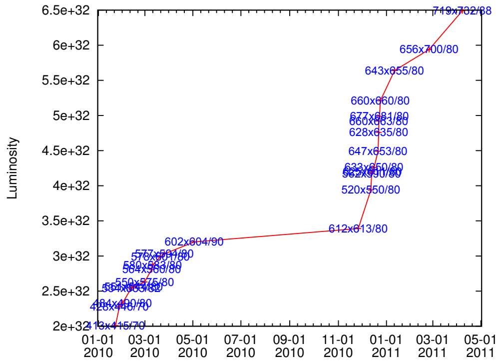


Figure 5: Peak luminosity record from the beginning of 2010 to the summer of 2011. The colliding beam current and bunch number is also shown in the figure.

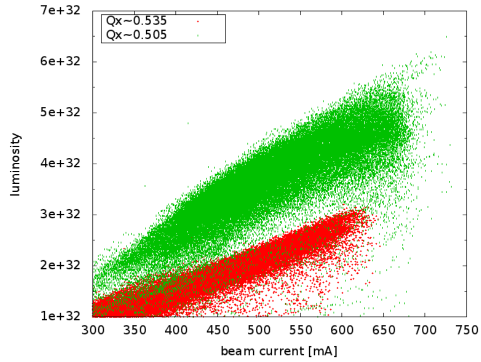


Figure 6: Luminosity performance at different working point.

Fig. 3 shows the luminostiy versus beam current and Fig. 4 shows the beam-beam parameter versus bunch current. The longitudinal coupled bunch instability still reduce the luminosity performance even after the removal of profile monitor in the positron ring, which has excited very strong instability. In order to increase the luminosity with same beam current, we try to move the horizontal tune closer to half integer in May, 2009. The peak luminosity increase from 2 to $3 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Since the detector background is too high to take data with $Q_x \sim 0.51$, the machine is still runing with $Q_x \sim 0.53$ in the following normal data taking commissioning. In the first half year of 2010, the longitudinal feedback system begins to work and the peak luminosity achieves $3 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with $Q_x \sim 0.53$. The maximum ξ_y is about 0.02 when $Q_x \sim 0.53$, which is less than the simulated(See Table. 2) 30% percent.

Phase II: Autumn of 2010 - Summer of 2011

The big events in this period are listed below:

- July, 2010. It was found that the final focus magnet and vacuum chamber on one side of the detector was displaced about 10mm in horizontal direction. It was aligned in the summer shutdown.
- December, 2010. Detector background was reduced with $Q_x \sim 0.51$. The physics people could take data near the 0.51 working point.

The most important advance in this period is the reduction of detector background with $Q_x \sim 0.51$, since the physics people could take data at the working point and the accelerator people have enough time to do the luminosity tuning. The detector background is mainly optimized by the closed orbit tuning along the ring. Fig. 5 shows the peak luminosity record from the beginning of 2010 to the summer of 2011. It is very exciting near the new year of 2011 since a new record would be born only in a few days. The peak luminosity is $6.5 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2011. The comparison of luminosity at different working point is shown in Fig. 6, which is very obvious that closer to half integer means higher luminosity.

The 2010~2011 commissioning year is very successfull and exciting, but there is some confusion when we see the beam-beam performance. The achieved ξ_y is shown in Fig. 7. There exist clear saturation phenomenon for ξ_y and the maximums is about 0.033. We should answer what cause the saturation.

Fig. 8 shows the bunch lengthing effect. It seems this effect does not bring very much luminosity loss, and the

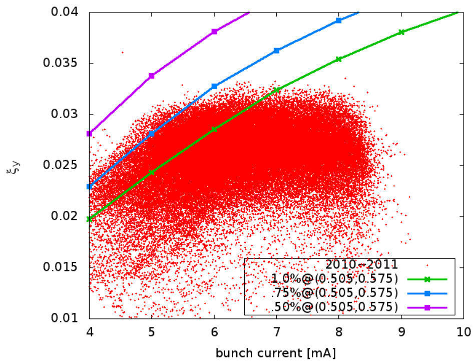


Figure 7: Achieved beam-beam parameter in 2010∼2011. The linespoint shows the simulation result with differnt coupling.

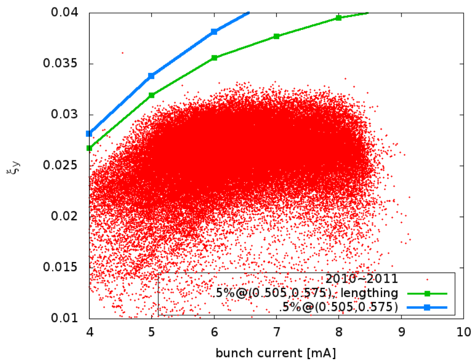


Figure 8: Beam-beam loss due to bunch lengthing, which does not explain the beam-beam parameter saturation in real machine.

maximum beam-beam parameter is still above 0.04.

The nonlinear arc may also reduce the luminosity performance. We use Hirata's BBC[3] code as a pass method in Acclerator Toolbox[7] to simulate the weak-strong beam-beam interaction. The map in the arc is implemented using the element-by-element symplectic tracking in AT. Fig. 9 shows the comparision between ideal transfer matrix map and element-by-element tracking in arc. The lattice really reduces the beam-beam performance, but we did not believe the saturation is mainly caused by the crosstalk between nonlinear arc and beam-beam force. On the other hand, we could not ignore the simulation result which tell us we should put more emphasis on the sexupole optimization.

There is another crossing point(NCP) in the north of the two rings, where the colliding beams are separated vertically about 8mm and the full horizontal angle is about 2×0.15rad (17.7°). We still use the weak strong code (AT+BBC) to study the parasitic beam-beam effect, which is shown in Fig. 10. The achieved ξ_y is only about 0.035 with 8mm separation at NCP.

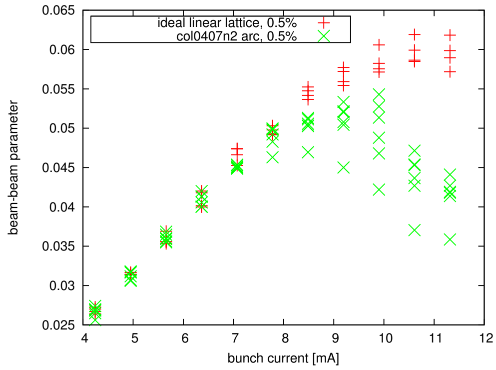


Figure 9: The luminosity loss due to the realistic arc. The arc map is implemented using element-by-element tracking. The ideal linear lattice means the map is represneted by a transfer matrix.

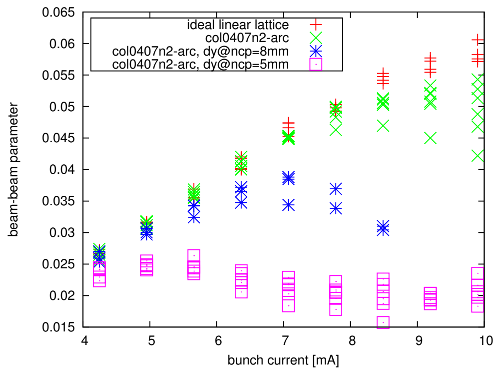


Figure 10: The luminosity loss due to nonlinear arc and long range beam-beam interaction at NCP.

Phase III: Autumn of 2011 - Summer of 2012

The big events in this period are listed below:

- In the summer shutdown of 2011, the NCP chambers and magnets were moved 15cm, 1/4 of the rf bucket. The horizontal separation between colliding bunches is greater than $30\sigma_x$.

After the hardware modification, the beam-beam performacne does not increase as expected, which is shown in Fig. 11. This could be explained to some extent by the large longitudinal offset of collision point . In 2011-2012 commissioning year, the offset is about 3mm, and it is about 6mm in Feburary, 2012. We didn't put enough emphasis on the monitor of the parameter during collision at that time.

Phase IV: Autumn of 2012 - March, 2013

The big events in this period are listed below:

- Lower alphap mode was first tested at 2.18 GeV in Feburary, 2013. The ξ_y record 0.033 was broken after about two years.

- One bunch every three bucket, and even one bunch every two bucket injection was tested in the machine

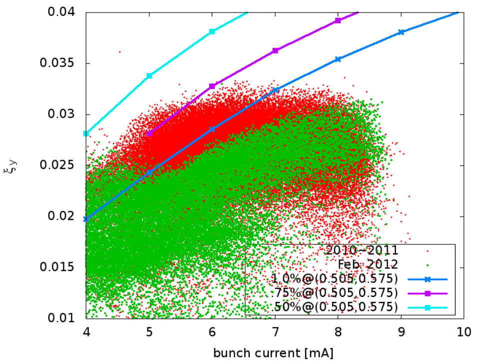


Figure 11: Beam-beam parameter achieved in 2011 and 2012. The mitigation of long-range beam-beam interaction at NCP does not bring any improvements.

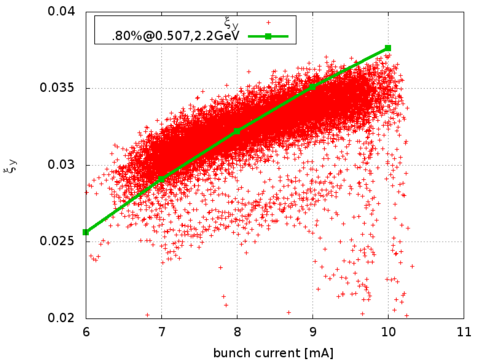


Figure 12: Achieved beam-beam parameter at 2.18GeV with new lattice in 2013.

study of March, 2013. The peak luminosity achieves $7.0 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ at 1.89GeV.

The momentum compaction factor of new lattice is about 0.017, and the old one is 0.024. The reduction of α_p is achieved by increase the horizontal tune from 6.5 to 7.5. During the lattice design, we also optimize the chromatic distrotion and some nonlinear some resonance driving terms. However we still not establish a so-called “standard” that could tell us the lattice is good enough.

The achieved beam-beam performance at 2.18GeV is shown in Fig. 12. We also do some machine study in order to increase the peak luminosity at 1.89GeV. The achieved beam-beam paramter with different bunch pattern is shown in Fig. 13. The maximum ξ_y is above 0.04. It seems the multibunch effect reduce the beam-beam performance, which would be a serious limitation for us to go on increase the luminosity.

SUMMARY

We review the collision optimization history of BEPCII in the paper. The suppression of multibunch longitudinal instability and moving the horozontal tune close to half integer help us a lot to increase the luminosity. The mitigation of long range beam-beam interaction seems not so effective as expected, maybe the real vertical separation is greater than estimation. The lower α_p lattice help us achieve the ξ_y record 0.04 at 1.89GeV.

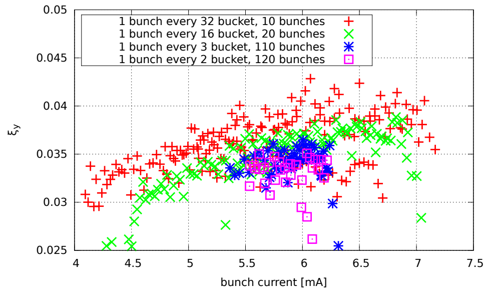


Figure 13: Achieved beam-beam parameter at 1.89GeV with different bunch pattern in 2013.

The simulation study is very imporatant both in the design and daily commisioning. It gives a benchmark in the normal operation and let us know if the status is optimized enough, even though we could apparoach the simulation result and never go beyond it. The difference between simulation and optimized result is about 10%-20%. It should also be emphasized that we would like to use the maximum achieved ξ_y in the simulation as the beam-beam limit in the simulation.

Increasing beam current is a must to increase the luminosity. However it seems the multibuch effect is very serious, the study to cure the instability and even find the instability source is very important in the following. In the near future, we'll test a new lattice with $alpha_p$ is about 0.017, larger emittance(100nm$\rightarrow$130nm) and lower β_y (1.5cm$\rightarrow$1.35cm). The colliding bunch current could be higher with the new mode and the beam current could be higher with same bunch number. It is expected this could help us increase the luminosity.

REFERENCES

[1] Design Report of BEPCII-Accelerator Part (2nd ed), 2003.

[2] Y. Zhang, K. Ohmi and L. Chen, Phys. Rev. ST Accel. Beams 8, 074402, 2005

[3] BBC: Program for Beam-Beam Interaction with Crossing Angle. http://wwwslap.cern.ch/collective/hirata/

[4] K. Hirata, Phys. Rev. Lett., 1995, 74, 2228-2231

[5] E. G. Stern, J.F. Amundson, P.G. Spentzouris, and A.A. Valishev, Phys. Rev. ST Accel. Beams 13, 024401, 2010

[6] K. Ohmi, Phys. Rev. E 62, 7287 (2000)

[7] A.Terebilo, SLAC-PUB-8732, 2001