Recent Advances of Beam-Beam Simulation in BEPCII

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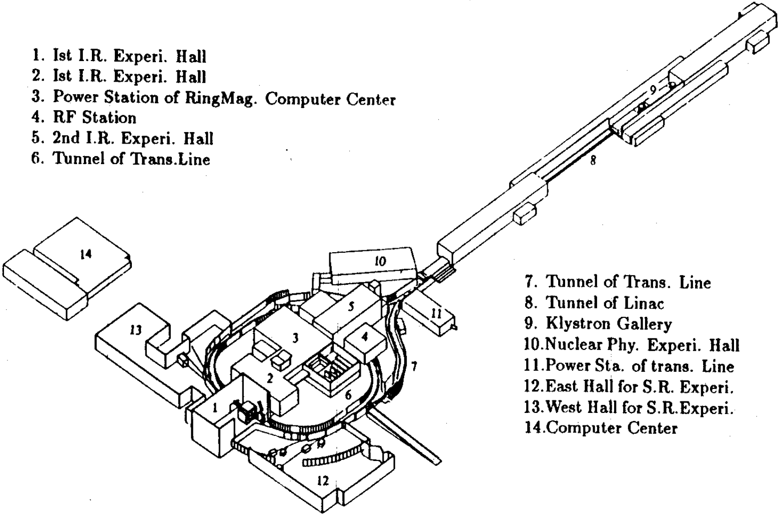
Outline

1. Introduction of BEPCII
2. Introduction of Beam-Beam Code
3. Beam-Beam Limit
4. Synchro-Betatron Resonances
5. Dynamic Effect
6. Crab-Waist Scheme
7. Summary

Bird’s Eye View of BEPC

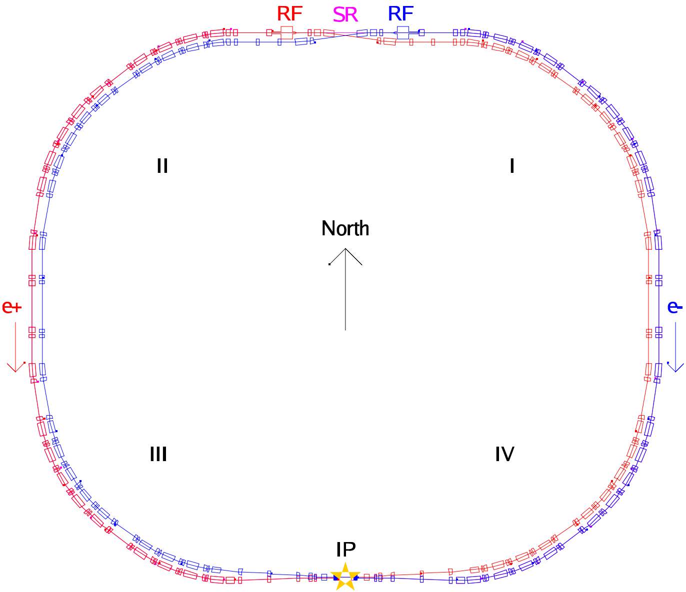


1. Ist I.R. Experi. Hall
2. Ist I.R. Experi. Hall
3. Power Station of RingMag. Computer Center
4. RF Station
5. 2nd I.R. Experi. Hall
6. Tunnel of Trans.Line
7. Tunnel of Trans. Line
8. Tunnel of Linac
9. Klystron Gallery
10. Nuclear Phy. Experi. Hall
11. Power Sta. of trans. Line
12. East Hall for S.R. Experi.
13. West Hall for S.R.Experi.
14. Computer Center

Upgrade from BEPC to BEPCII

- Single-Ring BEPC $\Longrightarrow$ Double-Ring BEPCII
- Same tunnel
- One machine, two uses: collider and synchrotron light source
- Most of beam SR lines unchanged
- The circumference between collider rings and SR ring must be matched. The ratio of harmonic number is 396:402.

Geomeric Survey of BEPCII



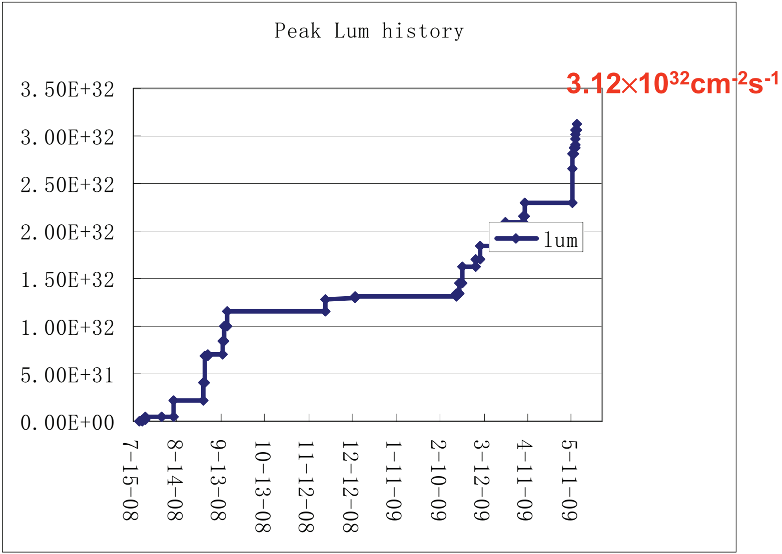
Main Parameters of BEPCII

	Design	Achieved
E [GeV]	1.89	1.89
C [m]	237.53	
N_b	93	70
I_b [mA]	9.8	8
Luminosity [$\times 10^{32} cm^{-2} s^{-1}$]	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	

Brief History of Machine Tuning

1. IR with conventional magnets as final focus quadrupole
   - $\beta_x/\beta_y = 2/0.05m$
   - Cherenkov luminosity detectors (barbar photon)
   - An exercise of luminosity optimization
2. IR with super conductive quadrupoles
   - $\beta_x/\beta_y = 1/0.015m$
   - Achieved Lum. = 0.5-1.0$\times10^{32}$
3. BEPCII + BESIII (Solenoid On)
   - CsI luminosity detector (hardon event)
   - Achieved Lum. = 3.0×10^{32}
   - Reviewed by the government!

Peak Luminosity History



Beam-Beam Code

- Strong-Strong Model: Particle-in-cell Code
- Synchrotron motion is included
- Finite Bunch Length Effect is included by longitudinal slices
- It is assumed that a particle in one slice will not jump into not-ajacent ones the next turn
- Lorentz Boost (by Hirata) is used to include the horizontal crossing angle effect

Transportation through the arc

- Same as Hirata's BBC code
- Synchrotron radiation is included
- The arc transportation in the normalized coordinates is

$$\begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{pmatrix} \rightarrow \lambda_u m_u \begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{pmatrix} + \sqrt{\epsilon_x(1-\lambda_u^2)} \begin{pmatrix} \hat{r}_1 \\ \hat{r}_2 \end{pmatrix},$$

$$\begin{pmatrix} \mathbf{X}_3 \\ \mathbf{X}_4 \end{pmatrix} \rightarrow \lambda_v m_v \begin{pmatrix} \mathbf{X}_3 \\ \mathbf{X}_4 \end{pmatrix} + \sqrt{\epsilon_y(1-\lambda_v^2)} \begin{pmatrix} \hat{r}_3 \\ \hat{r}_4 \end{pmatrix},$$

$$\begin{pmatrix} \mathbf{X}_5 \\ \mathbf{X}_6 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & \lambda_w^2 \end{pmatrix} m_w \begin{pmatrix} \mathbf{X}_5 \\ \mathbf{X}_6 \end{pmatrix} + \begin{pmatrix} 0 \\ \sqrt{\epsilon_z(1-\lambda_w^4)}\hat{r}_5 \end{pmatrix}.$$

Beam-Beam Force

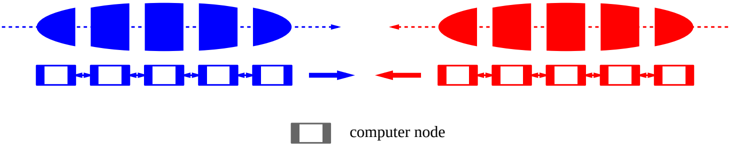
$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\phi(x,y)=-\frac{\rho(x,y)}{\epsilon_0}$$

$$\delta p_x=-\frac{e}{P_0c}\frac{\partial\phi(x,y)}{\partial x},\quad \delta p_y=-\frac{e}{P_0c}\frac{\partial\phi(x,y)}{\partial y},$$

Cai's method is used to solve the two-dimensional beam-beam field. And we use an optimized method to calculate the boundary potential.

- Particle-in-cell method is used
- The triangular-shaped colud (TSC) method is empolyed for the charge assignment
- The open boundary condition is assumed
- The poisson equation is solved directly by the FACR method (*the direct FFT method is also implemented, unnecessary to initialize the boundary potentail*)

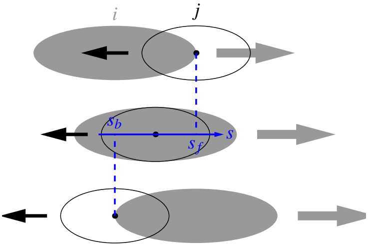
Beam Slices and Parallel Scheme



- The longitudinal boundaries of slices are chosen so that the number of macro-particles in each slice is uniform.
- A slice exchanges macro-particles with its adjacent ones at IP and before collision each turn.
- One MPI (Message Passing Interface) node is used to represent one slice.
- (It seems that) The computing time increases linearly by a factor of $(n+1)$, where n is the slice number in one bunch.
- Not efficient scheme, But work in our small farm which is not under strict control

Interpolation Scheme

The interpolation scheme (by Ohmi) is empolyed to improve the convergence of slice number.



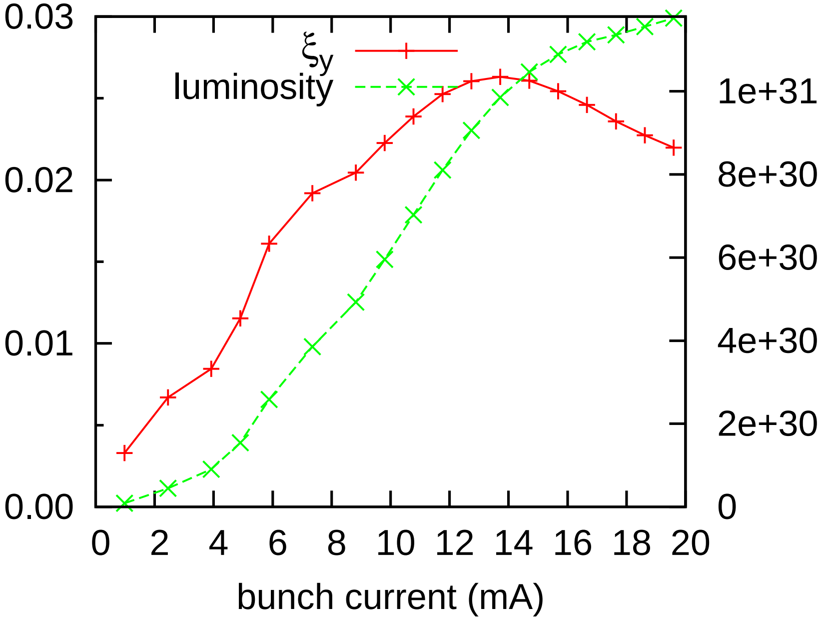
The beam-beam force experienced by slice i and generated by slice j is considered:

- The point s_f is the position where the front end of i meets the center of j, and s_b the position where the back end meets the center.
- The potential by j is computed twice at s_f and s_b.
- The potential by j at $s(s_b \leq s \leq s_f)$ can be calculated by linear interpolation.

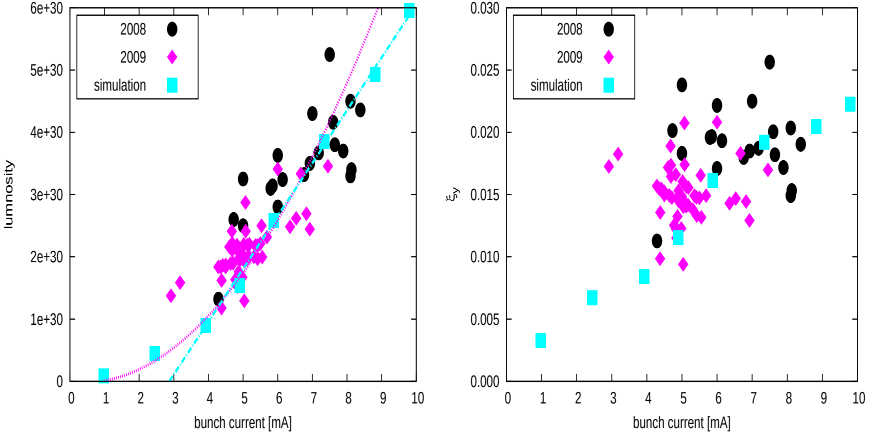
Beam-Beam Parameter

- the achieved beam-beam parameter ξ with collision is defined as
$$\xi_u = \frac{Nr_e}{2\pi\gamma}\frac{\beta_u^0}{\sigma_u(\sigma_x+\sigma_y)}$$
where β^0 is nominal beta function without collision, and σ is disturbed beam size with collision.
- Do not consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as
$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y}$$
where σ is disturbed beam size with collision.
- when beam $\sigma_y \ll \sigma_x$, the achived ξ_y can be represented by lum,
$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$

Simulated Beam-Beam Limit ($\nu_x \approx 0.53$)



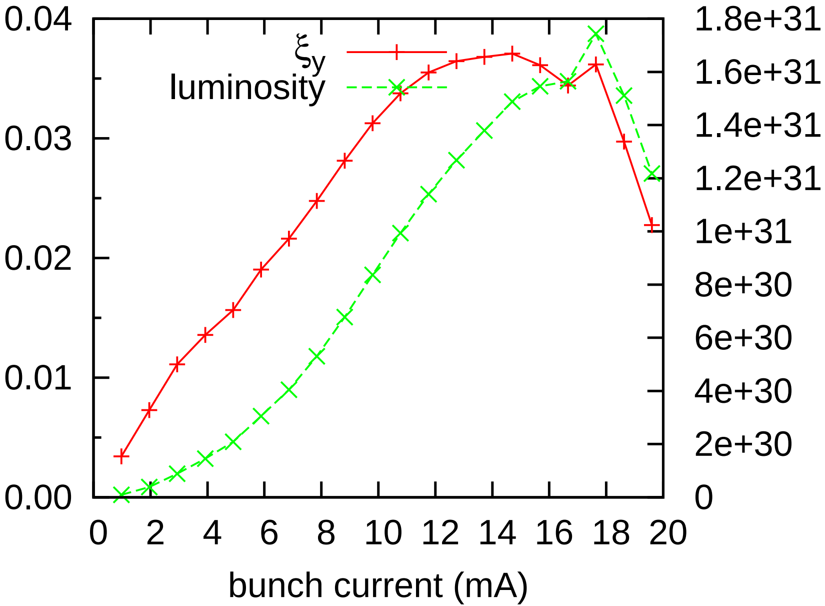
Achieved Beam-Beam Limit ($\nu_x \approx 0.53$)



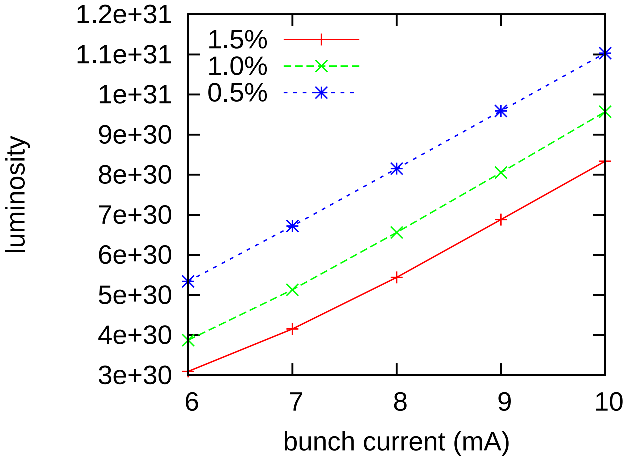
Before May-2009

- $\sim 2.0 \times 10^{32} cm^{-2} s^{-1}$ has been achived, it seems very hard to get higher lumnosity
- an October deadline for the project review
- the longitudinal instability limit the multi-bunch luminosity, however the feed-back system will be installed during summer shutdown
- we can try to approach the half-integer region ...

Simulated Beam-Beam Limit ($\nu_x \approx 0.51$)

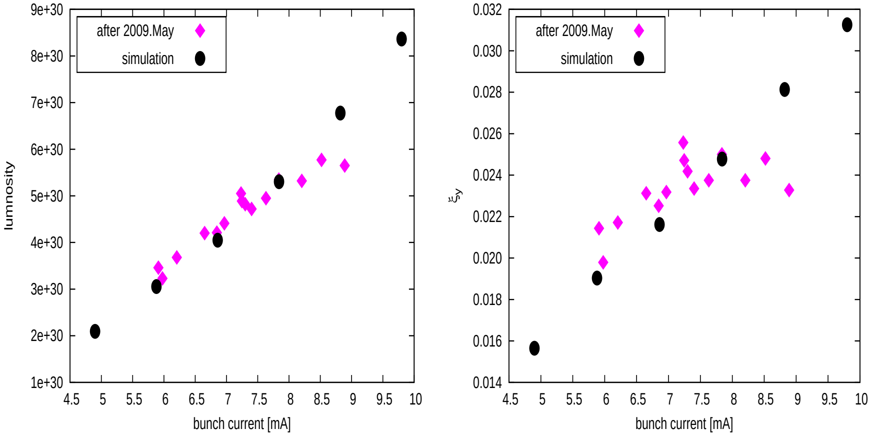


Luminosity vs Coupling ($\nu_x \approx 0.51$)

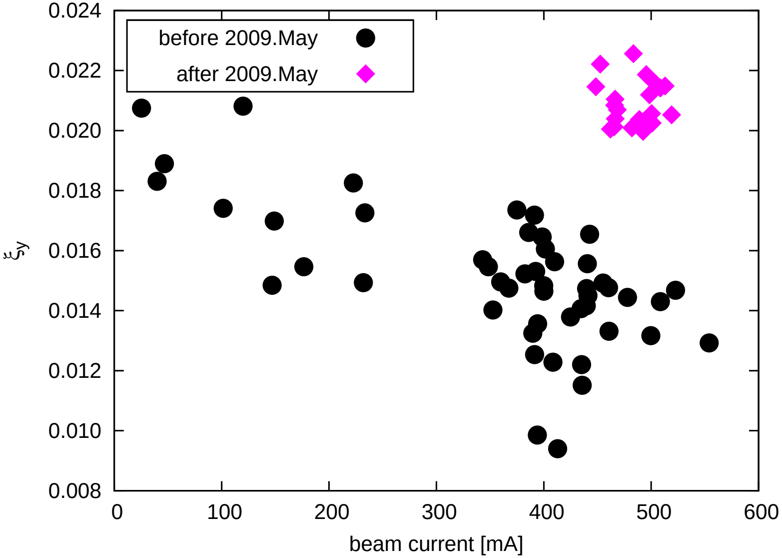


the simulation result encourge us to try the half-integer region at last

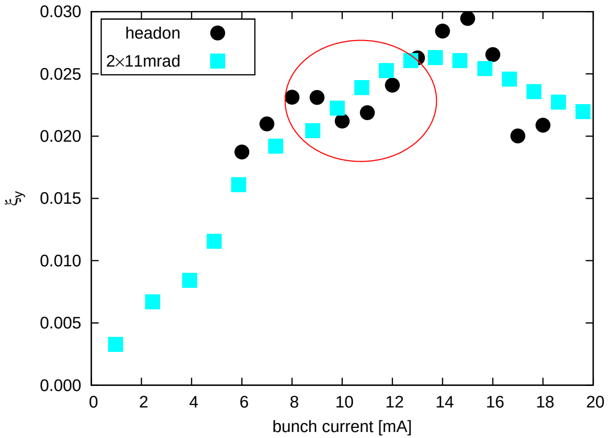
Achieved Beam-Beam Limit ($\nu_x \approx 0.51$)



Before vs After 2009 May, Namely 0.53 vs 0.51



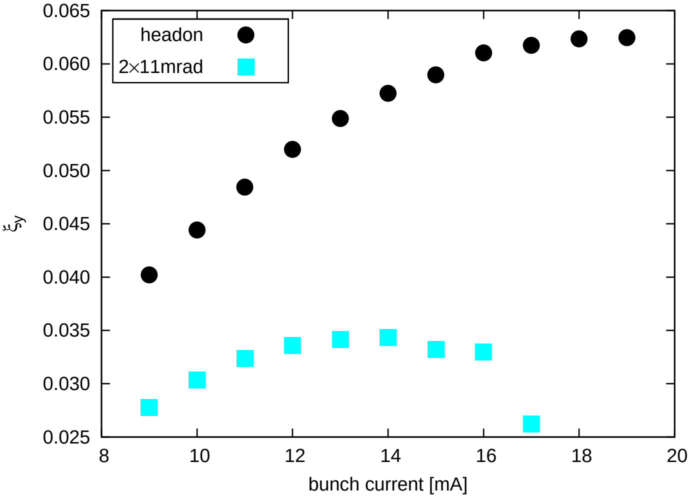
Crossing Angle ($\nu_x \sim 0.53$)



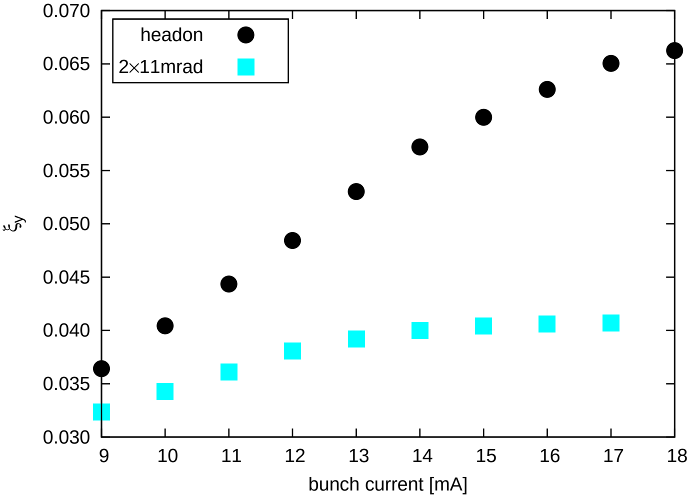
The abnormal luminosity disturbance near 10mA in the head-on case is due to:

- meets the resonance line $4\nu_y + \nu_x = n$
- the π-mode of horizontal tune is close to ν_y

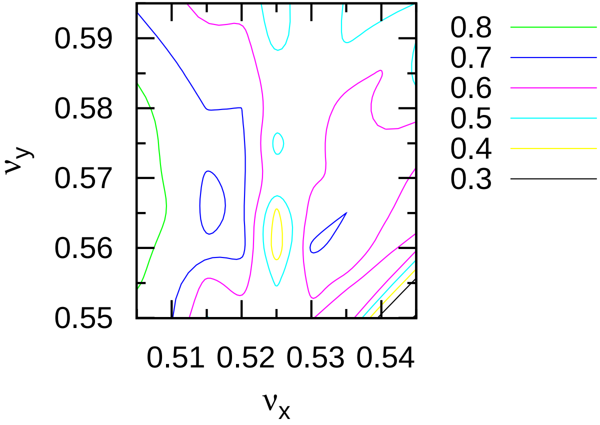
Crossing Angle Reduces the Beam-Beam Limit ($\nu_x \sim 0.51$)



Crossing Angle Reduces the Beam-Beam Limit ($\nu_x \sim 0.505$)

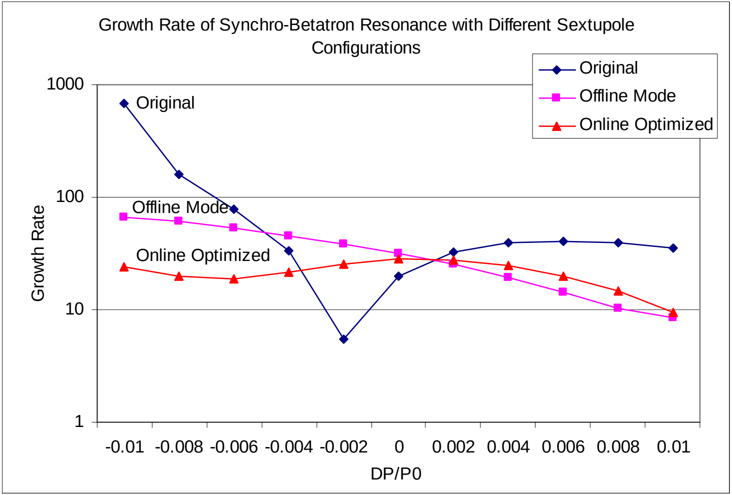


Synchrotron-Betatron Resonance



- due to beam-beam, $\nu_x \sim 0.525$ is inhibited
- due to nonlinearity in the arc, $\nu_x \sim 0.517$ is inhibited

Sextupole Configuration ($\nu_x \sim 0.51$)

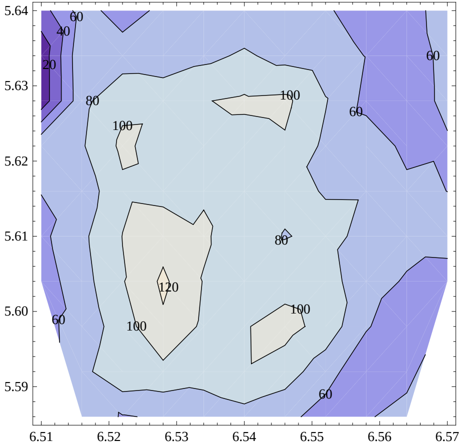


before optimization, the luminosity is very sensitive to tuning knobs: rf voltage, tune, and orbit etc.

Tune Scan of the Real Machine

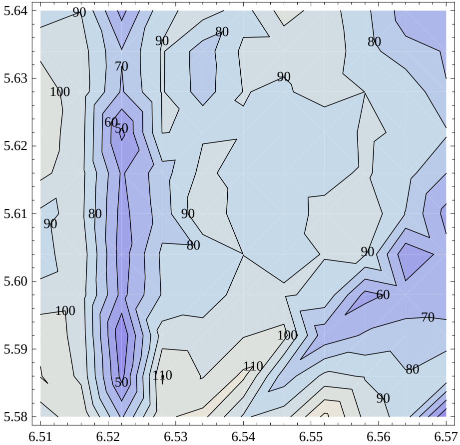
SCAN BPR

(BER: $\nu_x = 6.5355, \nu_y = 5.5845$)



SCAN BER

(BPR: $\nu_x = 6.5272, \nu_y = 5.6015$)



We acheived $3.0 \times 10^{32} cm^{-2} s^{-1}$, *but*

- The background is too high, the detector cannot take data in the case of $\nu_x \sim 0.51$
- We can reduce the background by tuning the horizontal orbit in the IR region when $\nu_x \sim 0.53$, and cannot when ν_x is closer to half integer
- The phenomenon can be explained by the dynamic beam-beam effect

Dynamic Beta and Dynamic Emittance

- Achieved Beam-Beam Parameter:

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

- Dynamic Beta:

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

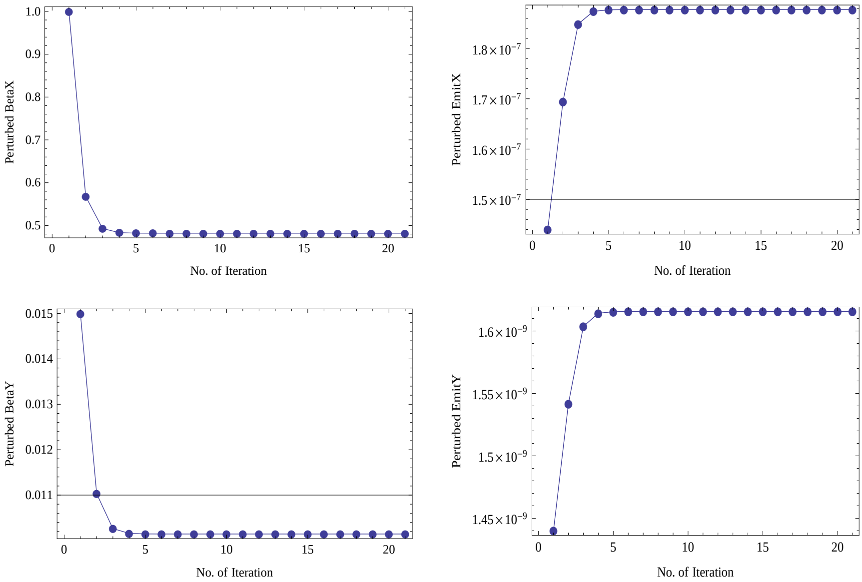
- Dynamic Emittance:

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

- If there exist horizontal crossing angle:

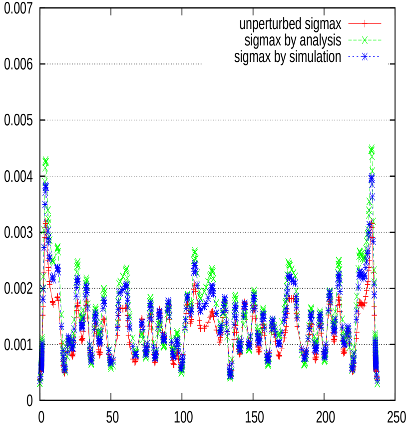
$$\sigma_x \longrightarrow \sqrt{\sigma_z^2\tan^2\theta + \sigma_x^2}$$

Calculation of Dynamic Parameters by Iteraion

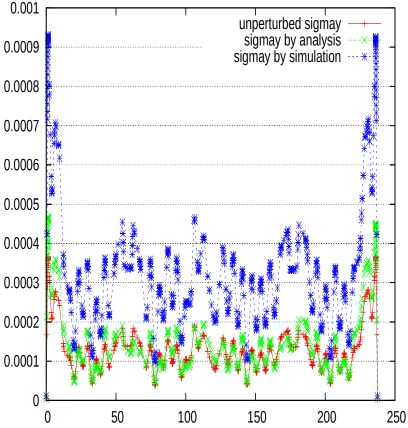


$$\nu_x/\nu_y = 0.53/0.58, I_b = 8mA$$

Beam Size along the Ring with Collision ($\nu_x \sim 0.53, I_b = 8mA$)

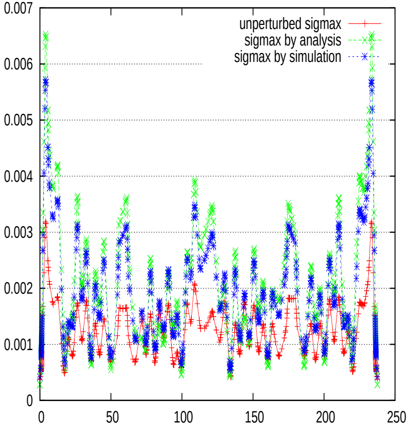


(a) $\nu_x = 0.530$,x

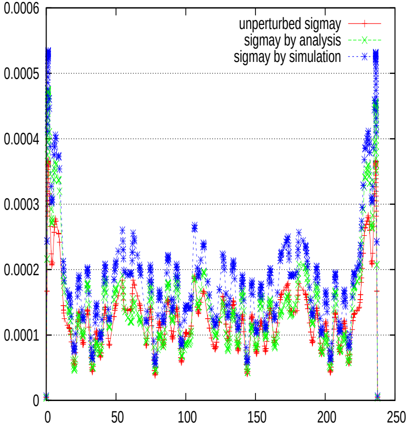


(b) $\nu_x = 0.530$, y

Beam Size along the Ring with Collision ($\nu_x \sim 0.51, I_b = 8mA$)

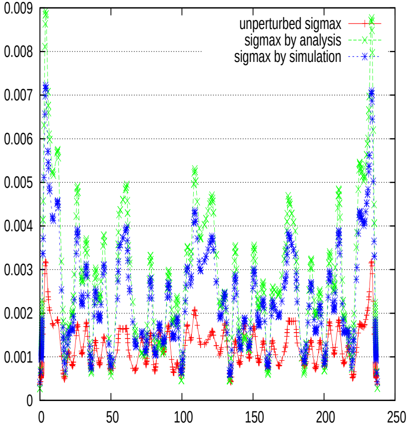


(a) $\nu_x = 0.510$,x

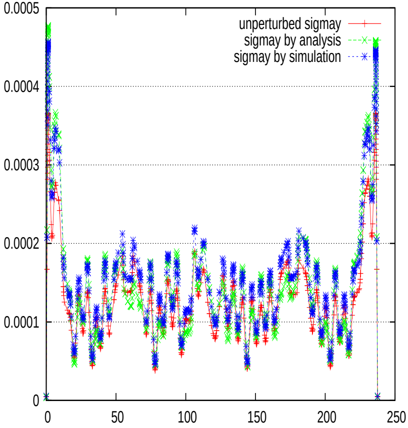


(b) $\nu_x = 0.510$, y

Beam Size along the Ring with Collision ($\nu_x \sim 0.505, I_b = 8mA$)



(a) $\nu_x = 0.505$,x



(b) $\nu_x = 0.505$,y

How can we achieve $1.0 \times 10^{33} cm^{-2} s^{-1}$

We will try our best to achieve *the design luminosity, 100 times higher than BEPC*

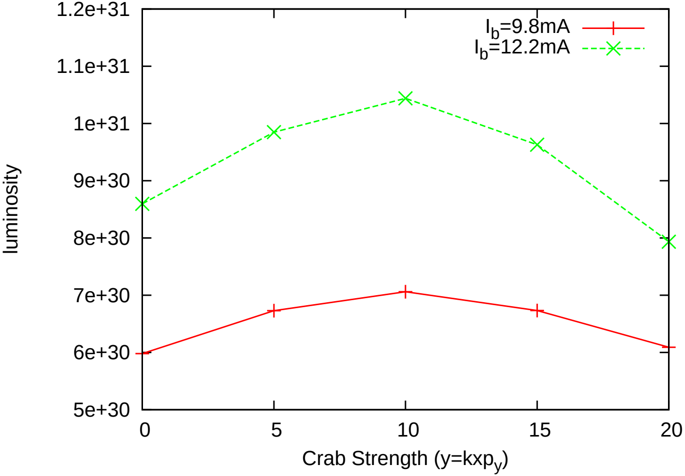
- Acoording to simulation, only 60% of the design luminosity can be achieved with the design parameters
- ν_x is closer to half integer would help us, but it seems that we've to change the IR layout or magnets due to the limited aperture and detector background
- Higher bunch current and more bunches, it may be limited by heat problem of some vacuum devices, at the same time it would challenge the feedback system
- The Crab-Waist Scheme, will it work in our machine?

Crab Waist in 3 Steps

- Large Piwinski angle $\phi = \sigma_z \tan\theta/\sigma_x$, only 0.43 in BEPCII
- Vertical β comparable to overlap area $\beta_y \approx \sigma_x/\theta$, and $\beta_y = 0.015 < \sigma_x/\theta = 0.034$ in BEPCII
- Crab Waist transformation $H = \frac{1}{4\theta} x p_y^2$, it means $H = 22 x p_y^2$ in BEPCII

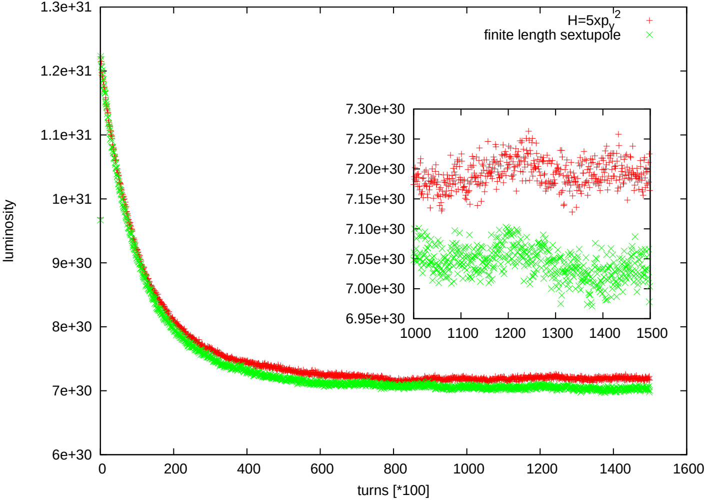
Crab Waist Transformation Stregnth

The optimum stregnth is only ~ 0.2 of the full waist rotation



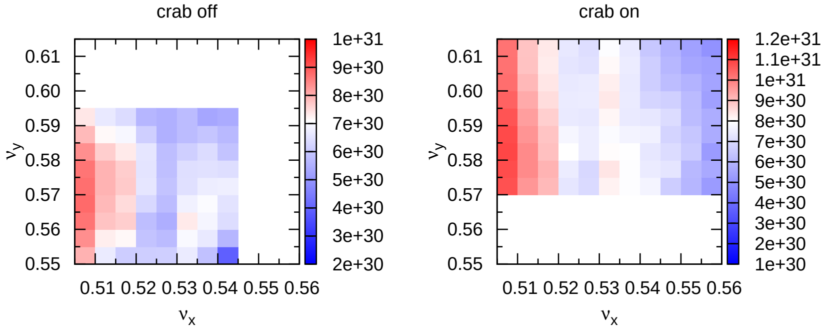
Finite Length of Crab-Waist Sextupoles

With the sextupole:
$K_2 = 35m^{-3}, L = 0.2m$, and $\beta_x/\beta_y = 7.5/35m$,
The finite length is not a serious problem in our case.

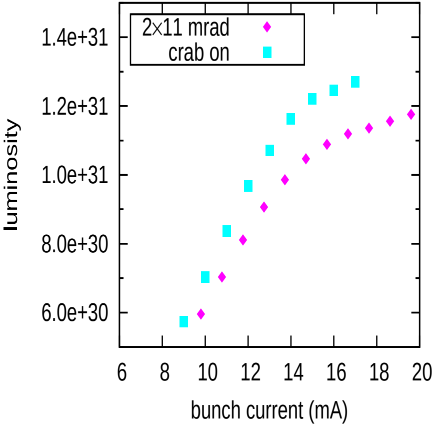


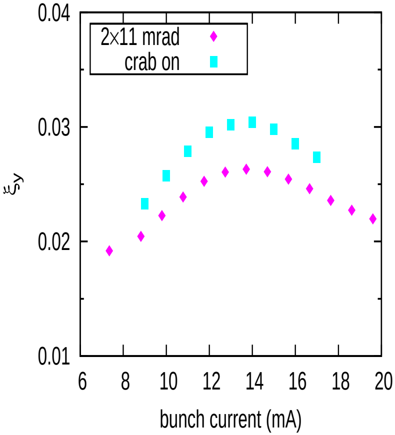
Luminosity vs Tune with Crab Off/On

The maximum luminosity is increased
from $\sim 9 \times 10^{30} cm^{-2} s^{-1}$ to $\sim 11 \times 10^{30} cm^{-2} s^{-1}$:

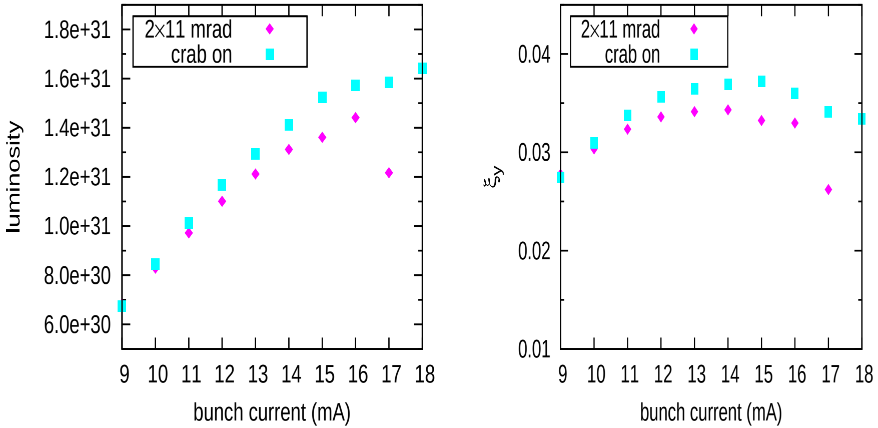


Beam-Beam Limit with Crab On ($\nu_x \approx 0.53$)

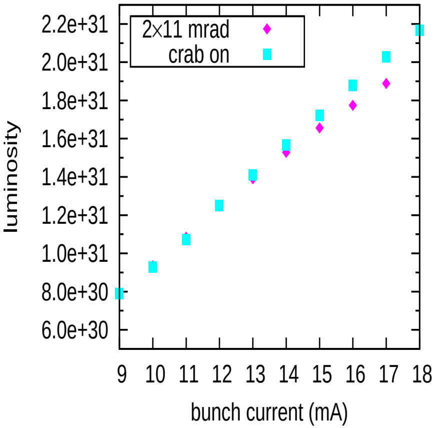


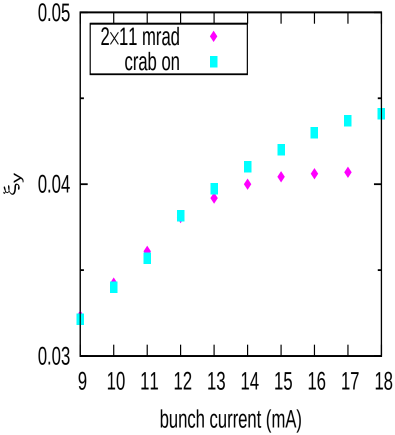


Beam-Beam Limit with Crab On ($\nu_x \approx 0.51$)



Beam-Beam Limit with Crab On ($\nu_x \approx 0.505$)





We need a Crab-Waist Lattice

- The simulation says that the luminosity contribution is not so good, but it may help us achieve the design luminosity
- Most of the time on the scheme feasibility study has been spent on the lattice design, however we did not find a solution, the dynamic aperture is limited
- Most of the efforts focus on using the existing sextupoles where is not dispersin free, since it's very hard to change the magnets layout in the arc
- We need more experienced colleagues join in the lattice design work
- In one words, it's hard work

Summary - 1

- 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
- In the real machine, $\xi_y = 0.020 \sim 0.025$ is achievable near $\nu_x = 0.51$, however the simulated beam-beam limit is ~ 0.035
- The difference between simulation and measurement may come from the crosstalk between beam-beam map and nonlinearity in the arc. The element-by-element tracking instead 6×6 linear map is in the schedule of code development and simulation
- The synchro-beatron resonance $2\nu_{x,\pi} + 2\nu_s = n$ would lead luminosity loss by simulation. We find similar phenomenon during tune scan of the real machine. However it seems not very strick to conclude they prove each other

Summary - 2

- Both the dynamic aperture and beam-beam effect is sensitive to the resonance $2\nu_x + \nu_s = n$
- The dynamic effect reduces the aperture near half integer, which makes the high luminosity region cannot be used to take data till now
- The crab waist scheme would not increase luminosity very much. We would optimze the beam paramters, but firstly we should find a lattice solution
- If the aperture near the final horizontal focus magnet can be enlarged, it would contribute to the luminosity increase with or without crab. That means we need to modify the IR region