Beam-beam effects in BEPC-II

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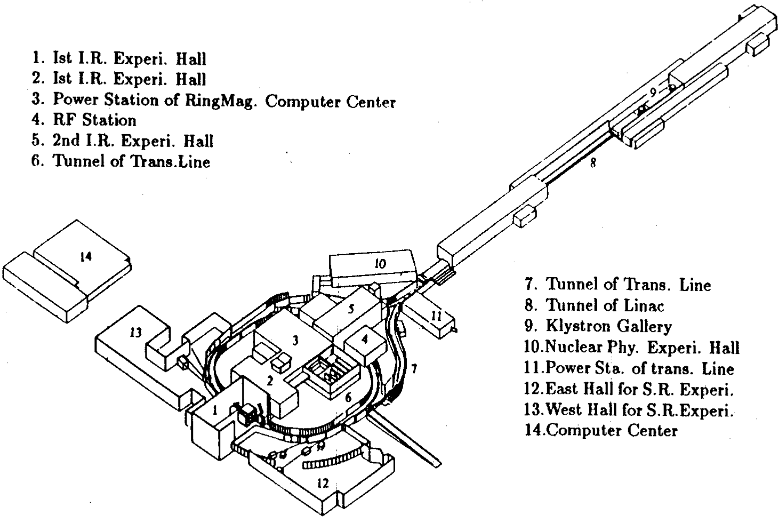
March 18, 2013
ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013)

Outline

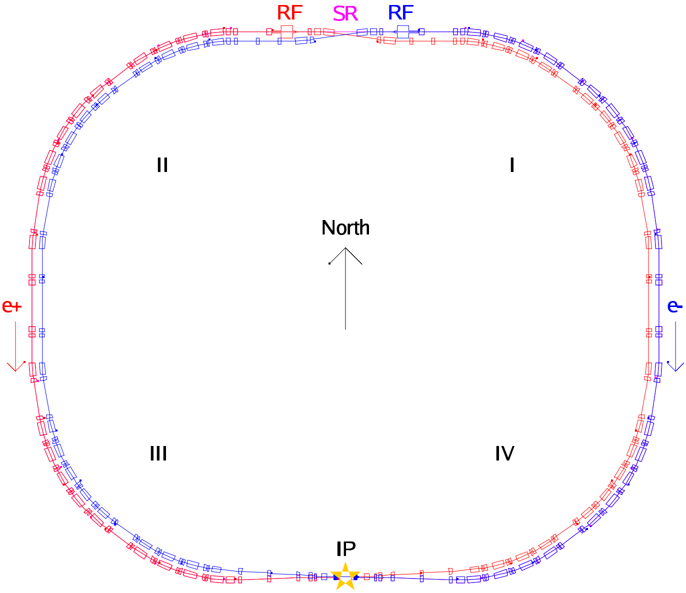
Bird's Eye View of BEPC



Upgrade from BEPC to BEPCII

- BEPCII is an upgrade project:
  Single-Ring BEPC $\Longrightarrow$ Double-Ring BEPCII
- Same tunnel
- One machine, two uses: collider and synchrotron light source
- Keep most of beam 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



Design Parameters

- General Parameters

Beam energy	1.0∼2.1 GeV
Optimized beam energy	1.89 GeV
Luminosity @ 1.89 GeV	1.0×10^{33} $cm^{-2}s^{-1}$
Full energy injection(e+)	1.55∼1.89 GeV
Dedicated SR operation	250 mA @ 2.5 GeV

- Collision Parameters

Energy	1.89 GeV	ν_s	0.034
Beam Current	910 mA	α_p	0.024
Bunch Current	9.8 mA	σ_{z0}	0.0135 m
Bunch Number	93	σ_z	0.015 m
RF Voltage	1.5 MV	Emittance	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
Crossing Angle	2×11 mrad	$\tau_x/\tau_y/\tau_z$	3.0e4/3.0e4/1.5e4 turns

Model of Simulation

- Particle-in-cell
- Synchrotron motion is included
- 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 crossing angle effect

Code Check: Head-on Collision with Low Bunch Current

- The bunch luminosity of BEPCII (zero bunch length and zero crossing angle) is

$$\mathscr{L}_0 = 1.09 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}, \quad (\ I_b = 9.8\mathrm{mA}\ )$$

- The loss in luminosity due to geometrical effect (for Gaussian beam) is

$$R = 86.0\%$$

The luminosity should be

$$\mathscr{L} = \mathscr{L}_0 \times R = 9.37 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}, \quad (\ I_b = 9.8\mathrm{mA}\ )$$

- The calculated luminosity using the code is

$$L = \begin{cases} 9.36 \times 10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}, & (I_b = 9.8 \times 10^{-2}\mathrm{mA}) \\ 9.44 \times 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}, & (I_b = 9.8 \times 10^{-1}\mathrm{mA}) \end{cases}$$

Code Check: Crossing Collision with Low Bunch Current

- The loss in luminosity due to the crossing angle (2×11mrad) is

$$R_L = 80.2\%$$

The theoretical value of luminosity is

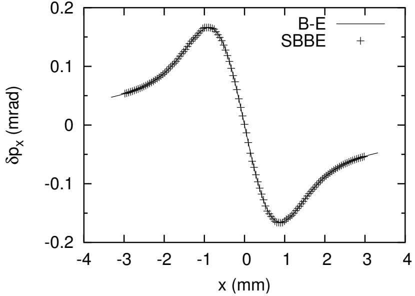
$$\mathscr{L} = \mathscr{L}_0 \times R_L = 8.74 \times 10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

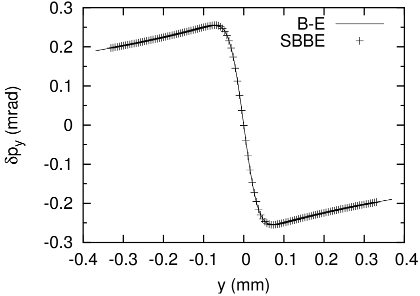
- The calculated luminosity using the code is

$$L = \begin{cases} 8.67 \times 10^{26} \mathrm{cm}^{-2}\mathrm{s}^{-1}, & (I_b = 9.8 \times 10^{-2} \mathrm{mA}) \\ 8.80 \times 10^{28} \mathrm{cm}^{-2}\mathrm{s}^{-1}, & (I_b = 9.8 \times 10^{-1} \mathrm{mA}) \end{cases}$$

Code Check: Beam-Beam Field by a 2D Gaussian Bunch

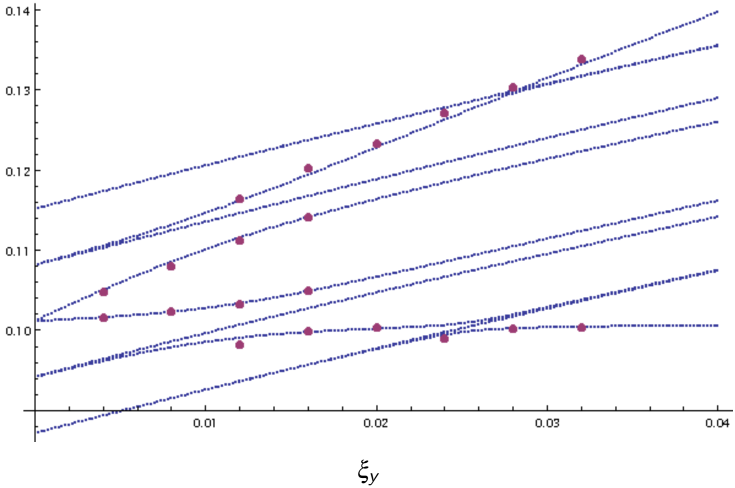
The simulation result agrees well with the Bassetti-Erskine's formula:



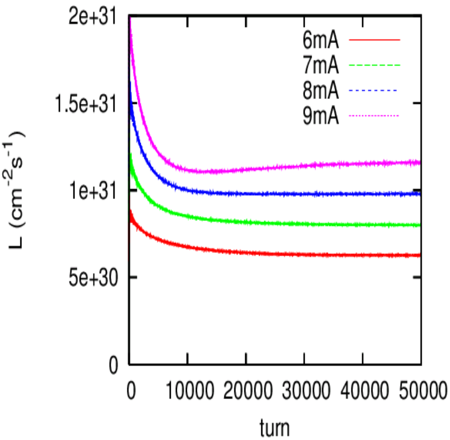


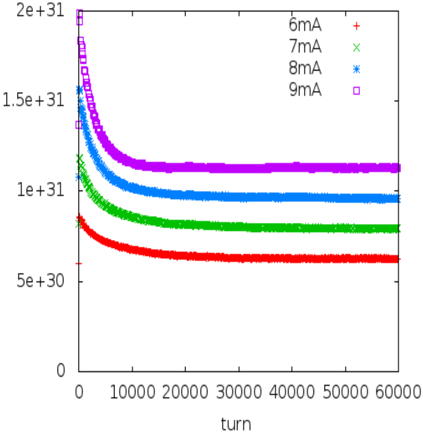
Code Check: SynchroBetatron Motion

Comparison between hollow beam matrix model [PRST-AB, 13, 024401 (2010)] and simulation code



Code Check: Cross Check





Simulation by K. Ohmi (KEK)

Beam-Beam Parameter

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

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

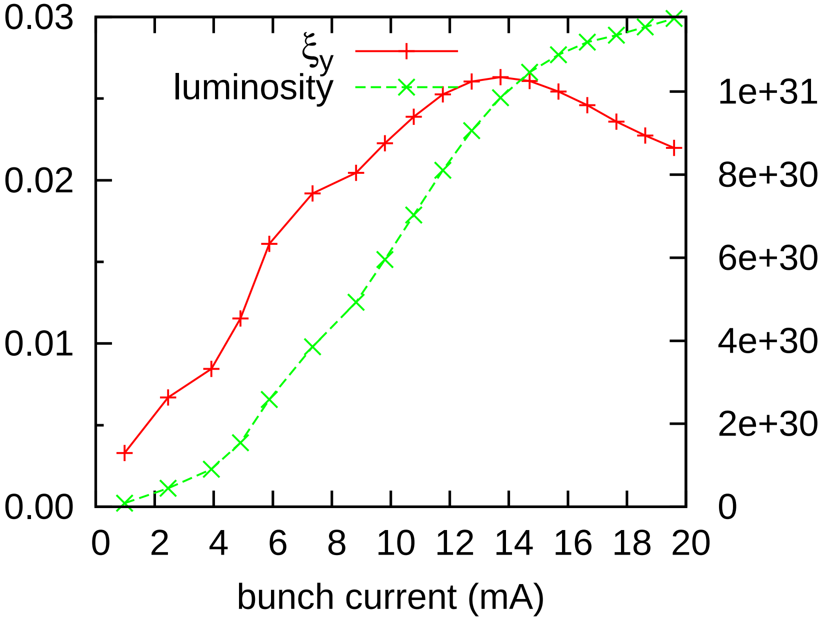
  where β^0 is nominal beta function without collision, and σ is disturbed beam size with collision.
- Do not consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as

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

  where σ is disturbed beam size with collision.
- when beam $\sigma_y \ll \sigma_x$, the achived ξ_y can be represented by lum,

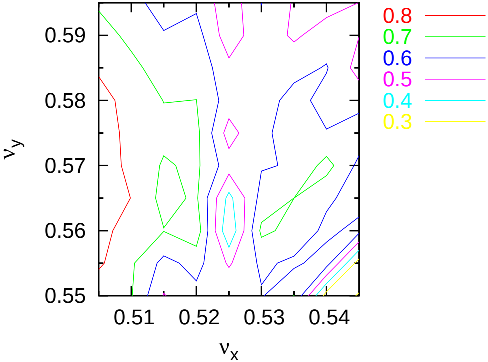
$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$

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



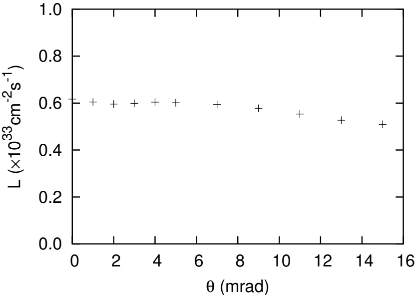
Tune Scan

The normalized luminosity versus tune is depicted in the following figure.

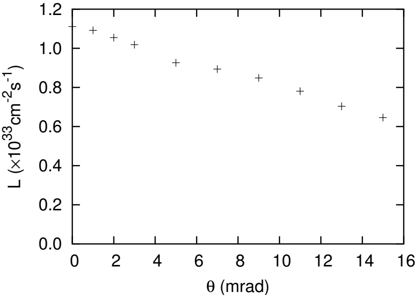


The best working point is near (0.505,0.57), where the luminosity is about 80% of the design value.

Crossing Angle



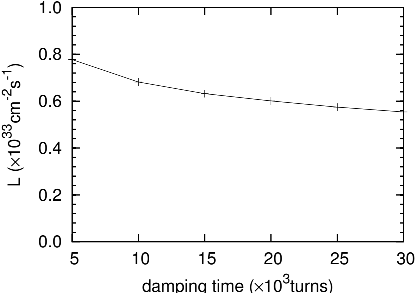
(a) @(0.53,0.58)



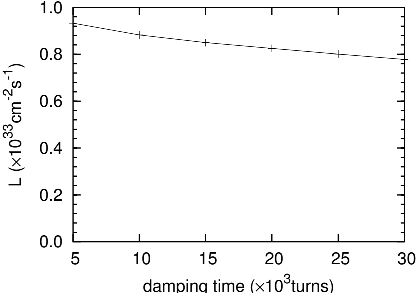
(b) @(0.51,0.57)

The luminosity degradation due to 2×11mrad @(0.53,0.58) is less than 10%, while @(0.51,0.57) is $\sim 30\%$.

Radiation Damping Effect



(a) @(0.53,0.58)



(b) @(0.51,0.57)

When the damping time reduces from 30,000 turns to 5,000 turns,
@(0.53,0.58) the luminosity increases $\sim 40\%$
@(0.51,0.57) the luminosity increases $\sim 20\%$

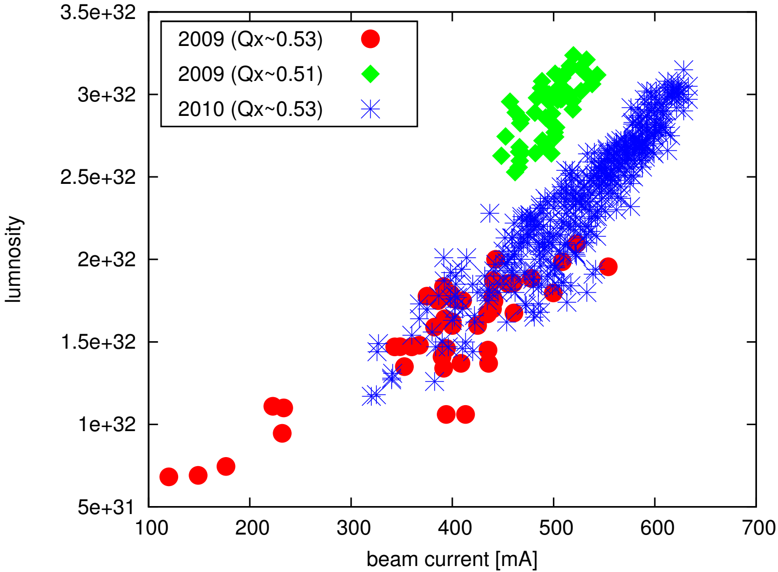
Emittance Coupling

tune	coupling	max ξ_y	max Lum	Lum@8mA
(0.510, 0.575)	0.5%	0.041@11mA	12.3e30	8.1e30
	1.0%	0.037@12mA	12.1e30	6.5e30
	1.5%	0.034@13mA	12.1e30	5.4e30
(0.530, 0.580)	0.5%	0.026@7mA	5.0e30	5.7e30
	1.5%	0.026@13mA	9.2e30	4.3e30
(0.535, 0.575)	0.5%	0.031@9mA	7.6e30	6.6e30
	1.0%	0.027@9mA	6.6e30	5.7e30
	1.5%	0.023@9mA	5.6e30	4.9e30
(0.540, 0.590)	0.5%	0.025@11mA	7.6e30	5.1e30
	1.0%	0.024@11mA	7.2e30	4.7e30

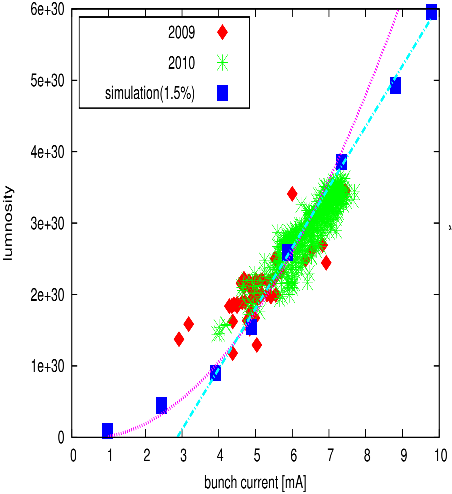
The Big Events in BEPCII (1)

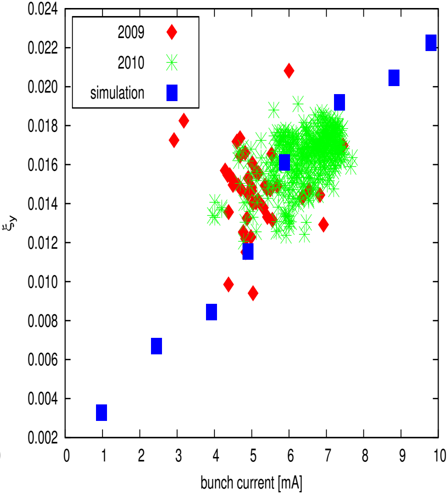
- June, 2008. Detector was installed in the ring. The real machine as a collider lives.
- January, 2009. Profile monitor was removed from the positron ring, which excite very strong longitudinal multibunch instability.
- May, 2009. Horizonatal tune was moved to 0.51 from 0.53. Luminosity was reached $3 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$. The "design goal" of the government funding agency was achieved!
- January, 2010. Longitudinal feedback system was installed and began to work.

Luminosity 2009 .vs. 2010

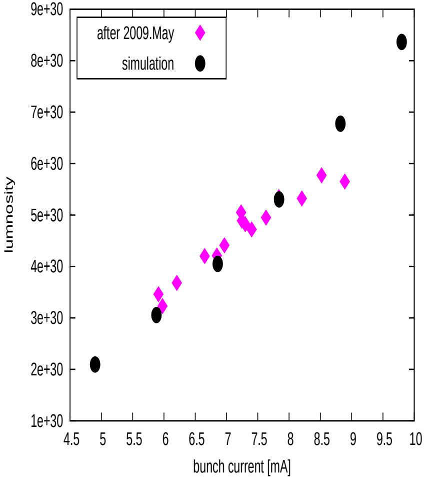


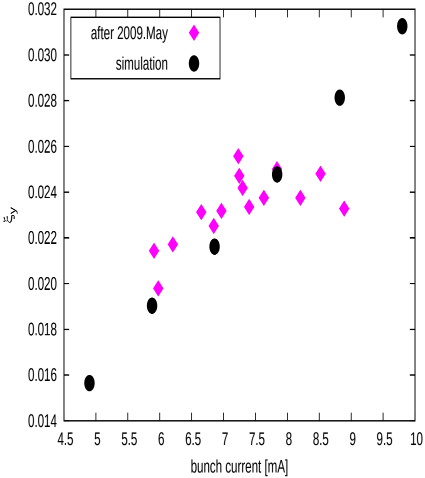
Achieved Beam-Beam Parameter ($\nu_x \sim 0.53$)





Achieved Beam-Beam Parameter ($\nu_x \sim 0.51$) in 2009

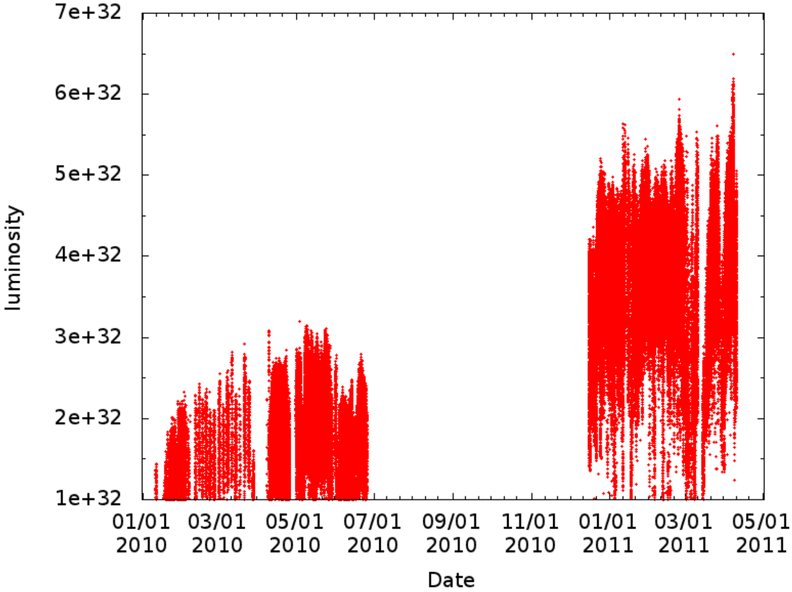




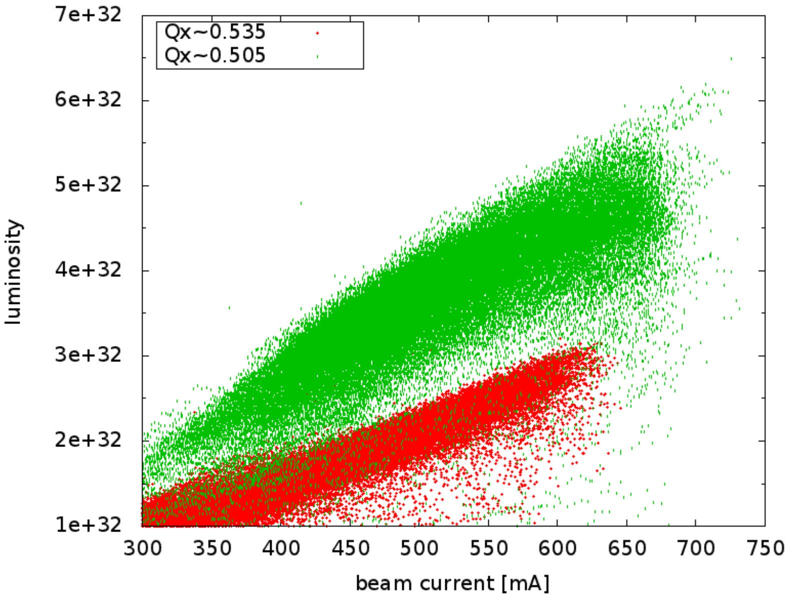
The Big Events in BEPCII (2)

- 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 when $Q_x \sim 0.51$. The physics people could take data near the 0.51 working point.

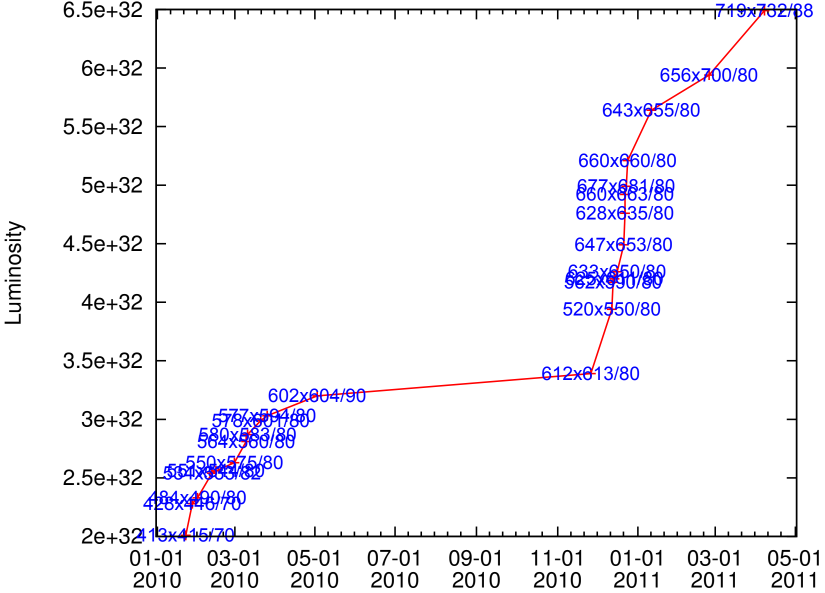
Luminosity History



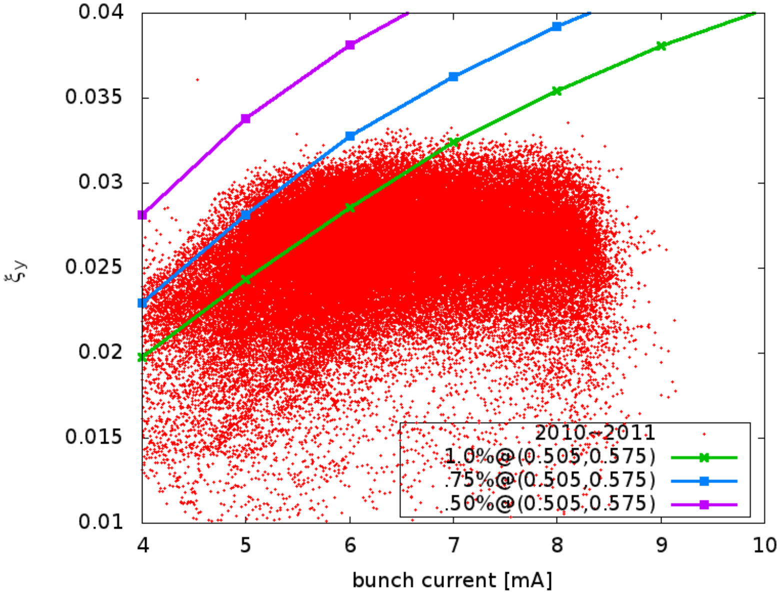
Luminosity vs Beam Current



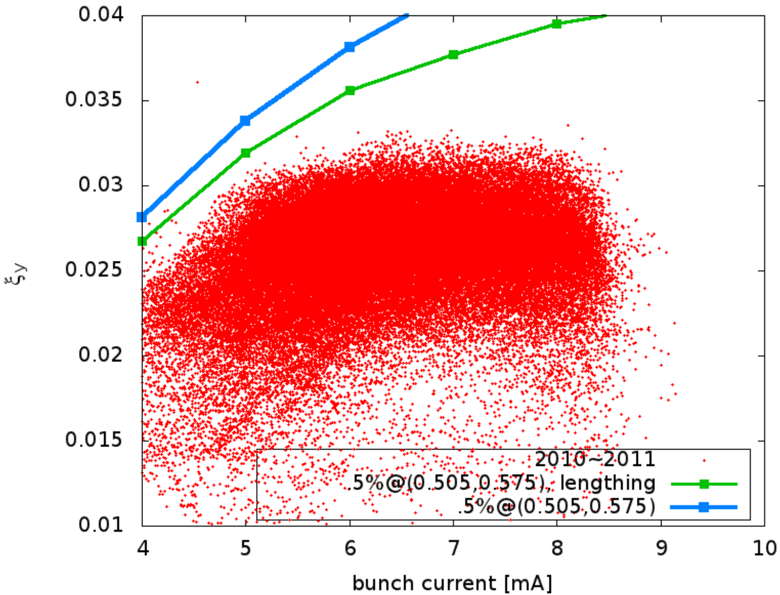
Peak Luminosity Records



Acheieved Beam-Beam Parameter in 2011



Bunch Lengthing Effect



Nonlinear Arc (1)

Beam Beam Interaction

Use Hirata's BBC [a] as a pass method in Accelerator Toolbox [b]

Matlab + C + Fortran

[a] K. Hirata, Phys. Rev. Lett., 1995, 74, 2228-2231
[b] A.Terebilo, SLAC-PUB-8732, 2001

Element-by-Element Tracking in Arc

symplectic pass method implemented in AT

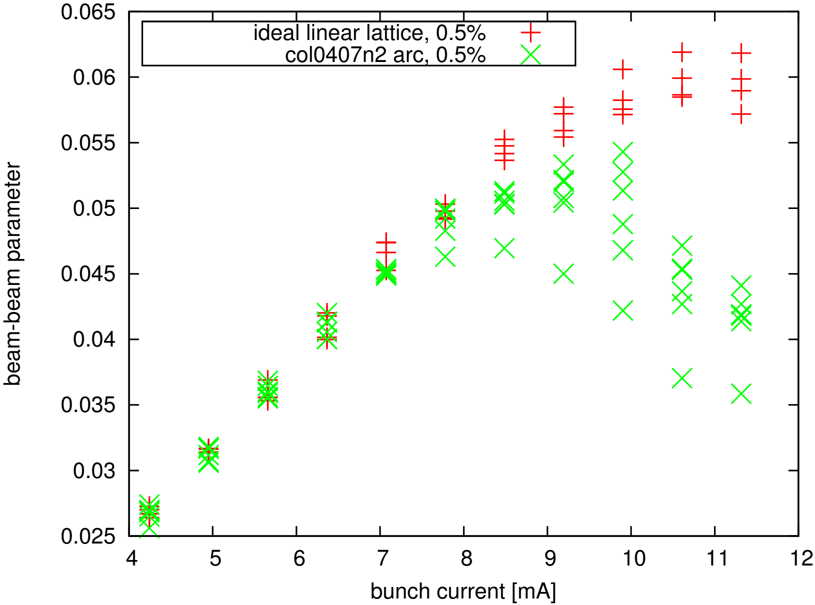
Synchrotron Oscilation

RF on

Radiation Damping and Quantum excitation

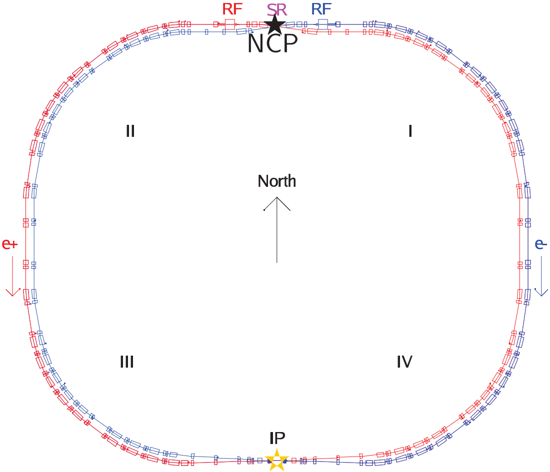
same as that in a strong-strong code

Nonlinear Arc (2)



Parasitic Beam-Beam Interaction at NCP

There is another crossing point(NCP) in the north of the two rings, where the beams are separated vertically about 5mm and the full horizontal angle is about 2×0.155rad (17.7°).

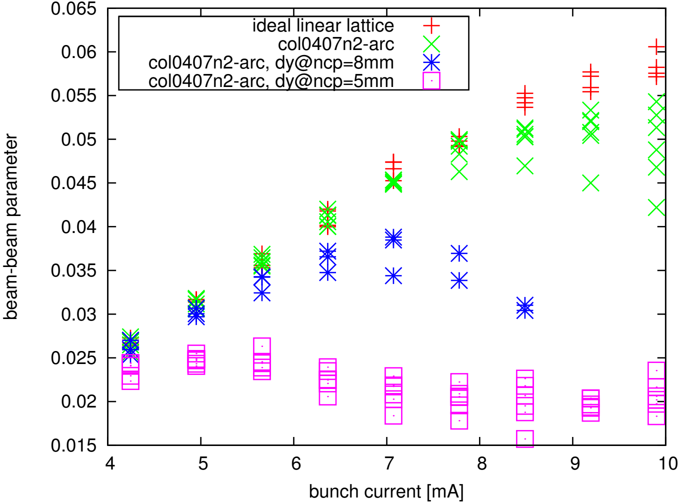


$\beta_x = 12/\beta_y = 8.5$ @ NCP,

- I_b=8mA, 1.0% coupling, $\xi_x/\xi_y = 0.03/0.26$@NCP, $\xi_x/\xi_y = 0.03/0.04$@IP
- vertical separation [5mm]: $\sim 4\sigma_x / \sim 50\sigma_y$
- Piwinski Angle: $\frac{\sigma_z \tan(\theta)}{\sigma_x} = 1.8$@NCP$/0.4$@IP

Nonlinear Arc + NCP

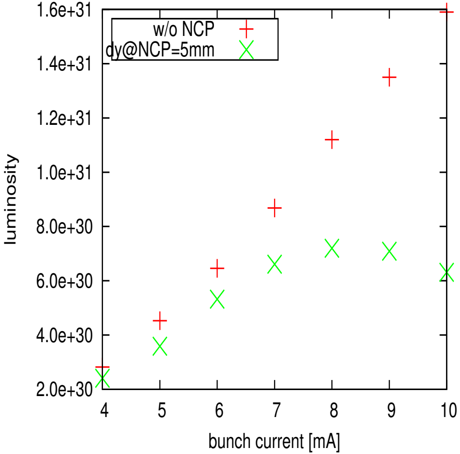
- AT + bbc(by Hirata)

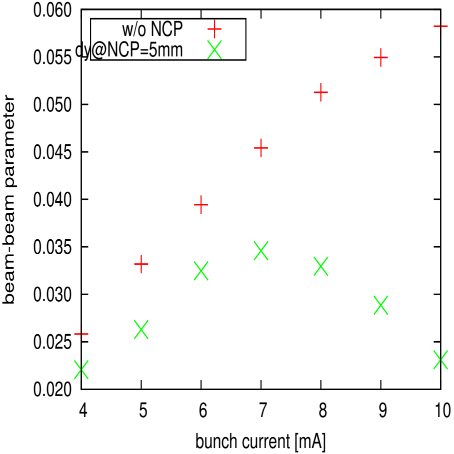


The luminosity loss is over estimated?

Luminosity Loss due to Parasitic Effect@NCP

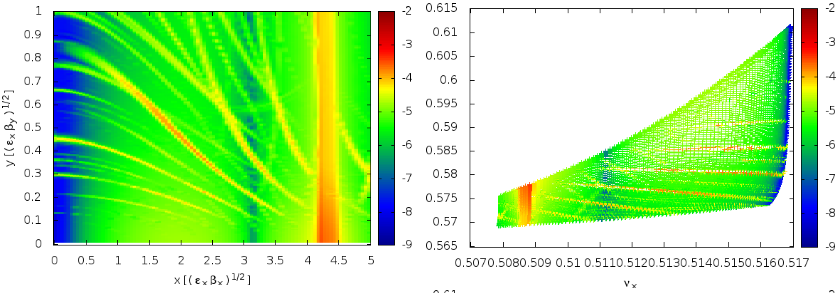
- **LIFETRAC** by Shatilov is used, Vertical separation is assumed 5mm
- lum@8mA: 11.2e30 $\longrightarrow$ 7.20e30, loss: 35%. SUPPRISE!
- maximum beam-beam parameter achieved at 7mA with parasitic effect@NCP



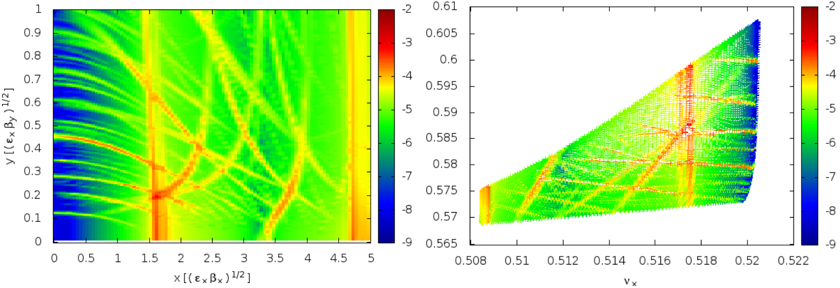


FMA of the Parasitic Effect

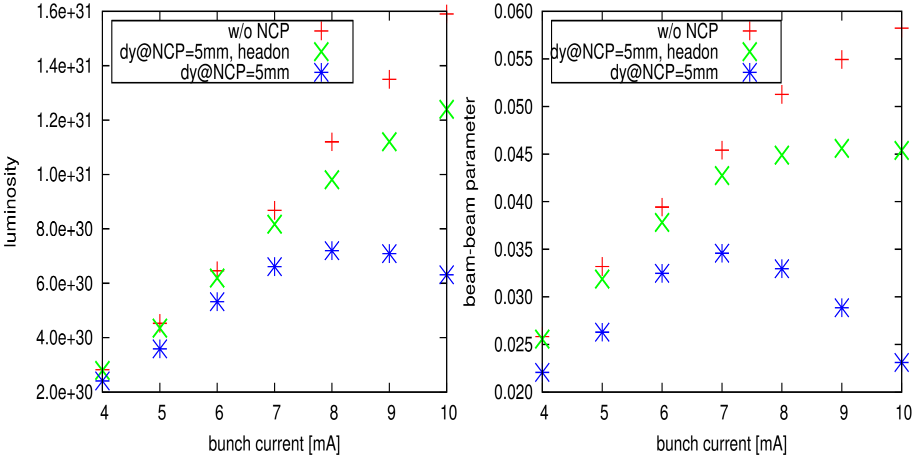
only ip
$\xi_y = 0.05$



ip+ncp
$\xi_y = 0.05$

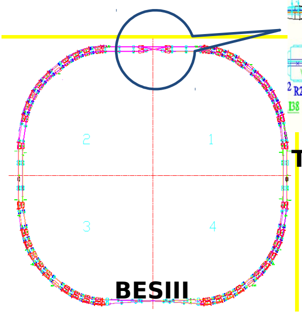


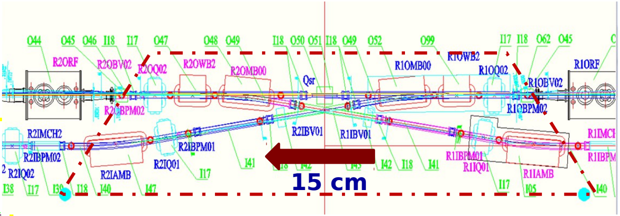
Crossing angle in the Parasitic Effect



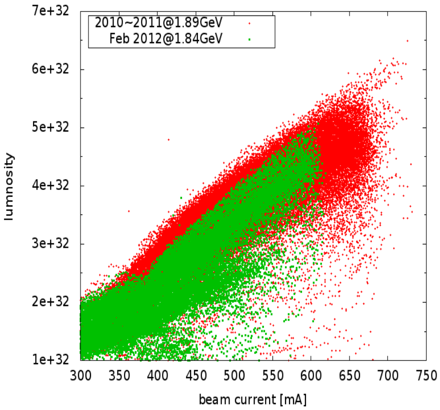
The Big Events in BEPCII (3)

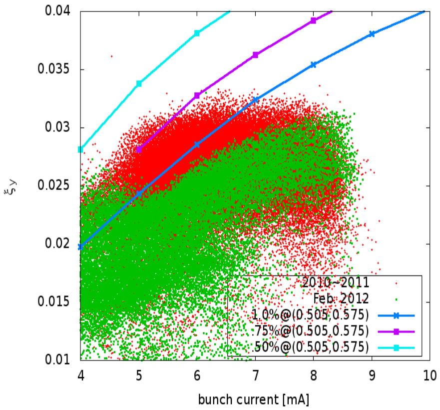
- In summer shutdown of 2011, the NCP chambers and magnets were moved 15 cm, 1/4 of the rf bucket. The horizontal separation between colliding bunches is $150 \times 0.31 = 46mm > 30\sigma_x$.



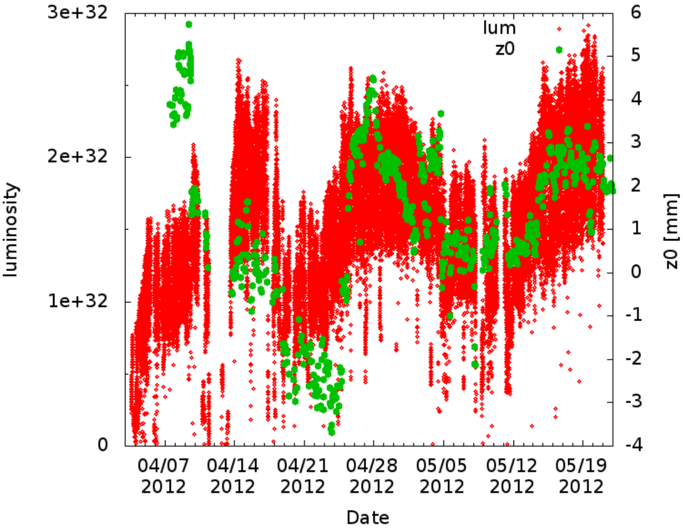


The EMS @ NCP region was moved by 15 cm too


2010~2011@1.89GeV
Feb 2012@1.84GeV
lumnosity
7e+32
6e+32
5e+32
4e+32
3e+32
2e+32
1e+32
300 350 400 450 500 550 600 650 700 750
beam current [mA]

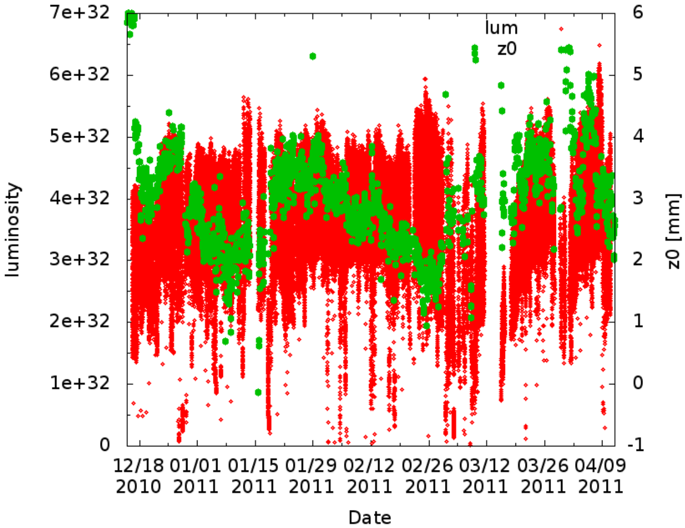

2010~2011
Feb 2012
1.0%@(0.505,0.575)
.75%@(0.505,0.575)
.50%@(0.505,0.575)
ξy
0.04
0.035
0.03
0.025
0.02
0.015
0.01
4 5 6 7 8 9 10
bunch current [mA]

z0 at 1.55GeV


3e+32
2e+32
1e+32
0
luminosity
lum
z0
6
5
4
3
2
1
0
-1
-2
-3
-4
z0 [mm]
04/07 2012
04/14 2012
04/21 2012
04/28 2012
05/05 2012
05/12 2012
05/19 2012
Date

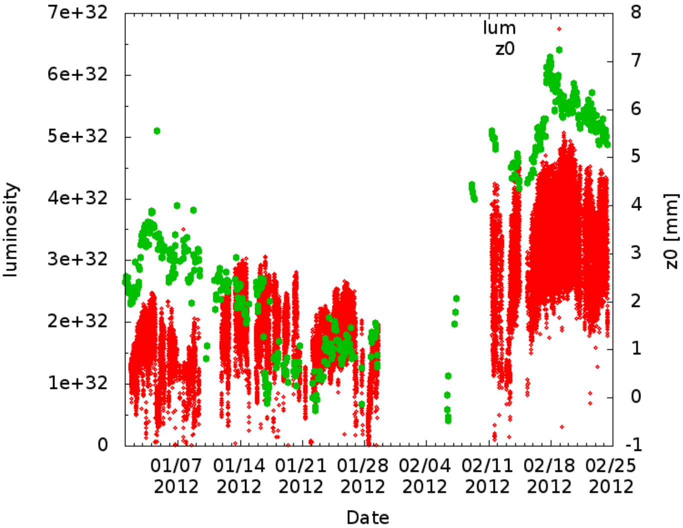
z0 at 2011 and 2012, ∼1.89GeV

- z0 and lum in 2010-2011
- z0 and lum in 2011-2012

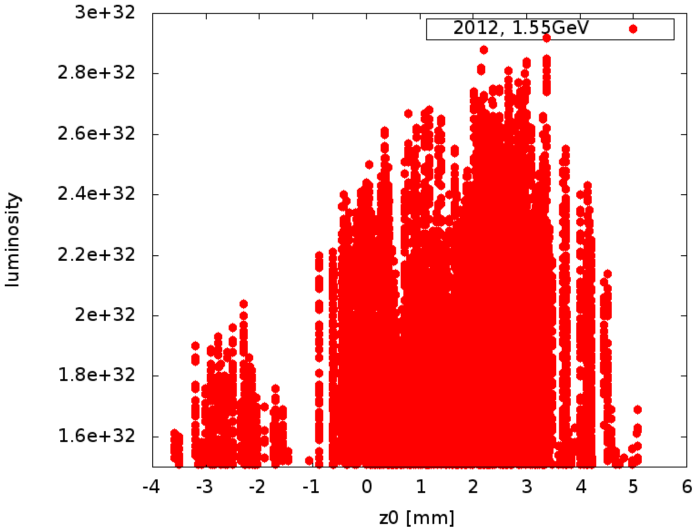


z0 at 2011 and 2012, ∼1.89GeV

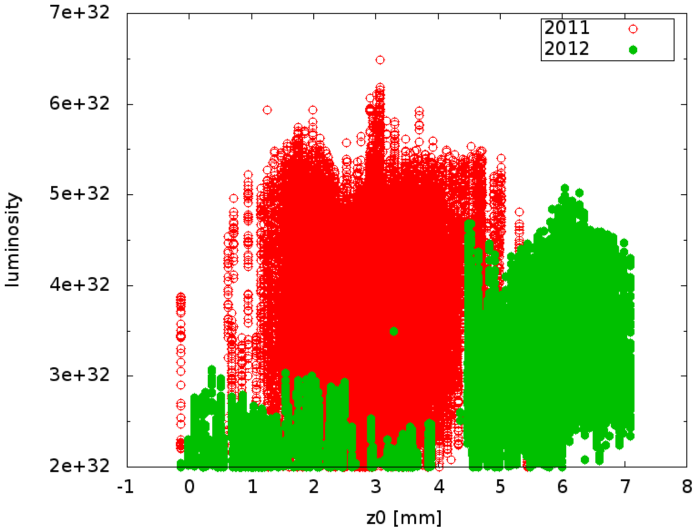
- z0 and lum in 2010-2011
- z0 and lum in 2011-2012



lum versus z0 at 1.55GeV



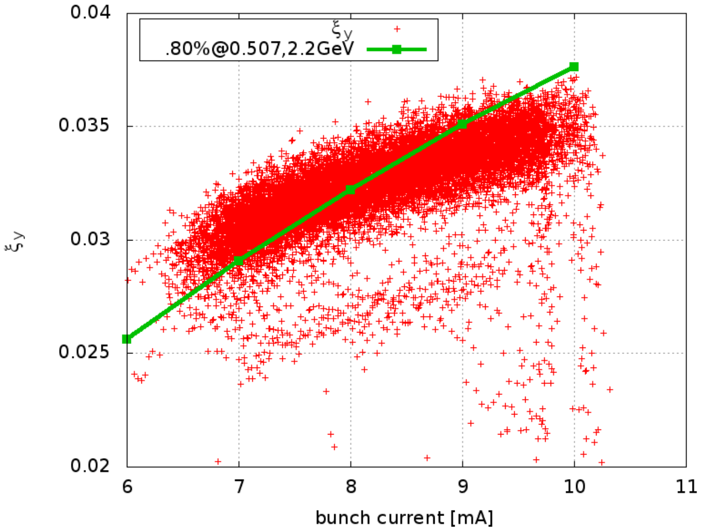
lum versus z0 at 2011 and 2012, ∼1.89GeV



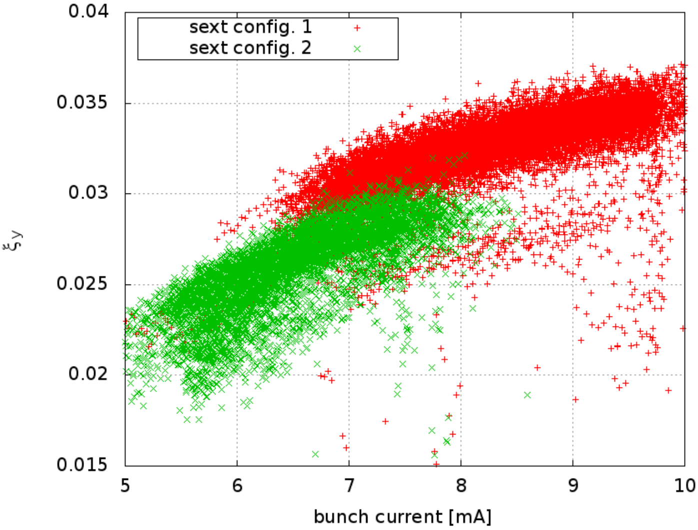
The Big Events in BEPCII (4)

- February 2013. Lower alphap mode was first tested at 2.18GeV, which help us break the ξ_y record of 0.033.
- March 2013. 1 bunch every 3 bucket, and even 1 bunch every 2 bucket injection was tested in the machine study. (design: 1 bunch every 4 bucket)

Achieved ξ_y @2.18GeV with lower α_p mode



Different Sextupole Configuration

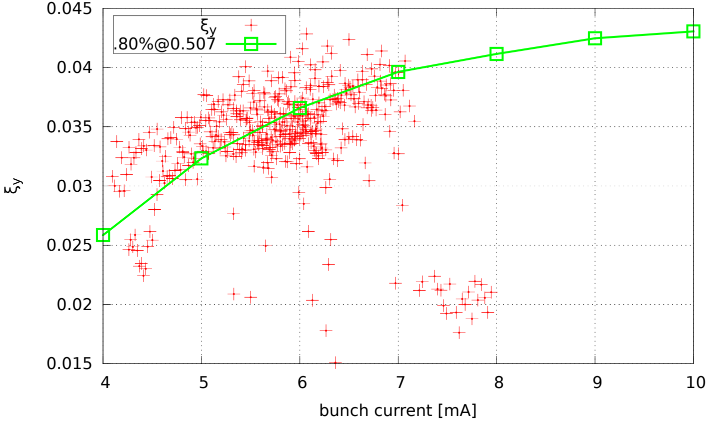


But it's inconclusive, since the config 2 may be not optimized enough.

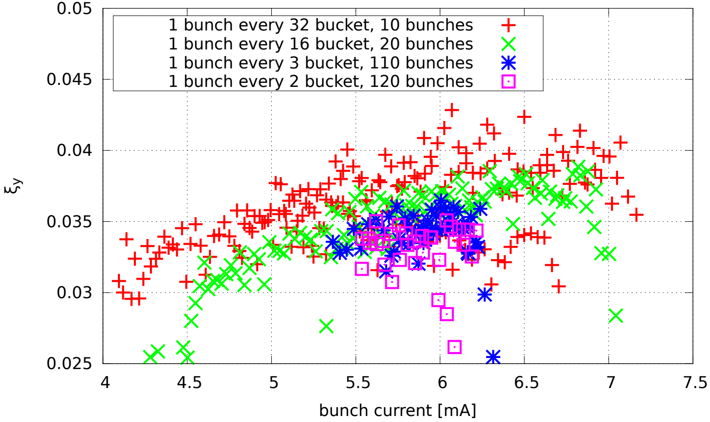
Chromatic Correction

- Better control of twiss@IP chromatic distortion (β/α and waist position). It seems it could also help us reduce the detector background.
- Not only enough dynamic aperture, but also some nonlinear resonance driving terms, especially GNFU(1,0,2,0), (1,0,1,1), (2,0,2,0), (2,0,1,1) and (1,1,2,0) are optimized, since the horizontal oscillation will be coupled to vertical by them.

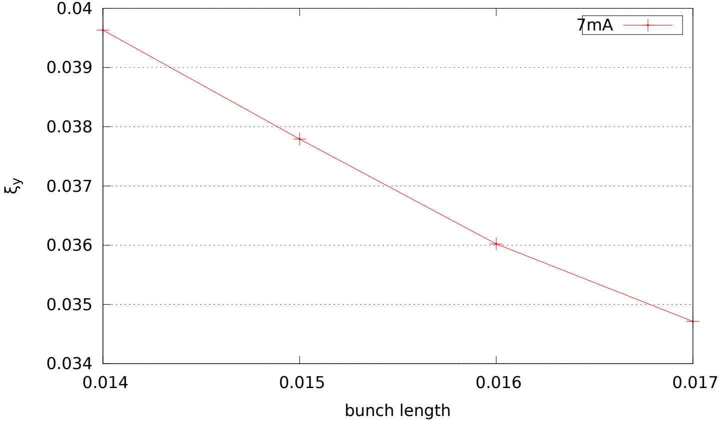
Beam-Beam Parameter @1.89GeV



Multibunch Effect @1.89GeV



Only Shorter Bunch Length help us @1.89GeV?



Luminosity Tuning Knobs

- transverse collision orbit: x,x',y,y'
- transverse tunes: it seems that it is easier to optimize luminosity when the horizontal tune is closer to half integer, since the high luminosity tune region is much narrower near $\nu_x \sim 0.508$ that that 0.535 :)
- local coupling @IP: four skew quadrupoles in the arc where is dispersion free
- another coupling knob: vertical local bump in some sextupoles (not dispersion free)
- yet another coupling knob: global vertical orbit tuning to minimize the vertical emittance by reduce $\overline{C}_{12}$ at BPMs
- we've to change the horizontal orbit during the decay of beam current in most cases but not all. the maximum offset is about 0.1mm. the causes is not known :(
- waist knob is almost not used
- dispersion knob does not exist

Summary

- ξ_y achieves 0.04 in the single bunch collision. More importantly we broke the record of 0.033.
- Lower α_p + bigger emittance + lower β_y may be tested in the near future.
- Simulation give us a clear goal, even though we could approach it but never go beyond it.
- Multibunch effect should be more emphasized in the following.