Beam-beam issues in the luminosity performance at BEPCII

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Outline

- Introduction
- Beam-beam simulation study
- Beam-beam parameter in luminosity performance
- Future perspective
- Conclusion

1. Introduction

- BEPC (1988 – 2005) ➔
  BEPCII (2006 – now) { A double-ring factory-like machine
  Deliver beams to both HEP & SR

Ways to increase luminosity

DR: multi-bunch, k_b=1 ➔ 93

Large ε_x & optimum param.: I_b=9.8mA, ξ_y=0.04

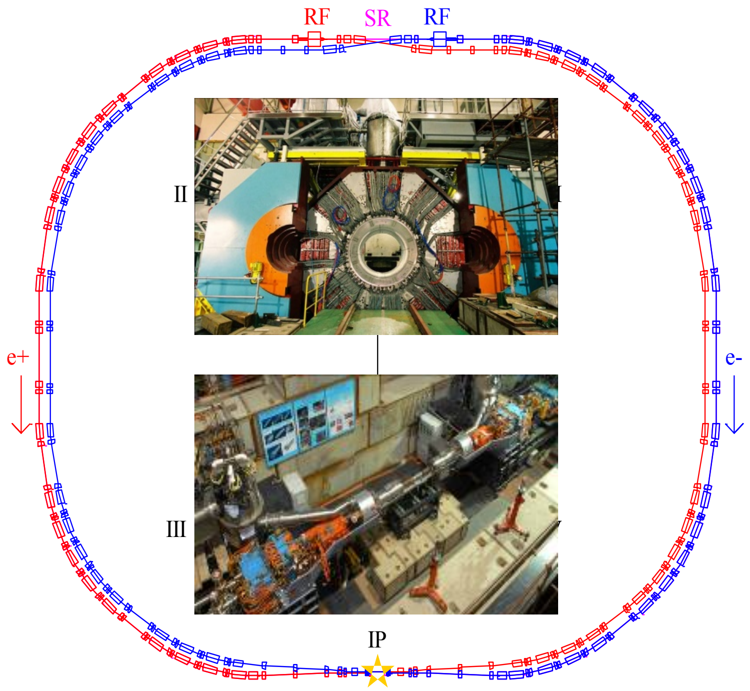
$$L(\mathrm{cm^{-2}s^{-1}}) = 2.17\times 10^{34}(1+R)\xi_y \frac{E(\mathrm{GeV})k_b I_b(\mathrm{A})}{\beta_y^*(\mathrm{cm})}$$

Micro-β: β_y^* =5cm ➔ 1.5 cm
SC insertion quads

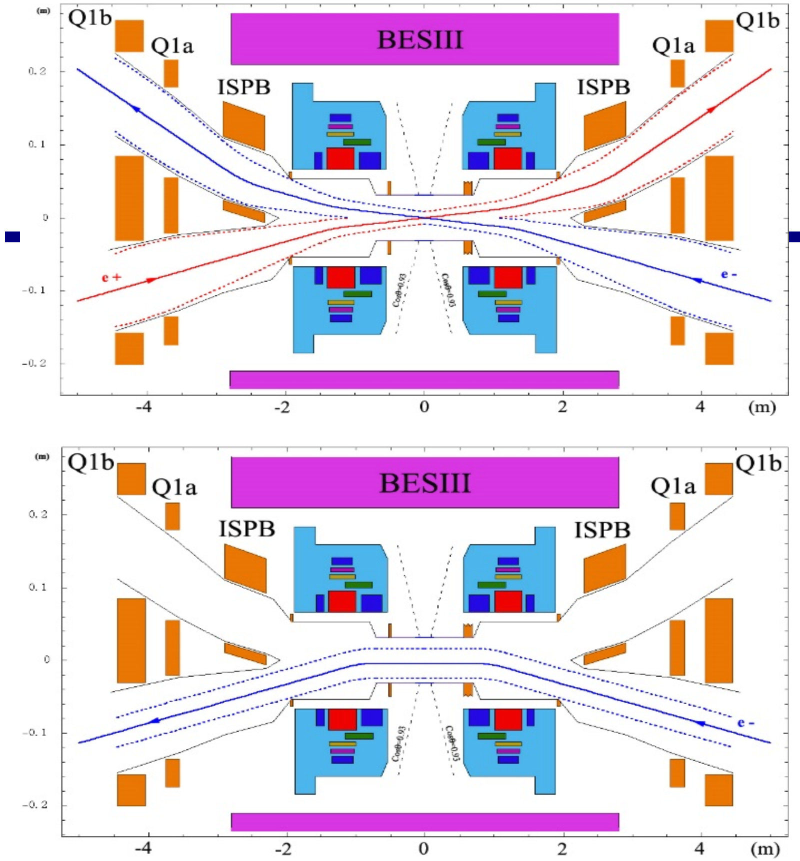
Low impedance + SC RF
σ_z =5cm ➔ <1.5cm

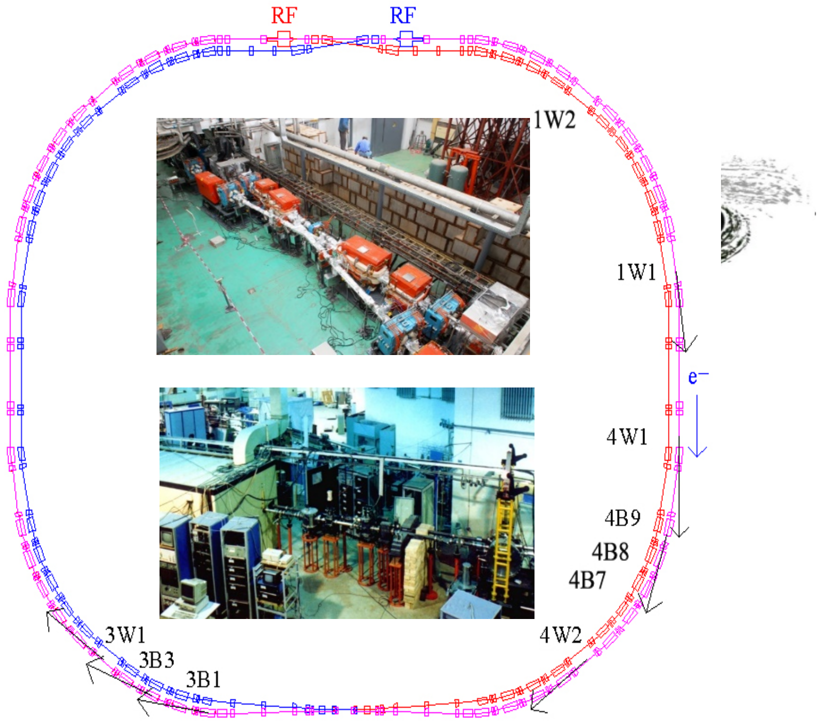
$(L_{BEPCII}/ L_{BEPC})_{D.R.}$=(5.5/1.5) ×93×9.8/35=96

$L_{BEPC}=1.0\times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$ ➔ $L_{BEPCII}=1\times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$



Collider





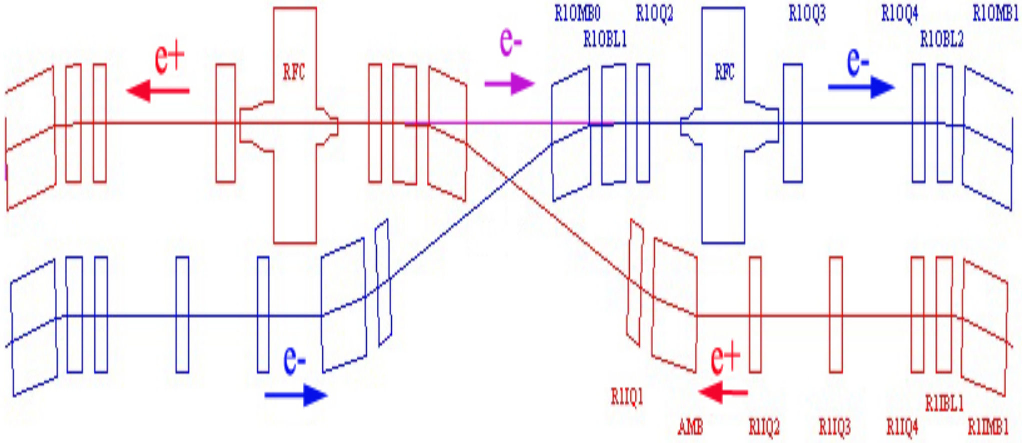
SR Facility

❑ Collision Mode

- Beam energy range — 1-2.1 GeV
- Optimized beam energy — 1.89 GeV
- Luminosity — 1×10^{33} cm^{-2}s^{-1}
- Full energy injection — 1-1.89 GeV

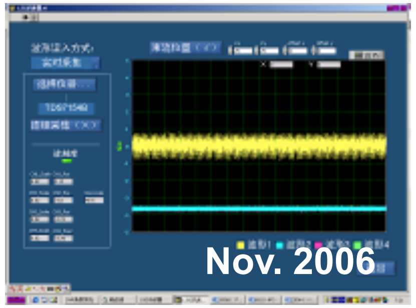
❑ SR Mode

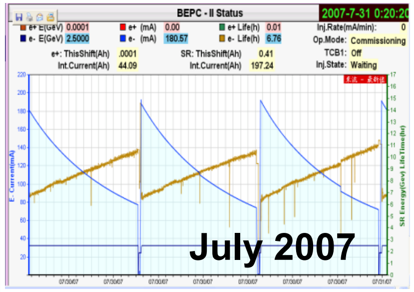
- Beam energy — 2.5 GeV
- Beam current — 250 mA

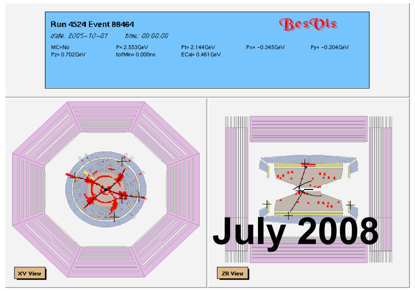


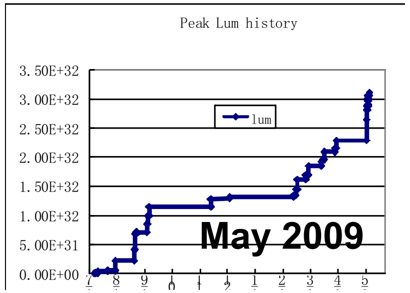
Milestones of BEPCII construction & operation

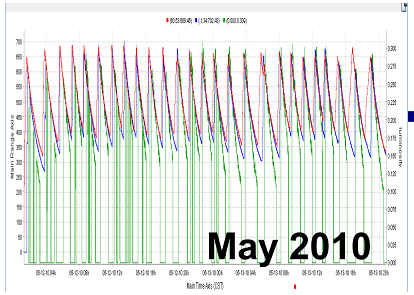
Jan. 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections
Dec. 1, 2004	Linac delivered e^- beams to BEPC
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Aug. 3, 2007	Shutdown for IR-SCQ installation
Mar. 28, 2008	Shutdown for BESIII installation
July 19, 2008	First hadron event observed
May 19, 2009	Luminosity reached $3.3\times10^{32}cm^{-2}s^{-1}$
July 17, 2009	Pass the National test & check
April 8, 2011	Luminosity reached $6.5\times10^{32}cm^{-2}s^{-1}$
April 2013	Zc(3900) found & confirmed
Nov. 20, 2014	Luminosity reached $8.53\times10^{32}cm^{-2}s^{-1}$
April 5, 2016	Luminosity reached $10.0\times10^{32}cm^{-2}s^{-1}$

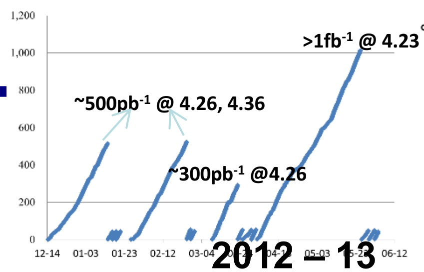


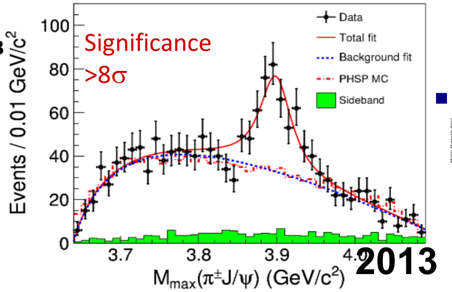


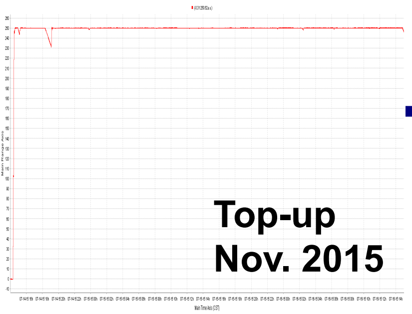


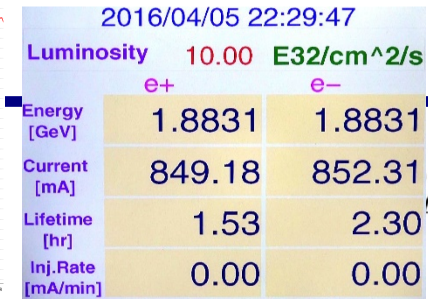


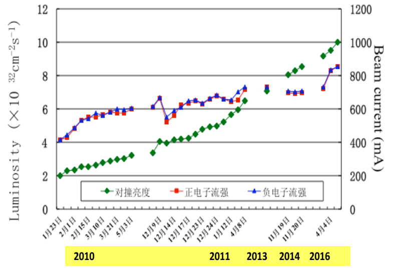












Main design parameters of three rings

Parameters	BER/BPR	BSR
Beam energy (GeV)	1.89	2.5
Circumference (m)	237.53	241.13
Beam current (A)	0.91	0.25
Bunch current (mA) / number	9.8 / 93	~1 / 160 - 300
Natural bunch length@1.5MV (mm)	13.6	12.0
RF frequency (MHz)	499.8	499.8
Harmonic number	396	402
Emittance (x/y) (nm·rad)	144/2.2	140
β function at IP (x/y) (m)	1.0/0.015	10.0/10.0
Crossing angle (mrad)	±11	0
Tune (x/y/s)	6.54/5.59/0.034	7.28/5.18/0.036
Momentum compaction	0.024	0.016
Energy spread	5.16×10^{-4}	6.67×10^{-4}
Natural chromaticity (x/y)	-10.8/-20.8	-9.0/-8.9
Luminosity ($cm^{-2}s^{-1}$)	1×10^{33}	—

2. Beam-beam study in the BEPCII

• Beam-beam interaction

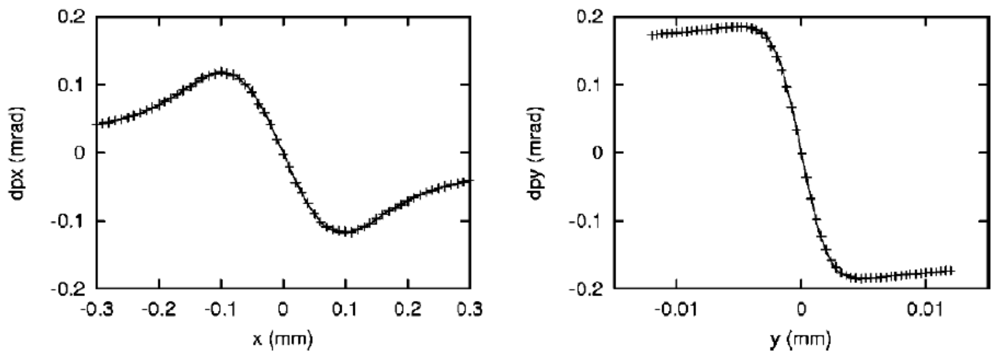
– For the case of flat Gaussian beams in electron-positron ring colliders, the deflection angle can be expressed analytically in terms of the complex error function

$$\Delta p_y + \Delta p_x = \frac{2N_b r_e}{\gamma}\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\left[w\left(\frac{x+iy}{2(\sigma_x^2-\sigma_y^2)}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)w\left(\frac{\frac{\sigma_y}{\sigma_x}x+\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

– A typical transverse beam-beam deflection. the vertical deflection strongly depends on the horizontal offset, which excite transverse betatron resonance

– At small amplitudes, where the deflection increases approximately linearly with displacement, it resembles the effect of an additional quadrupole, whose strength is characterized by the so-called beam-beam parameter ξ

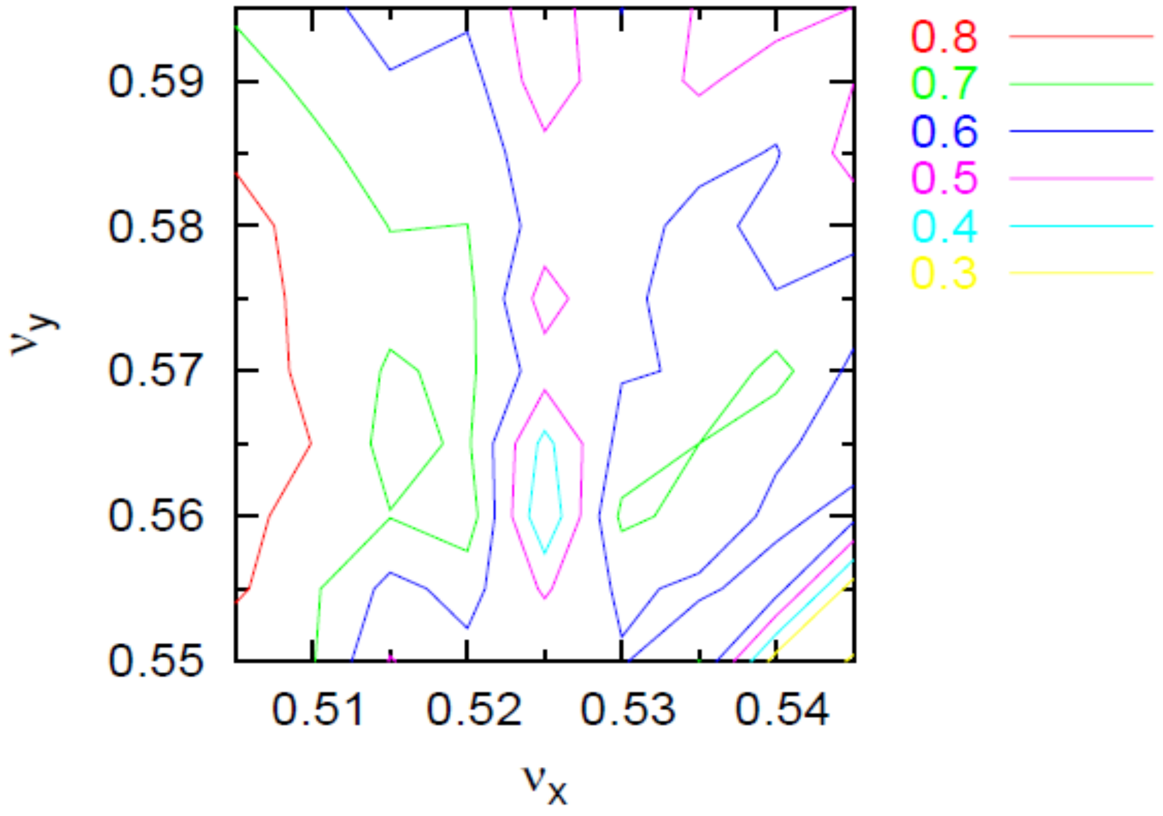
$$\xi_{x,y} = \frac{r_e \beta_{x,y} N_b}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$



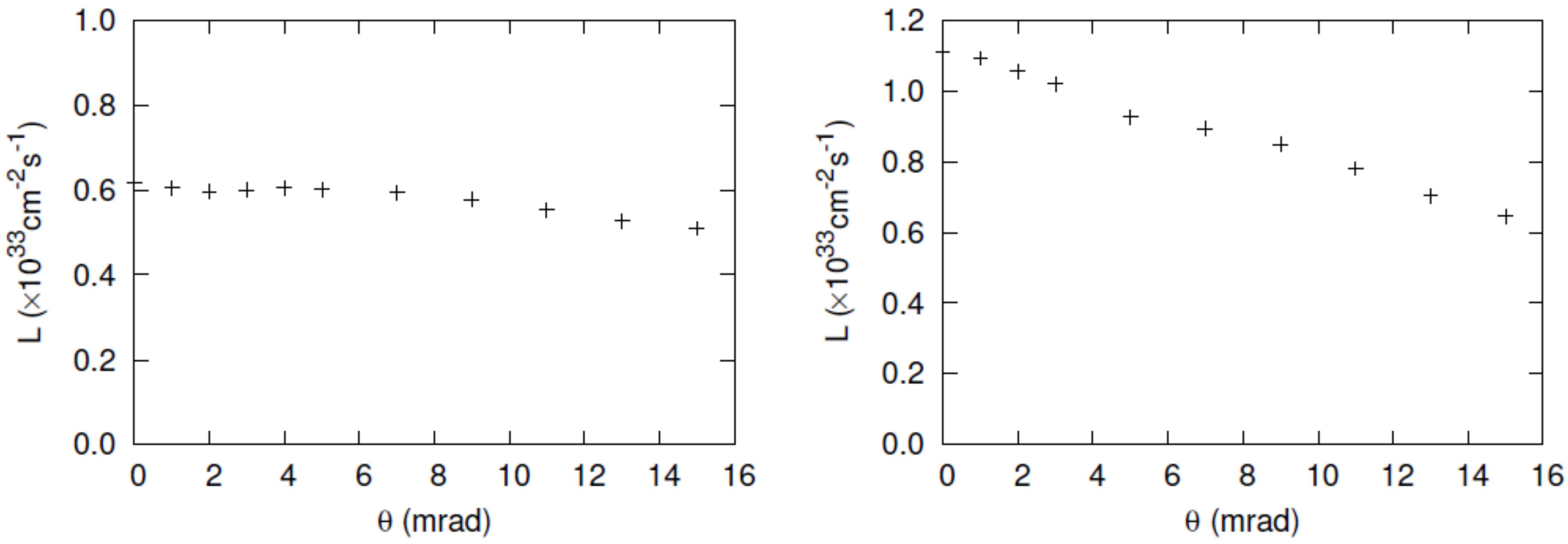
- **Bunch length**
  - The beam transverse sizes can vary significantly within the bunch length when the beams are focused extensively at IP. Bunch length effect must be considered [*S. Krishnagopal and R. Siemann, Phys. Rev. D41, 2312 1990*].
  - Synchro-beam map for a particle-slice interaction, a 6*6 symplectic mapping, which could be described the dependences of the transverse kick and long. position and vice versa. [*K. Hirata, H. Moshammer, and F. Ruggiero, Particle Accelerators 40, 205 (1993).*]
- **Crossing angle**
  - collision with crossing angle is popular. The kekb/dafne/bepcii all adopt a horizontal crossing, with a Piwinski angle about 0.5-1.0
  - The collision with a crossing angle causes an instability due to the synchrobetatron resonances
  - The simulation study shows that crossing with a large angle has less serious detrimental effect that is usually believed. The luminosity reduction is only of geometrical origin: Compared to $\phi = 0$, the luminosity reduction factor R_L is small, but ξ reduction factor R_ξ is even smaller, so that the beam blowup is less serious.

- **Beam-beam simulation on working points**

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



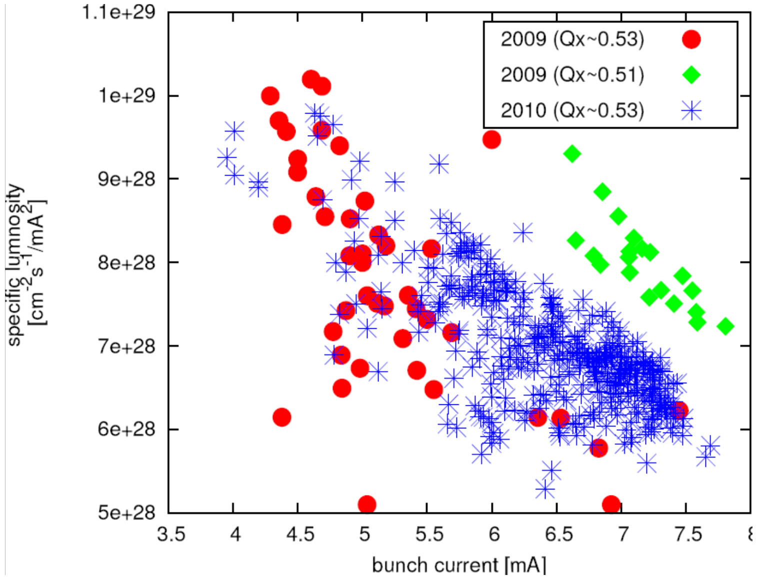
The best working point is near (0.505,0.57), where the luminosity is about 80% of the design value.

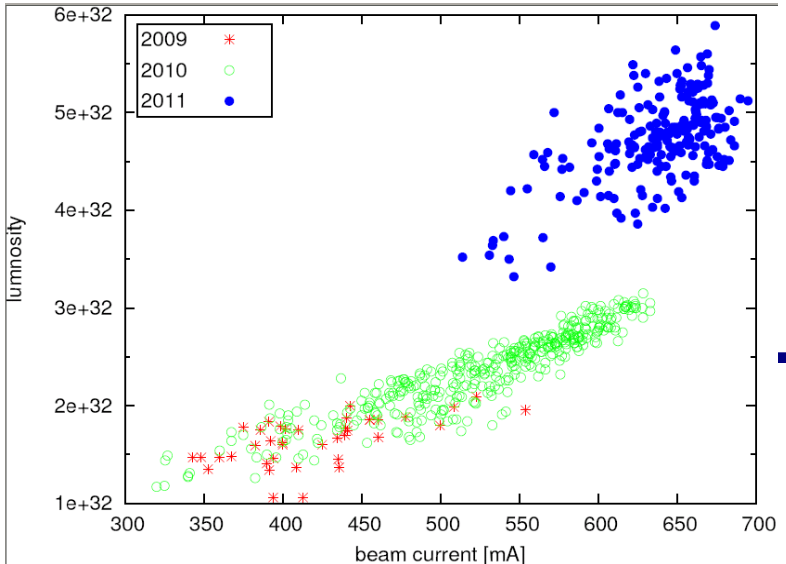


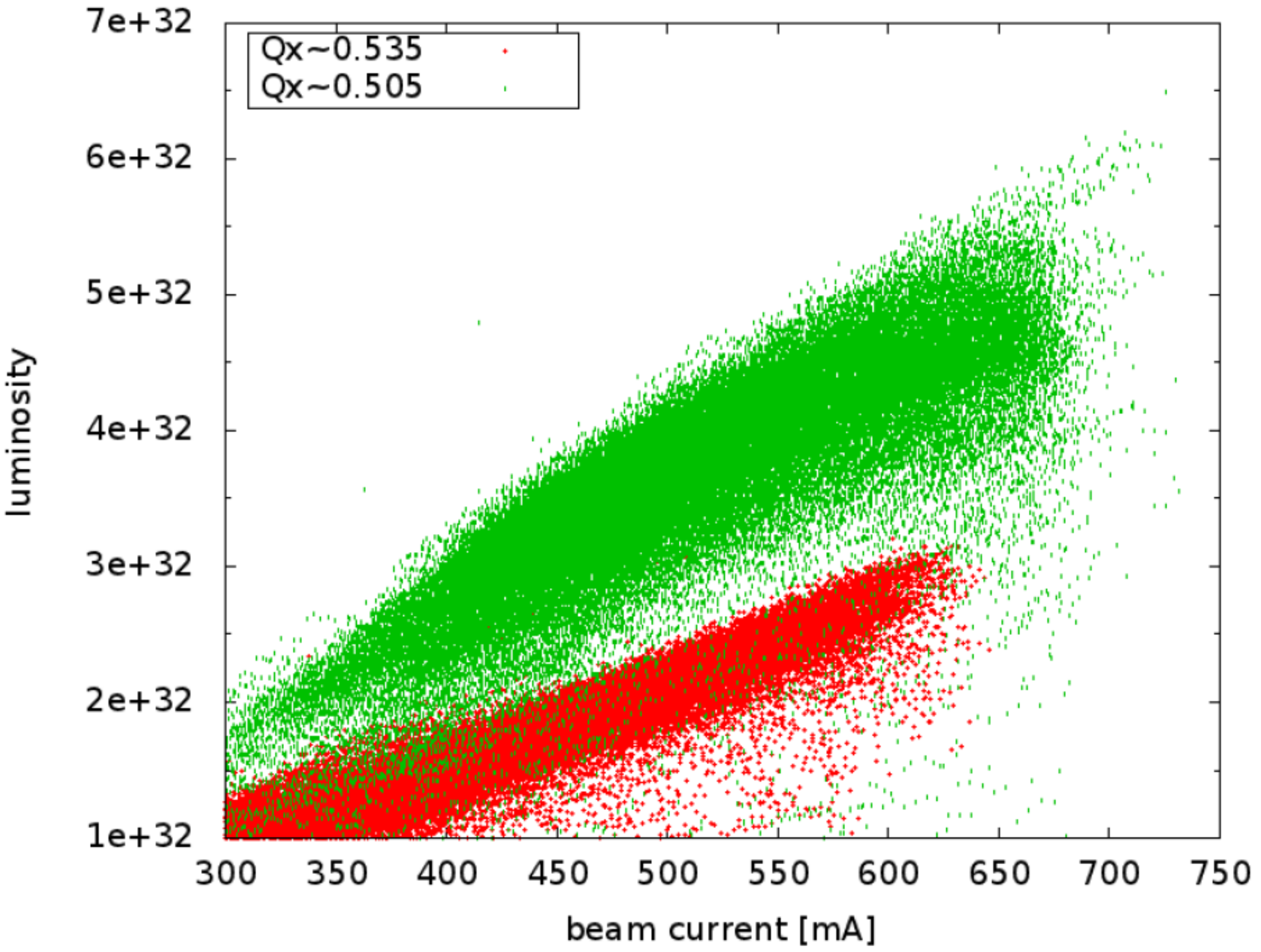
(a) @(0.53,0.58) (b) @(0.51,0.57)

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

• Operational results

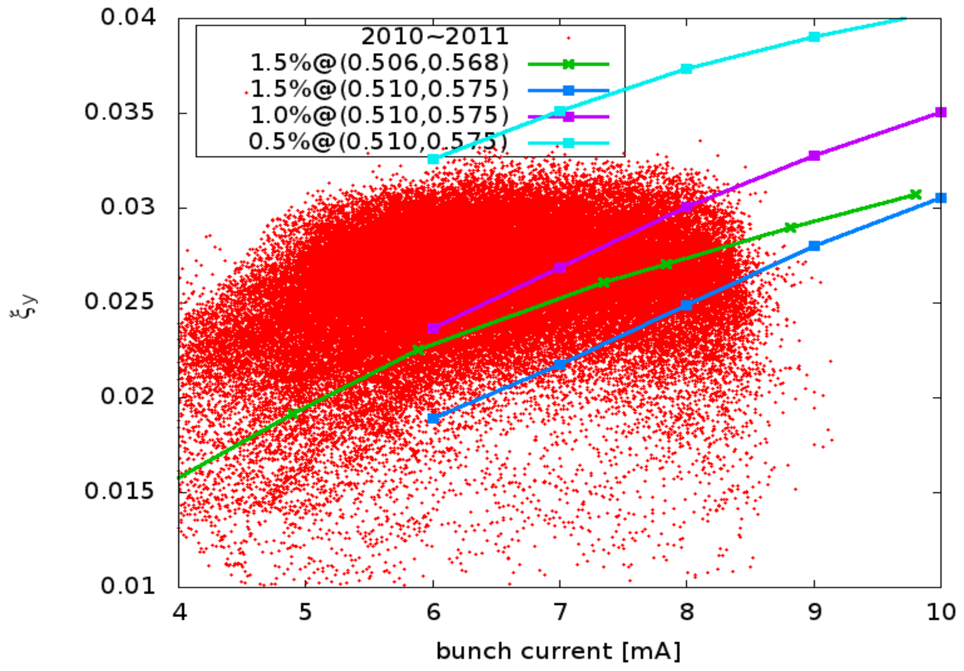


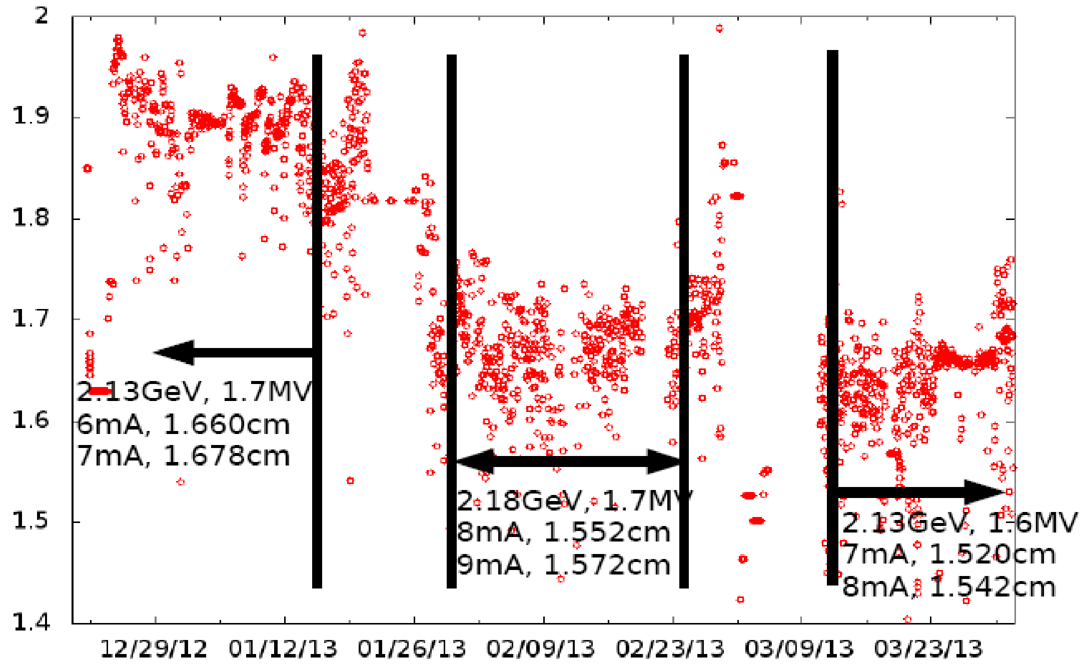




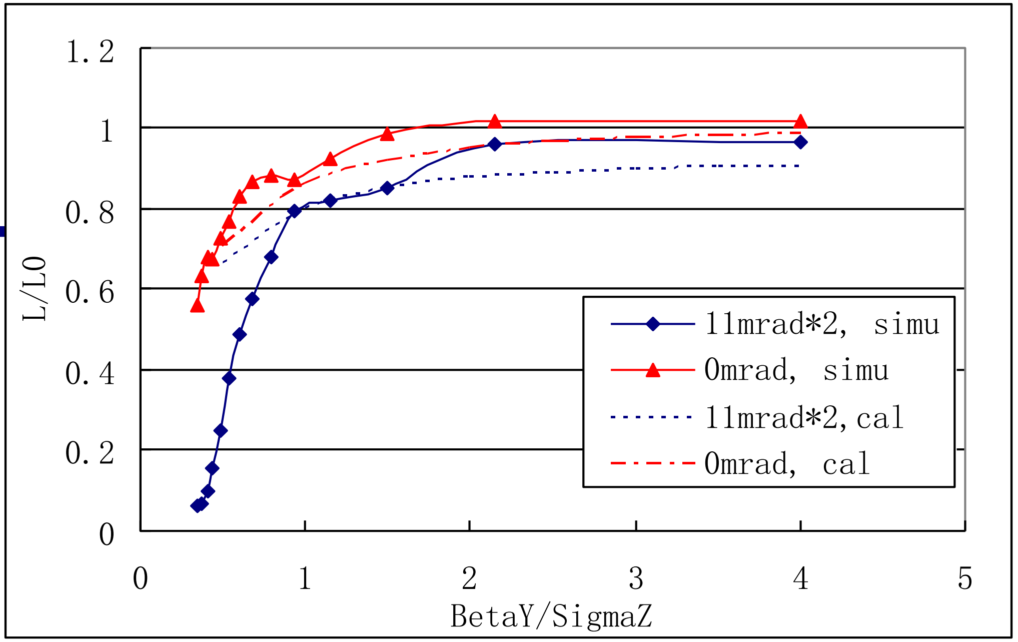
3. Beam-beam parameter in luminosity performance

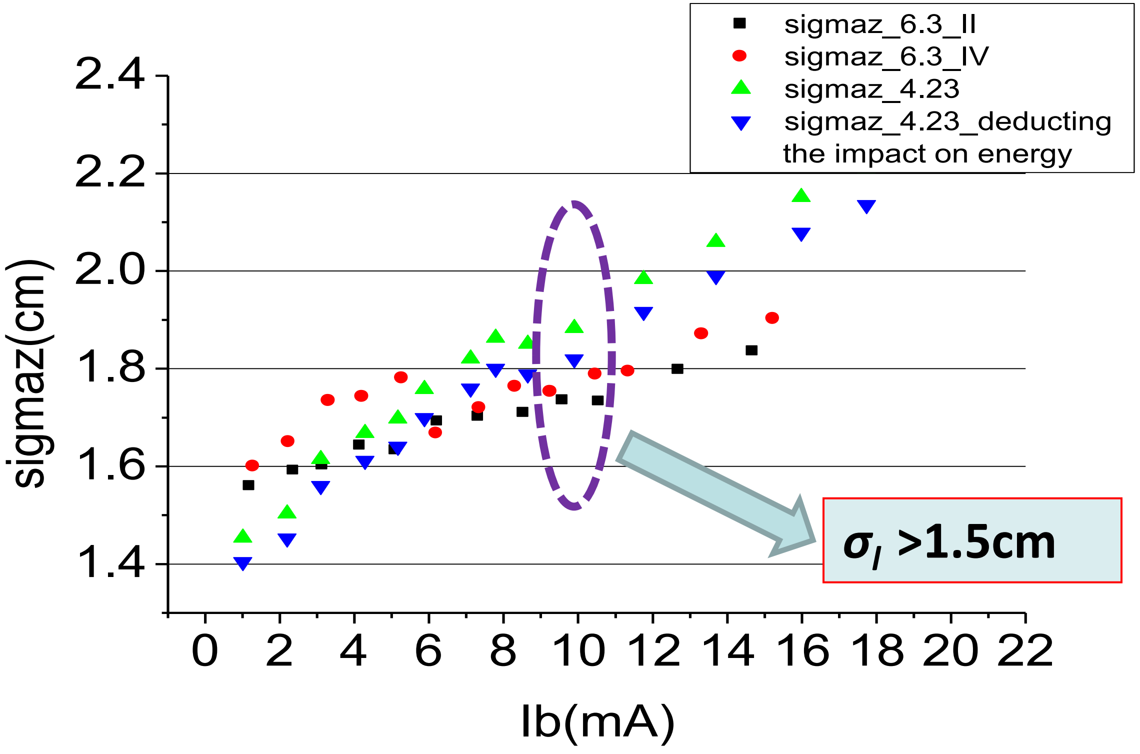
- **Effect of bunch length**
  - The beam-beam parameter was suppressed obviously under 0.033 at any bunch current even with sufficient collision tuning. Bunch lengthening effect was considered to explain the phenomenon



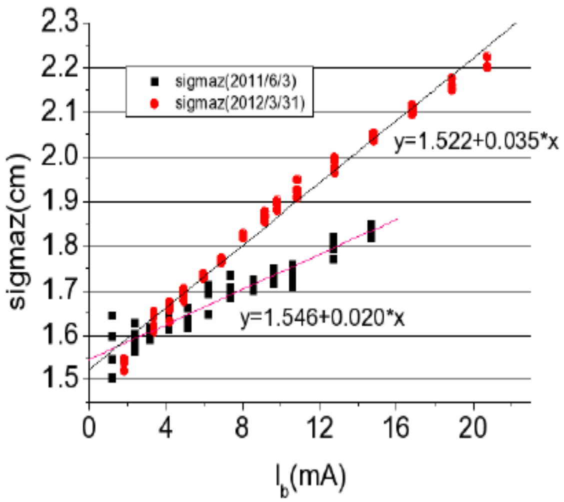


- **Bunch lengthening measurement**
  - **Longitudinal low frequency impedance is ~3 times higher than design value.**

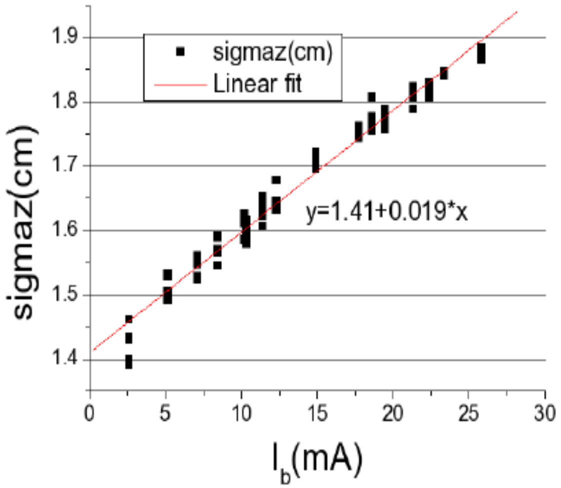




BPR



BER



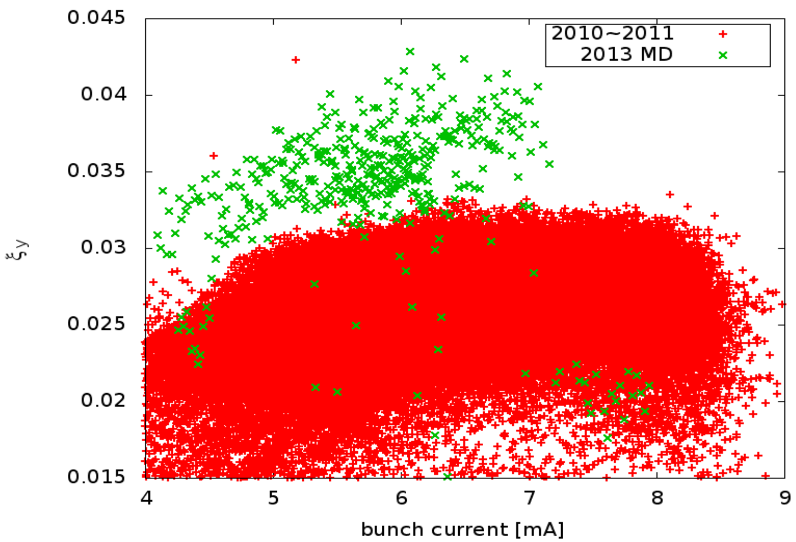
- **Lattice optimization for short bunch length**
  - **A new lattice was designed to control the bunch length. The natural bunch length @ V_{rf} = 1.5 MV was reduced from 1.35 cm to 1.15 cm by reducing the momentum compaction from 0.0235 to 0.0170. More collision bunches are needed.**

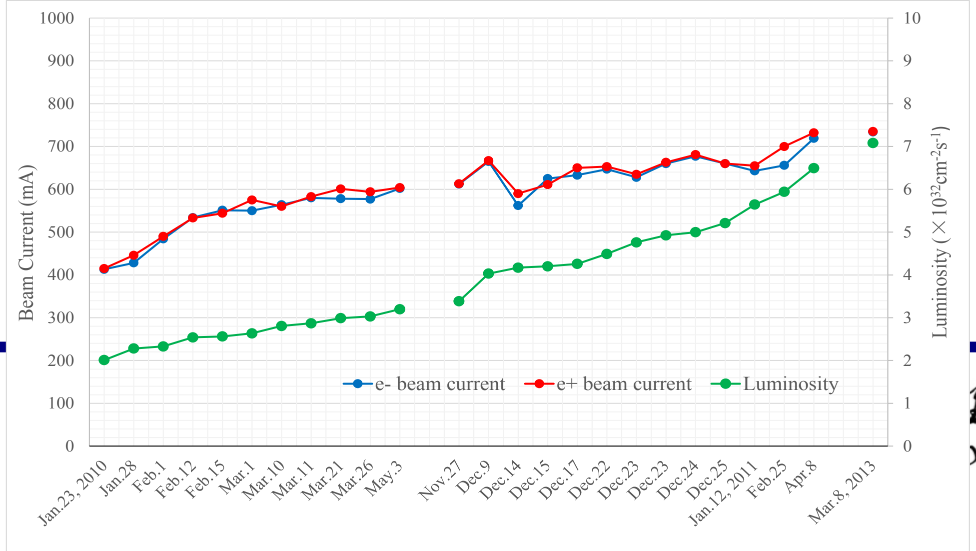
Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	9.8 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point	6.53/5.58
Harmonic number	396
Bunch number	93
Bunch spacing	2.4 m
RF voltage	1.5 MV
Momentum compaction	0.0235
Natural bunch length	1.35 cm
Beam-beam parameter	0.04
Luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$

→

Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	7.0 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	100 nm·rad
Working point u_x/u_y	7.505/5.580
Harmonic number	396
Bunch number	130
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0170
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$

- **Machine study with new lattice**
  - Test on the new lattice at the energy of 1.89 GeV was performed during February 28th to March 7th, 2013. The restriction to the beam-beam parameter was broken. The maximum beam-beam parameter reached 0.043.
  - The maximum luminosity reached 7.08×10^{32} cm^{-2}s^{-1} @ 734 mA*735 mA while the beam-beam parameter was 0.0349. Limitation comes from the trans. multi-bunch instability due to more bunches (N_b = 120 – 130).





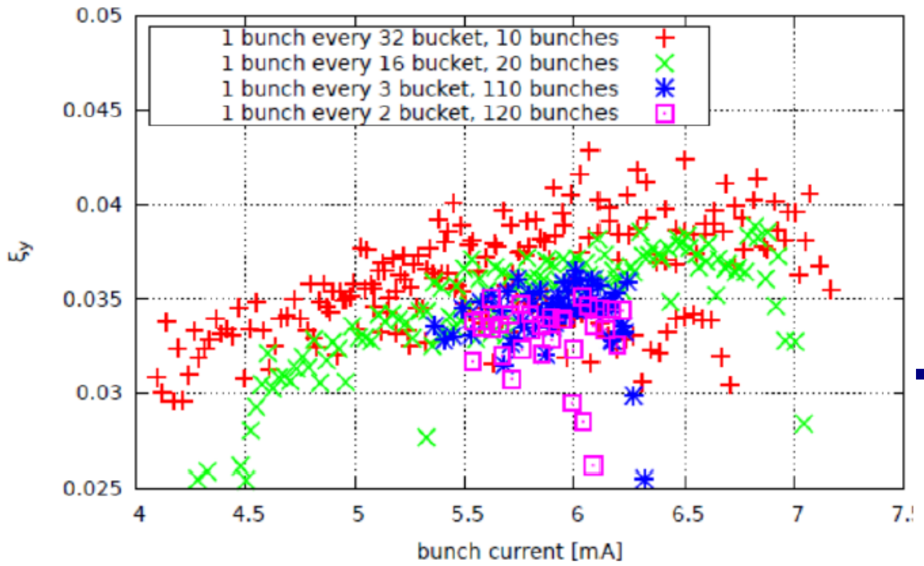
- **Machine study on multi-bunch effect (Nov 17 – 20, 2014)**

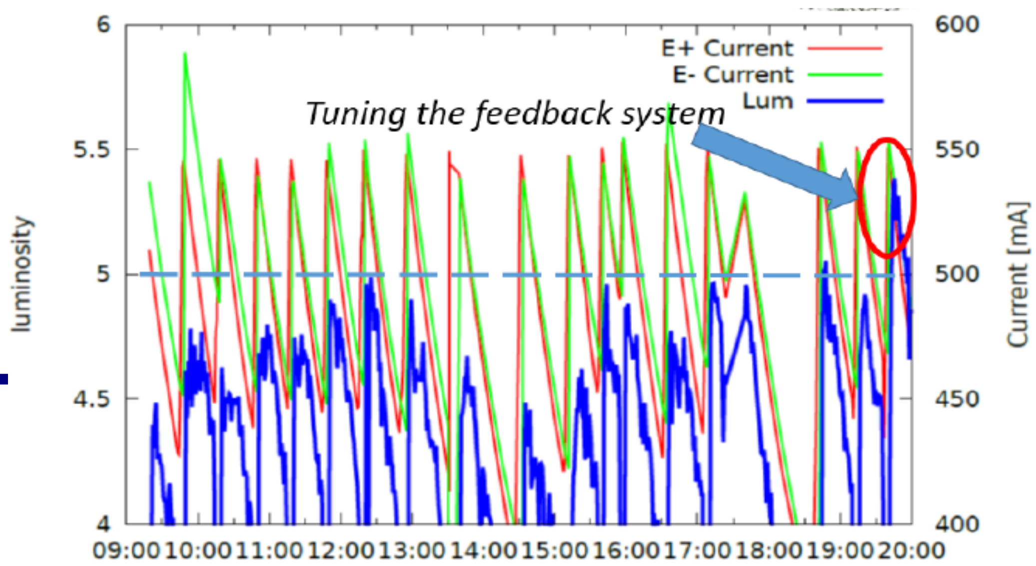
L = 7.16E32， @618×644mA， 79 bunches， Ib=8.0mA， beambeam=0.037

L = 7.89E32， @682×695mA， 87 bunches， Ib=7.9mA， beambeam=0.037

L = 8.04E32， @700×710mA， 92 bunches， Ib=7.7mA， beambeam=0.037

L = 8.53E32， @696×707mA， 92 bunches， Ib=7.7mA， beambeam=0.039





- **Lattice optimization again**
  - The bunch number should be controlled as less as possible to keep beam stable with a high beam current. The lattice with low momentum compaction was improved. The emittance was increased from 100 nm to 122 nm to increase the collision bunch current.

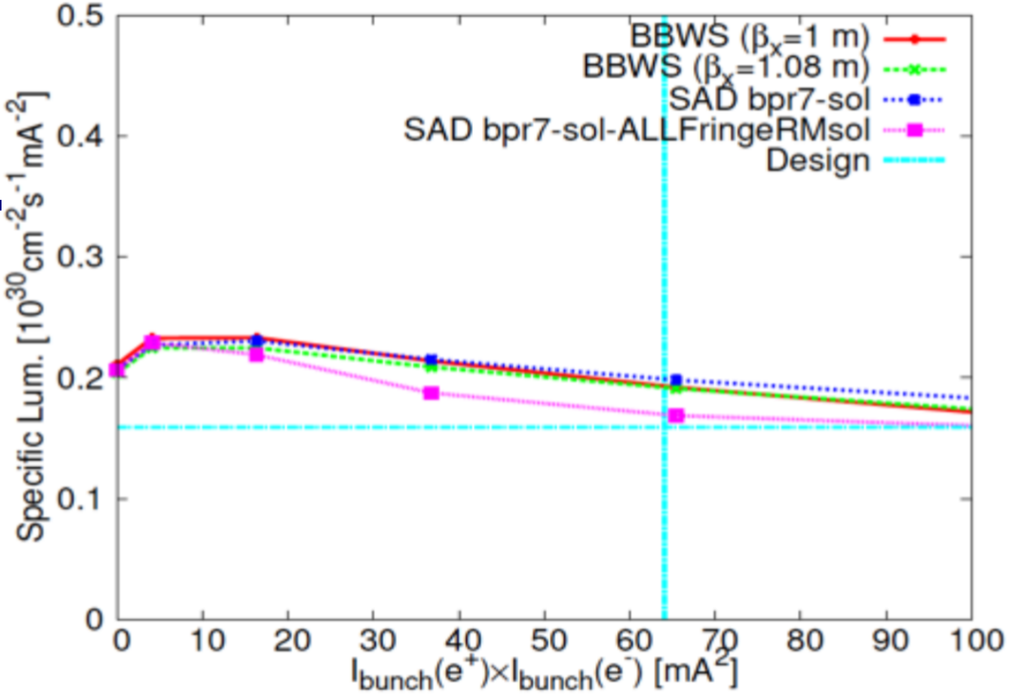
Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	9.8 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point	6.53/5.58
Harmonic number	396
Bunch number	93
Bunch spacing	2.4 m
RF voltage	1.5 MV
Momentum compaction	0.0235
Natural bunch length	1.35 cm
Beam-beam parameter	0.04
Luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$

Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	7.0 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	100 nm·rad
Working point	7.505/5.580
Harmonic number	396
Bunch number	130
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0170
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$

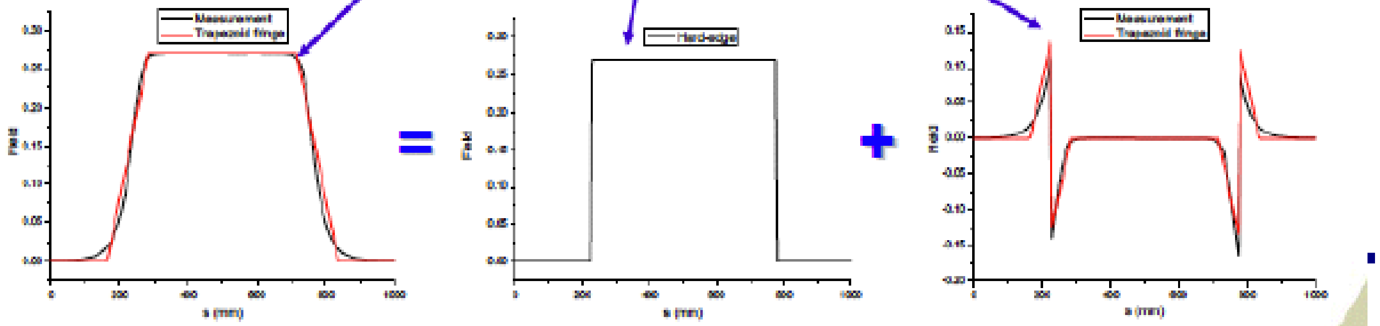
Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	8.3 mA
β function at IP	1.0 m/1.35 cm
Horizontal emittance	122 nm·rad
Working point	7.505/5.580
Harmonic number	396
Bunch number	110
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0181
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity	$1.1\times10^{33}cm^{-2}s^{-1}$

D. Zhou (KEK), Y. Zhang, D. Ji

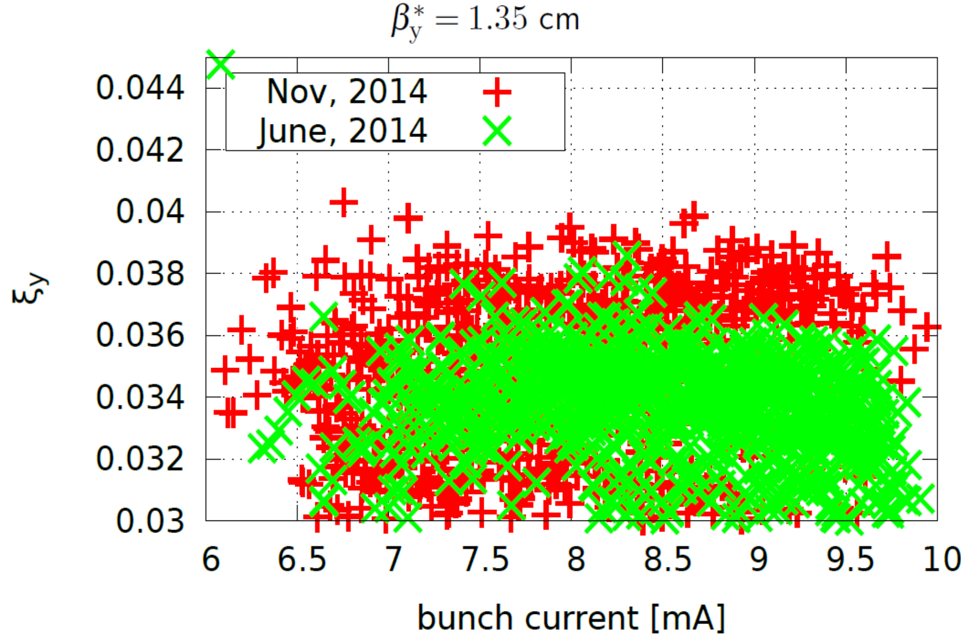
- **Magnet model optimization**
  - **Bend & Quad: Hard edge model -> Soft edge model + Nonlinear fringe field**
  - **Online optics correction only help control the linear model**
  - **Simulation shows about 10% luminosity reduction**



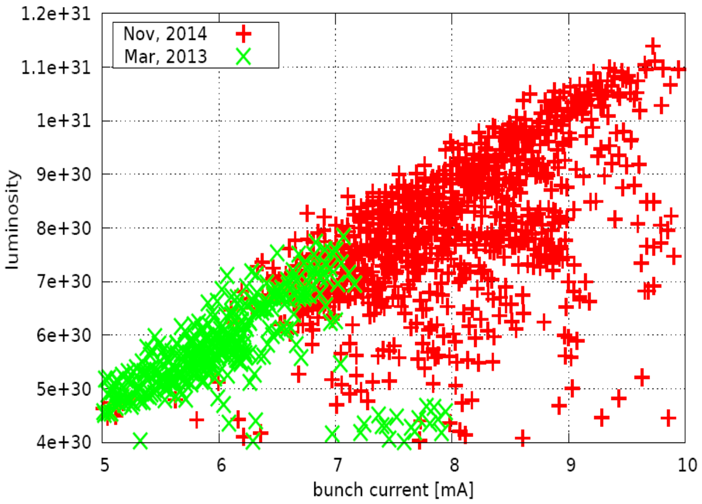
$$K(s) = K_0(s) + k(s)$$

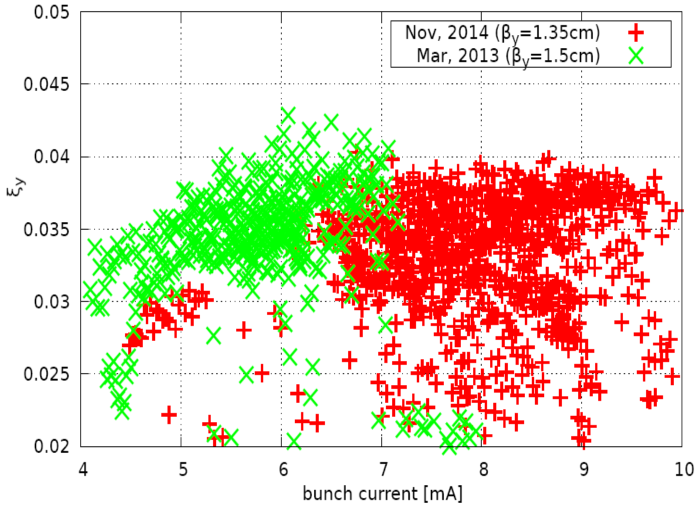


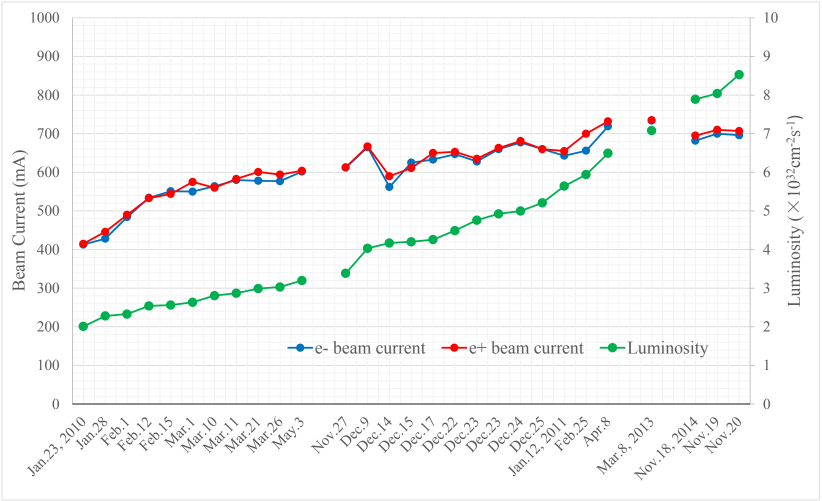
Real magnet = **Ideal magnet** + **Gradient errors**



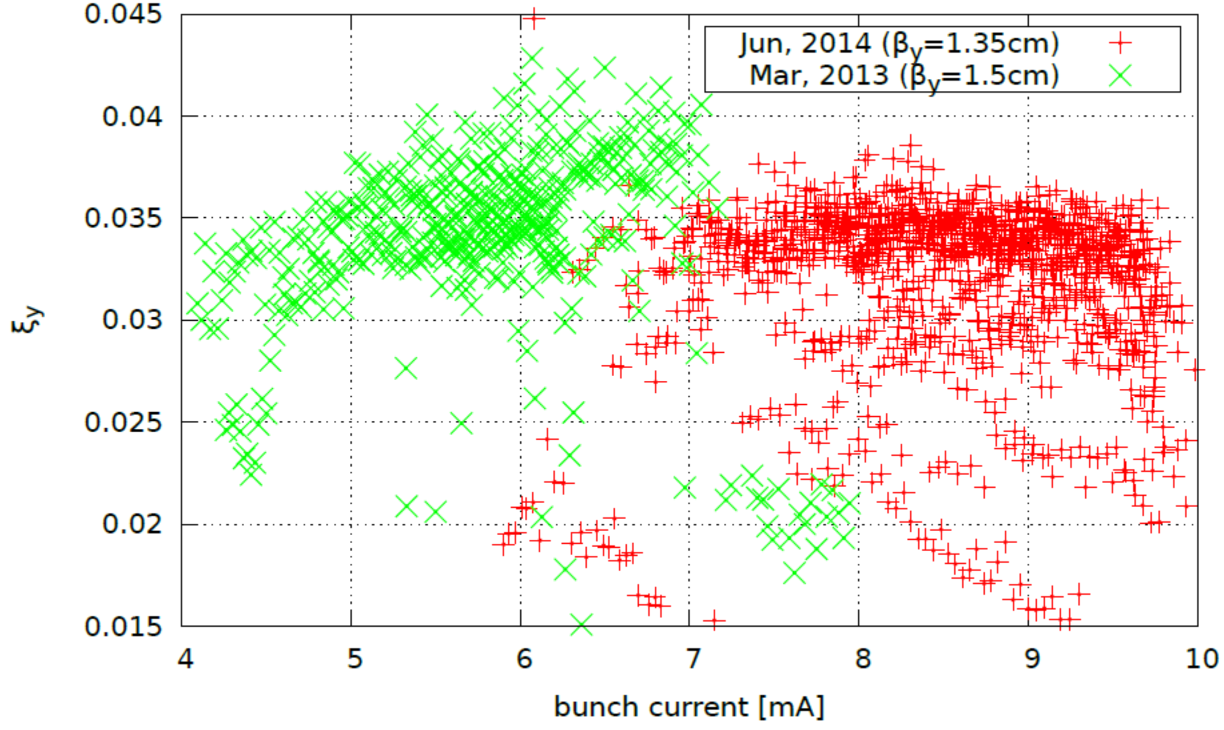
- **Machine study**
  - The maximum luminosity reached 8.53×10^{32} cm^{-2}s^{-1} with the beam current of 696 mA*707 mA and 92 bunches (I_b = 8.6 mA), while the beam-beam parameter was 0.0397 on Nov. 20th, 2014.

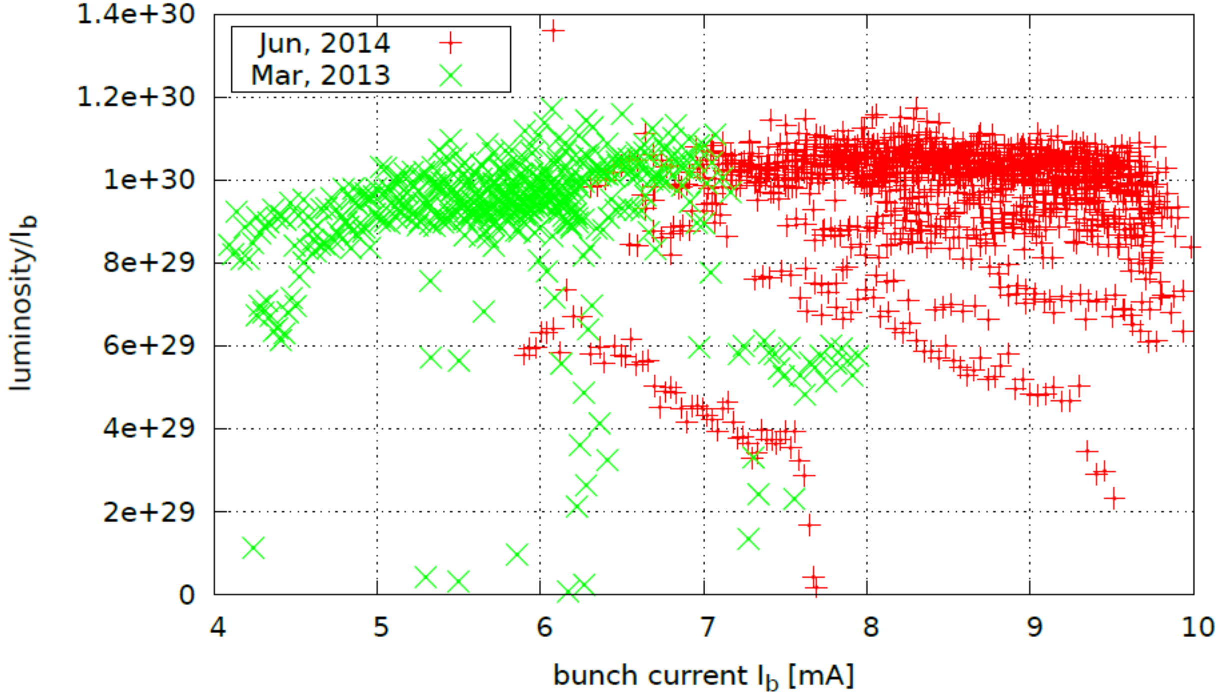






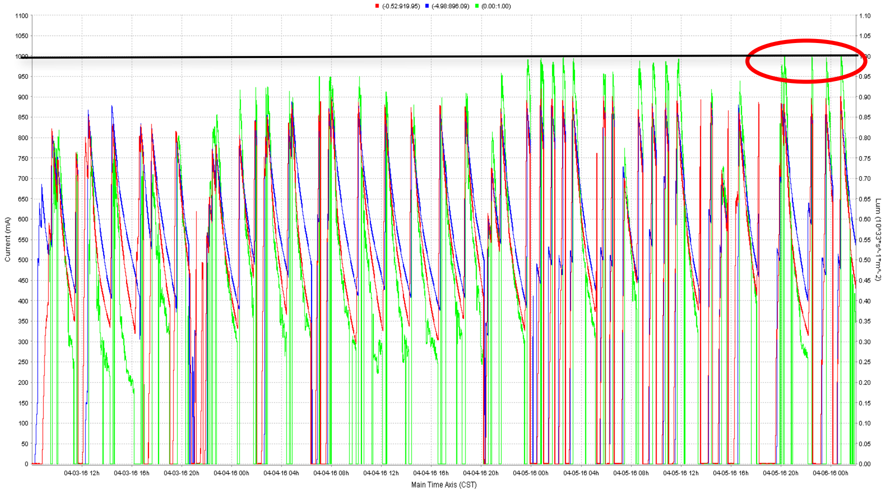
Different β_y@ IP for high luminosity

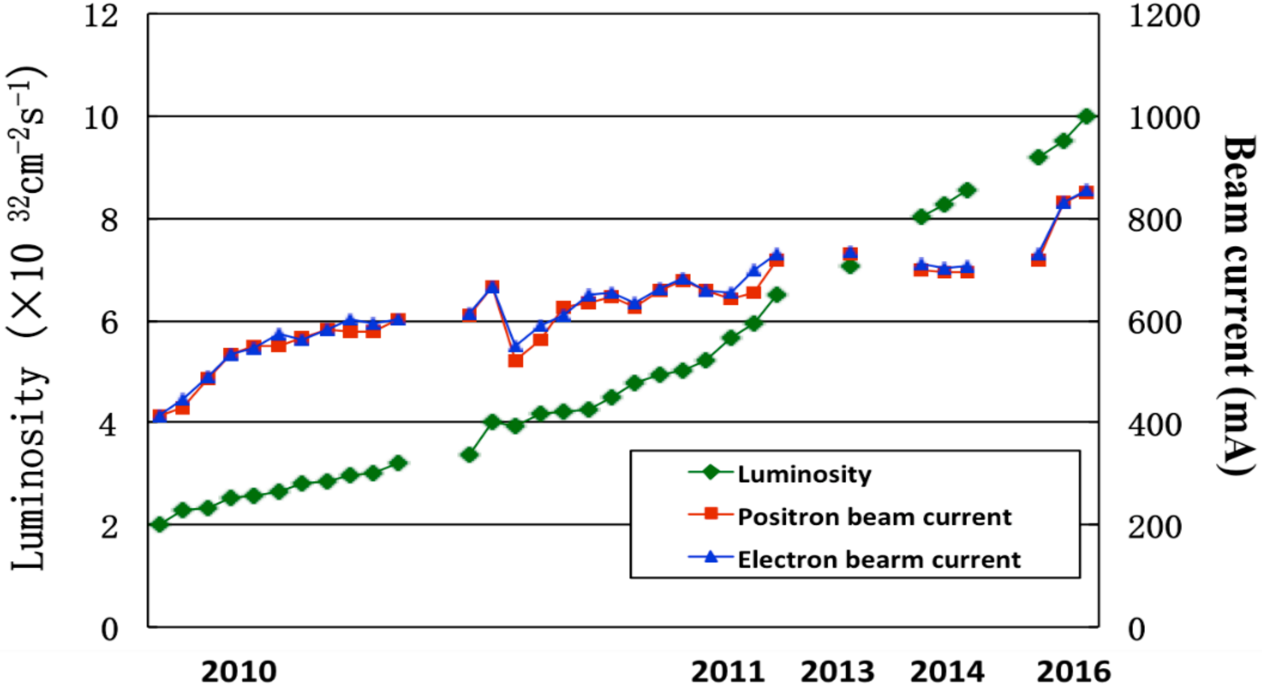




Designed luminosity achieved

- The designed luminosity 10.0×1032 cm-2s-1 achieved on April 5, 2016, with the beam current of 849mA*852mA, 119 b. The beam-beam parameter reached 0.0384.





Beam parameters for design luminosity

		Original design	Optimized value
Beam energy (GeV)		1.89	1.89
Vert. beta function at IP (cm)		1.5	1.35
Transverse tune (x/y)	Positron ring	6.53/5.58	7.502/5.544
	Electron ring	6.53/5.58	7.504/5.572
Natural emittance (mm · mrad)		0.144	0.122
Momentum compaction		0.0235	0.0181
Natural bunch length (cm)		1.3	1.1
Beam current at peak luminosity (mA)		910/910	850/850
Bunch number		93	119
Beam-beam parameter		0.04	0.04
RF voltage/cavity (MV)		1.5	1.7
Peak luminosity (10^{33} $cm^{-2}s^{-1}$)		1	1

4. Future perspectives

- **Different beam energy regions**
  - 1.0 – 1.6 GeV
  - 1.6 – 1.9 GeV
  - 1.9 – 2.3 GeV

Horizontal emittance

Bunch length

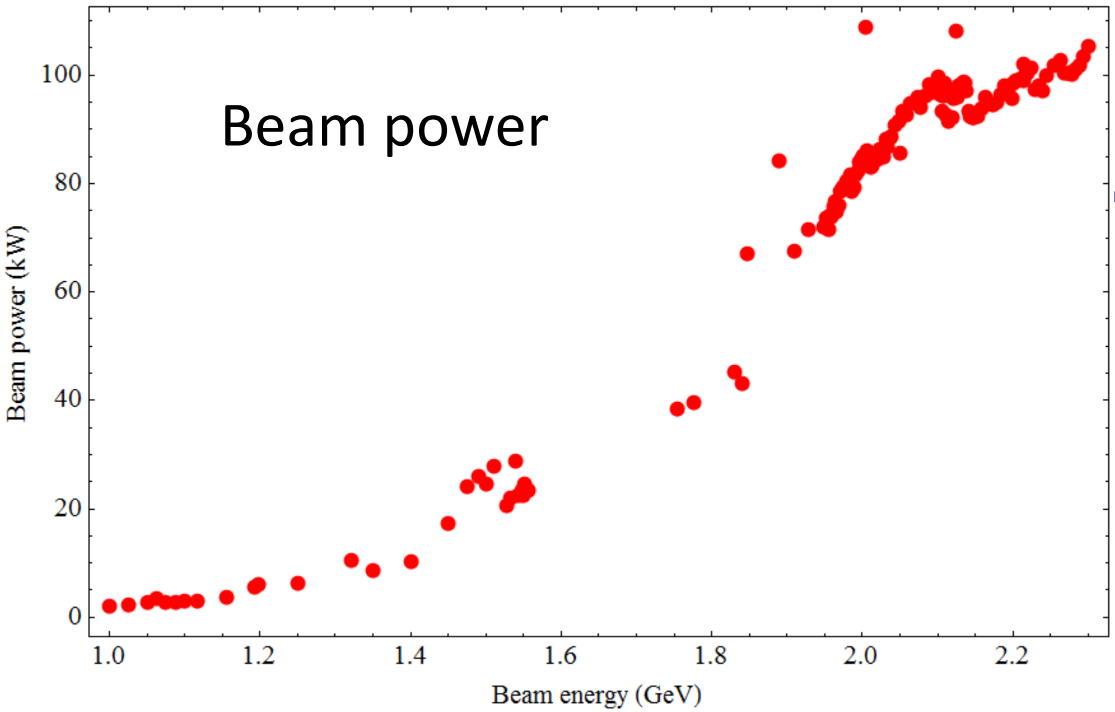
Different beam parameters

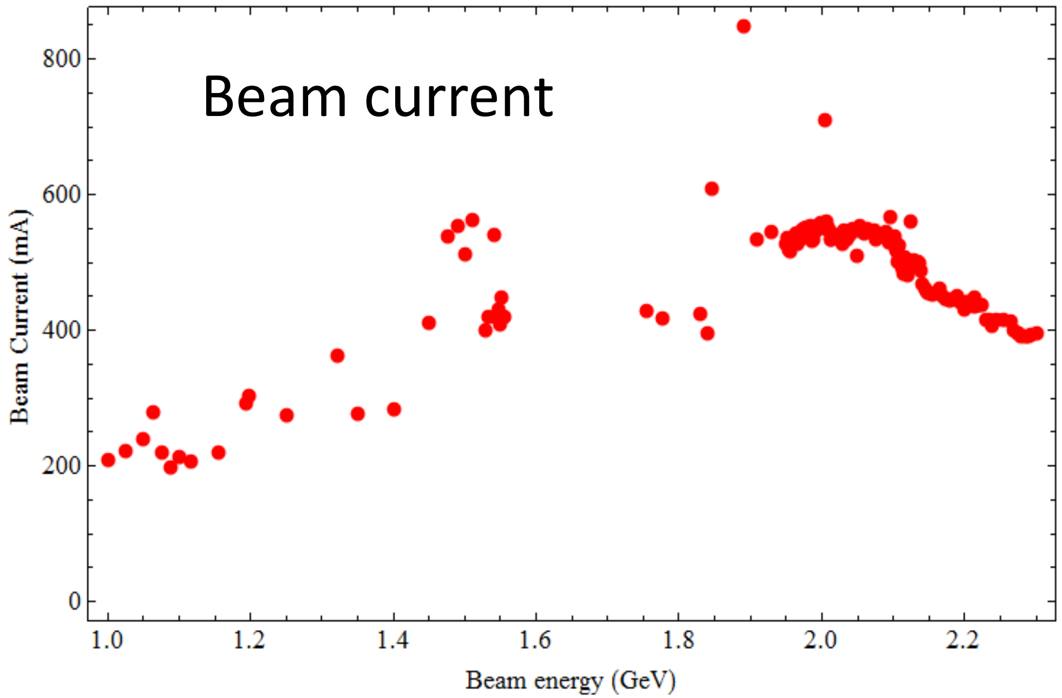
Parameters	Values
Beam energy	1.0 GeV
β function at IP	1.0 m/1.2 cm
Horizontal emittance	54 nm•rad
Working point	6.505/5.580
Momentum compaction	0.0286
Natural bunch length	0.6 cm

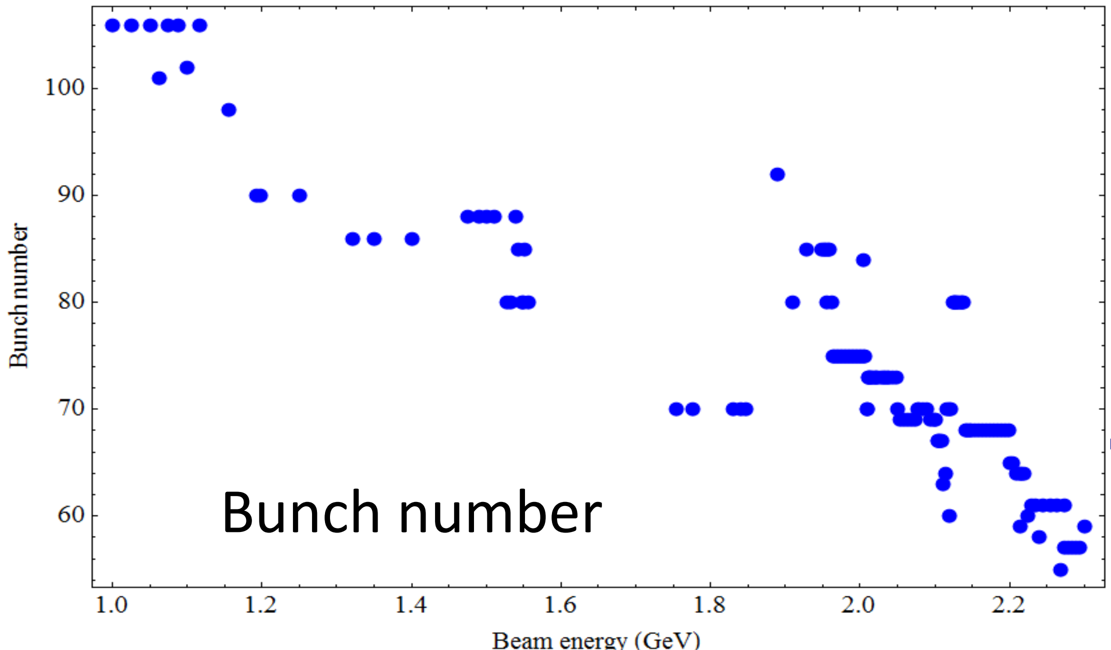
Parameters	Values
Beam energy	1.89 GeV
β function at IP	1.0 m/1.35 cm
Horizontal emittance	122 nm•rad
Working point	7.505/5.580
Momentum compaction	0.018
Natural bunch length	1.15 cm

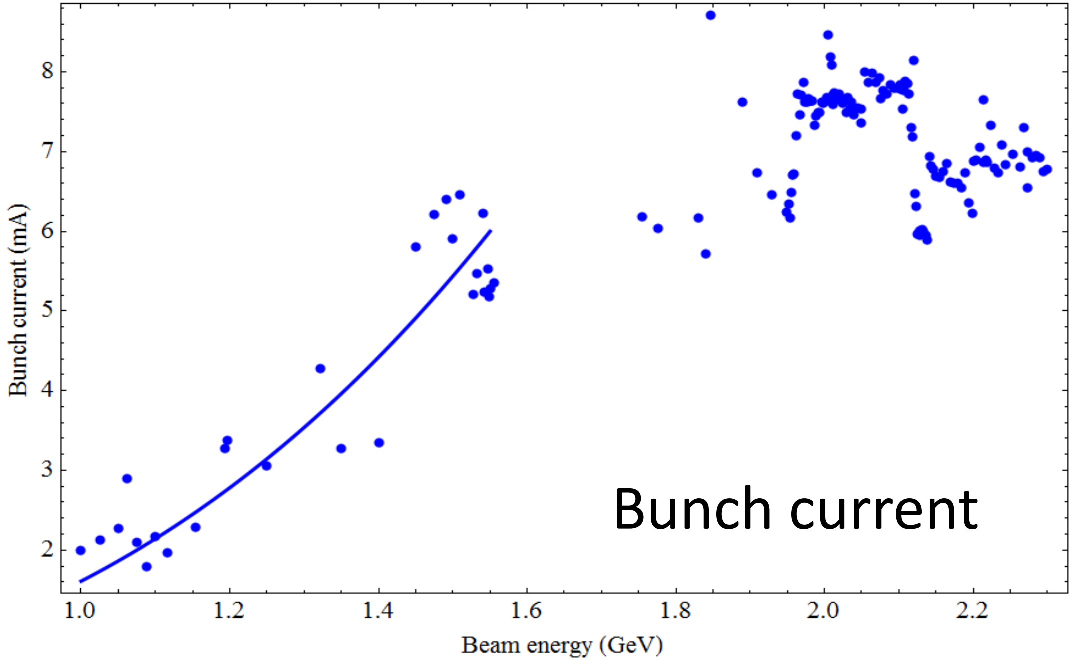
Parameters	Values
Beam energy	2.3 GeV
β function at IP	1.0 m/1.5 cm
Horizontal emittance	144 nm•rad
Working point	7.505/5.580
Momentum compaction	0.017
Natural bunch length	1.5 cm

Low energy   Medium energy   High energy


Beam power
Beam power (kW)
Beam energy (GeV)
0
20
40
60
80
100
1.0
1.2
1.4
1.6
1.8
2.0
2.2

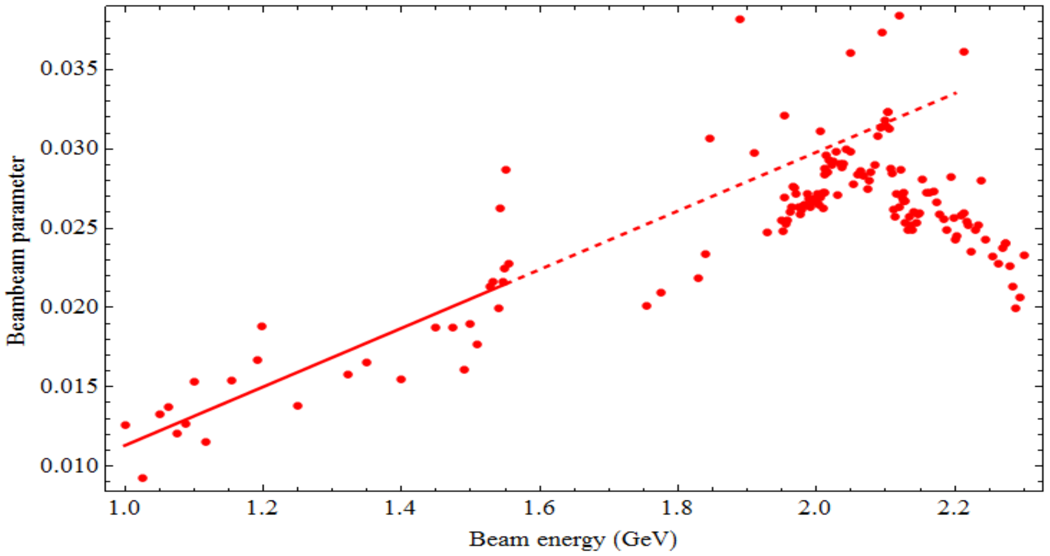

Beam current
Beam Current (mA)
Beam energy (GeV)
0
200
400
600
800
1.0
1.2
1.4
1.6
1.8
2.0
2.2

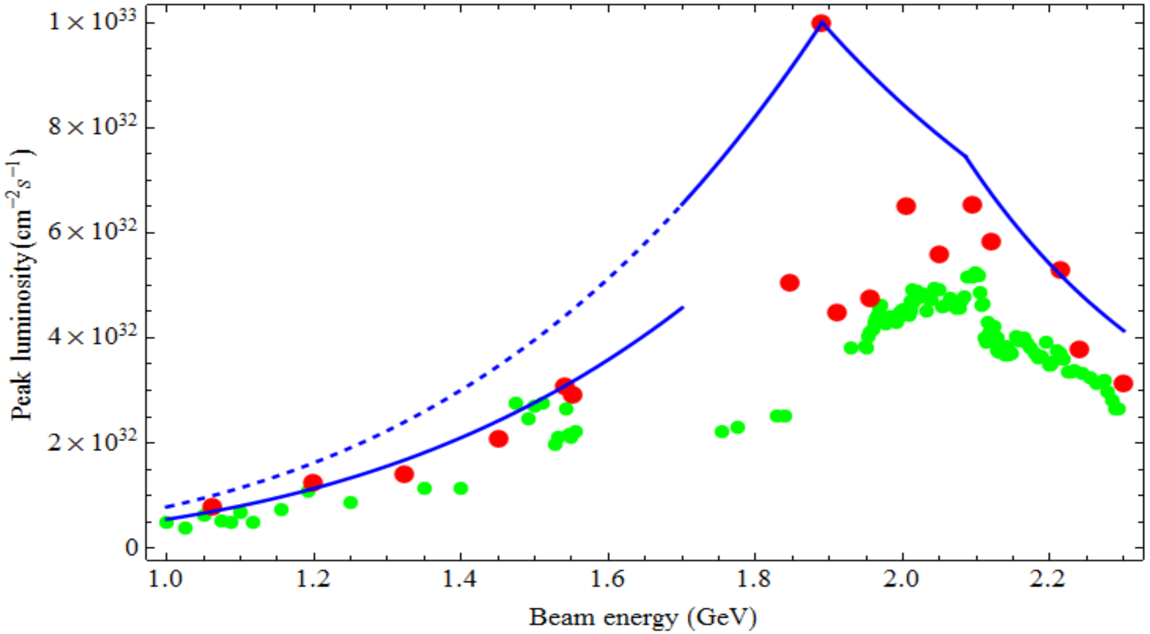

Bunch number
Bunch number
Beam energy (GeV)
60
70
80
90
100
1.0
1.2
1.4
1.6
1.8
2.0
2.2

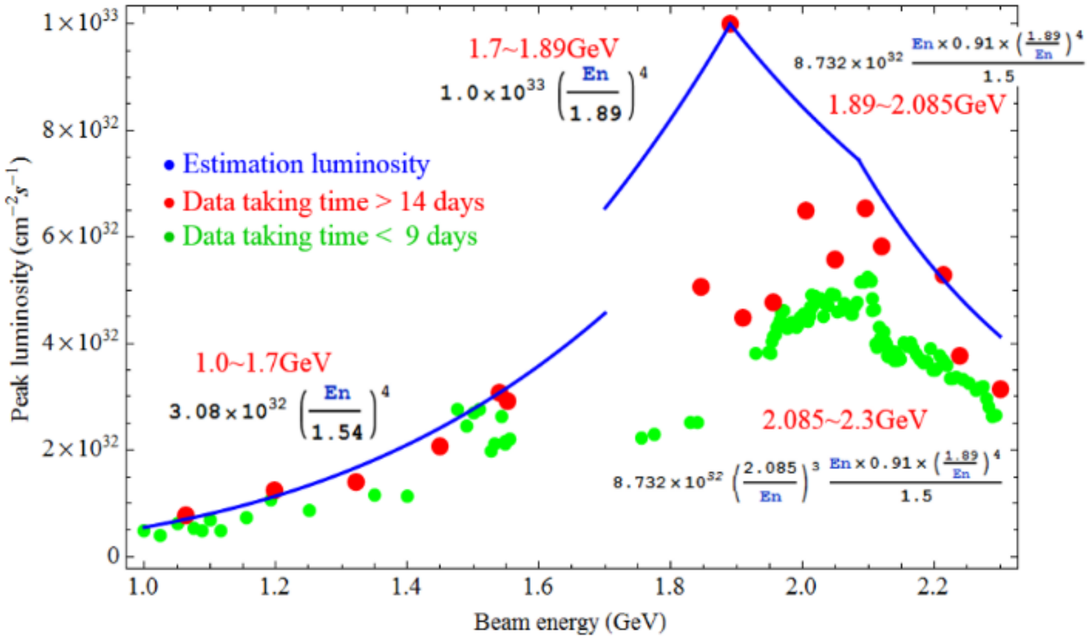

Bunch current
Bunch current (mA)
Beam energy (GeV)
2
3
4
5
6
7
8
1.0
1.2
1.4
1.6
1.8
2.0
2.2

Peak luminosity and scaling law wrt beam energy

- Lower energy – multi-bunch instability ↗
  damping time ↗, injection efficiency ↘
- Higher energy – beam current ↘
  bunch length & emittance optimized

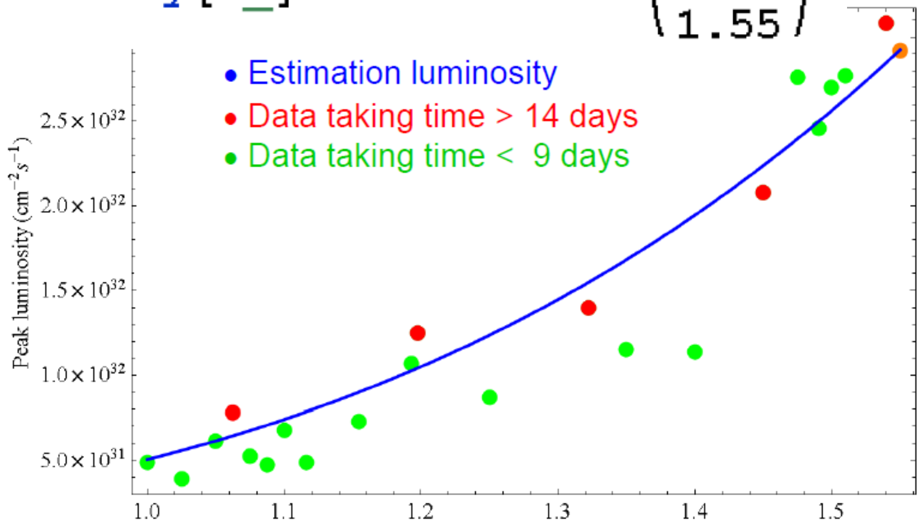




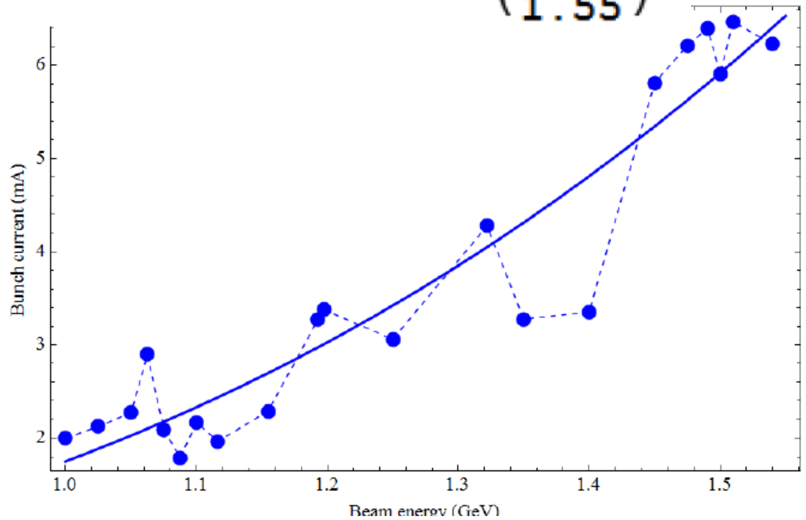


- # Performance versus Energy (2014-2015)

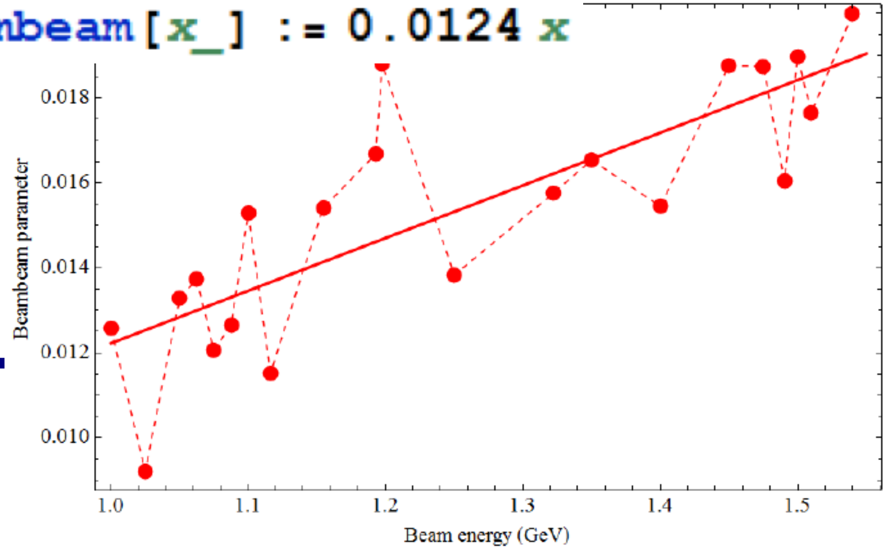
$$\text{Luminosity}[x\_] := 2.92\times10^{32}\left(\frac{x}{1.55}\right)^{4}$$

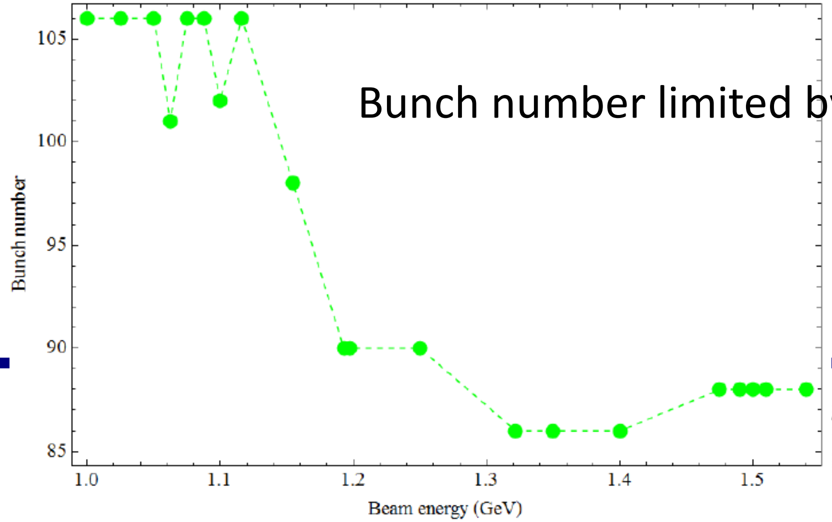


$$\text{BunchCurrent}[x\_] := 6.5283\left(\frac{x}{1.55}\right)^{3}$$



$$\text{Beambeam}[x\_] := 0.0124\,x$$





Bunch number limited by instability

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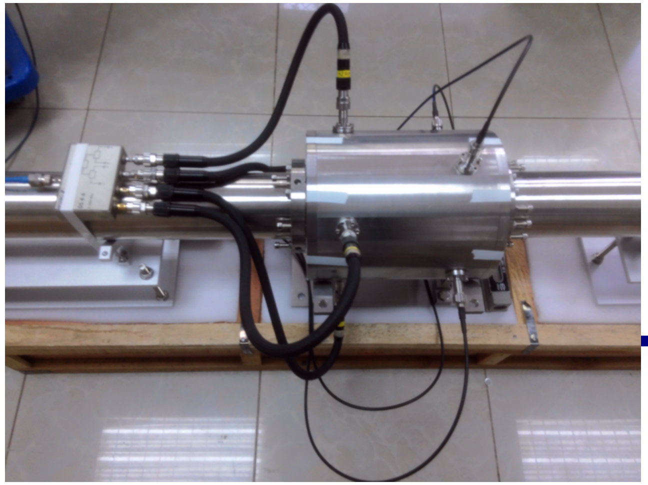
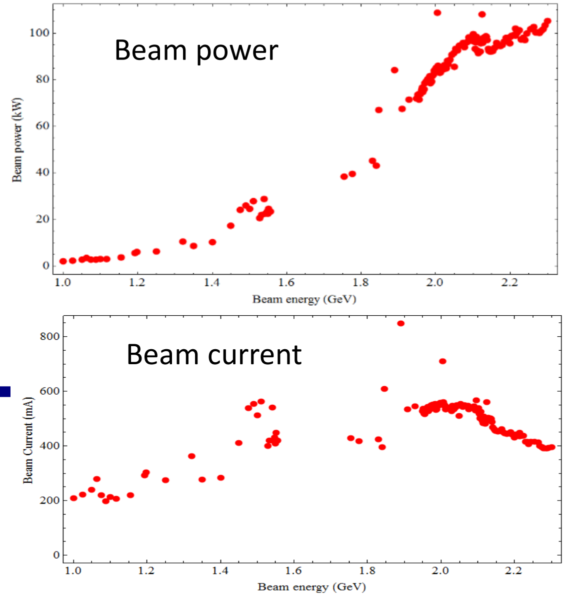
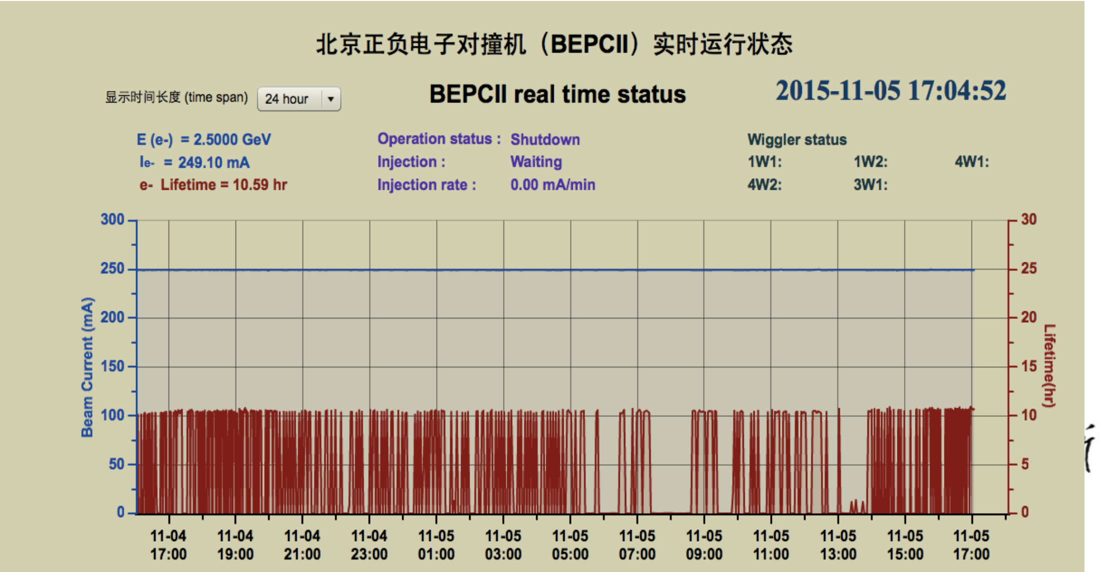
- **High luminosity performance**
  - Bunch current, beam power limit beam current @high beam energy
  - Lower the impedance & instability w/ new LF kicker (2016, 2018)
  - Look for new lattice parameters for higher luminosity
  - Top-up injection for higher integrated luminosity (tested in HEP running, ran in SR operation)







Conclusion

- From late 2008, BEPCII runs for HEP and SR for more than 9 years with an increasing luminosity, and a big energy span for various HEP exp.;
- A lot of work on AP and hardware improvements done in recent years help to enhance luminosity greatly;
- The design luminosity @ ψ(2S) energy was achieved, although most of the time accelerator was not run at that energy;
- A fruitful HEP results has been obtained and will be got in the near future with the high efficient operation and beam performance;
- High luminosity and high energy operations are foreseen in the near future.

Thanks for your attentions!