Performance and Prospects of BEPCII

Qing Qin (秦庆)

For the BEPCII Accelerator Team

Accelerator Center, IHEP

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Outline

- Introduction on BEPCII
- Accelerator physics issues
- Hardware improvements
- Routine user operations
- Problems and prospects
- Summary

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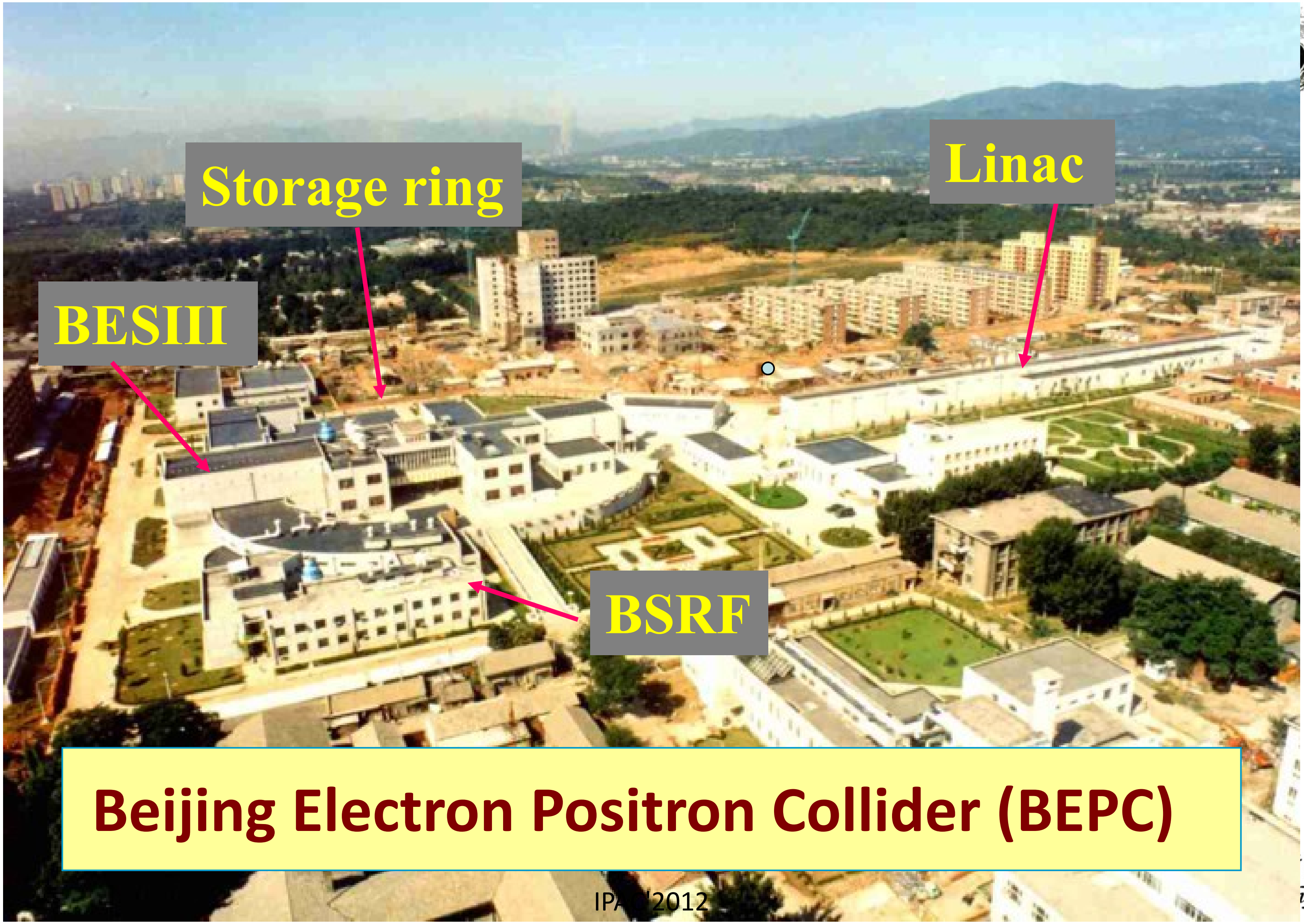


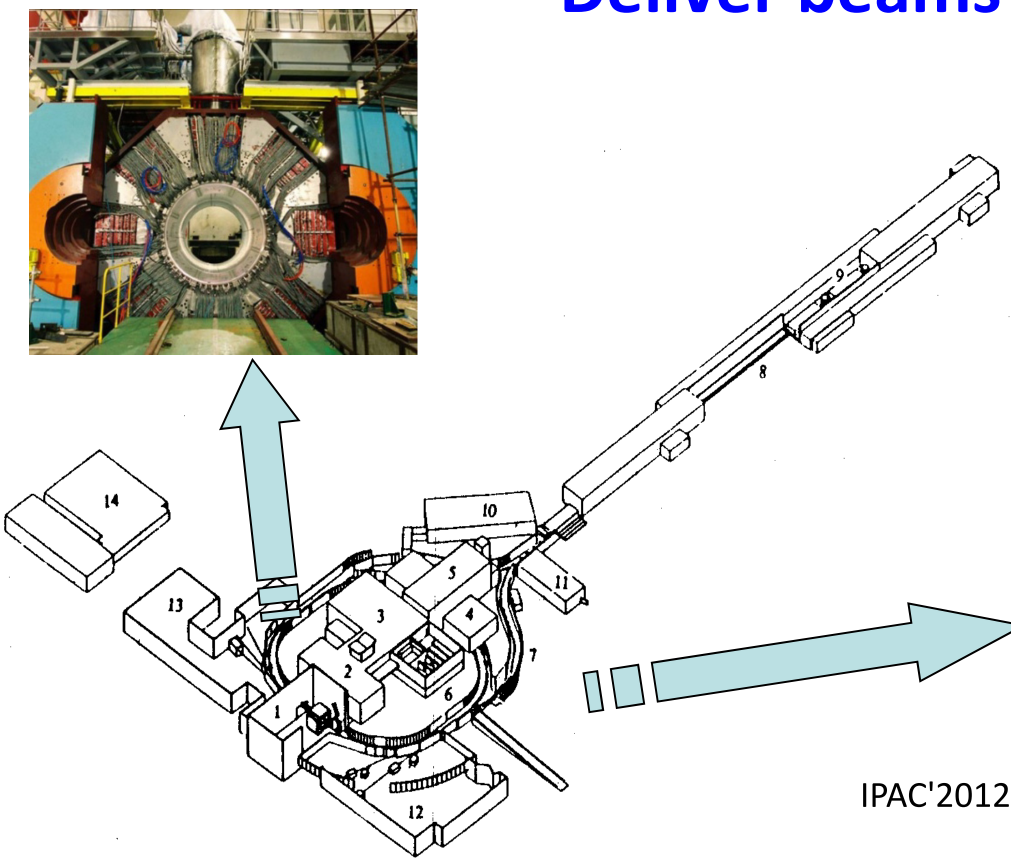
Beijing Electron Positron Collider (BEPC)

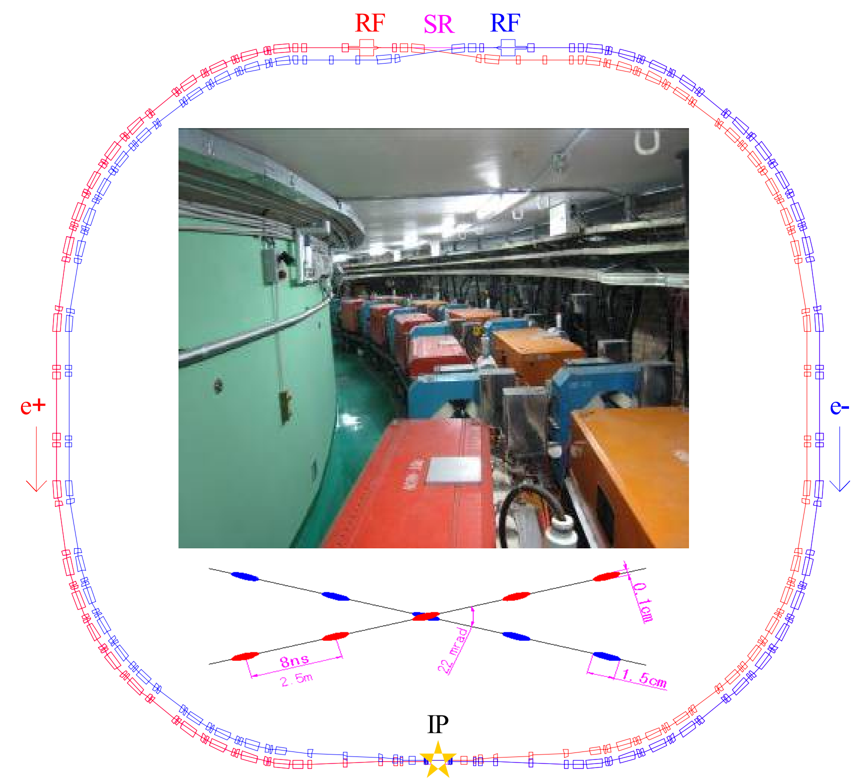
1. Introduction on BEPCII

BEPCII — An upgrade project of BEPC

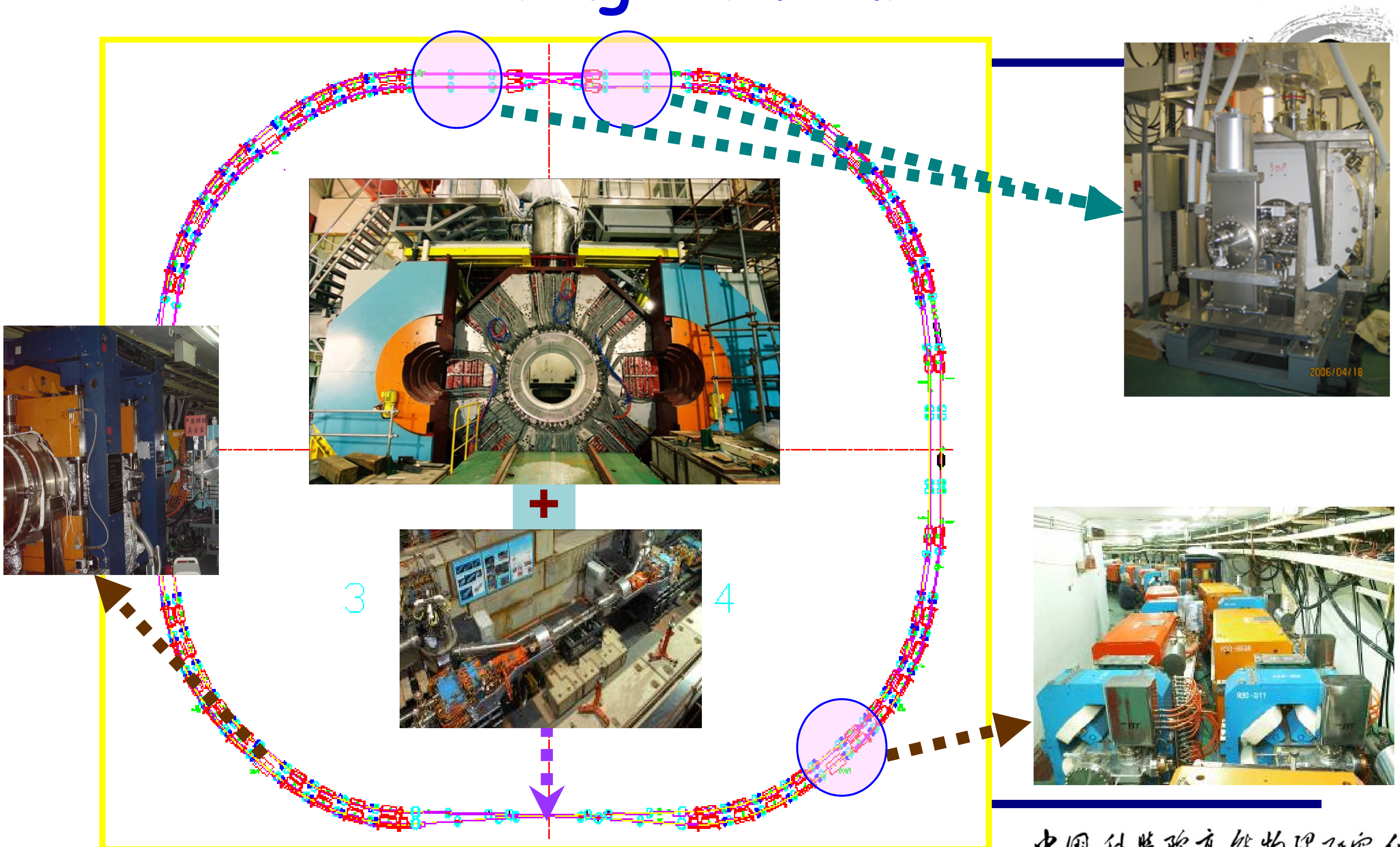
— A double-ring factory-like machine

— Deliver beams to both HEP & SR





3-ring structure



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Design Goals of BEPCII

- **Collision**
  - **Beam energy range** — 1-2.1 GeV
  - **Optimized beam energy** — 1.89 GeV
  - **Luminosity** — 1×10^{33} $cm^{-2}s^{-1}$ @1.89 GeV
  - **Full energy injection** — 1-1.89 GeV
- **Synchrotron radiation**
  - **Beam energy** — 2.5 GeV
  - **Beam current** — 250 mA
  - **Keep the existing beam lines unchanged**

BEPCII: One-machine, Two-purpose (HEP, SR)

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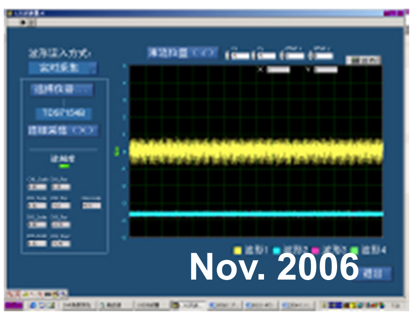
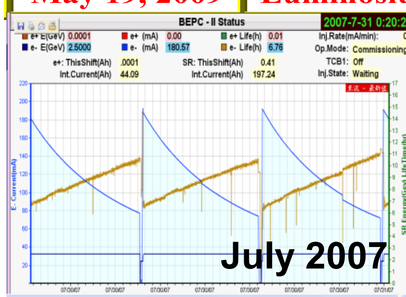
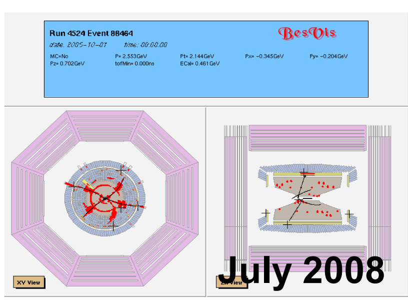
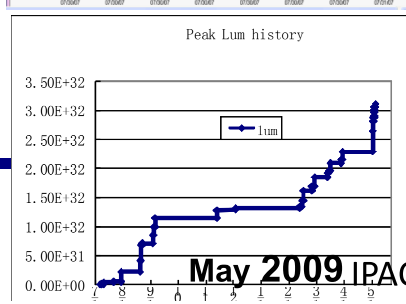
The Milestones

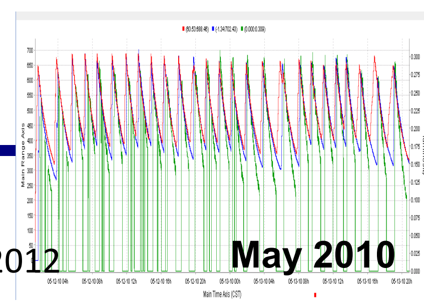
January 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections started
Dec. 1, 2004	Linac delivered e^- beams for BEPC
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Nov. 13, 2006	Phase 1 commissioning started
Aug. 3, 2007	Shutdown for installation of IR-SCQ's
Oct. 24, 2007	Phase 2 commissioning started
Mar.28, 2008	Shutdown for installation of detector
June 24, 2008	Phase 3 commissioning started
July 19, 2008	First hadron event observed
May 19, 2009	Luminosity reached $3.3\times10^{32}cm^{-2}s^{-1}$

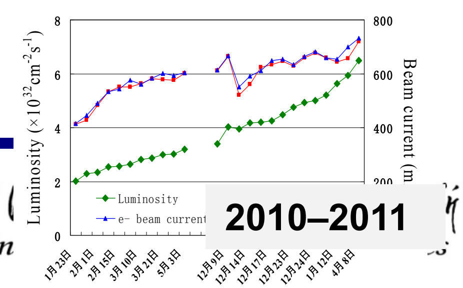








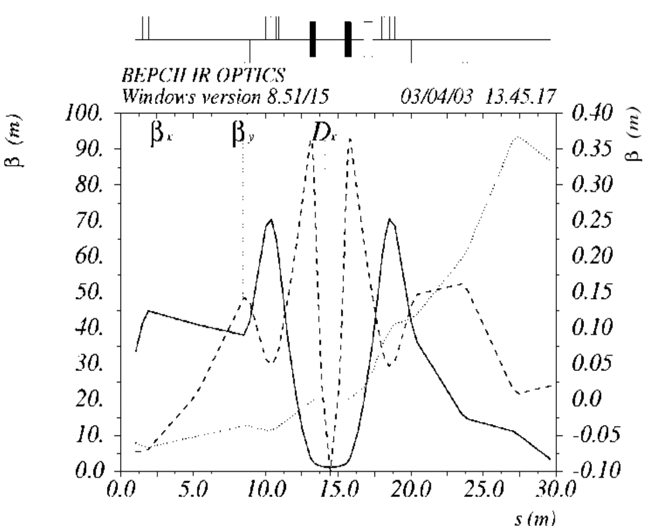


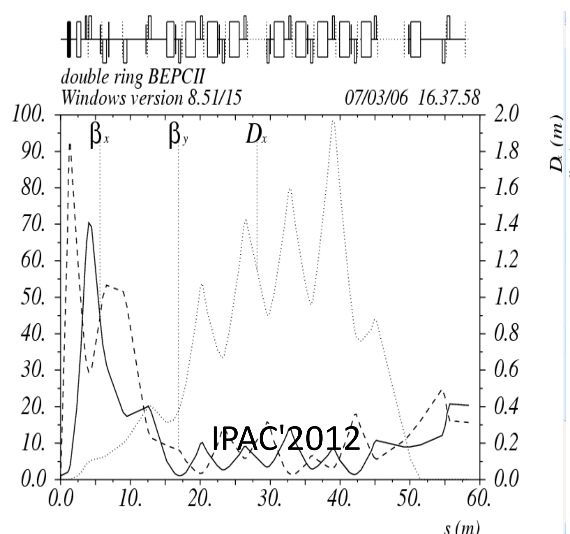


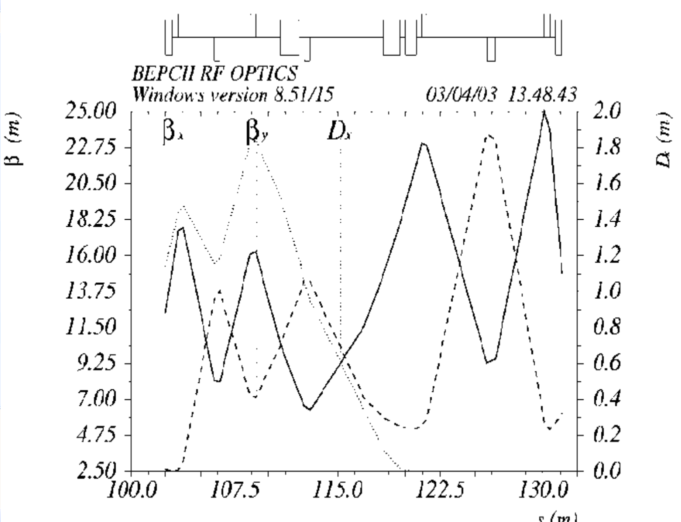
2. Accelerator Physics Issues

◆ Lattice of collision rings (BER & BPR)

- Keep the scheme of quasi-FODO lattice in the arcs, same as that in BEPC;
- Four Dx-free sections (IR, RF, Inj & NCP) connect four arcs;
- Each quad is independently powered;
- Lattice symmetry is broken thoroughly!







Main parameters of BEPCII 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) / No.	9.8 / 93	~1 / 160 - 300
Natural bunch length (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)	$\pm$11	0
Tune (x/y/s)	6.54/5.59/0.034	7.28/5.18/0.036
Momentum compaction	0.024	0.016
Energy spread	5.16×10^{-4}	6.67×10^{-4}
Natural chromaticity (x/y)	-10.8/-20.8	-9.0/-8.9
Luminosity ($cm^{-2}s^{-1}$)	1×10^{33}	—

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Beam optics correction

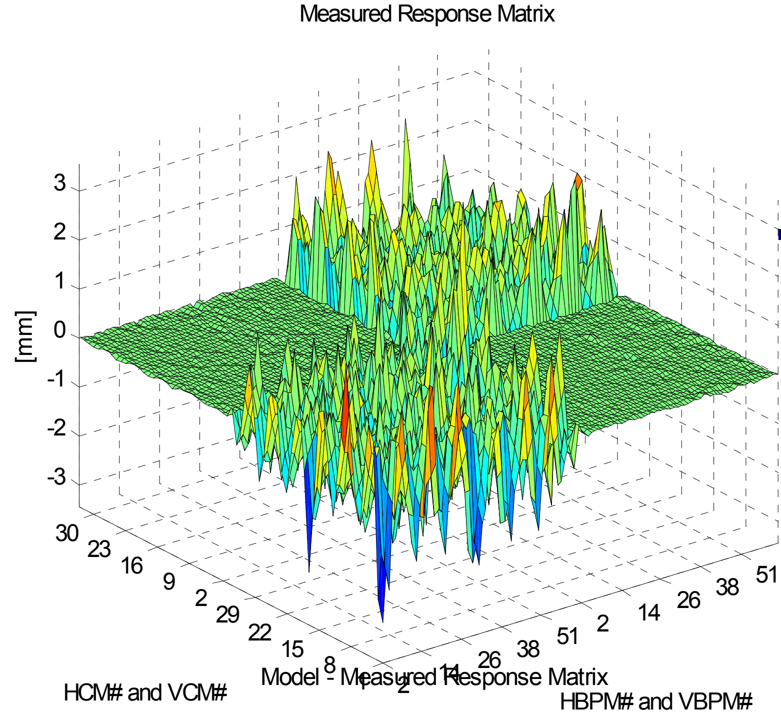
- **Method of Response Matrix Analysis**

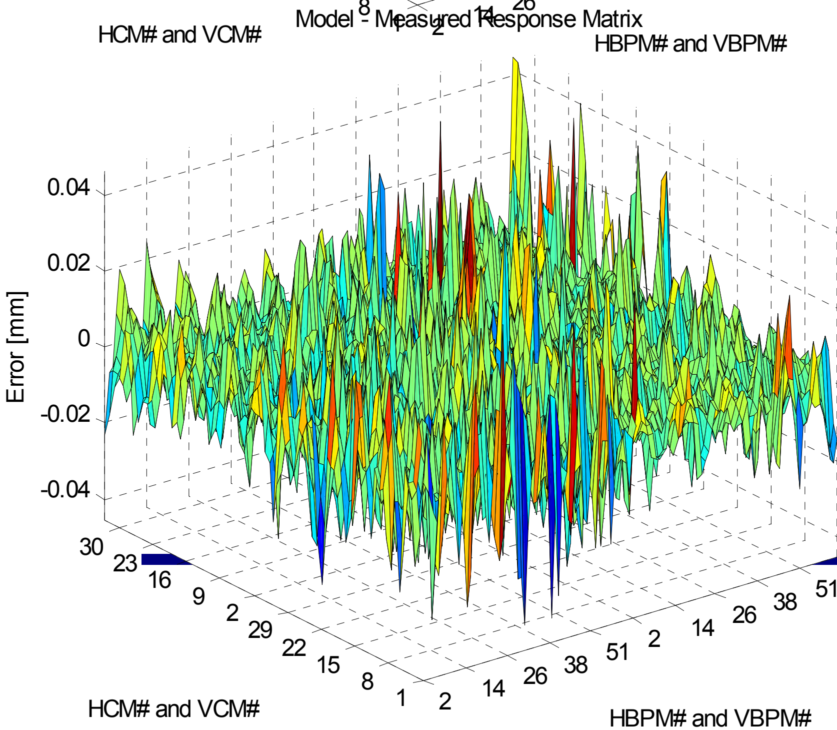
$$\begin{pmatrix}\Delta x \\ \Delta y\end{pmatrix} = R_{meas}\begin{pmatrix}\Delta\theta_x \\ \Delta\theta_y\end{pmatrix} \qquad \chi^2 = \sum_{i,j}\frac{(R_{\mathrm{mod},ij} - R_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2$$

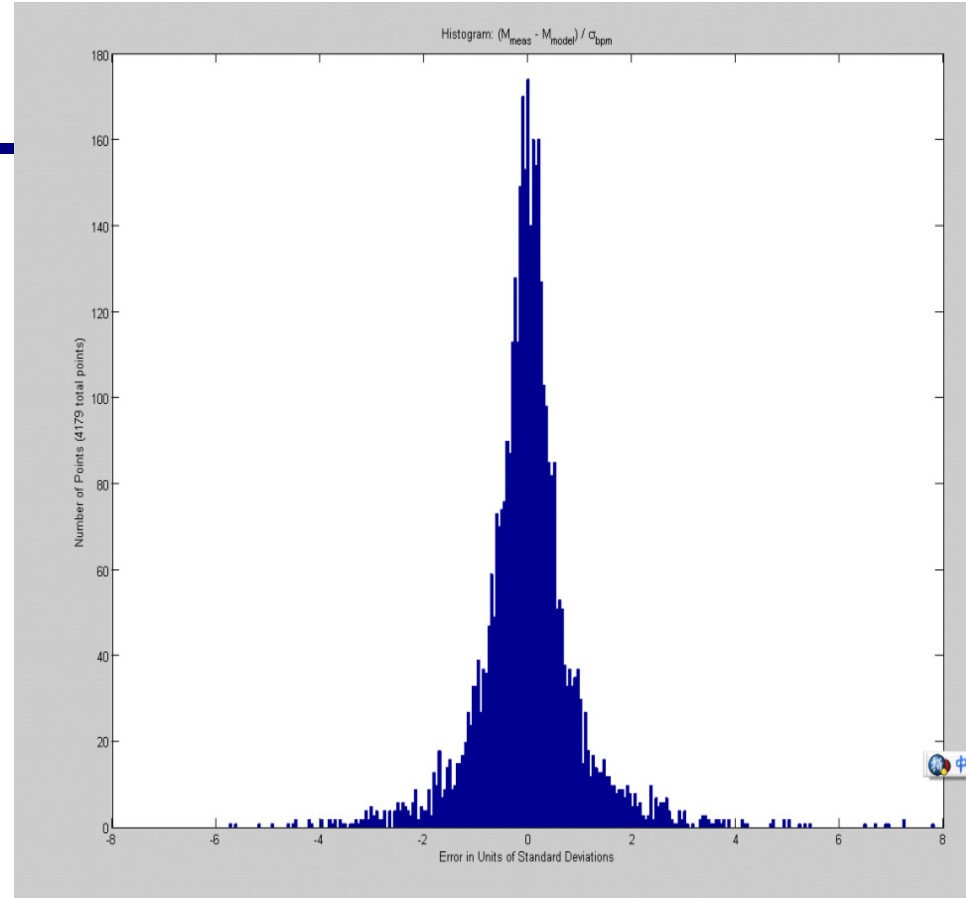
$$\Delta V_{ij} = \sum\frac{\partial V_{ij}}{\partial K_q}\Delta K_q + \sum\frac{\partial V_{ij}}{\partial G_i}\Delta G_i + \sum\frac{\partial V_{ij}}{\partial \theta_j}\Delta\theta_j + \sum\frac{\partial V_{ij}}{\partial \delta_j}\Delta\delta_j + \ldots\ldots$$

- **Fudge factors of quads：**

$$K = K_0 * AF \qquad \Delta AF = 1 - AF$$







σ = 0.006，BPM resolution = 0.01mm

(Courtesy D.H. Ji)

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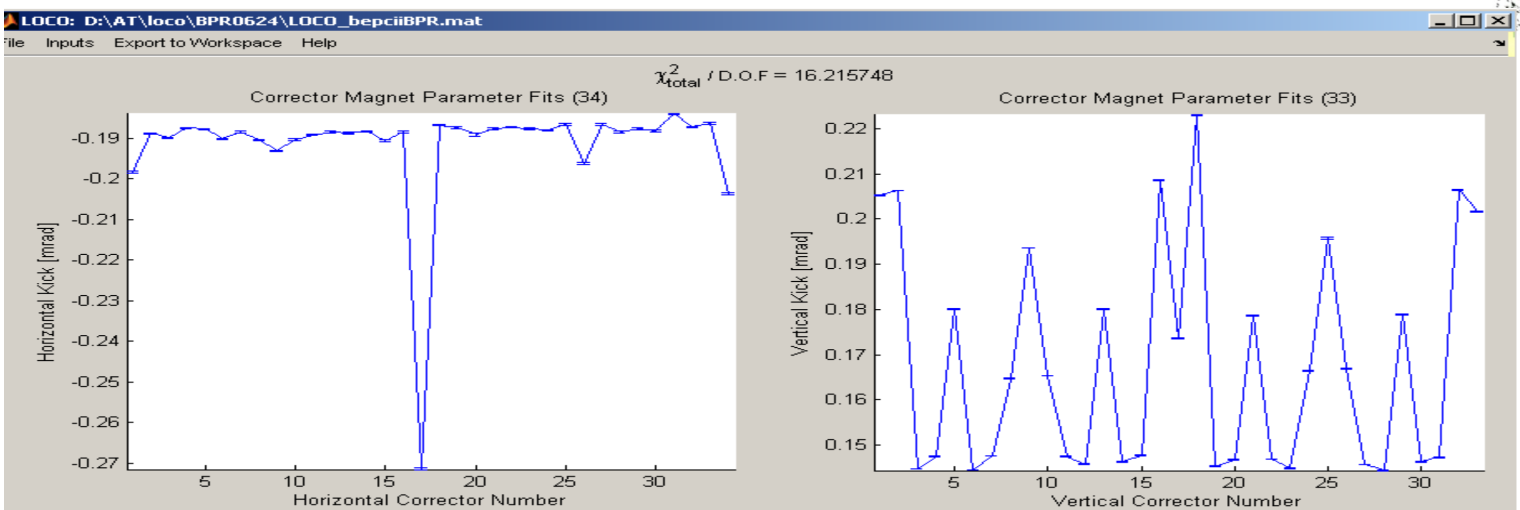
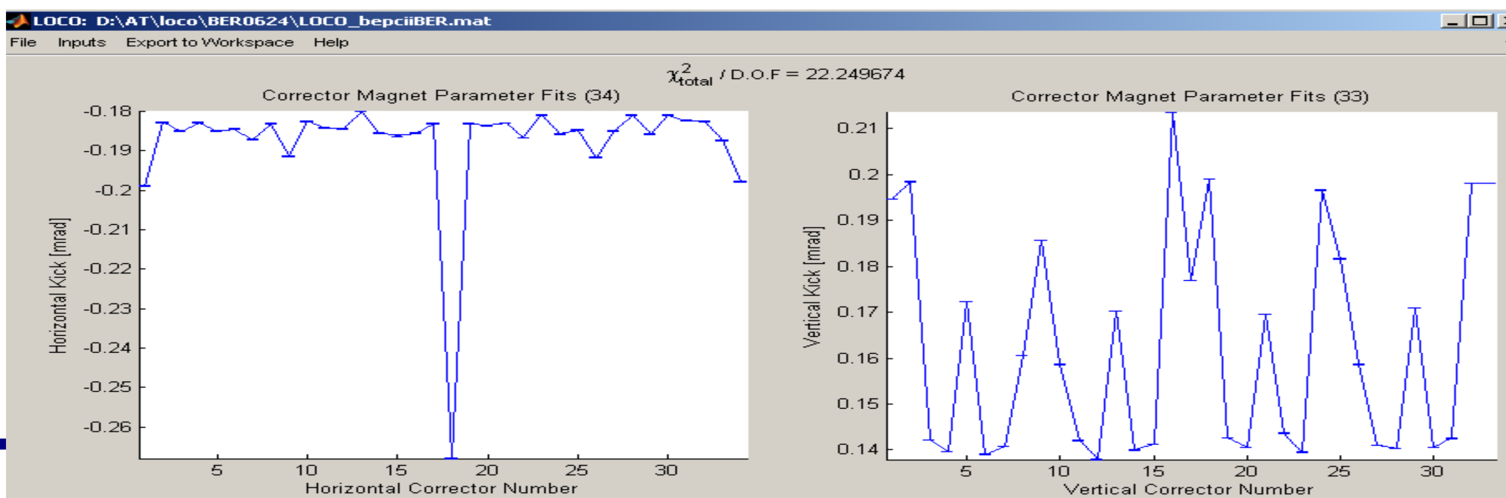
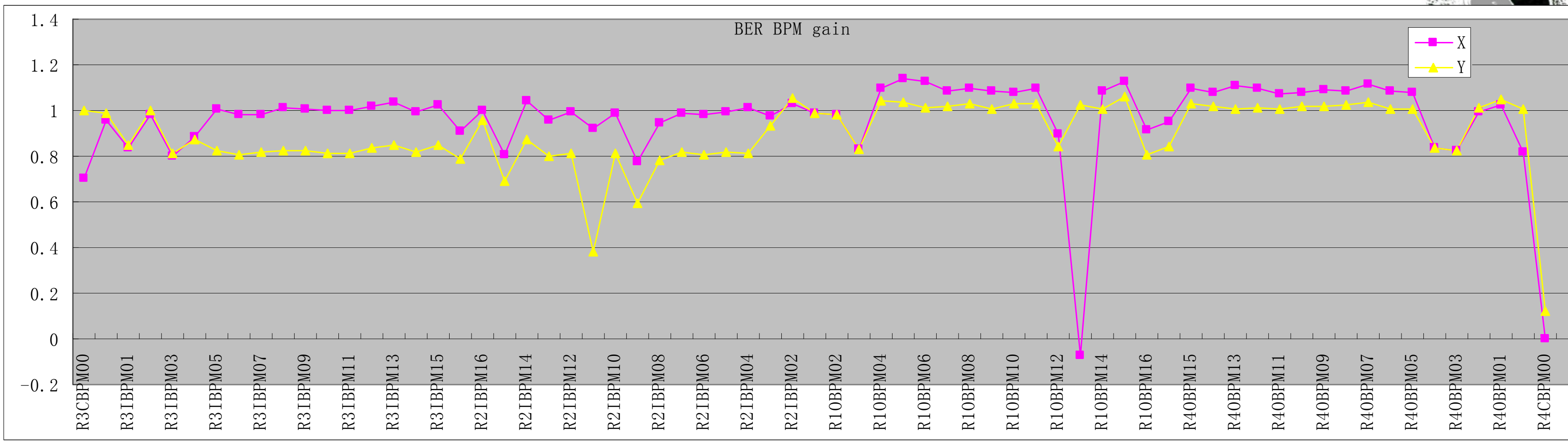
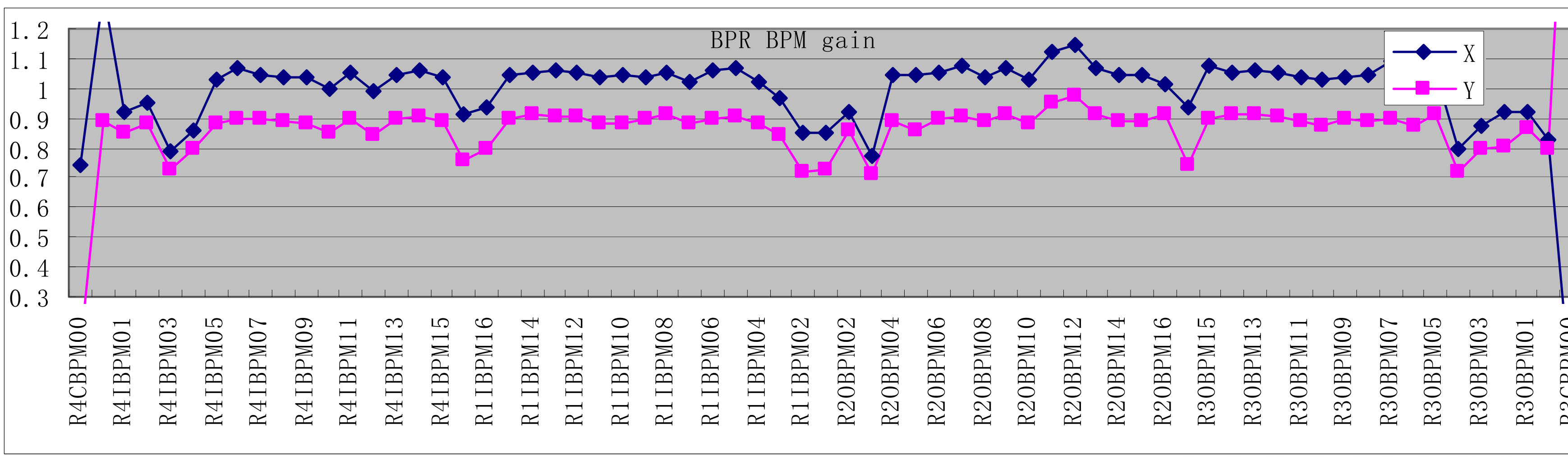
- **Gain of correctors' strength**





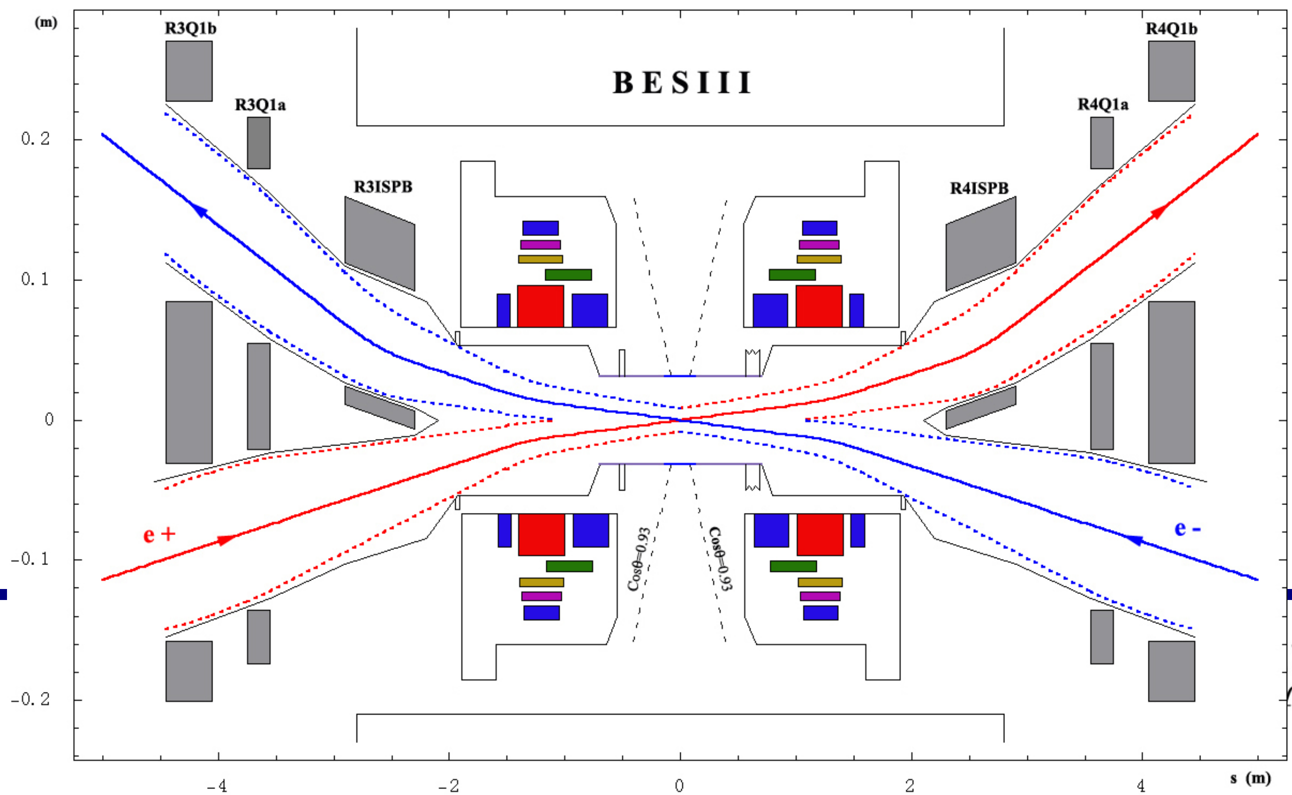
BPMs' gain


BER BPM gain
X
Y
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
R3CBPM00
R3IBPM01
R3IBPM03
R3IBPM05
R3IBPM07
R3IBPM09
R3IBPM11
R3IBPM13
R3IBPM15
R2IBPM16
R2IBPM14
R2IBPM12
R2IBPM10
R2IBPM08
R2IBPM06
R2IBPM04
R2IBPM02
R1OBPM02
R1OBPM04
R1OBPM06
R1OBPM08
R1OBPM10
R1OBPM12
R1OBPM14
R1OBPM16
R4OBPM15
R4OBPM13
R4OBPM11
R4OBPM09
R4OBPM07
R4OBPM05
R4OBPM03
R4OBPM01
R4CBPM00


BPR BPM gain
X
Y
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
R4CBPM00
R4IBPM01
R4IBPM03
R4IBPM05
R4IBPM07
R4IBPM09
R4IBPM11
R4IBPM13
R4IBPM15
R1IBPM16
R1IBPM14
R1IBPM12
R1IBPM10
R1IBPM08
R1IBPM06
R1IBPM04
R1IBPM02
R2OBPM02
R2OBPM04
R2OBPM06
R2OBPM08
R2OBPM10
R2OBPM12
R2OBPM14
R2OBPM16
R3OBPM15
R3OBPM13
R3OBPM11
R3OBPM09
R3OBPM07
R3OBPM05
R3OBPM03
R3OBPM01
R3CBPM00

Difficulties of optics correction in the IR

- Each SCQ has one power supply but shared by two rings.
- One 2-in-1 quads (Q1A) in each side of IP, share one power supply, respectively.
- Insufficient BPMs in the IR for RM measurement.



Beam energy variation

- Energy response due to the change of corrector strengths to the response matrix considered, finding the solution to satisfy both C.O.D. correction and beam energy variation:

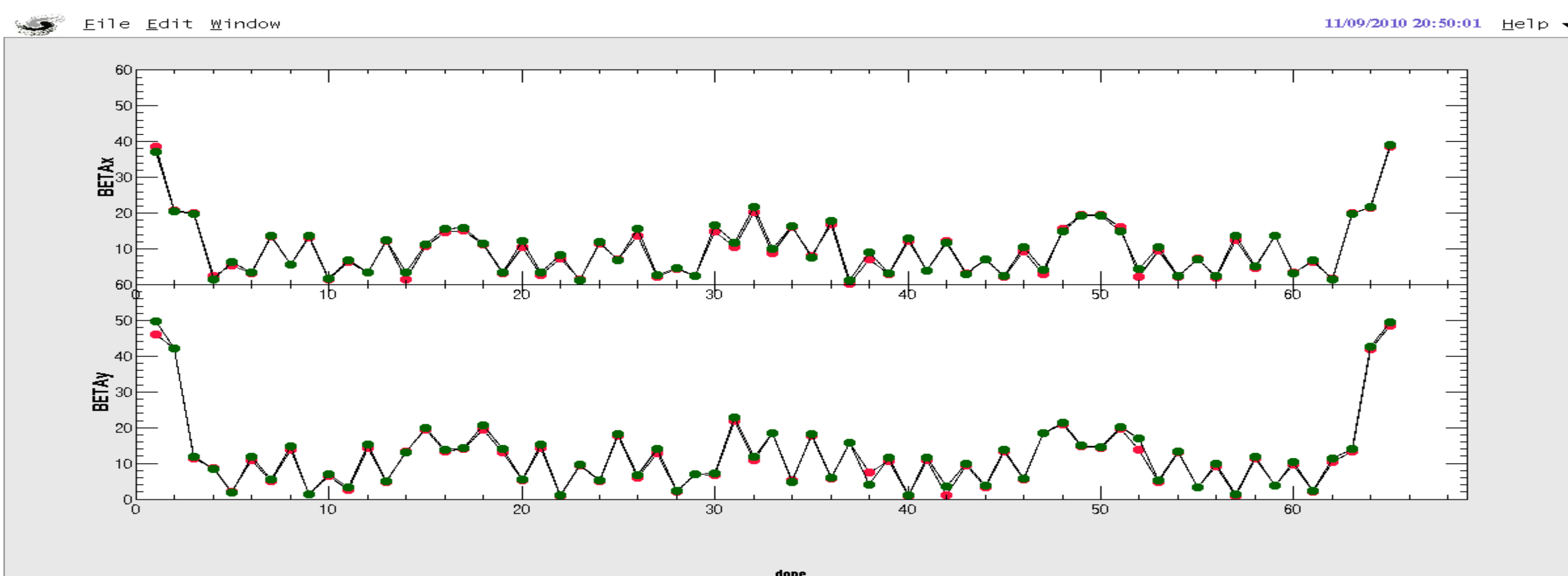
$$\frac{\Delta E}{E} = -\frac{1}{\alpha L_0} \sum_i D_x^i \Delta \theta_{cx}^i$$

- Correct the energy difference between two rings, making the energy of two rings the same
- Calculated energy difference is the same as the result given by the energy measurement system

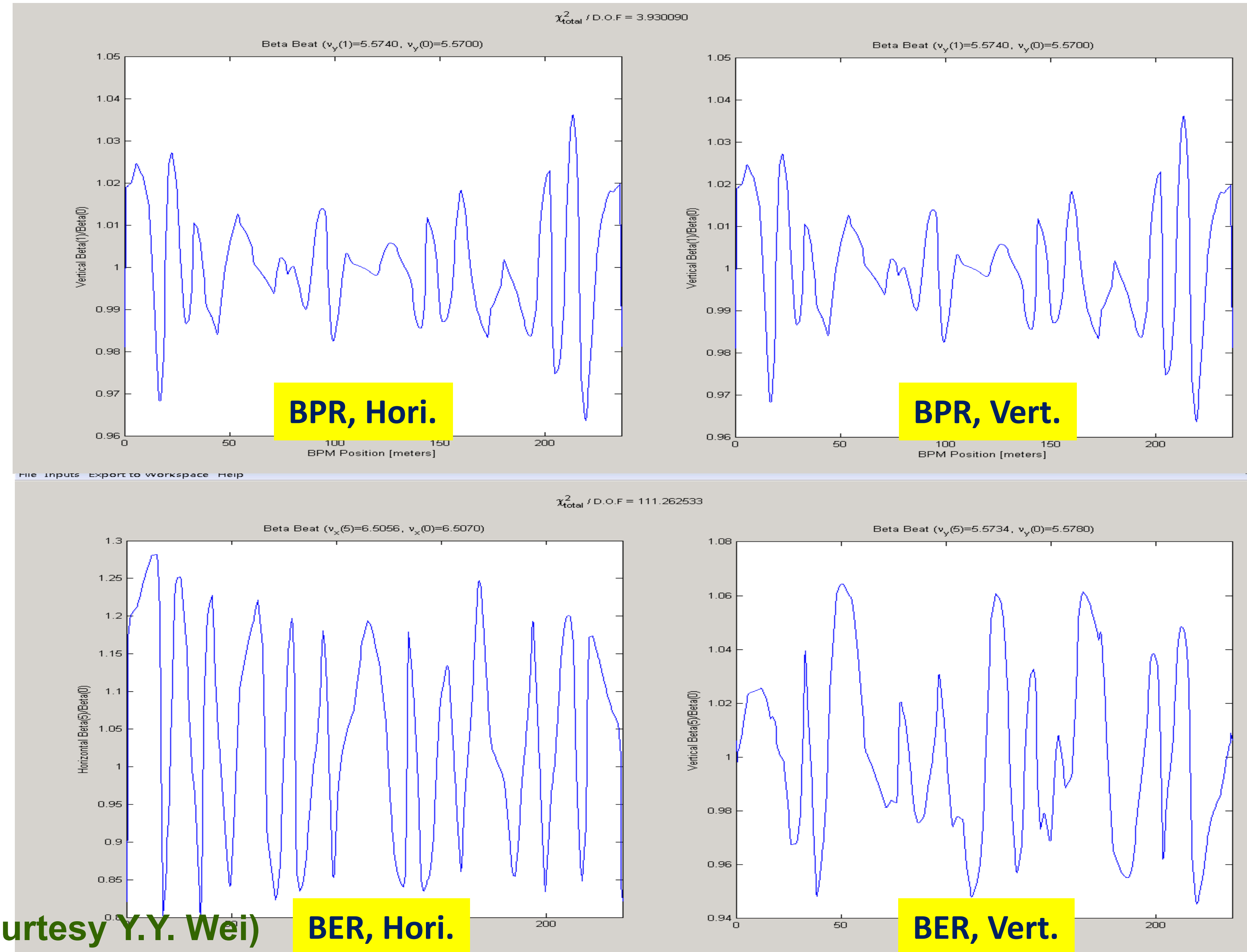
- **With these efforts, and the tool of code LOCO, Twiss functions of storage rings are very close to their setup.**

		BPR		BER	
		Setup	Meas.	Setup	Meas.
Tune	Hori.	6.509	6.510	6.5078	6.507
	Vert.	5.581	5.584	5.59	5.594

β_y @ IP	Theo.	After corrected
BER W/E（cm）	1.5/1.5	1.54/1.51
BPR W/E（cm）	1.5/1.5	1.47/1.43

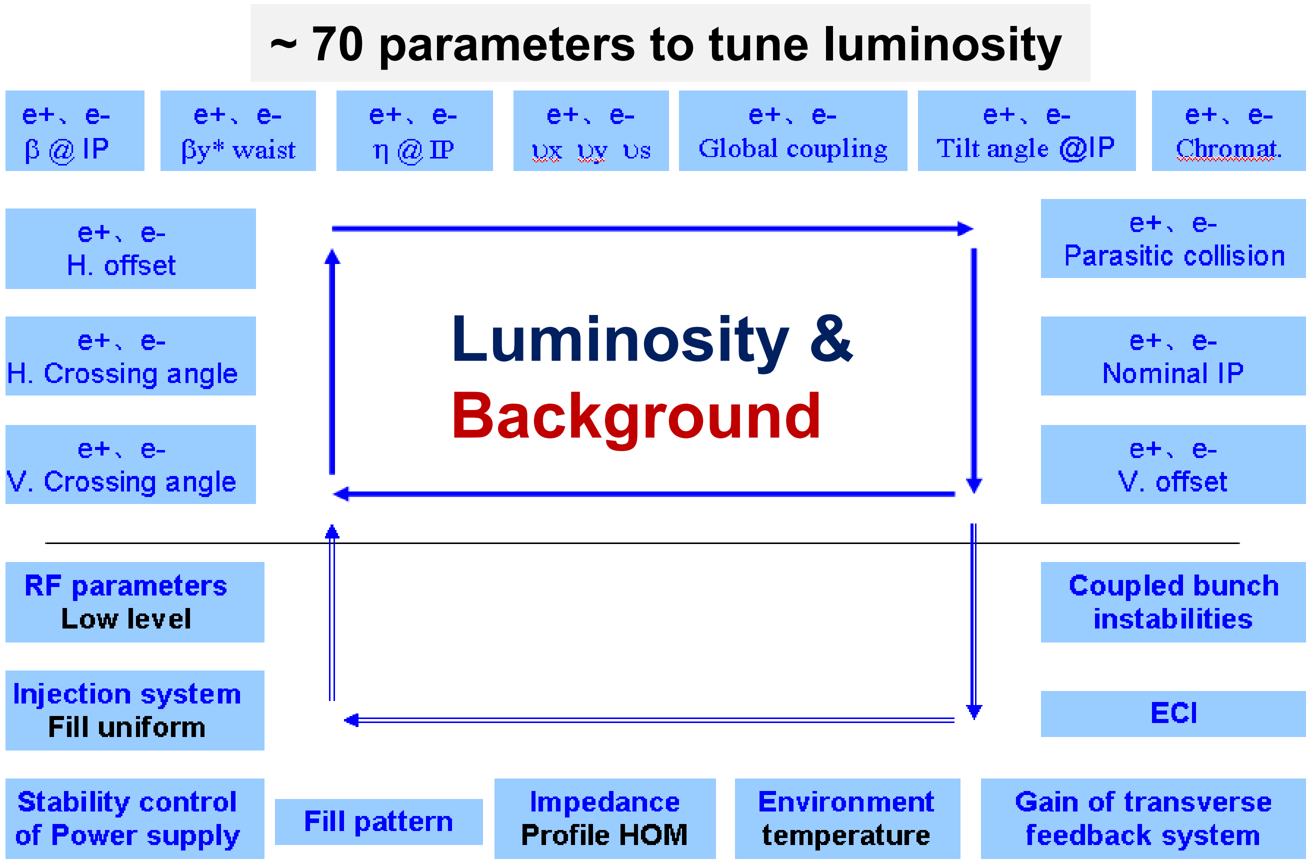


β-beating after optics correction



(Courtesy Y.Y. Wei)

Luminosity commissioning



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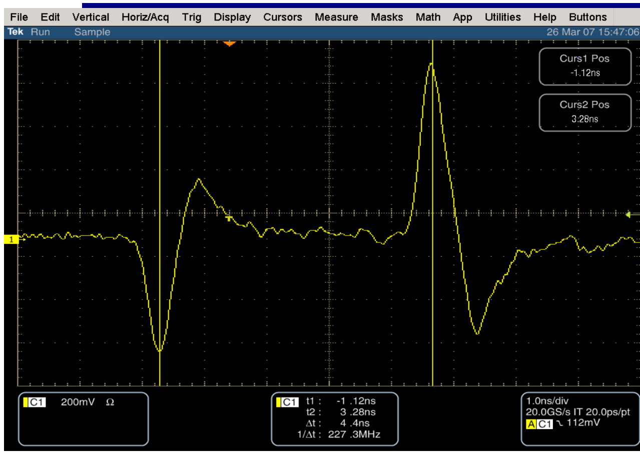
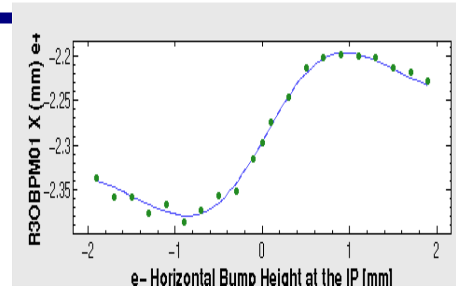
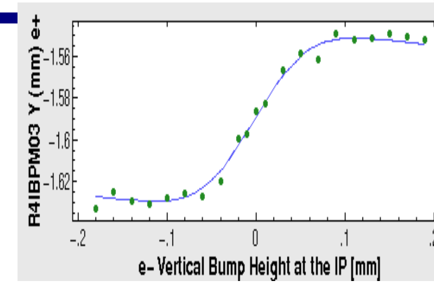
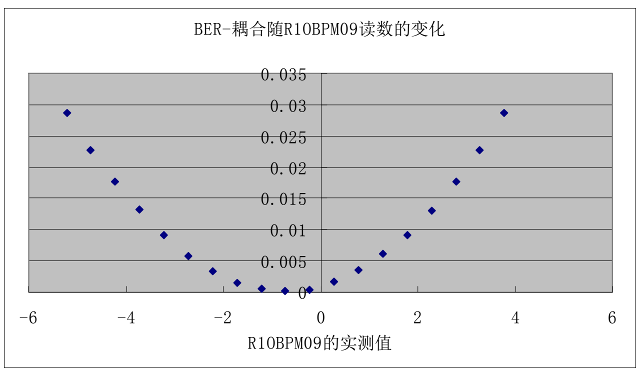
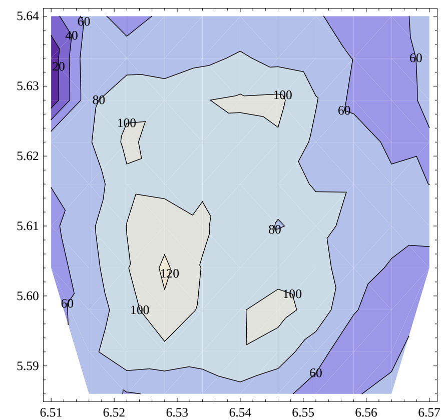
Ways to tune Luminosity

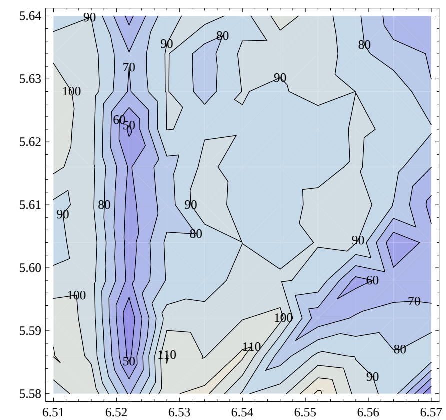


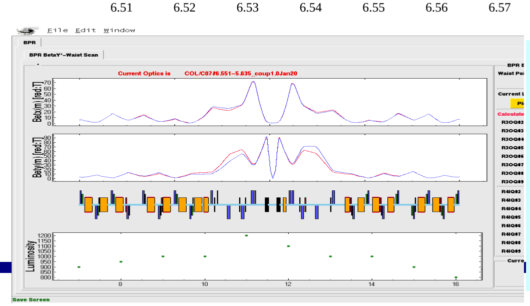


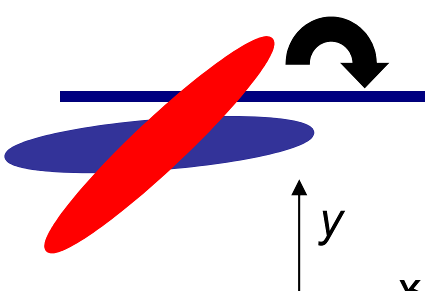












Single bunch collision

↓

Multi-bunch collision

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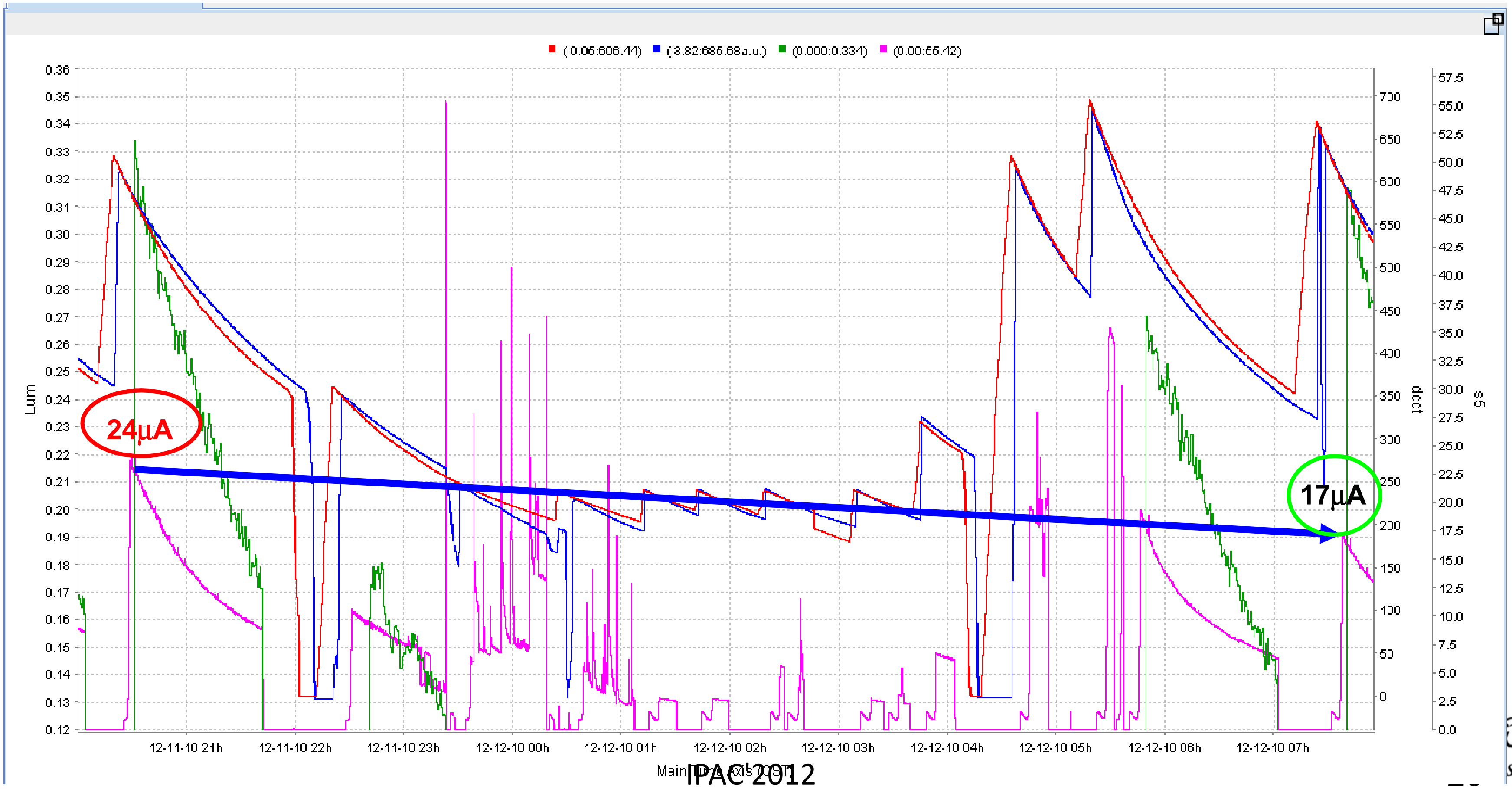
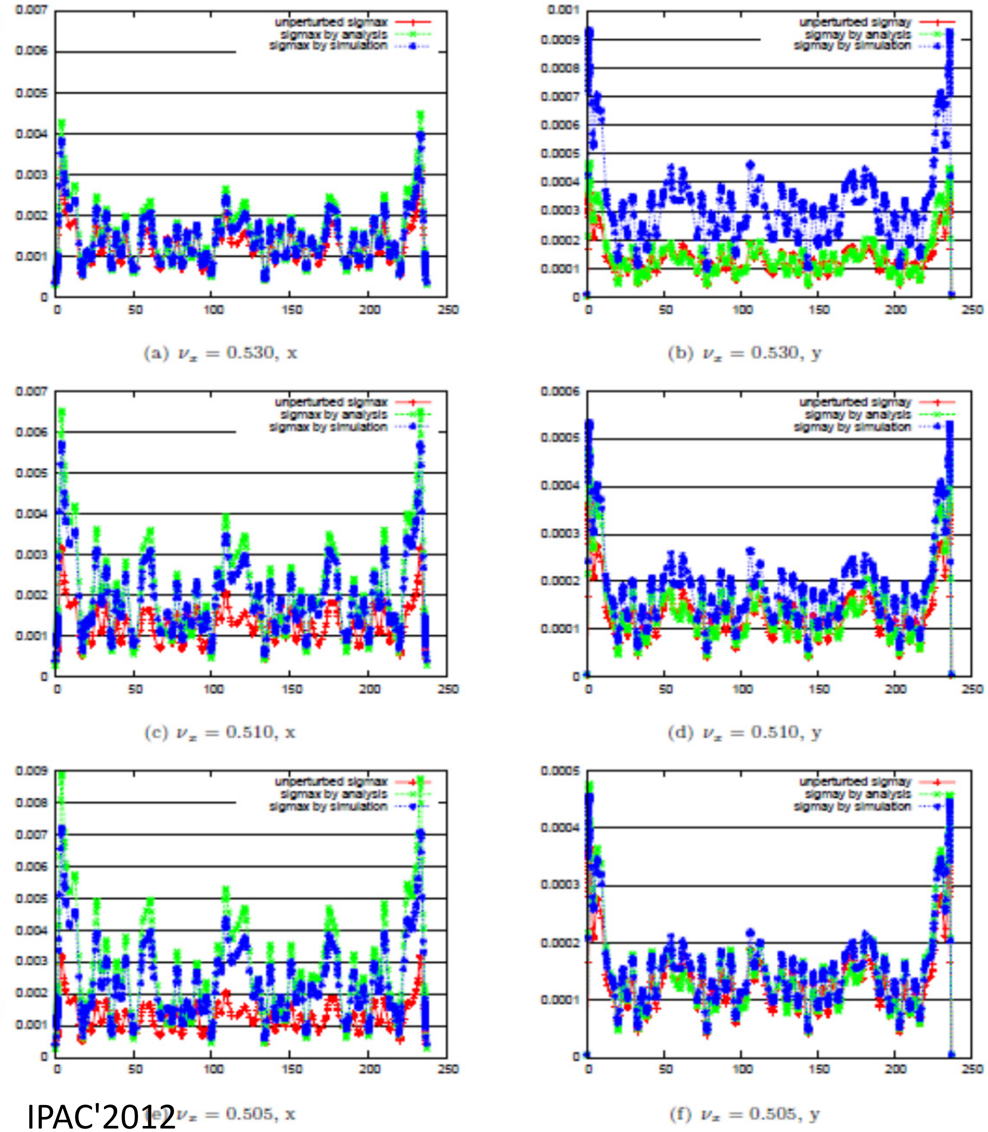
Big background of detector @ ν_x=0.51

Optimize beam orbit, working point, coupling coefficient, collimator position, etc.



Source of the background

- Vacuum
- Touschek effect
- Dynamic effect (beta function, emittance) of beam-beam when $\nu_x \rightarrow 0.5$
- Vertical separation @ NCP
- Others



(Courtesy Y. Zhang)

Luminosity at different tune regions

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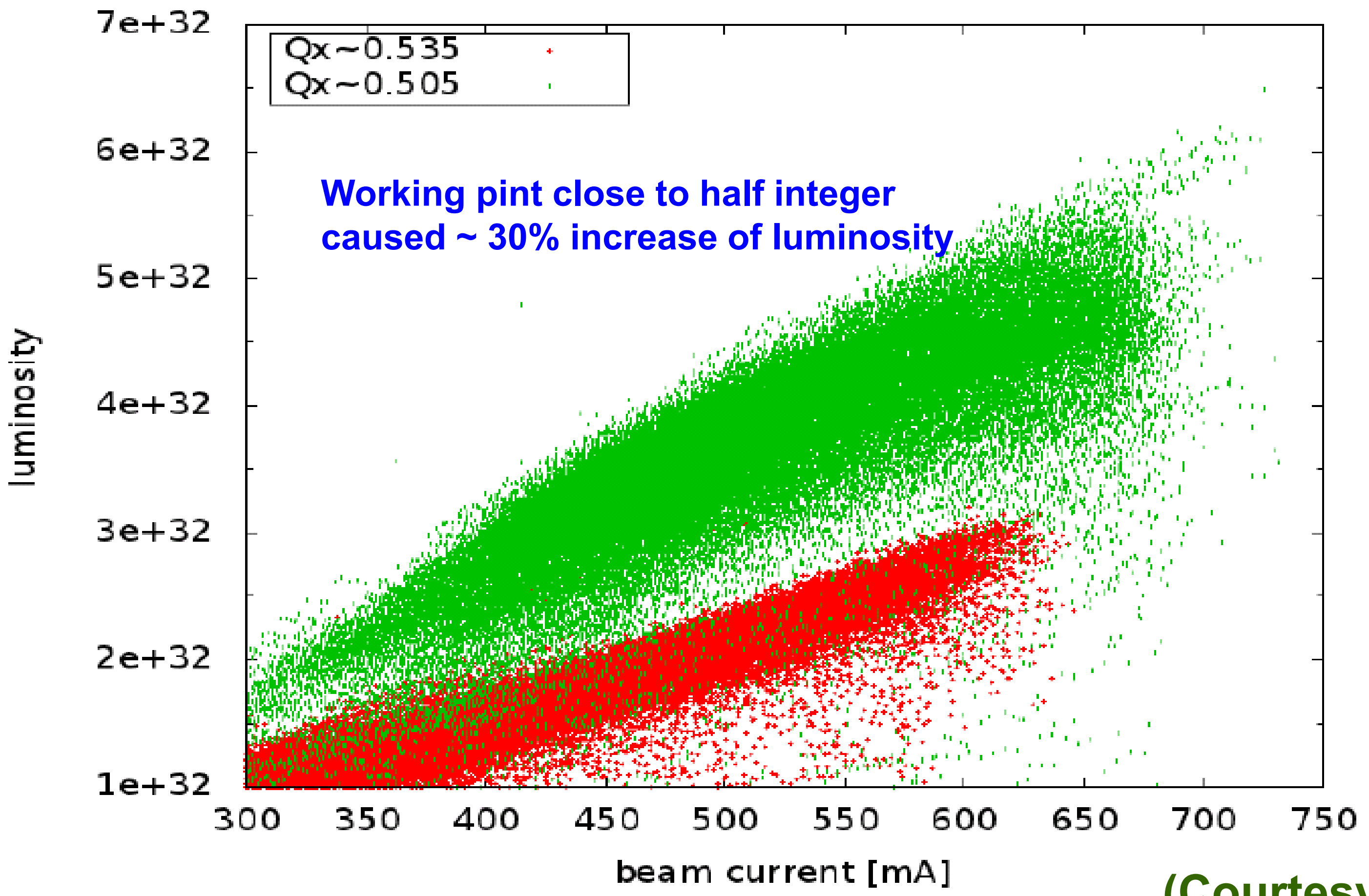

(Courtesy Y. Zhang)

Local coupling correction

- **4×4 One turn map**

$$\mathbf{T} = \begin{pmatrix} \mathbf{M} & \mathbf{m} \\ \mathbf{n} & \mathbf{N} \end{pmatrix} = \mathbf{VUV}^{-1}$$

where,

$$\mathbf{U} = \begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix}; \mathbf{V} = \begin{pmatrix} \gamma\mathbf{I} & \mathbf{C} \\ -\mathbf{C}^{+} & \gamma\mathbf{I} \end{pmatrix}; \gamma^2 + |\mathbf{C}| = 1$$

$$\mathbf{A} = \begin{pmatrix} \cos 2\pi\nu_A + \alpha_A \sin 2\pi\nu_A & \beta_A \sin 2\pi\nu_A \\ -\gamma_A \sin 2\pi\nu_A & \cos 2\pi\nu_a - \alpha_A \sin 2\pi\nu_A \end{pmatrix}$$

$$\mathbf{C}^{+} = \begin{pmatrix} C_{22} & -C_{12} \\ -C_{21} & C_{11} \end{pmatrix}$$

- **One turn coupled transfer matrix:**

$$\mathrm{T} = \mathrm{G}^{-1}\overline{\mathrm{V}}\,\overline{\mathrm{U}}\,\overline{\mathrm{V}}^{-1}\mathrm{G}$$

$$\mathbf{G} = \begin{pmatrix} \mathbf{G}_A & \mathbf{0} \\ 0 & \mathbf{G}_B \end{pmatrix}; \mathbf{G}_u = \begin{pmatrix} 1/\sqrt{\beta_u} & 0 \\ \alpha_u/\sqrt{\beta_u} & \sqrt{\beta_u} \end{pmatrix}$$

$$\bar{\mathbf{V}} = \mathbf{GVG}^{-1} = \begin{pmatrix} \gamma\mathbf{I} & \mathbf{G_A C G_B}^{-1} \\ -\mathbf{G_B C^{+} G_A}^{-1} & \gamma\mathbf{I} \end{pmatrix} = \begin{pmatrix} \gamma\mathbf{I} & \bar{\mathbf{C}} \\ -\bar{\mathbf{C}}^{+} & \gamma\mathbf{I} \end{pmatrix}$$

$$\bar{\mathbf{U}} = \mathbf{GUG}^{-1} = \begin{pmatrix} \mathbf{R}(2\pi\nu_A) & \mathbf{0} \\ 0 & \mathbf{R}(2\pi\nu_B) \end{pmatrix}$$

Ref: D. Sagan and D. Rubin, PRST-AB, 1999, 2, 074001.

- **For weak coupling, closed orbit response due to corrector kick can be**

$$\Delta x_{cod} = \frac{\theta_x}{2\sin \pi\nu_x}\sqrt{\beta_{b,x}\beta_{c,x}}\cos(\Delta\phi_x - \pi\nu_x)$$

$$\begin{aligned}\Delta y_{cod,1} = &- \frac{\theta_x}{2\sin \pi\nu_x}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{b,22}\cos(\Delta\phi_x - \pi\nu_x)\\ &- \frac{\theta_x}{2\sin \pi\nu_x}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{b,12}\sin(\Delta\phi_x - \pi\nu_x)\end{aligned}$$

$$\begin{aligned}\Delta y_{cod,2} = &+ \frac{\theta_x}{2\sin \pi\nu_y}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{c,11}\cos(\Delta\phi_y - \pi\nu_y)\\ &+ \frac{\theta_x}{2\sin \pi\nu_y}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{c,12}\sin(\Delta\phi_y - \pi\nu_y)\end{aligned}$$

$$\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{C}_{b,22}\mathrm{Cof}_1 + \bar{C}_{b,12}\mathrm{Cof}_2 + \bar{C}_{c,11}\mathrm{Cof}_3 + \bar{C}_{c,12}\mathrm{Cof}_4$$

Choose $\bar{C}_{b,12}$ to do coupling correction

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- **BEPCII case:**
  - **4 skew quads in each ring, not enough to do global correction**
  - **36 sextupoles in each ring, well distributed for coupling correction**
- **Way to realize coupling correction:**

Model ⟶ **simulate the response of $\bar{C}_{b,12}$ due to vertical corrector strength change**

⟶ **get the strength of correctors from measured $\bar{C}_{b,12}$**

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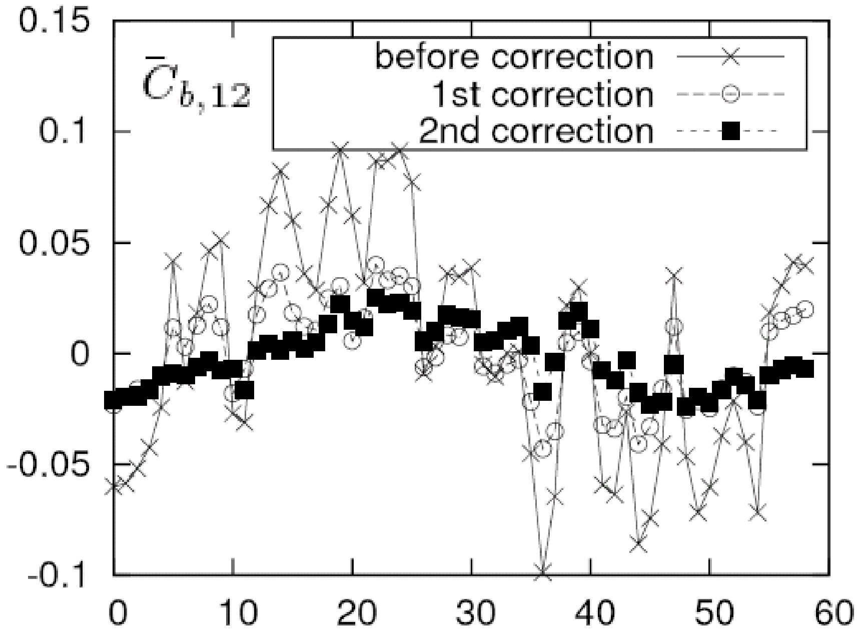
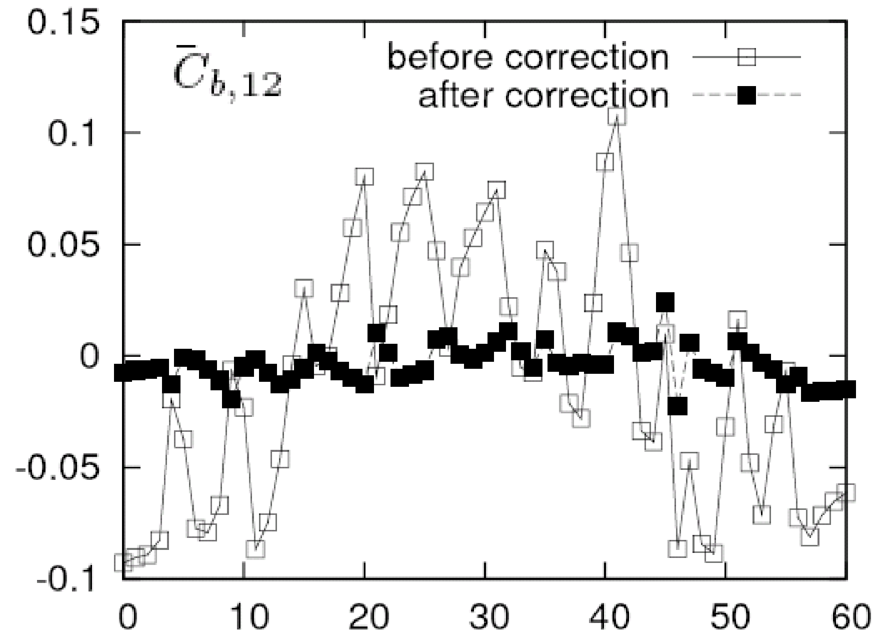
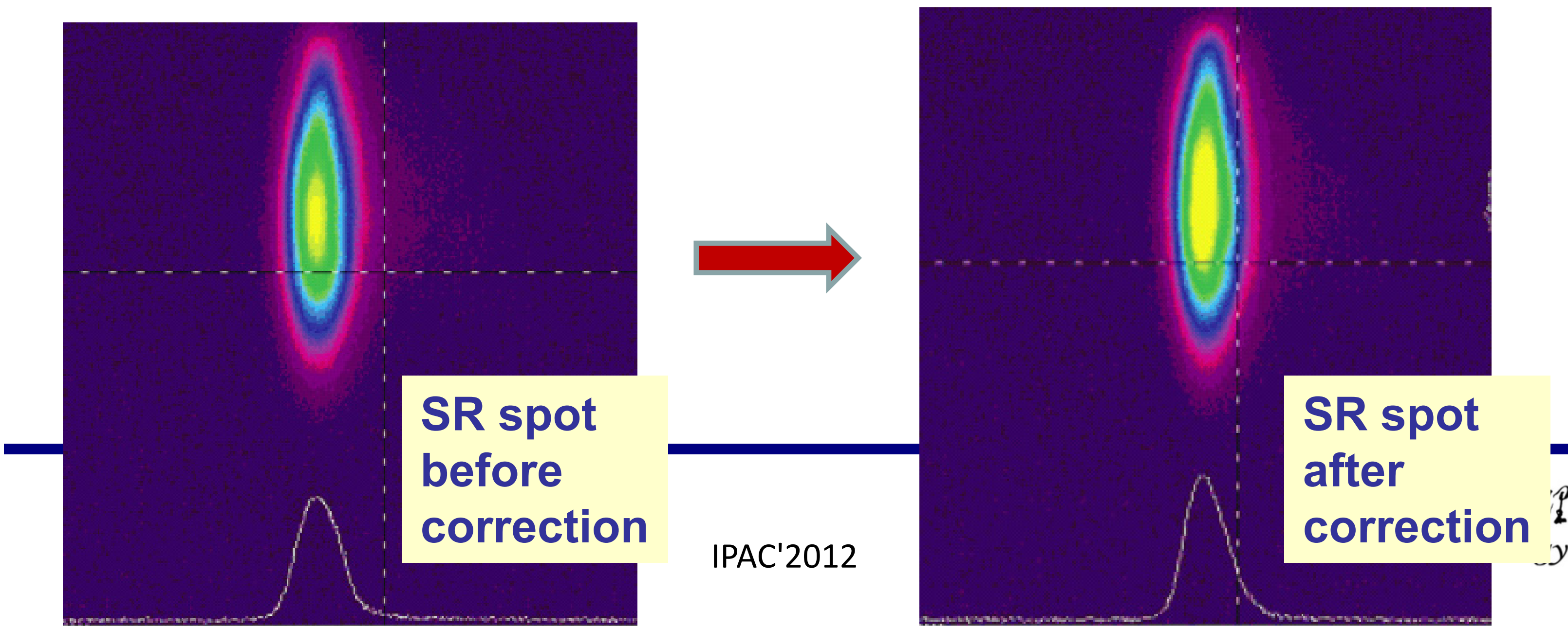




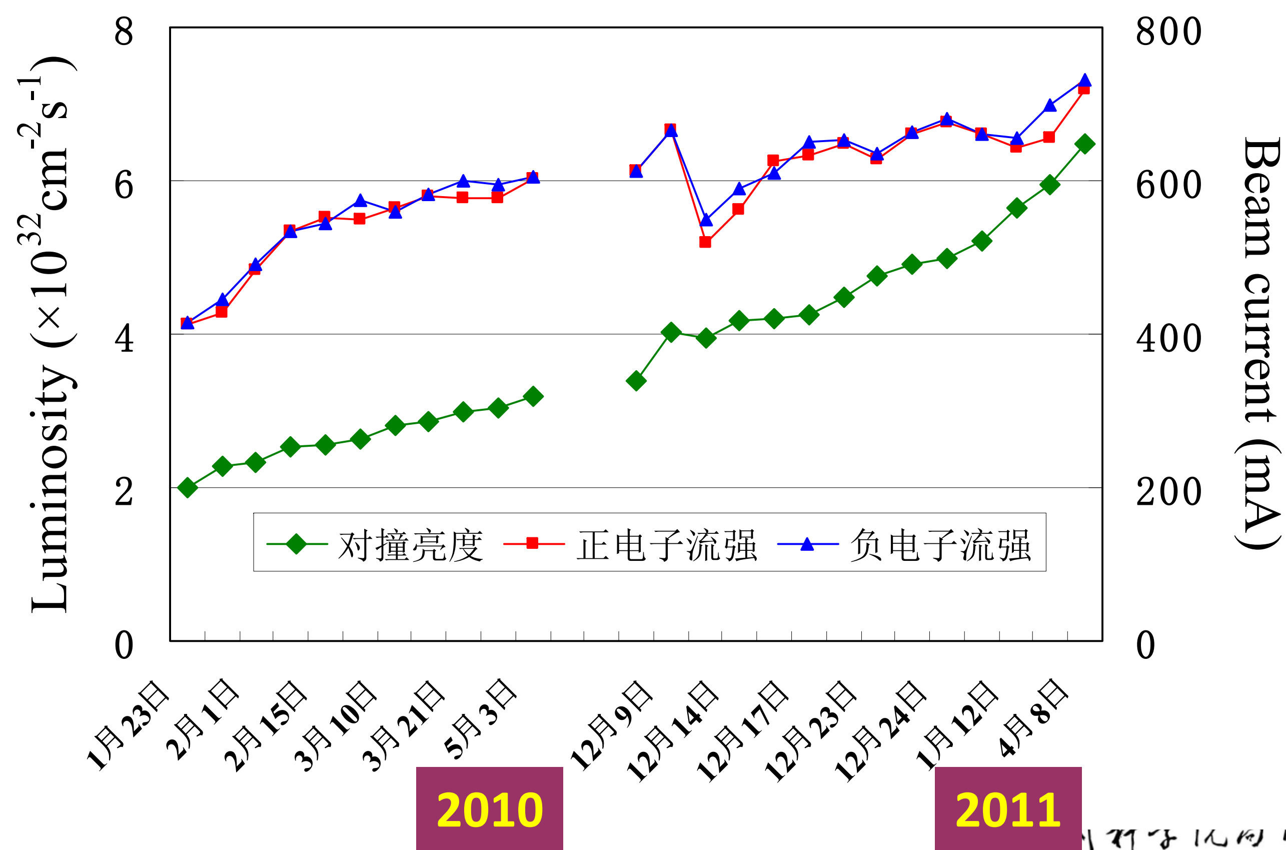
Local coupling measurement and correction in e- ring with solenoid off (left) and on (right)



- Two knobs of coupling correction were done for luminosity optimization
  --- vertical local bump in sextupoles
  --- global vertical orbit tuning to minimize vertical emittance by reducing $\overline{C}_{12}$ at BPMs
- Measurement of coupling was done by turn-by-turn BPM data

Ref: Y. Zhang, et al, Measurement and correction of coupling in BEPCII, Chinese Physics C, Vol. 35 (12), 2011.

- **Luminosity enhanced: ν_x --> 0.5 (0.506), reducing emittance coupling, and increasing beam current**

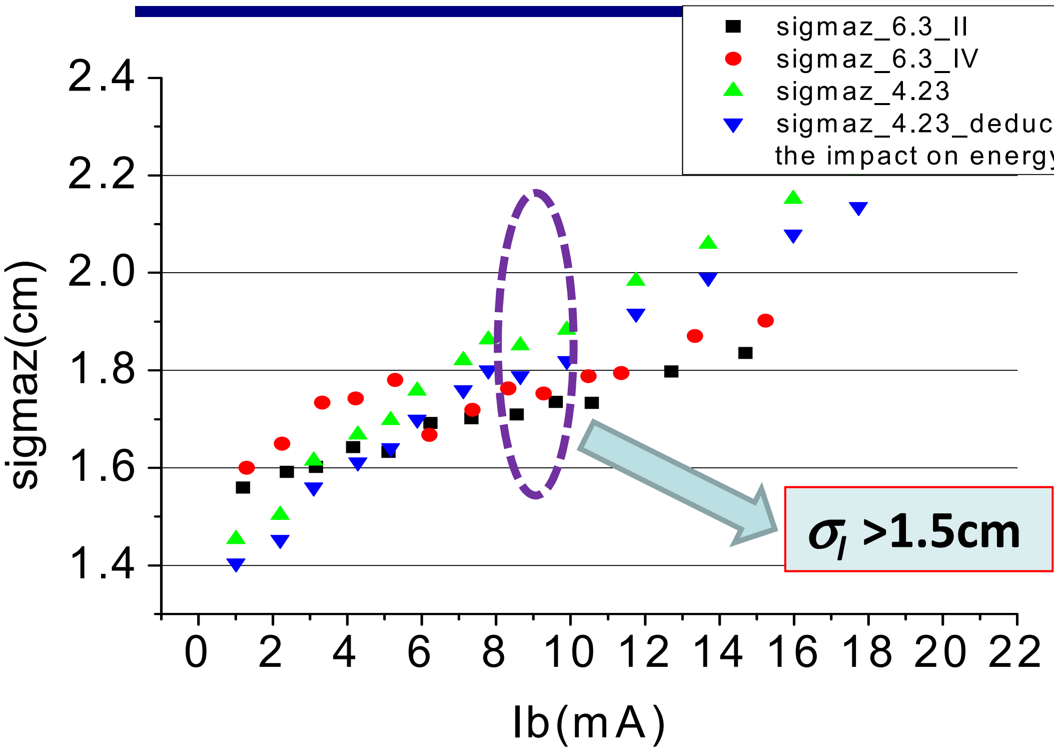


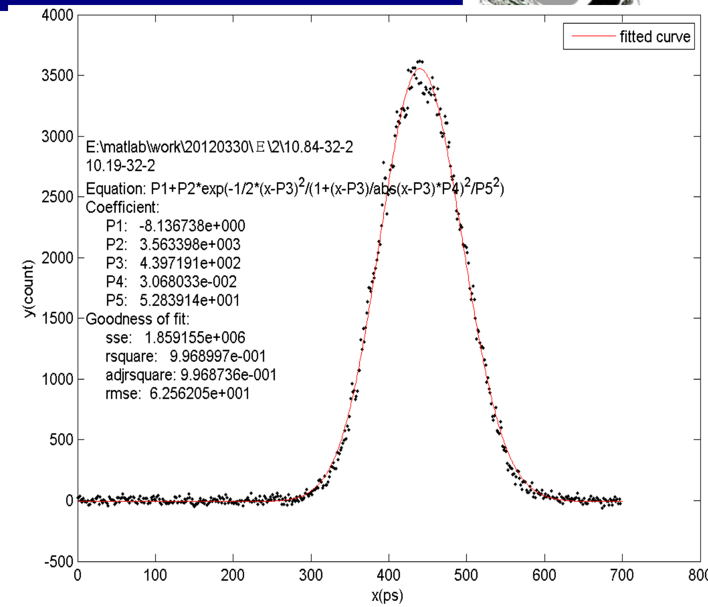
Beam instability issues

- Very important issue at the stage of design
- An impedance “police” was assigned during the construction
- Didn’t appear in the first phase of commissioning
- Show it’s power when beam current increased

Component	Number of items	Inductance L (nH)	Loss factor k_l(V/pC)	HOM power (kW) (9.8mA, 93)
SRF	1		~0.69	4.74
Resist. wall			0.11	0.78
BPM	68	3.3	0.08	0.57
Bellows	67	0.48	0.02	0.14
RF seals	200	3.0	0.003	0.02
Mask	40	2.8	0.06	0.42
Pumping ports		0.5		
Taper	8	4.4	0.05	0.35
Injection kicker	2	0.8	0.04	0.28
Y-shape	2	2.2	0.19	1.34
X-cross	1	0.8	0.03	0.21
IR	1	0.8	0.01	0.07
Collimator	3	3.81	0.06	0.42
Feedback kicker	2	6.0	0.44	2.82
Total		28.9	1.76	12.5

Single bunch instability – Bunch lengthening





(Courtesy Y. Li)

- **Bunch lengthening is more than 10% @ I_b =9.8mA.**
- **Longitudinal low frequency impedance is ~3 times higher than design value.**
- **The way of reducing β_y^* doesn't look effective as it was expected.**

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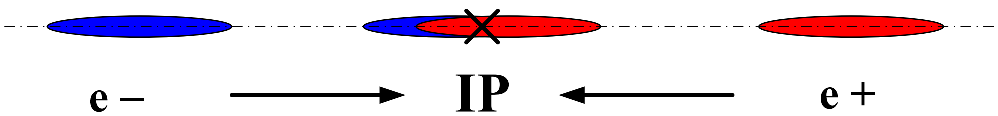
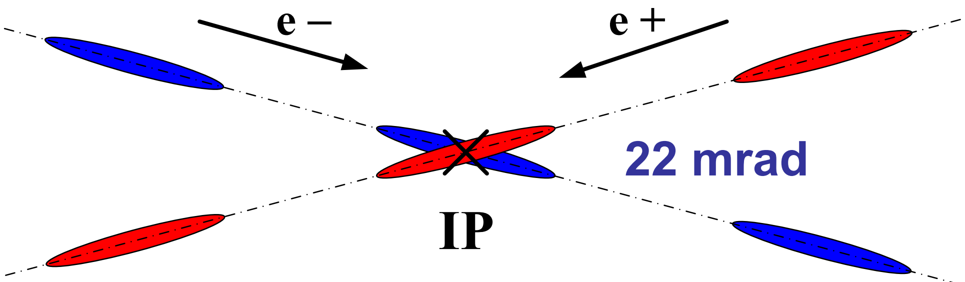
Beam-beam interaction

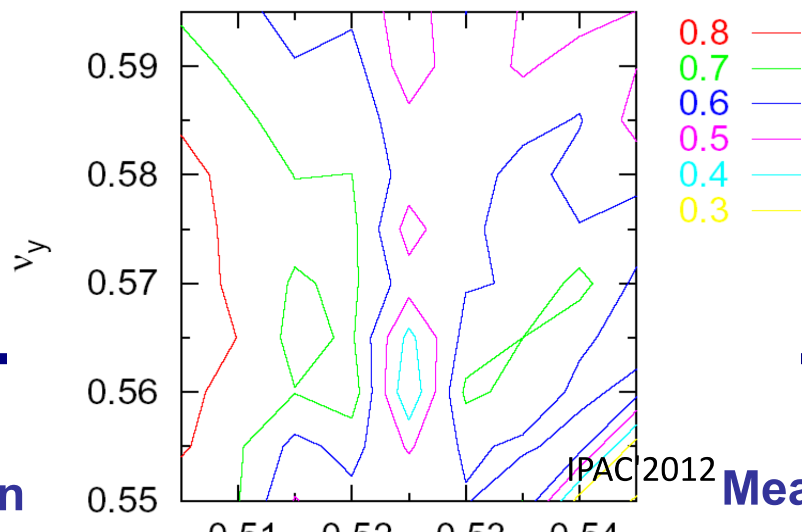


BEPC

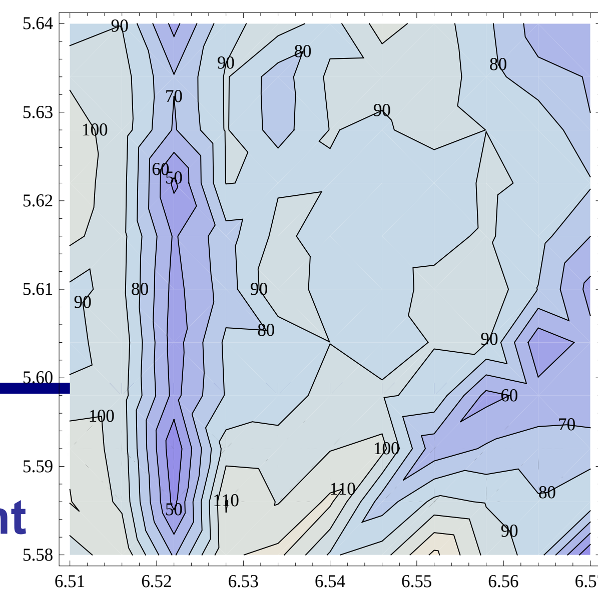


BEPCII

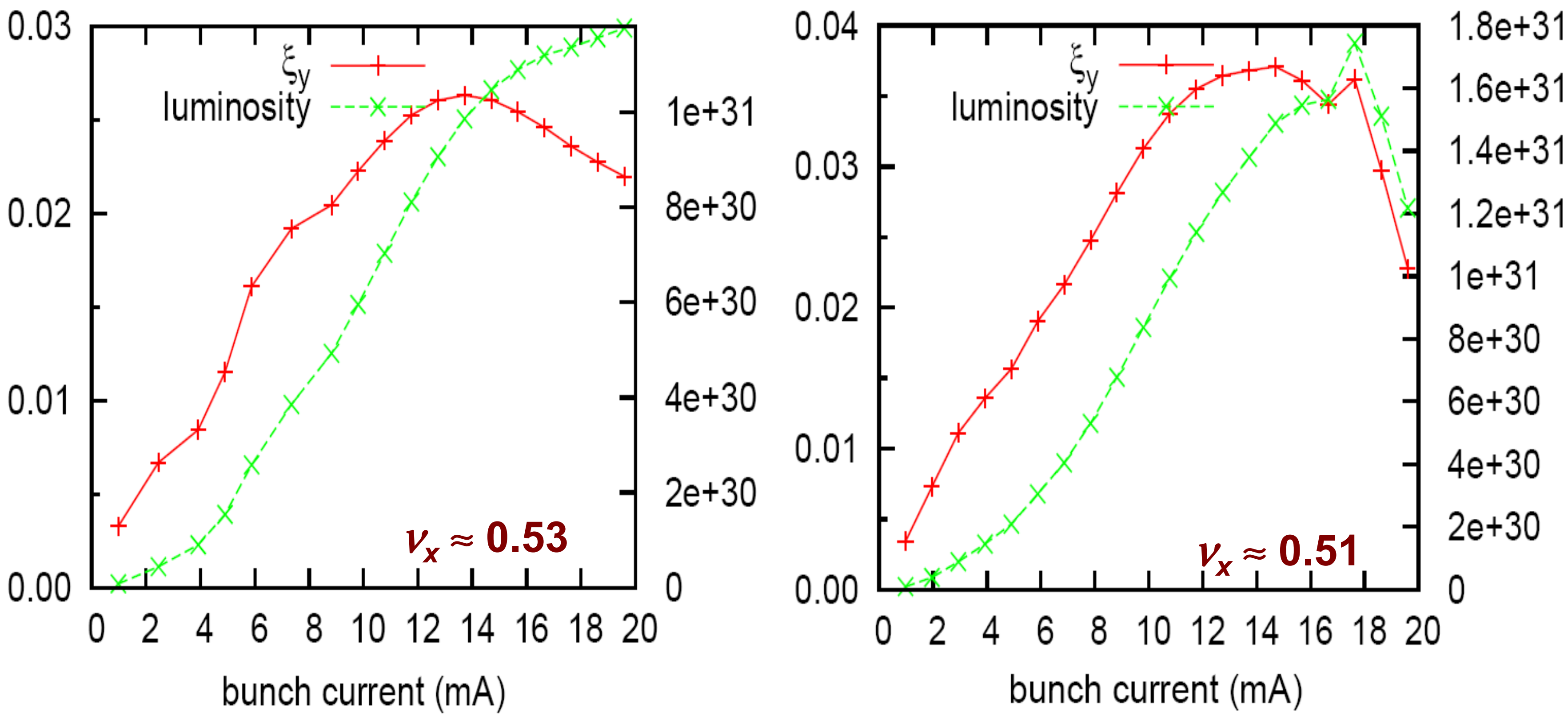
Simulation



Measurement



Strong-strong simulation results in different tune region



(Courtesy Y. Zhang)

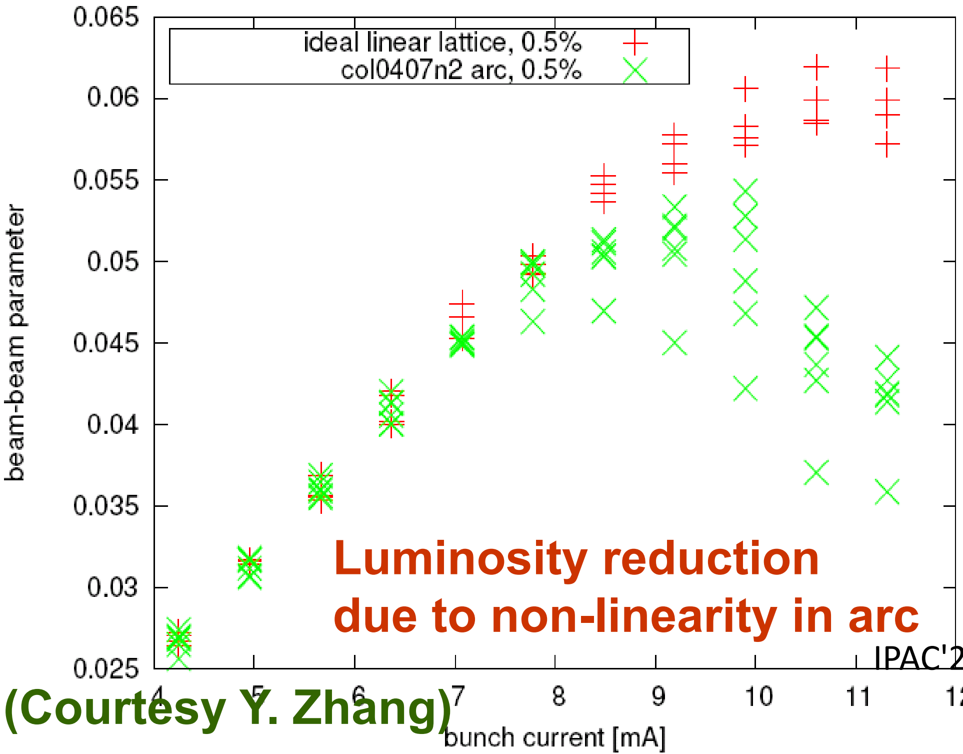
• Weak-strong model simulation study:

--- Hirata's BBC as a pass mathod in AT

--- Element-by-element tracking in arc

--- Synchrotron oscillation (RF on)

--- Radiation damping and quantum excitation included



Luminosity reduction
due to non-linearity in arc

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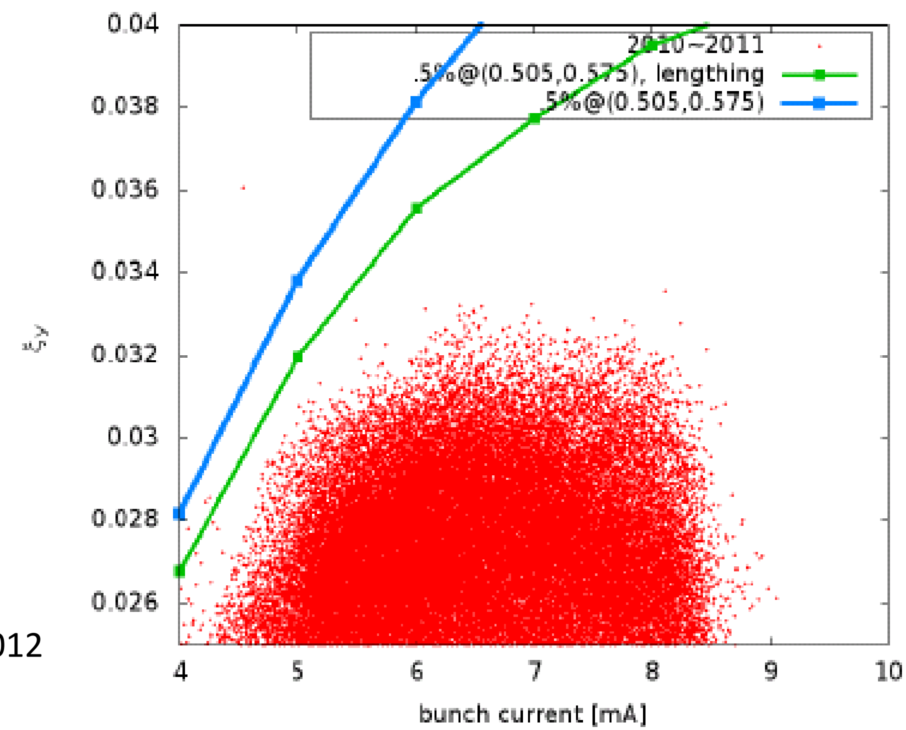
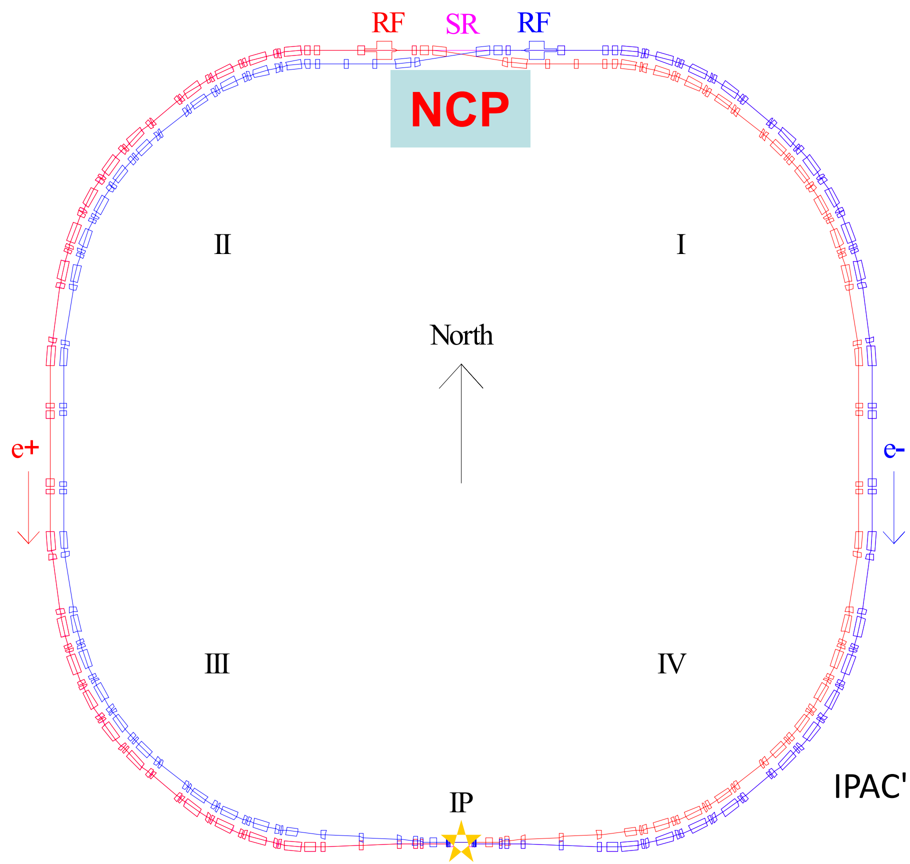
(Courtesy Y. Zhang)



Parasitic beam-beam interaction @ NCP

- At the north crossing point (NCP), two beams are separated vertically by ~5mm, with a full horizontal angle of 2×155 mrad

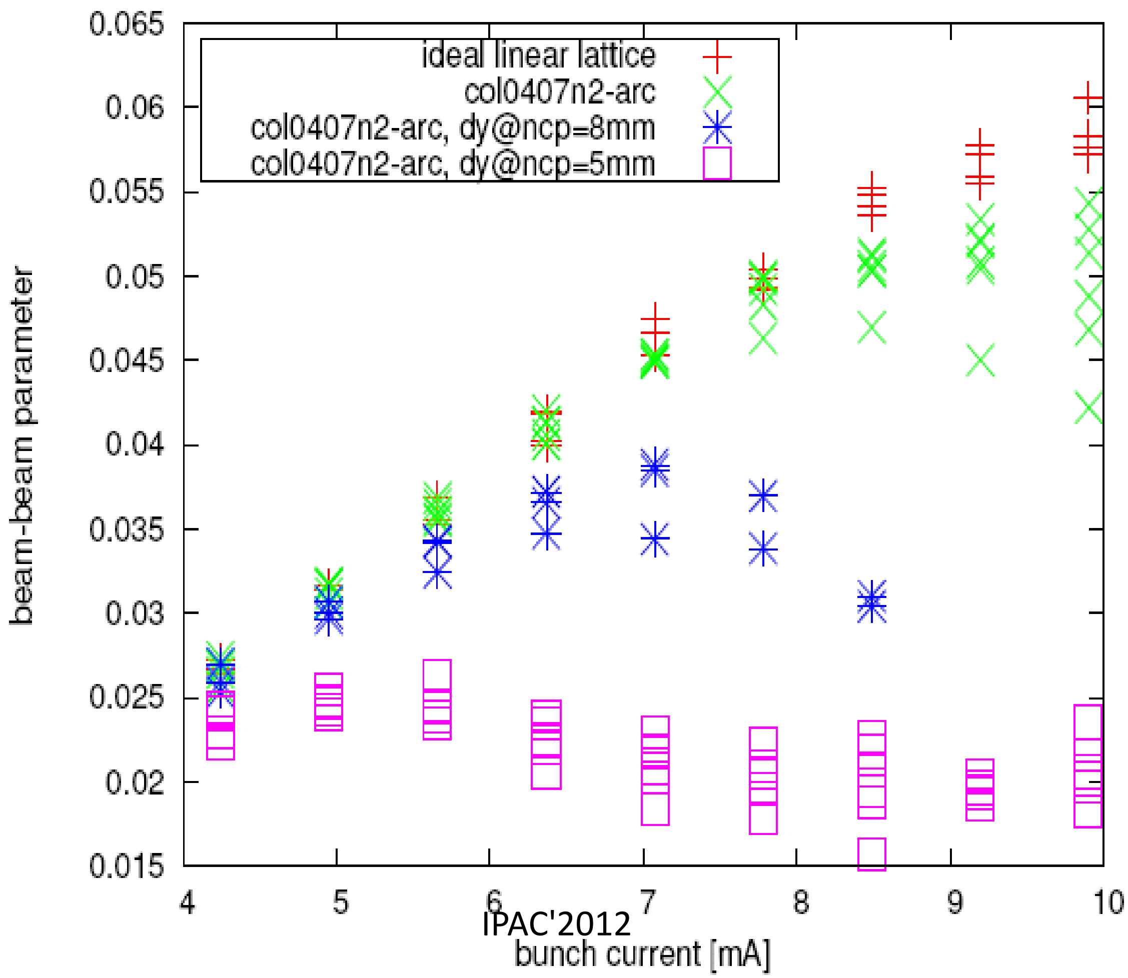


At NCP, Δy = 5mm (~$4\sigma_x$ and $50\sigma_y$)

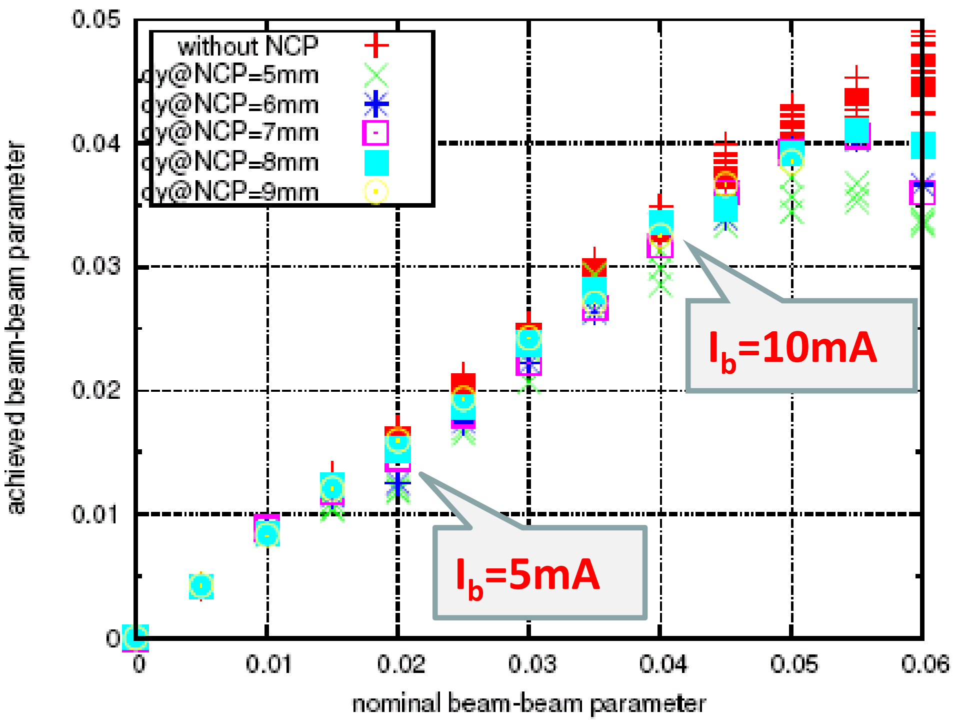
β_x / β_y = 12m / 8.5m

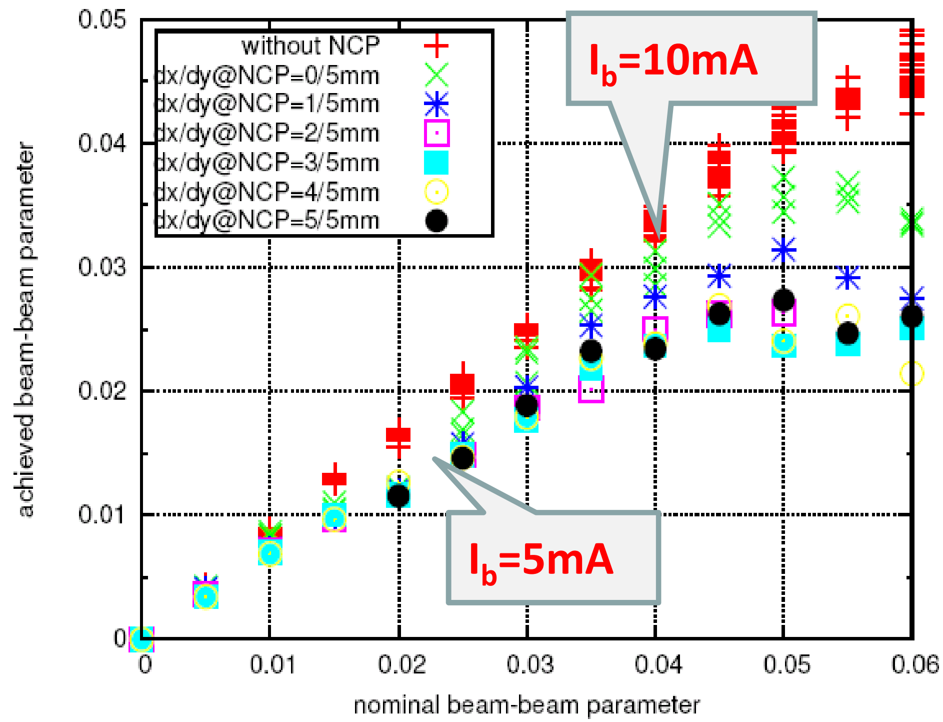
$(\tan\theta\ \sigma_z)/\sigma_x = 1.8$

- **Effect of non-linear arc + NCP separation**



- **Furthermore, horizontal separation @ NCP also affect the beam-beam interaction**

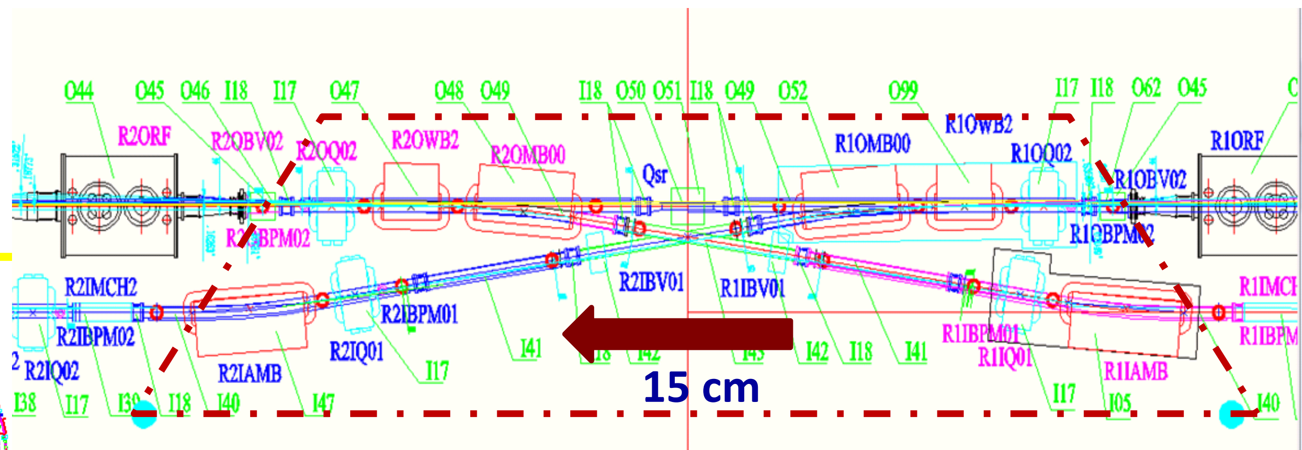


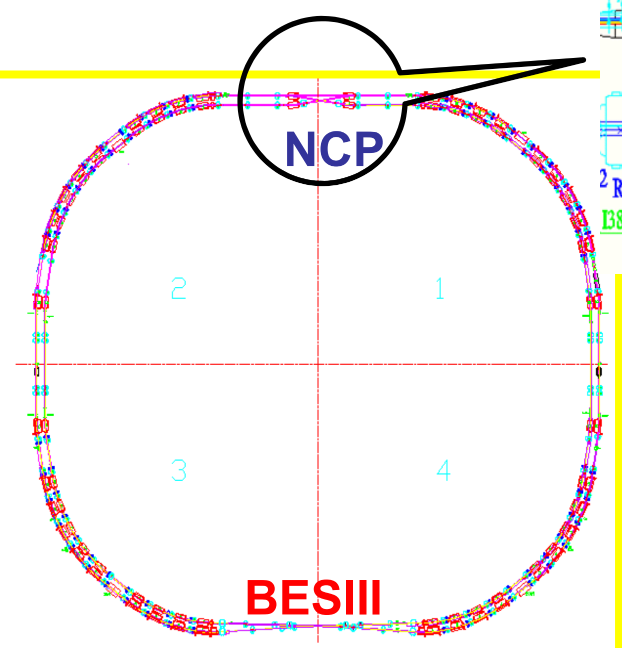


(Courtesy Y. Zhang)

What we did in last summer shutdown

- At the NCP region, the chambers of two rings were shifted by 15 cm, ¼ of the space of two successive rf buckets, towards west of the NCP.
- New results of luminosity will be shown in the run 2011–12.





The BEMS @ NCP region was moved by 15 cm too

3. Hardware Improvements

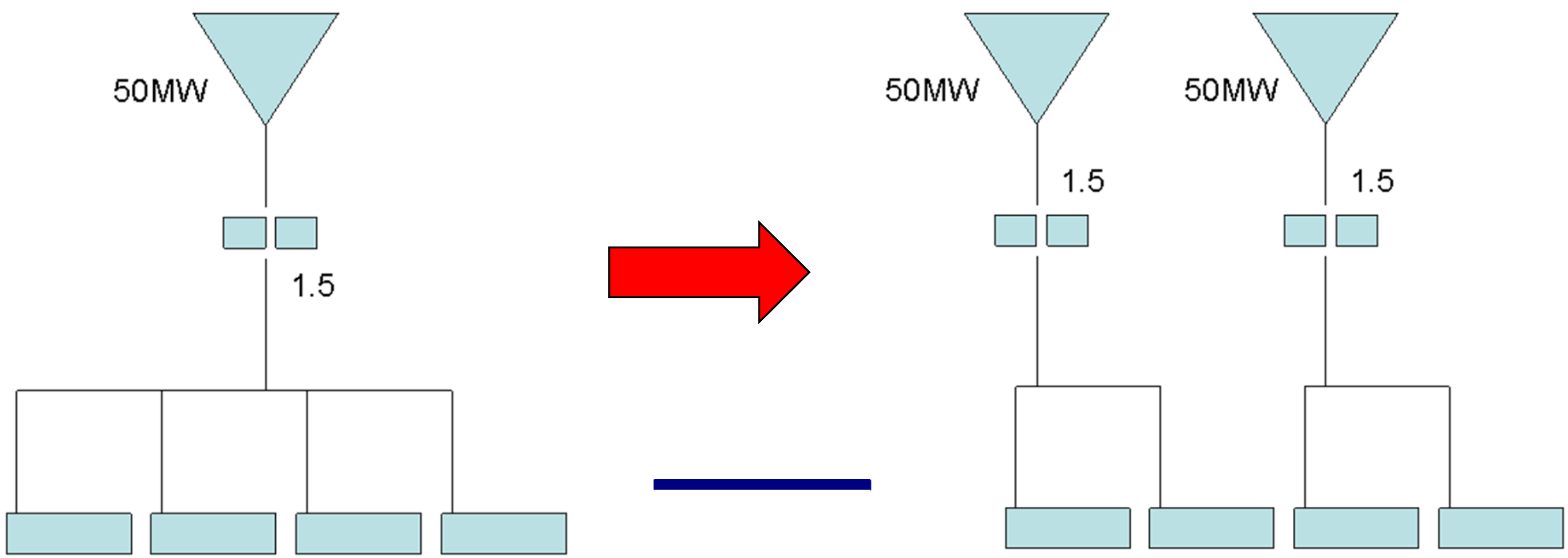
- **Linac energy promotion**

  Max. e^- beam energy = 2.5 GeV

  Max. e^+ beam energy = 2.1 GeV

HEP experiment requies: 2.3 GeV * 2.3 GeV

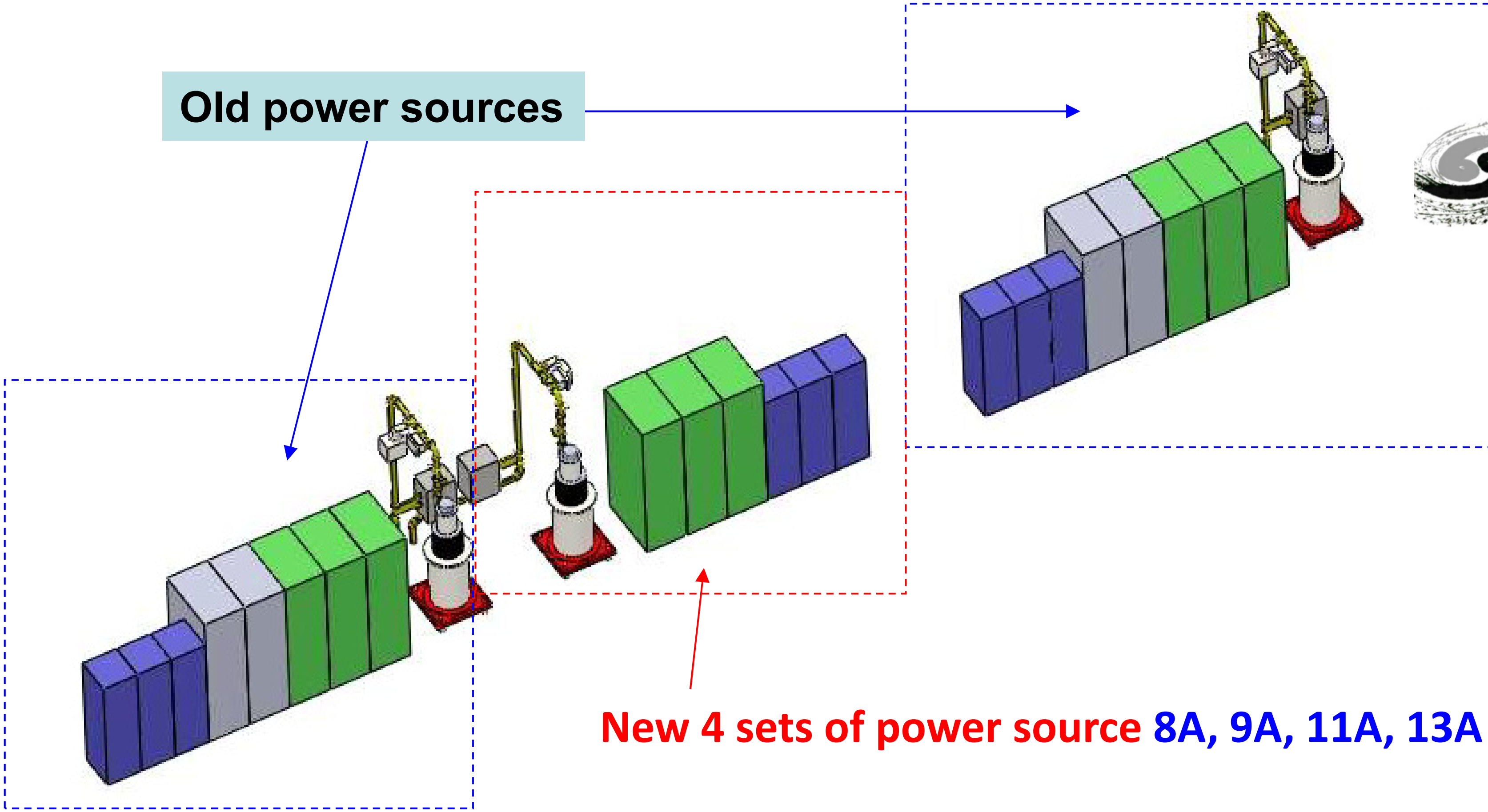
4 sets of power source are added (klys., mod., SLED, load, etc)



ΔE = 20 x 1.5 x (40)1/2 = 190MeV
190MeV / 12m = 16 MV/m

ΔE = 14 x 1.5 x (40)1/2 x2 = 266 MeV
266MeV / 12m = 22 MV/m

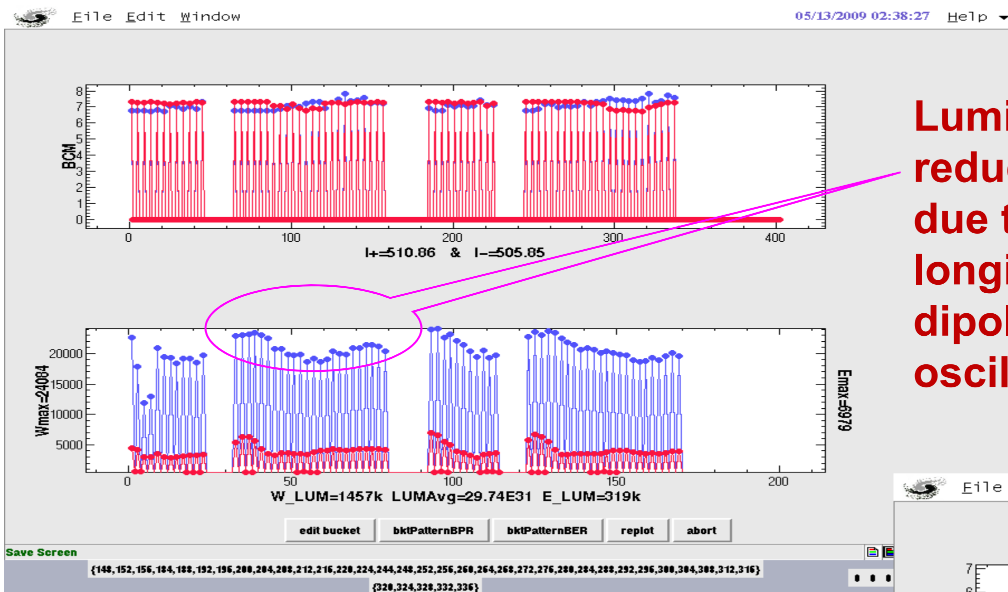
(Courtesy Y.L. Chi)



- **e+ energy：** 190MeV×8+70MeV+133MeV×2×3 =2.38 GeV
- **e- energy：** 190MeV×8+70MeV+133MeV×2×3+250MeV =2.63 GeV

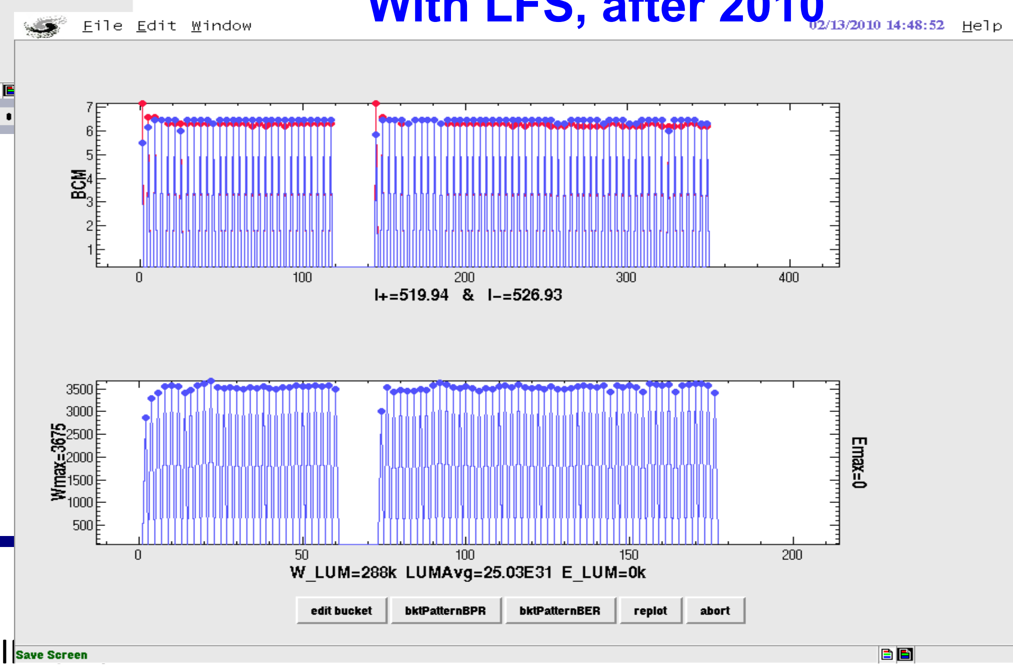
Will be finished at the end of 2012

• Longitudinal feedback system



Luminosity reduction due to longitudinal dipole oscillation

With LFS, after 2010



Luminosity increased ~20%

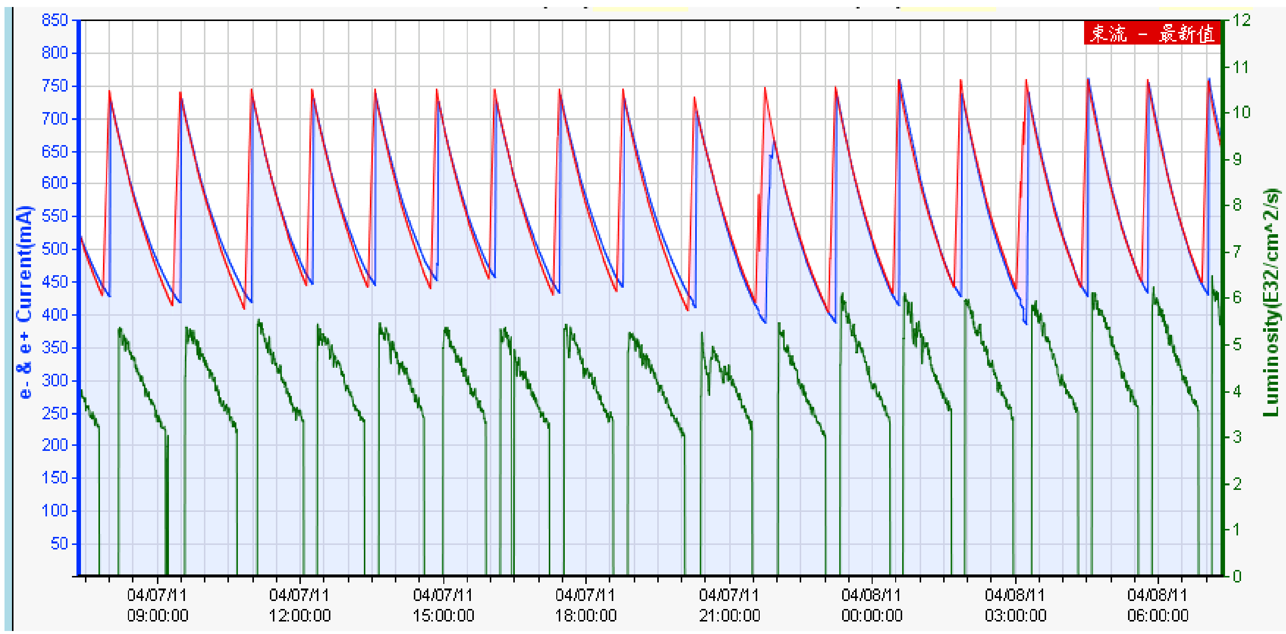
Energy spread decreased

Cross section @J/ψ increased 2000nb of BEPC, 1999, to 2860nb of BEPCII, 2009, and 3100nb of BEPCII, 2012

4. Operation of BEPCII

- **5 – 6 months operation for HEP experiments @ different beam energy: ψ(3770), D_s, ψ′, τ, J/ψ, etc.**
- **3 months for SR users, dedicated SR mode @ 2.5GeV**

Data taking @ ψ(3770)



Peak luminosity: $6.5\times10^{32}cm^{-2}s^{-1}$ @ 719 × 732mA ($e^+ \times e^-$)

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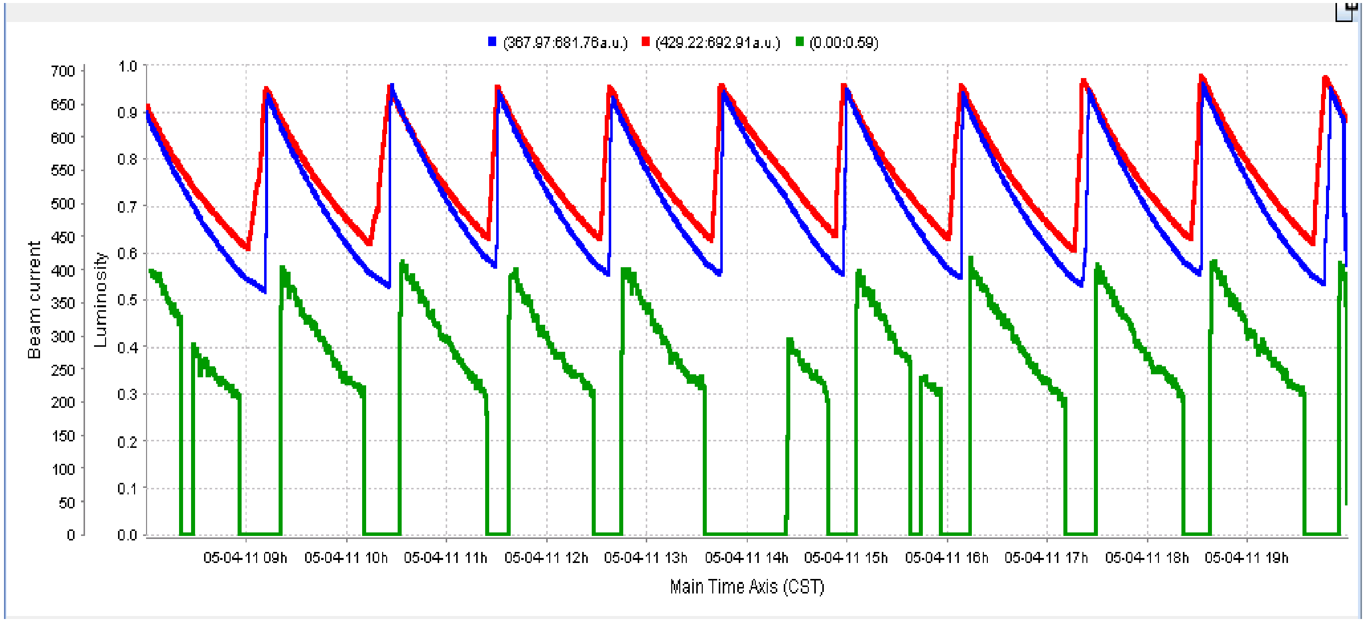
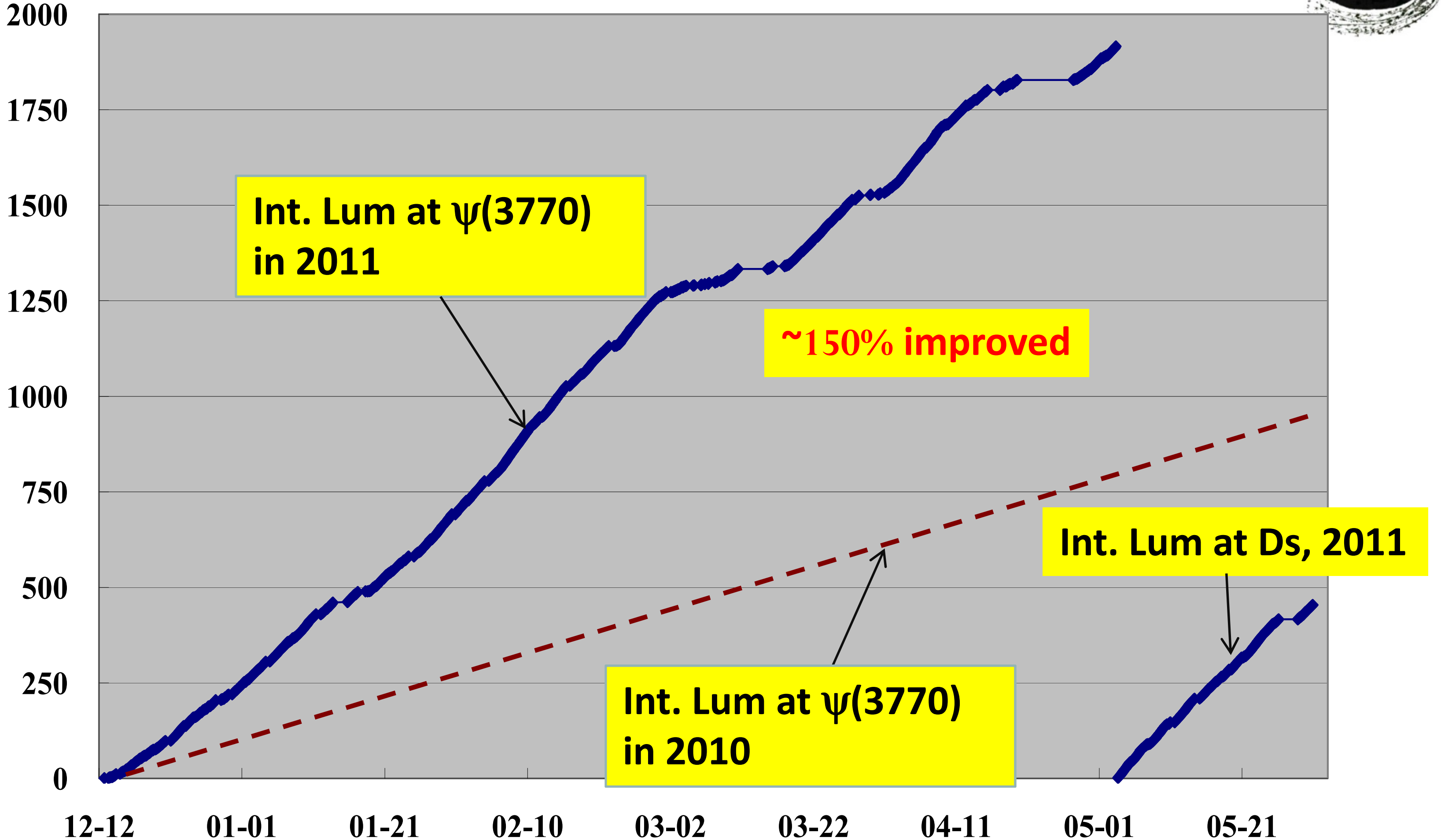
- **Data taking @ Ds, June 2011**



Peak luminosity reached $6.5\times10^{32}cm^{-2}s^{-1}$@$711\times711$mA

- Integrated luminosity in the run of 2010 – 2011



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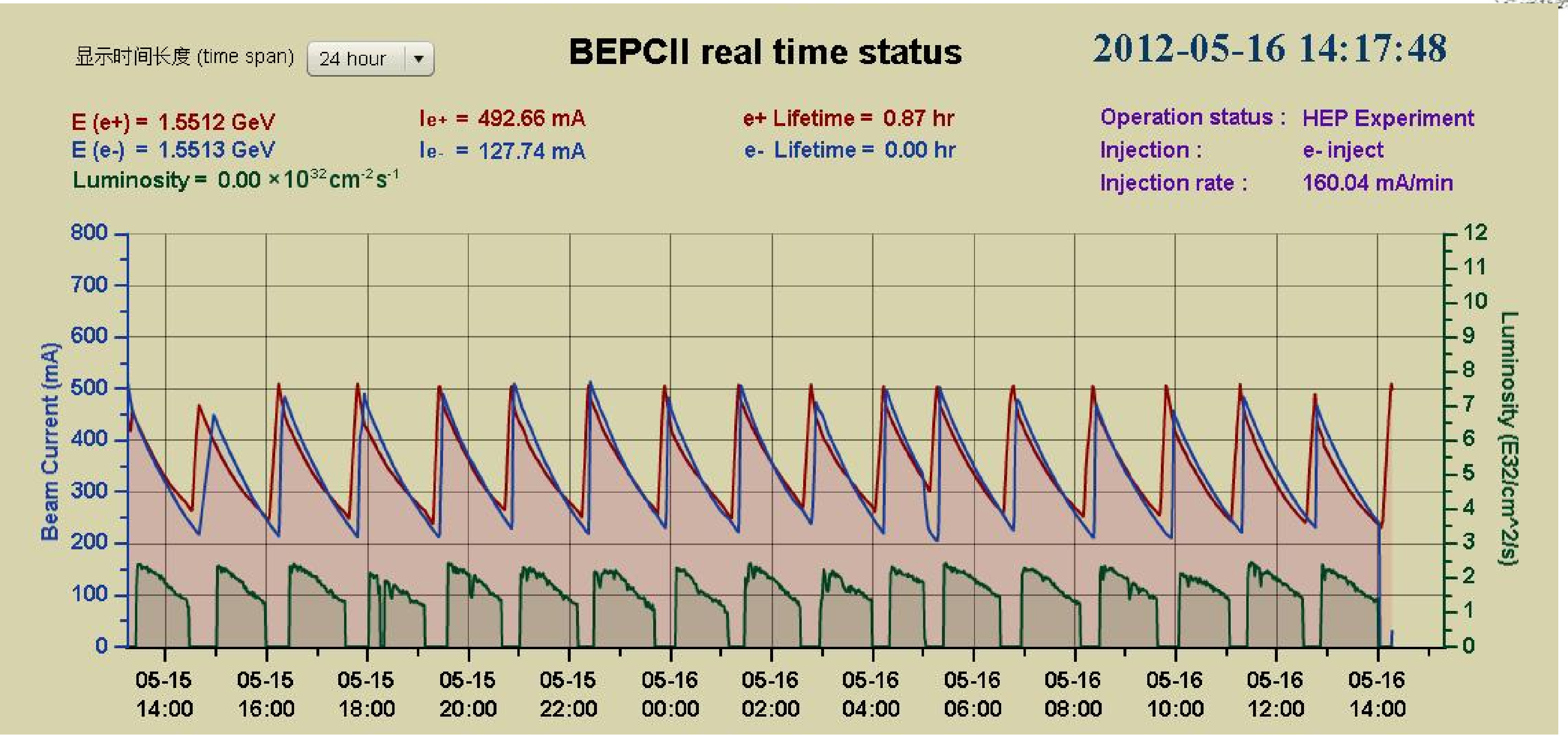
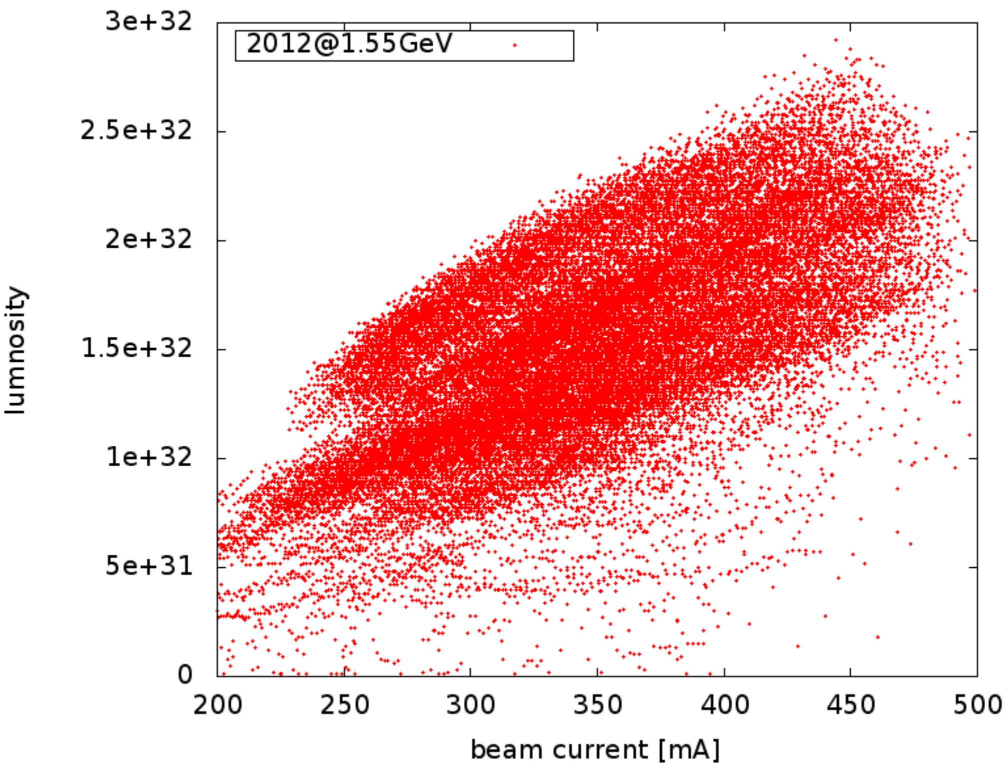
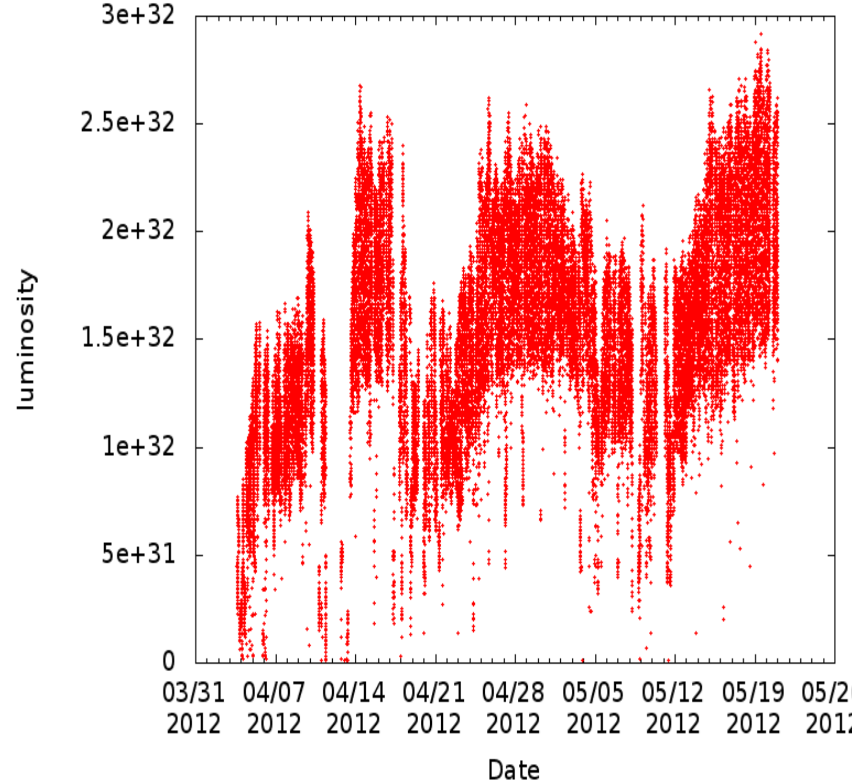
J/ψ operation in April – May, 2012



Peak luminosity: $2.923\times10^{32}cm^{-2}s^{-1}$@ 448×451mA, $\xi_y = 0.028$


2012@1.55GeV
lumnosity
beam current [mA]
3e+32
2.5e+32
2e+32
1.5e+32
1e+32
5e+31
0
200
250
300
350
400
450
500


luminosity
Date
3e+32
2.5e+32
2e+32
1.5e+32
1e+32
5e+31
0
03/31 2012
04/07 2012
04/14 2012
04/21 2012
04/28 2012
05/05 2012
05/12 2012
05/19 2012
05/26 2012

Data accumulation for physics

- July 19, 2008: first e^+e^- collision event in BESIII
- Nov. 2008: ~ 14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$ 4*CLEOc
  225M J/ψ 4*BESII
- 2010: 900 pb^{-1} $\psi(3770)$
- 2011: 1800 pb^{-1} $\psi(3770)$
  470 pb^{-1} @ 4.01 GeV

  } 3.5*CLEOc
- 2012: ~0.4 billion $\psi(2S)$
- 04/05 to 05/22, 2012: 1 billion J/ψ

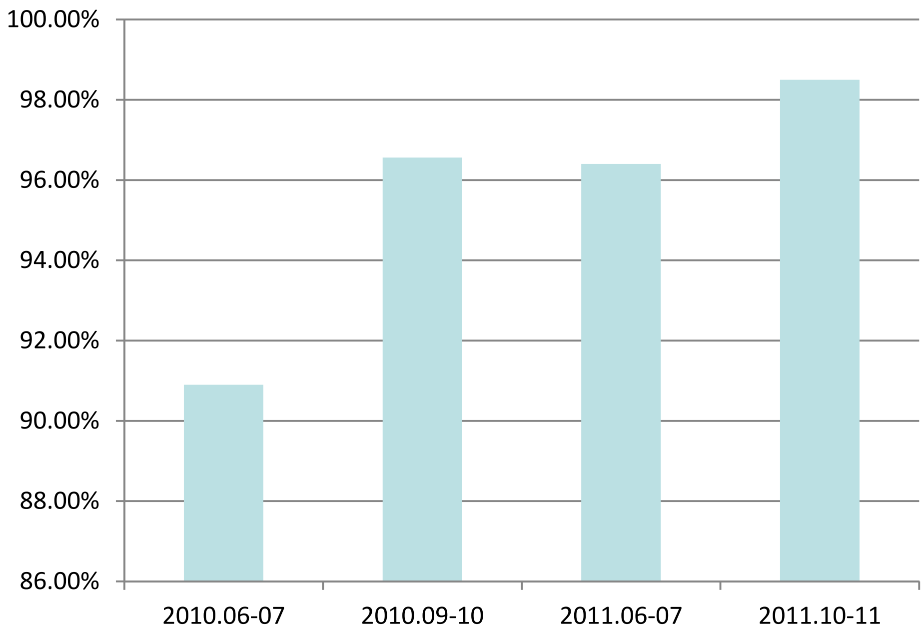
Dedicated SR mode operation

Running as a 2nd generation synchrotron radiation facility

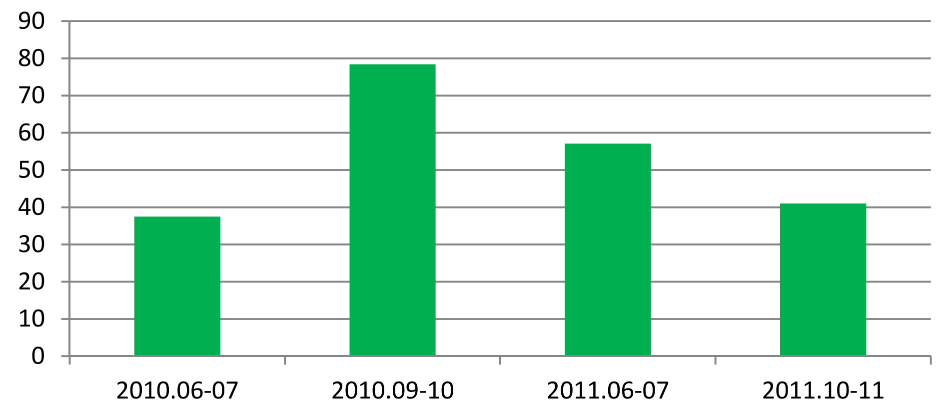
--- deliver beam to users for 3 months every year

--- 500 – 600 experiments done among 2000 applications

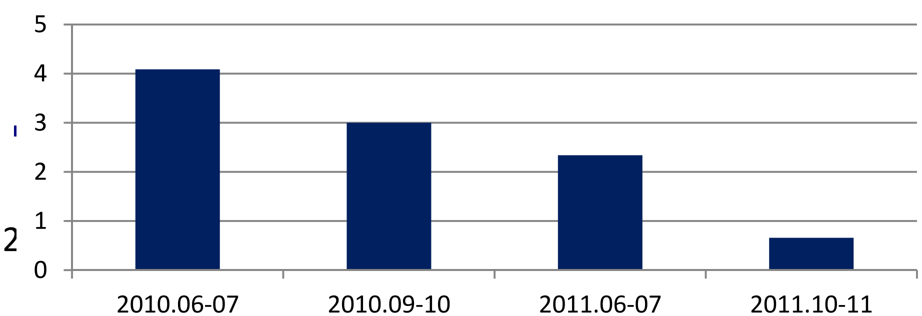
Availability



MTBF



MDF



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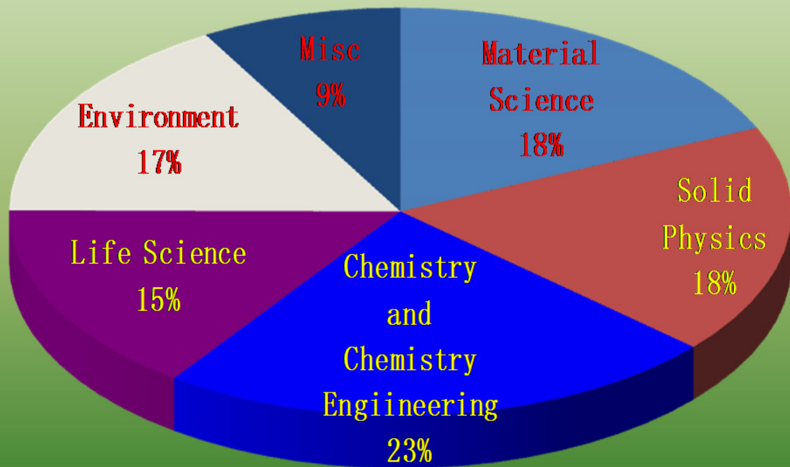
Distribution of user's subject

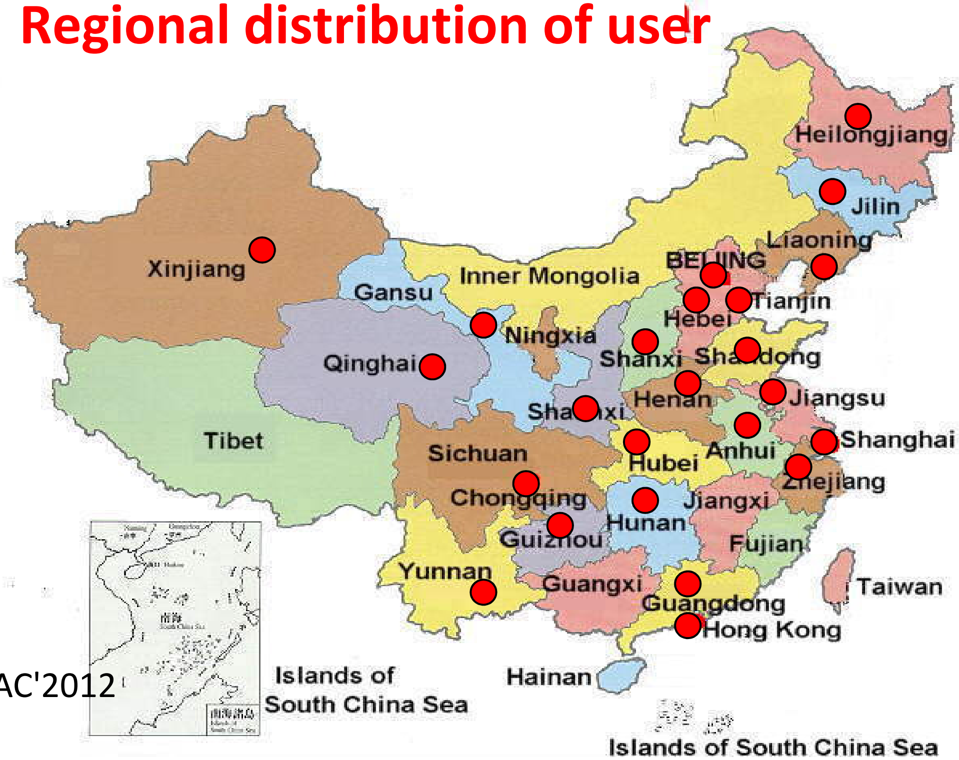


Two modes running for users:

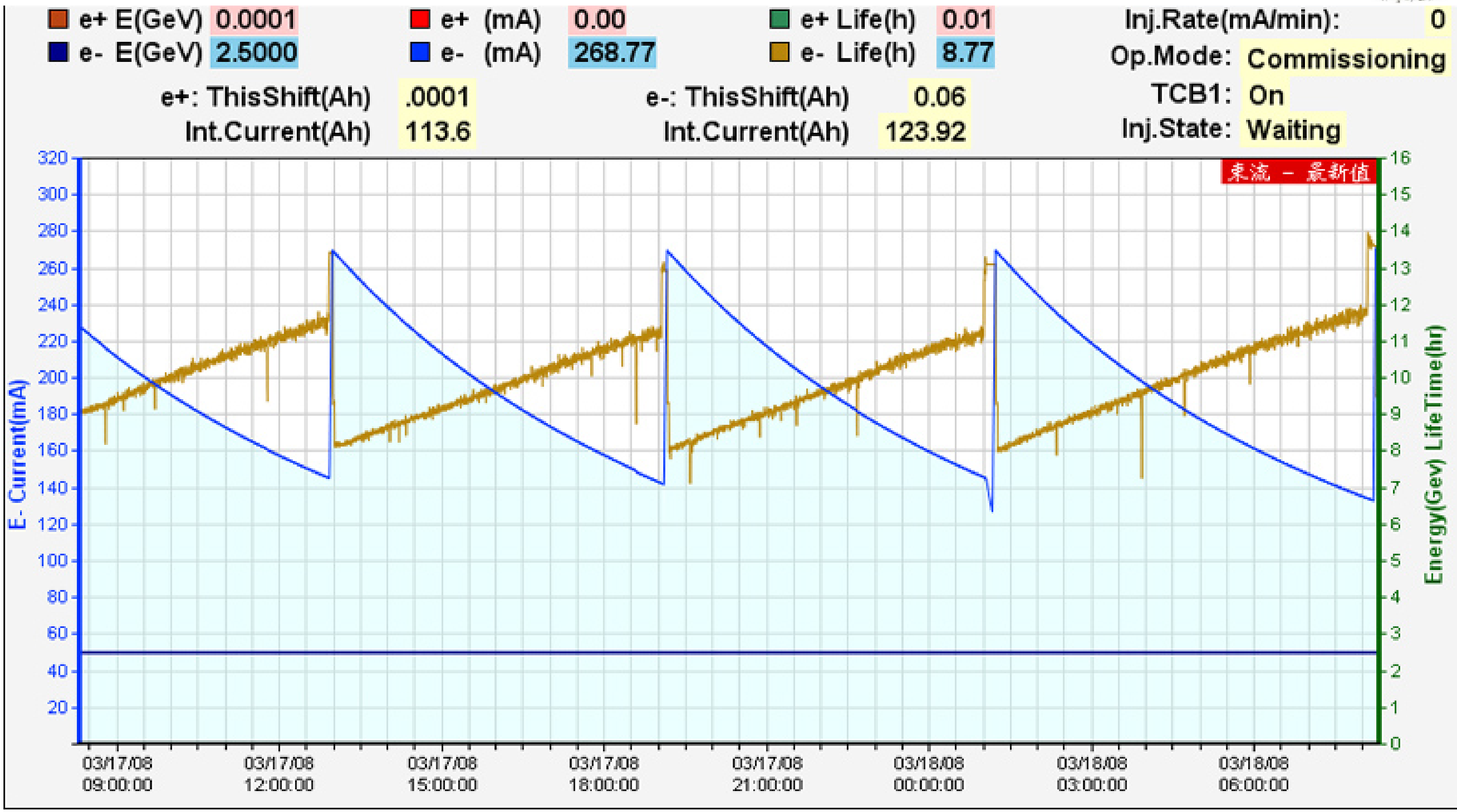
Dedicated mode, E = 2.5 GeV, 15 beam lines on

Parasitic mode, 6 beam lines on when running for HEP

Regional distribution of user



Dedicated synchrotron radiation operation



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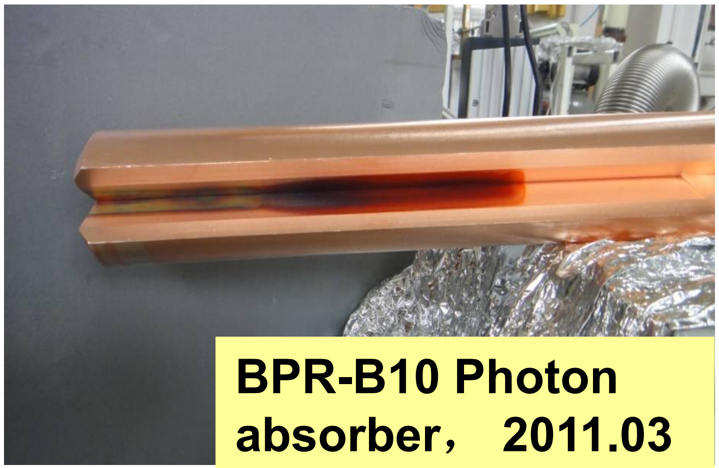
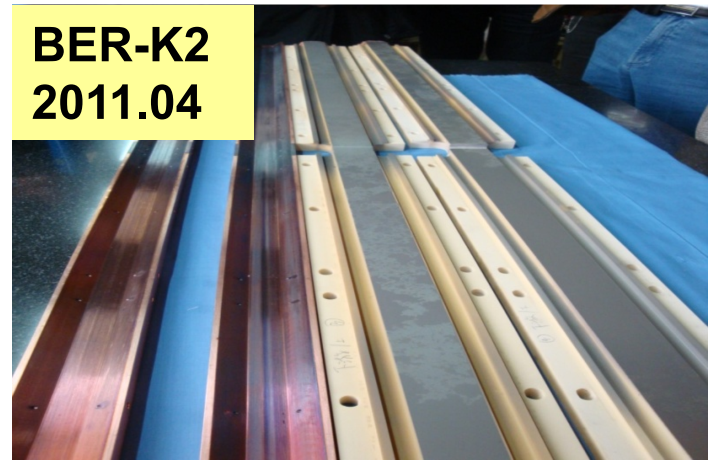
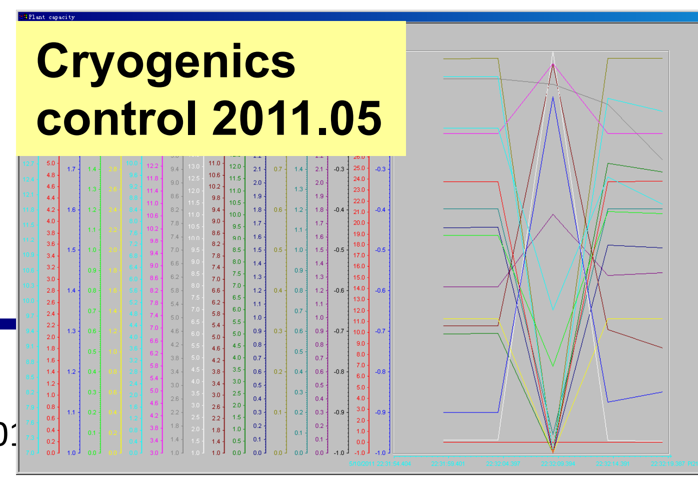
5. Problems and prospects

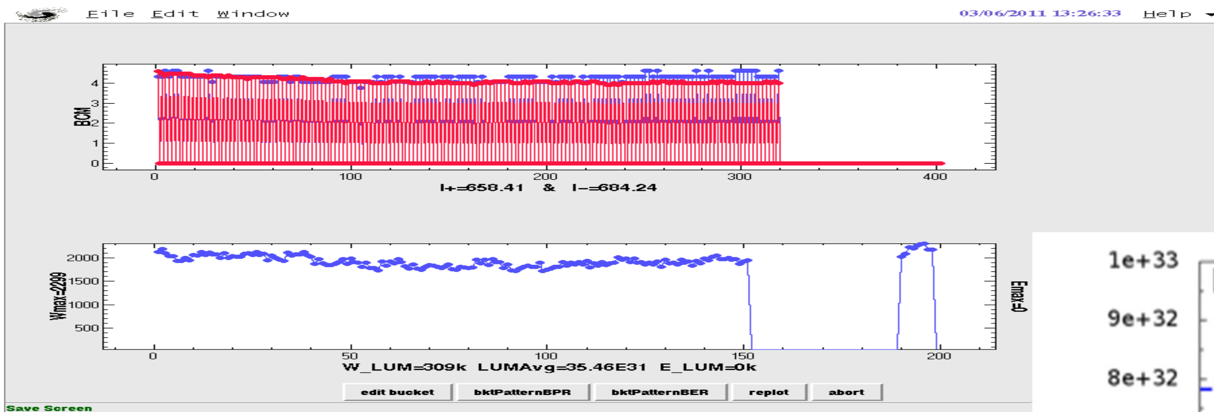
- **Hardware failures due to high beam current**

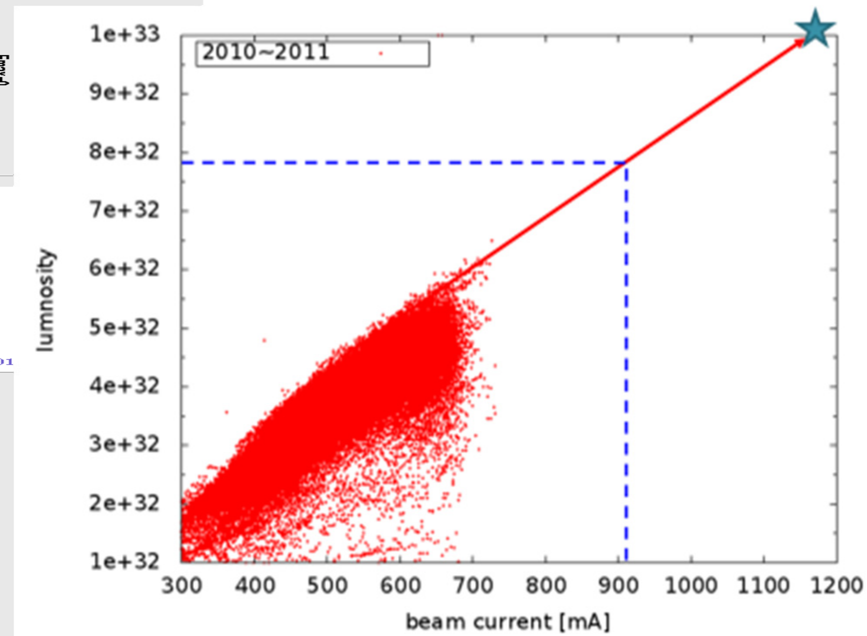






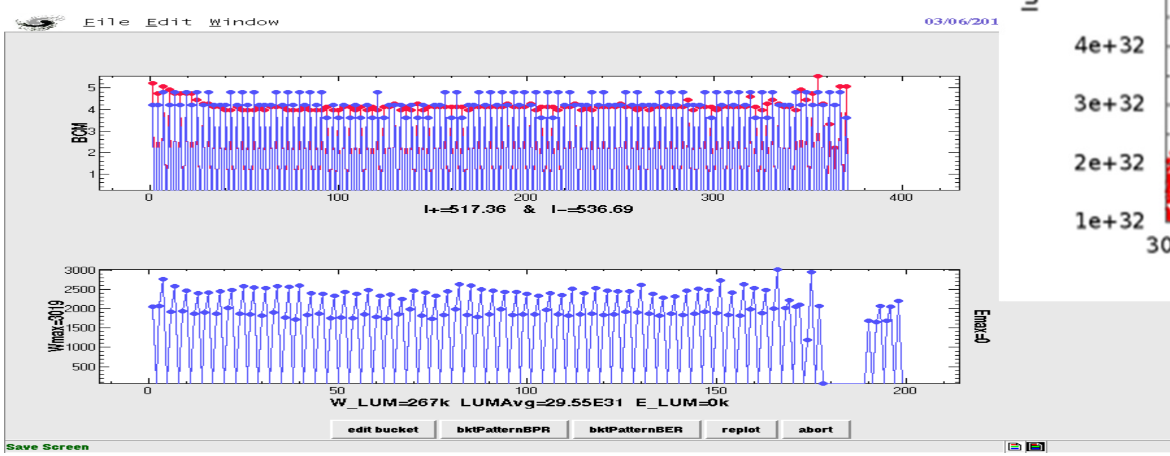
Machine studies with more bunches





160 bunches, **{0～318/2},**

708×708mA658×684@3.546E32



124 bunches, **{0～369/3 },**

705×704mA，517×537@2.955E32

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- **Luminosity calculations in different scenarios**

	Coupling	β_y^* (cm)	I_b(mA)	N_b	ΣI(mA)	Luminosity ($cm^{-2}s^{-1}$)
Case 1	0.01	1.5	8.2	140	1150	1.03×10^{33}
Case 2	0.01	1.3	8.2	120	980	1.02×10^{33}
Case 3	0.01	1.2	8.2	110	900	1.01×10^{33}
Case 1’	0.01	1.5	9.8	120	1150	1.03×10^{33}
Case 2’	0.01	1.3	9.8	100	1000	1.02×10^{33}
Case 3’	0.01	1.2	9.8	92	900	1.01×10^{33}
Design	0.015	1.5	9.8	93	910	1.0×10^{33}

Higher beam current is the most important!

Summary

- A lot of work, including AP and hardware improvements have been done from the beginning of the machine commissioning to the routine operation.
- Luminosity goes up with the optics optimization, instability cure, beam-beam study, and LFS.
- Integrated lum @ different energies to HEP, and beam to SR users with different mode during routine operations.
- Further luminosity enhancement is foreseen, by the means of increasing bunch current and bunch number, etc.
- Possibility of polarized e- beam is investigated for more physics results.

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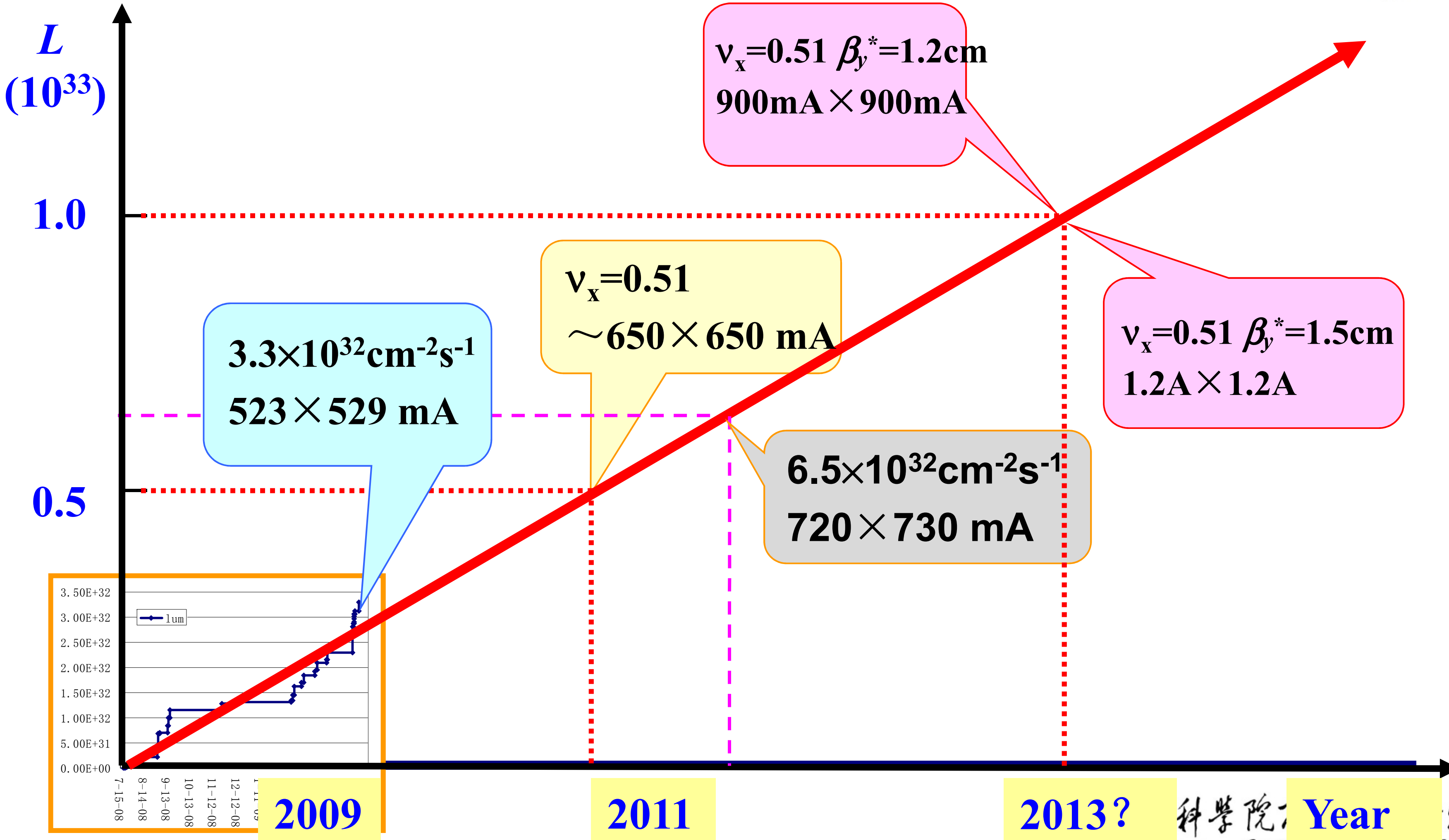
Main parameters of BEPCII achieved in operation

Parameters	Design	Achieved	
		BER	BPR
Energy (GeV)	1.89	1.89	1.89
Beam current (mA)	910	800	800
Bunch current (mA)	9.8	9.0	9.0
Bunch number	93	80 – 88	80 – 88
RF voltage (MV)	1.5	1.5 – 1.7	1.5 – 1.7
β_y^* (cm)	1.5	1.4 – 1.5	1.4 – 1.5
Lifetime (hrs)	3.5@910mA	~1.8@720mA	~1.8@720mA
Beam–beam parameter	0.04	0.0327	
Lum. ($\times 10^{32} cm^{-2}s^{-1}$)	10	6.492	

BEPCII Luminosity Roadmap



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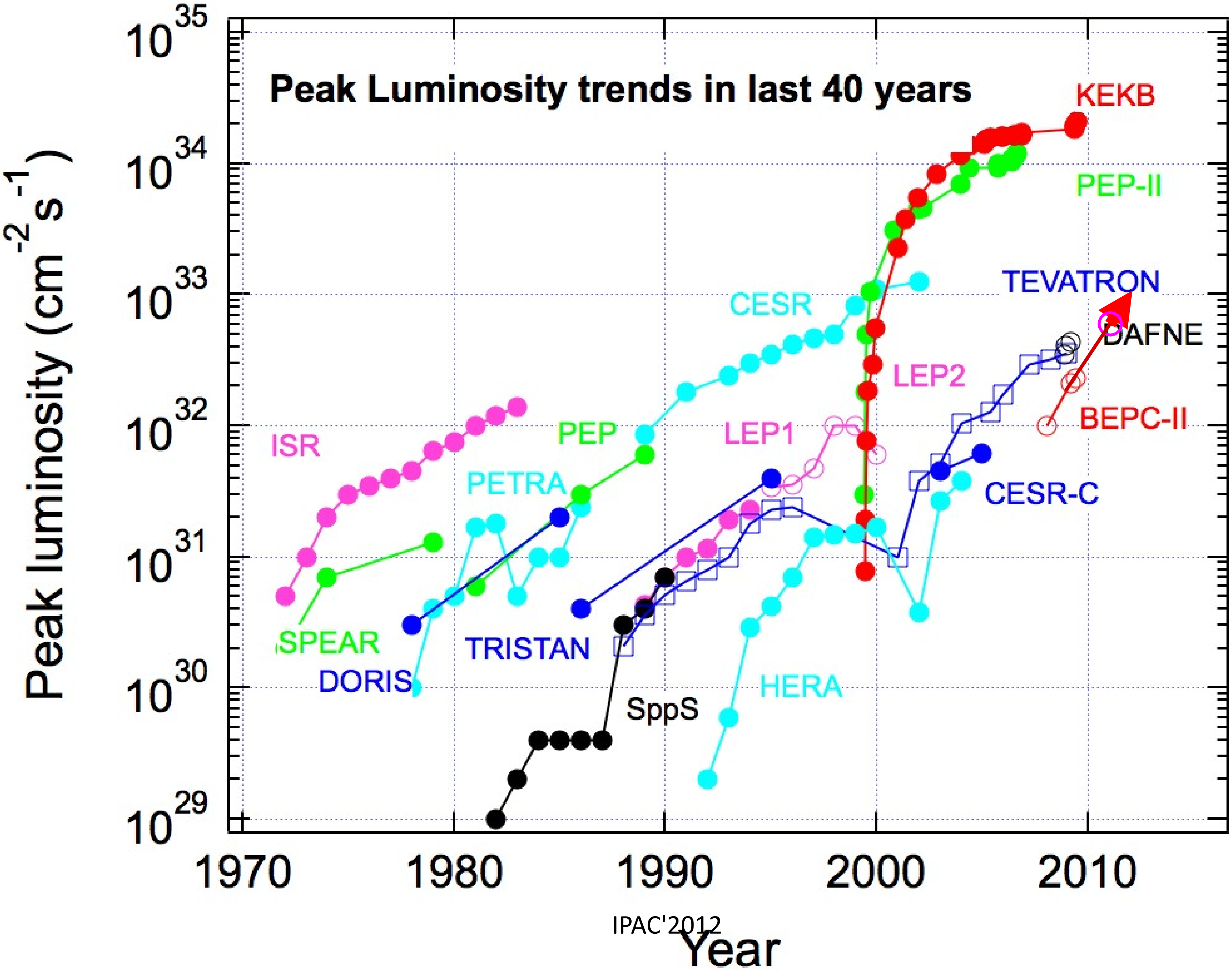

Peak Luminosity trends in last 40 years
Peak luminosity (cm^-2 s^-1)
Year
10^35
10^34
10^33
10^32
10^31
10^30
10^29
1970
1980
1990
2000
2010
KEKB
PEP-II
TEVATRON
DAFNE
CESR
LEP2
BEPC-II
LEP1
PEP
ISR
PETRA
CESR-C
SPEAR
TRISTAN
DORIS
HERA
SppS

Acknowledgement

- The commissioning and operation group of BEPCII.
- Great helps from KEK, SLAC, BNL, etc., in past several years.

Thanks for your attention !