Beam Studies in the BEPCII, towards higher luminosity

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Outline

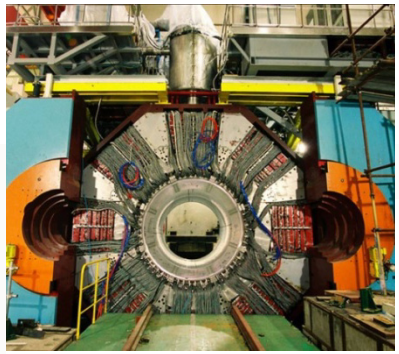
- Introduction on BEPCII
- Beam optics realization
- Beam instability issues
- Luminosity and background commissioning
- Beam-beam interaction
- Summary

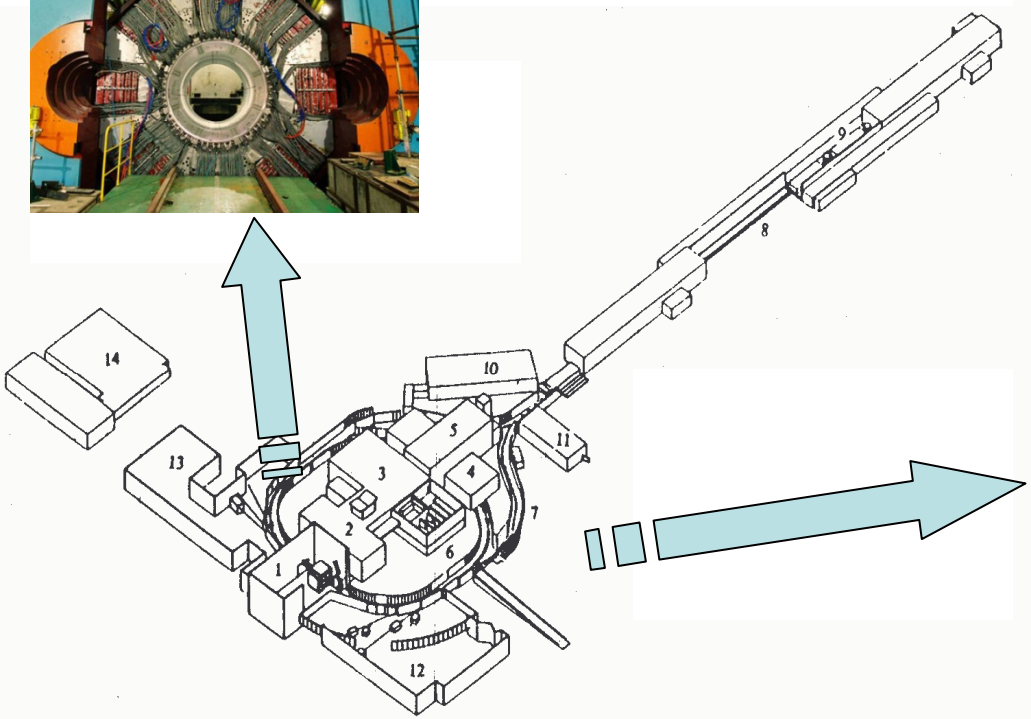
1. Introduction on BEPCII

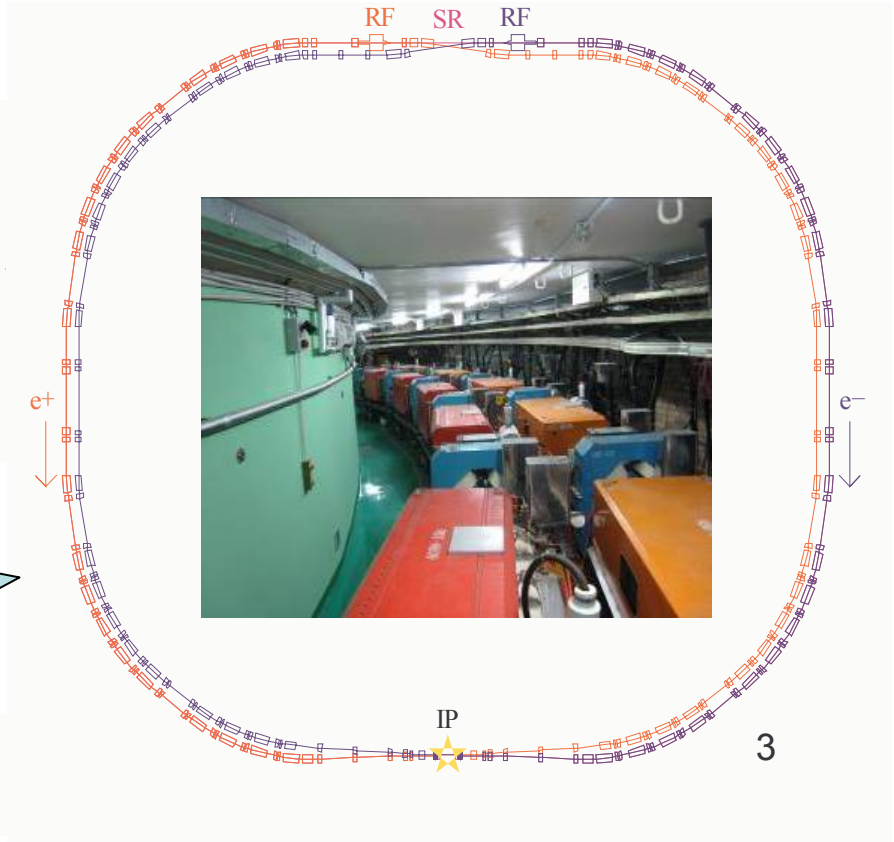
BEPCII — An upgrade project of BEPC

— A double-ring factory-like machine

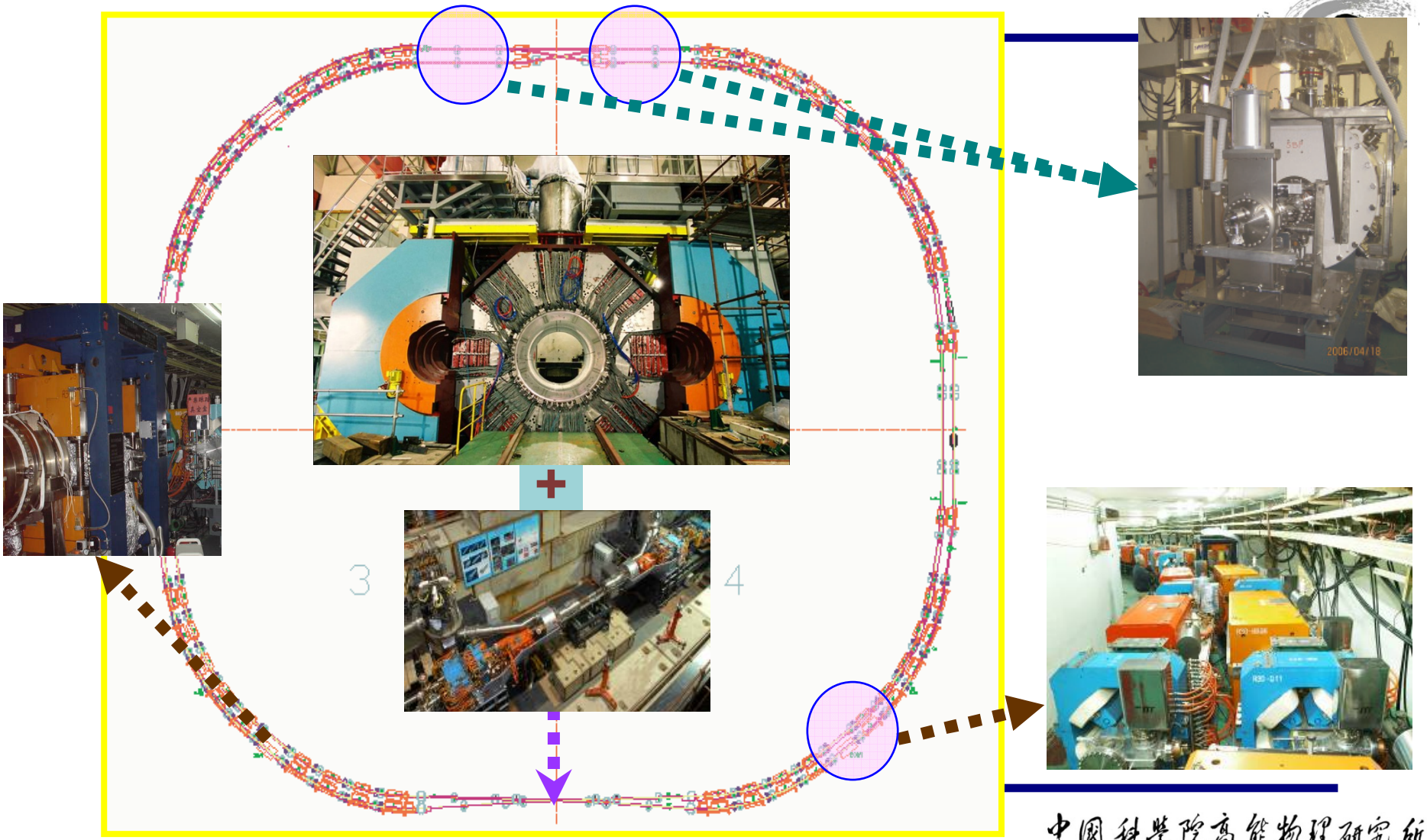
— Deliver beams to both HEP & SR







3-ring structure



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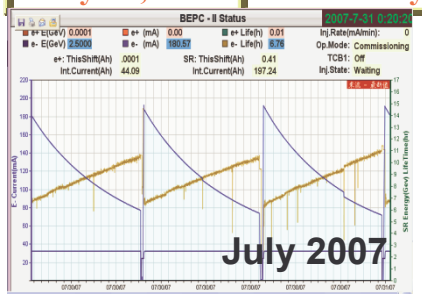
Design Goals of BEPCII

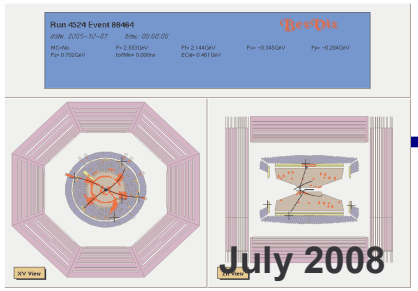
- **Collision**
  - Beam energy range — 1-2.1 GeV
  - Optimized beam energy — 1.89 GeV
  - Luminosity — 1×10^{33} $cm^{-2}s^{-1}$ @1.89 GeV
  - Full energy injection — 1-1.89 GeV
- **Synchrotron radiation**
  - Beam energy — 2.5 GeV
  - Beam current — 250 mA
  - Keep the existing beam lines unchanged

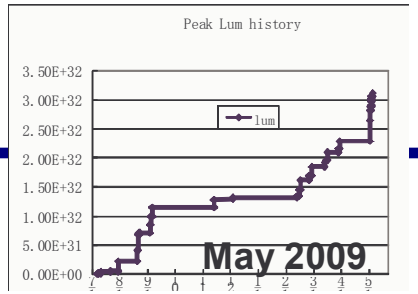
BEPCII: One-machine, Two-purpose (HEP, SR)

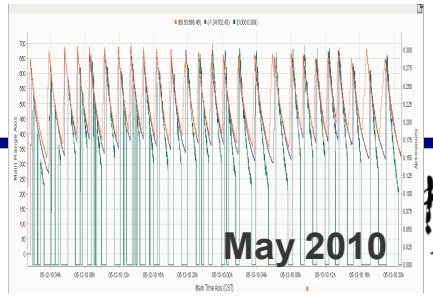
The Milestones

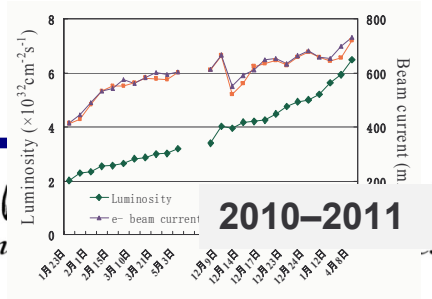
January 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections started
Dec. 1, 2004	Linac delivered e^- beams for BEPC
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Nov. 13, 2006	Phase 1 commissioning started
Aug. 3, 2007	Shutdown for installation 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 $3.3\times10^{32}cm^{-2}s^{-1}$





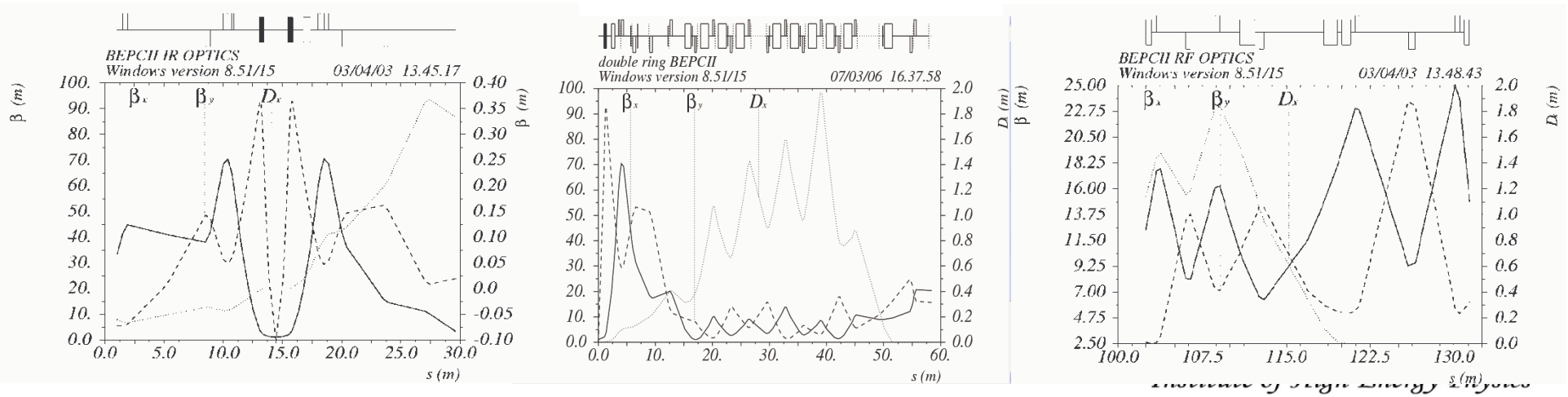






2. Beam optics realization

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



- **Method of Response Matrix Analysis**

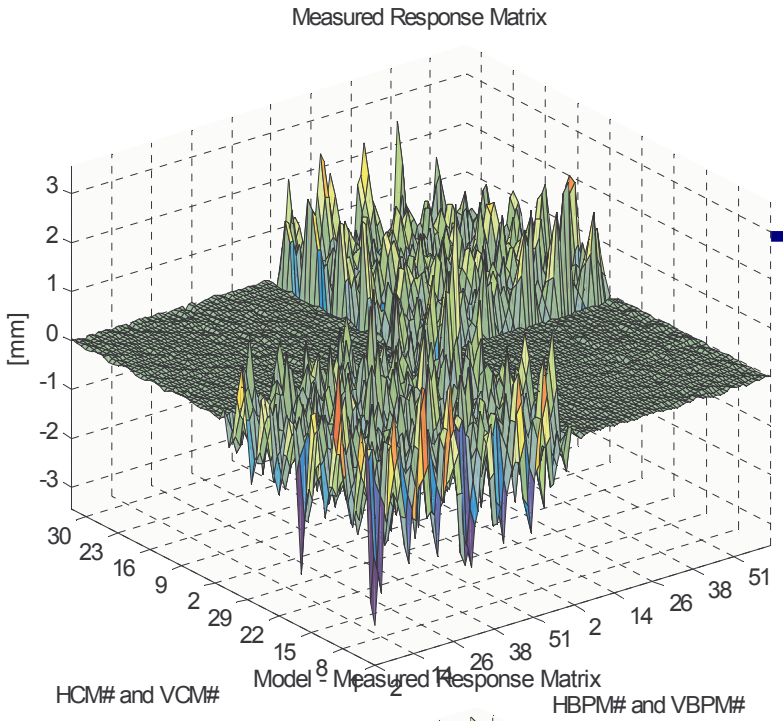
$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = R_{meas} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix}$$

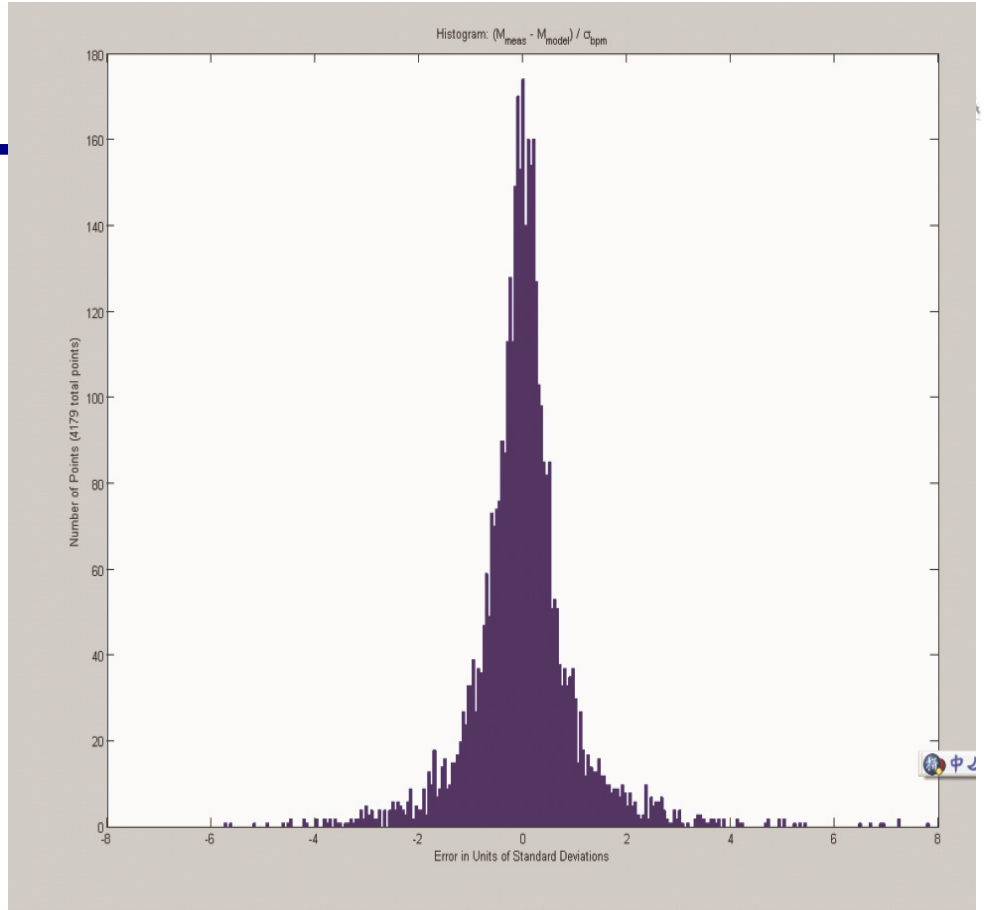
$$\chi^2 = \sum_{i,j} \frac{(R_{\mathrm{mod},ij} - R_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2$$

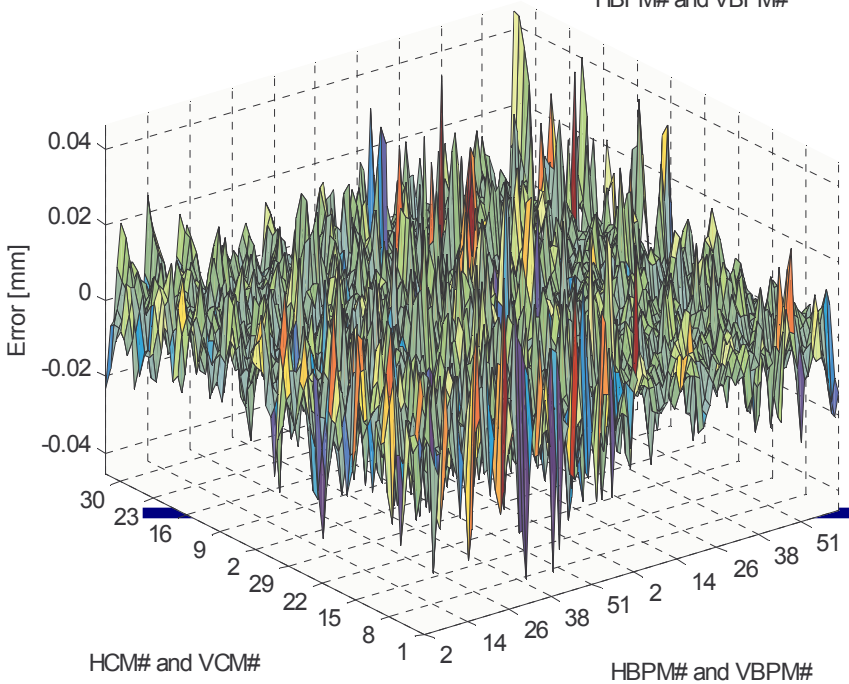
$$\Delta V_{ij} = \sum \frac{\partial V_{ij}}{\partial K_q} \Delta K_q + \sum \frac{\partial V_{ij}}{\partial G_i} \Delta G_i + \sum \frac{\partial V_{ij}}{\partial \theta_j} \Delta\theta_j + \sum \frac{\partial V_{ij}}{\partial \delta_j} \Delta\delta_j + \ldots\ldots$$

- **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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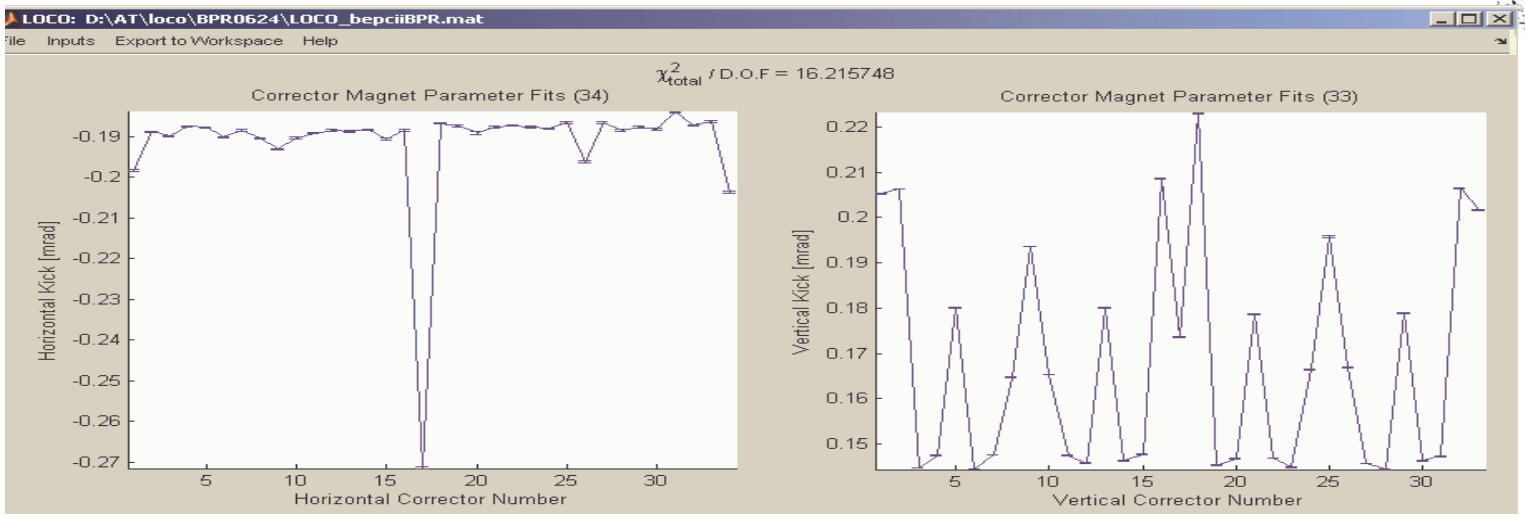
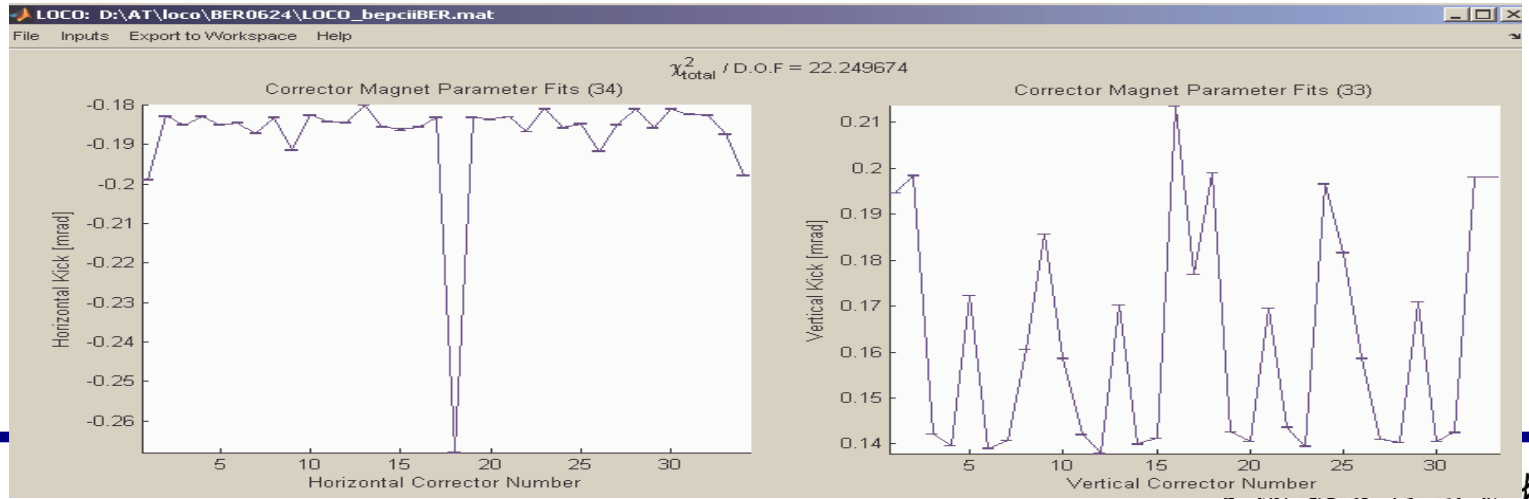
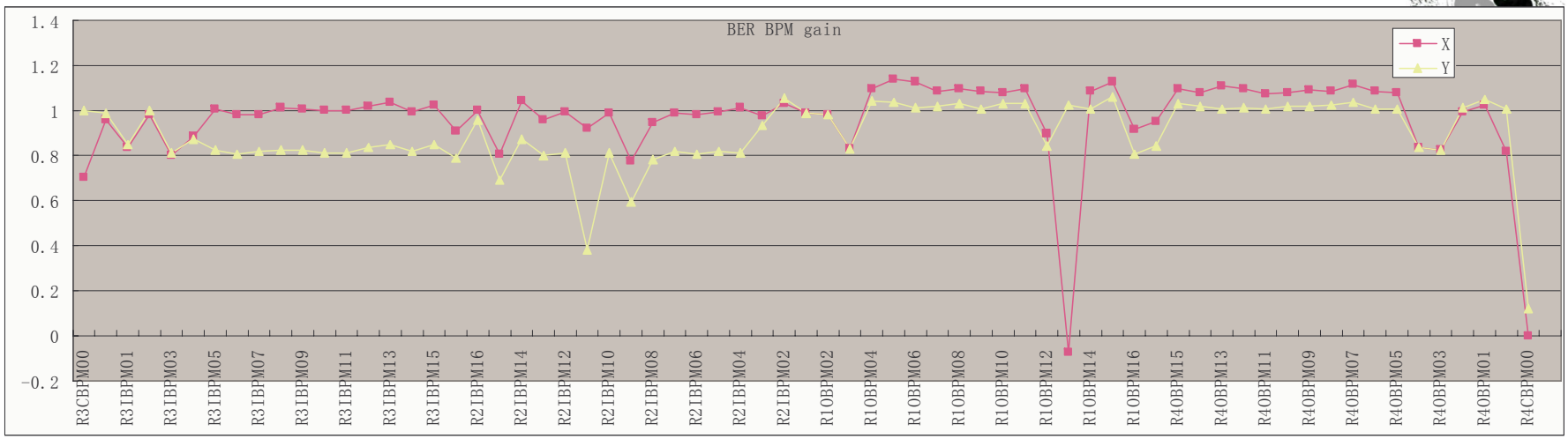
• Strength gain of corrector





BPM 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
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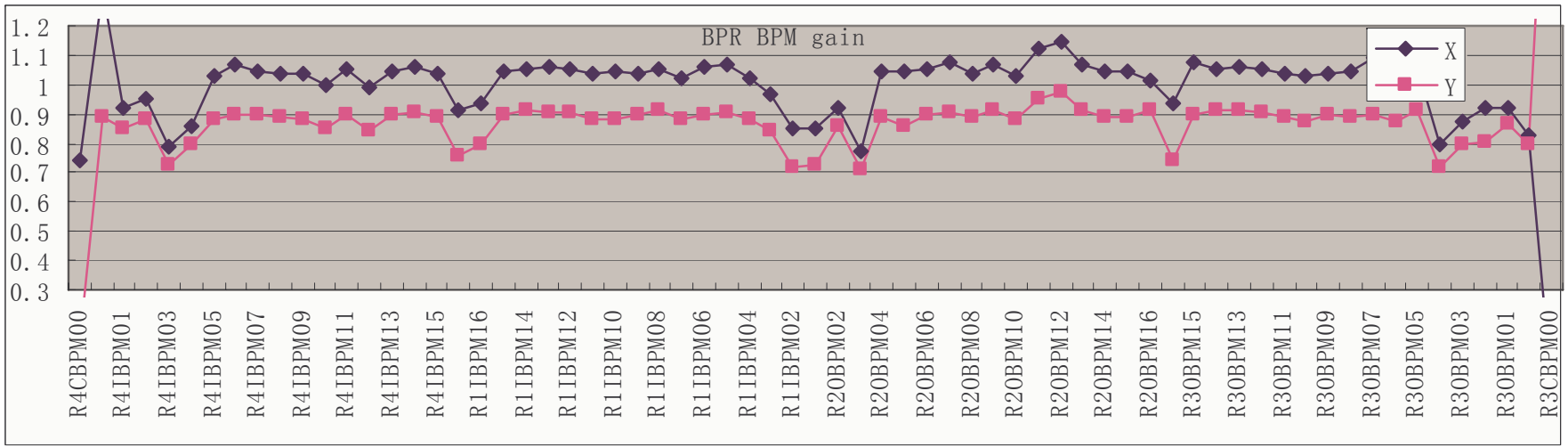
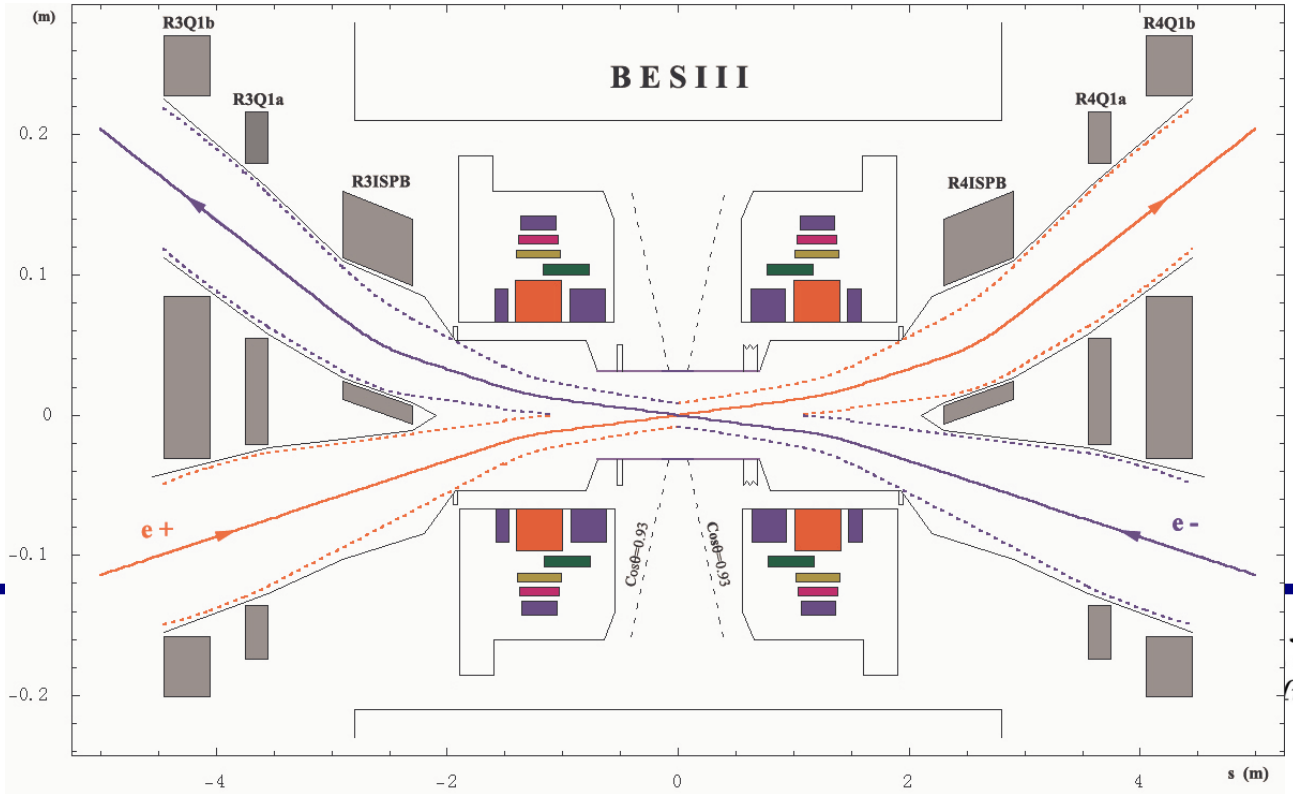
R4OBPM03
R4OBPM01
R4CBPM00


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 works for two rings.
- Two 2-in-1 quads (Q1A) in each side of IP, share one power supply, respectively.
- Insufficient BPMs in the IR for RM measurement.



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C.O.D. correction including beam energy variation

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

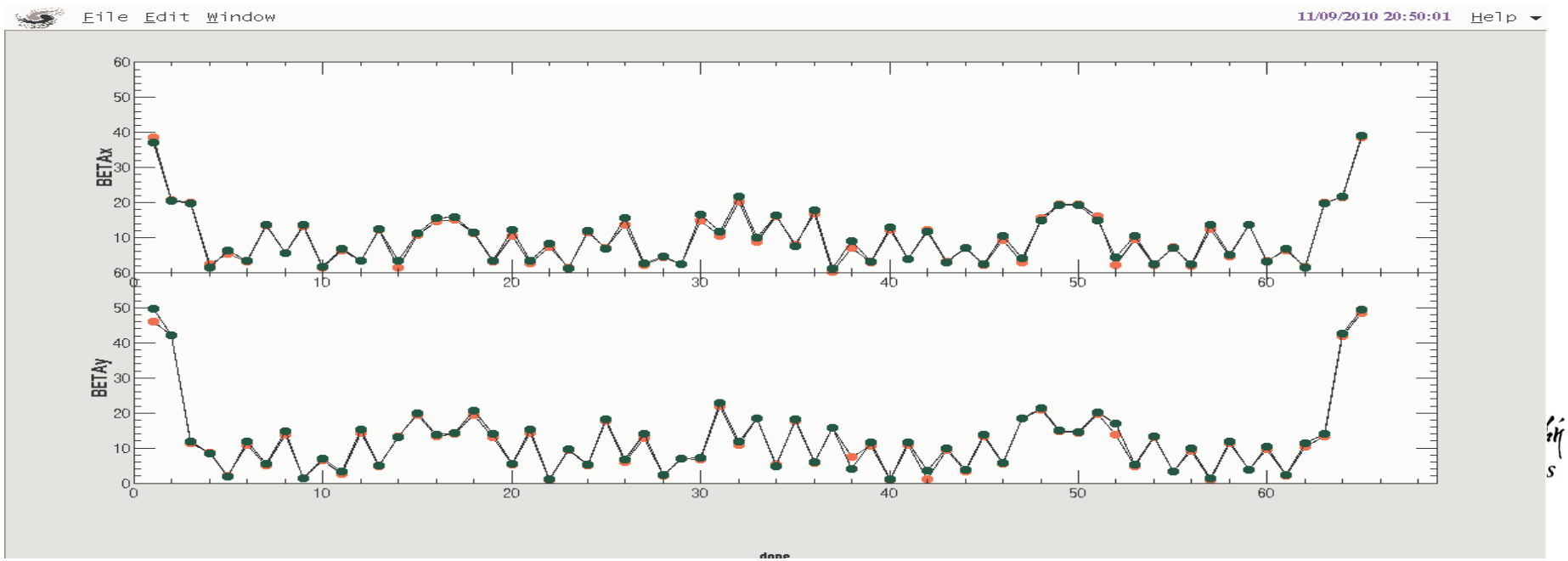
$$\frac{\Delta E}{E} = -\frac{1}{\alpha L_0} \sum_i D_x^i \Delta\theta_{cx}^i$$

- 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 the tool of code LOCO, some measured beam parameters 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

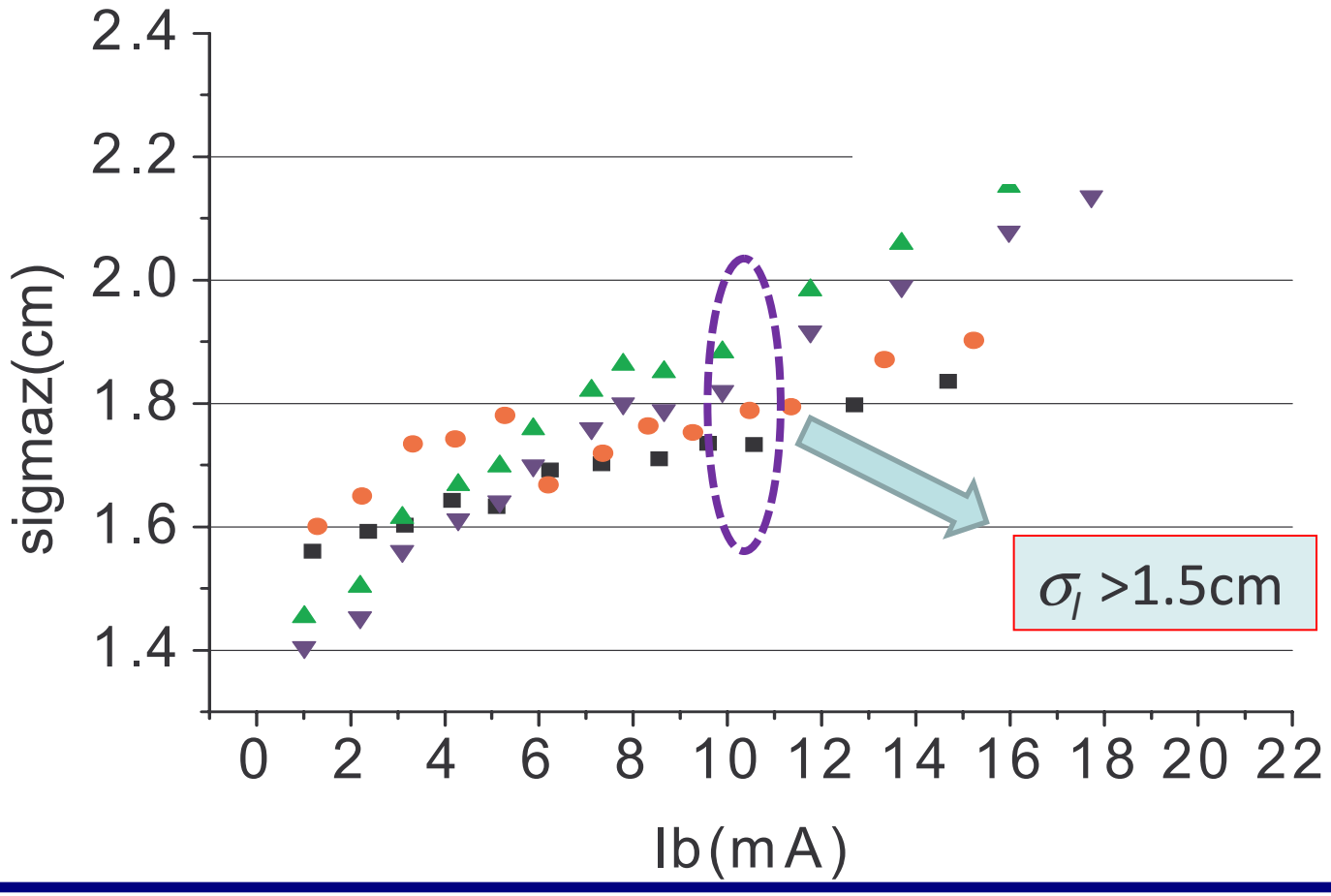


3. Beam instability issues

- 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

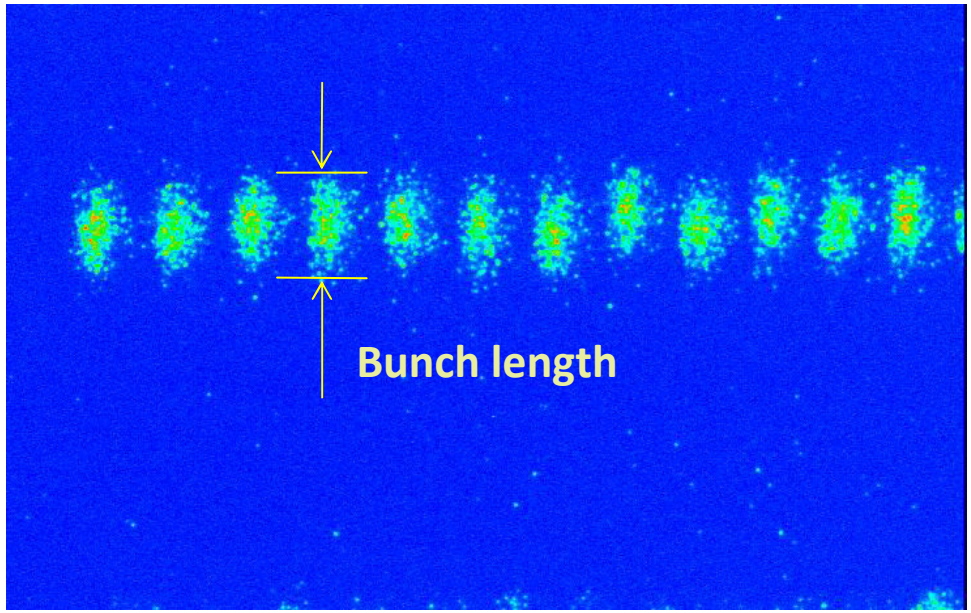
Single bunch instability – Bunch lengthening

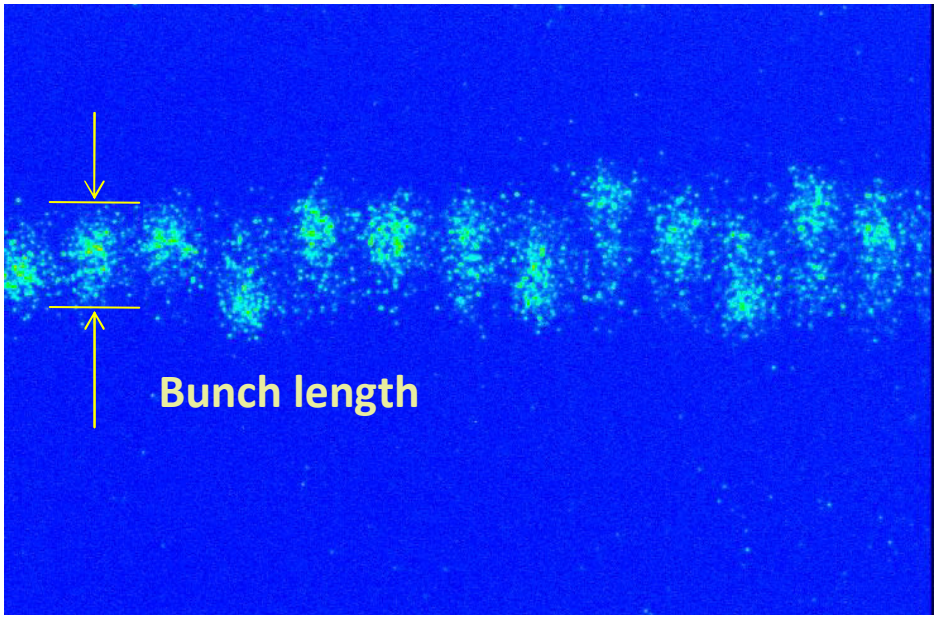


- **Bunch lengthening is more than 10% @ I_b = 9.8 mA.**
- **Measurement of bunch lengthening shows that the longitudinal low frequency impedance is ~3 times higher than the design value.**
- **The way of reducing β_y^* doesn't look effective as it was expected.**

Multi-bunch effect

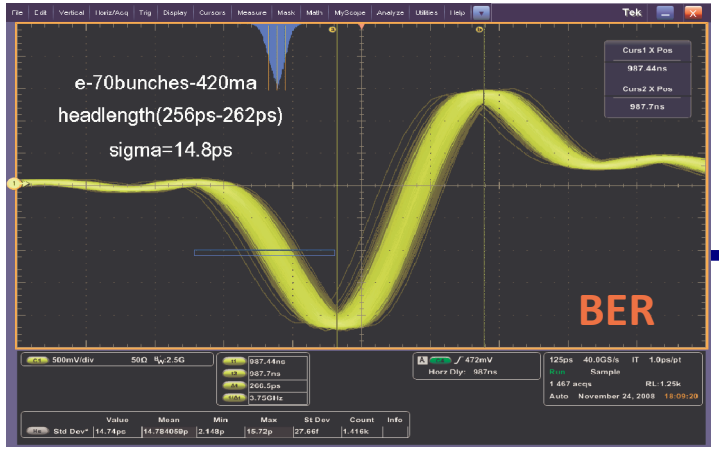
A bunch-by-bunch lengthening observed in BPR in late 2008.

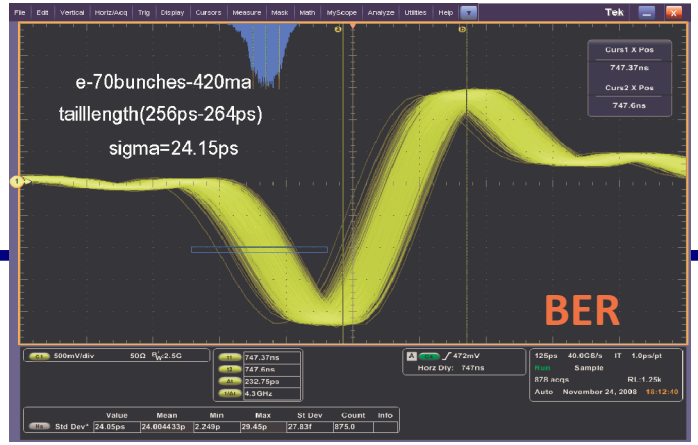


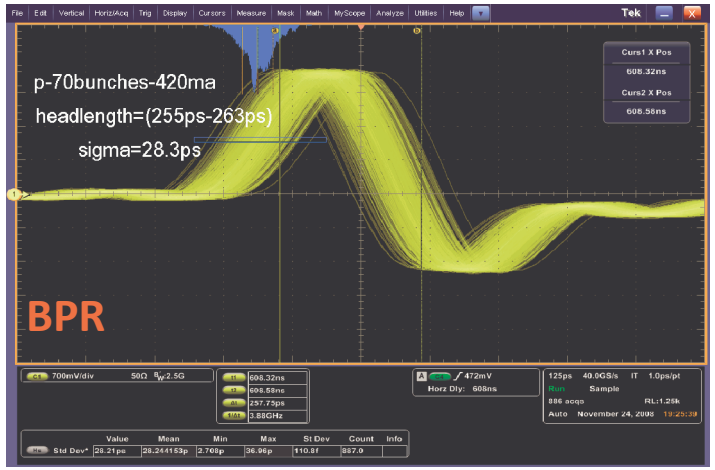


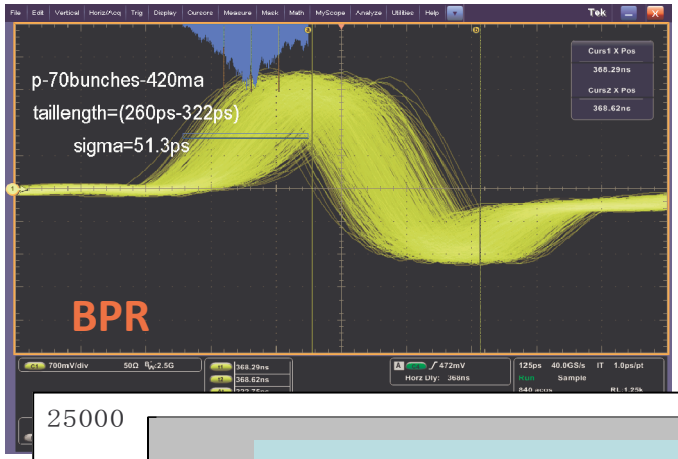
BER: 420mA/70 bunches

BPR: 386mA/70 bunches

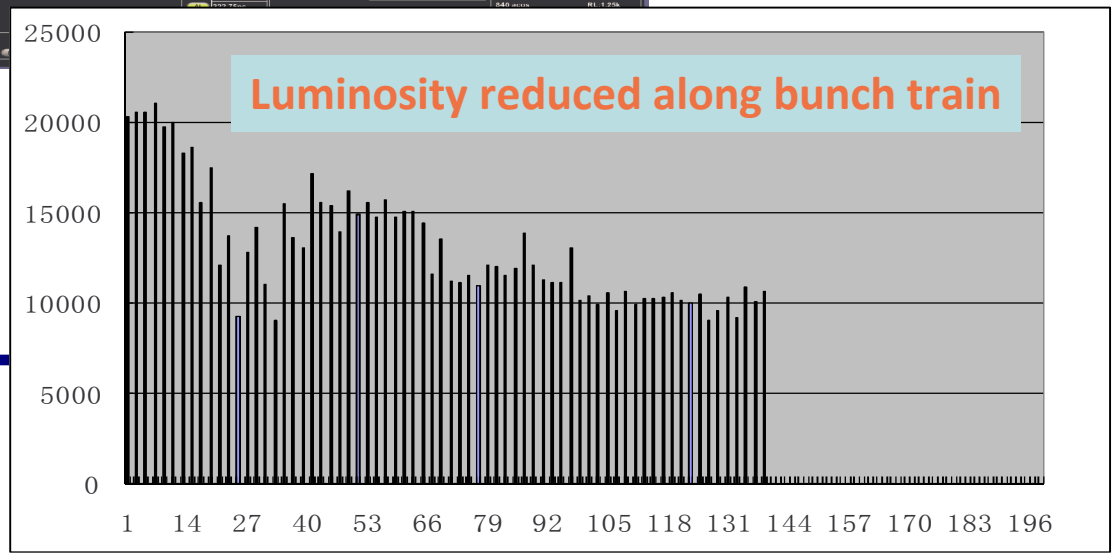






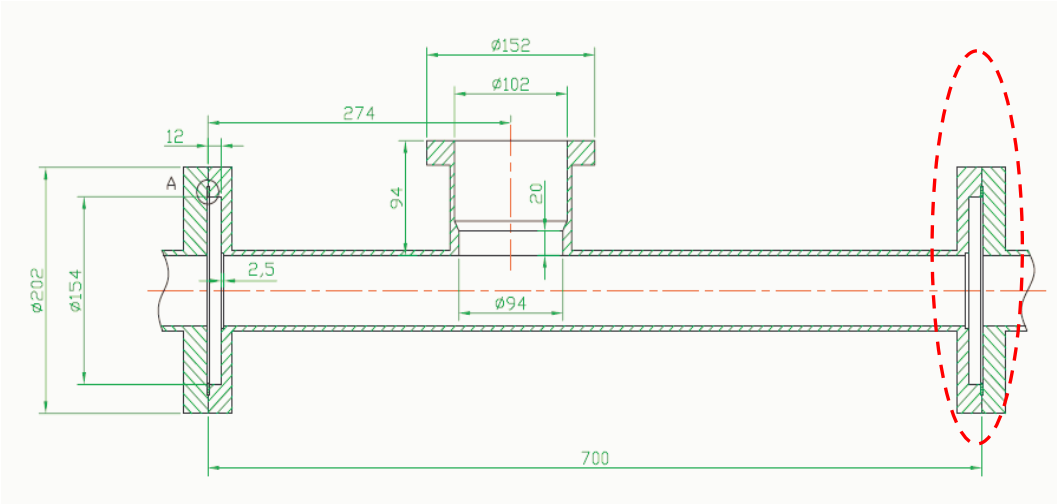


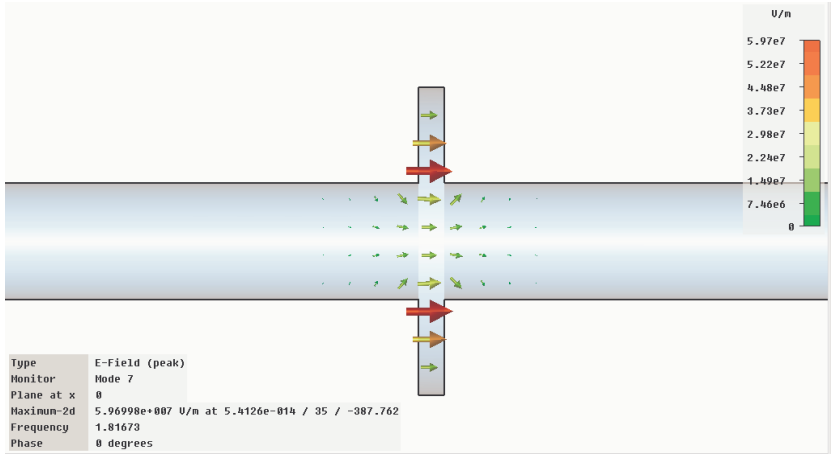
Longitudinal quadrupolar oscillation was observed in BPR



Search for the impedance source

A used screen monitor in BPR with two unshielded flanges, forming cavity structures and causing trapped mode

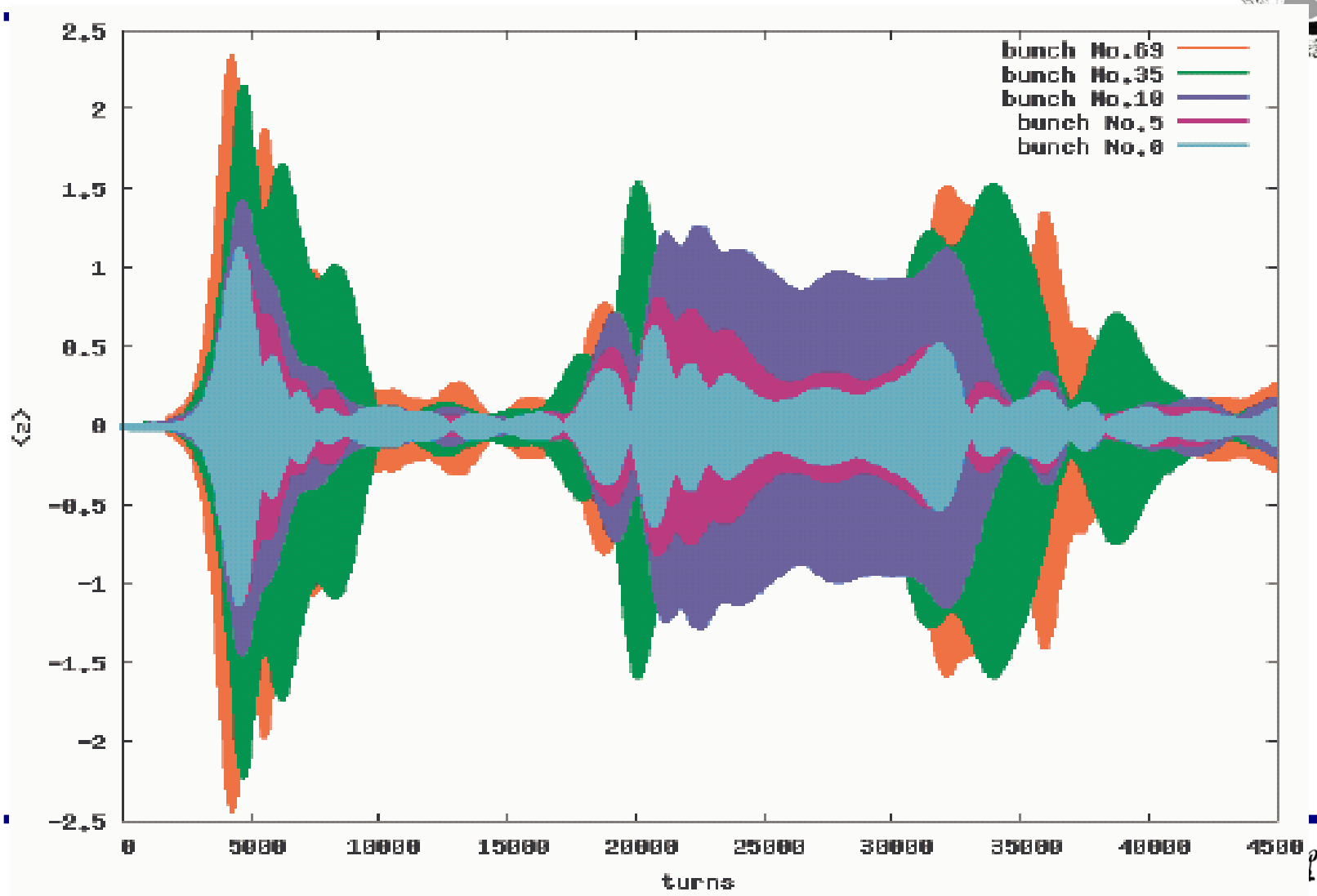




Model	Frequency (GHz)	Q	R	R/Q	Field decay time (ns)
Small cavity	1.8171	2256.9	86160	38.1774	198
Vacuum pump	2.3432	8335.6	4579	0.54933	556

(Courtesy N. Wang & T.M. Huang)

Simulation of longitudinal oscillation with the impedance source

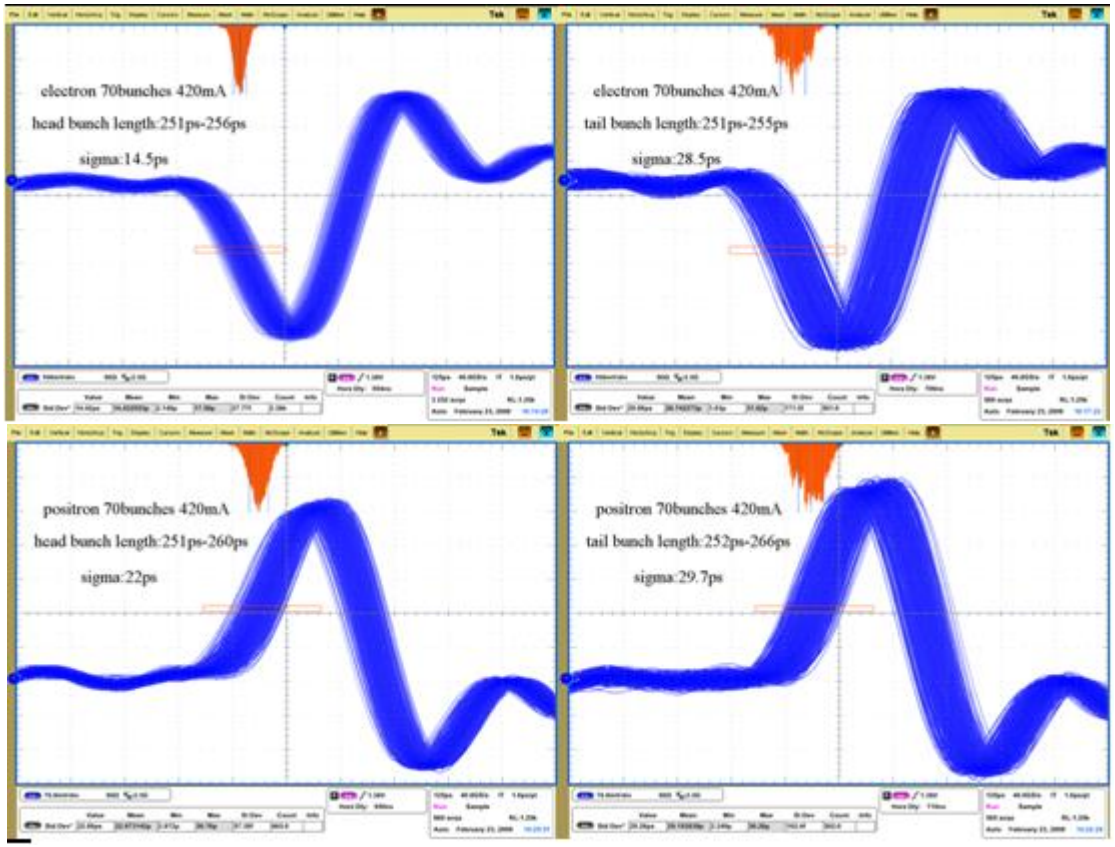


After removing the screen monitor

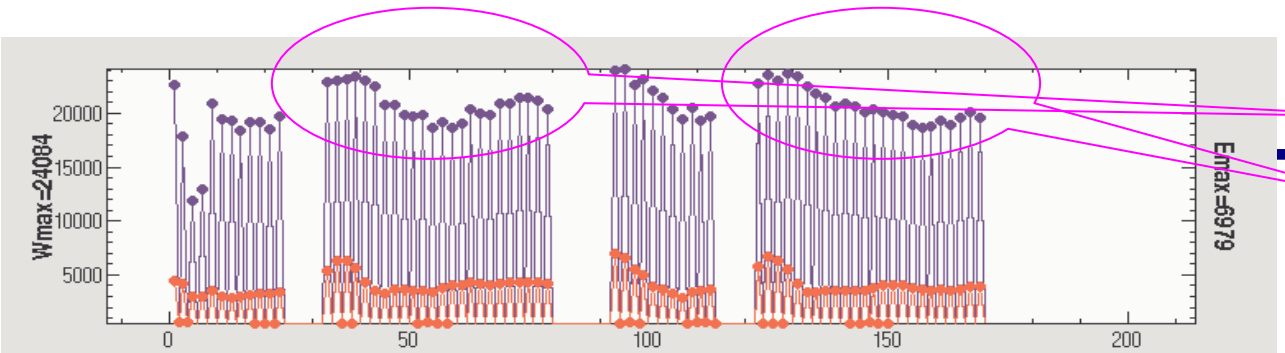
Bunch in head | Bunch in tail

e^- beam

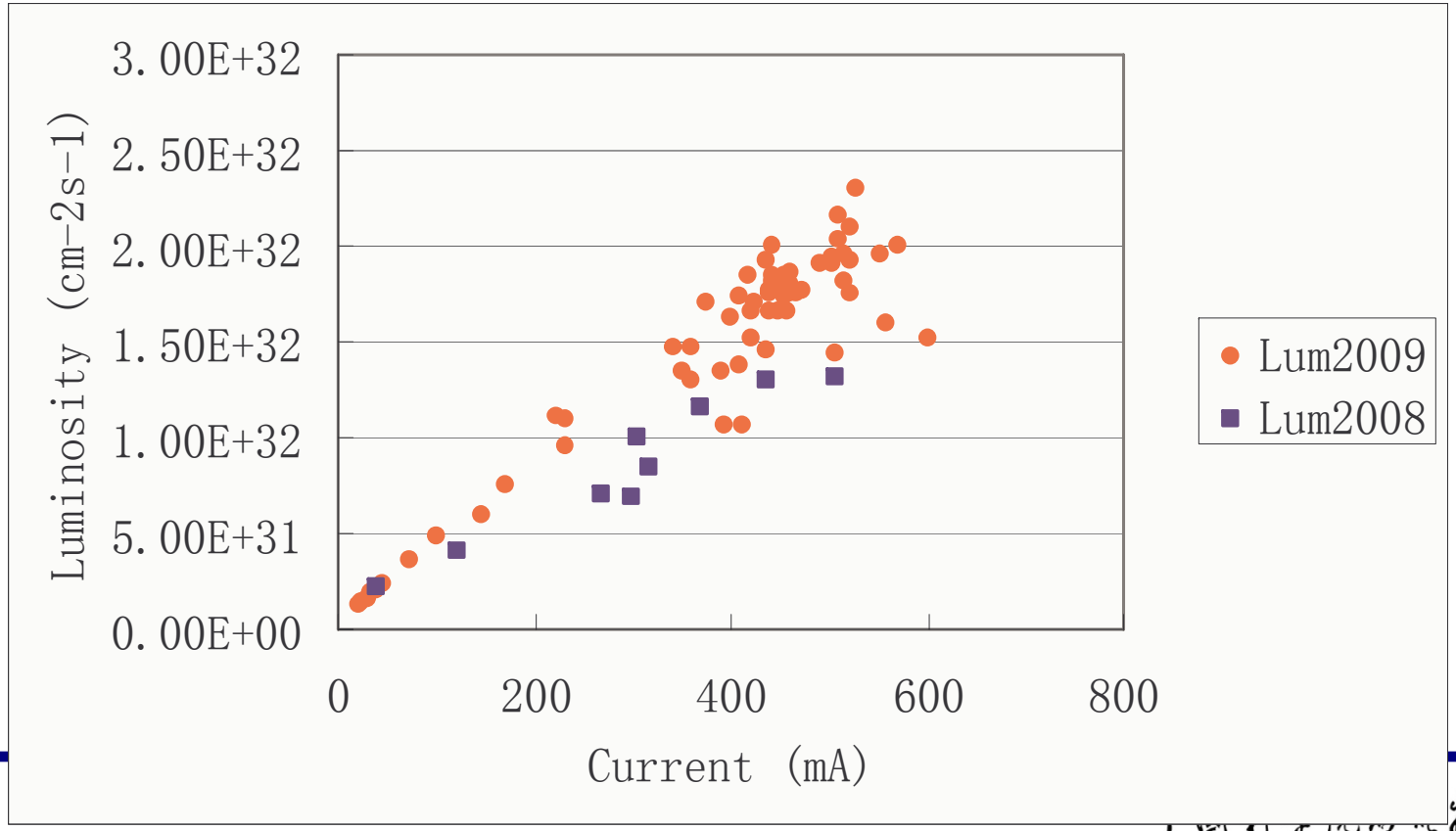
e^+ beam



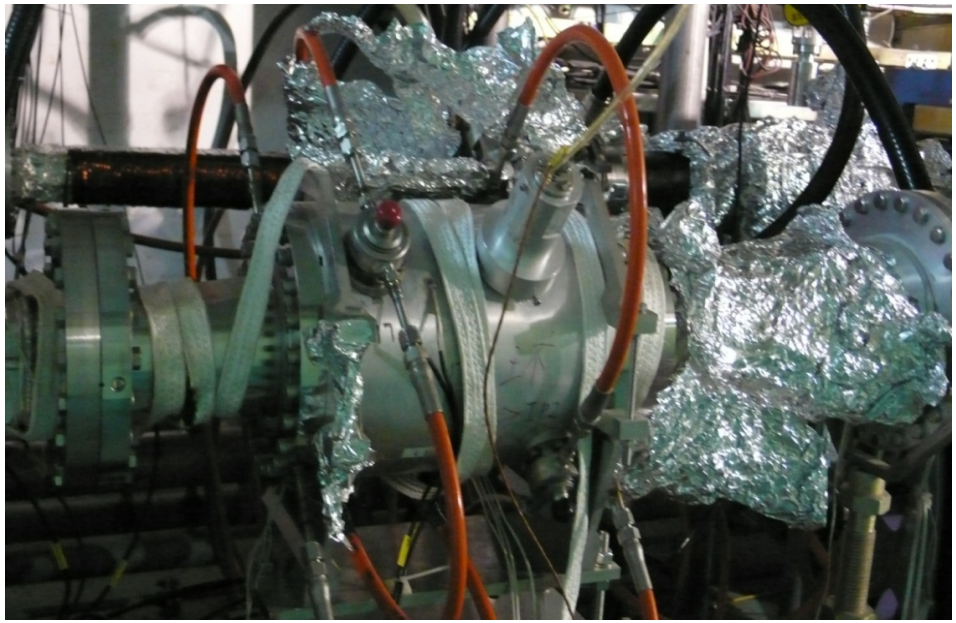
I = 420mA, 70bunches

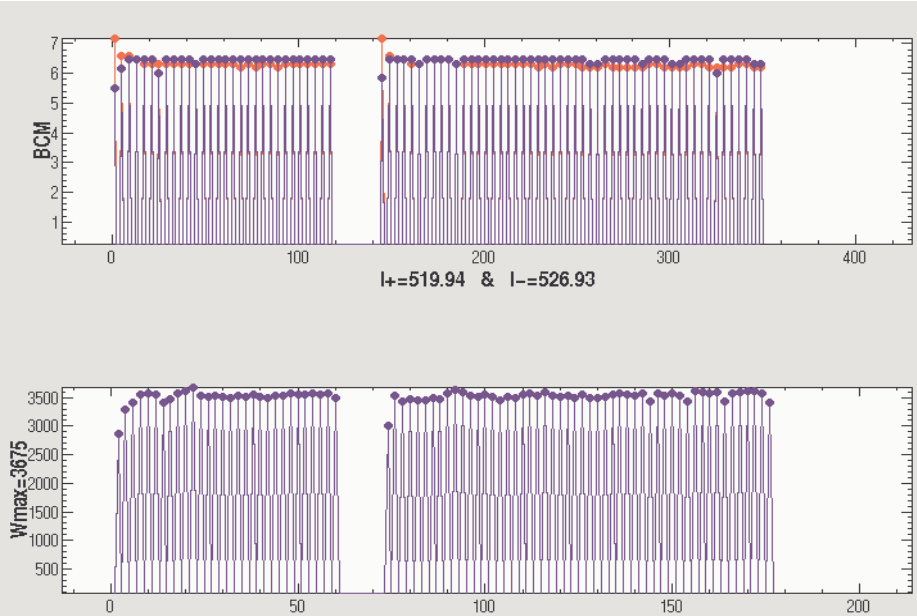


Luminosity reduction due to longitudinal dipole oscillation

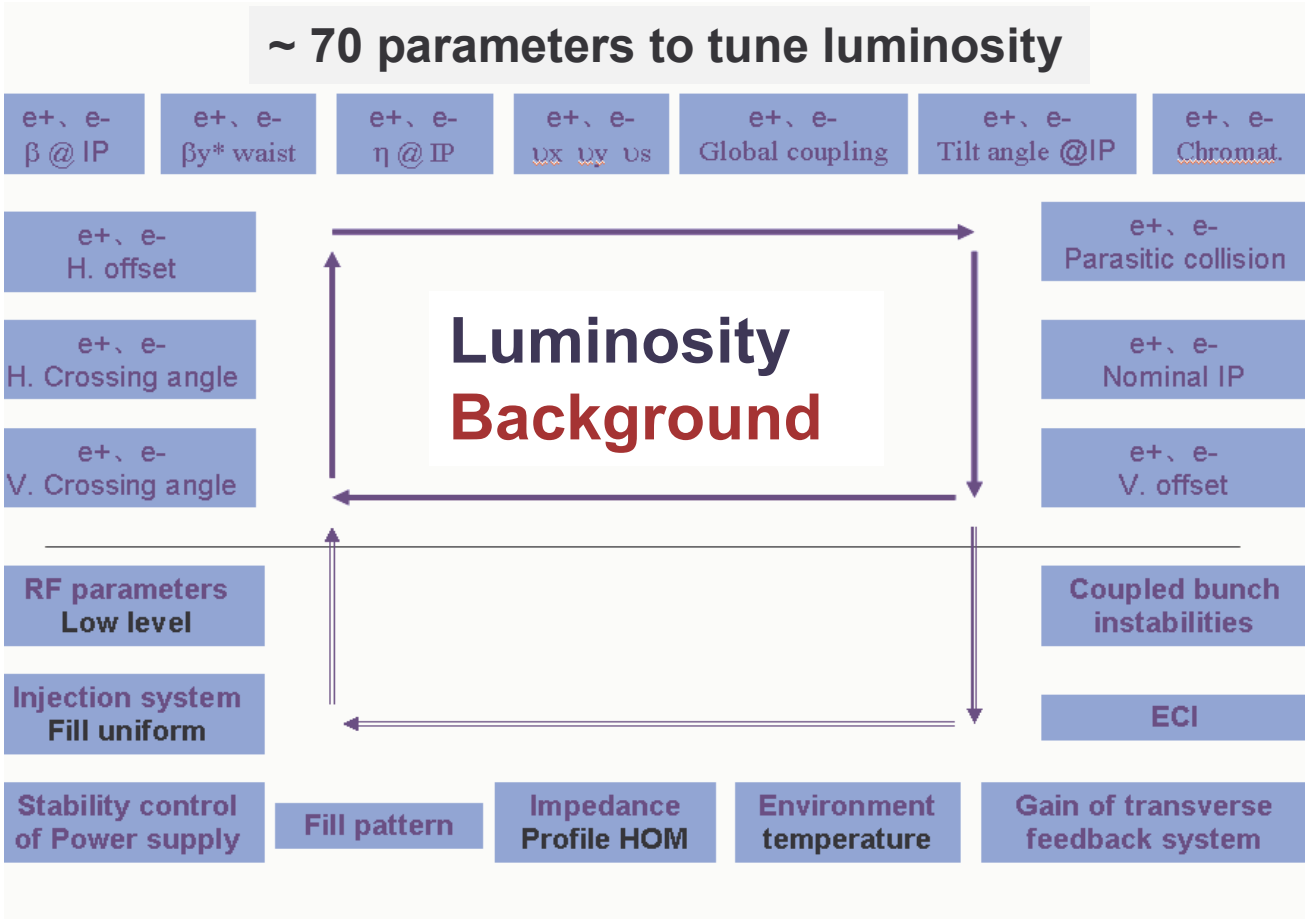


- **With longitudinal feedback systems installed in late 2009, bunch-by-bunch luminosity looked much better.**

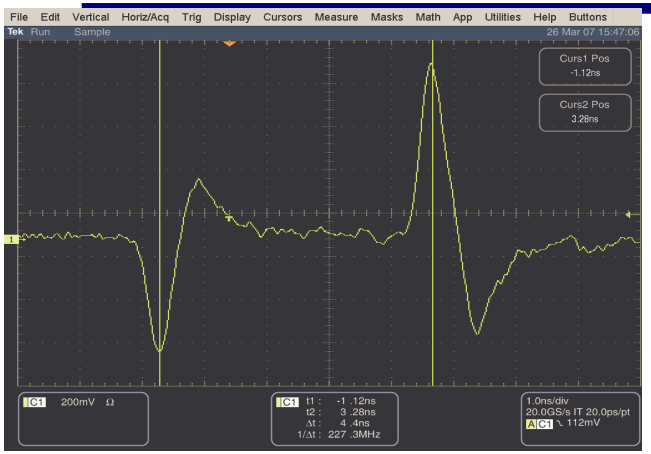


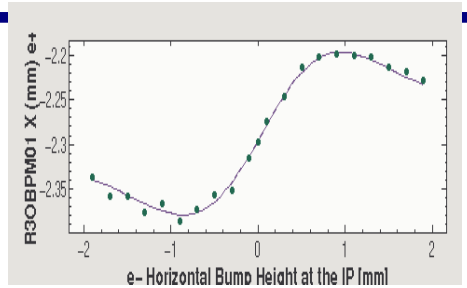


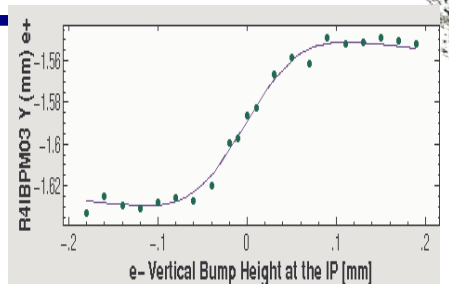
4. Luminosity & background commissioning

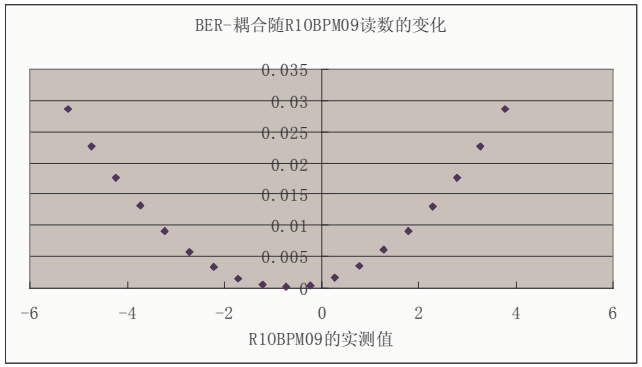


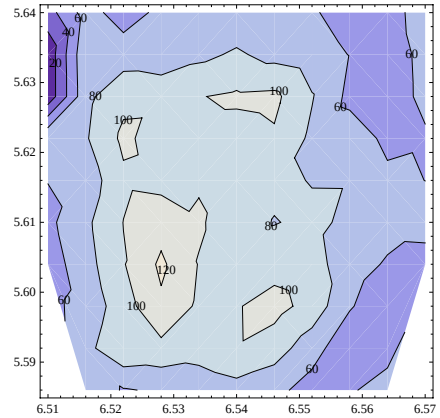
Luminosity commissioning

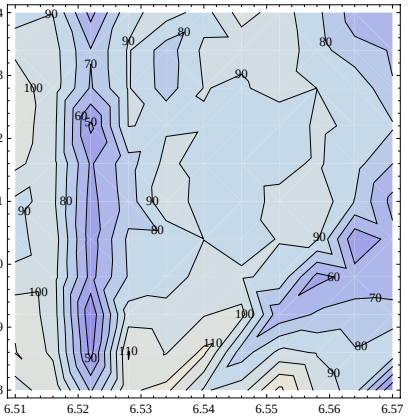


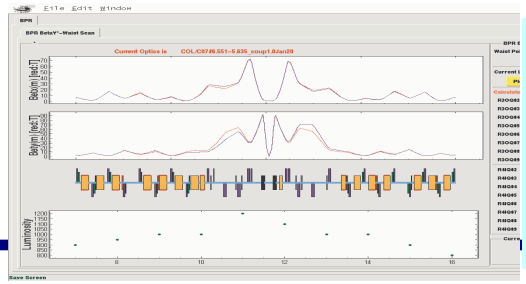


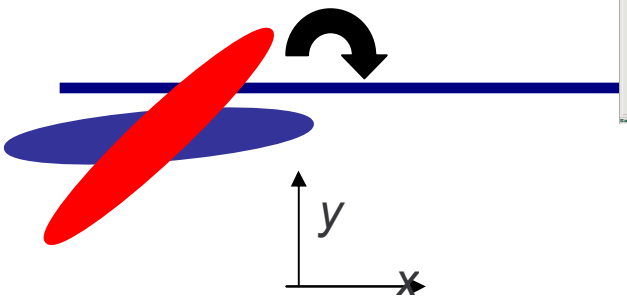












Single bunch collision

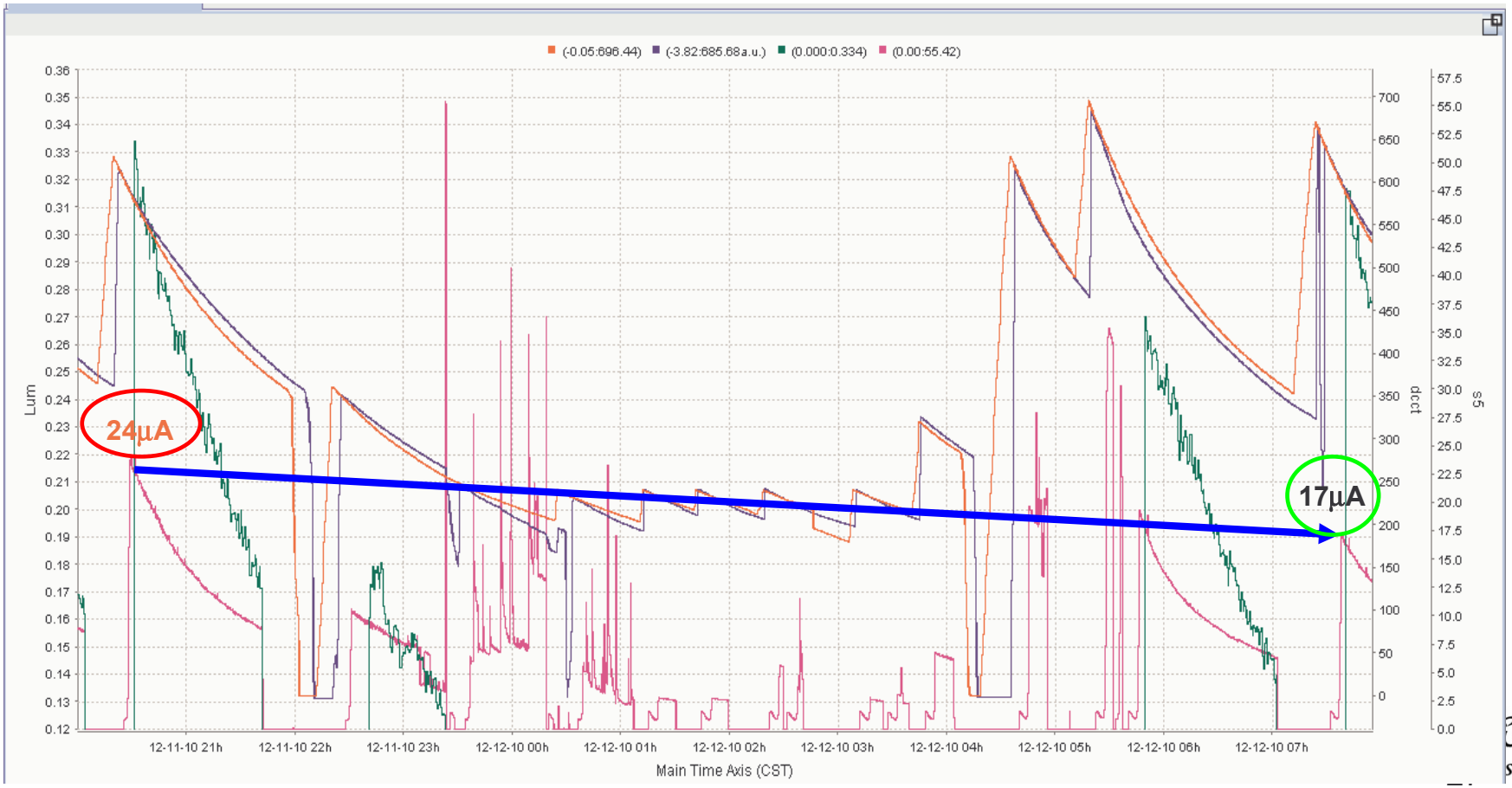
↓

Multi-bunch collision

中国科学院高能物理研究所
Institute of High Energy Physics

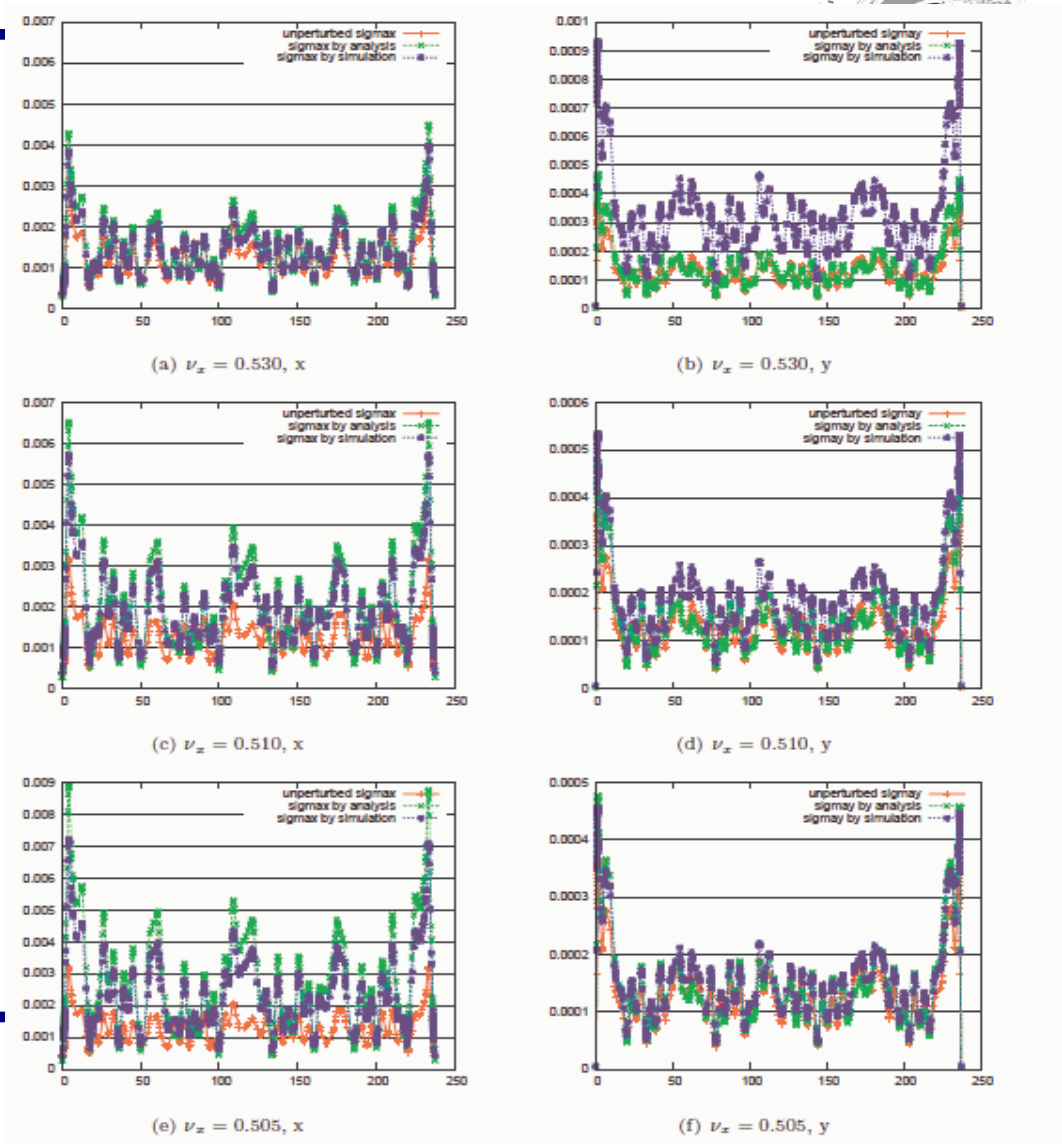
Big background of detector @ ν_x=0.51

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



(a) $\nu_x = 0.530$, x (b) $\nu_x = 0.530$, y

(c) $\nu_x = 0.510$, x (d) $\nu_x = 0.510$, y

(e) $\nu_x = 0.505$, x (f) $\nu_x = 0.505$, y

2009
2010
2011
6e+32
5e+32
4e+32
3e+32
2e+32
1e+32
lumnosity
300
350
400
450
500
550
600
650
700
beam current [mA]
Working pint close to half integer
caused ~ 30% increase of luminosity

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,

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

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

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

- For weak coupling, mode A and B similar to horizontal and vertical oscillation, respectively. ν_A & ν_B --- trans. Tunes
- One turn coupled transfer matrix: $T = G^{-1}\overline{V}\,\overline{U}\,\overline{V}^{-1}G$

  G is the Courant-Snyder transformation matrix, and

  R the rotation matrix

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

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

$$= \begin{pmatrix} \gamma\mathbf{I} & \bar{\mathbf{C}} \\ -\bar{\mathbf{C}}^{+} & \gamma\mathbf{I} \end{pmatrix}$$

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

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

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

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

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

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

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

- **BEPCII case:**

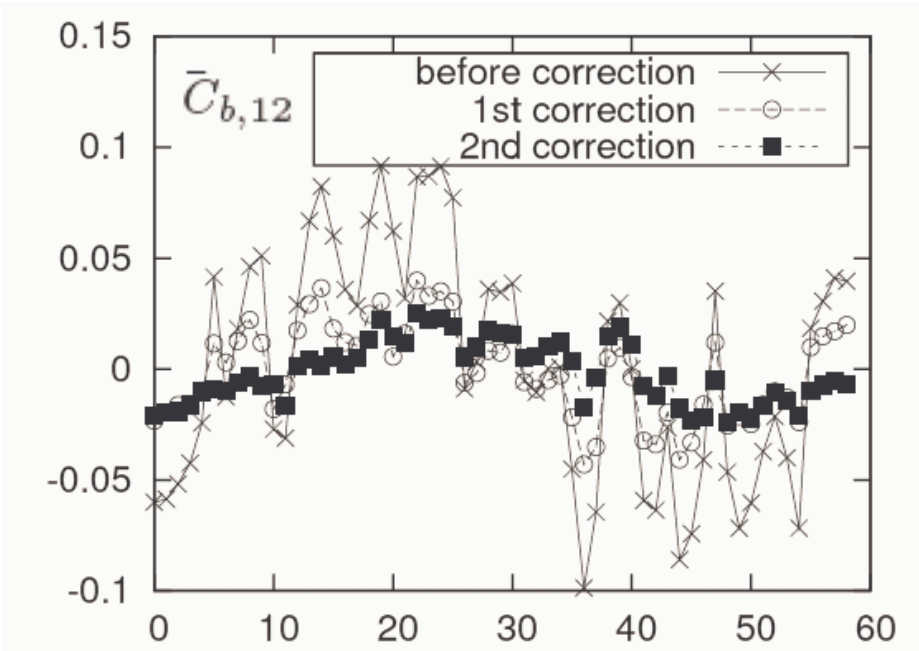
➢ **4 skew quads in each ring, not enough to do global correction**

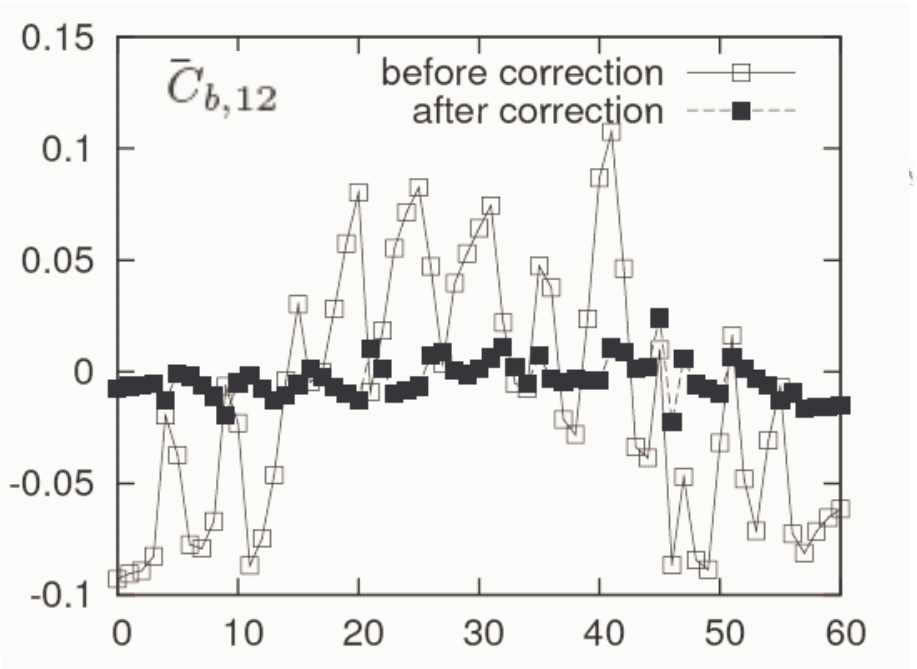
➢ **36 sextupoles in each ring, well distributed for coupling correction**

- **Way to realize coupling correction:**

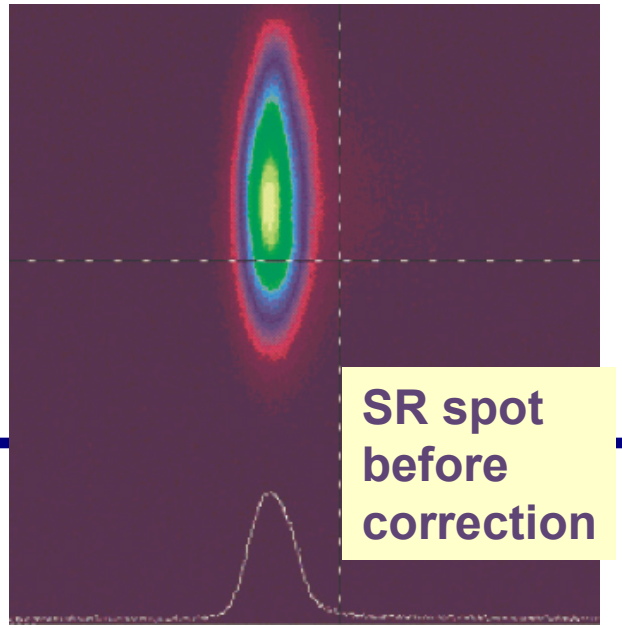
Model ⟹ **simulate the response of** $\bar{C}_{b,12}$ **due to vertical corrector strength change**

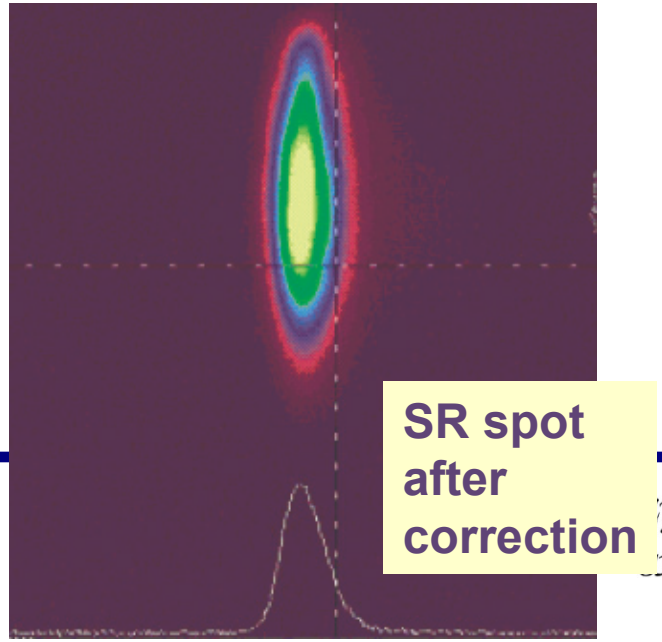
⟹ **get the strength of correctors from measured** $\bar{C}_{b,12}$





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

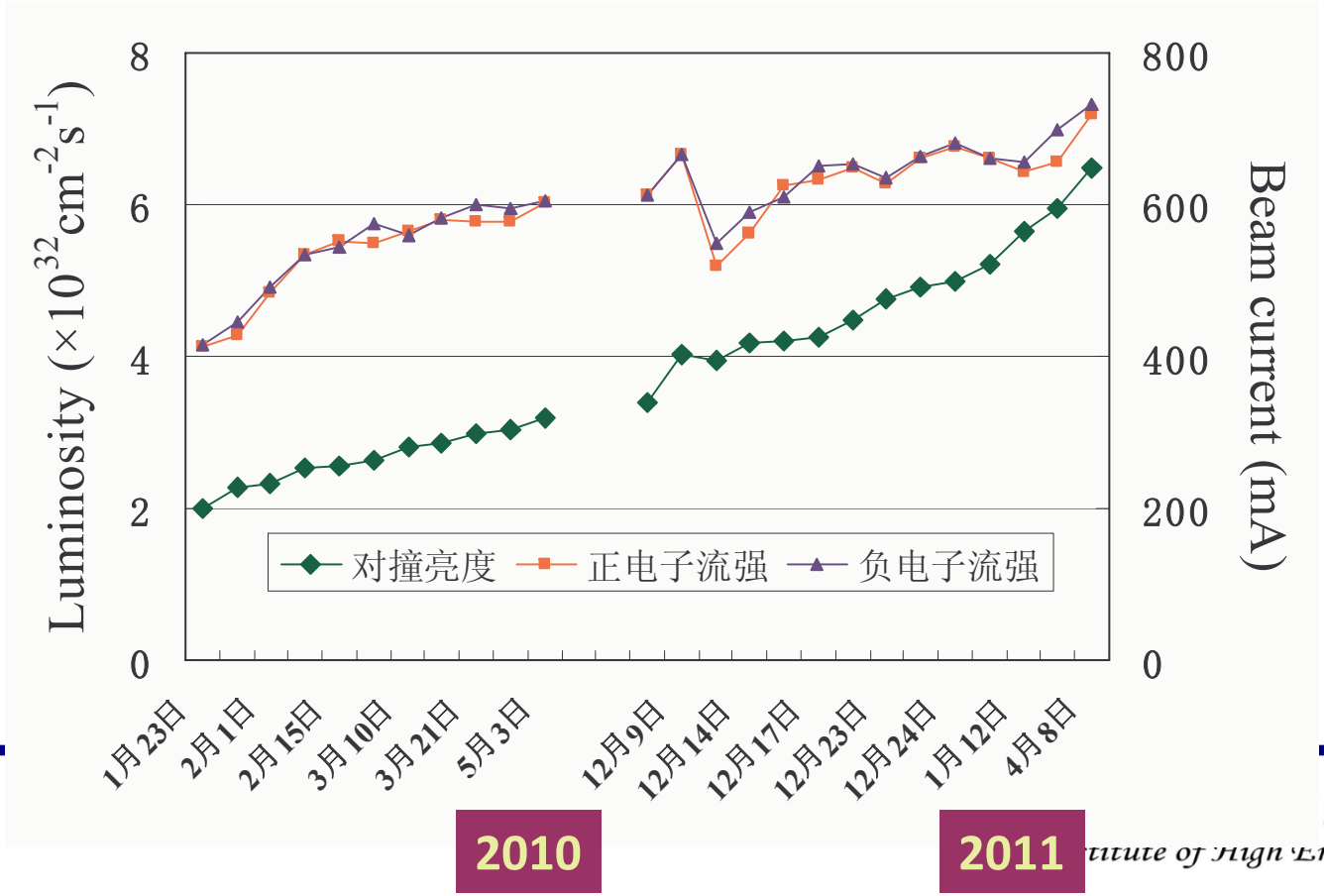




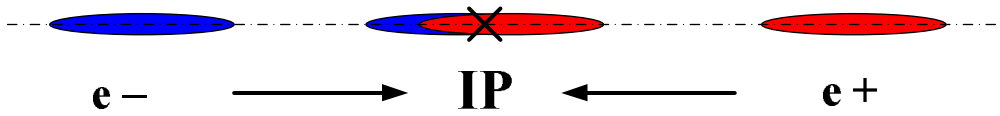
- Two knobs of coupling correction were done for luminosity optimization
  - --- vertical local bump in sextupoles
  - --- global vertical orbit tuning to minimize vertical emittance by reducing $\overline{C}_{12}$ at BPMs
- Measurement of coupling was done by turn-by-turn BPM data

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

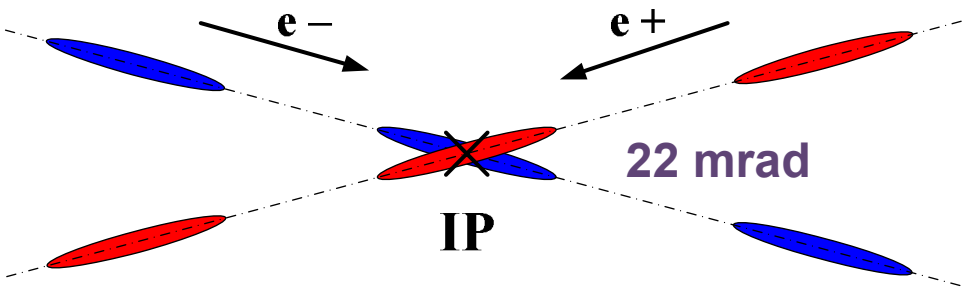
- **Luminosity enhanced by ν_x --> 0.5 (0.506), reducing emittance coupling, and increasing beam current**



5. Beam-beam interaction

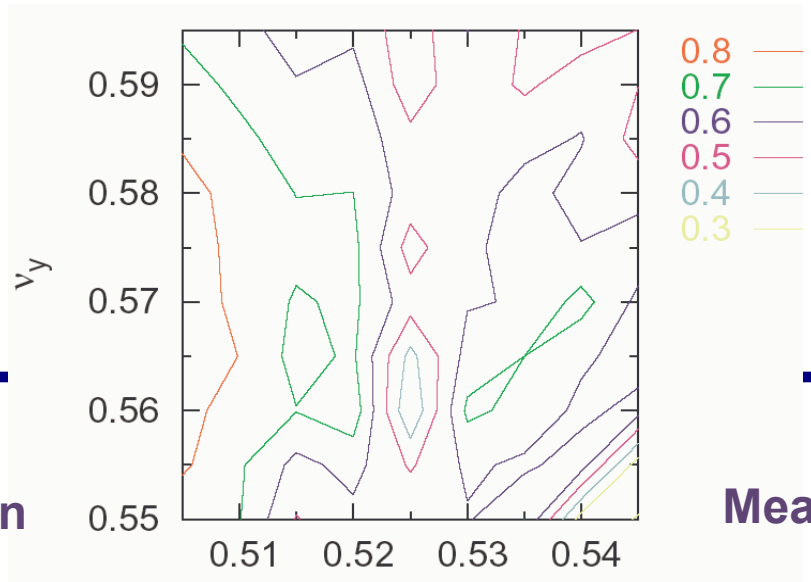


BEPC

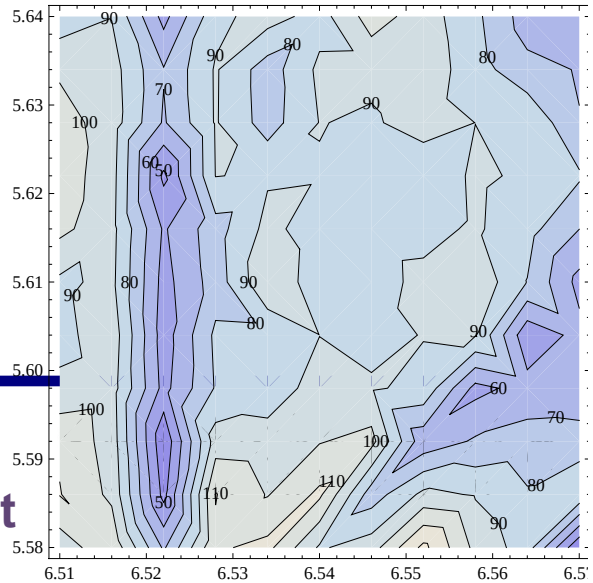


BEPCII

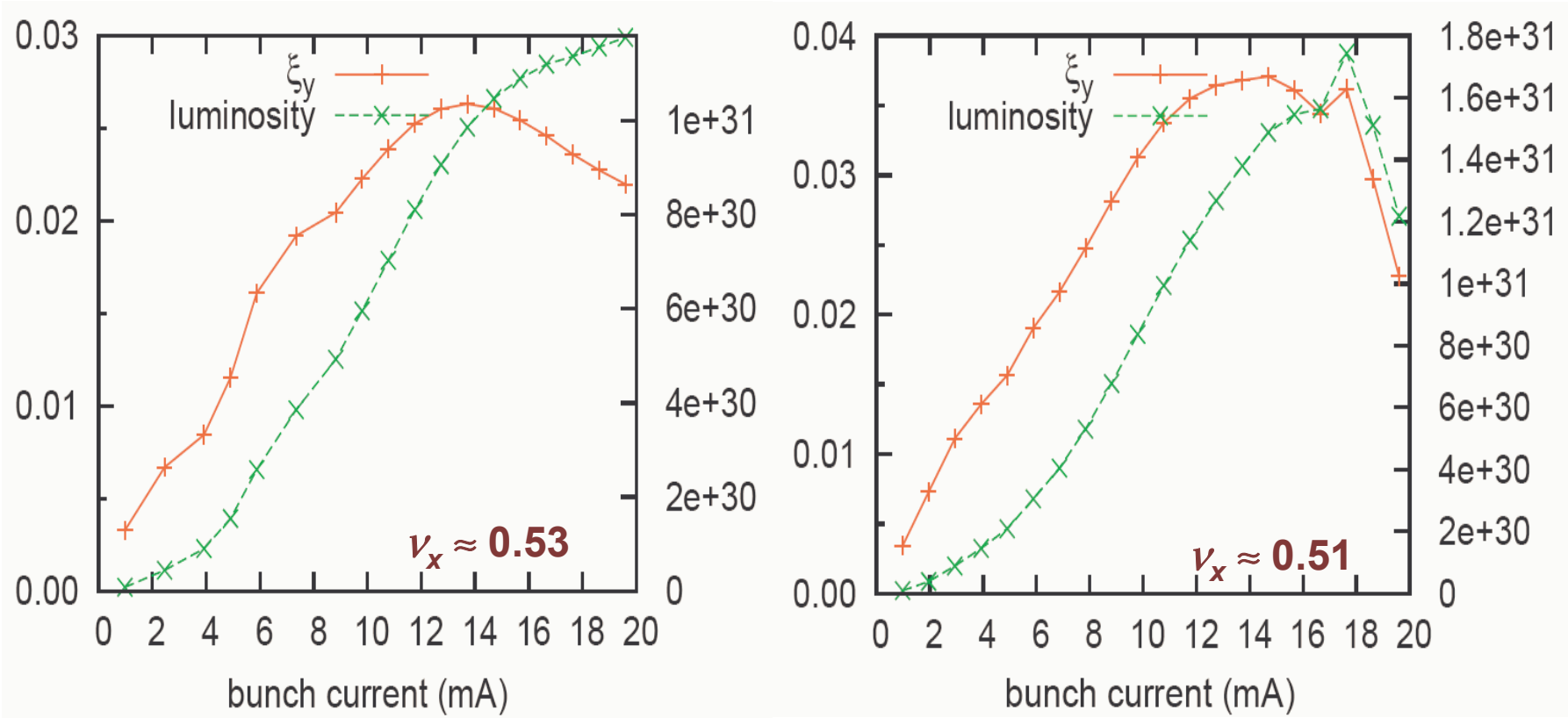
Simulation



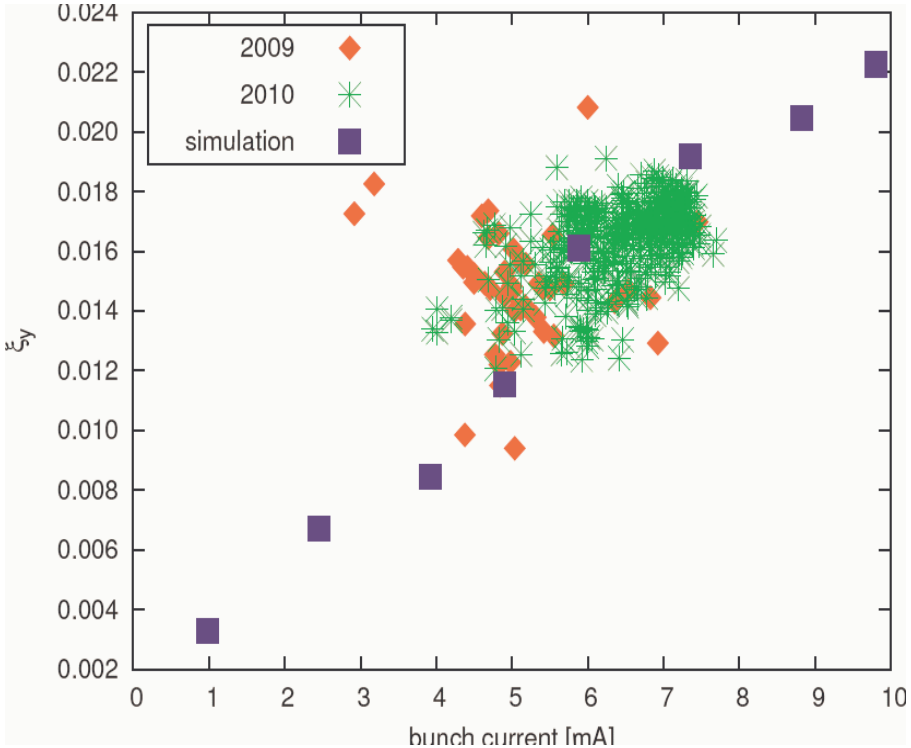
Measurement

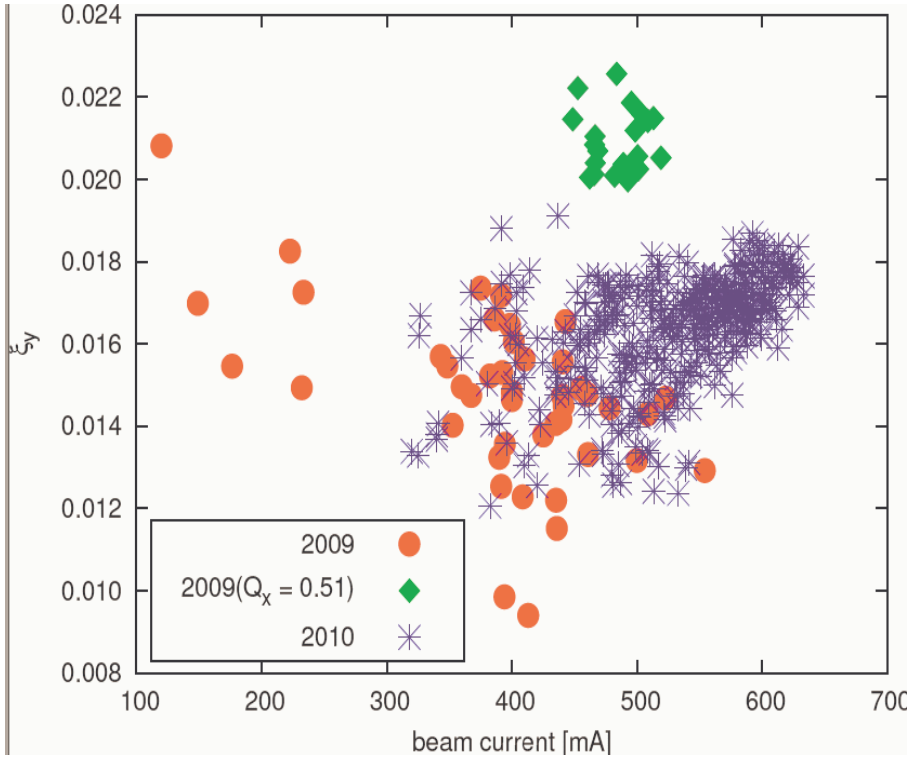


Strong-strong simulation results in different tune region



Simulated and achieved ξ_y in different tune region





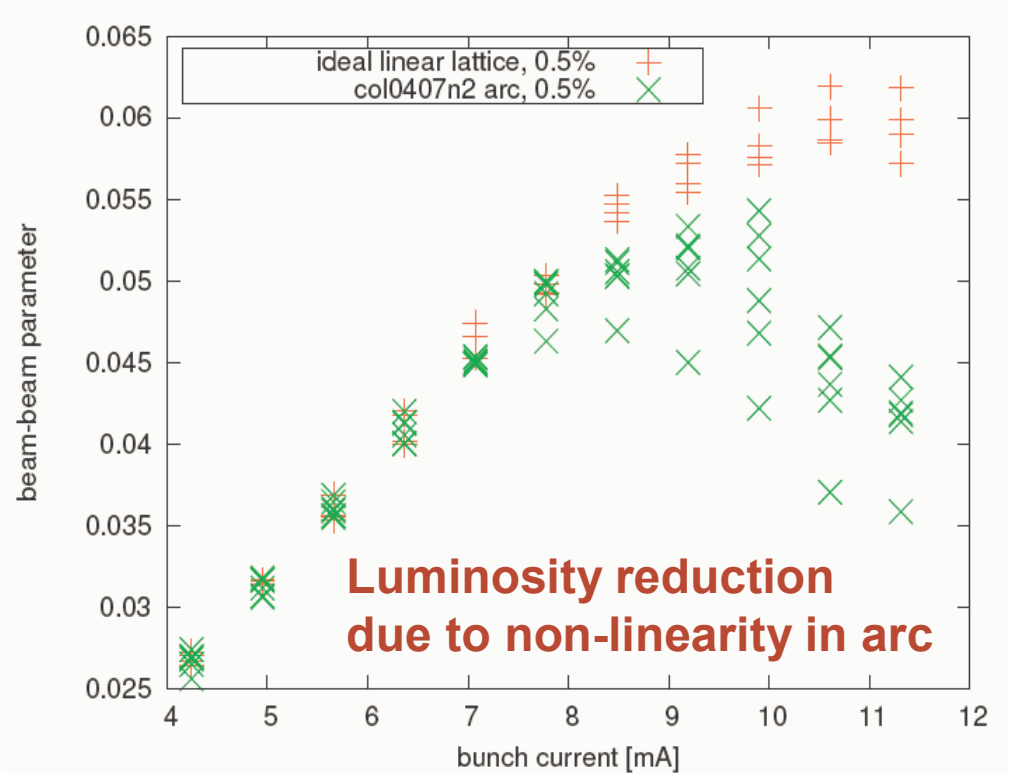
• Weak-strong model simulation study:

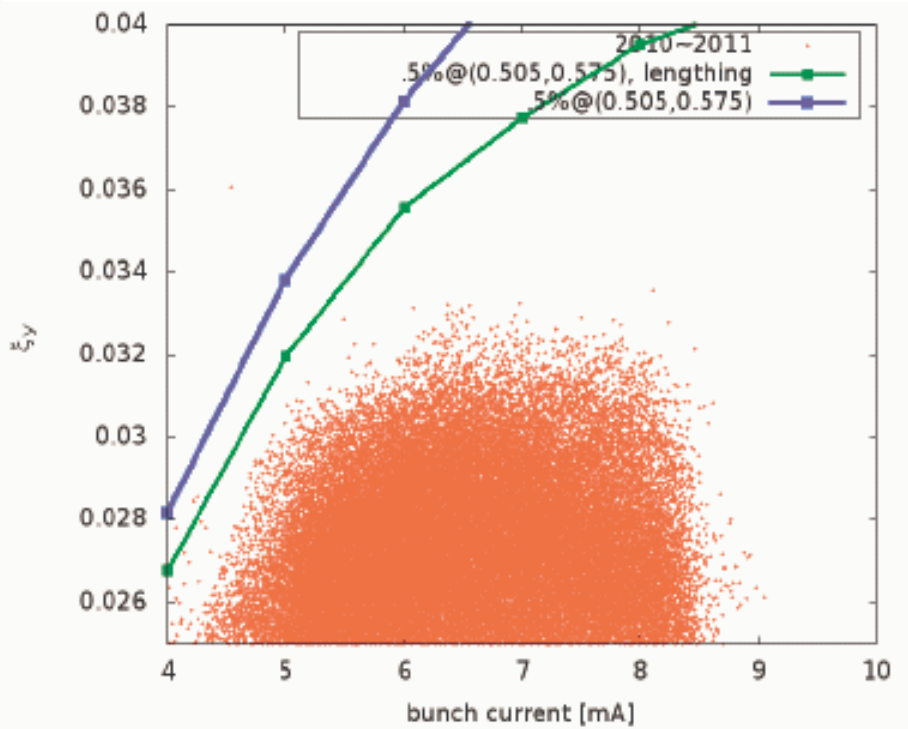
--- Hirata's BBC as a pass mathod in AT

--- Element-by-element tracking in arc

--- Synchrotron oscillation (RF on)

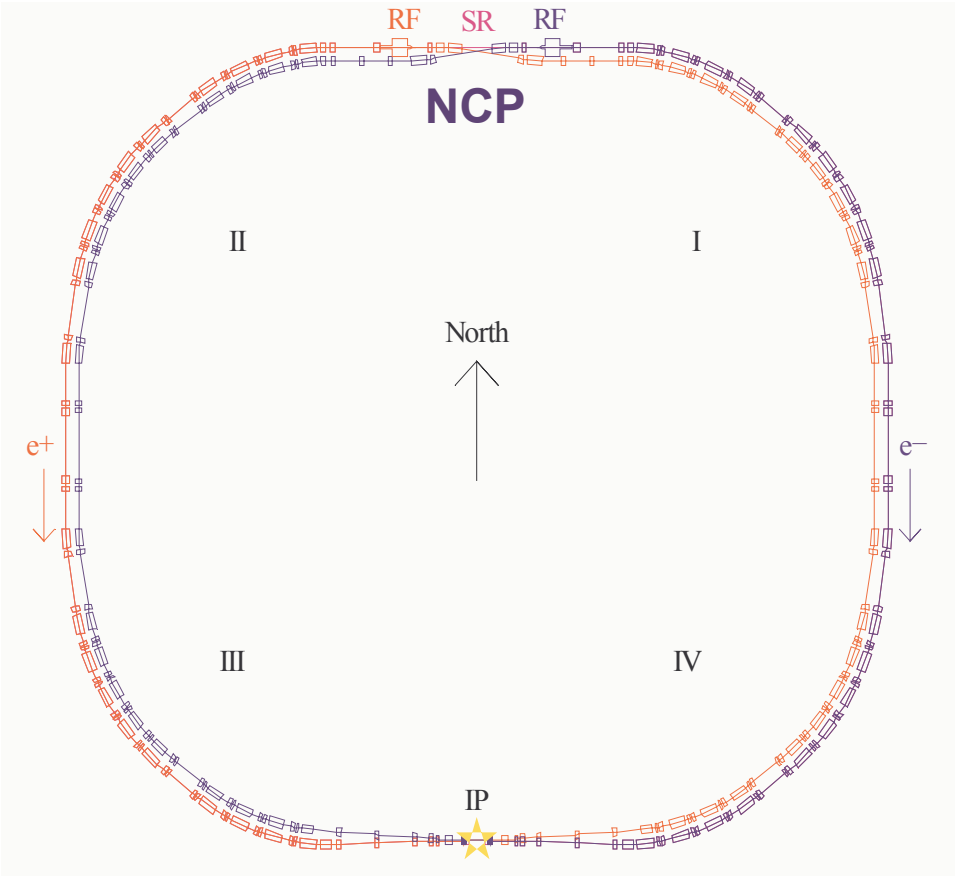
--- Radiation damping and quantum excitation included





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

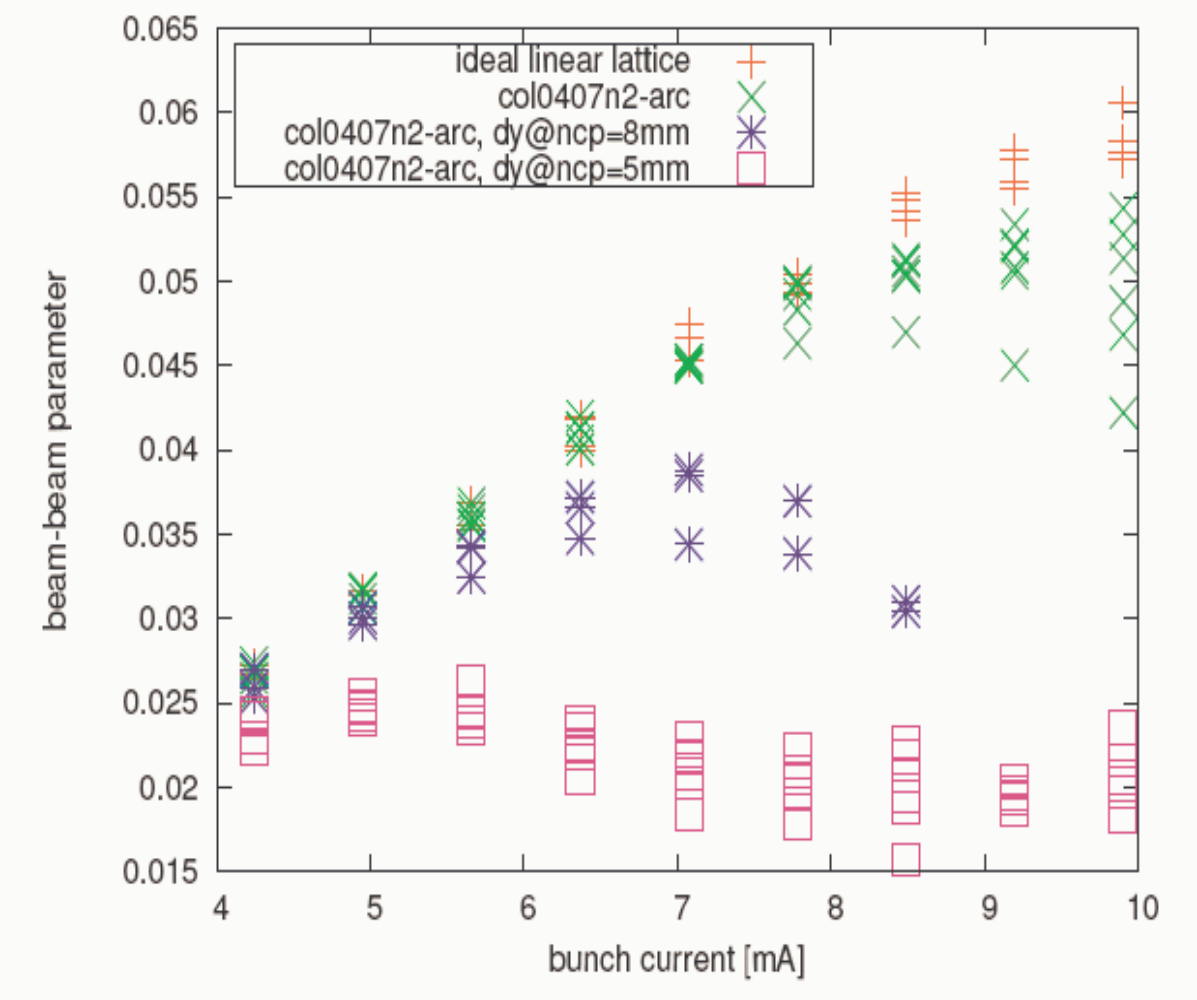


At NCP, Δy = 5mm (~$4\sigma_x$ and $50\sigma_y$)

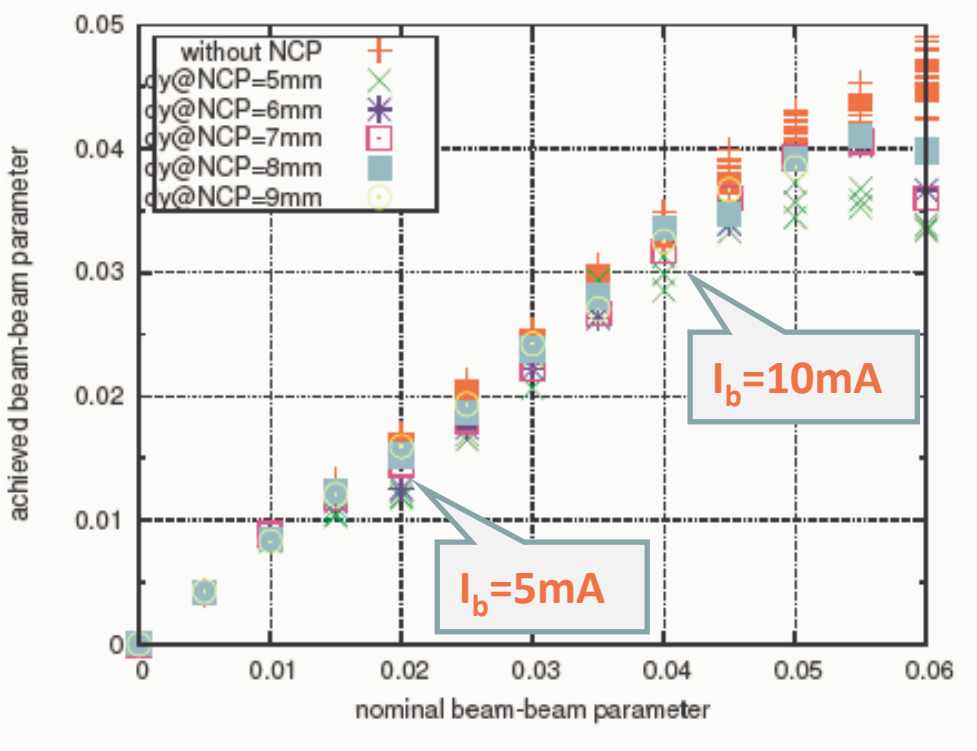
β_x / β_y = 12m / 8.5m

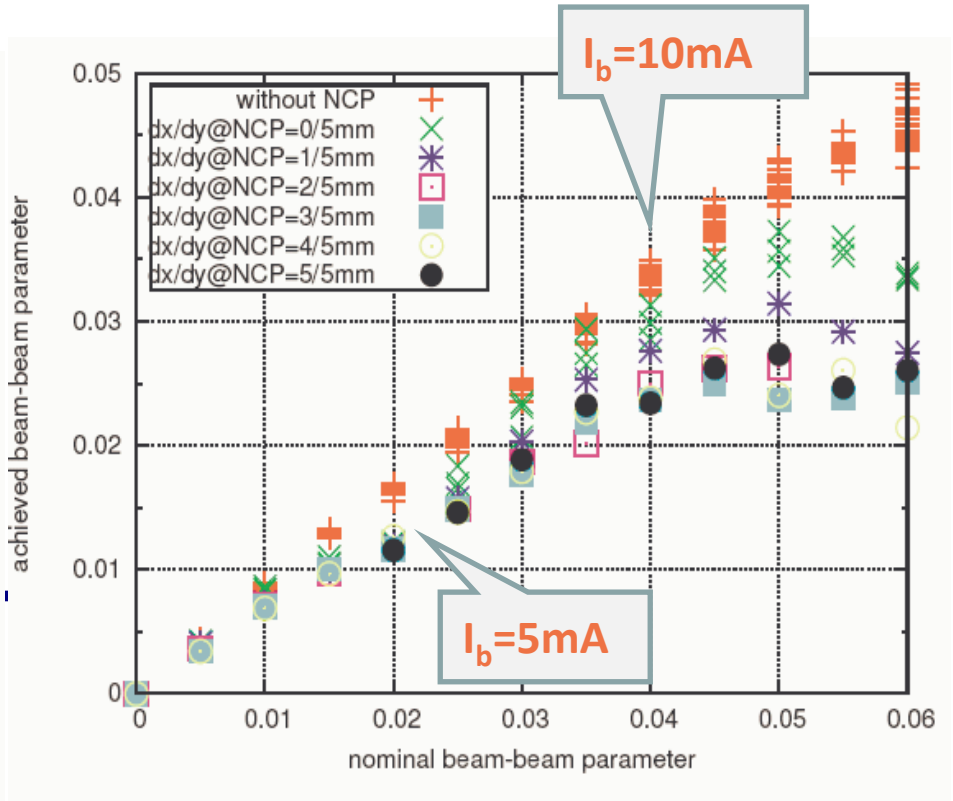
$(\tan\theta\ \sigma_z)/\sigma_x$ = 1.8

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



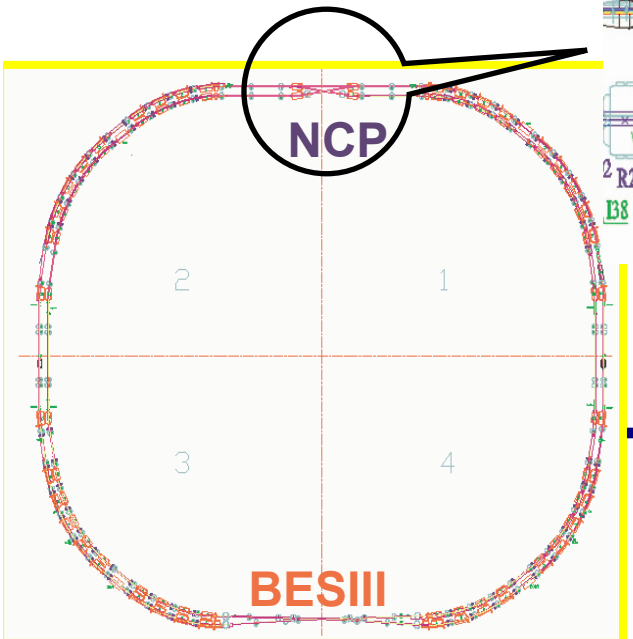
- **Furthermore, horizontal separation @ NCP also affect the beam-beam interaction**

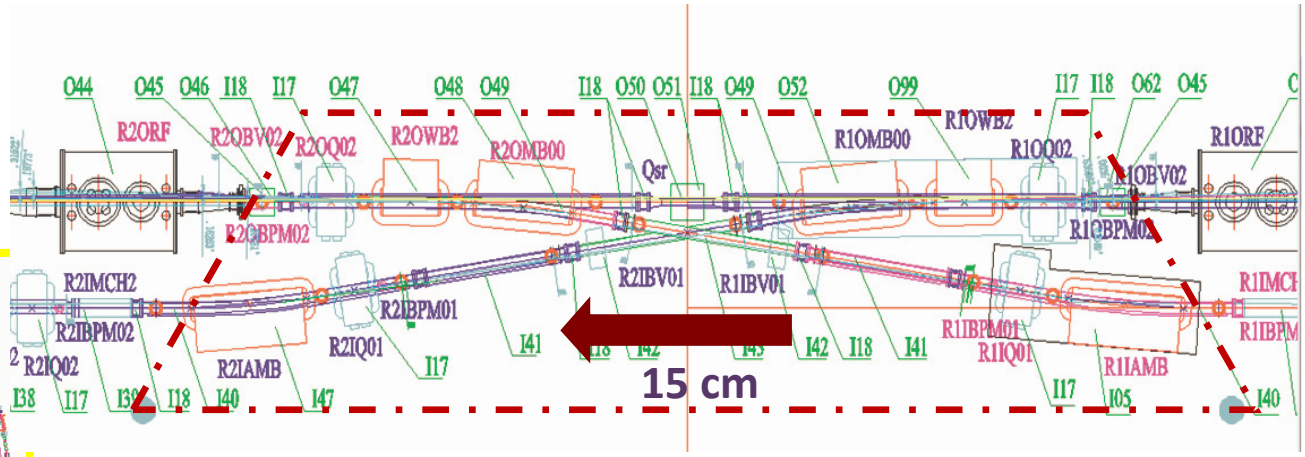




What we did in last summer shutdown

- 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

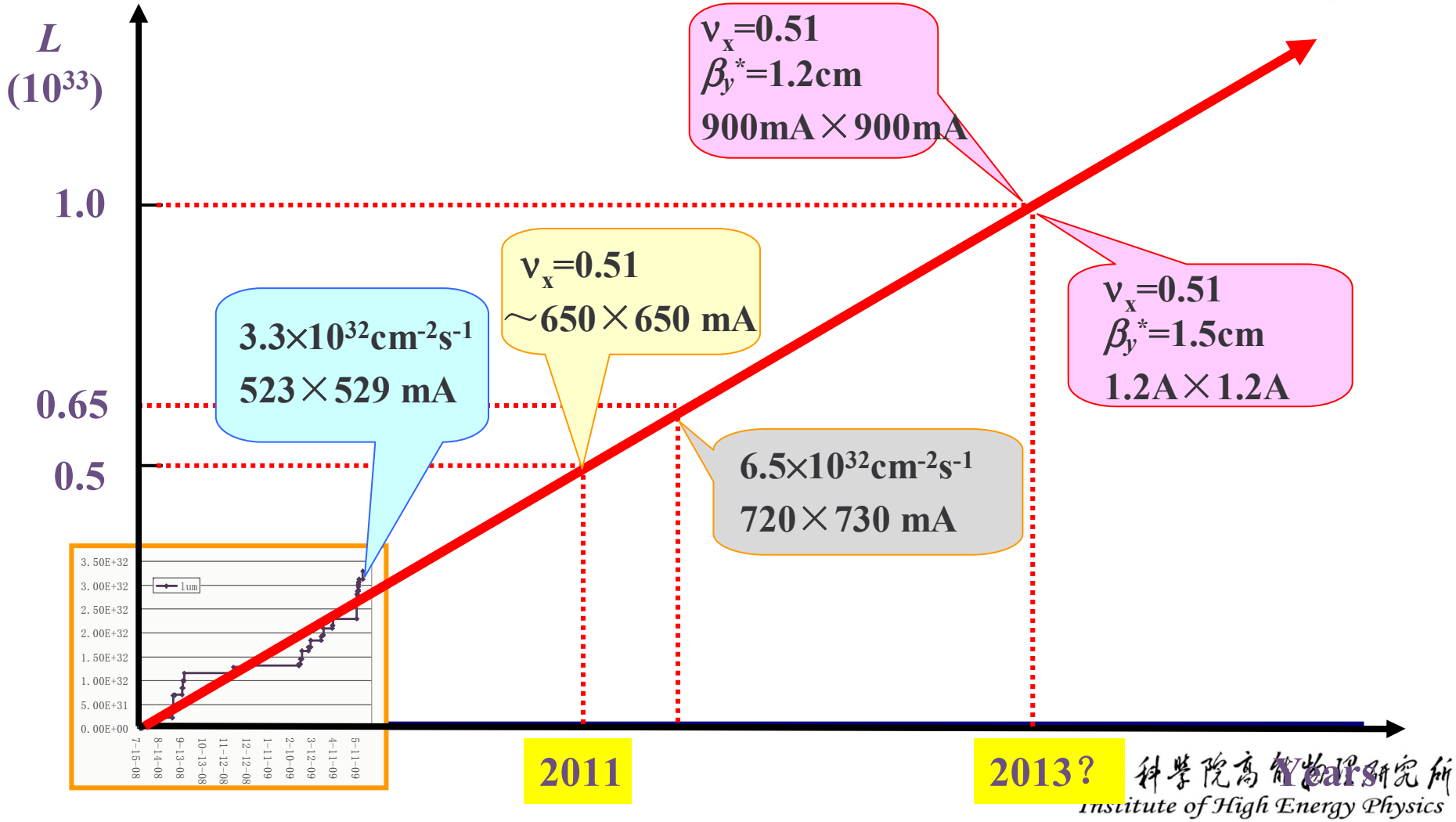
Summary

- A lot of AP work have been done from the beginning of the machine commissioning
- Luminosity goes up with the optics optimization, instability cure, and beam-beam studies
- Further luminosity enhancement is foreseen, by the means of increasing bunch current and bunch number, squeezing β_y^*, etc.
- Possibility of polarized e- beam is investigated for more physics results.

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



Acknowledgement

- Some inputs are from Y. Zhang, C.H. Yu, D.H. Ji, Y.Y. Wei, etc.
- The commissioning and operation groups of BEPCII

Thanks for your attentation !