Chromatic aberrations in the KEKB

Demin Zhou

Thanks to Y. Cai and G. Stupakov for hosting my visit.

and

Acknowledgements: K. Ohmi, Y. Funakoshi, Y. Ohnishi, Y. Seimiya and all KEKB group members

SLAC, Aug. 20, 2010

Outline

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2. Chromatic aberrations (momentum-dependent nonlinearities)

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2.2 Measurements (Y. Ohnishi, K. Ohmi, et al.)

2.3 Simulations (D. Zhou, K.Ohmi, et al.)

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3. Summary

KEKB B-Factory

Milestones since 2007

2007 Jan. Crab cavities installed

2007 Mar. Crab tuning started

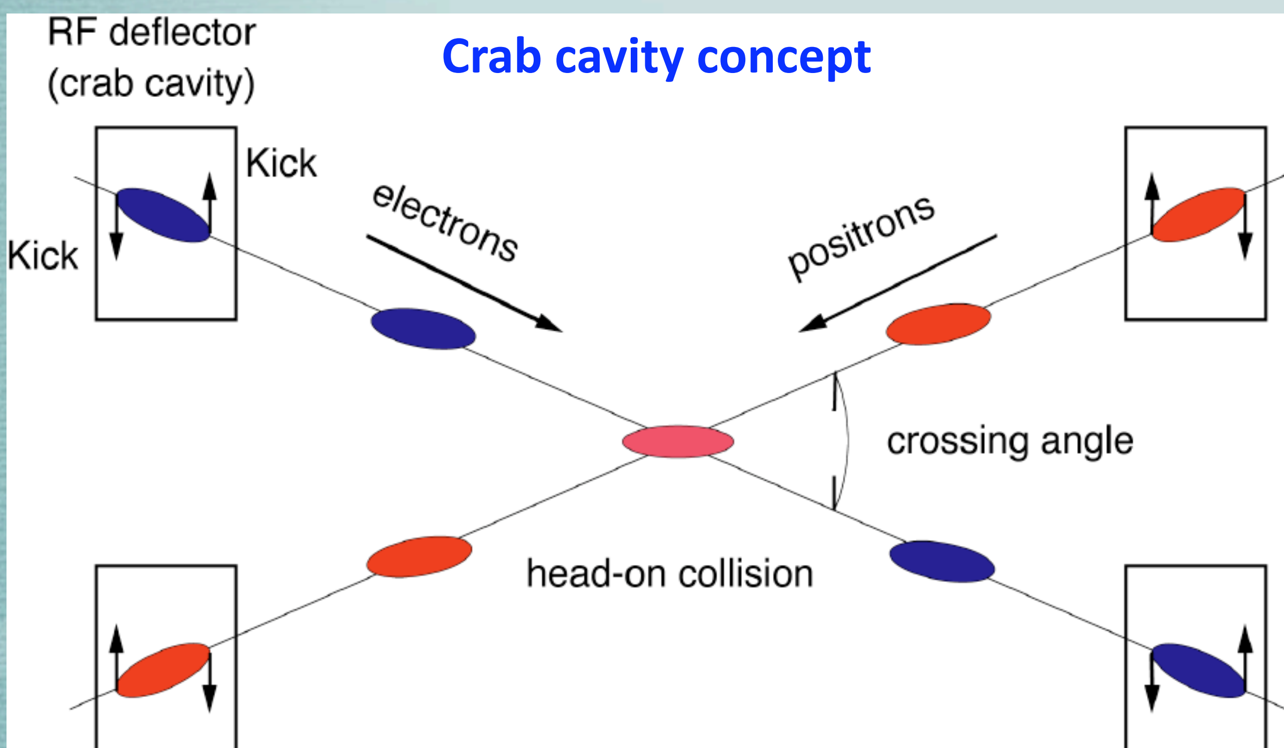
2009 Apr. Skew-sext. installed

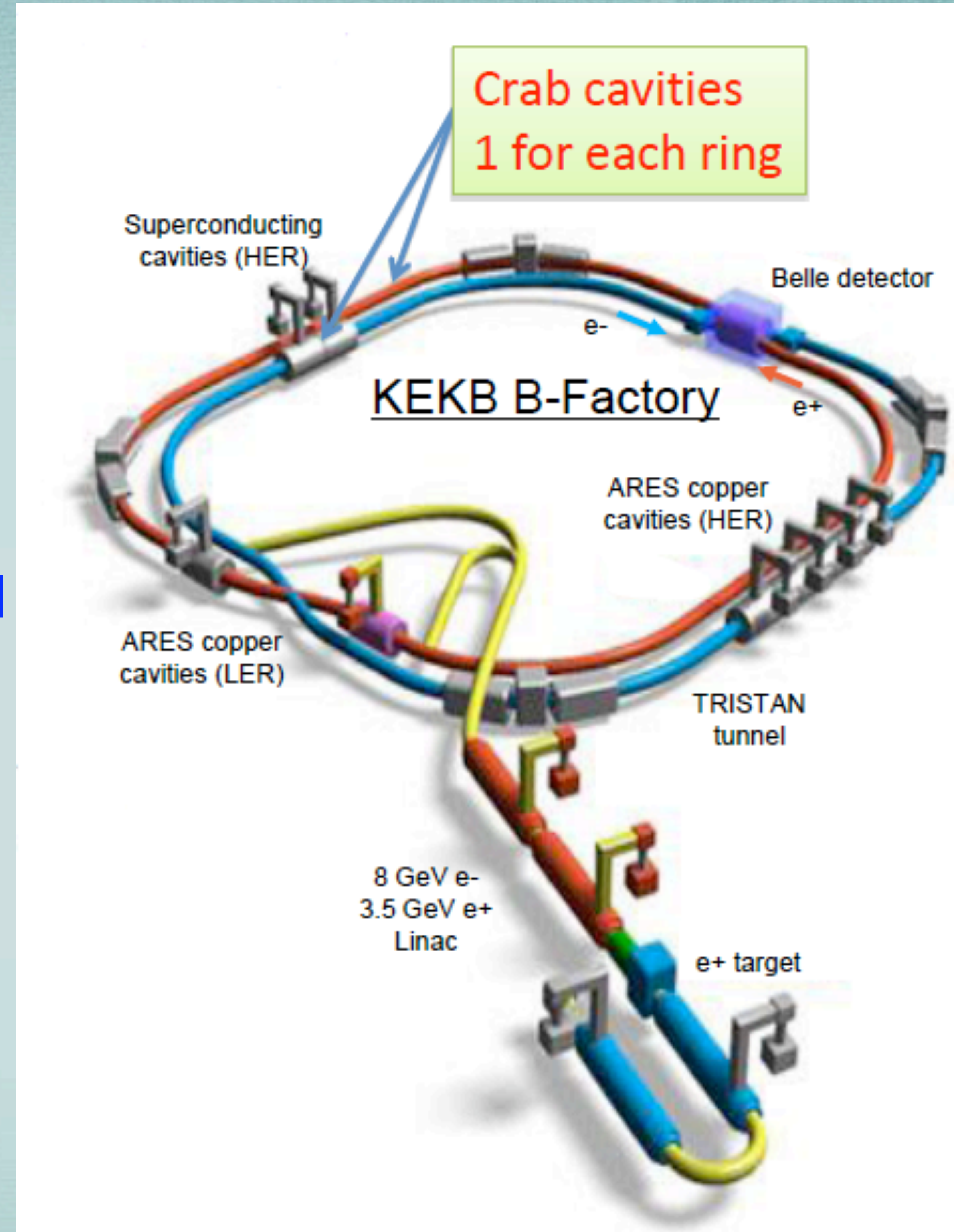
2009 Jun. Lum. ➸ $2.11 \times 10^{34} cm^{-2}s^{-1}$

2009 Nov. ∫Lum. ➸ 1000 fb^{-1}

2010 Jun. KEKB shut down

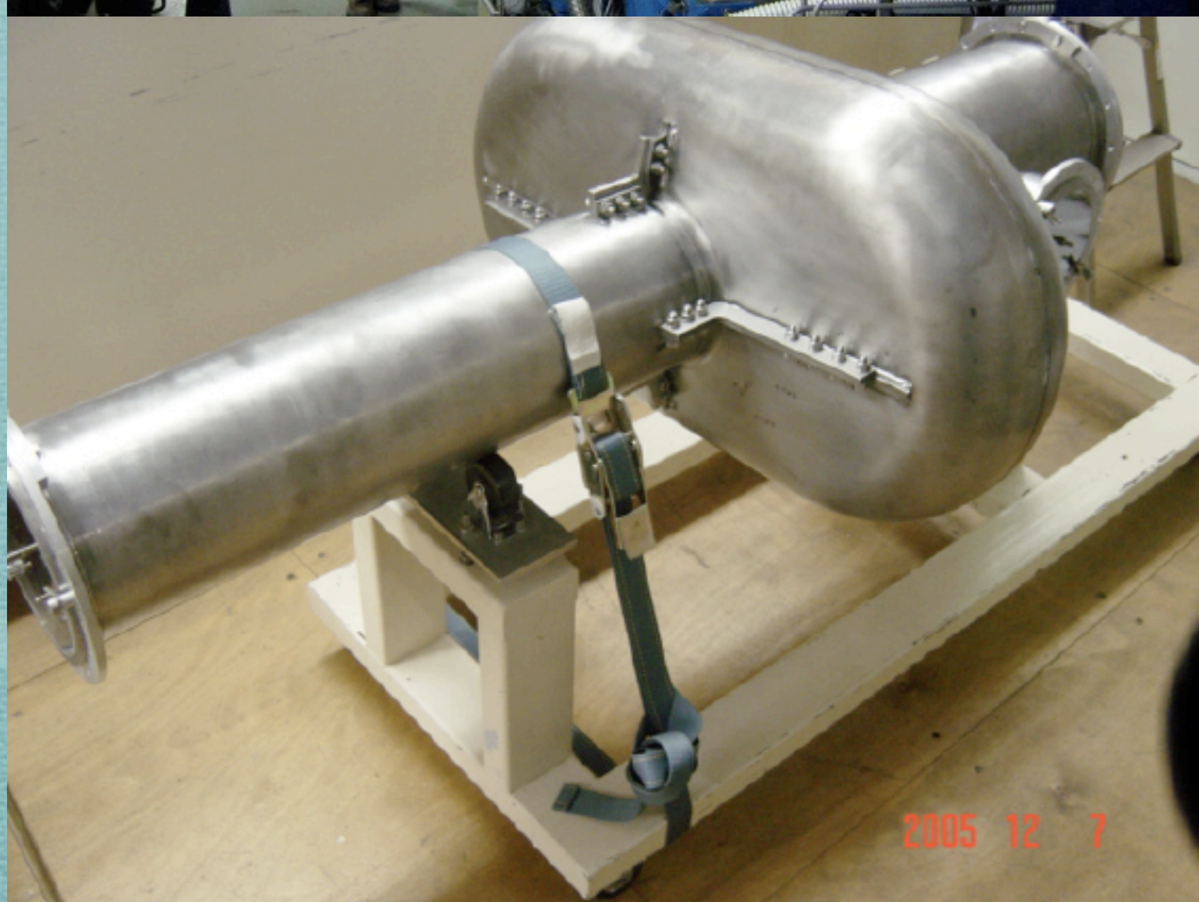
2010 Jun. SuperKEKB officially approved

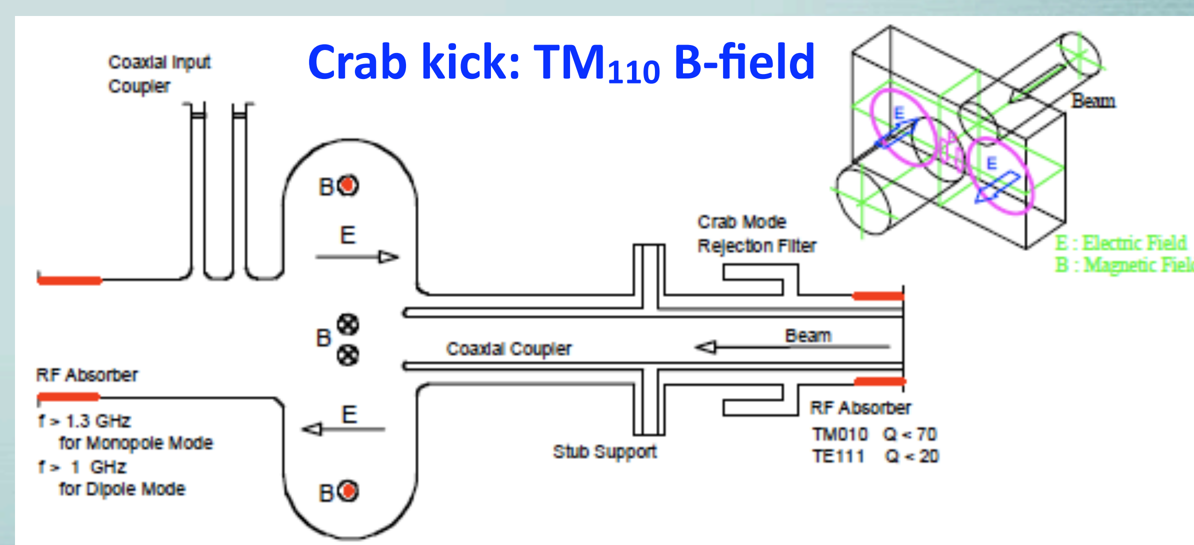




Ref. Y. Funakoshi, IPAC10

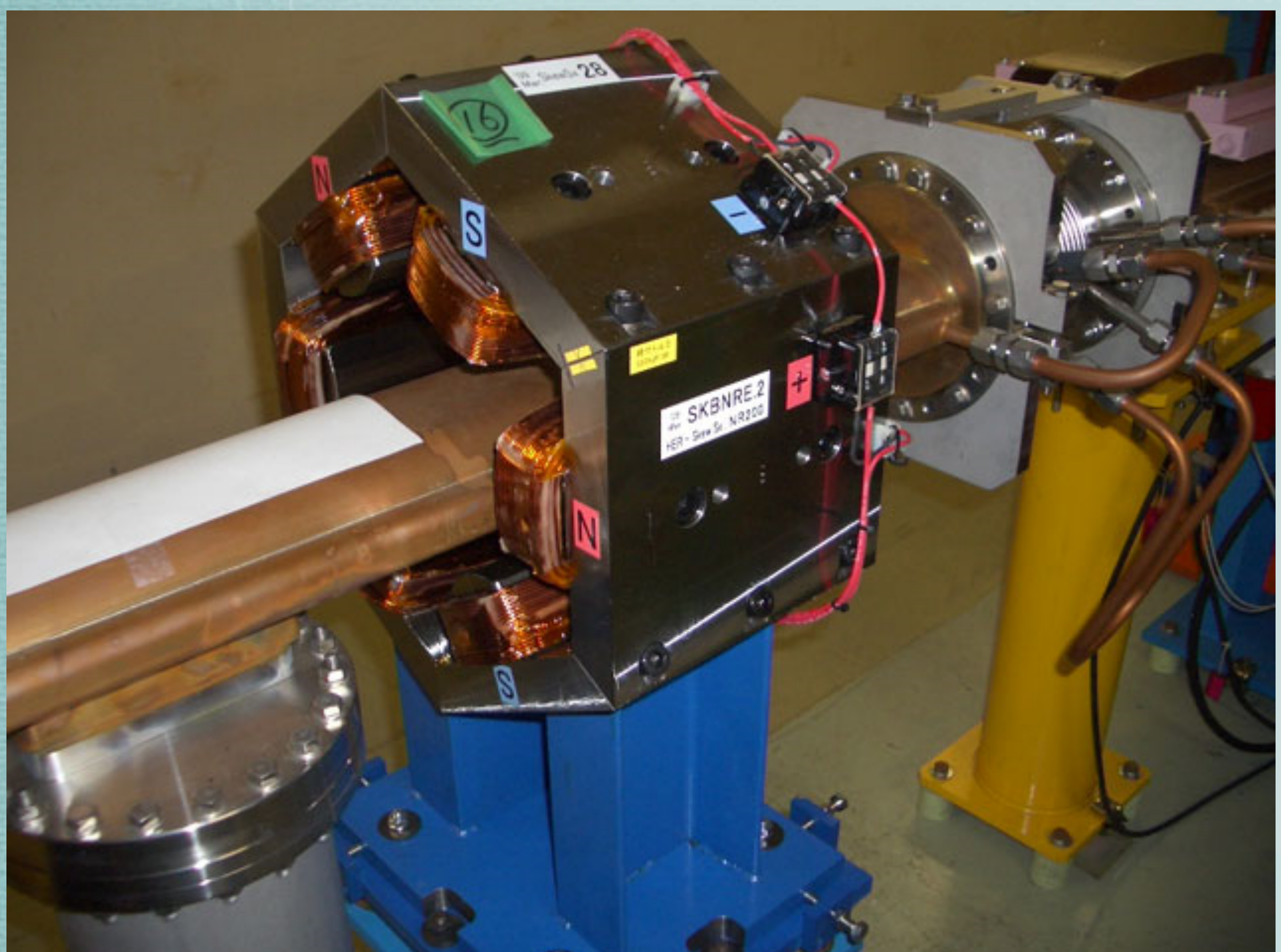
Crab cavity

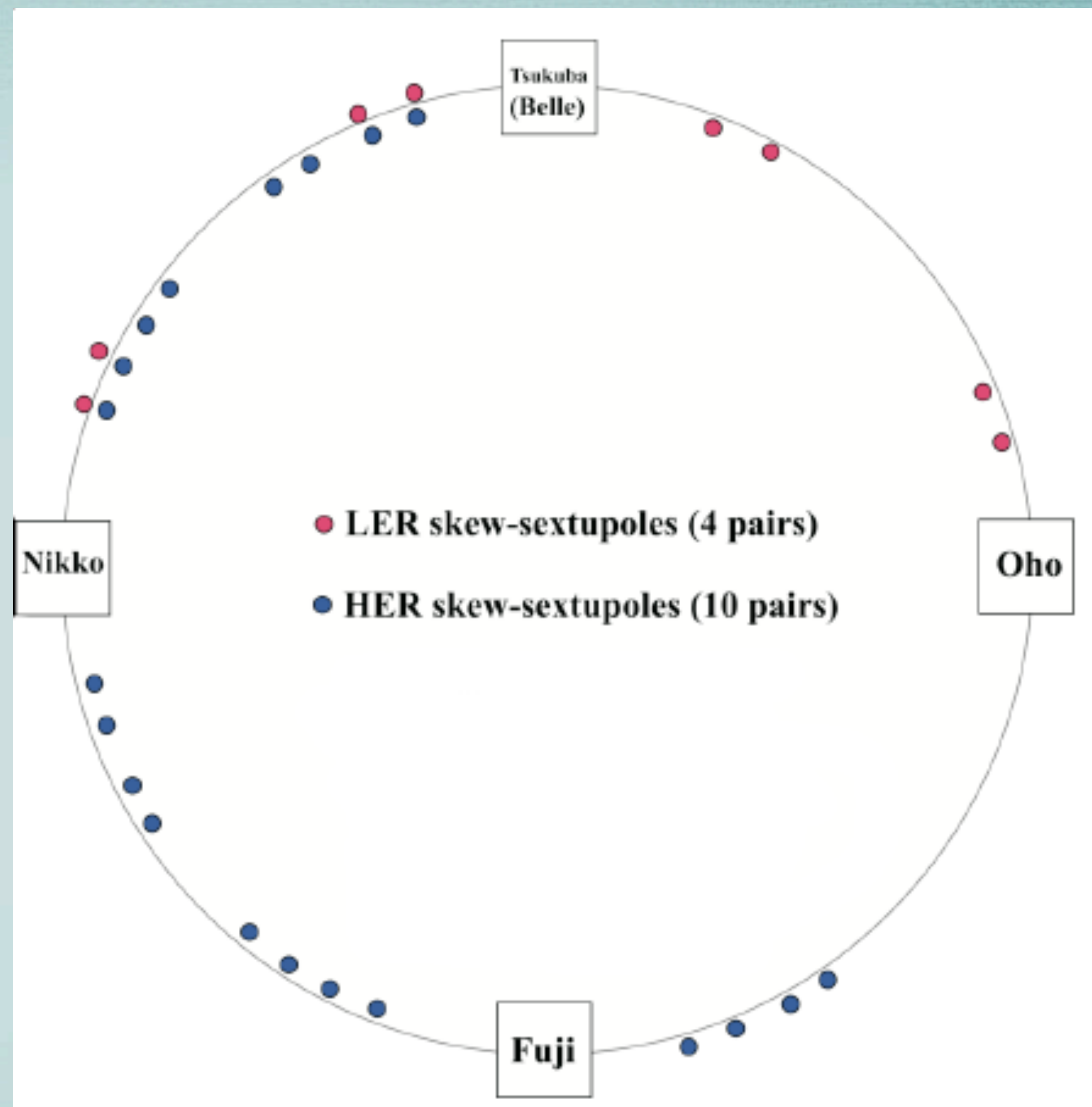




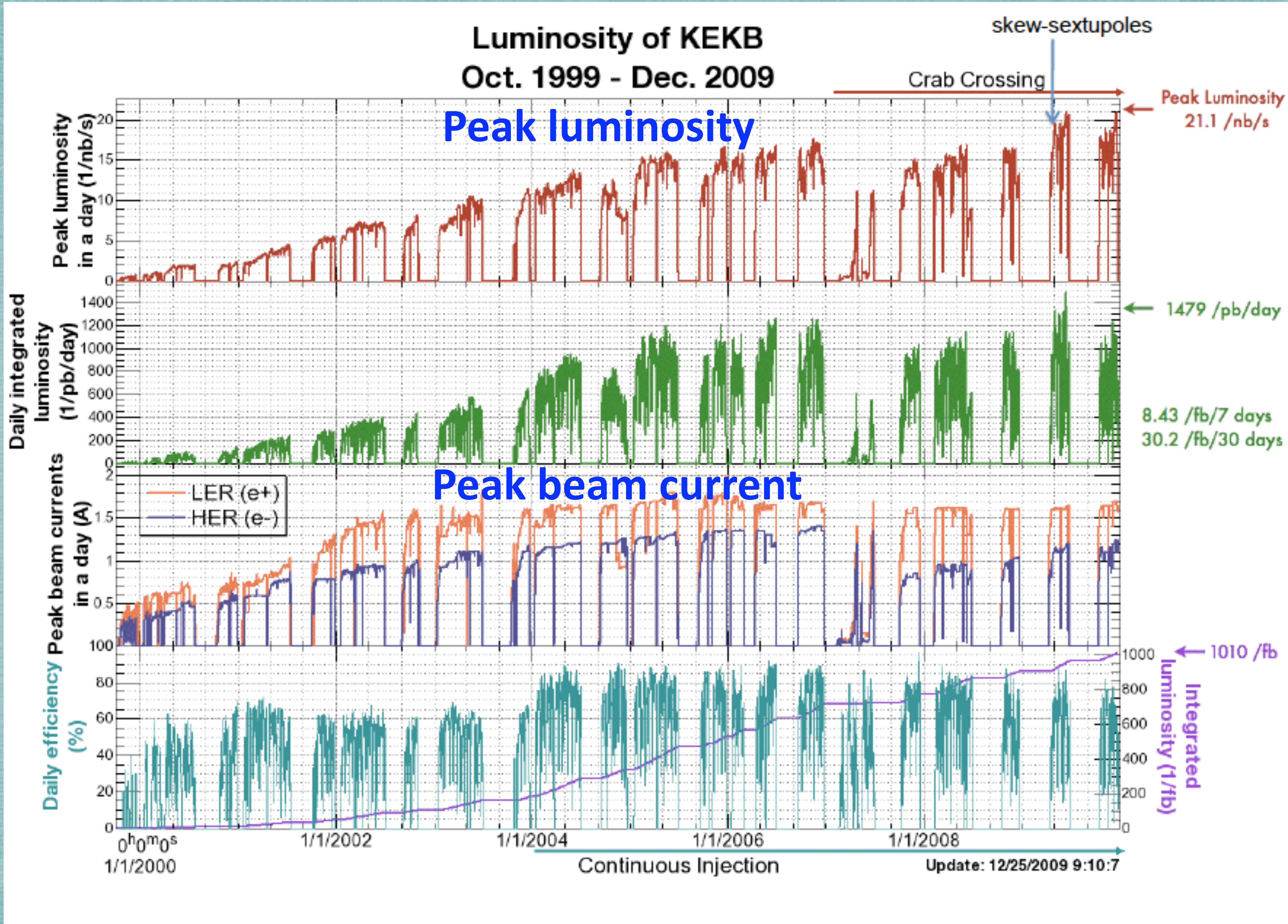
Ref. Y. Funakoshi, IPAC10
K. Hosoyama, EPAC08

Skew-sextupole





Ref. Y. Funakoshi, IPAC10



Ref. Y. Funakoshi, IPAC10

Machine parameters

Date	Nov.15 2006 before crab		Jun. 17 2009 with crab		
	LER	HER	LER	HER	
Current	1.65	1.33	1.64	1.19	A
Bunches	1389		1584		
Bunch current	1.19	0.96	1.03	0.750	mA
spacing	2.10		1.84		mA
emittance ε_x	18	24	18	24	nm
β_x^*	59	56	120	120	cm
β_y^*	6.5	5.9	5.9	5.9	mm
σ_x @IP	103	107	147	170	μm
σ_y @IP	1.8	1.8	0.94	0.94	μm
ν_x	45.505	43.534	45.506	44.511	
ν_y	44.509	41.565	43.561	41.585	
ν_s	-0.0246	-0.0226	-0.0246	-0.0209	
beam-beam ξ_x	0.117	0.070	0.127	0.102	
beam-beam ξ_y	0.108	0.058	0.129	0.090	
Luminosity	17.6		21.08		$10^{33}cm^{-2}s^{-1}$

NOTE:
With crab cavities installed, β_x^* could not be small enough due to poor beam lifetime.

Ref. Y. Funakoshi, IPAC10

Chromatic aberration - Theory

The ideas:

✓ All machine parameters depend on momentum deviation.
✓ Extend Courant-Snyder formalism to off-momentum particles.
✓ Re-construct the symplectic map in 6-D phase space to include the crosstalk between betatron and synchrotron motion.
✓ Implement the map for chromatic aberrations in beam-beam simulations.
✓ Evaluate the luminosity loss using simulations.

Chromatic aberrations (definition):

$$\alpha_u(\delta) = \sum_{i=0}^{\infty} \alpha_{ui}\delta^i \qquad \beta_u(\delta) = \sum_{i=0}^{\infty} \beta_{ui}\delta^i$$

$$\nu_u(\delta) = \sum_{i=0}^{\infty} \nu_{ui}\delta^i \qquad r_j(\delta) = \sum_{i=0}^{\infty} r_{ji}\delta^i$$

$$u = x, y \quad \text{and} \quad j = 1, 2, 3, 4,$$

$$\delta = (p - p_0)/p_0$$

NOTE:
Chromatic aberrations can be estimated using optics codes or measured using beam.

Y. Seimiya, et al., to be published.
D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Theory

Matrix formalism for transverse motion:

$$M_4(\delta) = R(\delta) \cdot M_{\rm lin}(\delta) \cdot R^{-1}(\delta)$$

$$M_{\rm lin}(\delta) = \begin{pmatrix} M_x & 0 \\ 0 & M_y \end{pmatrix}$$

$$R(\delta) = \begin{pmatrix} r_0 I_2 & -S_2 R_2^T(\delta) S_2 \\ -R_2(\delta) & r_0 I_2 \end{pmatrix}$$

$$M_u = \begin{pmatrix} \cos\mu_u(\delta) + \alpha_u(\delta)\sin\mu_u(\delta) & \beta_u(\delta)\sin\mu_u(\delta) \\ -\gamma_u(\delta)\sin\mu_u(\delta) & \cos\mu_u(\delta) - \alpha_u(\delta)\sin\mu_u(\delta) \end{pmatrix} \qquad u = x, y$$

$$R_2(\delta) = \begin{pmatrix} r_1(\delta) & r_2(\delta) \\ r_3(\delta) & r_4(\delta) \end{pmatrix}$$

$$I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad S_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$

Y. Seimiya, et al., to be published.
D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Theory

Hamiltonian of off-momentum particles (X-Z, X-Y-Z, Y-Z coupling):

$$H_I(x, p_x, y, p_y, \delta) = \sum_{n=1}^{\infty}(a_n x^2 + b_n x p_x + c_n p_x^2 + e_n x p_y + f_n p_x y + g_n p_x p_y + u_n y^2 + v_n y p_y + w_n p_y^2)\delta^n$$

Assume that matrix formalism and Hamiltonian formalism are equivalent:

$$M_4(\delta) = M_4(0) \cdot M_H(\delta)$$

Then the Hamiltonian coefficients are determined by expanding the above equation and equalizing the series term by term.

Y. Seimiya, et al., to be published.
D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Theory

Symplectic map for chromatic aberrations:

$$\bar{p}_x = \frac{(1+V)(p_x - Ax - Dy) - E(p_y - Uy - Dx)}{(1+B)(1+V) - EF}$$

$$\bar{p}_y = \frac{p_y - Ux - Dy - F\bar{p}_x}{1+V}$$

$$\bar{x} = (1+B)x + C\bar{p}_x + Fy + G\bar{p}_y$$

$$\bar{y} = (1+V)y + W\bar{p}_y + Ey + G\bar{p}_x$$

$$\bar{\delta} = \delta$$

$$\bar{z} = z + A'(\delta)x^2 + B'(\delta)x\bar{p}_x + C'(\delta)\bar{p}_x^2 + D'(\delta)xy + E'(\delta)x\bar{p}_y + F'(\delta)\bar{p}_x y + G'(\delta)\bar{p}_x\bar{p}_y + U'(\delta)y^2 + V'(\delta)y\bar{p}_y + W'(\delta)\bar{p}_y^2,$$

$$A(\delta) = \sum_{i=1}^{3} a_n\delta^n \qquad B(\delta) = \sum_{i=1}^{3} b_n\delta^n$$

$$C(\delta) = \sum_{i=1}^{3} c_n\delta^n \qquad D(\delta) = \sum_{i=1}^{3} d_n\delta^n$$

$$E(\delta) = \sum_{i=1}^{3} e_n\delta^n \qquad F(\delta) = \sum_{i=1}^{3} f_n\delta^n$$

$$G(\delta) = \sum_{i=1}^{3} g_n\delta^n \qquad U(\delta) = \sum_{i=1}^{3} u_n\delta^n$$

$$V(\delta) = \sum_{i=1}^{3} v_n\delta^n \qquad W(\delta) = \sum_{i=1}^{3} w_n\delta^n$$

The total one-turn map:

$$M = M_{rad} \circ M_{chr} \circ M_{bb} \circ M_{cw} \circ M_0$$

Note:
In our code, we can easily turn on or off the maps of chromatic aberrations, beam-beam interaction or crab crossing.

Y. Seimiya, et al., to be published.
D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Measurements

First measurement at KEKB HER (Oct. 27, 2008):

Tune chromaticity

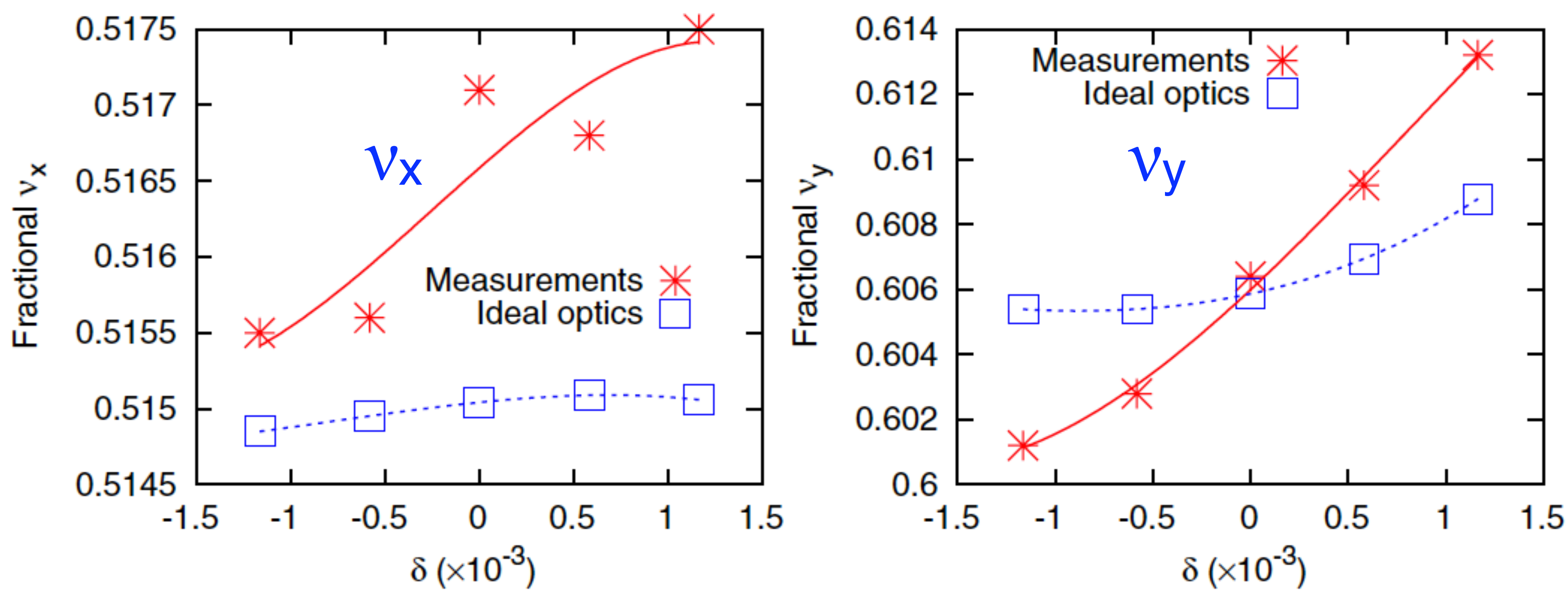


FIG. 1. (Color) Betatron tunes as a function of momentum deviation. The rf frequency shifts from −200 to 200 Hz with a 100 Hz interval. The solid and dashed lines represent third-order polynomial fittings.

NOTE:

Tunes and linear tune chromaticity were frequently knobbed.

They were not interesting to us.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Measurements

First measurement at KEKB HER (Oct. 27, 2008):

α and β chromaticity

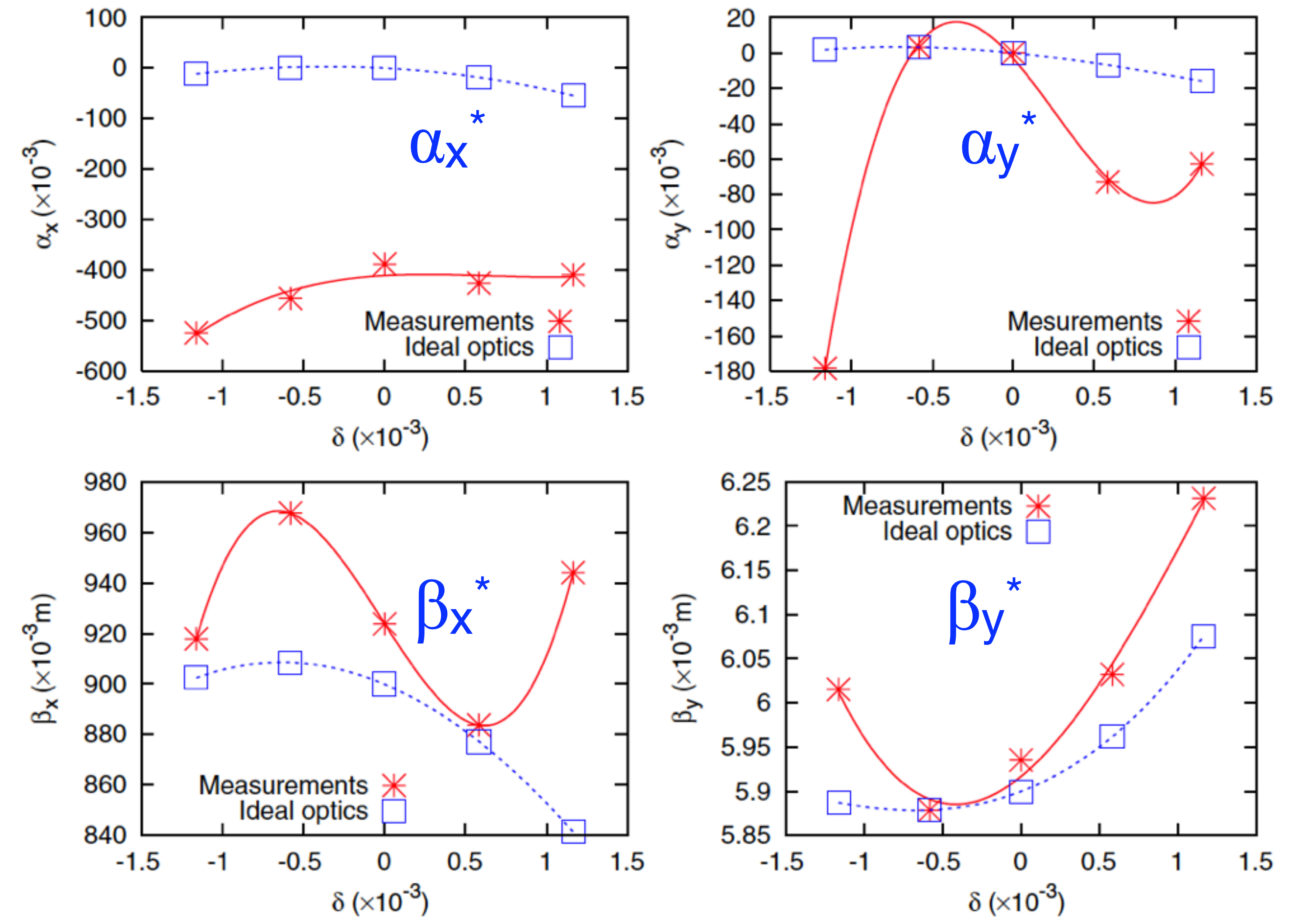


FIG. 2. (Color) Alpha and beta functions at the IP as a function of momentum deviation. The rf frequency shifts from −200 to 200 Hz with a 100 Hz interval. The solid and dashed lines represent third-order polynomial fittings.

NOTE:
α and β chromaticity was already controlled during the beam tuning.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Measurements

First measurement at KEKB HER (Oct. 27, 2008):
Chromatic X-Y coupling

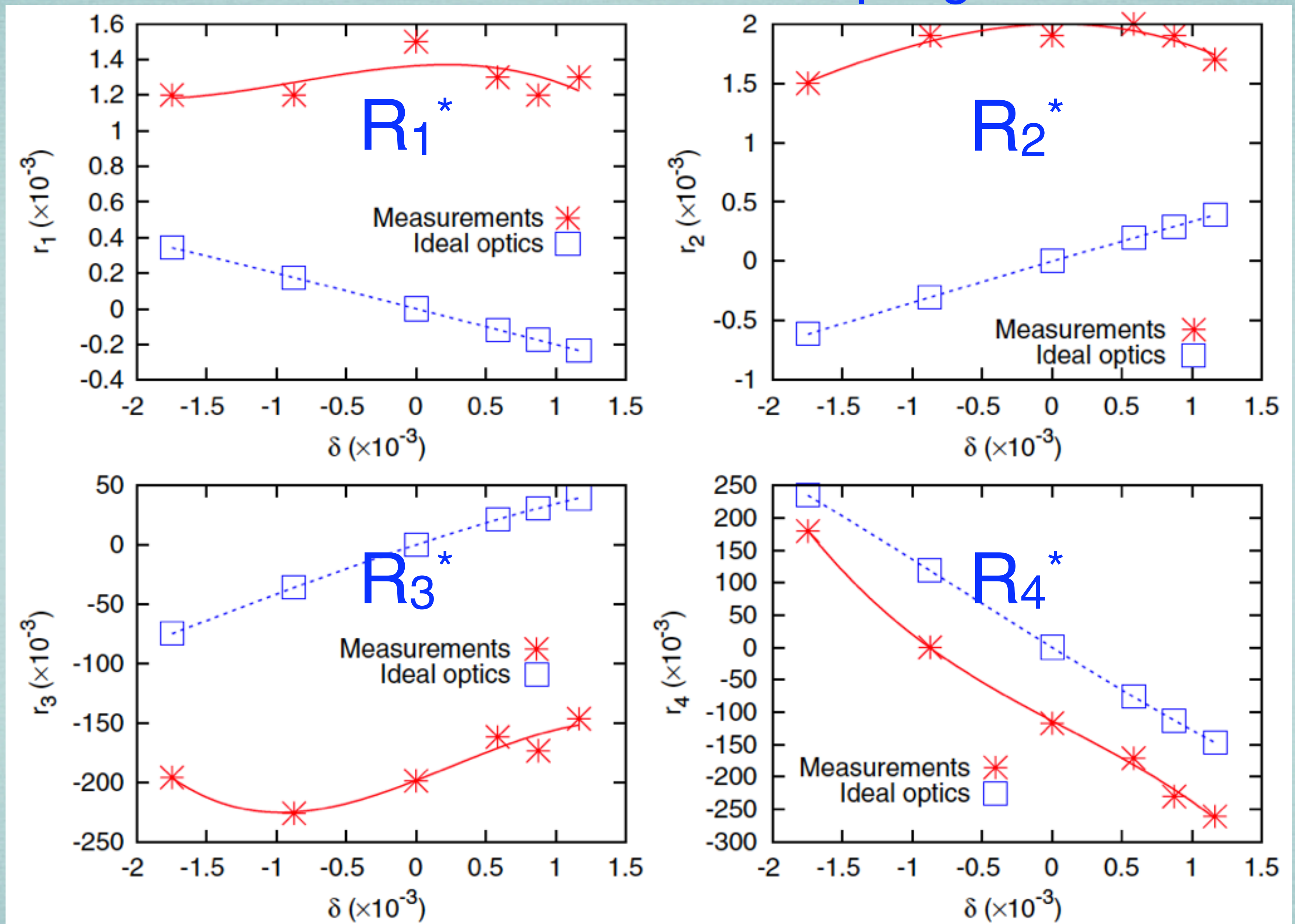


FIG. 3. (Color) *X-Y* coupling parameters at the IP as a function of momentum deviation. The rf frequency shifts from −300 to 200 Hz. The solid and dashed lines represent third-order polynomial fittings.

NOTE:
Chromatic X-Y couplings were never controlled w/ skew-sext.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Measurements

Improved measurements on chromatic X-Y couplings w/ and w/o skew-sextupoles.

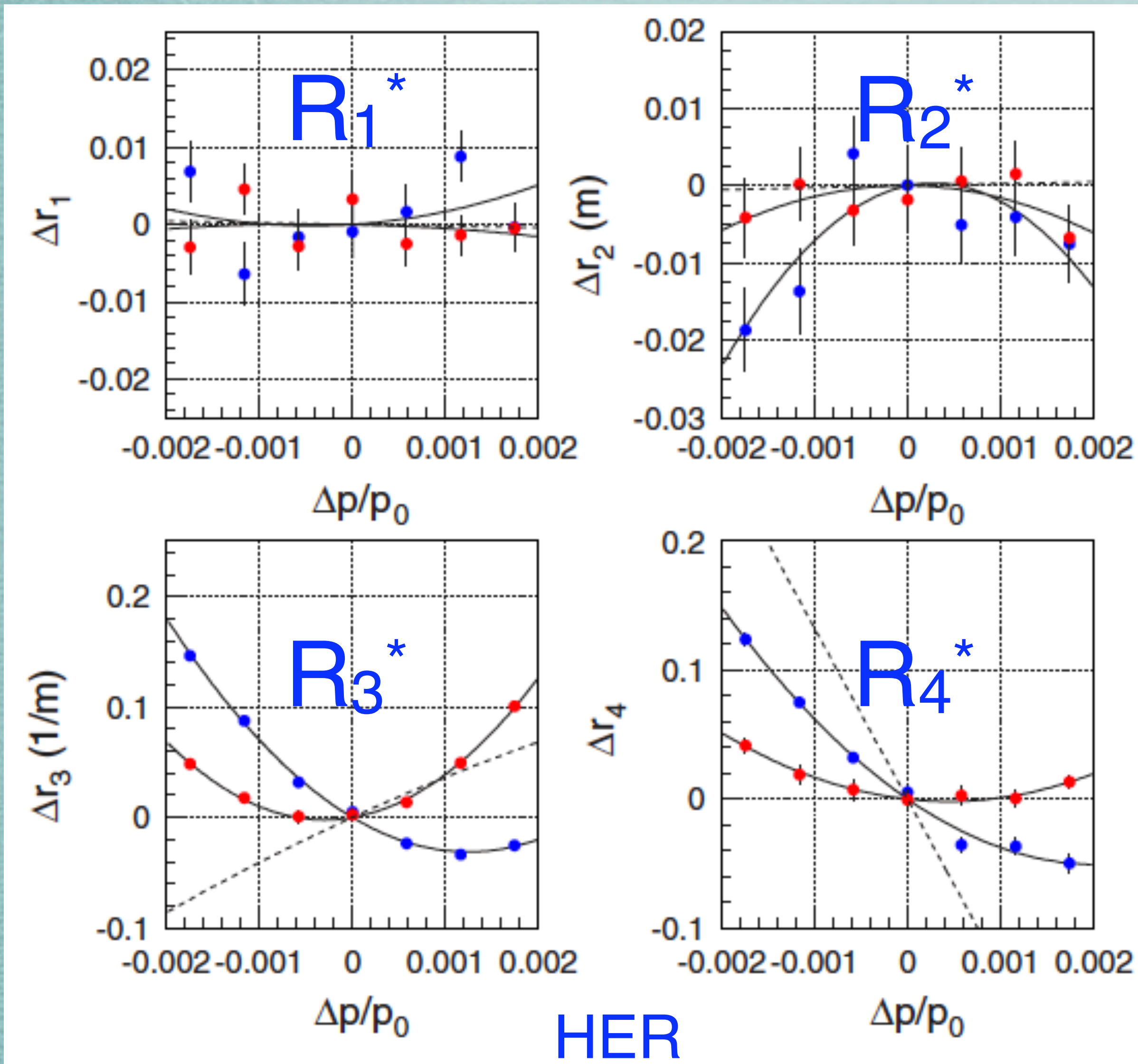


FIG. 3. (Color) Measured chromatic *X-Y* coupling at IP in HER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic *X-Y* coupling estimated using the model lattice by SAD.

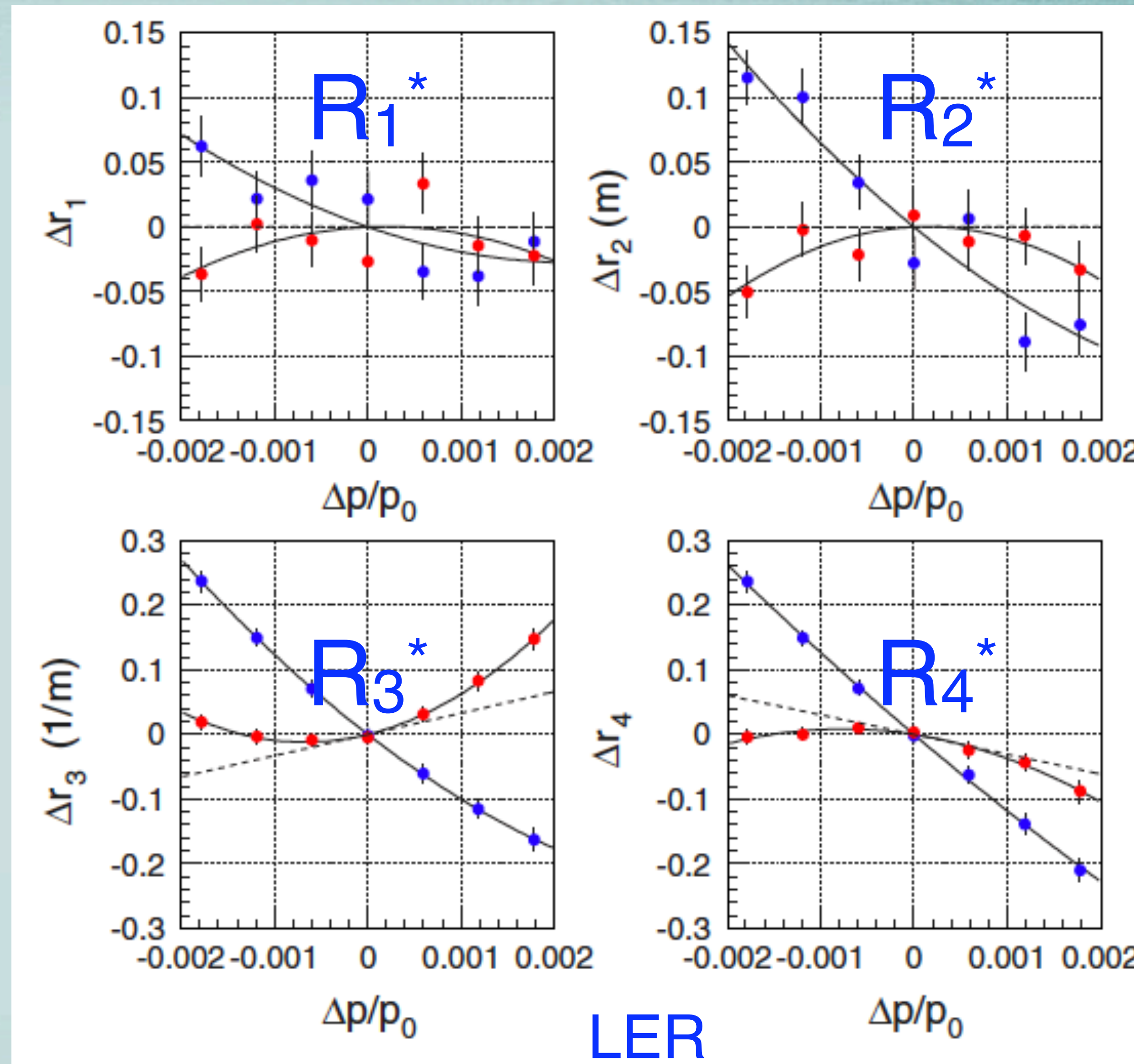


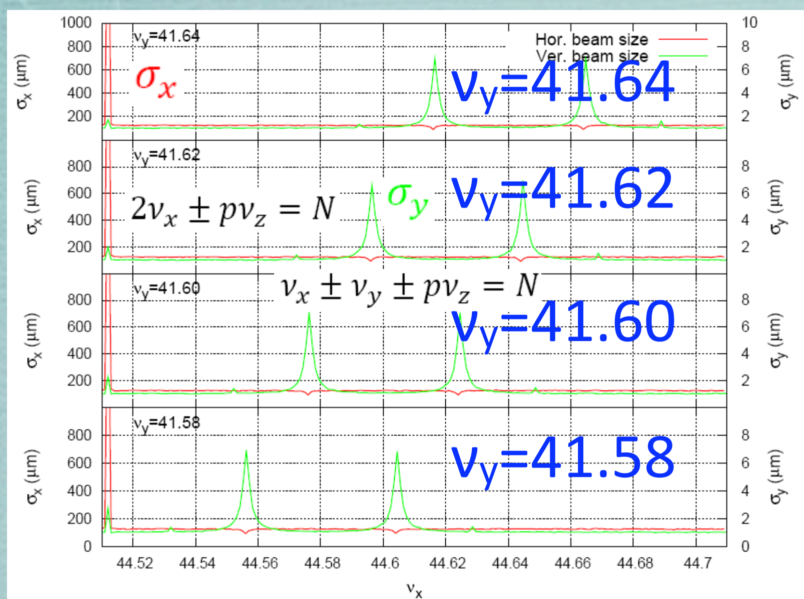
FIG. 4. (Color) Measured chromatic *X-Y* coupling at IP in LER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic *X-Y* coupling estimated using the model lattice by SAD.

Y. Ohnishi, et al., PRST-AB 12, 091002 (2009).

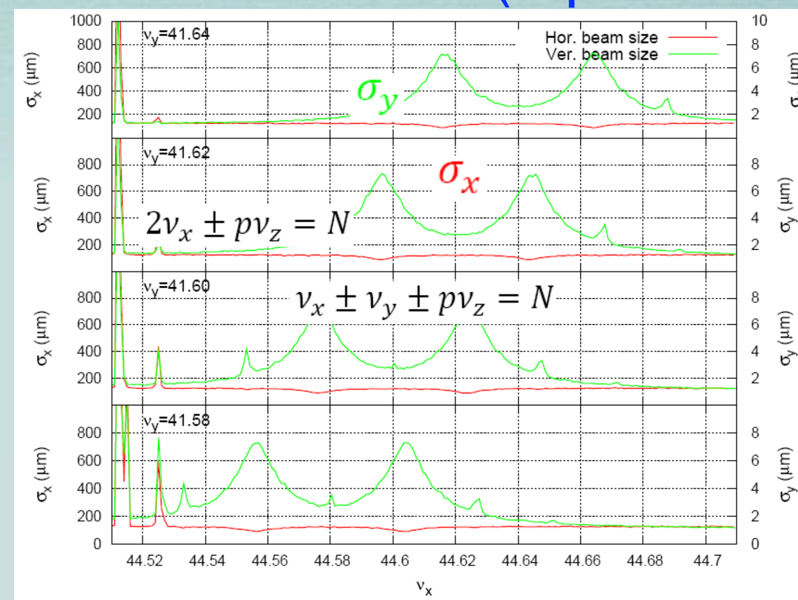
Chromatic aberration - Simulations

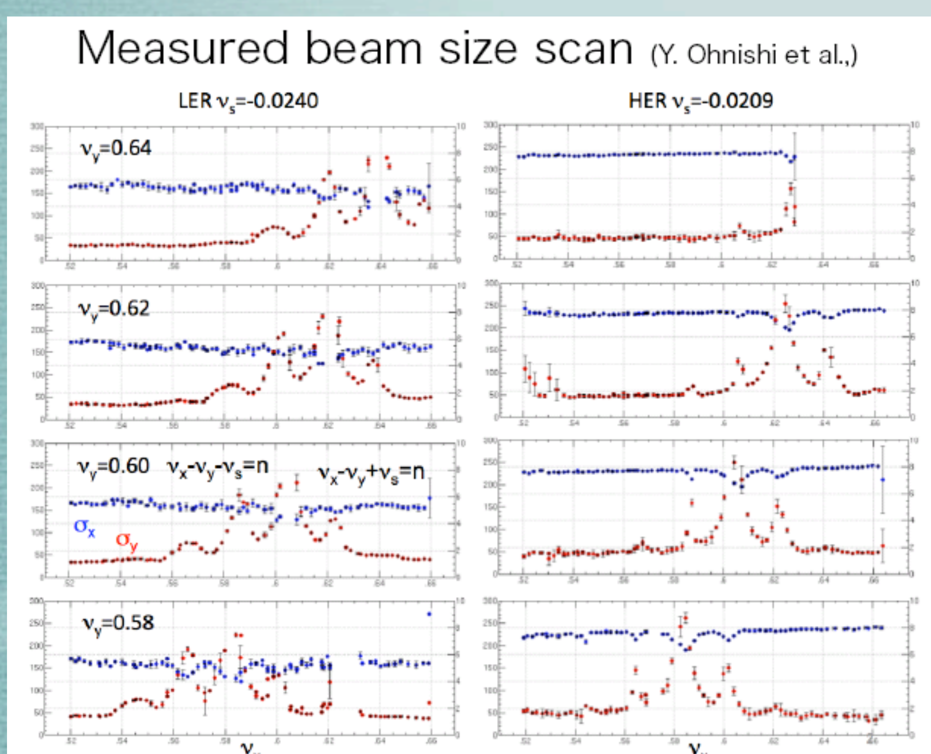
The theory of chromatic aberrations is consistent with Oide and Koiso's theory of "anomalous emittance":

Idea optics



w/ machine errors (a poor seed)





K. Ohmi, KEKB ARC 2009

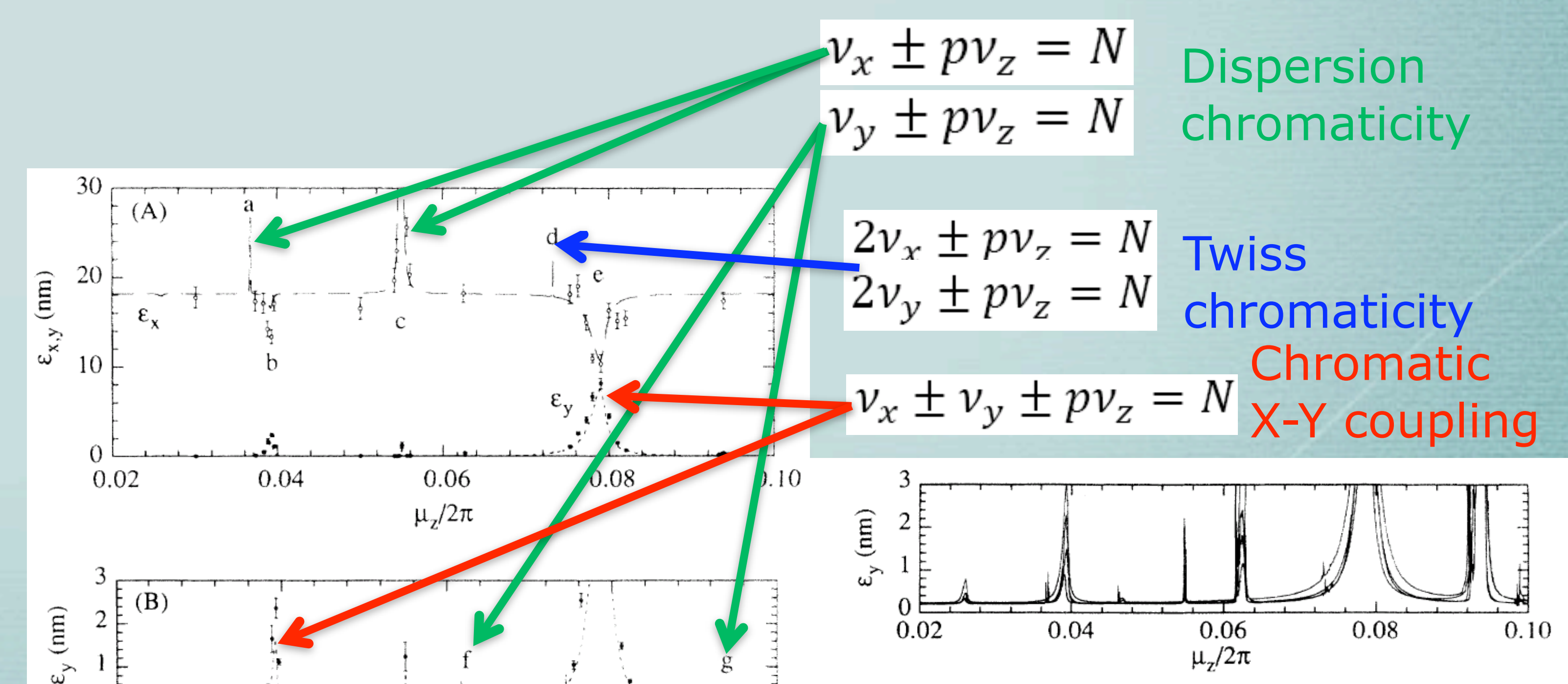


FIG. 3. Machine errors enhance the strengths of resonances of the anomalous emittance, comparing to those without errors (Fig. 1). Each trace corresponds to a different random-number seed.

K. Oide and H. Koiso, PRE 1994

Chromatic aberration - Simulations

Luminosity loss due to all chromatic aberrations:

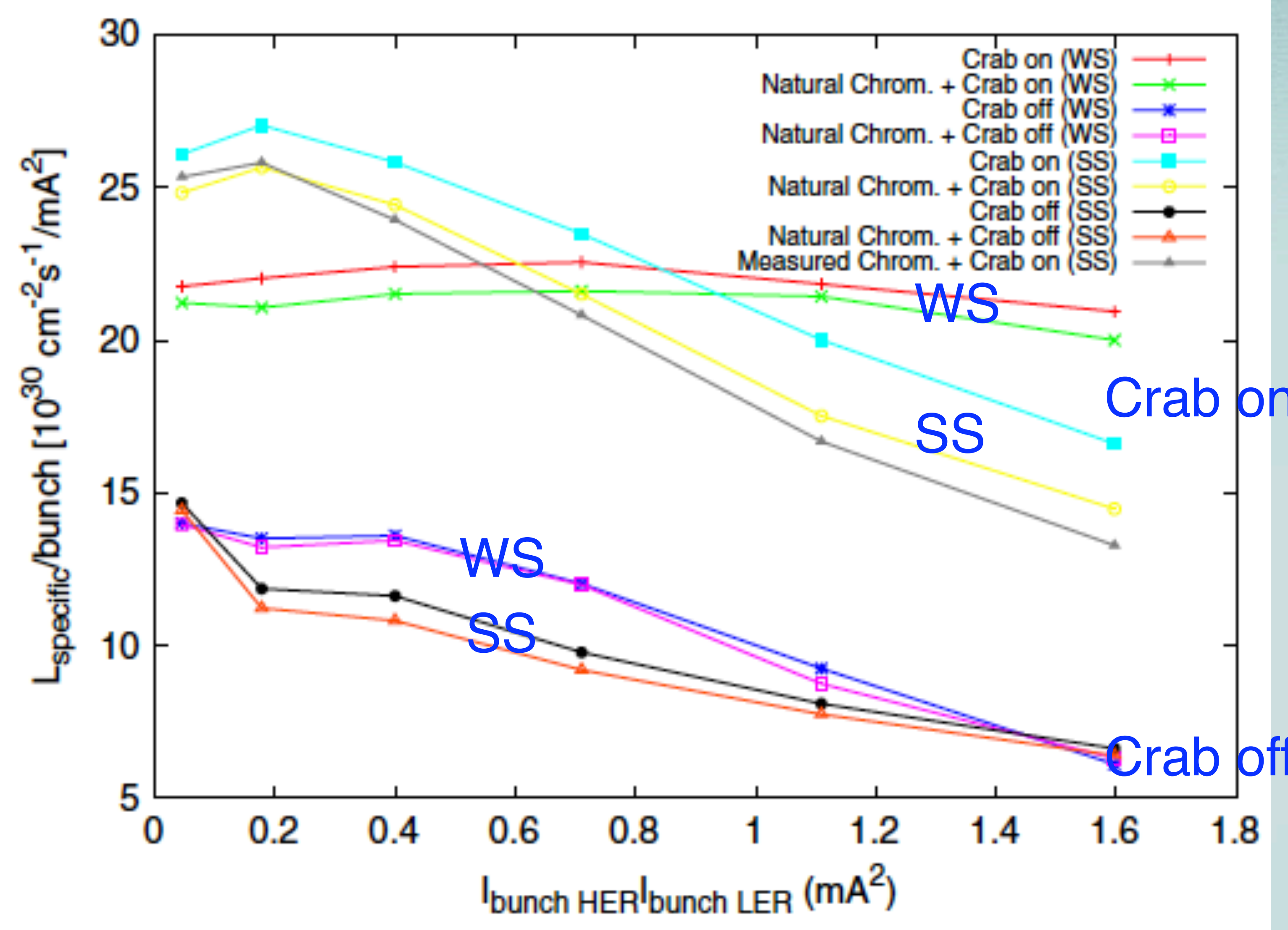


FIG. 5. (Color) Specific luminosity as a function of current product for KEKB. The natural chrom. and measured chrom. indicate natural chromaticity and measured chromaticity calculated from ideal optics and measurement data at KEKB HER, respectively. The WS and SS represent weak-strong and strong-strong simulations, respectively.

WS: weak-strong
SS: strong-strong

$\beta_x^* = 0.9m$ $\beta_y^* = 6mm$

$\nu_x = 44.515$ $\nu_y = 41.606$

$\kappa = 1\%$

NOTE:
Luminosity loss:
WS: ~5%
SS: ~10%

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Scan with first-order chromaticity of α and β function (WS, Crab on):

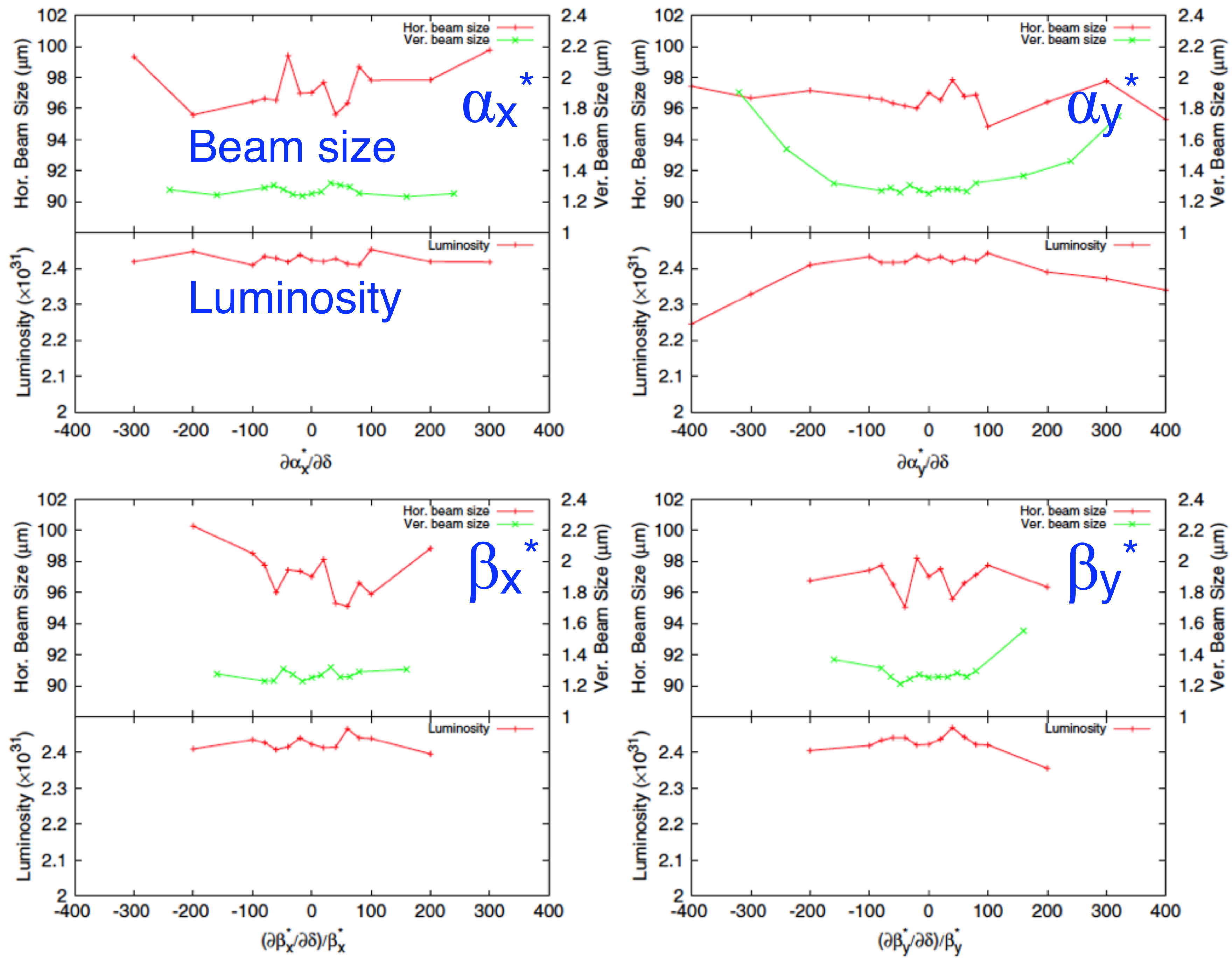


FIG. 6. (Color) Scan of first-order chromaticities of alpha and beta functions at the IP with beam-beam interaction. The beam suddenly becomes unstable when $|\partial\alpha_x^*/\partial\delta| > 300$, $|\partial\alpha_y^*/\partial\delta| > 400$, $|(\partial\beta_x^*/\partial\delta)/\beta_x^*| > 200$, and $|(\partial\beta_y^*/\partial\delta)/\beta_y^*| > 200$.

NOTE:
Simulations didn't predict significant luminosity loss. But, strong-strong simulations predicted particle loss at large chromaticity.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Compare knob scans with beam (Crab on):

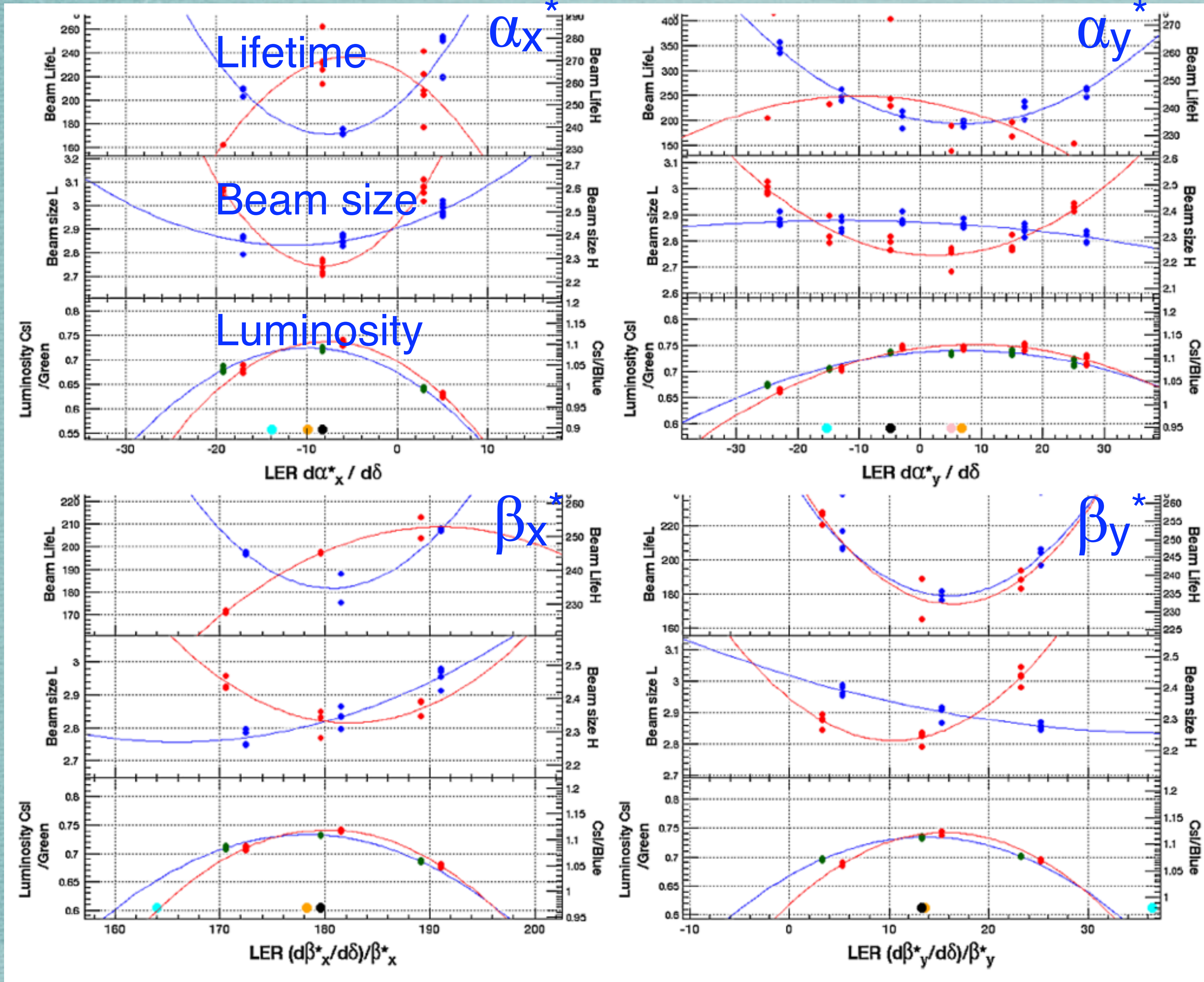


FIG. 7. (Color) Single knobs of chromaticities of alpha and beta functions at the IP of KEKB LER. In each subfigure, the red and blue dots represent data acquired from the LER and HER, respectively. The solid red and blue lines represent polynomial fittings.

NOTE:
Beam tuning did indicate luminosity loss. At the same time, lifetime also decreased. This agreed with observed lifetime in beam tuning.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Scan with first-order chromaticity of X-Y couplings (WS, Crab on):

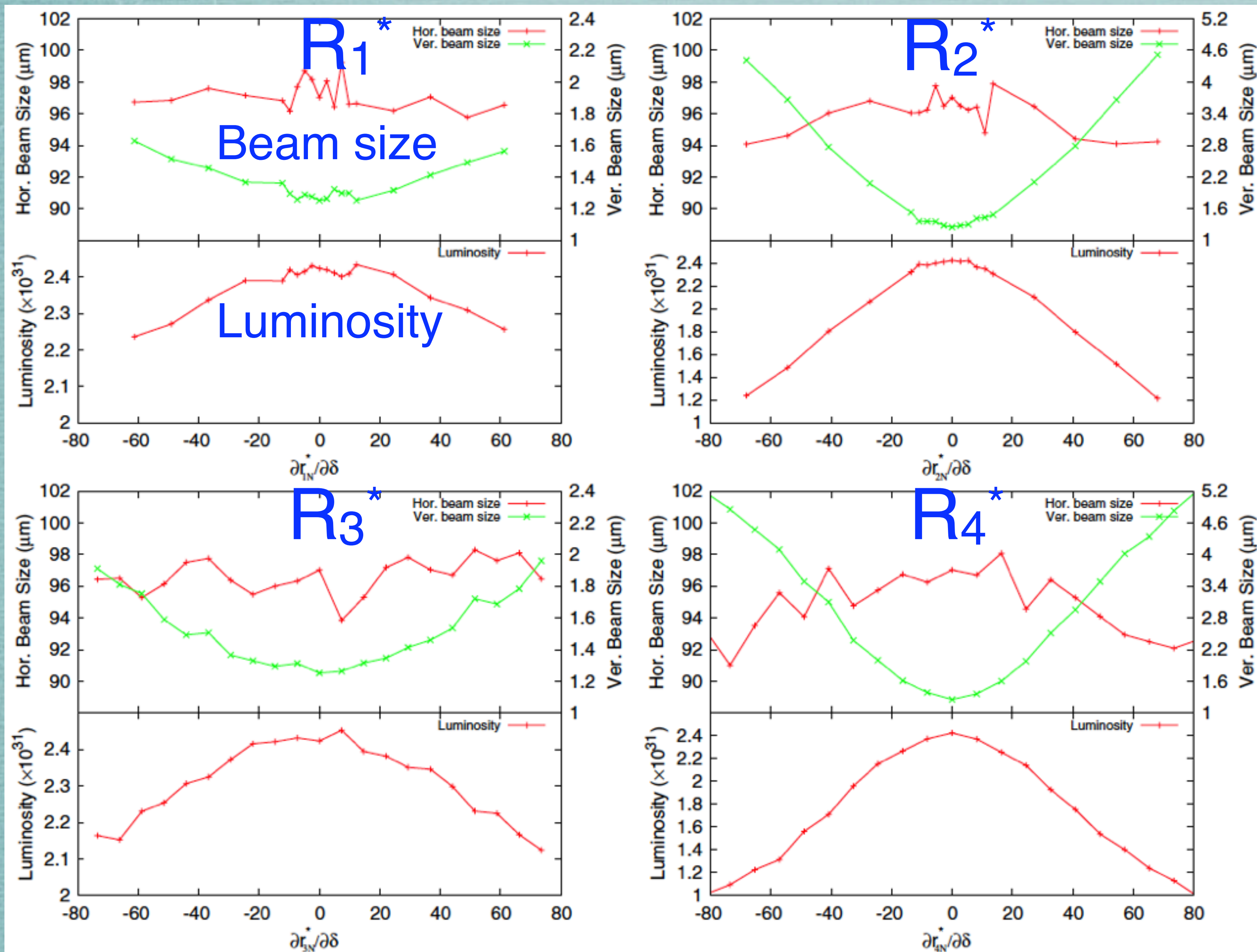


FIG. 8. (Color) Scan of first-order chromaticity of X-Y couplings at the IP.

$$\begin{pmatrix} r^*_{1N} & r^*_{2N} \\ r^*_{3N} & r^*_{4N} \end{pmatrix} = \begin{pmatrix} r^*_1\sqrt{\beta^*_x/\beta^*_y} & r^*_2/\sqrt{\beta^*_x\beta^*_y} \\ r^*_3\sqrt{\beta^*_x\beta^*_y} & r^*_4\sqrt{\beta^*_y/\beta^*_x} \end{pmatrix}$$

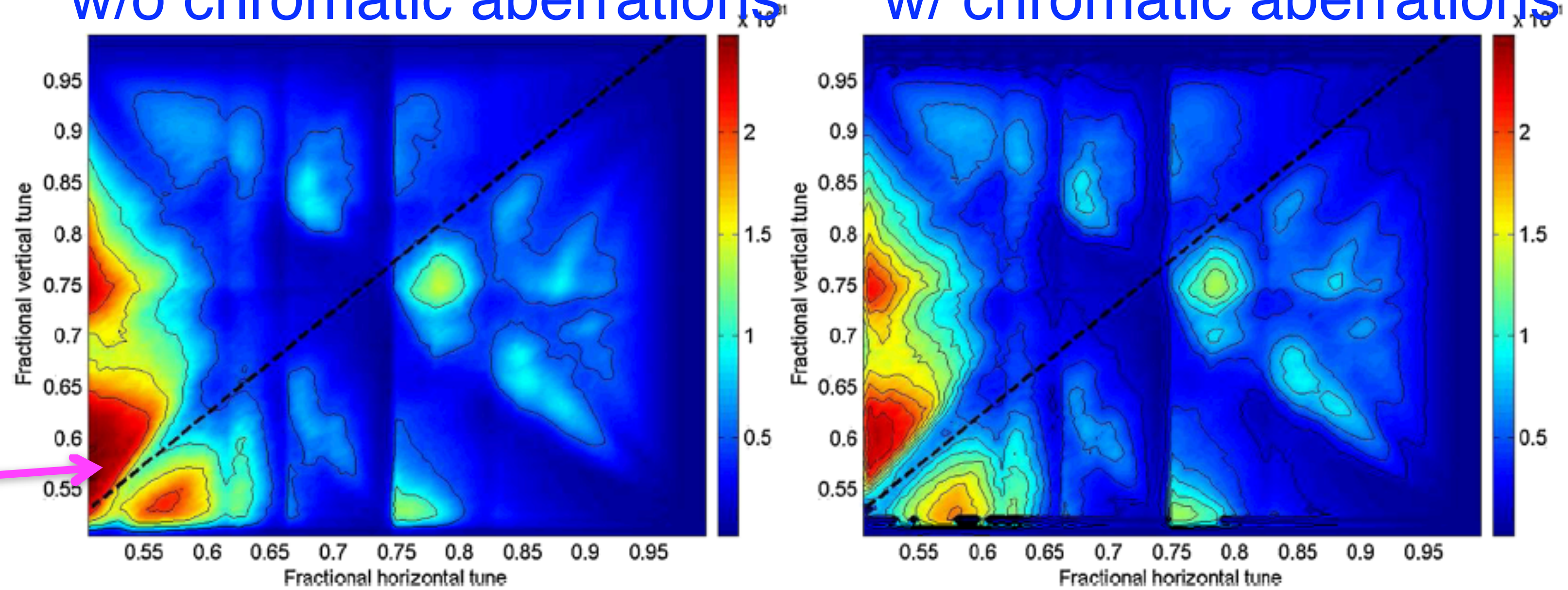
NOTE:
Simulations predicted significant luminosity loss. No particle loss was observed.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Tune dependence of chromatic effects (Natural chromaticity, Crab on):

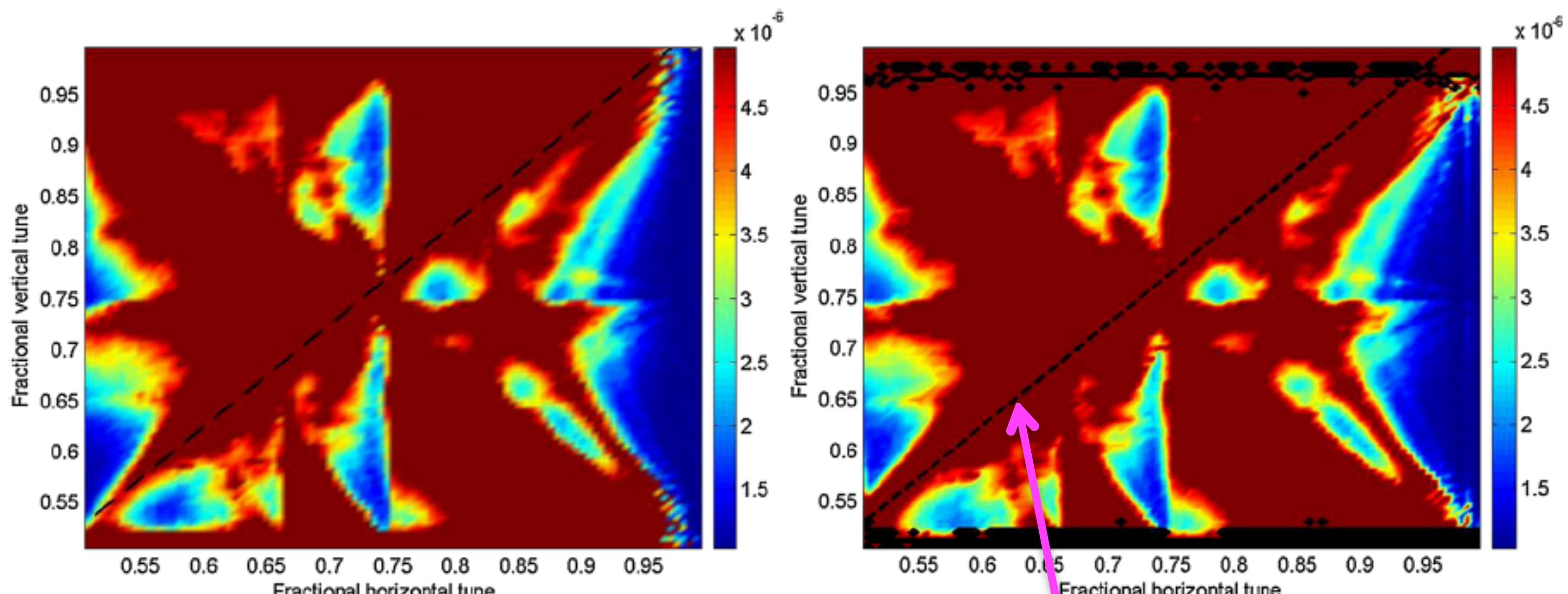
w/o chromatic aberrations w/ chromatic aberrations



Luminosity

working point

FIG. 10. (Color) Luminosity scans in tune space with and without chromaticity. The dashed line in each figure represents the synchrobeta resonance at $\nu_x - \nu_y + \nu_z = N$ (left: only beam-beam interaction; right: beam-beam interaction plus chromaticity of ideal optics).



σ_y

FIG. 12. (Color) Vertical beam size scans in tune space. The colors are set to dark red in areas where the beam sizes are larger than 5 μm. The dashed line in each figure represents the synchrobeta resonance at $\nu_x - \nu_y + \nu_z = N$ (left: only beam-beam interaction; right: beam-beam interaction plus chromaticity of ideal optics; the black areas indicate that beam is unstable because of strong synchrobeta resonances).

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Tune dependence of chromatic effects (Natural chromaticity, Crab on):

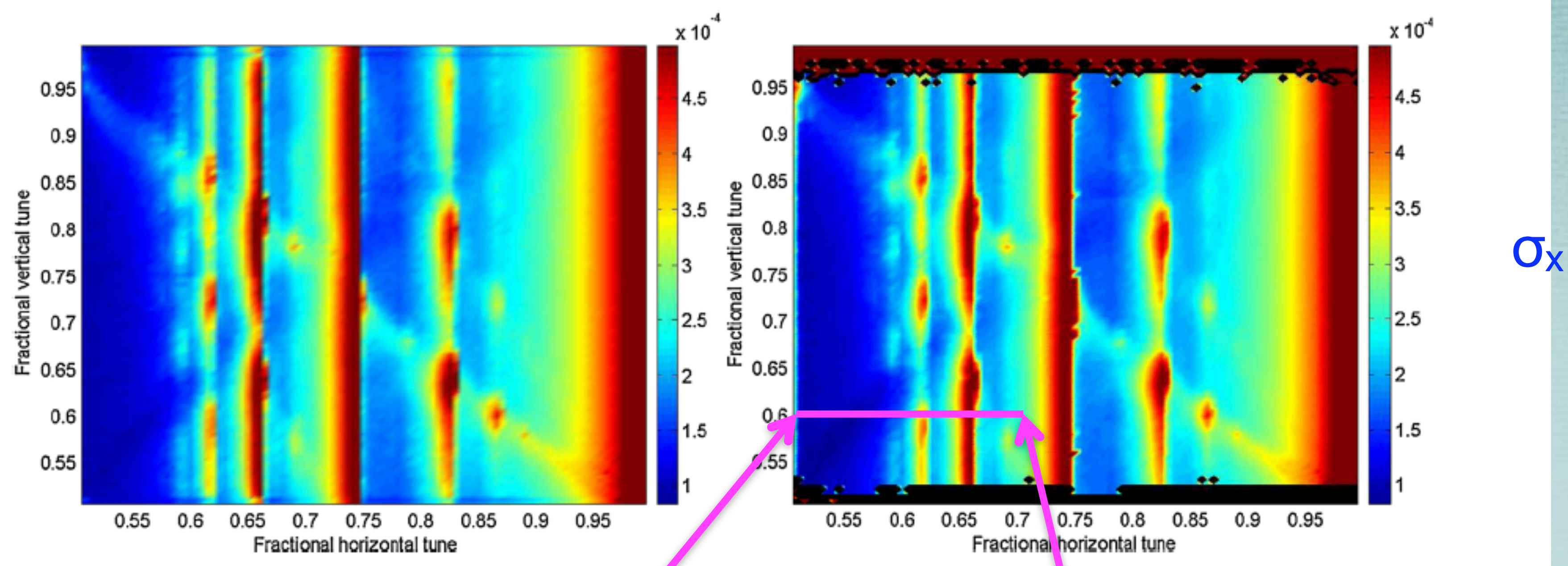


FIG. 11. (Color) Horizontal beam size scans in tune space (left: only beam-beam interaction; right: beam-beam interaction plus chromaticity of ideal optics; the black areas indicate that beam is unstable because of strong synchrobeta resonances).

$$\nu_y = 41.60$$

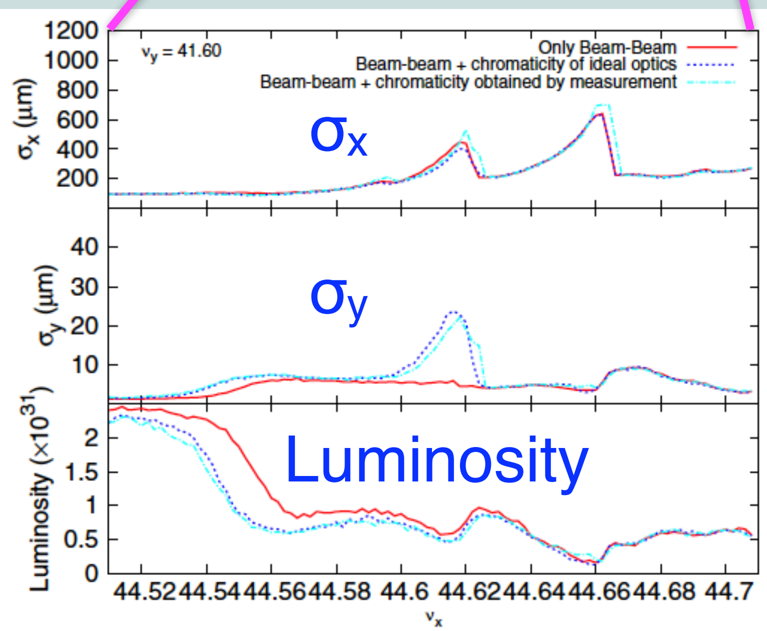


FIG. 13. (Color) Horizontal tune scan with beam-beam interaction only or plus first-order chromaticity. The first-order chromaticity was employed in the simulations.

NOTE:
The chromaticity of ideal optics and from measurement predicted similar luminosity loss.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Linear and chromatic X-Y couplings at the SuperKEKB:

Set the tolerances for the reference of optics design and optics corrections

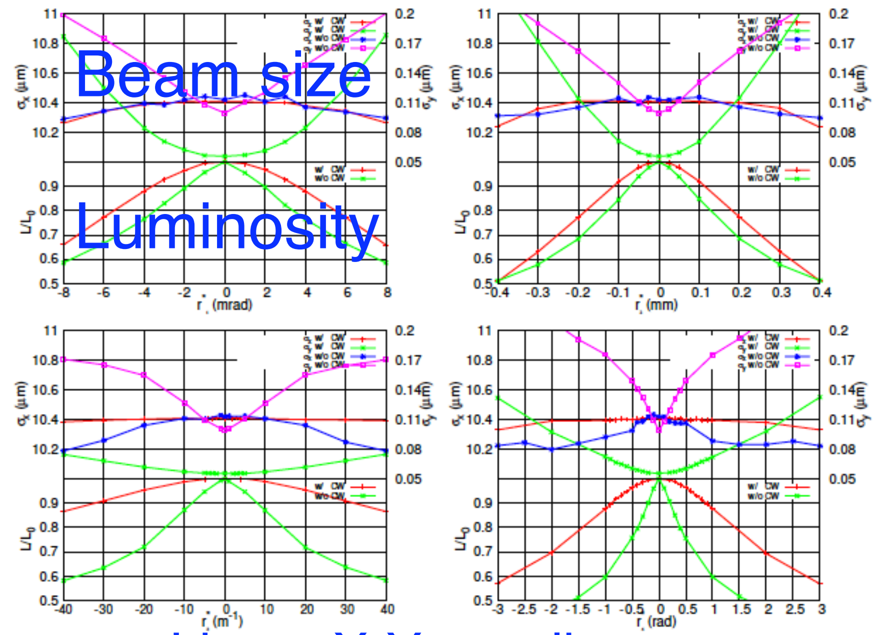


Figure 1: Beam sizes and relative luminosity as function of the linear X-Y couplings at the IP with and without crab waist.

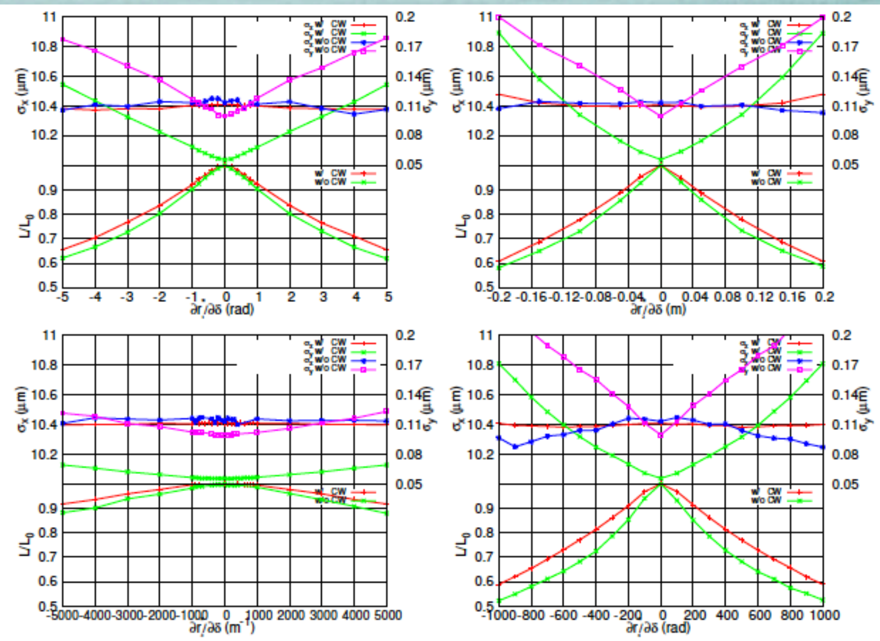


Figure 2: Beam sizes and relative luminosity as function of the chromatic X-Y couplings at the IP with and without crab waist.

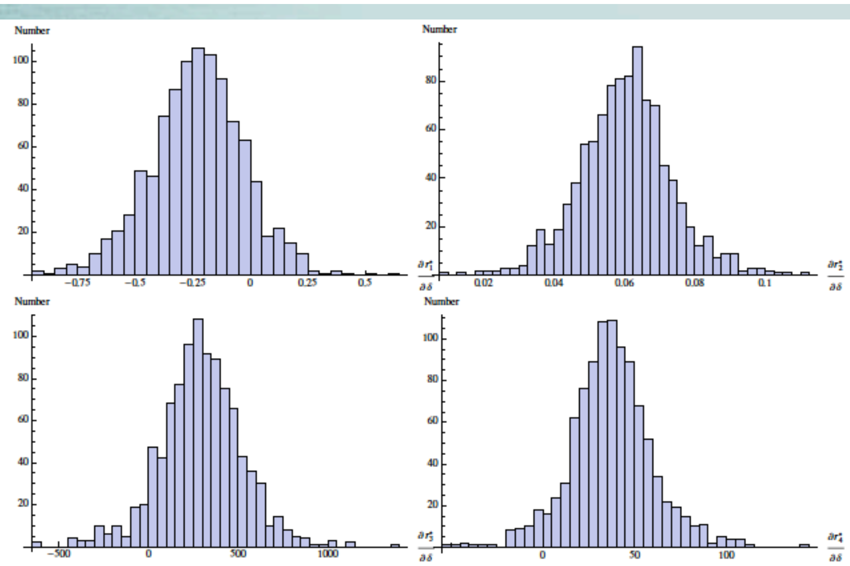


Figure 3: Distributions of the chromatic X-Y couplings with 1000 error seeds for the SuperKEKB LER.

Table 3: Tolerances for the linear and chromatic X-Y couplings at the IP of the SuperKEKB LER, assuming a rate of 20% luminosity degradation.

Parameter	w/ crab waist	w/o crab waist
$r_1^*\,(mrad)$	±5.3	±3.5
$r_2^*\,(mm)$	±0.18	±0.13
$r_3^*\,(m^{-1})$	±55	±15
$r_4^*\,(rad)$	±1.4	±0.4
$r_{11}\,(rad)$	±2.3	±2.0
$r_{21}\,(m)$	±0.09	±0.07
$r_{31}\,(m^{-1})$	±11000	±9400
$r_{41}\,(rad)$	±430	±280

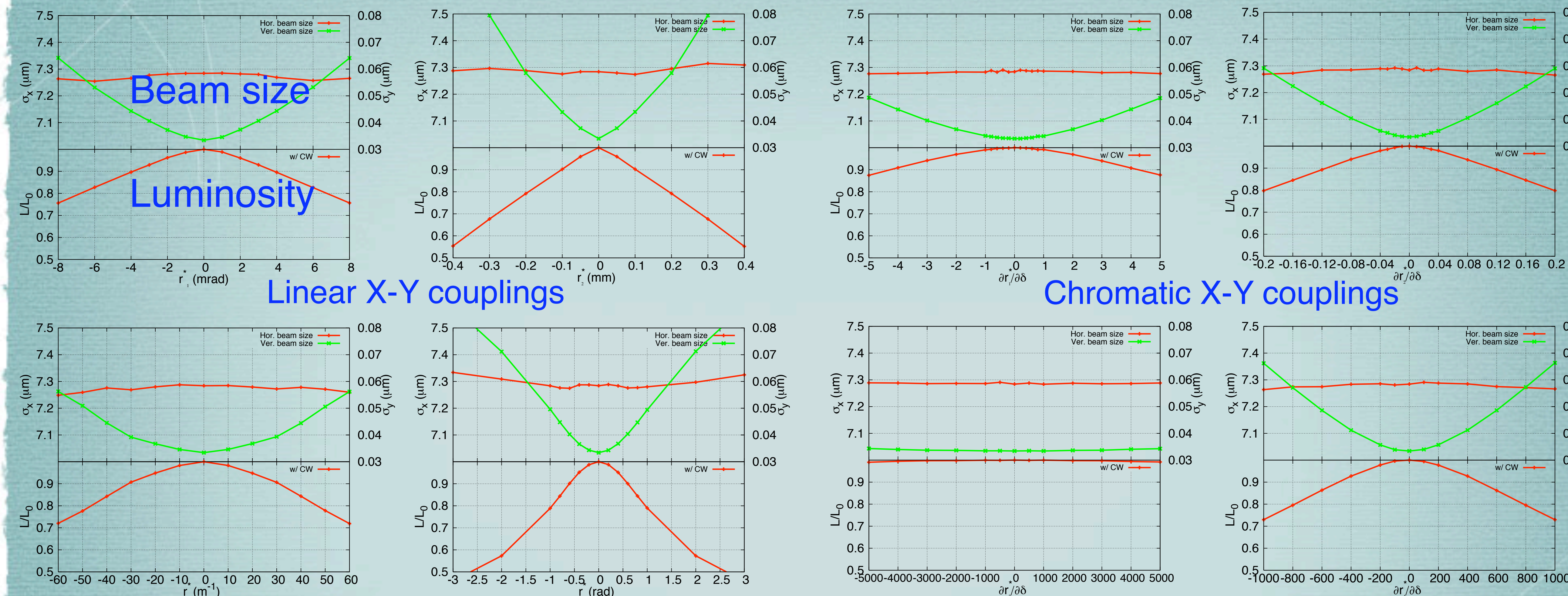
Tolerances

D. Zhou, et al., IPAC10

Chromatic aberration - Simulations

Linear and chromatic X-Y couplings at the SuperB (w/ CW):

Set the tolerances for the reference of optics design and optics corrections



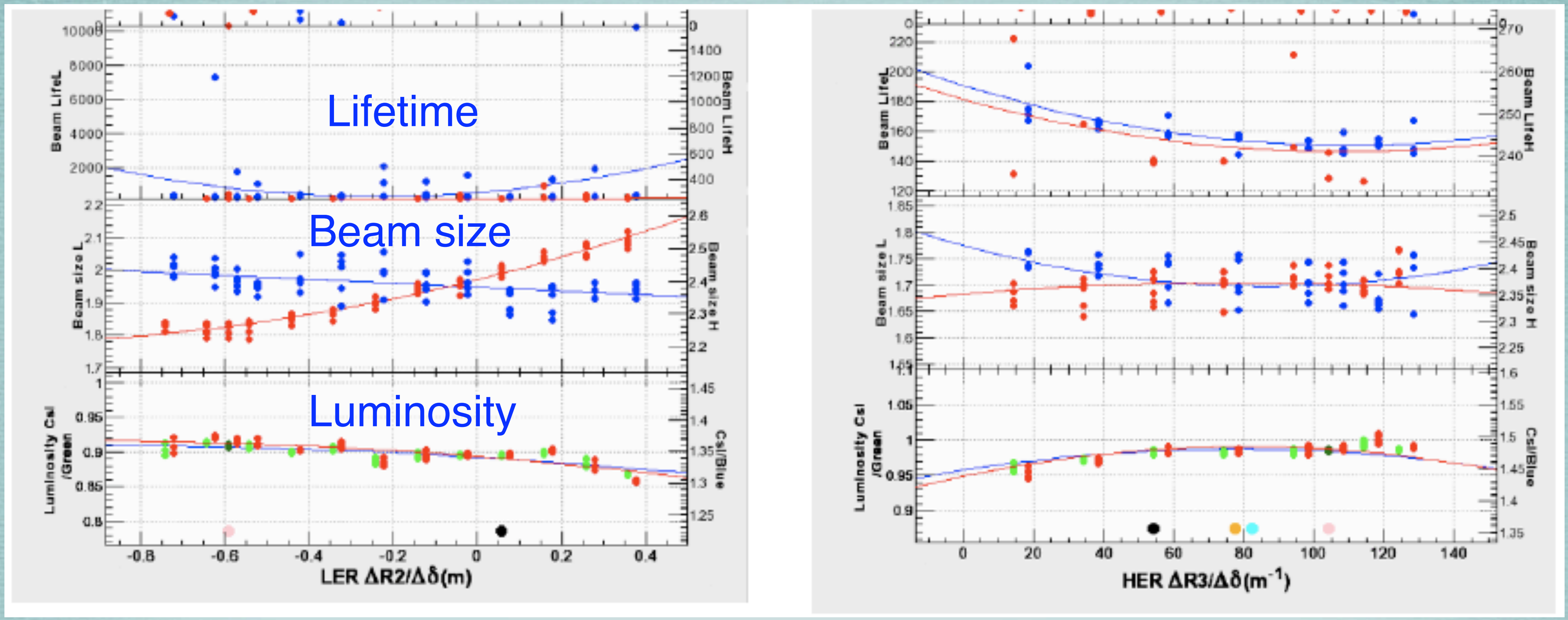
Tolerances

Parameter	Tolerance
r_1^* (mrad)	±6.7
r_2^* (mm)	±0.19
r_3^* (m^{-1})	±46
r_4^* (rad)	±0.96
$\partial r_1^*/\partial\delta$ (rad)	±7
$\partial r_2^*/\partial\delta$ (m)	±0.19
$\partial r_3^*/\partial\delta$ (m^{-1})	>5000 or <-5000
$\partial r_4^*/\partial\delta$ (rad)	±770

Collaborate with M. Zobov (INFN)

Observed luminosity performance

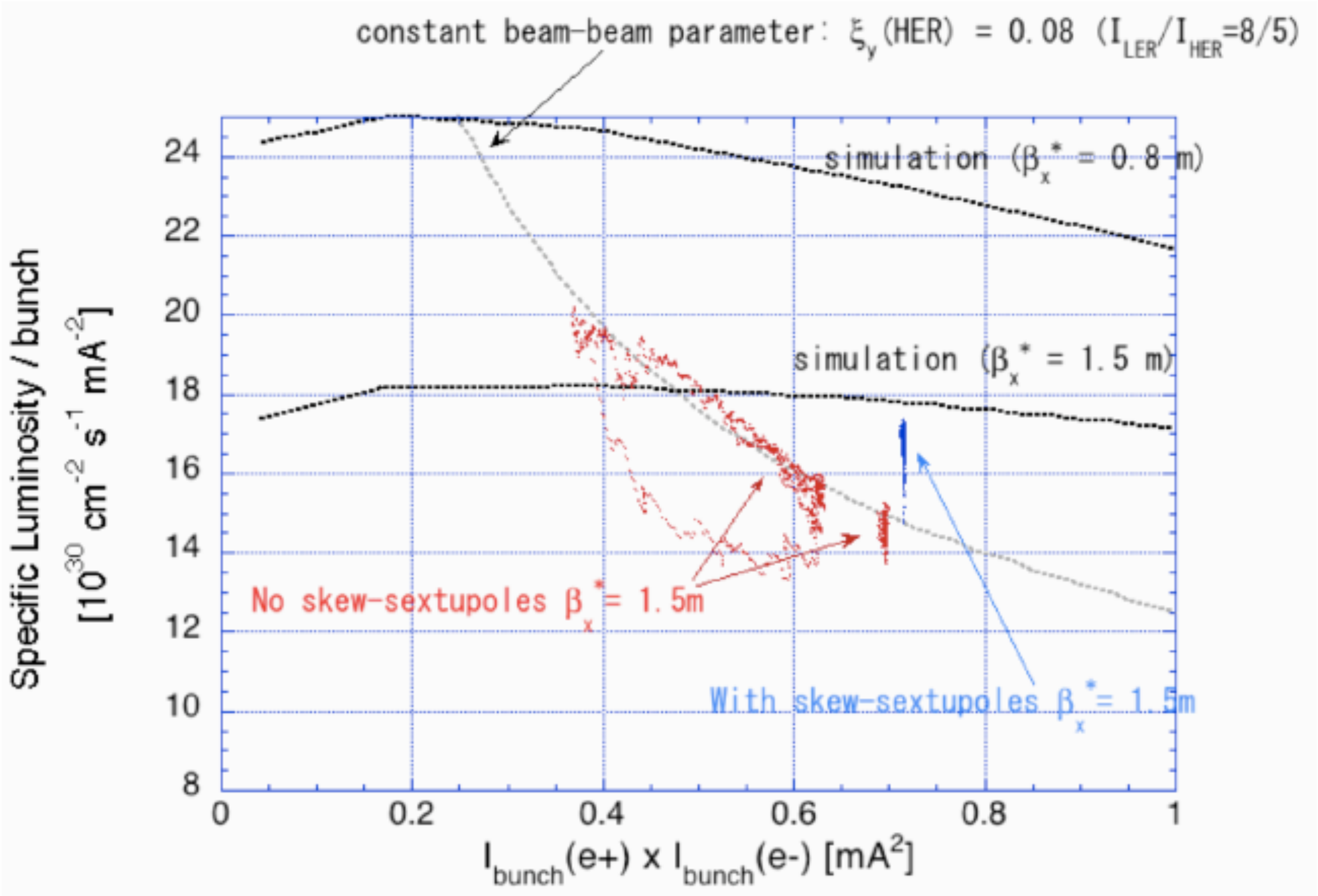
Typical examples of scanning chromatic X-Y couplings at IP during the KEKB operation:



Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

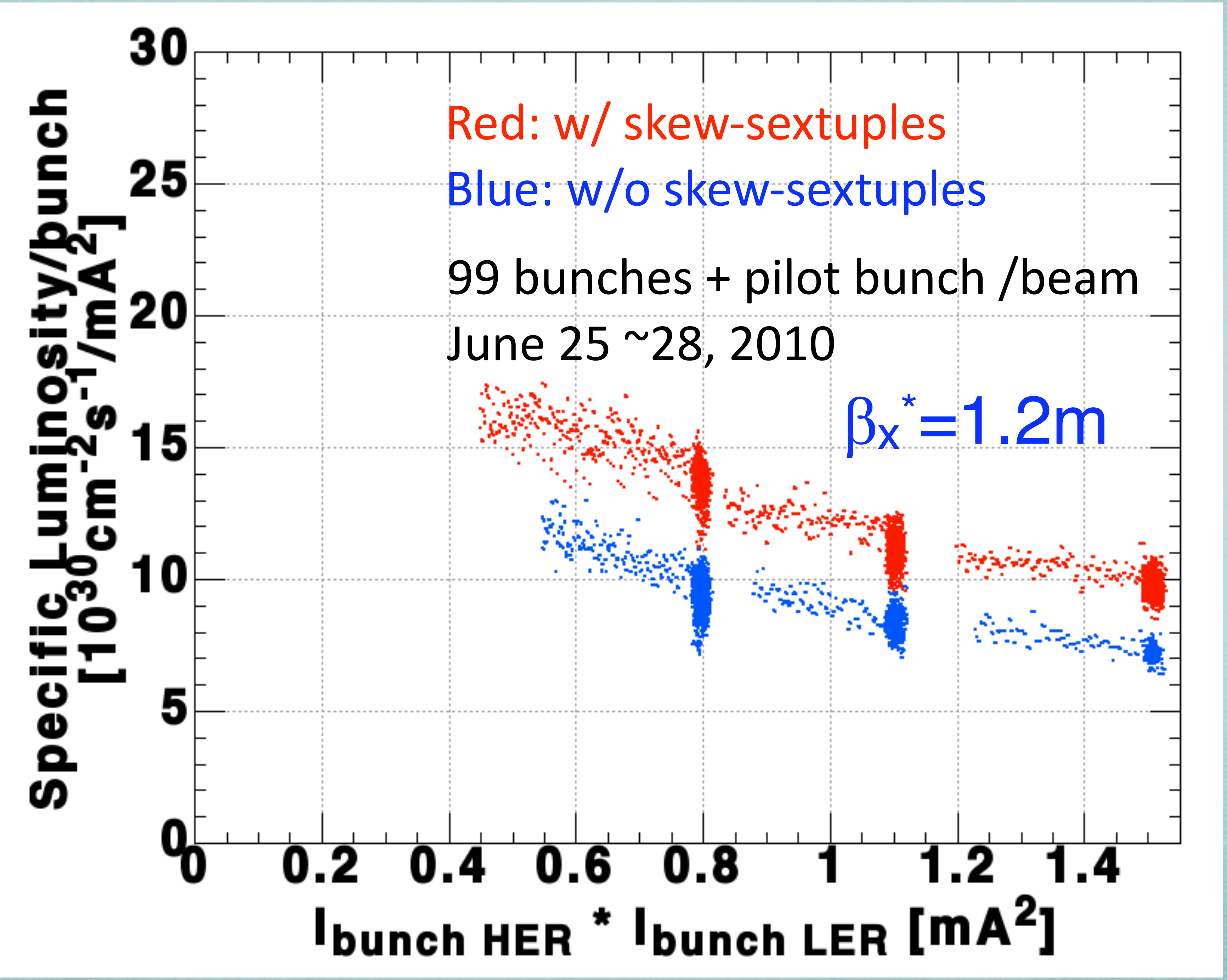
Effectiveness of skew-sextupole magnets (crab on)



Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

Effectiveness of skew-sextupoles (Crab off)

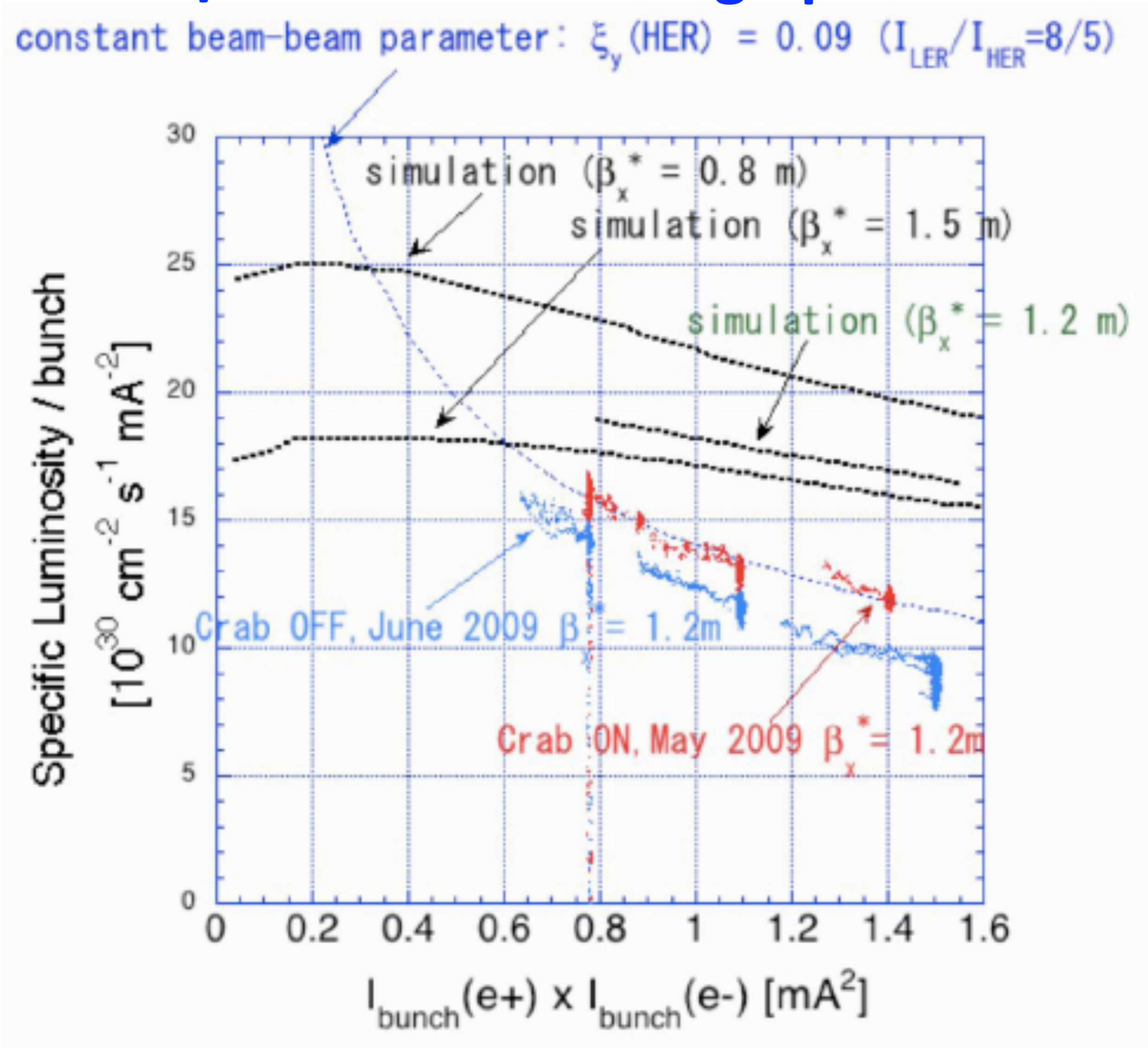


Courtesy of Y. Funakoshi

Observed luminosity performance

Specific luminosity (crab on/off)

W/ skew-sext. tuning optimized

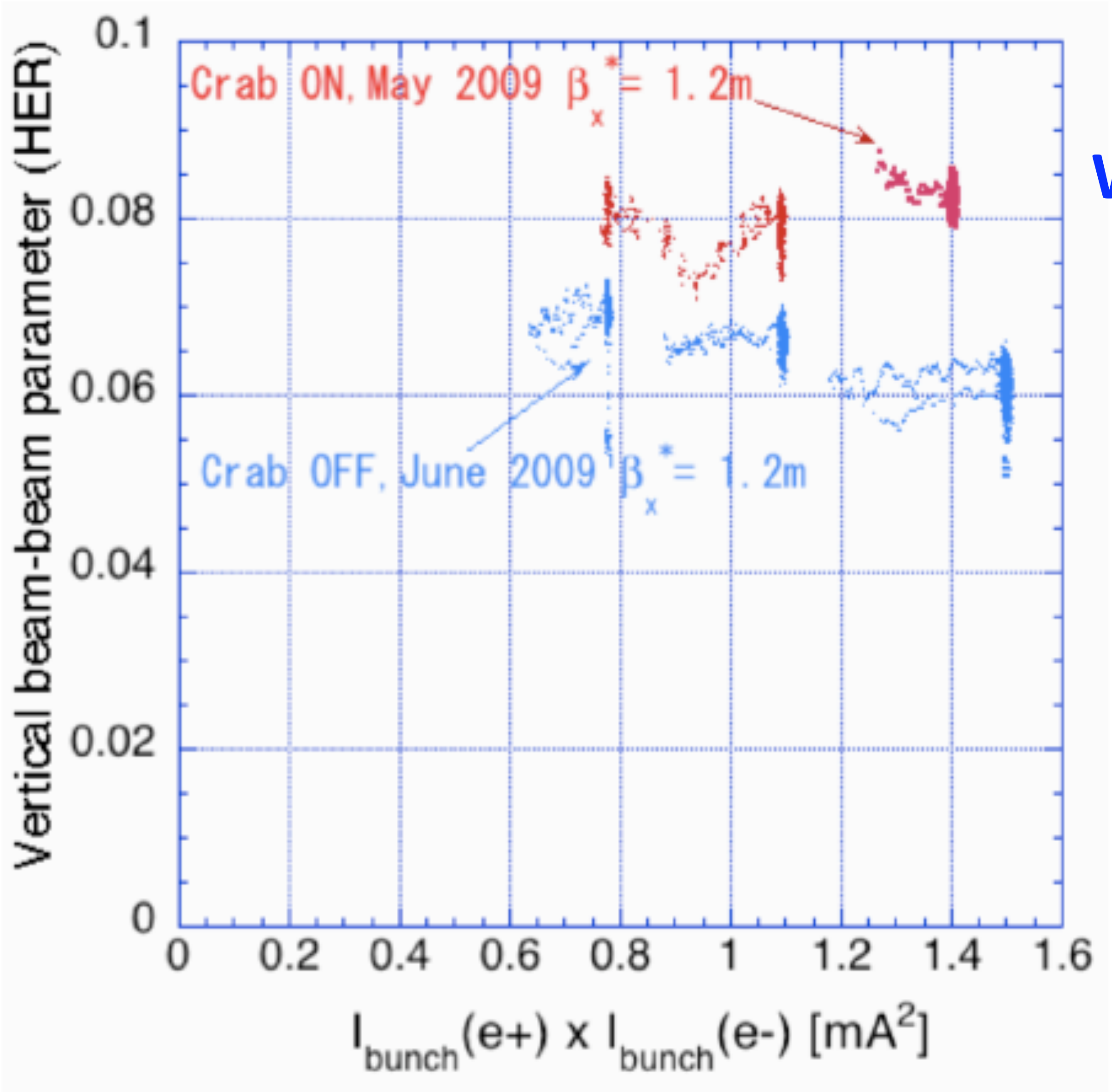


Luminosity improvement by crab cavities is about 20%.
Geometrical loss due to the crossing angle is about 11%.

Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

Beam-beam parameter (crab on/off)



W/ skew-sext. tuning optimized

	Crab on	Crab off
R_L	0.828	0.763
$R_{\xi y}$(HER)	1.15	0.993

Ref. Y. Funakoshi, IPAC10

Summary

❖ The theory of chromatic aberrations looks pretty good.
❖ The simulations were quite reliable and did lead to the remarkable achievements in KEKB.
❖ The beam tuning in the KEKB revealed that chromatic X-Y couplings are very important in the KEKB.
❖ The crab cavities did contribute to luminosity gain (~20%).
❖ The skew-sextupoles contributed additional luminosity gain (~15%).
❖ But the strong-strong simulations predicted the luminosity gain in a factor of 2(@β_x^*=0.8m). There is still big discrepancy.

Thanks for your attention!