Review of crosstalk between beam-beam interaction and lattice nonlinearity in e+e- colliders

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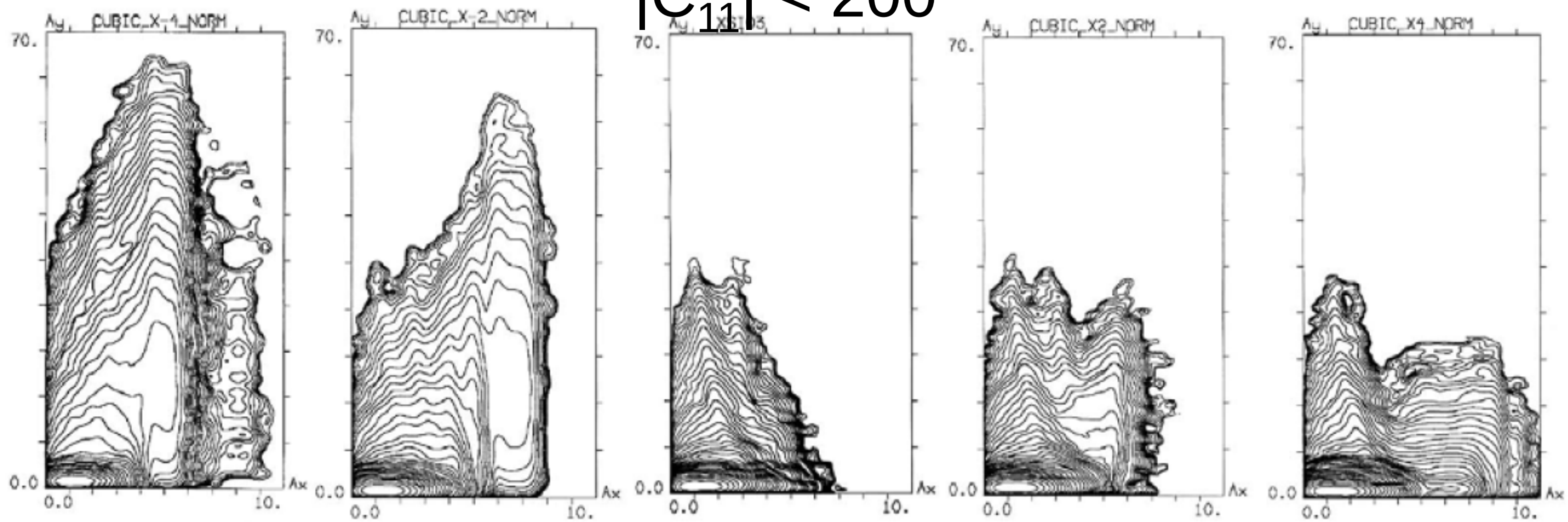
Outline

- DAFNE
- DAFNE upgrade
- KEKB
- Super-KEKB
- BEPCII

- DAFNE

DAFNE: Cubic lattice nonlinearity
Only one IP

$|C_{11}| < 200$



$C_{11} = -400$	$C_{11} = -200$	$C_{11} = 0$	$C_{11} = 200$	$C_{11} = 400$
$\sigma_x/\sigma_{x0} = 1.053$	$\sigma_x/\sigma_{x0} = 1.075$	$\sigma_x/\sigma_{x0} = 1.067$	$\sigma_x/\sigma_{x0} = 1.110$	$\sigma_x/\sigma_{x0} = 1.160$
$\sigma_y/\sigma_{y0} = 1.30$	$\sigma_y/\sigma_{y0} = 1.038$	$\sigma_y/\sigma_{y0} = 1.047$	$\sigma_y/\sigma_{y0} = 1.055$	$\sigma_y/\sigma_{y0} = 1.044$

Figure 3. Beam-beam blow up and tail growth as a function of the cubic lattice nonlinearity (numerical simulations). Equilibrium density contour plots in the space of normalised betatron amplitudes are shown.

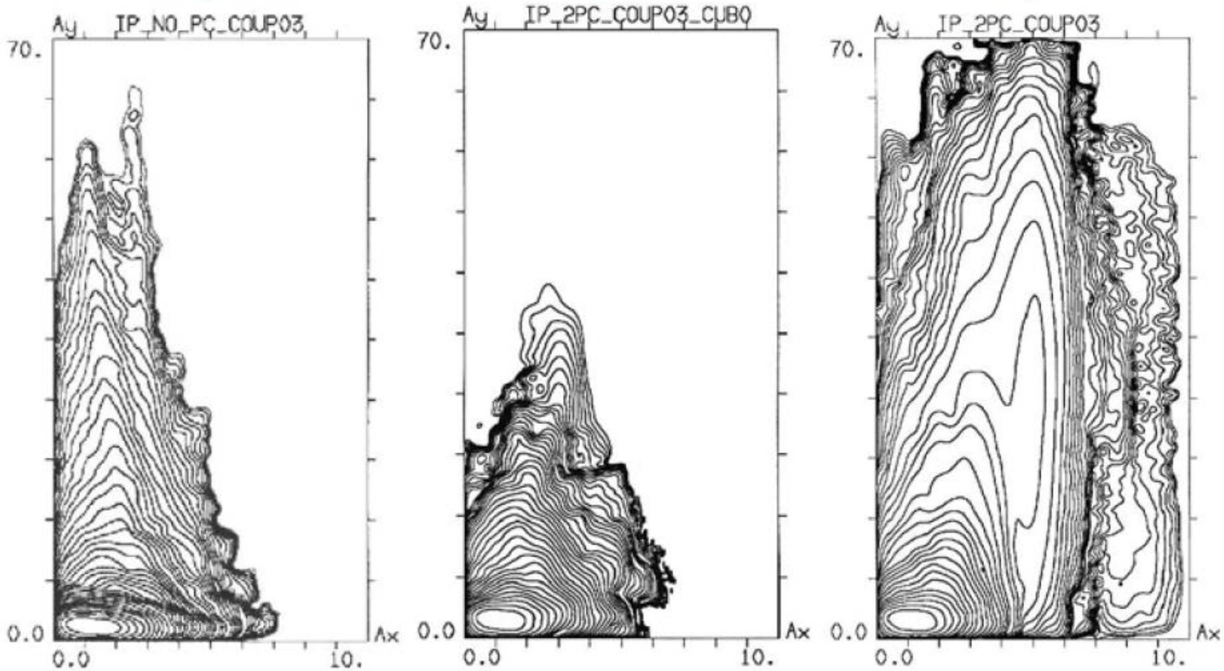
$$\Delta \nu_x = 2c_{11}J_x$$

M. Zobov, DAFNE Techinial Note G-57, 2001

DAFNE: Cubic lattice nonlinearity One IP + 2 nearest PC

$c_{11} = -350$

1 IP a)　　1 IP + 2PC b)　　1 IP + 2PC + C11 c)



$\sigma_x/\sigma_y = 1.076$　$\sigma_y/\sigma_{y0} = 1.449$　$\tau = \infty$

$\sigma_x/\sigma_{x0} = 1.097$　$\sigma_y/\sigma_{y0} = 1.954$　$\tau = \infty$

$\sigma_x/\sigma_{x0} = 1.099$　$\sigma_y/\sigma_{y0} = 2.498$　$\tau = 36$ sec

Figure 4. Equilibrium density contour plots taking into account 2 Parasitic Crossings and lattice nonlinearities.

M. Zobov, DAFNE Techinial Note G-57, 2001

- DAFNE-Upgrade

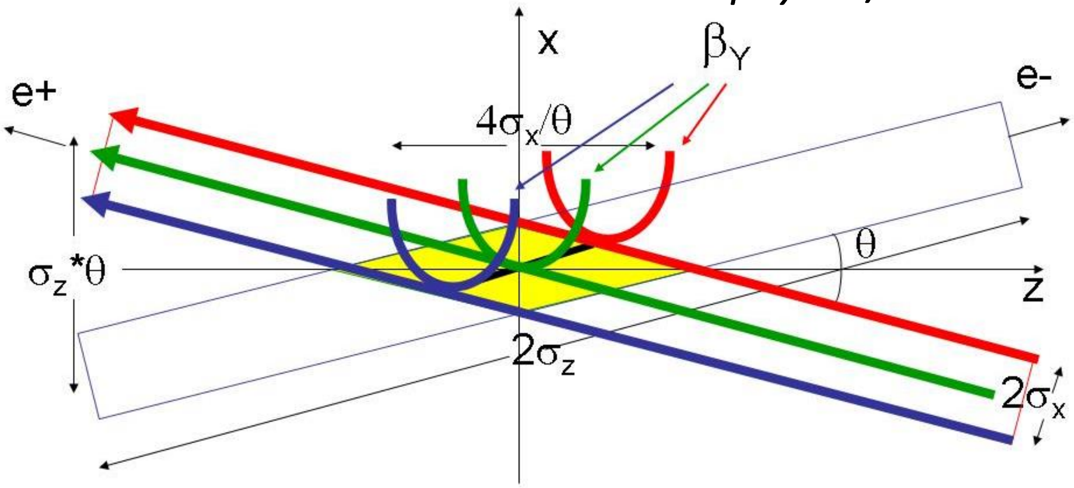
Crab Waist in 3 Steps

1. Large Piwinski's angle $\Phi = tg(\theta/2)\sigma_z/\sigma_x$

2. Vertical beta comparable with overlap area $\beta_y \approx 2\sigma_x/\theta$

3. Crab waist transformation $y = xy'/\theta$

physics/0702033



1. *P.Raimondi, 2° SuperB Workshop, March 2006*

2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033*

Crabbed Waist Advantages

1. Large Piwinski's angle

$$\Phi = tg(\theta/2)\sigma_z/\sigma_x$$

- a) Luminosity gain with N
- b) Very low horizontal tune shift
- c) Vertical tune shift decreases with oscillation amplitude

2. Vertical beta comparable with overlap area

$$\beta_y \approx 2\sigma_x/\theta$$

- a) Geometric luminosity gain
- b) Lower vertical tune shift
- c) Suppression of vertical synchro-betatron resonances

3. Crabbed waist transformation

$$y = xy'/\theta$$

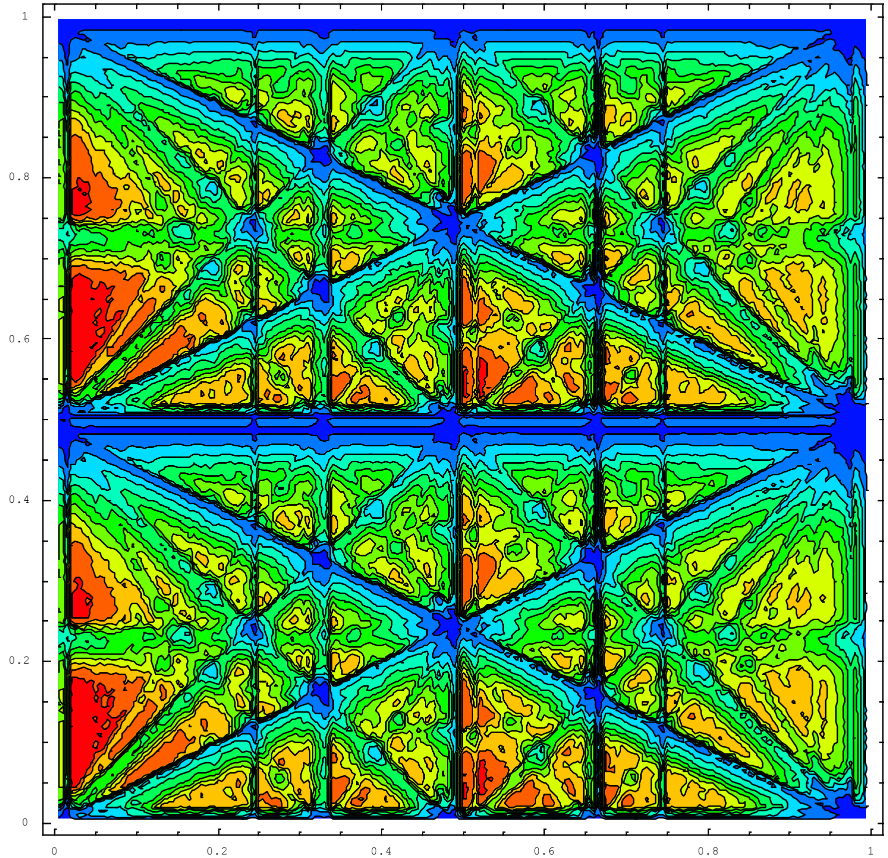
- a) Geometric luminosity gain
- b) Suppression of X-Y betatron and synchro-betatron resonances

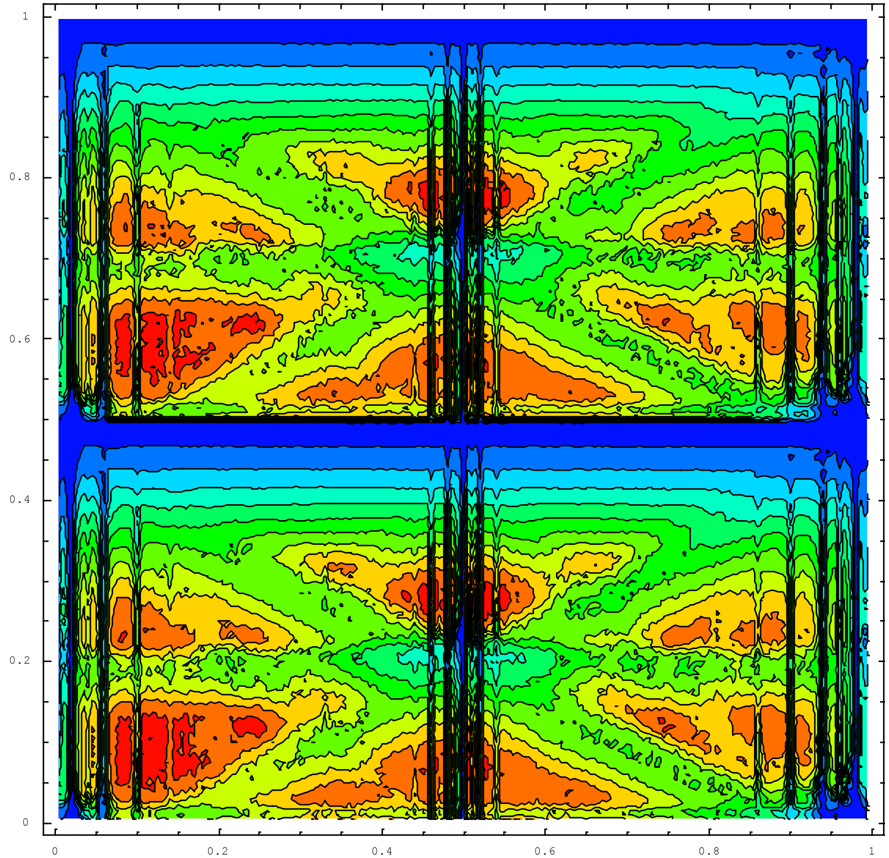
M.Zobov, C.Milardi， BB'2013

M.Zobov, C.Milardi， BB’2013

X-Y Resonance Suppression

Much higher luminosity!





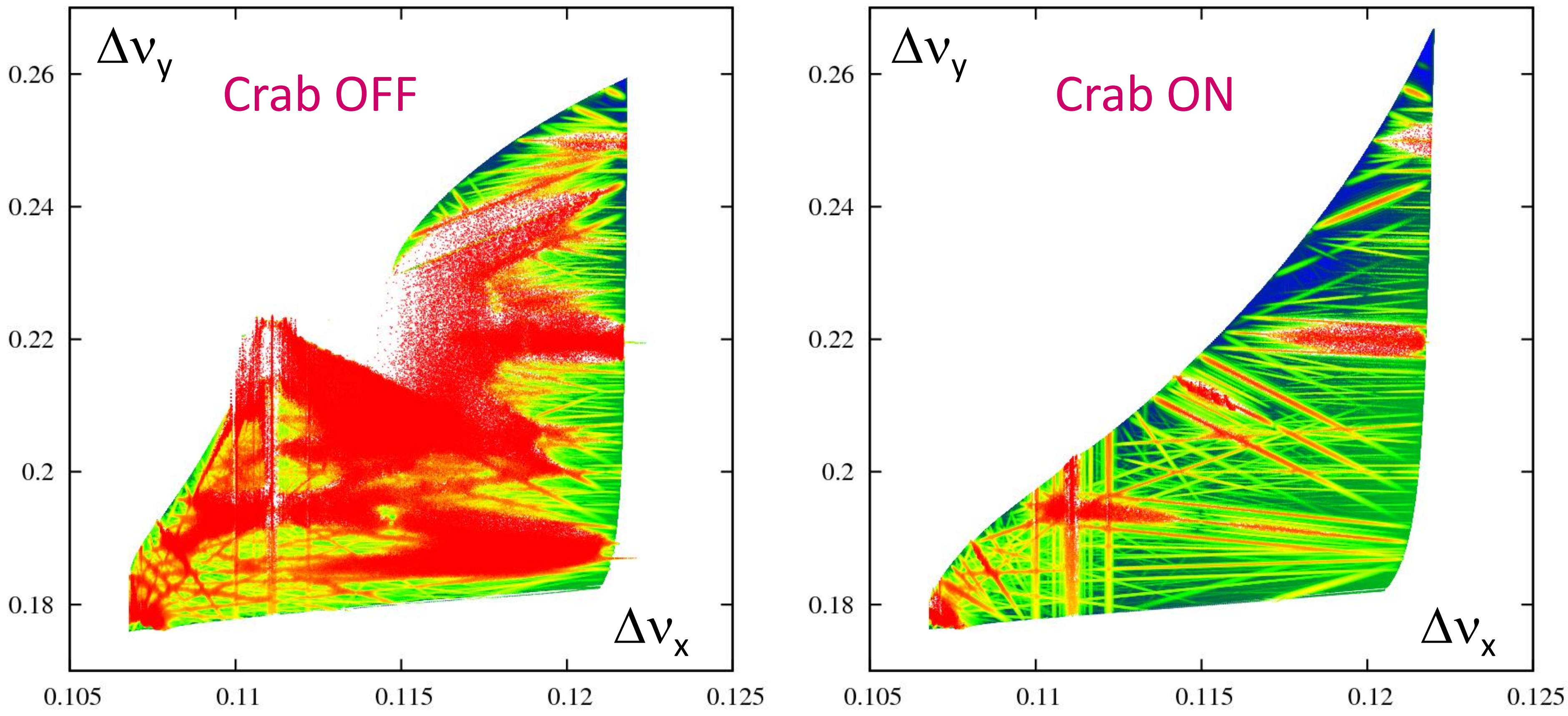
Typical case (KEKB, DAΦNE etc.):

1. low Piwinski angle $\Phi < 1$
2. β_y comparable with σ_z

Crab Waist On:

1. large Piwinski angle $\Phi >> 1$
2. β_y comparable with σ_x/θ

Frequency Map Analysis of Beam-Beam Interaction

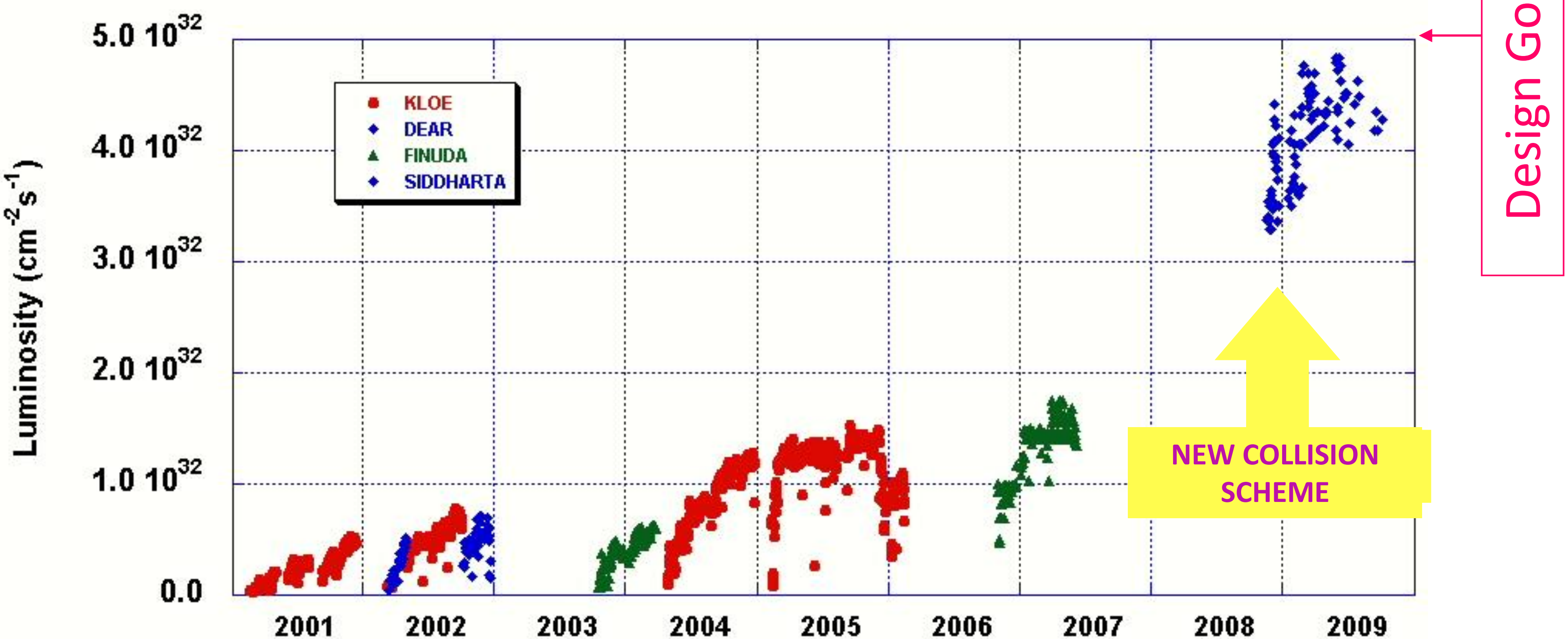


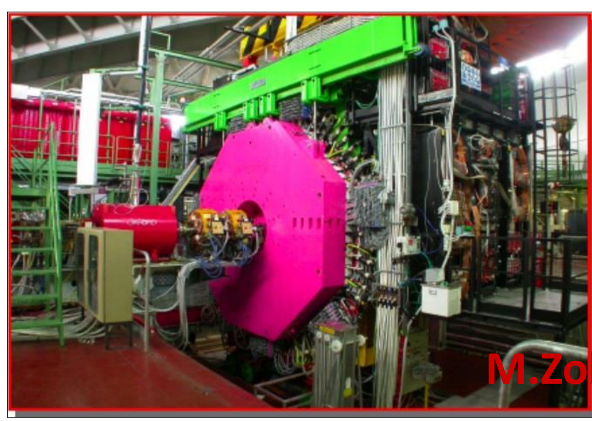
D.Shatilov, E.Levichev, E.Simonov and M.Zobov

Phys.Rev.ST Accel.Beams 14 (2011) 014001

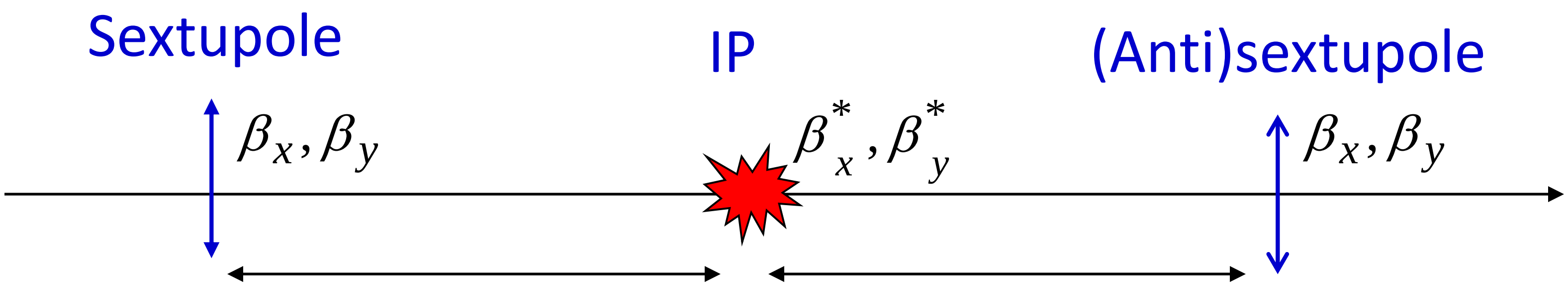
M.Zobov, C.Milardi， BB’2013

DAΦNE Peak Luminosity





Crabbed Waist Scheme



$$\Delta\mu_y = \frac{\pi}{2} \qquad \Delta\mu_y = \frac{\pi}{2}$$

$$\Delta\mu_x = \pi \qquad \Delta\mu_x = \pi$$

Sextupole strength

$$K = \frac{1}{2\theta}\frac{1}{\beta^*_y \beta_y}\sqrt{\frac{\beta^*_x}{\beta_x}}$$

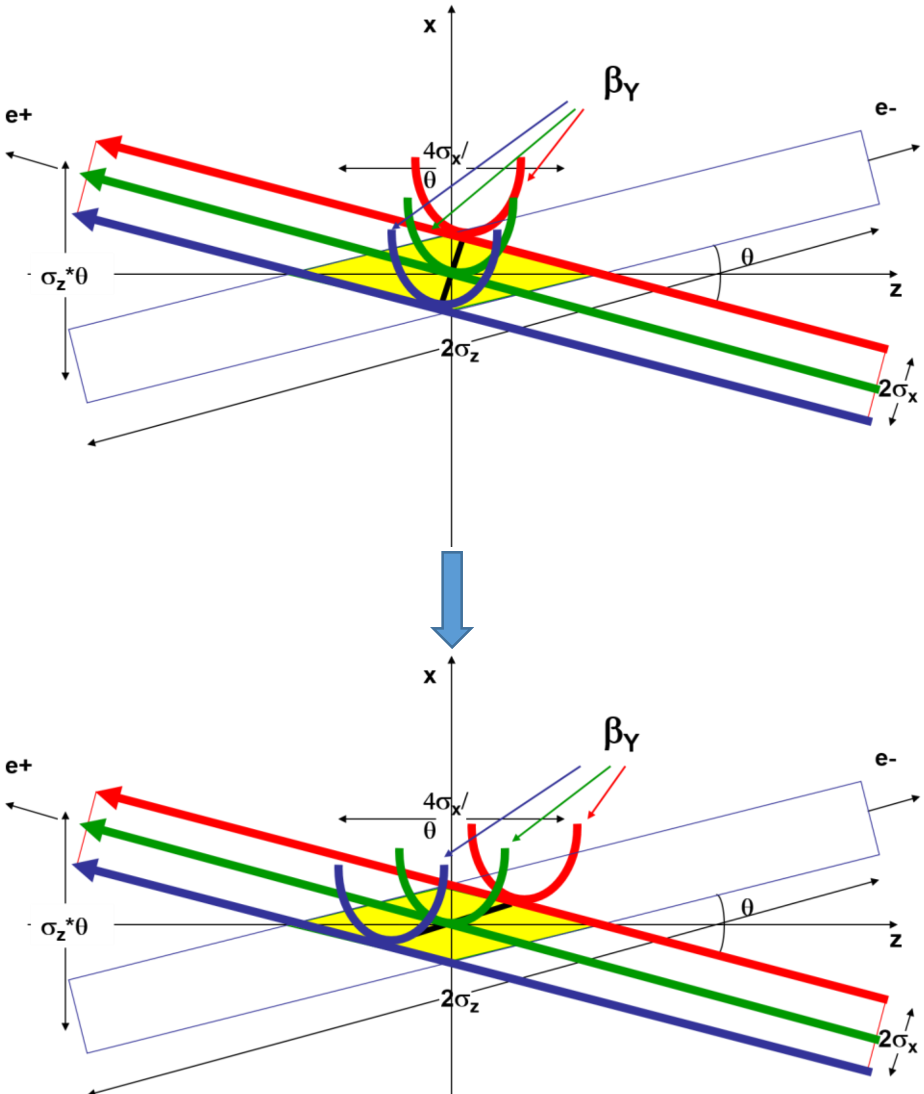
Equivalent Hamiltonian

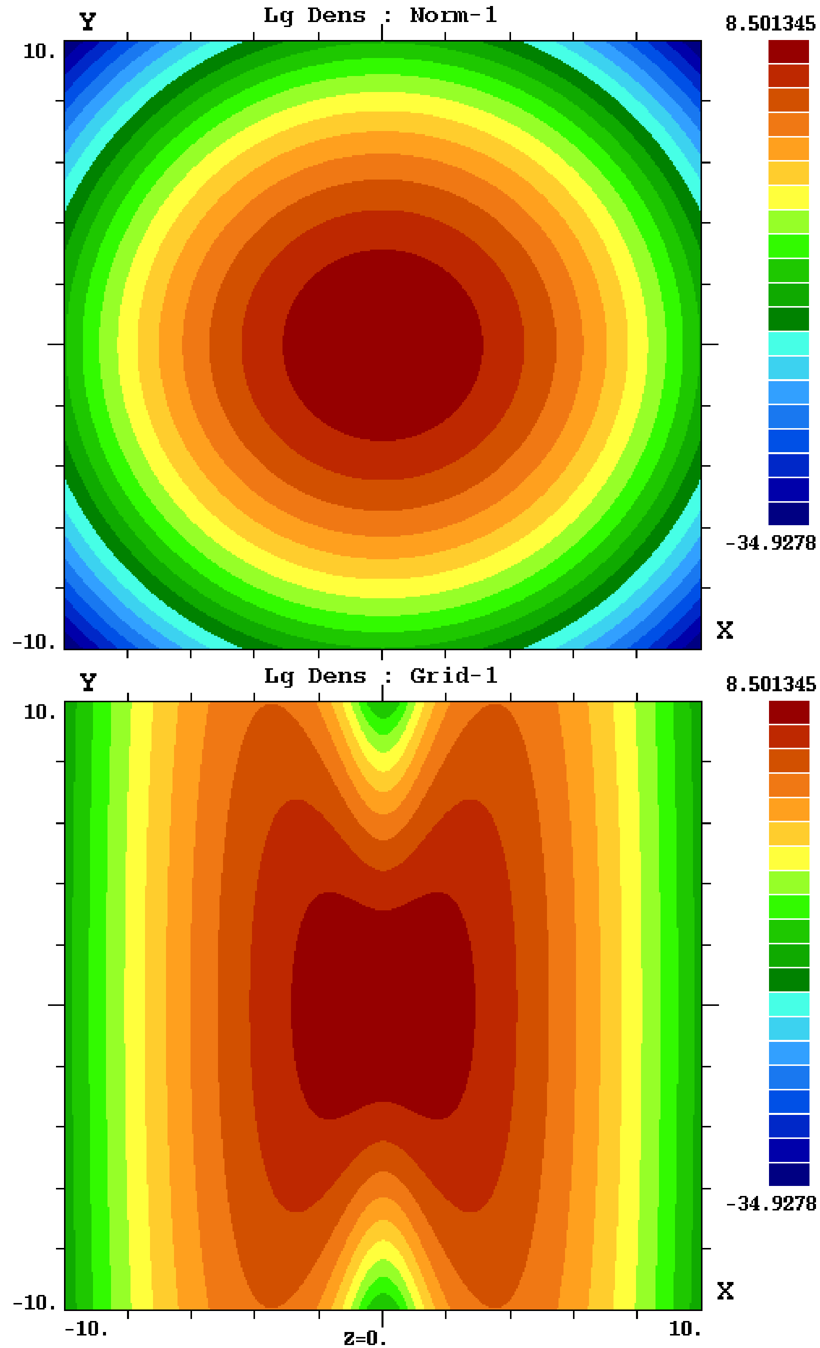
$$H = H_0 + \frac{1}{2\theta} x p_y^2$$

$$\beta_y = \beta^*_y + \frac{(s - x/\theta)^2}{\beta^*_y}$$

M.Zobov, C.Milardi, BB'2013

M.Zobov, C.Milardi， BB’2013





Logarithm of the bunch density at IP (z=0).
The scales are ± 10 sigma for X and Y.

D. Shatilov

Normal form analysis of crabed- wasit transformtaion

- One-turn map with beam-beam

$$\exp(:-axp_y^2:)\exp(:H_{bb}:)\exp(:axp_y^2:)\exp(:H_{arc}:)$$

- One-turn map without beam-beam at IP

$$\exp(:axp_y^2:)\exp(:H_{arc}:)\exp(:-axp_y^2:)$$

$$\exp^{:f_2(X):}\exp^{:f_3(X):}\exp^{:f_4(X):}$$

$$f_3=\exp^{:-f_2(X):}bxp_y^2-bxp_y^2$$
$$=b(\cos\mu_x x-\sin\mu_x p_x)(\sin\mu_y y+\cos\mu_y p_y)^2-bxp_y^2$$

$$f_4=-\frac{1}{2}:\exp^{:-f_2(X):}bxp_y^2:bxp_y^2$$

There only exist 3rd order generating function：

以工作点$Q_x/Q_y=0.51/0.58$, $\beta_x/\beta_y=1.0/0.015$, $a=10$ 为例，

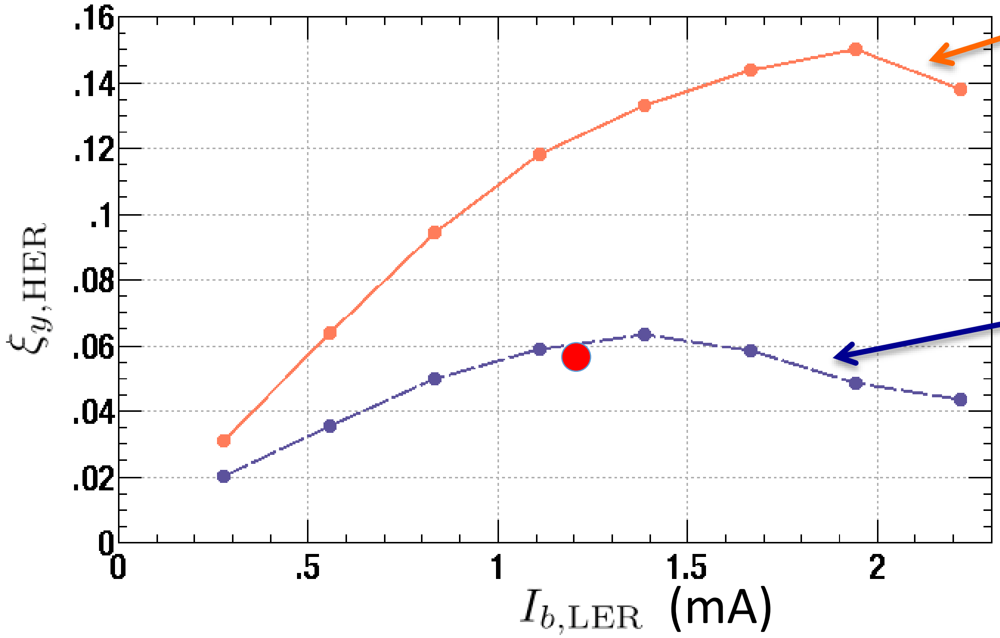
$$\begin{aligned}F_3=&(-235.7+3.200564813177209\times10^{-15}\mathrm{i})e^{-\mathrm{i}\phi_x}\sqrt{A_x}A_y\\&-(235.7+3.200564813177209\times10^{-15}\mathrm{i})e^{\mathrm{i}\phi_x}\sqrt{A_x}A_y\\&+(117.85+4.947431353485854\times10^{-15}\mathrm{i})e^{-\mathrm{i}\phi_x-2\mathrm{i}\phi_y}\sqrt{A_x}A_y\\&+(117.85+2.779027008514845\times10^{-15}\mathrm{i})e^{\mathrm{i}\phi_x-2\mathrm{i}\phi_y}\sqrt{A_x}A_y\\&+(117.85-2.779027008514845\times10^{-15}\mathrm{i})e^{-\mathrm{i}\phi_x+2\mathrm{i}\phi_y}\sqrt{A_x}A_y\\&+(117.85-4.947431353485854\times10^{-15}\mathrm{i})e^{\mathrm{i}\phi_x+2\mathrm{i}\phi_y}\sqrt{A_x}A_y\end{aligned}$$

- KEKB

Motivation of crab cavity at KEKB

Y. Funakoshi, Beam-Beam Workshop, CERN, 2013

- Crab Crossing can boost the beam-beam parameter higher than 0.15 ! (K. Ohmi)

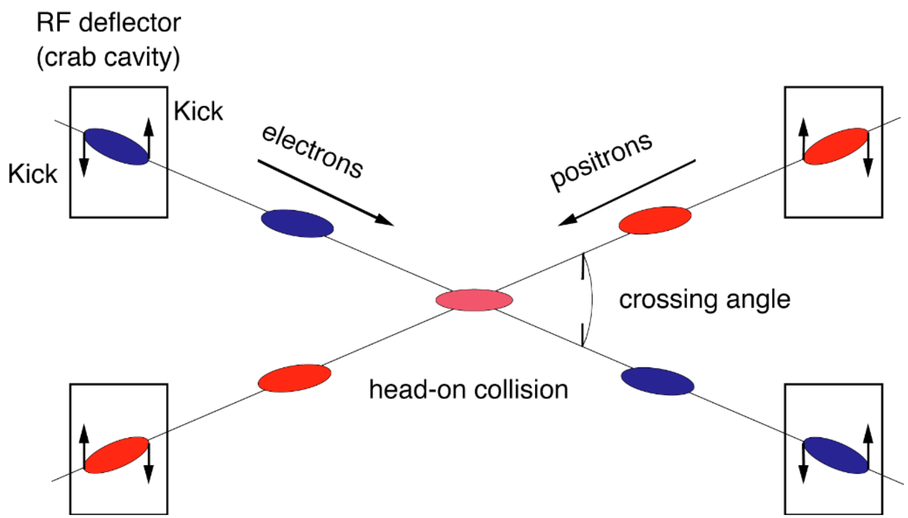


Head-on (crab)

Strong-strong beam-beam simulation

22mrad crossing angle

Head-on ν_x =.508	} → ξ_y ~0.15

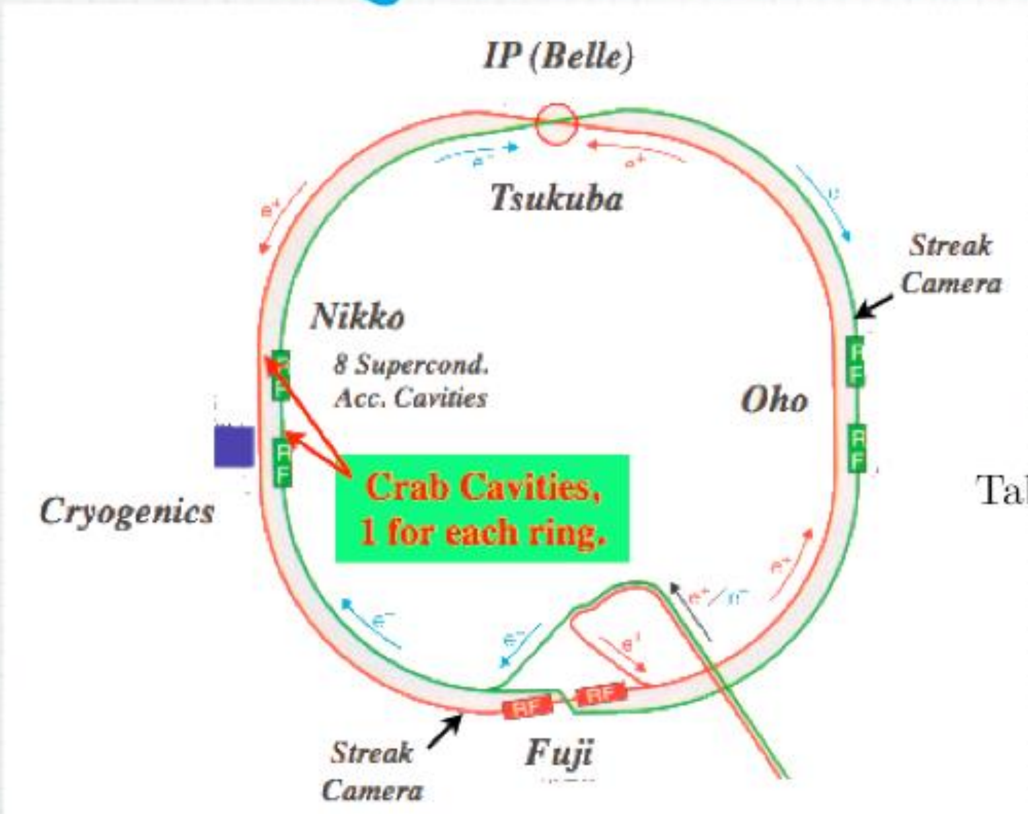


First proposed by R. B. Palmer in 1988 for linear colliders.

Luminosity would be doubled with crab cavities!!!

- After this simulation appeared, the development of crab cavities was revitalized.

Single Crab Cavity Scheme



Beam tilts all around the ring.

z-dependent horizontal closed orbit.

tilt at the IP:

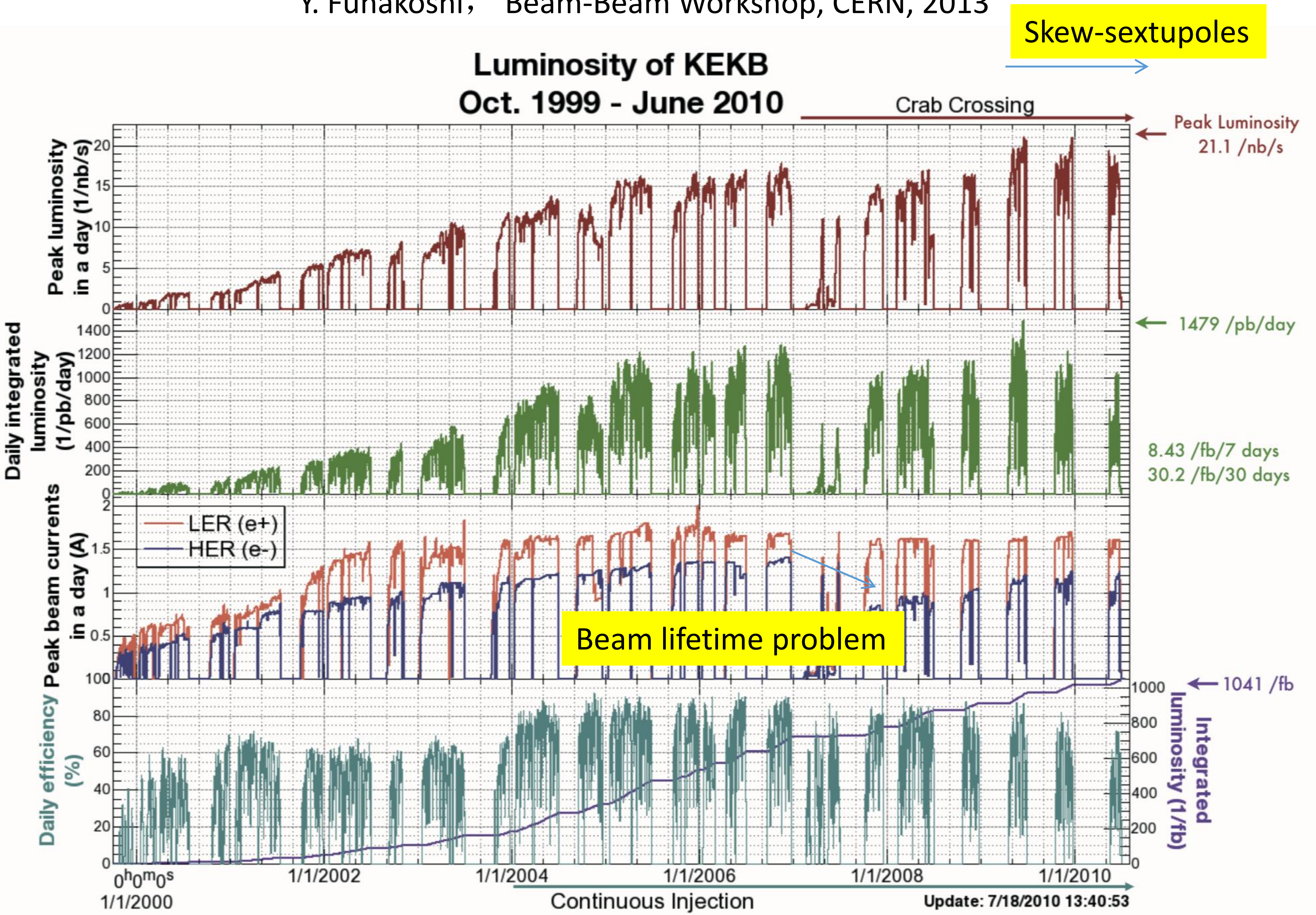
$$\frac{\theta_x}{2} = \frac{\sqrt{\beta_x^C \beta_x^*}\cos(\psi_x^C - \mu_x/2)}{2\sin(\mu_x/2)} \frac{V_C \omega_{rf}}{Ec}$$

Table 1: Typical parameters for the crab crossing.

Ring	LER	HER	
θ_x	22		mrad
β_x^*	80	80	cm
β_x^C	73	162	m
$\mu_x/2\pi$	0.505	0.511	
$\psi_x^C/2\pi$	~ 0.25	~ 0.25	
V_C	0.95	1.45	V
$\omega_{rf}/2\pi$	509		MHz

* 1 crab cavity per ring.
* saves the cost of the cavity and cryogenics.
* avoids synchrotron radiation hitting the cavity.

Y. Funakoshi， Beam-Beam Workshop, CERN, 2013



K. Ohmi, ICAP-09
D. Zhou, K. Ohmi, Y. Seimiya etal., PRST-AB 13, 021001, 2010
Y. Seimiya, K. Ohmi, D. Zhou etal,
Prog. Theor. Phys. (2012) 127 (6): 1099-1119

General Chromaticity

The chromaticities of Twiss parameters and X-Y couplings

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

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

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

The δ-dependent transverse matrix can be split into the product of two matrices. All the chromatic dependences are lumped into $M_H(\delta)$

$$M(\delta) = M(0)M_H(\delta)$$

Generating function F_2 is used to represent the transformation of $M_H(\delta)$. The generating function guarantees the 6D symplectic condition. Hamiltonian which expresses generalized chromaticity is given by

$$F_2(q_i, \bar{p}_i, z, \bar{\delta}) = x\bar{p}_x + y\bar{p}_y + z\bar{\delta} + H_I(x, \bar{p}_x, y, \bar{p}_y, \bar{\delta})$$

$$H_I(x, \bar{p}_x, y, \bar{p}_y, \bar{\delta}) = \sum_{n=1}(a_n x^2 + 2b_n x\bar{p}_x + c_n\bar{p}_x^2 + 2d_n xy + 2e_n x\bar{p}_y + 2f_n y\bar{p}_x + 2g_n\bar{p}_x\bar{p}_y + u_n y^2 + 2v_n y\bar{p}_y + w_n\bar{p}_y^2)\bar{\delta}^n/2. \quad (1)$$

Alternative way is the direct map for the betatron variables $\boldsymbol{x} = (x, p_x, y, p_y)^T$ and z as

$$\boldsymbol{x}(s+L) = M_4(\delta)\boldsymbol{x}(s).$$

$$z(s+L) = z(s) + \boldsymbol{x}^t M_4^t(\delta) S_4 \partial_\delta M_4(\delta)\boldsymbol{x}/2$$

Measurement of chromatic coupling

HER

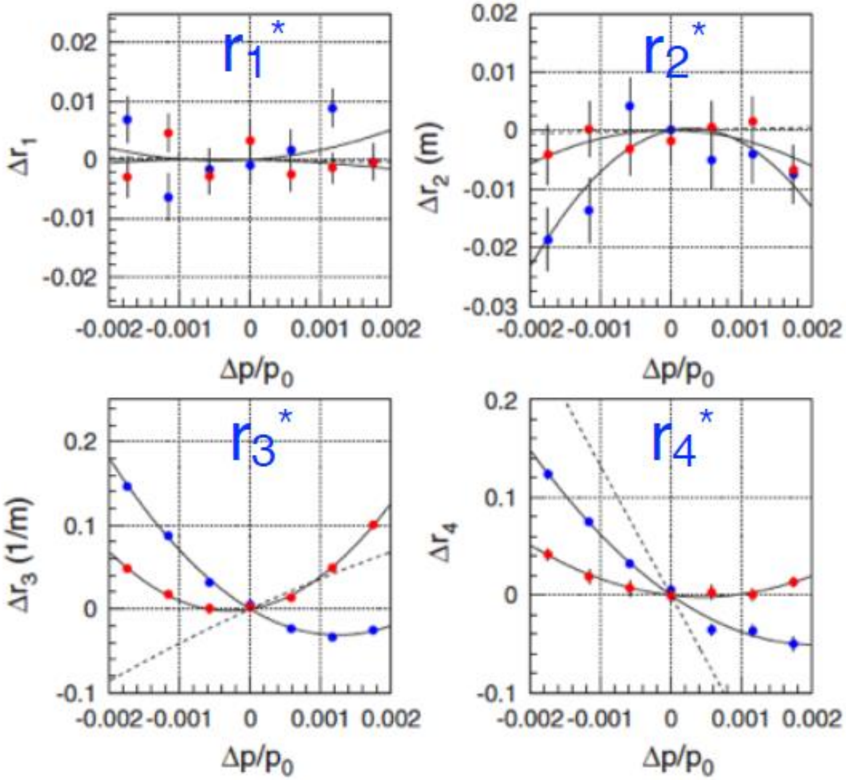


FIG. 3. (Color) Measured chromatic X-Y coupling at IP in HER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic X-Y coupling estimated using the model lattice by SAD.

LER

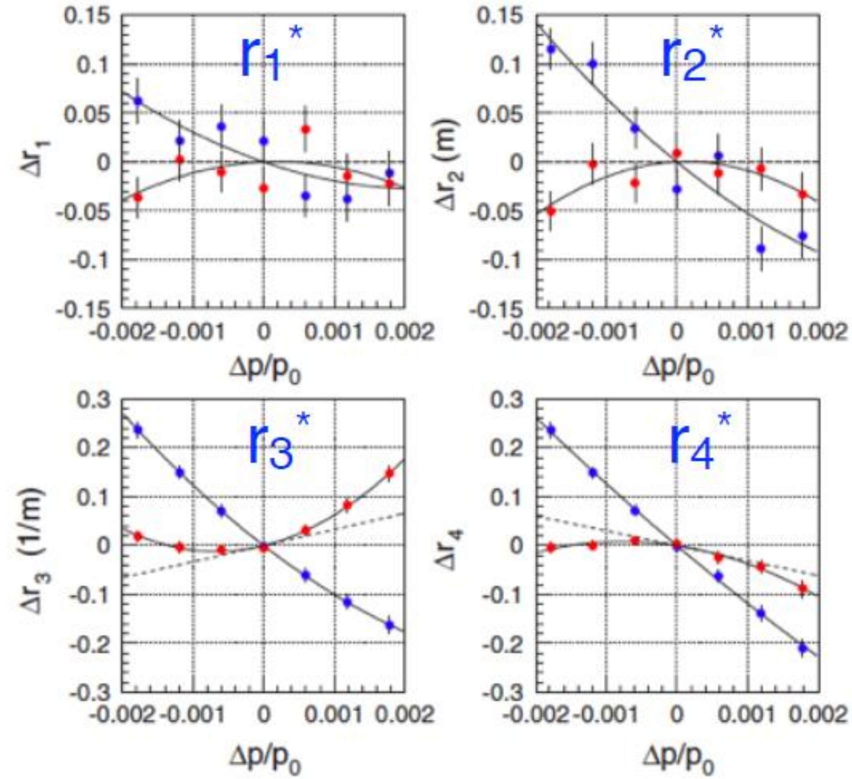
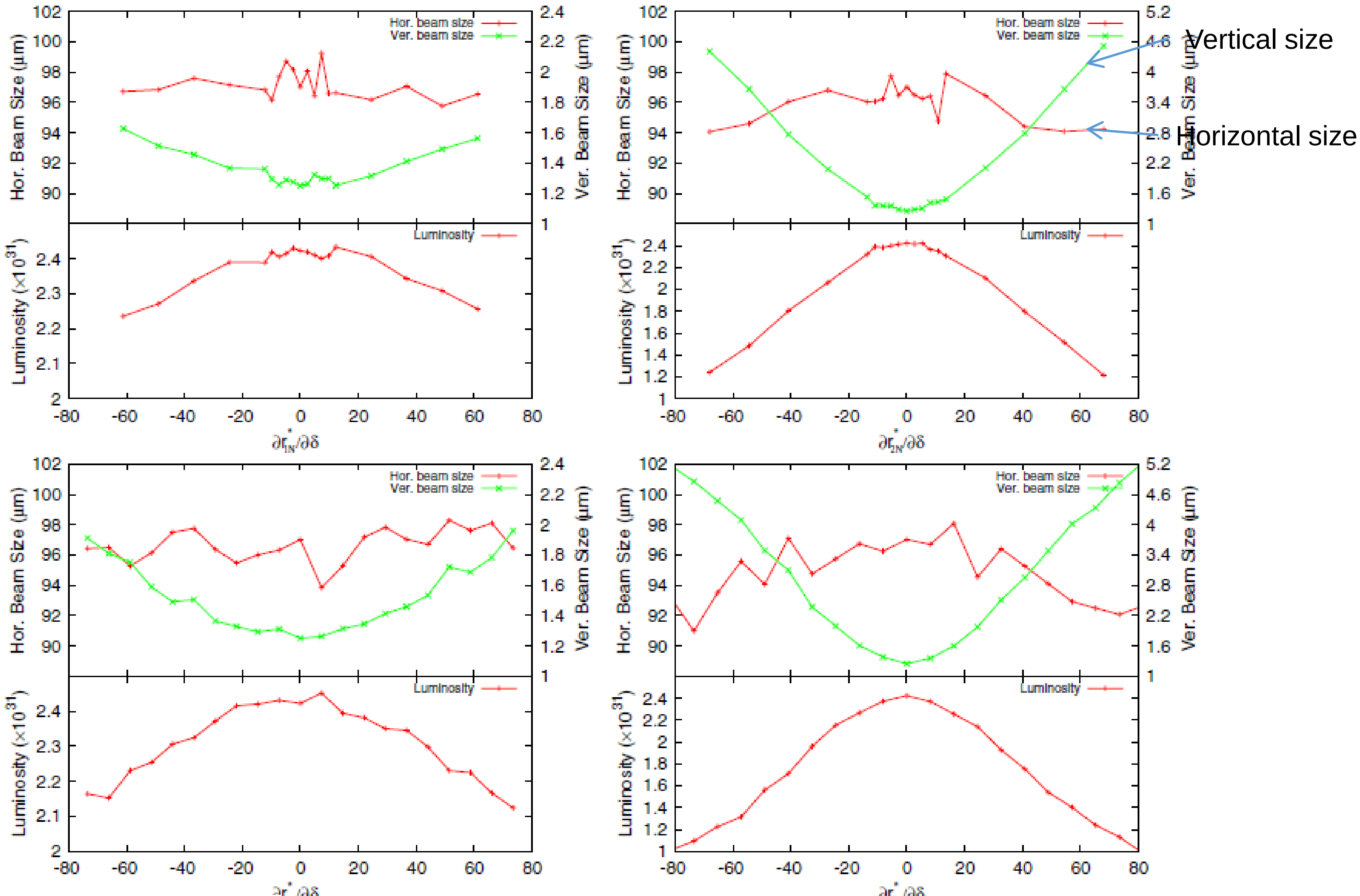


FIG. 4. (Color) Measured chromatic X-Y coupling at IP in LER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic X-Y coupling estimated using the model lattice by SAD.

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

Scan of first-order chromatic coupling (WS, Crab on)

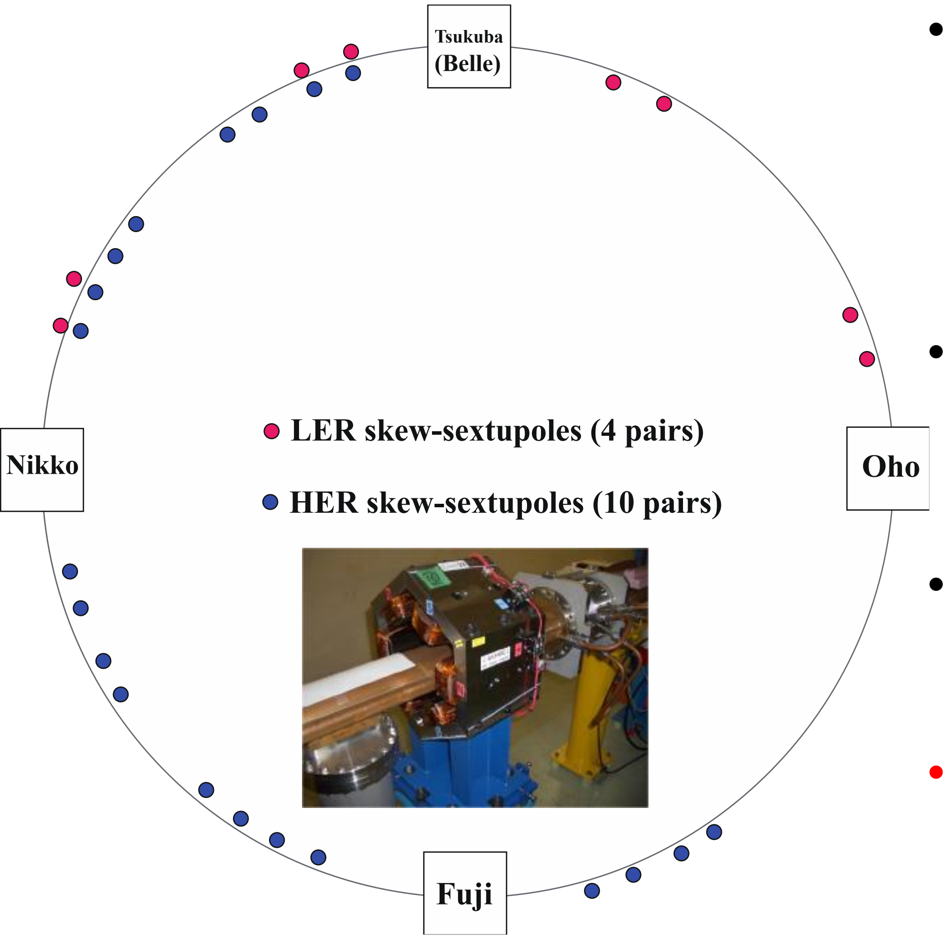
D. Zhou, et al., PRST--AB 13, 021001 (2010).



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

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

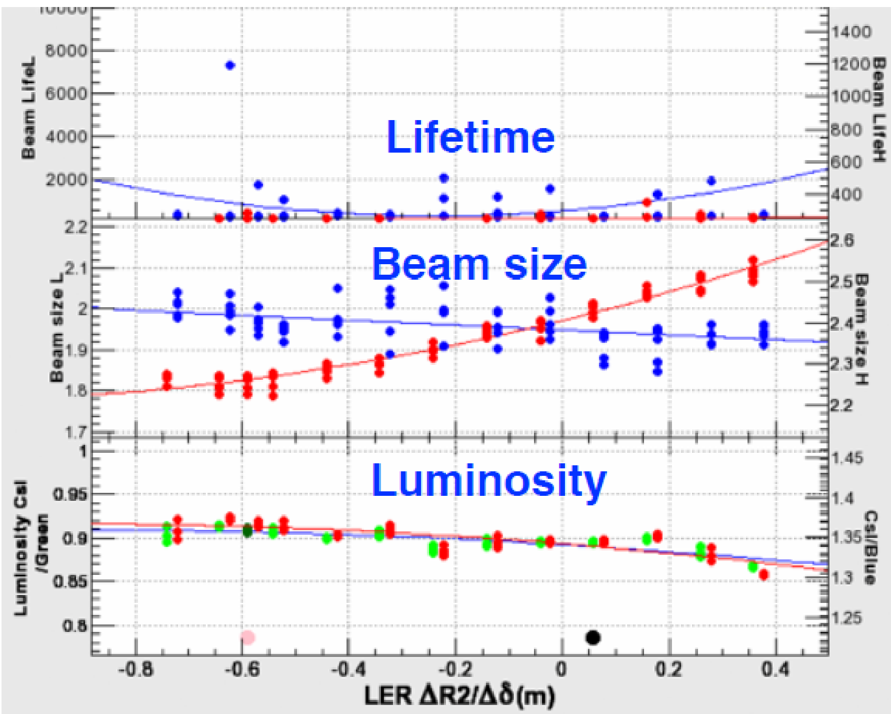
Chromaticity of x-y coupling at IP

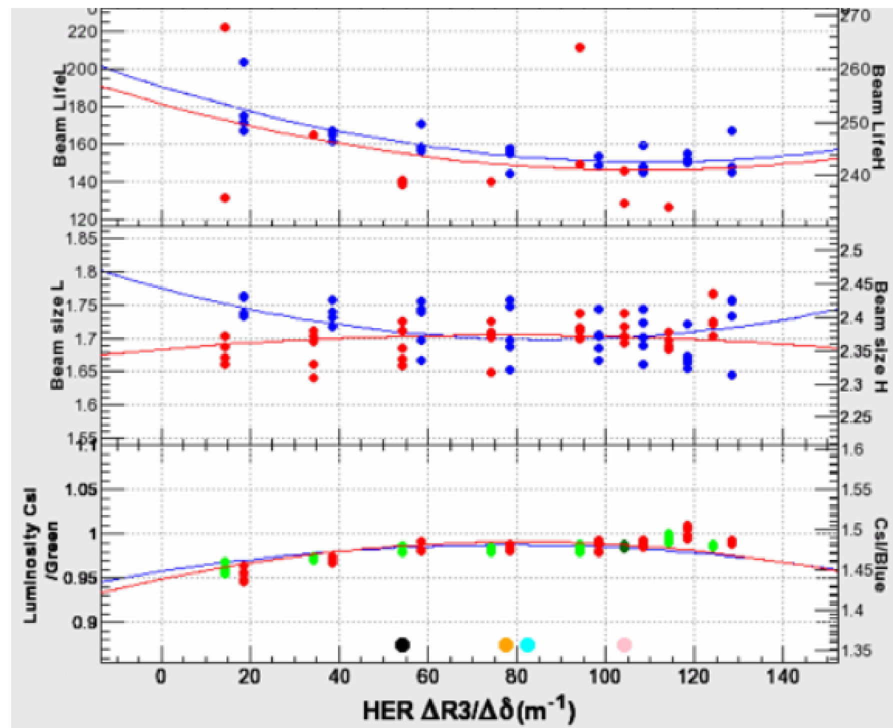


- Ohmi et al. showed that the linear chromaticity of x-y coupling parameters at IP could degrade the luminosity, if the residual values, which depend on machine errors, are large.
- To control the chromaticity, skew sextupole magnets were installed during winter shutdown 2009.
- The skew sextuples are very effective to increase the luminosity at KEKB.
- The gain of the luminosity by these magnets is ~15%.

Experimental observations

The first scans of chromatic coupling at IP during the KEKB operation:

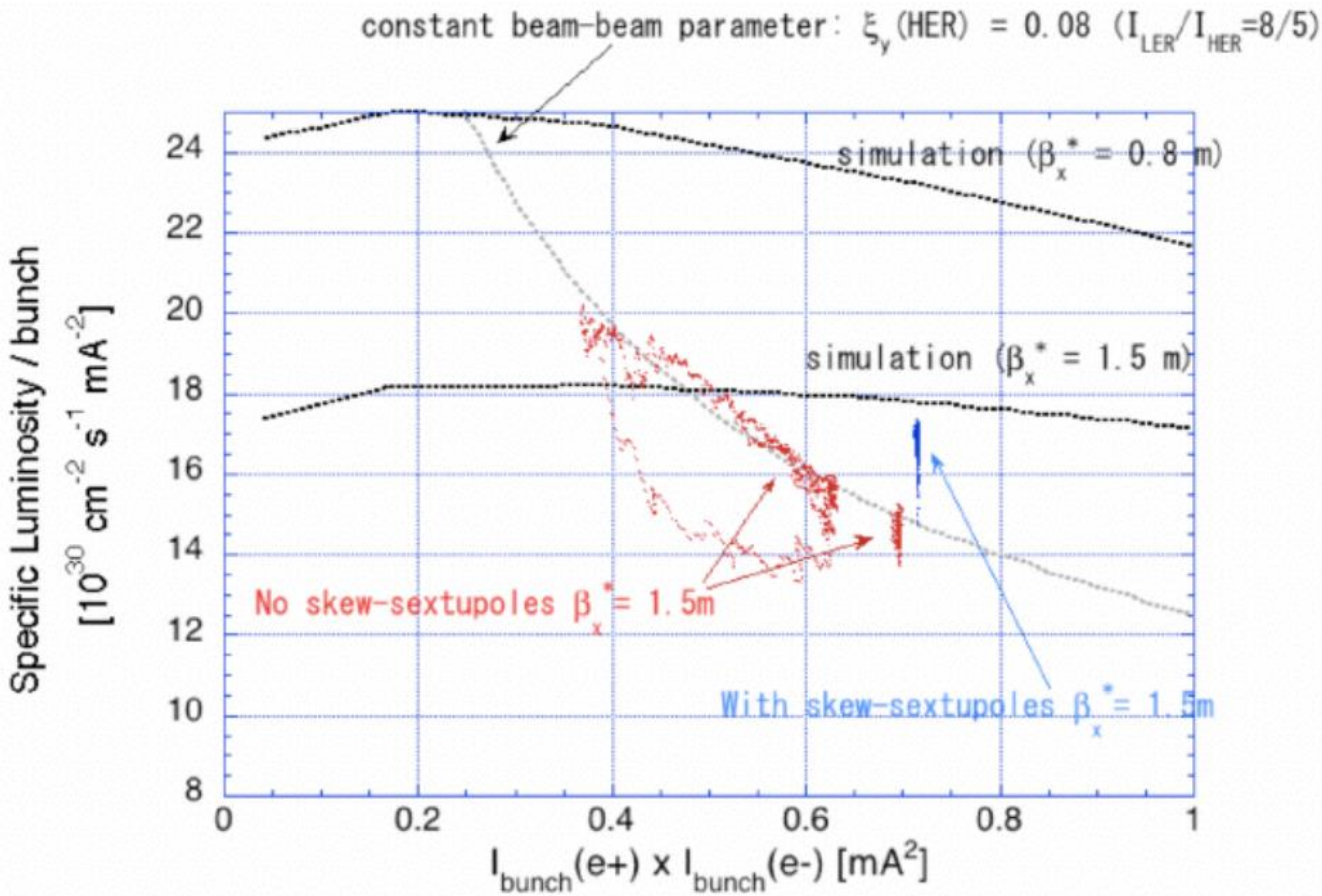




D. Zhou, 2011

Experimental observations (cont'd)

Skew-sextupole tuning was very effective w/ crab on ...

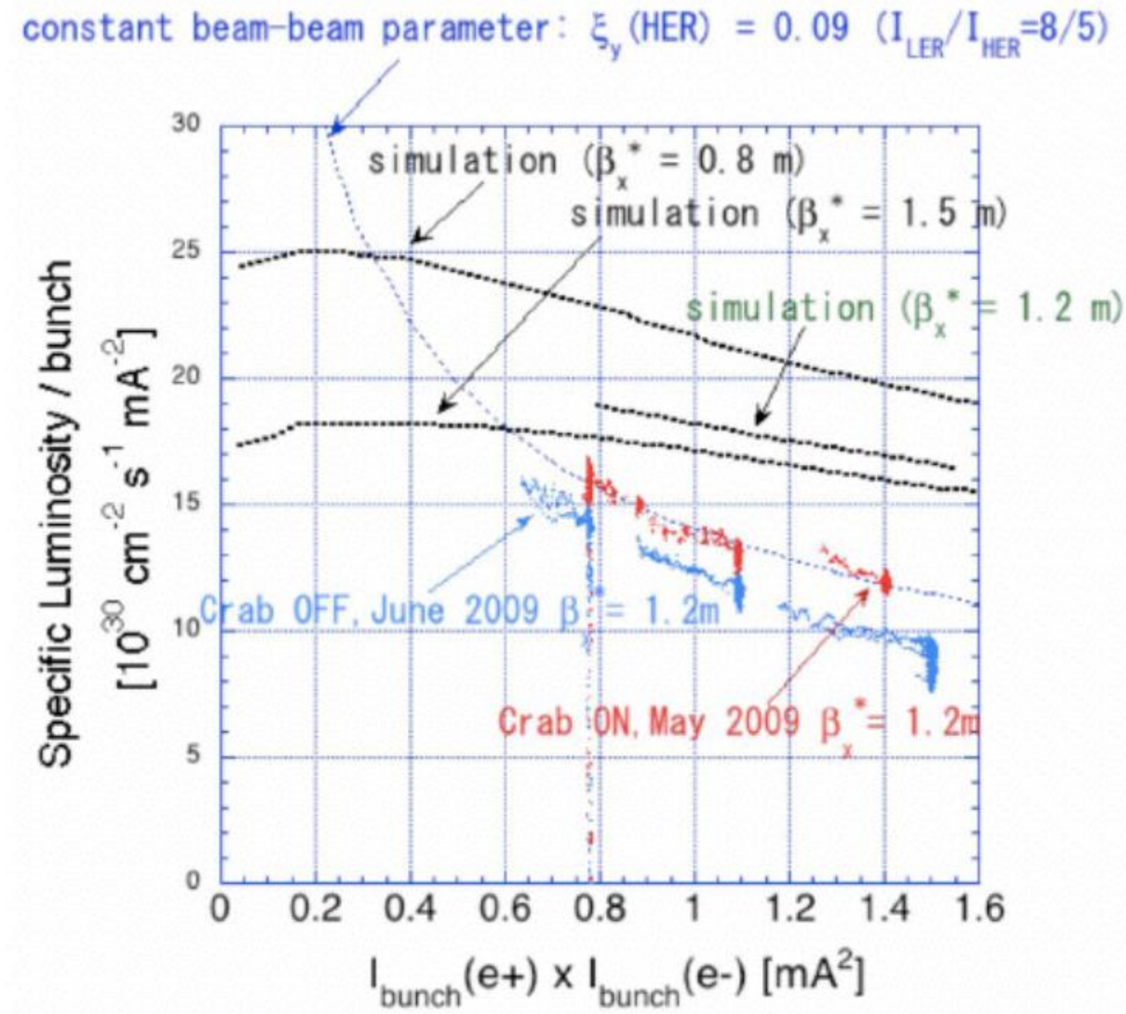


Y. Funakoshi, et al., WEOAMH02, IPAC'10 (2010)

Experimental observations (cont'd)

Specific lum. w/ crab on and w/ skew-sext. tuning optimized

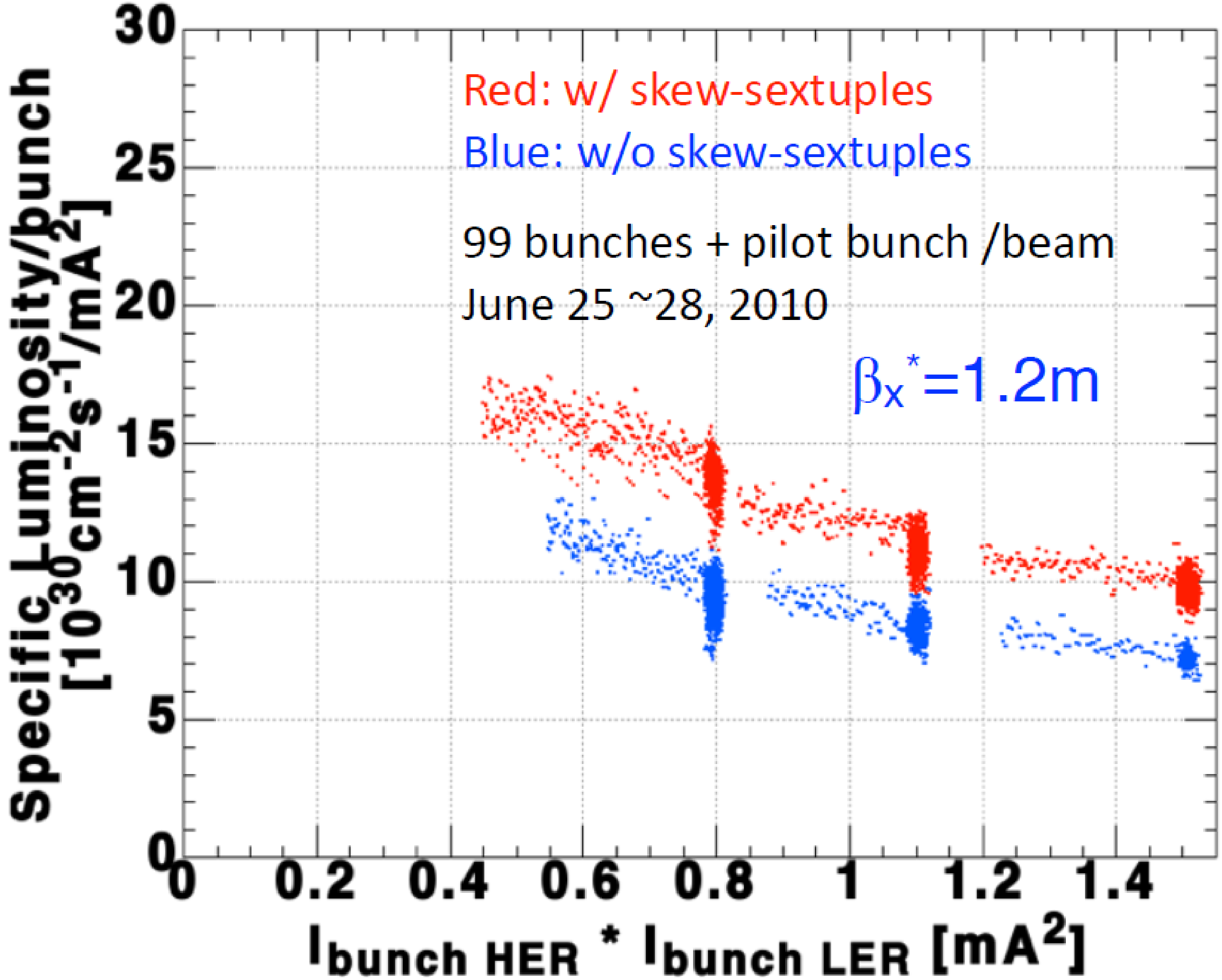
Lum. gain from crab cavities: ~20%, Lum. gain from skew-sext.: ~15%



Y. Funakoshi, et al., WEOAMH02, IPAC'10 (2010)

Experimental observations (cont'd)

Skew-sextupole tuning was very effective even w/ crab off. This was a surprise...

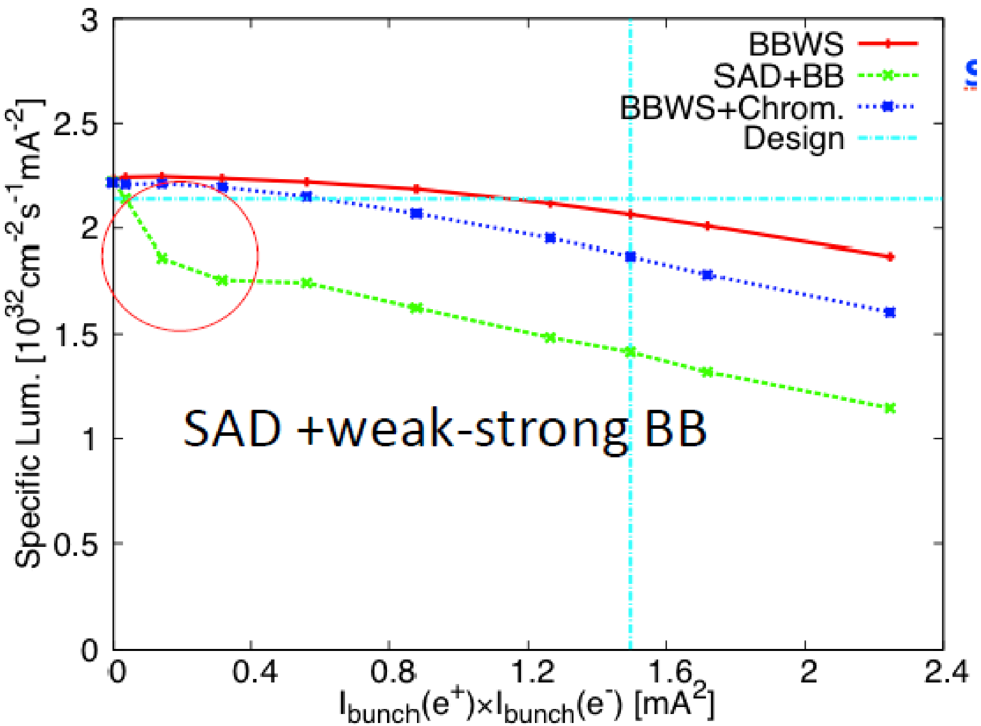


Y. Funakoshi, et al., WEOAMH02, IPAC'10 (2010)

- Super-KEKB

Weak-strong Simulation for LER lattice

- Even low current, luminosity loss ~20% is seen.
- 30% loss at the design current.
- Chromatic effect can not explain the lum. Loss.

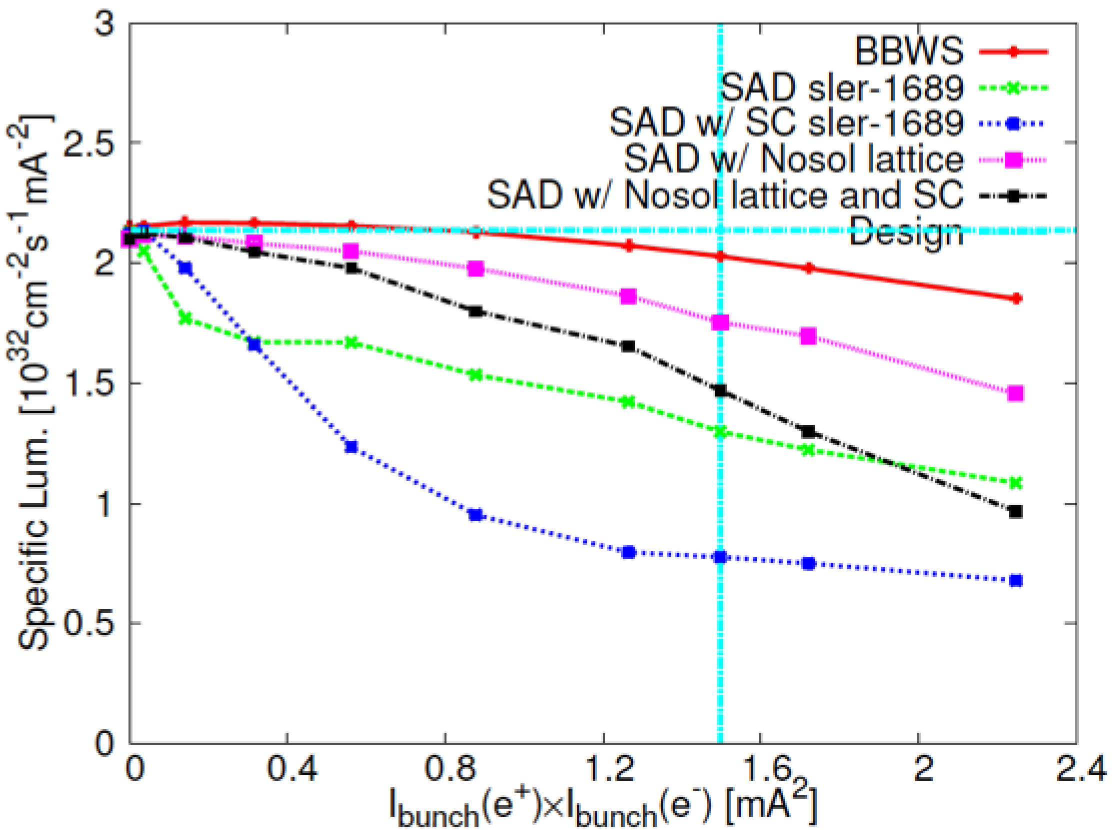


sler_1684

K. Ohmi, D. Zhou
SuperKEKB MAC2014, Mar 3-4, 2014

LER: Simplied IR

- Simplified lattice by H. Sugimoto
- Sler_simple001.sad: no solenoid but preserve main optics parameters
- No significant luminosity degradation at low current
- Solenoid is the main source of lattice nonlinearity?

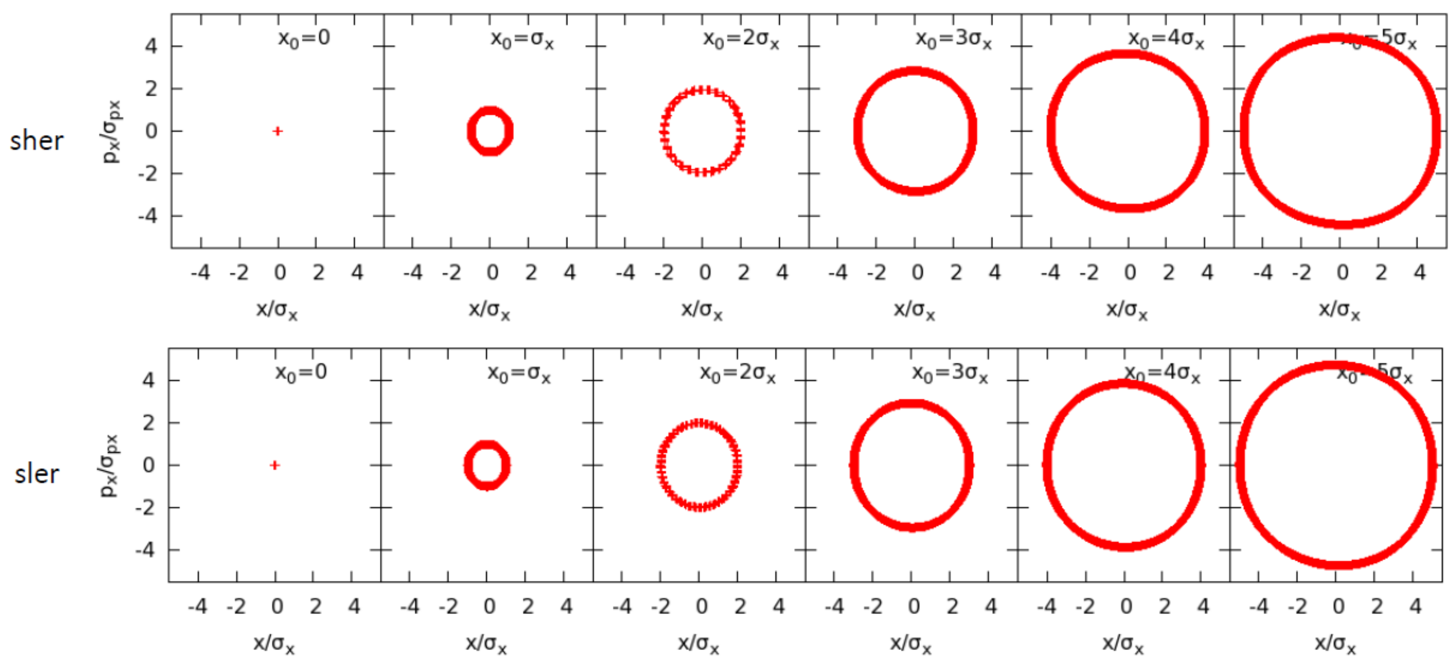


D. Zhou and Y. Zhang(IHEP), SuperKEKB optics meeting, Apr.17, 2014

Lattice nonlinearity from turn-by-turn data

- Initial coordinates (x0, 0, 0, 0, 0, 0);
- x0 changes from 0 to $5\sigma_x$
- Watch point is at IP, beam-beam is off

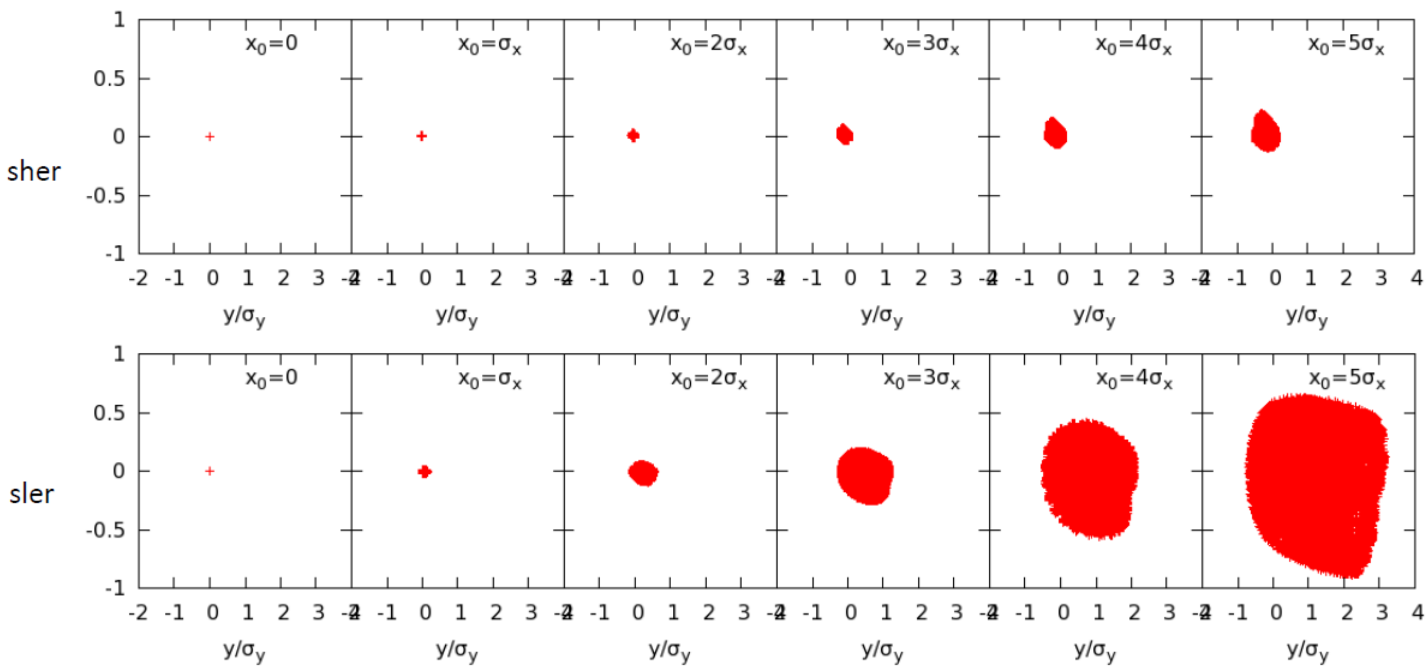
sher-5767 vs ler-1689 in X direction



Lattice nonlinearity from turn-by-turn data (Cont.)

- Evidence of nonlinear X-Y coupling
- COD in Y direction as function of X offset

sher-5767 vs ler-1689 in Y direction



Frequency Analysis

- Linear Normalized Coordinate

$$\hat{x} = \frac{x}{\sqrt{\beta_x}}, \hat{p}_x = p_x * \sqrt{\beta_x}$$

$$\hat{y} = \frac{y}{\sqrt{\beta_y}}, \hat{p}_y = p_y * \sqrt{\beta_y},$$

- Turn-by-Turn data could be represented by (with first order approximation)

$$\begin{aligned}\hat{x}(m) - i\hat{p}_x(m) &= \sqrt{2A_x}e^{i(m\mu_x+\phi_{x,0})} \\ &- \sum_{abcd} 2iaf^{(3)}_{abcd}(2A_x)^{\frac{a+b-1}{2}}(2A_y)^{\frac{c+d}{2}}e^{i(b-a+1)(m\mu_x+\phi_{x,0})}e^{i(d-c)(m\mu_y+\phi_{y,0})} \\ \hat{y}(m) - i\hat{p}_y(m) &= \sqrt{2A_y}e^{i(m\mu_y+\phi_{y,0})} \\ &- \sum_{abcd} 2icf^{(3)}_{abcd}(2A_x)^{\frac{a+b}{2}}(2A_y)^{\frac{c+d-1}{2}}e^{i(b-a)(m\mu_x+\phi_{x,0})}e^{i(d-c+1)(m\mu_y+\phi_{y,0})}\end{aligned}$$

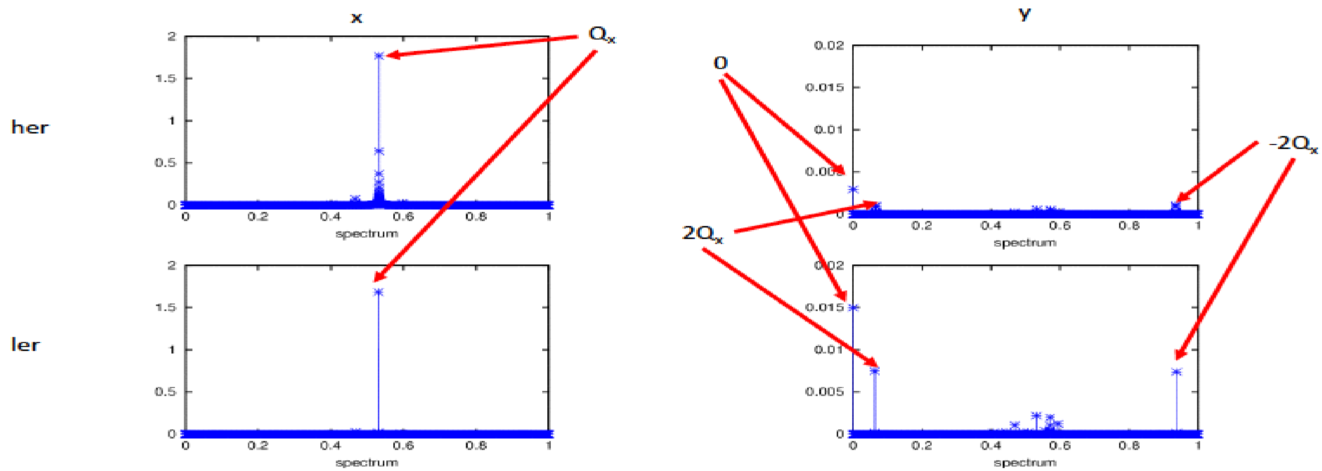
- FFT with

  $\hat{x} - i\hat{p}_x$ in x direction

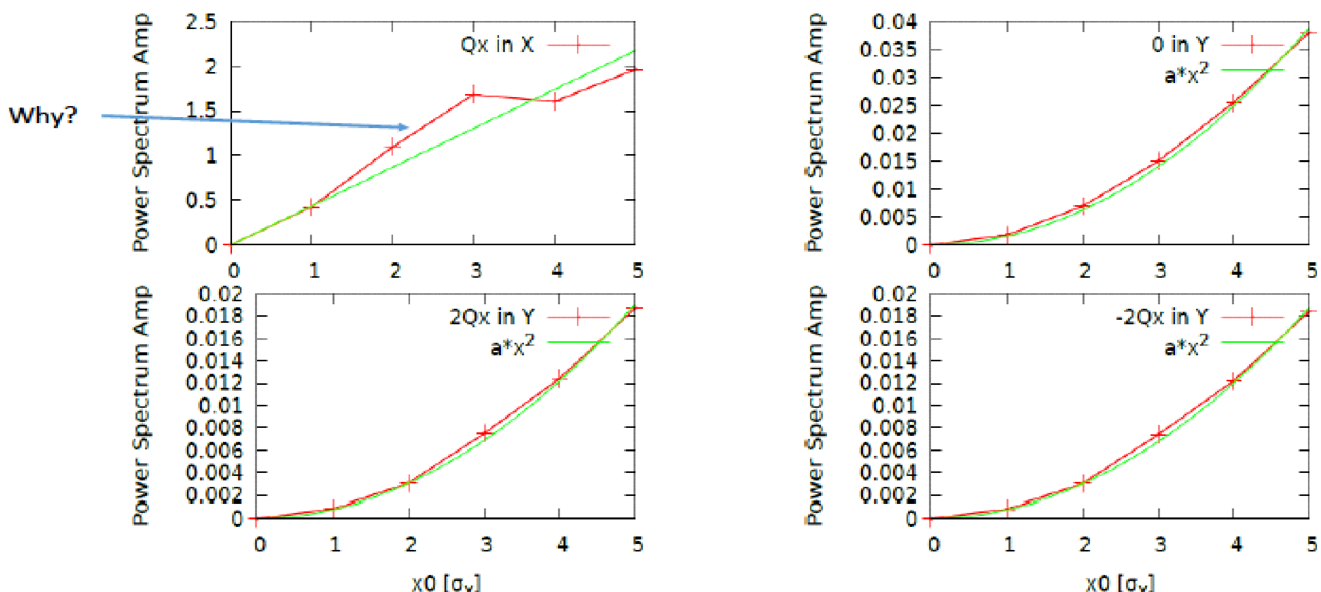
  $\hat{y} - i\hat{p}_y$ in y direction

Frequency Analysis (cont.)

Spectrum (x0=3σ_x)



Power spectrum analysis (LER)



- There exist very strong ‘oscilation’ at 0, 2Qx, -2Qx for LER
- It is suspected the cause is

f1110 -> 0 in vertical direction, the amplitude is proportional to $(2A_x)$

f0210 -> 2Qx in vertical direction, the amplitude is proportional to $(2A_x)$

f2010 -> -2Qx in vertical direction, the amplitude is proportional to $(2A_x)$

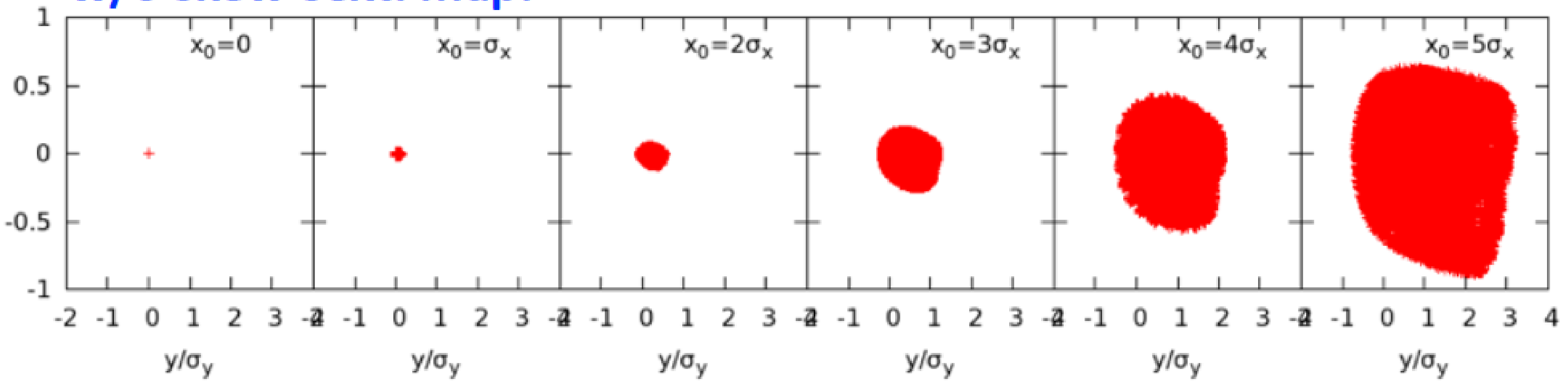
All these terms may come from a skew sextupole like magnet.

$H \sim 3x^2y-y^3$

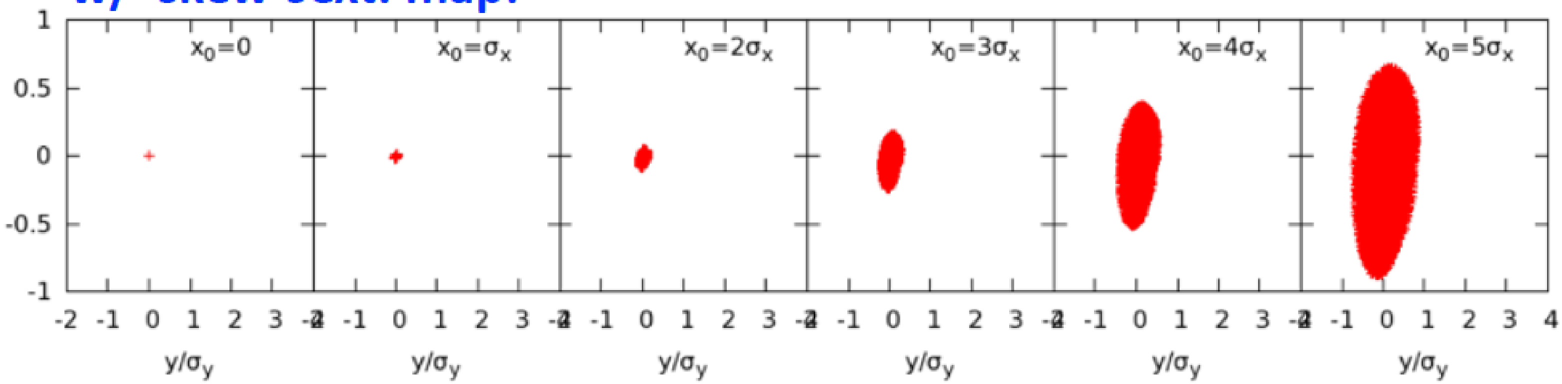
Compensation with a skew-sext map

- Test by inserting a map of $H=K*x^2y$ into the LER lattice
- COD and oscillation amplitude in y are well suppressed as expected

w/o skew-sext. map:



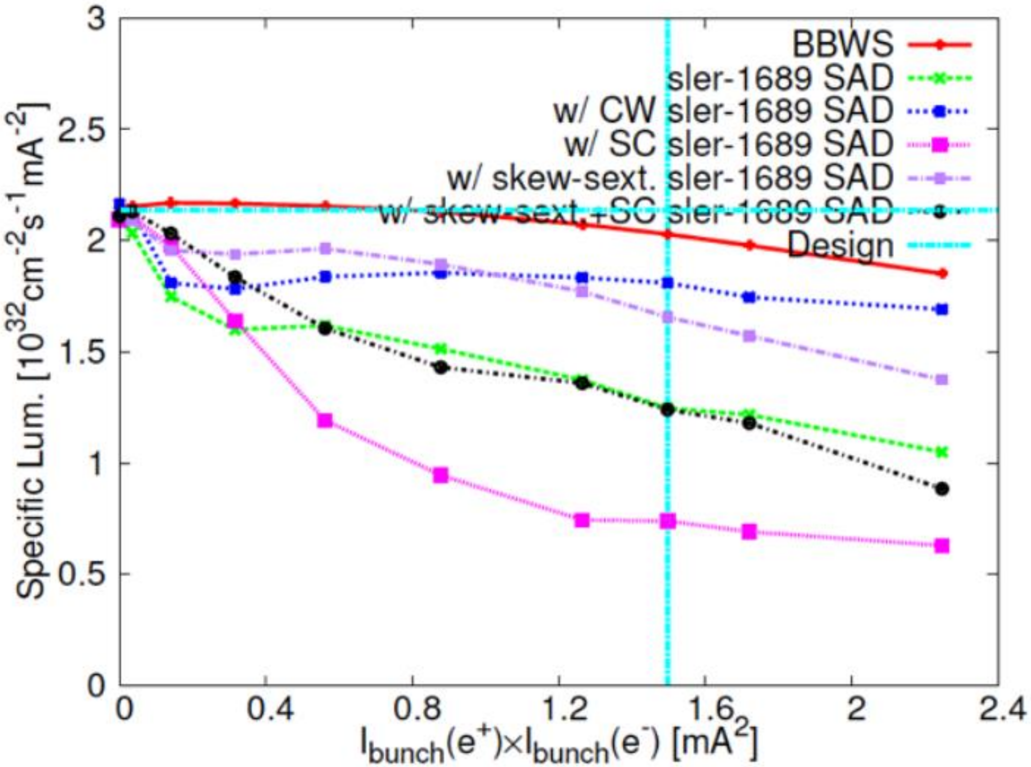
w/ skew-sext. map:



Compensation with a skew-sext map (Cont.)

➤ **Skew-sext. map:**

- **to cancel the nonlinear term from solenoid**
- **work well at both low and high currents**
- **interplay of SC and lattice nonlin. also mitigated partially**



Compensation with a skew-sext map (Cont.)

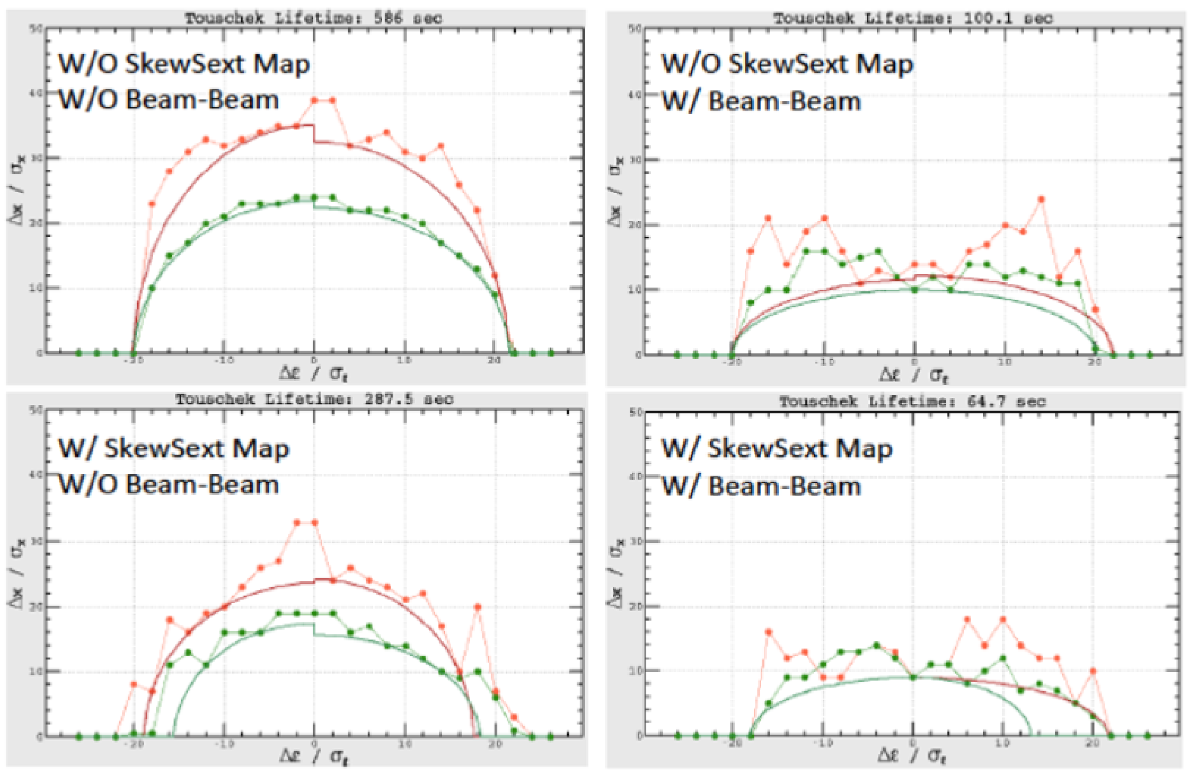
➤ **Skew-sext. map:**

- **cause loss in DA and lifetime (to be understood)**

sler_1689

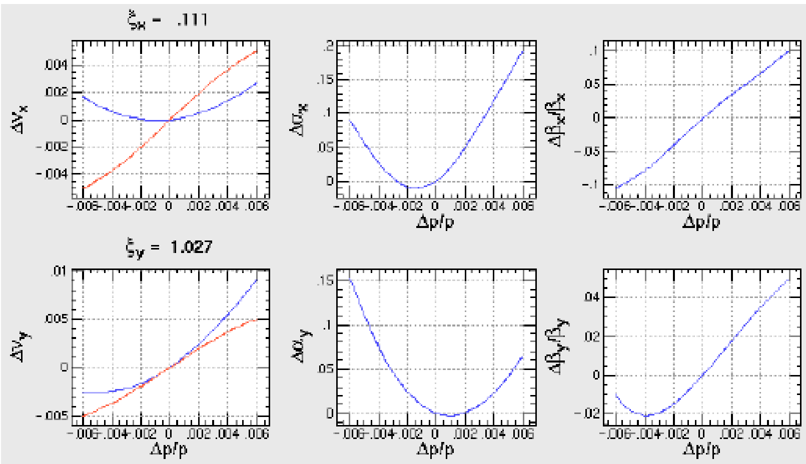
DA and Lifetime

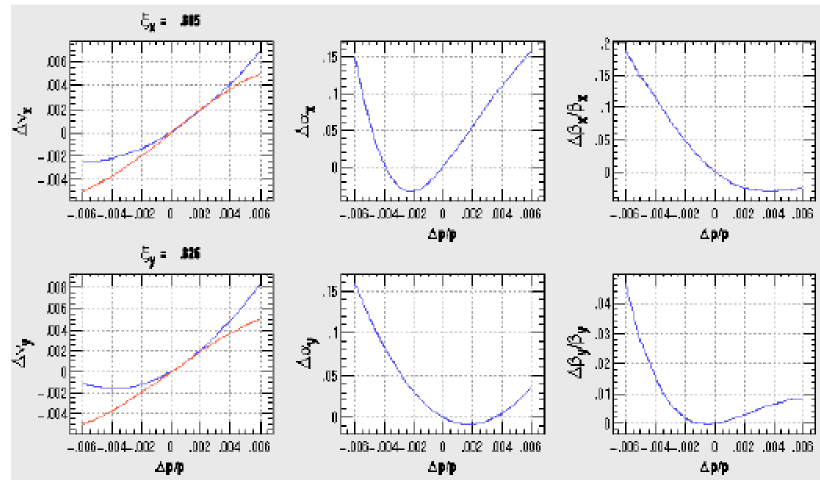
From H. Sugimoto



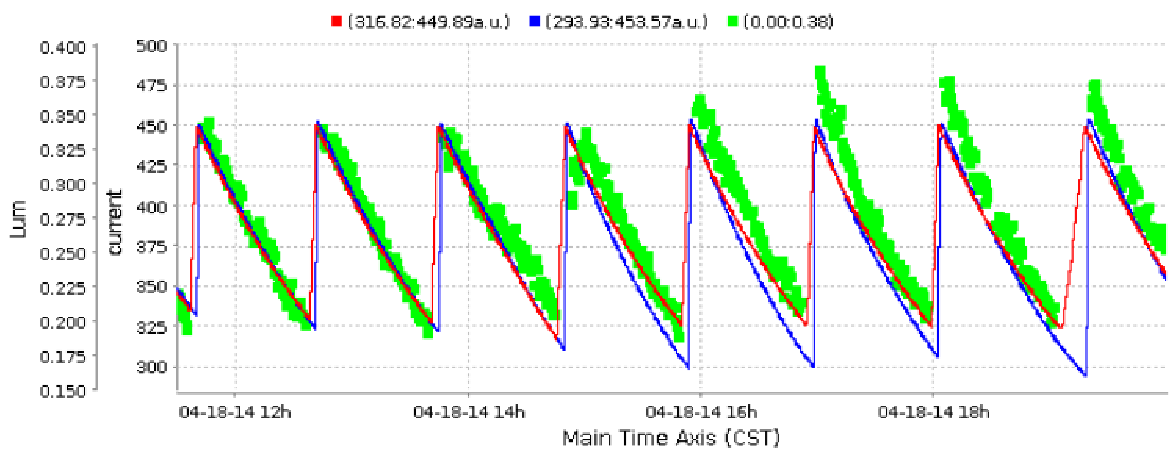
- BEPCII

- 2014 上半年，开始投入使用 1W1。Q 铁强度重新匹配，但六极铁保持不变。经过连续几个班的优化，亮度仍然偏低（3.4e32@430mA）
- 检查色品；优化六极铁，水平色品由 0.1 增加到 0.8





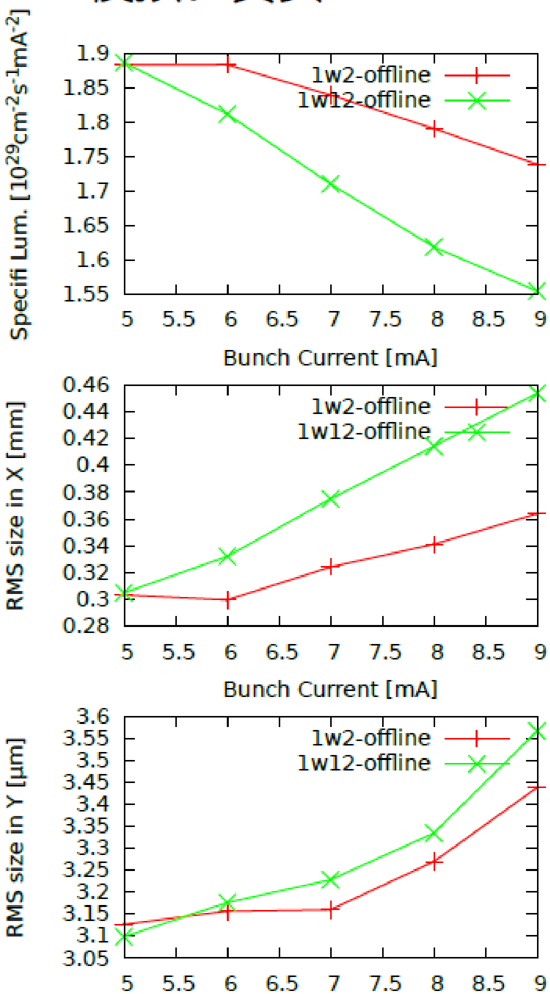
- 经过几个 run 的优化，亮度迅速提高至 3.8e32，亮度提升超 10%。



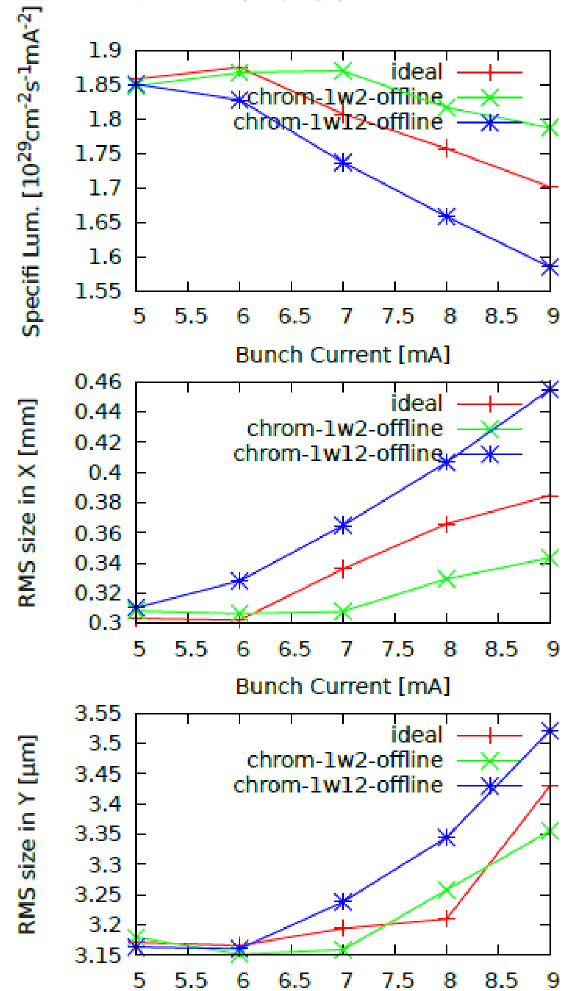
1W1 兼用模式 - Simulation

实际调束，新的六极铁搭配（1w12-offline）亮度高，但模拟结果反而低。不稳定性的贡献?

模拟：真实 lattice



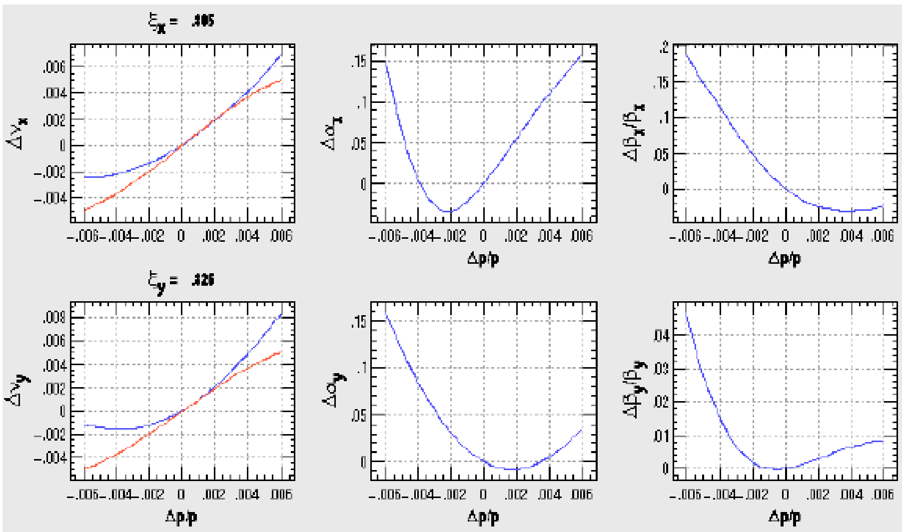
模拟：只考虑色品



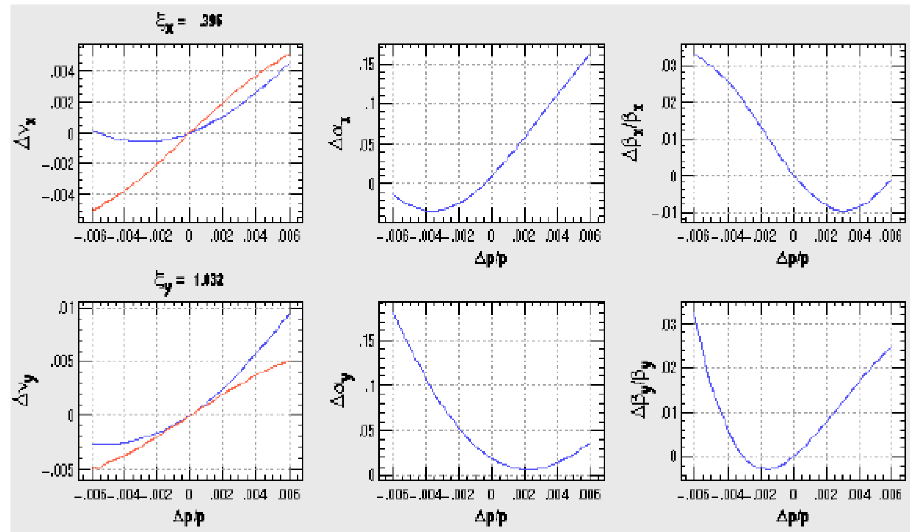
新的亮度在线调节方法 - chromaticity knob

第一次投入使用 @2014-05-09n，亮度提升超 10%!

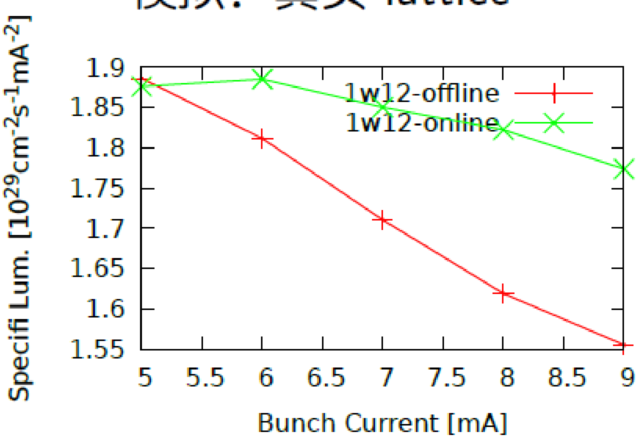
之前：最高亮度 4.6e32@450m*450mA



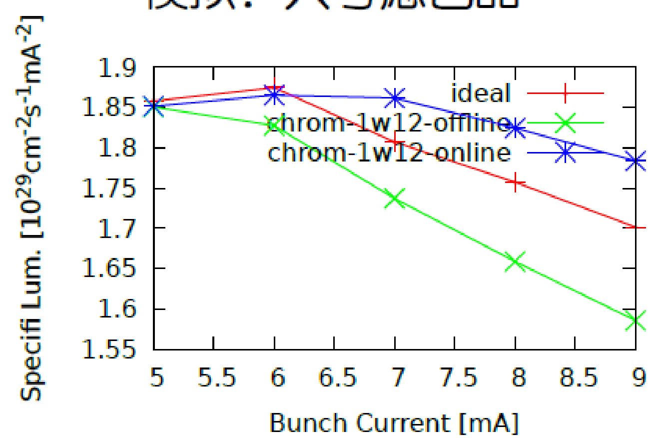
之后：最高亮度 5.2e32@450mA*450mA



模拟：真实 lattice



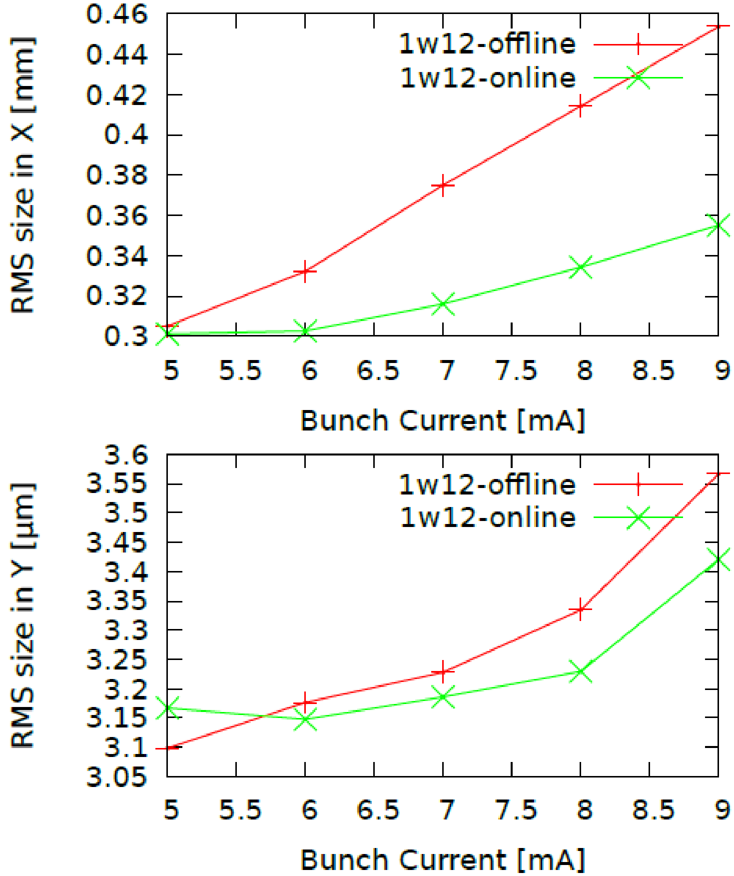
模拟：只考虑色品



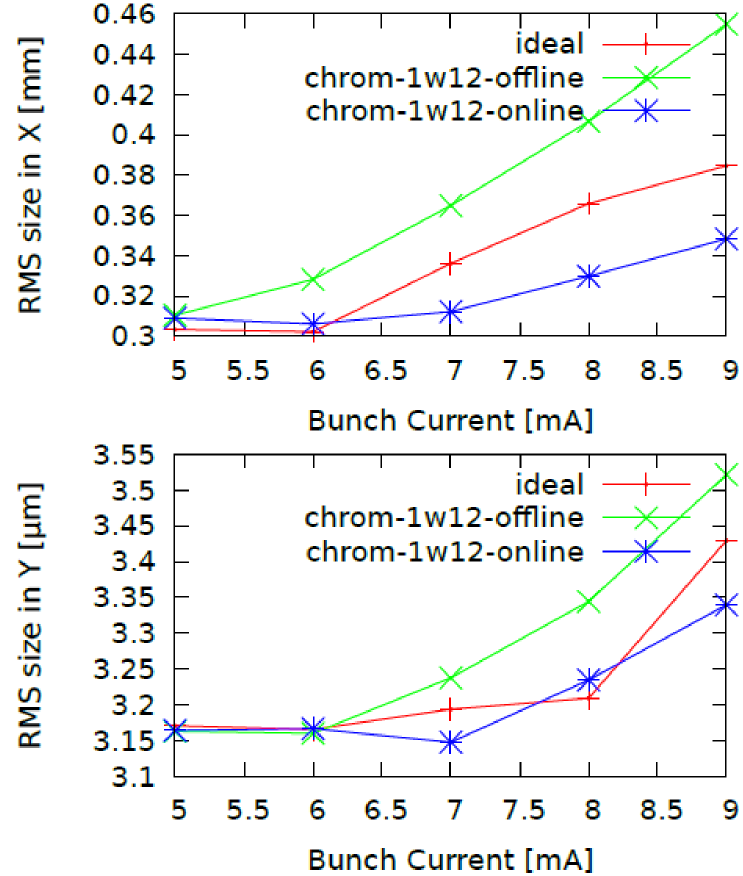
新的亮度在线调节方法 - chromaticity knob (2)

亮度的高低主要来自水平方向的尺寸差别，即水平方向的色品导致了水平和纵向的共振。

模拟：真实 lattice

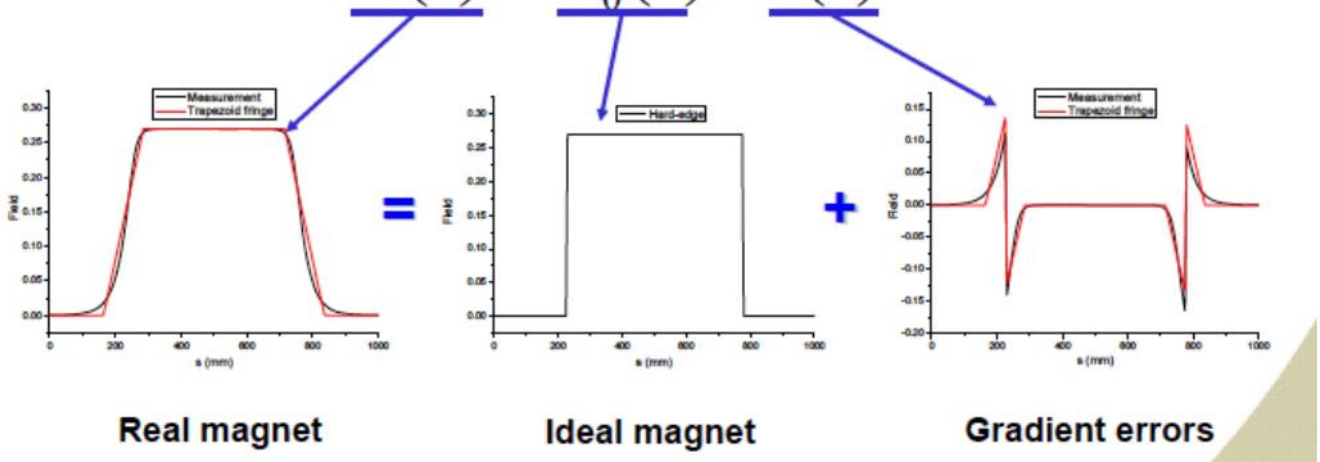


模拟：只考虑色品



Fringe effect in BEPCII （using SAD）

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



二极铁

原始定义，例子：

R4IMB02 =(L= 1.414956 ANGLE= 0.154685006 E1= 0.5 E2= 0.5 K1= 0.
)

修改为：

R4IMB02 =(L= 1.414956 ANGLE= 0.154685006 E1= 0.5 E2= 0.5 K1= 0.
F1=0.177 FRINGE=1)

四极铁

原始定义，例子：

R3IQ02 =(L= 0.54800000000000004 K1= -6.1350440677200004E-002)

修改为：

R3IQ02 =(L= 0.54800000000000004 K1= -6.1350440677200004E-002 F1 =.
133 FRINGE =3)

超导四极铁

原始定义，例子：

SSCQ01I =(L= 0.025 K1=-0.000370337)

修改为：

SSCQ01I =(L= 0.025 K1=-0.000370337 F1 =.025 FRINGE =3)

螺线管场

原始定义：

ESOL001 =(BZ= 0)

改为：

ESOL001 =(BZ= 0 F1=0.02)

D. Zhou(KEK)，2014

Linear optics parameters

使用 SAD(Ver.1.0.10.5.7a3) 计算 BPR(Ver. bpr7-sol.sad) 的线性 optics 参数 (@IP)：

Fringe type	None	B	Q	SCQ	SOL	All
C (m)	237.531	237.531	237.531	237.531	237.531	237.531
β_x (m)	1.082	1.082	1.089	1.078	1.082	1.090
β_y (m)	0.0153	0.01535	0.0135	0.0150	0.0153	0.0095
ν_x	7.506	7.506	7.461	7.506	7.506	7.461
ν_y	5.577	5.558	5.536	5.575	5.577	5.514
α_x	8.32E-5	8.32E-5	-0.0245	8.44E-5	8.32E-5	-0.0244
α_y	4.22E-6	-0.015	0.016	4.31E-6	4.22E-6	-0.0470
α_p	0.017	0.017	0.0172	0.0170	0.0170	0.0172
τ_x (ms)	24.701	25.696	24.700	24.701	24.701	25.696
τ_y (ms)	24.744	25.743	24.744	24.744	24.744	25.743
τ_s (ms)	12.383	12.884	12.384	12.383	12.383	12.884
ϵ_x (nm)	97.645	95.185	97.986	97.619	97.645	95.521
ϵ_z (μm)	5.956	5.836	5.990	5.956	5.956	5.870
σ_p (10^{-4})	5.2075	5.154	5.208	5.2075	5.2075	5.1546
σ_z (cm)	1.144	1.132	1.151	1.144	1.144	1.139

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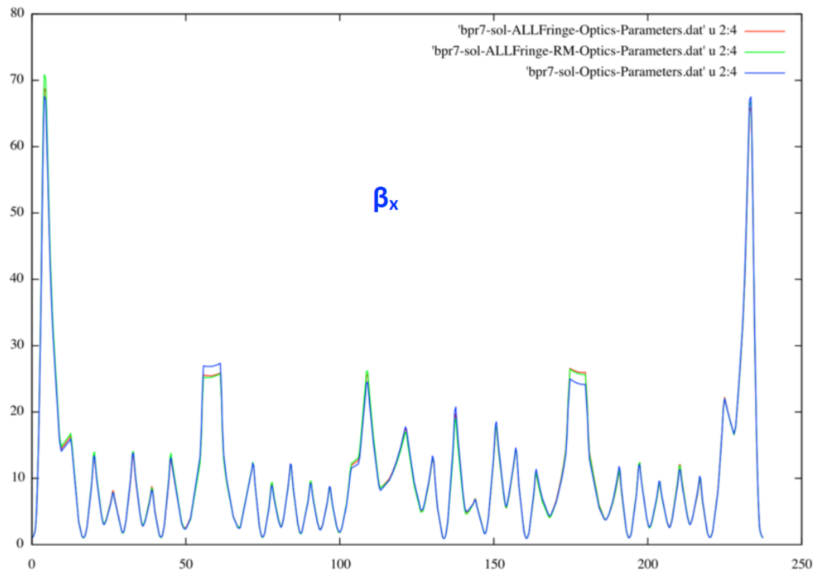
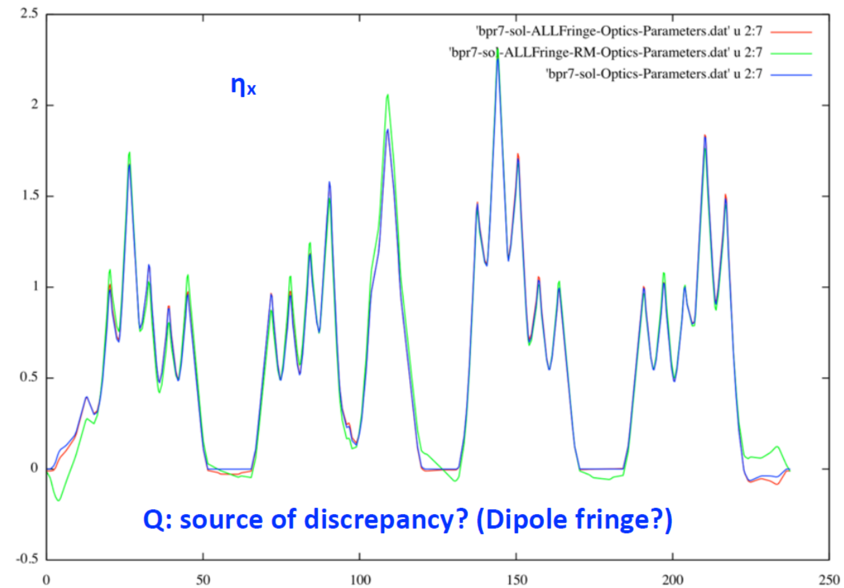
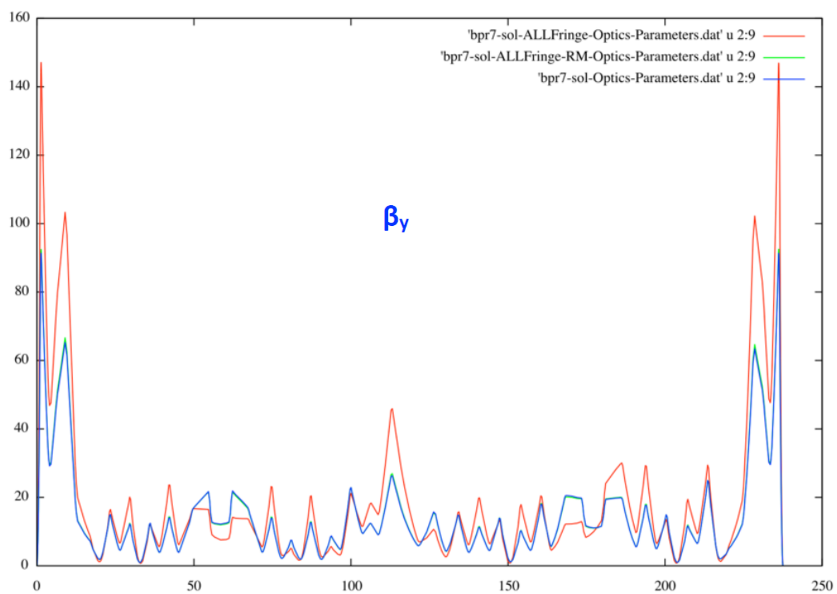
原始模型，+边缘场，+LOCO校正







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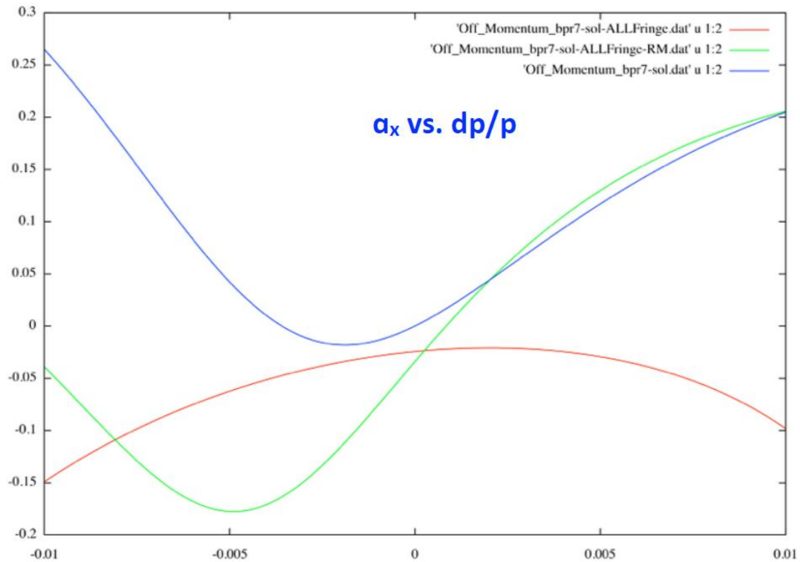
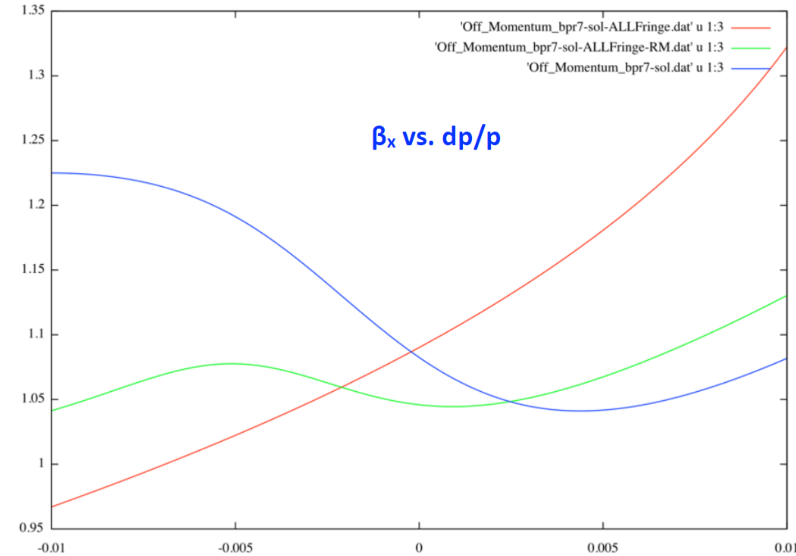
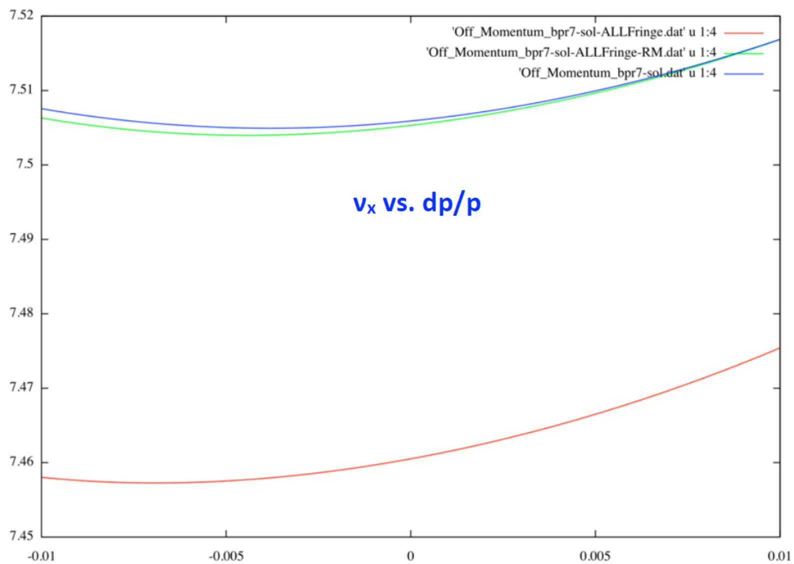
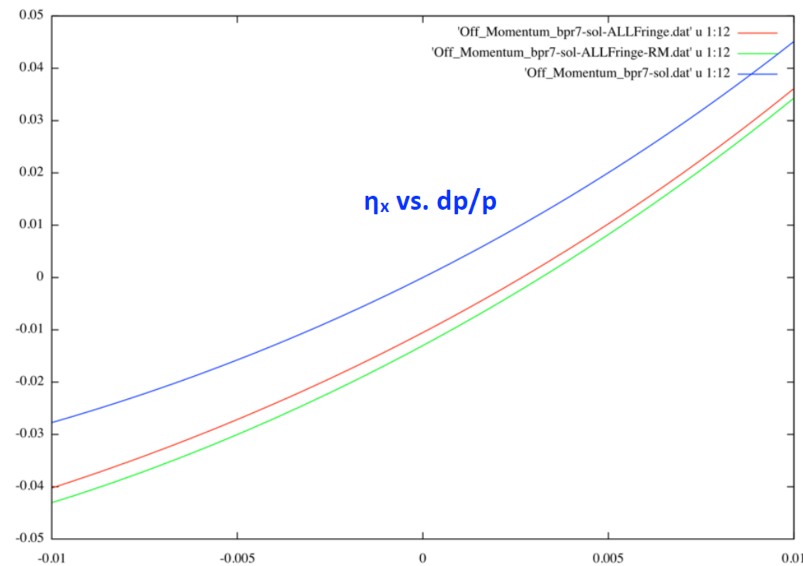
原始模型，+边缘场，+LOCO校正（cont.）









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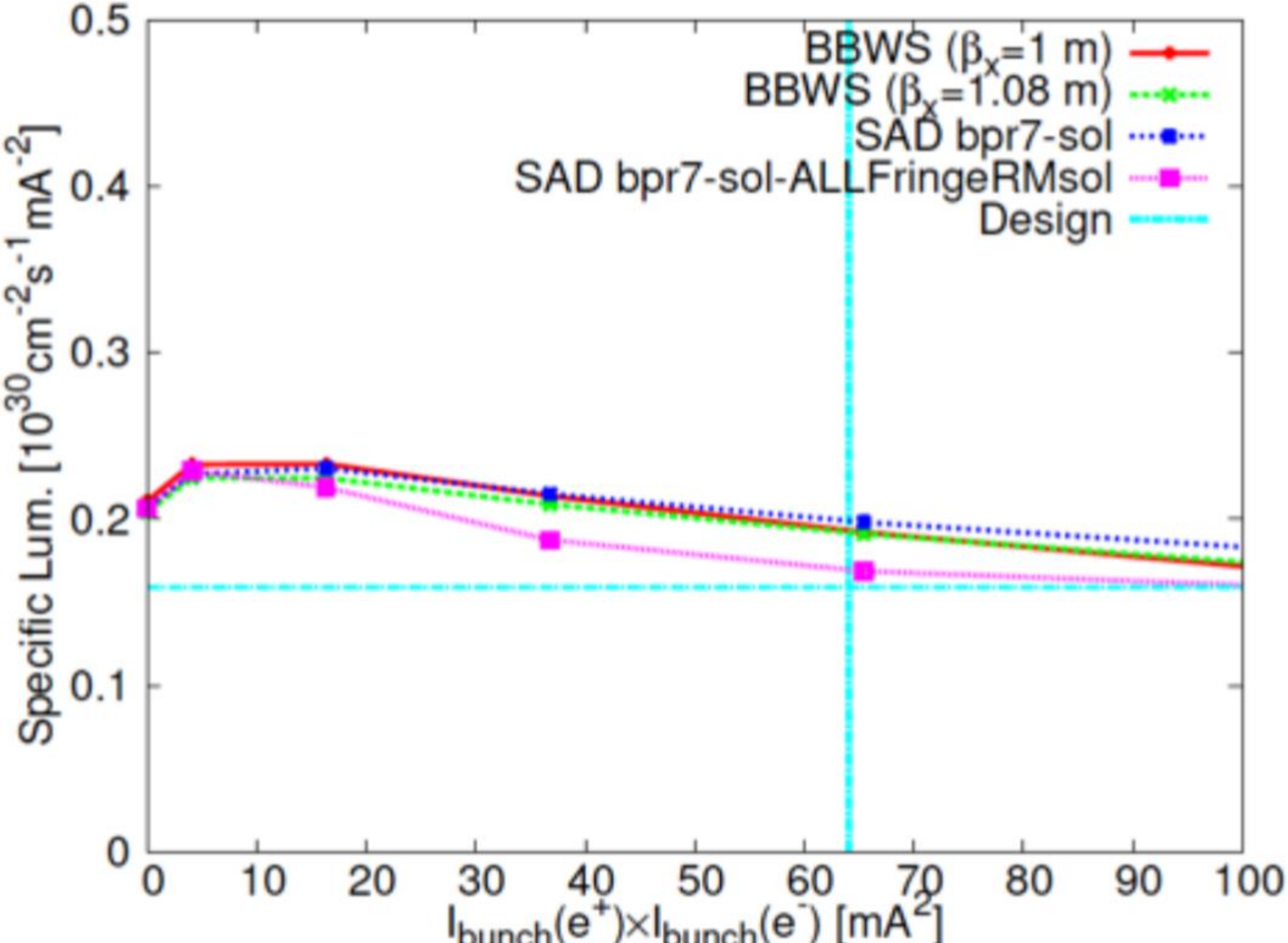
亮度： 原始模型 vs 边缘场+LOCO校正

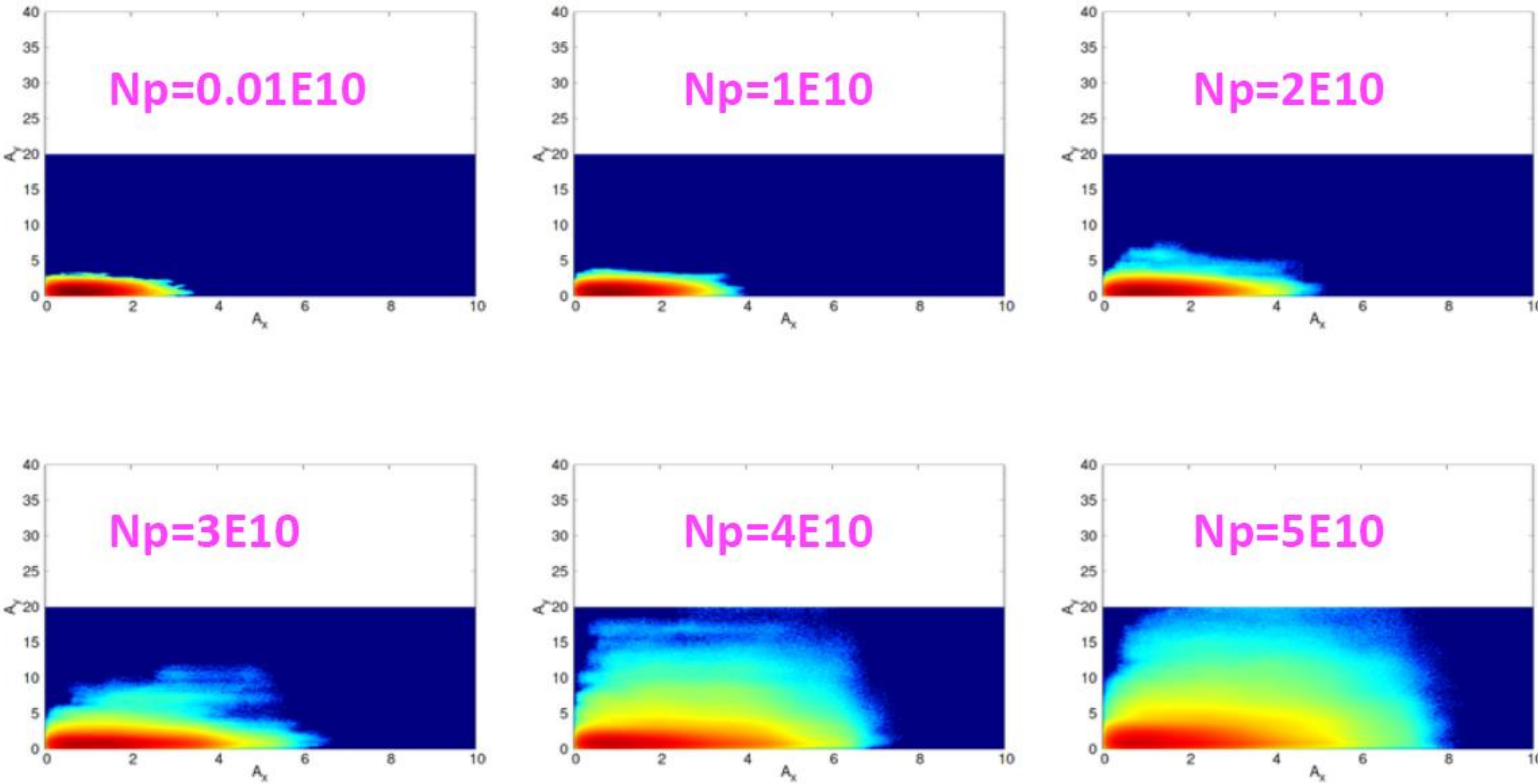
loss~15%



D. Zhou(KEK)，2014

Beam tail

➤ **bpr7-sol:**



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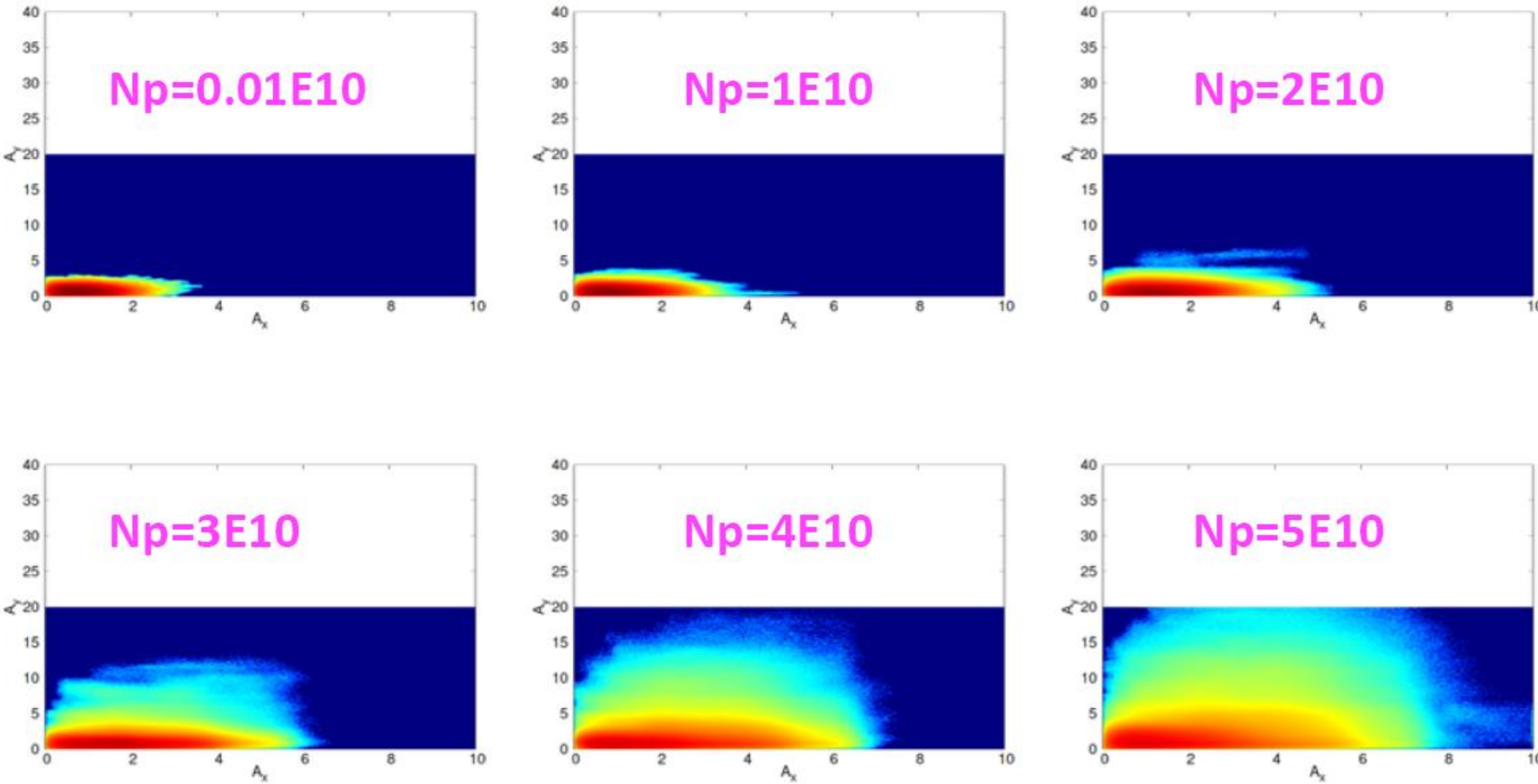
Beam tail

➤ bpr7-sol-AllFringeRMsol:



D. Zhou(KEK), 2014

Summary

所有的非线性都已经在“实际”机器中被发现对亮度产生影响：

- Detuning
- Choromaticity（tune/twiss parameters/coupling）
- noraml/skew multipole magnet