KEKB Experience

Optics measurements and corrections

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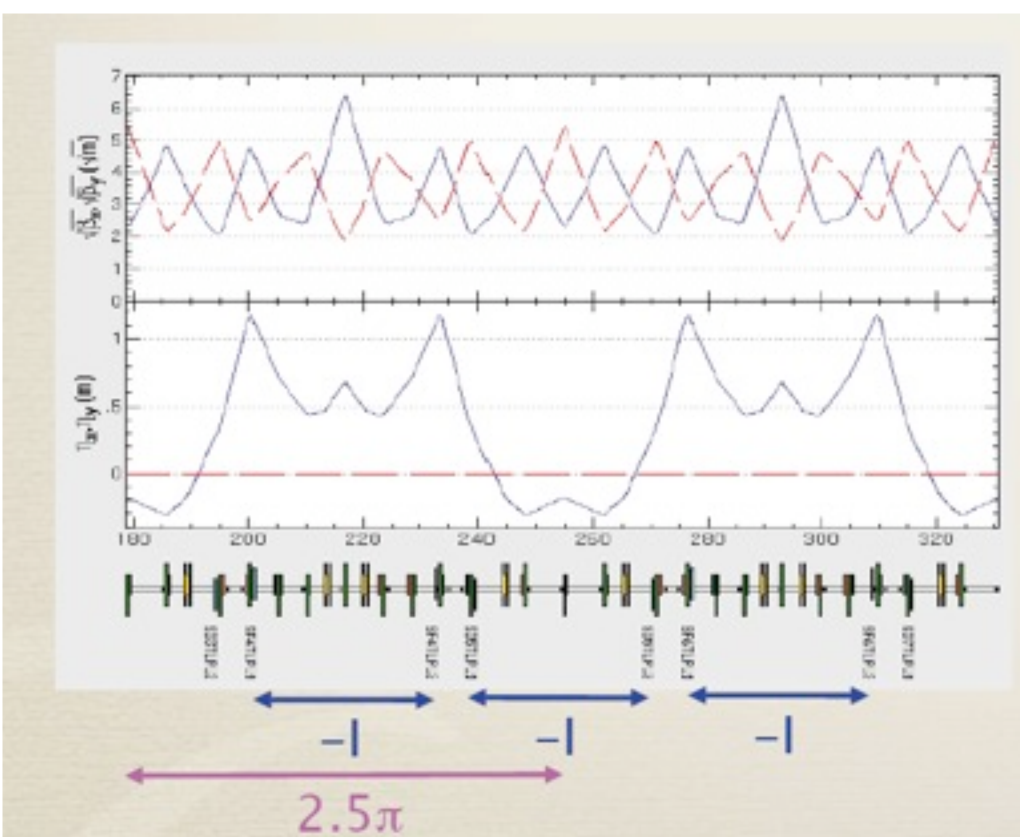
KEKB Overview

- 3.5 x 8 GeV double-ring collider (C ~3 km)
- 2.5π unit cell, non-interleaved sextupoles
- ν_x is close to half-integer
- Peak L = 2.1×10^{34}



Machine Parameters of the KEKB (June 17 2009)

	LER	HER	
Circumference	3016		m
RF Frequency	508.88		MHz
Horizontal Emittance	18	24	nm
Beam current	1637	1188	mA
Number of bunches	1584 + 1		
Bunch current	1.03	0.750	mA
Bunch spacing	1.84		m
Bunch trains	1		
Total RF volatage Vc	8.0	13.0	MV
Synchrotron tune ν_s	-0.0246	-0.0209	
Betatron tune ν_x / ν_y	45.506/43.561	44.511/41.585	
beta's at IP β_x^* / β_y^*	120/0.59	120/0.59	cm
momentum compaction a	3.31×10^{-4}	3.43×10^{-4}	
Estimated vertical beam size at IP from luminosity σ_y^*	0.94	0.94	µm
beam-beam parameters ξ_x / ξ_y	0.127/0.129	0.102/0.090	
Beam lifetime	133@1637	200@1188	min.@mA
Luminosity (Belle CsI)	2.1×10^{34} cm^{-2}s^{-1}		
Luminosity records per day / 7days/ 30days	1.479/8.428/30.208		/fb

Global Optics Correction

- Global correction uses information of **closed orbit distortions** measured by about 450 BPMs.
- Measurement of X-Y coupling and beta function is based on response between steering magnets and orbits.
- Dispersions are obtained by orbit deviations by changing rf frequency.
- Correctors consist of sextupole offset(54/52), skew quadrupoles (8/12), and fudge factors of quadrupole families(~120).
- Iterative corrections of X-Y coupling, dispersions, beta functions.
- Beam current is 30 mA during the measurement.

X-Y Coupling and Physical Dispersions

2.5π Normal Cell in Arc

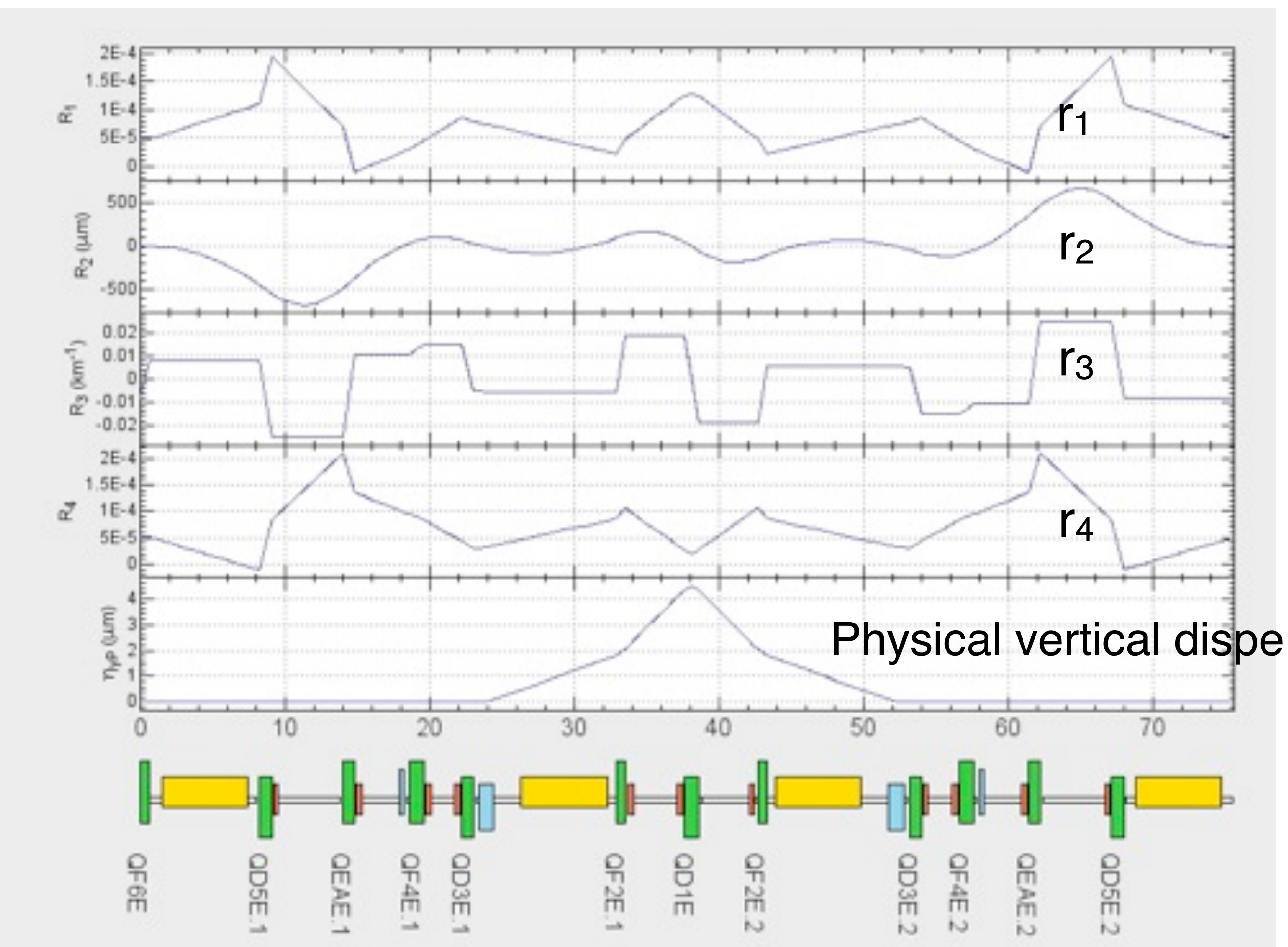
Symmetric bump

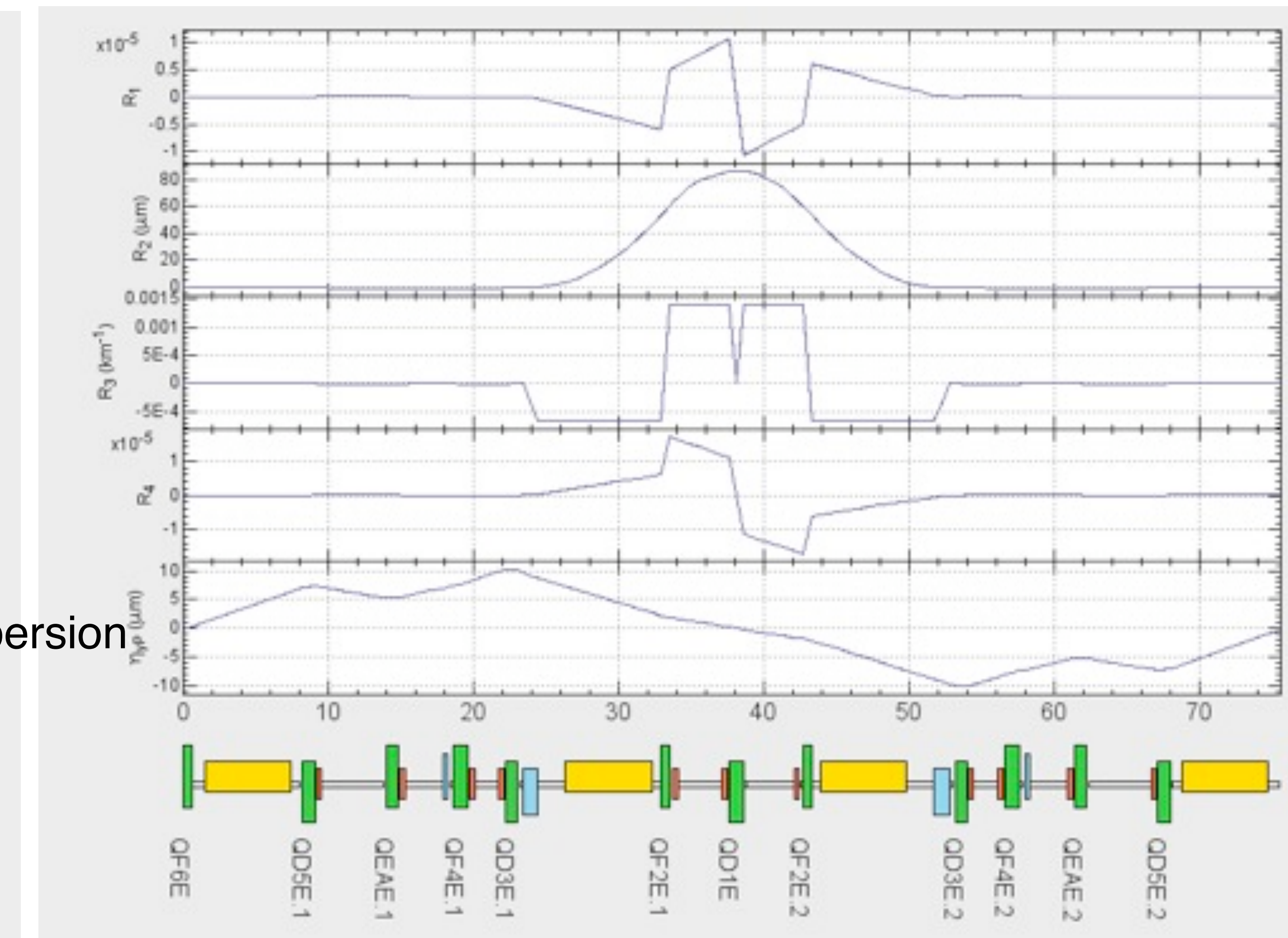
$\Delta y_{(SD1)} = +0.1$ mm
$\Delta y_{(SD2)} = +0.1$ mm

SD1 and SD2 are identical.

Asymmetric bump

$\Delta y_{(SD1)} = +0.1$ mm
$\Delta y_{(SD2)} = -0.1$ mm





SD1 -I' SD2

Orthogonal knob

SD1 -I' SD2

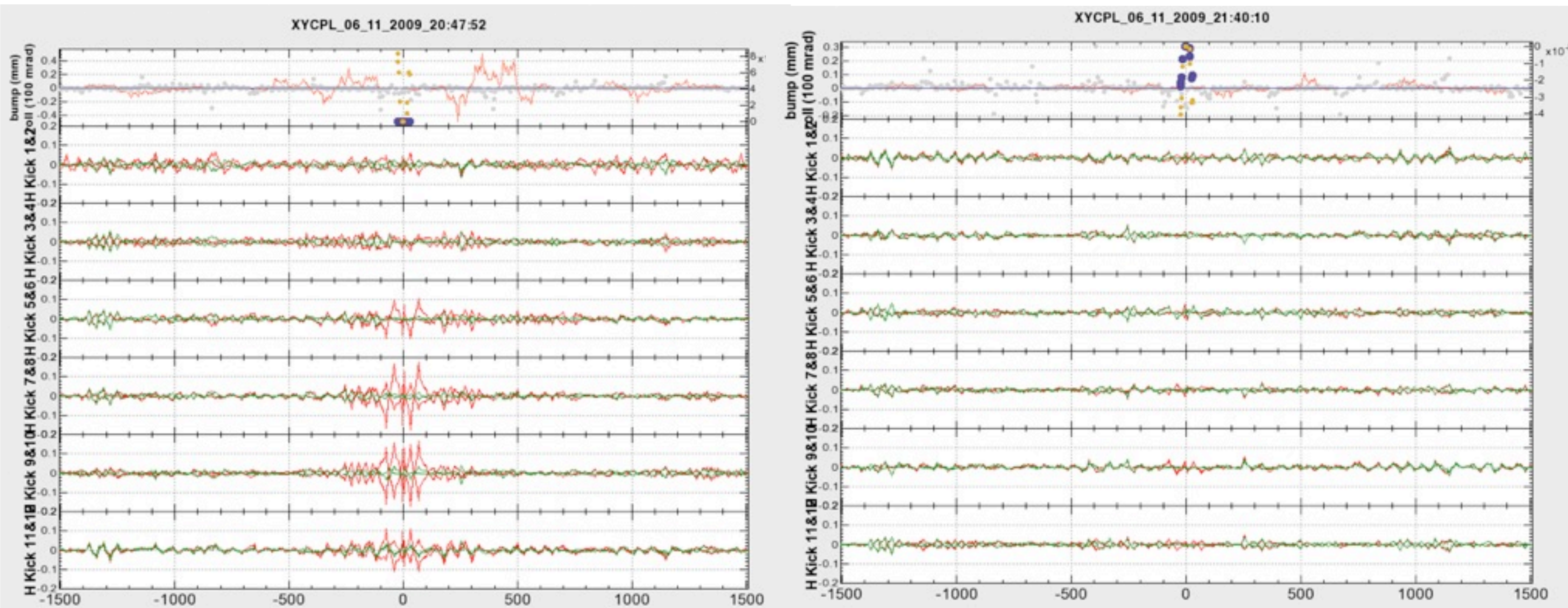
Physical dispersion is localized.

x-y coupling is localized.

X-Y Coupling

- 12 kinds of CODs are made by horizontal steering(coupling and dispersion free).
- Correct the leakage vertical orbit by vertical symmetric local bumps at sextupole pairs.

before 12 vertical orbit residuals **after**



	before	after
Ave. 12 RMS of Δy	19.6 μm	11.0 μm

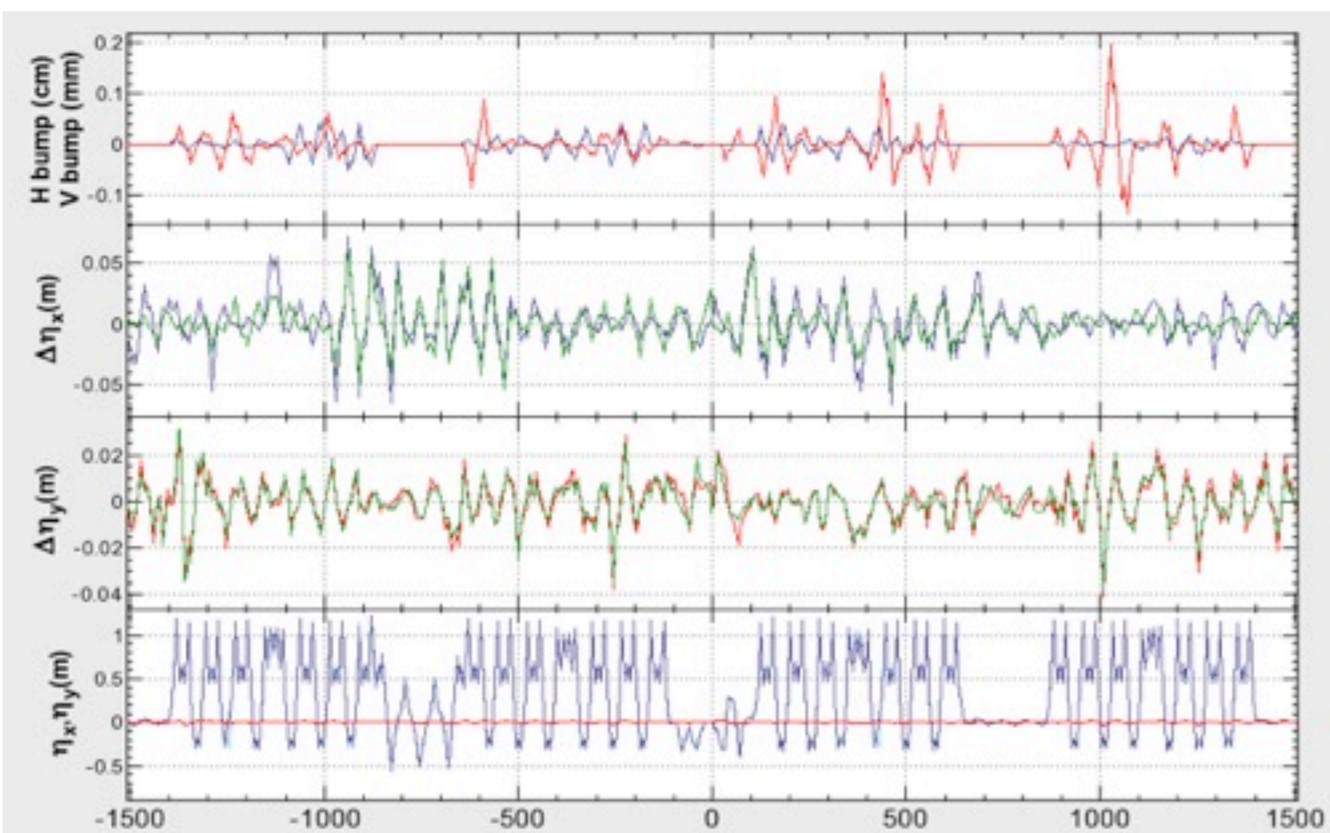
Dispersions

- Dispersions are obtained by measurement of orbit change due to change of RF frequency.

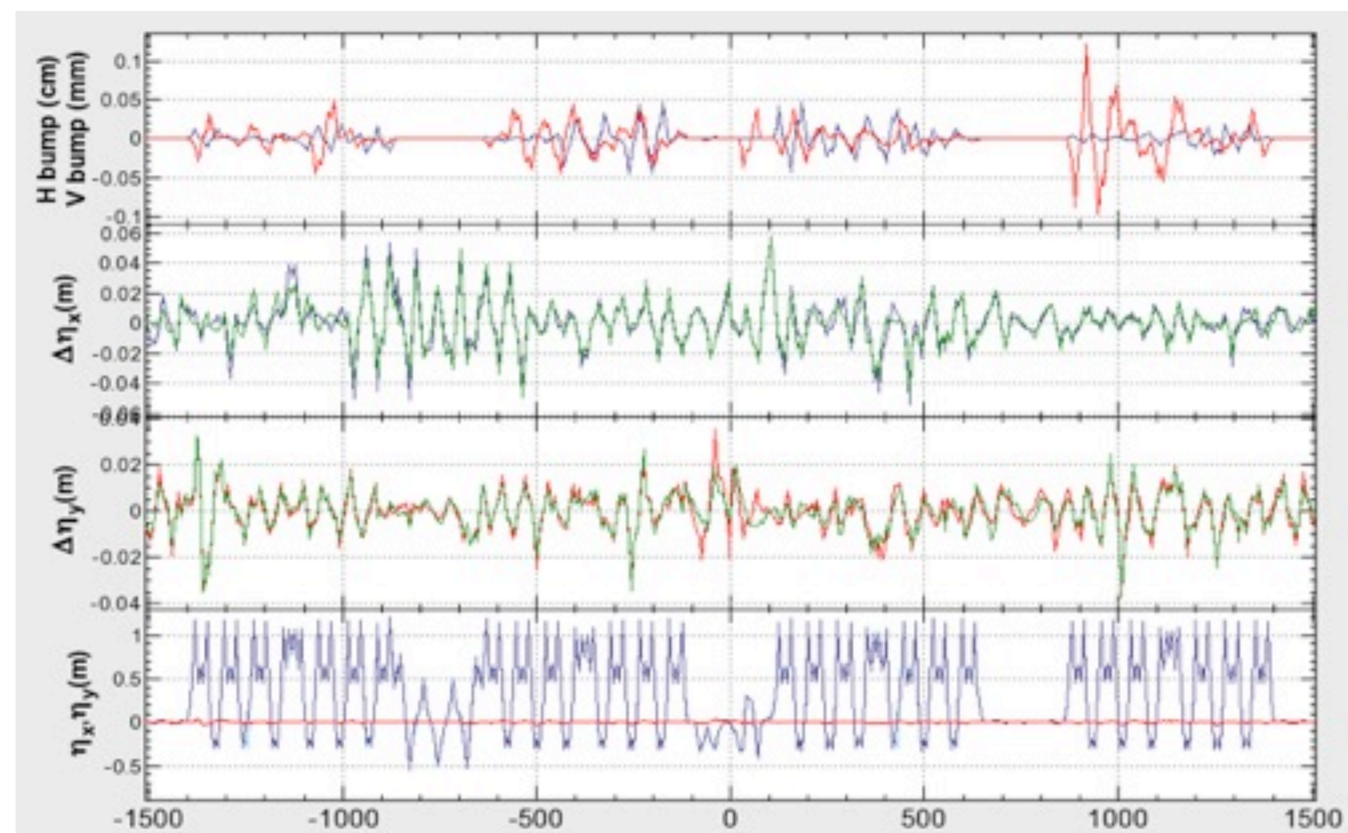
- Dispersions are corrected by horizontal and vertical asymmetric local bumps at sextupole pairs.

$$\vec{\eta}_x = \frac{\vec{x}_2 - \vec{x}_1}{\delta_2 - \delta_1} \qquad \delta = -\frac{1}{\left(\alpha_c - \frac{1}{\gamma^2}\right)} \frac{\Delta f}{f_0}$$

before



after

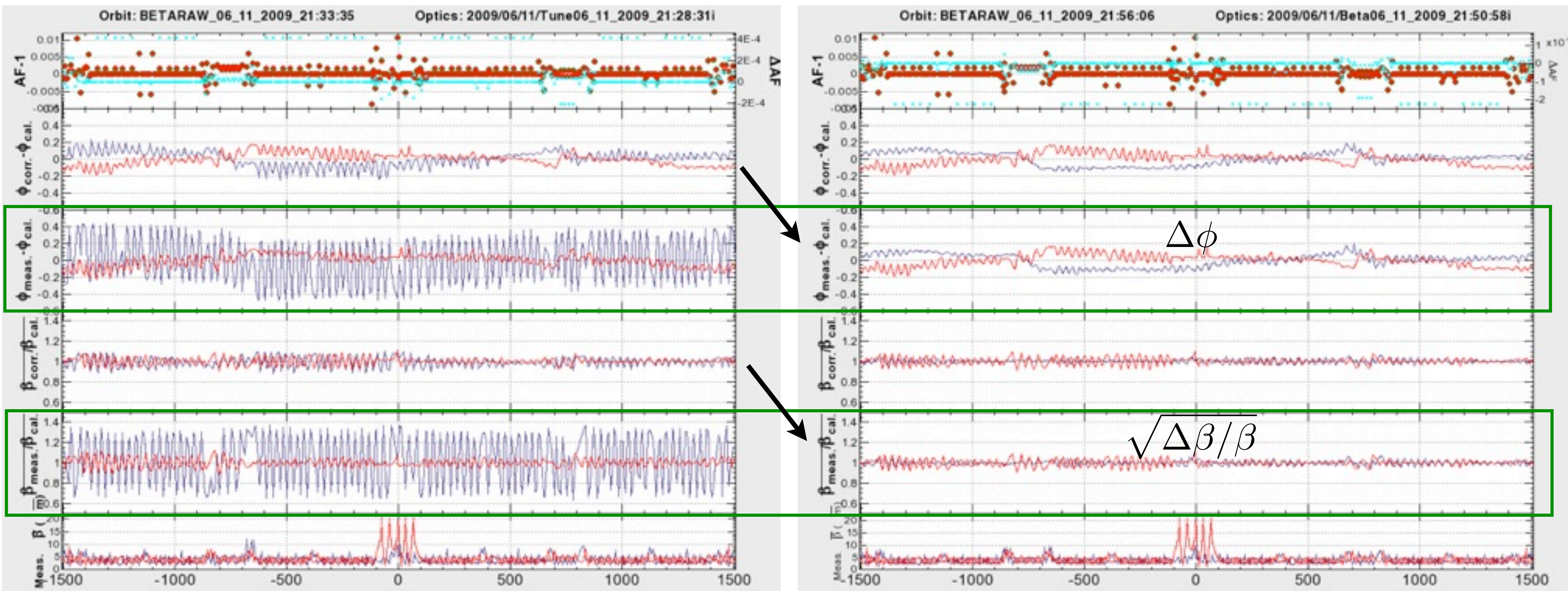


	before	after
RMS of $\Delta\eta_x$	18.4 mm	14.5 mm
RMS of $\Delta\eta_y$	9.1 mm	9.0 mm

Beta Functions

- Orbit deviations by 6 single kicks in the horizontal and vertical plane are measured.
- Beta functions and phases are obtained by fitting the responses(X-Y coupling is already corrected.). The difference from the model is corrected by fudge factors of quads.

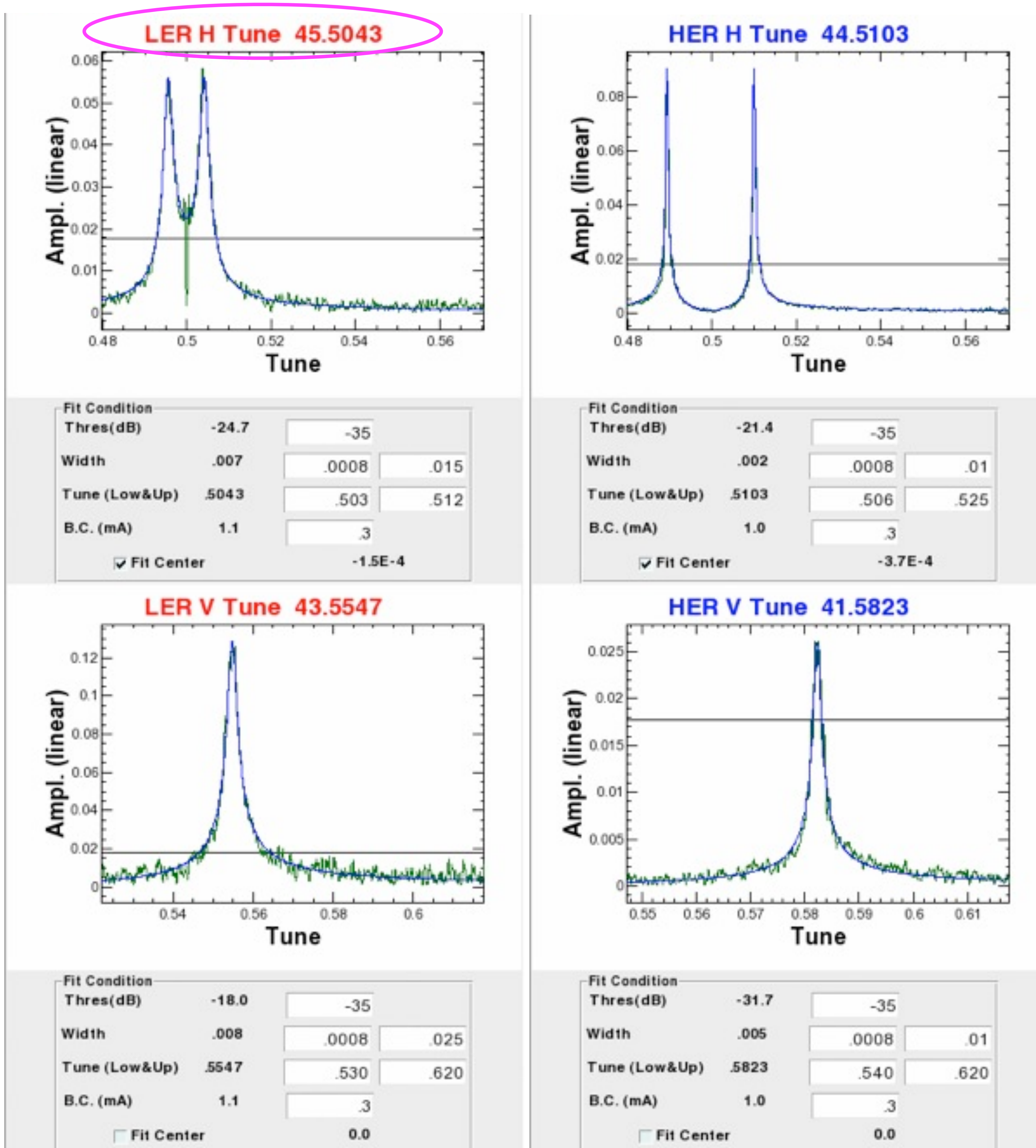
before **after**



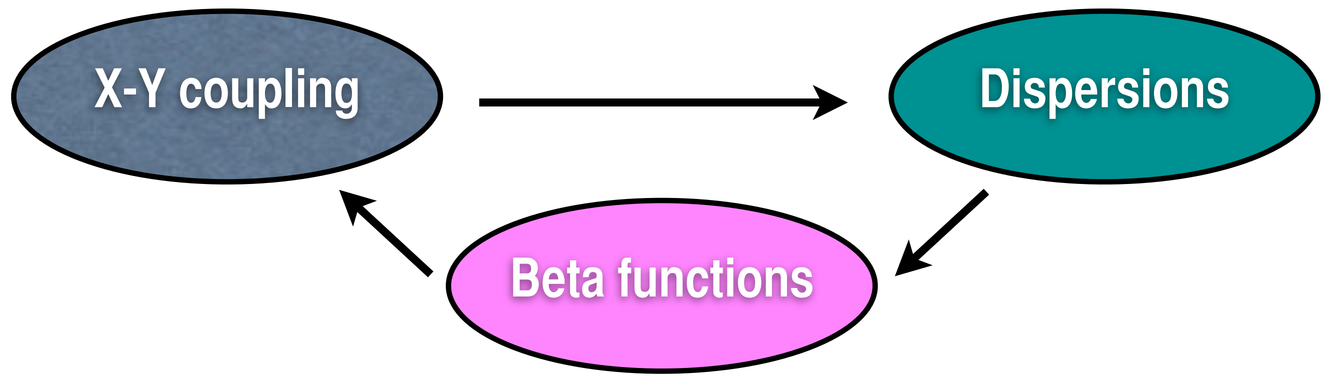
	before	after
RMS of Δβ/β (x/y)	47 % / 8.5 %	4.4 % / 6.9 %
RMS of Δφ (x/y)	14.7 deg. / 4.2 deg.	4.4 deg. / 4.0 deg.

Horizontal tune is close to half integer.

Betatron Tunes



Summary of Global Optics Correction



- Corrector is an orthogonal knob in principle based on -I' relationship between an identical sextupole pair.
- We do not solve an entire problem at once by using a big matrix.
- Iterative procedure of X-Y coupling, dispersions, and beta function correction.
- A loop of iteration takes 30-60 minutes for each ring to converge.
- Dispersions: rms of $\Delta\eta_x \sim 15$ mm, rms of $\Delta\eta_y \sim 10$ mm
- Beta functions: rms of $\Delta\beta_x / \beta_x \sim 7$ %, rms of $\Delta\beta_y / \beta_y \sim 5$ %
- rms of $\Delta\phi_{x,y} \sim 4$ deg.

Measurement of Optics by using Single-pass BPMs

X-Y Coupling
Chromatic X-Y Coupling

There are 38 single-pass BPMs for LER and HER, respectively.

X-Y Coupling

- The canonical momenta normalized by a design momentum are expressed by(existing solenoid field):

$$p_x = (1+\delta)x' - \frac{B_z}{2B\rho_0}y \qquad p_y = (1+\delta)y' + \frac{B_z}{2B\rho_0}x \qquad \delta = \frac{\Delta p}{p_0}$$

- The physical coordinate and decoupled coordinate can be written by:

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \overbrace{\begin{pmatrix} \mu & 0 & -r_4 & r_2 \\ 0 & \mu & r_3 & -r_1 \\ r_1 & r_2 & \mu & 0 \\ r_3 & r_4 & 0 & \mu \end{pmatrix}}^{R} \left\{ \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} - \begin{pmatrix} \eta_x \\ \eta_{px} \\ \eta_y \\ \eta_{py} \end{pmatrix} \delta \right\}$$

decoupled coordinate

$$\mu^2 + (r_1 r_4 - r_2 r_3) = 1$$

physical coordinate

Normal dispersion

$$\begin{pmatrix} \eta_u \\ \eta_{pu} \\ \eta_v \\ \eta_{pv} \end{pmatrix} = R \begin{pmatrix} \eta_x \\ \eta_{px} \\ \eta_y \\ \eta_{py} \end{pmatrix}$$

Physical dispersion

Measurement of X-Y Coupling

- In the case of H-mode($v=0$, $p_v=0$):

$$
\begin{aligned}
x &= \mu u \\
p_x &= \mu p_u \\
y &= -r_1 u - r_2 p_u \\
p_y &= -r_3 u - r_4 p_u
\end{aligned}
$$

- The x-y coupling parameters are derived as:

$$
\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = -\mu \Sigma^{-1} \begin{pmatrix} < xy > \\ < p_x y > \end{pmatrix}
$$

$$
\begin{pmatrix} r_3 \\ r_4 \end{pmatrix} = -\mu \Sigma^{-1} \begin{pmatrix} < x p_y > \\ < p_x p_y > \end{pmatrix}
$$

$$
\beta_u = \frac{< x^2 >}{\sqrt{\det \Sigma}}
$$

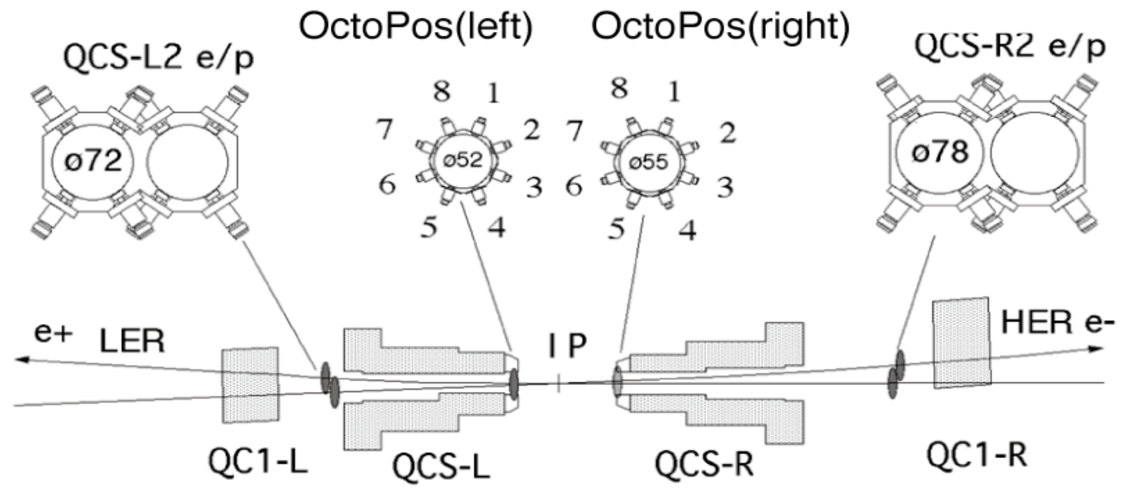
$$
\alpha_u = -\frac{< x p_x >}{\sqrt{\det \Sigma}}
$$

$$
\Sigma = \begin{pmatrix} < x^2 > & < x p_x > \\ < x p_x > & < p_x^2 > \end{pmatrix}
$$

Ref. Phys. Rev. SP-AB, 12, 091002 (2009)
K. Ohmi et al., Proc. of IPAC'10

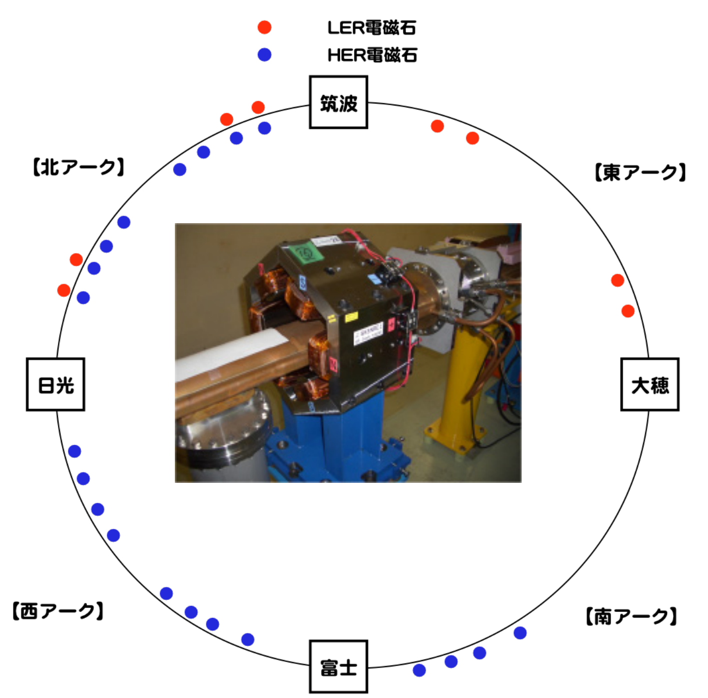
Chromatic X-Y Coupling at IP

- Two BPMs in the vicinity of IP are used to reconstruct phase space at IP. BPMs are used as single-pass mode.



Total 38 single-pass BPMS for each ring

- X-Y coupling at IP is adjusted by sextupole bumps near IP.
- Chromatic X-Y coupling is adjusted by skew sextupoles.

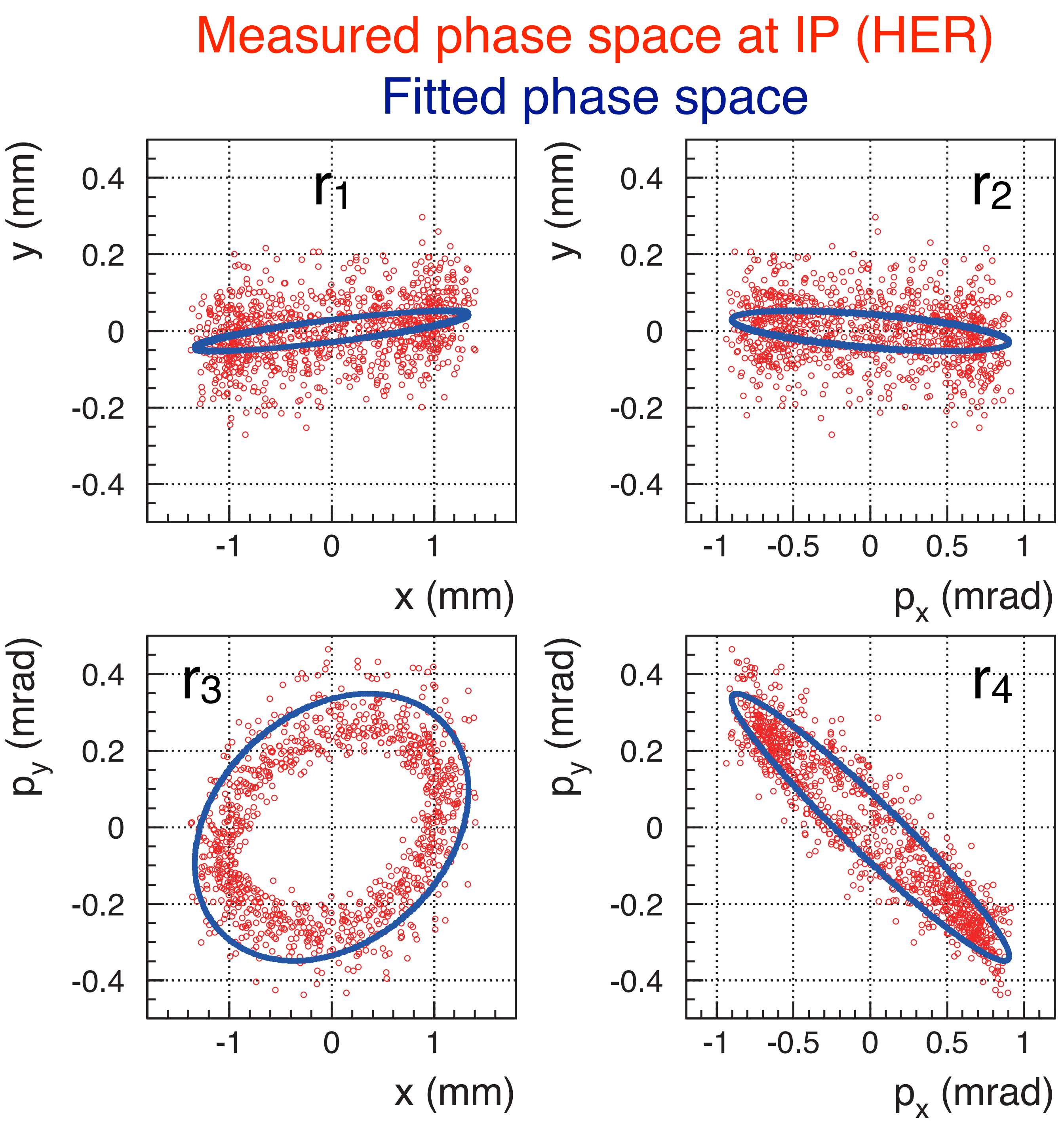


LER: skew sextupoles (4 pairs)

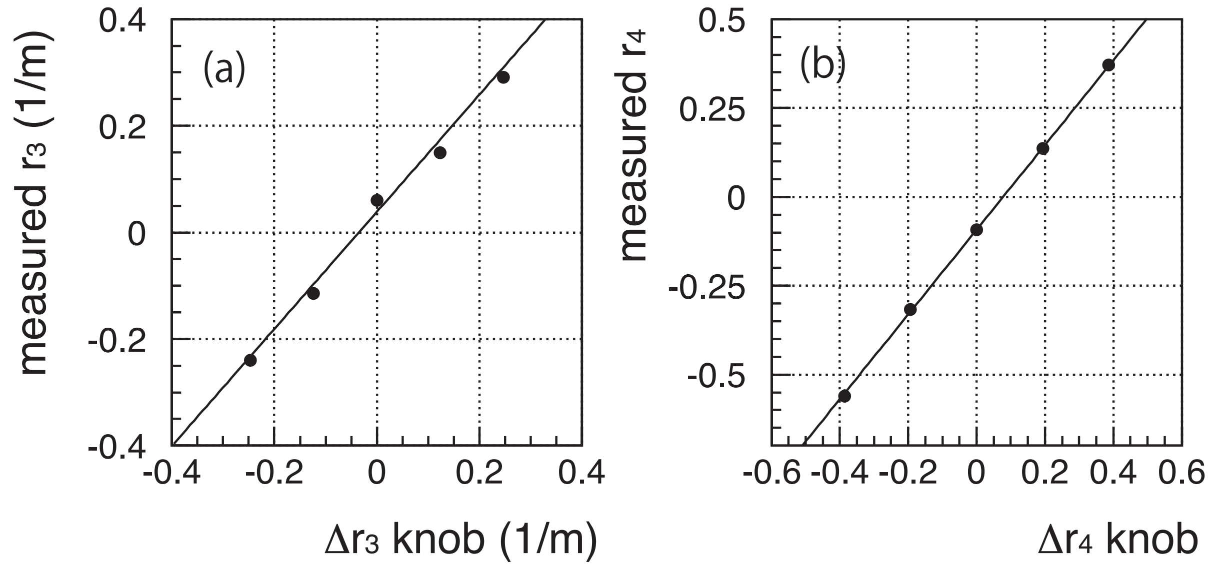
HER: skew sextupoles (10 pairs)

Measurement of X-Y Coupling

- Slant of ellipse indicates X-Y coupling parameter.



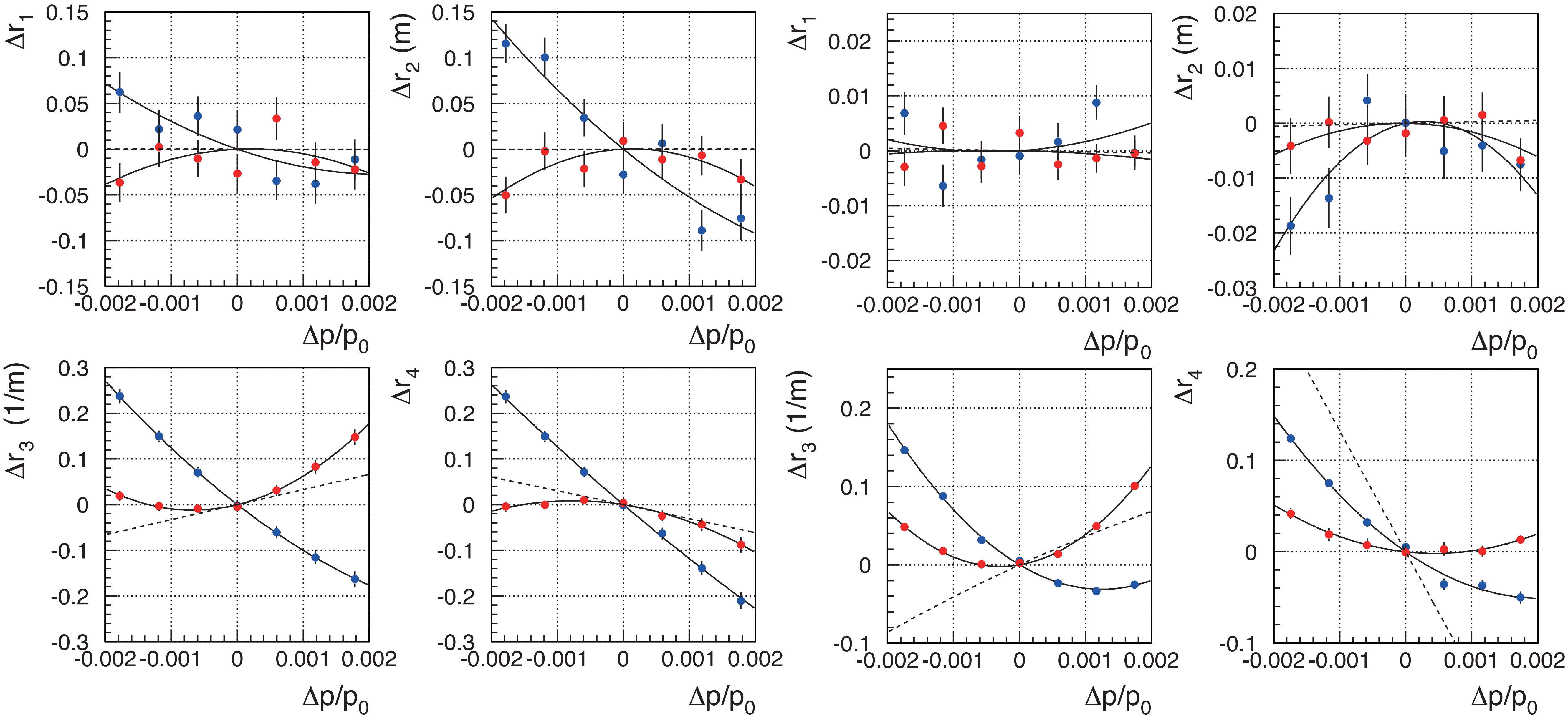
IP tilt knob VS measurement (HER)



Chromatic X-Y Coupling at IP

- Measurements: **before** and **after correction by skew sextupoles(inc. luminosity tuning)**

LER **HER**



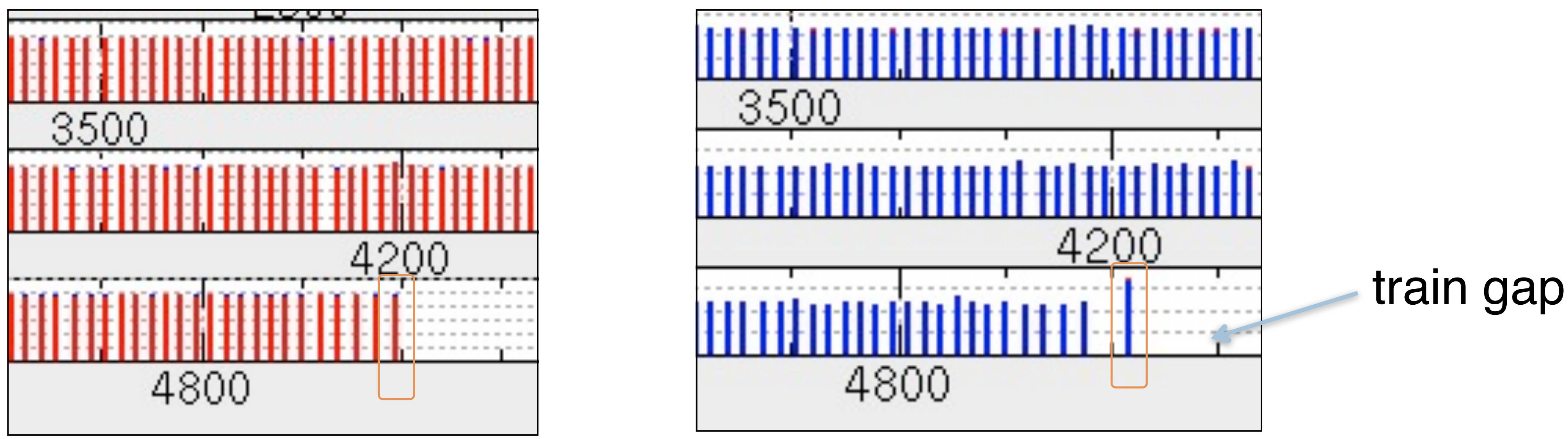
Summary

- Global correction works well to keep good machine condition. We had a maintenance day every two weeks and performed the global correction before resuming physics run.
- Chromatic X-Y coupling at IP is measured by single-pass BPMs and corrected by using skew sextupoles.
- The luminosity gain is ~20 % by means of chromatic X-Y coupling correction and/or scan.
- Optics measurement is based on low beam current(~30 mA). If one of thousands bunches could be picked up and optical functions could be measured during physics run or high current operation, it would be very useful to keep higher luminosity.

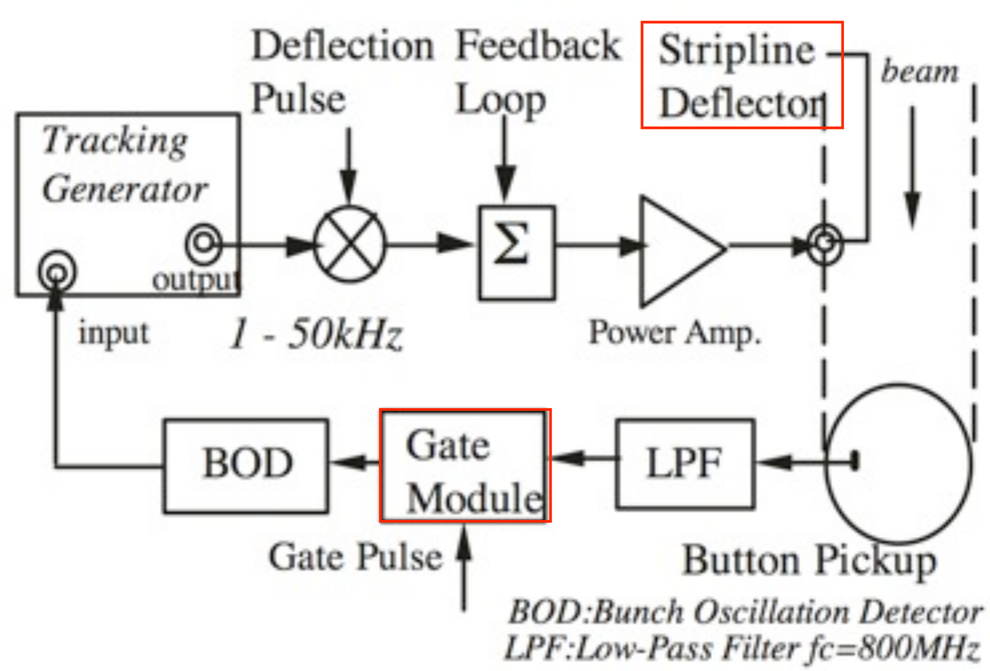
Appendix

Betatron Tunes of Pilot Bunch

- Pilot bunch (non-collision bunch)



- Betatron tunes are measured with a swept-frequency method using a tracking analyzer and a gate module.



Physical and Normal Dispersion

- Dispersion

$$\vec{u} + \vec{\eta}_u \delta = R\vec{x}$$
$$\vec{\eta}_u = R\vec{\eta}_x$$

$$\vec{u} + R\vec{\eta}_x \delta_1 = R\vec{x}_1$$
$$\vec{u} + R\vec{\eta}_x \delta_2 = R\vec{x}_2$$

$\vec{u} = (u, p_u, v, p_v)^t$ decoupled coordinate

$\vec{x} = (x, p_x, y, p_y)^t$ physical coordinate

$\vec{\eta}_u = (\eta_u, \eta_{pu}, \eta_v, \eta_{pv})^t$ decoupled dispersion

$\vec{\eta}_x = (\eta_x, \eta_{px}, \eta_y, \eta_{py})^t$ physical dispersion

R is a x-y coupling matrix

$$\vec{\eta}_x = \frac{\vec{x}_2 - \vec{x}_1}{\delta_2 - \delta_1}$$ The measured dispersion is a physical dispersion

COD based measurement uses a change of RF frequency

$$\delta = -\frac{1}{\left(\alpha_c - \frac{1}{\gamma^2}\right)} \frac{\Delta f}{f_0}$$

In the case of single-pass BPMs with RF kick,
η_{px} and η_{py} can be estimated by using two locations

Parameterization at CESR

- Definition: one-turn transfer matrix (4x4), T:
  - CESR:

$$T = V^{-1}UV = \begin{pmatrix} \gamma I & C \\ -C^{+} & \gamma I \end{pmatrix} \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \begin{pmatrix} \gamma I & -C \\ C^{+} & \gamma I \end{pmatrix}$$

  - KEKB

$$T = V^{-1}UV = \begin{pmatrix} \mu I & -SR^{T}S \\ -R & \mu I \end{pmatrix} \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \begin{pmatrix} \mu I & SR^{T}S \\ R & \mu I \end{pmatrix}$$

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix}$$

$$A = I\cos\psi_u + J_u \sin\psi_u \qquad B = I\cos\psi_v + J_v \sin\psi_v$$

$$J_{u,v} = \begin{pmatrix} \alpha_{u,v} & \beta_{u,v} \\ -\gamma_{u,v} & -\alpha_{u,v} \end{pmatrix}$$

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} r_4 & -r_2 \\ -r_3 & r_1 \end{pmatrix} \qquad \gamma = \mu$$

Measurement of X-Y Coupling

- In the case of V-mode($u=0$, $p_u=0$):

$$y = \mu v$$
$$p_y = \mu p_v$$
$$x = r_4 v - r_2 p_v$$
$$p_x = -r_3 v + r_1 p_v$$

- The x-y coupling parameters are derived as:

$$\begin{pmatrix} r_4 \\ -r_2 \end{pmatrix} = \mu \Sigma^{-1} \begin{pmatrix} < yx > \\ < p_y x > \end{pmatrix}$$
$$\begin{pmatrix} -r_3 \\ r_1 \end{pmatrix} = \mu \Sigma^{-1} \begin{pmatrix} < y p_x > \\ < p_y p_x > \end{pmatrix}$$

$$\Sigma = \begin{pmatrix} < y^2 > & < y p_y > \\ < y p_y > & < p_y^2 > \end{pmatrix}$$

$$\beta_v = \frac{< y^2 >}{\sqrt{\det \Sigma}}$$
$$\alpha_v = -\frac{< y p_y >}{\sqrt{\det \Sigma}}$$

Ref. Phys. Rev. SP-AB, 12, 091002 (2009)
K. Ohmi et al., Proc. of IPAC'10

Hamiltonian

- p_x and p_y are canonical momenta normalized by a design momentum, p_0.

$$H = -\frac{e}{p_0}A_s - \left(1+\frac{x}{\rho}\right)\left\{(1+\delta)^2 - \left(p_x - \frac{e}{p_0}A_x\right)^2 - \left(p_y - \frac{e}{p_0}A_y\right)^2\right\}^{1/2}$$

$$x' = \frac{\partial H}{\partial p_x} = \left(1+\frac{x}{\rho}\right)\frac{p_x - \frac{e}{p_0}A_x}{\sqrt{(1+\delta)^2 - \left(p_x - \frac{e}{p_0}A_x\right)^2 - \left(p_y - \frac{e}{p_0}A_y\right)^2}} \simeq \frac{p_x - \frac{e}{p_0}A_x}{1+\delta}$$

- In case of solenoid field:

$$A_x = -\frac{1}{2}B_z y$$

$$A_y = \frac{1}{2}B_z x$$

$$\frac{e}{p_0} = \frac{1}{B\rho_0}$$