Optics Tuning and Issues

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on behalf of

SuperKEKB Beam Optics & Commissioning Group

Super KEKB

Belle II

KEK Unravelling the mysteries of matter, life and the universe.

Overview

- We have successfully squeezed beta* down to 2 mm in both rings.
- Beam optics measurement is based on closed orbit analysis.
  - Beam measurement with Turn-by-Turn BPMs are partially performed, but still not mature for the daily optics correction. (Need more experience)
- The correction of IP parameters mainly based on measured luminosity and beam size.
- Beam orbit in the interaction region (IR) strongly affects performance of optics tuning.
- Unexpected degradation of LER global XY-coupling.
- Off-momentum optics analysis has just started.

Global and Local Optics Correction

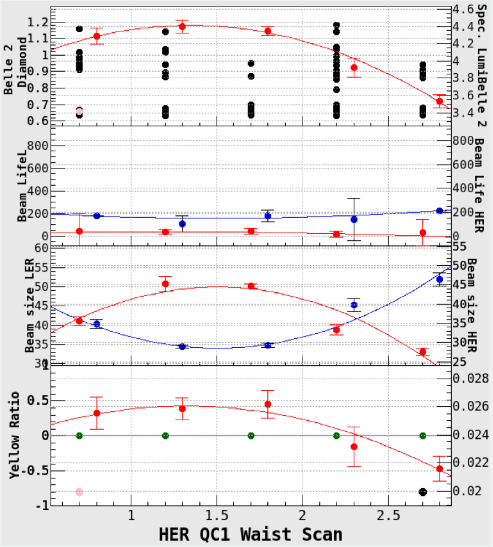
- **Global correction and low emittance tuning**

  - Same as Phase 1 operation except for the region near IR.

- **Optics parameters at IP**

  - Estimation is, in principle, possible.
  - However, It's difficult to confirm its reliability.
    - ~ Poor sensitivity due to the very small beta*
    - ~ Connection failure of QC1L{EP} BPMs
  - Therefore the correction mainly relies on luminosity performance and beam size so far.

Waist scan



Region in the vicinity of IR

- Normal skew magnet affects both XY-coupling and vertical dispersion.

- Minimize,

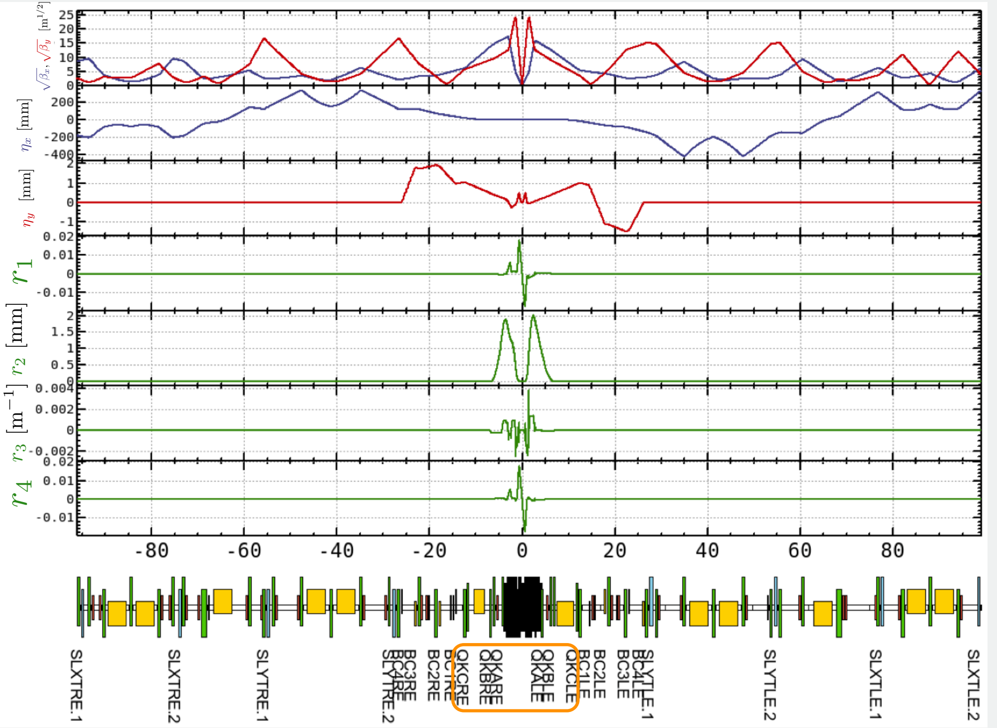
$$\chi^2 \equiv \Delta\eta_y^2 + w^2 \Delta y^2$$

V. dispersion

Weighting Factor

V. leakage orbit

- The weighting factor is empirically chosen.

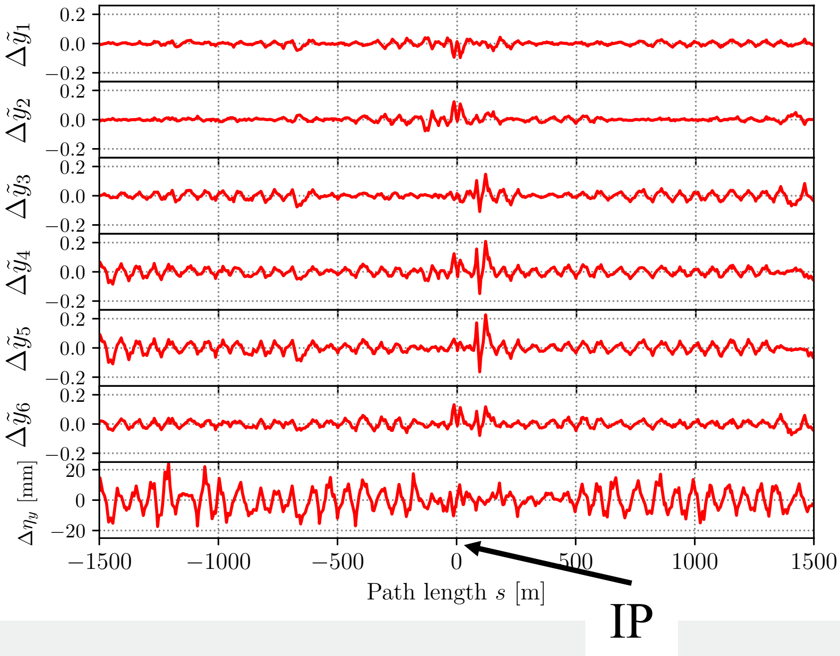


Example of Optics Correction - Phase 2 -

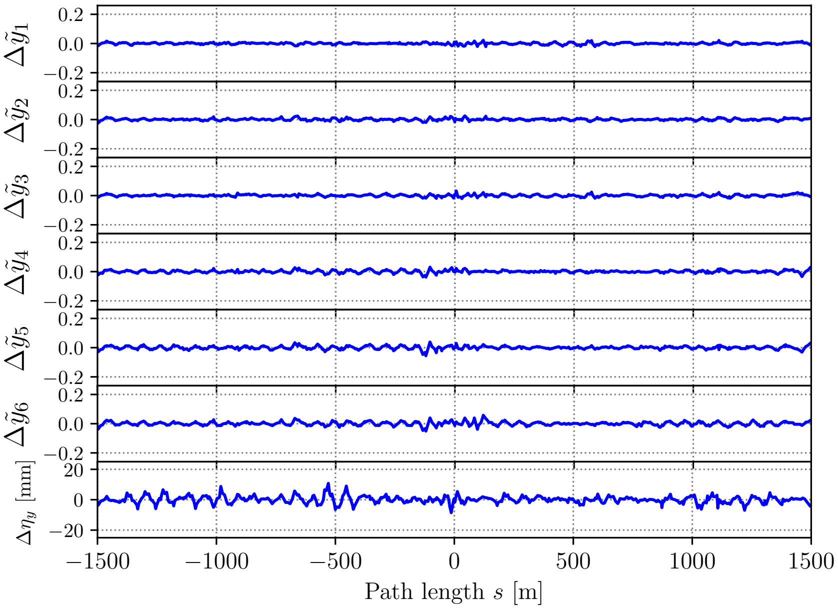
HER

- XY-coupling and vertical dispersion before and after the optics correction.

Before Correction

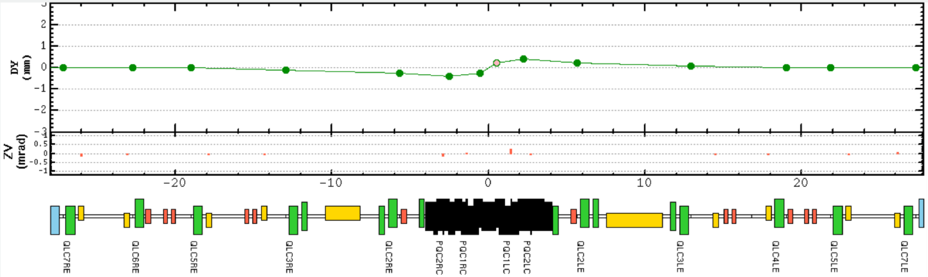


After Correction

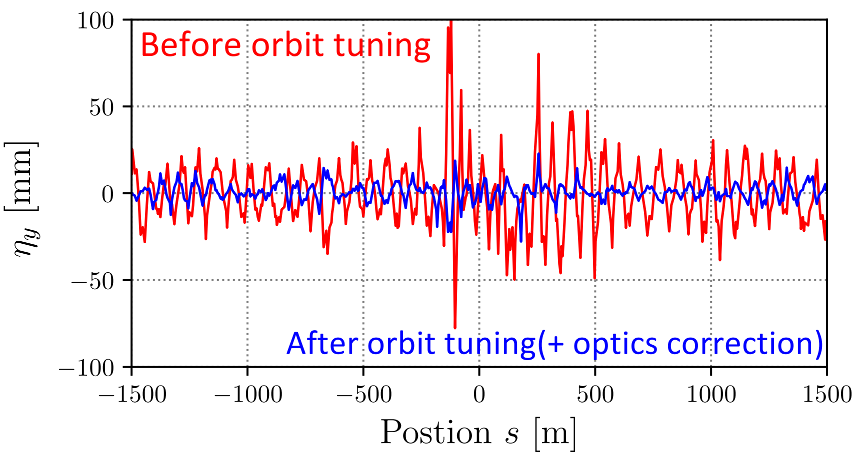


Beam Orbit in IR and the Performance of Optics Correction

- IR beam orbit is sometimes adjusted locally to mitigate beam pipe heating and/or background (BG) level of the physics detector.
- It affects beam optics and performance of optics tuning also.
- Example: IP localized vertical angle and vertical dispersion in HER.



The large vertical dispersion leaked from IR was not correctable owing to hardware limit of correctors.



Performance of Global Optics Correction

	Phase 1		Phase 2		Phase 3	
	LER	HER	LER	HER	LER	HER
$(\Delta\beta_{x,y}/\beta_{x,y})^{\mathrm{rms}}$ [%]	3 / 3	3 / 3	2 / 4	3 / 3	3 / 7	3 / 4
$(\Delta y)^{\mathrm{rms}} / (\Delta x)^{\mathrm{rms}}$	0.009	0.006	0.014	0.008	0.016	0.009
$(\Delta\eta_{x,y})^{\mathrm{rms}}$ [mm]	8 / 2	11 / 2	10 / 4	9 / 3	14 / 3	20 / 3

HER $(\beta_x^*,\ \beta_y^*) = (100\ \mathrm{mm},\ 3\ \mathrm{mm})$ $(\beta_x^*,\ \beta_y^*) = (80\ \mathrm{mm},\ 2\ \mathrm{mm})$

LER $(\beta_x^*,\ \beta_y^*) = (200\ \mathrm{mm},\ 3\ \mathrm{mm})$ $(\beta_x^*,\ \beta_y^*) = (80\ \mathrm{mm},\ 2\ \mathrm{mm})$

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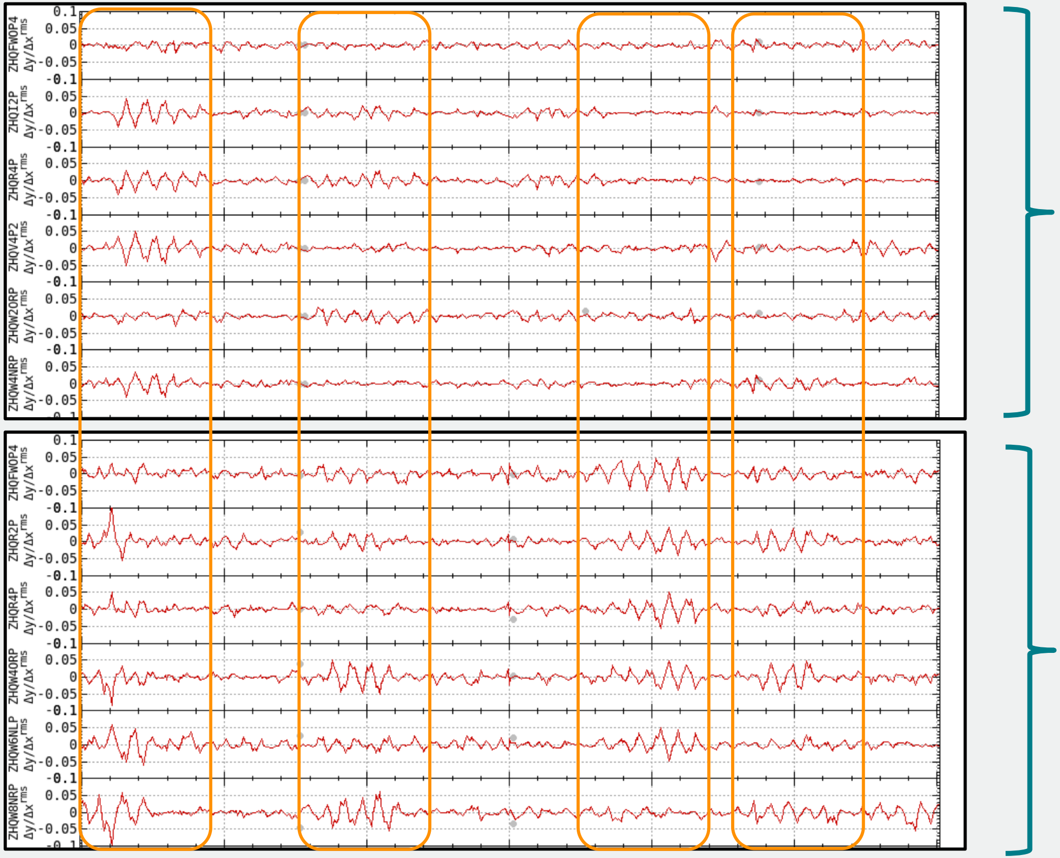
LER Global XY-coupling in Phase 1 and 2



* Steering magnets used in the measurements are different.

A Possible Source of the XY-coupling Degradation

- A large number of permanent magnets (PMs) are attached to the LER beam pipe for suppression of e-cloud effects.

- It creates unexpected effects to the LER beam?

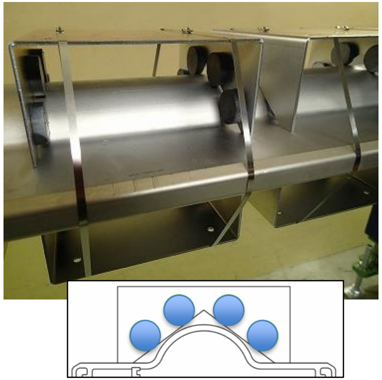
Configuration Change of PMs after Phase 2

Electron cloud in LER (1/3): Re-alignment of PMs -2

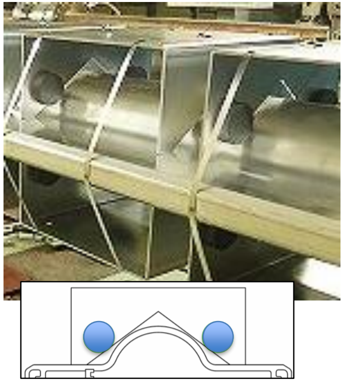
- To study the influence of PM units during Phase-3, 3 areas with different conditions were prepared; (with Optics group)
  - East arc: PMs were just re-aligned using a tool .
  - South arc: PMs were re-aligned, and also the number was reduced from 4 to 2. (only near antechambers)
  - North and West arc: Almost the same condition to that in Phase-2 (no re-alignment).

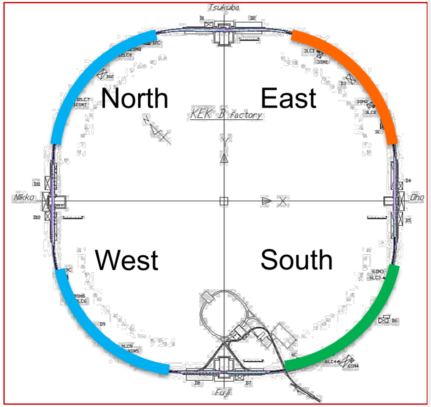
Y. Suetsugu

PM unit with 4 PMs



PM unit with 2 PMs





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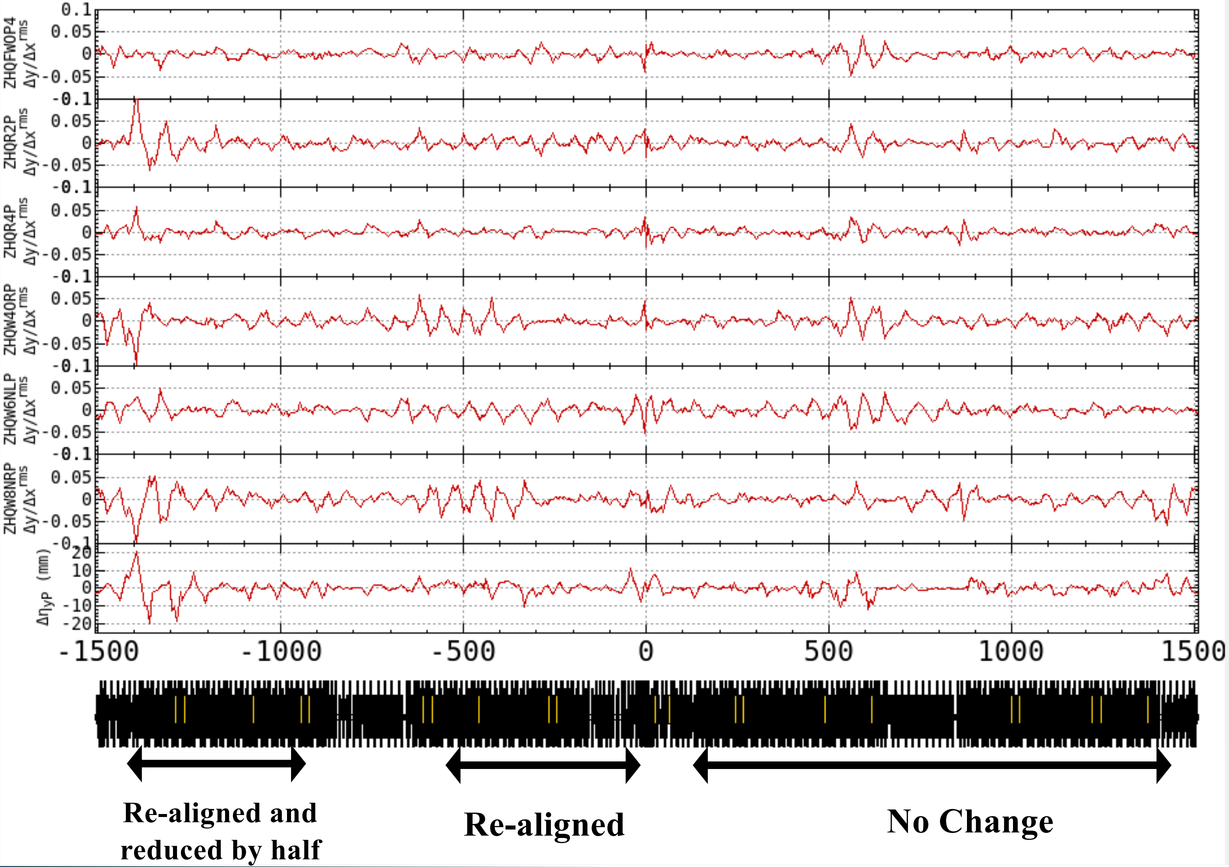
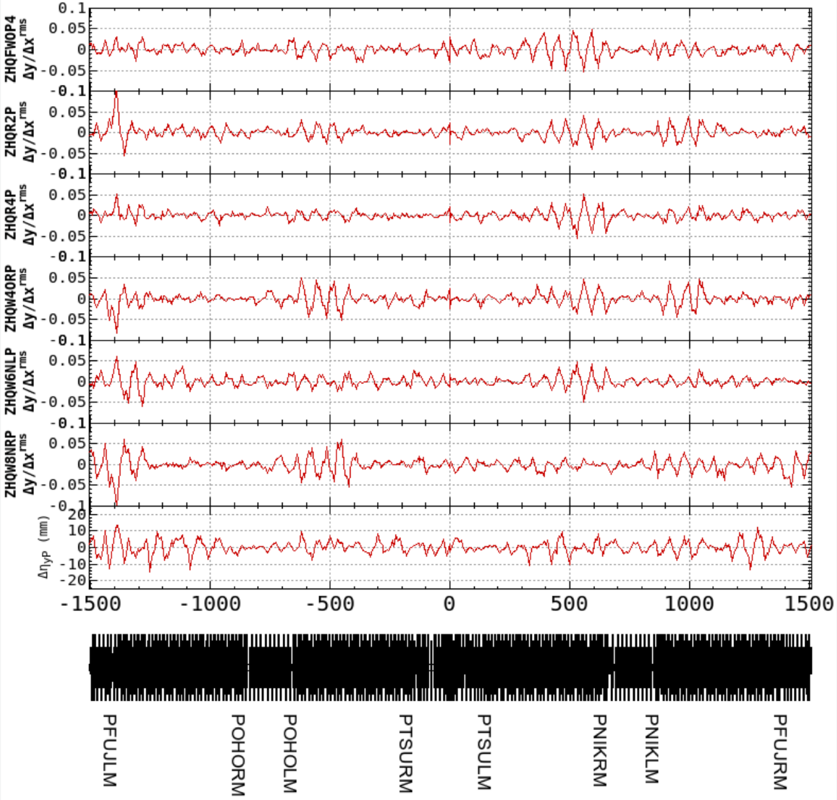
Measurement in Phase 3

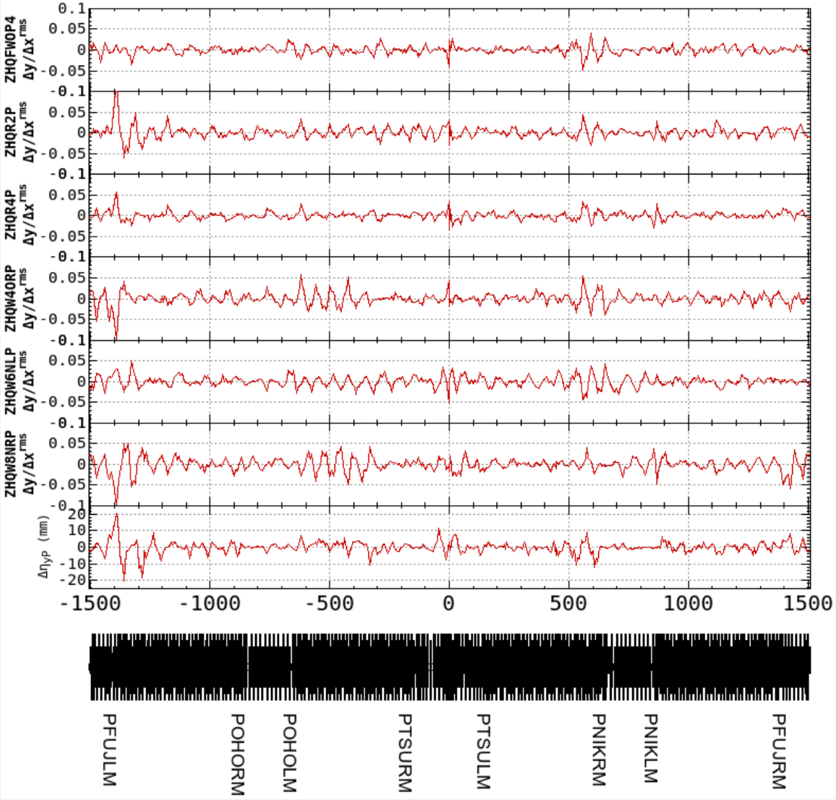


Comparison

Phase 2



Phase 3



Observation in Phase 3 and Next Plan

- Does the configuration change of PMs improve XY-coupling?

  -> It looks no improvement so far.

- We should consider strategy again to identify the source of degradation.

- we may have to re-check offset of some of quadrupole magnets with beam-based alignment technique.

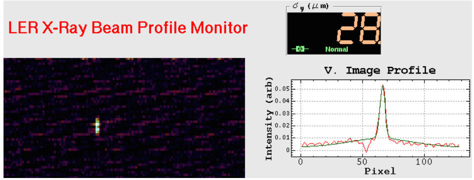
Issue on Vertical Beam Size Measurement in Phase 1 HER

- Discrepancy between measured beam size and that expected by beam optics in HER.

MAC'16

Vertical Emittance

LER



$\beta_y = 67$ m → $\varepsilon_y \sim 12$ pm

HER

Estimation with beam size measurement

$\varepsilon_y \sim 120$ pm

→ Flanagan-san's talk?

Estimation with measured optics

$\varepsilon_y \sim 10$ pm

The exact value is still under discussion.

2016/06/13 The 21th KEKB Accelerator Review Committee 21

Summary of series of investigation after MAC16

	LER	HER
X-ray Monitor	10 pm	40 pm
Beam Optics	10 pm	10 pm

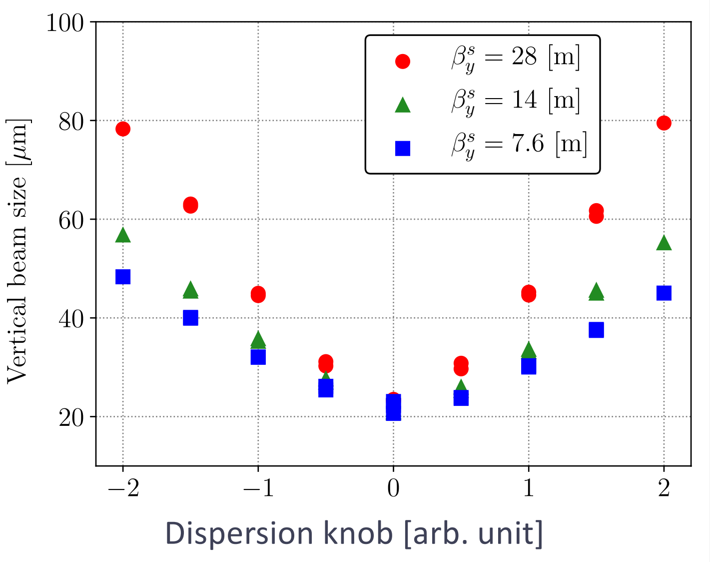
- A difference between LER and HER is beta function at the x-ray source point.

LER $\beta_y = 67$ m HER $\beta_y = 7.6$ m

Study on X-ray Beam Sime Monitor (XRM) in Phase 2

HER

- Vertical beam size is measured with changing global vertical dispersion and beta function β_y^s at the X-ray source point.



We Find that

- Measured size becomes less sensitive to the vertical-dispersion knob when β_y^s becomes smaller as expected.
- The minimum measured beam size is independent on β_y^s
- The monitor system has some smearing effects which limit the resolution. Comprehensive study estimates the size of smearing effect is ~7 μm.

Performance of Global Optics Correction

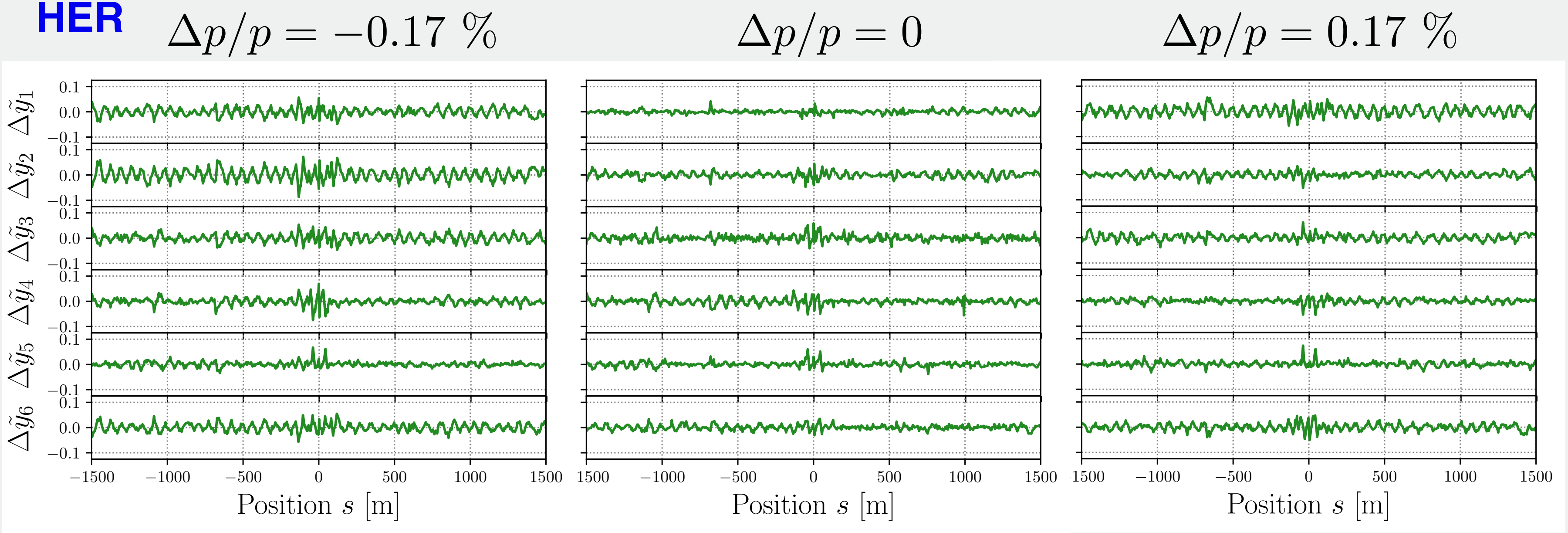
- Measurement at low beam current ~40mA.
- The LER vertical emittance in Phase 3 is somehow lower than that of Phase 2.
  <- Is it true?

	Phase 1		Phase 2		Phase 3	
	LER	HER	LER	HER	LER	HER
$(\Delta\beta_{x,y}/\beta_{x,y})^{\mathrm{rms}}$ [%]	3 / 3	3 / 3	2 / 4	3 / 3	3 / 7	3 / 4
$(\Delta y)^{\mathrm{rms}}$ / $(\Delta x)^{\mathrm{rms}}$	0.009	0.006	0.014	0.008	0.016	0.009
$(\Delta\eta_{x,y})^{\mathrm{rms}}$ [mm]	8 / 2	11 / 2	10 / 4	9 / 3	14 / 3	20 / 3
ε_y [pm]	~10	(~40)	~20	~10	~10	~10
$\varepsilon_y/\varepsilon_x$ [%]	~0.6	(~0.9)	~1.1	~0.2	~0.6	~0.2

Off-momentum XY-coupling

- Vertical beam size blowup with rf-frequency change.
- Off-momentum XY-coupling is indeed larger than that of on-momentum.
- Its error source and countermeasure is under discussion.

HER



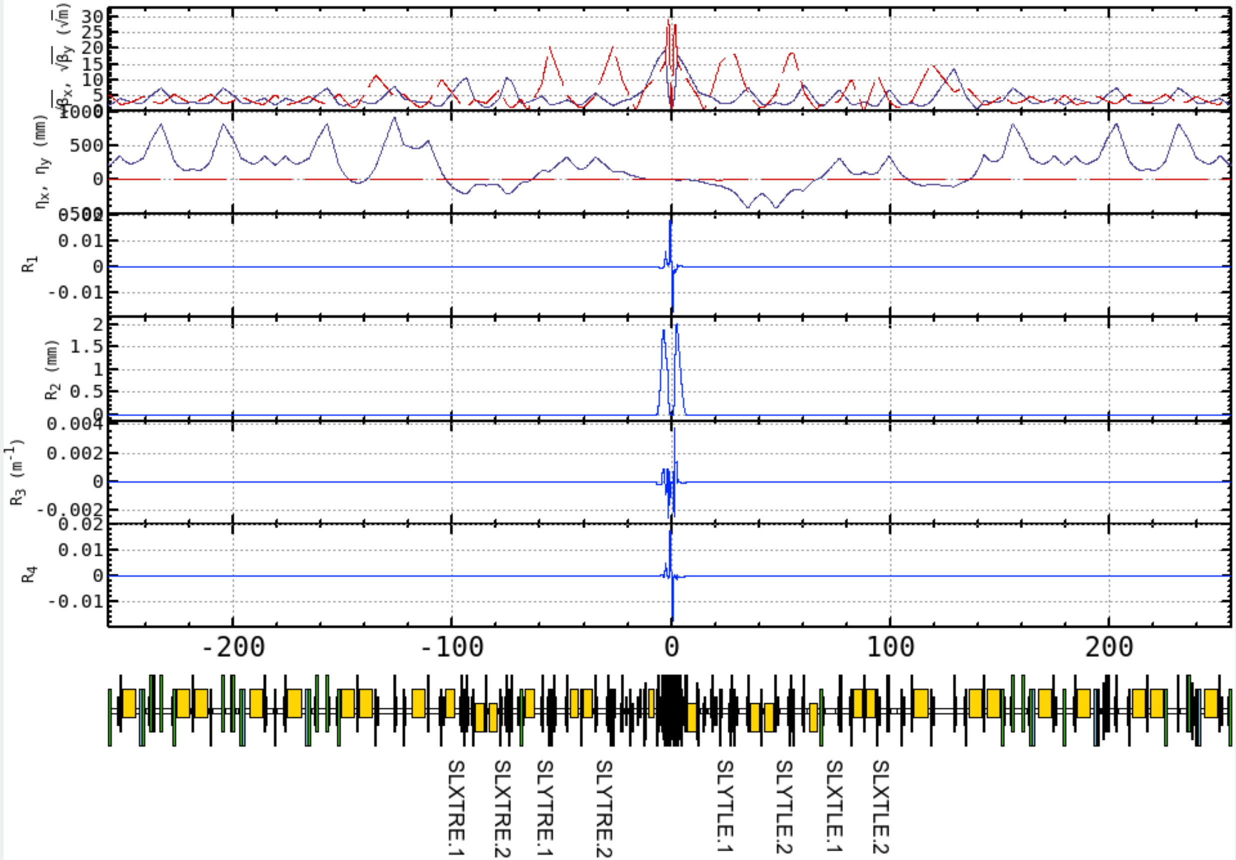
Summary

- We have successfully squeezed beta* down to 2 mm in both rings.
- Beam orbit in IR strongly affects performance of global optics correction.
  - We should take care not only beam optics but also beam pipe heating and BG level.
- Tuning of IP parameters is mainly based on luminosity performance and beam size.
- Degradation of LER XY-coupling compared with that of Phase 1.
- Need more consideration on the measured vertical emittance including calibration of measurement system.
- Off-momentum optics analysis has just started.

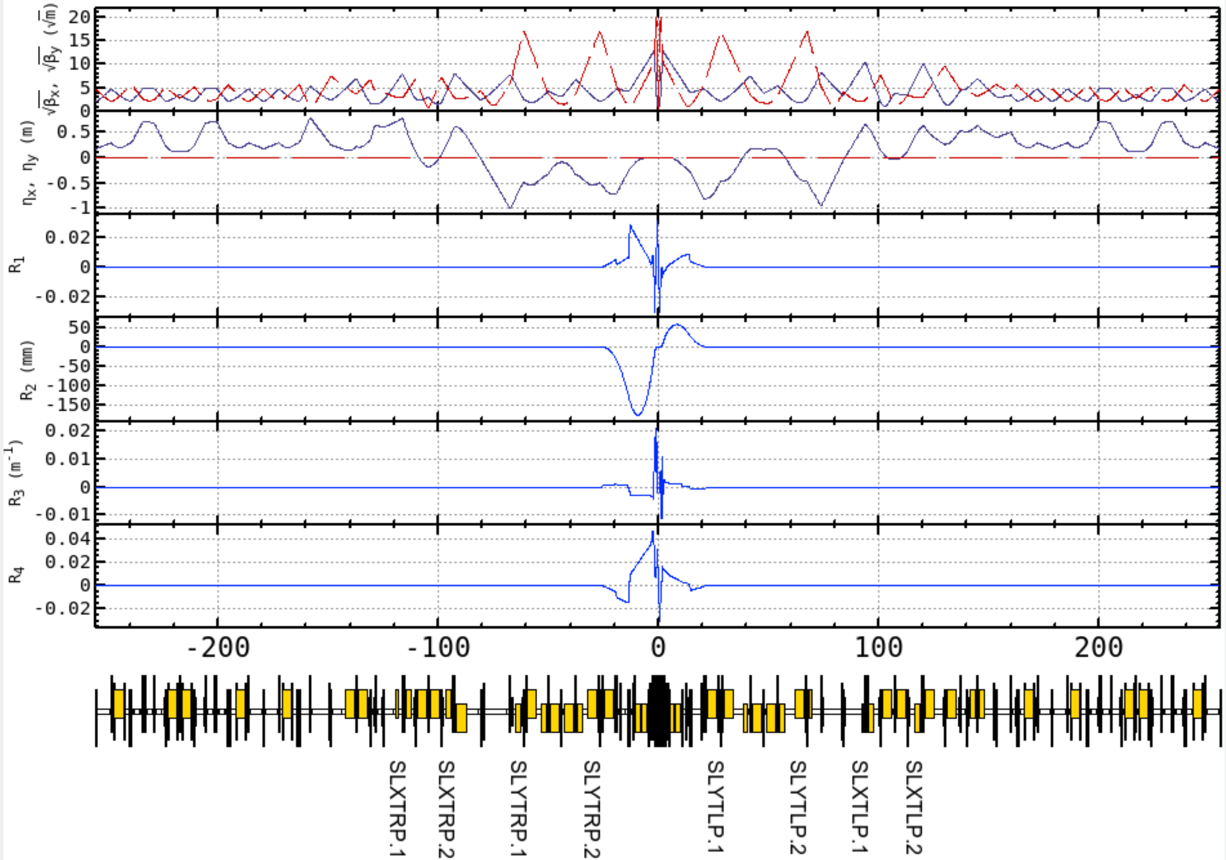
Thank You for Your Kind Attention.

Spare Slides

HER Optics in the Vicinity of IP



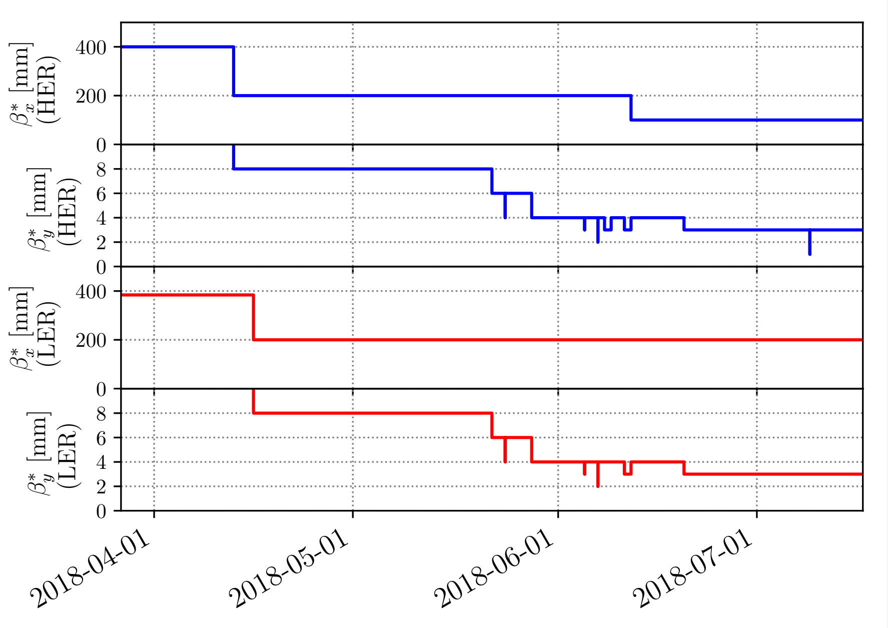
LER Optics in the Vicinity of IP



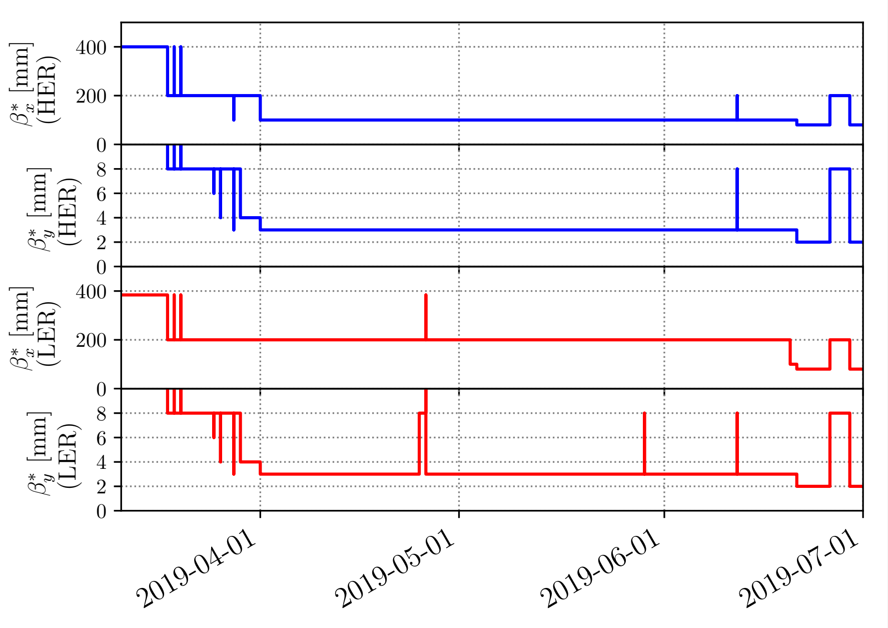
Beta Squeezing

- Phase 2: Step by step squeezing with optics correction is essential.
- Phase 3: Experience in Phase2 helps the squeezing.

Phase 2

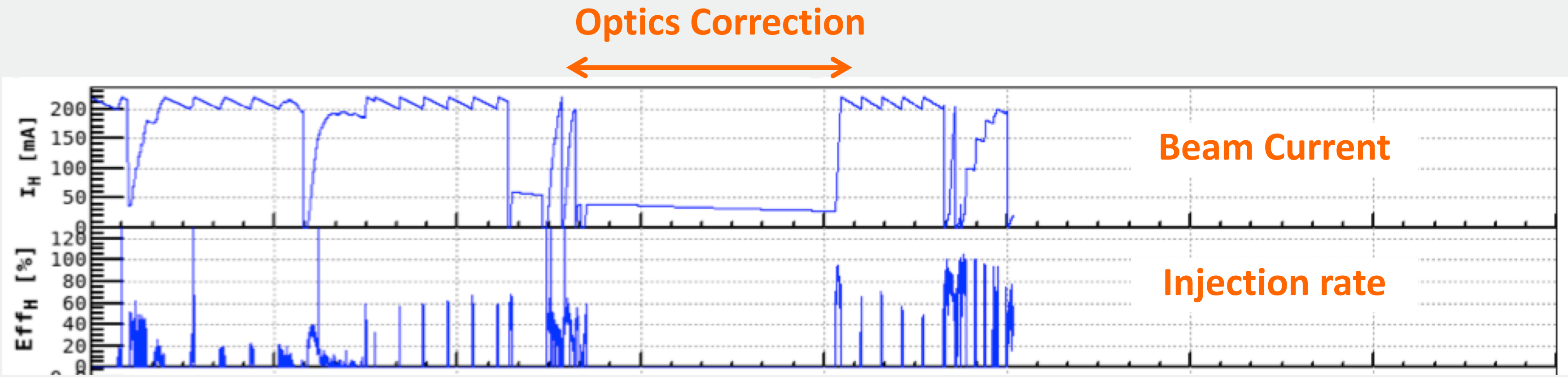


Phase 3

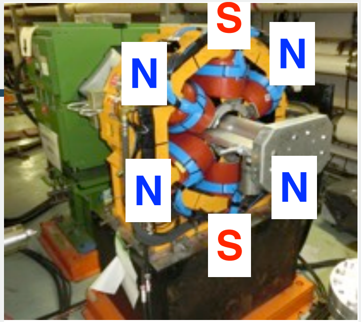


Optics Correction and Beam Injection

- Beam injection is very sensitive to optics distortion as well we injected beam quality.
- XY-coupling is important for high injection efficiency and low BG.



Orthogonal Correctors

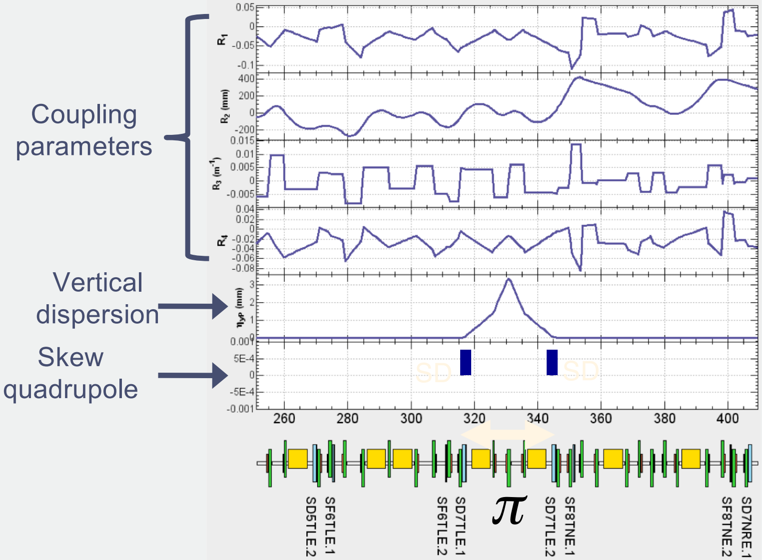


- **Some of sextupole magnets have skew quadrupole coils.**

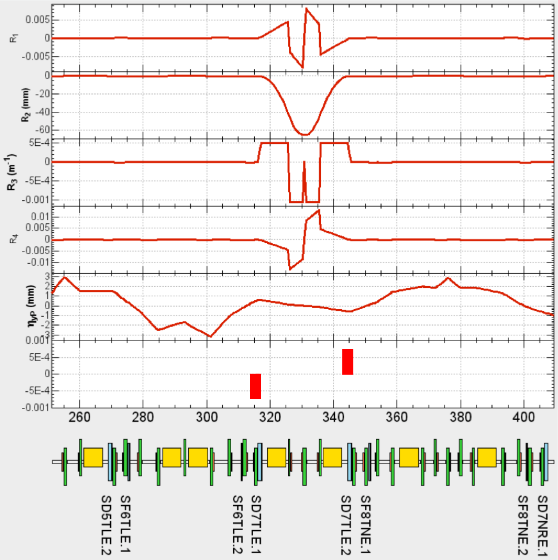
  Symmetrical / asymmetrical excitation of skew-corrector pare can be used as orthogonal correctors for coupling and vertical dispersion.

  The orthogonality allows us to reduce size of the matrix to be solved.

Symmetrical Excitation
(XY-coupling corrector)

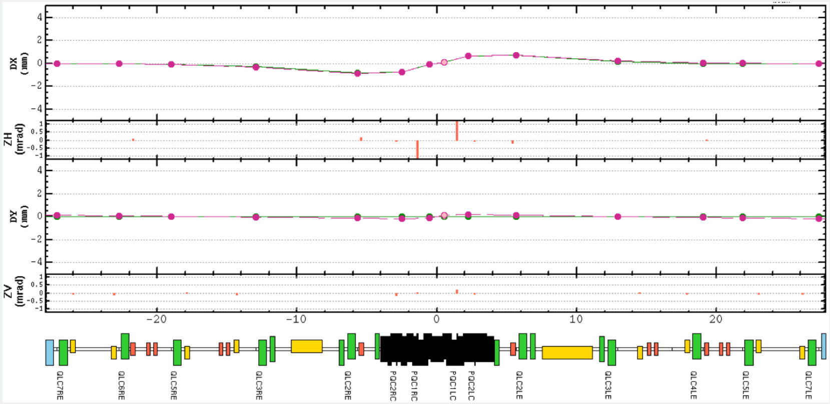


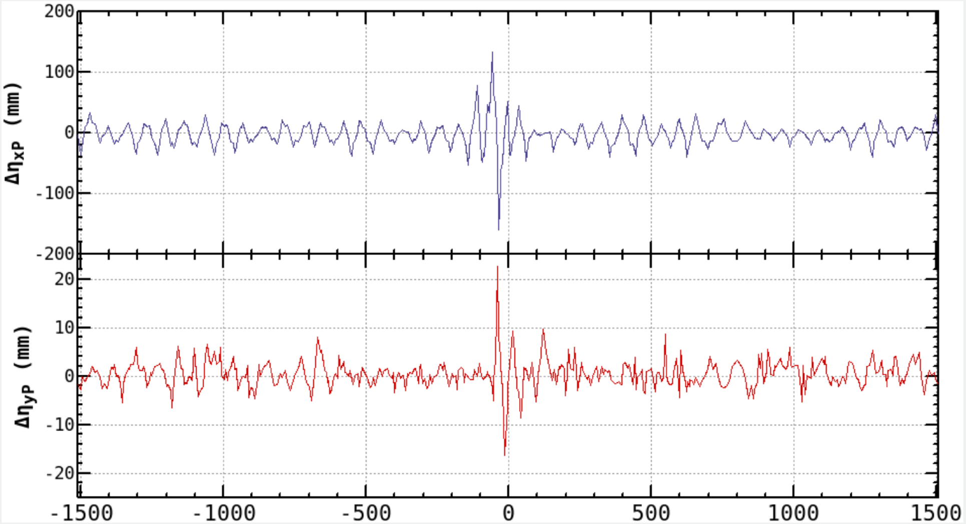
Asymmetrical Excitation
(Vertical-dispersion corrector)



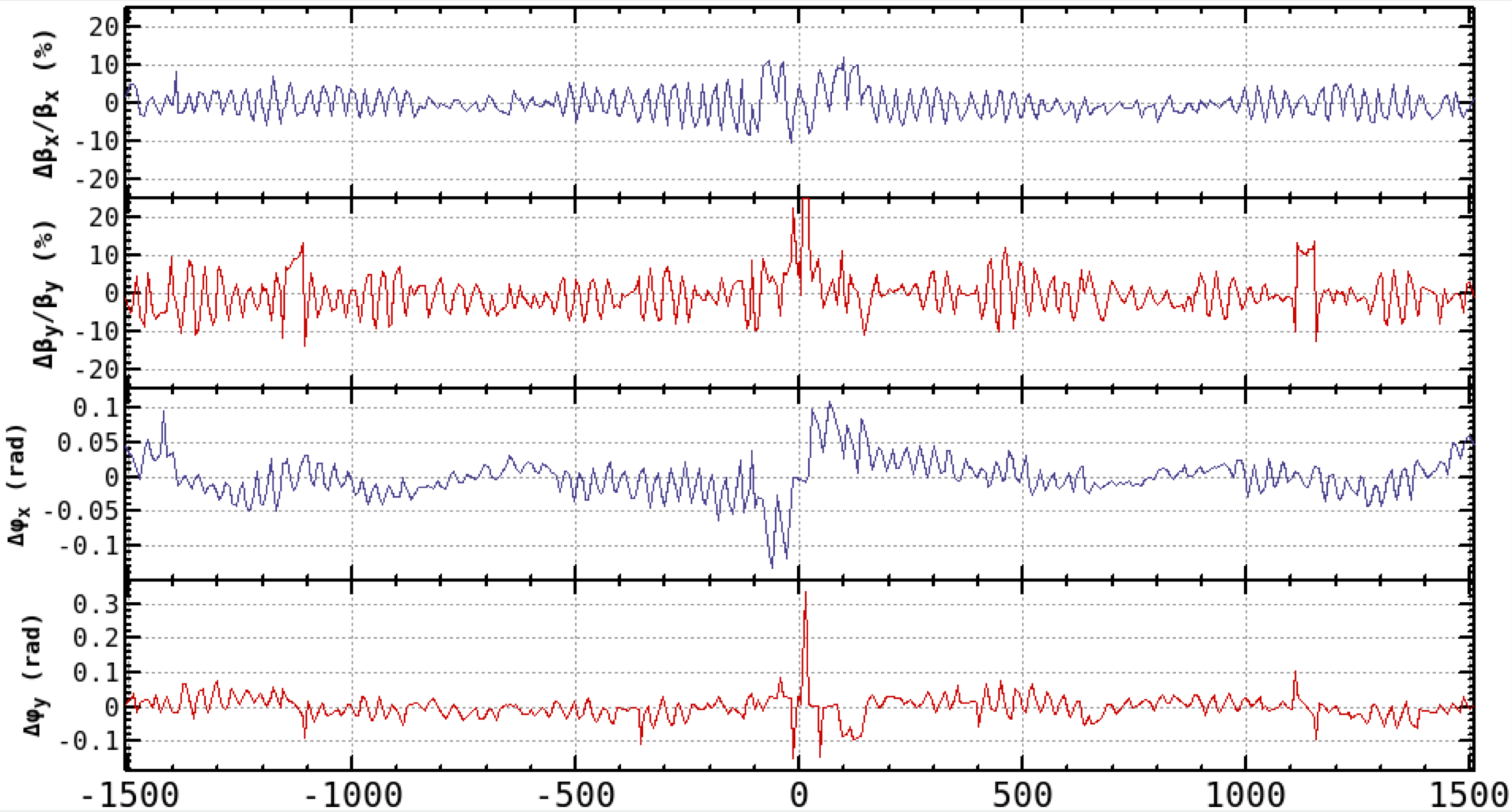
Horizontal Dispersion in the Vicinity of IR - HER -

- Horizontal localized angle bump is applied to mitigate BG.
- As the result, Horizontal residual dispersion is large in the vicinity of IP.

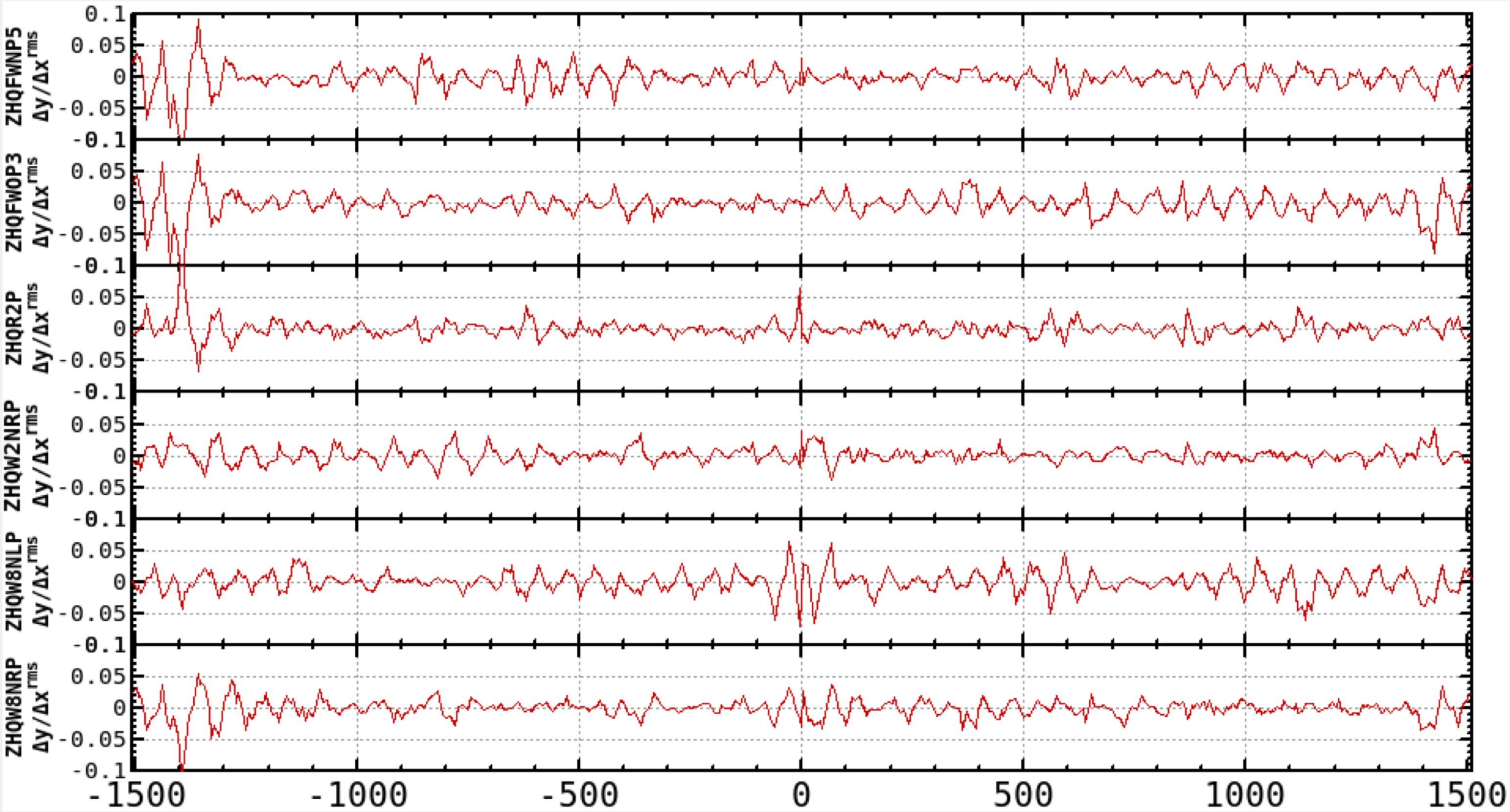




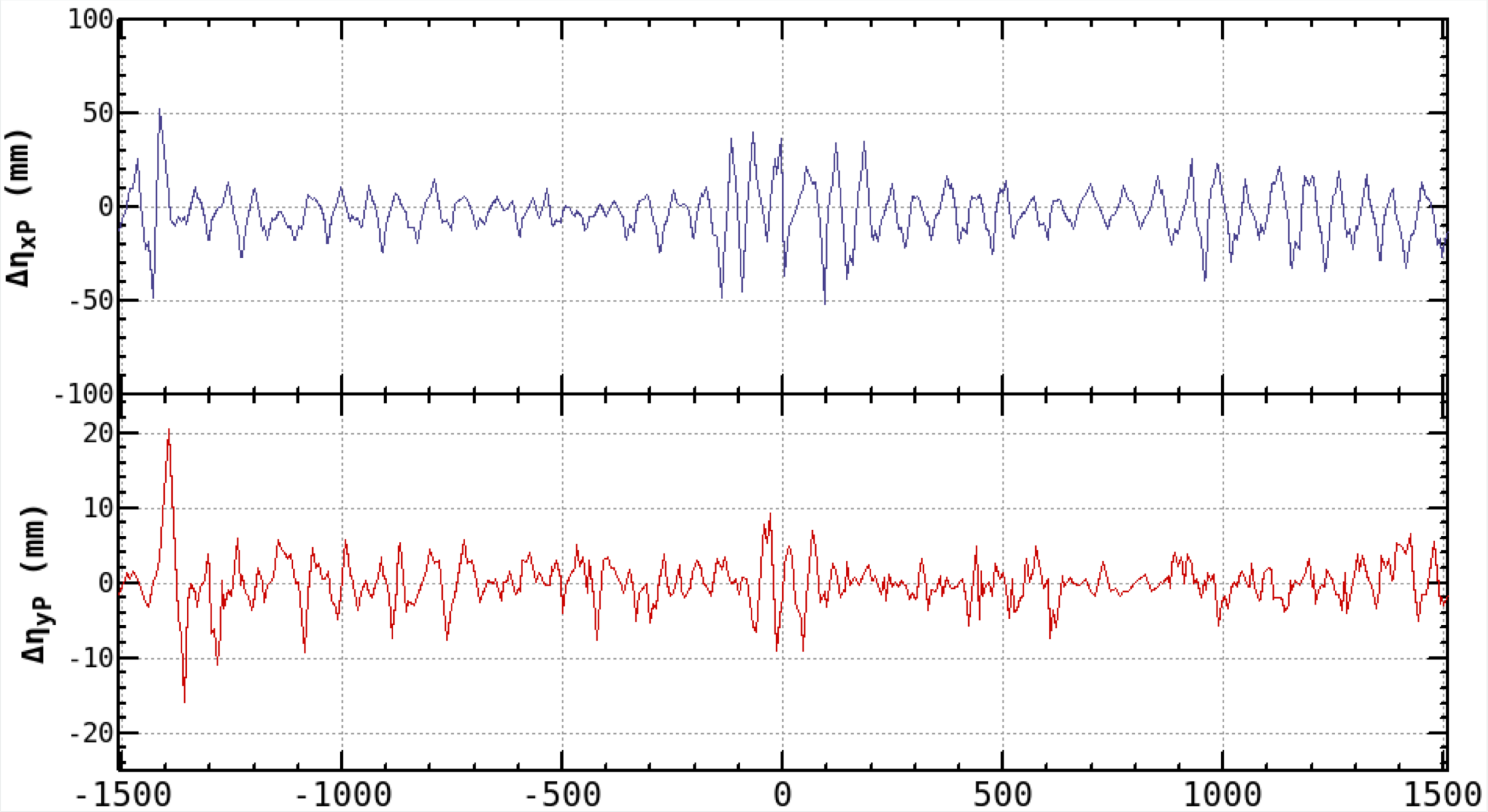
Beta Beating - LER -



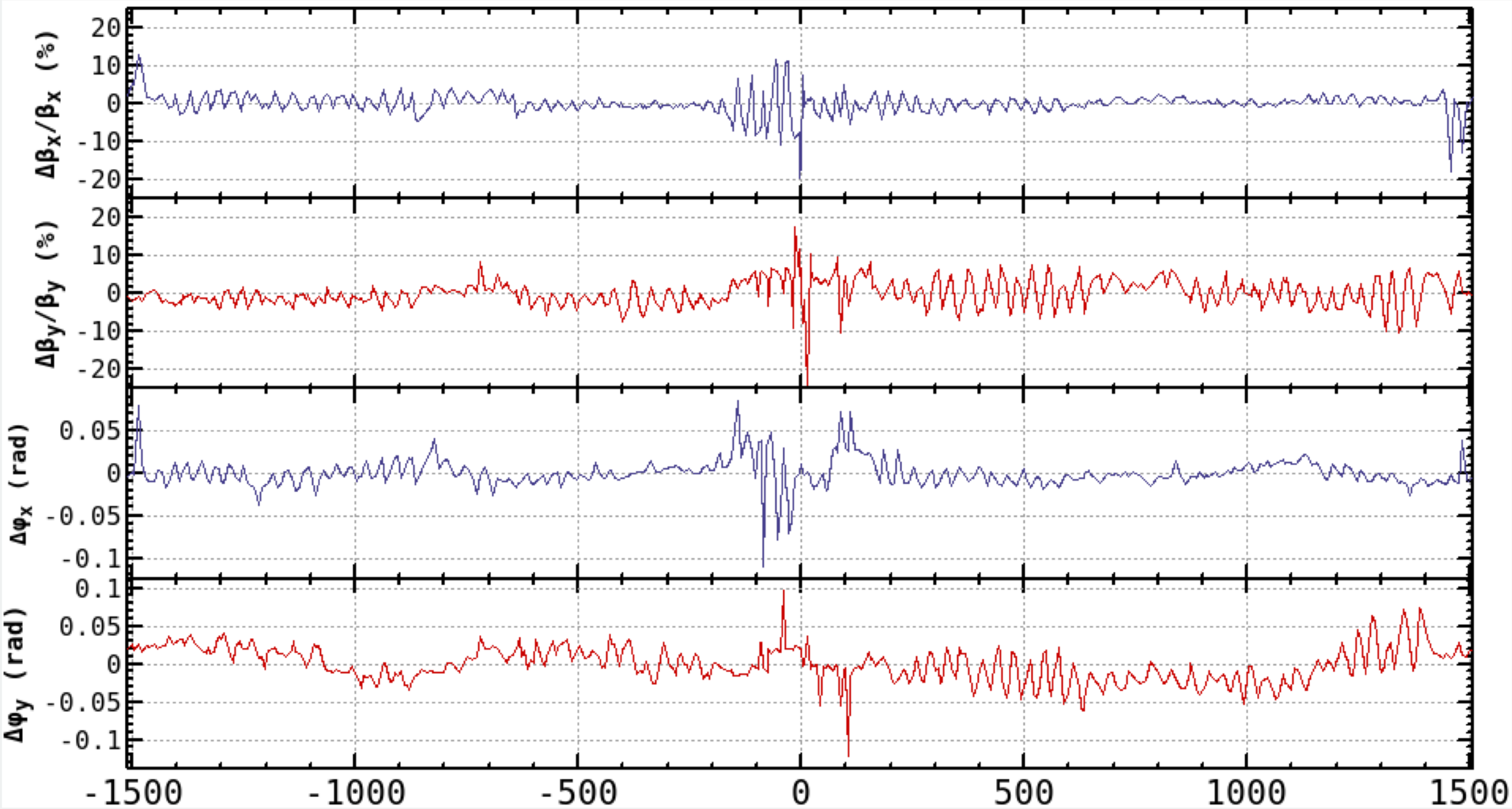
Residual XY-coupling - LER -



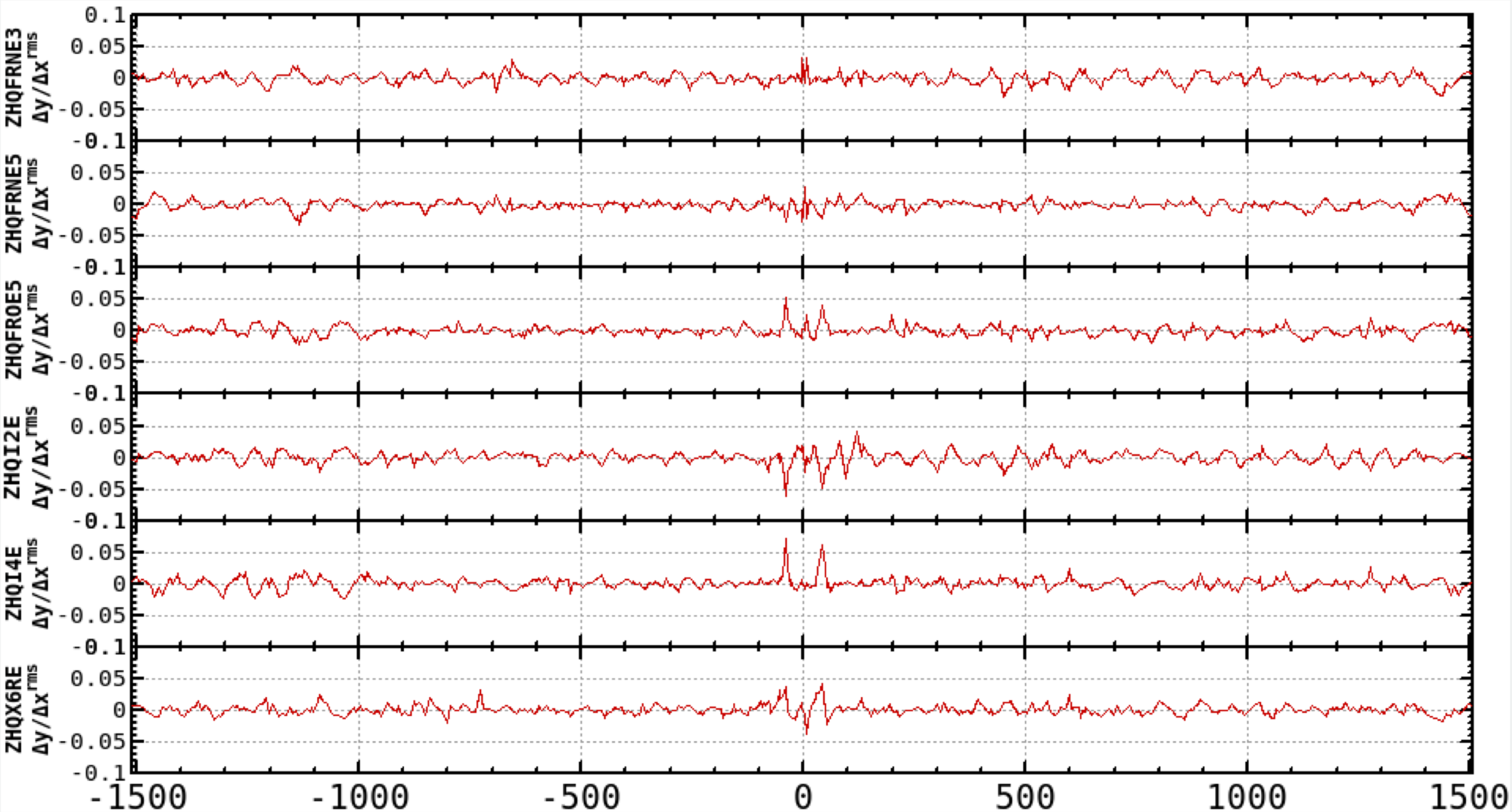
Residual Dispersion - LER -



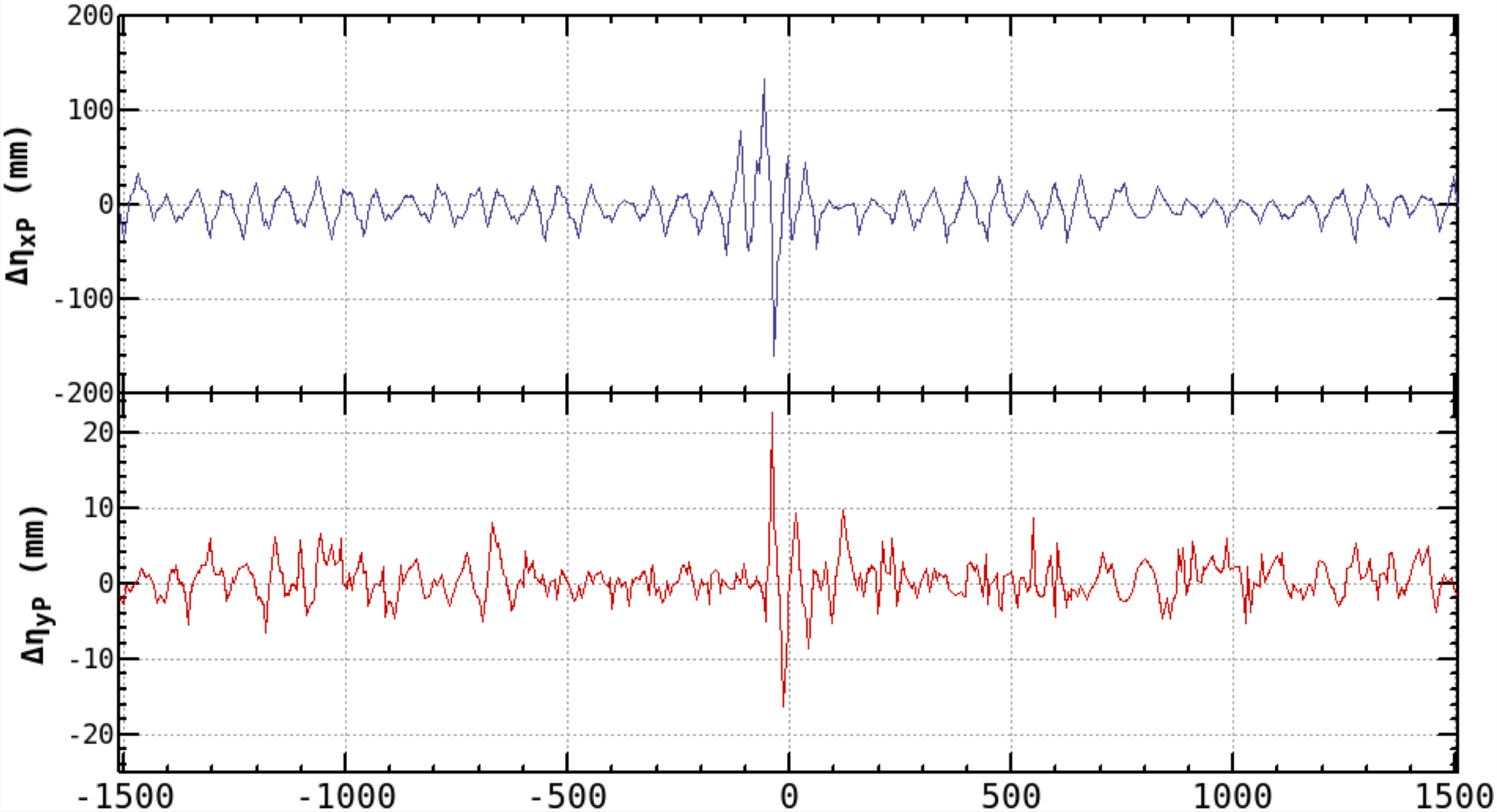
Beta Beating - HER -



Residual XY-coupling - HER -

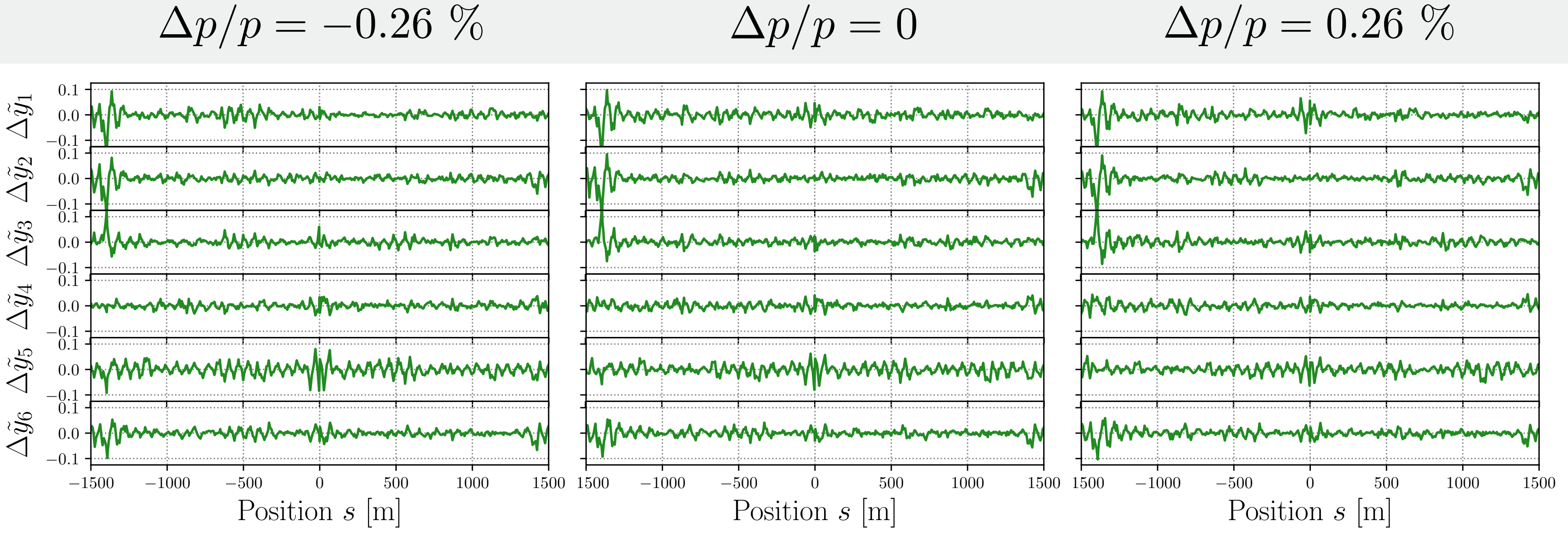


Residual Dispersion - HER -



Off-momentum XY-coupling

LER



Optics Measurement

- Beta function:

  Orbit response analysis with DC dipole kicks.

$$\Delta x_i = \frac{\sqrt{\beta_i \beta_0}}{2\sin \pi\nu}\theta \cos\left(|\phi_i - \phi_0| - \pi\nu\right)$$

- Dispersion function:

  Orbit response with RF frequency change

$$\eta_x = f_0 \frac{\Delta x}{\Delta f} \xi$$

RF frequency (f_0), Orbit change (Δx), Frequency change (Δf), Phase slip factor (ξ)

- Betatron (XY-) coupling:

  Vertical leakage orbits induced by horizontal dipole kicks.

- Turn-by-Turn measurement:

  Partially performed, but not mature for the daily operation.

  <- Need more experience and investigation.

Estimation of IP Parameters

- Twiss parameter propagation with model transfer matrix.

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_{\rm IP} = \begin{pmatrix} C^2 & -2SC & S^2 \\ -CC' & SC' + CS' & -SS' \\ C'^2 & -2S'C' & S'^2 \end{pmatrix} \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_{\rm BPM}$$

- Solving nonlinear equation numerically with measured optics at QC{12} BPMs.

$$\beta_{\rm BPM} = C^2\beta_{\rm IP} - 2SC\alpha_{\rm IP} + S^2(1+\alpha_{\rm IP}^2)/\beta_{\rm IP}$$

- Estimation of waist assuming drift motion.

$$\beta_{\rm waist} \sim \beta_{\rm IP}/(1+\alpha_{\rm IP}^2)$$

$$\Delta s \sim \alpha_{\rm IP}\beta_{\rm IP}/(1+\alpha_{\rm IP}^2)$$

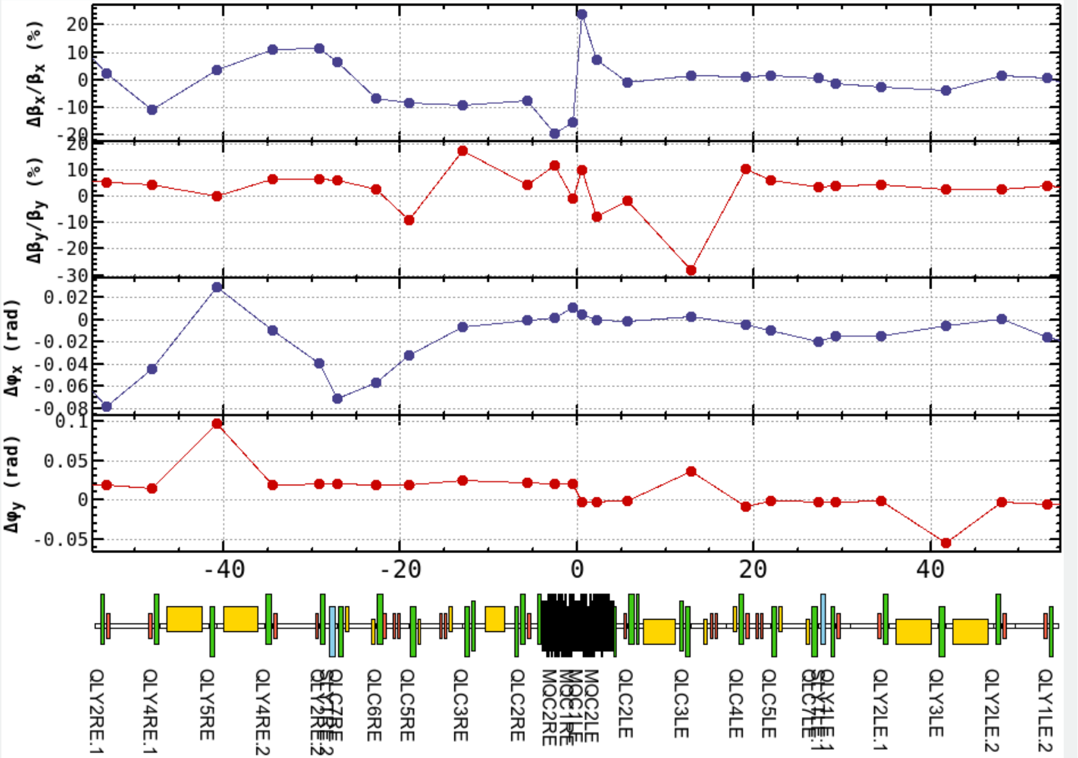
Estimation of IP Parameters - HER -

- Estimation with measured optics and model transfer matrix

$$\beta_{\rm IP} = 282 \text{ mm } / \ 2.6 \text{ mm}$$

$$\beta_{\rm waist} = 86 \text{ mm } / \ 2.0 \text{ mm}$$

$$\Delta s = -130 \text{ mm } / \ -1.1 \text{ mm}$$



- Large offset of horizontal waist position is not understood.
- We tried luminosity run with adjusted horizontal waist.

However the luminosity performance is not improved or rather worse.

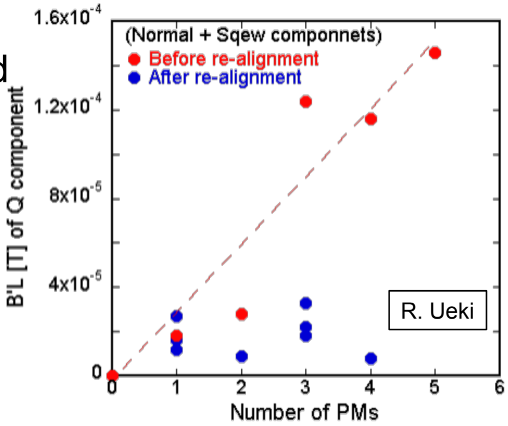
Vacuum system updates for Phase-3

Electron cloud in LER (1/3): Re-alignment of PMs -1

- Permanent magnets (PMs) around beam pipes, which is adopted as a countermeasure against the electron cloud effect, worked very well, but they were suspected to have an influence on the beam optics, i.e., the x-y coupling.
- It was pointed out that the misalignment of PM units along beam pipes is likely to increase the quadrupole component, and can be a cause of x-y coupling. (R. Ueki, MAG Group)

PM units attached to LER beam pipes

Measurement of quadrupole component



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Design Machine Parameters

Machine Parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.18×10^{-4}	4.53×10^{-4}		
σ_δ	$8.10(7.73) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	