Optics Correction and Low Emittance Tuning

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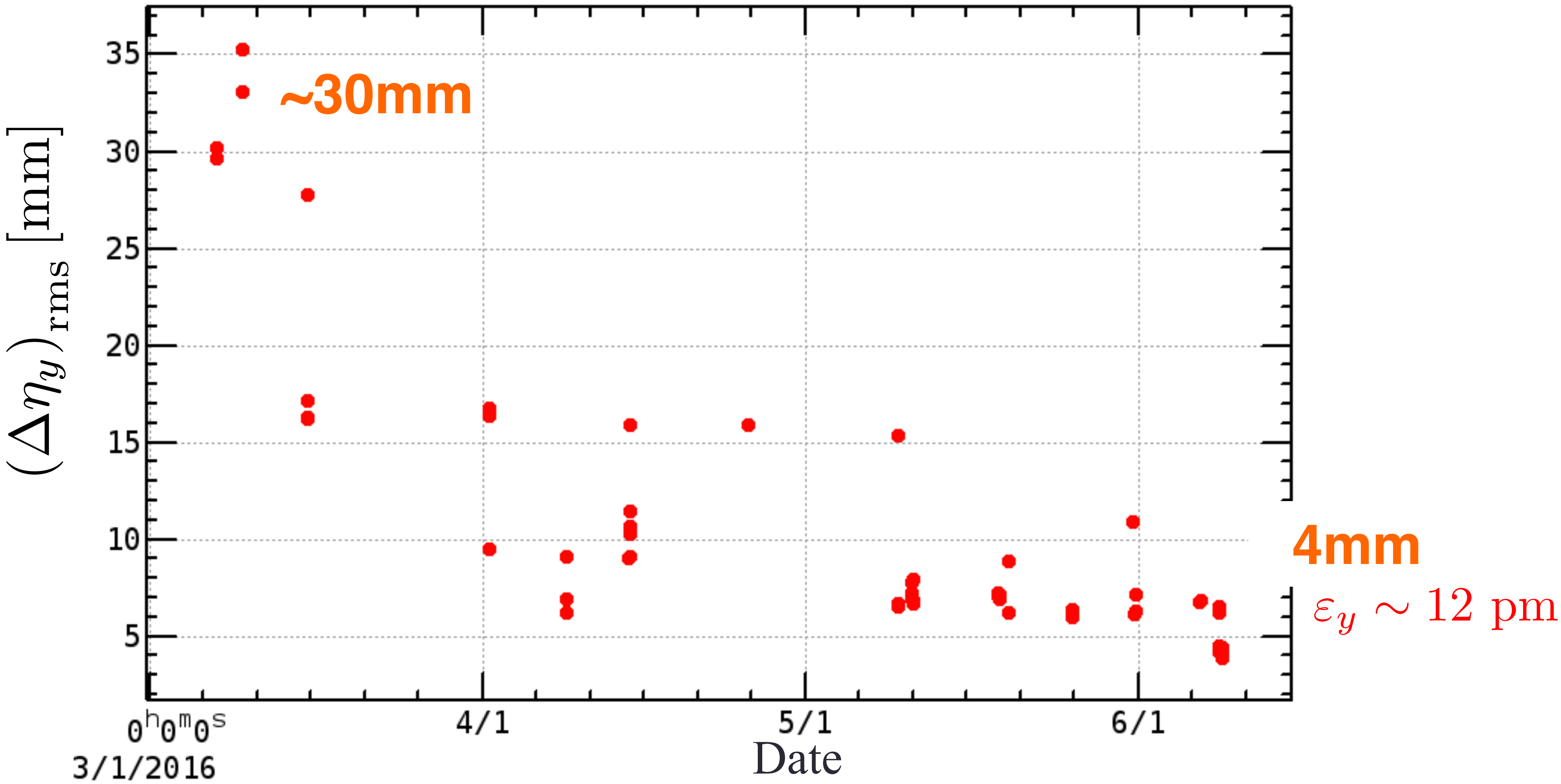
for SuperKEKB Optics&Commissioning Group

This Talk

History of residual vertical dispersion (LER)



- Optics correction and hardware calibration are iteratively repeated.
- Some details of optics correction are reported in this talk.

Mission

Establish optics measurement and correction tools

- Optics and orbit servers to control the magnet system.
- Continuous Closed orbit correction
- Tune Changer
- Optics measurement and correction
- Local-bump control
- etc…

Hardware calibration and bug hunt

- Polarity check of the magnet using beam measurement.
- Check BPM system (e.g. cabling, aging effect)
- Beam based alignment (BBA)
- etc…

Others

- Check validity of the model lattice and correct the model if needed.

Low emittance tuning (LET)

Target vertical emittance is < 5-10 pm.

Measurement Method

- **Optics measurement with orbit response analysis**

  - Horizontal-vertical (XY) coupling:
    Vertical leakage orbits induced by horizontal kicks.

  - Dispersion:
    Response with RF frequency change.

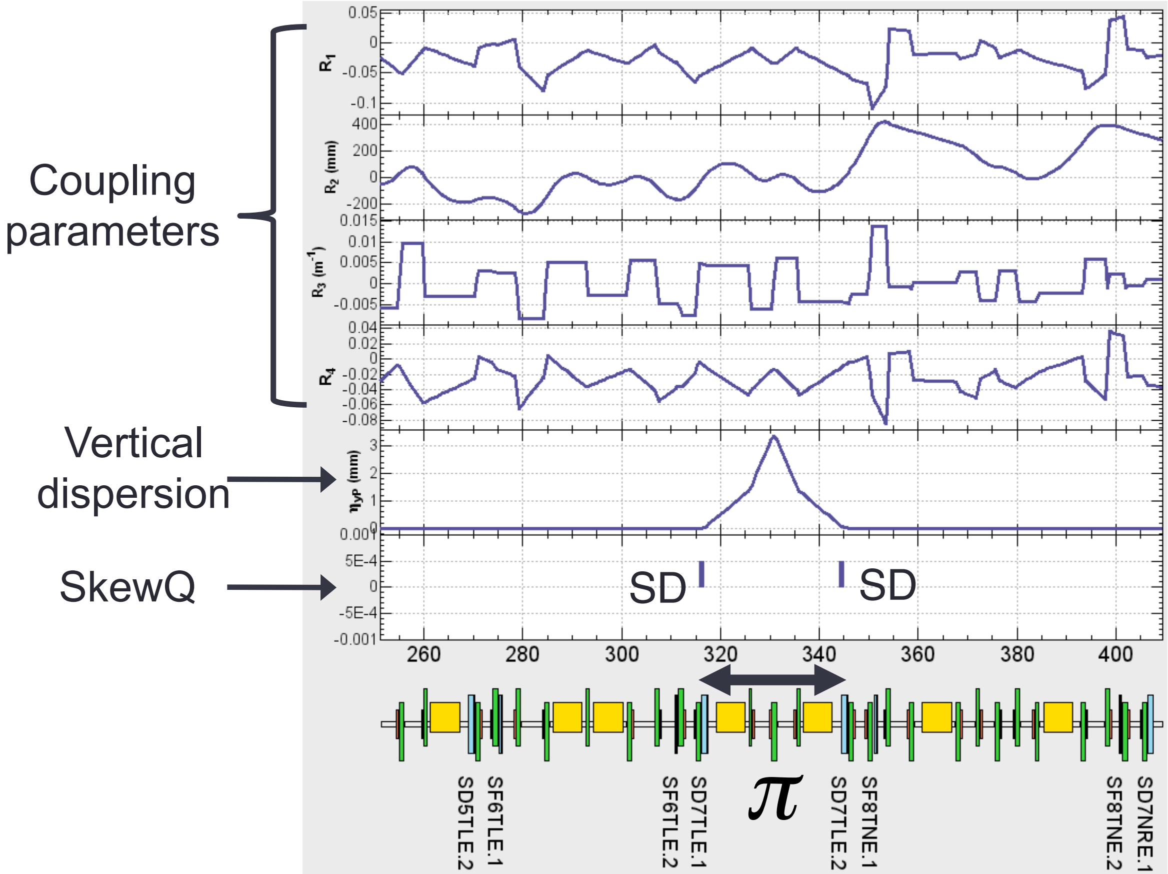
  - Beta function:
    Orbit response analysis with steering kicks.

- ~60 BPMs (per ring) can be used with turn by turn (TBT) mode.
  - Results are preliminary and not presented this report.

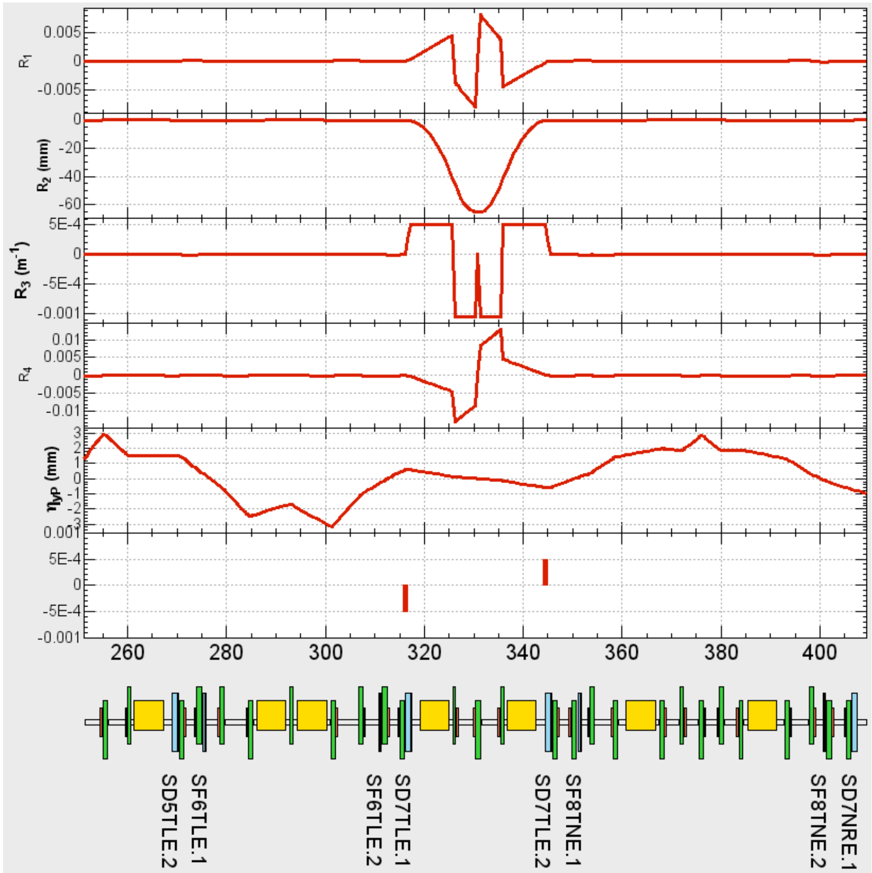
Orthogonal Correctors

- **Skew quadrupole(SkewQ) coil of sextupole magnet**
  Symmetric / asymmetric 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 problem.

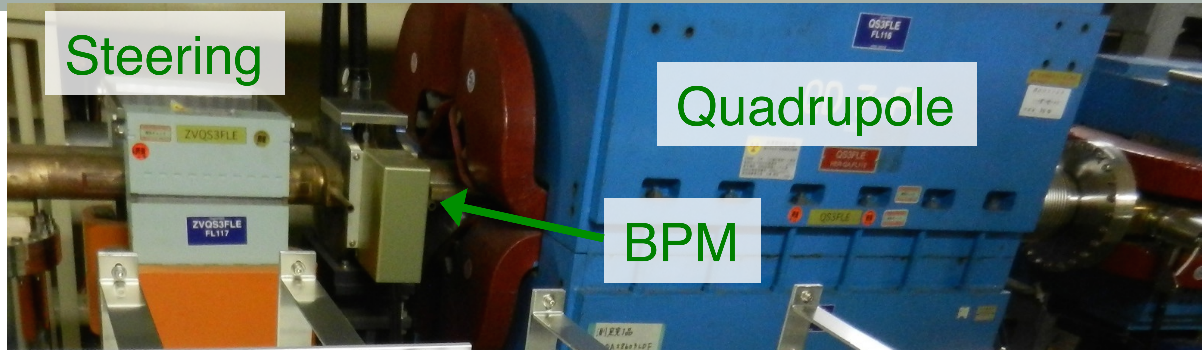
Symmetric Excitation
(XY-coupling corrector)



Asymmetric Excitation
(Vertical-dispersion corrector)



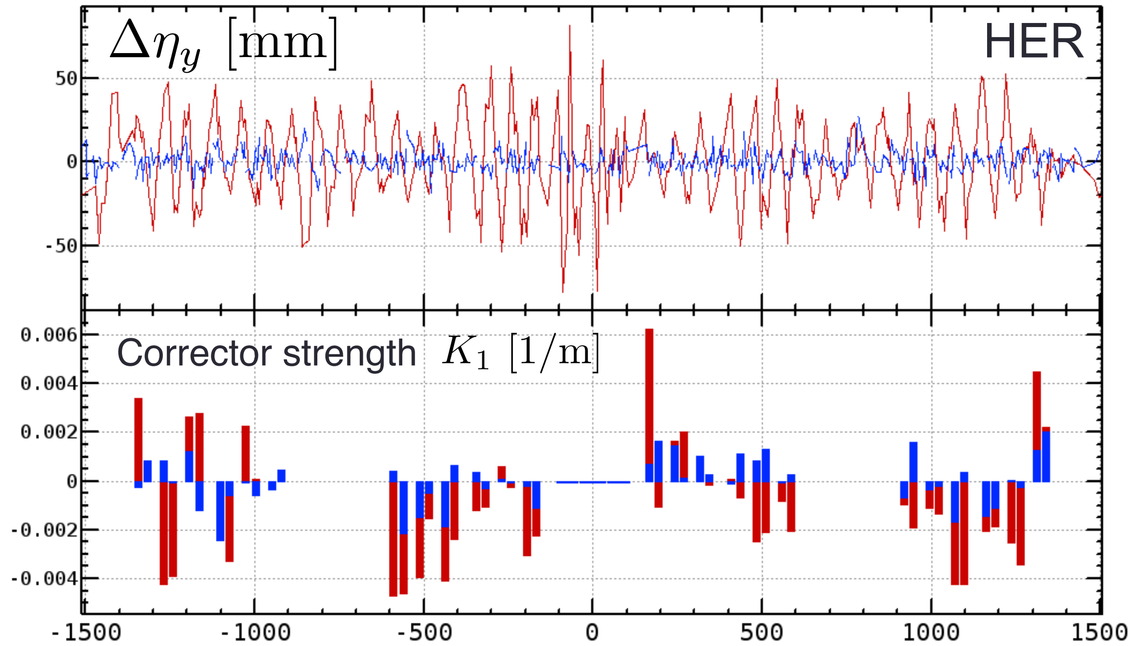
Beam Based Alignment (BBA)



- All quadrupole magnets have BPM. (~ 450 BPMs per ring)
- Calibrate BPM offset so that the beam passes through the magnetic center of the nearby magnet
- The measurement is carried out in spare moments from vacuum scrubbing.

Benefit from BBA

- Before BBA: Hit hardware limit of corrector strength.
- After BBA: Required corrector strength is remarkably reduced and allows us to further correction.



Beta-Beat before Correction

- Beta and phase functions are extracted from orbit response.

  12 orbit responses are used.(6 per each direction)

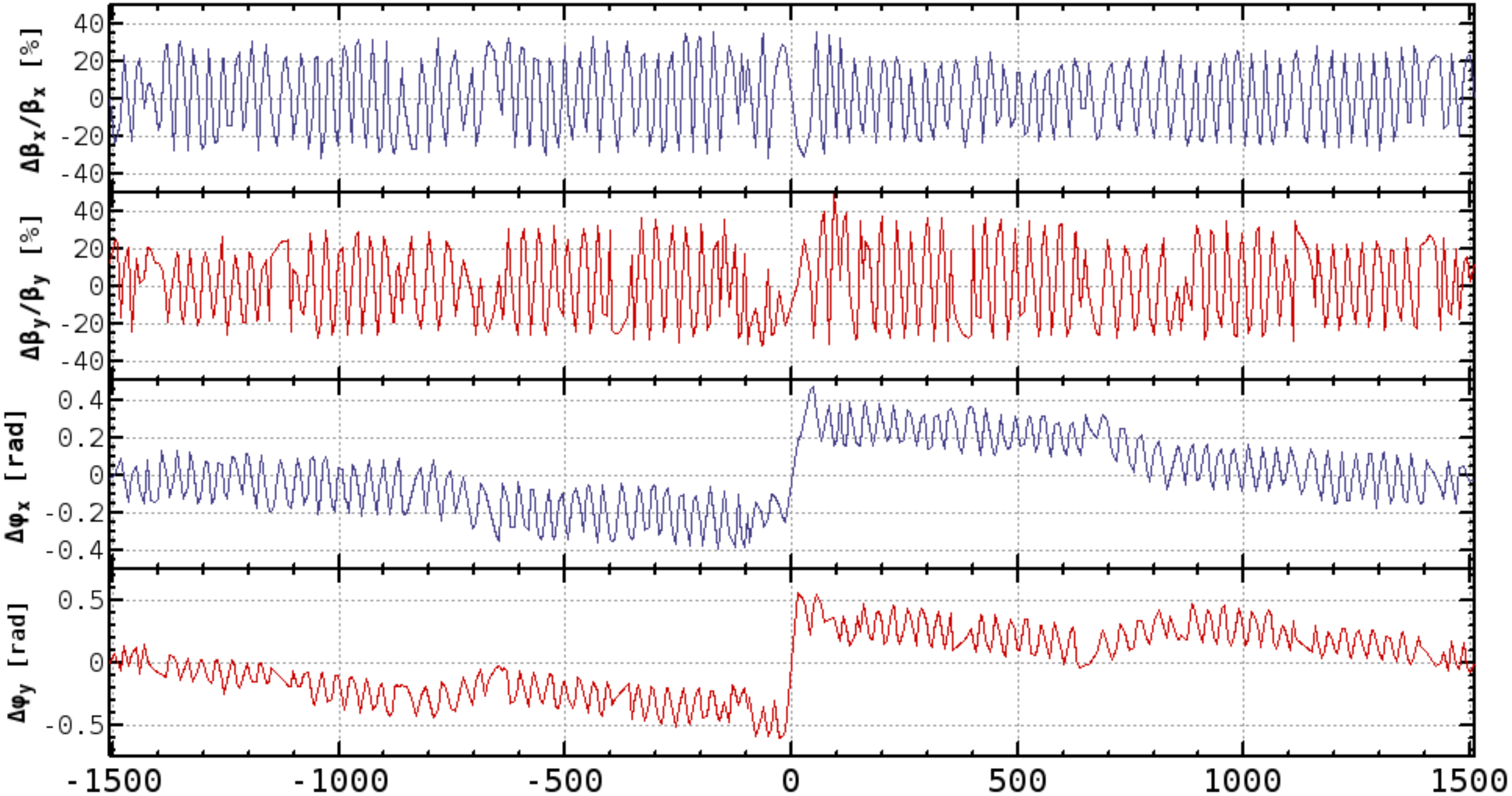
LER

$\Delta\beta_x/\beta_x$ [%]

$\Delta\beta_y/\beta_y$ [%]

$\phi_x^{\text{meas}} - \phi_x^{\text{model}}$ [rad]

$\phi_y^{\text{meas}} - \phi_y^{\text{model}}$ [rad]

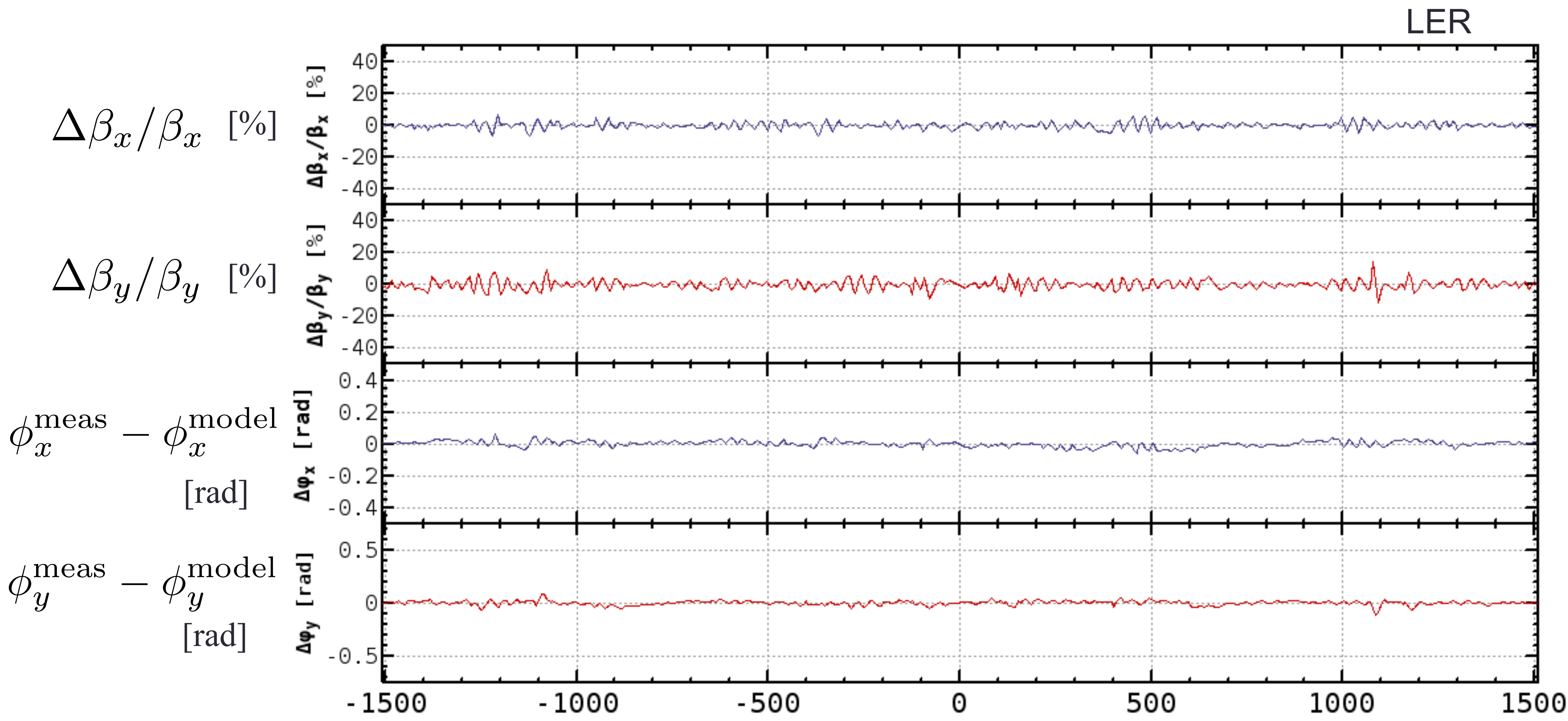


$(\Delta\beta_x/\beta_x)_{\text{rms}} \sim 19.5\ \%$ $\Delta\nu_x \sim -0.074$

$(\Delta\beta_y/\beta_y)_{\text{rms}} \sim 20.5\ \%$ $\Delta\nu_y \sim -0.141$

Beta-Beat after Correction

- Use quadrupole families distributed over the ring.

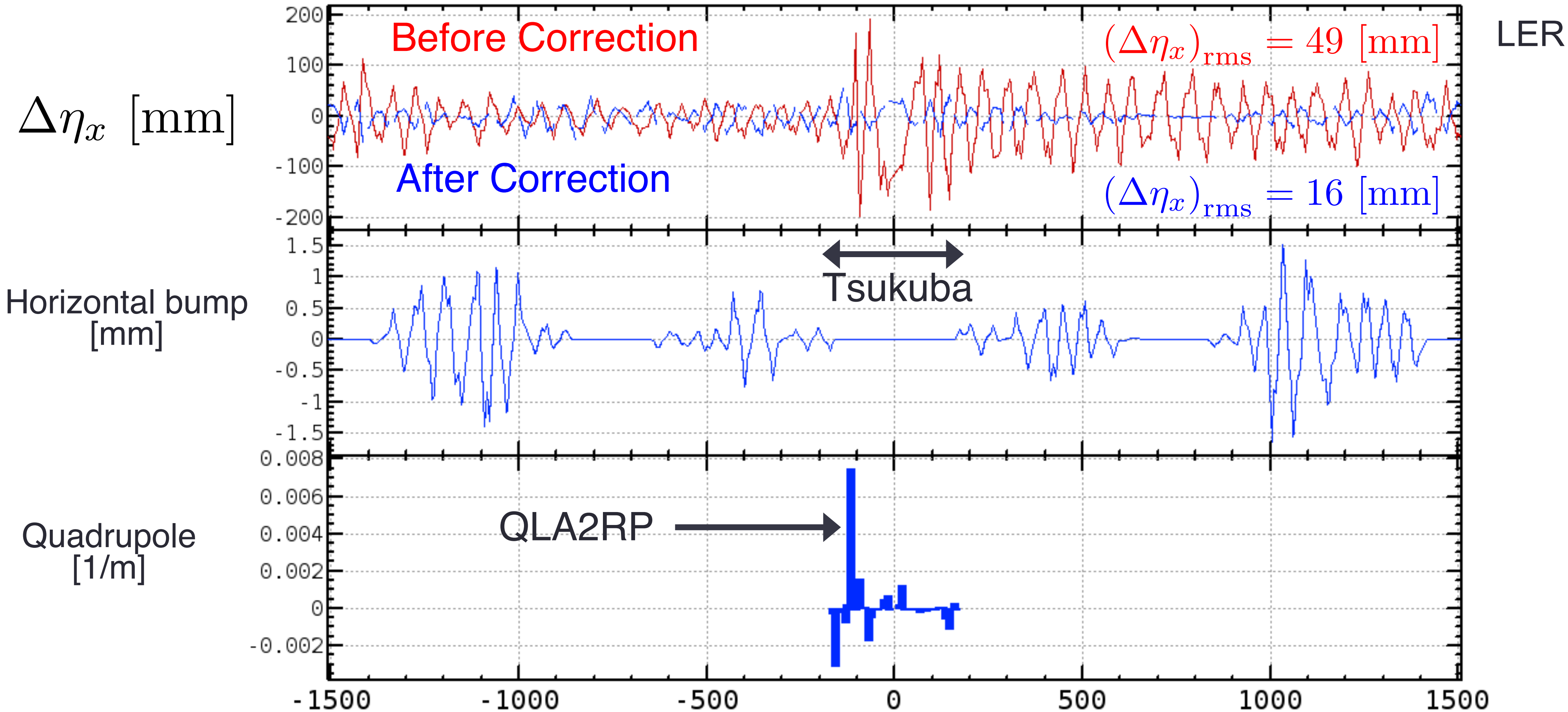


$$(\Delta\beta_x/\beta_x)_{\mathrm{rms}} \sim 2.0\ \% \qquad \Delta\nu_x \sim 0.004$$

$$(\Delta\beta_y/\beta_y)_{\mathrm{rms}} \sim 2.9\ \% \qquad \Delta\nu_y \sim 0.001$$

Horizontal Dispersion

- **Correction with horizontal orbital bumps at sextupoles.**
  Found that uncorrectable dispersion remains.
  The error source seems to be located in the Tsukuba straight section.
- **Quadrupoles in the Tsukuba section is additionally used.**
  A magnet name QLA2RP somehow shows the strongest corrector strength.



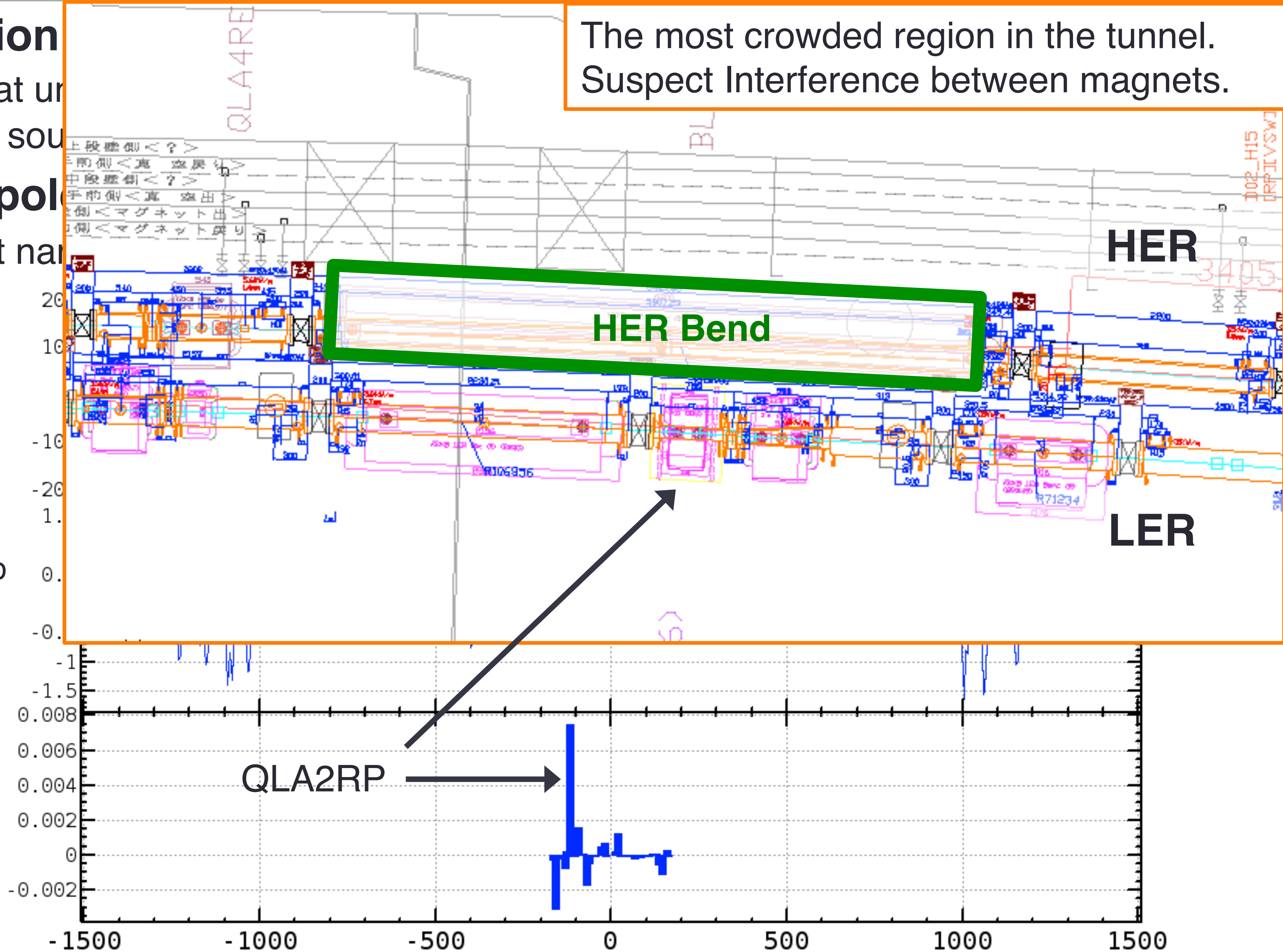
- **Correction**

  Found that ur

  The error sou

- **Quadrupol**

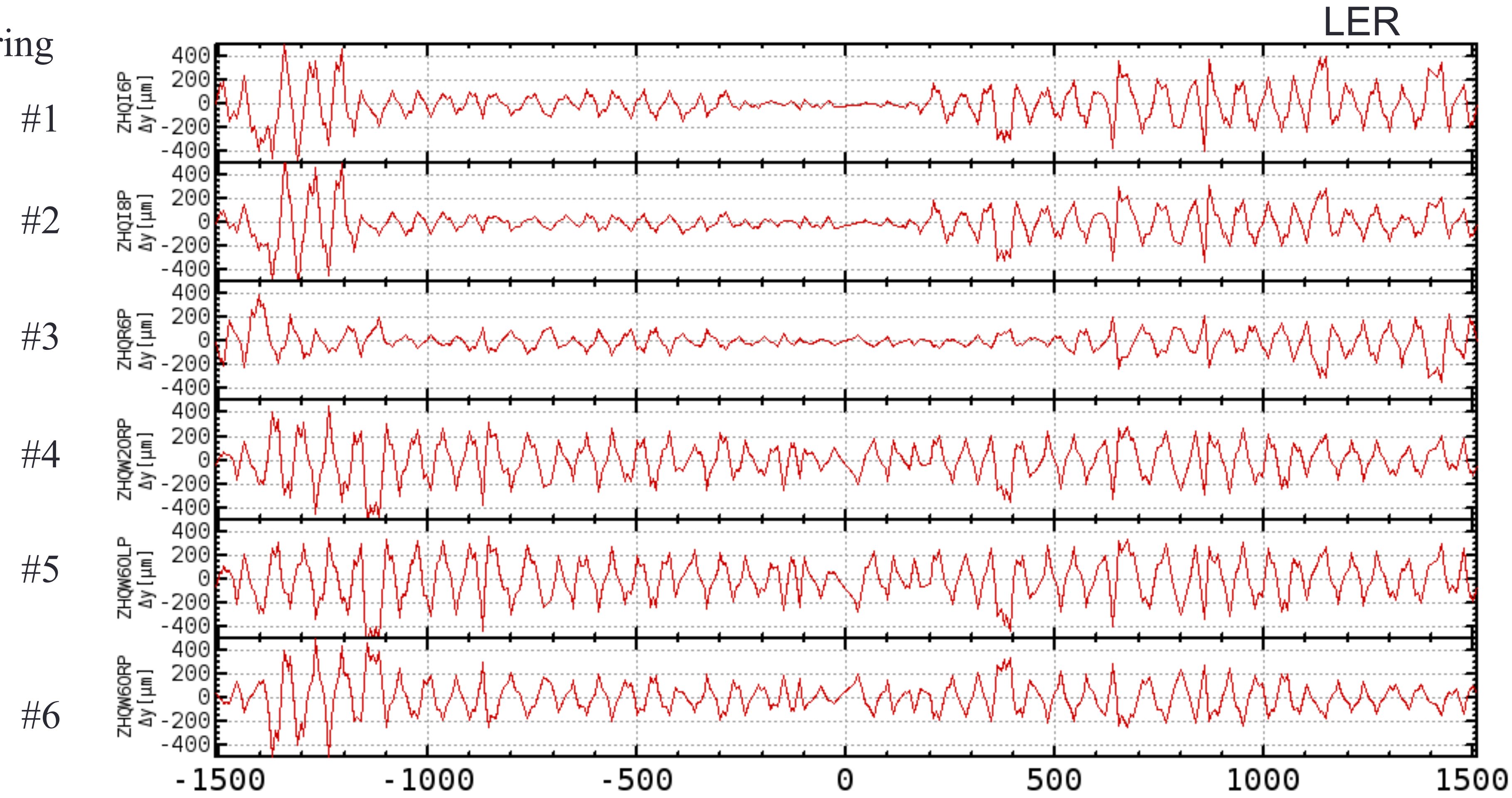
  A magnet nar



XY-Coupling Measurement

- Not so easy to extract optical coupling parameters $R_{1\text{-}4}$ from closed orbit response.
- **Measure vertical leakage orbits induced by 6 steering kicks.**

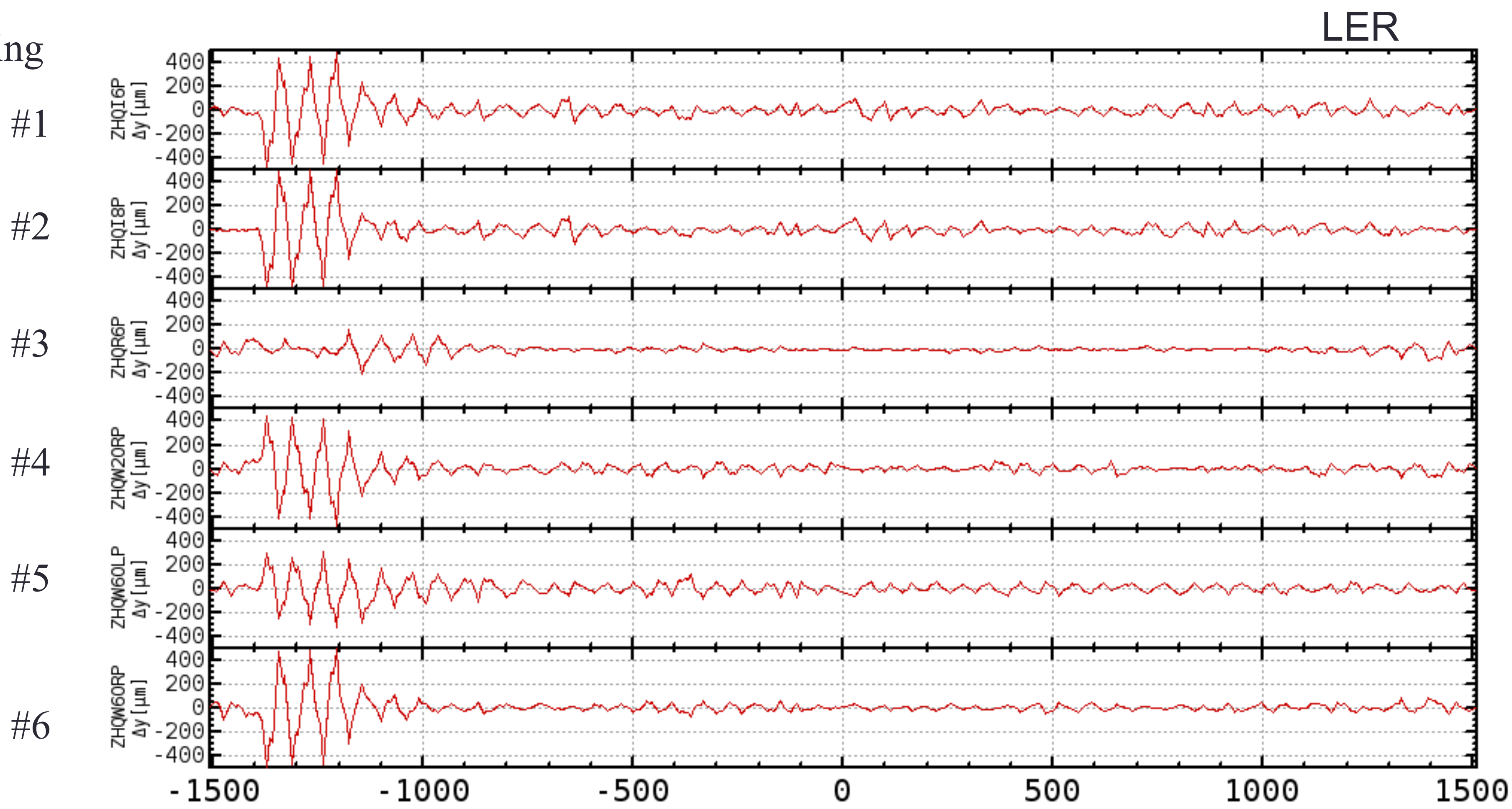
V. orbit by H. steering



XY-Coupling Correction

- Use the orthogonal correctors.
- The presented correction scheme effectively works, but…

V. orbit by H. steering



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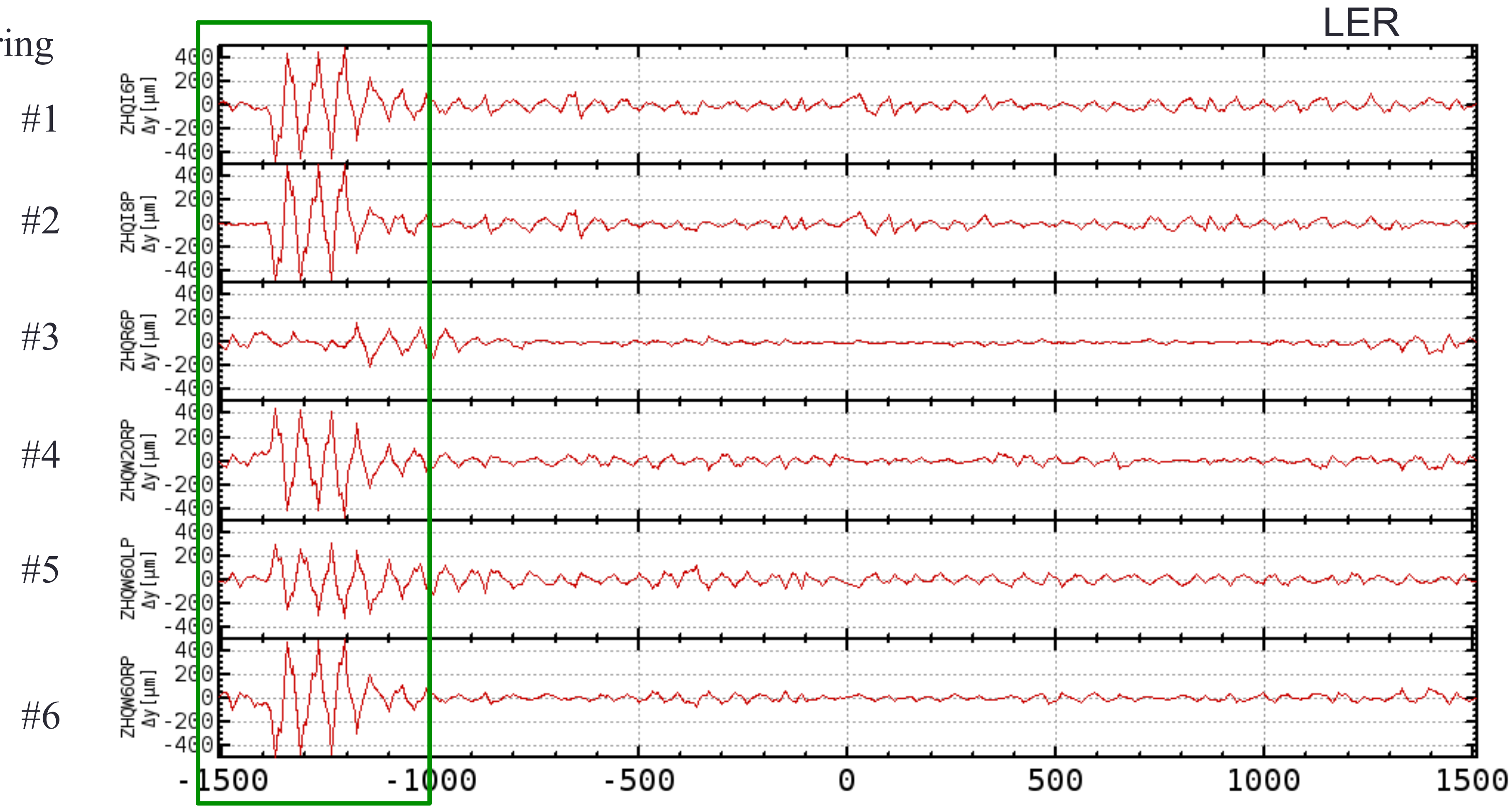
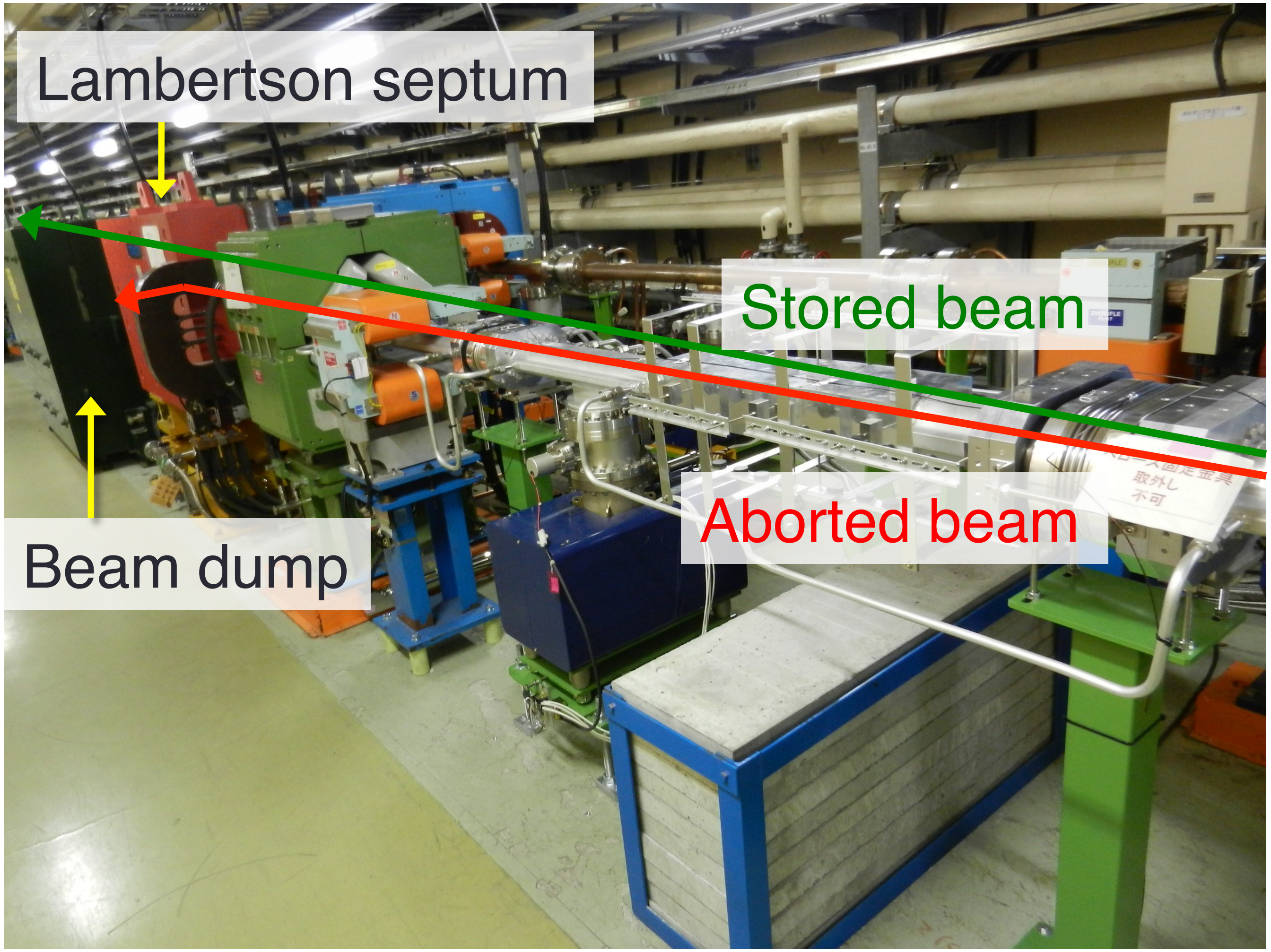


Uncorrectable XY-coupling remains.

Leakage Field from Lambertson Septum

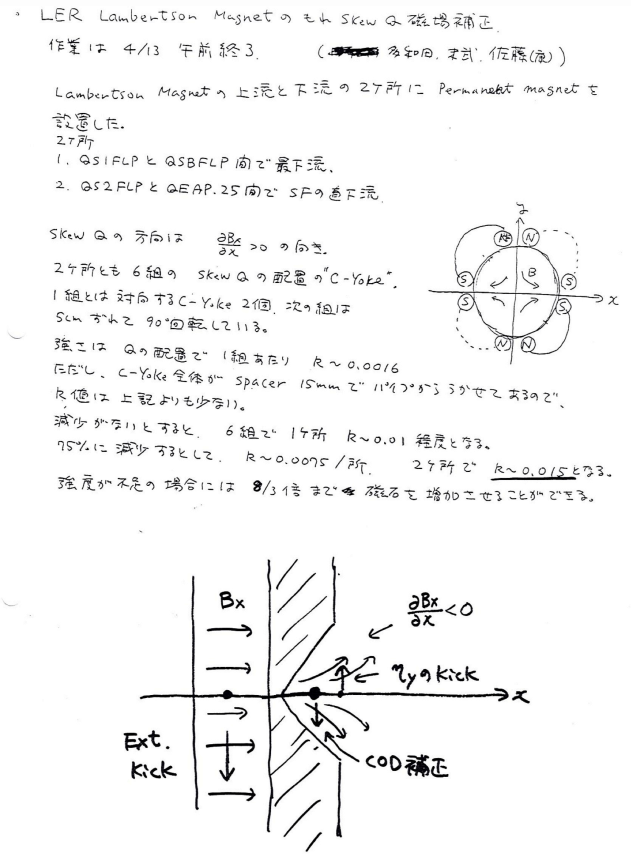
- A Lambertson septum is used to deliver aborted beam to a beam dump.
- This magnet creates unexpected leakage field to stored beam line.



Historical Background

- **The problem was founded at the previous KEKB commissioning already.**
  - They installed permanent magnets to cure this problem (04/2000)
- **The leakage field gets stronger in SuperKEKB.**
  - The vacuum chamber is replaced by an anti-chamber.
  - A magnetic shielding system gets less effective due to clearance problem of the wider aperture. → Mimashi-san's talk?

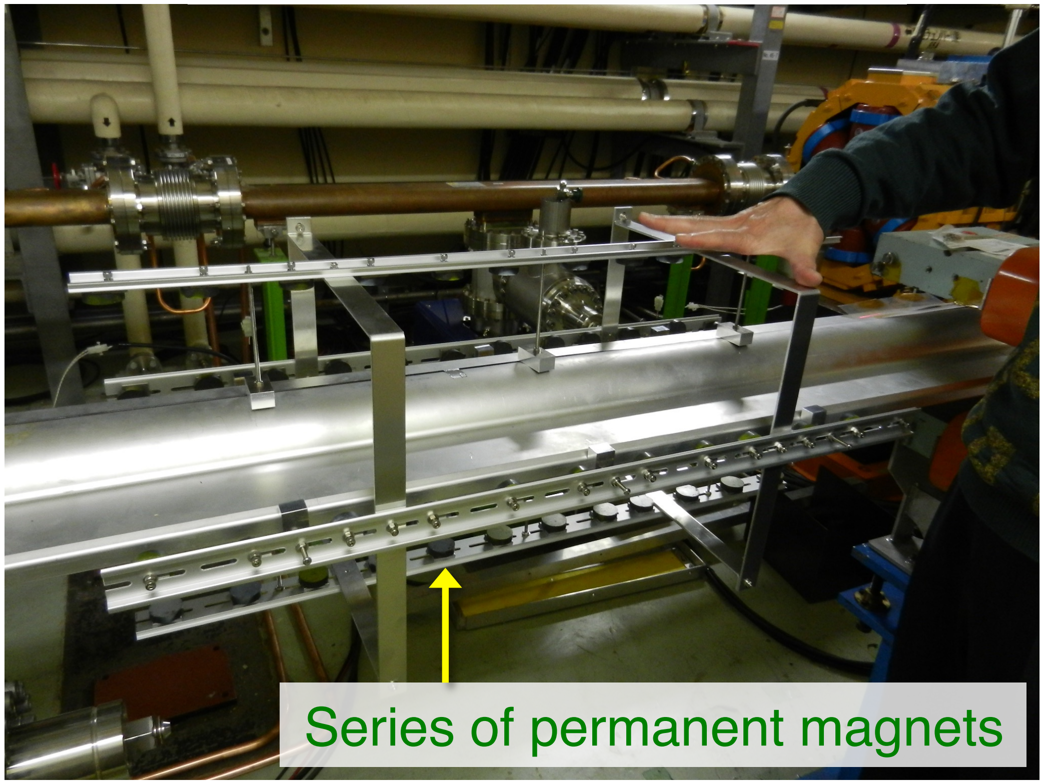
A note from the previous KEKB commissioing


・LER Lambertson Magnetのもれ Skew Q 磁場補正.
作業は 4/13 午前終了. ([redacted] 多和田, 末武, 佐藤(康))

Lambertson Magnetの上流と下流の2ケ所に Permanent magnet を設置した.
2ケ所
1. QS1FLP と QSBFLP 間で最下流.
2. QS2FLP と QEAP.25 間で SFの直下流.

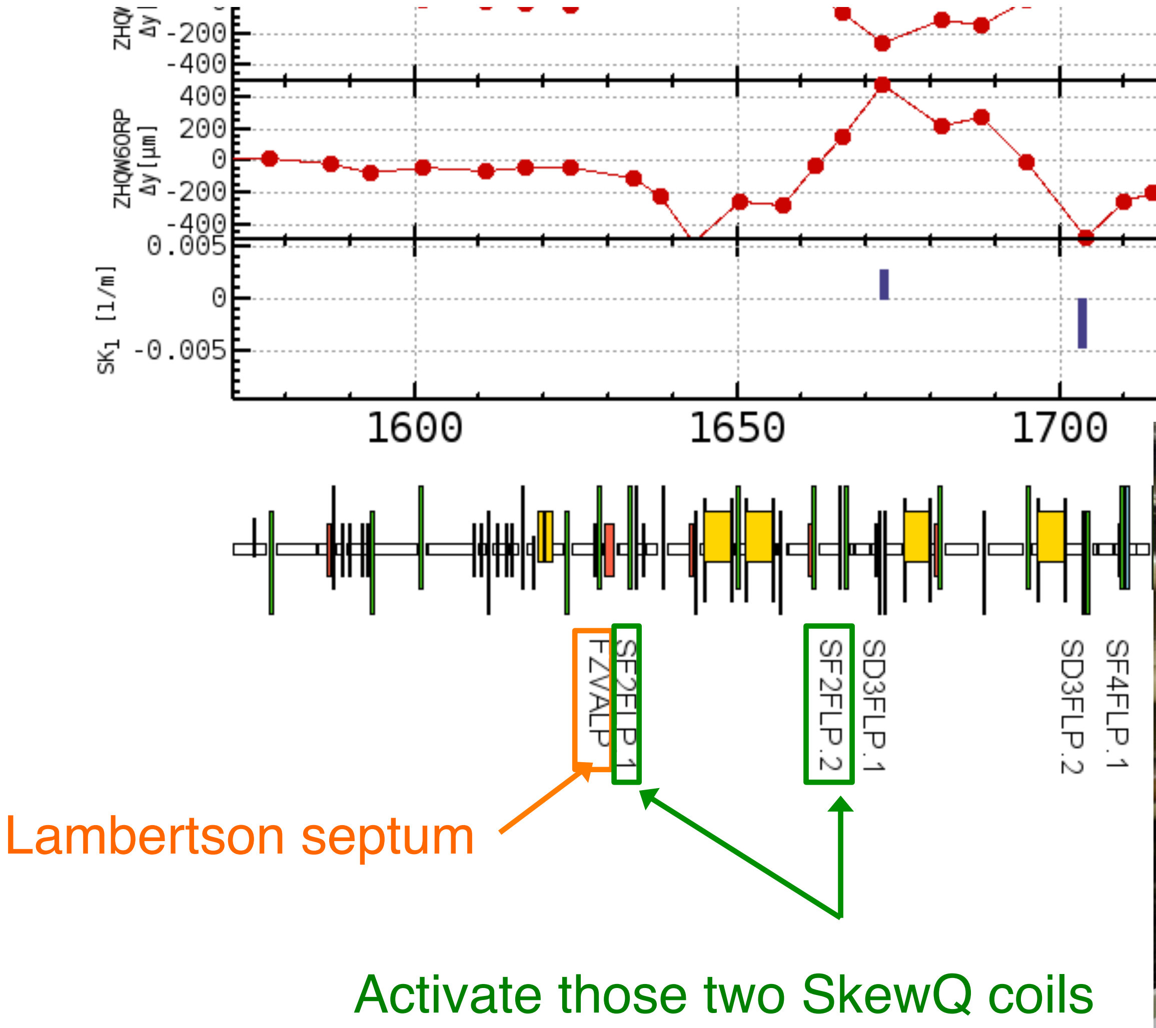
Skew Q の方向は $\frac{\partial B_x}{\partial x} > 0$ の向き.
2ケ所とも 6組の Skew Q の配置の "C-Yoke".
1組とは対向するC-Yoke 2個. 次の組は 5cm ずれて 90°回転している。
強さは Qの配置で 1組あたり k ~ 0.0016
ただし、C-Yoke全体が spacer 15mm でパイプからうかせてあるので、k値は上記よりも少ない。
減少がないとすると、6組で 1ケ所 k~0.01 程度となる。
75%に減少するとして、k~0.0075 / 所. 2ケ所で k~0.015となる。
強度が不足の場合には 8/3倍まで磁石を増加させることができる。

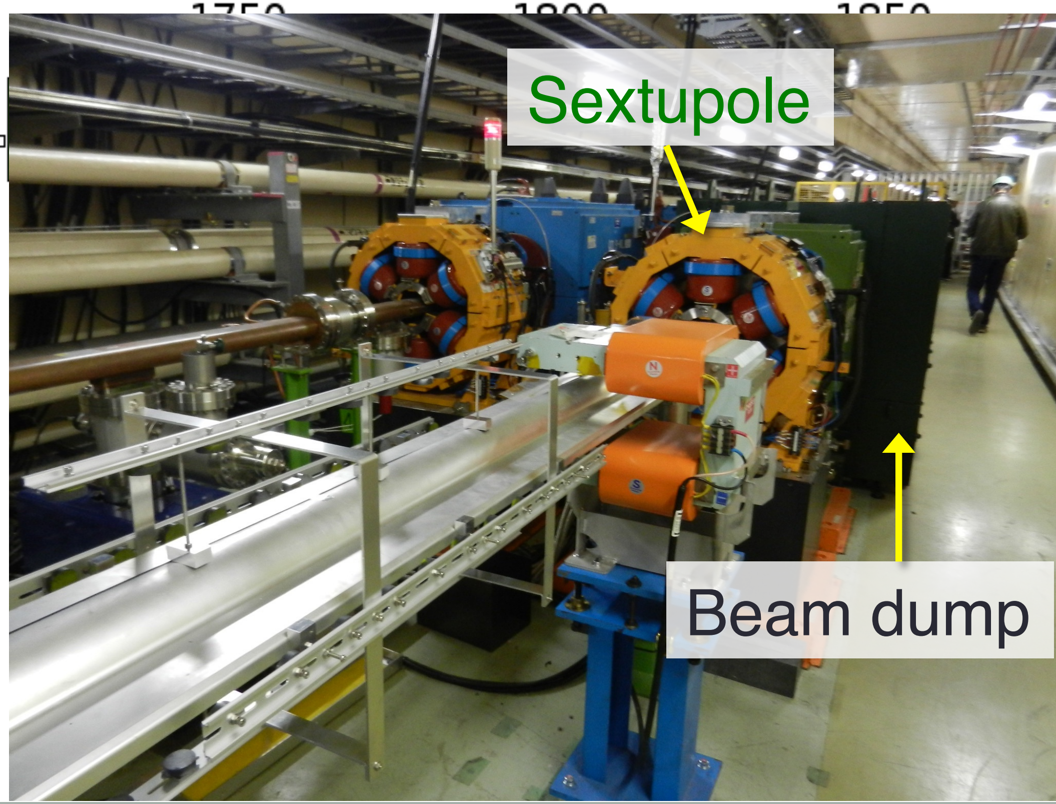
Tunnel survey@03/17/2016



Cure to the Leakage Field

- Activate two SkewQ coils installed in SF magnets using standby PS.

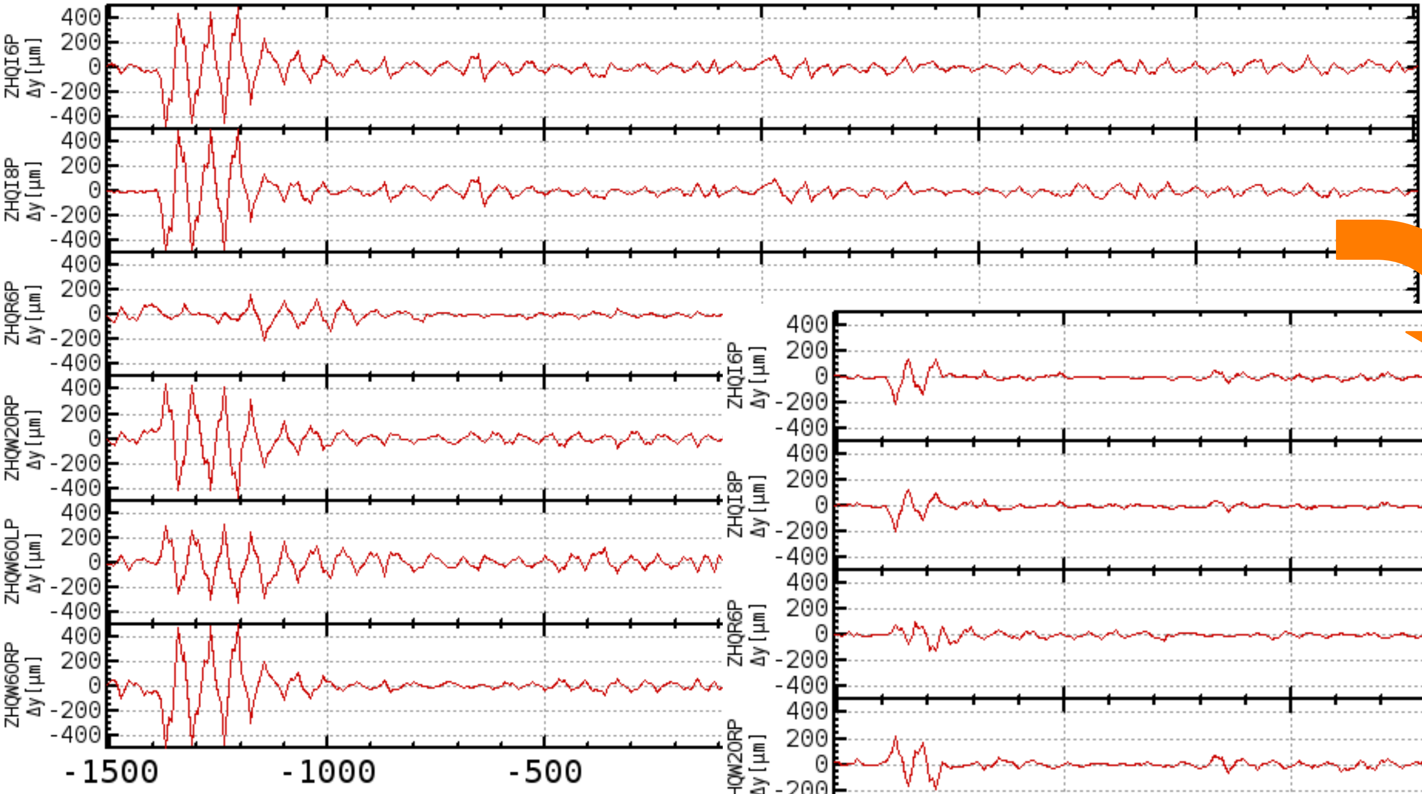




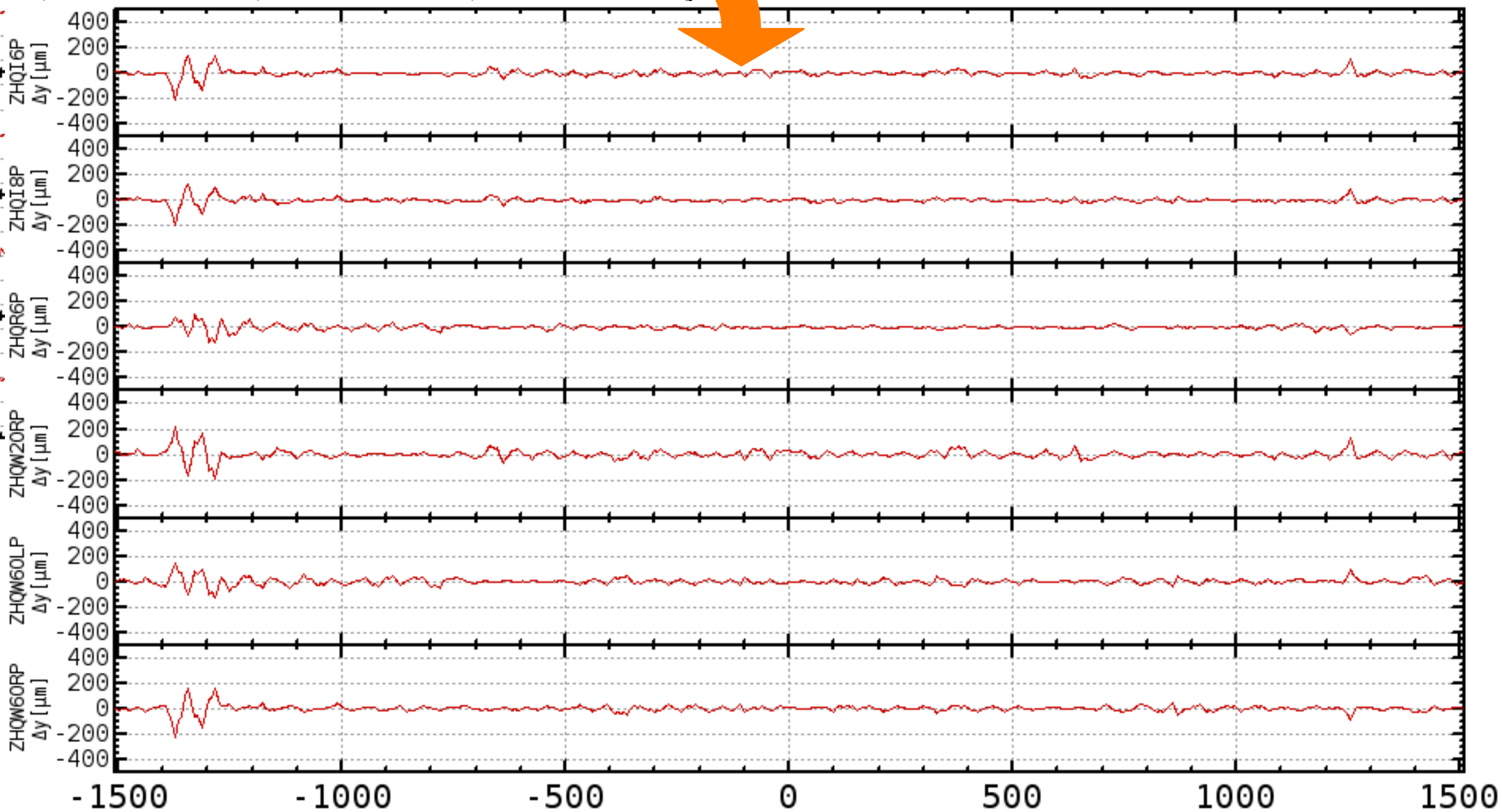
Correction with the Additional SkewQ

- The vertical leakage orbit is reduced.

Before



After

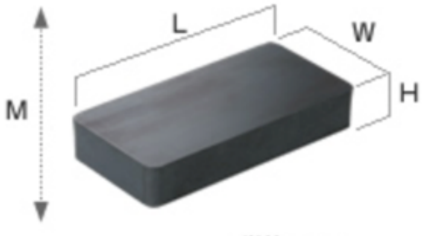


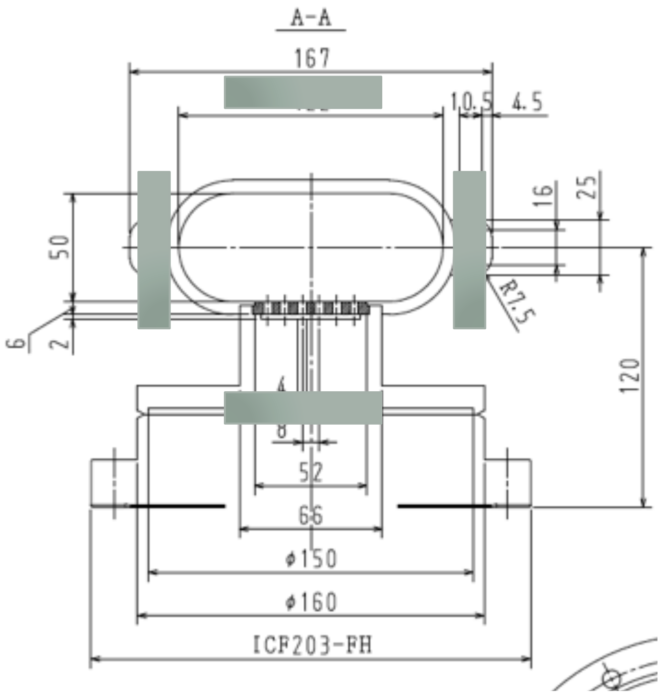
For Further Improvement

- A hardware group proposes a permanent SkewQ using Ferrite magnets.
- Installed it last Wednesday (June 8).

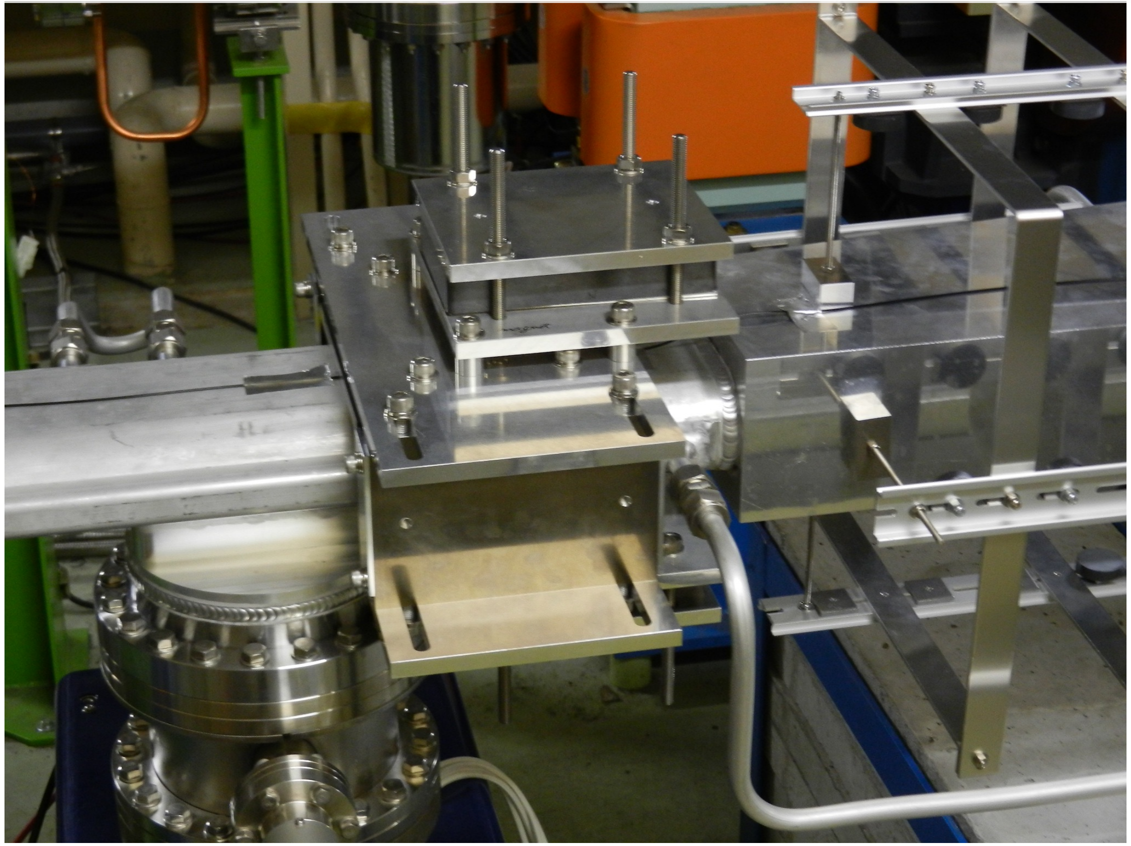
Ferrite magnets

$B \sim 0.07$ [T]





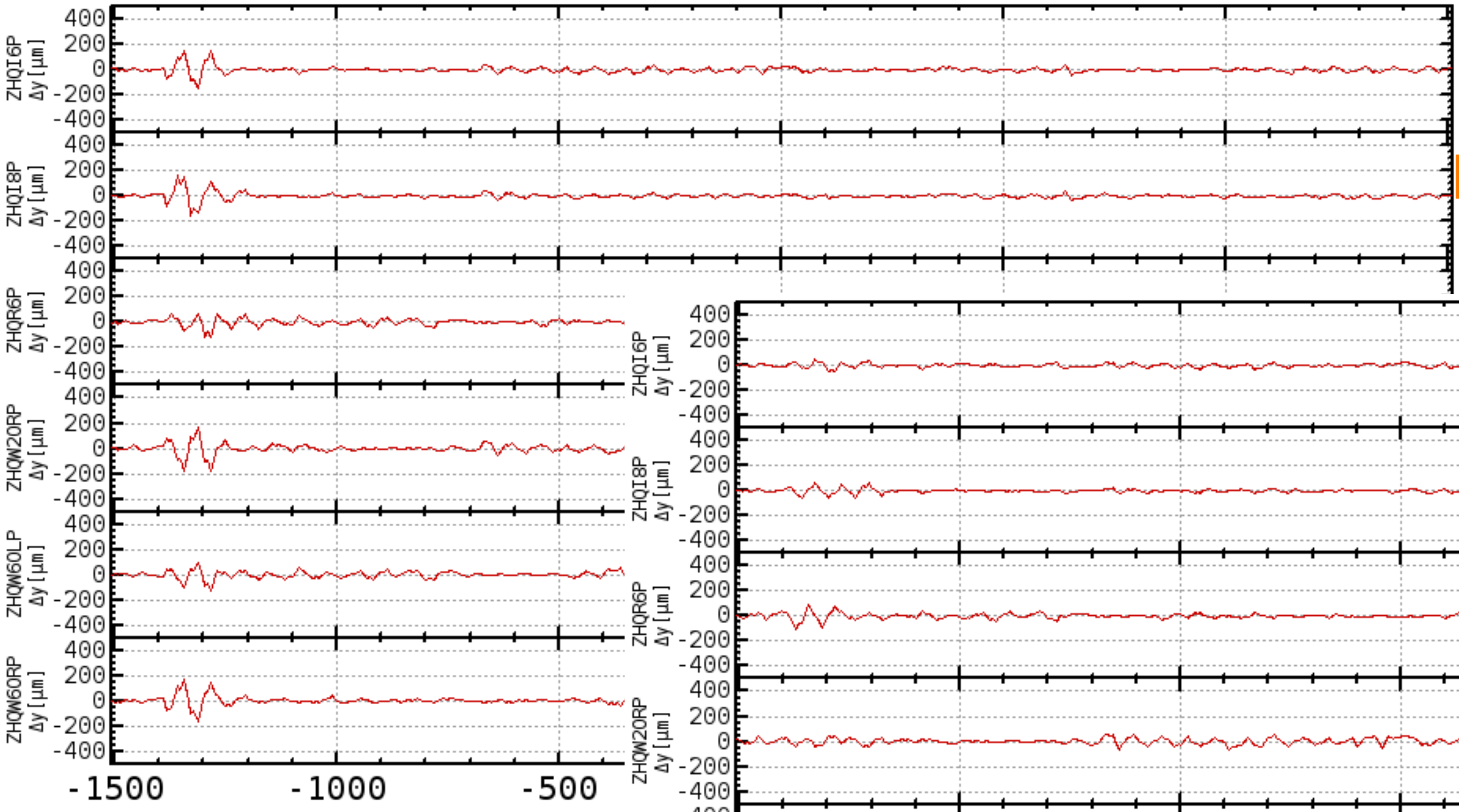
Ferrite magnets installed with supporting system



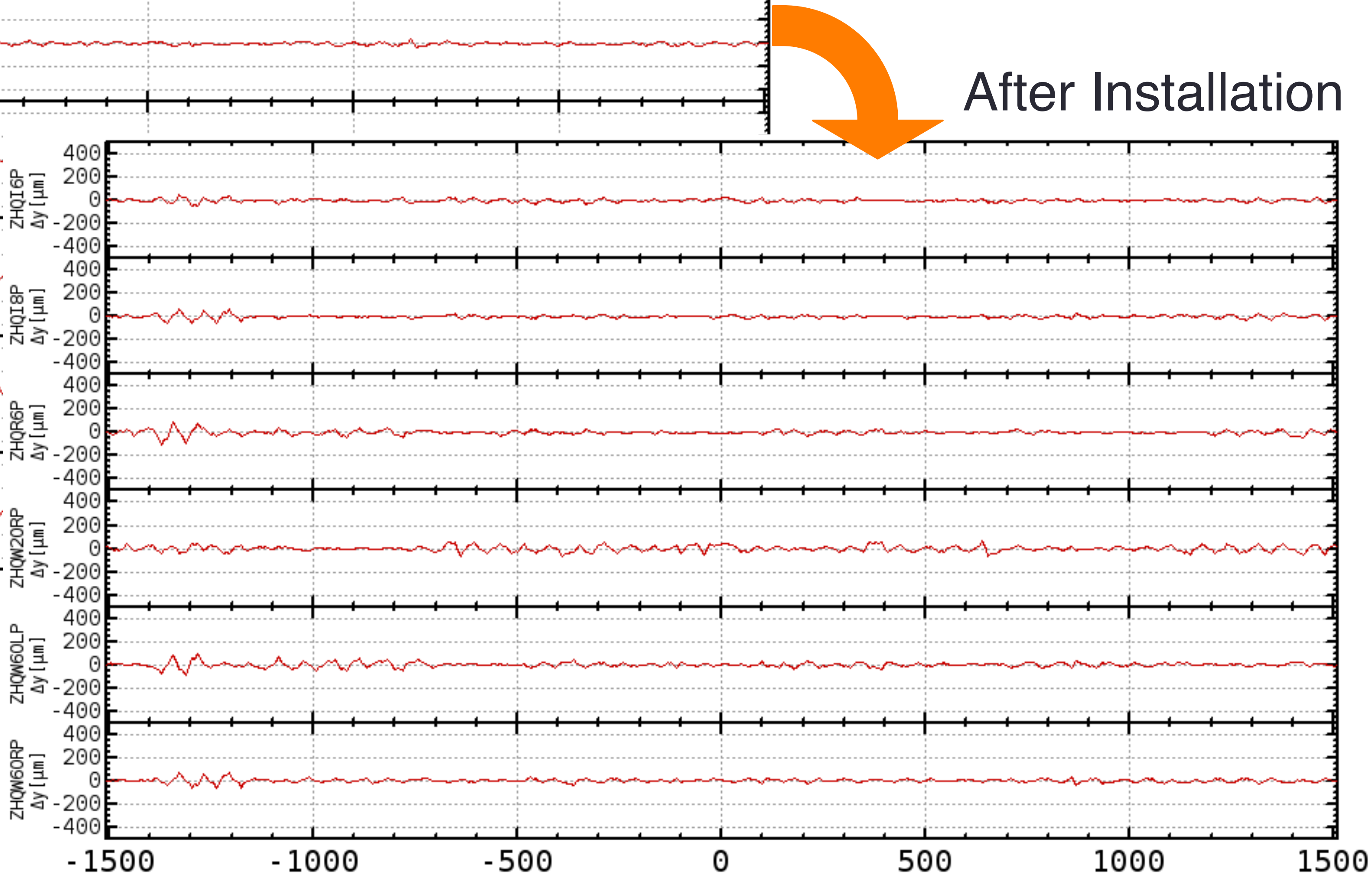
Measurement before&after Installation

- Further improvement in the vertical leakage orbit.

Before Installation

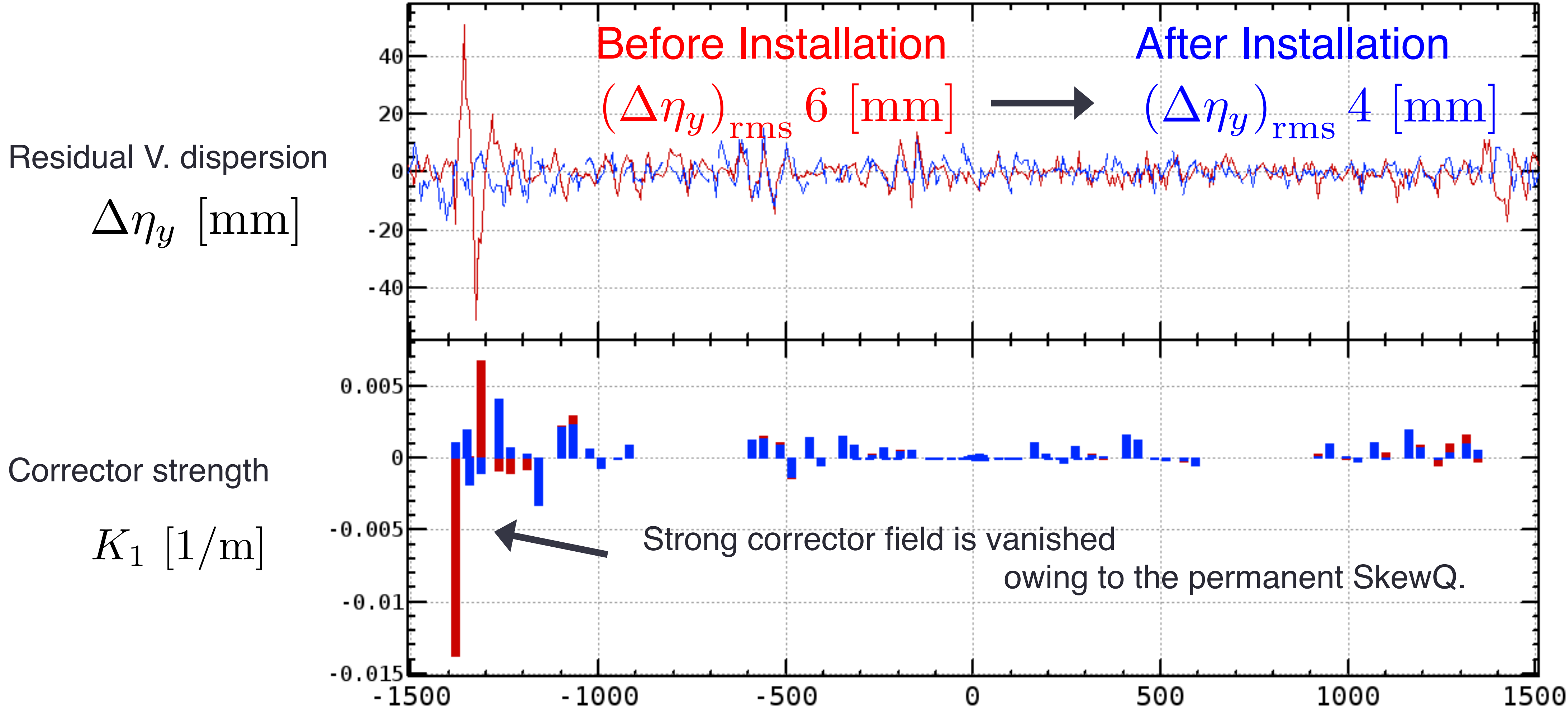


After Installation



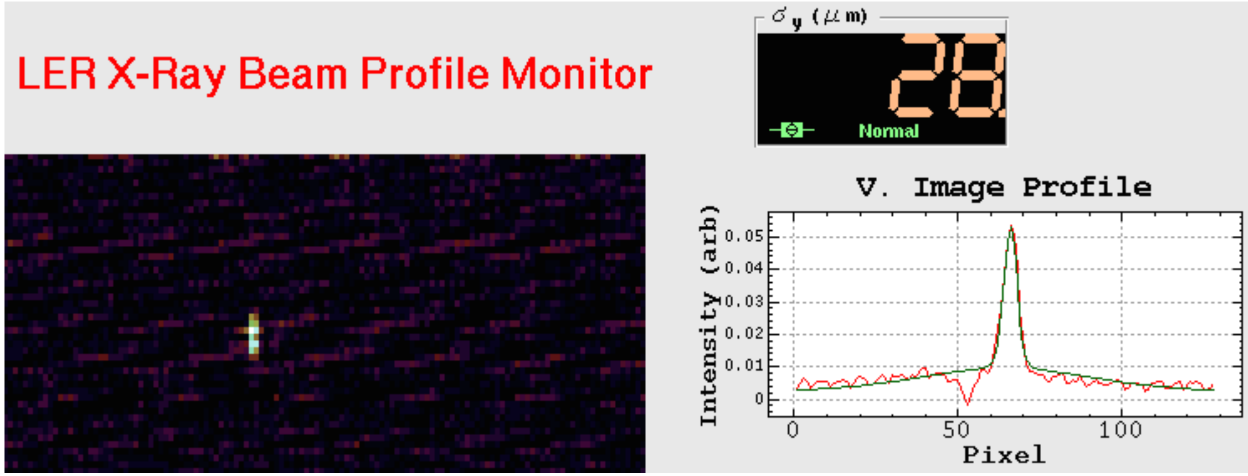
Vertical Dispersion after Installation

- A sharp peak of vertical dispersion is vanished.
- As a result RMS residual is reduced from 6 mm to 4 mm.



Vertical Emittance

LER



$\beta_y = 67\ \mathrm{m}$ → $\varepsilon_y \sim 12\ \mathrm{pm}$

HER

Estimation with beam size measurement

$$\varepsilon_y \sim 120\ \mathrm{pm}$$

→ Flanagan-san's talk?

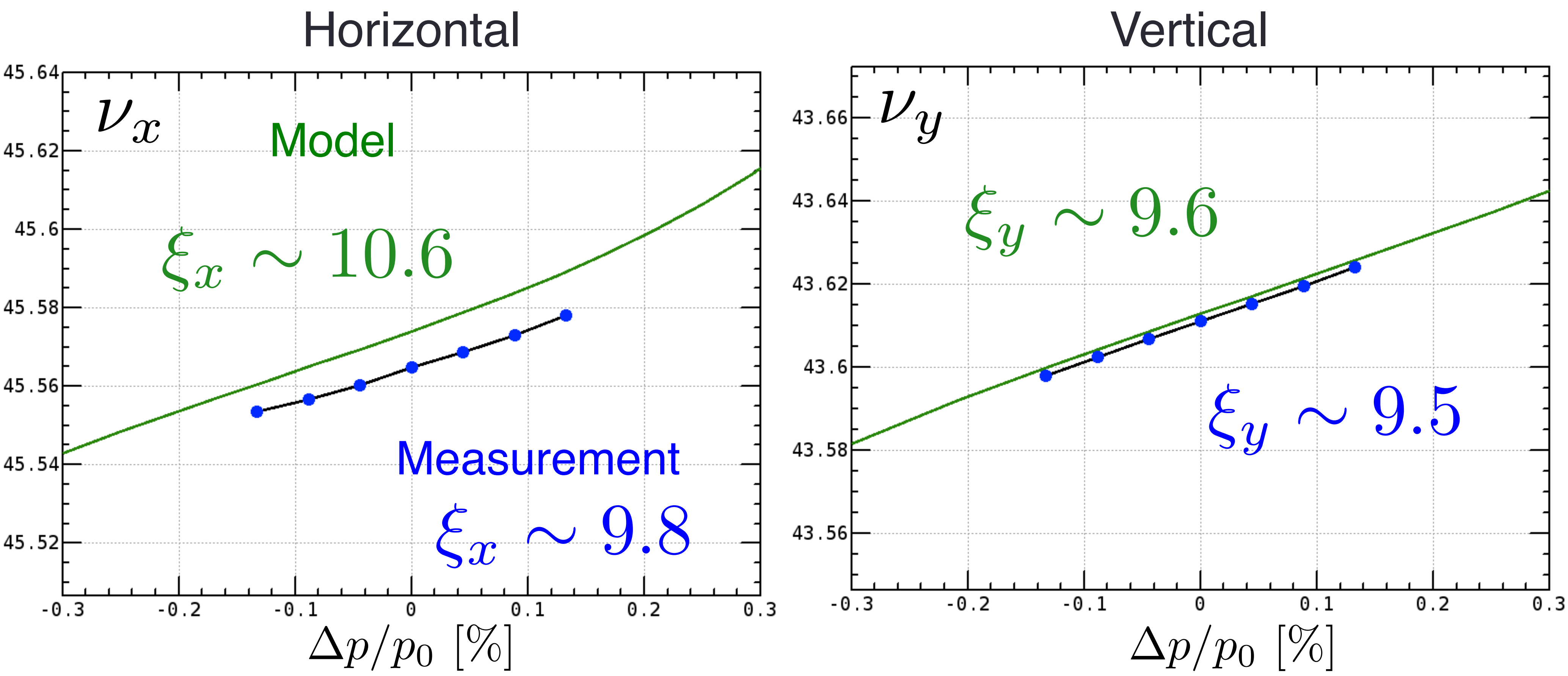
Estimation with measured optics

$$\varepsilon_y \sim 10\ \mathrm{pm}$$

The exact value is still under discussion.

Tune Chromaticity - HER -

- Measure Betatron tune with changing RF frequency.

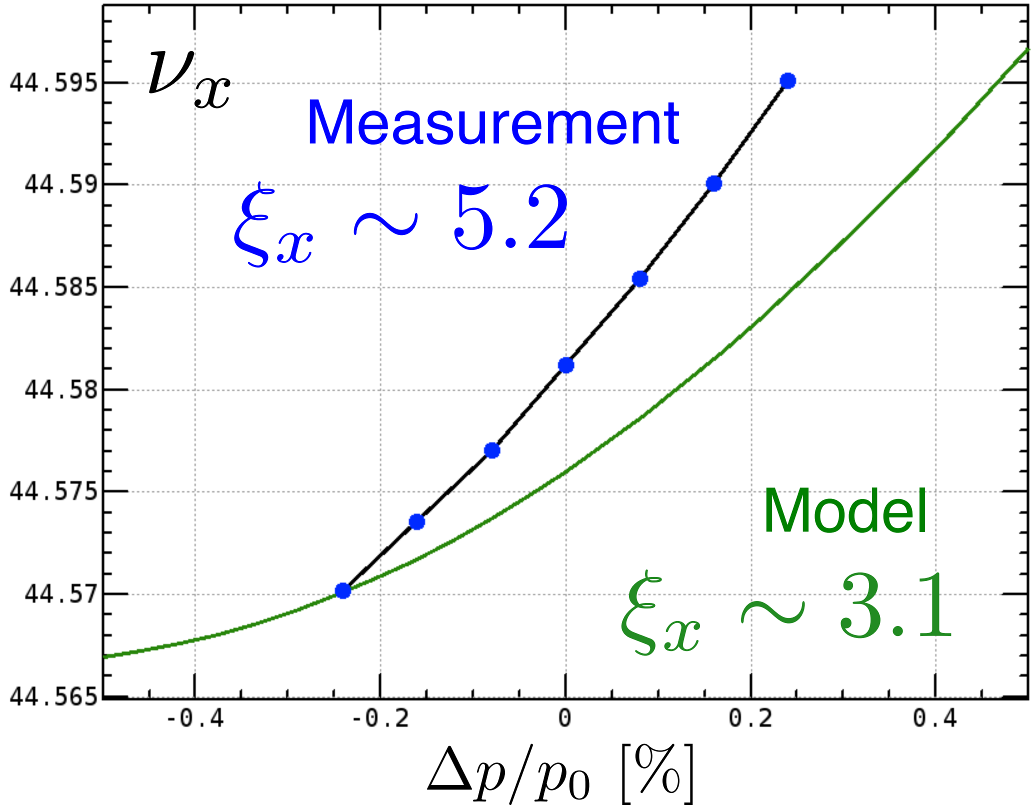


- **Good agreement between the real and model lattice.**

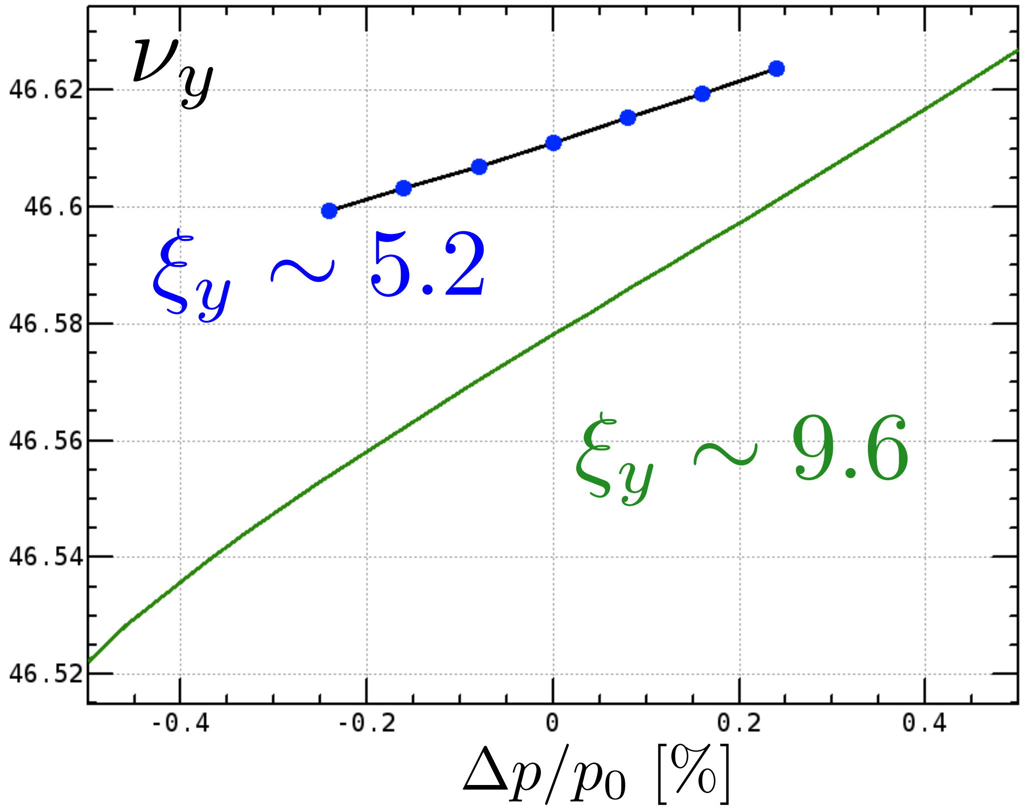
Tune Chromaticity - LER -

- Measure Betatron tune with changing RF frequency.

Horizontal



Vertical



- **Large discrepancy compared with that of HER.**
- Off-momentum beta and phase are measured and analyzed. No big error sources are founded so far.
- Need more study to clarify the source of the discrepancy.

Optics Correction Summary

	LER	HER
$\Delta\beta_x/\beta_x$ / $\Delta\beta_y/\beta_y$ [%]	2 / 3	3 / 4
$\Delta\eta_x$ / $\Delta\eta_y$ [mm]	13 / 4	17 / 5
$\Delta\xi_x$ / $\Delta\xi_y$	2 / -4	< 1 / < 1
ε_y [pm]	~12?	~10?

- Error of the linear chromaticity in LER is still mystery.
- The exact value of vertical emittance is still unknown.

Mission

Establish optics measurement and correction tools.

- Optics and orbit servers to control the magnet system.
- Continuous Closed orbit correction
- Tune Changer
- Optics measurement and correction
- Local-bump control
- etc…

Hardware calibration and bug hunt.

- Polarity check of the magnet using beam measurement.
- Check BPM system (e.g. cabling, aging effect)
- Beam based alignment (BBA)
- etc…

Others

- Check validity of the model lattice and correct the model if needed.

Low emittance tuning (LET)

Target vertical emittance is < 5-10 pm.

Status

Establish optics measurement and correction tools.

- Optics and orbit servers to control the magnet system.
- Continuous Closed orbit correc…
- Tune Changer
- Optics measurement a… …orrection
- Local-bump control
- etc…

Completed

Hardware calibration and bug hunt.

- Polarity check of the magnet usi… …am measurement.
- Check BPM system (e.g. cabli… …ing effect)
- Beam based alignmen… (B…
- etc…

Completed?

Maybe related

Others

- Check validi… …el if needed.

Mystery of tune chromaticity in LER

Low emittance tuning (LET)

Reached ~10pm?, the exact value is still under discussion.

Thank you for listening

Machine Parameters in Phase I

	LER	HER	Units
Beam energy	4.000	7.007	GeV
Beam current	910	830	mA
# of bunches	1576	1576	
Bunch current	0.58	0.52	mA
Hor. emittance	1.8	4.6	
Momentum compaction	2.45×10^{-4}	4.44×10^{-4}	
Energy spread	7.5×10^{-4}	6.3×10^{-4}	
Total V_c	7.56	12.45	MV
Bunch length	4.6	5.3	mm
ν_s	-0.019	-0.025	
Tune ν_x/ν_y	44.59/44.63	45.57/43.61	
U_0	1.76	2.43	
$\tau_{x,y}/\tau_x$	46/23	58/29	

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	$8.10(7.73)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():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}		$cm^{-2}s^{-1}$	