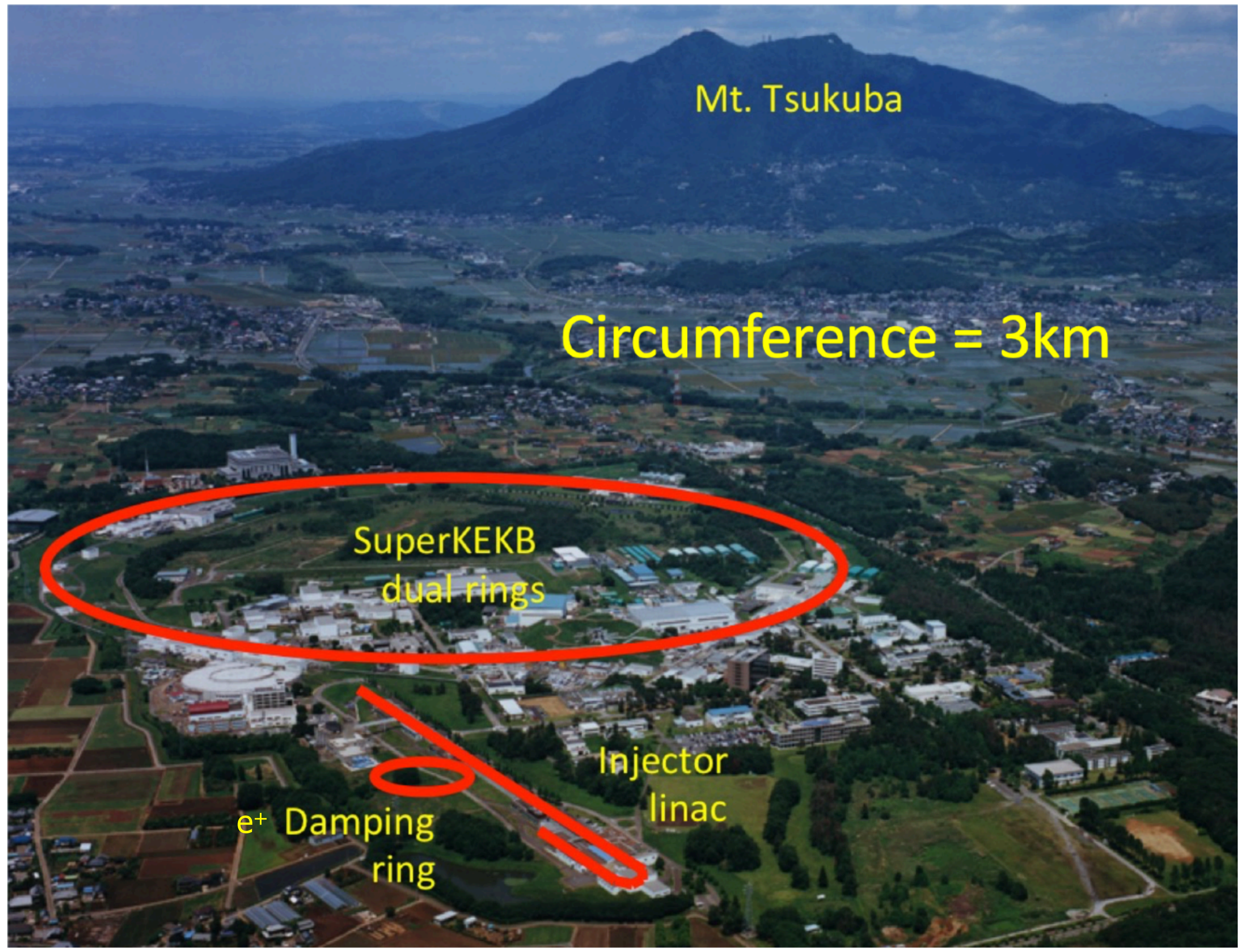
SuperKEKB Status Report And Emittance Issue

Y. Ohnishi (KEK)

10th Low Emittance Rings Workshop 2025
October 8-10. 2025
DESY



e^+e^- Double Ring Collider

4 GeV e^+ x 7 GeV e^-

LER HER

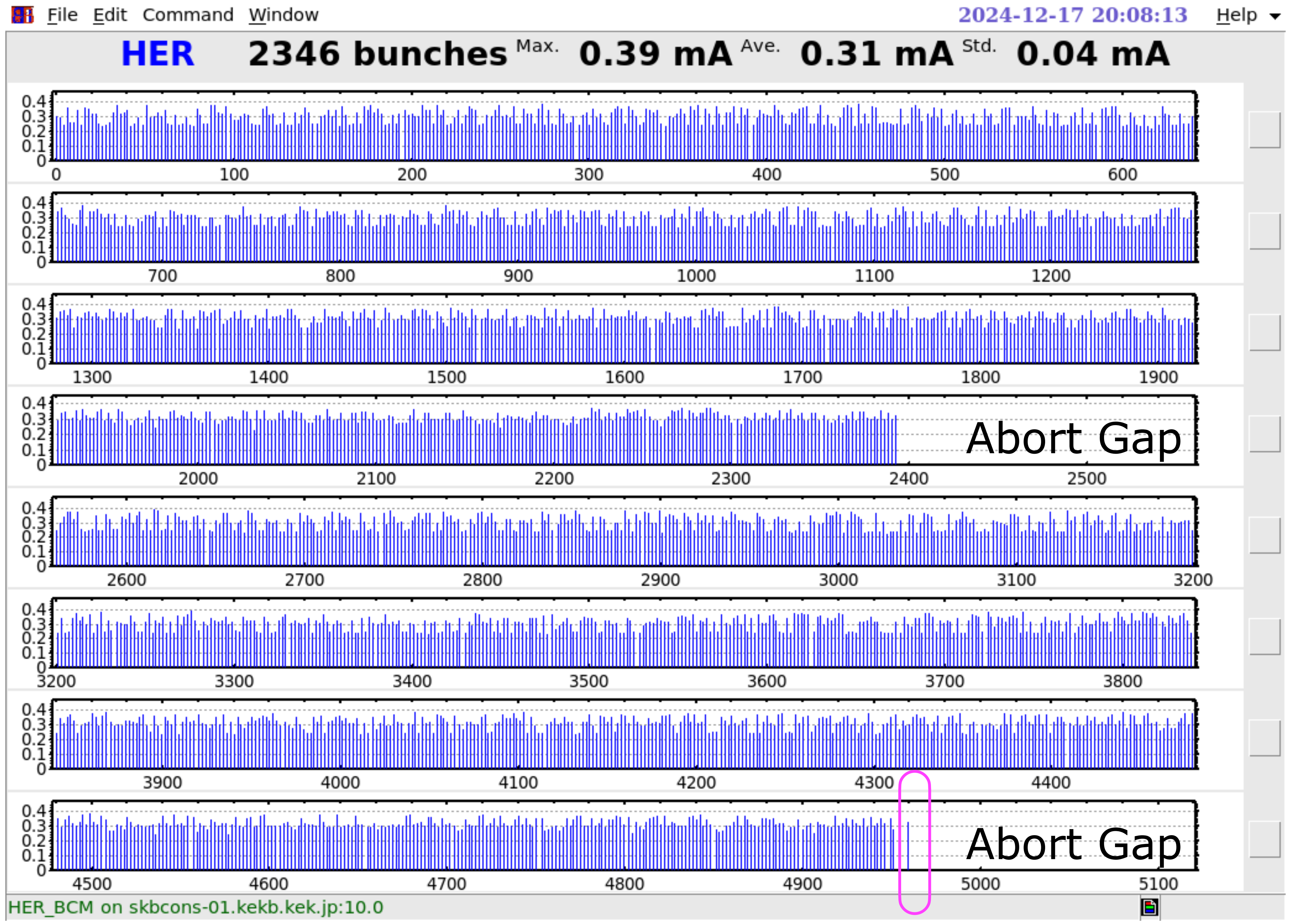
Crossing Angle: 83 mrad

Number of Bunches: 2346

Harmonic Number: 5012

Off-Axis Top-Up Injection

2346 Bunches , Two Trains



Pilot Bunch
(Non Collision)

Used for Tune Feedback

Pilot Bunch
(Non Collision)

Used for Tune Feedback

Achievements in 2024

	LER	HER
Beam Current	1.7 A	1.3 A
Emittance	4.0 nm	4.6 nm
Hor./Ver. Beta (IP)	60 mm / 1 mm	
Ver. Beam Size (IP)	265 nm*	
Beam-Beam (ξ_y)	0.036	0.027
Luminosity	5.1×10^{34} cm^{-2}s^{-1}	

Highest Luminosity in the World

* Estimated by luminosity and equal size between LER and HER is assumed.


SuperKEKB Operation History
Crab Waist
$\beta_y^* = 1\ mm$
$\beta_y^* = 3\ mm$
$\beta_y^* = 2\ mm$
$\beta_y^* = 0.8\ mm$
$\beta_y^* = 0.8\ mm$
Electron Beam (7 GeV)
I (mA) in HER
1.3 A
Positron Beam (4 GeV)
I (mA) in LER
1.7 A
New Record !
Peak Luminosity
L ×10^{34} ($cm^{-2}s^{-1}$)
5.1 x 10^{34} $cm^{-2}s^{-1}$
Long Shutdown LS1
Int. Luminosity
int. L (fb^{-1})
delivered
recorded
01/01
2019
2020
2021
2022
2023
2024

$$L = \frac{N_+ N_- n_b f_0}{2\pi\sqrt{\sigma_{x+}^{*2} + \sigma_{x-}^{*2}}\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}} R_L$$

Geometrical Loss
Hourglass Effect, Crossing Angle.

In the flat beam, σ_y^* = **30 - 50 nm** is a target. → β_y^* **< 1 mm and** ε_y **< 10 pm**

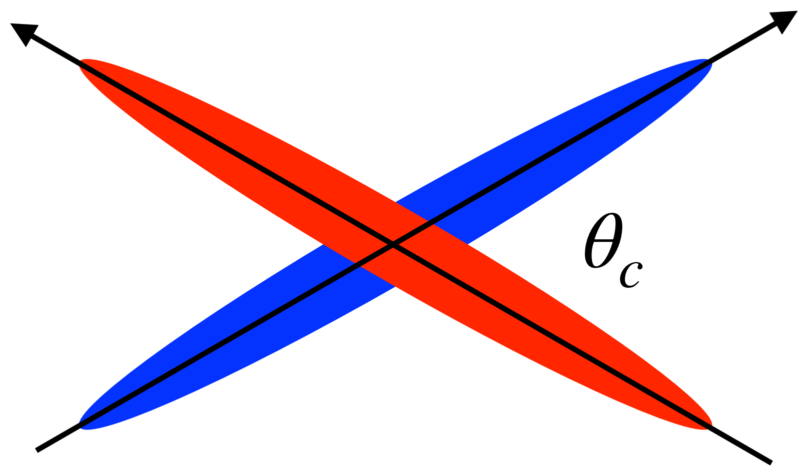
Overcoming **Hourglass Effect** to squeeze β_y^* **"Depth of Focus"**

$$\beta_y^* > \frac{\sigma_z}{\sqrt{1+\Phi^2}} \qquad \Phi = \frac{\sigma_z}{\sigma_x^*}\tan\frac{\theta_c}{2}$$

Difficult to make σ_z shorter
← **Creating a Large Piwinski Angle to Make Short "Bunch" Effectively**

Large Crossing Angle with Low Emittance = **Nano-Beam Scheme**

$$R_L = \left(1 + \frac{\sigma_{z+}^2 + \sigma_{z-}^2}{\sigma_{x+}^{*2} + \sigma_{x-}^{*2}}\tan^2\frac{\theta_c}{2}\right)^{-\frac{1}{2}} R_H$$



$$L = \frac{N_+ N_- n_b f_0}{\pi\theta_c\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

DAΦNE: Φ = 1.7
SuperKEKB: Φ = 12.3 / 12.7

Luminosity Challenge (cont'd)

$$L = \frac{N_+ N_- n_b f_0}{\pi \theta_c \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

$$\xi_{y\pm} = \frac{r_e}{\pi \gamma_\pm} \frac{\beta_{y\pm}^* N_\mp}{\theta_c \sigma_{z\mp} \sigma_{y\mp}^*} \propto N_\mp \sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}$$

Beam-Beam Parameter

Ratio of β_y^* to ε_y

Vertical Beam Size at the IP

$$\sigma_y^{*2} = \mu^2 \varepsilon_y \beta_y^* + \underbrace{(\eta_y^* \sigma_\delta)^2}_{} + \underbrace{\varepsilon_x \frac{(r_2^*)^2}{\beta_x^*} + \varepsilon_x \beta_x^* (r_1^*)^2}_{}$$

$\mu \simeq 1$ Waist position is adjusted.

Vertical Dispersion X-Y Couplings ← Machine Imperfection

Vertical Emittance

Combined Effect of Collimator Impedance and BxB Feedback Noise → -1 Mode Instability
Optics Distortion due to Machine Imperfection

Beam-Beam Blowup

Betatron Resonance affects beam size. ← **Crab Waist Scheme can mitigate.**
Combined Effect of Lattice Nonlinear, Beam-Beam, and Wakefield

Definition of X-Y Coupling

* Time-Dependent Dispersions = 0
(No Dispersions at RF Cavities)

Normal Coordinate Physical Coordinate

$$\begin{pmatrix} X \\ P_X \\ Y \\ P_Y \end{pmatrix} = U \left\{ \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} - \begin{pmatrix} \eta_x \\ \eta_{px} \\ \eta_y \\ \eta_{py} \end{pmatrix} \delta \right\}$$

Physical Dispersions

$$U = \begin{pmatrix} \mu I & J R^T J \\ R & \mu I \end{pmatrix} \qquad R = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} \qquad J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

in case $\det R < 1$

$$\mu^2 + \det R = 1$$

X-Y Coupling Parameters

Transfer Matrix From s_1 To s_2

$$M_{21} = U_2^{-1} \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} U_1$$

Twiss Parameters and Emittance Are Defined in the Normal Coordinate.
Effective Emittance, $\sigma_{x,y}^2/\beta_{x,y}$ Is Sometimes Used To Evaluate Machine Performance.

R. T. Garcia et al., arXiv.2506.12361

Vertical Beam Size at IP

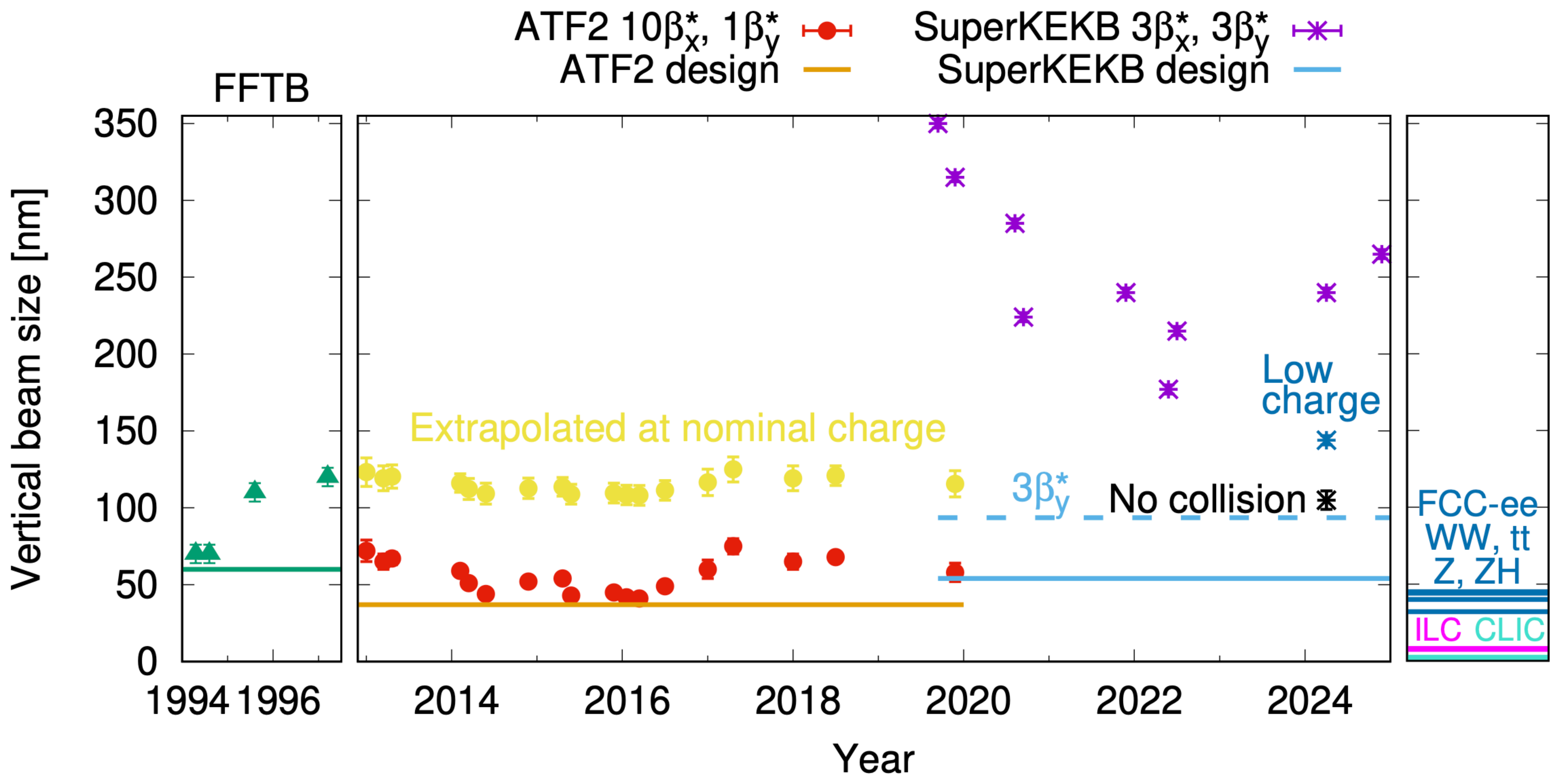


Figure 1: Design, measured or extrapolated vertical beam size versus time for FFTB (green), ATF2 (orange, red and yellow), SuperKEKB (blue, violet and black), FCC–ee (dark blue), ILC (magenta) and CLIC (turquoise).

SuperKEKB No Collision: X-Ray Beam Size Monitor
SuperKEKB Collision: Estimated From Luminosity

Normalized Effective Vertical Emittance

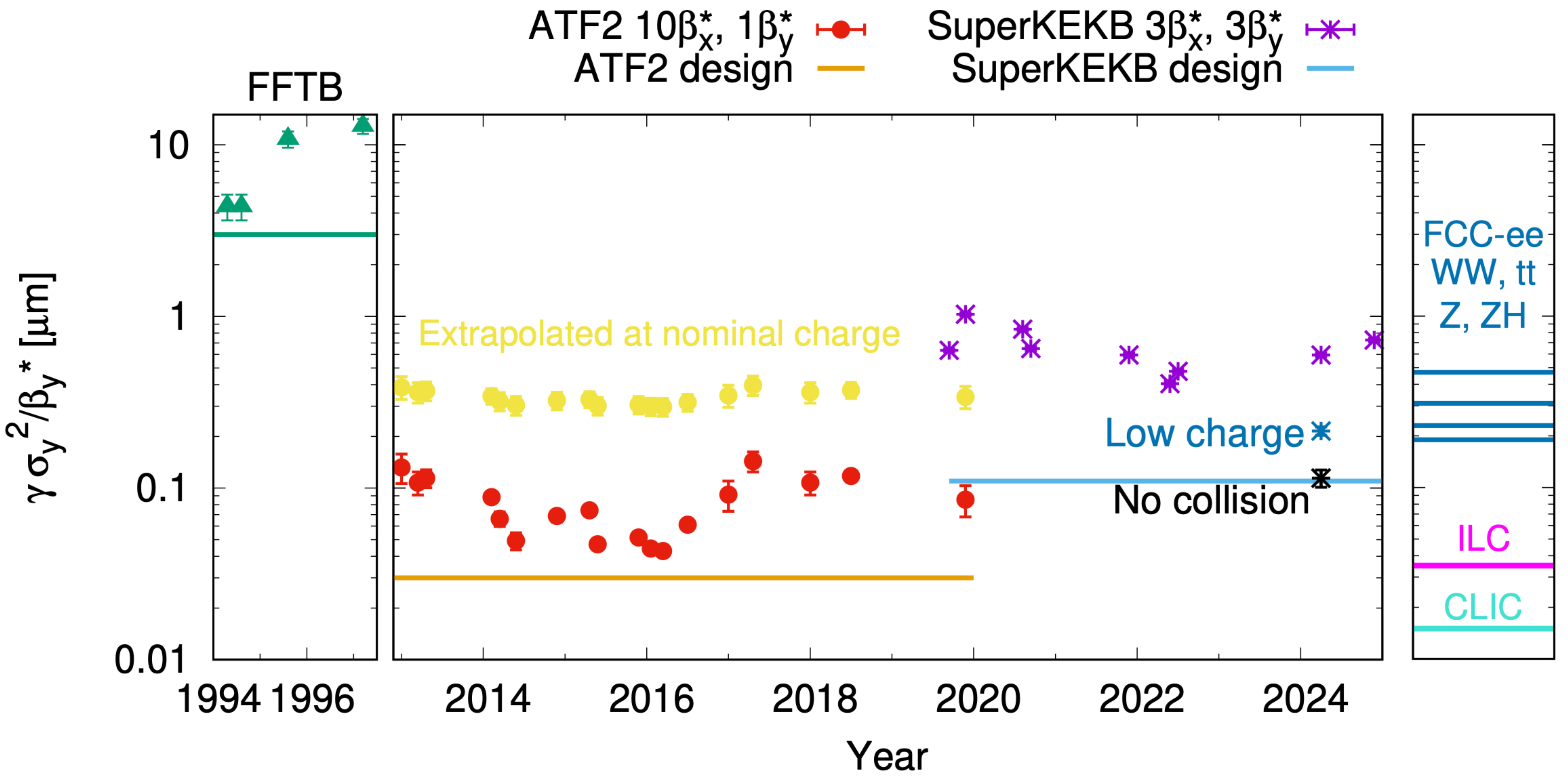


Figure 3: Effective normalized vertical emittance at the IP as measured from the beam size versus time. The projects and the color code are the same as in Figs. 1 and 2.

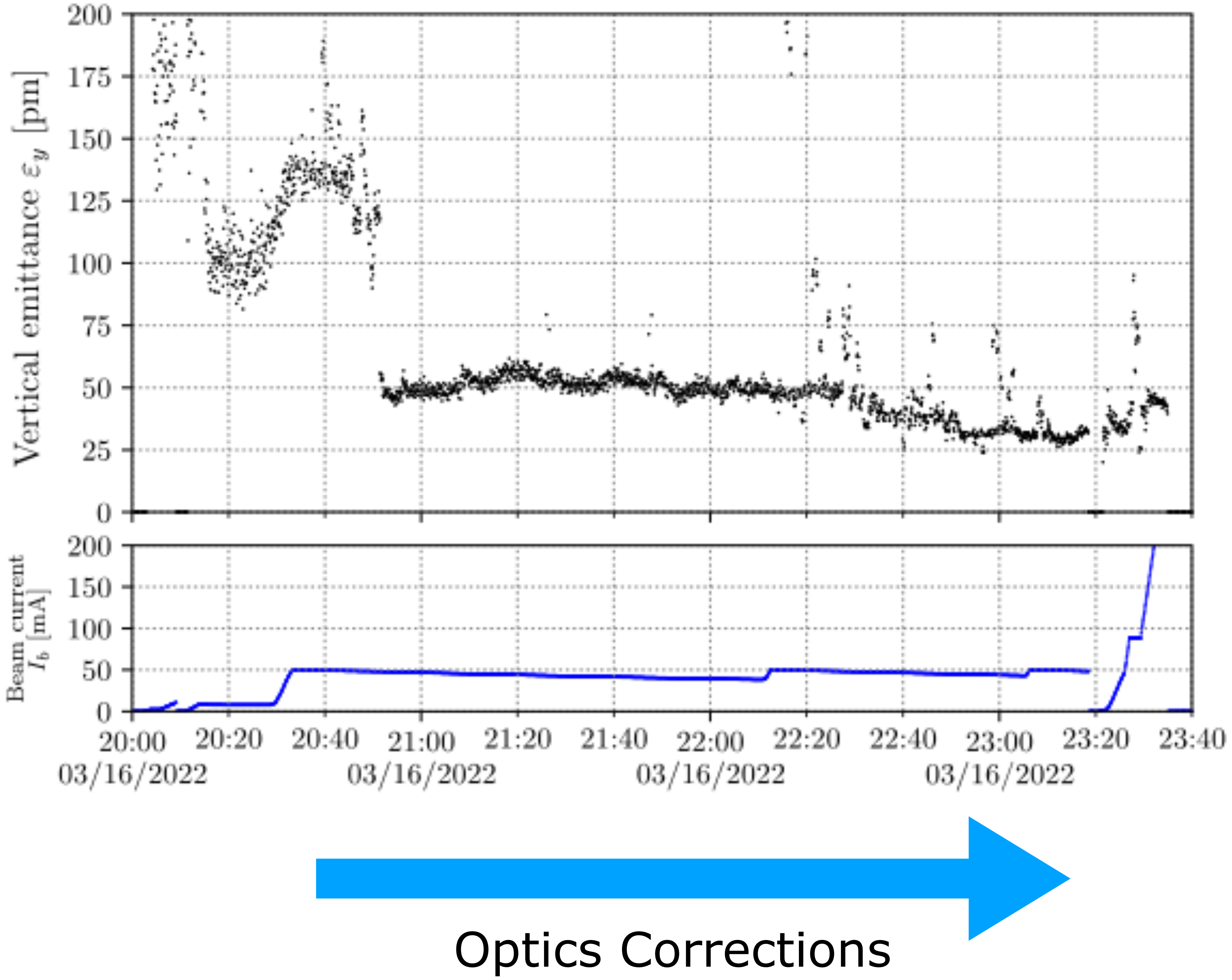
Optics Tuning

Optics Corrections Are Base on COD Measurements.

Typical Deviation from Design

Optics Functions	LER	HER
$(\Delta\beta_{x,y}/\beta_{x,y})_{rms}$	5 % / 5 %	5 % / 5 %
$(\Delta y)_{rms}/(\Delta x)_{rms}$	0.016	0.012
$(\Delta\eta_{x,y})_{rms}$	10 mm / 5 mm	30 mm / 5 mm
ε_y	20 pm ~ 40 pm	20 pm ~ 40 pm

Optics Correction Performed at 50 mA

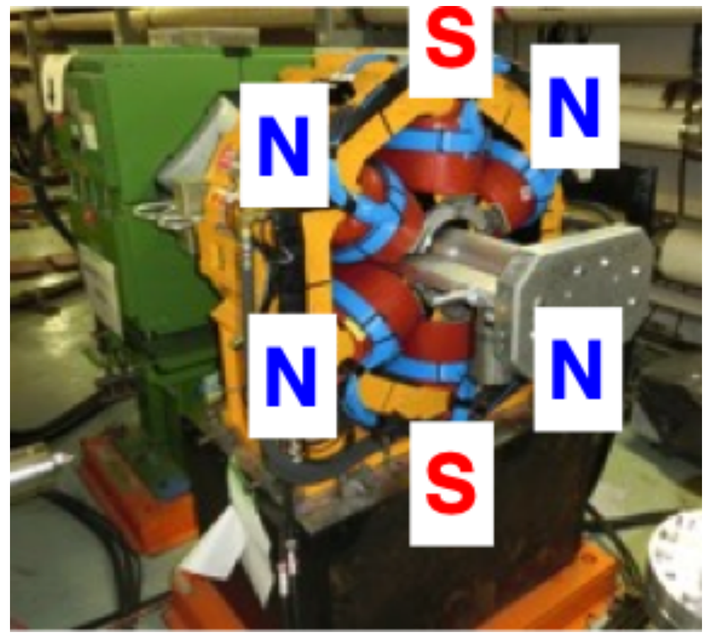


H. Sugimoto (KEK)

Optics Correction for X-Y Couplings and Vertical Dispersions

Skew Quadrupole-like Correction Coils at Sextupoles
Identical Sextupole Pair Connected By -I' Transfer Matrix
Orthogonal Knobs for X-Y Coupling and Vertical Dispersion

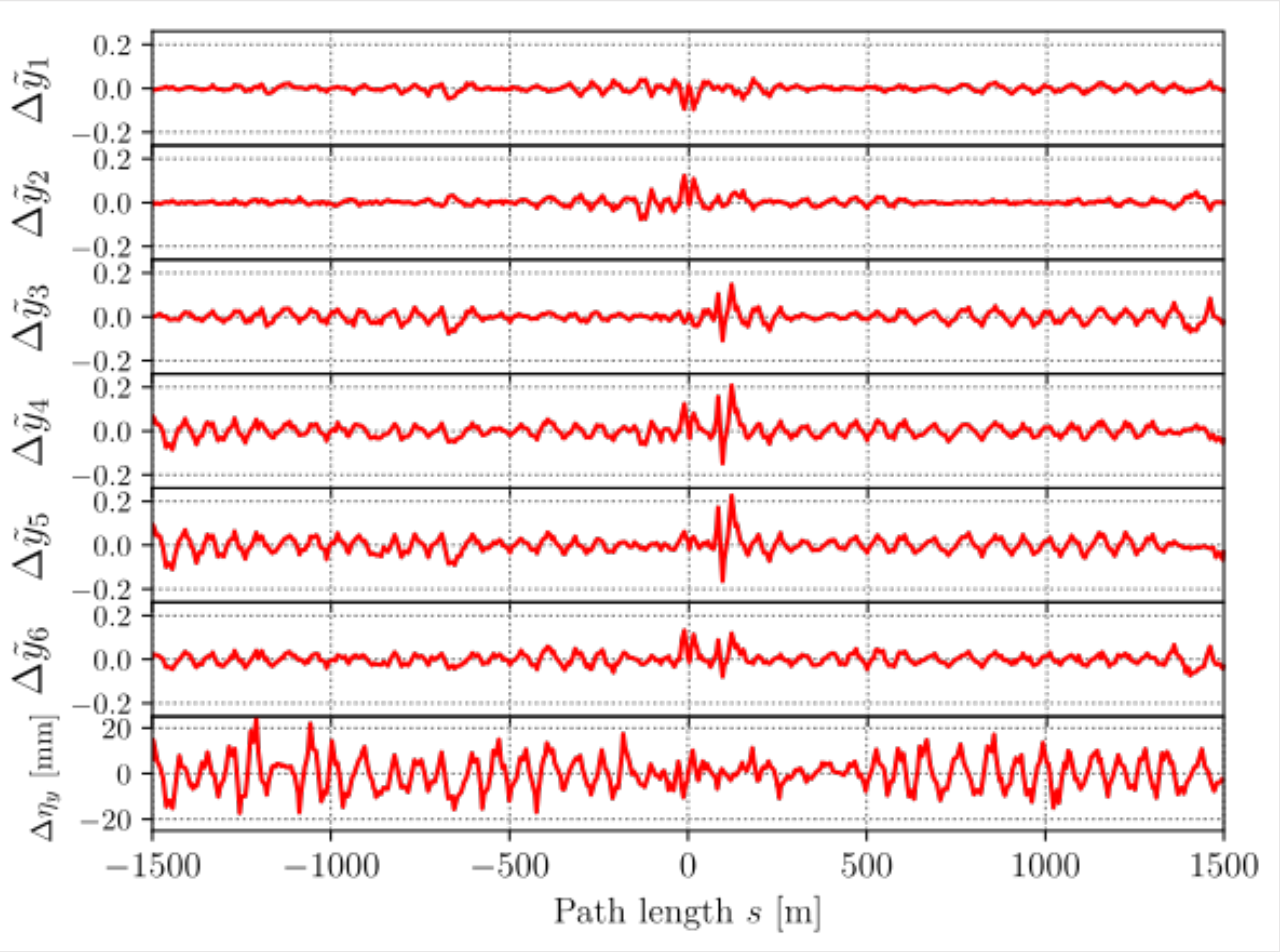
Skew Quad. Corrector



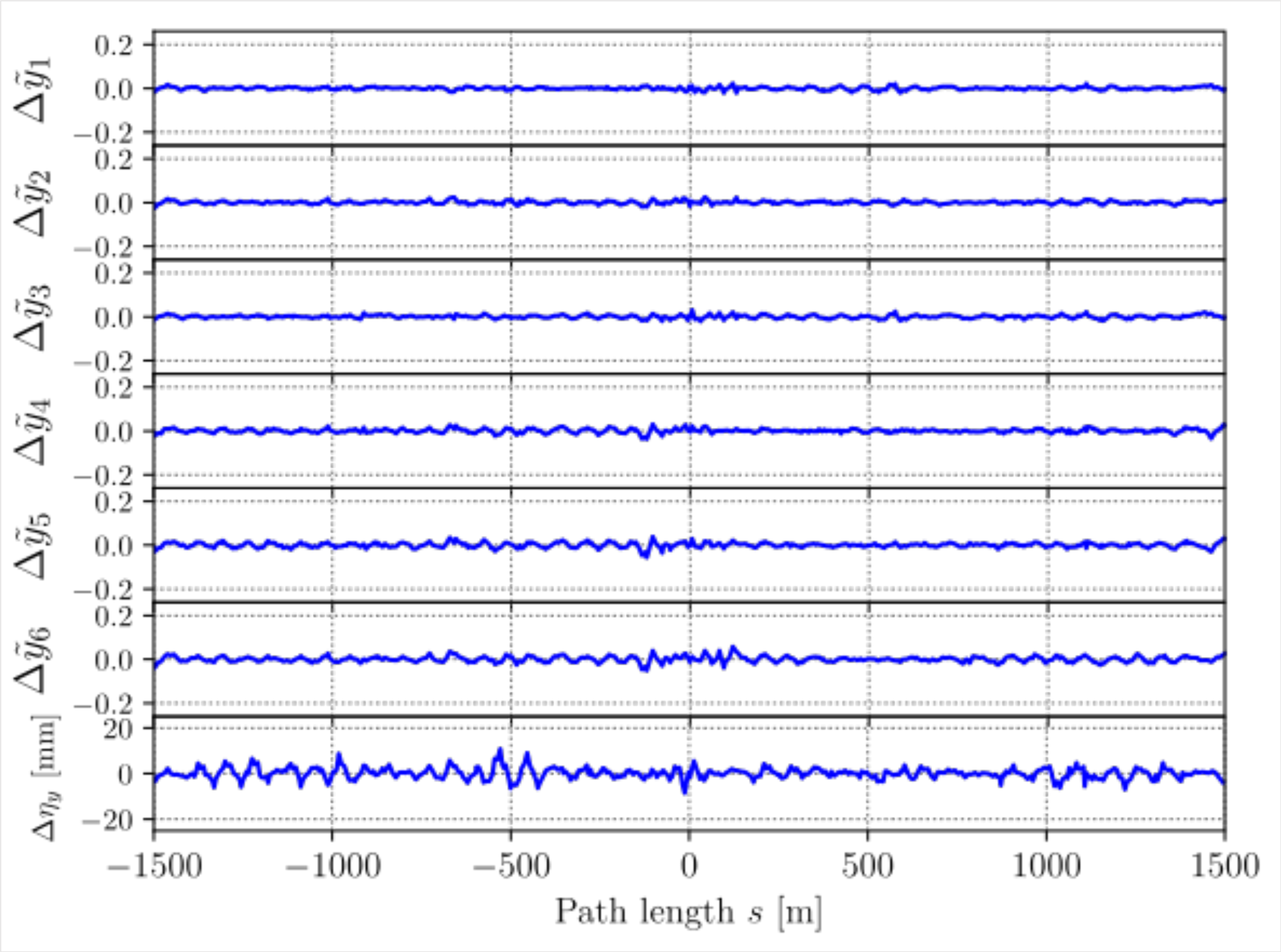
Typical X-Y Coupling Correction

Vertical Orbit Response (Single Kick) Relative to Horizontal Orbit

Before Correction

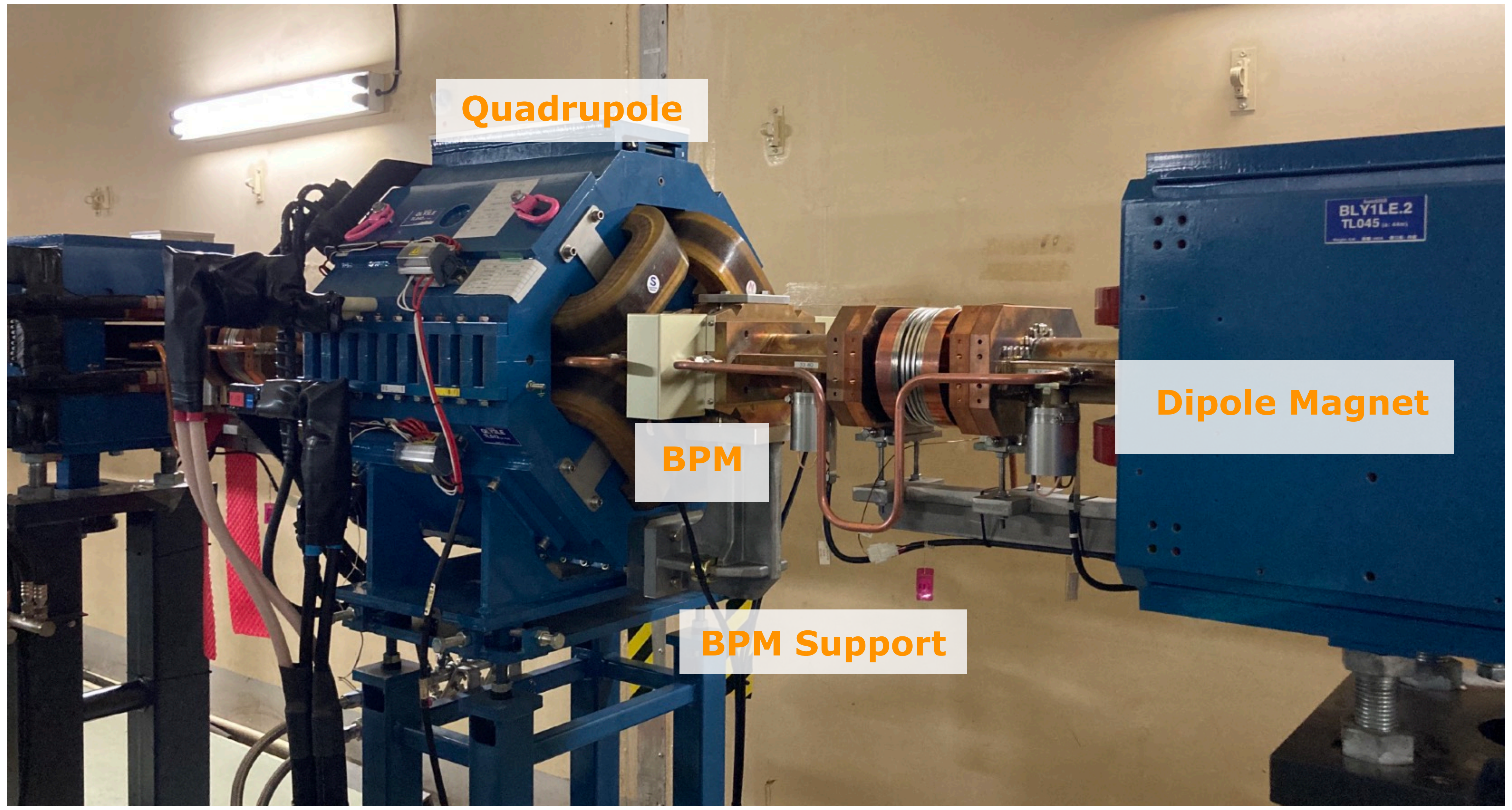


After Correction

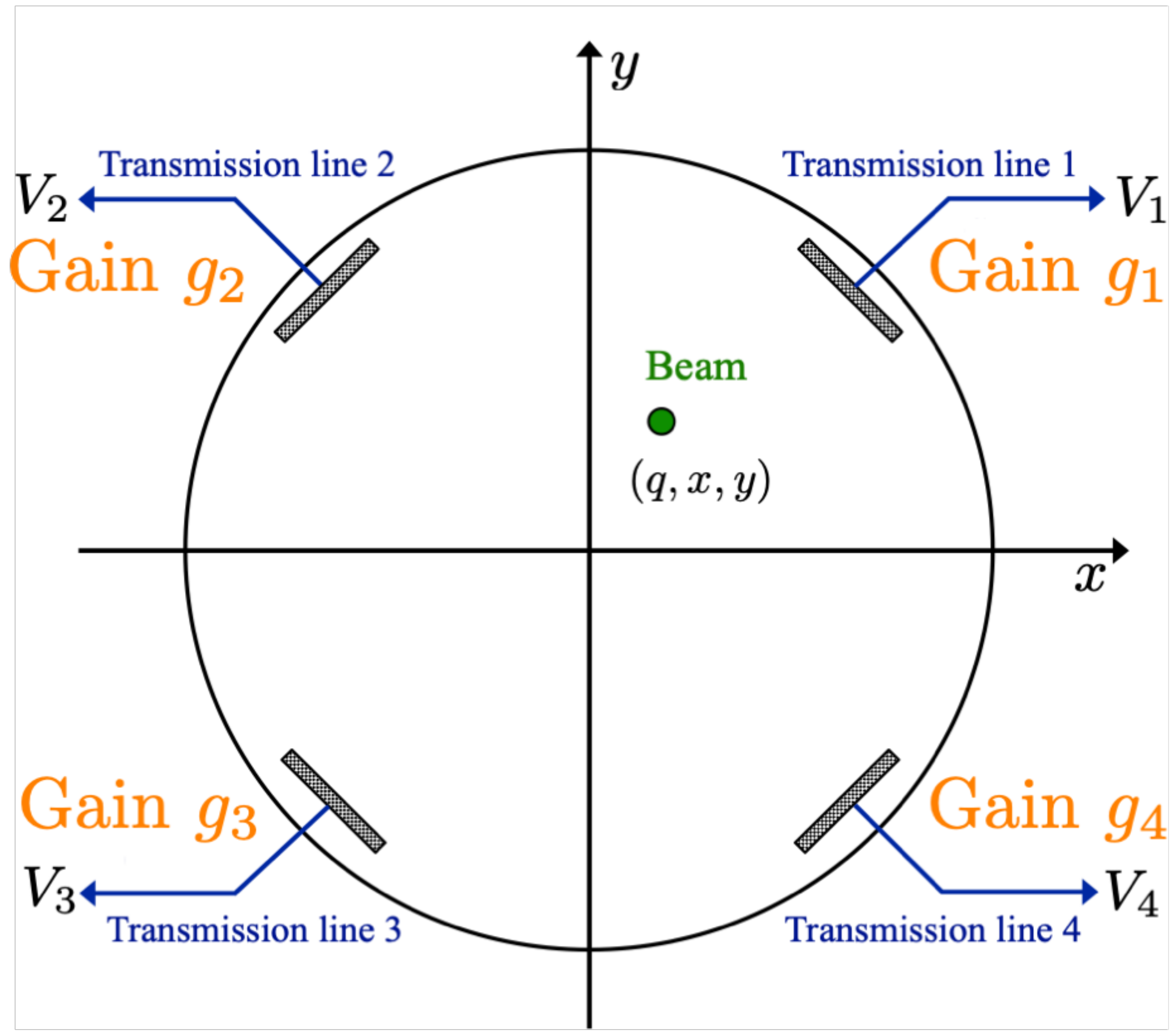


Beam Position Monitor

- About 450 BPMs in LER and HER for Every Quadrupoles
  - Averaged Mode (~0.25 Hz)
  - Position Resolution: a few microns
  - Continuous Orbit Correction
  - Optics Corrections
  - BPM Gain Mapping and BBA (BPM Offset)
- Gated Turn-By-Turn BPMs: ~70 out of ~450 BPMs
  - Position Resolution: ~100 μm
  - Injection Beam Optimization
  - Physical and Dynamic Aperture (Injection Kicker, Vertical Kicker)
  - Lattice Nonlinear (Amplitude Detuning, Decoherence, etc.)



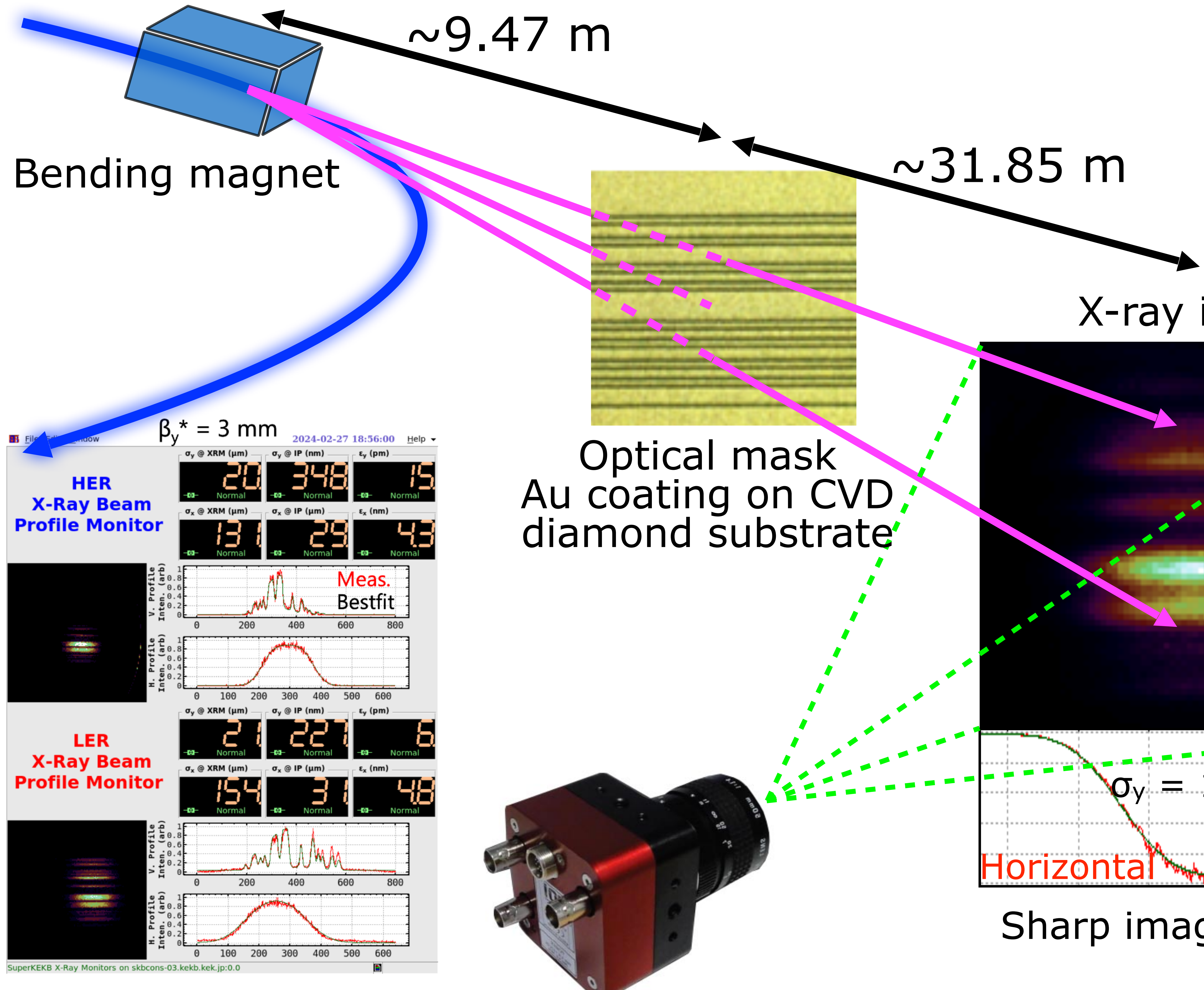
Four-Button Type BPM



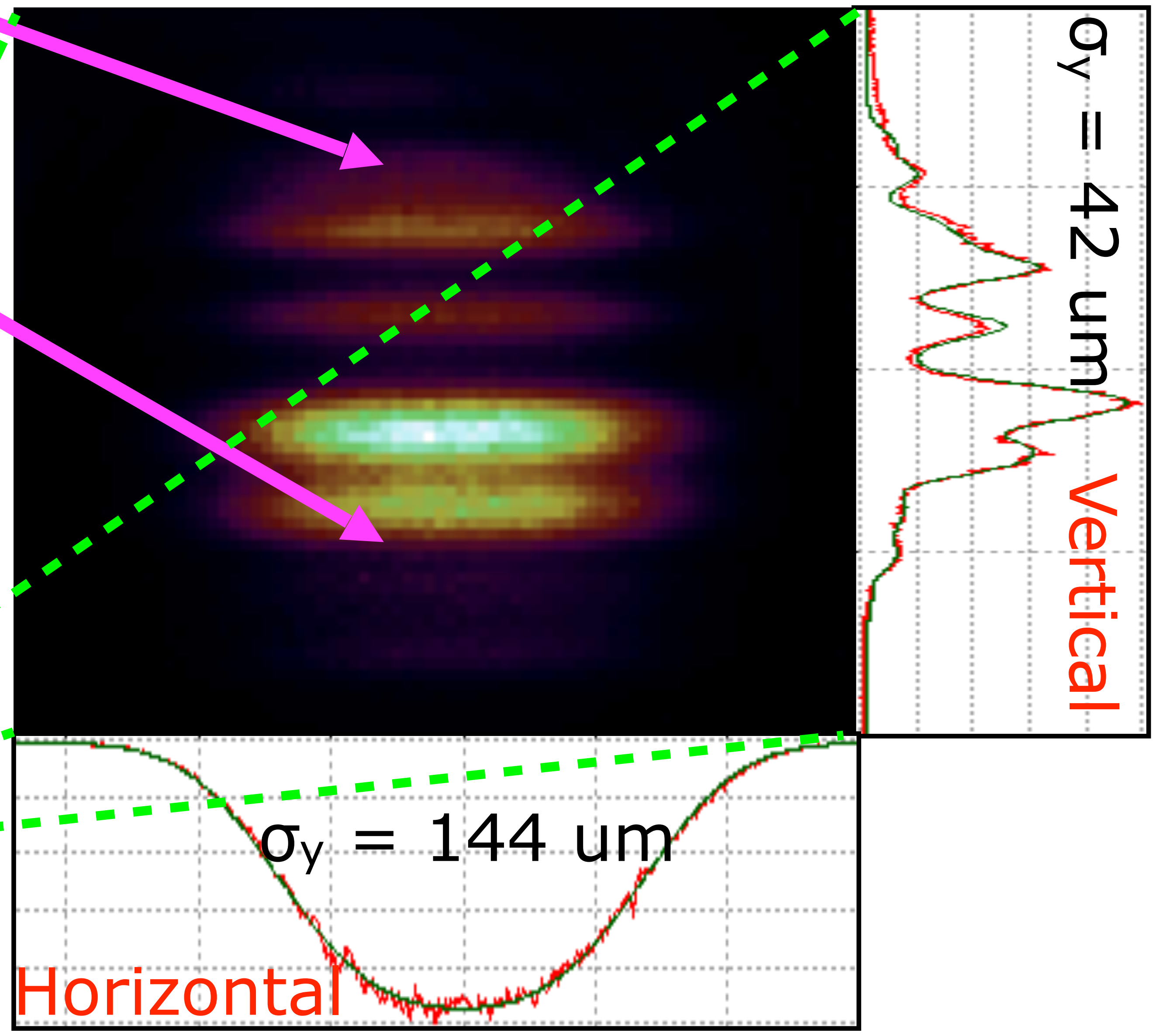
G. Mitsuka (KEK)

Same idea as an X-ray pin-hole camera

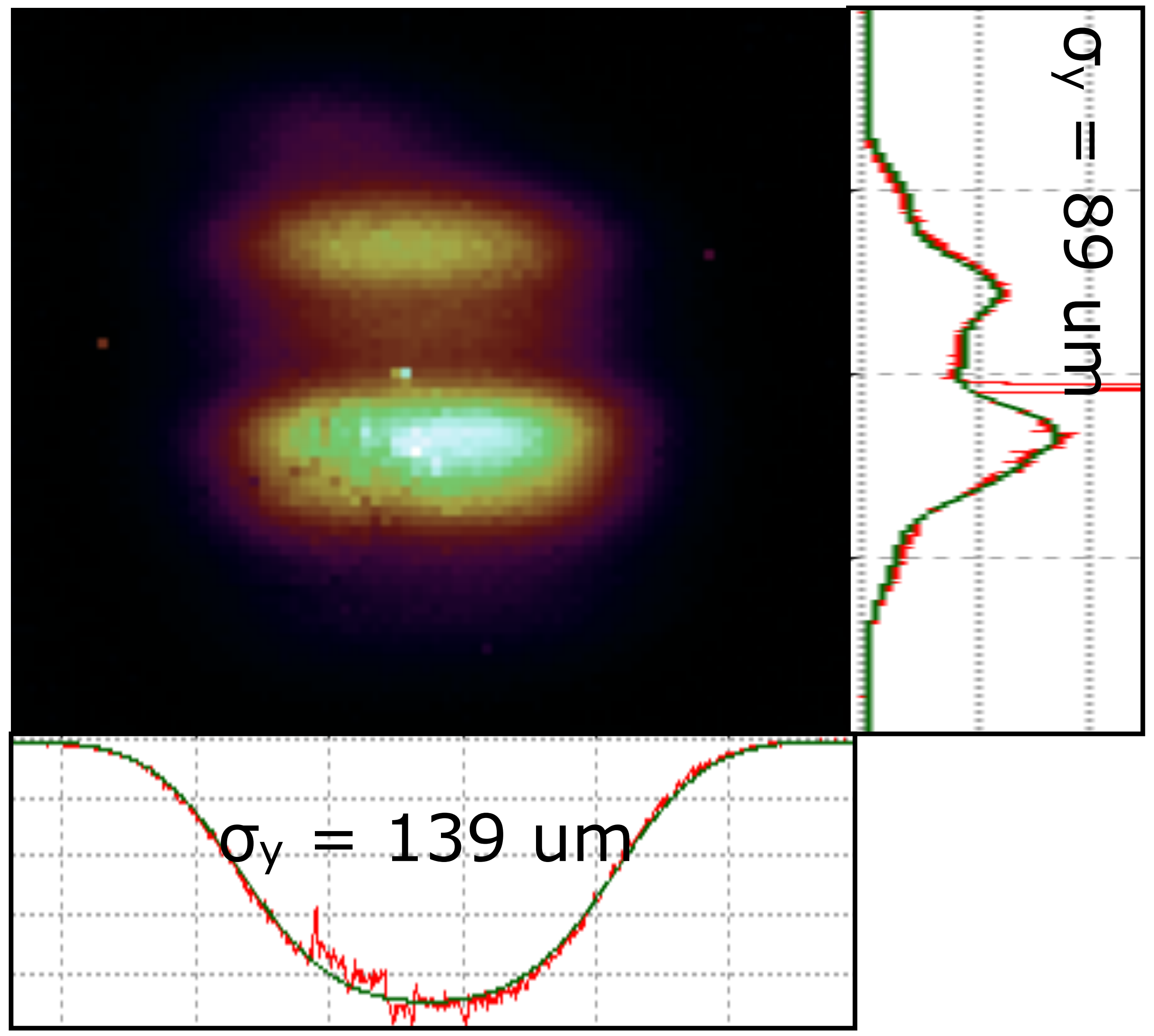
Wavelength	X ray (~0.1 nm) Since SuperKEKB	Visible light (~500 nm) Since KEKB era		
Monitor	X-ray monitor	Interferometer	Gated camera	Streak camera
Sensitivity	X, Y	X, Y	X, Y	Z
σ_{min}	X : ~ 130 μm **Y : ~ 10 μm**	X : ~ 200 μm Y : ~ 40 μm	X/Y : ~100 μm	Z : ~0.5 mm
Precision	X : ~ 5 μm **Y : < 1 μm**	X : ~ 3 μm Y : < 1 μm	X/Y : ~100 μm	Z : ~0.5 mm
Meas. rate Analysis rate	~ 300 Hz < 100 Hz	~ 10 Hz ~ 0.5 Hz	~1 Hz Offline	Manual Offline



X-ray images projected to a YAG/LuAG scintillator



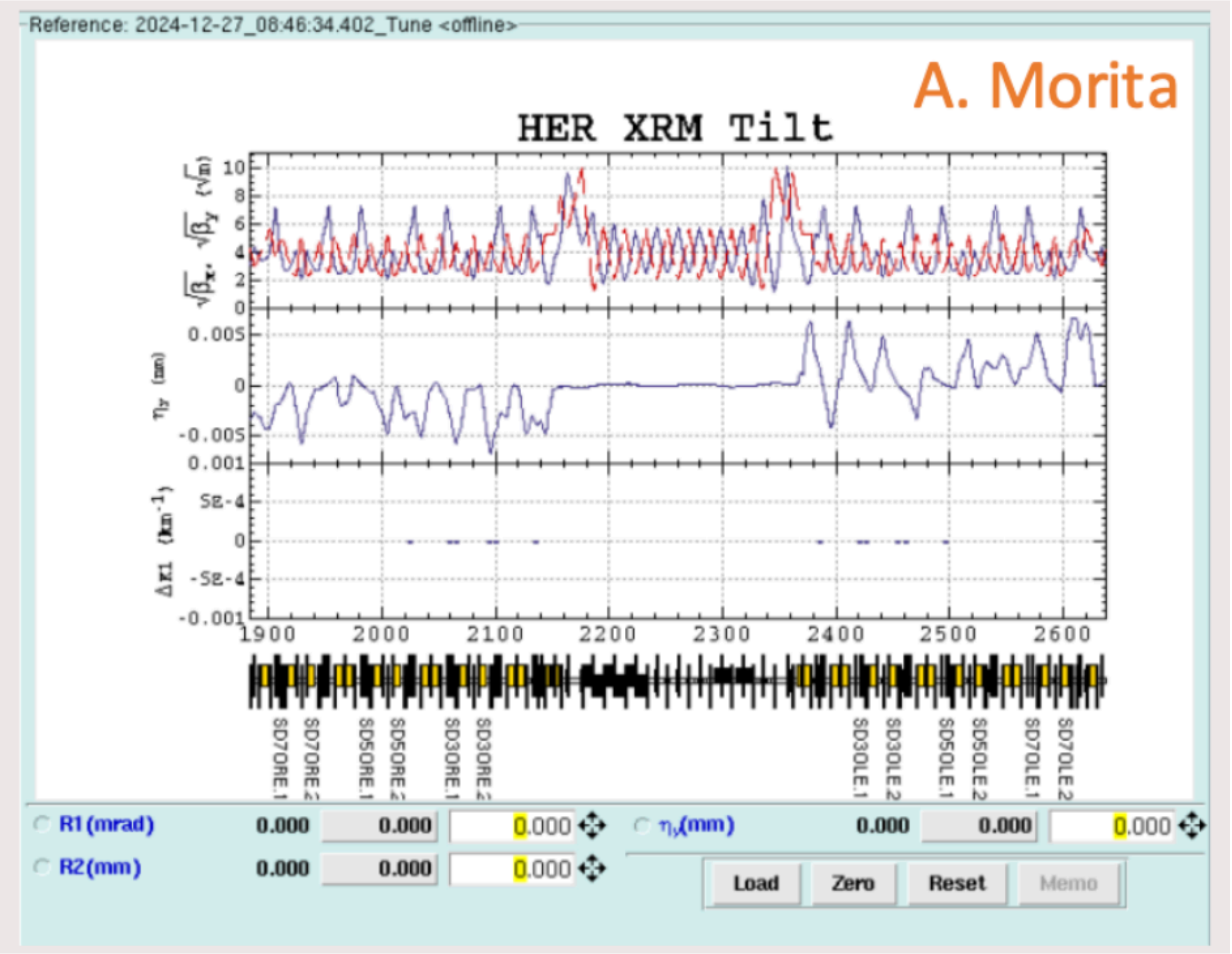
Sharp image → Small σ



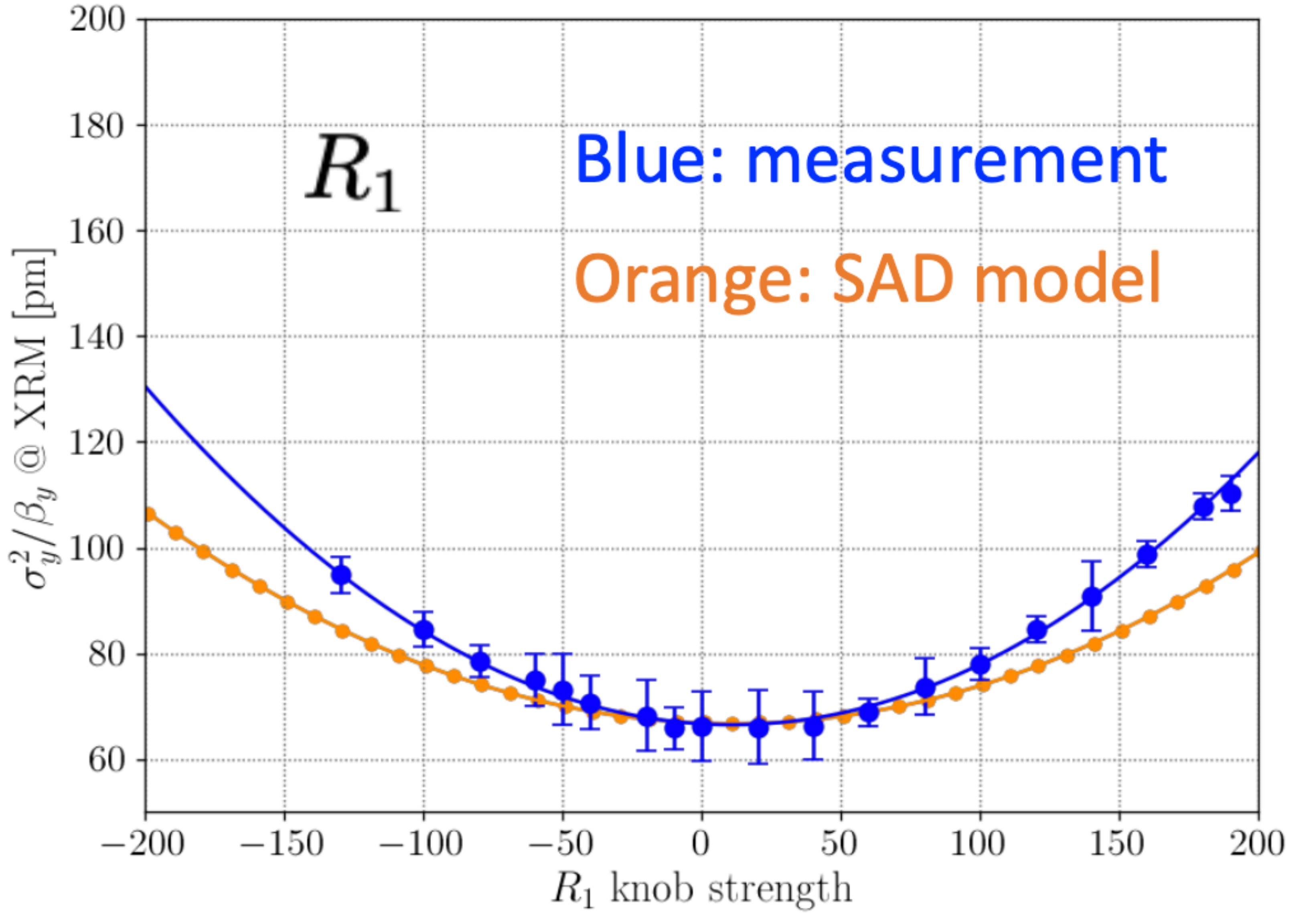
Broad image → Large σ

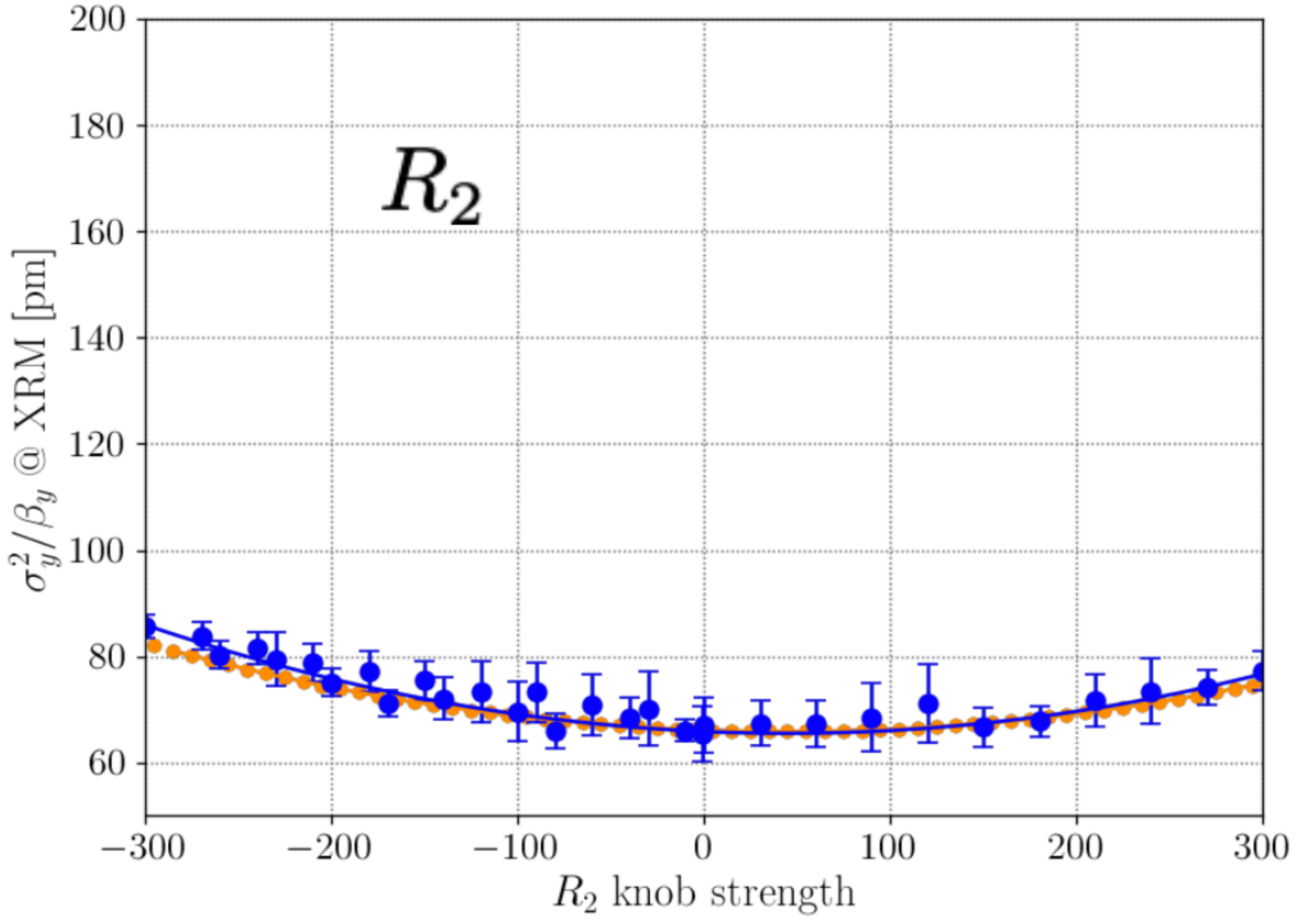
Calibration of XRM

- Beam size at XRM is calibrated by changing locally X-Y coupling and vertical dispersion at XRM. (induced by skew quad. at sextupoles)
- Response of measured vertical beam size is consistent with optics calculation.

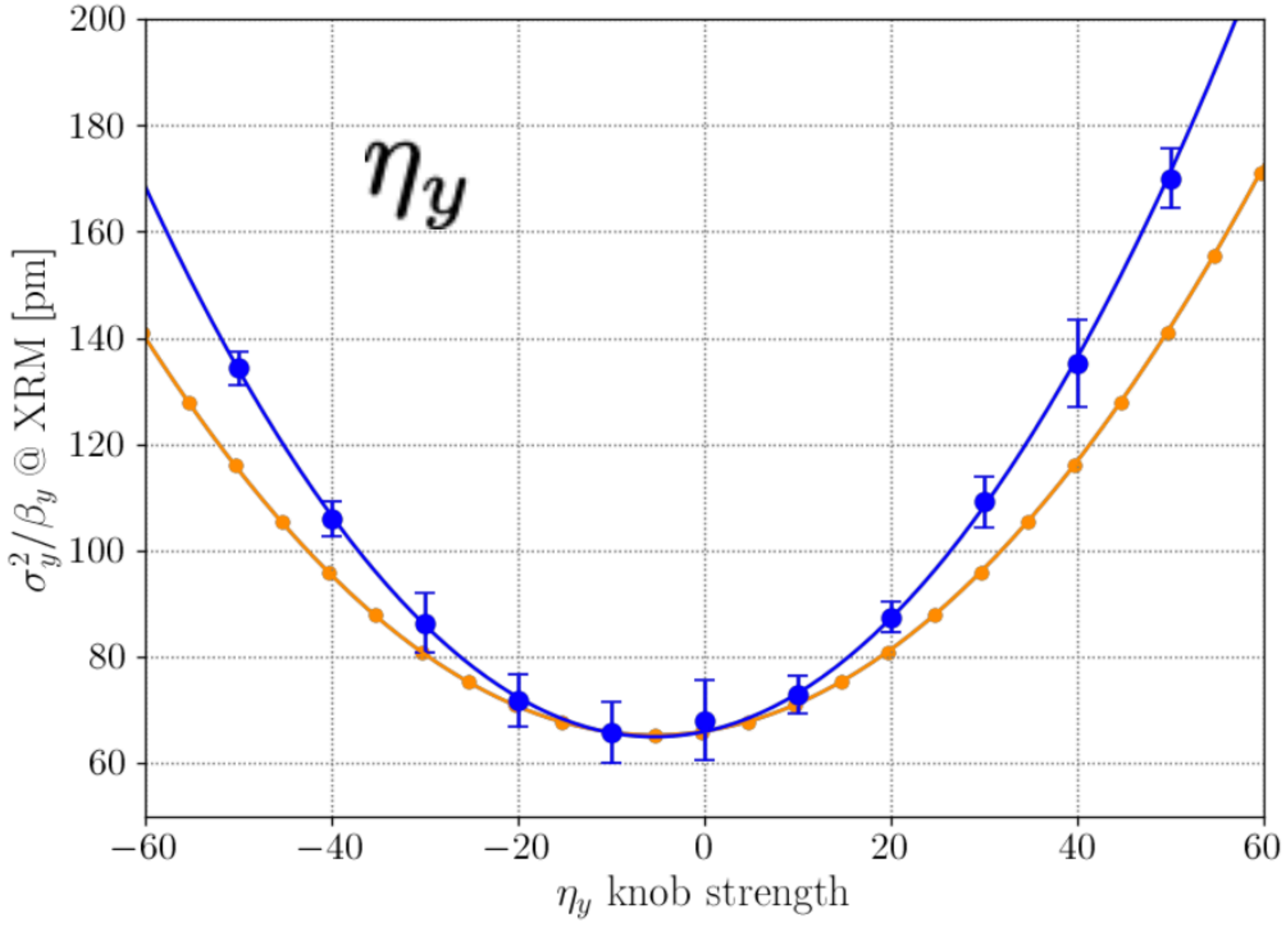


X-Y Coupling Parameters





Vertical Dispersion



H. Sugimoto (KEK)

Normal Coordinate (Decoupled)

$$\boxed{\begin{aligned} X &= \sqrt{2J_x\beta_x}\cos\psi \\ P_X &= -\sqrt{\frac{2J_x}{\beta_x}}\left(\alpha_x\cos\psi + \sin\psi\right) \\ \psi &= 2\pi\nu_x n + \phi_0 \end{aligned}}$$

Physical Coordinate | Normal Coordinate

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} = \begin{pmatrix} \mu & 0 & r_4 & -r_2 \\ 0 & \mu & -r_3 & r_1 \\ -r_1 & -r_2 & \mu & 0 \\ -r_3 & -r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} X \\ P_X \\ Y \\ P_Y \end{pmatrix}$$

Definition of X-Y Coupling Parameters

X-Y Coupling Can Be Measured By Horizontal Kicker.

H-mode ($Y = 0$ and $P_Y = 0$):

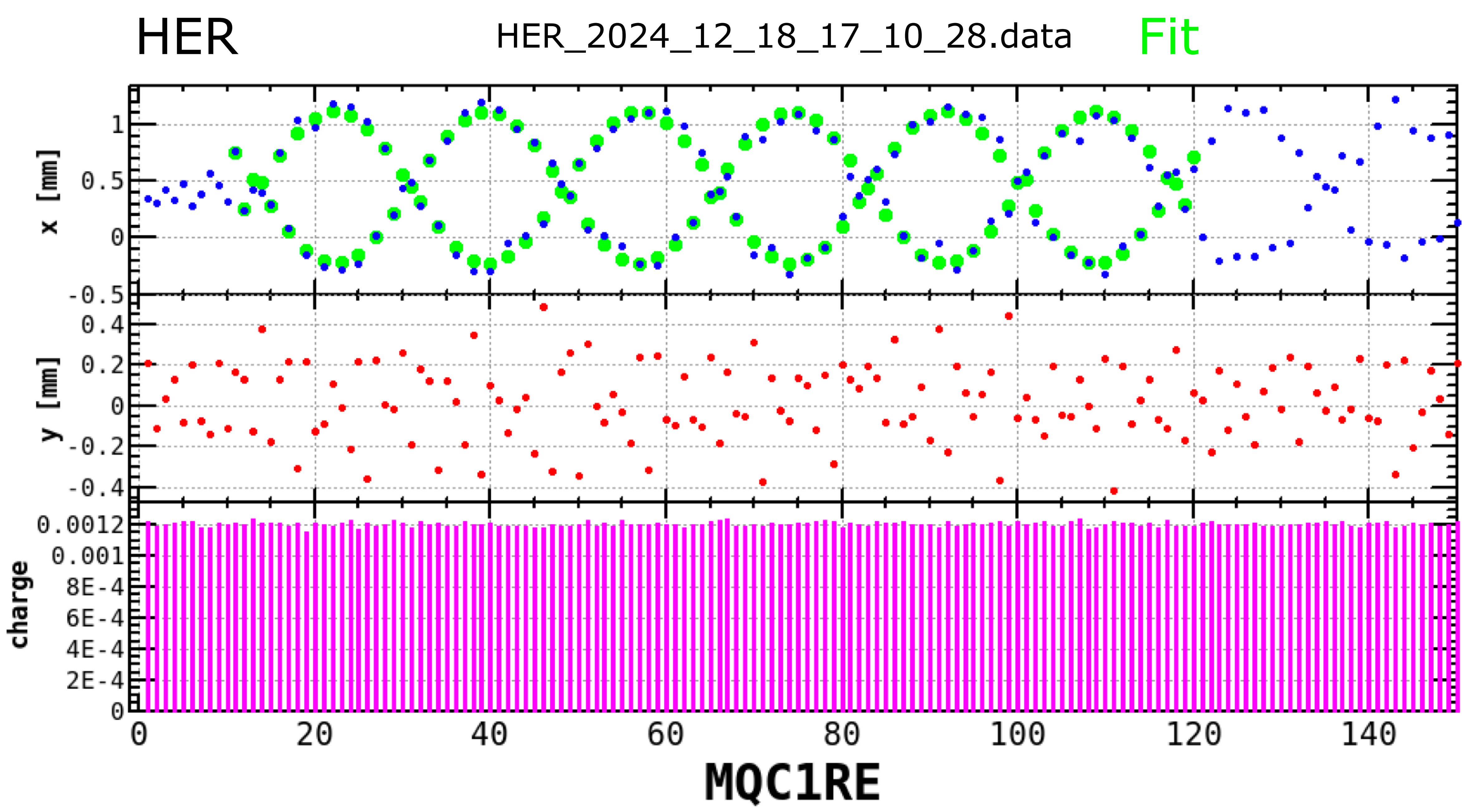
$$y = -r_1 X - r_2 P_X \qquad x = \mu X$$

$$\begin{aligned} y &= \left(-r_1 + r_2\frac{\alpha_x}{\beta_x}\right)\sqrt{2J_x\beta_x}\cos\psi + \frac{r_2}{\beta_x}\sqrt{2J_x\beta_x}\sin\psi \\ &= a\sqrt{2J_x\beta_x}\cos\psi + b\sqrt{2J_x\beta_x}\sin\psi \\ &= \sqrt{a^2+b^2}\sqrt{2J_x\beta_x}\sin(\psi+\psi_0) \end{aligned}$$

$$\sqrt{a^2+b^2} = \sqrt{\left(r_1 - 2r_2\frac{\alpha_x}{\beta_x}\right)r_1 + \frac{1+\alpha_x^2}{\beta_x^2}r_2^2}$$

$$\frac{\bar{y}}{\bar{x}} = \frac{\sqrt{a^2+b^2}}{\mu}$$

Turn-By-Turn Data with Horizontal Kicker (Injection Kicker)



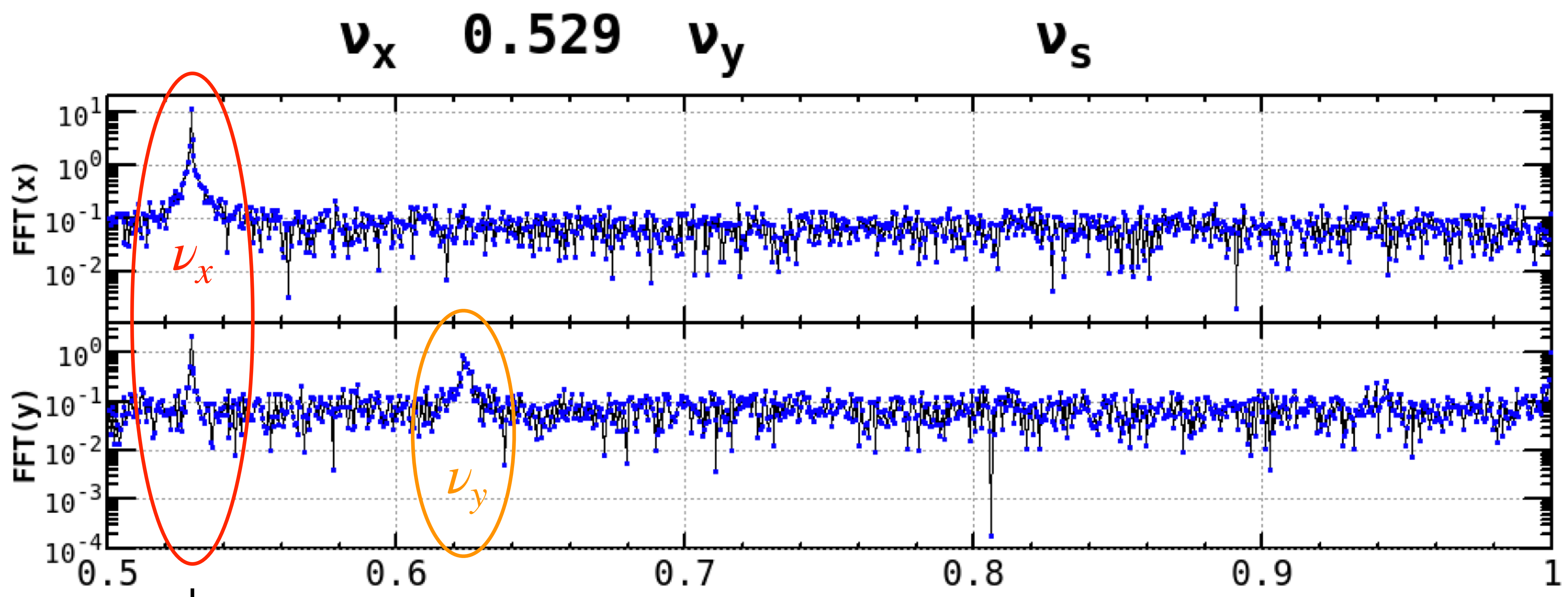
Initial amplitude of x_0 is determined from 120-turn fit.

$$2J_{x0} = \frac{x_0^2}{\beta_x}$$

H-mode:

$$x = \mu X \qquad p_x = \mu P_X$$

$$y = -r_1 X - r_2 P_X$$

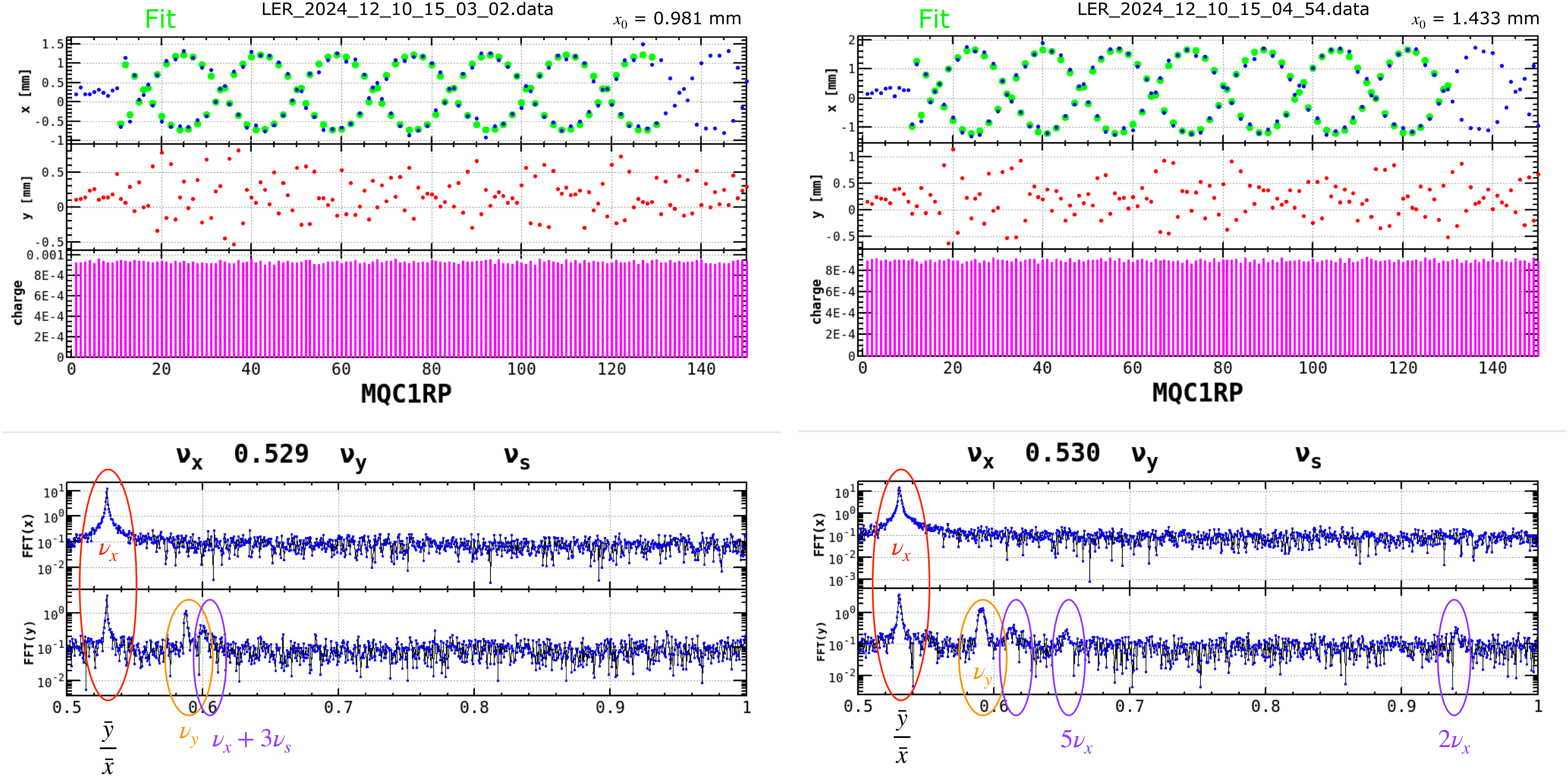


$\bar{x}$: FFT amplitude of TBT data (x) over 2024 turns

$\bar{y}$: FFT amplitude of TBT data (y) over 2024 turns

$\frac{\bar{y}}{\bar{x}}$ X-Y Couplings is evaluated from the ratio of the measured vertical to horizontal orbit amplitudes.

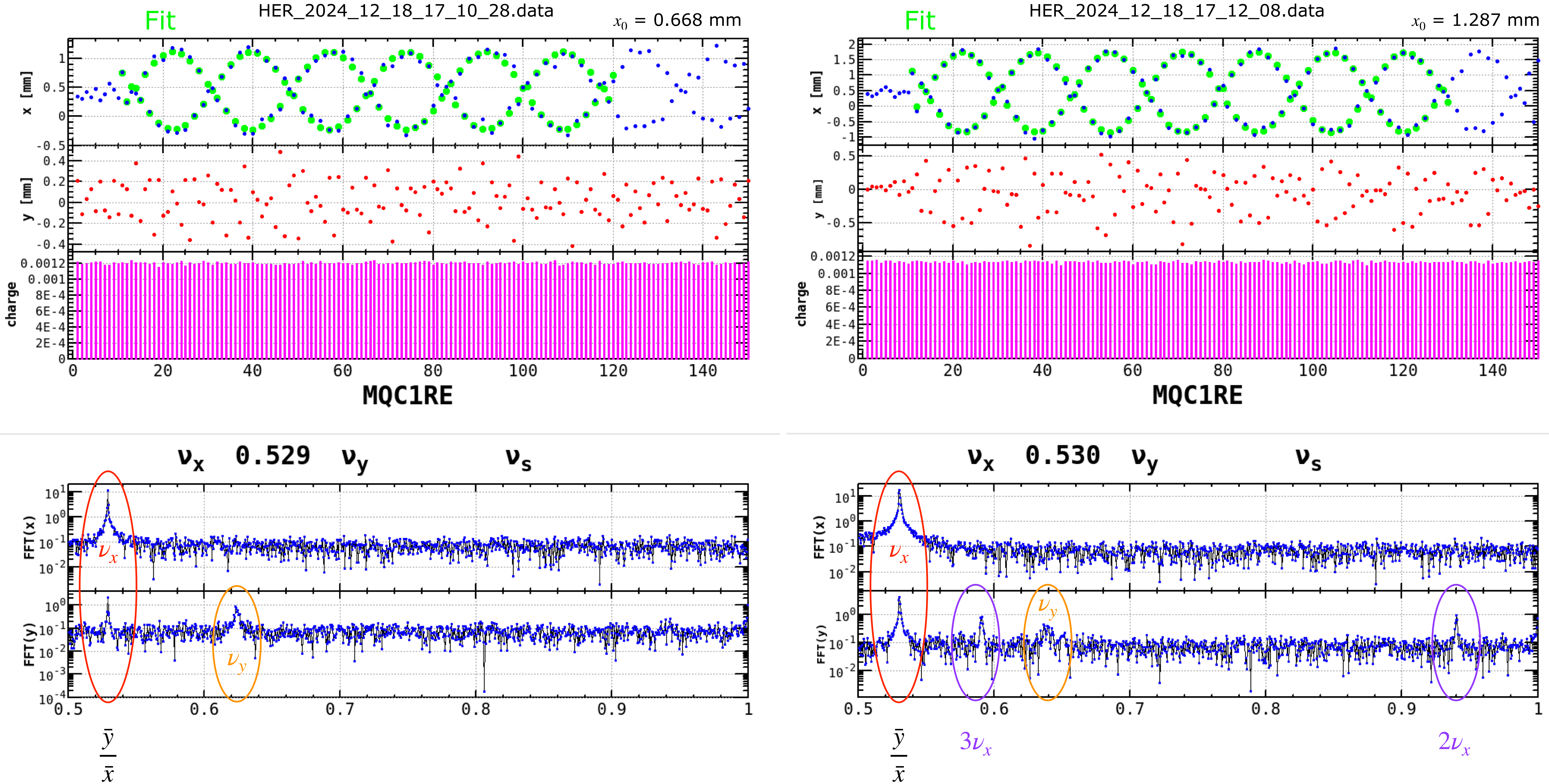
LER



Small Horizontal Amplitude

Large Horizontal Amplitude

HER

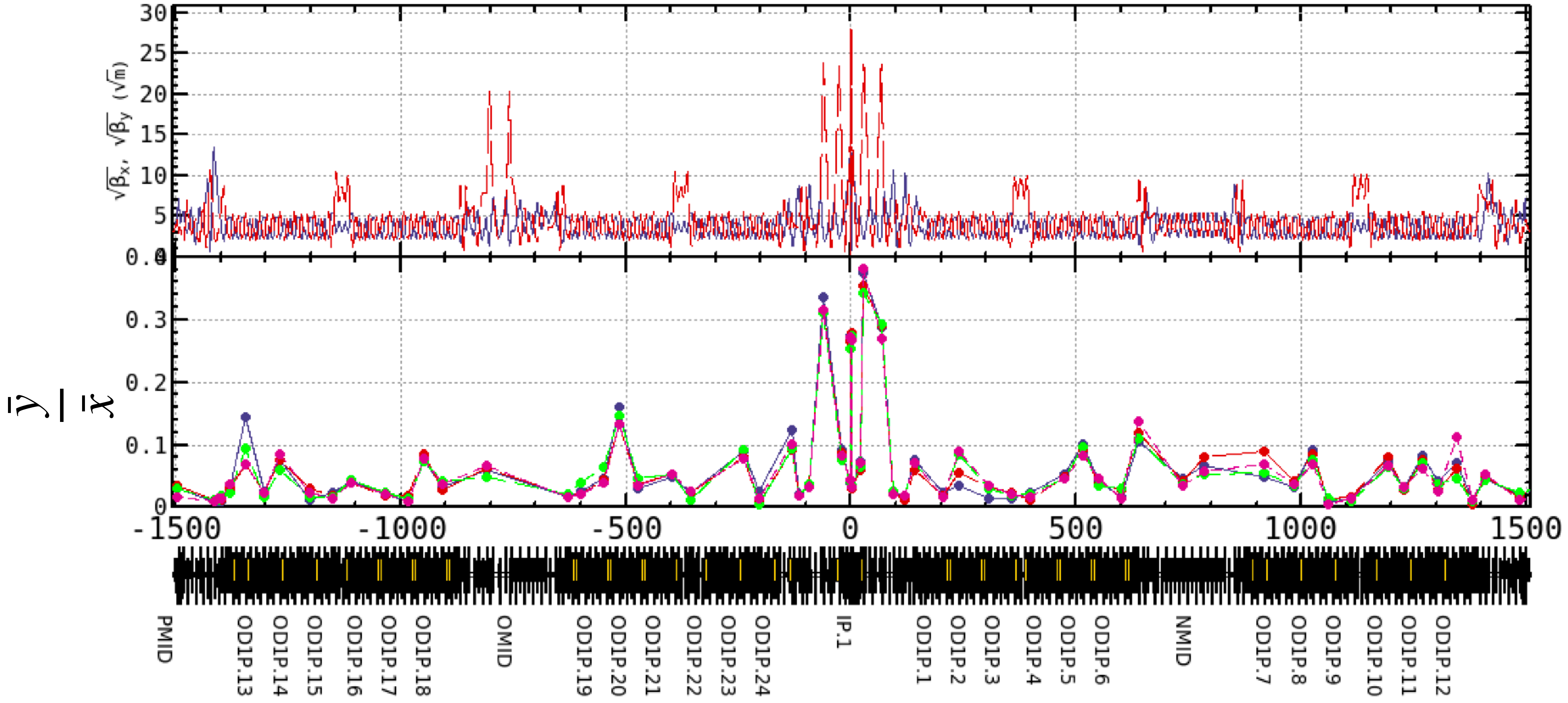


Small Horizontal Amplitude

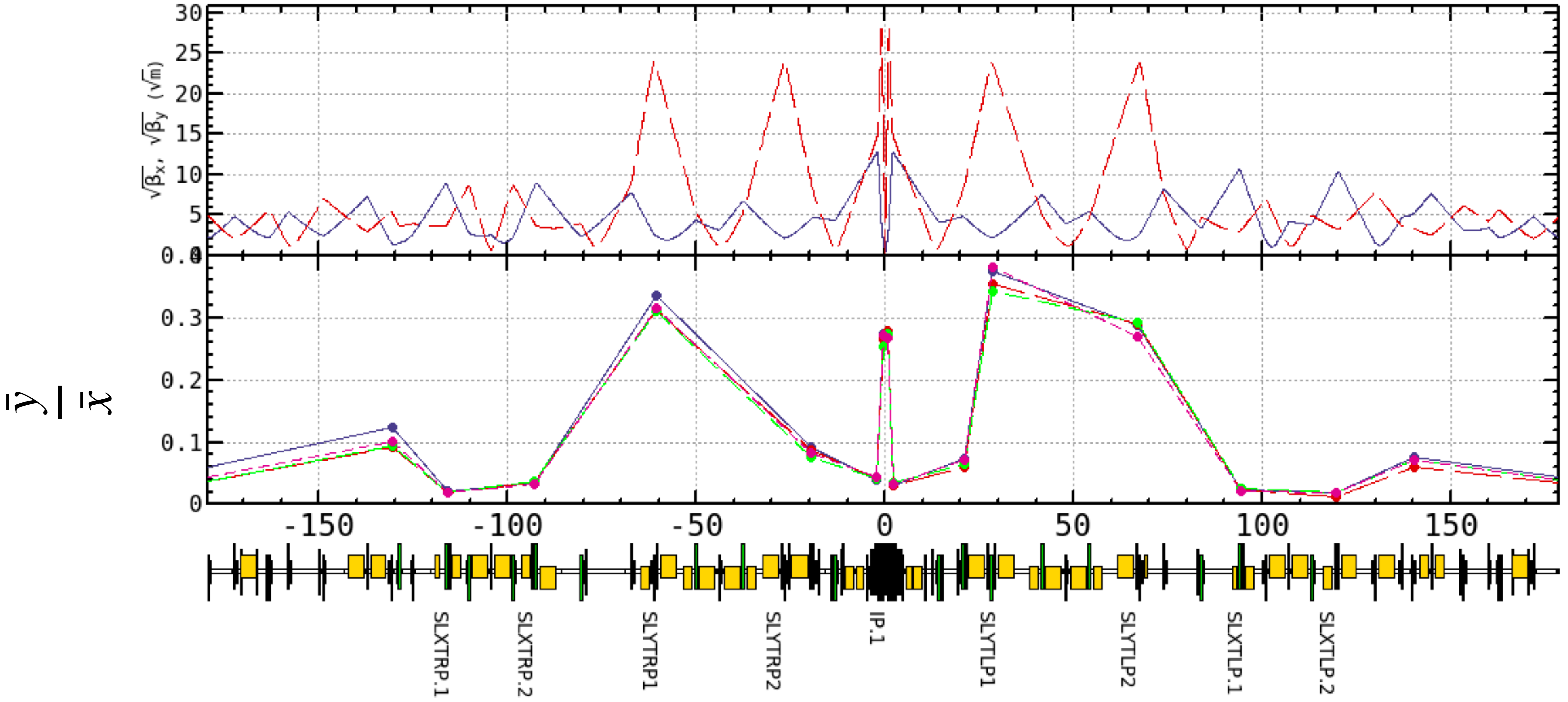
Large Horizontal Amplitude

LER
12/10 2024
HER
12/18 2024
$\frac{\bar{y}}{\bar{x}}$
s (m)
65 BPMs
62 BPMs
$2J_{x0}$ (m)
x10^{-7}
Different Horizontal Amplitudes

LER Autumn Run
12/10 2024

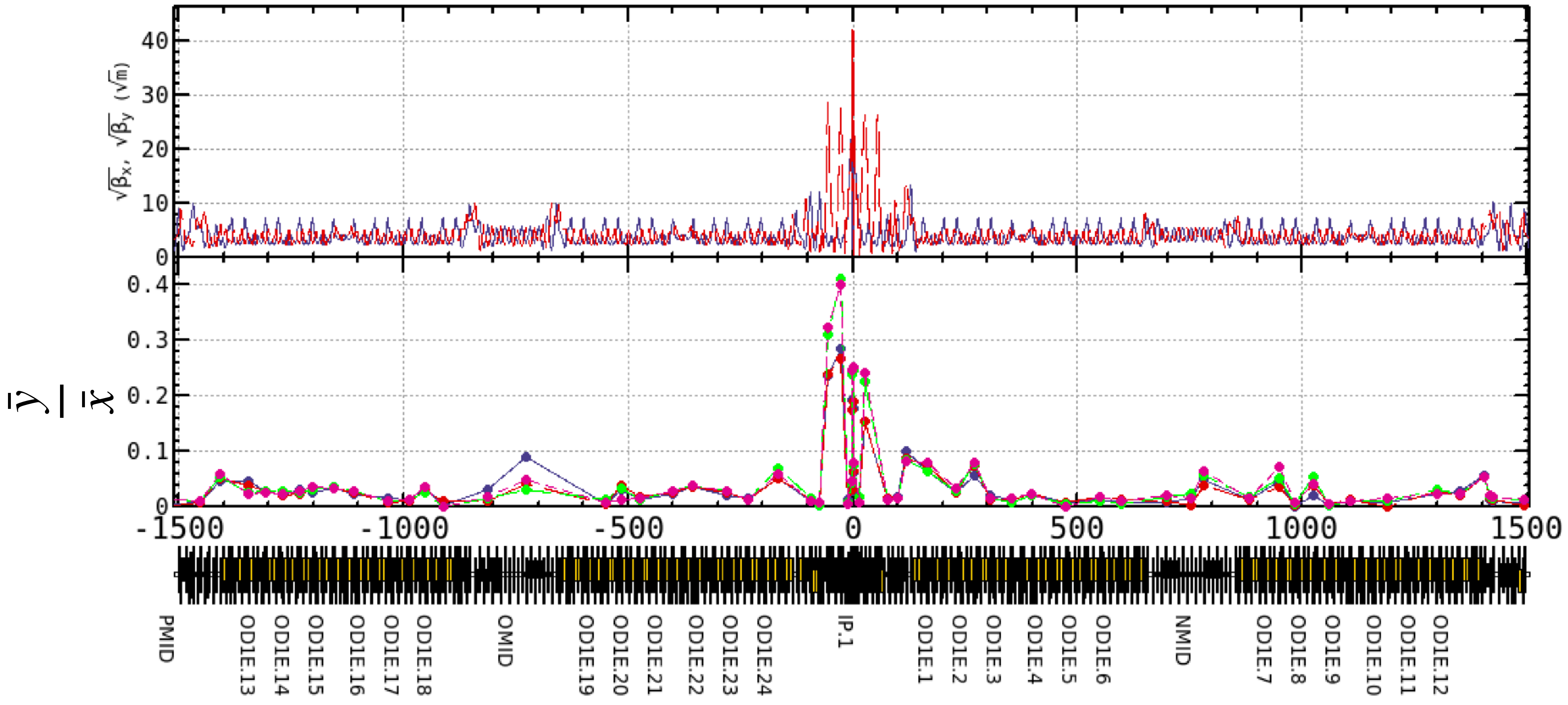


Interaction Region

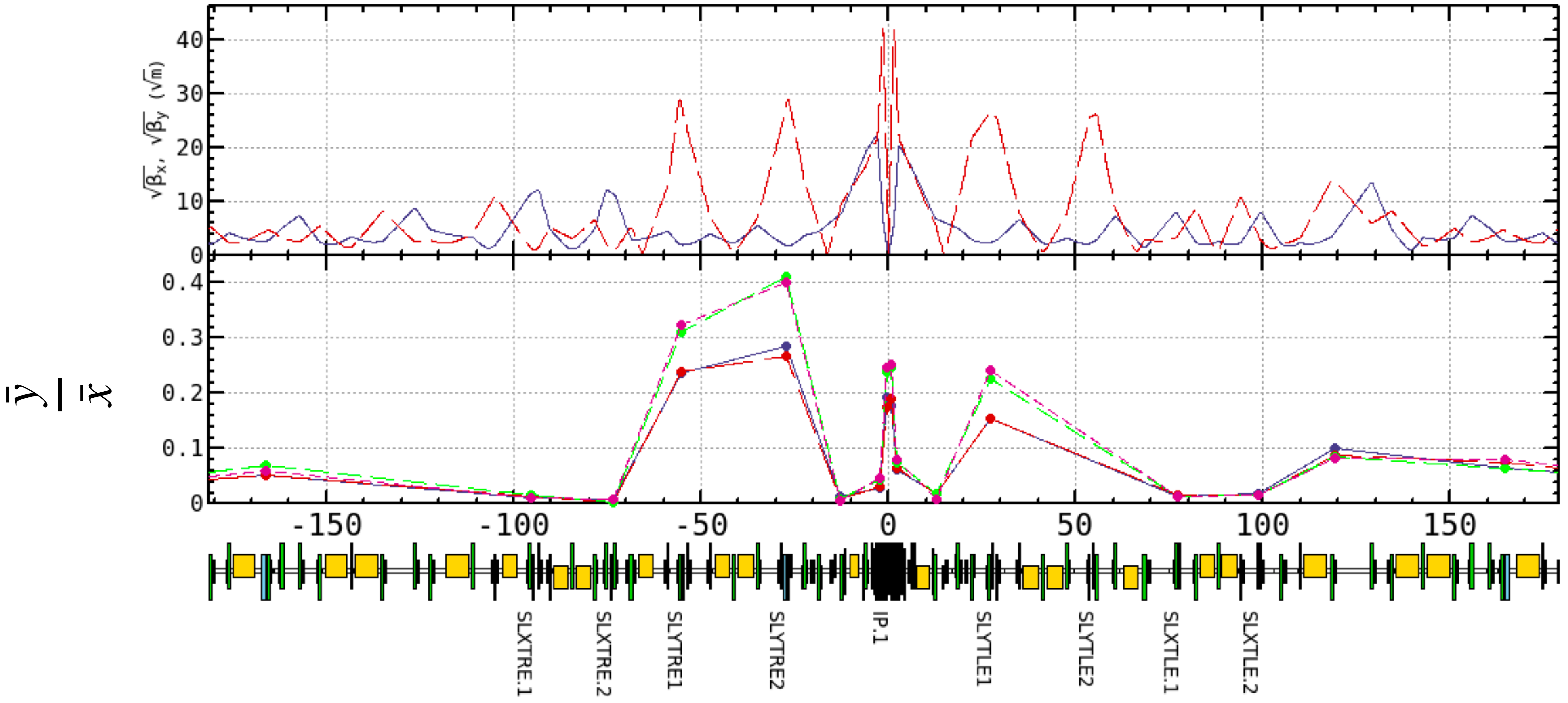


Y-LCC Y-LCC

HER Autumn Run
12/18 2024



Interaction Region



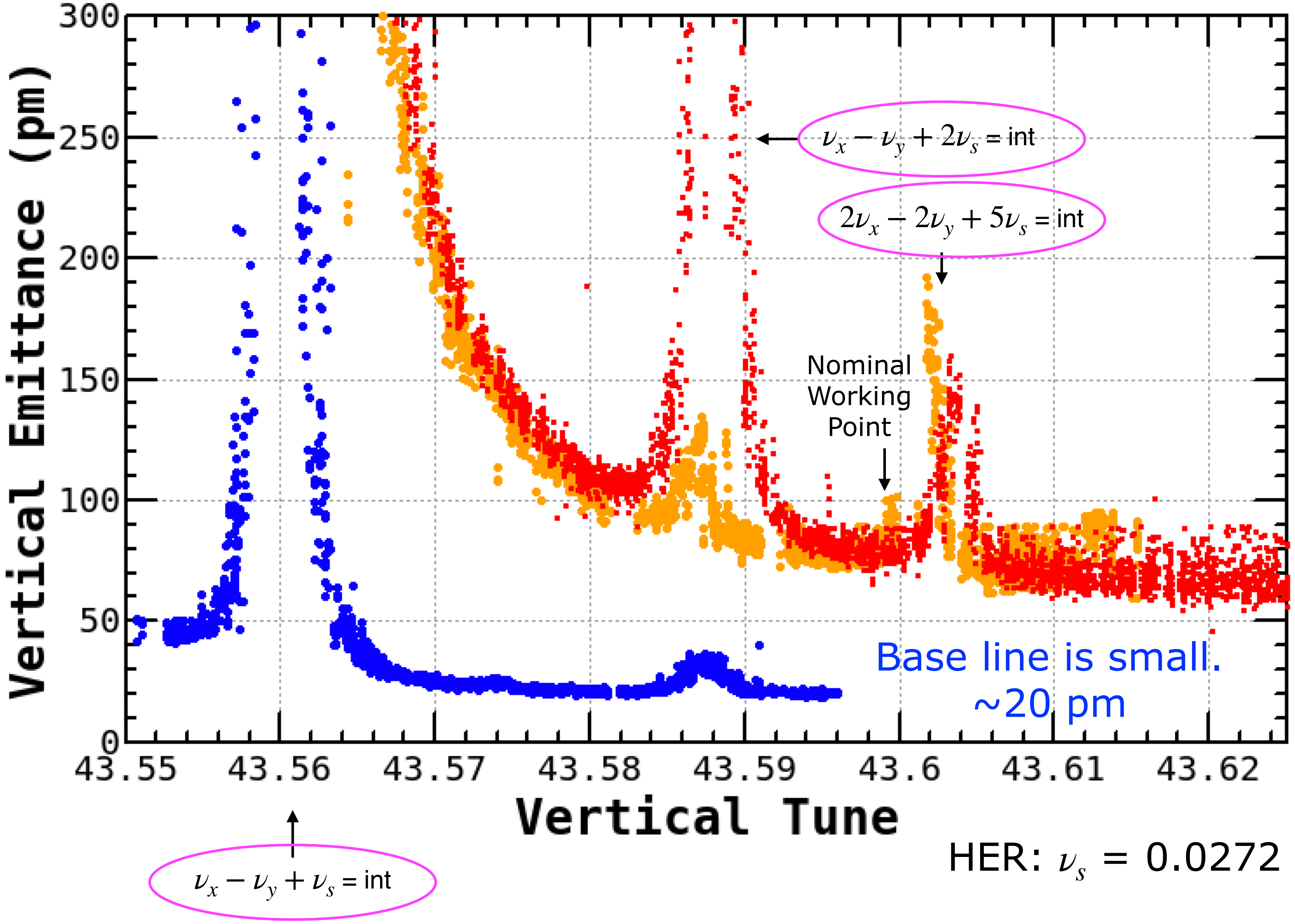
Y-LCC Y-LCC

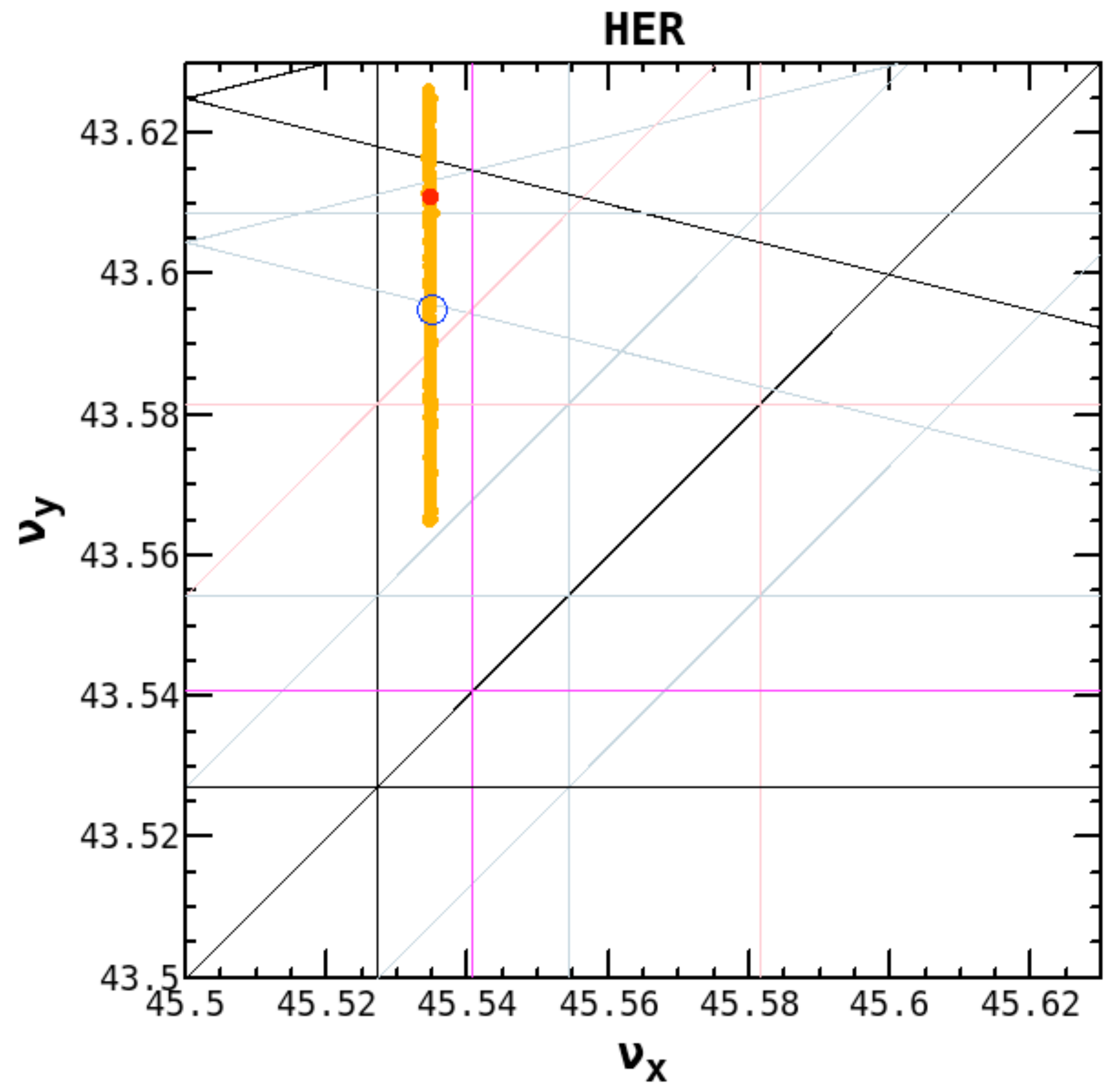
Vertical Emittance in 2022 and 2024 Spring Is Small, But Large in 2024 Autumn Run.

2022 March 29 (2022)

2024 Nov. 22 (2024)

2024 Nov. 29 (2024)
Another different optics correction





Base line is large.
~70 pm

HER: ν_s = 0.0272

What's happen ?

Lowest Order to Higher Order Synchro-Beta X-Y Coupling Resonance (9th)

Measurement of X-Y Couplings with COD Based

X-Y Couplings is evaluated from the ratio of the measured vertical to horizontal orbit responses.

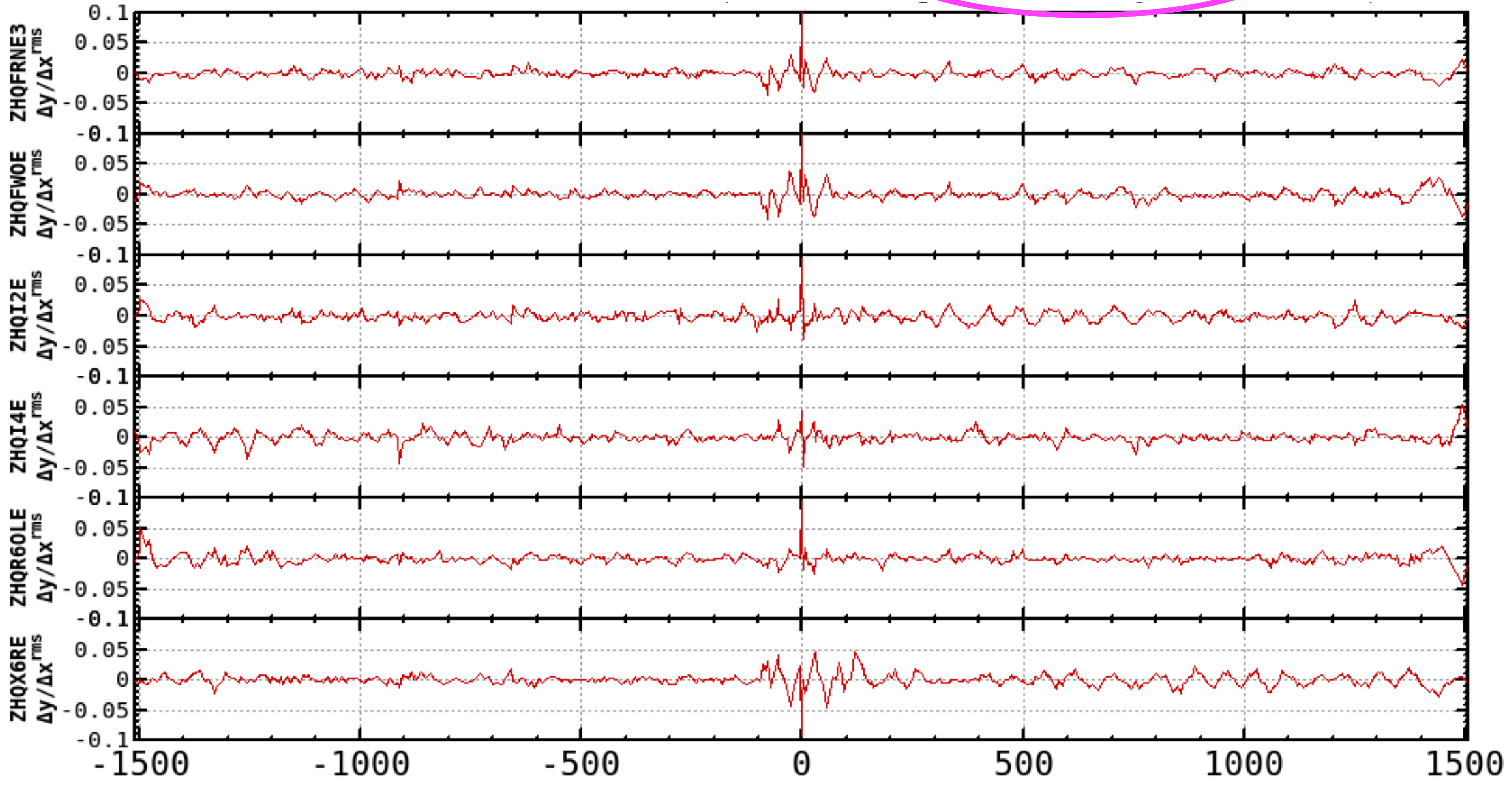
$$\Delta\tilde{y} = \frac{\Delta y}{(\Delta x)_{rms}}$$

March 5, 2024 $\beta_y{}^* = 1$ mm

Nov. 13, 2024 $\beta_y{}^* = 1$ mm

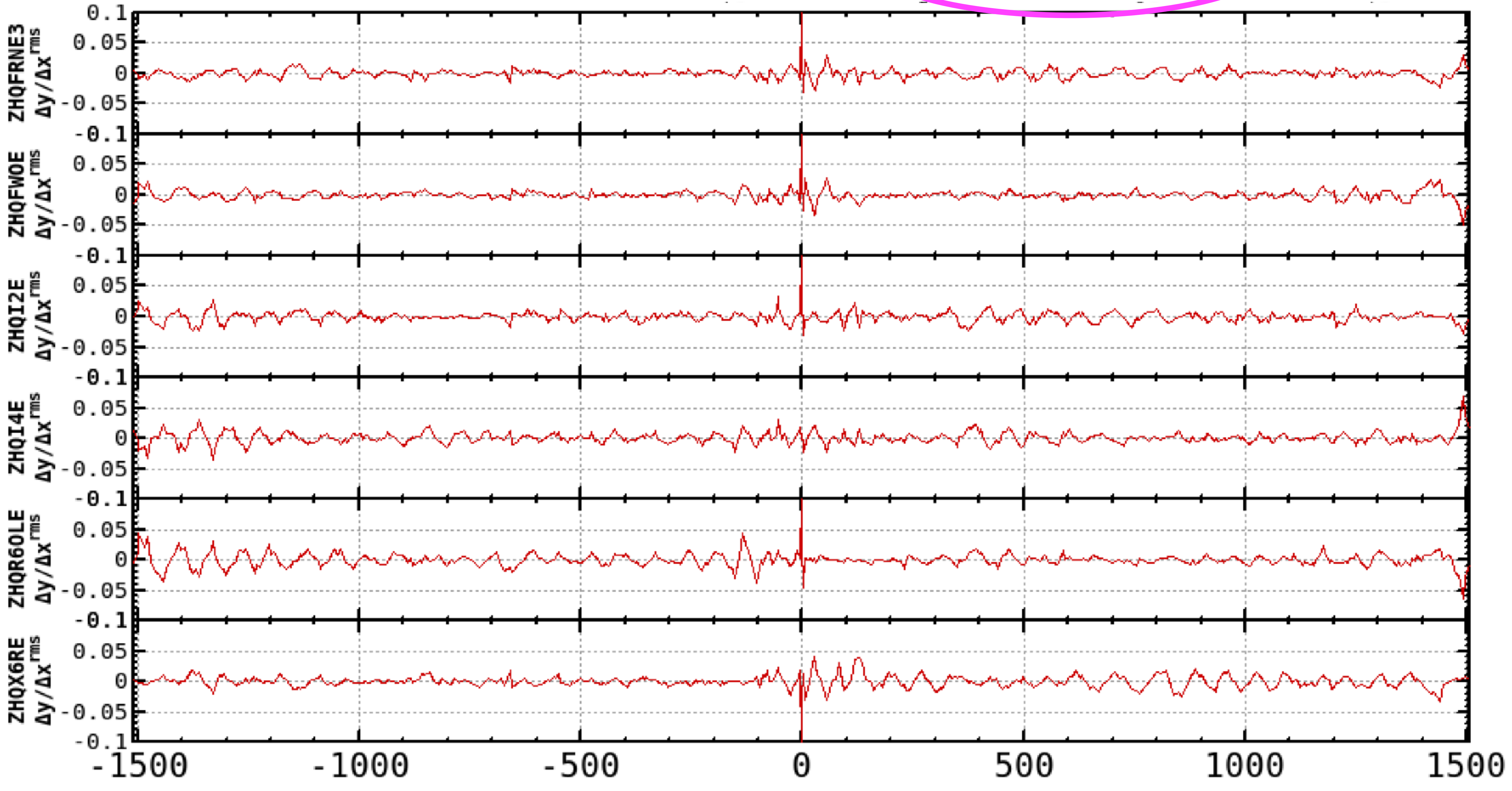
No Significant Difference

$\Delta y^{\mathrm{rms}}/\Delta x^{\mathrm{rms}} = 0.01$ $\varepsilon_y = \sim 20$ pm



IP

$\Delta y^{\mathrm{rms}}/\Delta x^{\mathrm{rms}} = 0.01$ $\varepsilon_y = \sim 70$ pm



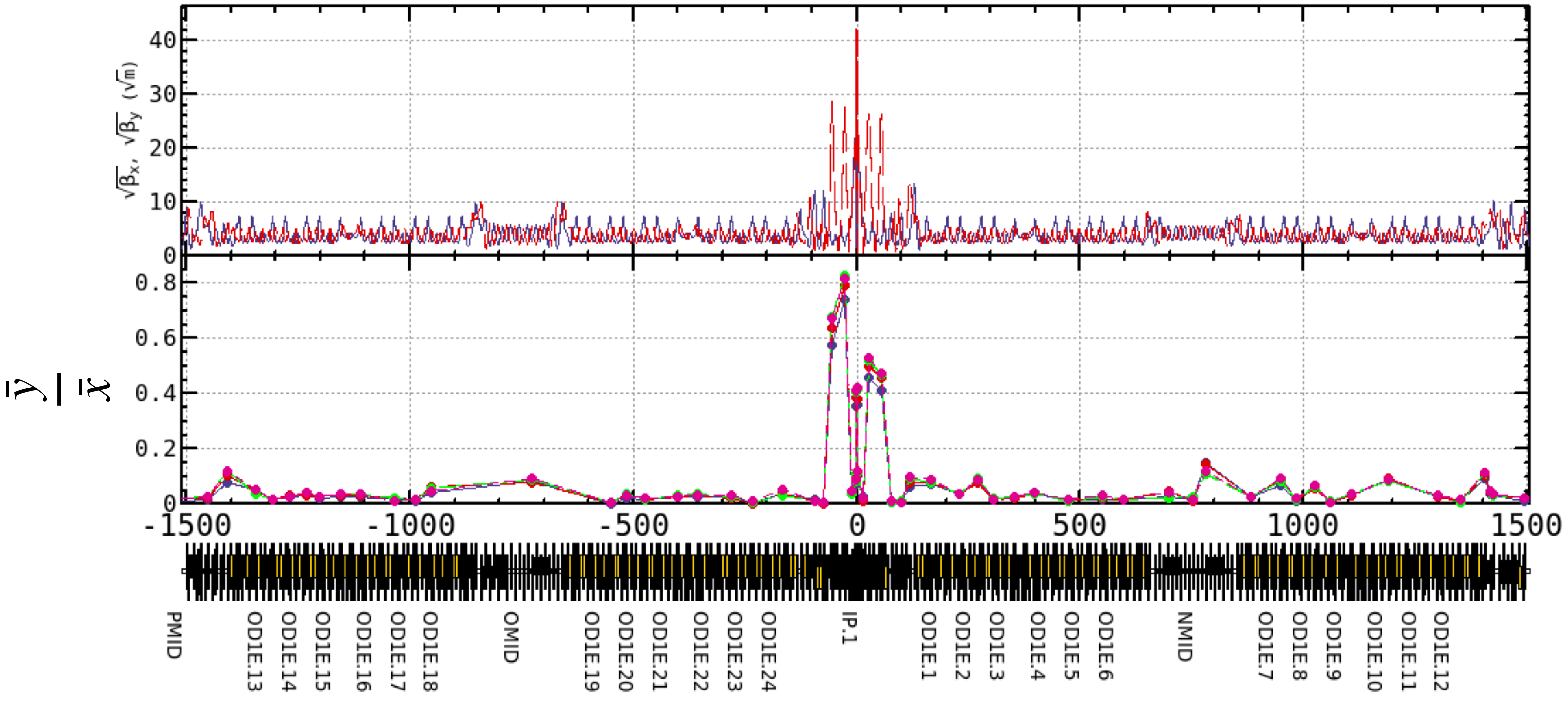
IP

X-Y Coupling Measurement by TBT BPMs

2024 Spring Run

HER
06/17 2024

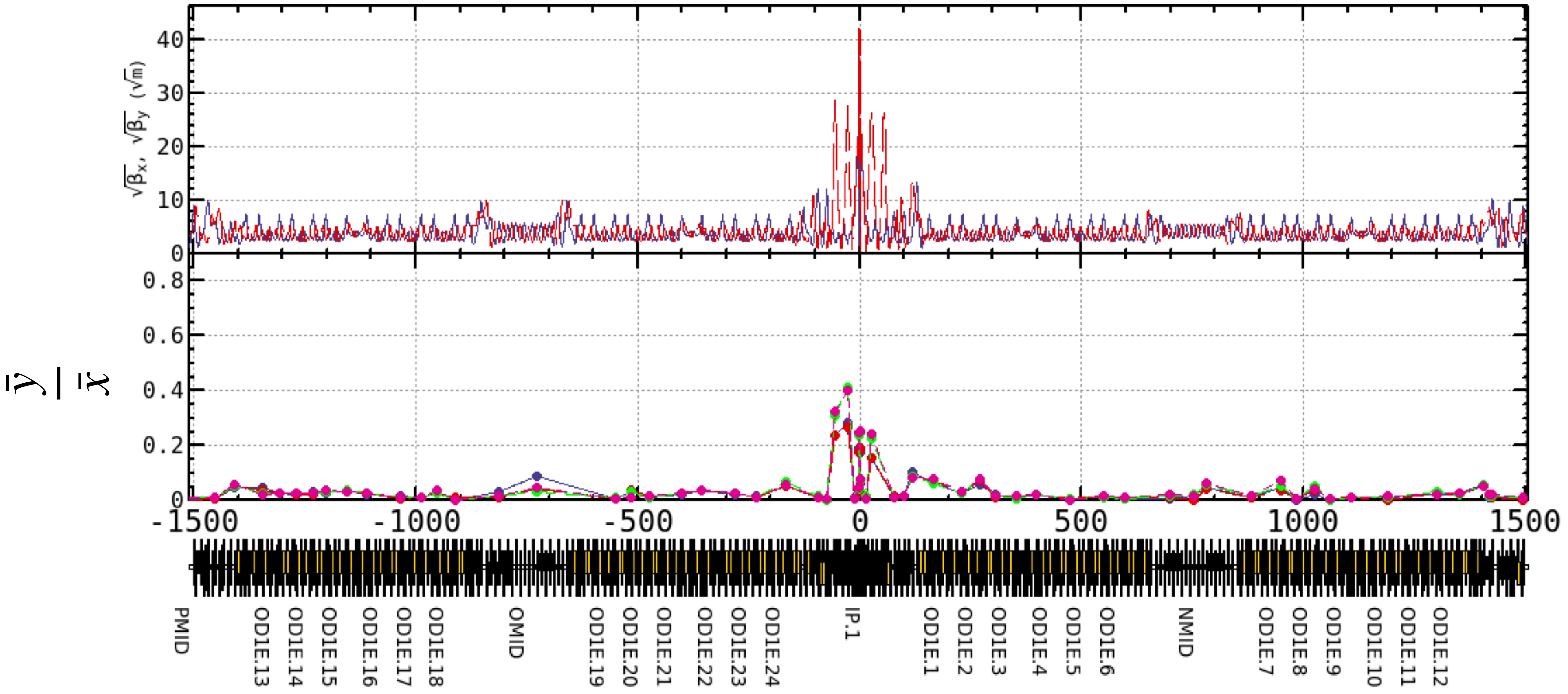
ν_x/ν_y = 45.539 / 43.575



2024 Autumn Run

HER
12/18 2024

ν_x/ν_y = 45.529 / 43.625



X-Y Coupling Looks Like Good.

ε_y = ~20 pm

Effective Emittance

$$\varepsilon_y = \frac{\sigma_y^2}{\beta_y}$$

ε_y = ~70 pm

Unexpected Large Vertical Emittance Occurs in Autumn Run

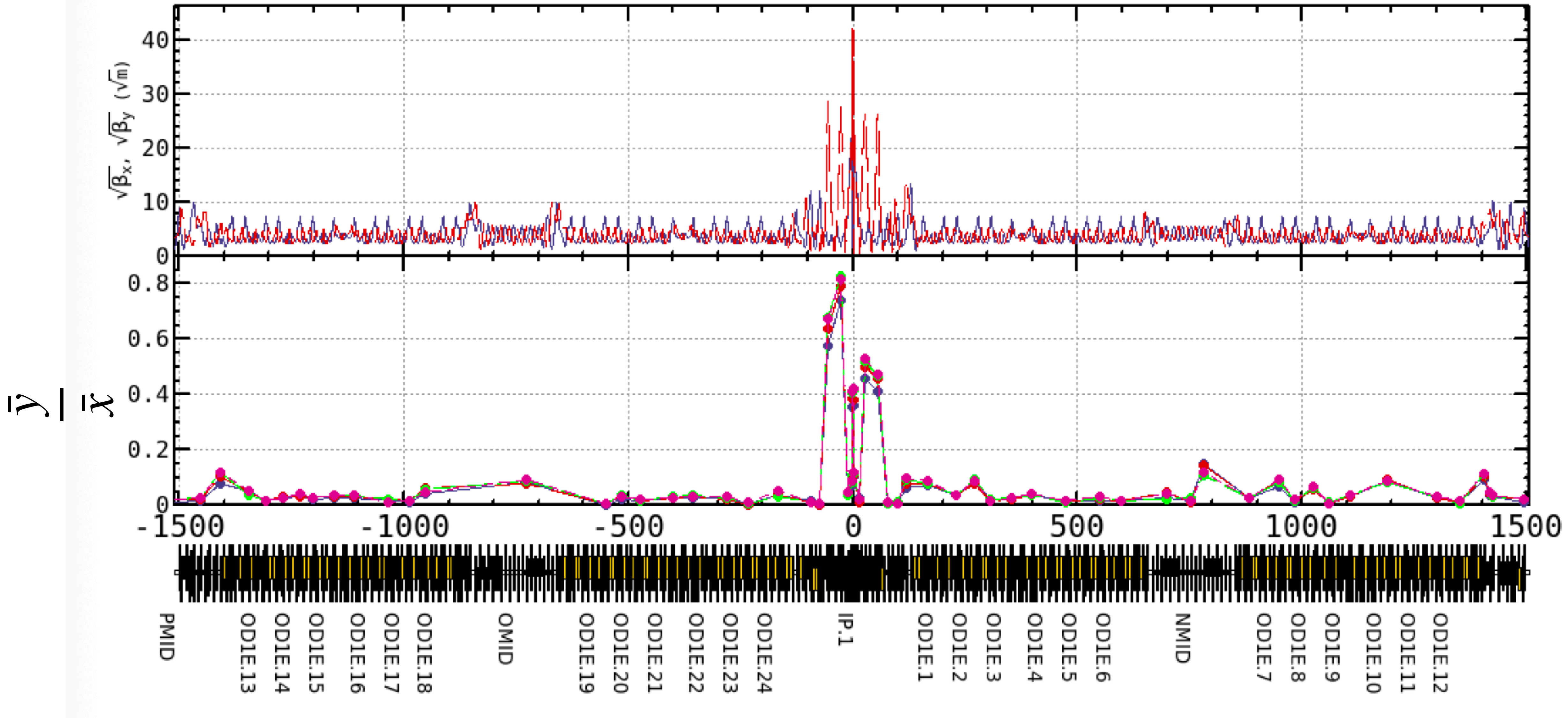
Summary

- Vertical Emittance Affects Luminosity Significantly. In Particular, For Nano-Beam Scheme.
- Emittance for Single Beam (No Collision)
  - X-Y Couplings and Dispersions Affects Effective Emittance (σ_y^2/β_y)
  - Orbit Offset at Sextupole as well as IR Changes X-Y Couplings and Vertical Dispersions
    - Key Point: How To Keep Orbit For Long Time ?
  - Unexpected Large Vertical Emittance in HER (in 2024 Autumn Run)
    - No Such Large Emittance Was Observed Before 2024 Autumn Run.
    - No Abnormal X-Y Couplings and Vertical Dispersions
    - Cause of Large Emittance Still Under Investigation
- Emittance for Two Beam (Collision)
  - Beam-Beam Blowup Under Investigation
  - Combined Effects of Beam-Beam, Lattice Nonlinear, and Wakefield

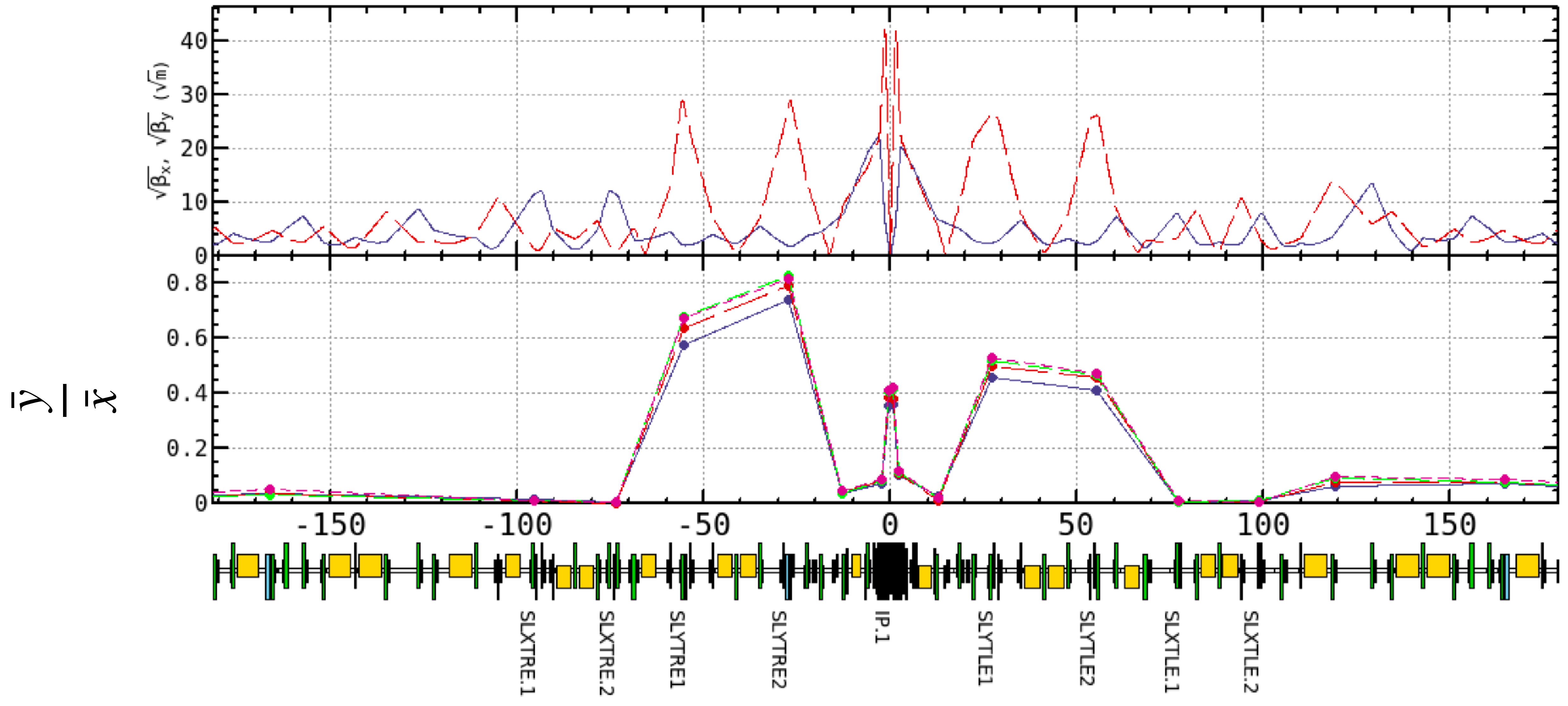
Appendix

HER Spring Run
06/17 2024

ν_x/ν_y = 45.539 / 43.575

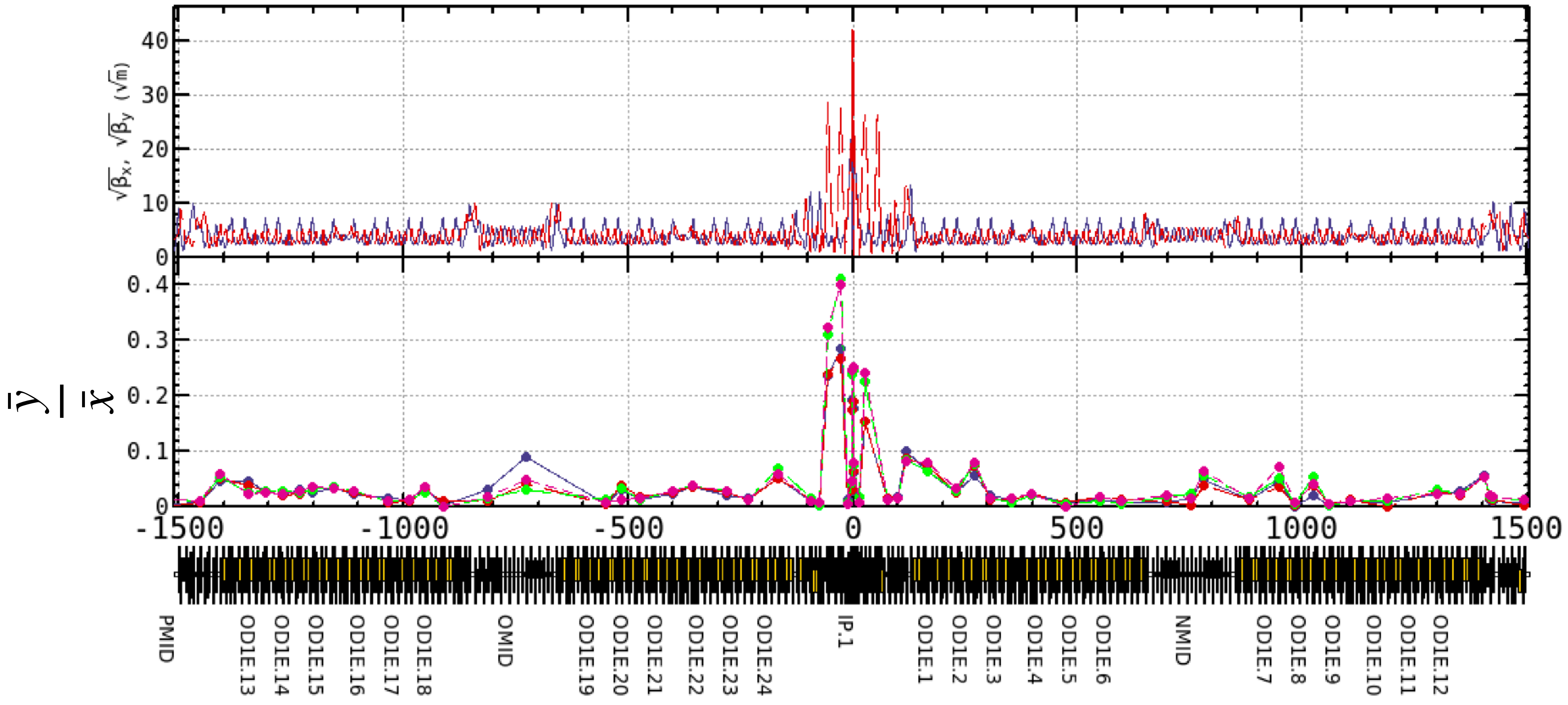


Interaction Region

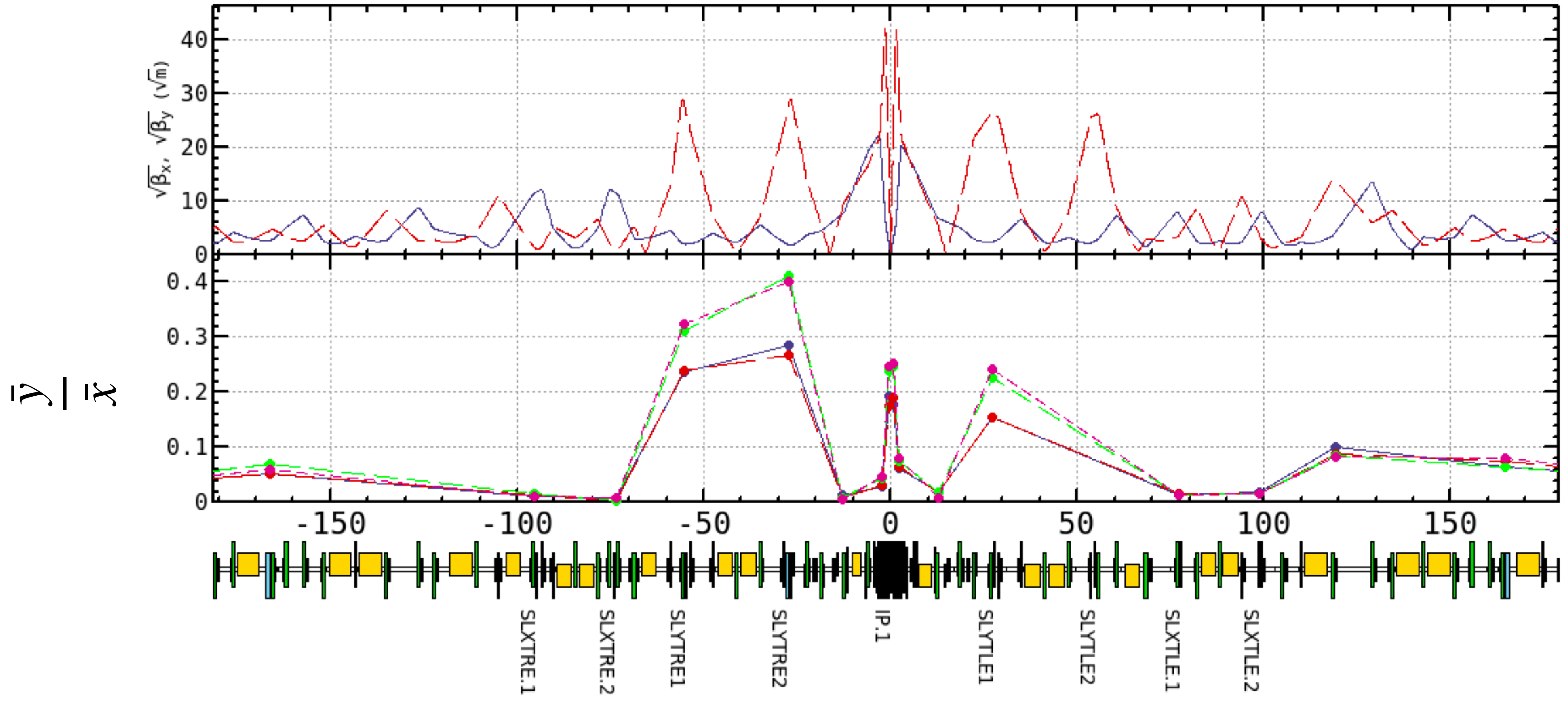


HER Autumn Run
12/18 2024

ν_x/ν_y = 45.529 / 43.625



Interaction Region



Machine Parameters of SuperKEKB

Step-by-Step Improvement

	December 27, 2024		Next Target		Target before LS2		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	1632	1259	2080	1480	3026	2000	mA
Number of bunches	2346		2346		2346		
Bunch current	0.696	0.537	0.89	0.63	1.29	0.85	mA
Horizontal size σ_x*	15.5	16.6	15.5	16.6	15.5	16.6	μm
Vertical cap sigma Σ_y*	375		217		159		mm
Vertical size σ_y*	265		154		112		nm
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.531 / 43.599	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	
β_x* / β_y*	60 / 1.0	60 / 1.0	60 / 0.8	60 / 0.8	60 / 0.6	60 / 0.6	mm
σ_z	4.6 (6.0*)	5.1 (6.1*)	4.6 (6.5*)	5.1 (6.4*)	4.6 (7.5*)	5.1 (6.9*)	mm
Piwinski angle	12.3	12.7	12.3	12.7	12.3	12.7	
Crab waist ratio	80	60	80	80	80	80	%
Beam-Beam ξ_y	0.036	0.027	0.0444	0.0356	0.0549	0.0475	
Specific luminosity	5.8×10^{31}		7.62×10^{31}		9.30×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	**5.1×10^{34}**		**1×10^{35}**		**2.4×10^{35}**		$cm^{-2}s^{-1}$

Luminosity is expected from the achieved values obtained at the beam-beam study.