

Optics

Beam orbit is an integral part of beam optics

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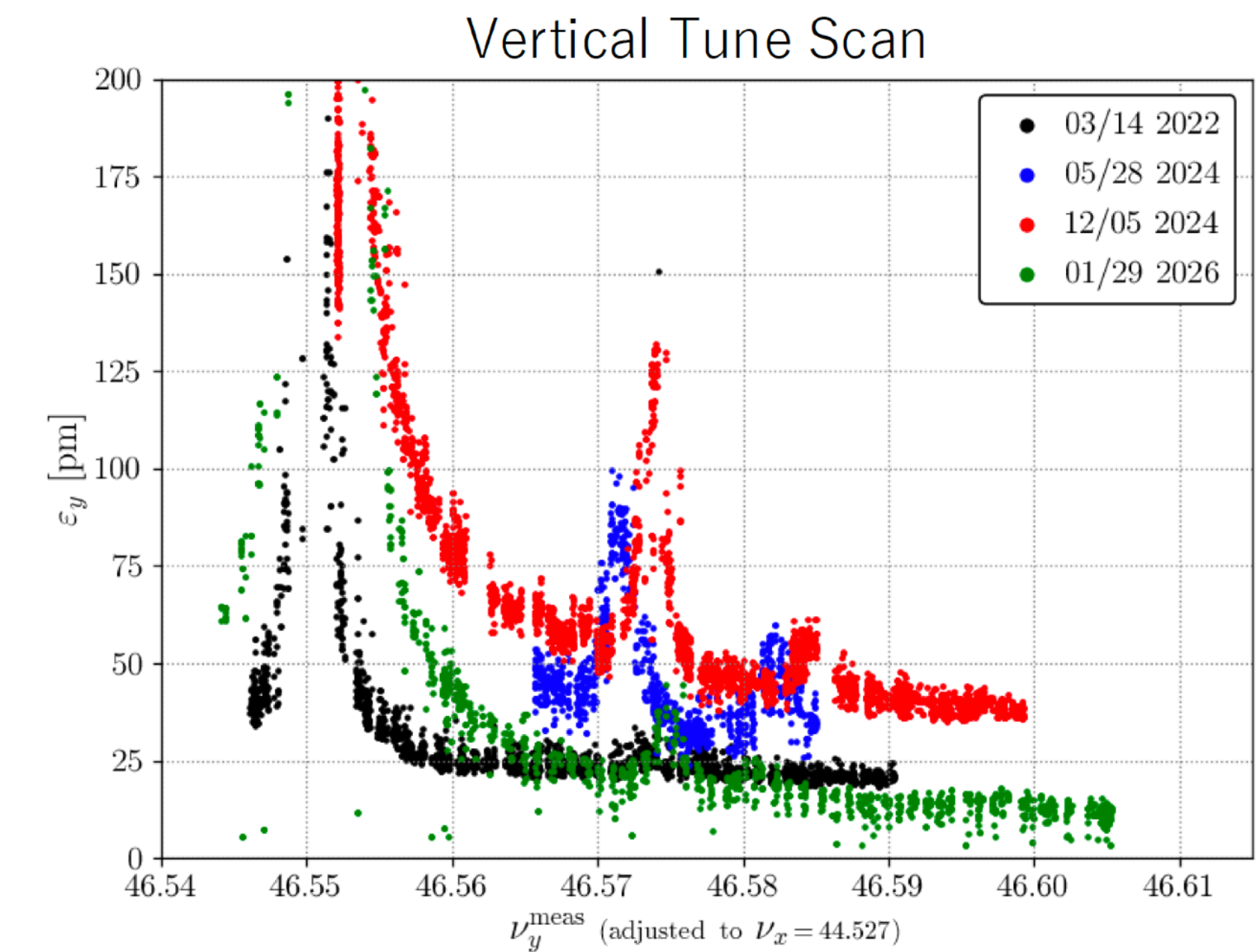
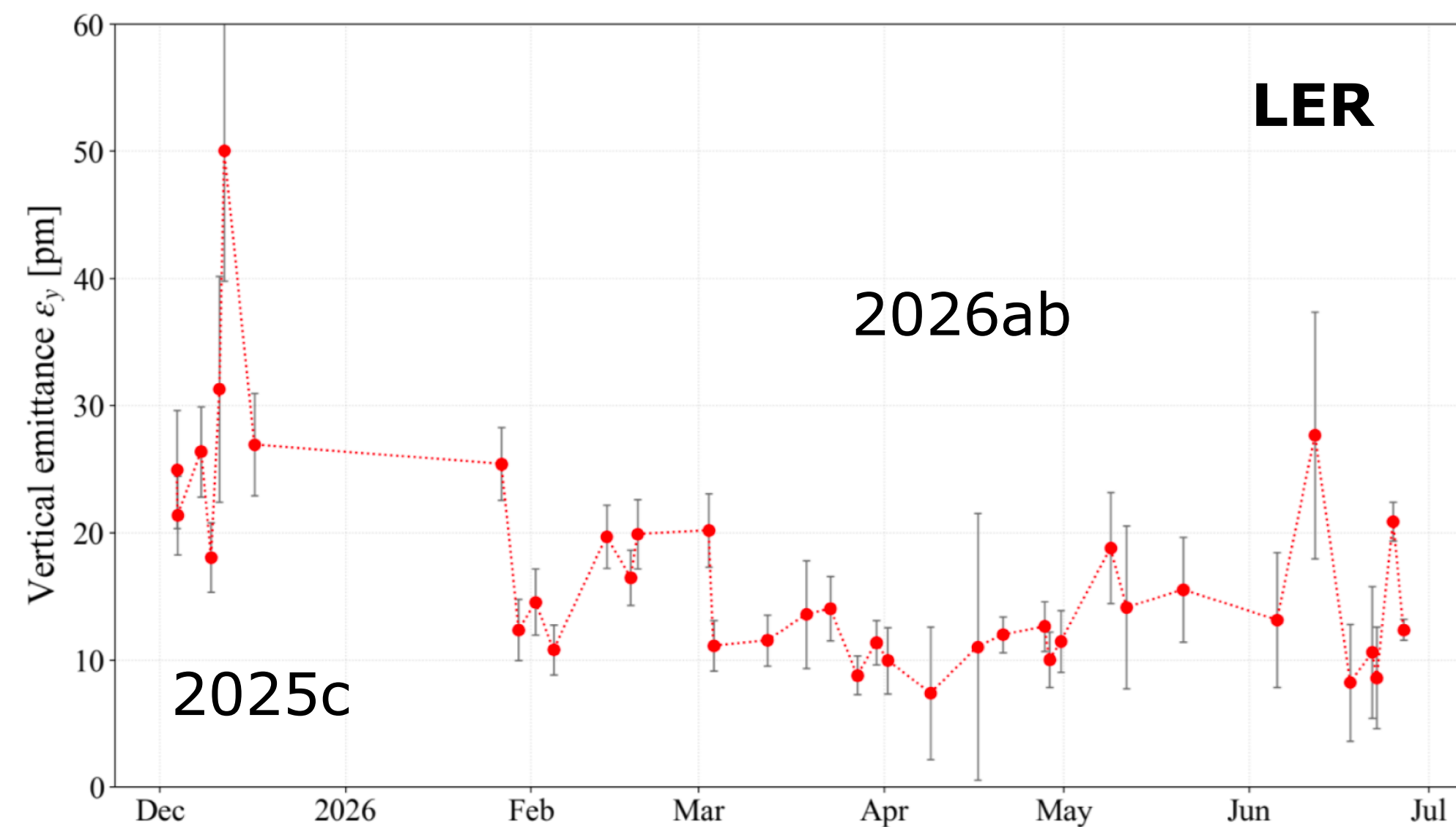
M. Le Garrec, R. Tomas, J. Keintzel (CERN)

The 29th KEKB Accelerator Review Committee

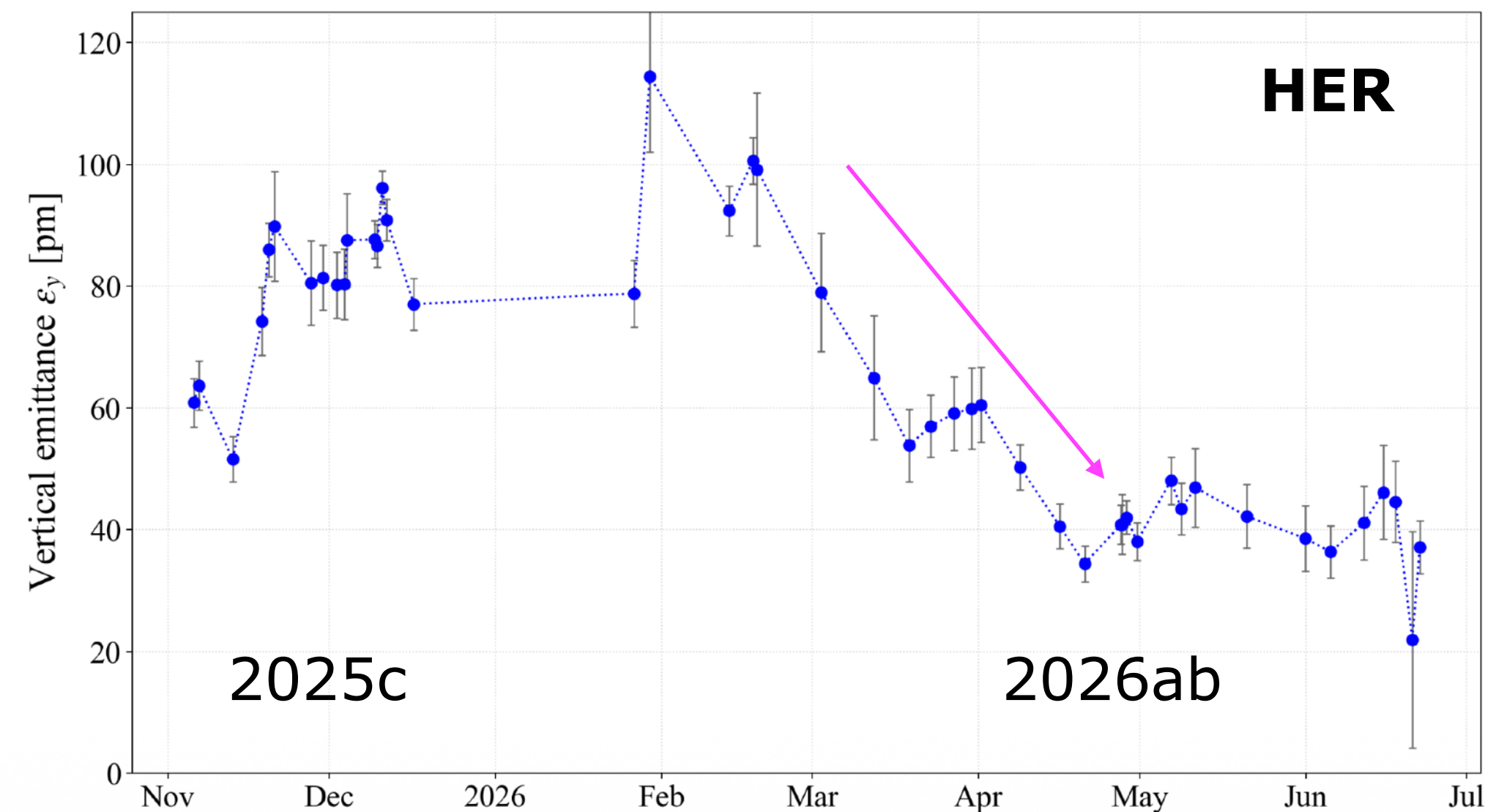
How well can we control the optics at SuperKEKB?

Importance of distinguishing between single-particle optics and collective effects

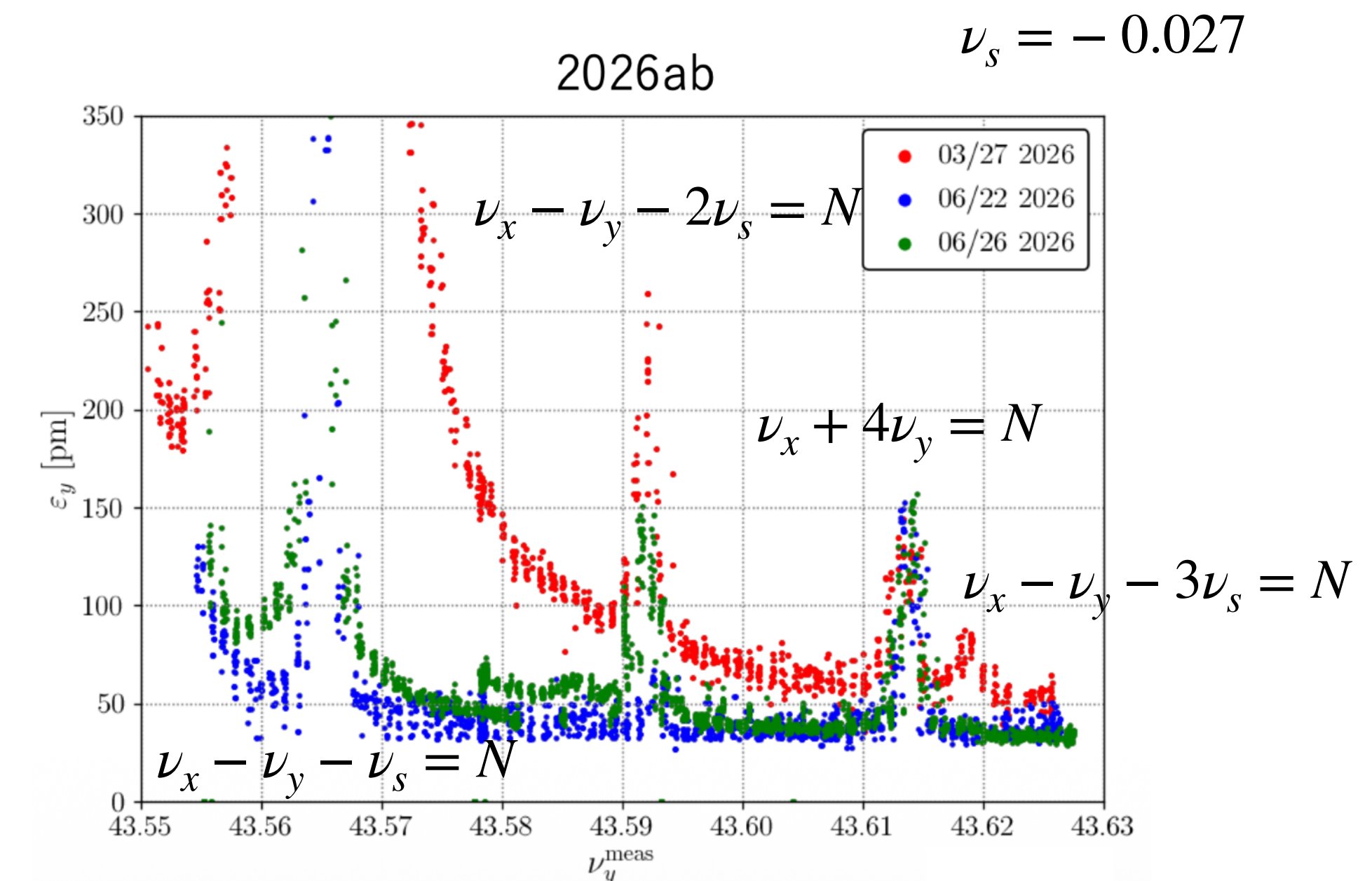
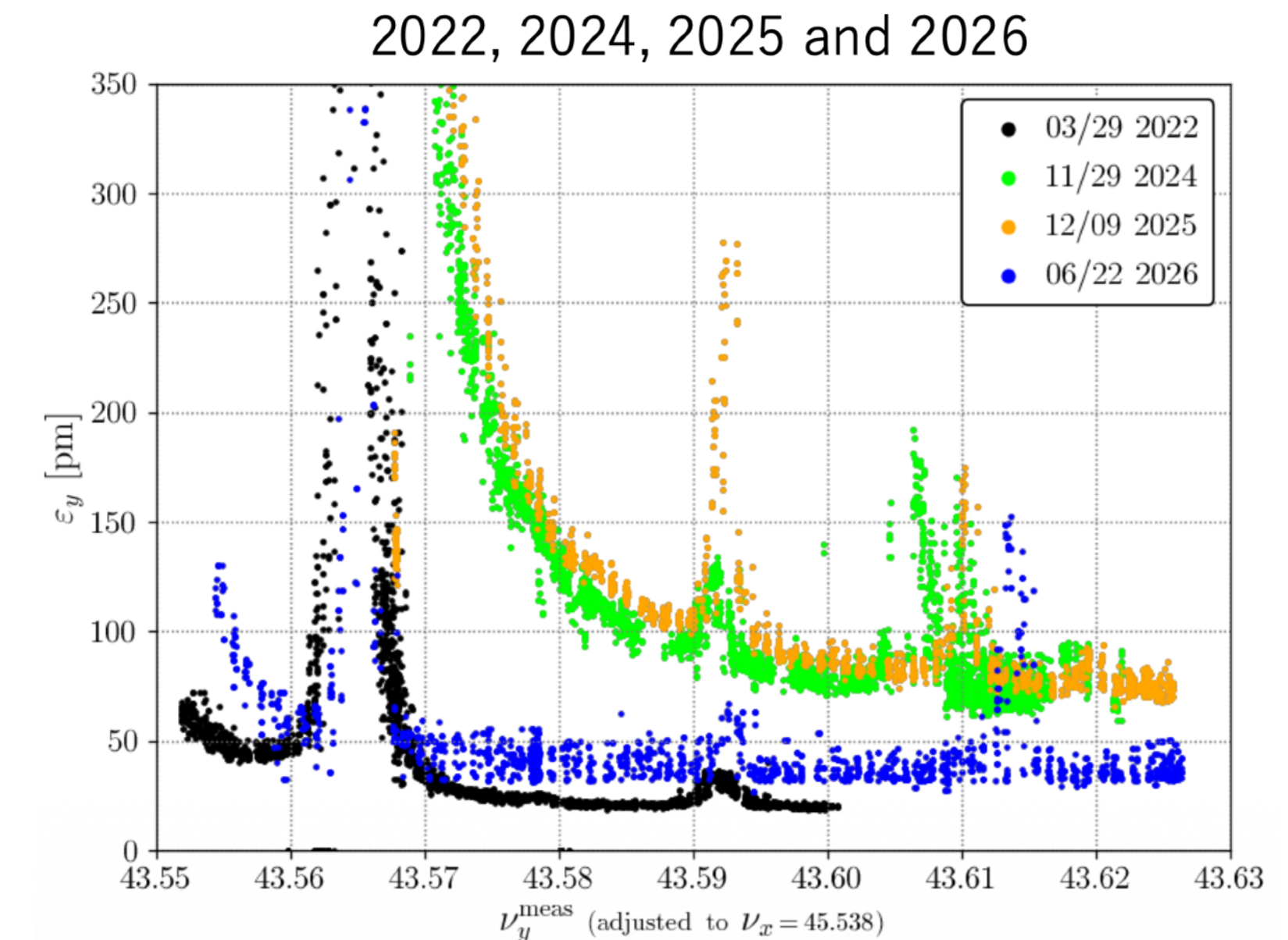
The measured beam properties can be affected not only by machine errors, but also by beam current.



- ε_y is typically 10 - 20 pm in LER. The minimum value is below 10 pm.
- The synchro-beta X-Y resonance sidebands are smaller in 2026 than in 2024, but, still larger than in 2022.
- Importance of the correction of chromatic X-Y coupling using the rotatable sextupoles

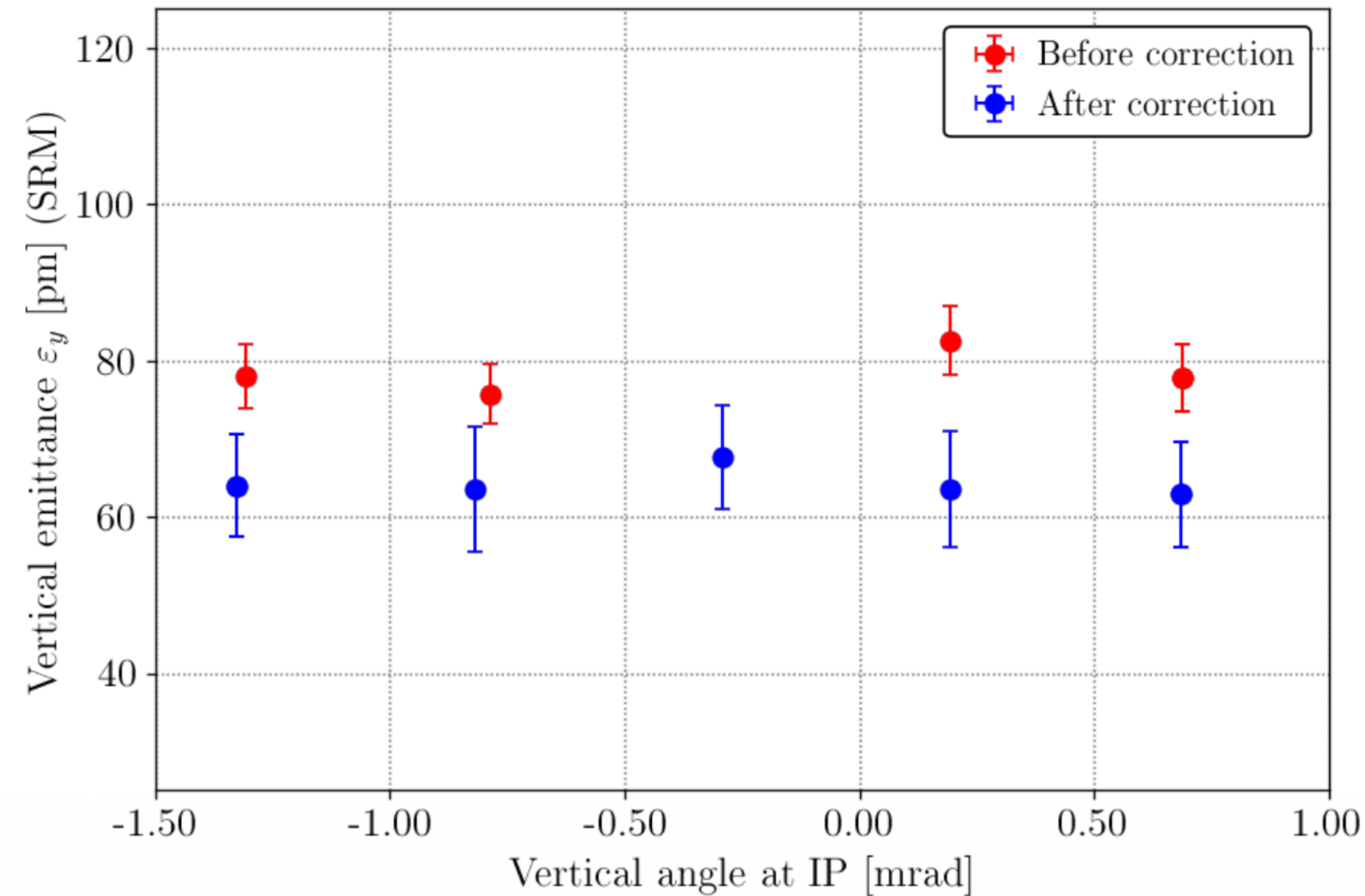


- ε_y was typically 20 - 30 pm in the HER before LS1.
- ε_y became 80 - 100 pm after LS1. The reason for this increase is still mystery.
- Then, ε_y gradually decreases during the 2026ab run.
- The sidebands of synchro-beta X-Y resonances drastically change.
- The underlying mechanism is not clear.



Vertical Emittance and Vertical Angle at the IP in the HER

Range of vertical angle is ± 1 mrad



- The vertical orbit angle was varied over a range of ± 1 mrad, with optics corrections for X-Y coupling and vertical dispersion performed at each point.
- The vertical emittance remains stable after optics corrections, even though the vertical orbit angle at the IP is varied.

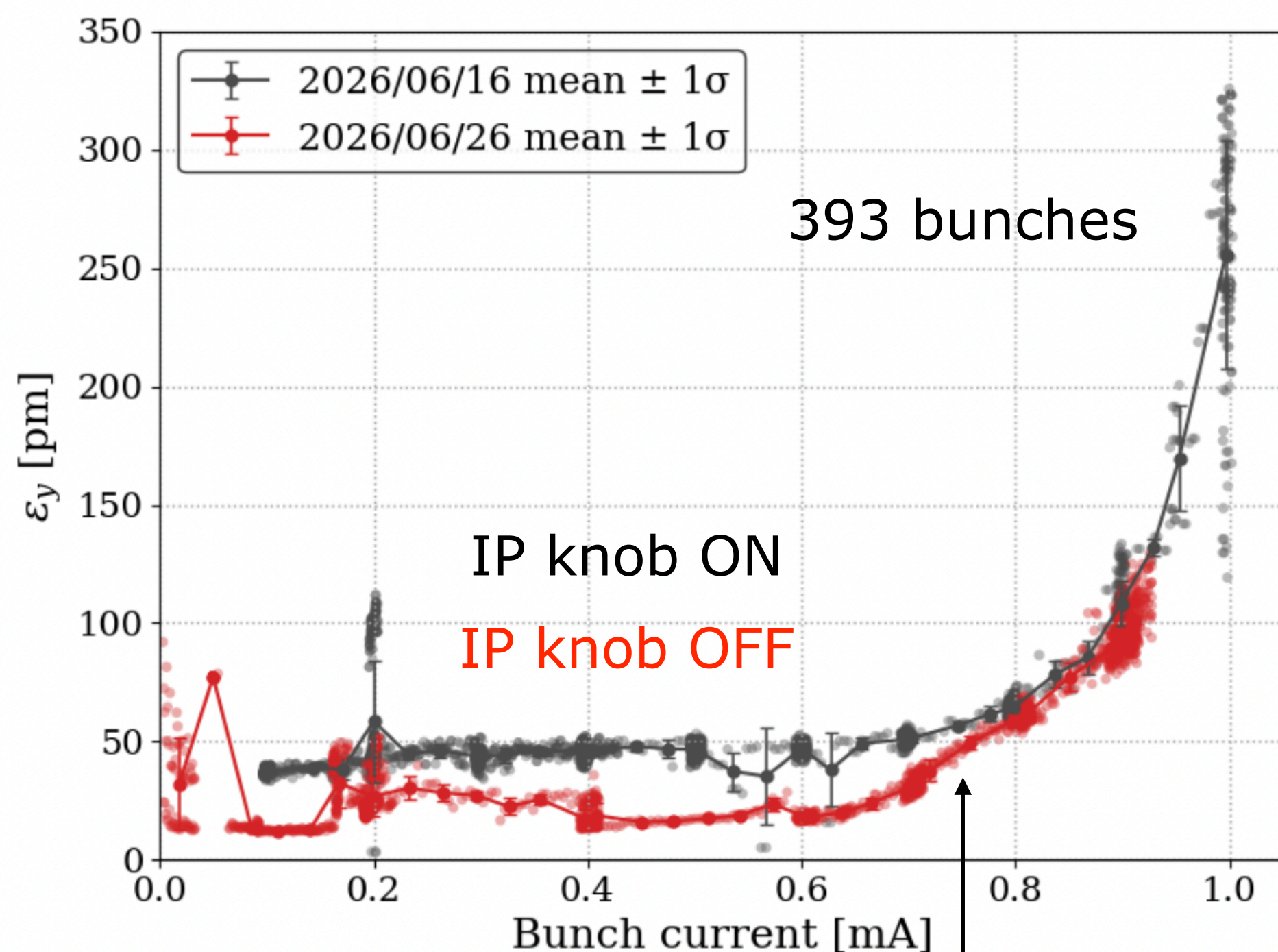
Note: Luminosity performance and vertical angle at the IP will be presented at the Beam-Beam TF talk.

Vertical Emittance of Single Beam: Bunch Current Dependence

No Collision

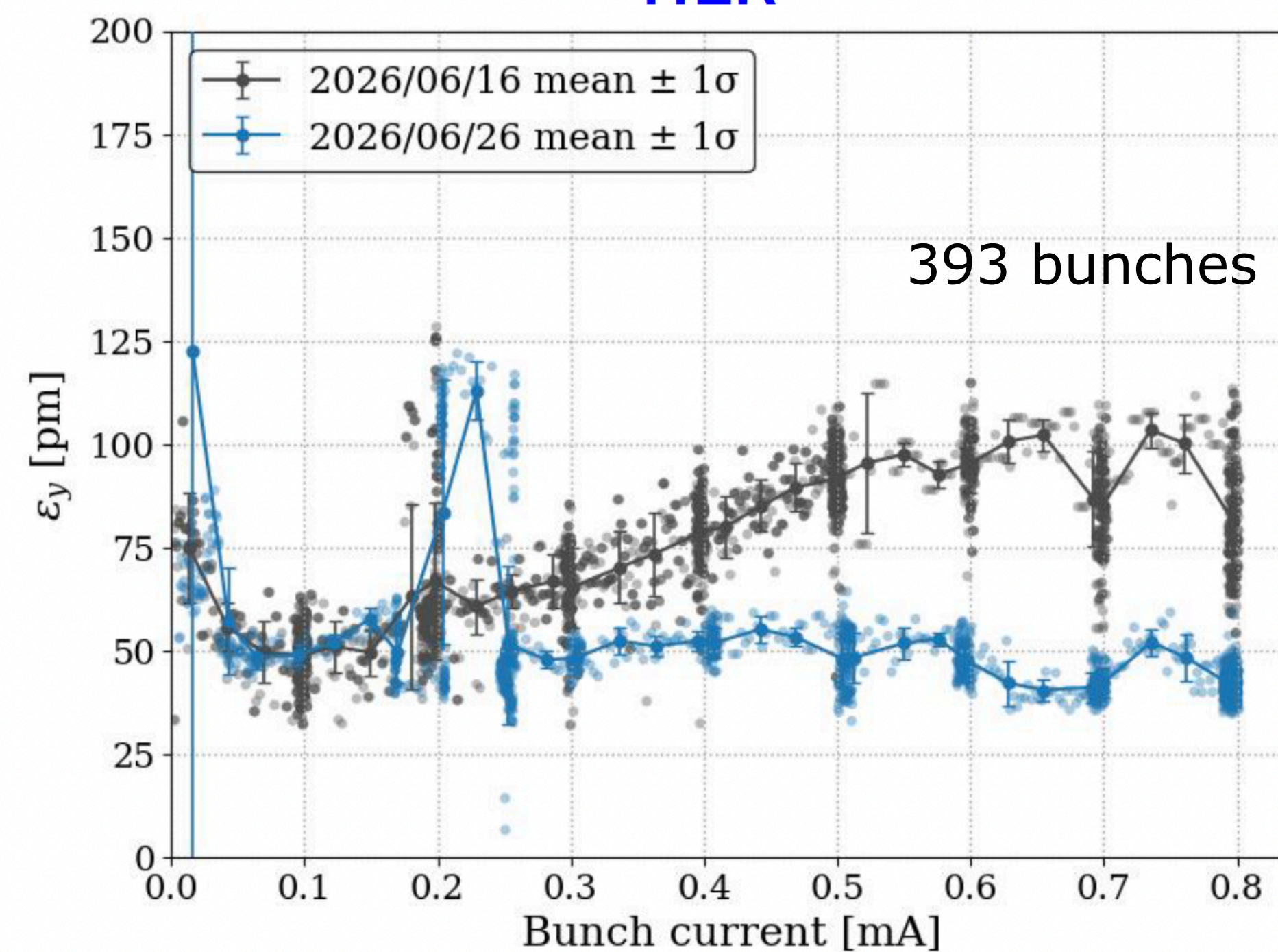
LER

HER



ϵ_y increases from about 10 pm to 50 pm when IP knob is turned on.

Impedance effect: -1 mode instability ?



ϵ_y depends on bunch current in the HER when BxB FB was slightly reactive on June 16.

The BxB FB gain and phase were not sufficiently optimized.

Impact of IP knob on the vertical emittance is significant in the LER.
Optimization of the BxB FB is essential before measuring the vertical emittance.

Dynamic Aperture

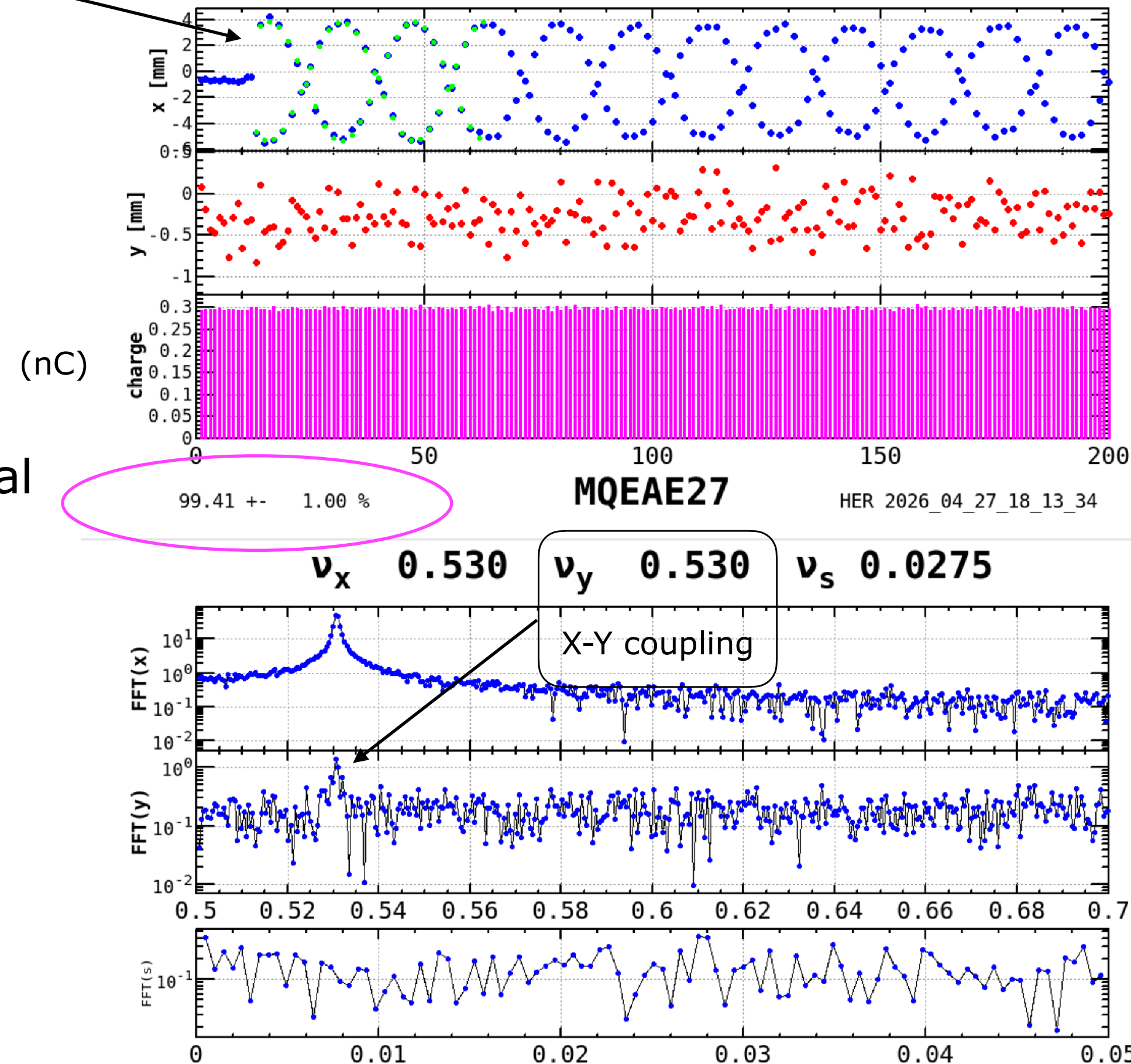
- Measurement of DA
- Optimization of DA
- Constrained downhill simplex method (range of sextupole strengths, chromaticity, etc.)
 - Downhill simplex method is highly dependent on initial values.
 - We need a more robust approach. → CMA-ES + surrogate method (ML/AI talk)
- We plan to test new sets of sextupole strengths at the machine.

Measured orbit and intensity of a single bunch by TBT BPM (Horizontal kick): 2048 turns

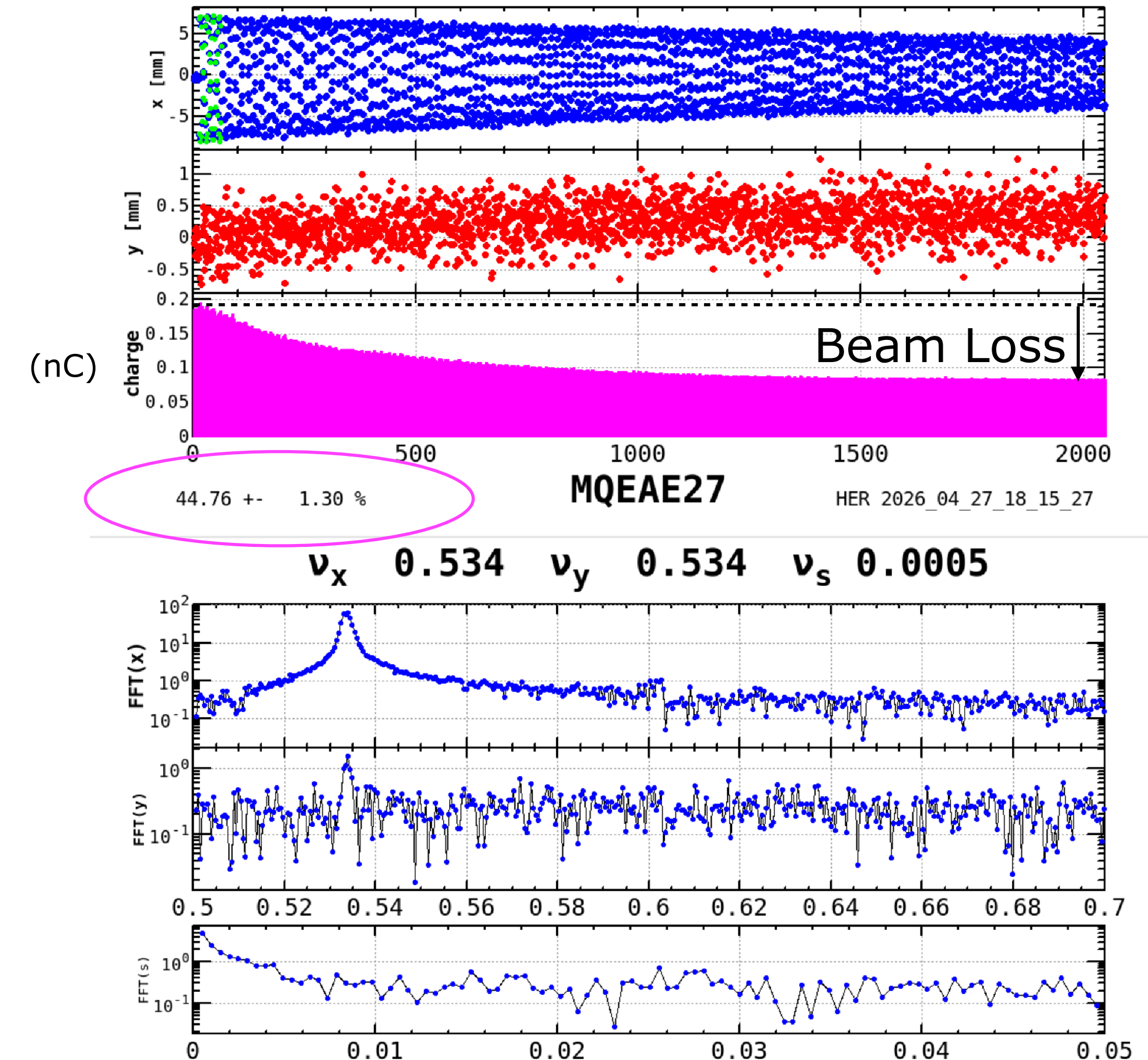
Single Kick
by Kicker

Horizontal kick: $\nu_x / \nu_y = 45.530 / 43.603$

Survival
Rate



Horizontal kick: $\nu_x / \nu_y = 45.534 / 43.603$



A single bunch is kicked once. The subsequent orbit motion is recorded for 2048 turns.
Fit the data over ~ 50 turns to extract the initial amplitude.
By changing the kick amplitude and measuring the survival rate, we can determine the DA.

Dynamic Aperture Measurements in the LER and HER

$$\beta_x^* = 60 \text{ mm} / \beta_y^* = 1 \text{ mm}$$

$$\beta_x^* = 55 \text{ mm} / \beta_y^* = 0.9 \text{ mm}$$

Transverse Aperture

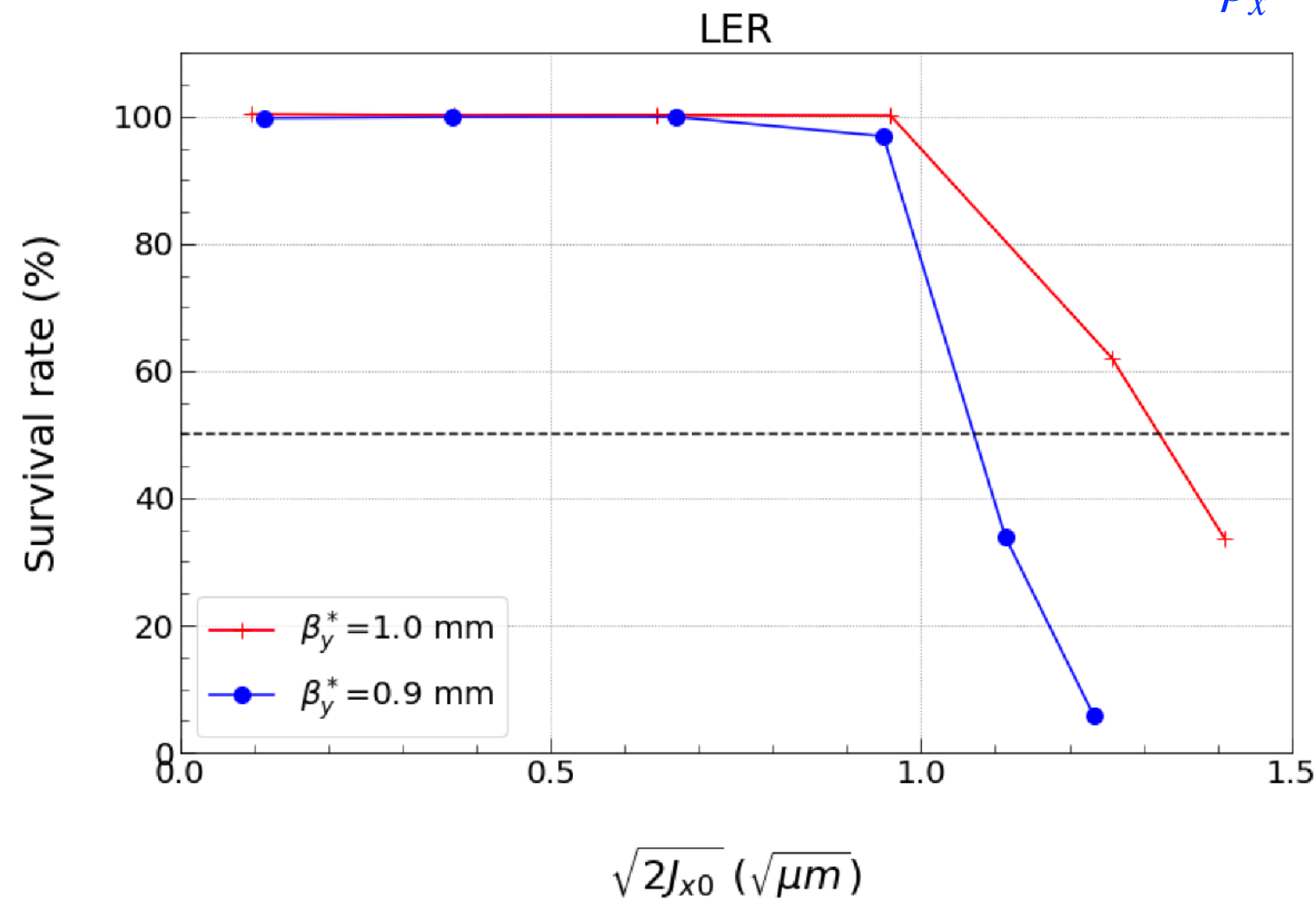
Collimator settings are the same for $\beta_y^* = 1 \text{ mm}$ and 0.9 mm .
(nominal settings for physics run)

Sextupole strengths are adjusted according to β_y^* and β_x^* .

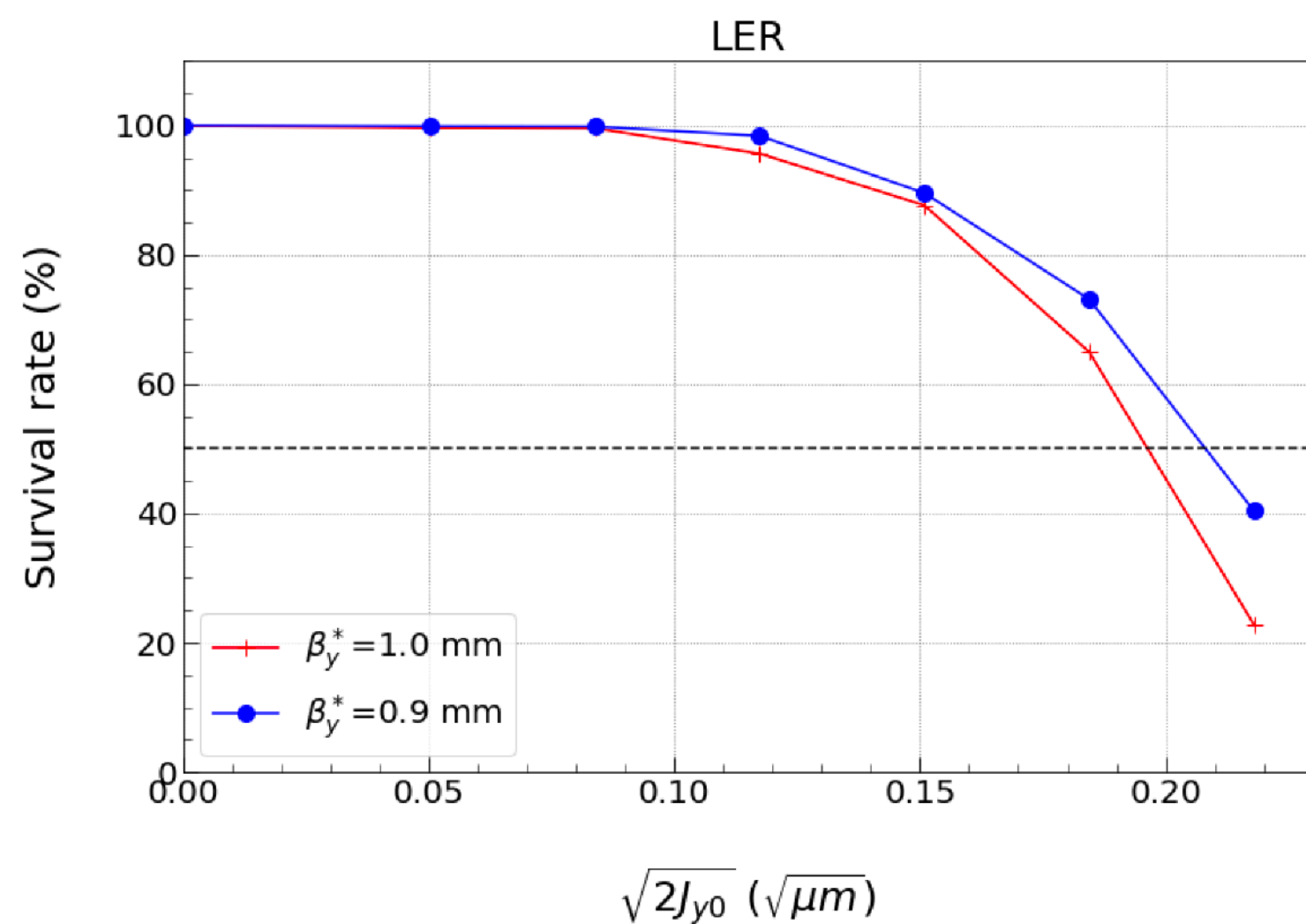
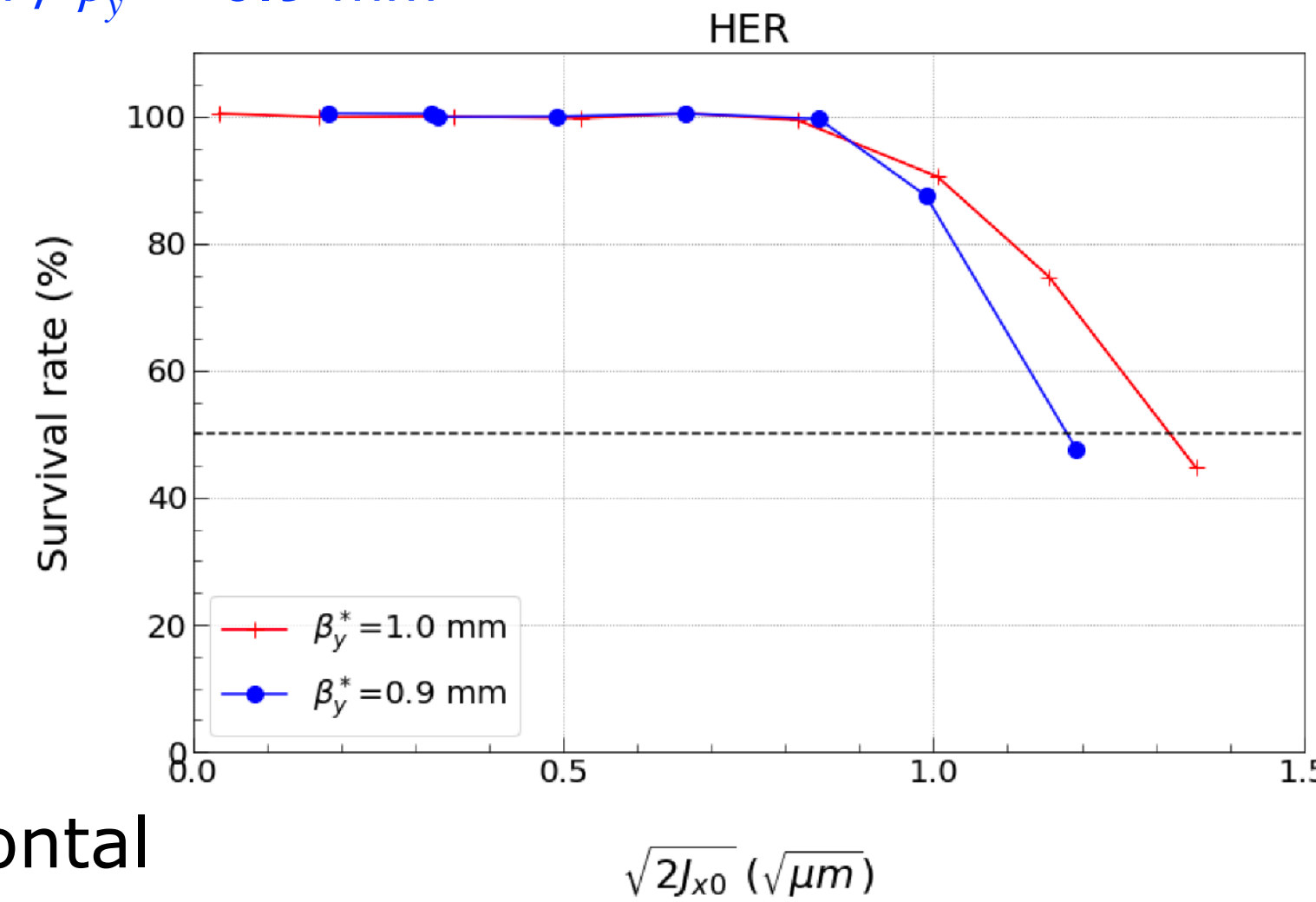
A significant reduction in the horizontal dynamic aperture is observed for the smaller β_x^* and β_y^* optics, particularly in the LER

The vertical dynamic aperture shows smaller changes.

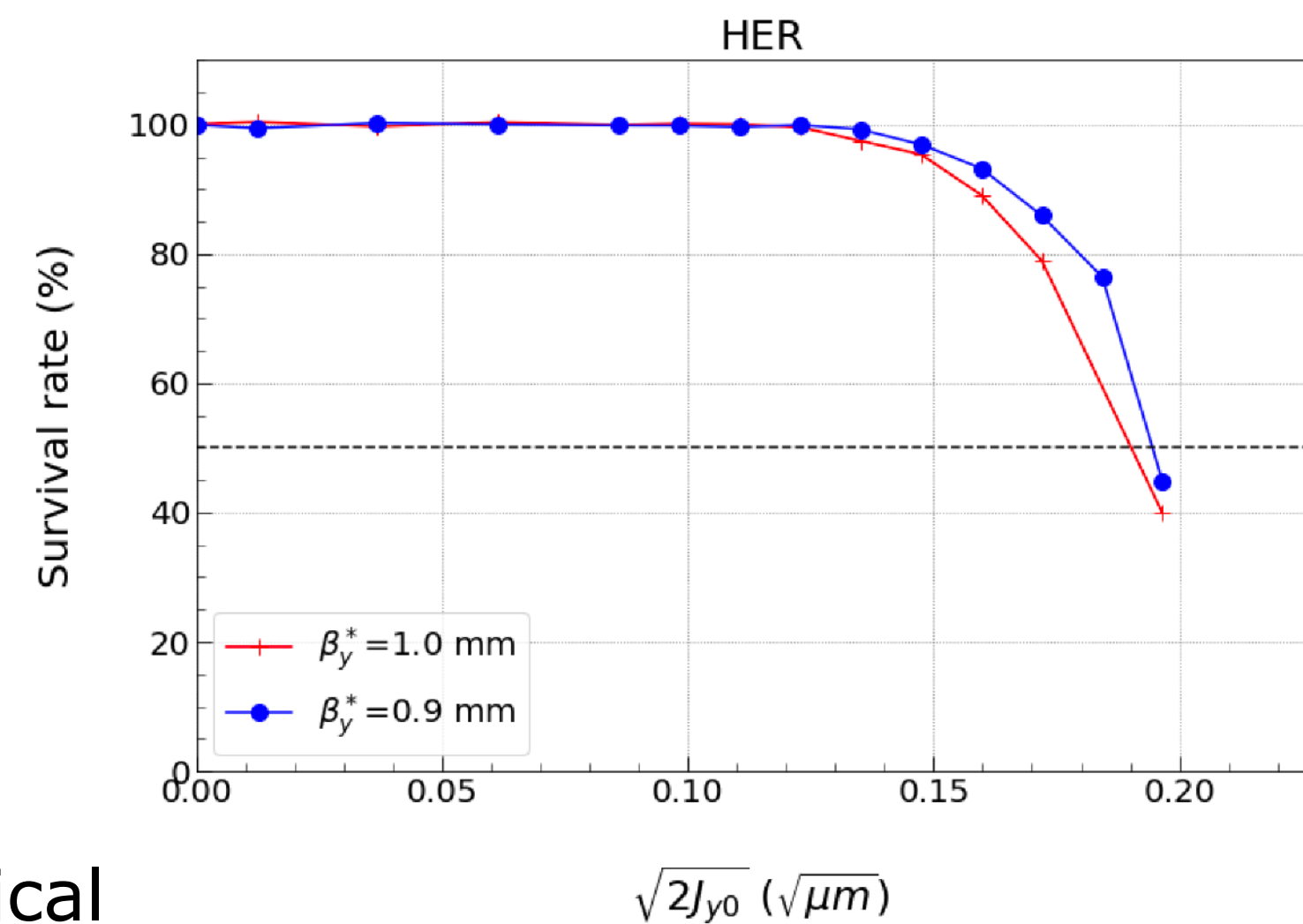
Definition of the dynamic aperture is the amplitude at 50 % loss here.



Horizontal

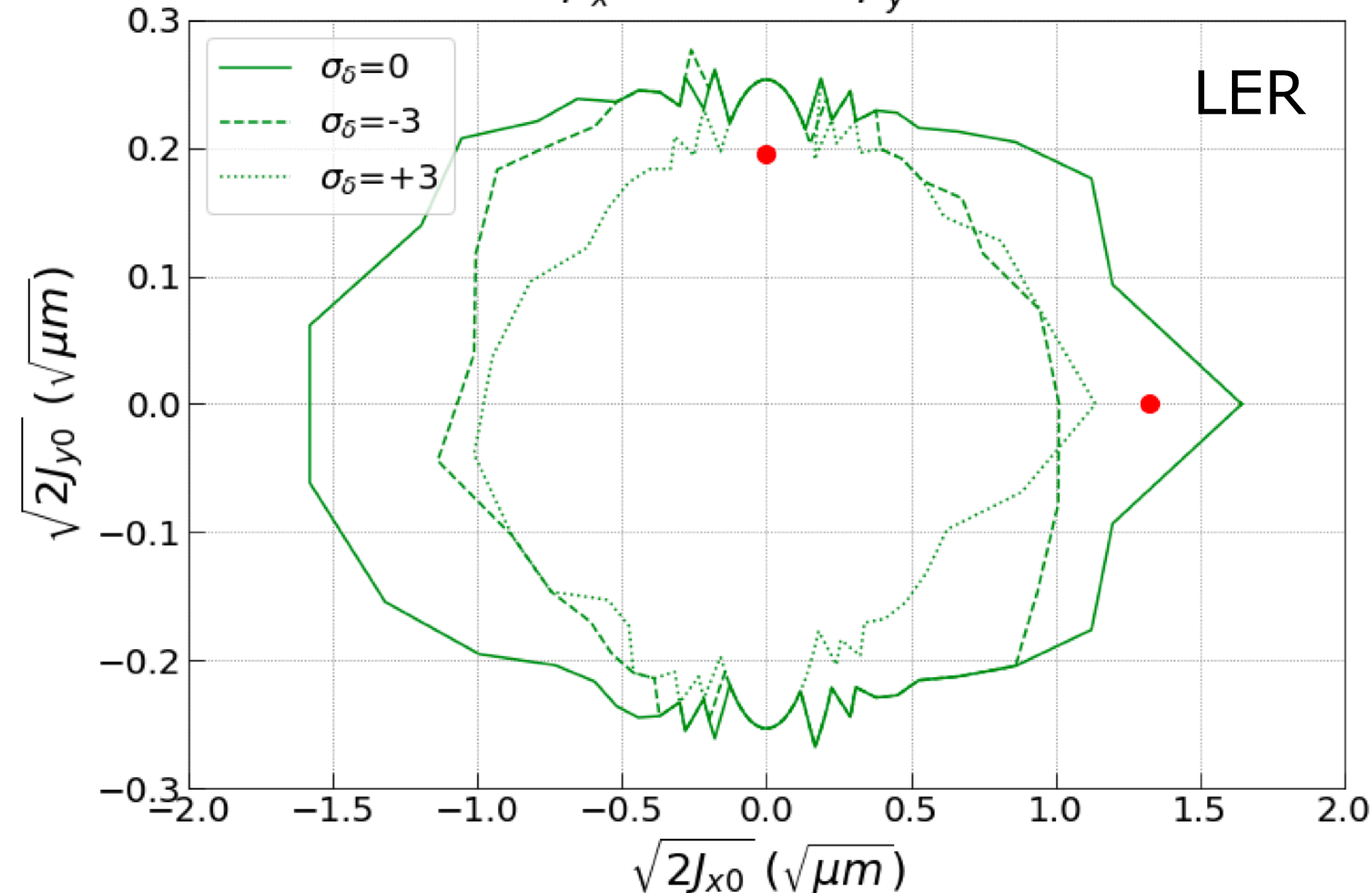


Vertical



Comparison between Measurements and Simulations in the LER

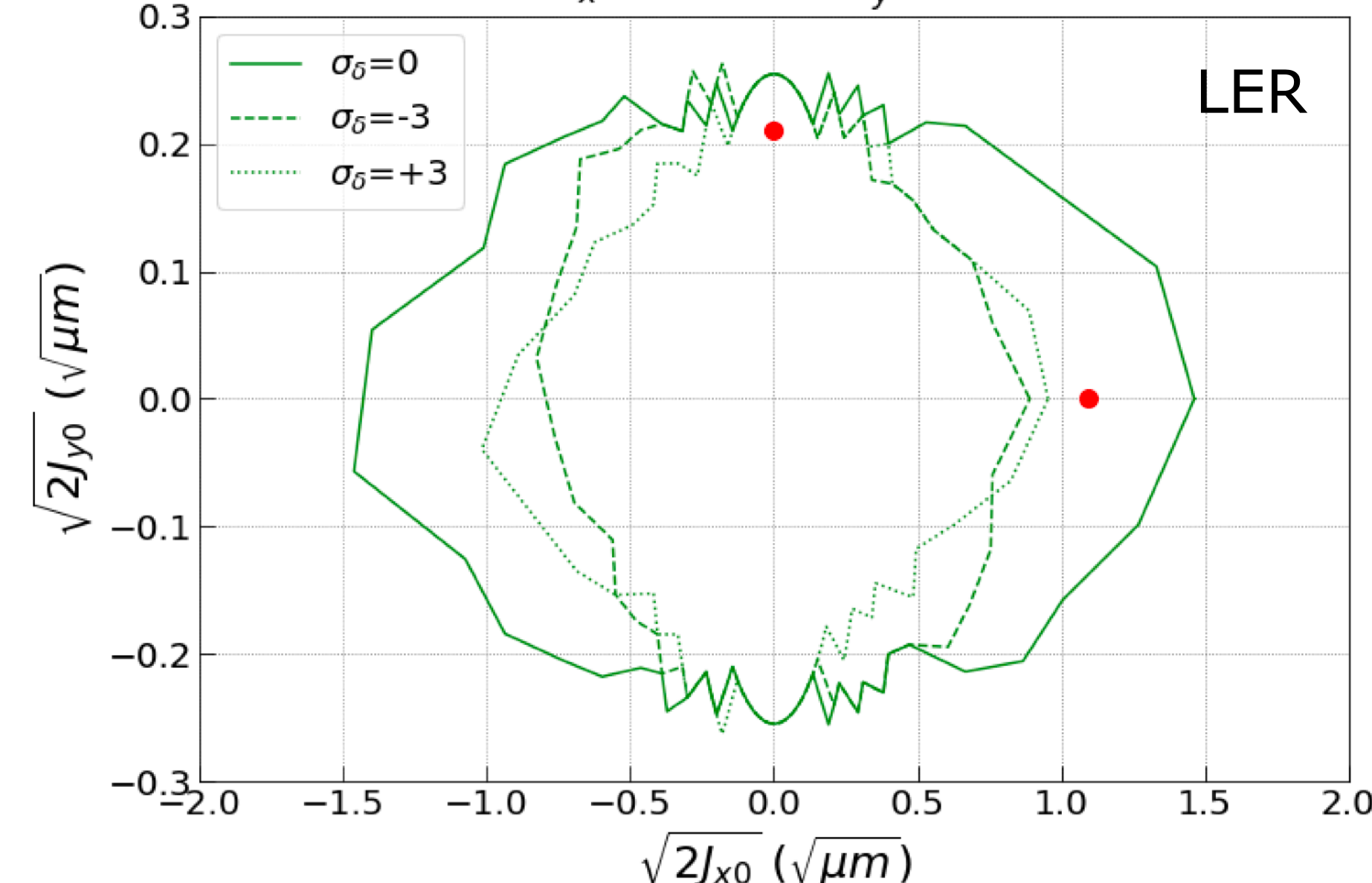
LER: $\beta_x^* = 60 \text{ mm} / \beta_y^* = 1 \text{ mm}$



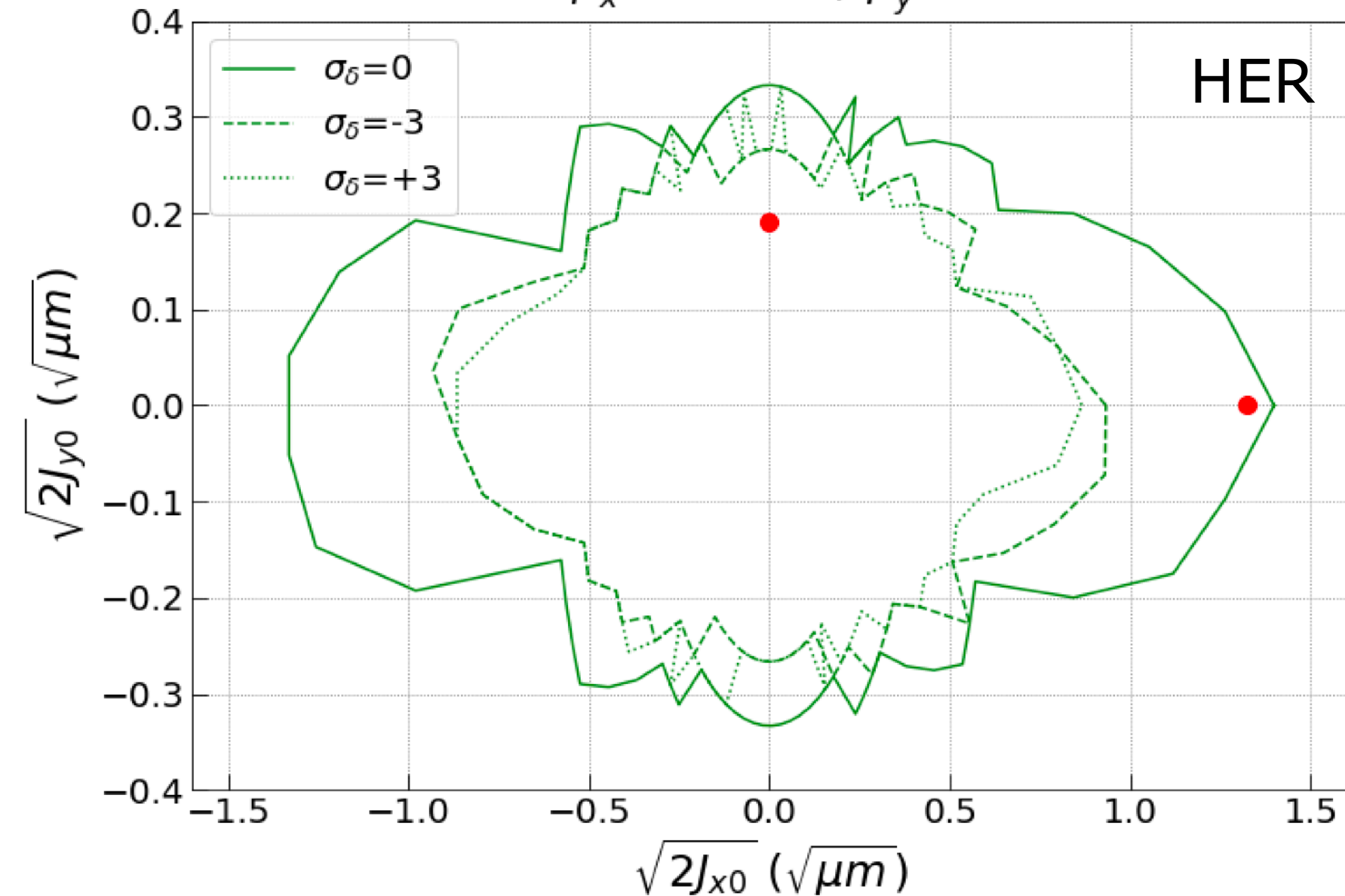
Measured
Aperture

Calculation of DA (2048 turns)
Synchrotron rad: ON
Collimators: ON
No machine error

LER: $\beta_x^* = 55 \text{ mm} / \beta_y^* = 0.9 \text{ mm}$



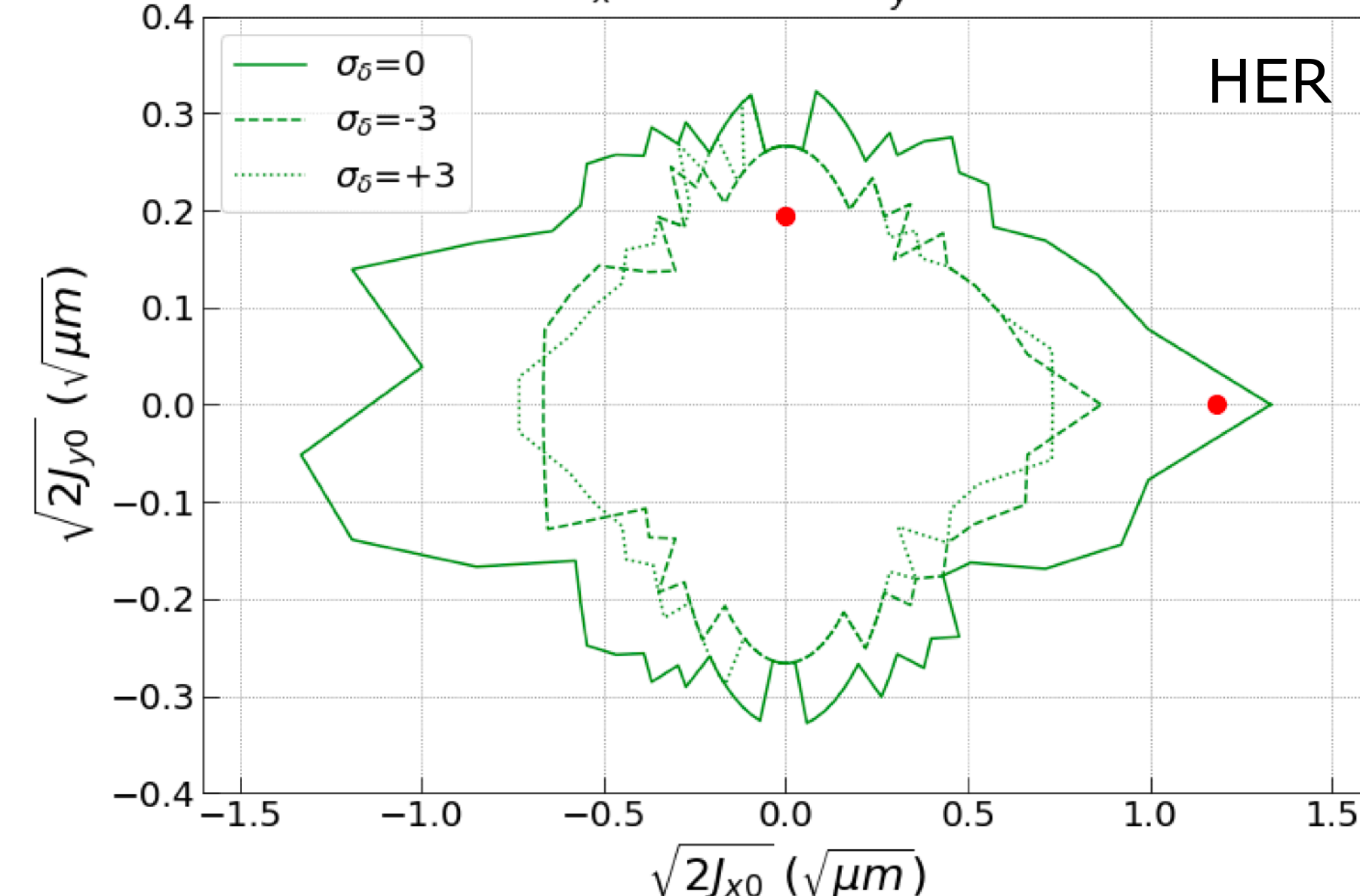
HER: $\beta_x^* = 60 \text{ mm} / \beta_y^* = 1 \text{ mm}$



The measured vertical
aperture is smaller than the
simulation.

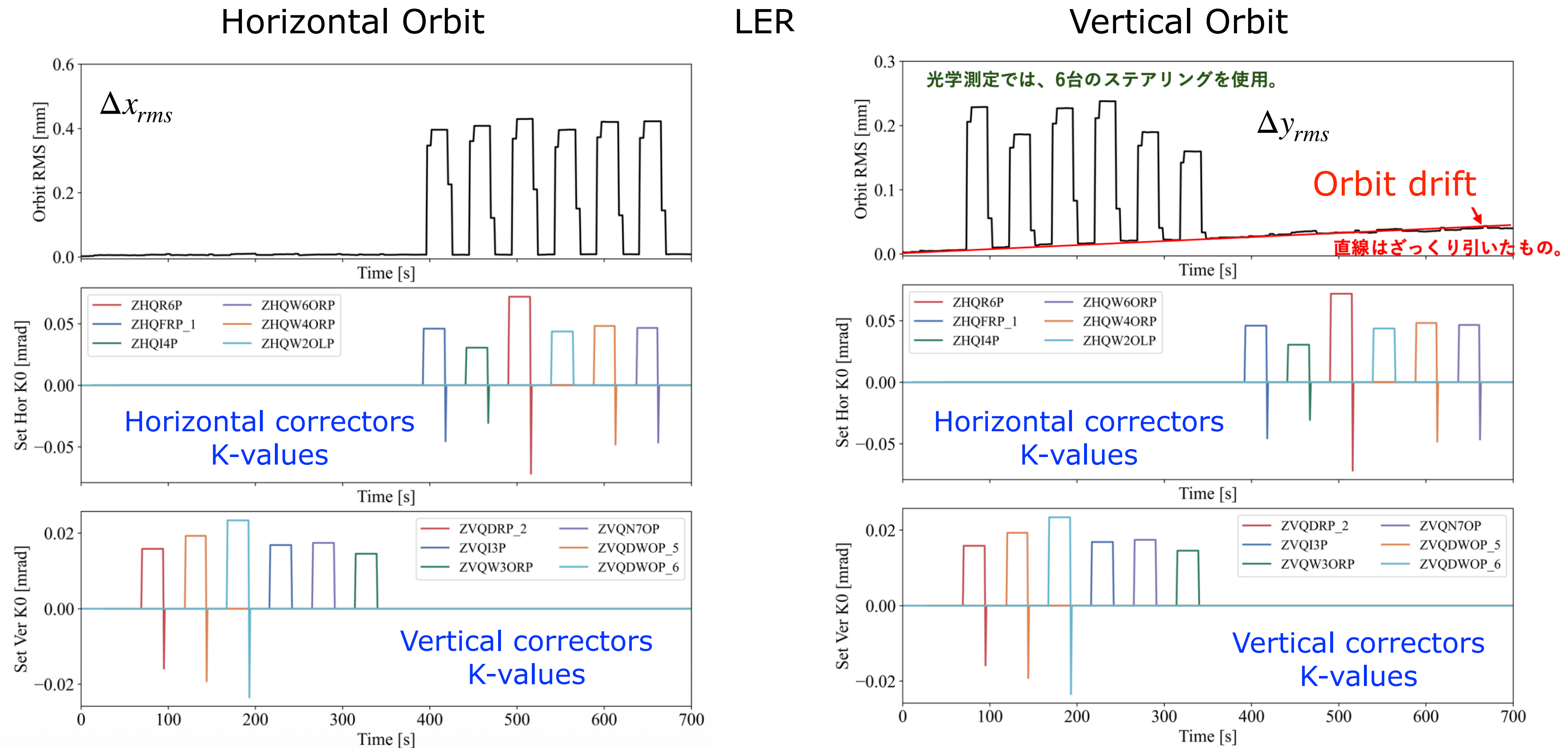
The vertical apertures in the
LER and HER are almost the
same.

HER: $\beta_x^* = 55 \text{ mm} / \beta_y^* = 0.9 \text{ mm}$



Optics Issues

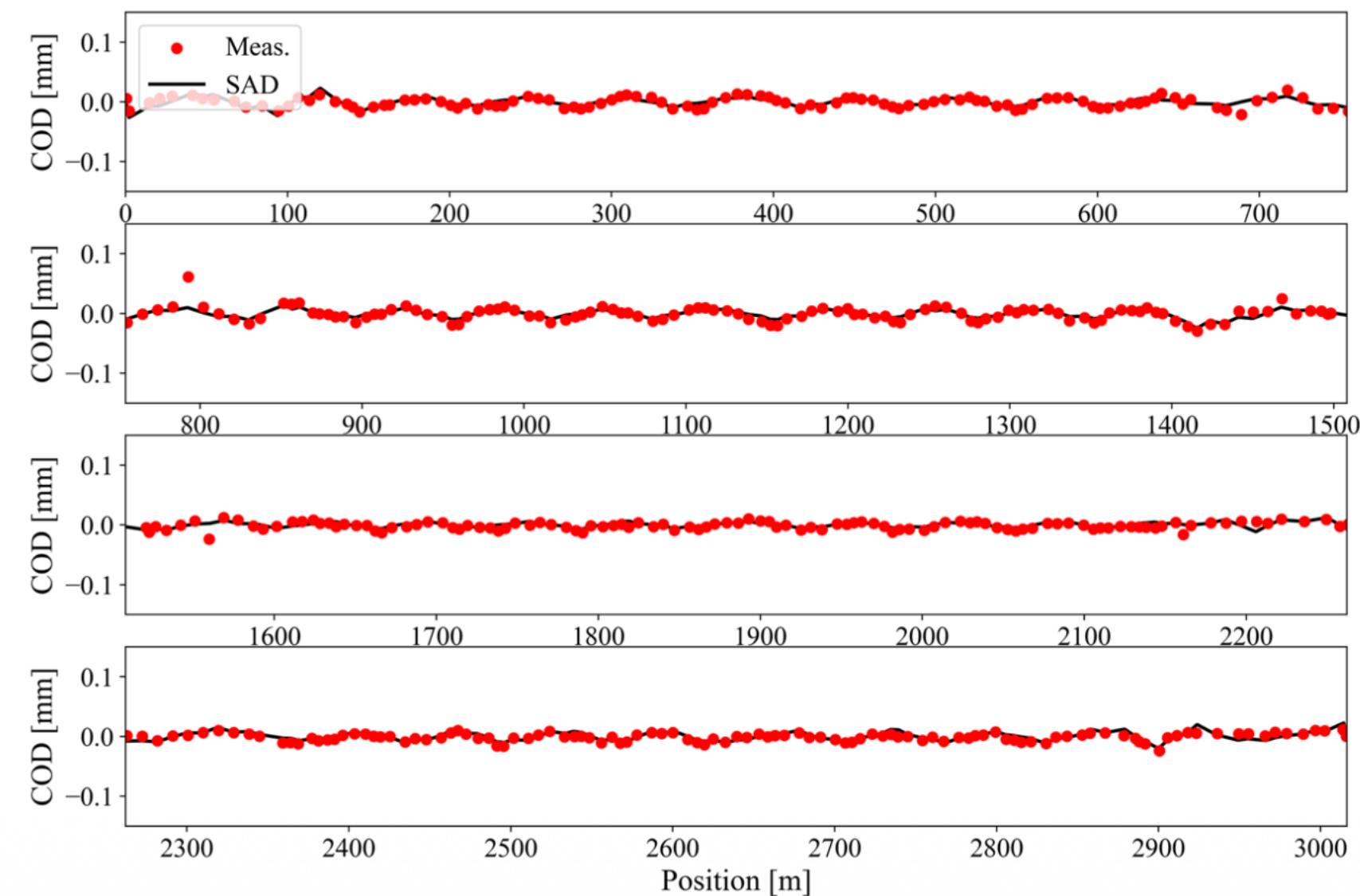
Measurement of beta functions is based on six single-kick-orbit responses in each plane.



The beta measurement takes about 11 min.
 During the period, the beam orbit can drift.
 How much does the orbit drift affect the optics measurement?

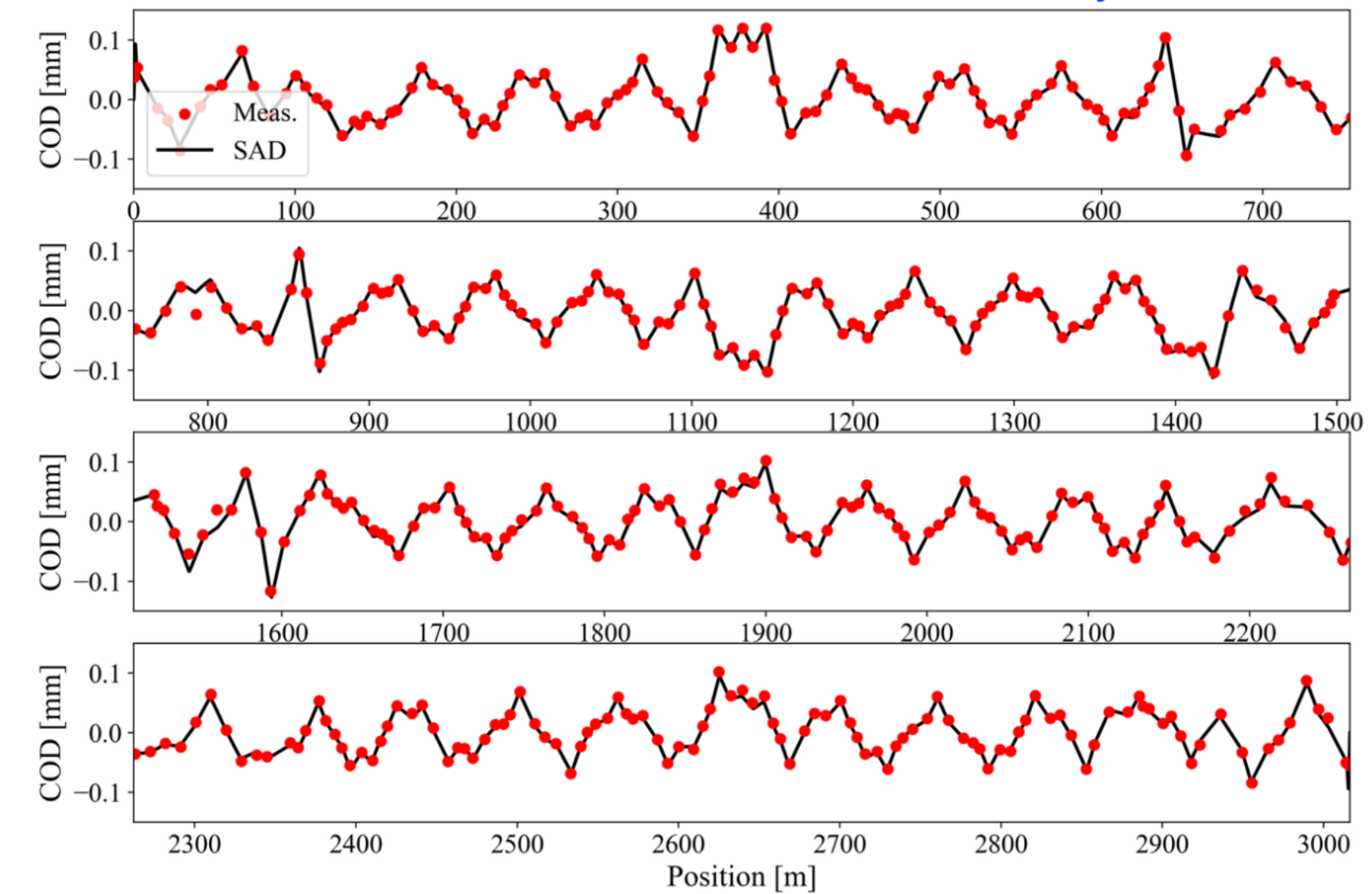
Investigation of the source of the orbit variation

Horizontal Orbit (from IP to IP)



LER

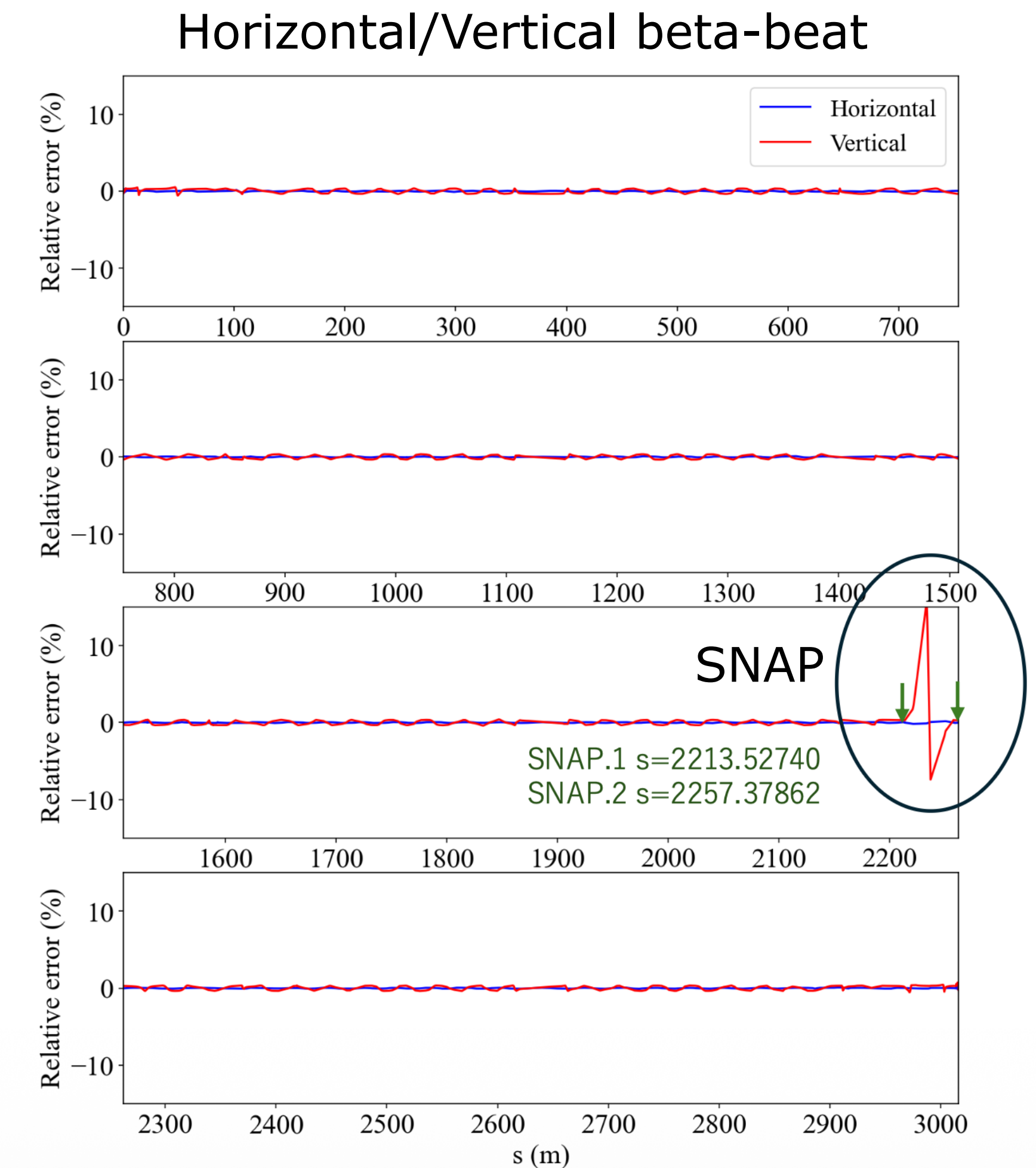
Vertical Orbit (from IP to IP)



Horizontal orbit variation can be explained by hysteresis in the correctors used to generate COD.

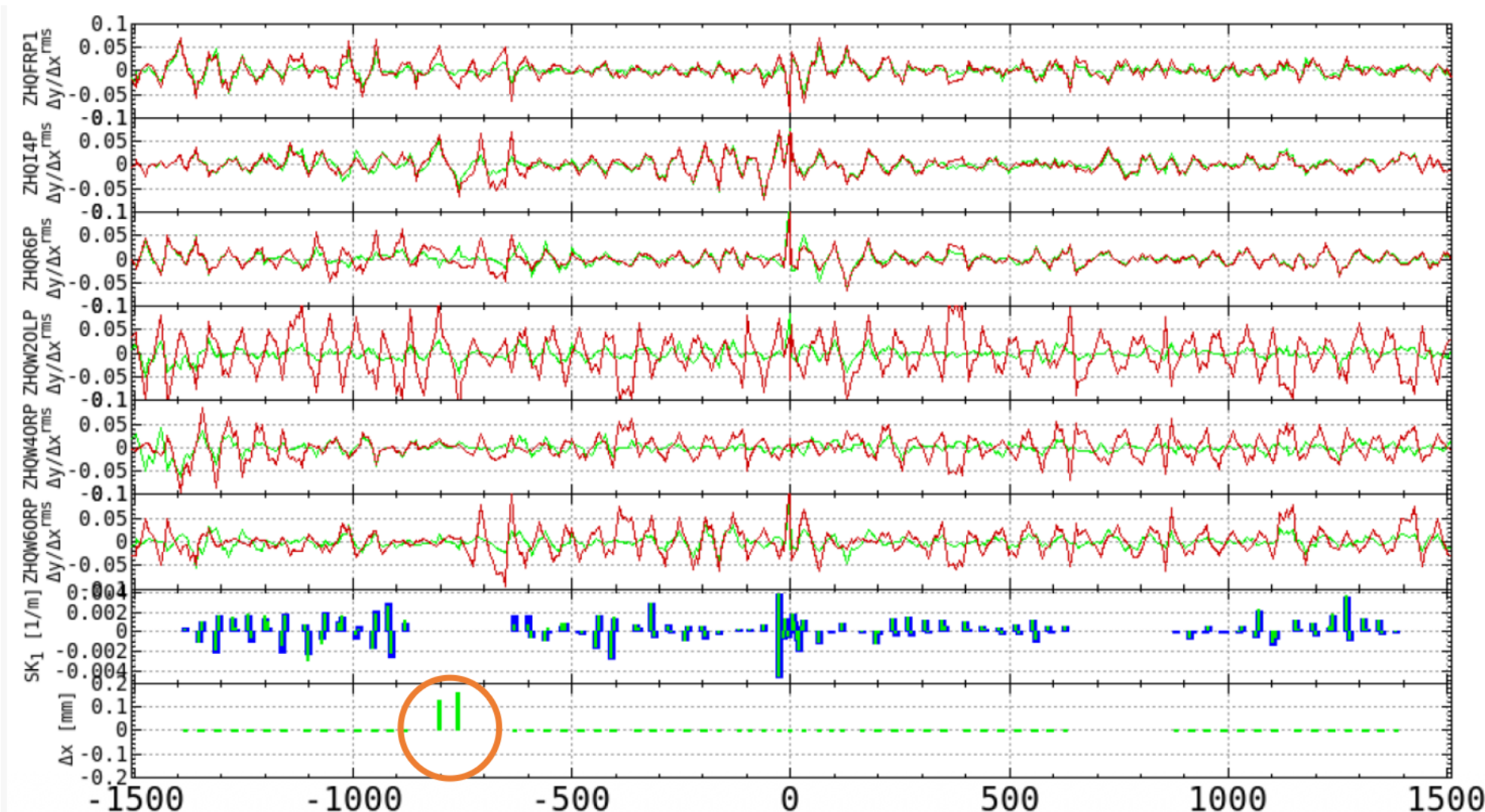
Vertical orbit variation can be explained by the dipole field in the QC1s (final focus) due to quadrupole feed-down.

- The impact of orbit drift on the optics measurement can be estimated.
- Beta-beat due to orbit drift:
 - The horizontal beta-beat is about 0.06%.
 - The vertical beta-beat is about 0.3%.
- In particular, a vertical orbit offset at the SNAPs (skew sextupoles) for the nonlinear collimator in the LER produces a large local beta-beat. Since this is an asymmetric orbit offset (see the previous slide), the beta-beat is cancelled due to $-I'$. (The kick source is outside of $-I'$, vertical dipole field of QC1s.)
- No quadrupole trim is used inside $-I'$.
- Orbit drift during the measurement does not affect the measured optical functions.

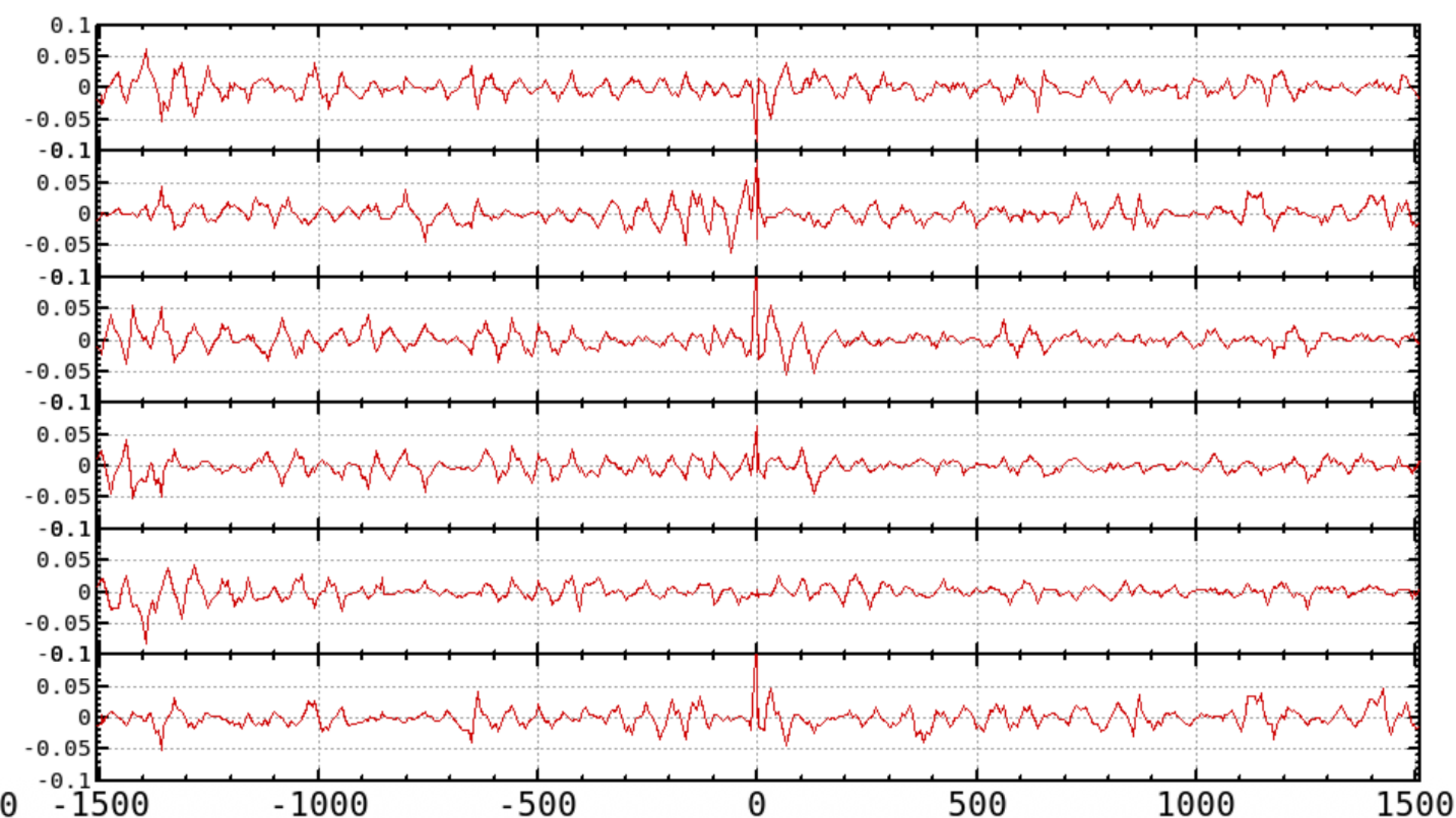


- Horizontal orbit offset sum at SNAPs (two skew sextupoles) generates X-Y coupling.
- Horizontal orbit offset was estimated to be about $150\ \mu\text{m}$ to correct the X-Y coupling.
- Constrained global orbit correction was applied to keep the orbit sum.

Before correction



After correction



SUPERKEKB HER · ANALYSIS OF NOVEMBER 2025 DATA · FOR DISCUSSION

A small optics error in the abort section, seen in COD and turn-by-turn data

The COD orbit response finds the same quadrupole errors at $\beta y^* = 8$ mm and 1 mm. They break the cancellation of the SXABE sextupole pair, and explain the measured sextupolar RDTs, β -beating and amplitude detuning.

Maël Le Garrec (CNRS/IN2P3-LAPP), with Rogelio Tomás and Jacqueline Keintzel (CERN) · 2026-09-25

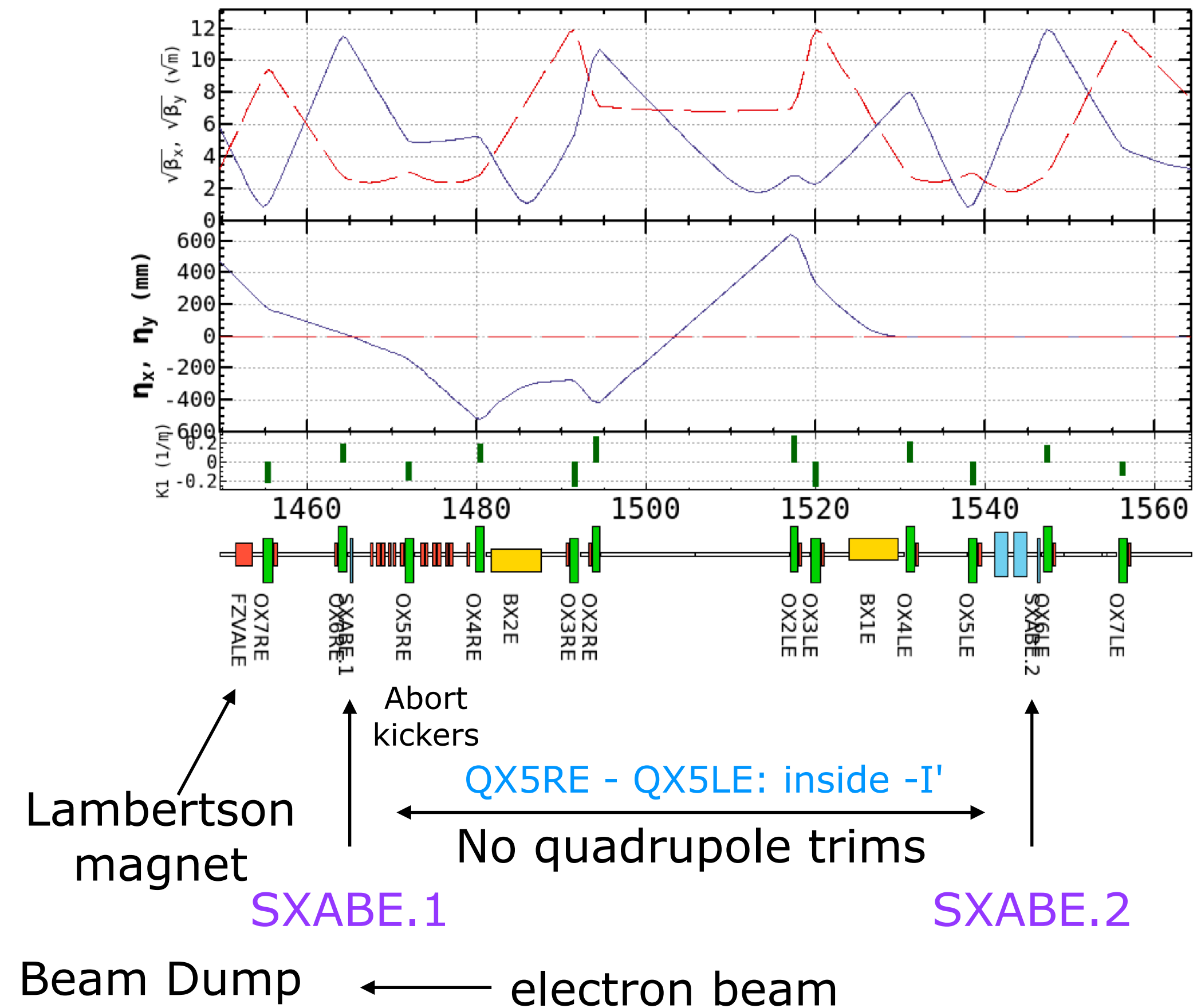
Summary

1. The measured sextupolar resonance driving terms (RDTs) of the HER are 5 to 12 times larger than in the design model. Their phases alone point to **the SXABE sextupole pair in the abort section**, at $\beta y^* = 8$ mm and at 1 mm.
2. The COD orbit-response measurements show **the same pattern of small quadrupole errors in the abort section** at both optics, over all 14 quadrupoles. The largest, 0.35–0.52 %, are on QX4RE, QX6RE and QX7LE.
3. These errors break the cancellation of the two SXABE sextupoles. With them in the model, the **β -beating, the sextupolar RDTs and the amplitude detuning** are reproduced. At 1 mm the agreement is partial: 64–70 % of the RDT amplitude, and the octupolar RDTs are not explained.

Sections 1–6 tell the story in six short steps; each ends with its conclusion ($\Rightarrow$).

One of the joint activities between CERN and KEK

Synchrotron injection optics



Sum of horizontal orbit offset at SXABEs produces beta-beat. It is difficult to distinguish quadrupole errors and orbit offset at the sextupoles.

4 The quadrupole errors from the COD orbit response

We fitted all quadrupoles to the operation team's COD orbit-response measurements (LOCO fit):

- 2025-11-18 11:15, $\beta y^* = 8\text{ mm}^{[C1]}$: taken on the same optics file as the kicks of 11-17 22:30.
- 2025-11-19 18:16, $\beta y^* = 1\text{ mm}^{[C2]}$: nearly the optics of the kicks of 11-20 09:52 (8 quadrupole settings differ; see C2).

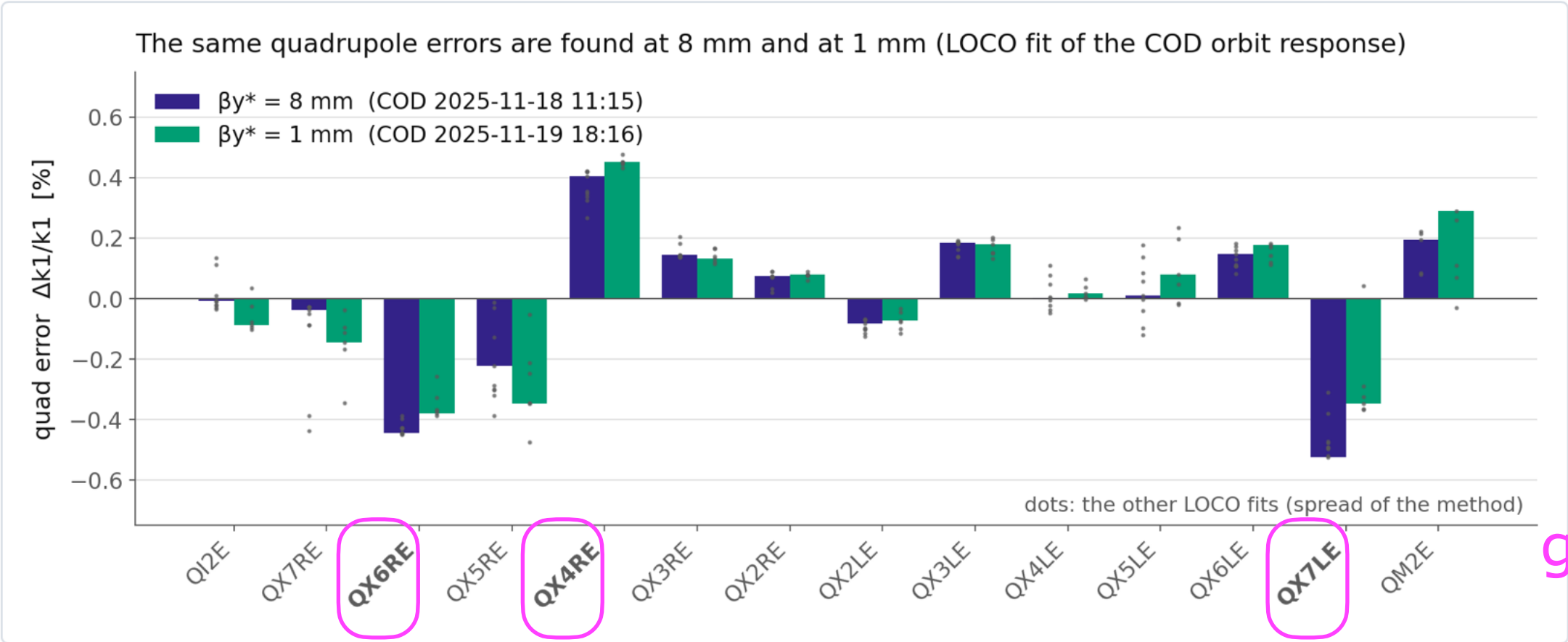


Figure 4. Errors of the 14 abort-section quadrupoles in the two LOCO fits. Dots: other fits of the same data (different regularisation, BPM gains, the session before or after).

gradient error
estimation

6 Comparison with the turn-by-turn data

2025c Run

β -beating

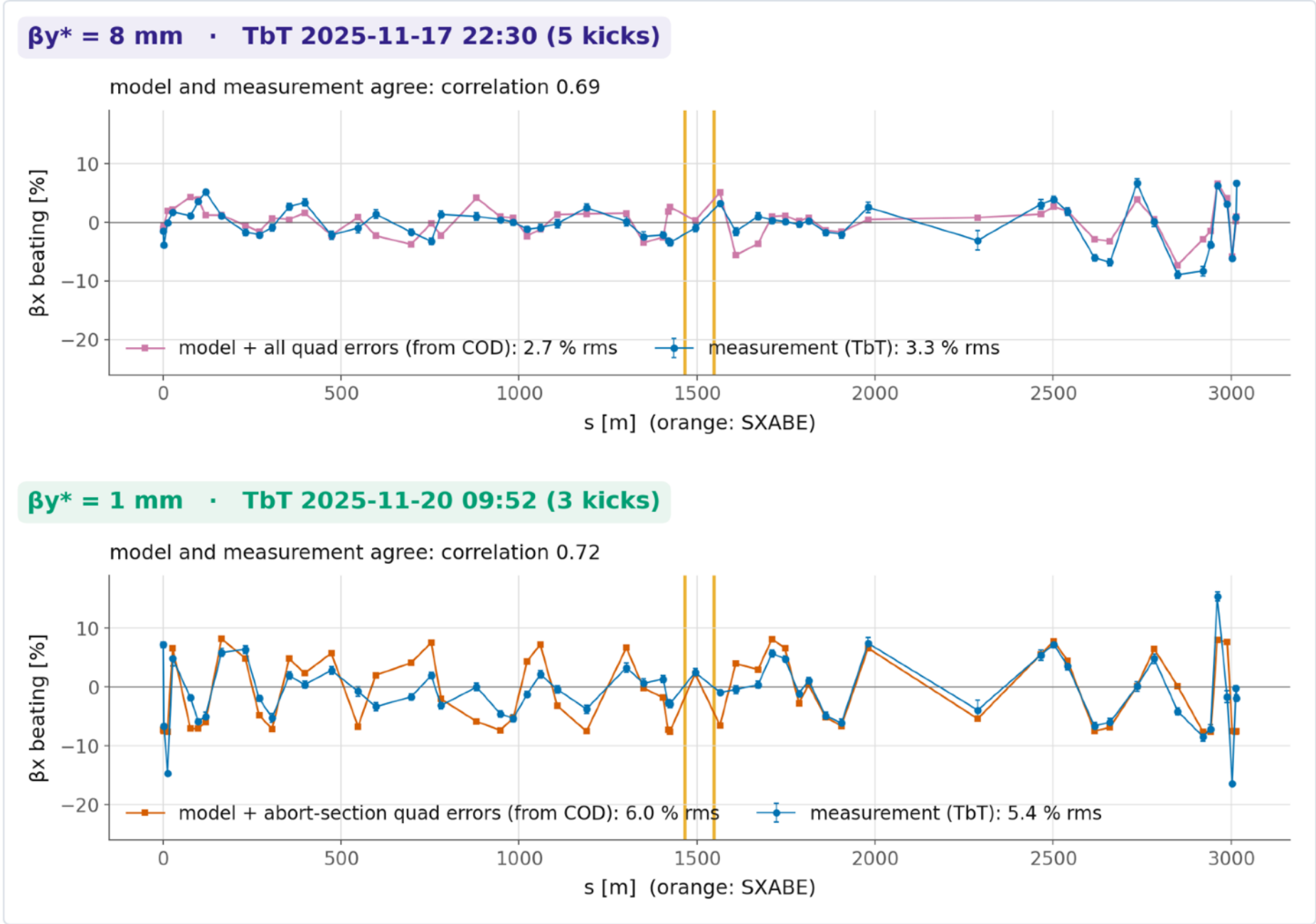


Figure 6. Horizontal β -beating from the smallest kick of each set, against the model with the COD errors.

Gradient Error

Mael	QX7RE	QX6RE	QX6LE	QX7LE	QX4RE
$\Delta K_1/K_1$ at 8 mm	-0.04%	-0.44%	0.15%	-0.52%	0.40%
$\Delta K_1/K_1$ at 1 mm	-0.14%	-0.38%	0.18%	-0.35%	0.45%

Quadrupole Trim
(Correction)

SuperKEKB	QX7RE	QX6RE	QX6LE	QX7LE
ΔK_1 (1/m) at 8 mm	0.0004139	-0.001302	-0.0007385	0.0007525
$\Delta K_1/K_1$	-0.197%	-0.693%	-0.400%	-0.556%
ΔK_1 (1/m) at 1 mm	0.0005368	-0.00121	-0.0006463	0.0006182
$\Delta K_1/K_1$	-0.256%	-0.644%	-0.351%	-0.456%

Gradient error and quad. trim have similar effects.

This implies that horizontal orbit offset at SXABEs may contribute to some of the beta-beat.

RDTs

Only the 14 abort-section quadrupole errors are added to the model, which is then tracked and analysed like the measurement.

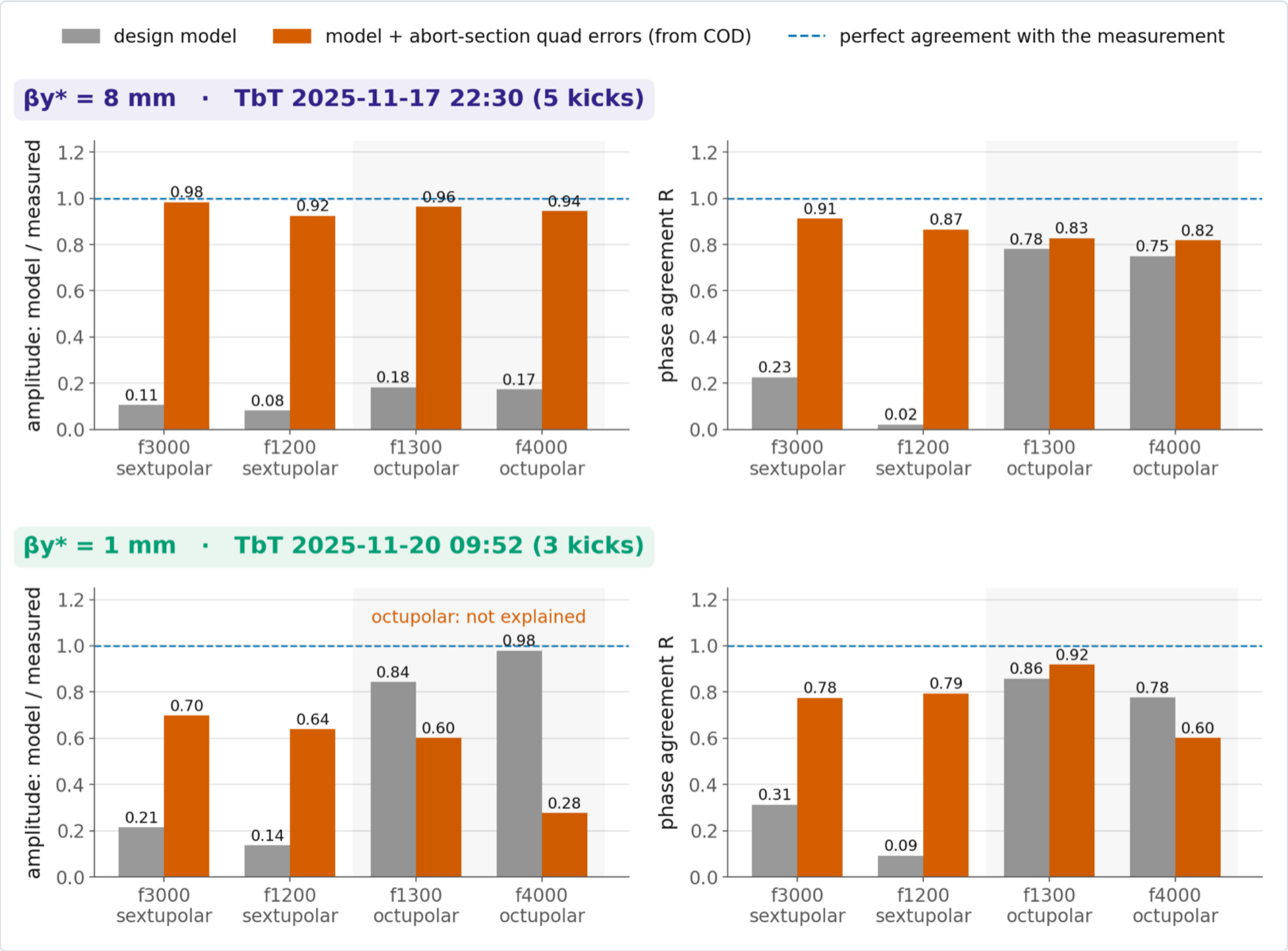


Figure 7. All four RDTs at a glance. Amplitude ratio = model / measurement; phase R = 1 for the same phase pattern. Dashed line: perfect agreement.

The model + gradient error is almost consistent with the measured RDTs and amplitude detuning.
The octupolar can not be explained for $\beta_y^* = 1$ mm.

Amplitude detuning

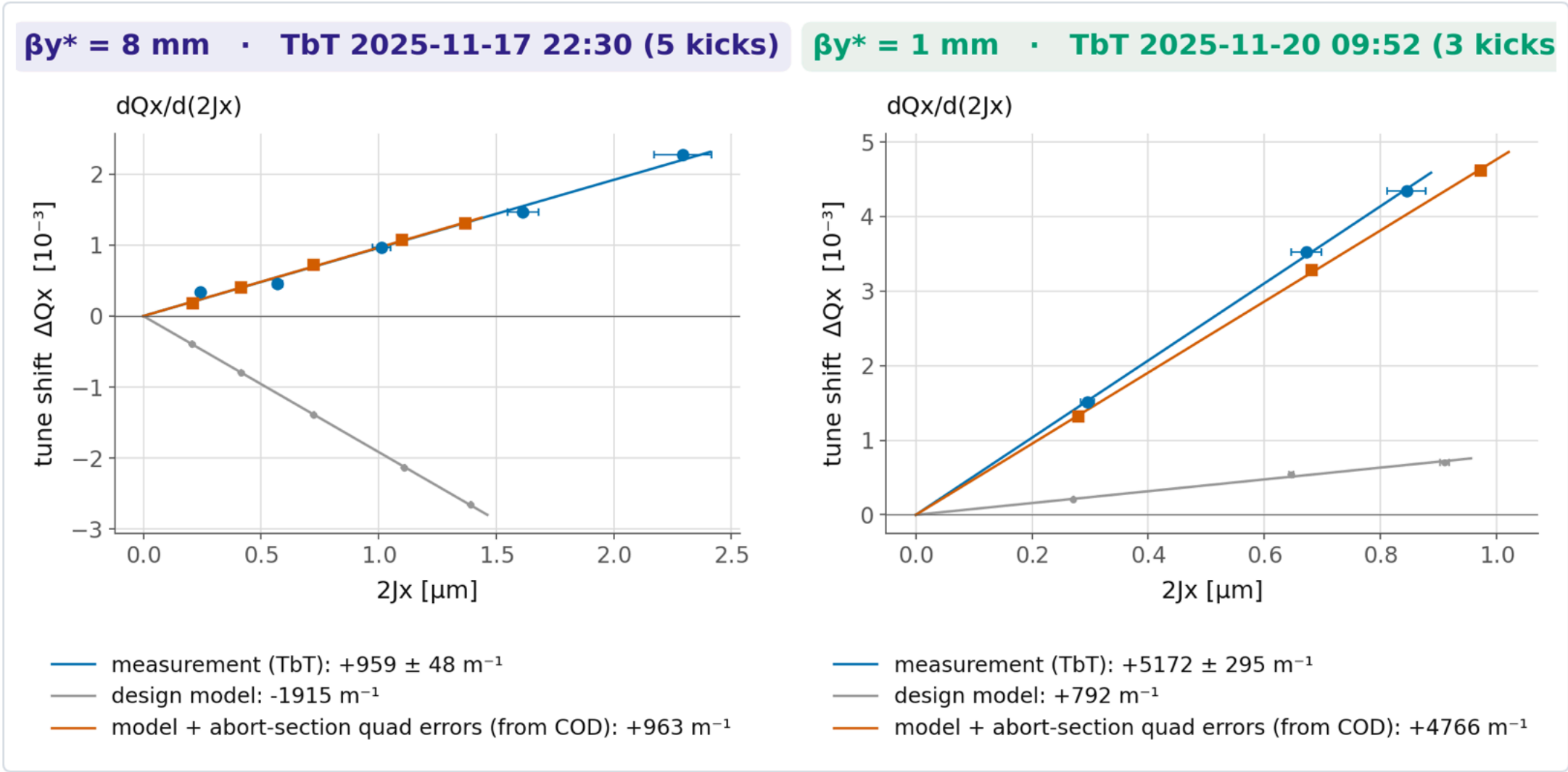


Figure 10. dQx/d(2Jx) from the kicks, with the same estimator for measurement and model (512 turns after each kick).

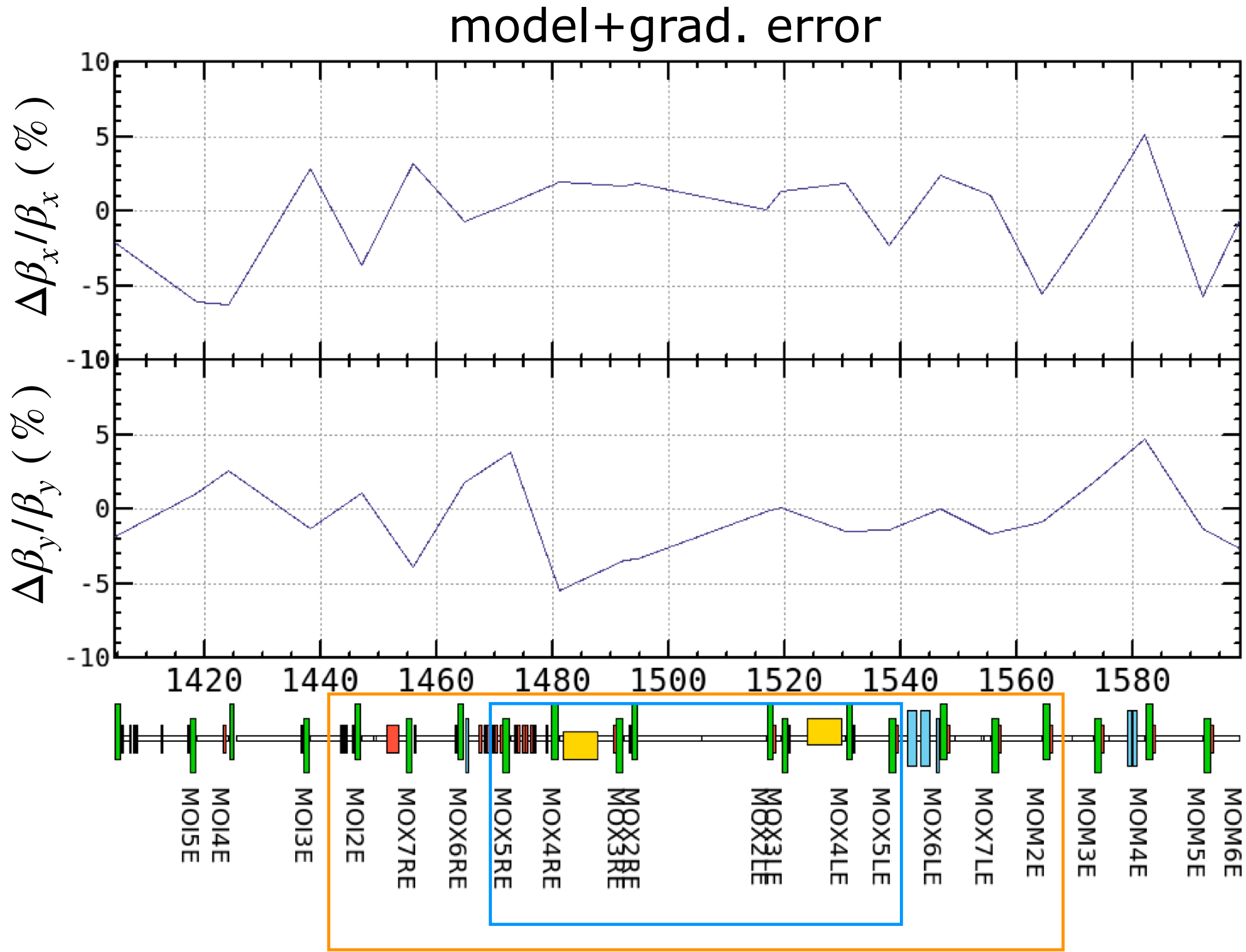
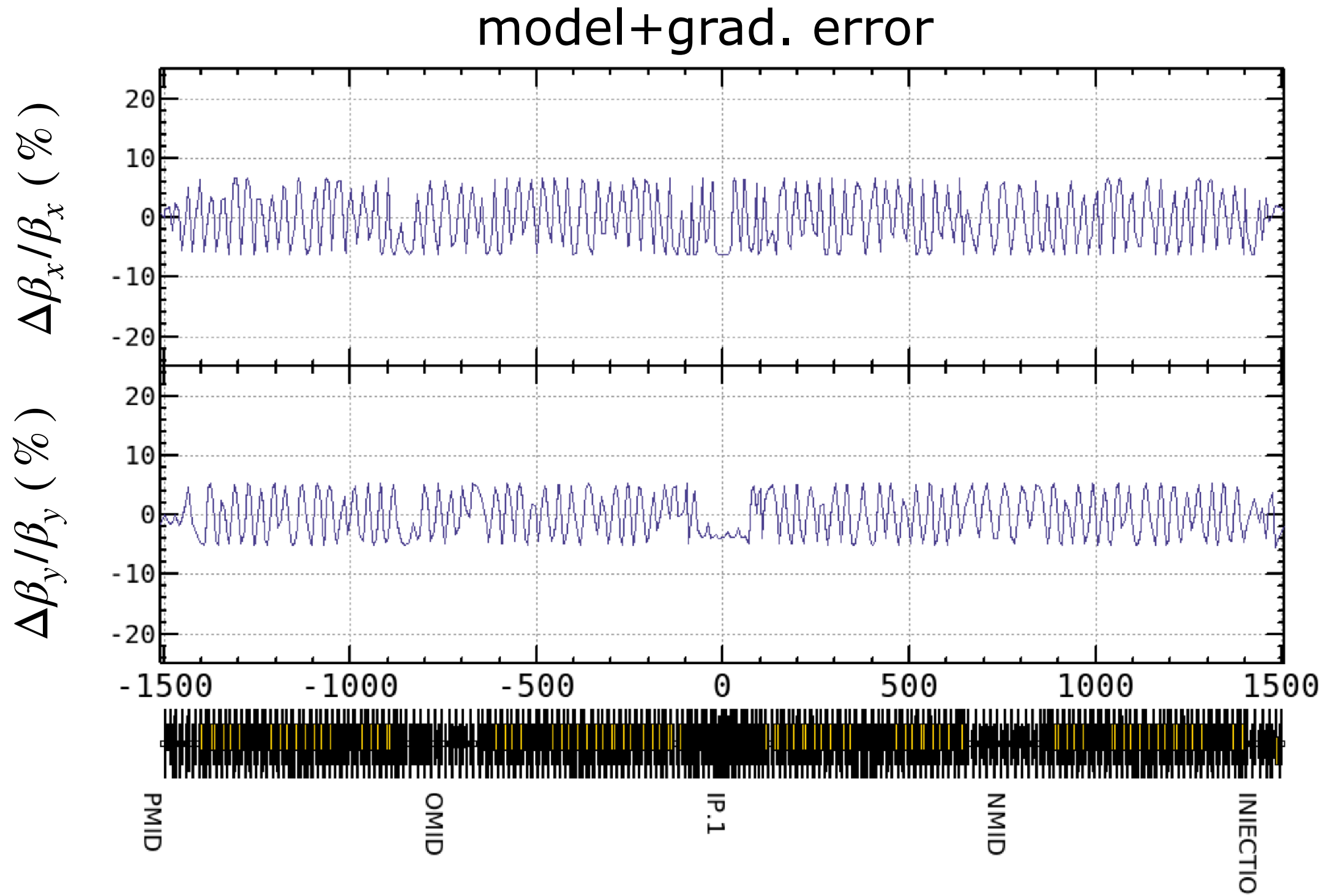
At 8 mm the design model has the wrong sign (-1915 m^{-1}); with the errors, $+963 \text{ m}^{-1}$ against $+959 \pm 48 \text{ m}^{-1}$ measured. At 1 mm, $+4766 \text{ m}^{-1}$ against $+5172 \pm 295 \text{ m}^{-1}$ (design $+792 \text{ m}^{-1}$).

	f3000	f1200	f1300	f4000	βx-beat	dQx/d(2Jx) [m ⁻¹]
βy* = 8 mm (TbT 2025-11-17, COD 2025-11-18)						
measurement	–	–	–	–	3.3 % rms	+959 ± 48
design model: phase R	0.23	0.02	0.78	0.75	–	–
design model: amplitude	0.11	0.08	0.18	0.17	–	–1915
with COD errors: phase R	0.91	0.87	0.83	0.82	corr. 0.69*	–
with COD errors: amplitude	0.98	0.92	0.96	0.94	2.7 %*	+963
βy* = 1 mm (TbT 2025-11-20, COD 2025-11-19)						
measurement	–	–	–	–	5.4 % rms	+5172 ± 295
design model: phase R	0.31	0.09	0.86	0.78	–	–
design model: amplitude	0.21	0.14	0.84	0.98	–	+792
with COD errors: phase R	0.78	0.79	0.92	0.60	corr. 0.72	–
with COD errors: amplitude	0.70	0.64	0.60	0.28	6.0 %	+4766

$\Delta k1/k1$	8 mm	1 mm
QI2E	-0.01 %	-0.09 %
QX7RE	-0.04 %	-0.14 %
QX6RE	-0.44 %	-0.38 %
QX5RE	-0.22 %	-0.35 %
QX4RE	+0.40 %	+0.45 %
QX3RE	+0.14 %	+0.13 %
QX2RE	+0.07 %	+0.08 %
QX2LE	-0.08 %	-0.07 %
QX3LE	+0.18 %	+0.18 %
QX4LE	0.00 %	+0.02 %
QX5LE	+0.01 %	+0.08 %
QX6LE	+0.15 %	+0.18 %
QX7LE	-0.52 %	-0.35 %
QM2E	+0.20 %	+0.29 %

Gradient errors estimated by Mael.

-I'



Optics Name: 2025-11-19_18:04:42.112_PEYC

$\beta_y^* = 1 \text{ mm} + \text{grad. error}$

QX5RE - QX5LE : inside -I'

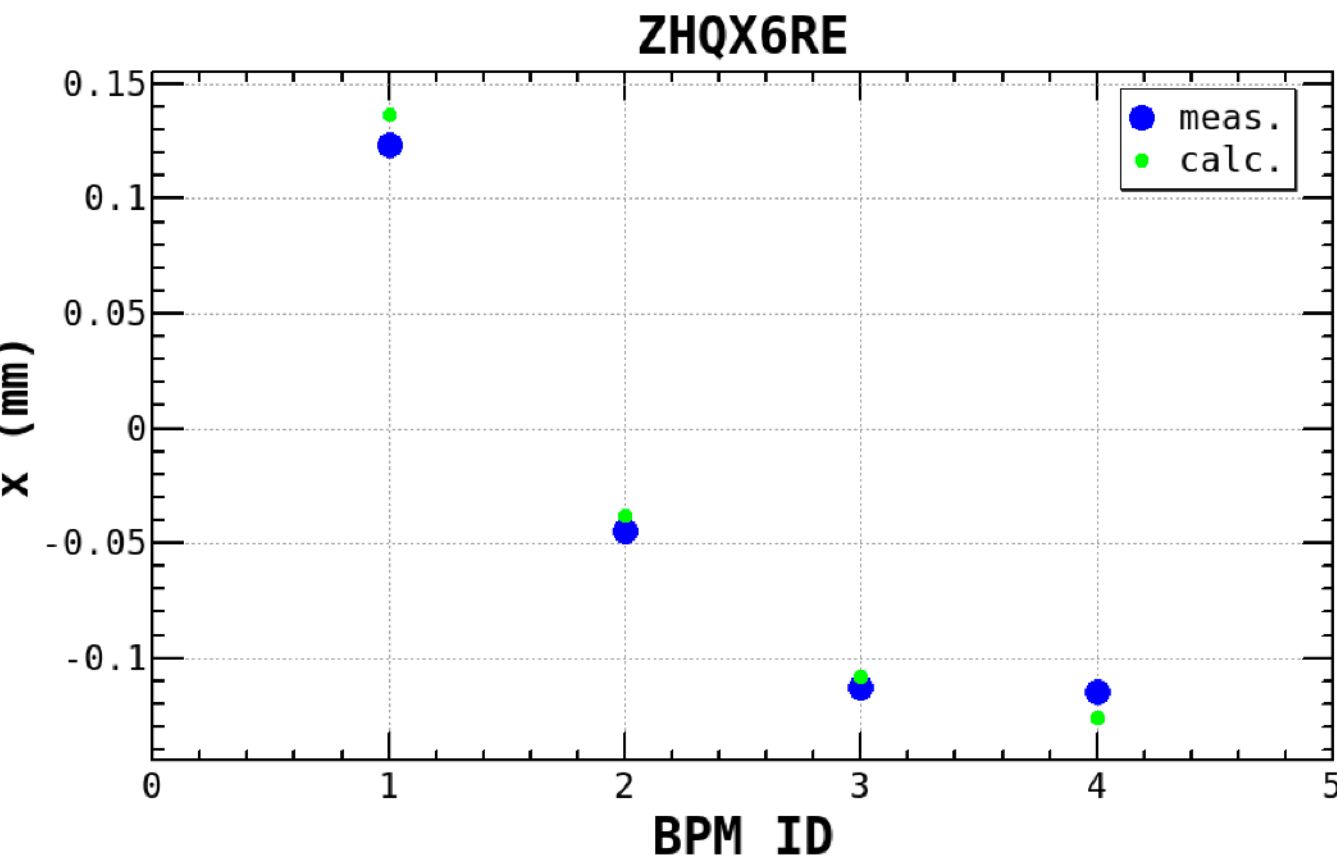
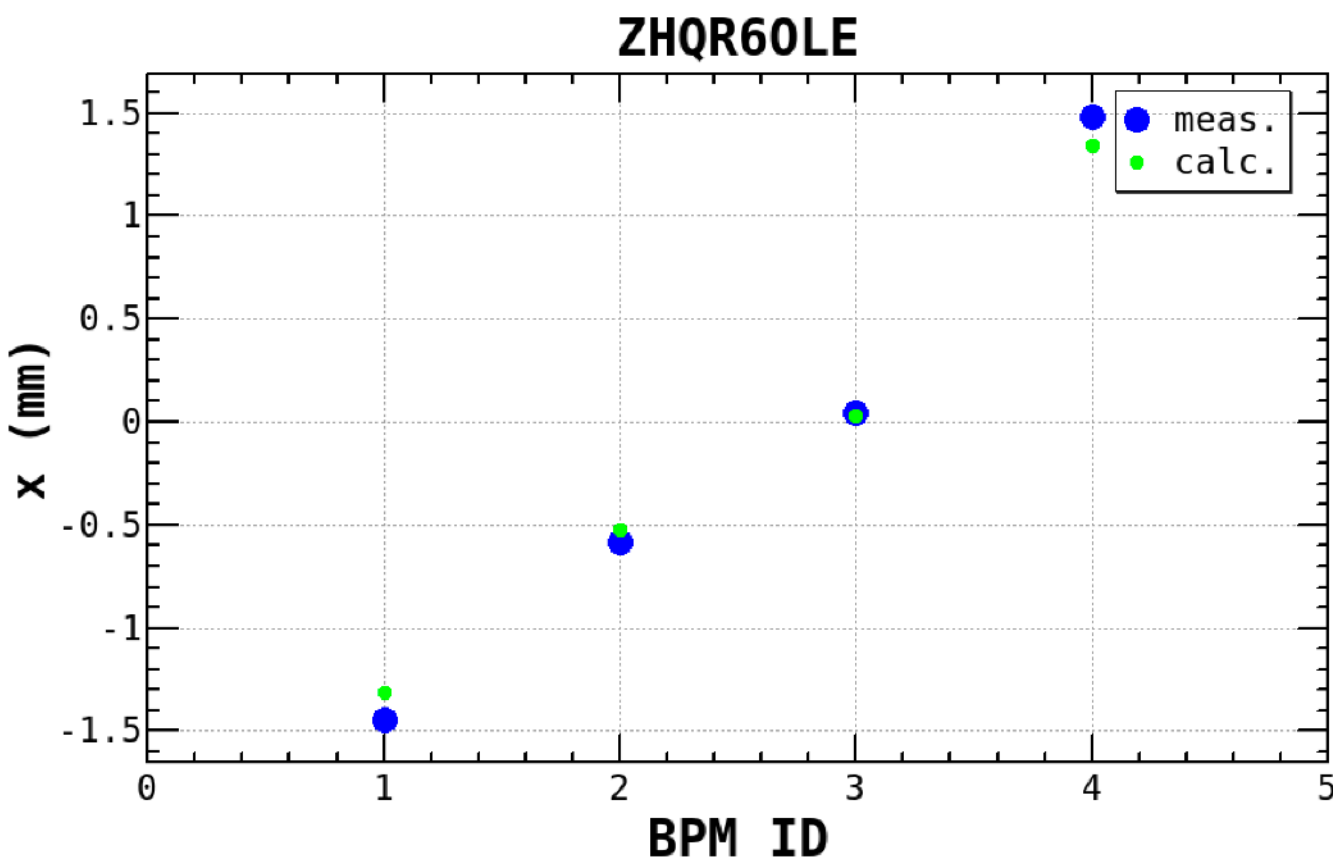
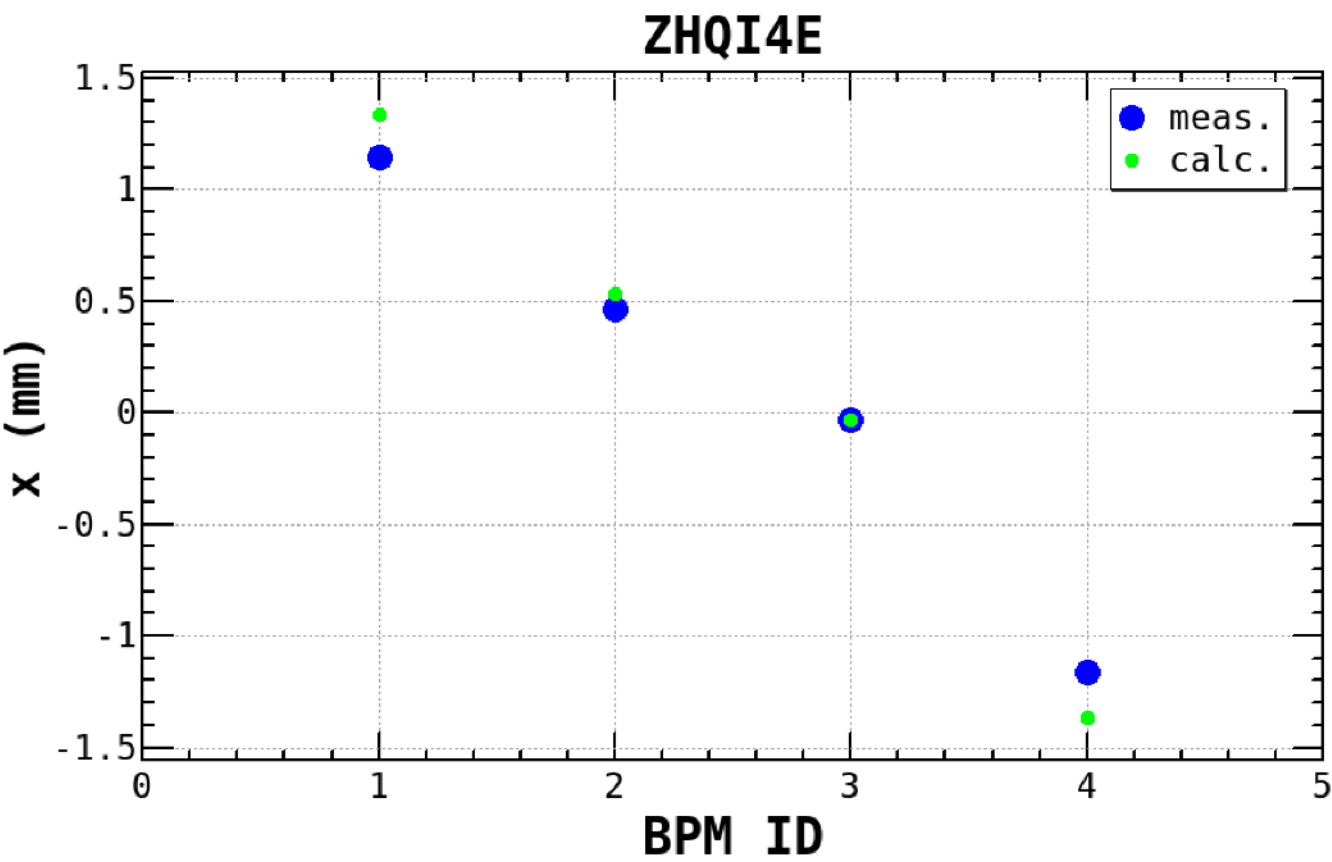
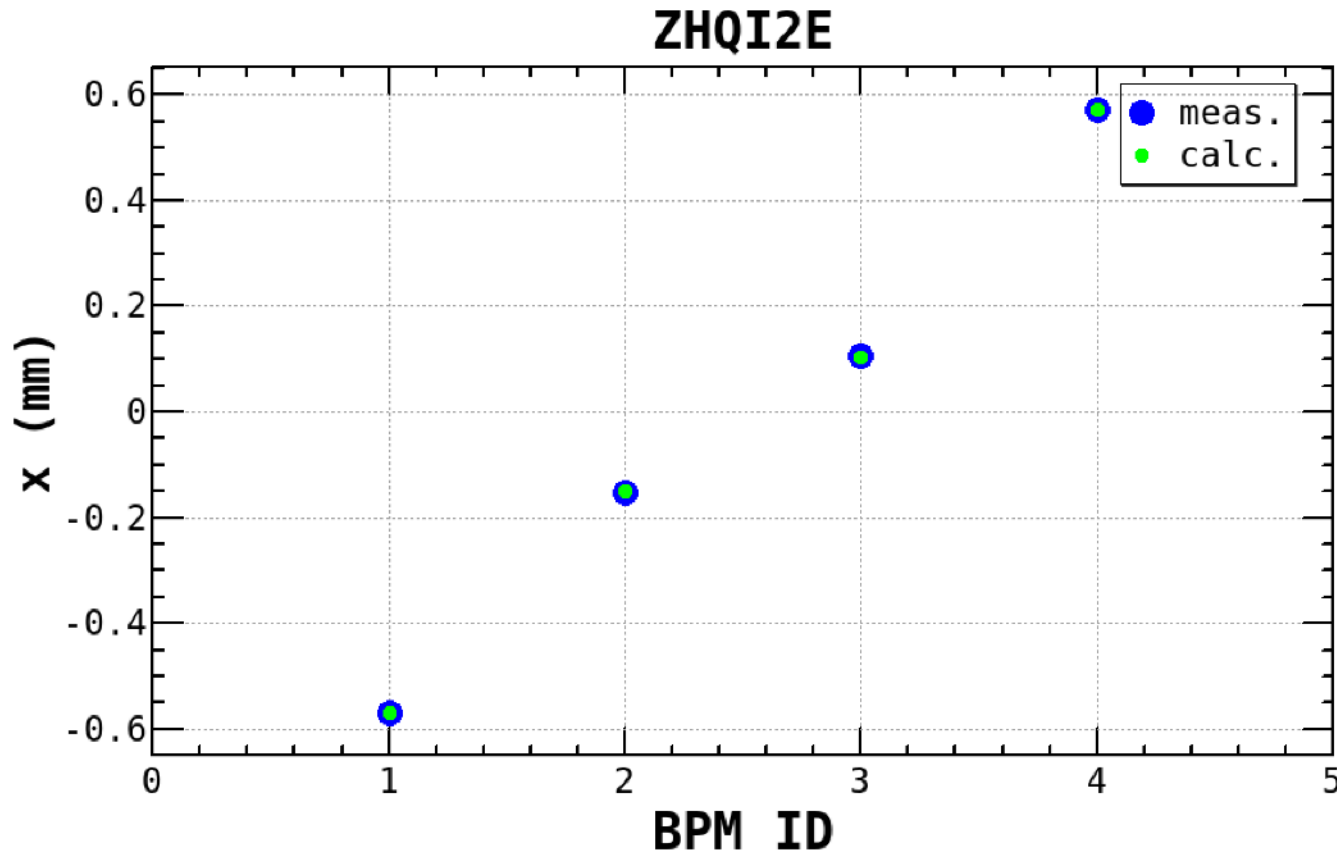
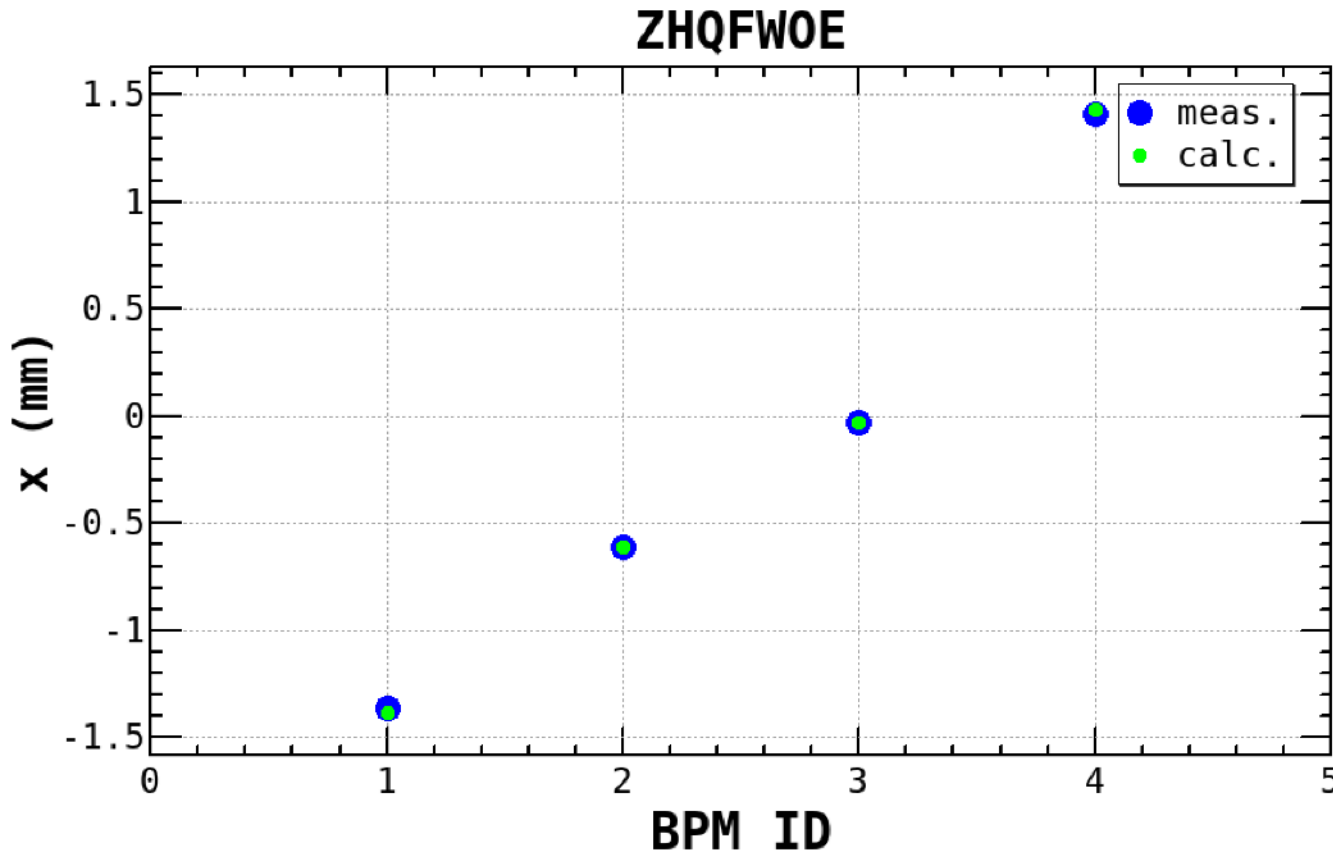
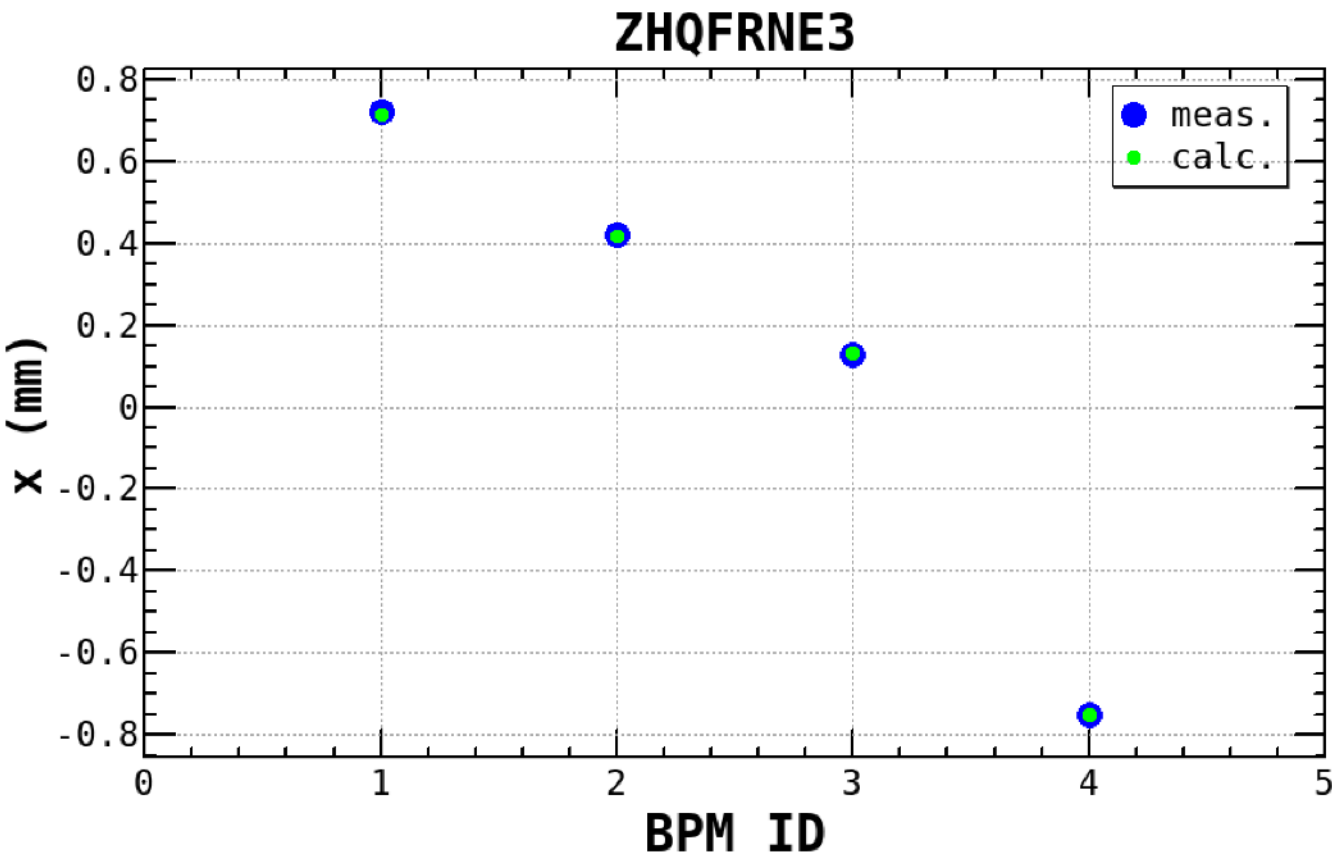
Beta measurement: 2025 11/19 18:10 - 18:16

model+grad. error

BPM ID

- 1: MQX6RE
- 2: MQX5RE
- 3: MQX5LE
- 4: MQX6LE

Measurement of beta functions is based on six single-kick-orbit responses for each x and y.
(Horizontal correctors: ZHQFRNE3, ZHQFWOE, ZHQI2E, ZHQI4E, ZHQR6OLE, ZHQX6RE)
The horizontal orbit at SXABEs can be estimated by using four BPMs.

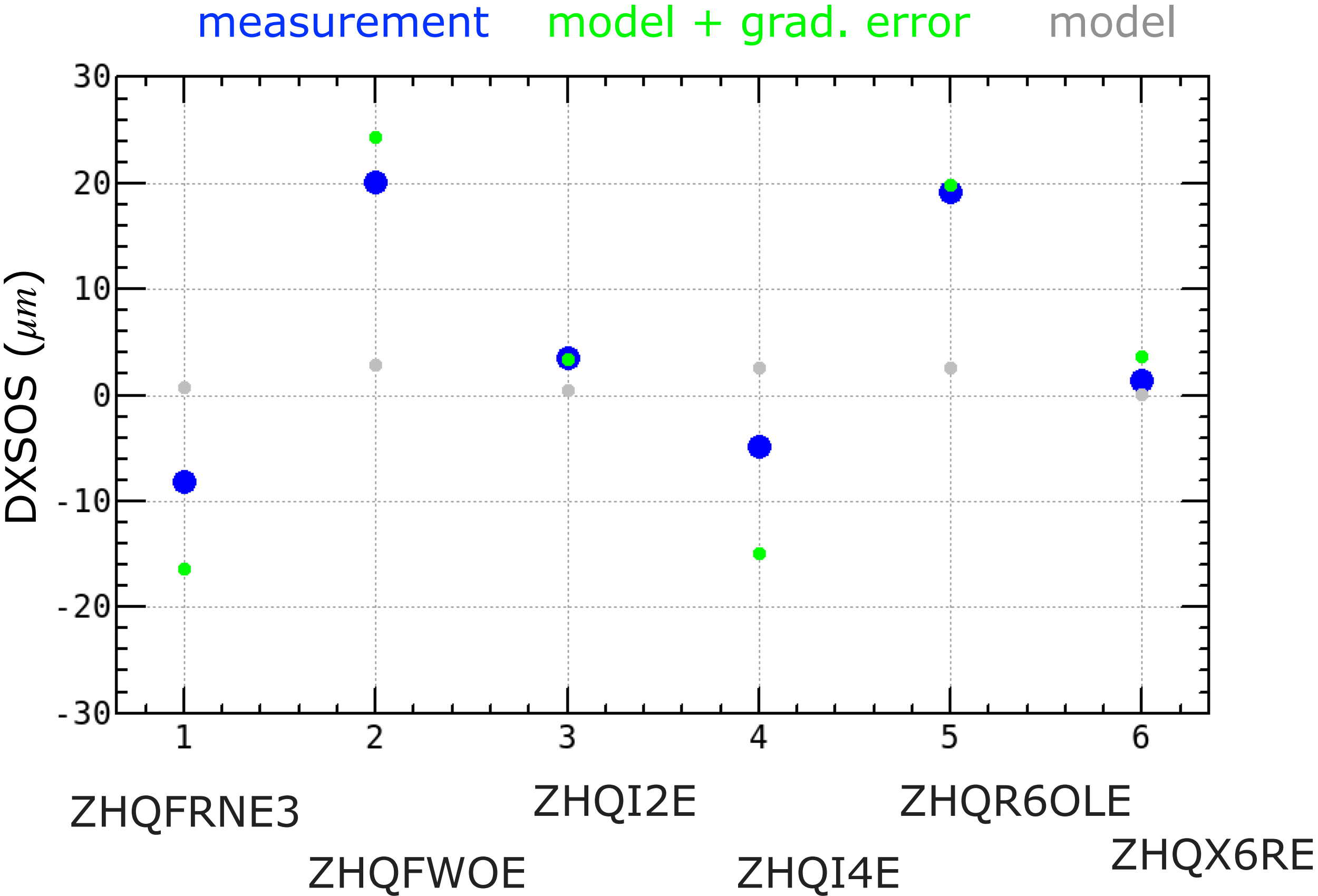


Imperfection of the -I' Transformation at SXABEs

Horizontal orbit offsets at SXABEs:

$$\text{DXSOS} = \Delta x_{\text{SXABE}.1} + \Delta x_{\text{SXABE}.2}$$

Gray plots: Perfect -I' transformation

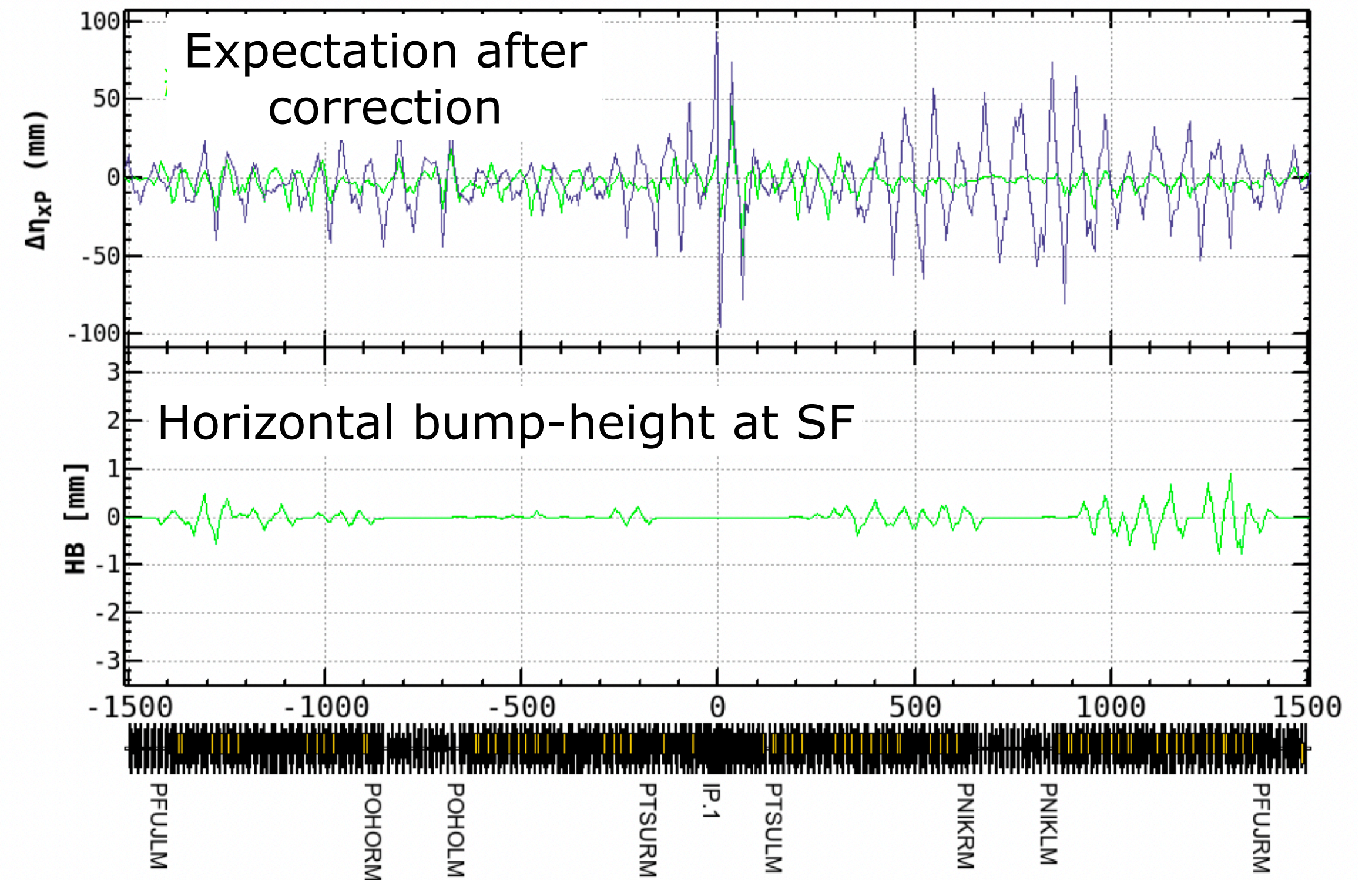
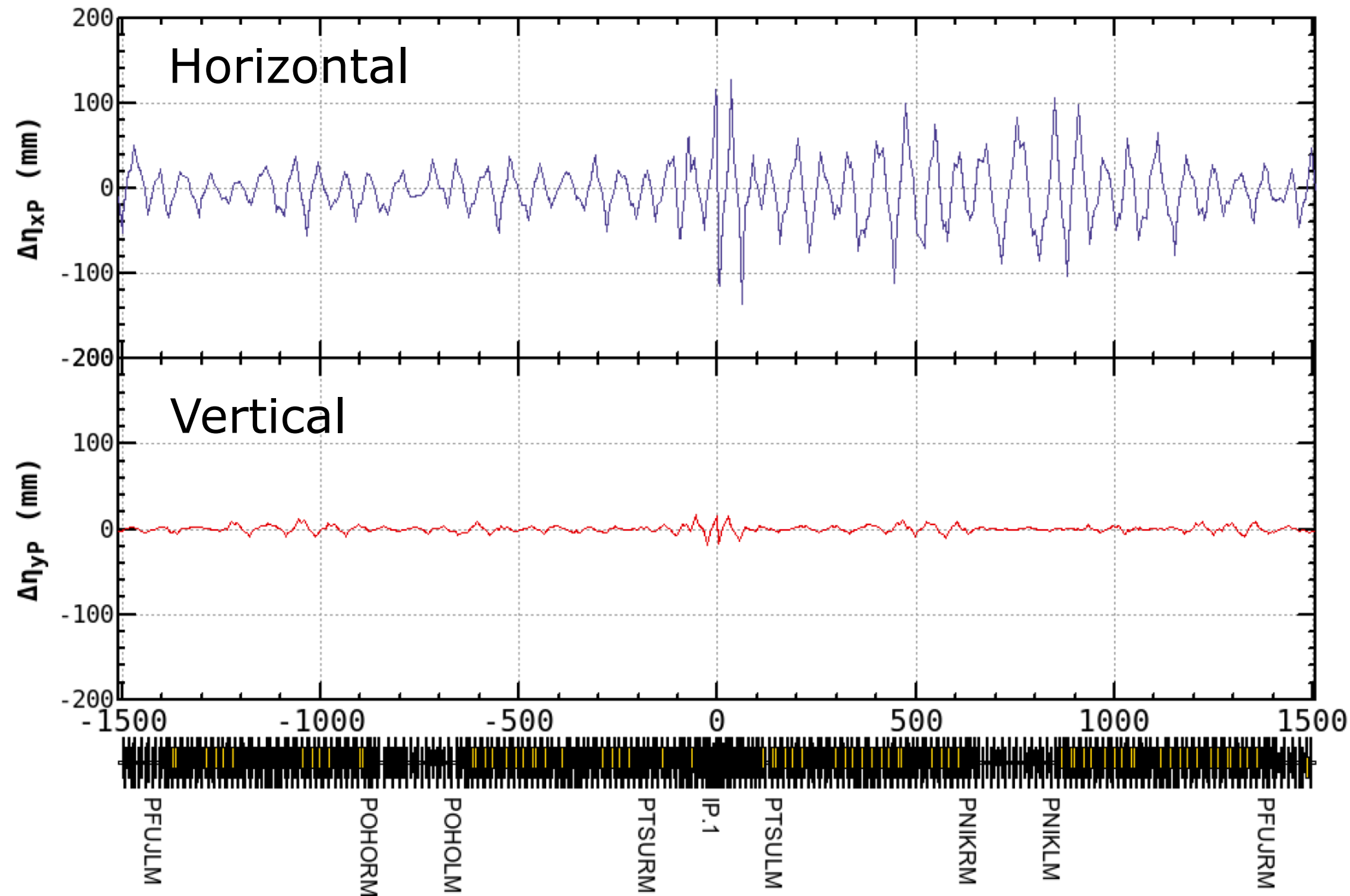


QX5RE	-0.35 %
QX4RE	+0.45 %
QX3RE	+0.13 %
QX2RE	+0.08 %
QX2LE	-0.07 %
QX3LE	+0.18 %
QX4LE	+0.02 %
QX5LE	+0.08 %

-I'

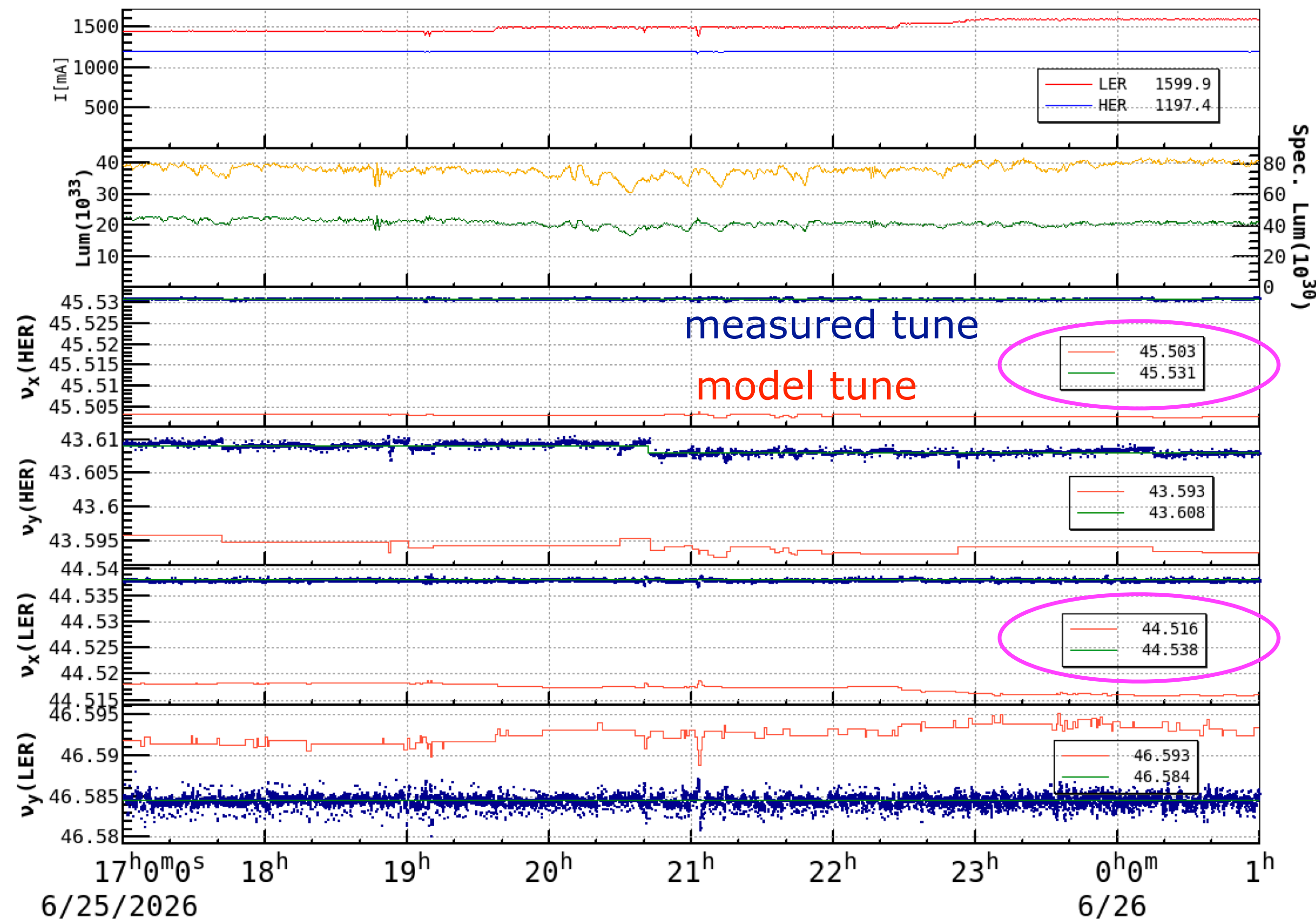
The estimated gradient errors inside -I' are reasonable. We have a plan to set corrections at the 14 quads.
 This level of the -I' imperfection does not affect the dynamic aperture.

$\Delta\eta_x = 33.9 \text{ mm} / \Delta\eta_y = 4.3 \text{ mm}$ (physical dispersion)



- Impact on the luminosity performance due to horizontal dispersion-error is small (from experience).
- Residual horizontal-dispersions can be corrected by using horizontal orbit-angle at IP and horizontal bumps at sextupoles (SF) → Future work in the 2027a run?

- Horizontal model tune is set close to the half integer to keep the measured tune constant at high beam current, e.g., 1.2 A in the HER.
- At higher beam currents, the model tune falls below the half-integer. Optics distortions will become much larger.



R4.1: Devote time to recovering the small vertical emittance in the HER

- The vertical emittance gradually decreases during the 2026ab run. The underlying mechanism remains unclear.
- A vertical orbit angle at the IP generates vertical dispersion, leading to an increase in ε_y . Dispersion correction can recover ε_y . We consider to keep the vertical orbit angle at the IP.

R4.2: Consider the possibility to reconnect the BPMs which isolated in 2024 to the adjacent quadrupoles, and stabilize the quadrupole position by mechanical means. → Not done in 2026. More BPMs will be isolated for the 2027 operation.

R4.3: Develop efficient tools for the robust measurement of coupling and amplitude detuning.

- TBT measurements, RDTs, and amplitude detuning by M. Le Garrec et al. (CERN–KEK joint activity)
- The COD-based optics measurement works well. The impact of orbit drift is negligible.

R4.4: At the start of the next run, a thorough optics commissioning should be performed to avoid that better optics corrections are found later in the run.

- Orbit offsets at sextupoles were investigated before optics measurements to assess their impact on optics distortions.

R4.5: Continue with the implementation of the nonlinear IR optics model.

- Under consideration

- Vertical emittance
 - Vertical orbit angle at the IP → Online monitoring and alarm → [Correct the orbit angle on demand](#)
 - Vertical (horizontal) orbit offset at sextupoles (skew sextupoles) → [Constrained global orbit correction](#)
 - Effect of IP knob → [Rematch the optics design to include finite X-Y coupling and vertical dispersion at the IP](#)
 - Chromatic X-Y coupling → [Rotatable sextupoles in the LER](#)
- Dynamic aperture
 - Optimization of sextupole strengths → CMA-ES+surrogate method, constrained downhill simplex method → [Test during machine operation](#). TBT BPMs with kickers are useful together with lifetime measurement.
 - Correction of linear and nonlinear optics → Under consideration, but TBT BPMs are powerful tools.
 - Optics at high beam current (e.g., large tune shift caused by long-range wakefield from resistive-wall impedance)
 - Optics distortion → Measure phase advance using gated TbT BPMs with an AC dipole (need to develop if possible)?
- Toward a luminosity of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$
 - [Explore the optics with a smaller \$\beta_y^*\$, down to 0.8 mm](#)

Apendix

- Closed orbit measurement and optics measurement (repetition: 0.25 Hz)

- LER: 444 BPMs / HER: 466 BPMs
- Narrow-band system (LER: 509 MHz, HER: 1 GHz)

- Resolution: 2-3 μm

- BPM gain calibration
$$\chi^2 = \sum_i^4 \sum_j^m \frac{(V_{ij} - g_i q_j F(x_i, y_i))^2}{\sigma_{ij}^2}$$
 m : number of different kinds of orbit $g_1 = 1$

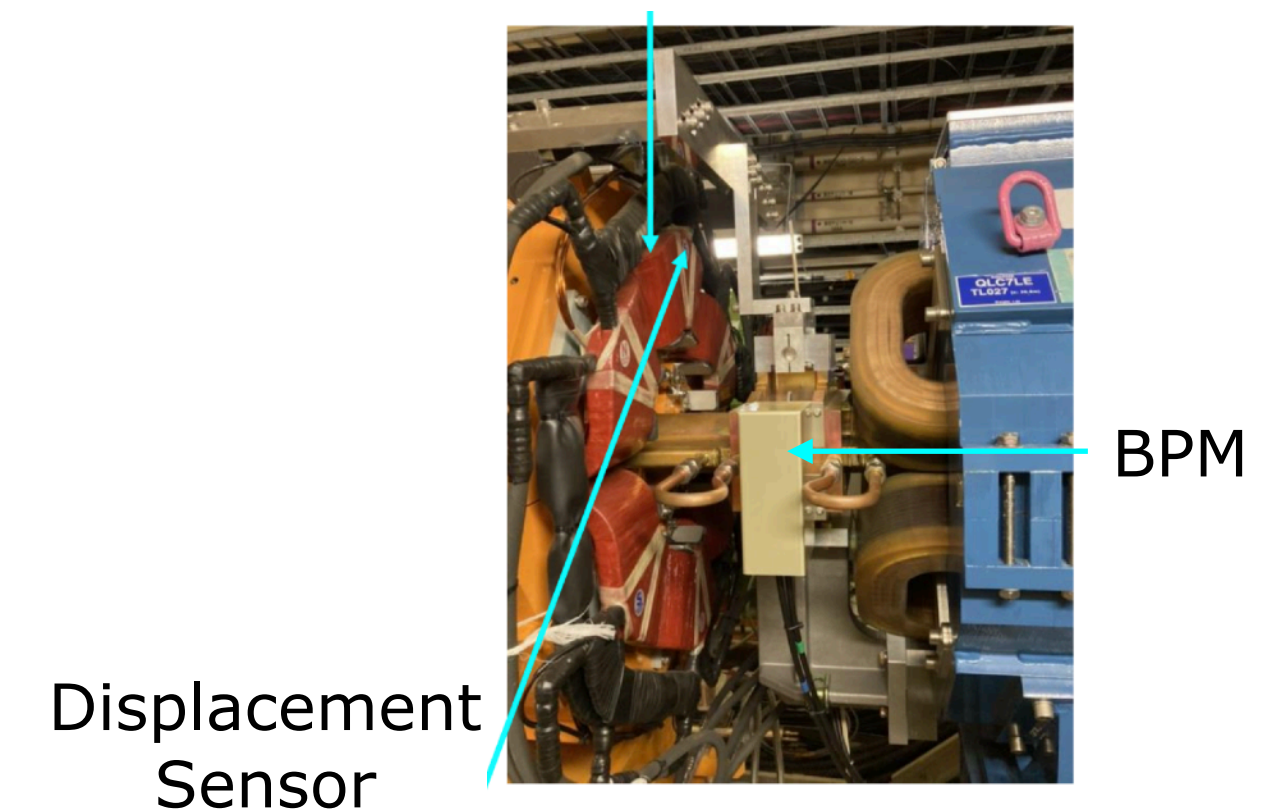
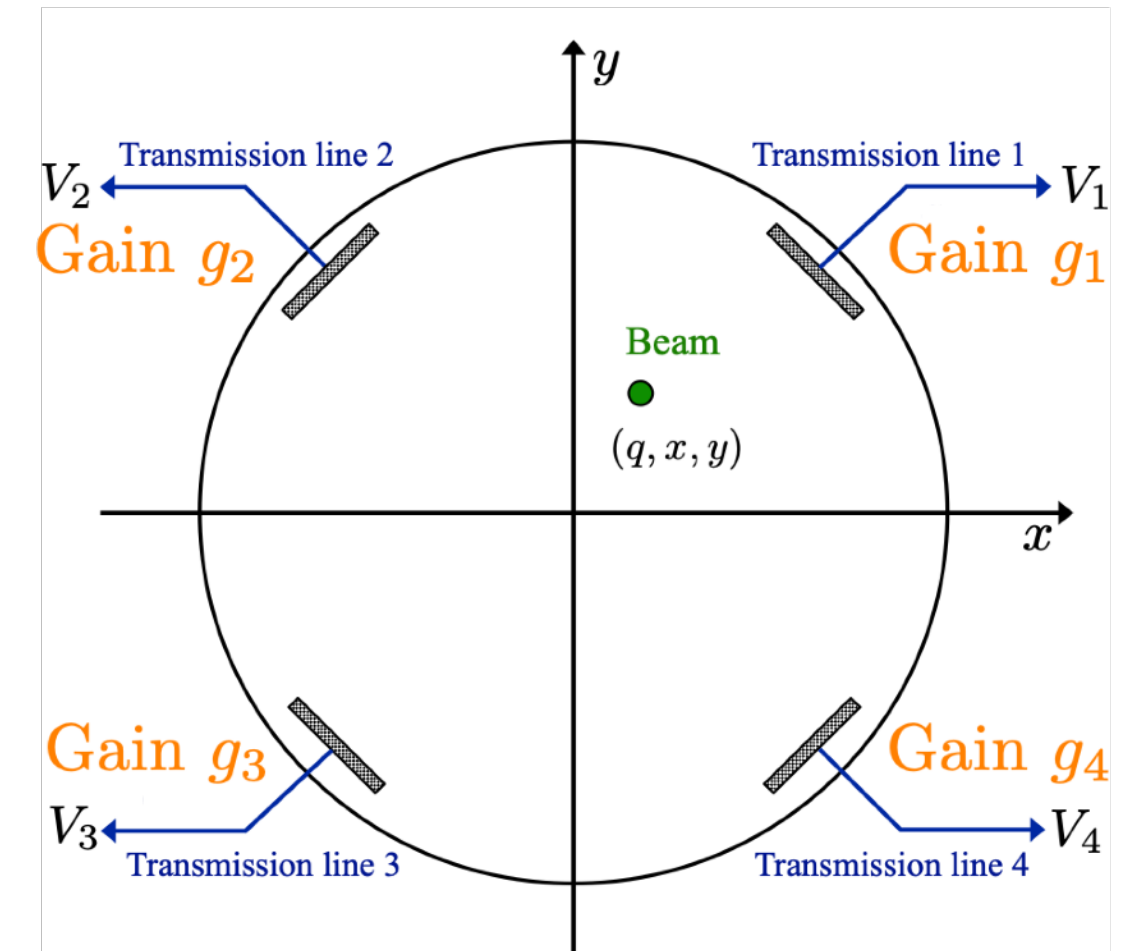
- Beam based alignment: BPM offset from quad.

- Displacement sensors to measure relative mechanical displacement between BPM and neighbor sextupole magnet.

- Gated Turn-By-Turn mode measurement (repetition: 100 kHz)

- LER: 65 BPMs / HER: 62 BPMs ← Aperture measurements

- Resolution: 50-100 μm



* 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

$$U = \begin{pmatrix} \mu I & JR^T J \\ R & \mu I \end{pmatrix} \quad R = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} \quad J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad \text{in case } \det R < 1$$

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

 $\uparrow$
 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.