Lessons Learned from SuperKEKB

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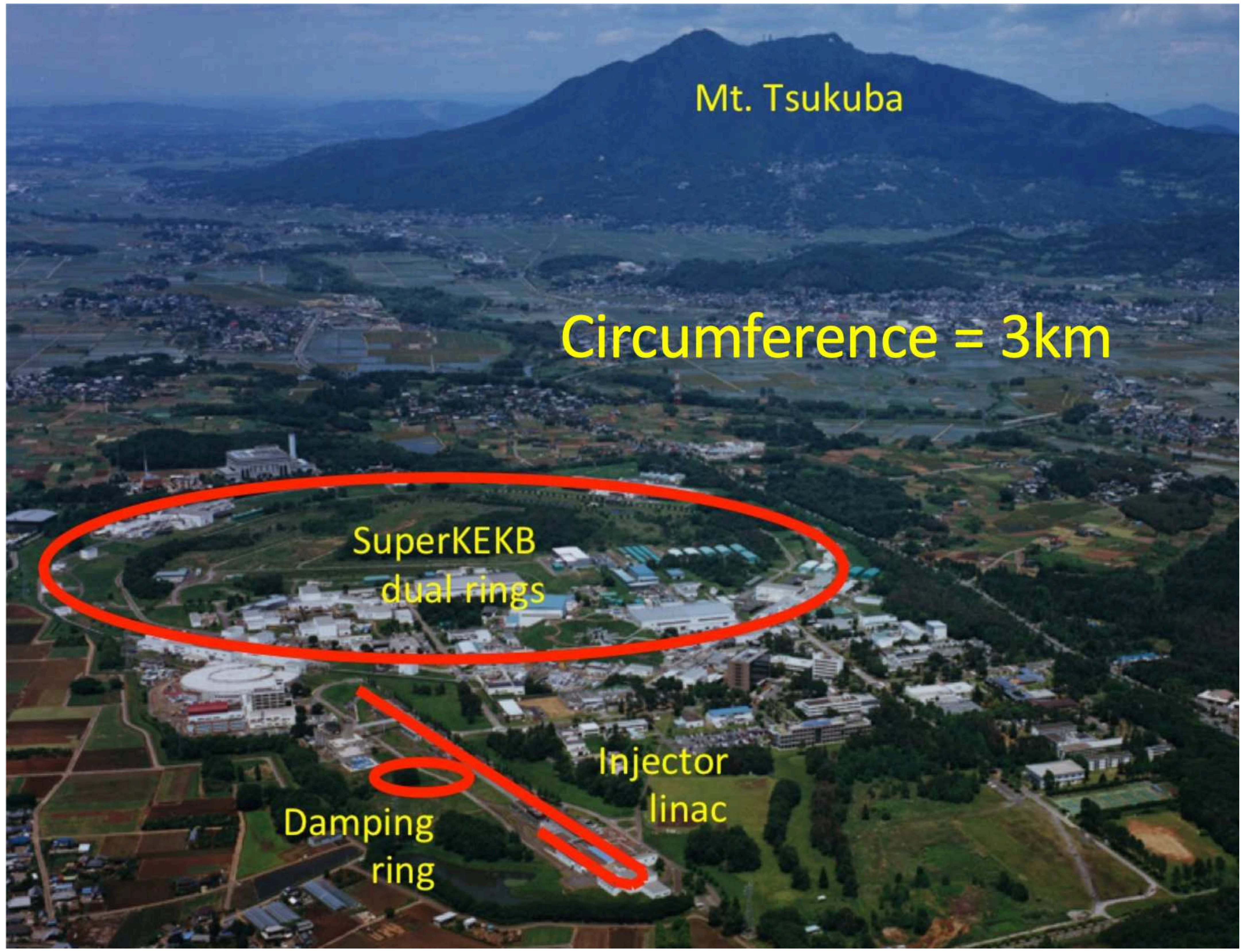
KEK

FUTURE CIRCULAR COLLIDER
1st FCCee Beam Instrumentation Workshop
Nov 21, 2022, 2:00 PM → Nov 22, 2022, 6:30 PM Europe/Zurich
6/2-024 - BE Auditorium Meyrin (CERN)

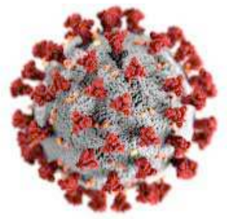
Electron-Positron Asymmetric-Energy Double-Ring Collider

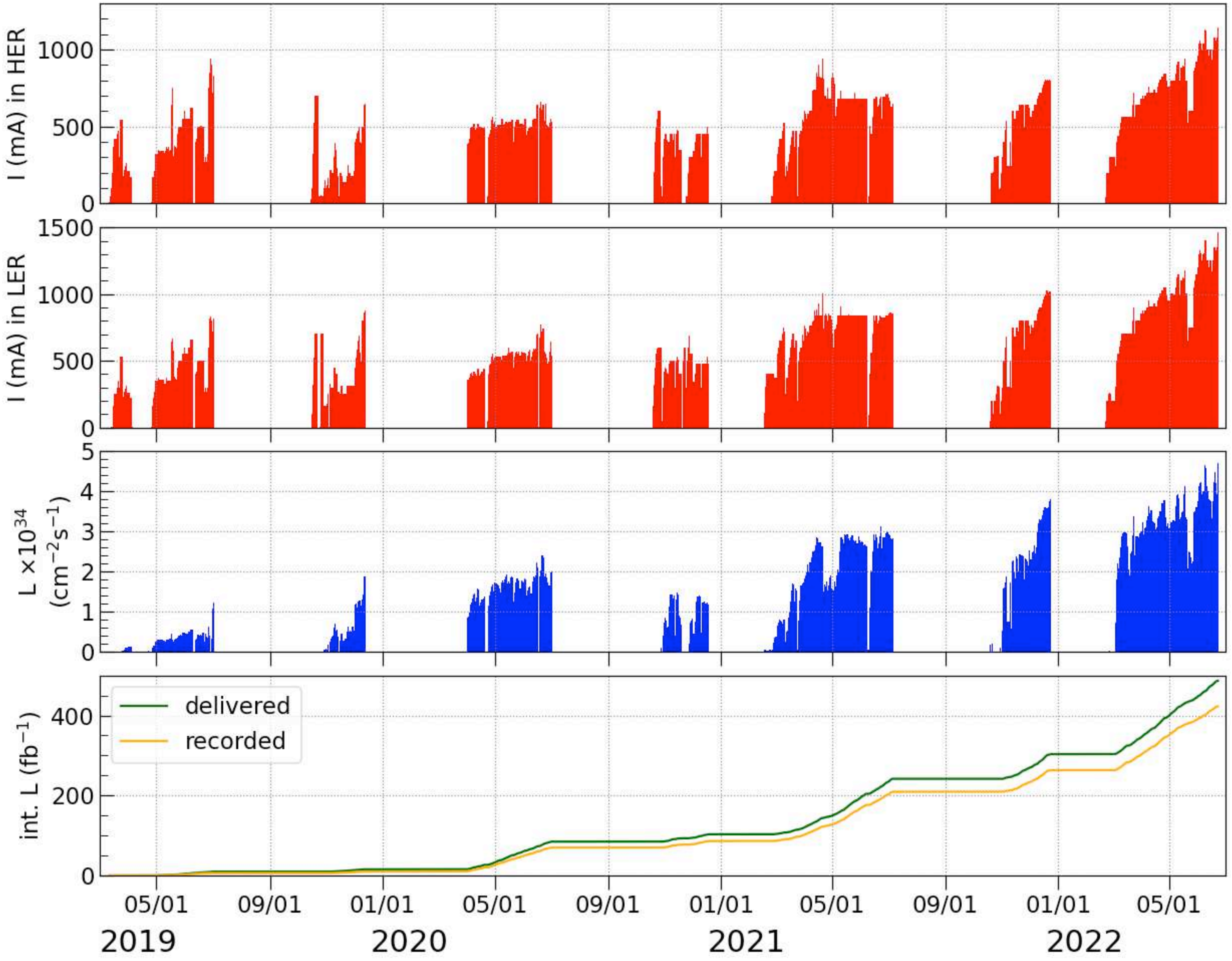
LER (positron): 4 GeV **HER (electron): 7 GeV**



Peak Luminosity is 4.7 x 10^{34} $cm^{-2}s^{-1}$

$\sigma_y^* = 0.2\ \mu m$ ← twice the size of COVID-19 virus





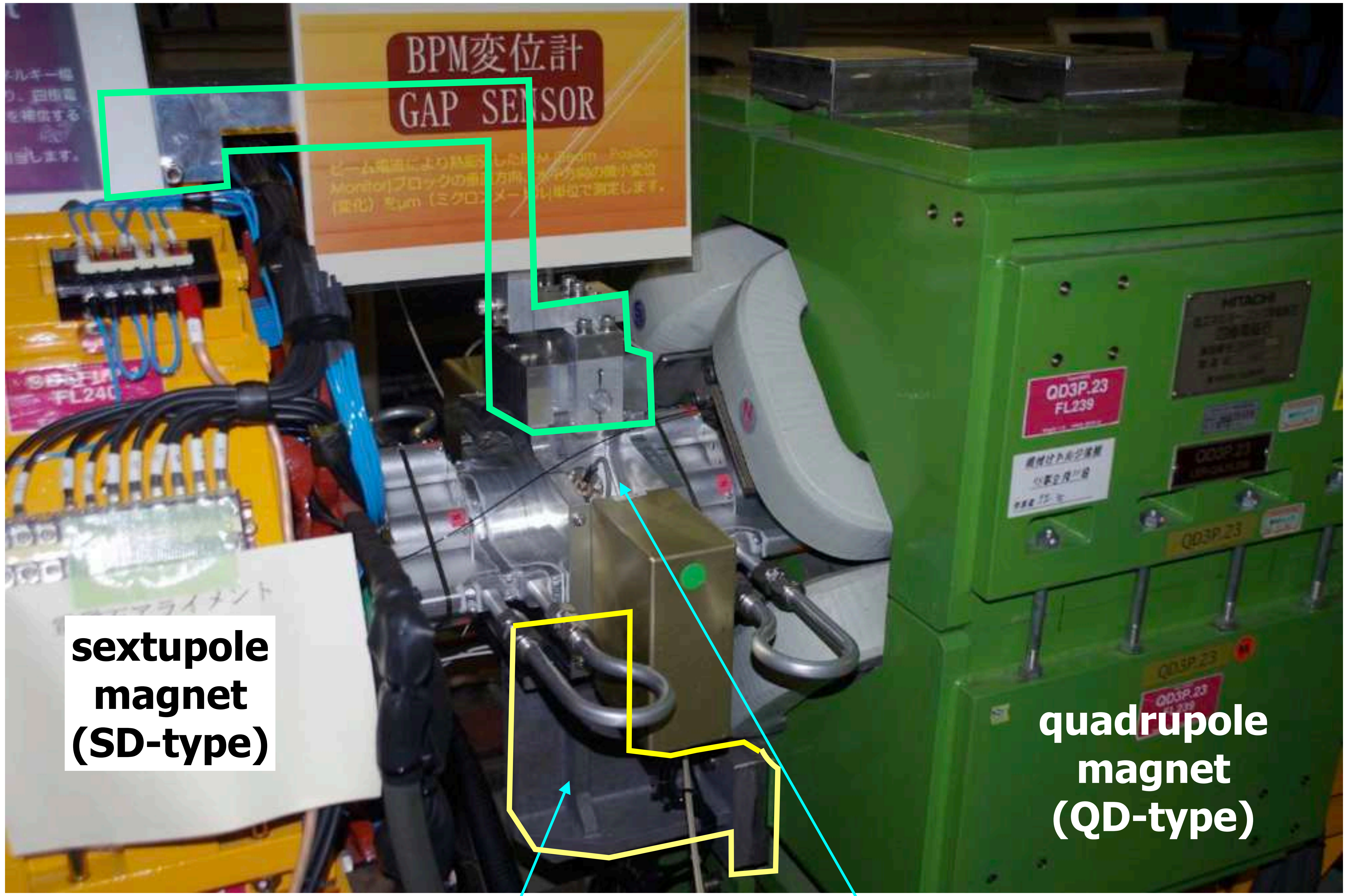
More details of the recent performance is found in eeFACT2022 (https://agenda.infn.it/event/21199/) .

Beam Monitor System

- Beam Position Monitor (BPM)
  - The BPM is installed near each quadrupole magnets and fixed at the quadrupole magnet. The alignment between the BPM and quadrupole magnet does not change in principle. Beam-based alignment (Quad-BPM) is performed to determine the relationship between the center of BPM reading and magnetic field center. Defocusing sextupole magnets (SD-type) are installed near defocusing quadrupole magnets (QD-type). In this case, a displacement monitor is used to measure the relative misalignment between the BPM and the sextupole magnet because beam position at the sextupole is important to evaluate and correct X-Y couplings and vertical dispersions.
  - Gain calibration for each electrode is performed every two weeks. (before Quad-BPM)
  - LER: 444 BPMs based on 509 MHz narrow band detector (measurement is every 4 seconds)
  - HER: 466 BPMs based on 1 GHz narrow band detector (measurement is every 4 seconds)
  - Gated turn-by-turn BPMs (70 BPMs) for each ring.
    - Beam position of any bunch can be measured among many bunch.

BPM and Displacement Monitor (Gap Sensor)

BPM is fixed at quadrupole magnet and displacement monitor measures a relative deviation (horizontal and vertical) between the BPM and the sextupole magnet.



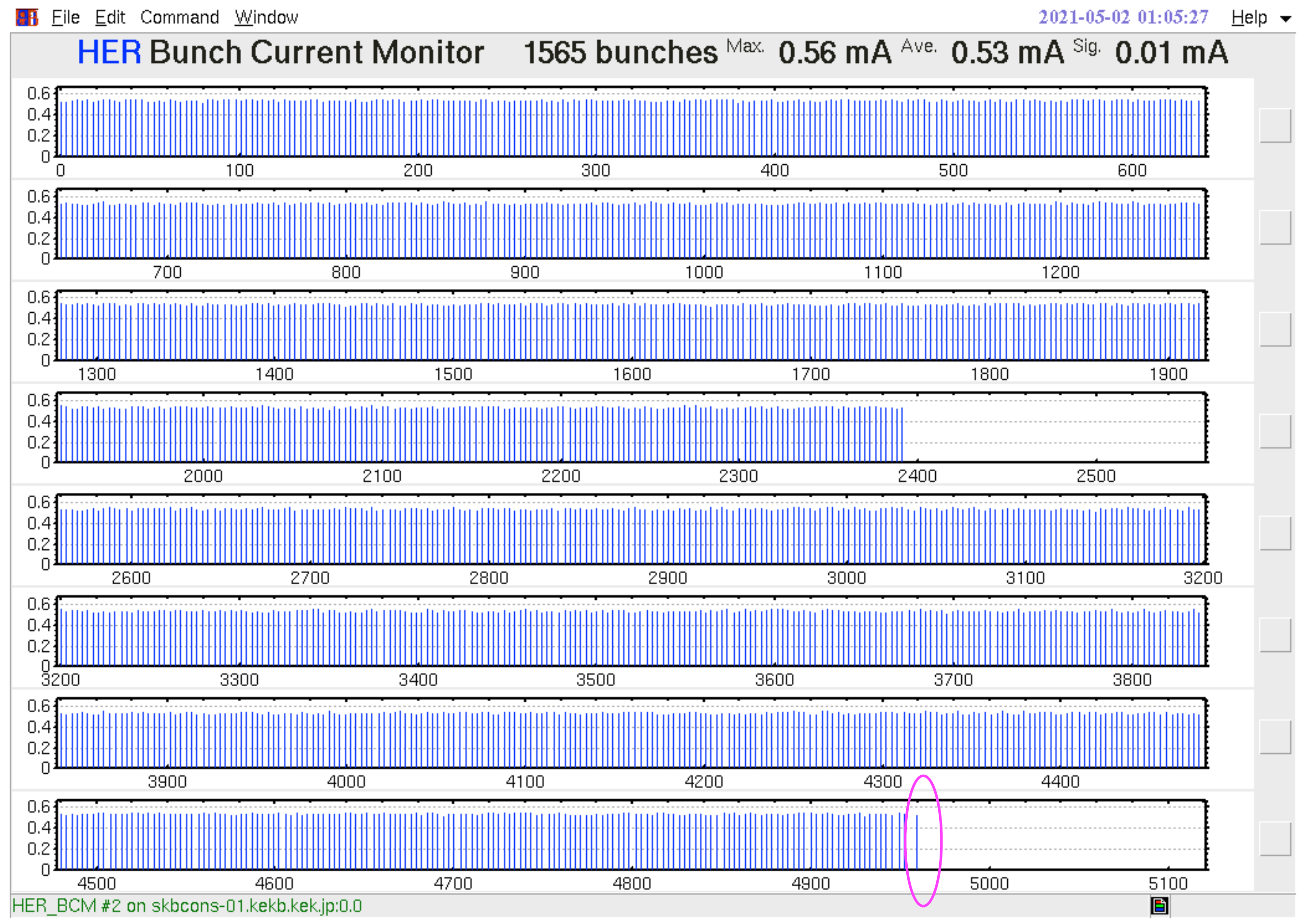
The support arm fixes the alignment of BPM and quadrupole magnet.

BPM

Beam Monitor System (Cont'd)

- Tune Measurement
  - Gated tune meter for each ring
  - Tune of the pilot bunch (non collision) is always measured by gated tune meter every 4 seconds.
    - Tune feedback system works to keep a target tune with the tune measurement.
- Beam Size Monitor
  - X-ray beam size monitor
  - SR beam size monitor
  - Vertical emittance is essential for "nano-beam" scheme.

It is used to evaluate optics corrections and luminosity tuning.

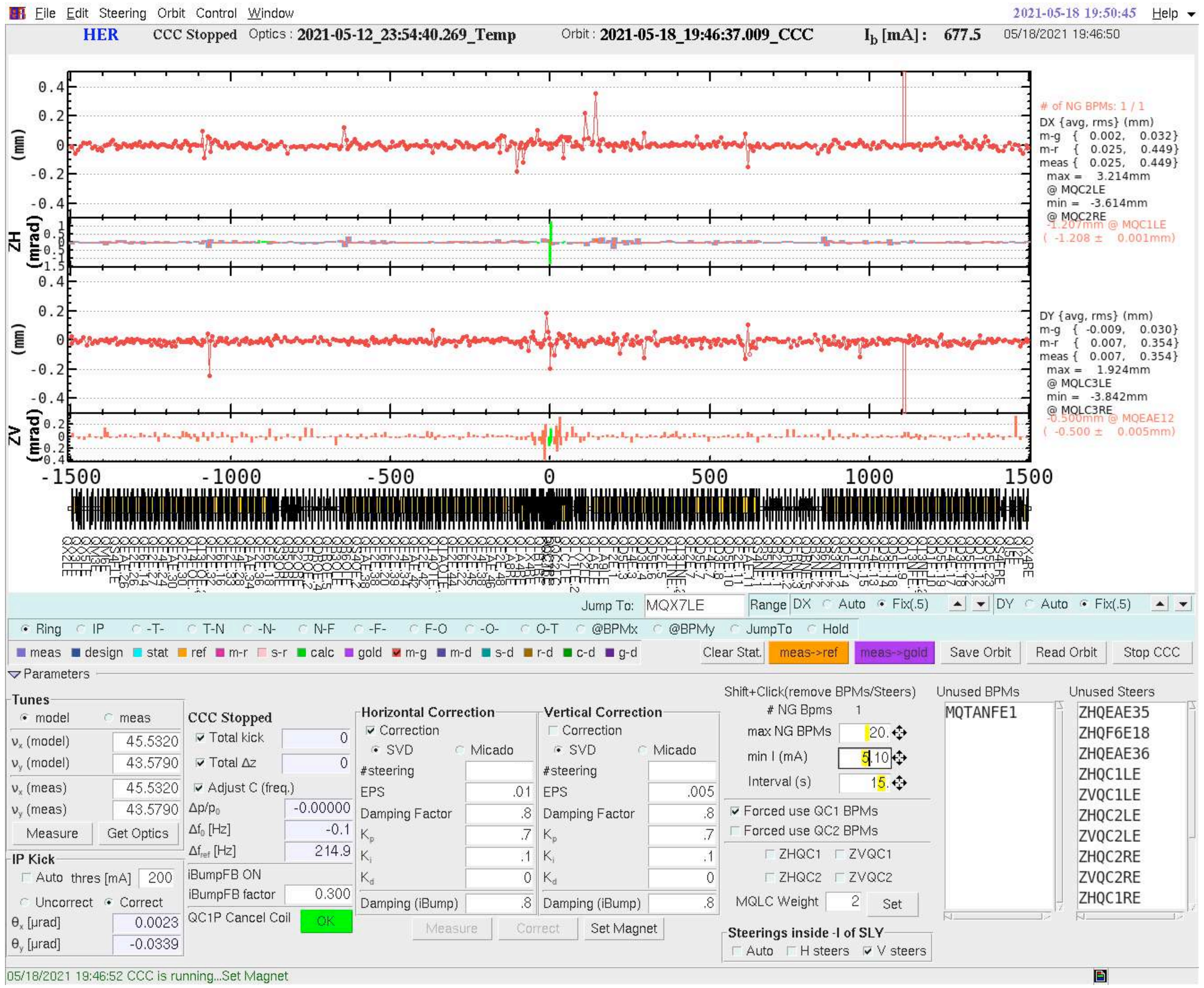


- Beam Loss Monitor
  - many kinds of loss monitors... to abort beam as quick as possible if beam becomes unstable
- Bunch Oscillation Recorder and Bunch Current Monitor based on Bunch-by-Bunch feedback system
- Coronagraph to measure beam tail (halo), streak camera to measure bunch length

Global Continuous Orbit Correction

Beam orbit is corrected to "GOLD orbit" every 15 seconds (not strict).

The GOLD orbit is registered just after optics corrections. Optics corrections are performed every two weeks in principle.

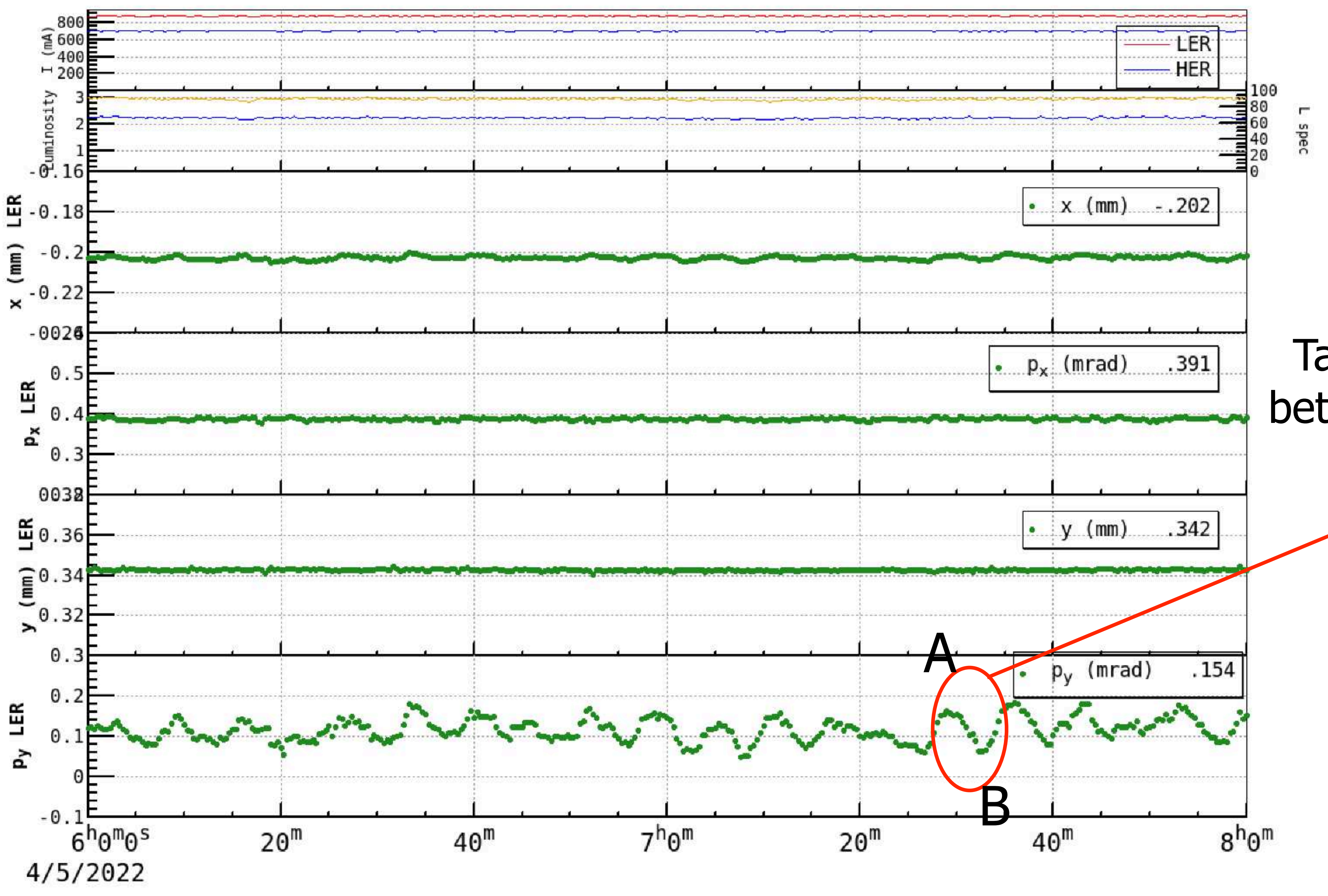


The optics and orbit correction are performed online and SAD code is used.

Vertical Angle Fluctuation at IP in LER

Orbit (x, p_x, y, p_y) can be estimated by two BPMs near the IP.

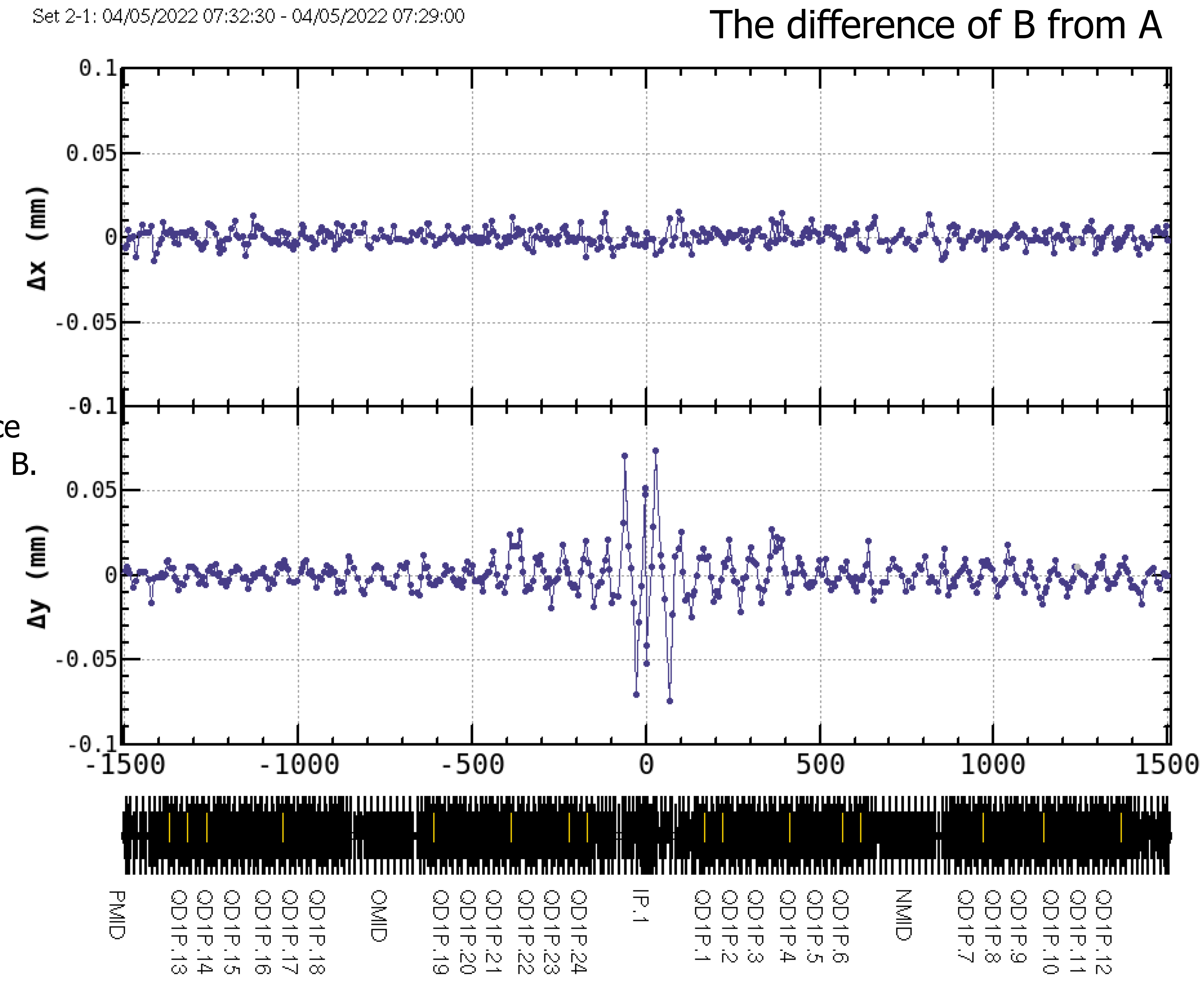
time span ~ 2 hours



Take difference between A and B.

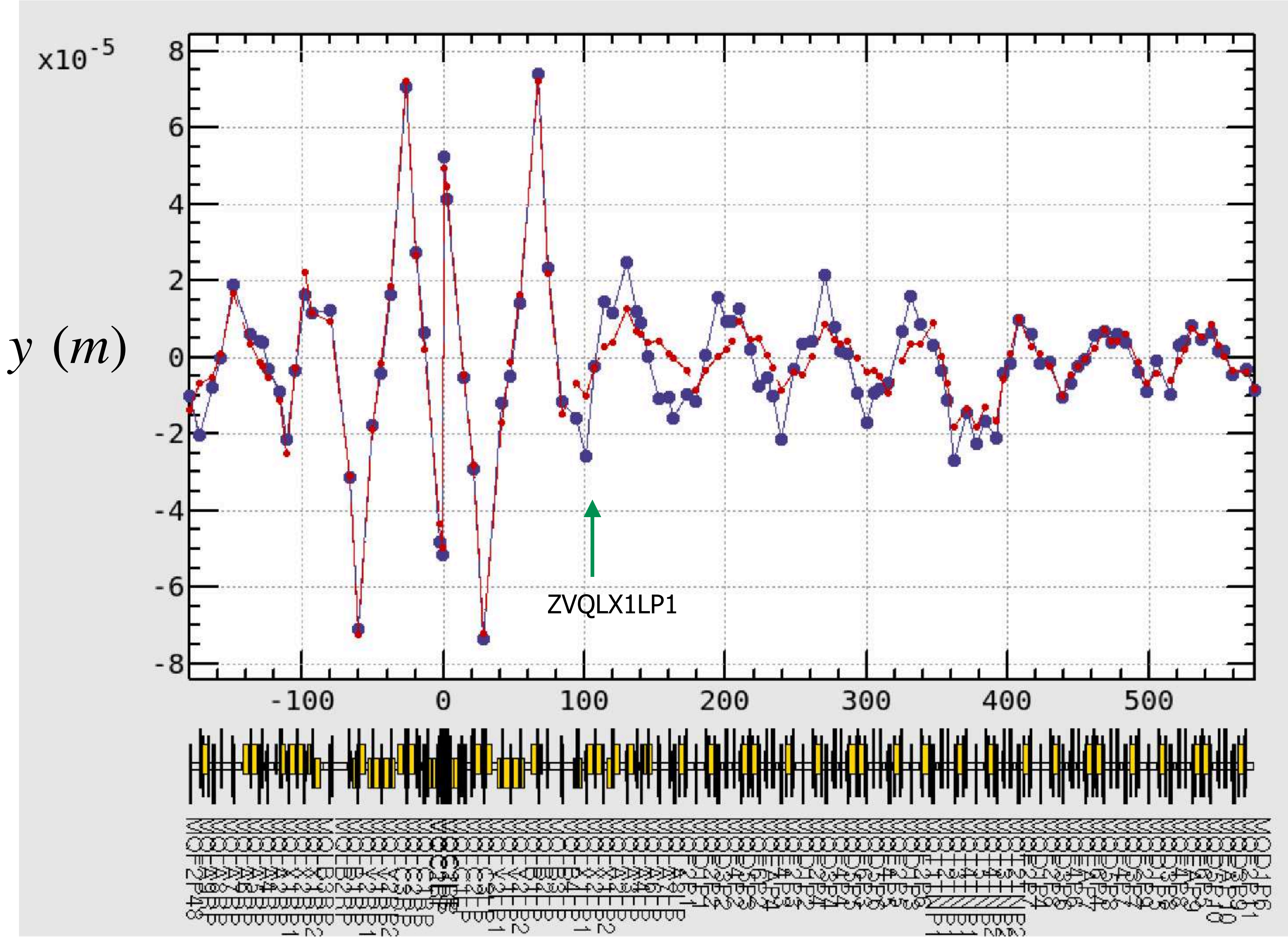
We observed the orbit fluctuation with 6 - 7 min frequency.

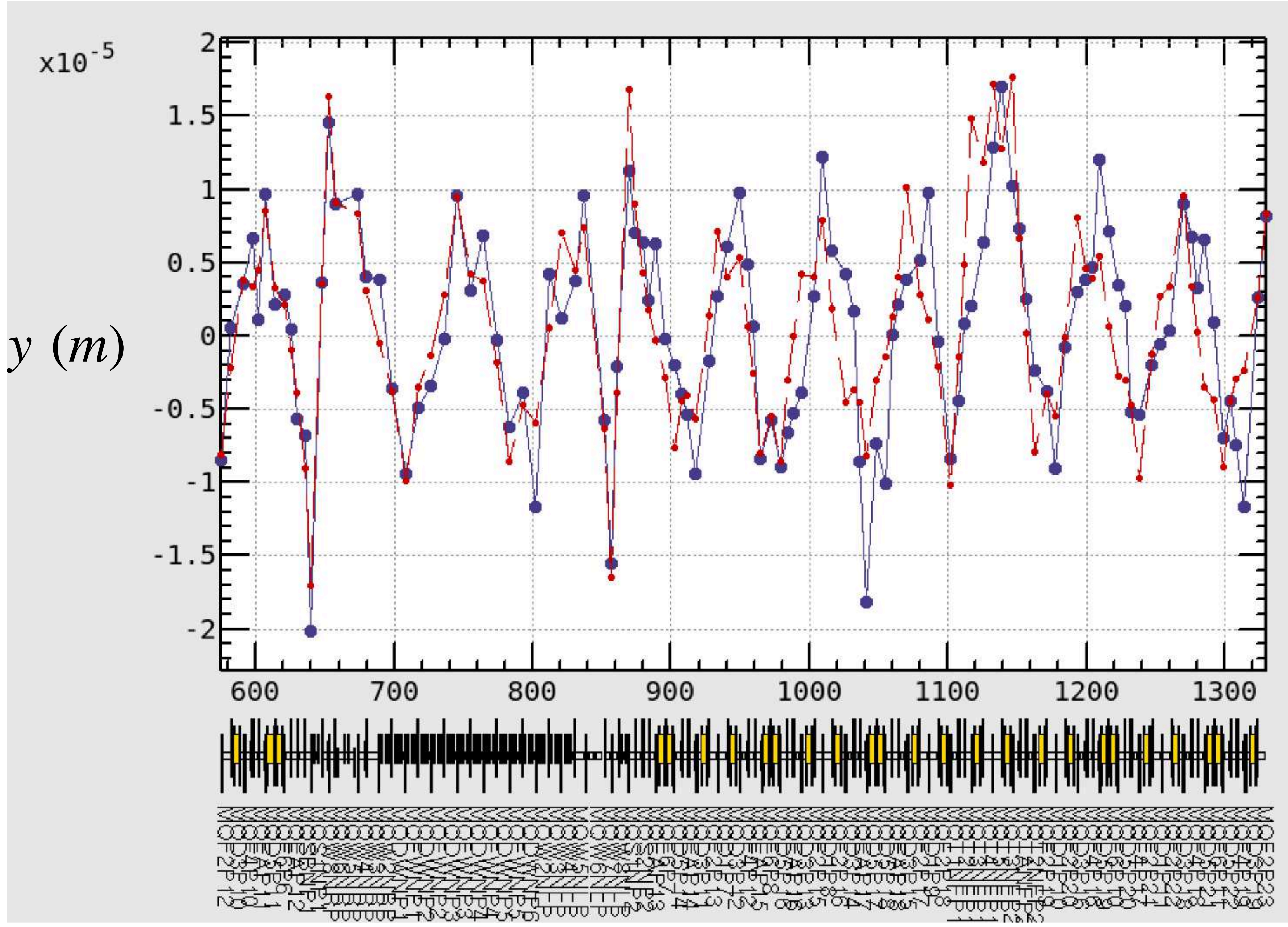
The difference of B from A

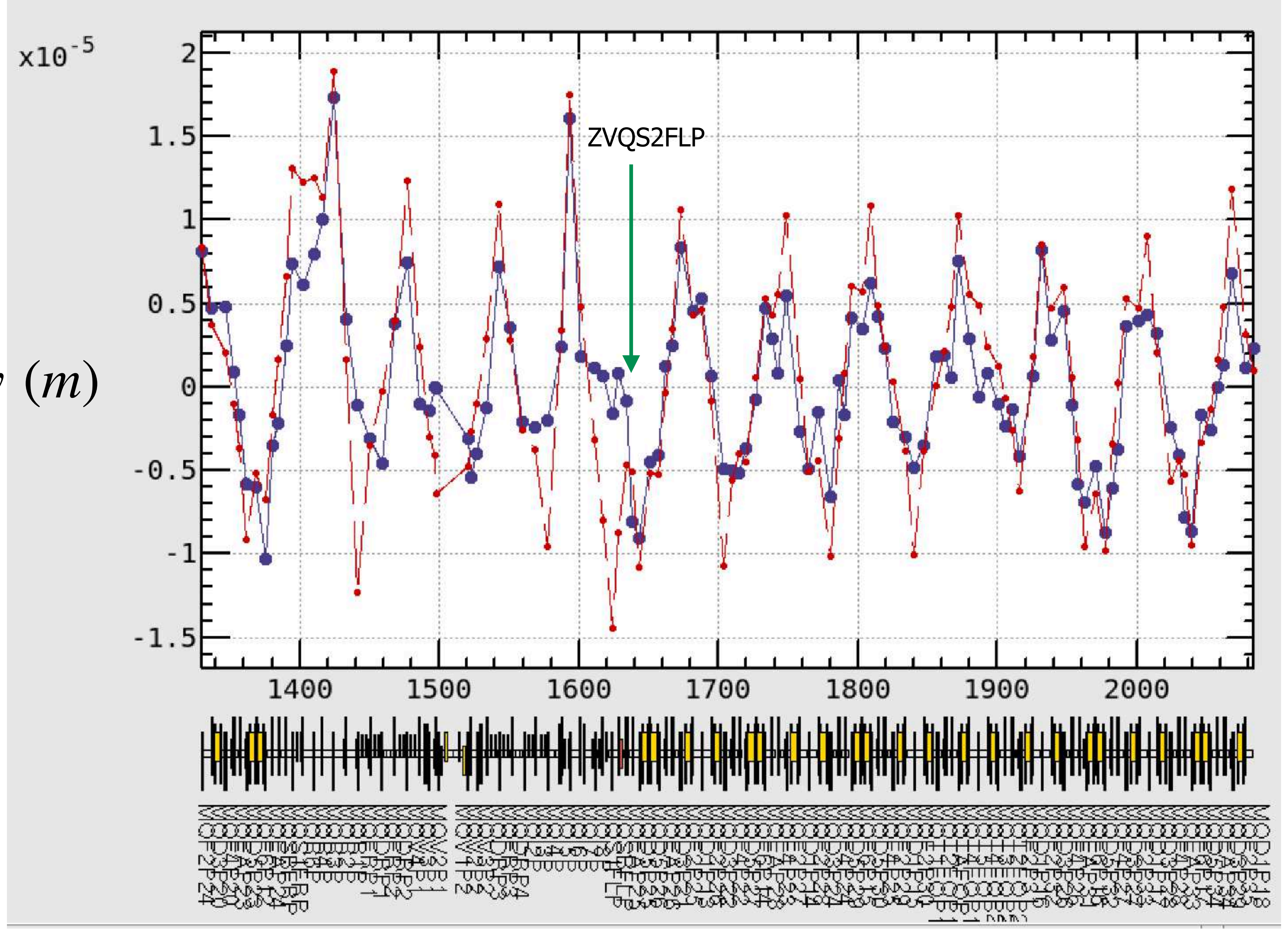


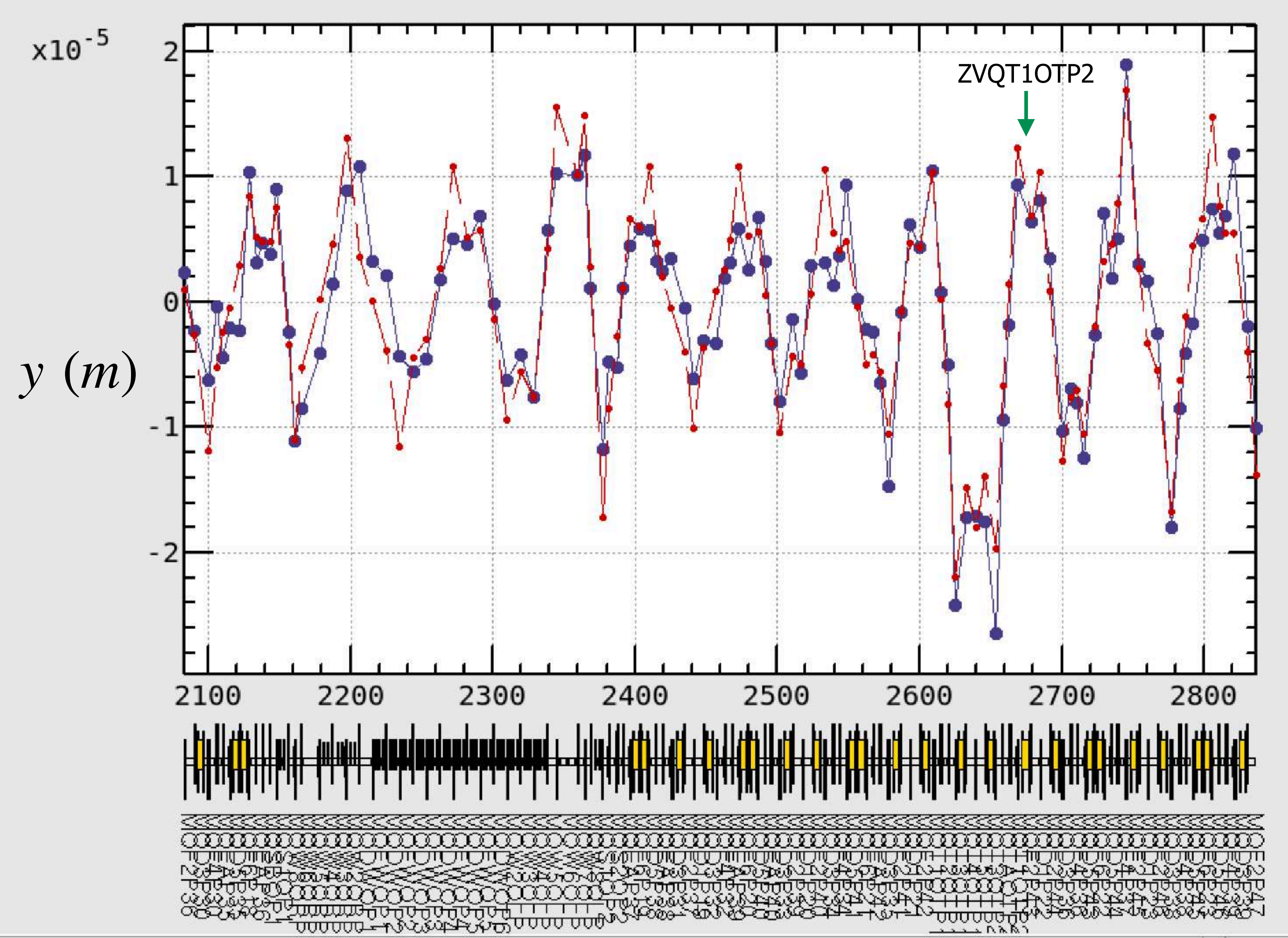
The single kick-like orbit distortion can be corrected by using a few steerings.

Why we cannot correct the orbit fluctuation by the continuous orbit correction (CCC) ?









LER

Orbit can be corrected by three correctors with MICADO.

	corrector	kick angle (μrad)
10	ZVQLX1LP1	-0.588
109	ZVQS2FLP	-0.959
175	ZVQT1OTP2	0.408

Stability of 0.5 ~ 1 μrad is necessary.

Possibility of a displacement of quadrupole magnets.

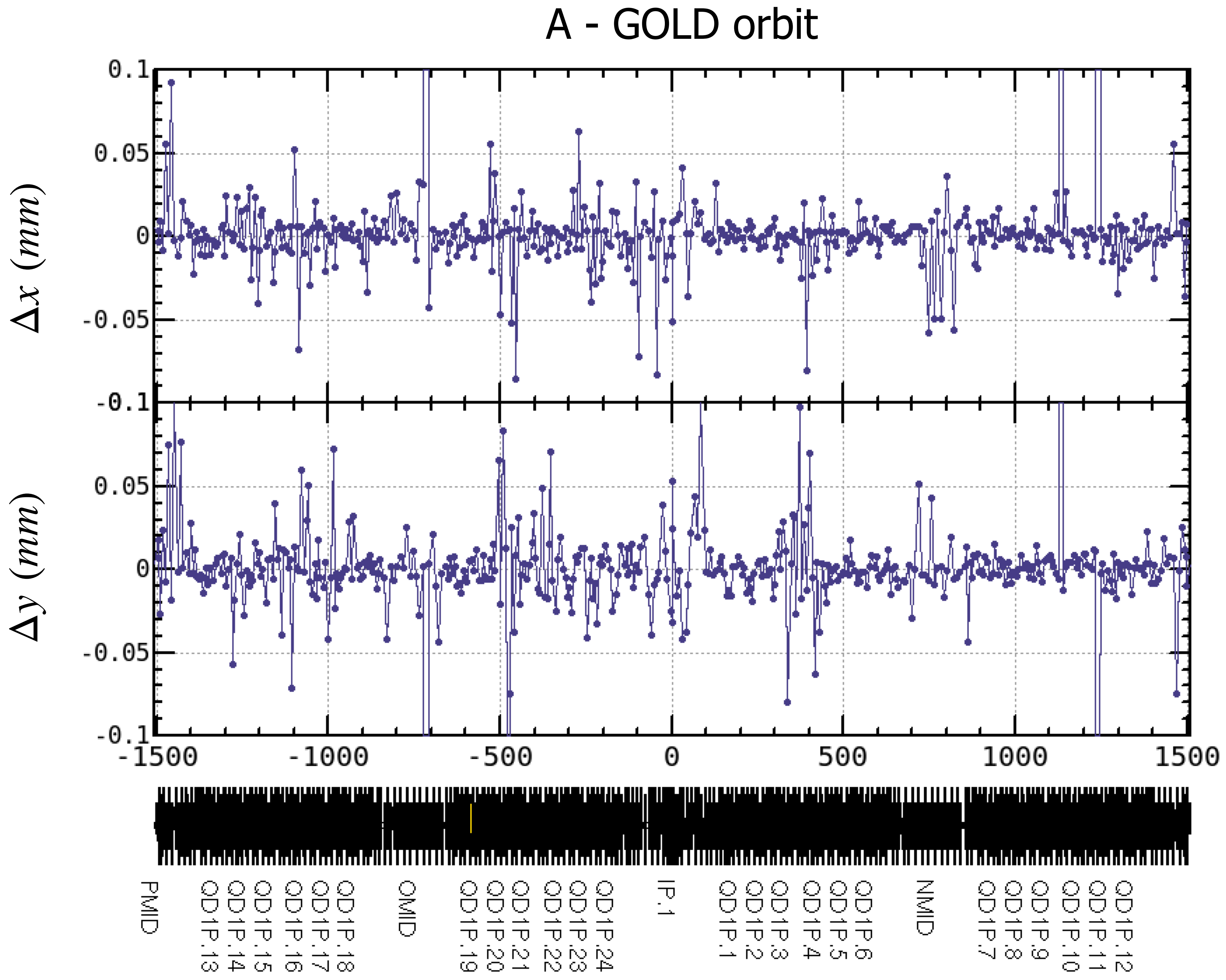
QS2FLP : K1 = 0.049 (1/m)

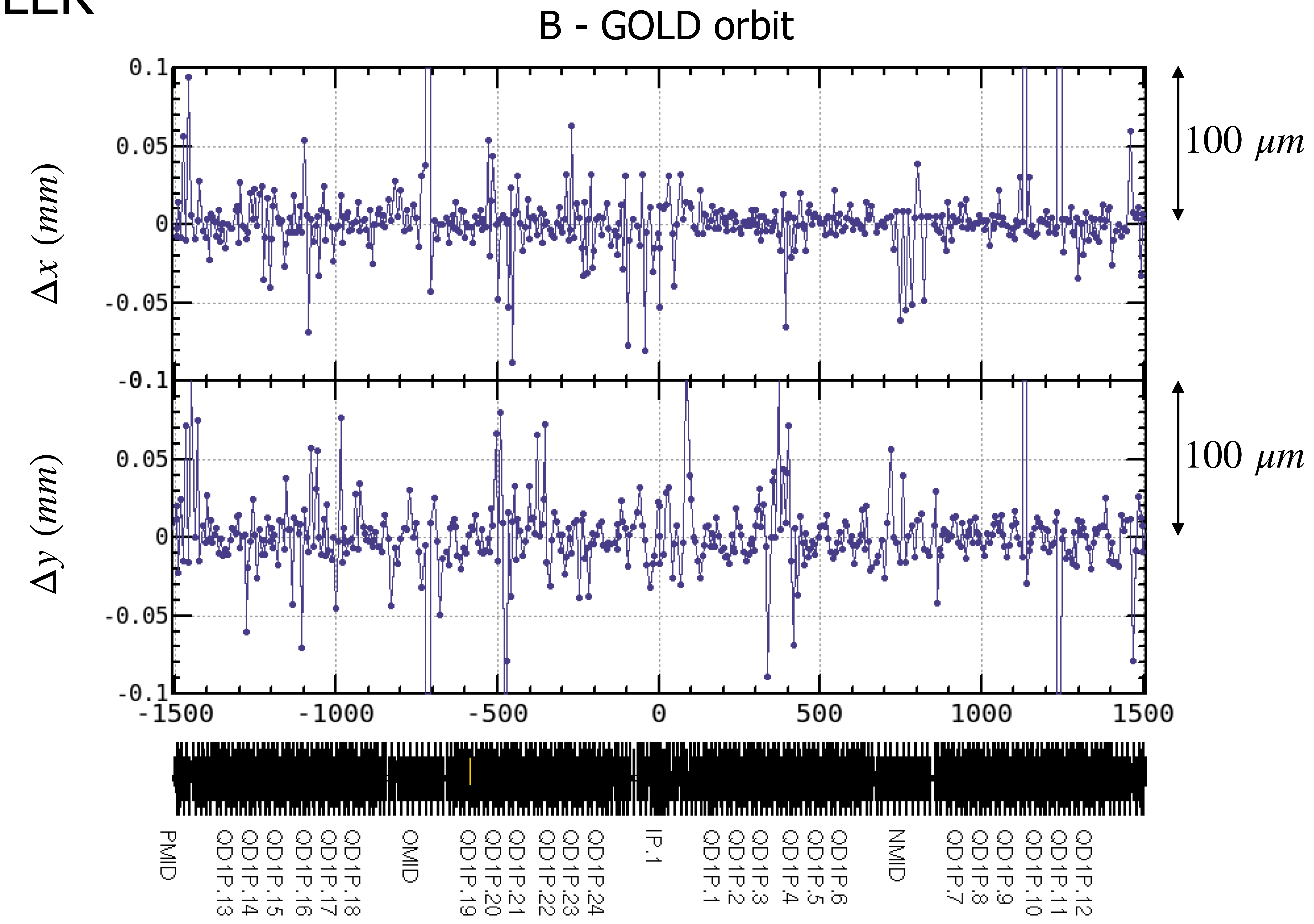
This corresponds to $\Delta y = 20\ \mu m$ movement.

Or 0.85 % fluctuation of K-value (y = 0.32 mm)

However, the difference between a measured orbit and the GOLD orbit becomes large in several days after optics corrections.

LER

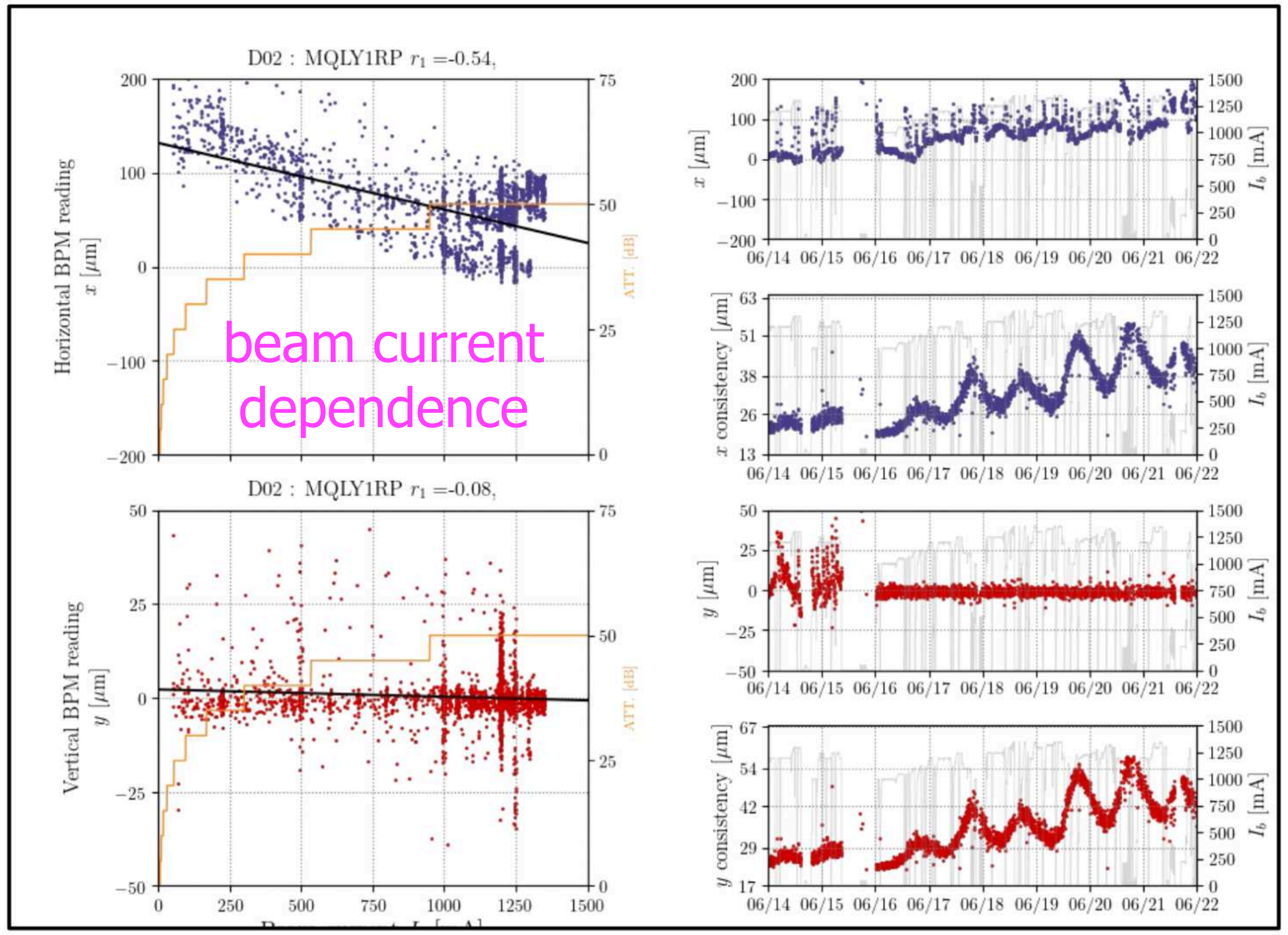


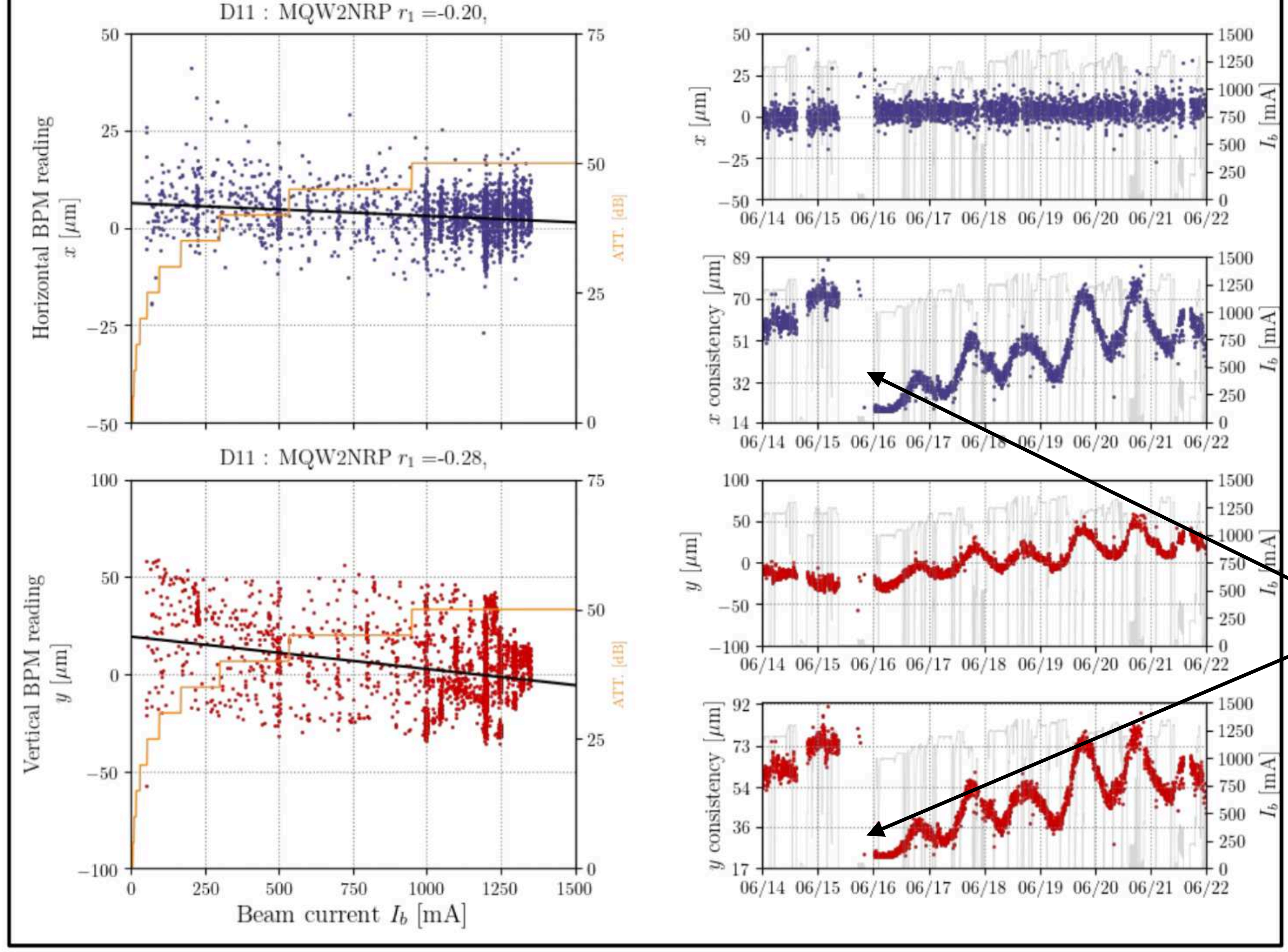


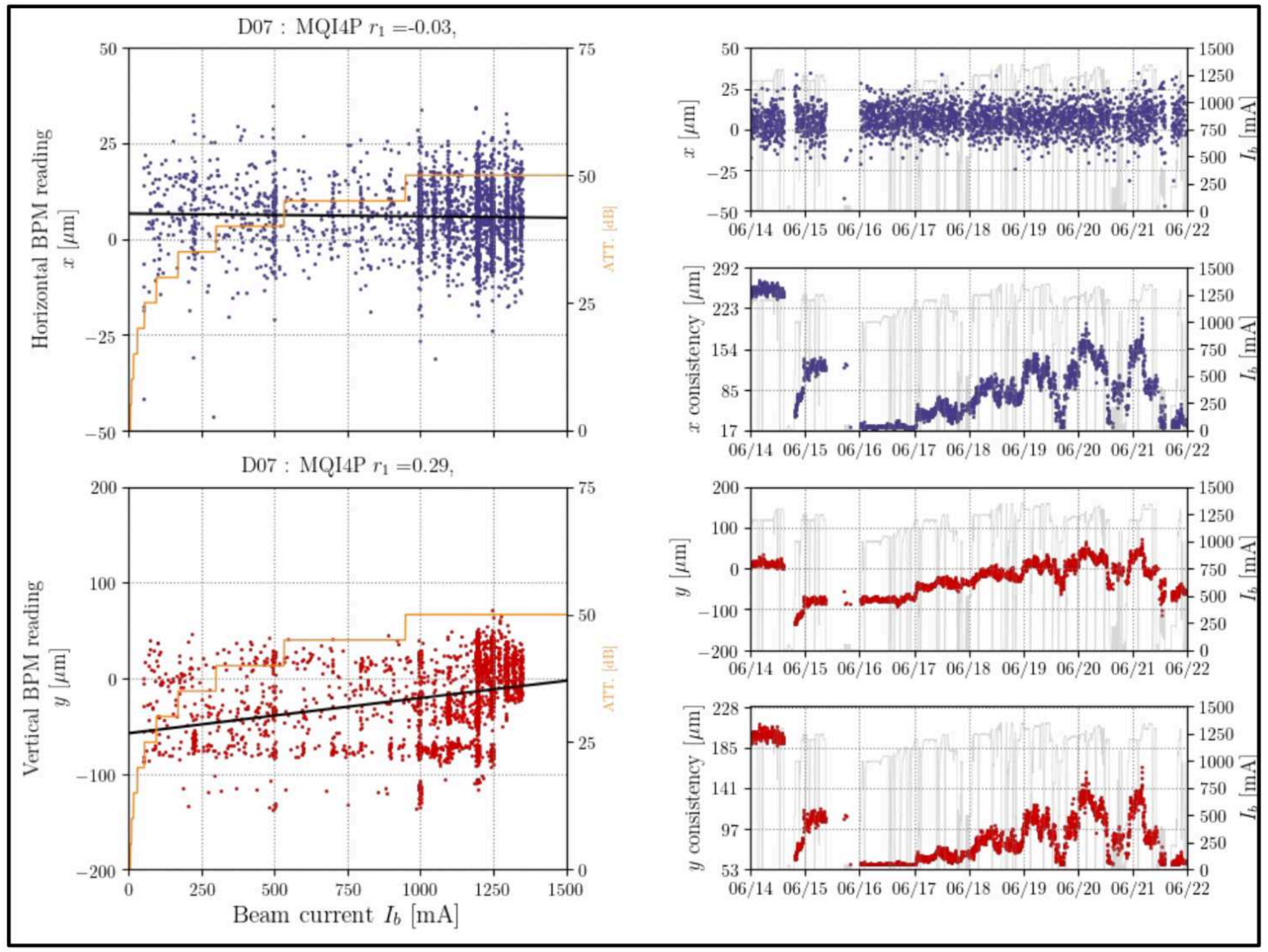
Number of spikes (a large difference between the measurement and GOLD orbit) is about 20 -30 BPMs.

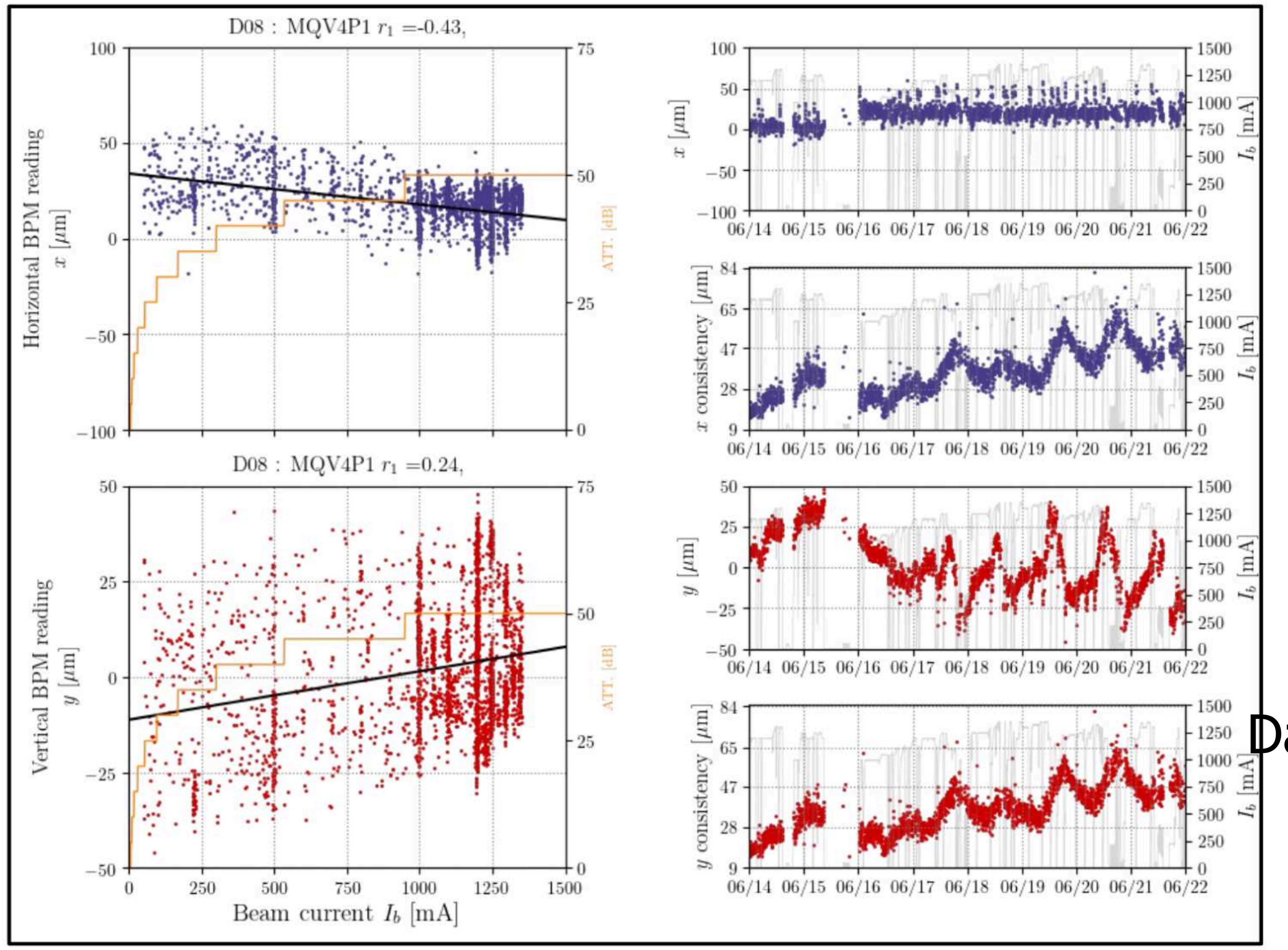
The actual orbit cannot be adjusted to the GOLD orbit over time.

/users/onishi/svn-work/SuperKEKB/operation/orbit/CCC









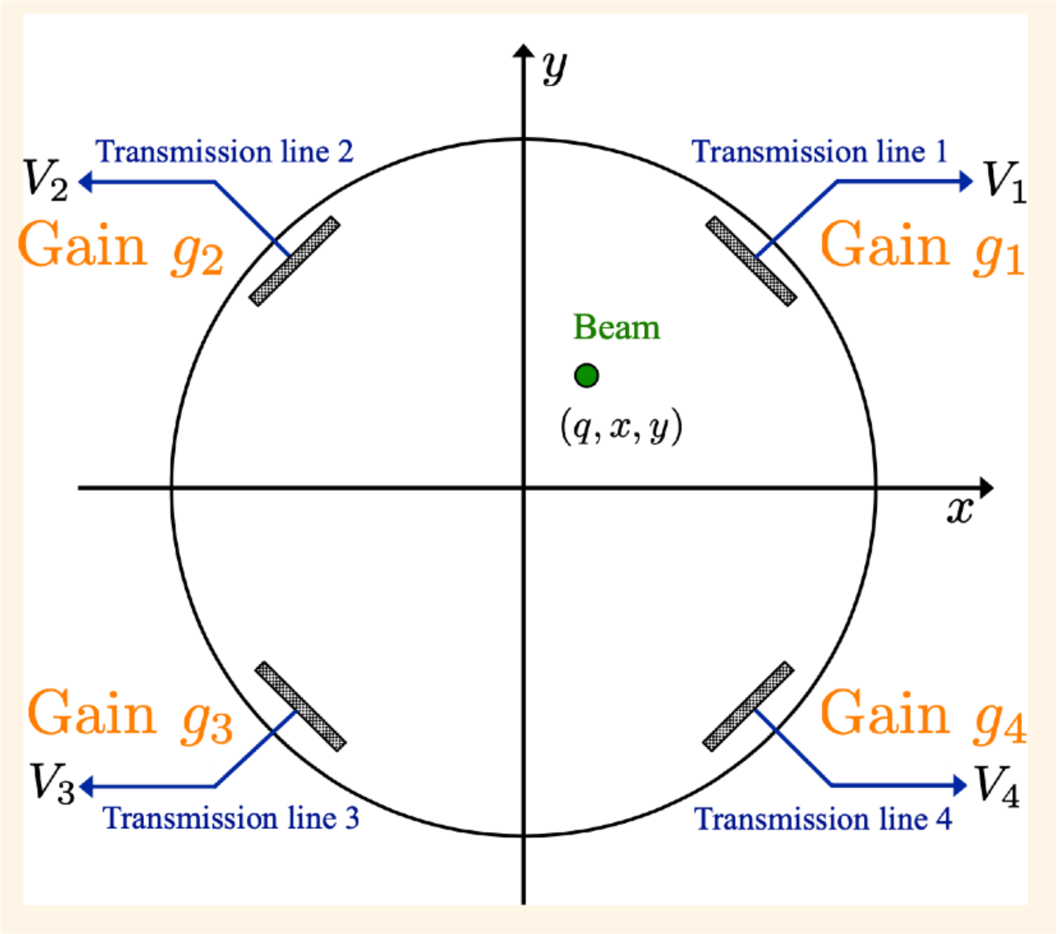
Definition of "consistency"

$$C_z = \sqrt{\frac{1}{4} \sum_{i=a,b,c,d} (z_i - \langle z \rangle)^2}$$

$z = x$ or y

a - d means combination of 3 electrodes

gain calibration on June 15



Consistency becomes bad in several days after gain calibration.

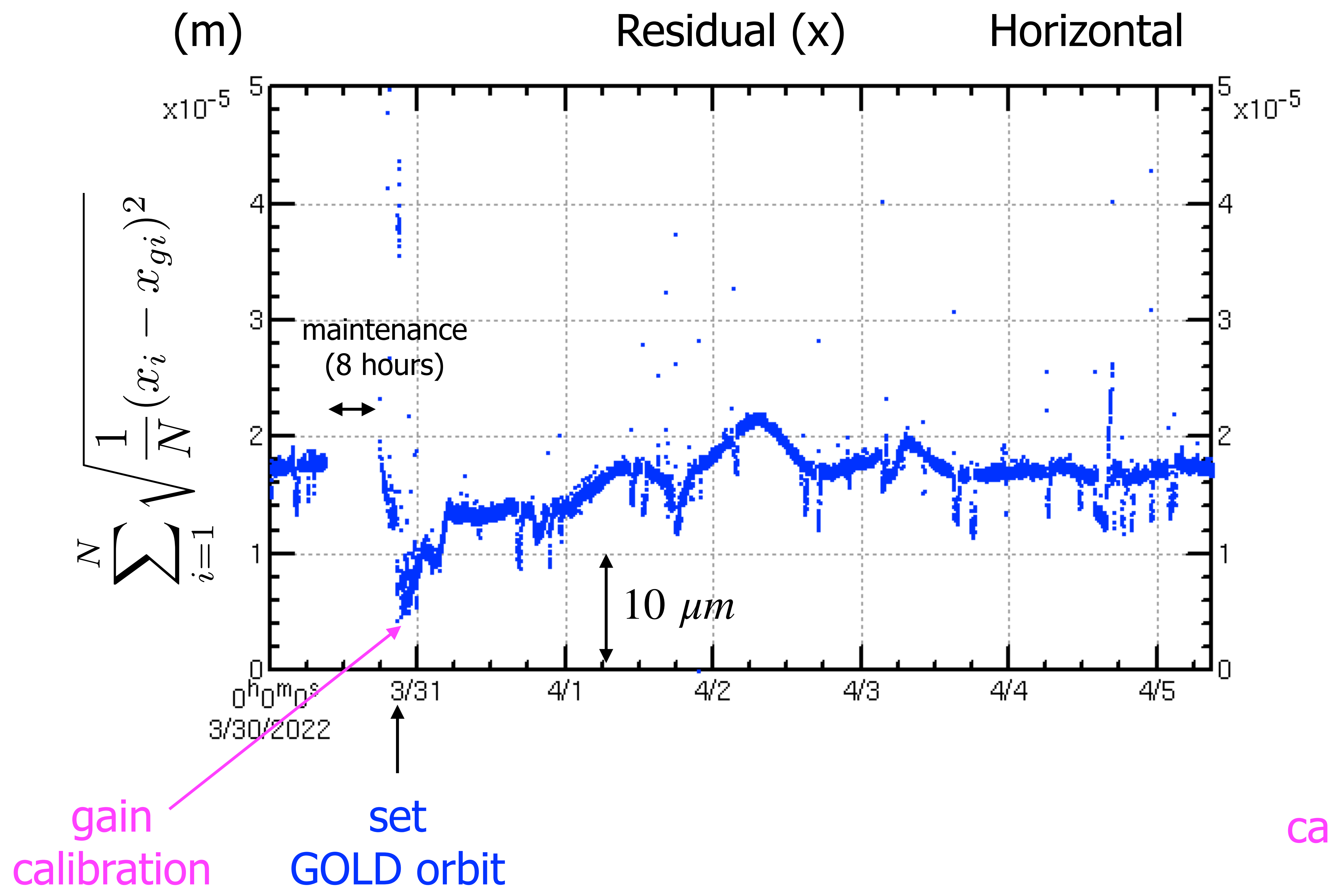
Day-night effect was also observed.

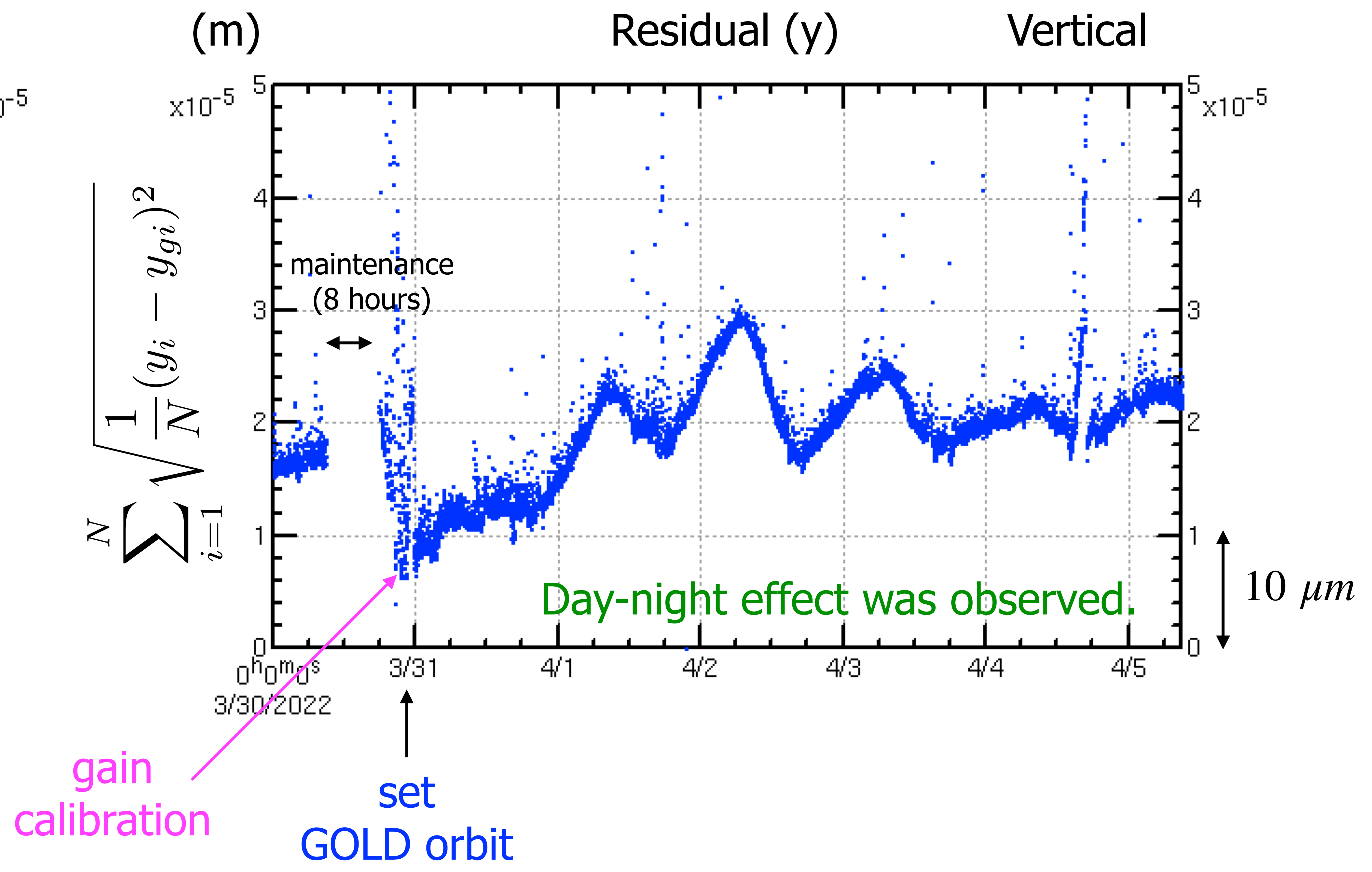
H. Sugimoto, mini optics meeting (Nov. 10)

Residuals from GOLD Orbit in LER

The residual less than 20 μm is not enough. More stability is necessary.

time span ~ 7 days





The reasons that the measured orbit can not corrected to the GOLD orbit.

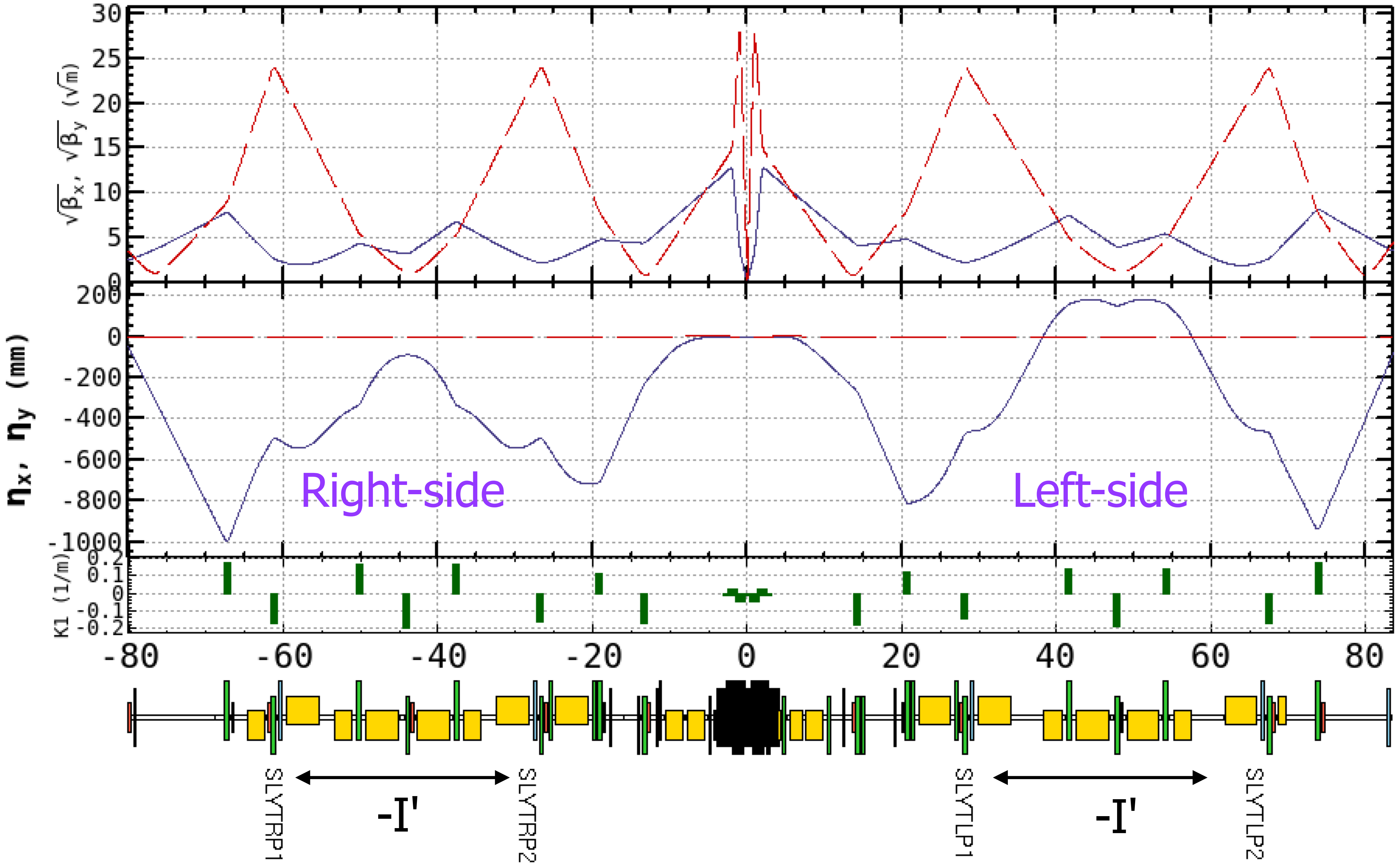
- Beam current dependence
- Day-night effect
- BPM gain changes (cables or circuit?)

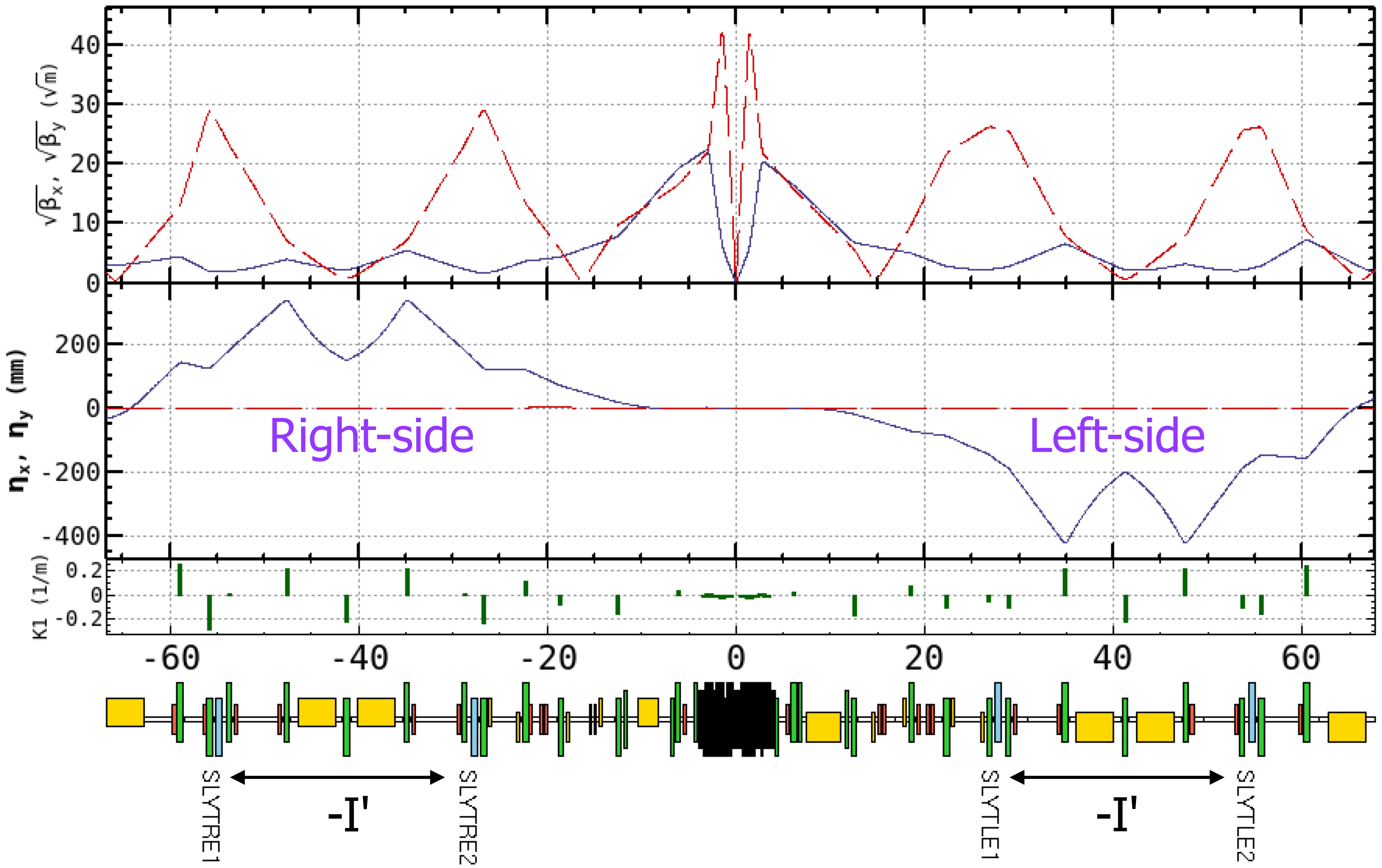
Local Chromaticity Correction: Strong Sextupoles (SLY)

LER

$\beta_y^* = 1\ mm$

HER





K2: 1.23 1/m² K2: 3.48 1/m² K2: 1.33 1/m² K2: 3.53 1/m² K2: -8.76 1/m² K2: -9.62 1/m² K2: 8.36 1/m² K2: 7.66 1/m²

$\beta_y = 521\ m$ $\beta_y = 525\ m$ $\beta_y = 702\ m$ $\beta_y = 675\ m$

$$\Delta\nu_y = \frac{\beta_y}{4\pi} K_2 \Delta x$$ ~0.0028 for $\Delta x = 20\ \mu m$

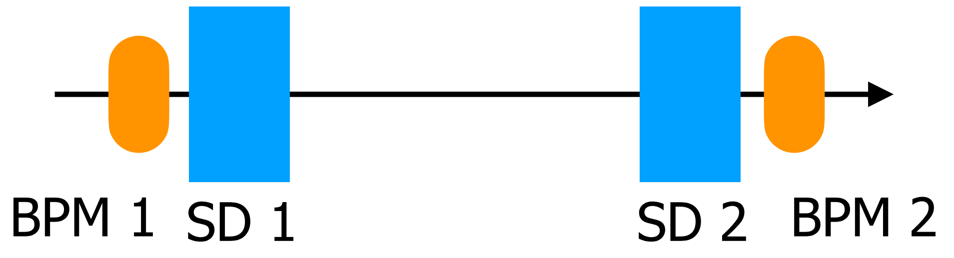
Horizontal tune shift can be ignored.

Horizontal orbit in-phase for each pair induces large beta-beat which changes β_y^*.

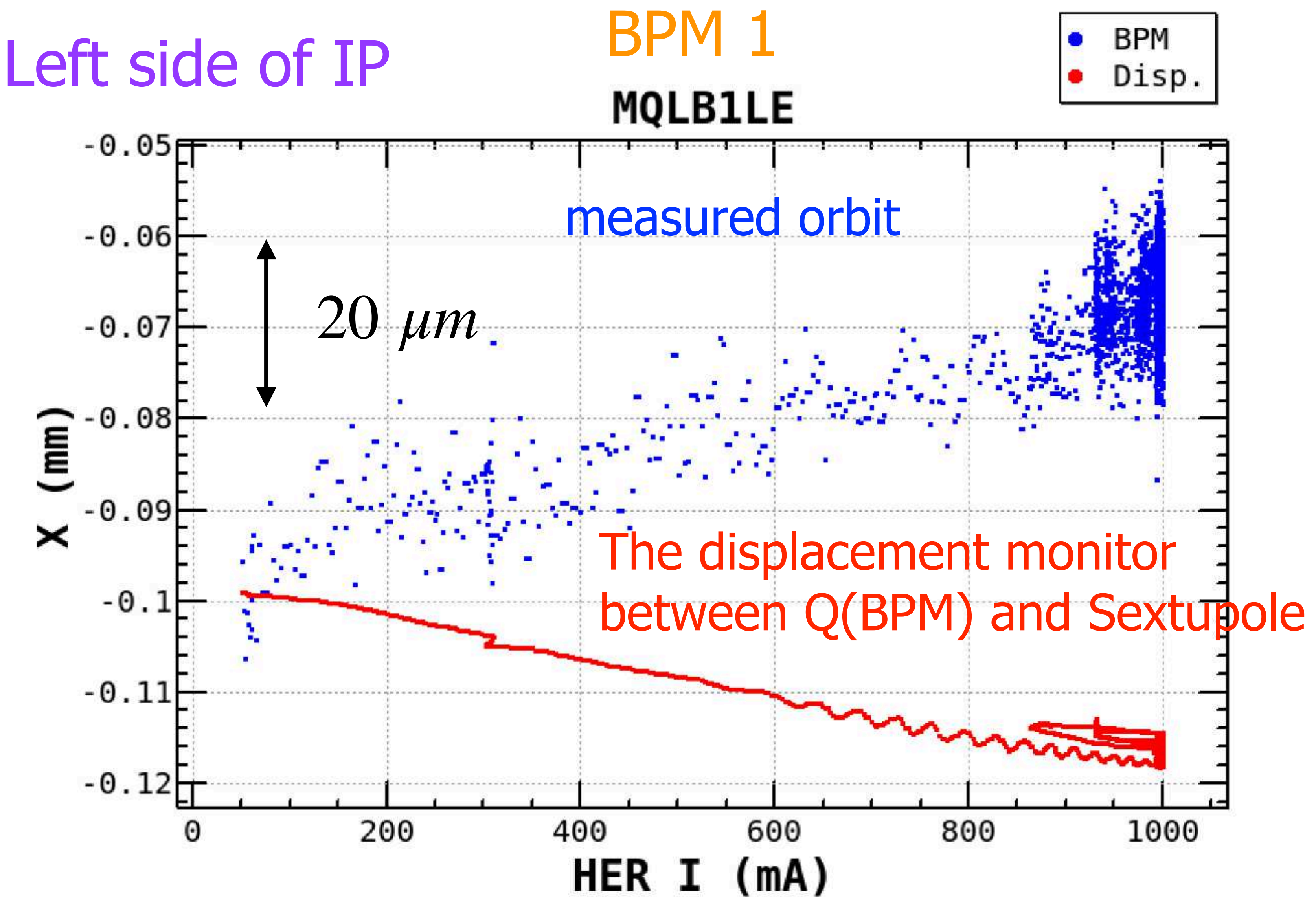
$\Delta\nu_y$ ~0.01 for $\Delta x = 20\ \mu m$

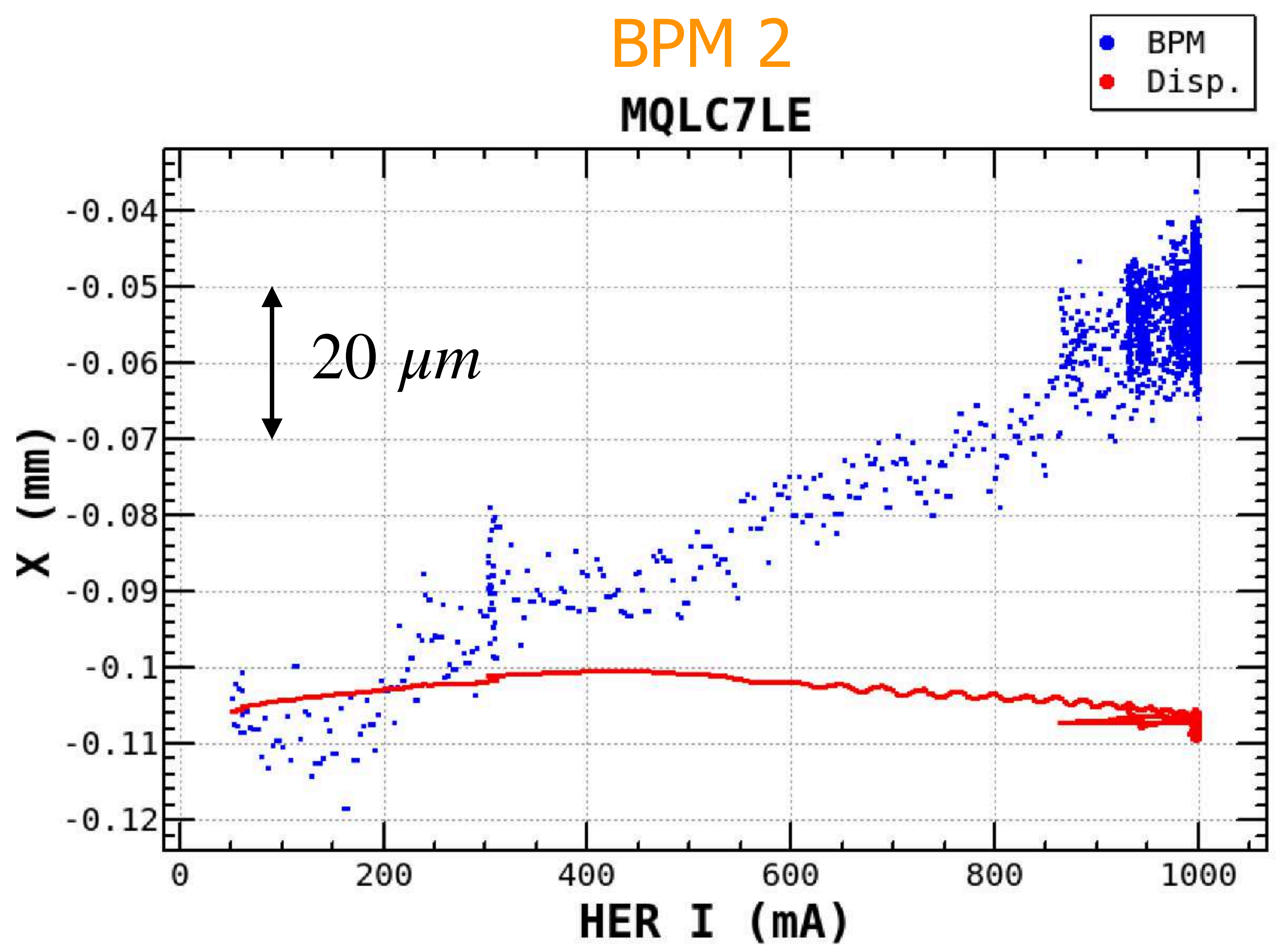
3.6 times larger than LER

The beam orbit at the local chromaticity correction in the HER



Left side of IP





Beam orbit depends on the beam current. The beam line is deformed by SR heating as one of the possible causes.

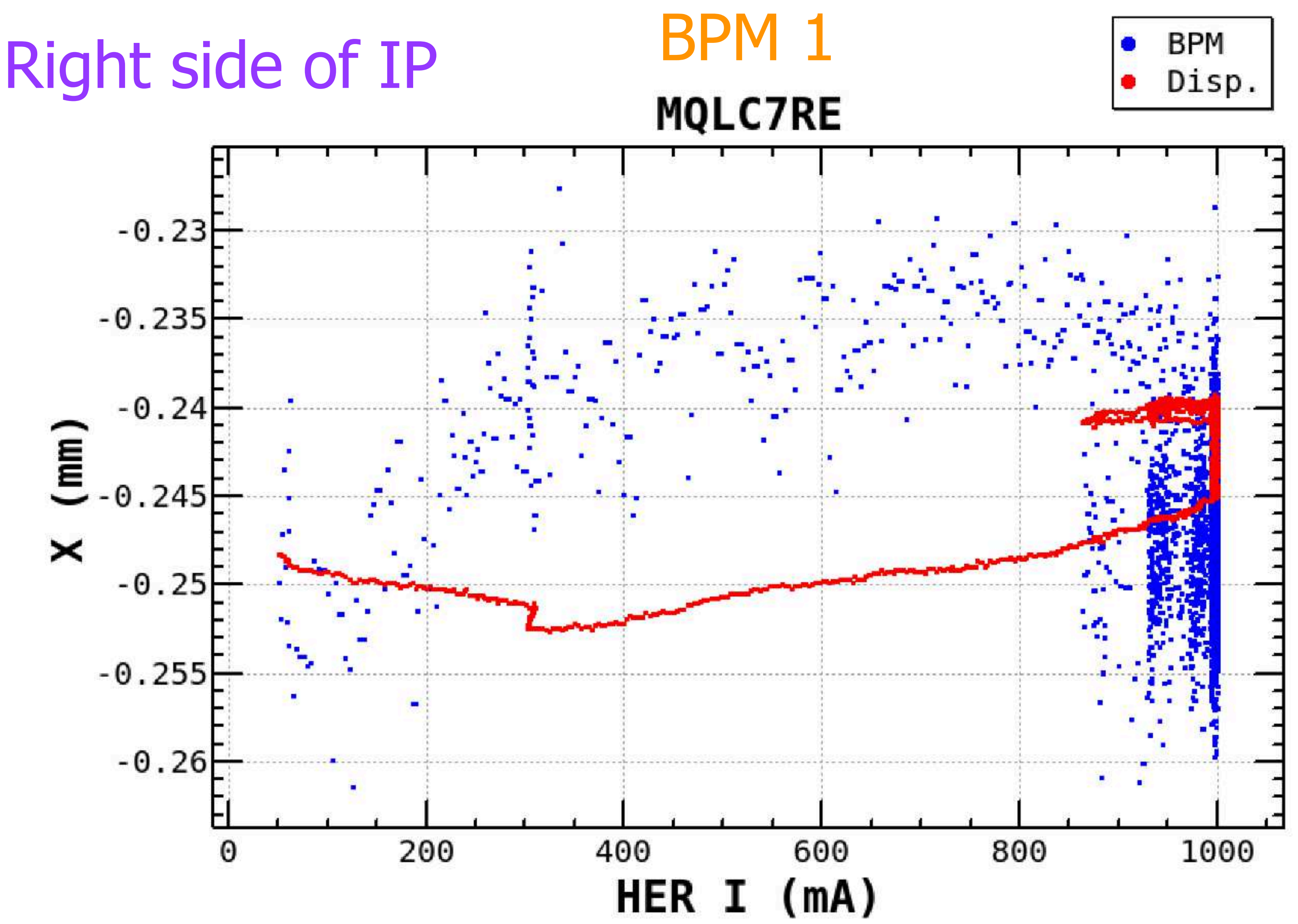
$$\Delta\nu_{x,y} = \frac{\beta_{x,y}}{4\pi}(K_2\Delta x)$$

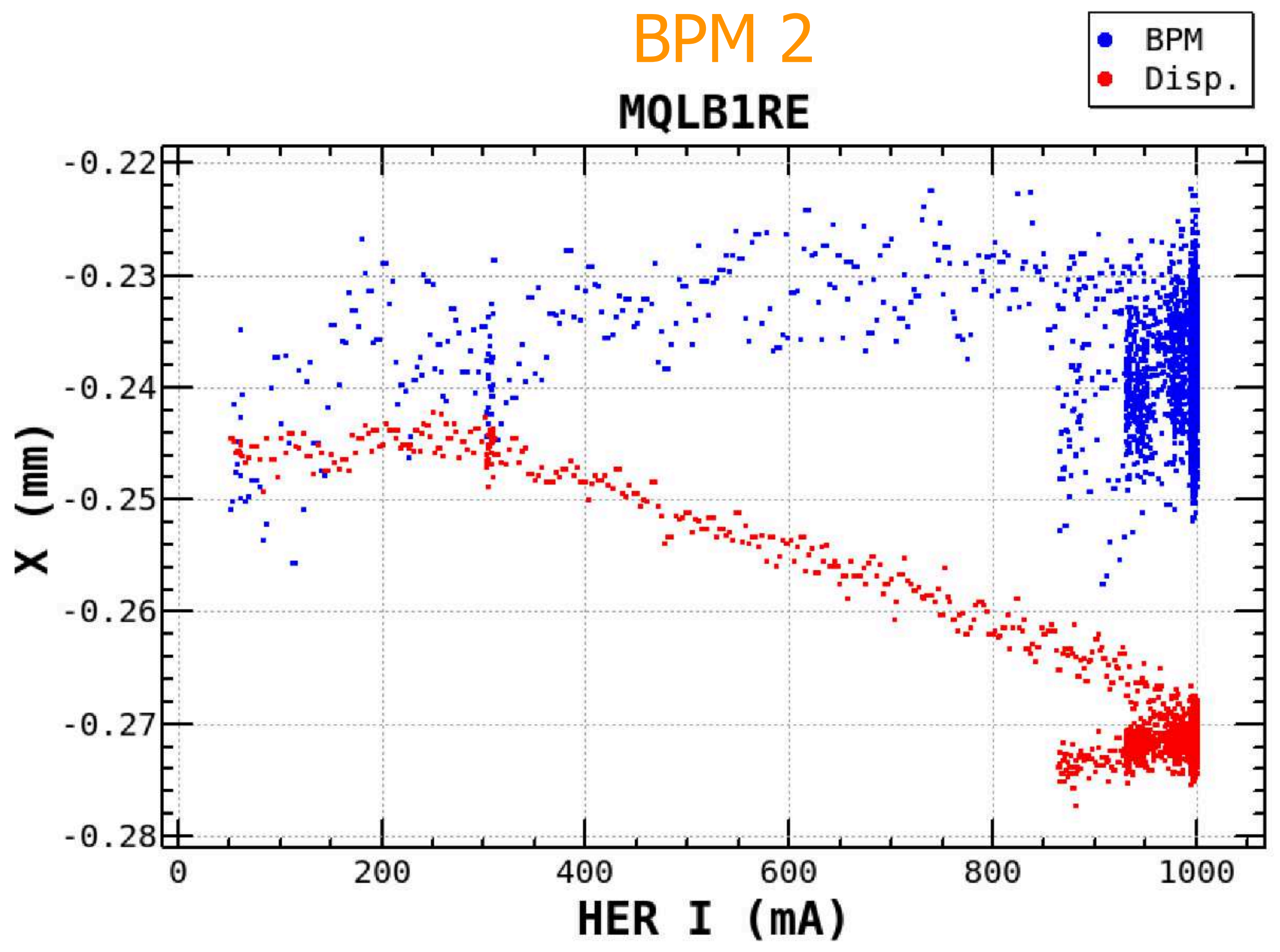
$$\frac{\Delta\beta_y^*}{\beta_y^*} = \frac{1}{2\sin 2\pi\nu_y}\oint \beta_y(K_2\Delta x)\cos\{2(\pi\nu_y + \psi_0 - \psi)\}ds$$

BPM position includes offset from the displacement monitor

$\beta_y^* = 0.89mm$ for $\Delta x = +20\ \mu m$ at SLYTLE1
(from 1 mm)

Right side of IP



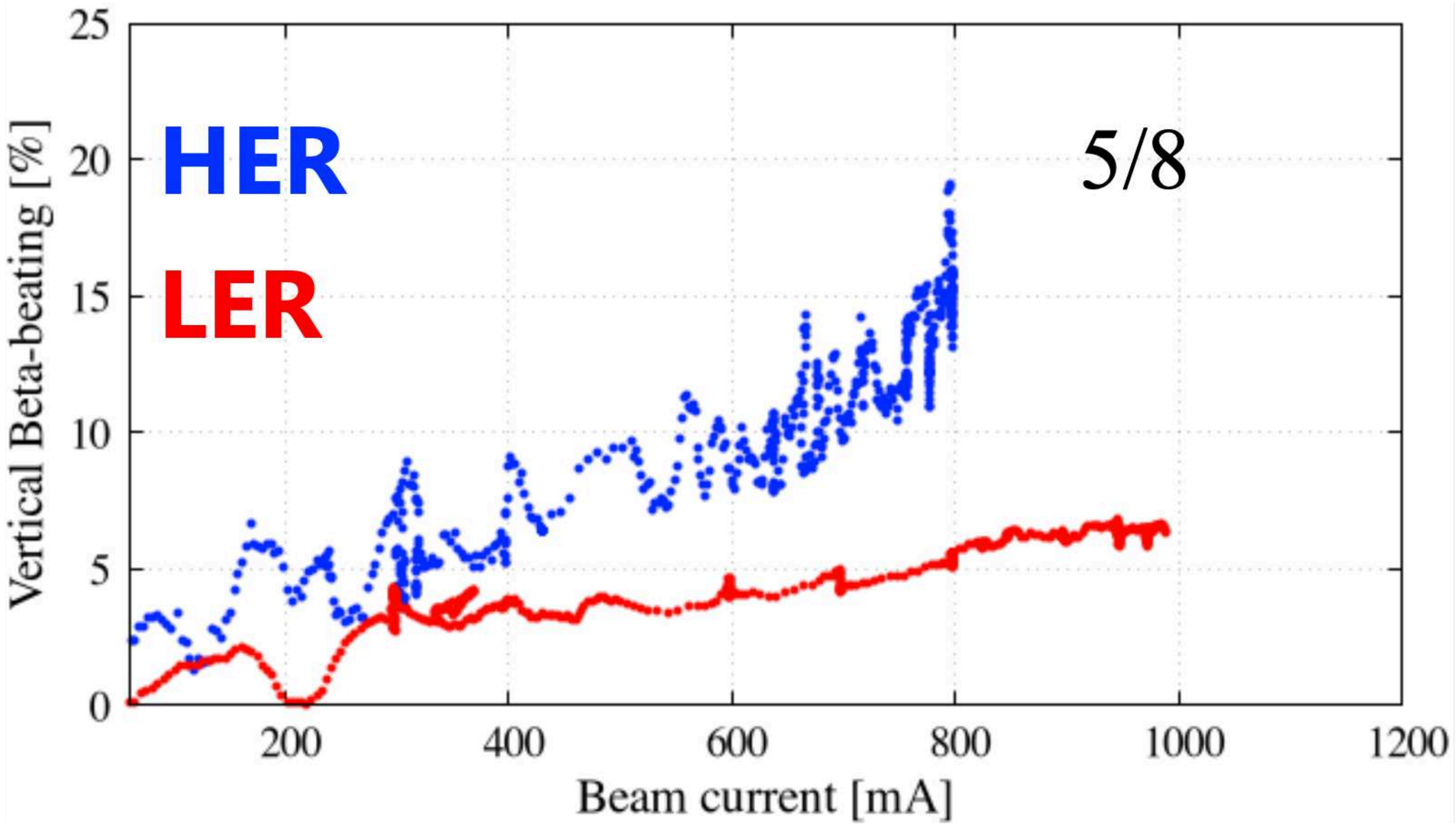


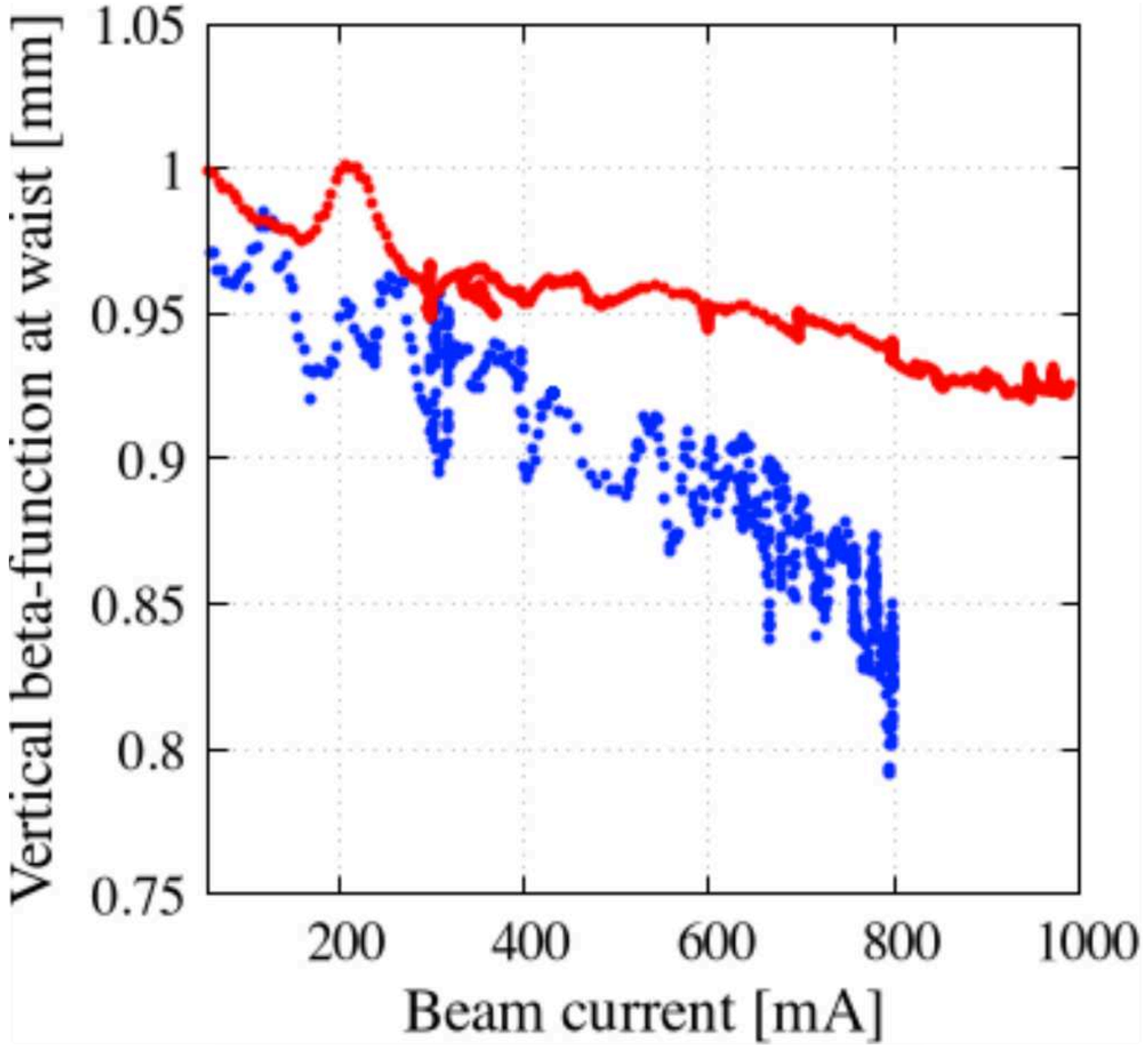
In order to increase the beam current stably, the orbit control within 10 μm should be necessary.

The local chromaticity correction is an example, the 50 sextupoles in arc sections should be considered.

H. Sugimoto, 2022ab Summary Meeting

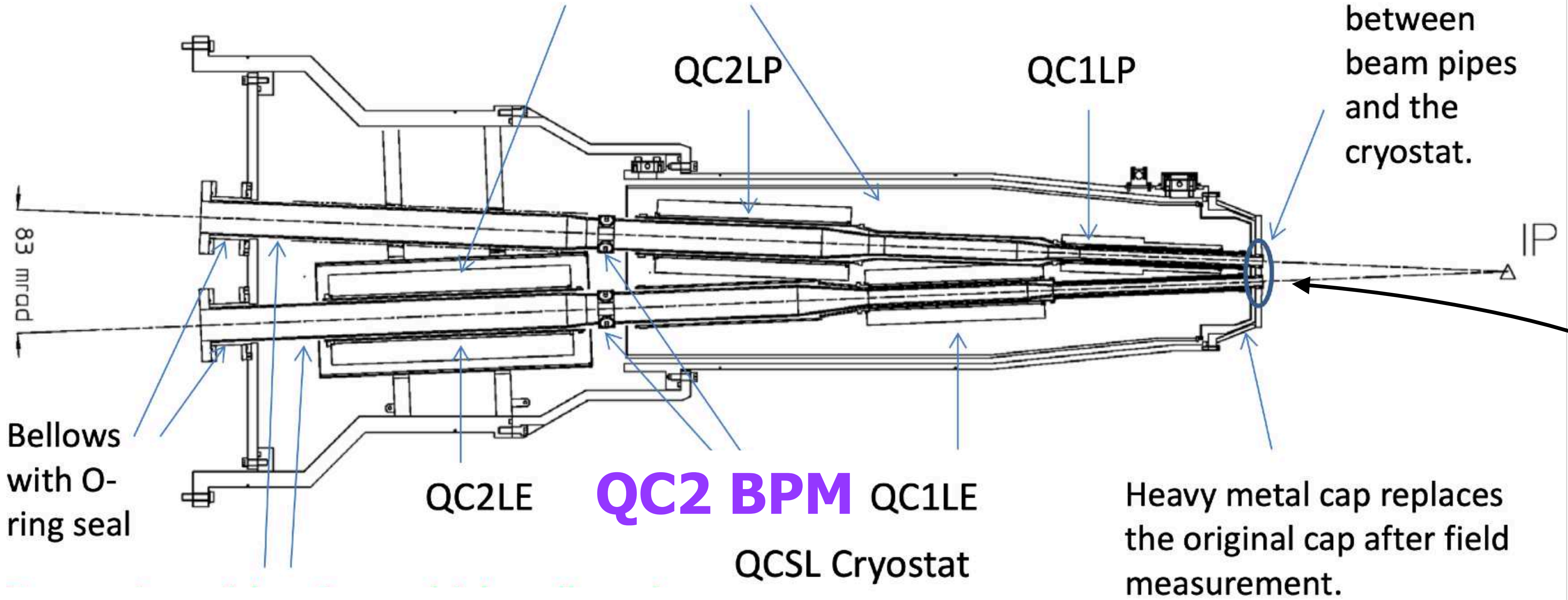
The SR heating deforms the beam line.
The horizontal orbit deviation induces tune shift and beta-beat. As the result, β_y^* also changes.
The orbit deviation in the local chromaticity correction (SLY) is always in the outward direction of the ring.
This implies a squeezing of β_y^*.
The HER is larger effects rather than the LER.
In order to reduce optics degradation, the local bumps correct the orbit at the strong sextupoles.
(Horizontal bump for beta-beat and vertical bump for X-Y couplings)





BPMs near Final Focus (QCS)

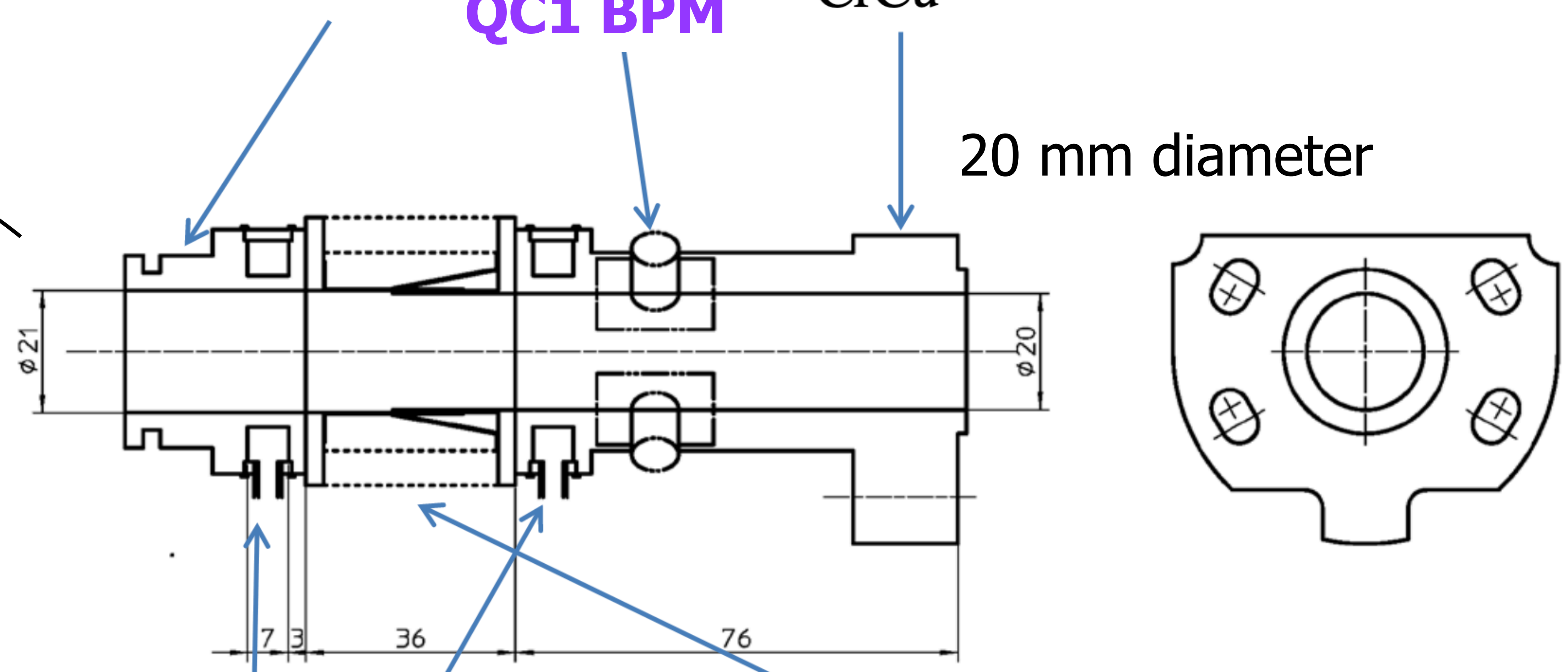
K. Kanazawa, FCC-ee MDI WS, 2018



Beam pipe with 4 mm thick wall, and with water cooling channels

QCS side

BPM-bellows tube between IP chamber and QCS

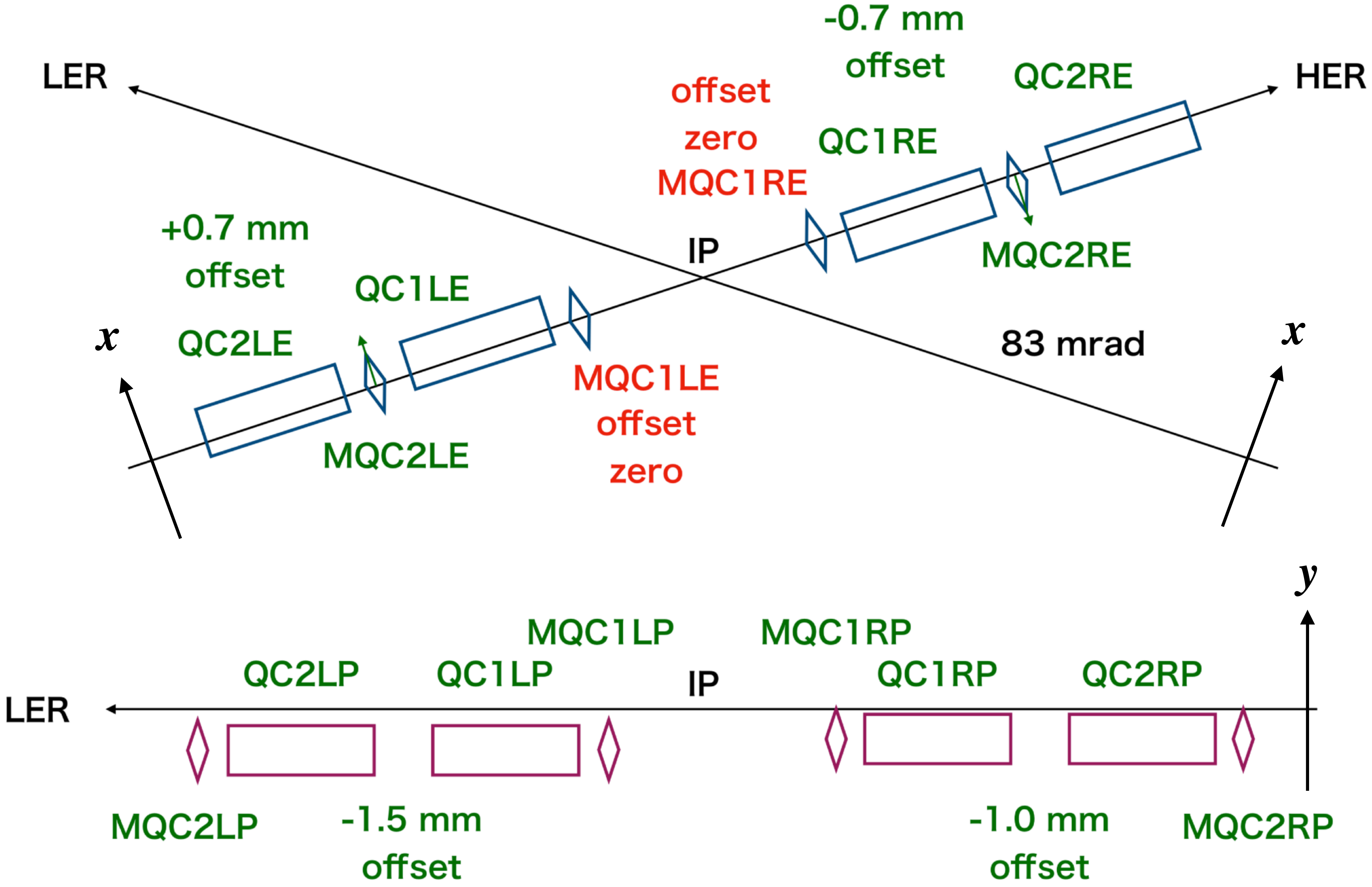


Bellows unit with a conventional RF-bridge.
A comb-type structure cannot give a sufficient flexibility for a small diameter.

QC1 BPM is not fixed at QC1 because there is a bellows between QCS and QC1 BPMs.

Calibration of BPMs at Final Focus (QCS)

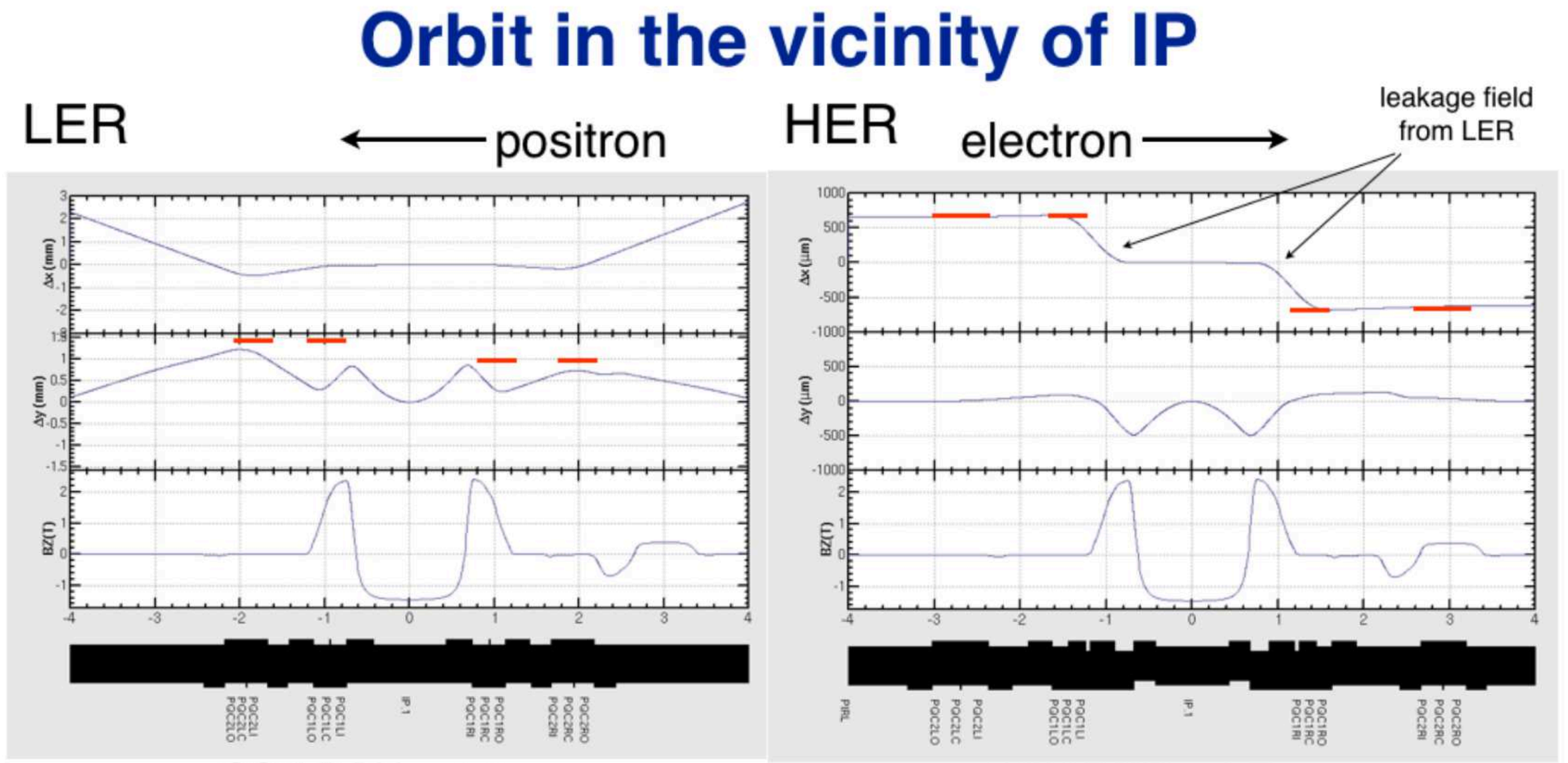
Horizontal crossing angle: 83 mrad



BPM coordinate

Left Side

Right Side

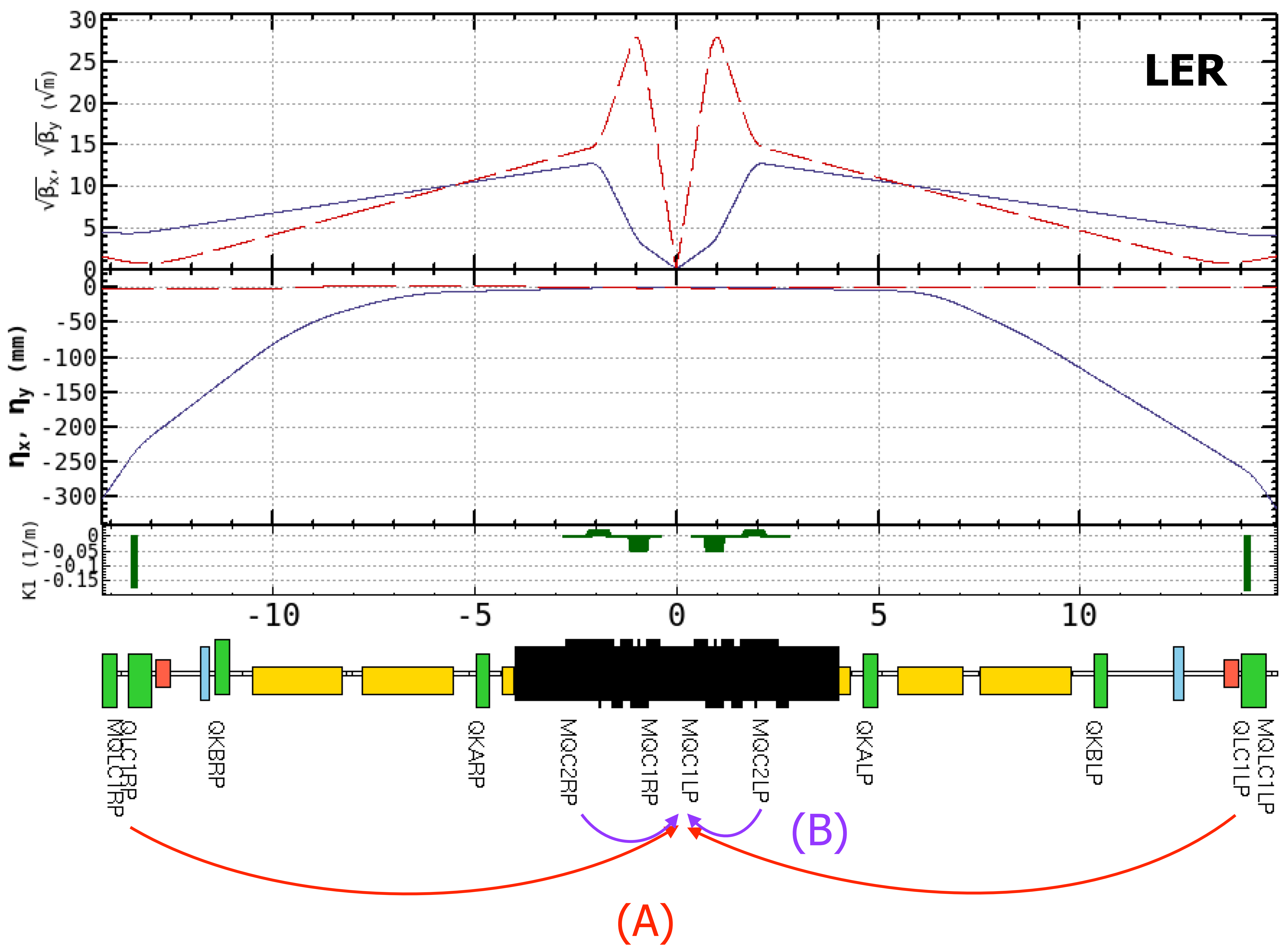


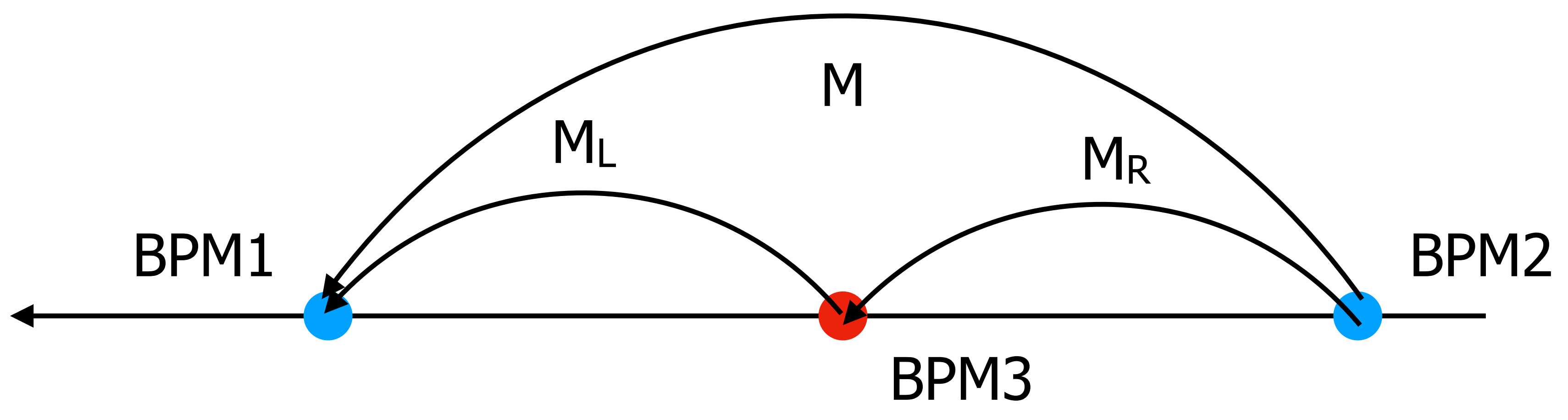
QC2LP DY= +1.5 mm
QC1LP DY= +1.5 mm
QC1RP DY= +1.0 mm
QC2RP DY= +1.0 mm
(+y means downward)

QC2LE DX= +0.7 mm
QC1LE DX= +0.7 mm
QC1RE DX= -0.7 mm
QC2RE DX= -0.7 mm
(+x means outer of the ring)

SAD coordinate

Estimation of BPM Reading with 3 BPMs





$$\begin{pmatrix} x_L \\ y_L \end{pmatrix} \quad \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \quad \begin{pmatrix} x_R \\ y_R \end{pmatrix}$$

$$\begin{pmatrix} x_L \\ p_{xL} \end{pmatrix} = \begin{pmatrix} m_L^{11} & m_L^{12} \\ m_L^{21} & m_L^{22} \end{pmatrix} \begin{pmatrix} x_0 \\ p_{x0} \end{pmatrix}$$

$$\begin{pmatrix} x_R \\ p_{xR} \end{pmatrix} = \begin{pmatrix} m_R^{22} & -m_R^{12} \\ -m_R^{21} & m_R^{11} \end{pmatrix} \begin{pmatrix} x_0 \\ p_{x0} \end{pmatrix}$$

$$\begin{pmatrix} x_L \\ x_R \end{pmatrix} = \begin{pmatrix} m_L^{11} & m_L^{12} \\ m_R^{22} & -m_R^{12} \end{pmatrix} \begin{pmatrix} x_0 \\ p_{x0} \end{pmatrix}$$

$$\begin{pmatrix} x_0 \\ p_{x0} \end{pmatrix} = \frac{1}{m_L^{11} m_R^{12} + m_L^{12} m_R^{22}} \begin{pmatrix} m_R^{12} & m_L^{12} \\ m_R^{22} & -m_L^{11} \end{pmatrix} \begin{pmatrix} x_L \\ x_R \end{pmatrix}$$

$$m^{12} = m_L^{11} m_R^{12} + m_L^{12} m_R^{22}$$

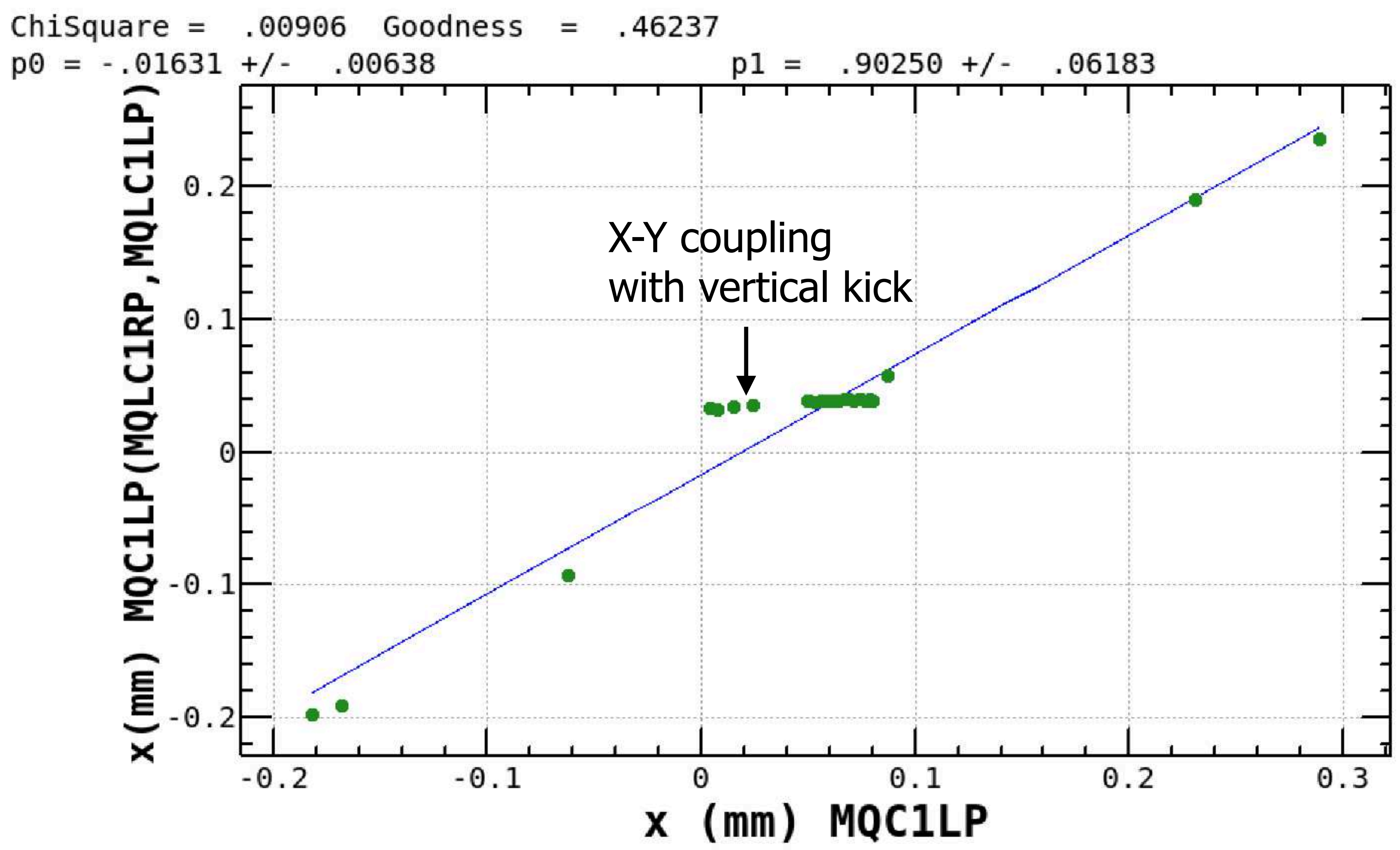
Estimate the beam position at MQC1LP or MQC1RP
by using MQLC1RP and MQLC1LP (A) or QC2RP and QC2LP (B).

The data is used at the beta measurement (one of the optics corrections).
It contains six single kicks each in the vertical and horizontal directions.

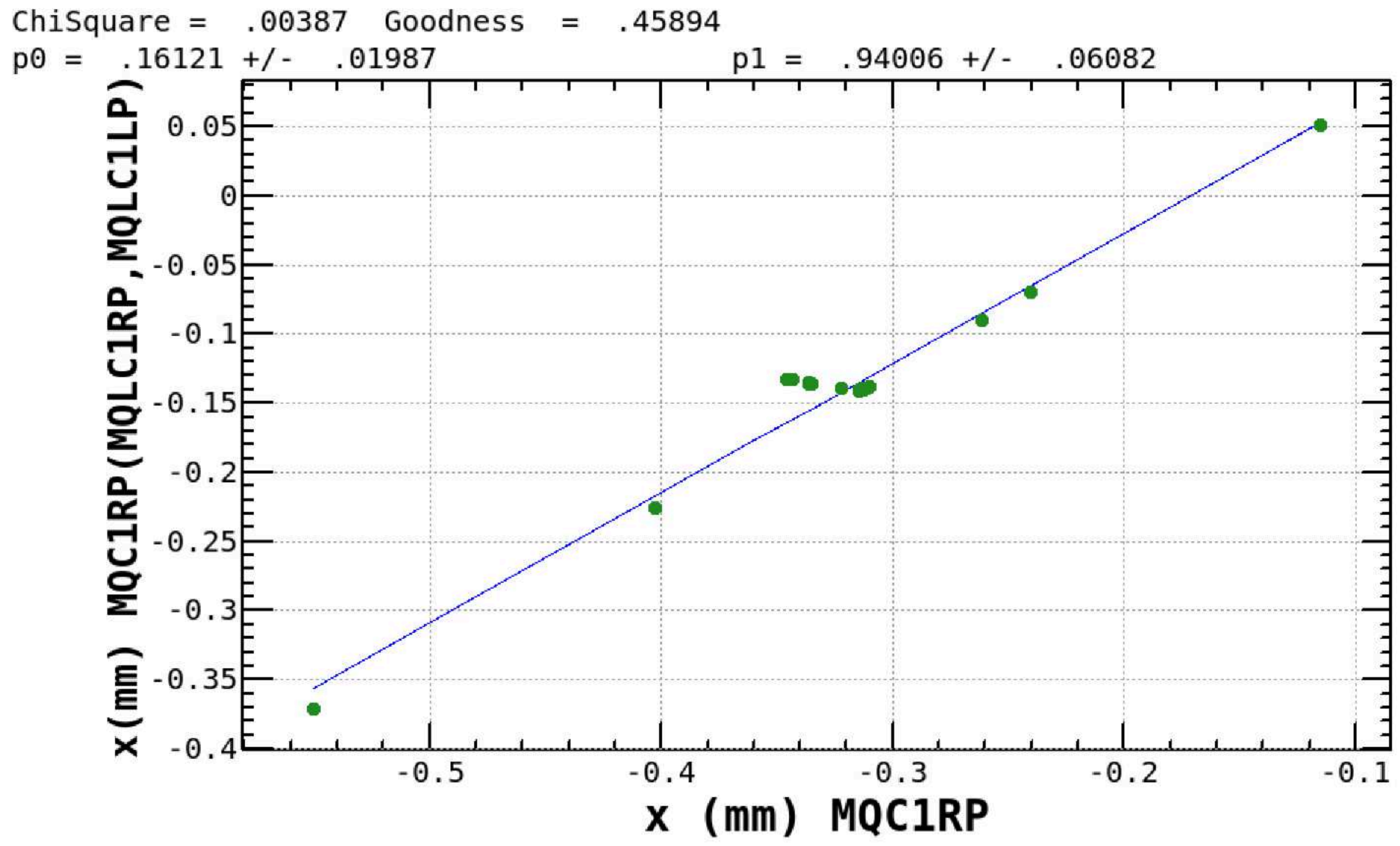
Horizontal Response of QC1 BPMs

Each point is an averaged value of 4-times measurements.

(A)

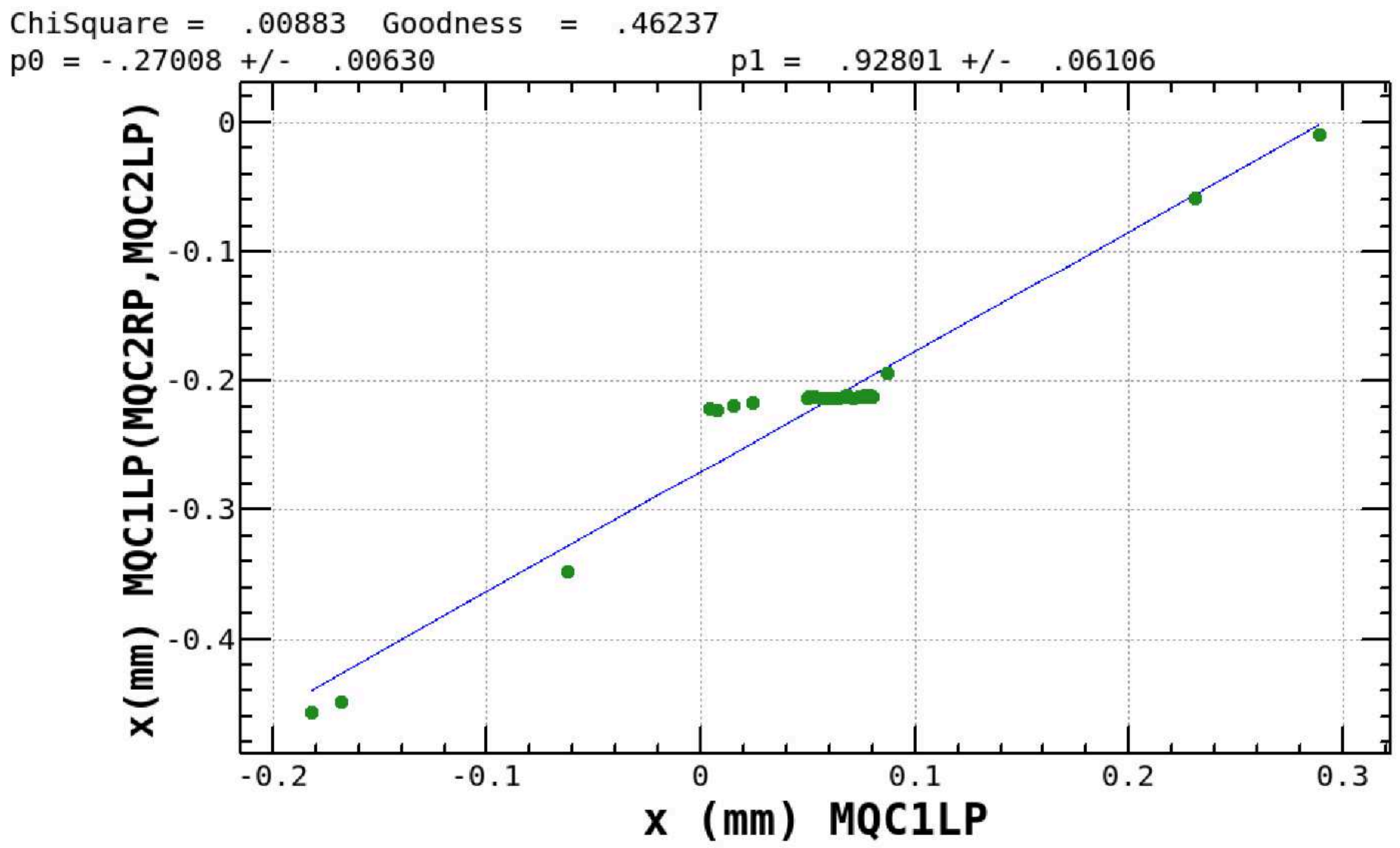


QC1P
QC2P
QLC1LP
QLC1RP
QKALP
QKARP
QKBLP
QKBRP

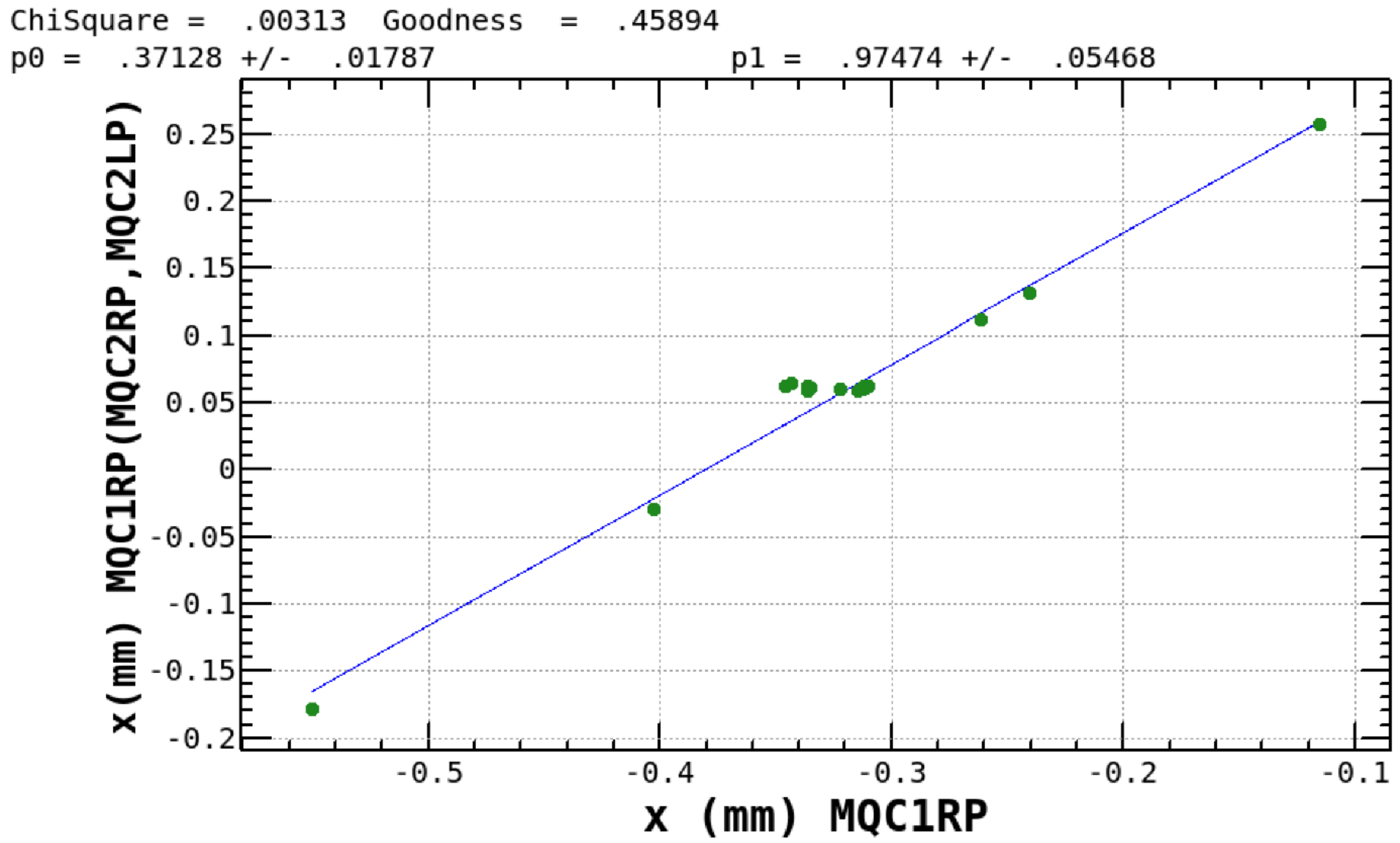


QC1P
QC2P
QLC1LP
QLC1RP
QKALP
QKARP
QKBLP
QKBRP

(B)



QC1P
QC2P



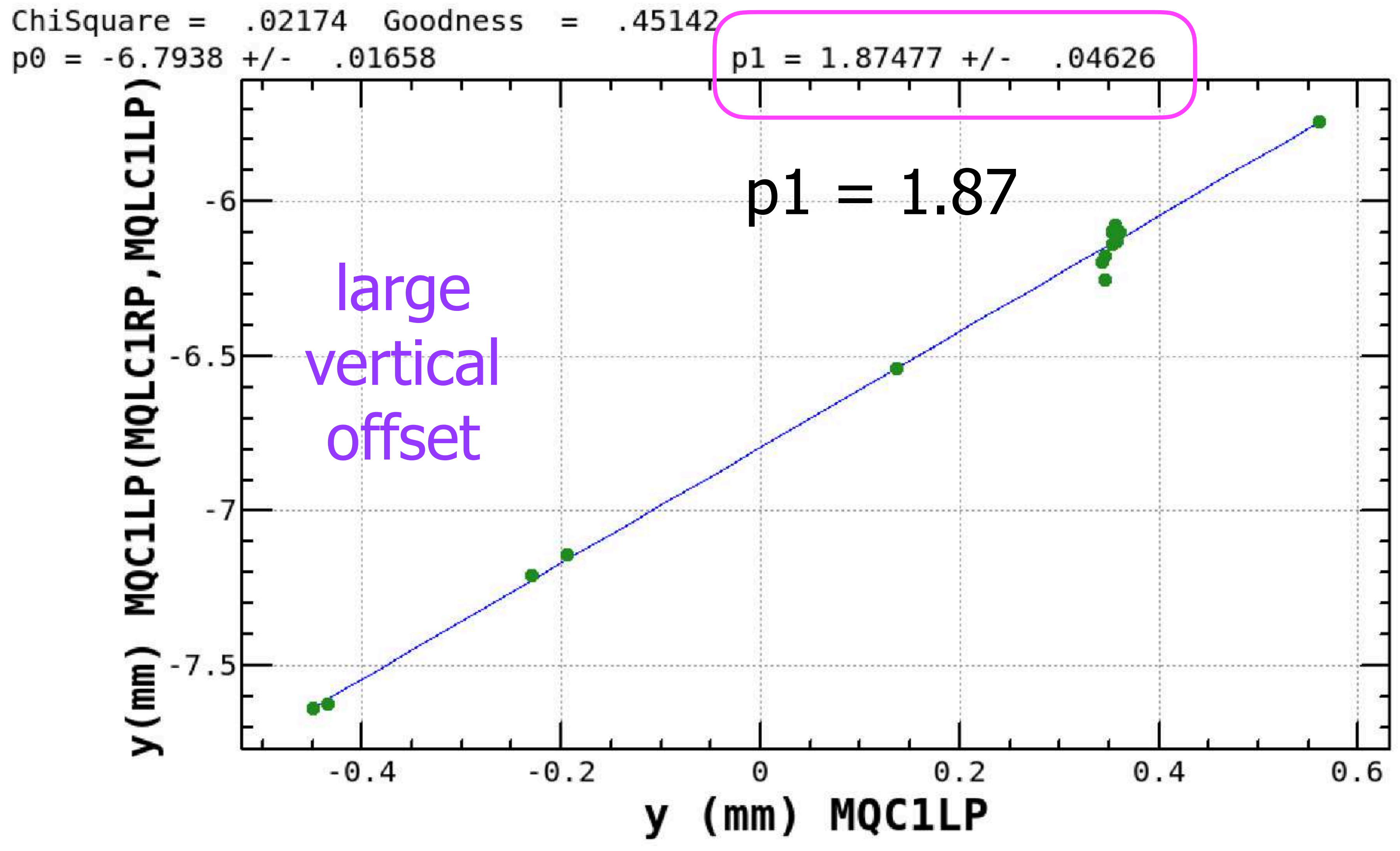
QC1P
QC2P

Vertical Response of QC1 BPMs

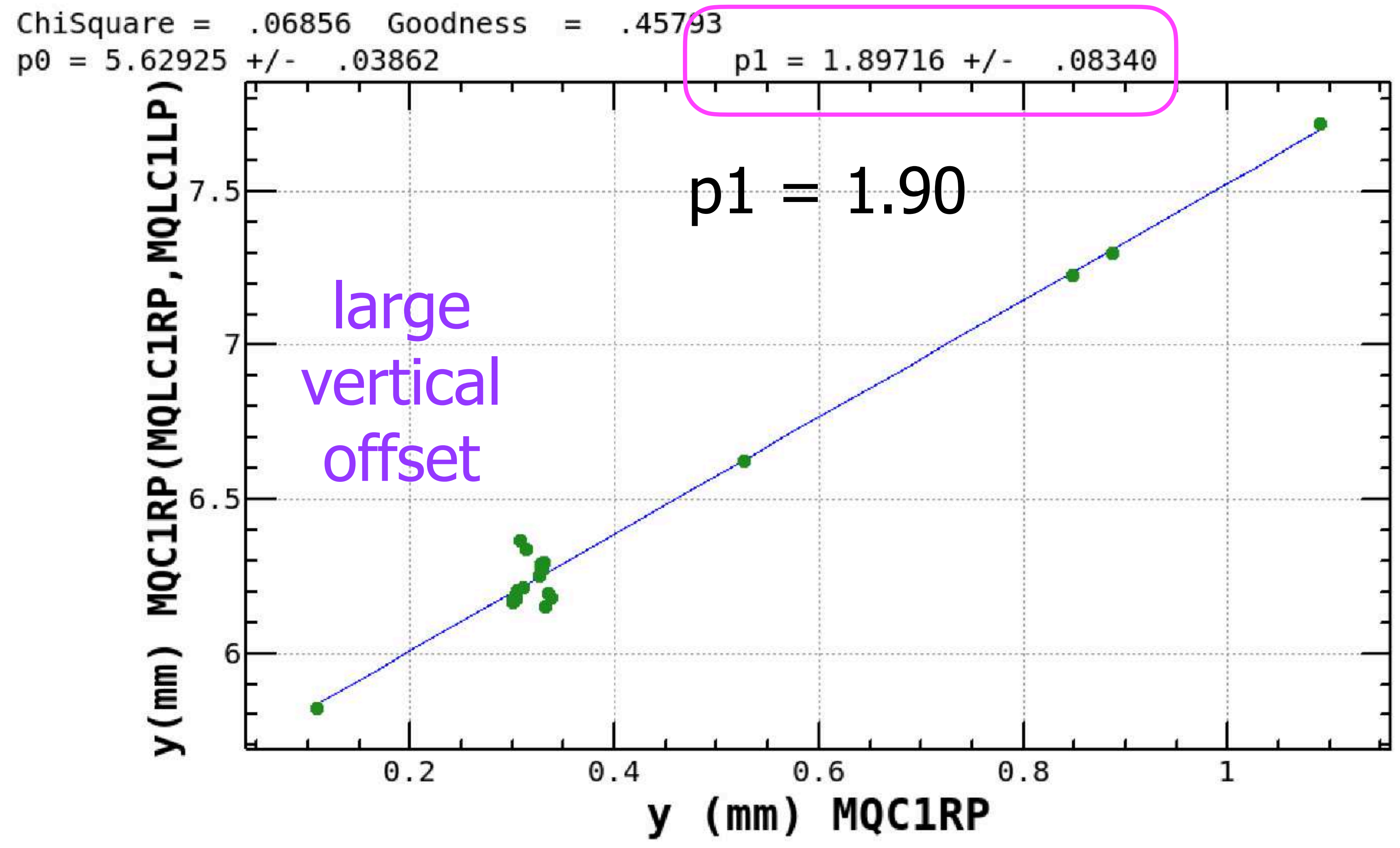
Each point is an averaged value of 4-times measurements.

Response from QLC1RP and QLC1LP is **1.9** times larger than QC1 BPM.

(A)

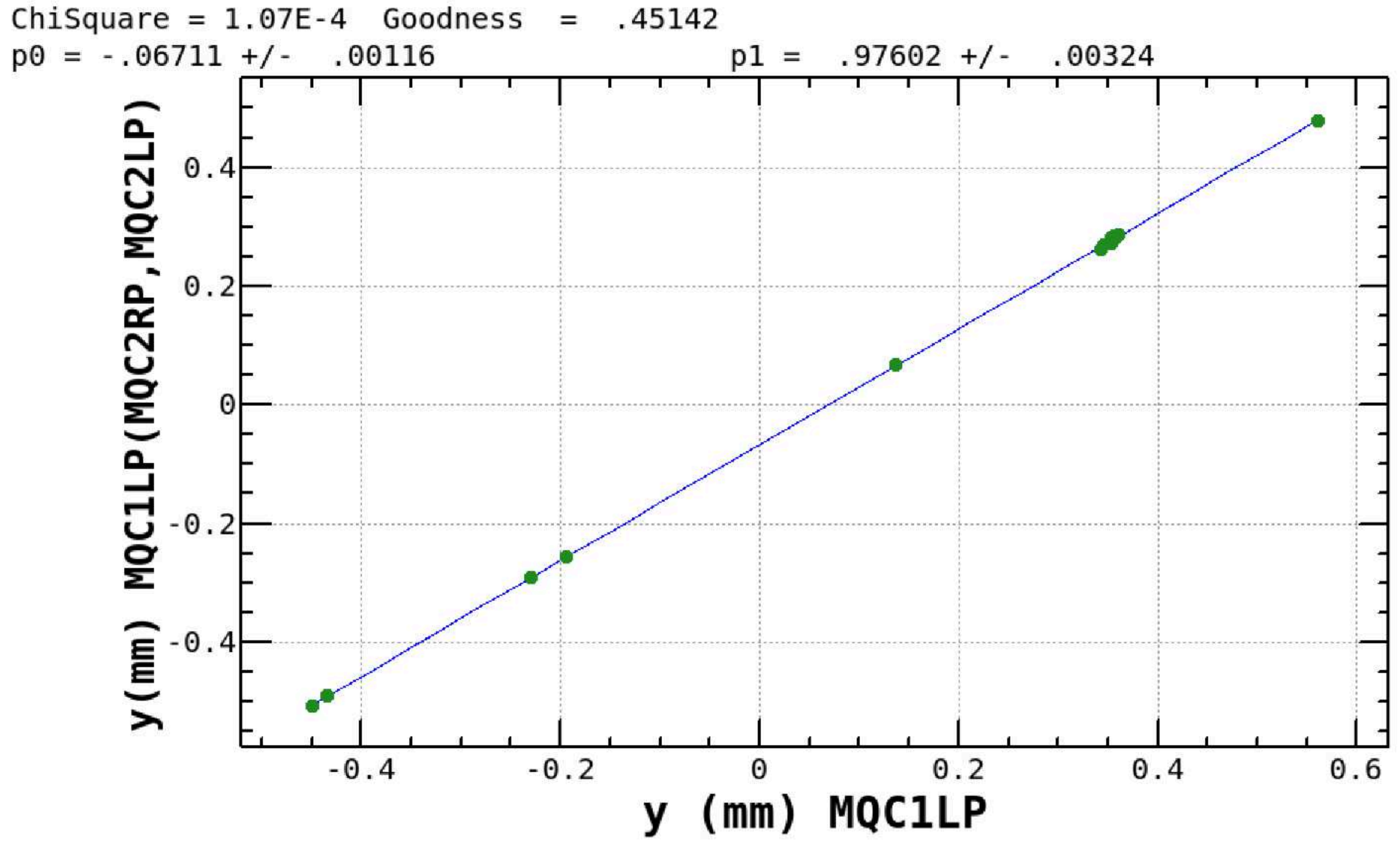


QC1P
QC2P
QLC1LP
QLC1RP
QKALP
QKARP
QKBLP
QKBRP

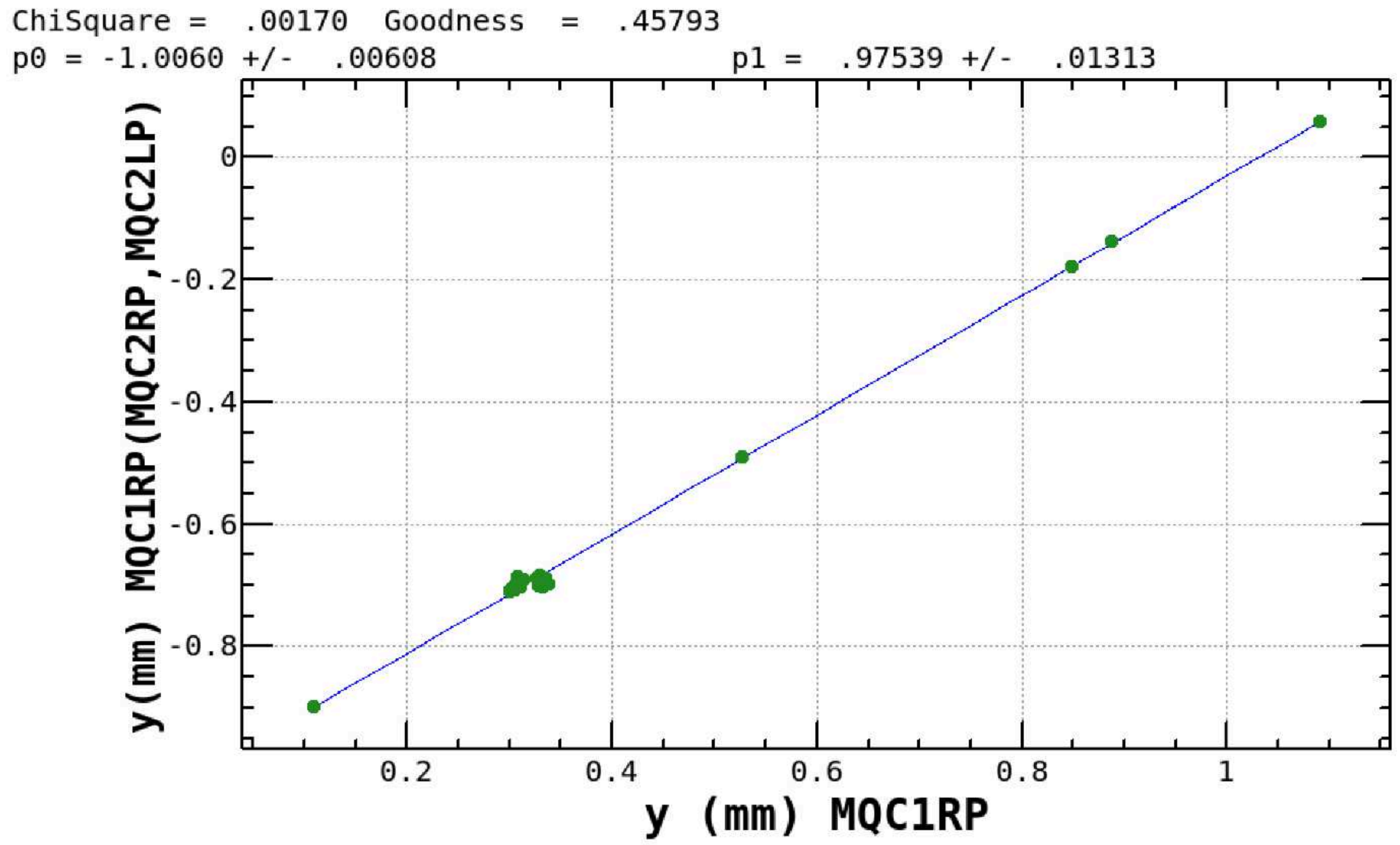


QC1P
QC2P
QLC1LP
QLC1RP
QKALP
QKARP
QKBLP
QKBRP

(B)



QC1P
QC2P

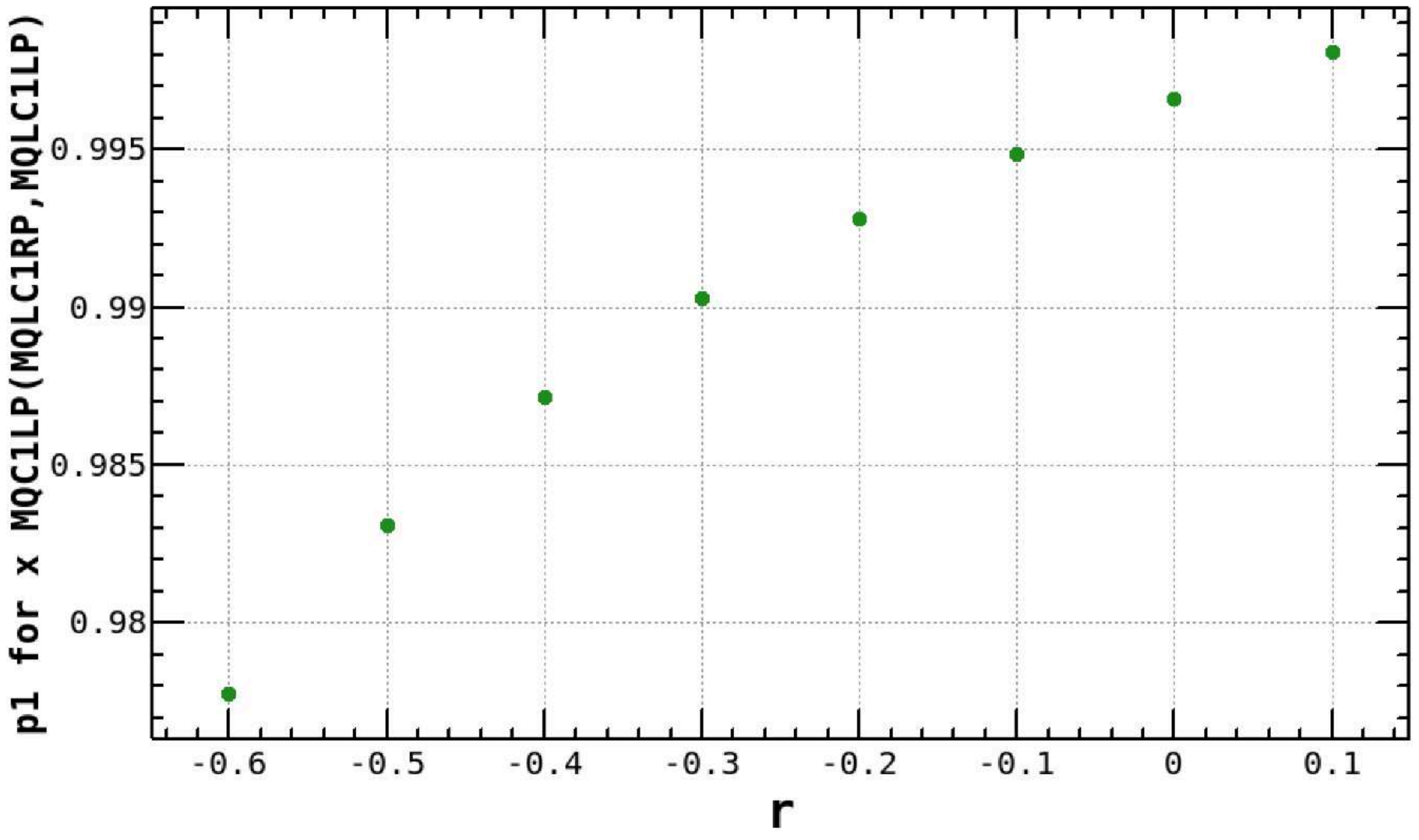


QC1P
QC2P

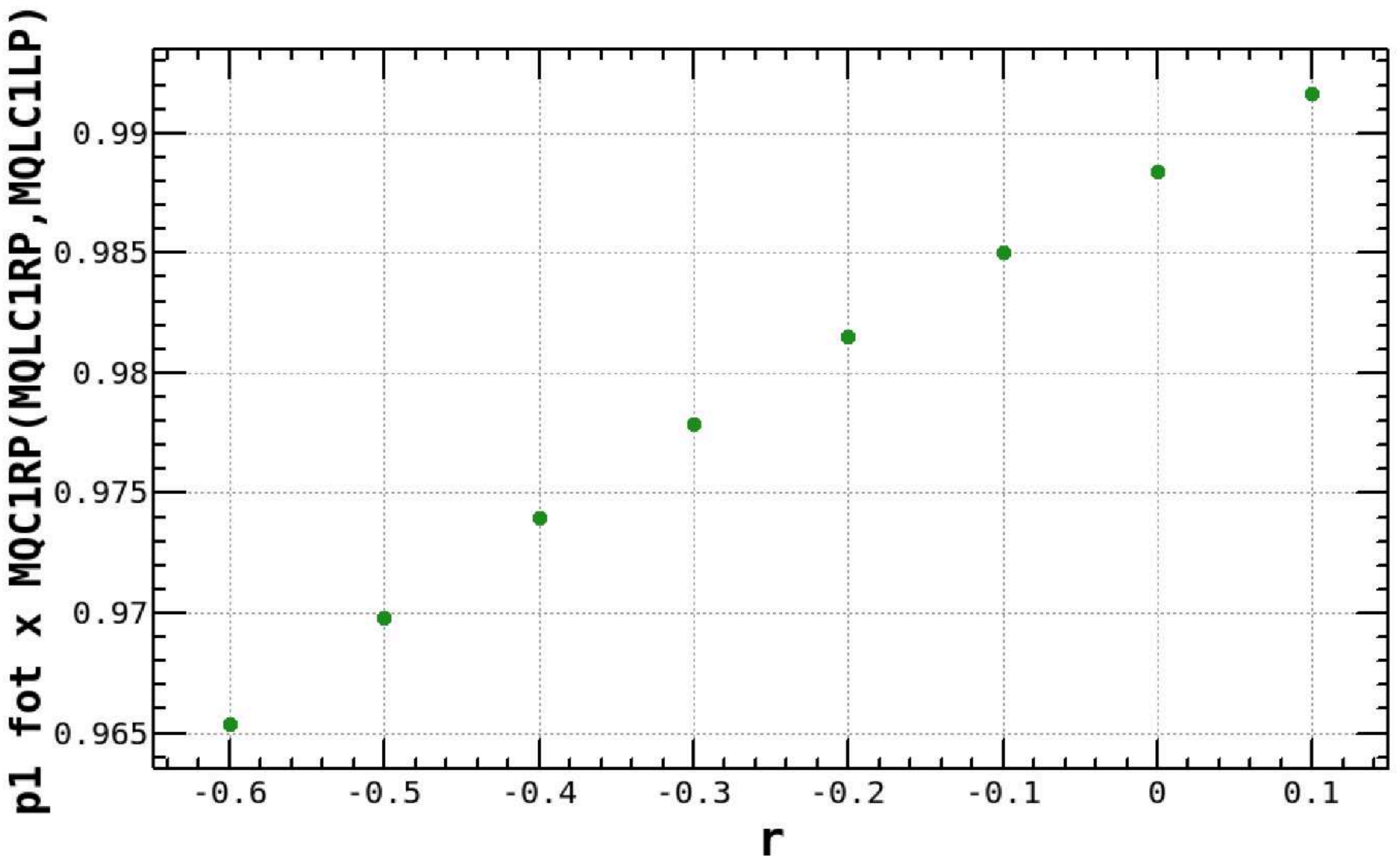
K1(real) - K1(model) $\Delta K1(QC1LP) = 0.00211\ (1/m)$ $\Delta K1(QC1RP) = 0.00440\ (1/m)$ $\Delta K1(QC2LP) = -0.0008575\ (1/m)$ $\Delta K1(QC2RP) = -0.0006042\ (1/m)$

$$K1 \rightarrow K1 + r \cdot \Delta K1$$

(A)

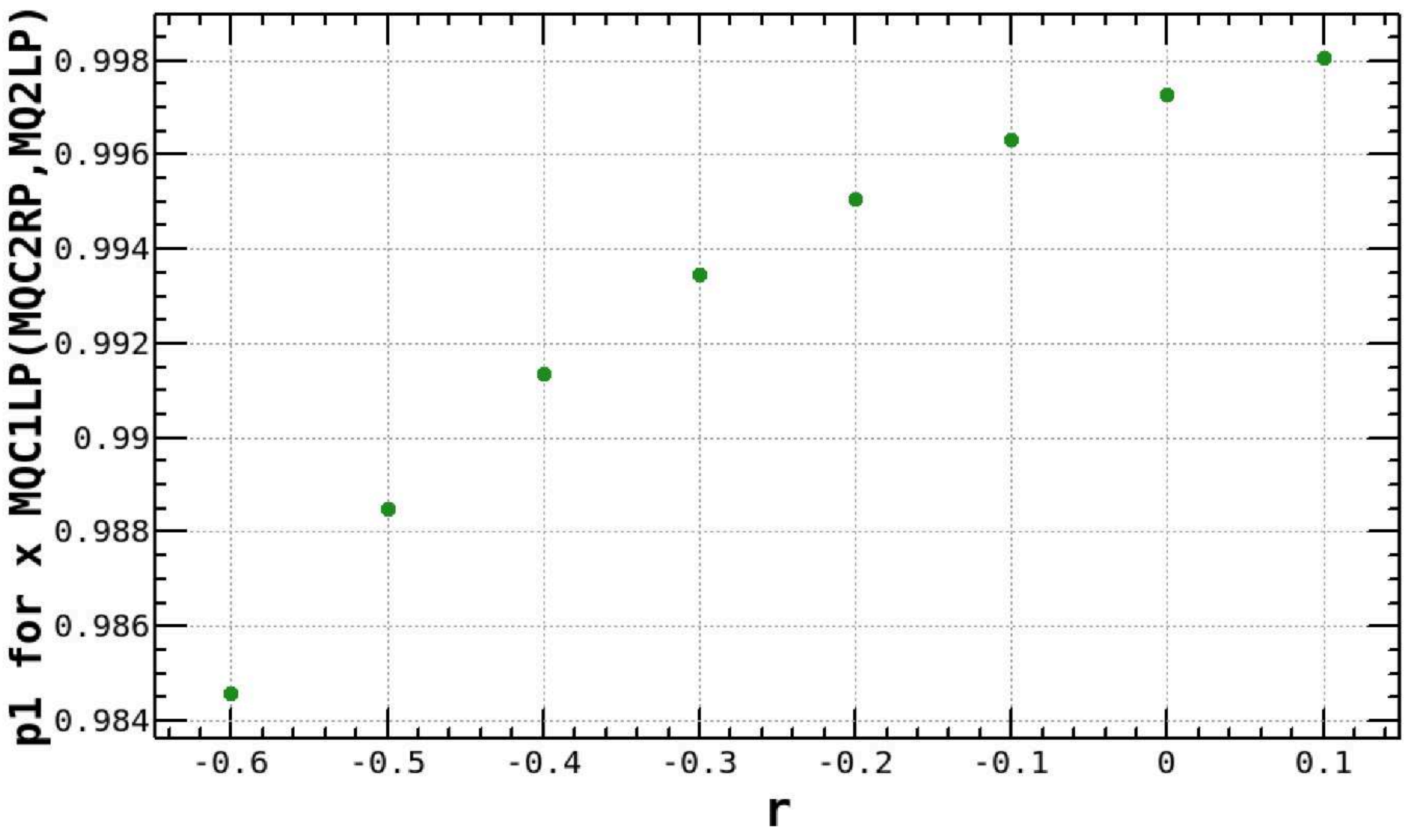


(A)

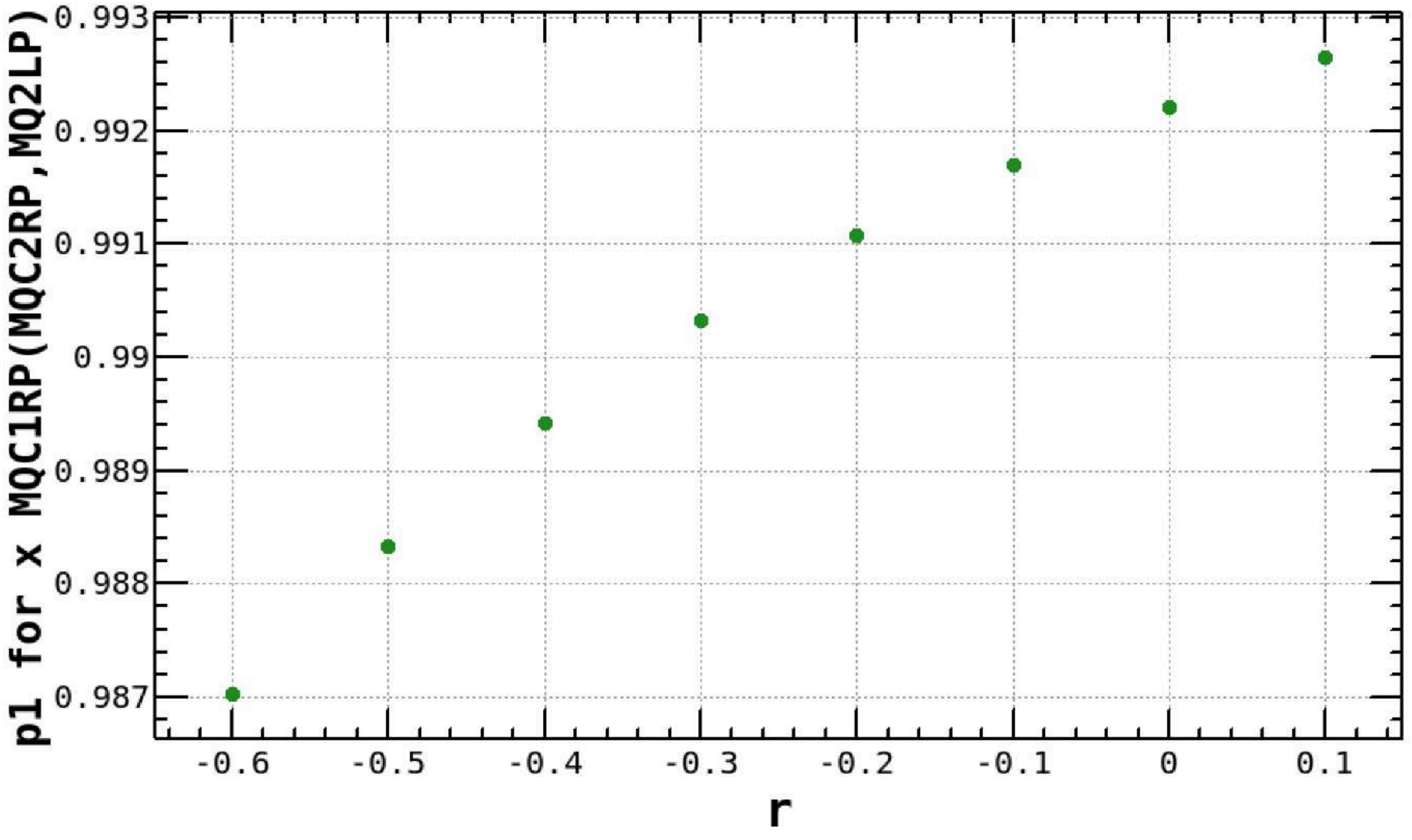


less sensitivity for the horizontal direction

(B)



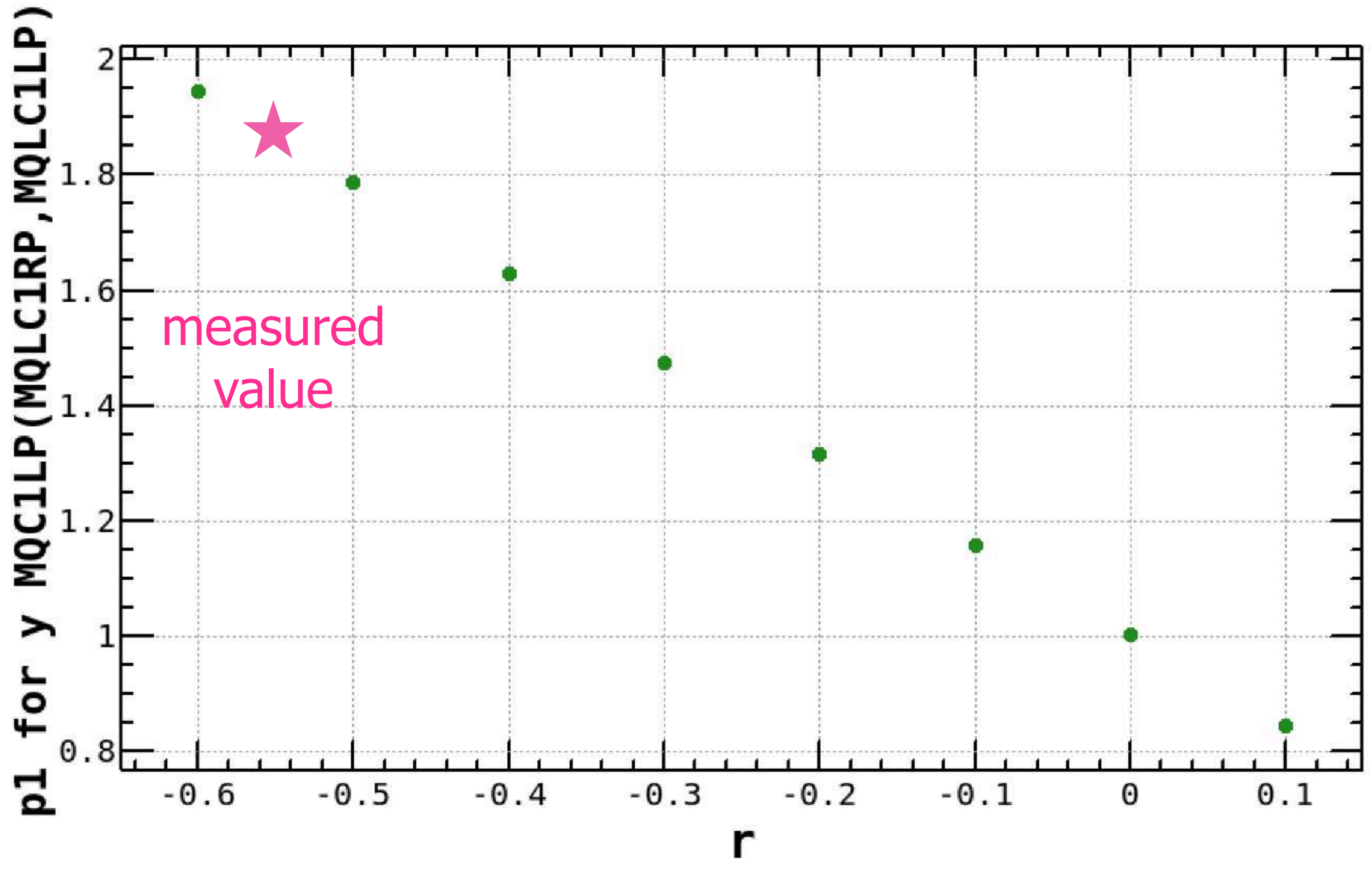
(B)



K1(real) - K1(model) $\Delta K1(QC1LP) = 0.00211\ (1/m)$ $\Delta K1(QC1RP) = 0.00440\ (1/m)$ $\Delta K1(QC2LP) = -0.0008575\ (1/m)$ $\Delta K1(QC2RP) = -0.0006042\ (1/m)$

$$K1 \rightarrow K1 + r \cdot \Delta K1$$

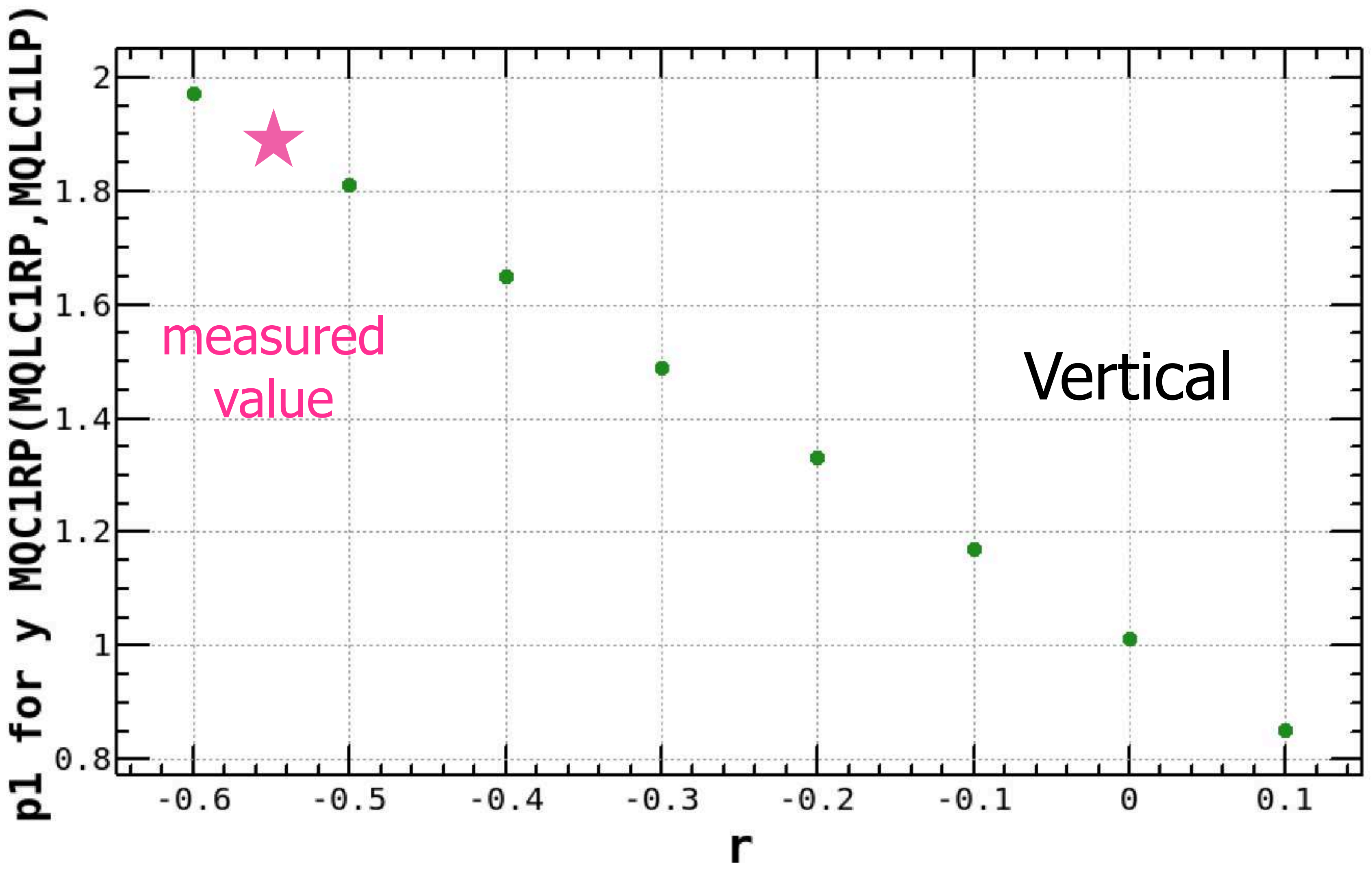
(A)



$\dfrac{\Delta K_1}{K_1}$ = 6.7 x 10^{-4} in QC1LP

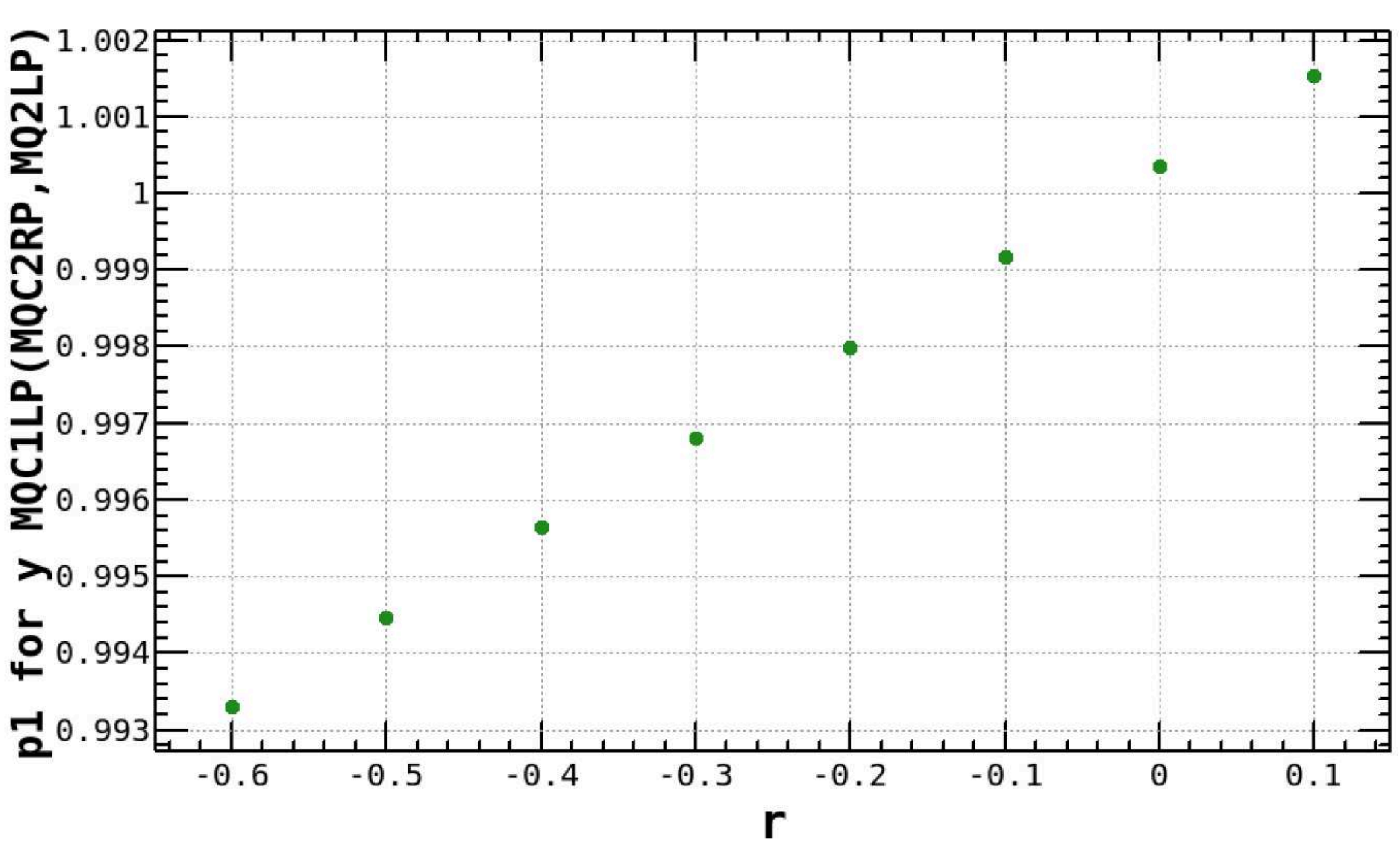
$\dfrac{\Delta K_1}{K_1}$ = 1.4 x 10^{-3} in QC1RP

(A)

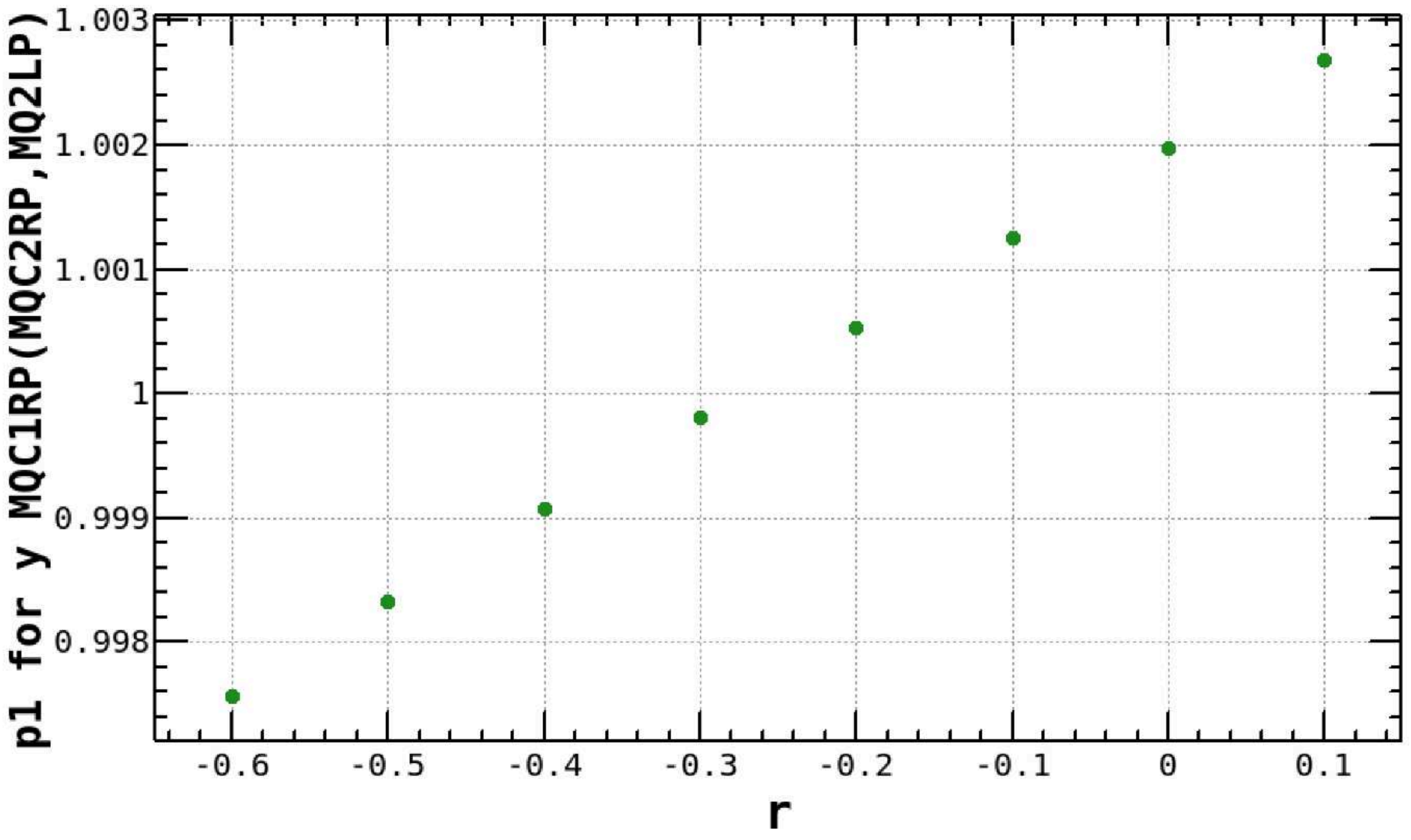


The response with QLC1LP and QLC1RP becomes consistent with the measurements as increasing QC1P magnetic field (r = -0.55).

(B)



(B)



less sensitivity with QC2P

Summary

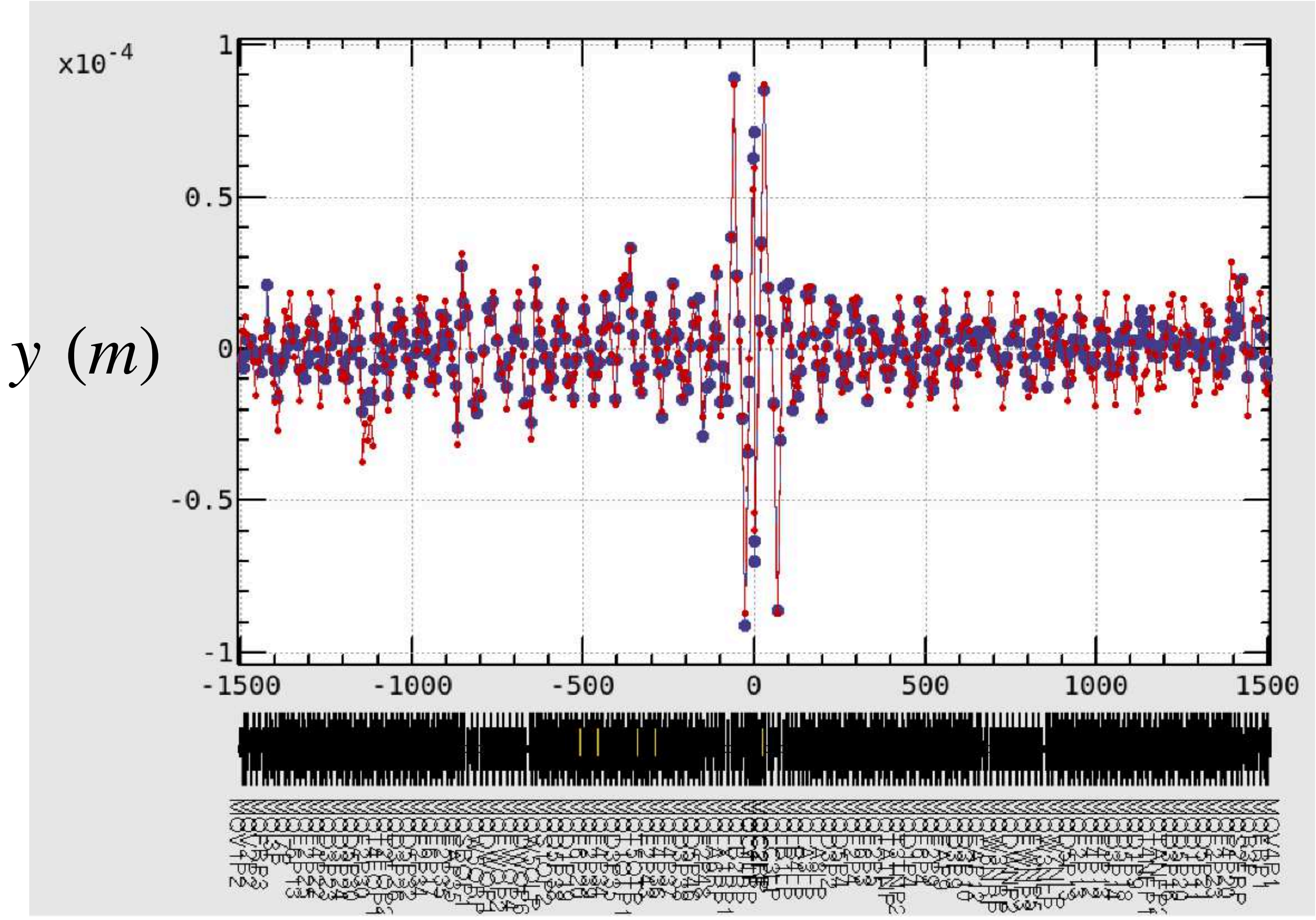
- Control of beam orbit as well as stability is very important.
- The beam orbit cannot be considered in isolation from the beam optics.
- BPM gain calibration is performed before optics correction, Quad-BPM (BBA) is sometimes performed if necessary (after cabling work of BPMs).
- Optics correction is scheduled every two weeks (maintenance day) or when we found luminosity degradation. Magnet initialization is performed every maintenance.
- We set the reference orbit, so called "GOLD orbit" when the optics correction is performed. But it is difficult to adjust a measured orbit to the GOLD orbit in several days after the registration.
    - Degradation of consistency, beam-line deformation, change of cable length due to temperature at day and night, etc.
- There are many sources to induce orbit fluctuation. Cooling water cycle, all environment as well as earthquake
- Moreover, SR becomes intense and the heating might deform the beam-line. Difficulties arise how to treat of the orbit.
- What is the "optics" ? Obviously, the design optics is that of zero current. In the real accelerator, we have to consider the optics under the influence of resistive wall and collimator impedance in the high current operation, lattice nonlinear in the large betatron amplitude which are additional considerations.

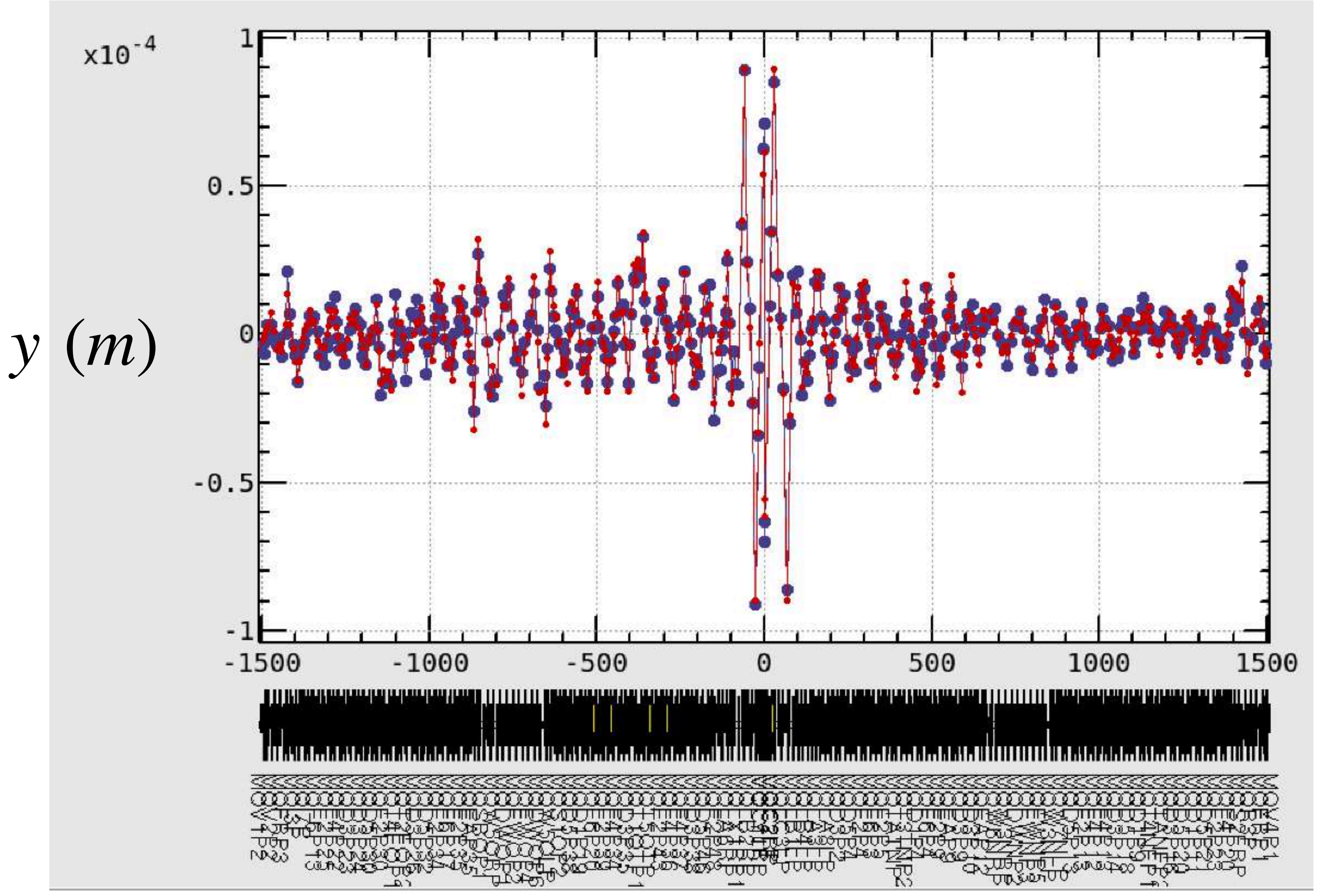
Appendix

Other Samples

04/07/2022 15:26:38 - 15:30:57

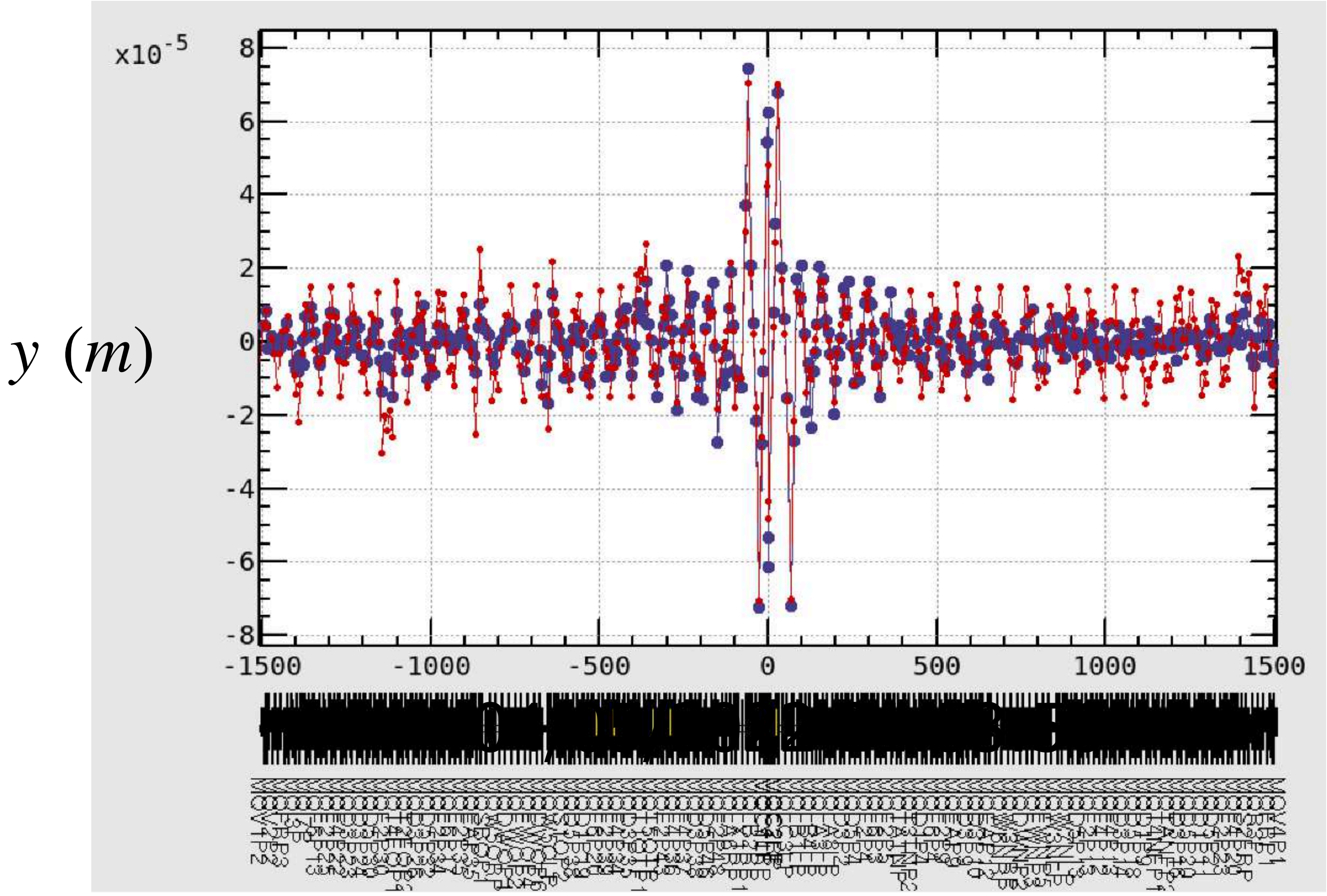
83 ZVQD3P17 K0 = 1.3120810177190797e-06





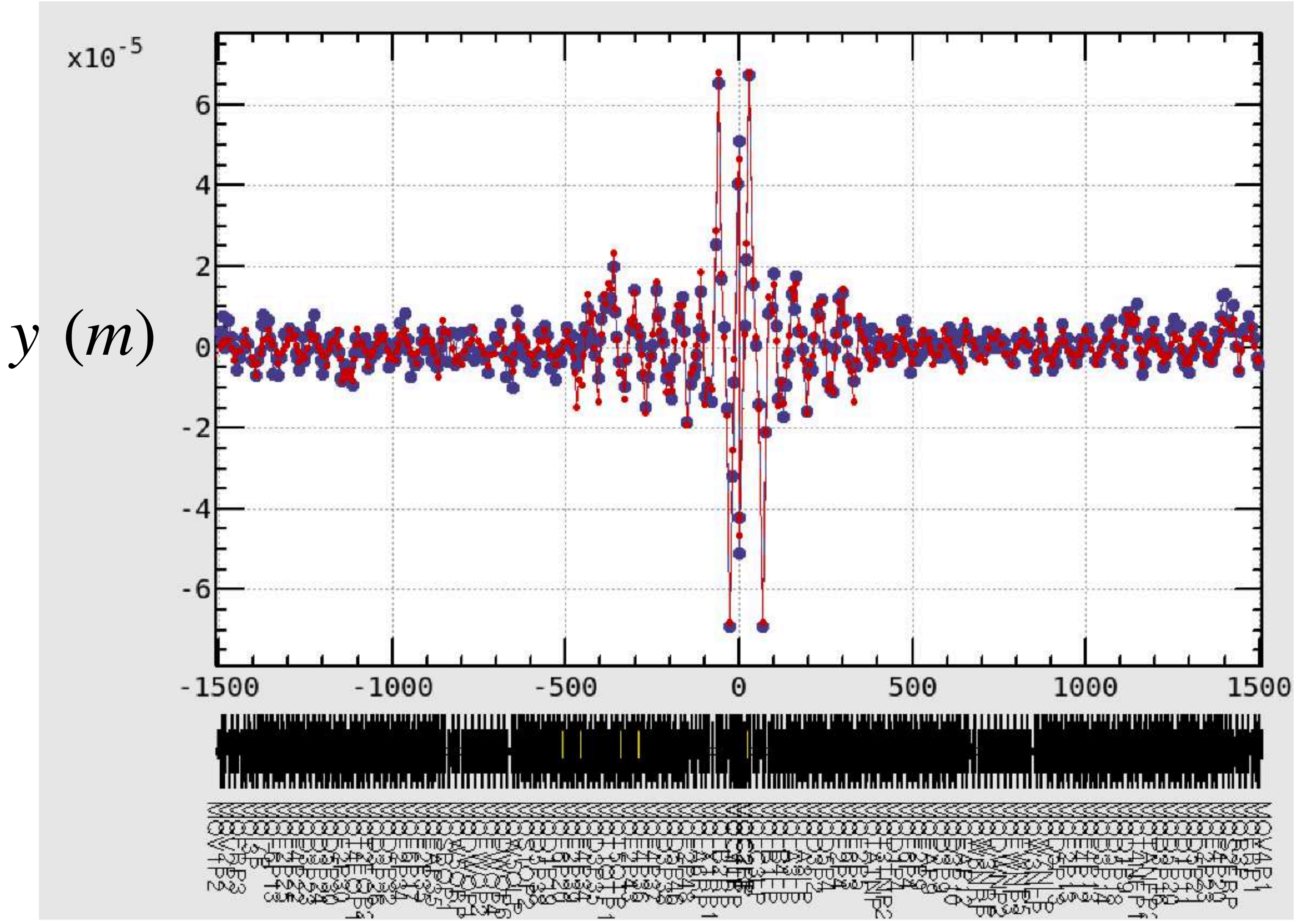
04/07/2022 16:31:10 - 16:35:00

83 ZVQD3P17 K0 = 1.0609695979205709e-06



	K0 (rad)
44 ZVQD5P11	-6.25734008966841E-07
83 ZVQD3P17	3.27231022225253E-07
135 ZVQD3P28	4.69360773145465E-07

04/05/2022 21:53:56 - 21:56:20



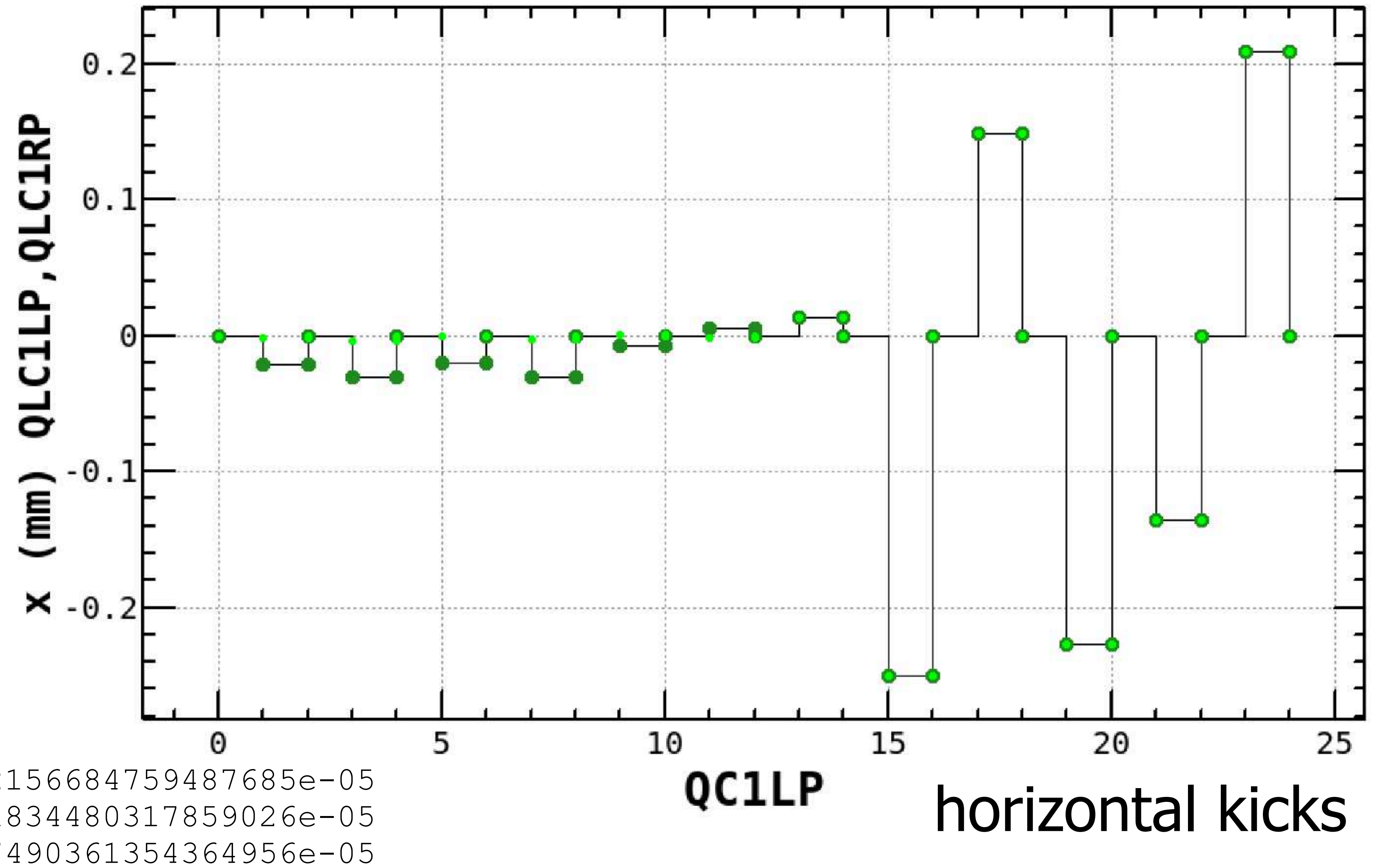
	K0 (rad)
26 ZVQD1P3	1.33191876977297E-07
29 ZVQT5TNP	3.78680058183411E-07
166 ZVQD3P34	-3.91913056325357E-07

A kick angle of 1 μrad induces the orbit fluctuation of 20 μm.

BPM Response with Model Lattice

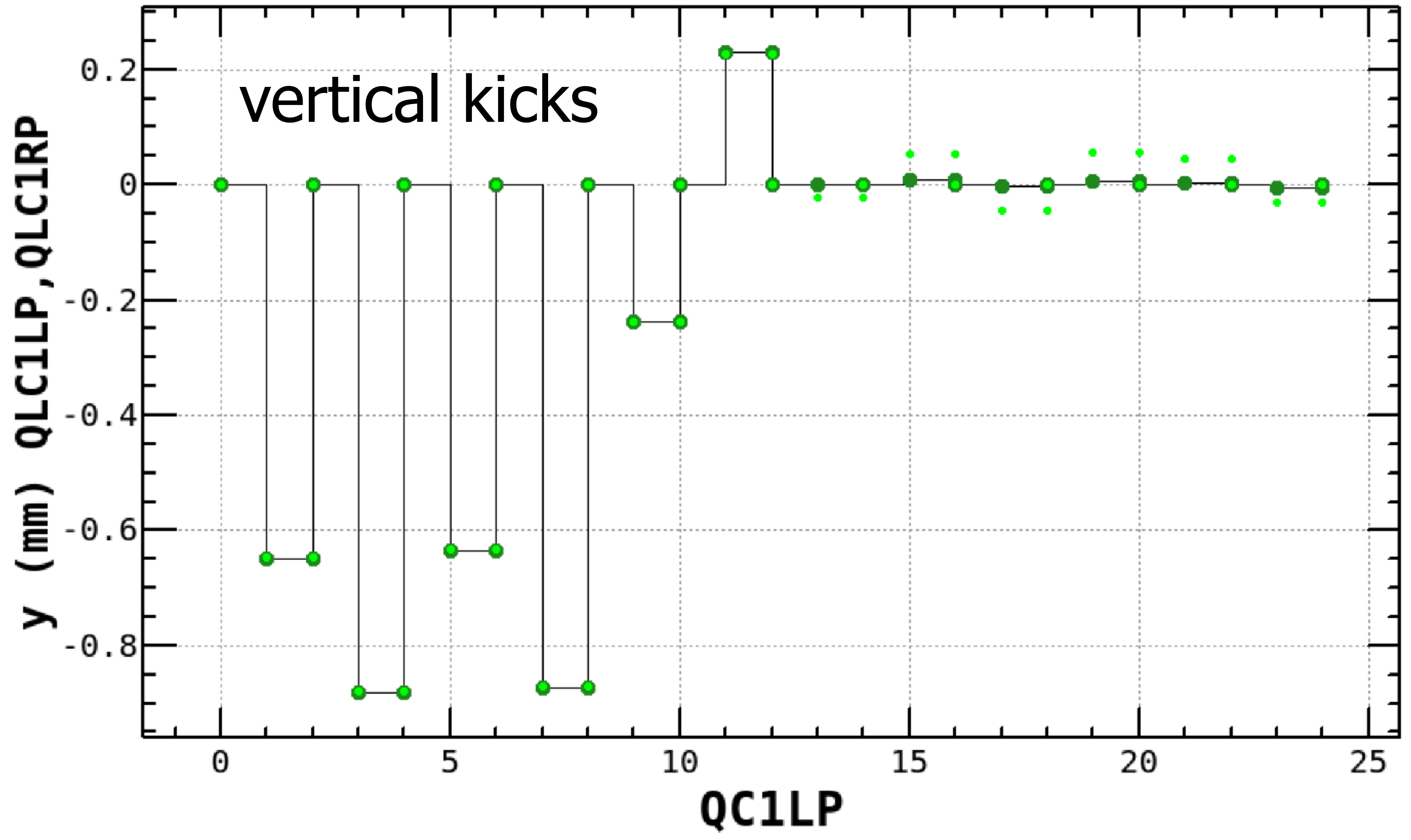
estimated by BPMs at QLC1LP and QLC1RP

(A)



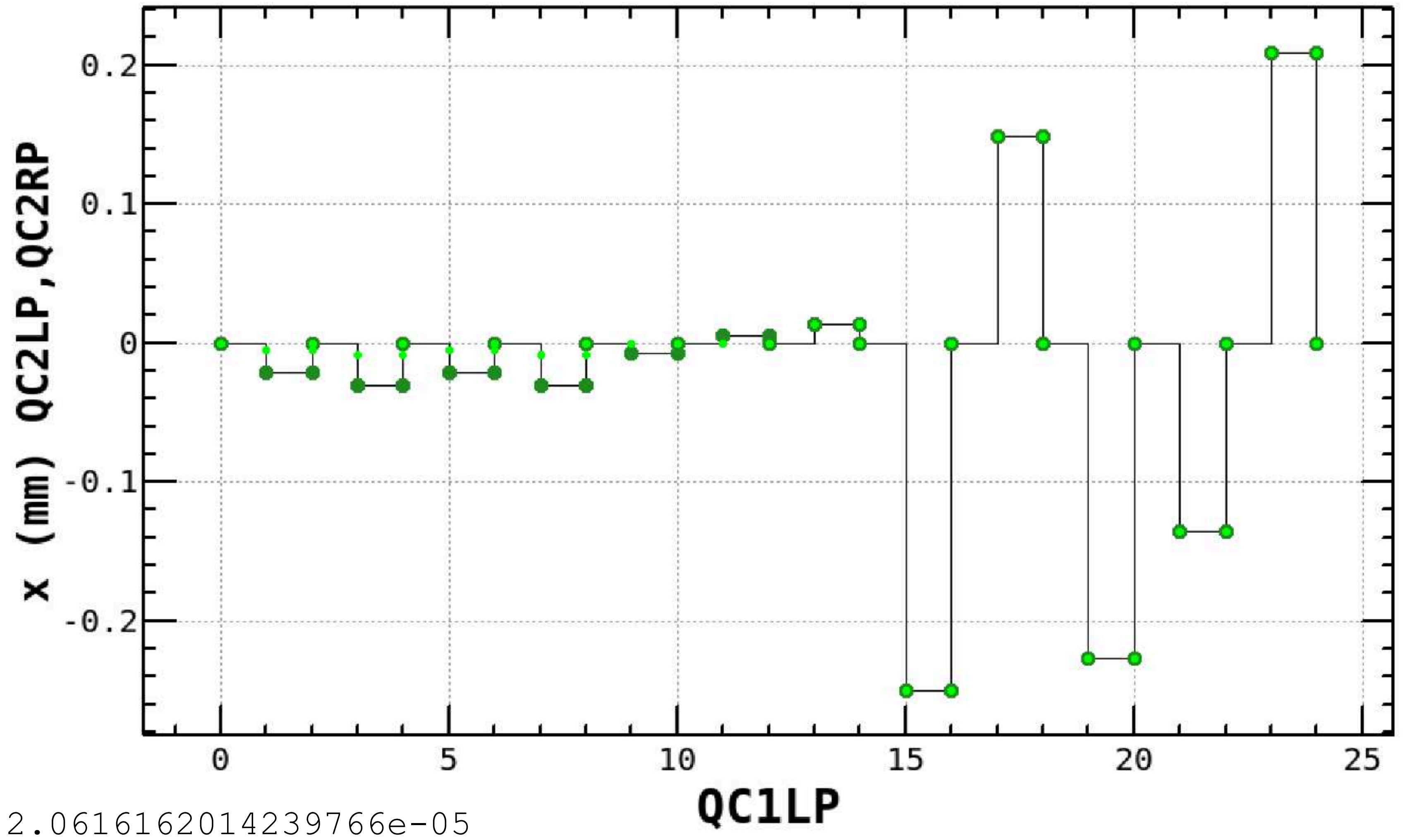

```
ZHQFWNP1 .05 5.2156684759487685e-05
ZHQFWOP4 .05 5.1834480317859026e-05
ZHQI2P   .05 4.7490361354364956e-05
ZHQW2ORP .05 5.202191337423323e-05
ZHQW4NRP .05 4.5071641739144215e-05
ZHQW4ORP .05 4.0643669040745206e-05
```

(A)



estimated by BPMs at QC2LP and QC2RP

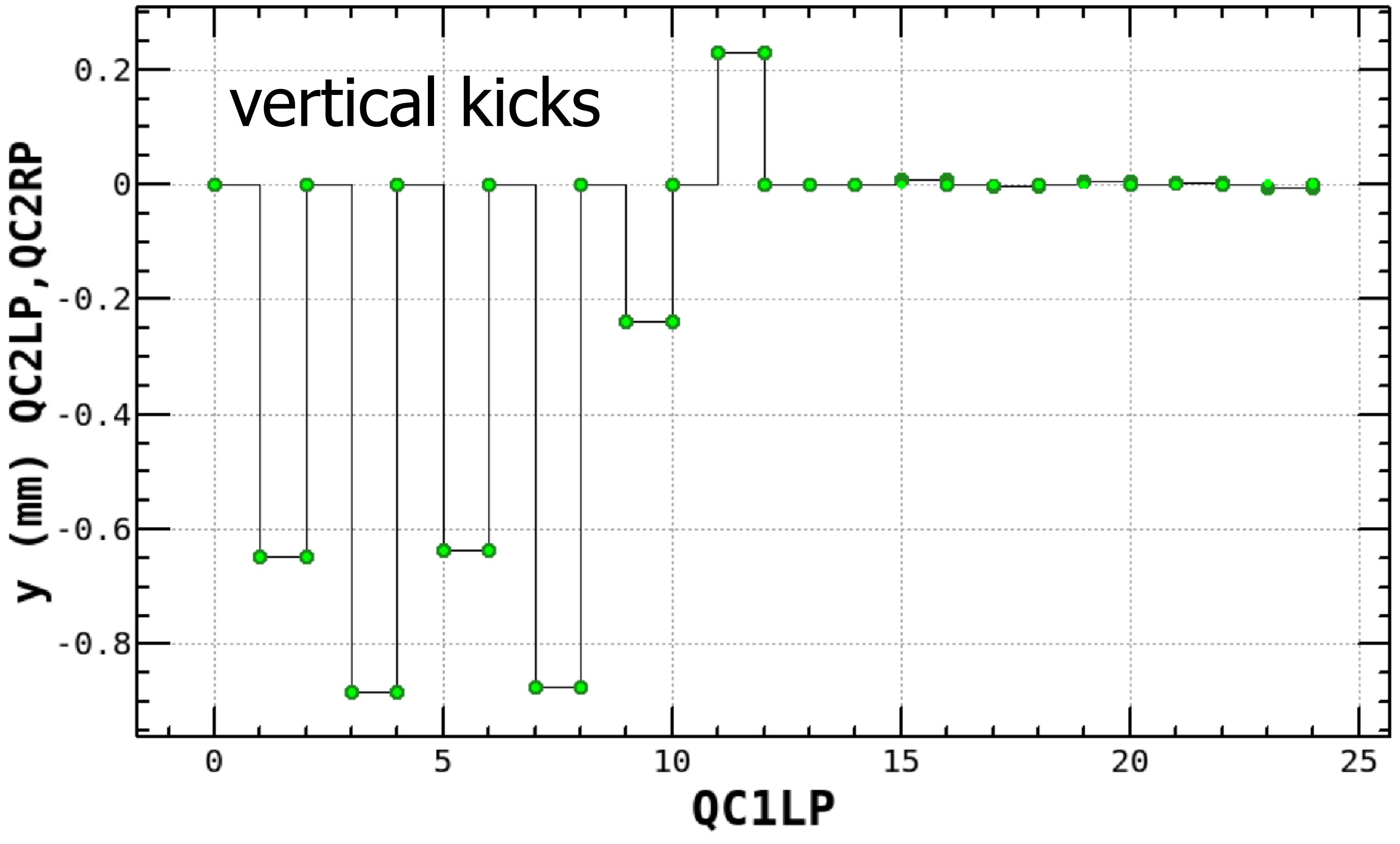
(B)




```
ZVQDWOP2 .02 2.0616162014239766e-05
ZVQDWOP6 .02 2.0605460685726935e-05
ZVQLA7RP .02 1.5878804943887847e-05
ZVQS1NP1 .02 1.2180594779069905e-05
ZVQS1OP2 .02 1.3070386891523781e-05
ZVQW7ORP .02 1.3722310034910458e-05
```

horizontal kicks

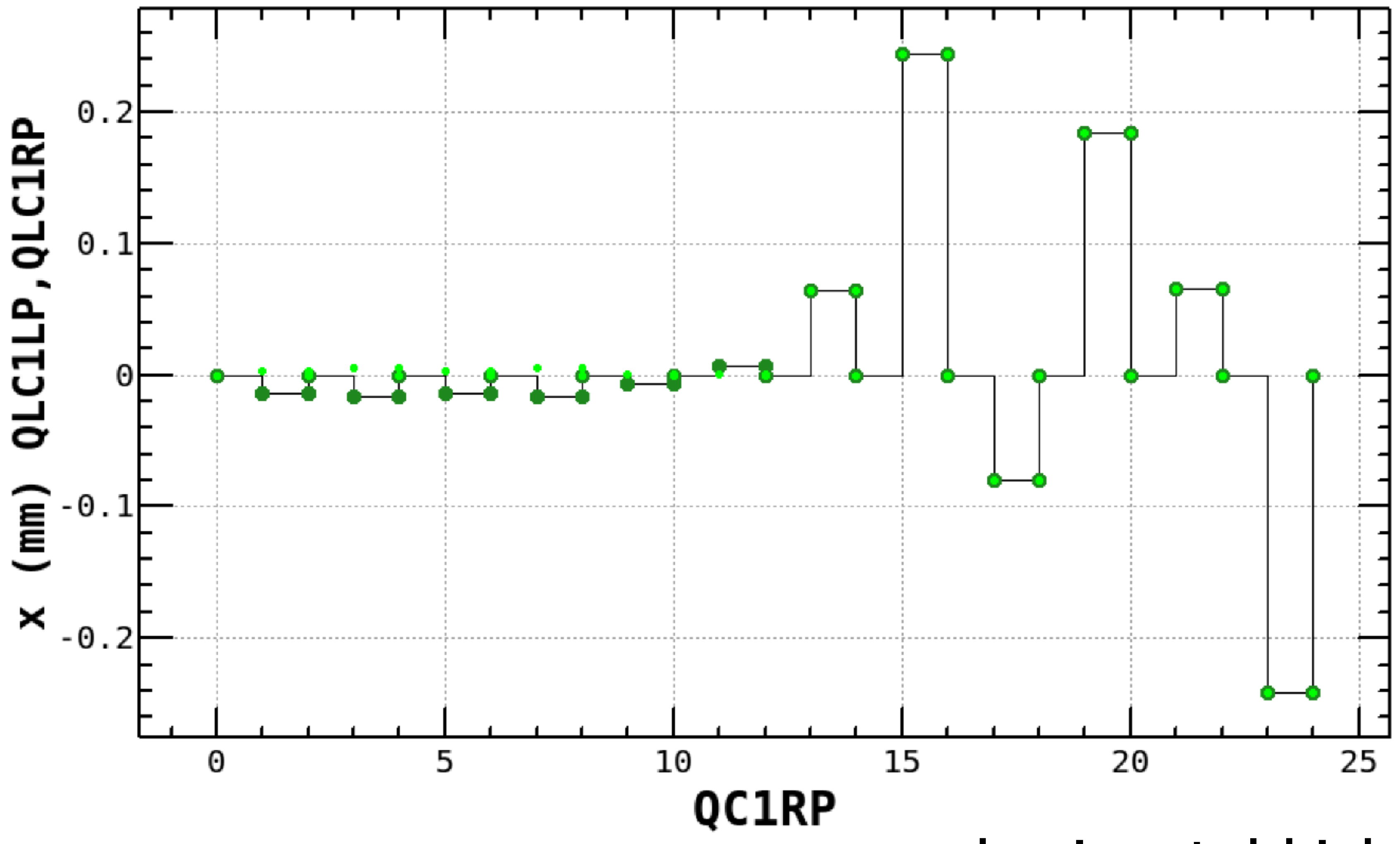
(B)



BPM Response with Model Lattice

estimated by BPMS at QLC1LP and QLC1RP

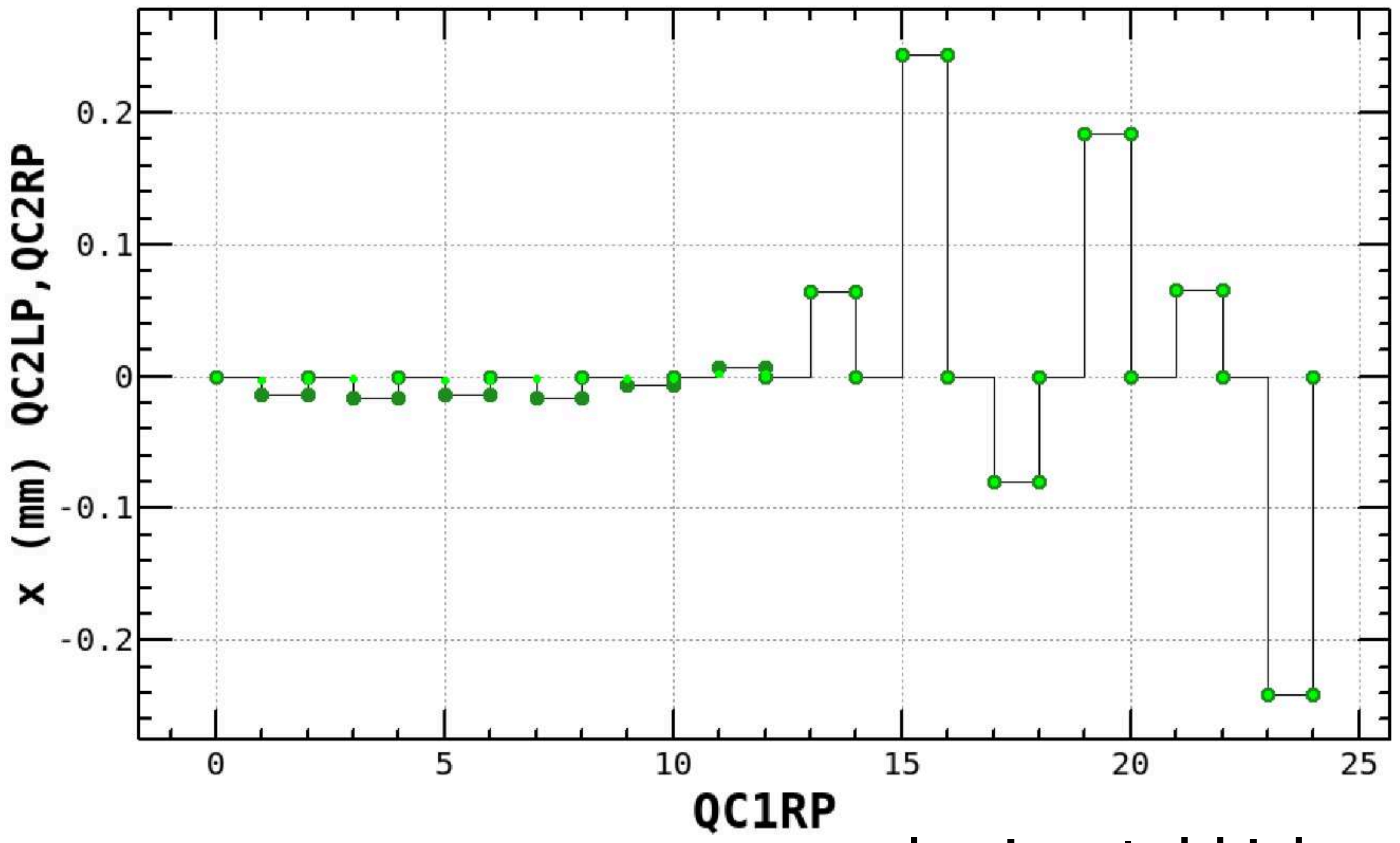
(A)



horizontal kicks

estimated by BPMs at QC2LP and QC2RP

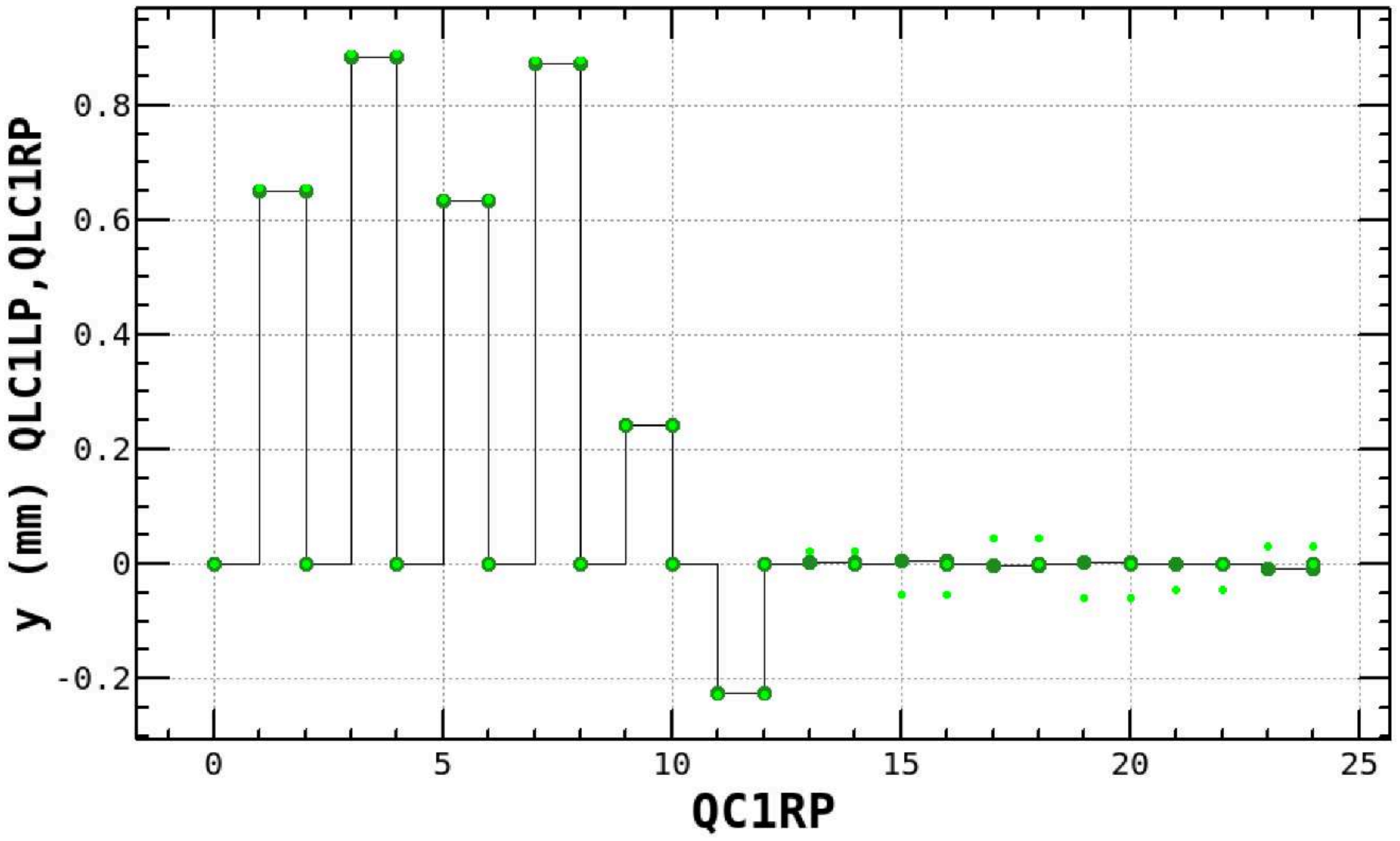
(B)



horizontal kicks

vertical kicks

(A)



vertical kicks

(B)