SuperKEKB Luminosity Quest

eeFACT2022

Y. Ohnishi, KEK

Frascati, Italy

on behalf of the SuperKEKB commissioning group

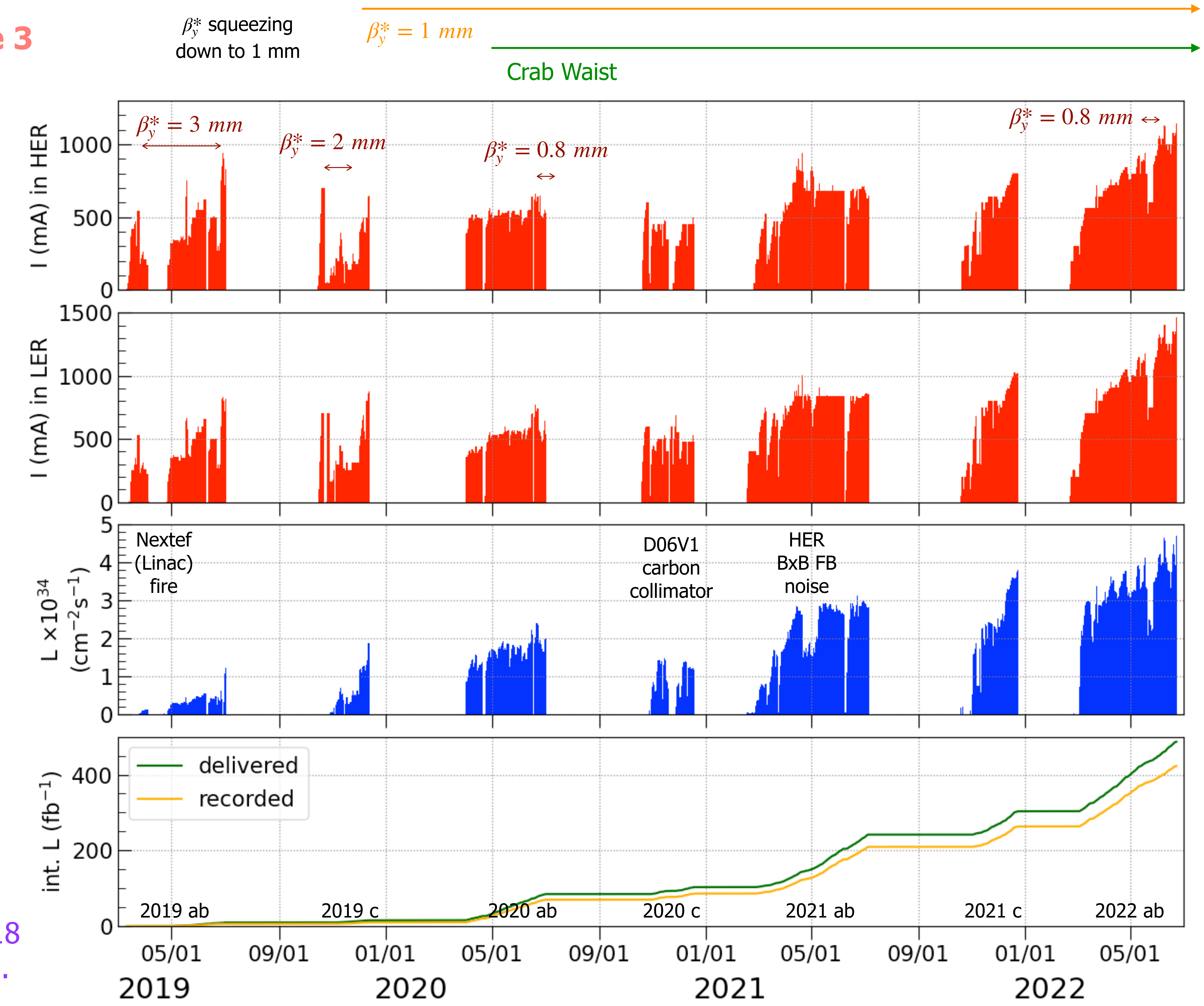
Achievements until 2022 (1)

- Peak luminosity : 4.65 x 10^{34} $cm^{-2}s^{-1}$ (4.71 x 10^{34} $cm^{-2}s^{-1}$ w/o Belle II data taking)
- Integrated luminosity : 424 fb^{-1} (491 fb^{-1})
- Peak currents : 1.46 A (LER) / 1.14 A (HER), 2346 bunches (2-bucket spacing)
- β_y^* : 1 mm (0.8 mm) << bunch length ~6 mm → proof of the nano-beam scheme
- Crab waist scheme has been applied (80 % in the LER, 40 % in the HER). → luminosity improvement
- Beam-Beam parameter : 0.035 at 0.7 mA (0.045 at 1.1 mA for small number of bunches)
- Bunch-by-bunch FB tuning (gain, noise reduction) in the HER → luminosity improvements
- Bunch-by-bunch FB tuning (number of taps) in the LER → suppress single bunch blowup, luminosity improvements
- Chromatic X-Y coupling correction with rotatable sextupoles in the LER → luminosity improvements

Achievements until 2022 (2)

- Long-term drift of QCS magnetic field (beta-beat) ← reduced by new QCS initialization procedure
- Orbit deviation due to IP knob tuning (beta-beat) ← suppressed with QCS corrector (ZHQC2RP)
- Increase of positron charge for the LER injection : 3 nC at the end of e^+ beam transport line
- 2-bunch injection for the LER and HER → improve injection efficiency
- Adjustment of injection orbit in the HER (septum, kicker) → improve injection efficiency (not enough)
- Reduce leakage orbit from injection kickers ← reduced by additional inductance for the coils

SuperKEKB Phase 3



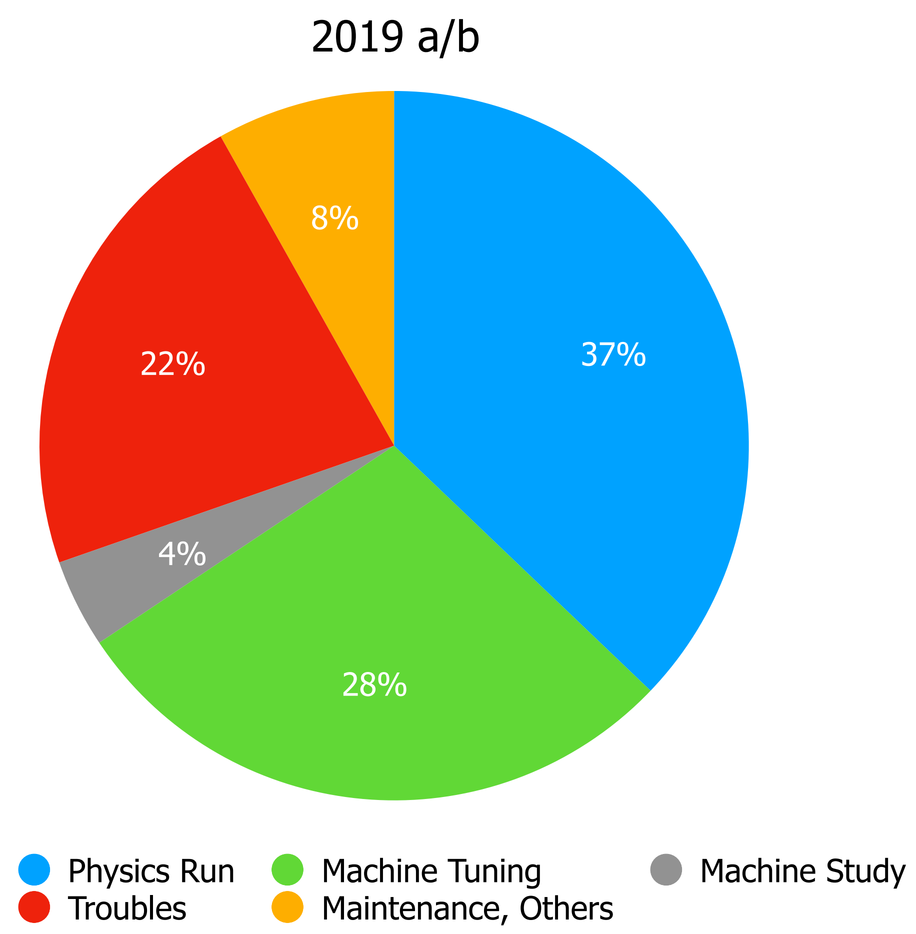
1145 mA

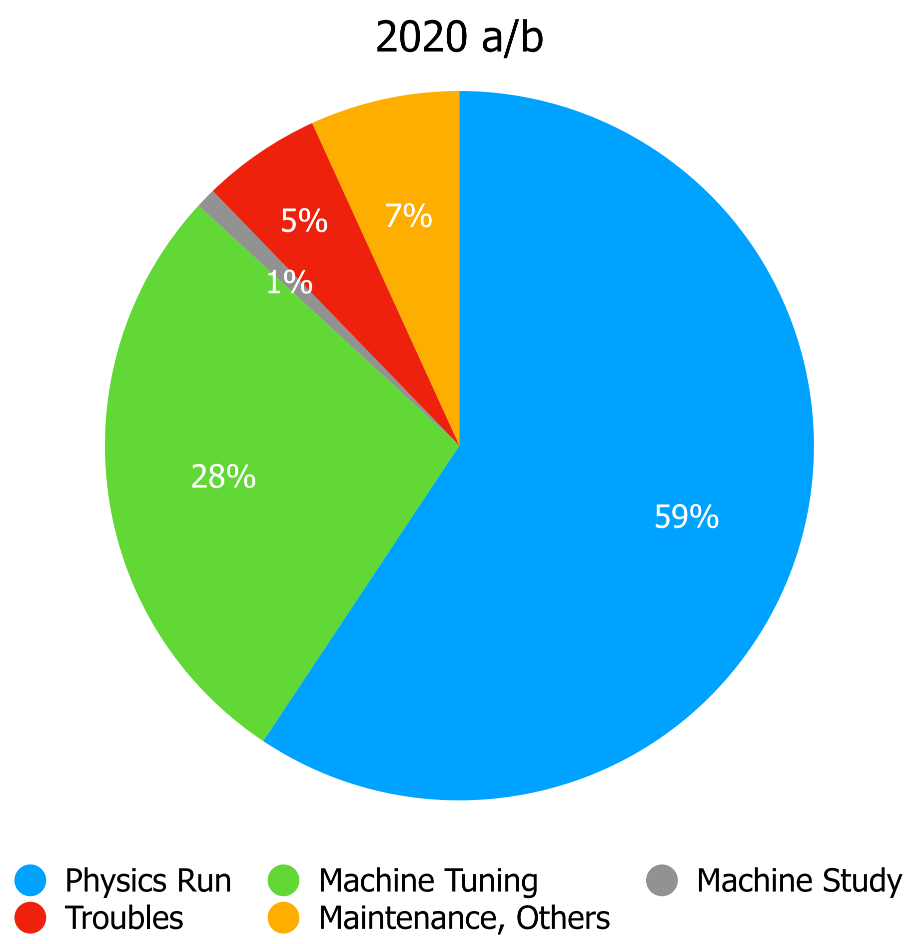
1460 mA

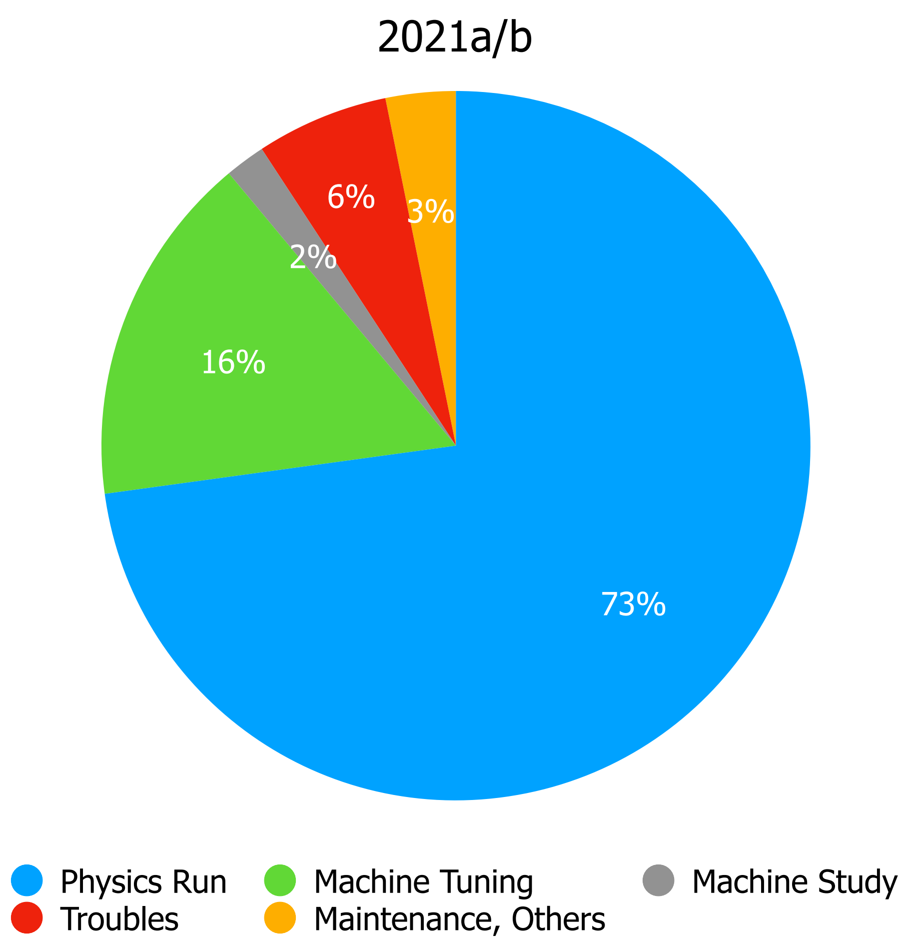
4.65 x 10^{34} cm^{-2}s^{-1}
(4.71 x 10^{34} cm^{-2}s^{-1})

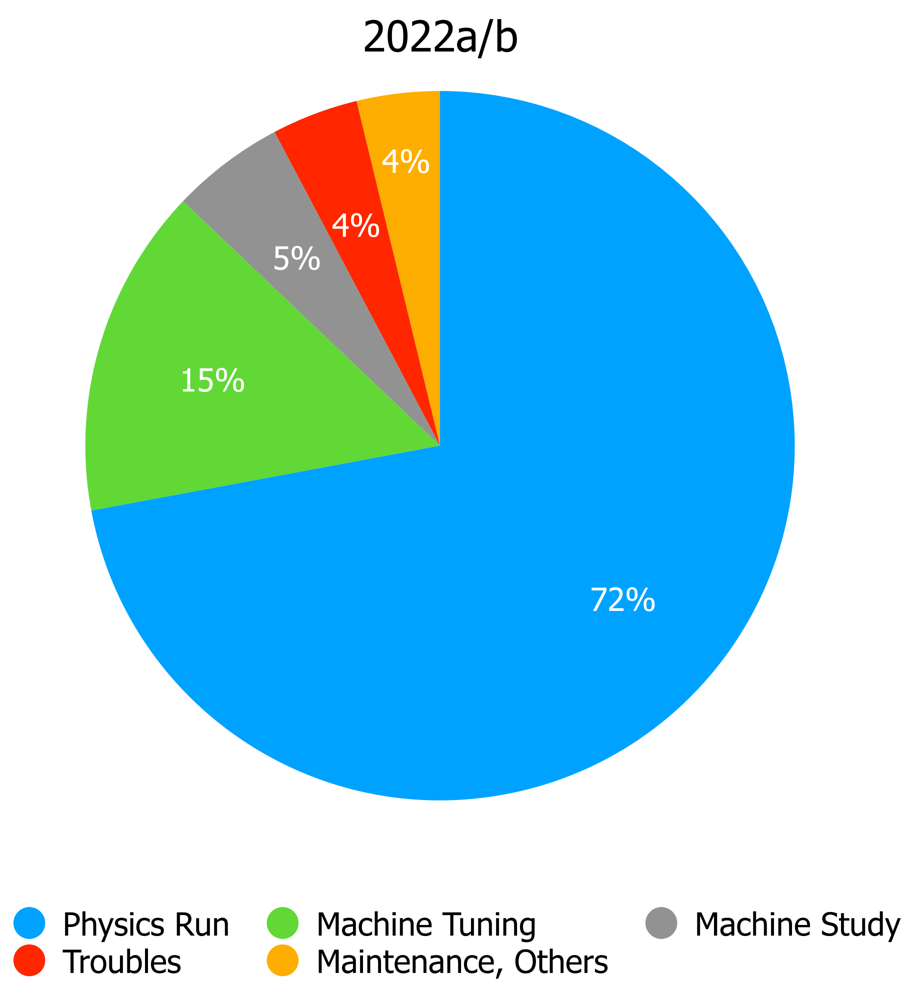
424 fb^{-1} / 491 fb^{-1}

The last eeFACT 2018 was before Phase 3.







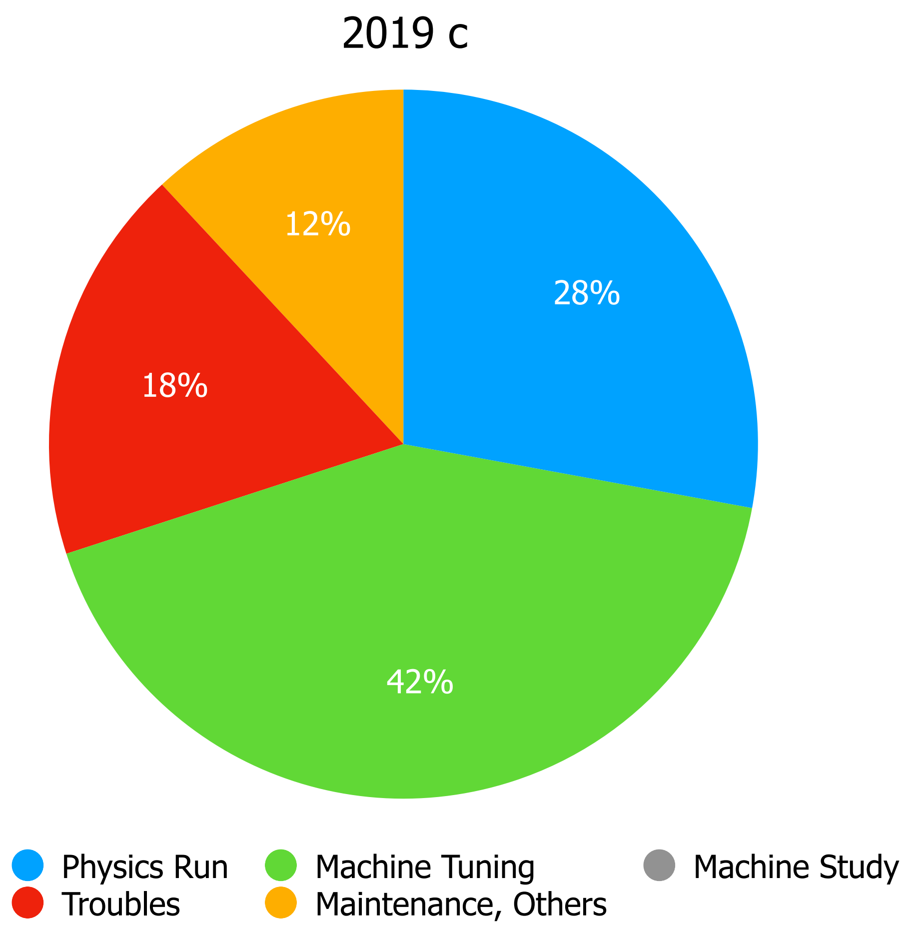


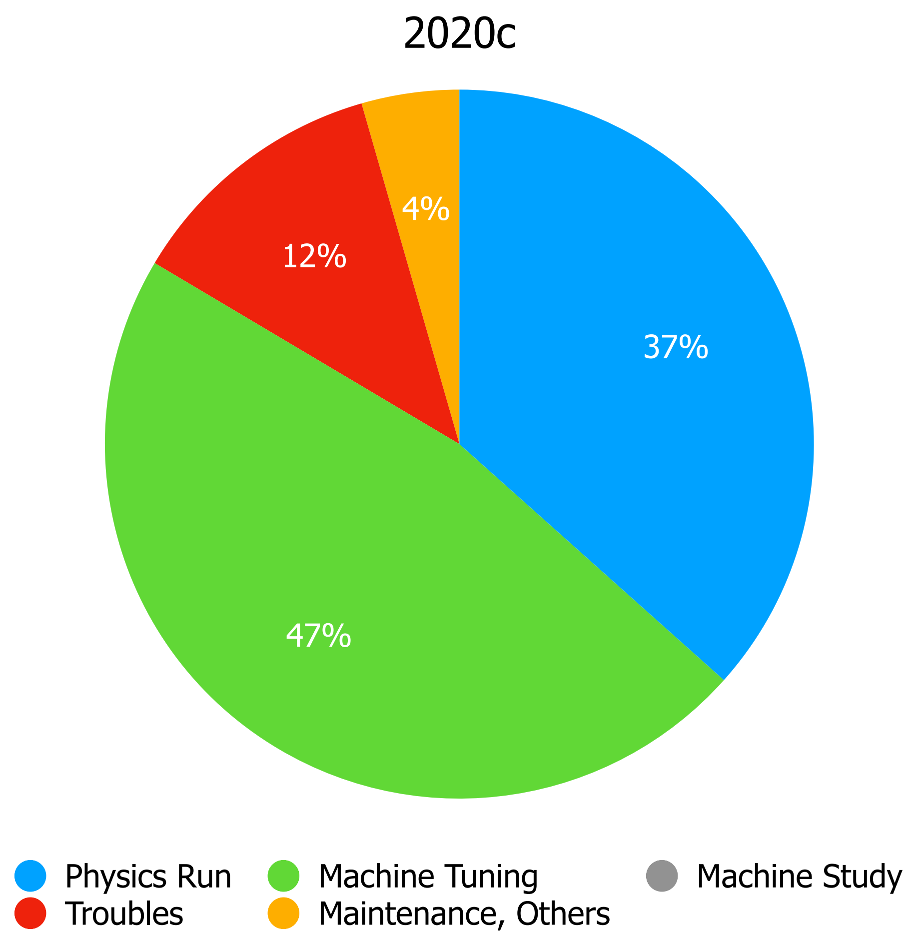
2019

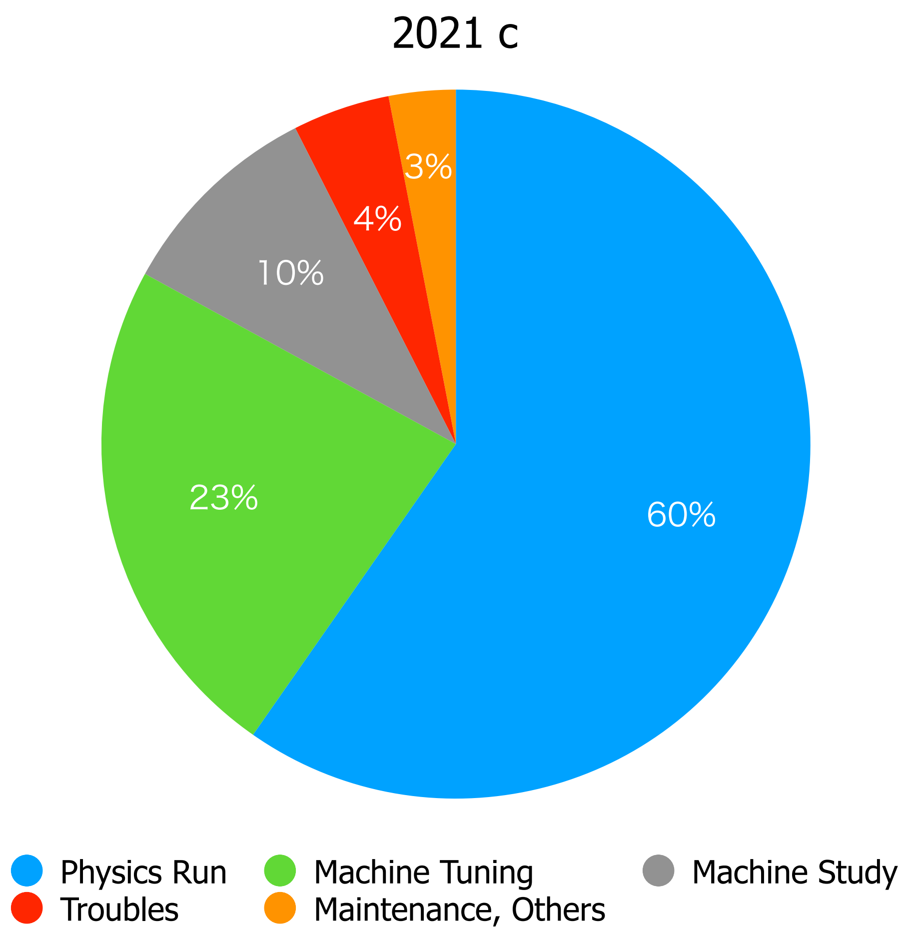
2020

2021

2022





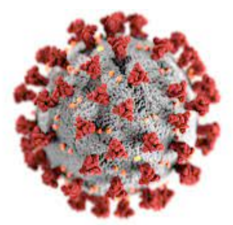


Operation statistics 2019 -2022

Machine Parameters

	SuperKEKB : June 8, 2022		SuperKEKB : May 22, 2022		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	1321	1099	744	600	mA
Number of bunches	2249		1565		
Bunch current	0.587	0.489	0.475	0.383	mA
Horizontal size σ_x*	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.303		0.250		μm*1
Vertical size σ_y*	0.215		0.177		μm*2
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.574	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	mm
Piwinski angle	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	40	%
Beam-Beam parameter ξ_y	0.0407	0.0279	0.0309	0.0219	
Specific luminosity	7.21×10^{31}		8.74×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	4.65×10^{34}		2.49×10^{34}		$cm^{-2}s^{-1}$

← twice the size of COVID-19 virus



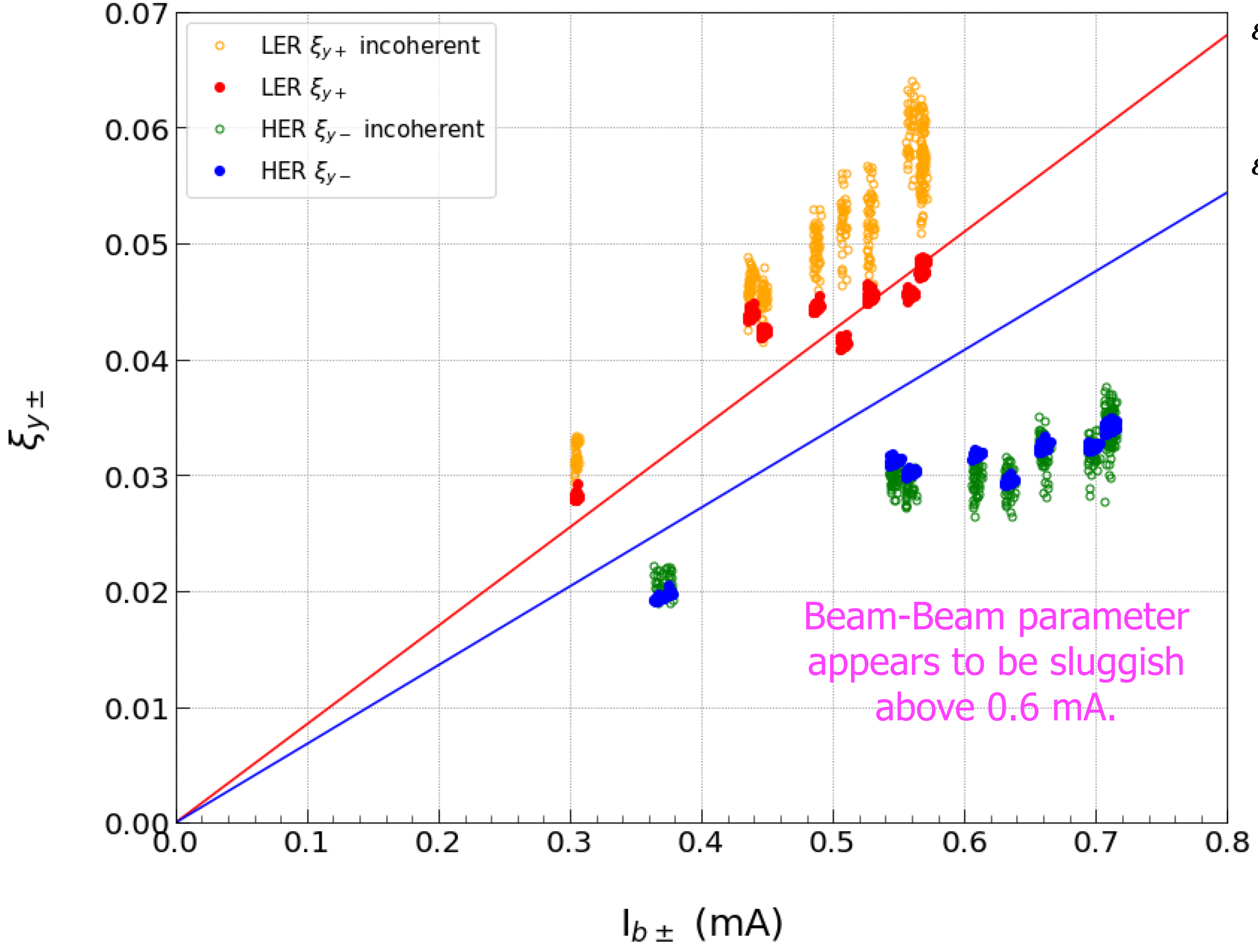
*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

Beam-Beam Interaction

- Lower beam current in the HER tends to cause beam blowup.
- This means that the HER beam size is more easy to blow-up when the beam current of the HER decreases.
- Therefore, the beam current of the HER is larger than the energy ratio (4 GeV / 7 GeV). $\boxed{\gamma_+ I_+ < \gamma_- I_-}$
- The optimum ratio of LER to HER beam current is 5:4 from luminosity tuning.
- The beam-beam parameter of the LER are larger than that of the HER.
- The current ratio is kept constant for daily operation in principle.
- The beam-beam parameter is sluggish with LER beam currents of around 0.6 ~ 0.8 mA.
- D. Zhou, more details will be reported on Wednesday, September 14. (WG4)

Beam-Beam Parameter

$\beta_y^* = 1\ mm$



single beam emittance

$\varepsilon_{y-}^0 = 40\ pm$

$\varepsilon_{y+}^0 = 25\ pm$

Vertical beam-beam parameter

$$\xi_{y\pm} = 2er_e \frac{\beta_{y\pm}^* L}{\gamma_\pm I_\pm}$$

Vertical beam-beam parameter (incoherent)

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\left(\frac{I_{b\mp}}{ef_0}\right)\frac{\beta_{y\pm}^*}{\phi_x \sigma_{z\mp}\sigma_{y\mp}^*} \propto I_{b\mp}\sqrt{\frac{\beta_{y\pm}^*}{\varepsilon_{y\mp}}}$$

↑ measured by X-ray size monitor

Bunch lengthening is an important parameter.
Here, the nominal bunch length is used.

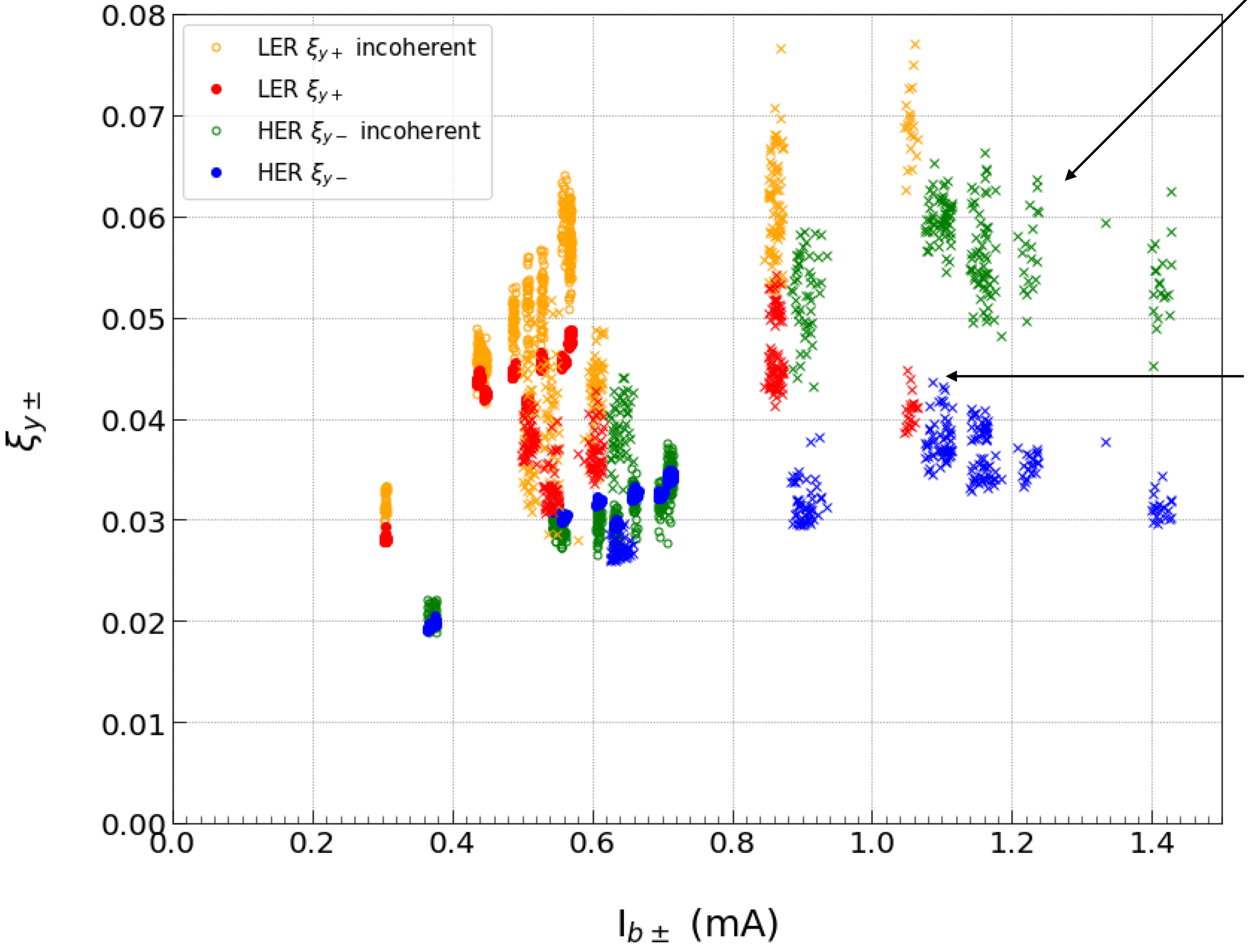
$$\sigma_{z+} = 4.6\ mm$$
$$\sigma_{z-} = 5.1\ mm$$

Beam-Beam Parameter (include HBCC)

*HBCC = High Bunch Current Collision

$\beta_y^* = 1\ mm$

High Bunch Current Collision study on March 28, 2022; n_b = 393 (indicated by x mark)



ξ_{y-}~ 0.045 at I_{b+} = 1.1 mA

Specific Luminosity

- The definition of specific luminosity:

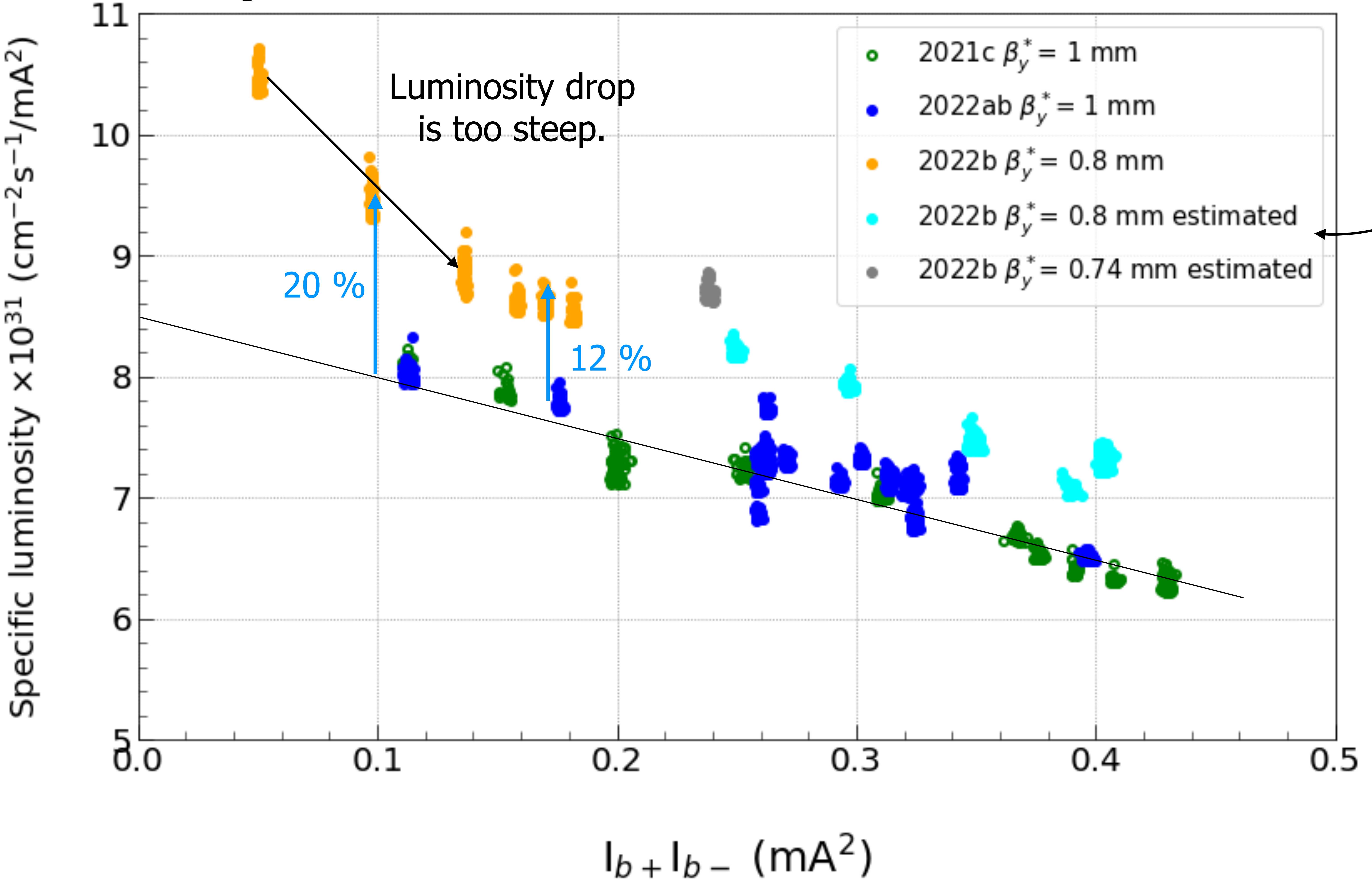
$$L_{sp} = \frac{L}{n_b I_{b+} I_{b-}} \propto \frac{1}{\Sigma_z \Sigma_y^*}$$

- It was found that even if the setting is 1 mm, β_y^* can be shifted due to beta-beat caused by a deviation of the horizontal beam orbit at the strong sextupoles in the local chromaticity correction.
  - The orbit deviation is caused by beam line deformation due to intense SR heating.
  - This effect is more significant for the HER rather than the LER.
- Higher specific luminosity for β_y^* = 0.8 mm is obtained at a bunch current product of 0.05 mA^2, but the specific luminosity rapidly decreases around 0.1 mA^2.
  - L_{sp} for β_y^* = 0.8 mm is about 20 % higher than 1 mm at 0.05 mA^2 and decreases to about 12 % at 0.1 mA^2 and above.
- This implies that the corrections of the chromatic X-Y coupling and other parameters are not optimized yet for β_y^* = 0.8 mm which affect beam-beam blowup.

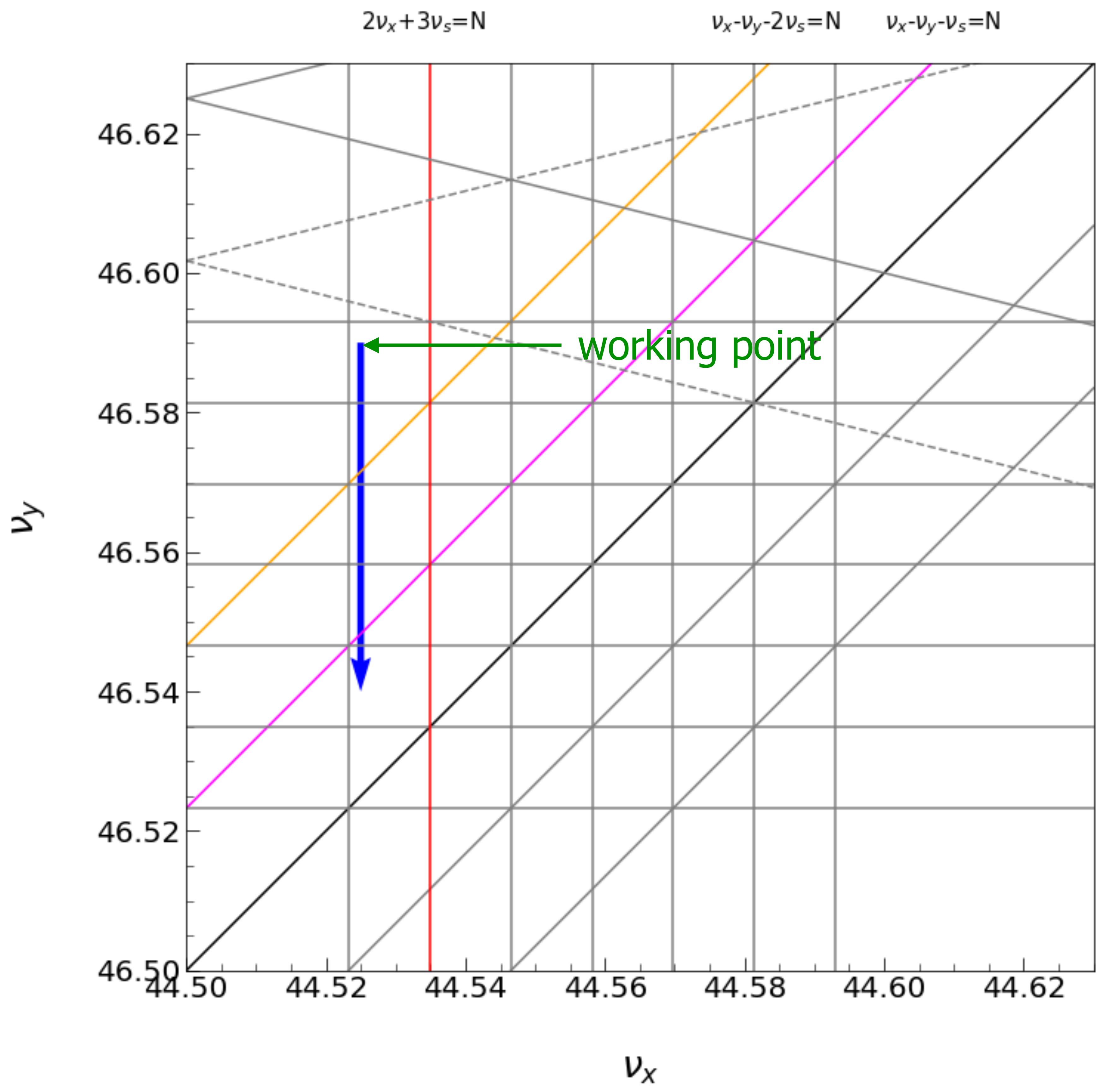
Specific Luminosity

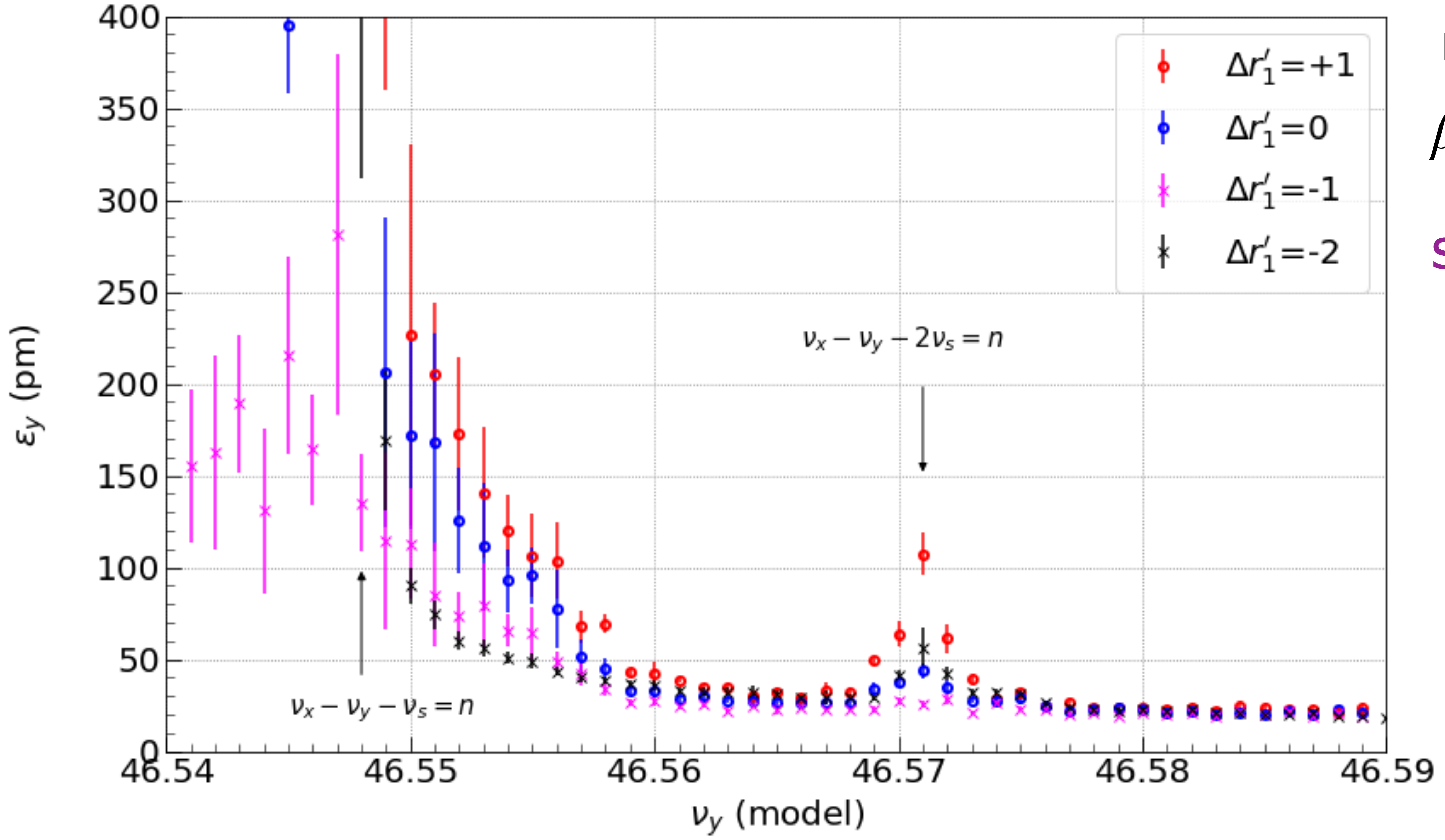
The geometrical luminosity is good.

"estimated" means β_y^* is calculated by the horizontal orbit deviation at SLY(strong sextupoles) in HER due to beam-line deformation.



Chromatic X-Y Coupling Correction with Rotatable Sextupoles in LER

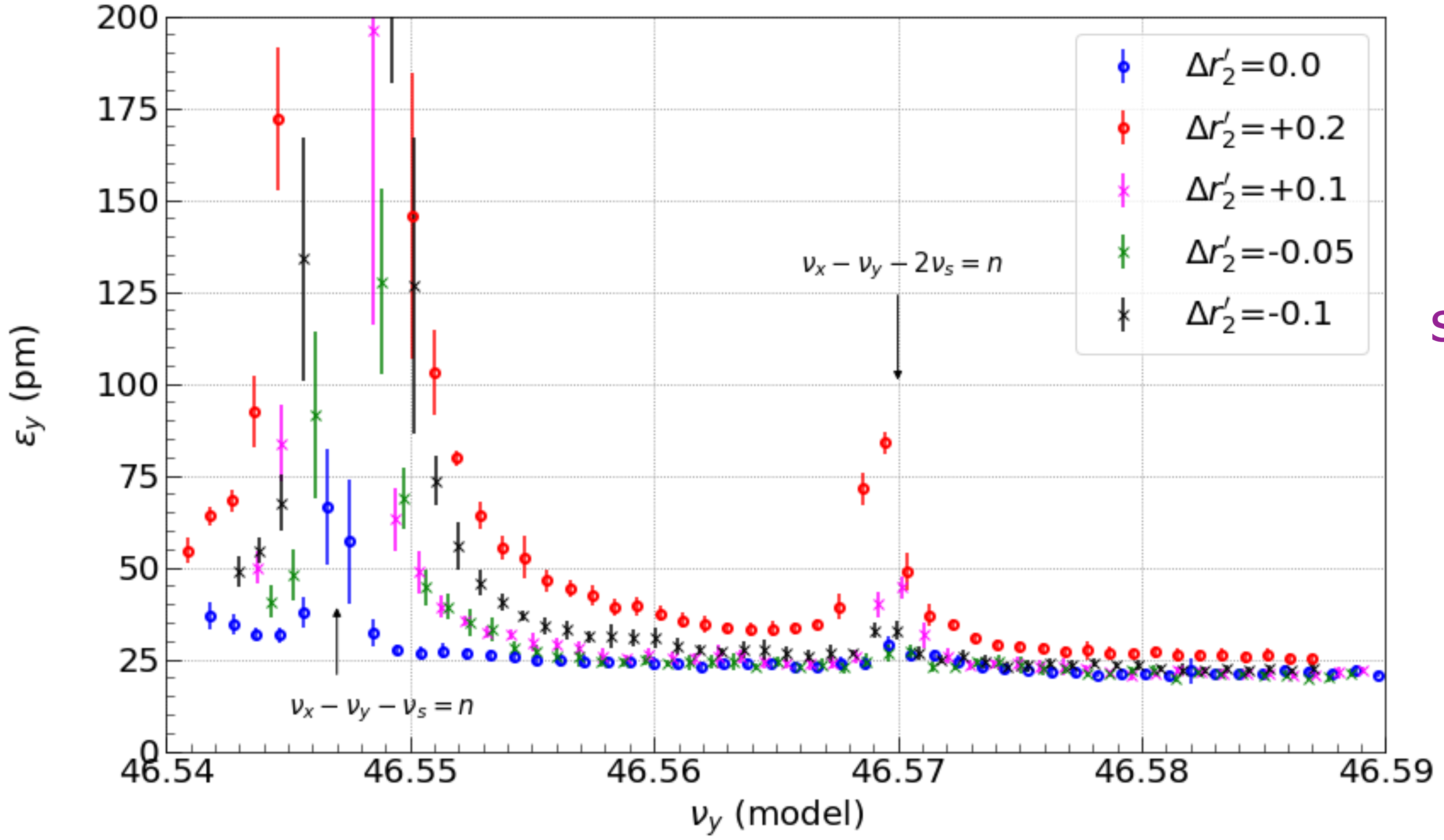




Dec. 20, 2021

$\beta_y^* = 1\ mm$

single beam



March 14, 2022

$\beta_y^* = 1\ mm$

$\Delta r_1' = -1$

single beam

$\Delta r_2' = 0$ is optimal.

The rotatable sextupoles (6 families for right and left side of IP) are used to make the first synchro-beta coupling resonance weak together with the second resonance.

SLYTLPs and SLYTRPs were not used here.

Rotatable sextupoles:
M. Masuzawa, T. Kawamoto et al.

Rotatable Sextupole in LER

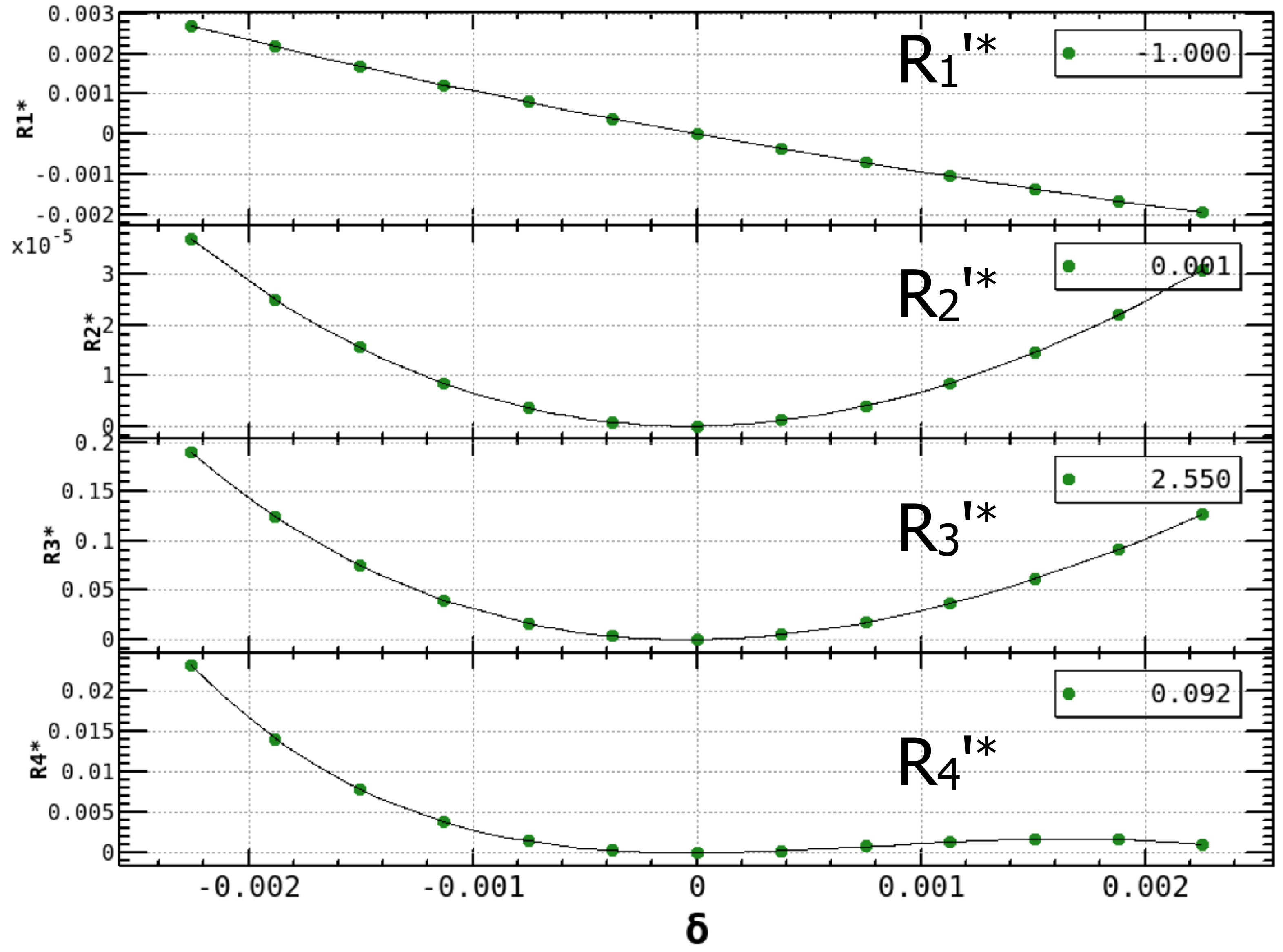
There are 24 sextupole magnet (12 families) supporting tables in the LER and make them roll to induce skew sextupole field.

The 12 sextupoles (6 families) are located at each side of the IP among 54 sextupoles in total.

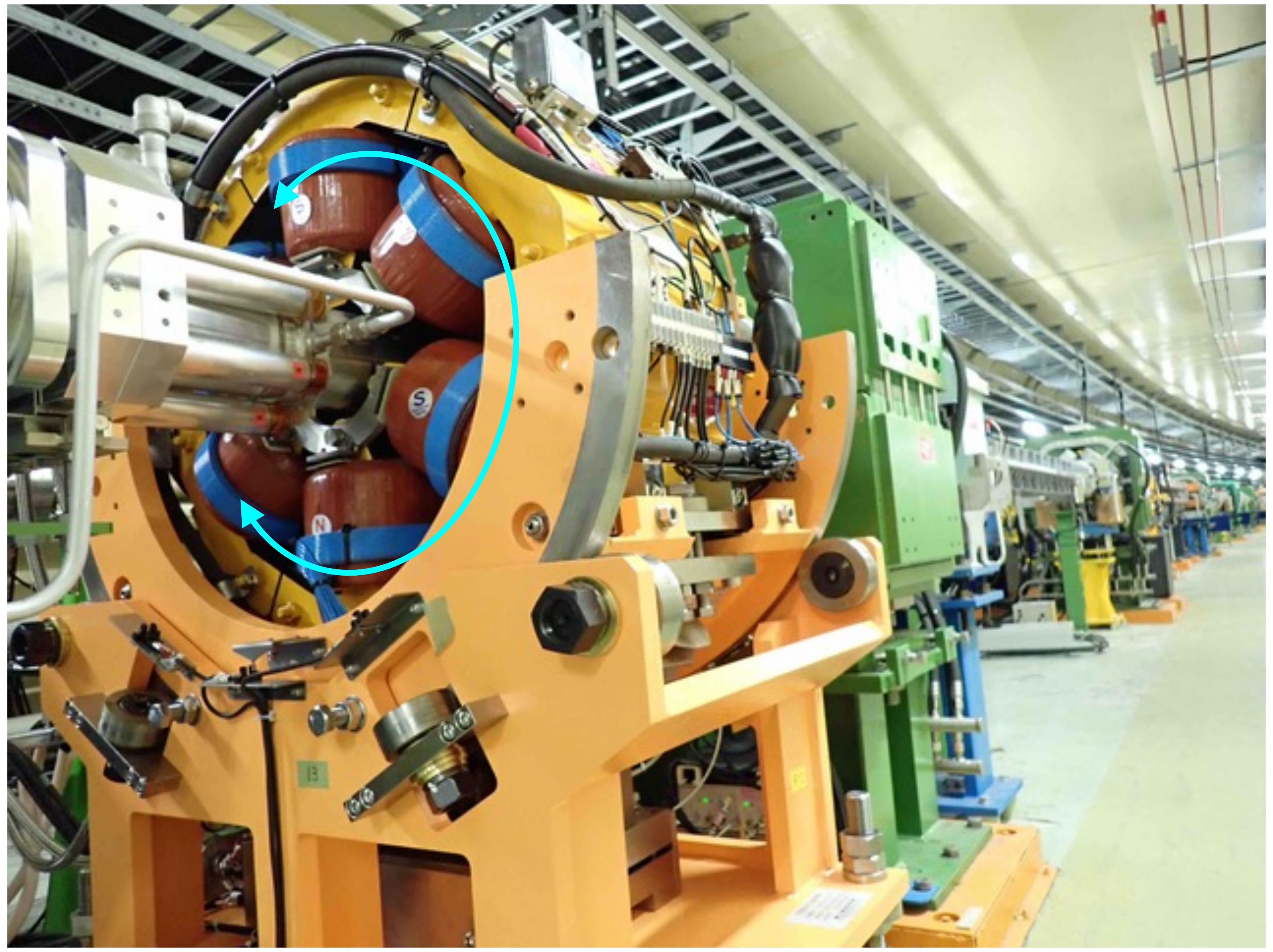
Those sextupoles are used to make chromatic X-Y couplings at the IP by matching procedure with chromaticity correction.
The X-Y couplings, R_1^* and R_2^* are effective for luminosity.

Roughly θ to make $R_1'^* = -1$ or $R_2'^* = -0.1$ m is smaller than 0.1 rad.

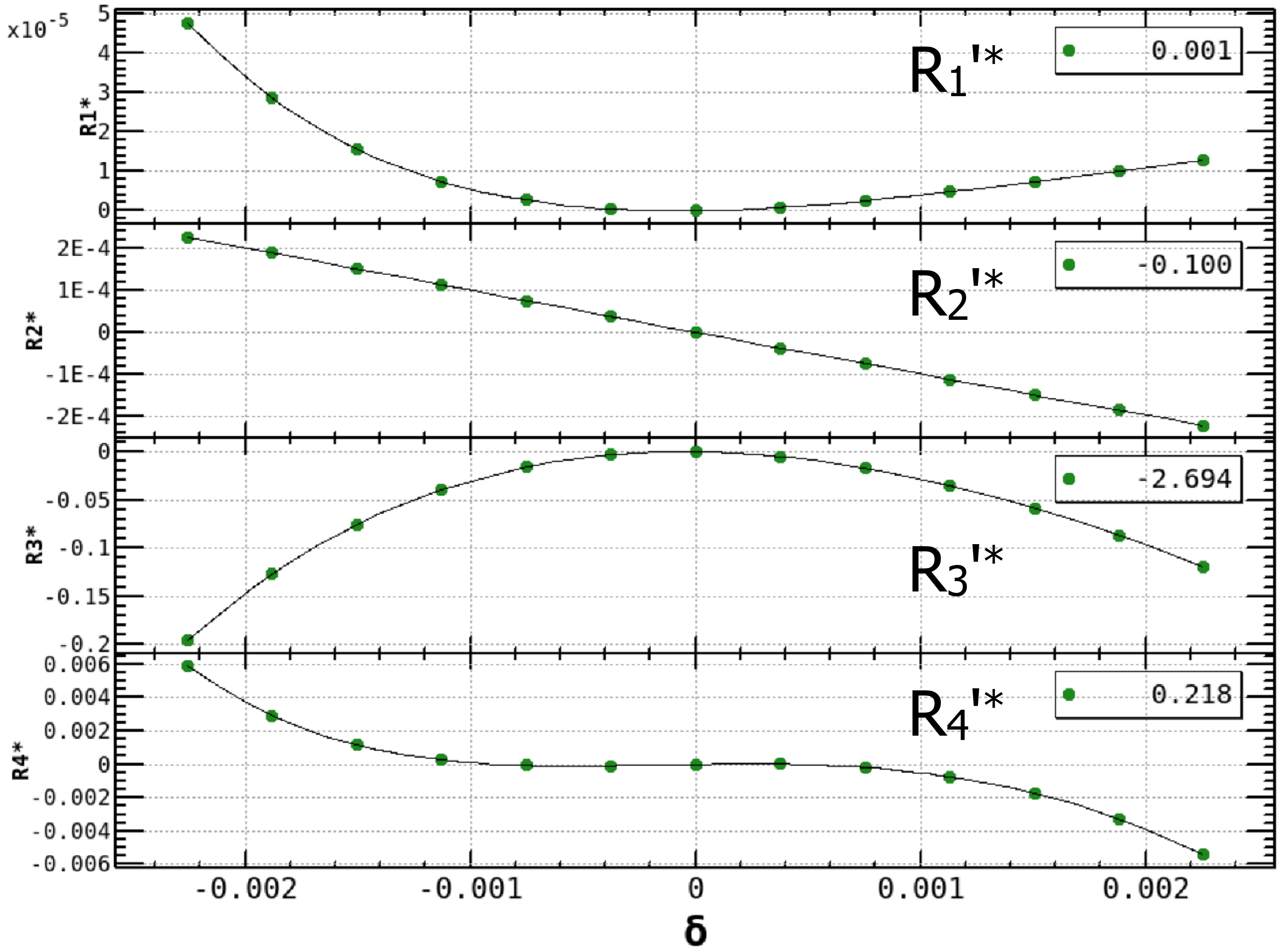
$$\frac{\partial R_1^*}{\partial \delta} = -1$$



$$\frac{\Delta p}{p_0}$$



$$\frac{\partial R_2^*}{\partial \delta} = -0.1\ m$$



$$\frac{\Delta p}{p_0}$$

* Lattice model and matching at IP is performed by SAD.

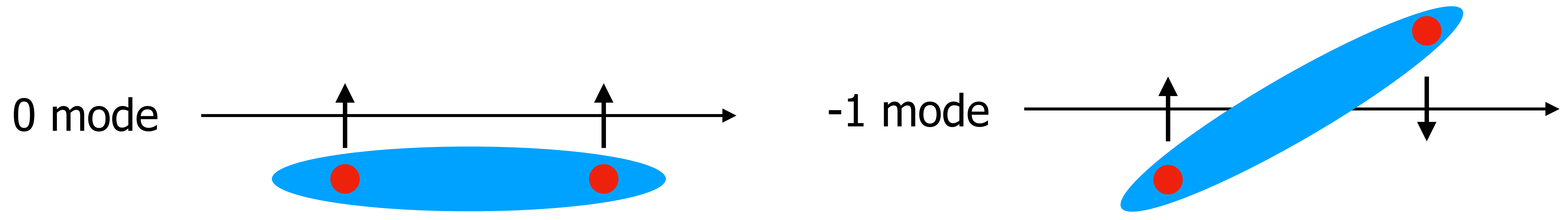
Obstacles to Luminosity Improvement

- Beam blowup in the LER (single beam, non-collision) : "-1 mode instability"
- Sudden beam loss (fast beam loss, especially in the LER)
  - Damage of collimator head due to large beam loss
- Lower beam-beam parameter: ~0.035 at 0.7 mA
- Beam current dependence of beam orbit
  - Orbit deviation at strong sextupoles is caused by beam line deformation due to intense SR heating.
- Short beam lifetime (dynamic aperture, physical aperture) : LER 8 min(1.25 A) / HER 25 min(1 A) n_b=2346
- Beam related background (optimization of collimator, QCS aperture, IR orbit)
  - A. Natochii, Tuesday, September 13 (WG5)
- Beam injection (small physical aperture of injection region, emittance growth in the beam transport line)
  - T. Natsui, Thursday, September 15 (WG6)
- Earthquake : The beam aborts invariably. The ε_y becomes large in the HER. The optics correction is needed.

Beam Blowup in LER

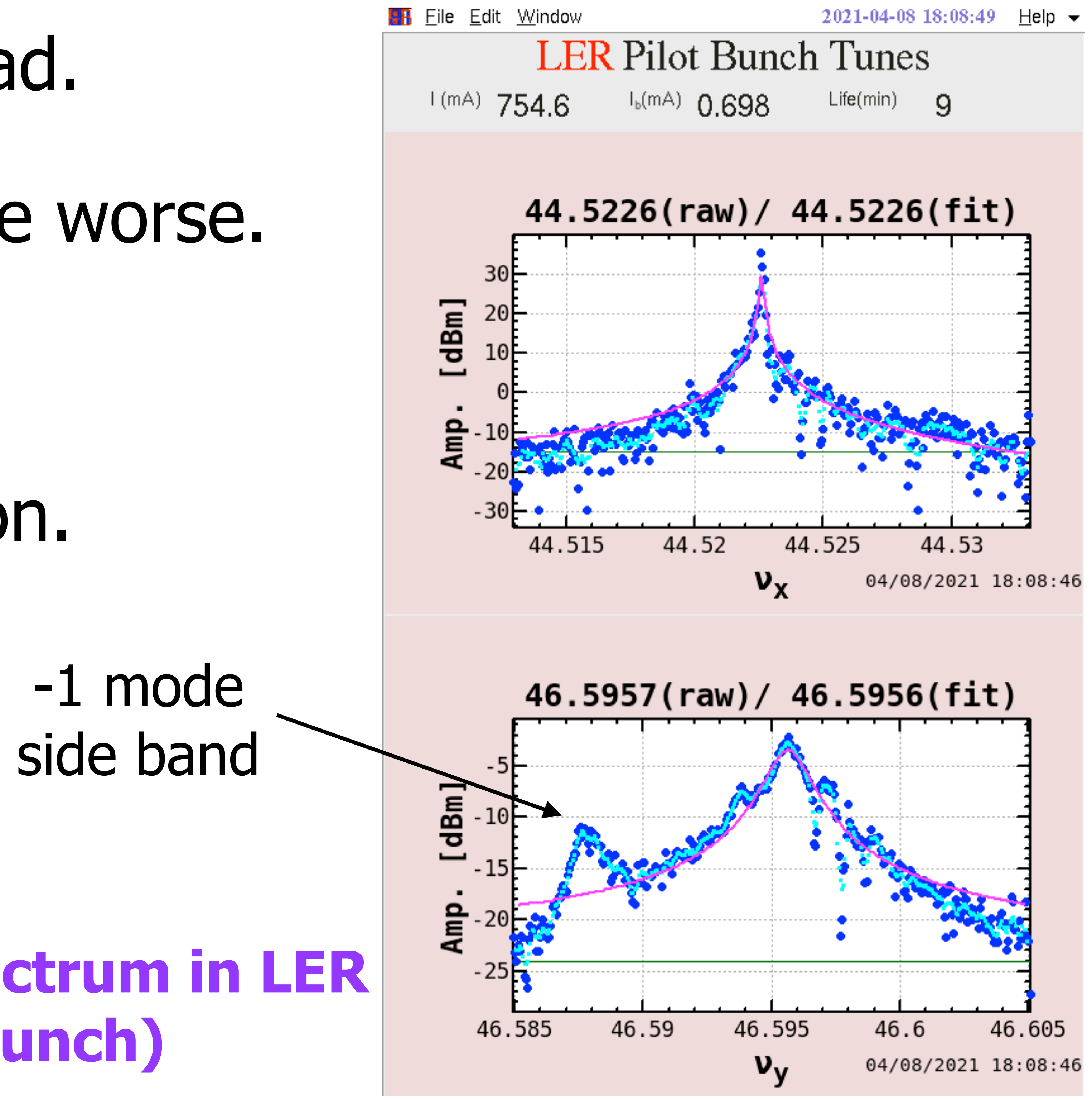
Related issues will be reported by
K. Ohmi on Wednesday, September 14 (WG4).
T. Ishibashi on Thursday, September 15 (WG6).

Beam Blowup in LER (1)



- Non-collision and single-bunch phenomenon
- As the bunch current increases, the blowup appears with the side band $(\nu_y + \nu_s)$ observable. This is called **"-1 mode (head-tail) instability".**
- The threshold of -1 mode instability is quite low (about **0.8 mA**). It appears much smaller than TMCI.
- **Fine-tuning bunch-by-bunch FB** and **opening collimators** can relax the instability.
- TMCI: When 0 mode and -1 mode are fully coupled, the tune becomes imaginary and unstable.
  - Tune shift measurement shows that TMCI occurs at a bunch current of 2.3 mA (> 1.4 mA design value).
- -1 mode instability can appear due to the interplay of bunch-by-bunch FB and transverse wake field (under investigation). FB gain and multi taps seem to be fundamental. FB noise also induces the instability.
- To increase the threshold of -1 mode instability, **optimization of the bunch-by-bunch FB**, **reduction of collimator impedance** are needed. Also **higher vertical tune** is helpful.

- It is important to reduce collimator impedance. (Collimators account for about 75 % of the total.)
  - Coating of the collimator head with copper helps. (It evaporates in case of damage.)
  - Adopting of the nonlinear collimator may reduce the vertical impedance after LS1.
  - If the collimator is damaged, the impedance increases. Avoid damage as far as possible.
- When we set the vertical tune too high, injection efficiency becomes bad.
- One option is to increase the chromaticity, but as the injection would be worse.
  - It is not considered at the moment.
- -1 mode instability can be relaxed by beam-beam effects during collision.

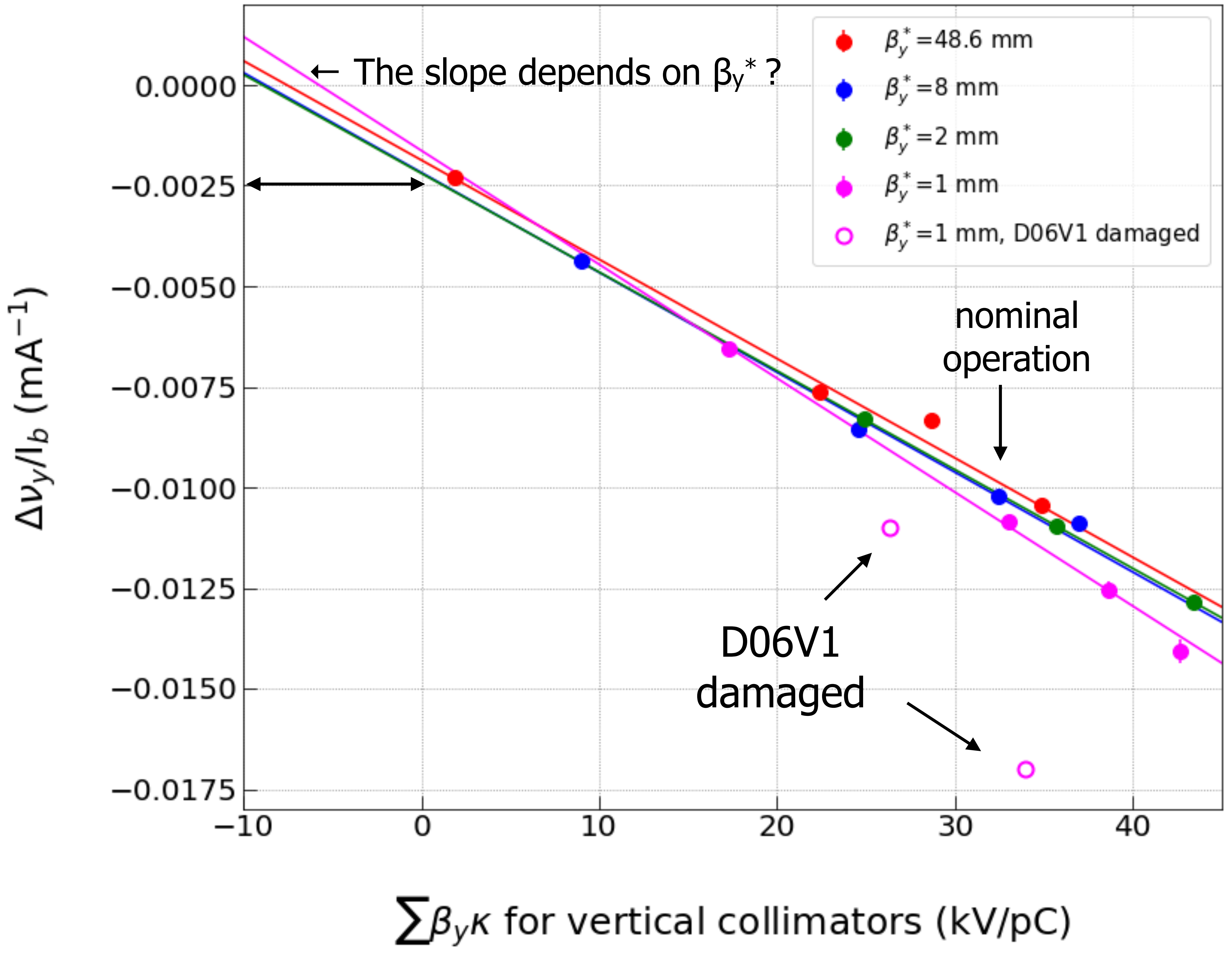


Pilot Bunch Tune Spectrum in LER (no collision bunch)

Measurement of Single Bunch Tune Shift in LER

Tune shift as a function of $\sum \beta_y \kappa$. $$\frac{\Delta\nu_y}{I_b} = -\frac{T_0}{4\pi(E/e)}\sum_i \beta_{yi}\kappa_i(d) \rightarrow \frac{T_0}{4\pi(E/e)} = 0.2\ (ps/kV)$$

Estimated Beta functions are used.



The others are about 10 kV/pC.
β_y^* 1 mm is slightly deferent from those of 2 mm, 8 mm, and 48.6 mm.

Approximately 75 % of the vertical impedance is contributed by the collimators.

estimation of loss factor :

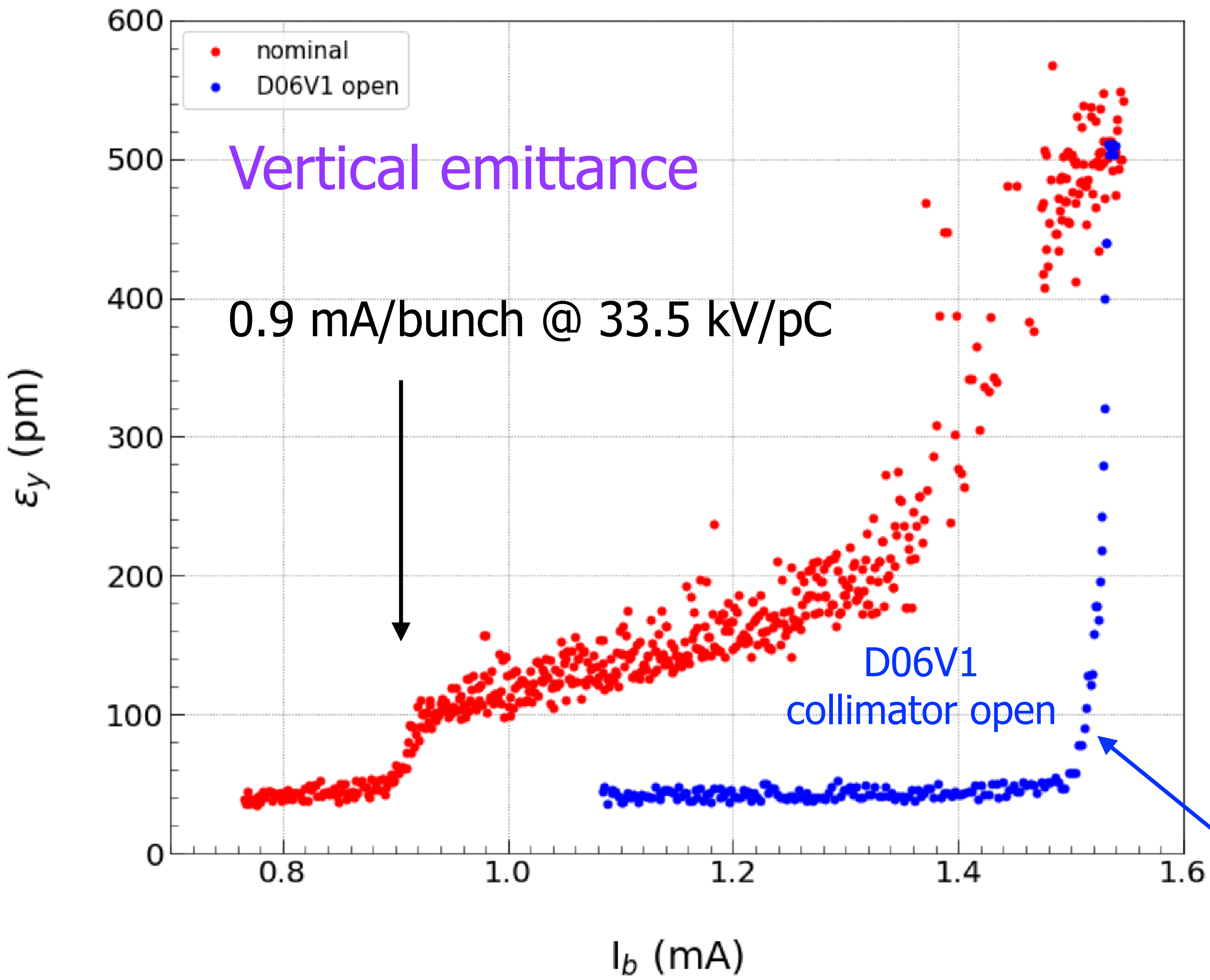
$$\kappa(d) = ad^b$$ d: aperture (mm)

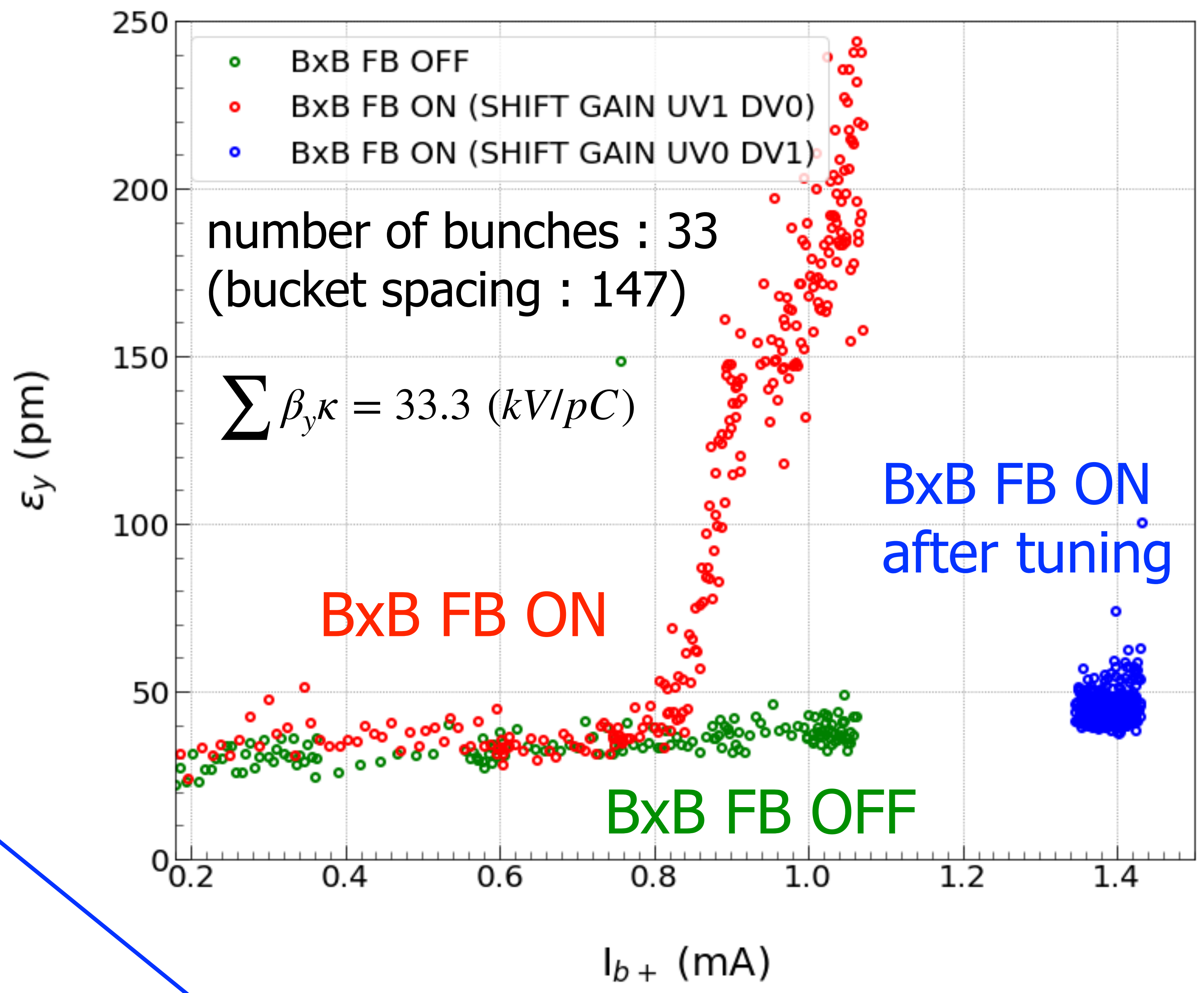
Feb. 24 and Feb. 28, 2022

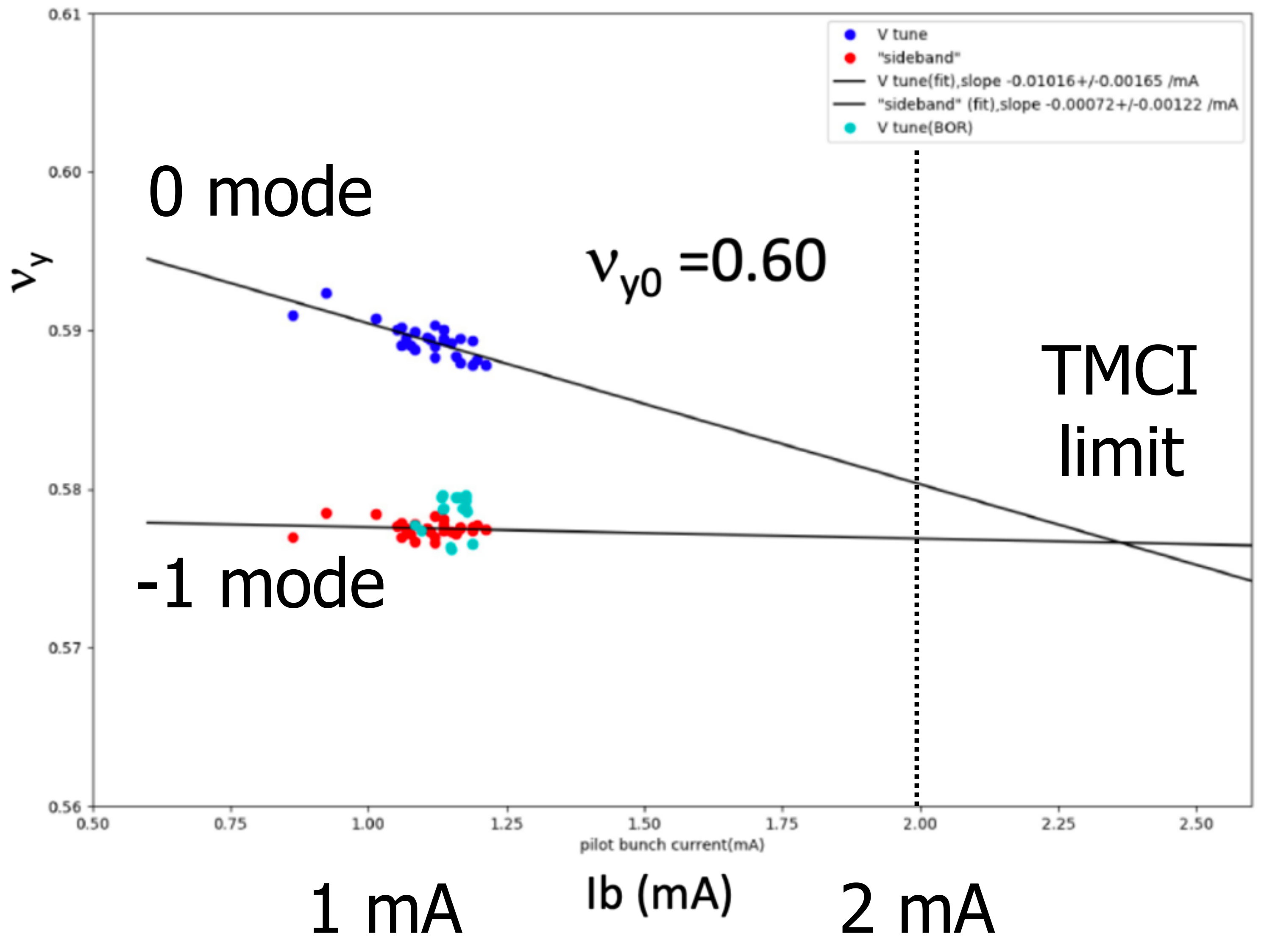
collimator	D06V1	D06V2	D03V1	D02V1	Remarks
a	1.26	1.24	1.24	1.24	
b	-1.69	-1.54	-1.54	-1.54	
β_y (m) model	67.35	20.57	16.96	11.89	β_y^* =1 mm
	↑	↑	↑	10.26	β_y^* =2 mm
	↑	↑	↑	9.93	β_y^* =8 mm
	↑	↑	↑	8.25	β_y^* =48.6 mm

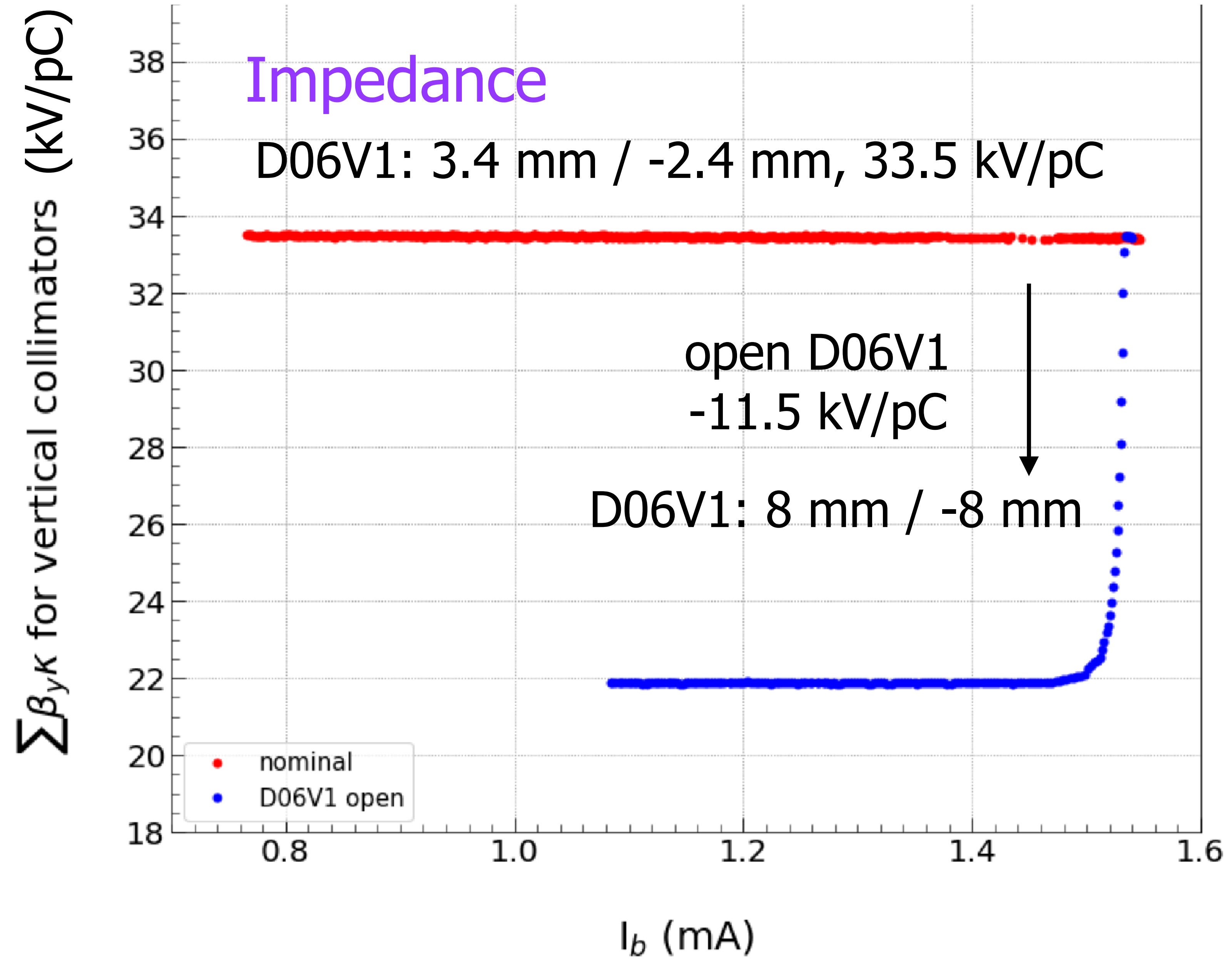
Y. Ohnishi, K. Ohmi, S. Terui, T. Ishibashi

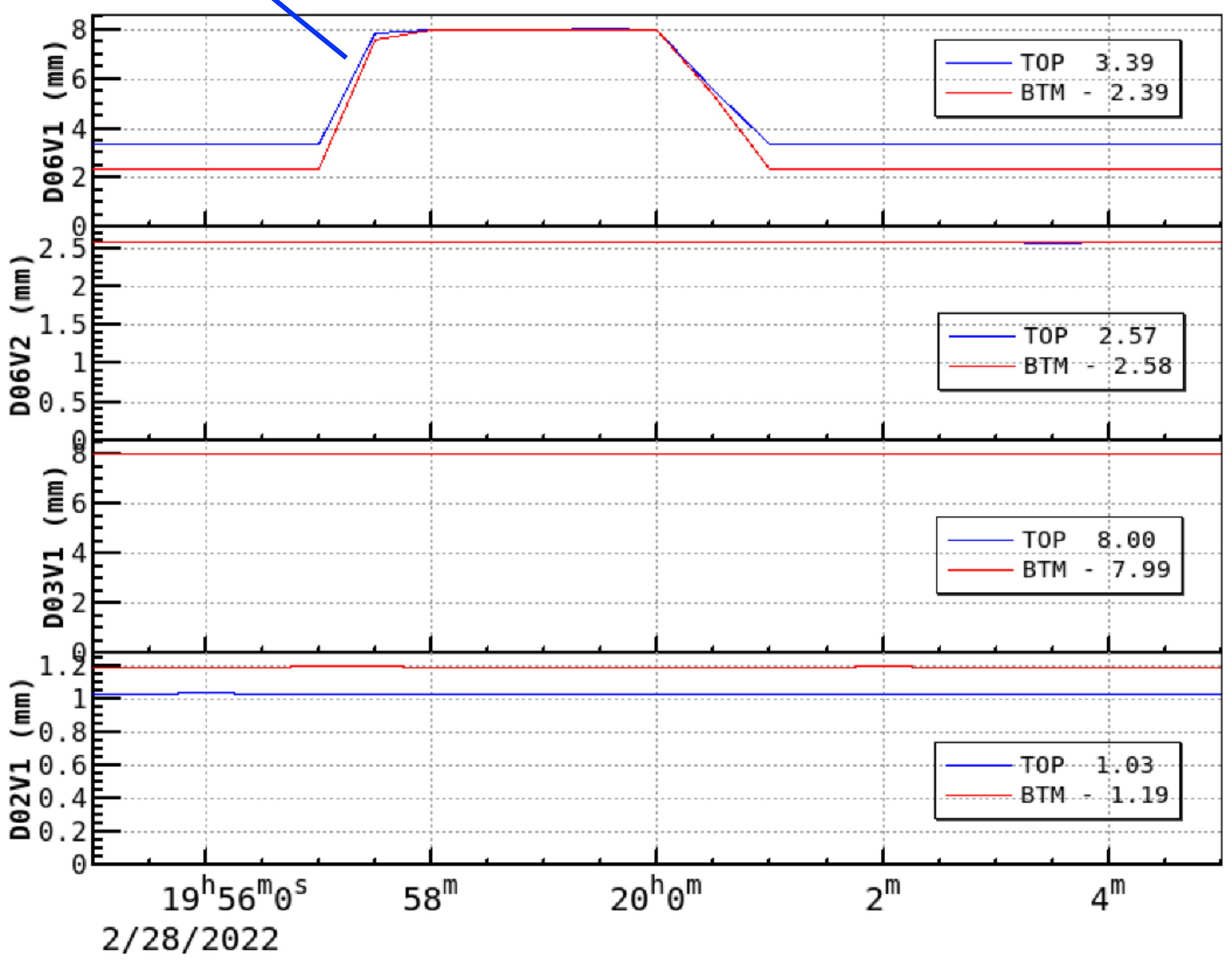
Beam Blowup for BxB FB and Impedance in LER











D06V1 : $\beta_y \kappa$ = 13.25 kV/pC
$2J_y$ = 0.134 μm
66.7 σ_y (30 pm)

D06V2 : $\beta_y \kappa$ = 5.86 kV/pC
$2J_y$ = 0.329 μm

D02V1 : $\beta_y \kappa$ =12.73 kV/pC
$2J_y$ = 0.102 μm

D03V1 : $\beta_y \kappa$ = 0.86 kV/pC
$2J_y$ = 3.77 μm

Collimator aperture, BxB FB tuning, vertical tune affect the beam blowup.

S. Terui, T. Ishibashi, K. Ohmi, Y. Funakoshi H. Fukuma

Sudden Beam Loss (Fast Beam Loss) Challenge to understand the Phenomena

Related issues will be reported by H. Ikeda on Wednesday, September 14 (WG7).

Sudden Beam Loss (1)

- **No sign appears in advance.** Suddenly, beam loss was observed with in a few turns. No beam dynamics model and prediction. We call this fast beam loss "**sudden beam loss**".
- In the LER, the probability of sudden beam loss increases when **the bunch current exceeds 0.7 mA**. (This is called "Matsuoka limit". Matsuoka-san, the run coordinator from Belle II group, found the rule.)
- It looks like sudden beam loss does not depend on the total beam current.
- Large beam loss causes QCS quench and damage to the collimator head.
- Damage to the collimator head increases impedance. As impedance increases, the threshold for bunch currents causing sudden beam loss is lowered. It is a vicious circle.
- Sudden beam loss in the LER has in common with the phenomenon of beam blowup in that impedance is involved.
- Sudden beam loss occurs in the HER, too. However, there is no experience of QCS quenches. Damage to collimator heads is rare. (D09V1 in 2022b)

Sudden Beam Loss (2)

- It is unknown whether they differ between **collision** and **non-collision.**
- The beam loss might occur in the single bunch, but it is unknown whether this is the same phenomenon.
- This has never happened in small number of bunches/high bunch current collision studies.
- **It appears to depend on the machine tuning and the state of damage. → Why it is not possible to easily increase the beam current.**
- Vacuum pressure rise is observed, probably it is the result of beam loss.
- Sudden beam loss is observed in terms of turn-by-turn bunch current monitor (BCM), bunch orbit (BOR), and fast X-ray beam size monitor (XRM).
- The source is thought to be **near the vertical collimator**. Fireball and other hypotheses are considered.
- Observation with optical fiber loss monitors and acoustic sensors were introduced in the vicinity of the vertical collimators.
- Recently, the sudden beam loss group was formed under the international task force (ITF) to investigate this phenomenon.

Sudden Beam Loss (3)

H. Ikeda
H. Nakayama
M. Tobiyama

Beam loss occurs within 2 turns.

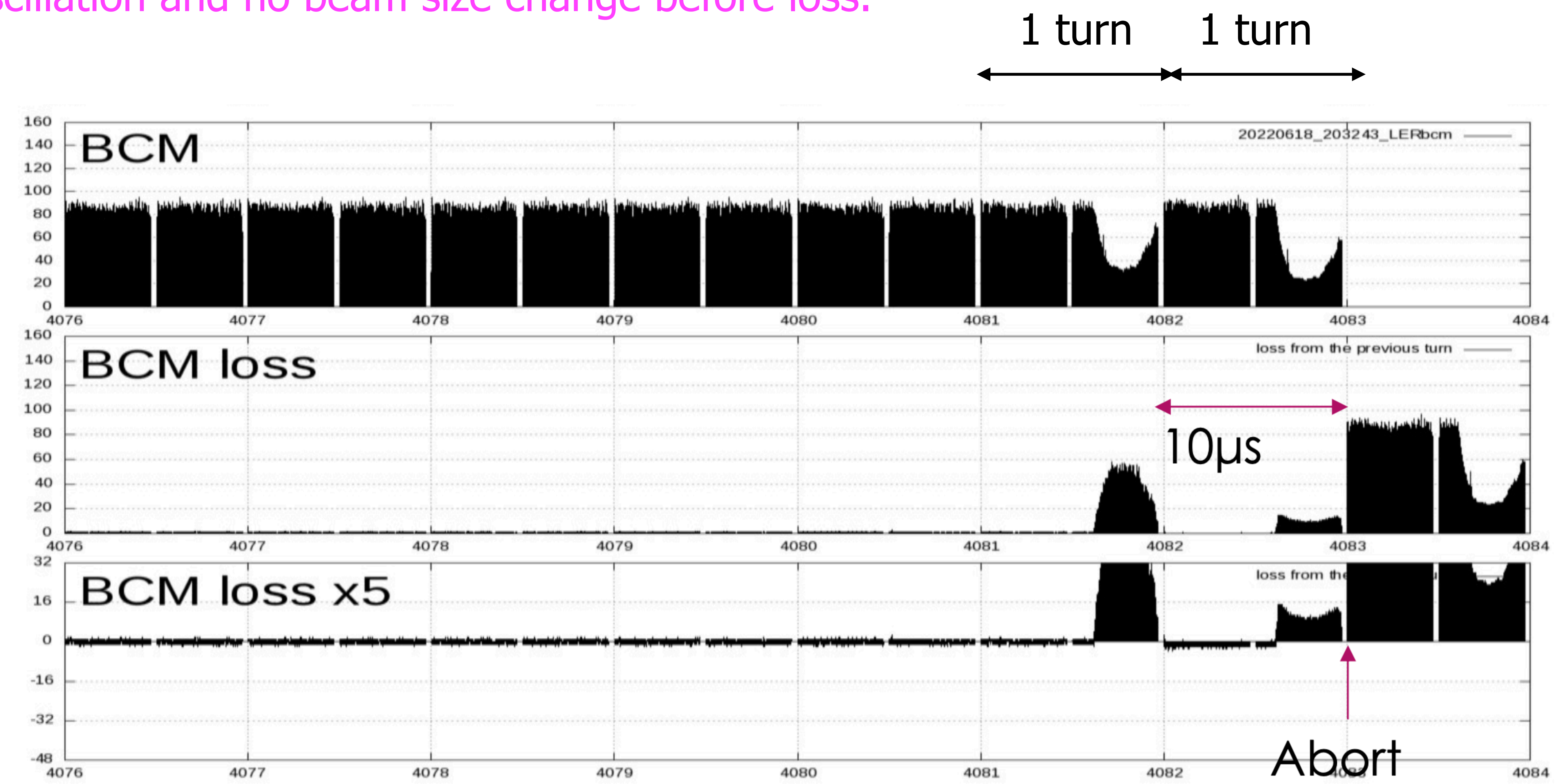
No oscillation and no beam size change before loss.

1 turn = 10 μs
2 trains, 2 abort gaps

Bunch current

Loss of bunch current

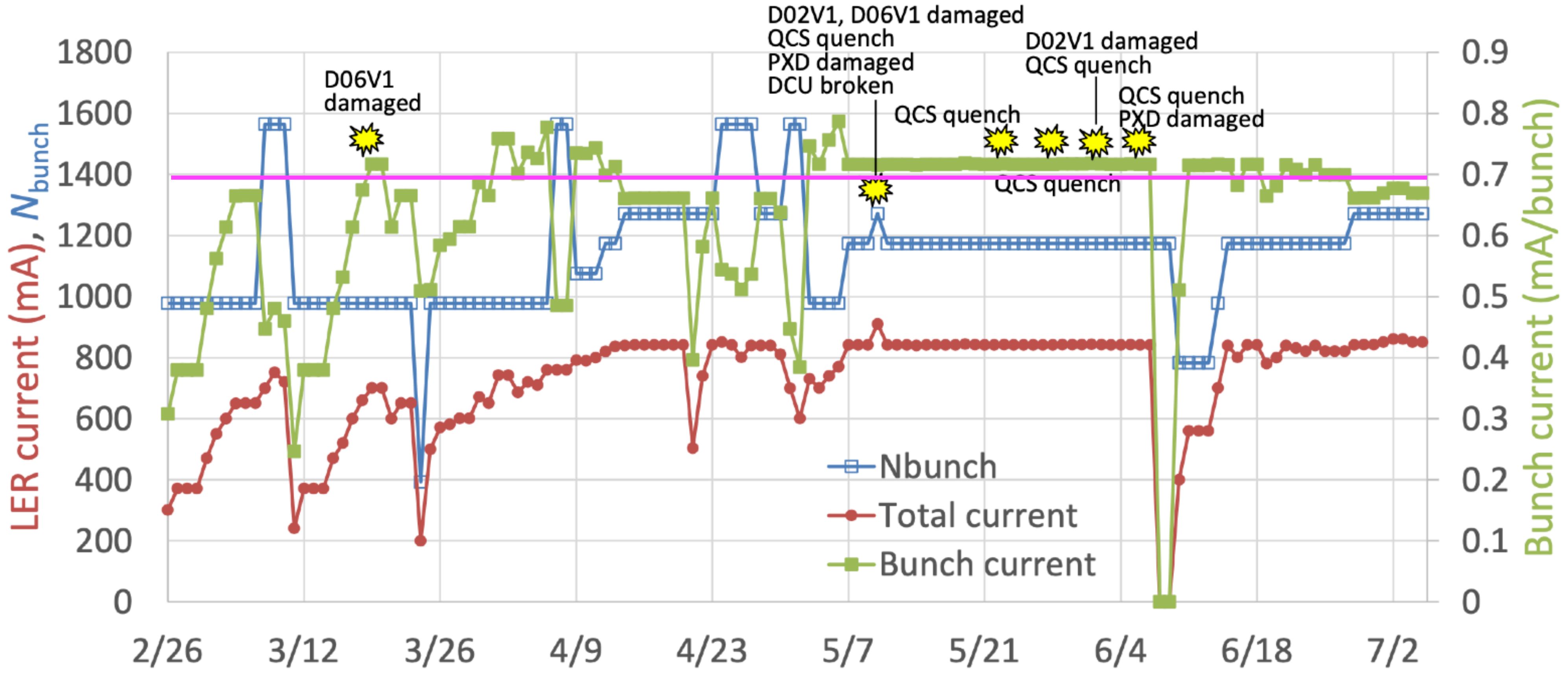
Loss of bunch current (magnified)



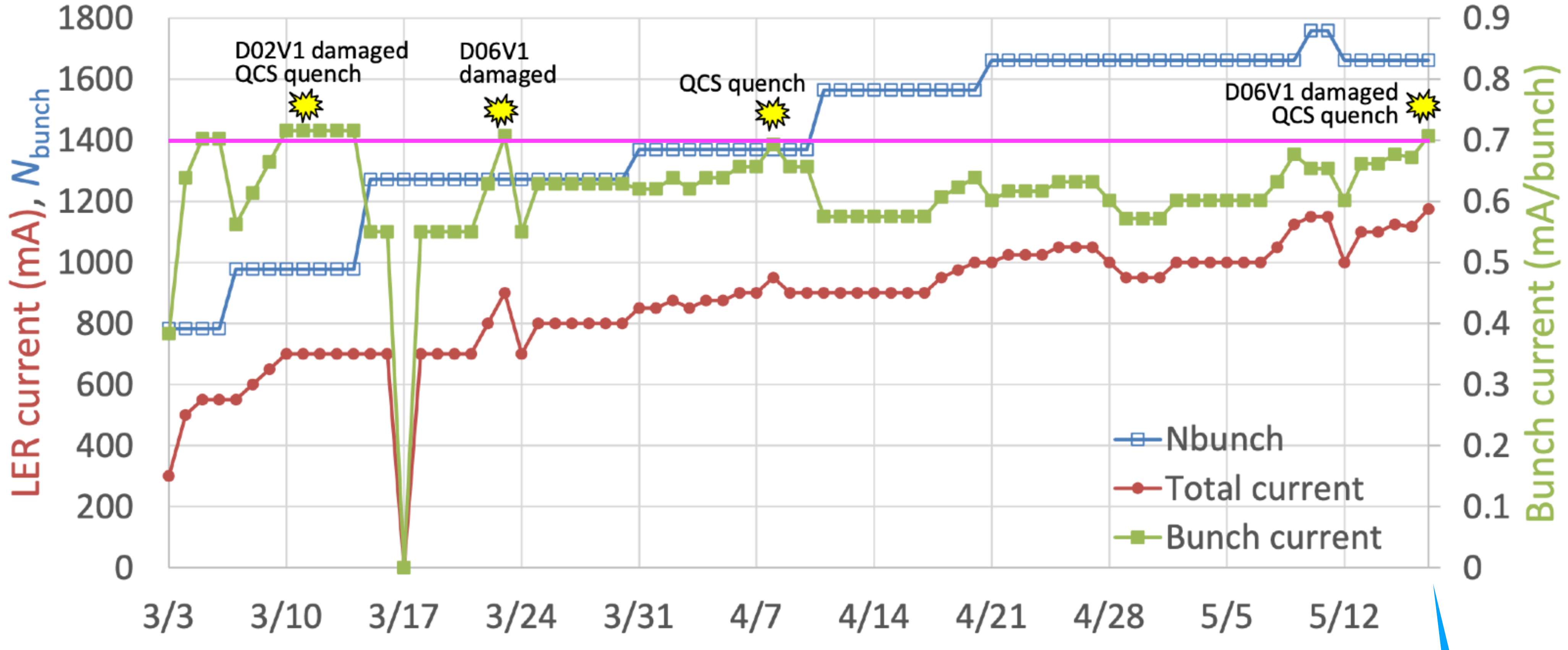
Bunch Current and Sudden Beam Loss in LER

K. Matsuoka

2021 ab



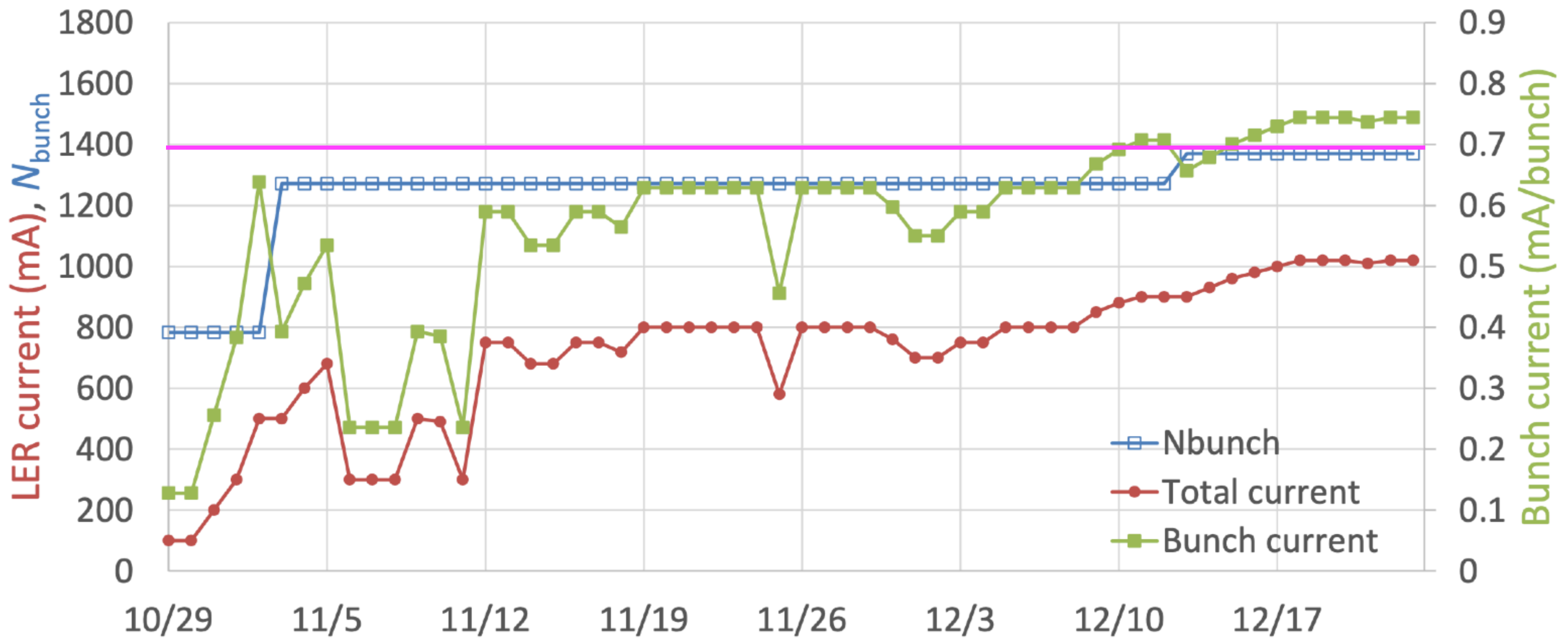
2022 ab



keep Matsuoka limit

test to increase bunch current

2021 c



Bunch current was smaller than 0.7 mA in the most of operation time

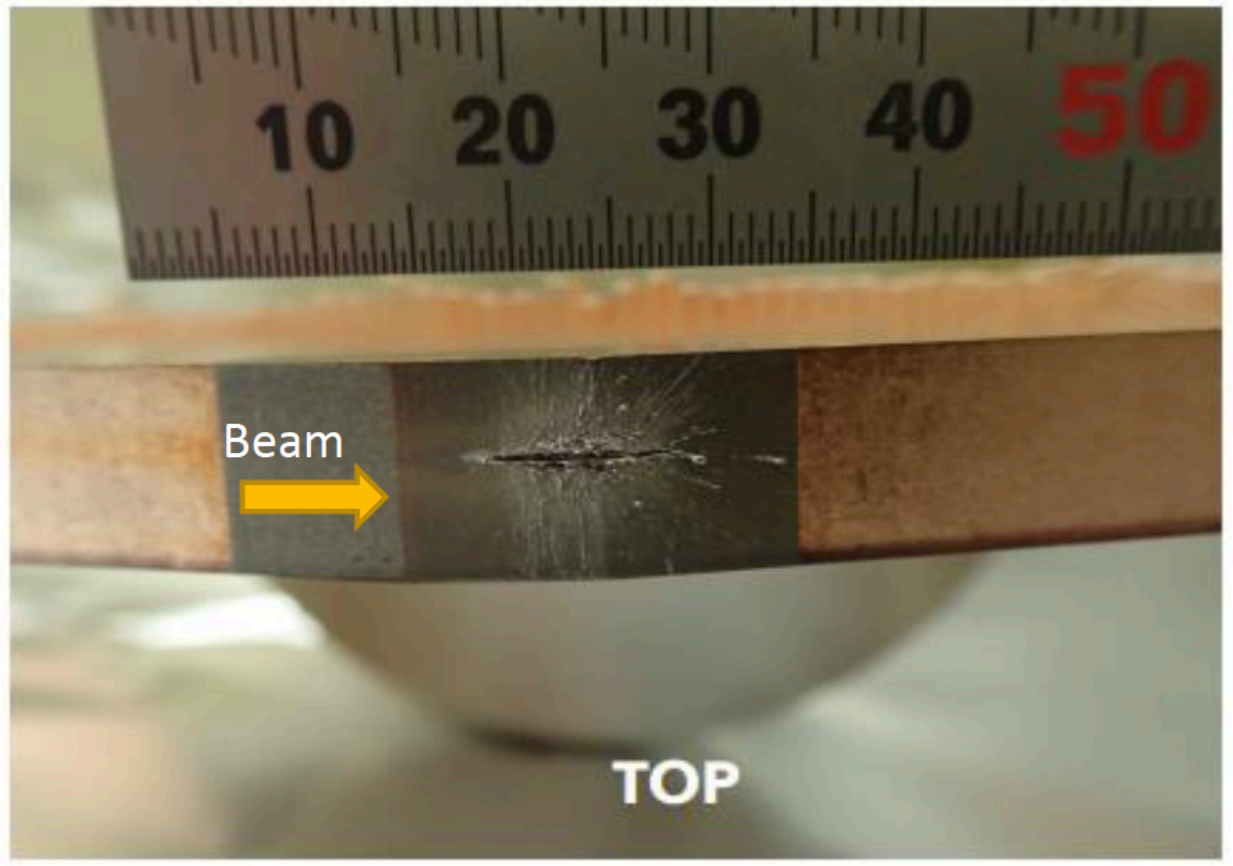
No QCS quench and collimator damage

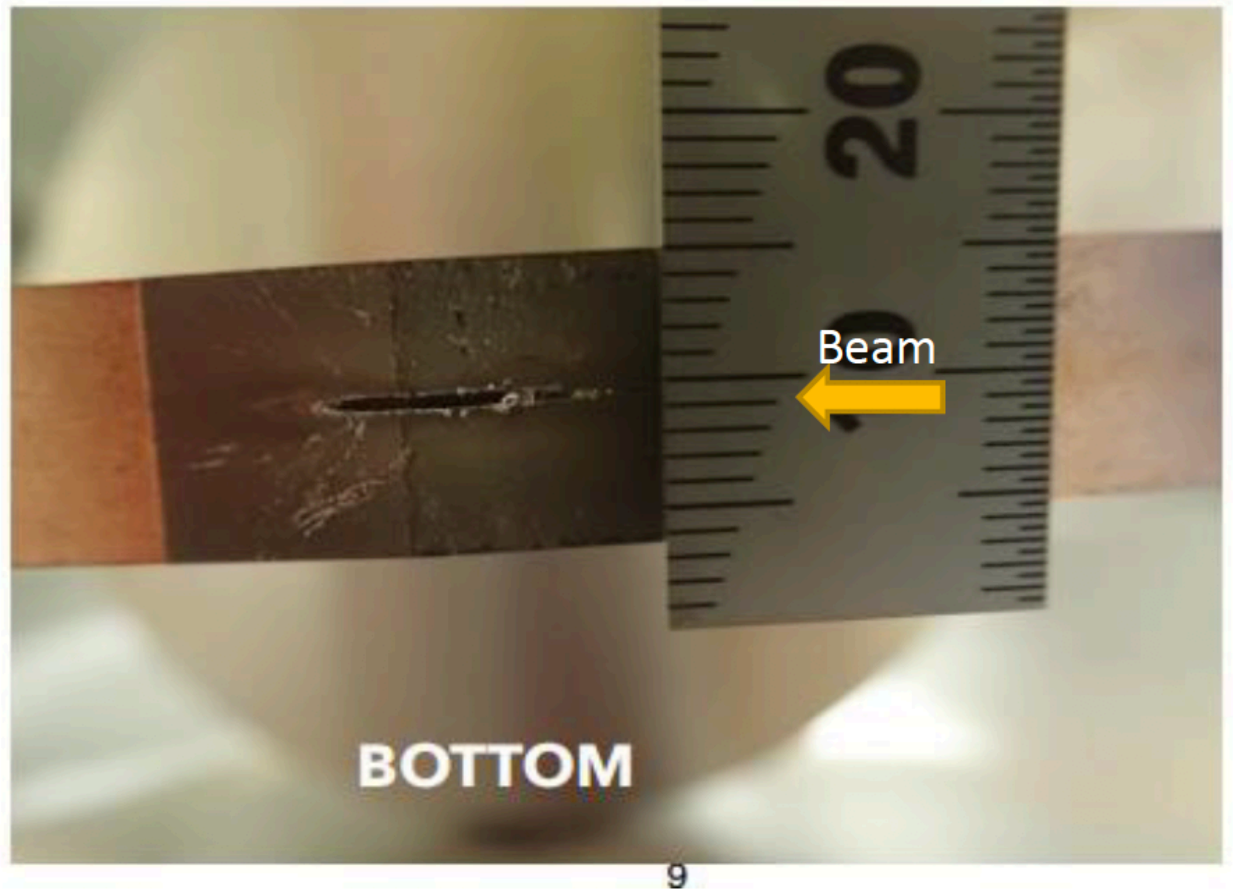
We introduced Matsuoka Limit $I_{b+} < 0.7\ mA$.

In order to avoid sudden beam loss which causes QCS quench and collimator damages, we set the upper limit of 0.65 mA/bunch in LER.

The sudden beam loss becomes a serious problem to increase total beam current.

Damage of Collimator Head due to Sudden Beam Loss





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- After a huge beam loss event on June 6th in 2021, LER BG increase significantly.
- D02V1 collimator jaws were severely damaged (deep scar on the bottom jaw).
- Typically, collimator replacement work and the baking runs take 3~4 days.

Optics Changes due to Beam Line Deformation and Orbit Measurement

Related issues will be reported by
H. Sugimoto on Tuesday, September 13 (WG3).

Optics Correction

Optics correction is based on measurement of orbit response.

1. Beta function: orbit response with DC dipole kicks

$$\Delta x_i = \frac{\beta_i \beta_j}{2\sin \pi\nu}\theta_j \cos(\mid \phi_i - \phi_j \mid - \pi\nu)$$

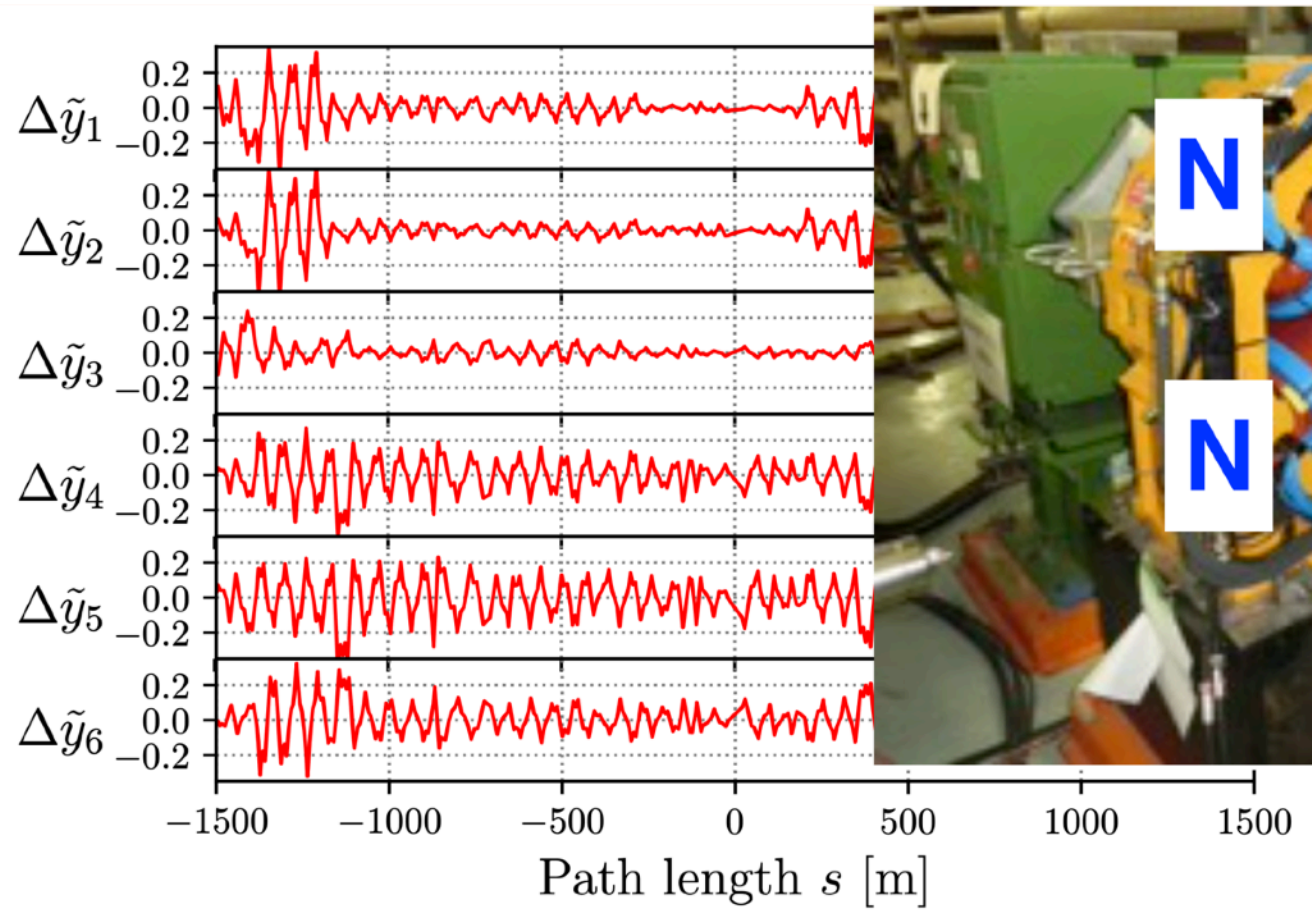
2. Dispersions

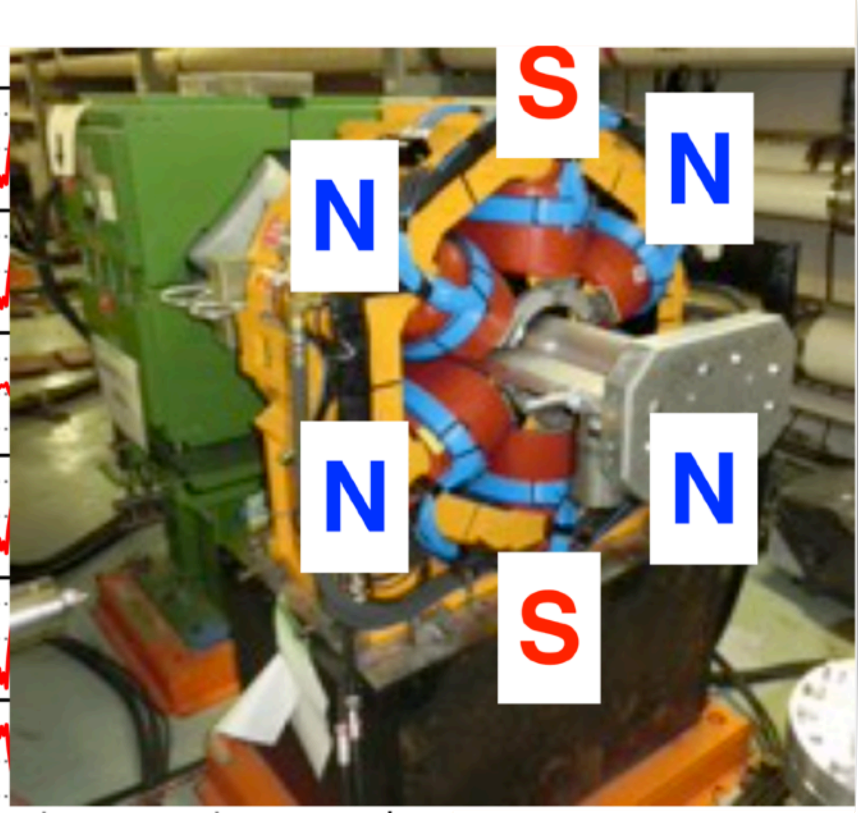
$$\eta_{xi} = -\alpha_p f_{RF} \frac{\Delta x_i}{\Delta f}$$

LER $\alpha_p = 3 \times 10^{-4}$

HER $\alpha_p = 4.5 \times 10^{-4}$

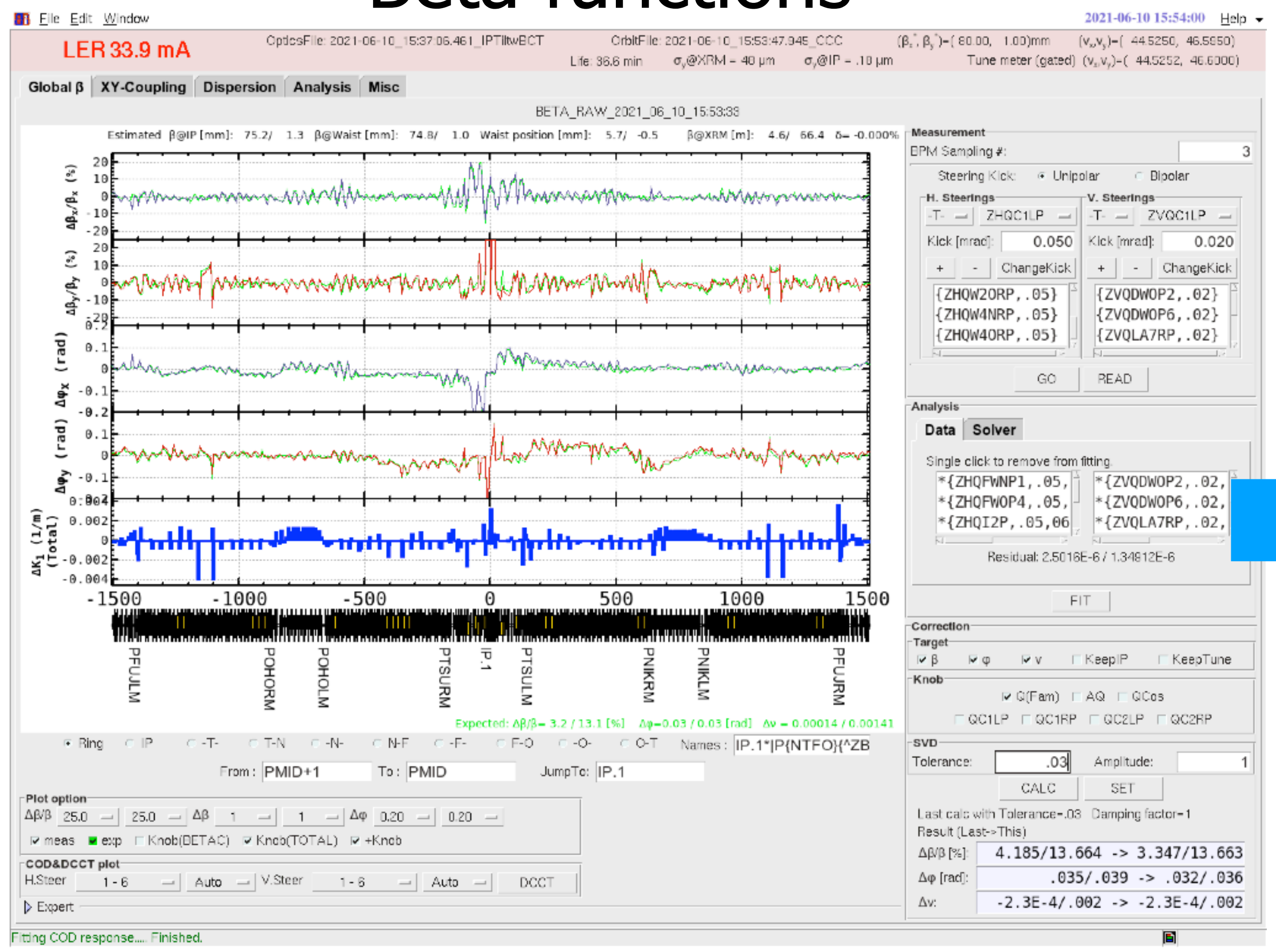
3. X-Y coupling: vertical leakage orbits induced by horizontal kicks



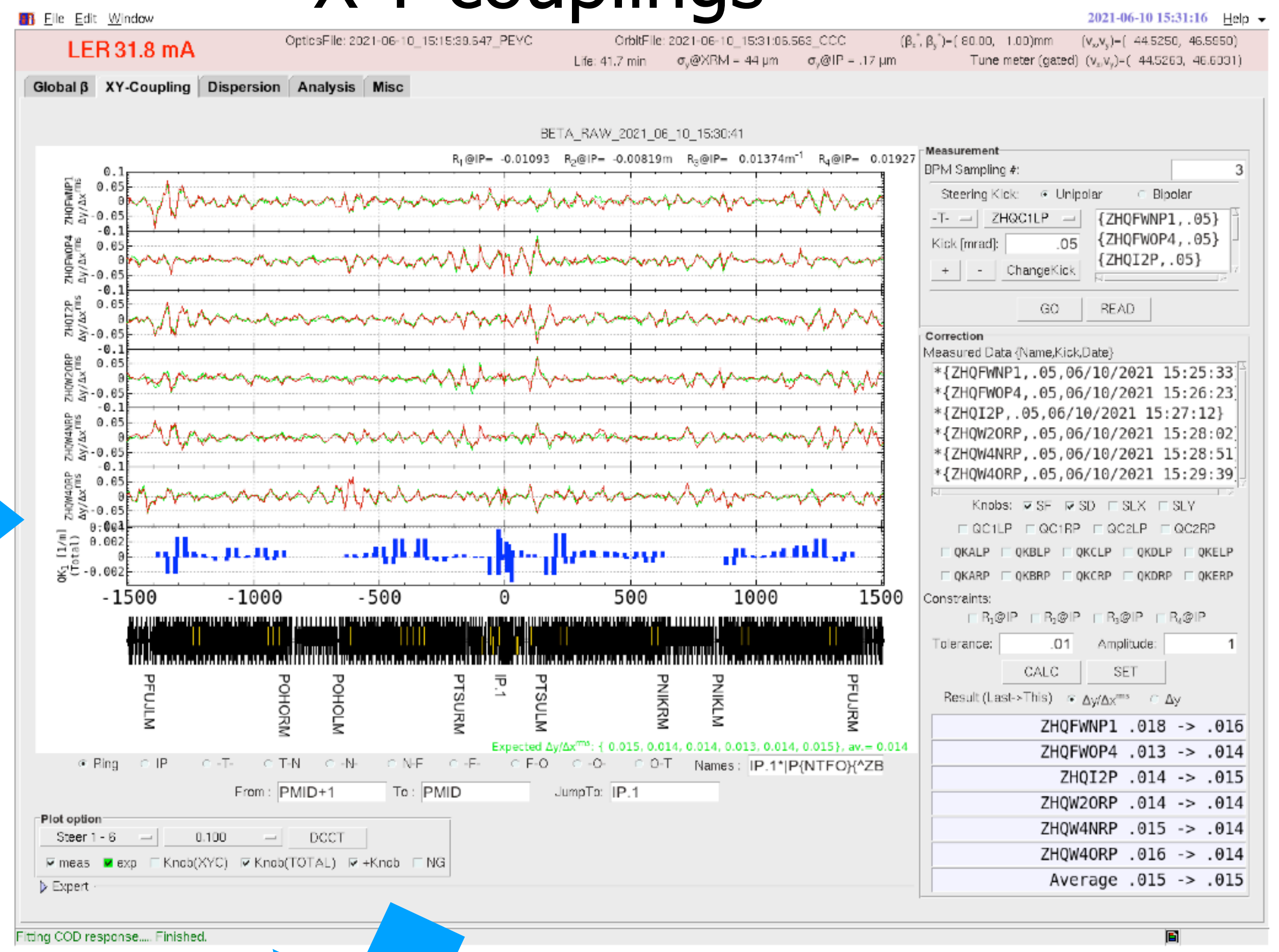


Skew quad coils are utilized to correct X-Y couplings and vertical dispersions.

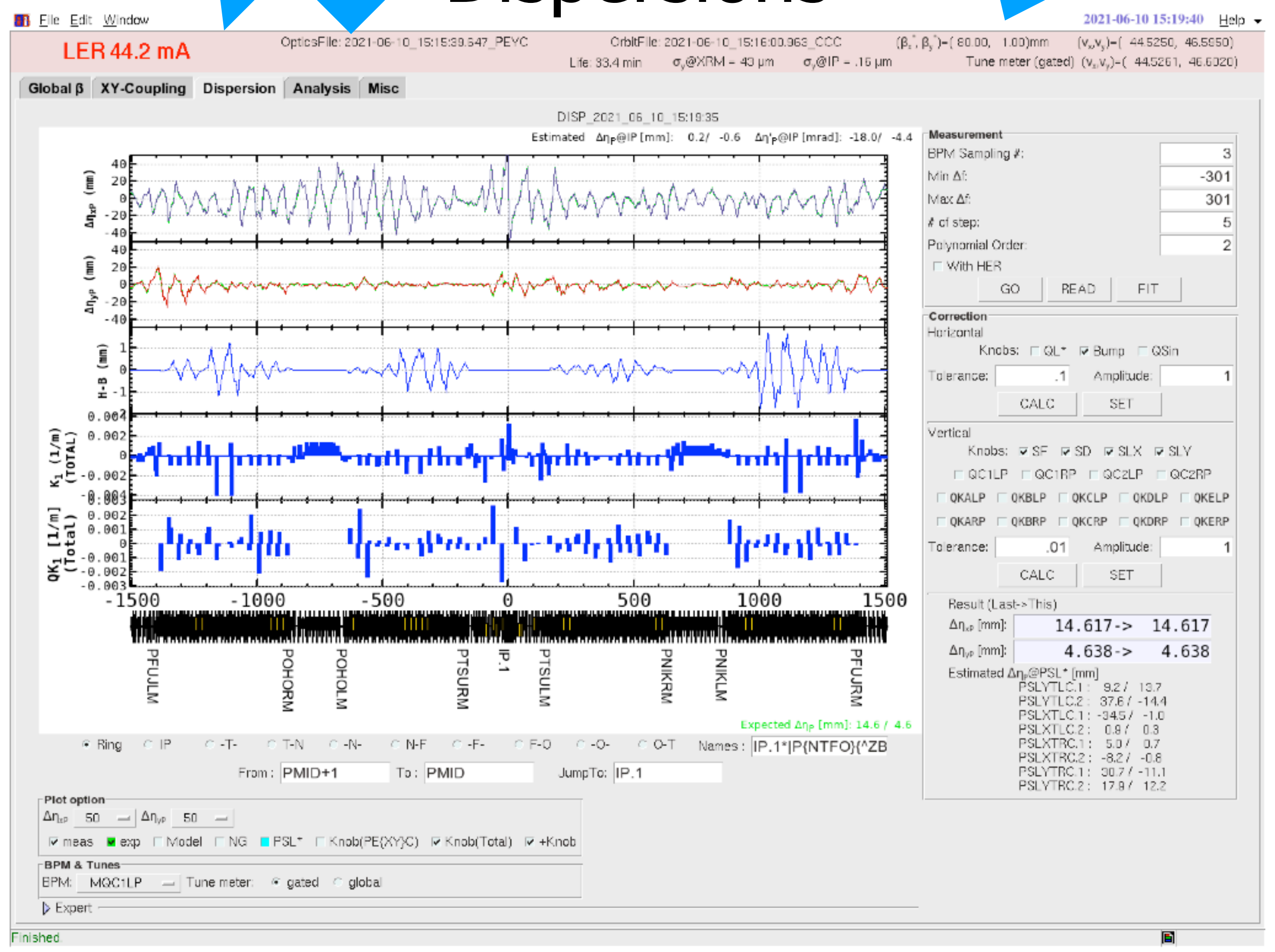
Beta functions



X-Y couplings



Dispersions



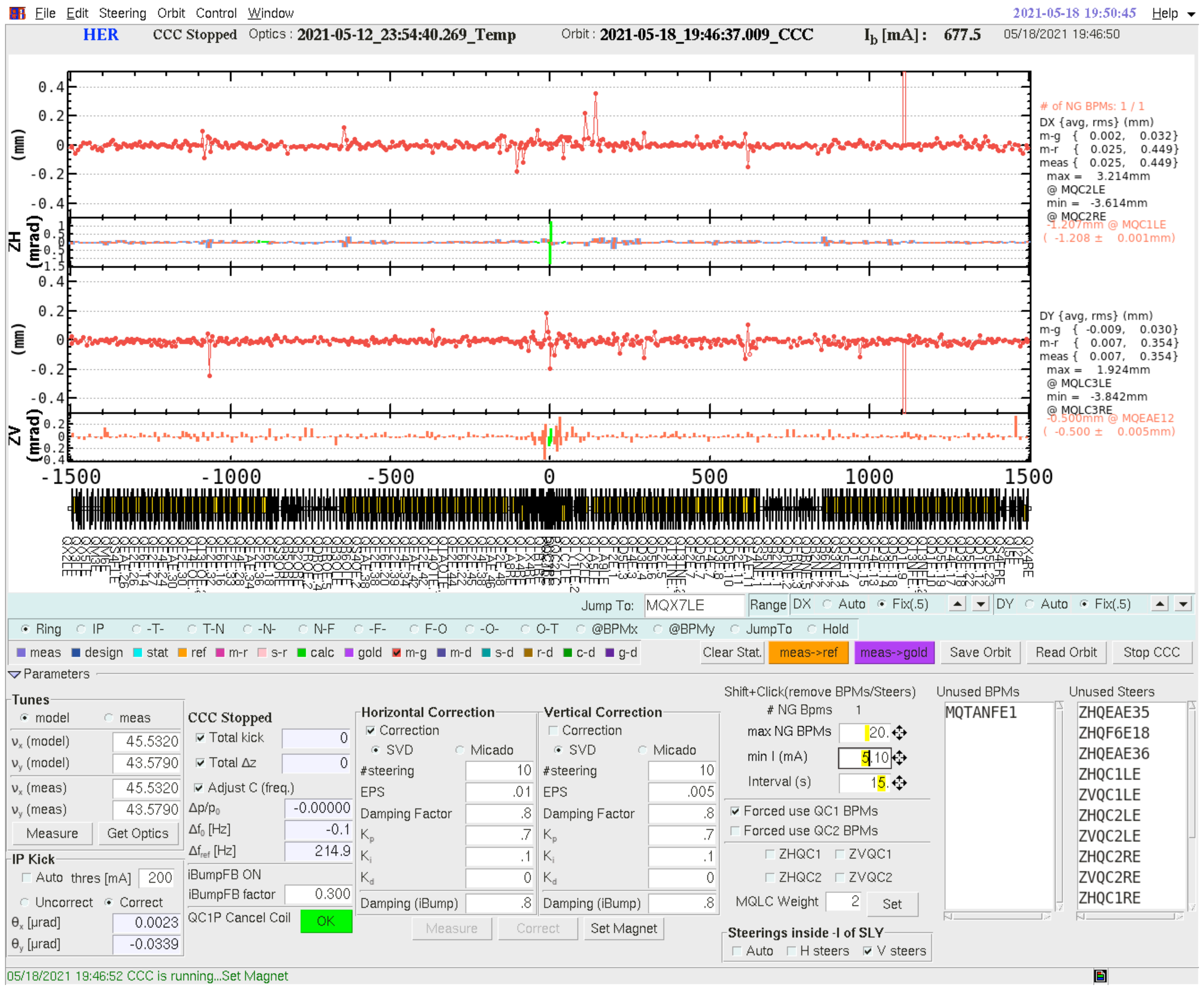
Beam current is 50 mA.

We set "gold orbit" after optics correction for each ring.

We check vertical emittance by XRM monitor after the optics correction.

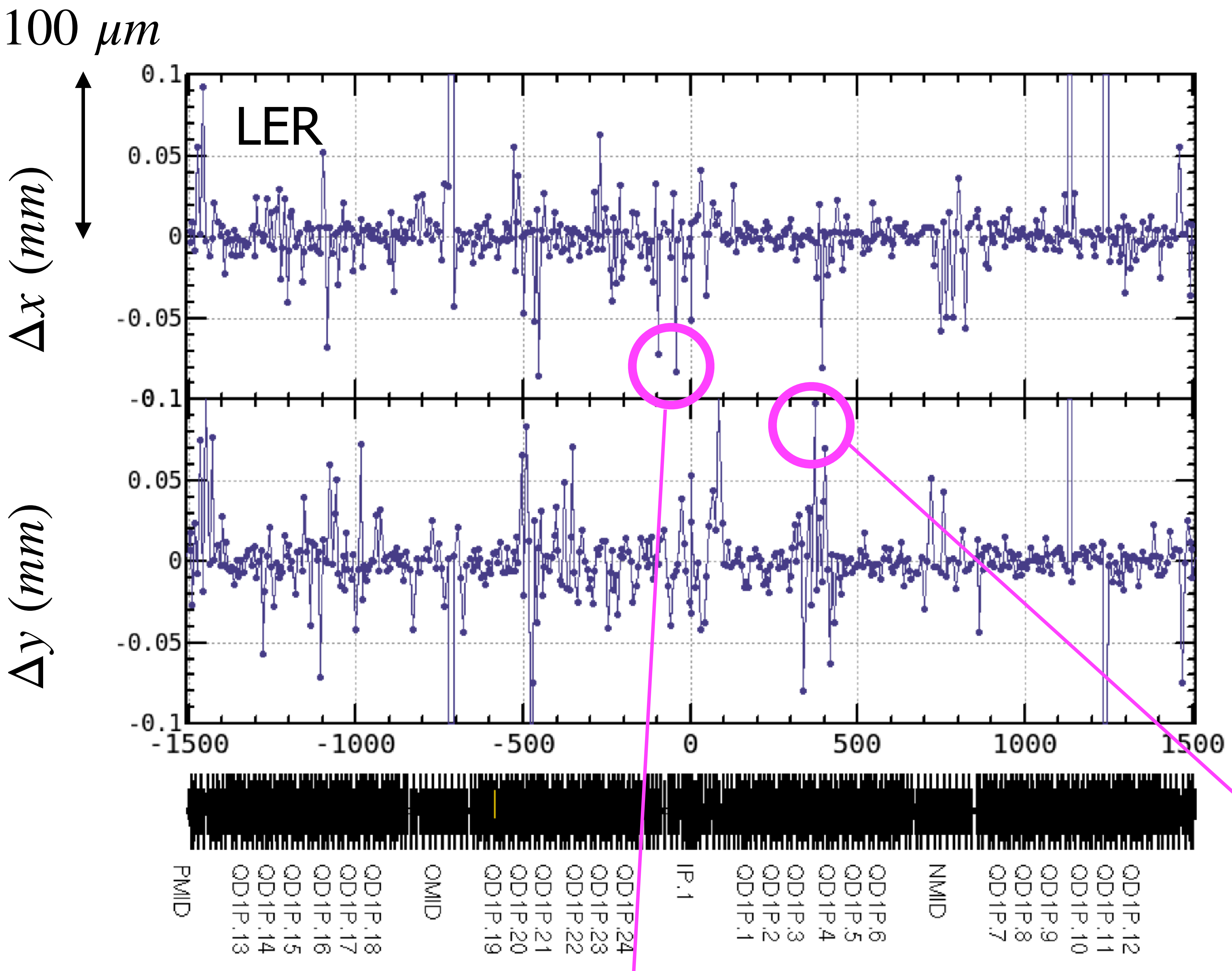
Global Continuous Orbit Correction

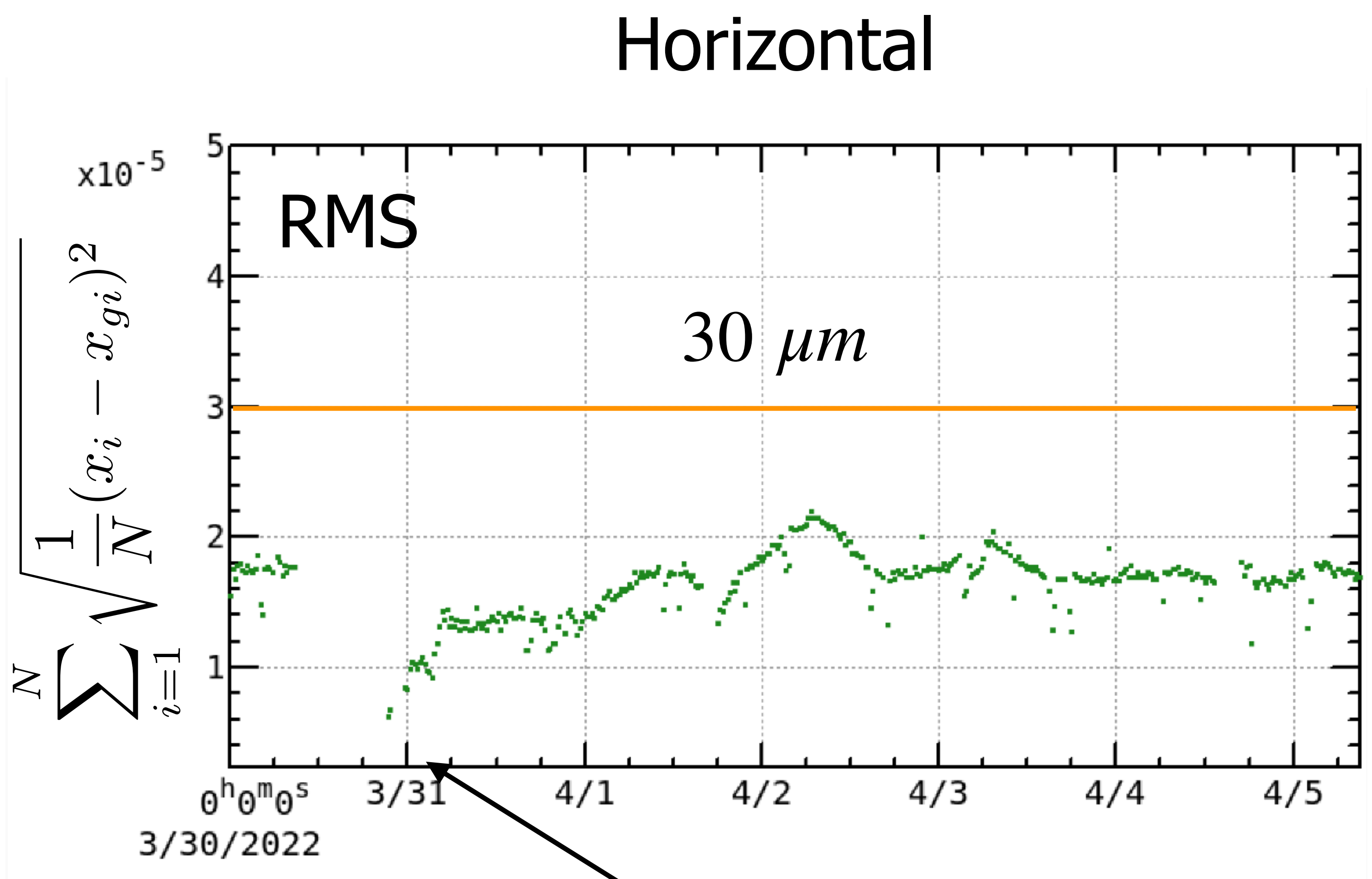
Beam orbit is corrected to "gold orbit" every 15 seconds (not strict).

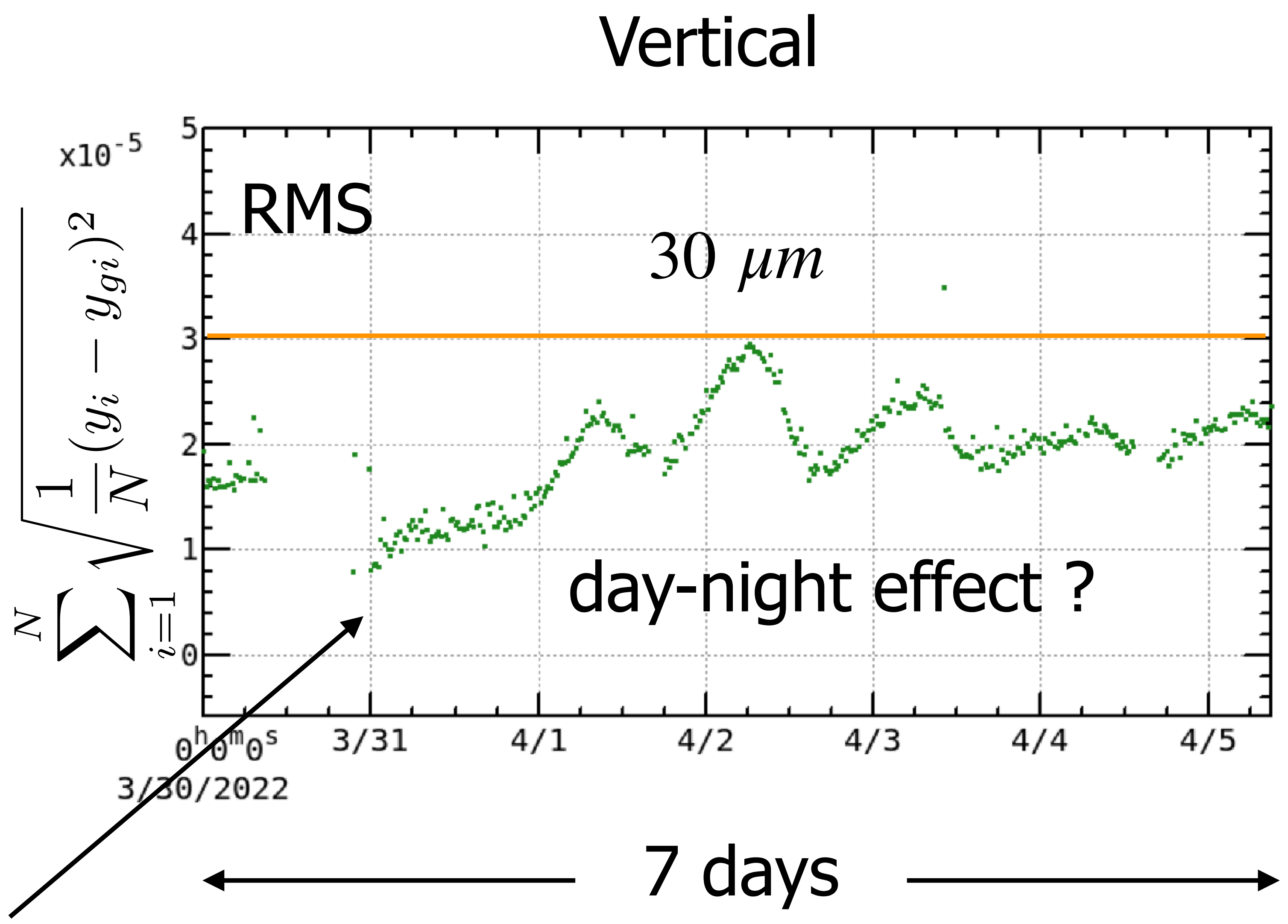


The optics and orbit correction are performed online and SAD code is used.

measured orbit - gold orbit (after 7 days)



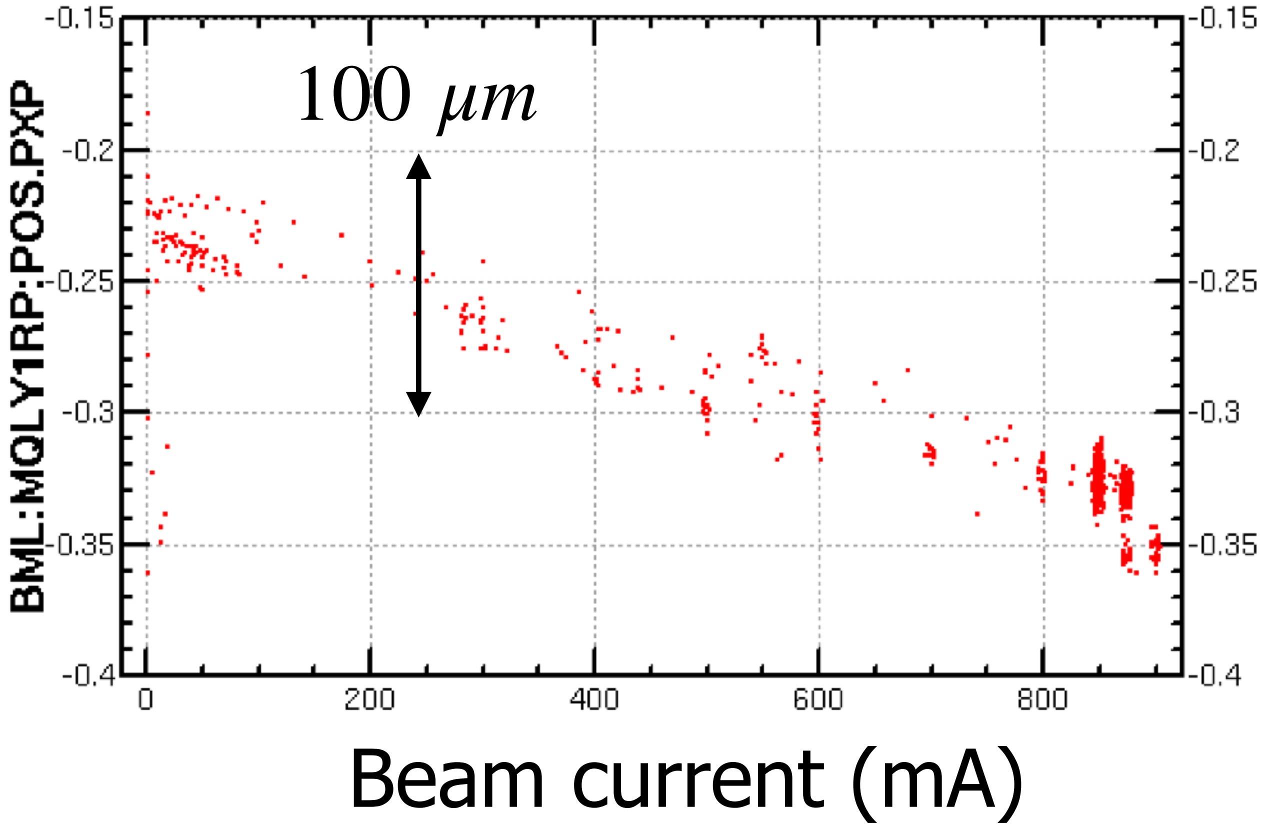




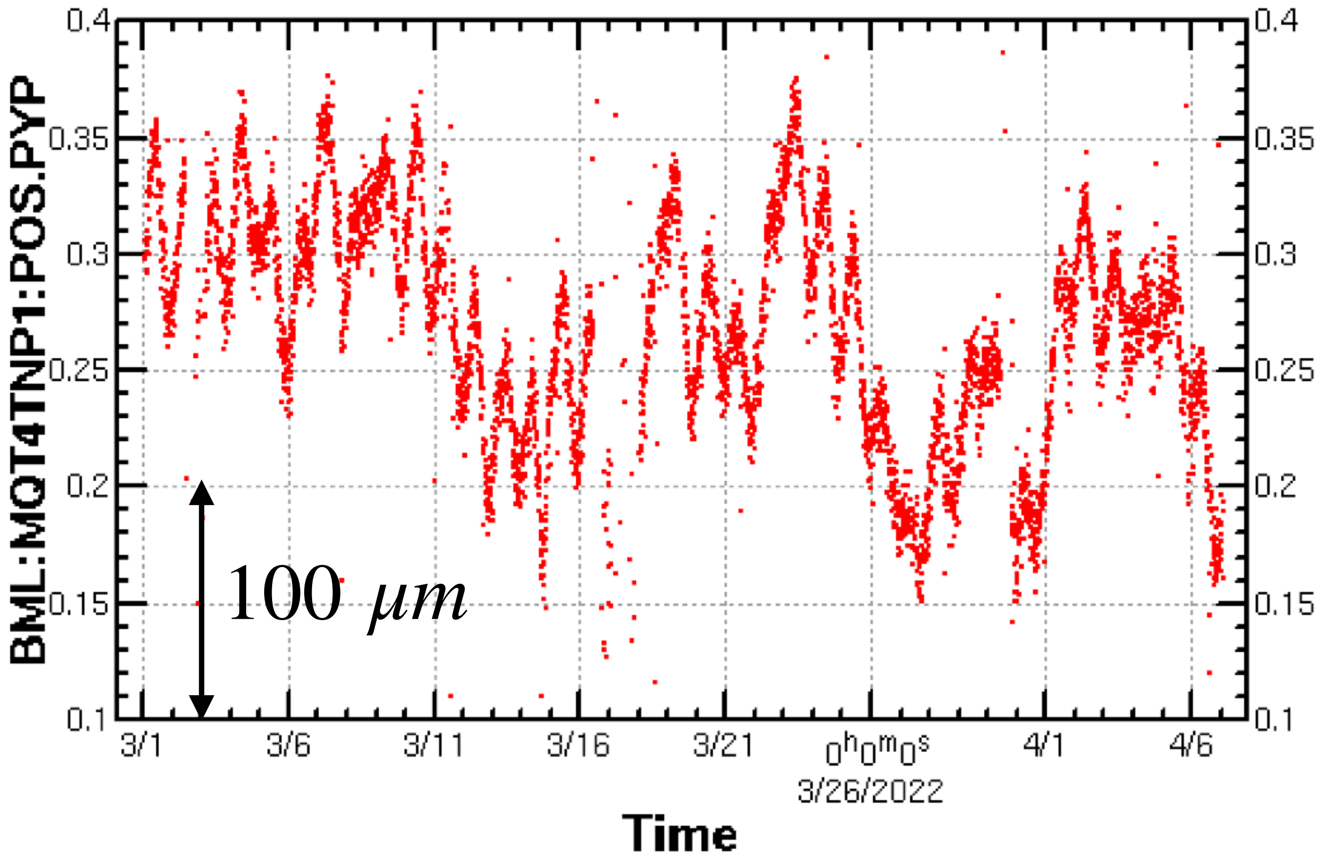
BPM gain mapping
optics correction
set the gold orbit

Number of large deviation of BPMs is about 20 - 30.
(RMS is larger than 40 μm)

Beam current dependence



day-night effect + long drift



The deviation comes from:

1. beam current dependence
(beam line deformation due to intense SR)

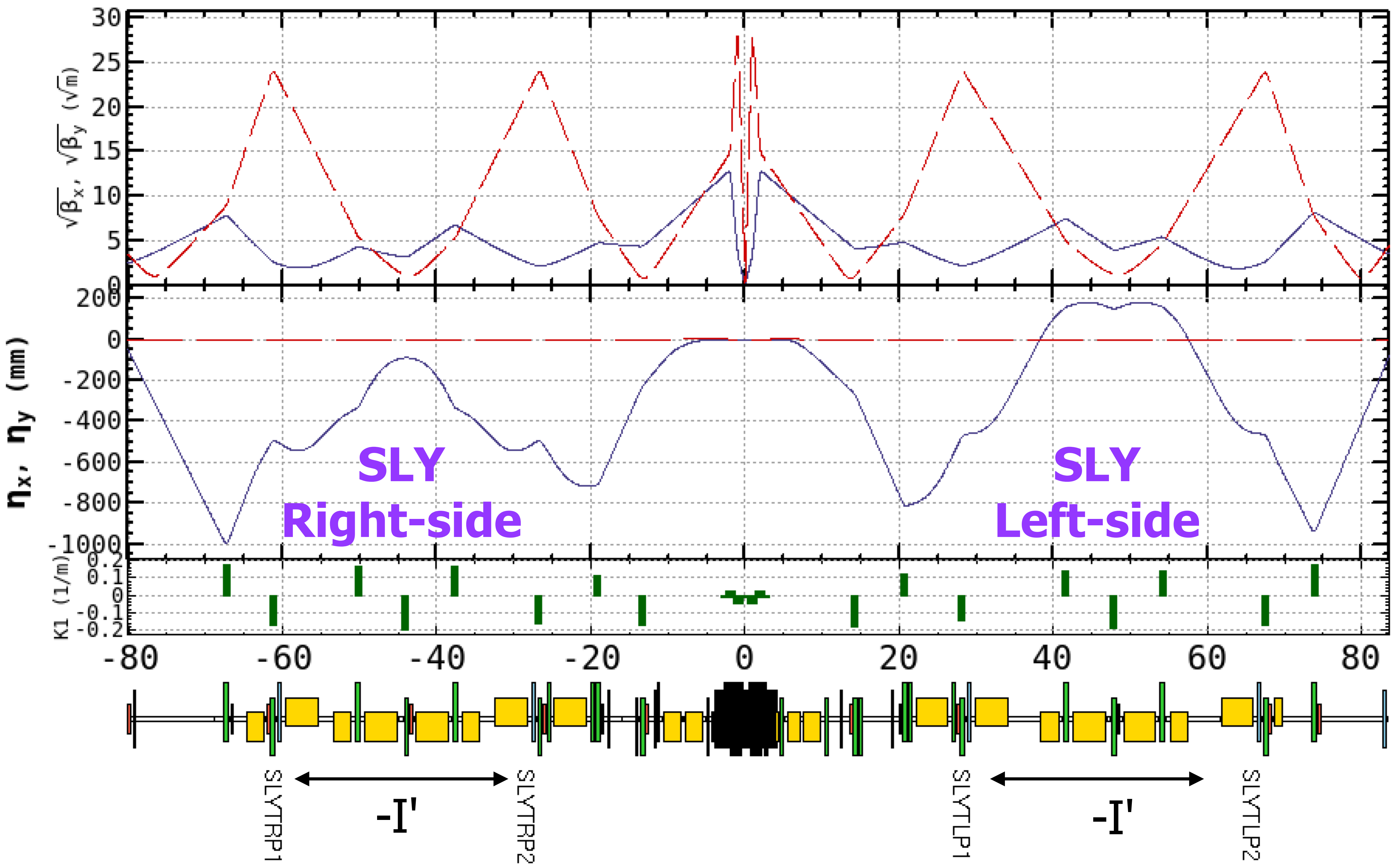
2. day-night effect (atmospheric temperature)

3. Gain of each probe changes.

Strong Sextupoles (SLY) for Local Chromaticity Correction

$\beta_y^* = 1\ mm$

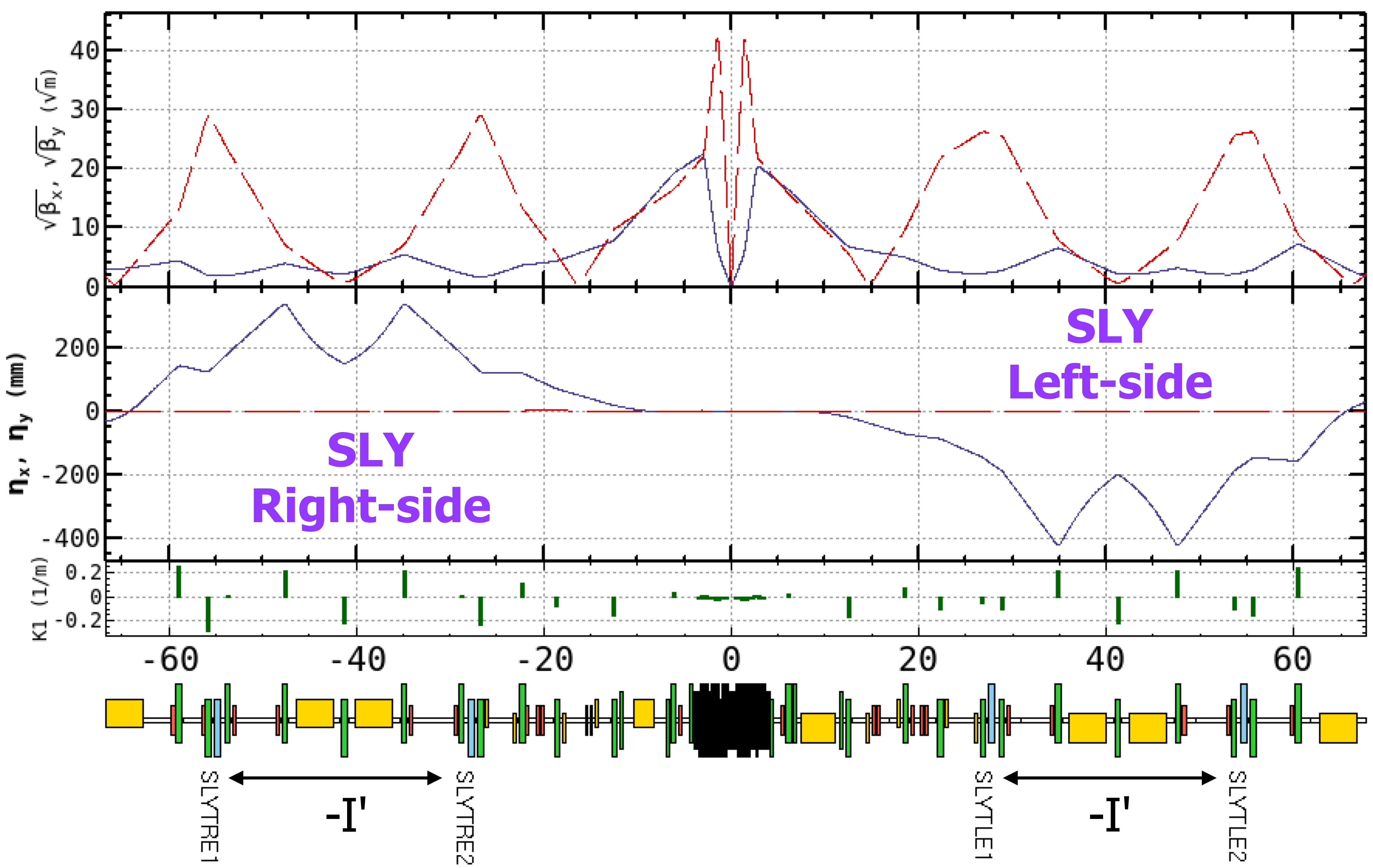
LER



K2: 1.23 1/m² K2: 3.48 1/m² K2: 1.33 1/m² K2: 3.53 1/m²

$\beta_y = 521\ m$ $\beta_y = 525\ m$

HER



K2: -8.76 1/m² K2: -9.62 1/m² K2: 8.36 1/m² K2: 7.66 1/m²

$\beta_y = 702\ m$ $\beta_y = 675\ m$

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

Horizontal tune shift can be ignored.

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

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

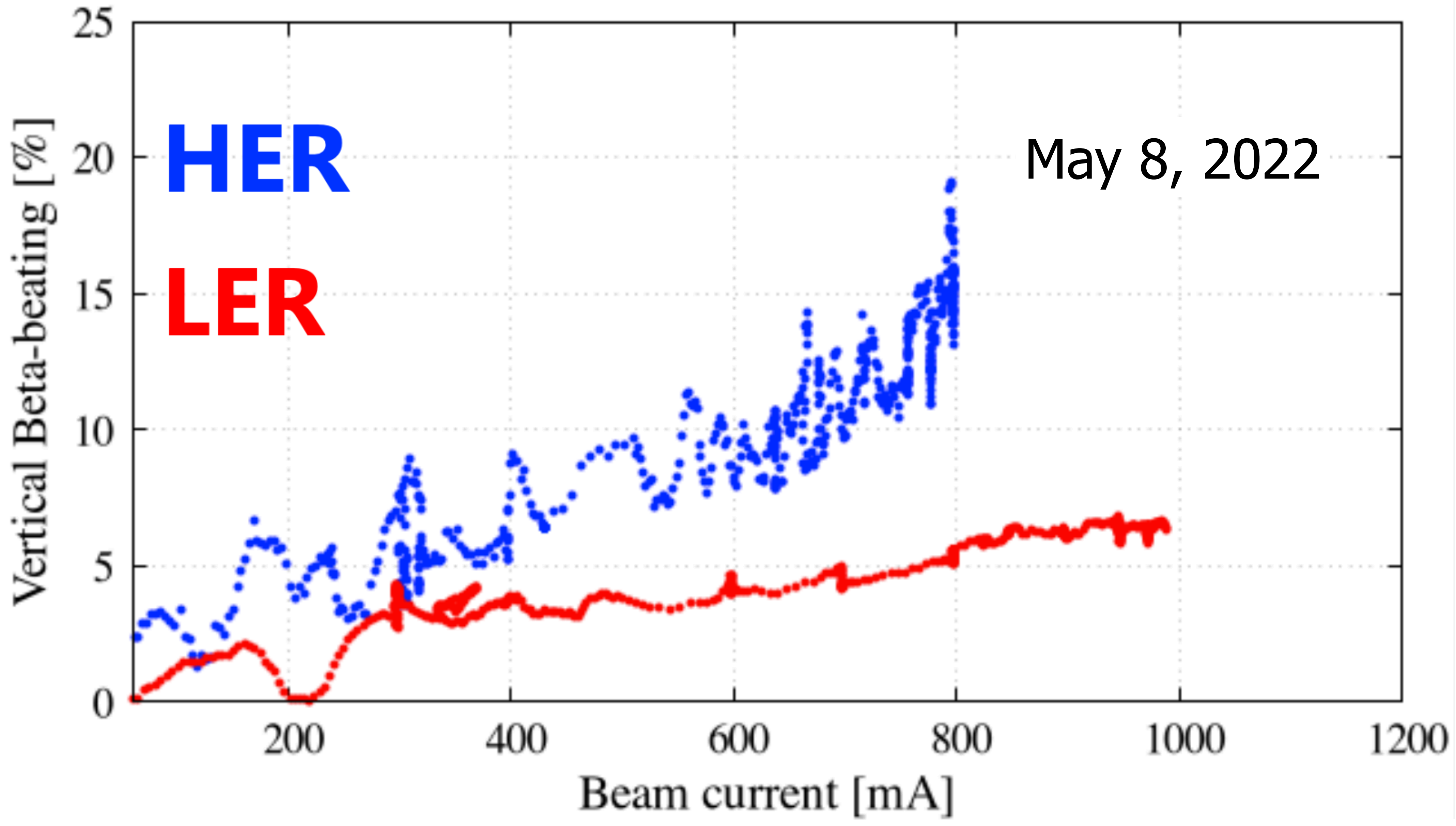
3.6 times larger than LER

Beta-Beat due to Horizontal Orbit Deviation

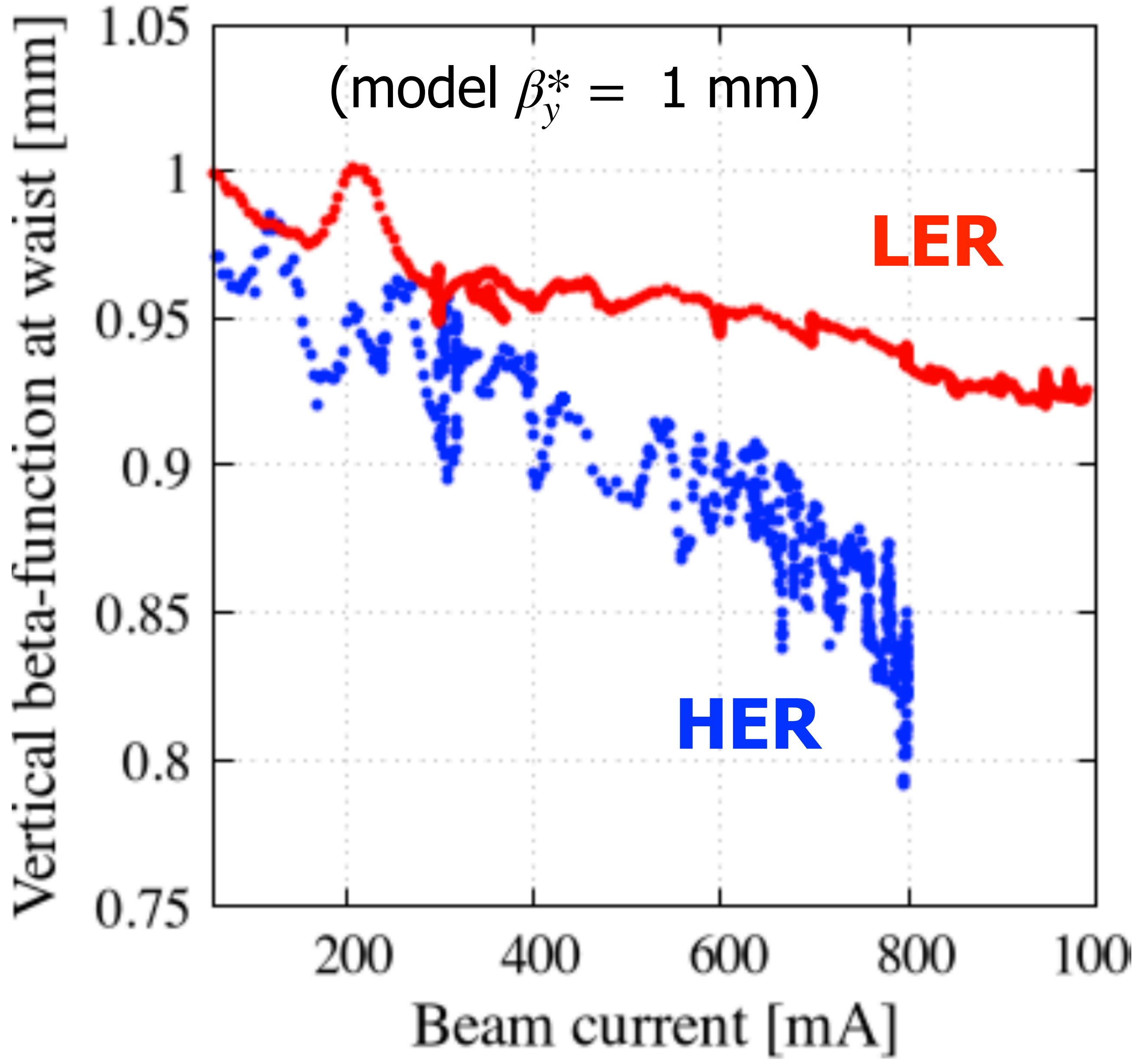
H. Sugimoto
H. Koiso

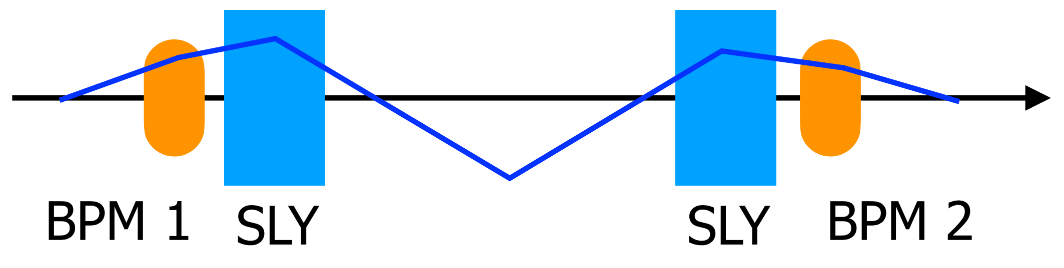
The SR heating deforms the beam line.
The horizontal orbit deviation induces tune shift and beta-beat. As the result, β_y^* also changes.
The orbit deviation in the local chromaticity correction (SLY) is always in the outward direction of the ring.
This implies a squeezing of β_y^*. The HER is larger effects rather than the LER.

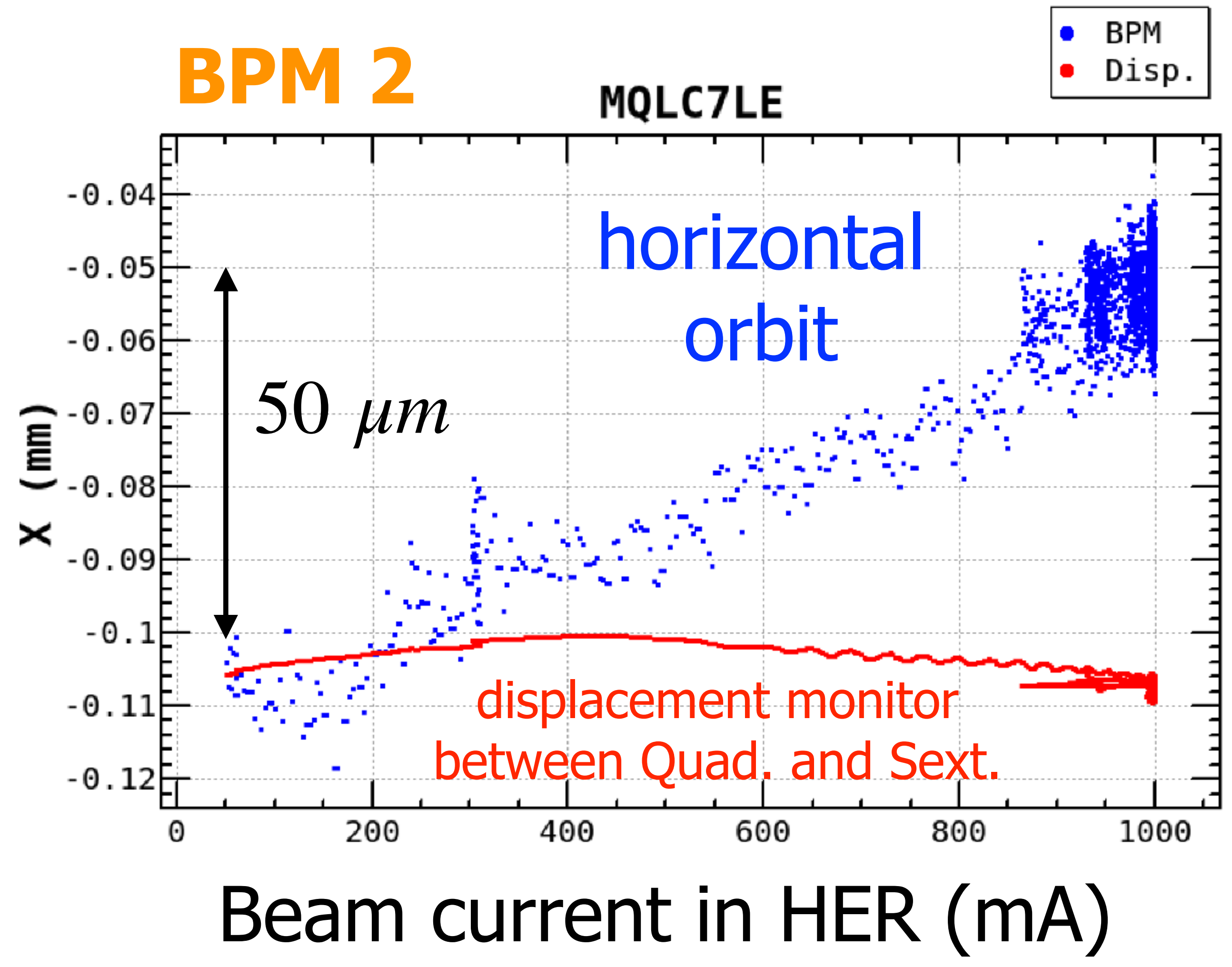
$$\frac{\Delta\beta_y}{\beta_y} = \frac{1}{2\sin 2\pi\nu_y} \oint \beta_y (K_2 \Delta x) \cos\{2(\pi\nu_y + \psi_s - \psi)\} ds$$



$\beta_y^* = 0.89mm$ for $\Delta x = +20\ \mu m$
at the strong sextupole (SLYTLE1)





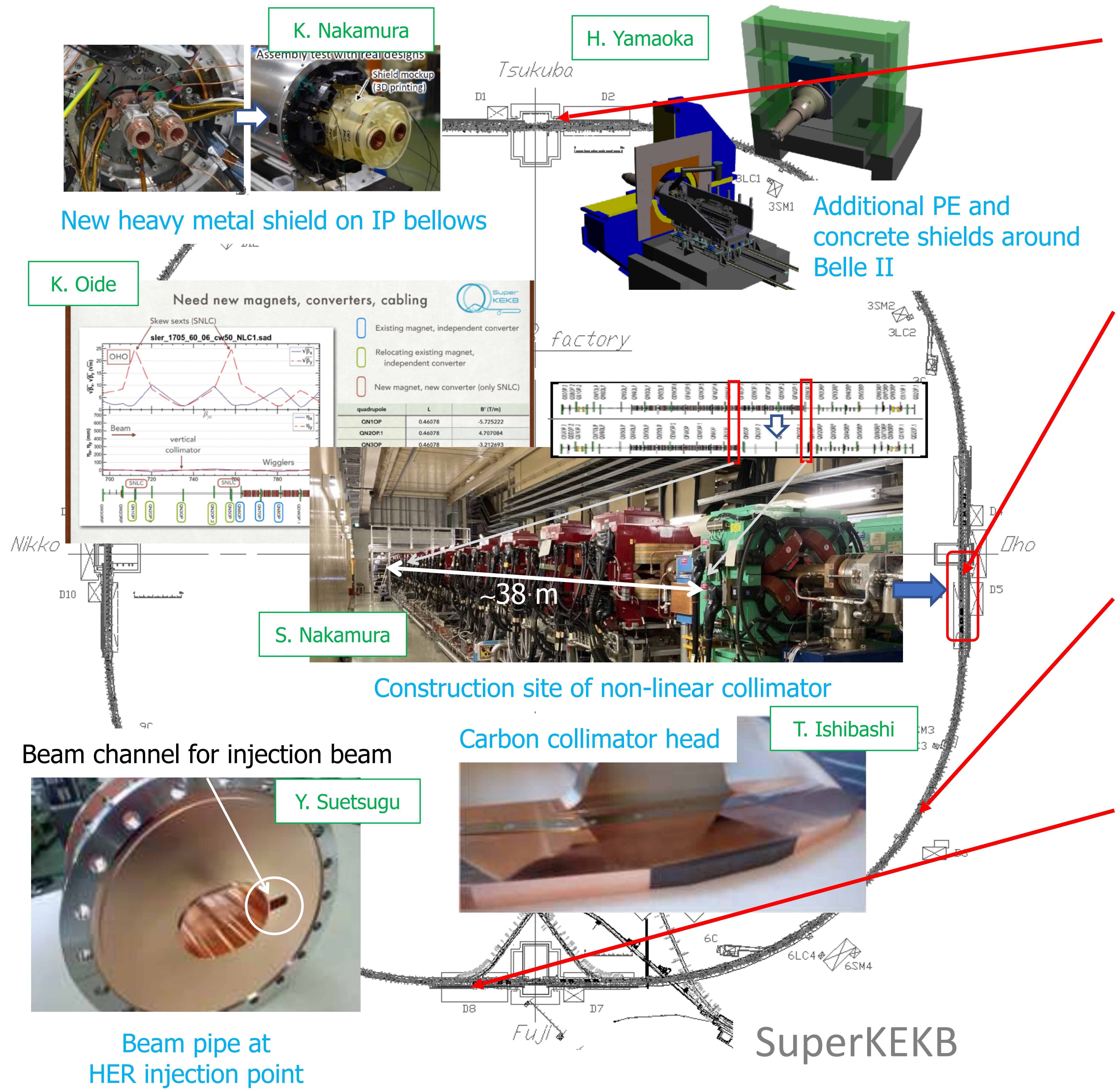


We adopted the local orbit feedback by using local bumps at the strong sextupoles since the end of May, 2022.

Summary

- Peak luminosity of 4.65 (4.71) x 10^{34} $cm^{-2}s^{-1}$ was achieved in 2022.
- Stable operation over 1 A in the LER is possible if the bunch current is smaller than 0.7 mA.
- "Sudden beam loss" is the most serious problem to increase beam current so far.
- Beam blowup in the LER is still unclear. Lower impedance of collimators, BxB FB tuning, and higher vertical tune help to suppress the beam blowup above I_b = 0.8 mA. (single bunch issue)
- Beam line deformation as a function of beam current induces the large beta-beat (change of β_y^*) and global X-Y couplings. The deformation is due to SR heating. The orbit deviation at the strong sextupoles affects optics.
- BPM accuracy for all beam current region is required since the optics correction is performed at 50 mA and physics run is over 1 A.
- High current operation over 1 A is quit different from a few hundreds of mA. The 2022 run was the dawn of a new window for SuperKEKB.
- Short beam lifetime; both of dynamic aperture and physical aperture, need to check crab waist ON and OFF.
- Injection efficiency becomes poor as squeezing β_y^*. It is important to achieve 10^{35} $cm^{-2}s^{-1}$ to solve issues such as emittance growth of injection beams (CSR), injection backgrounds, and so on.

Upgrade Items during Long Shutdown (LS1)



- **IR radiation shield modification**
  - For BG reduction
    - New heavy metal shields around IP bellows
    - Additional concrete & polyethylene shields around Belle II
    - Material change from W to SUS of QCS cryostat front plate
- **Nonlinear collimator (LER)**
  - For impedance and BG reduction
    - New collimation scheme less likely to cause TMCI
    - Removal of 50 wiggler magnets
    - Installation of 2 skew sextupole and 5 quadrupole magnets
    - Installation of new vertical collimator with wider aperture
- **Robust collimator head (LER)**
  - As countermeasure against kicker-pulser misfiring and resulting destruction of collimator
    - Replacement with carbon head of horizontal collimator D06H3
- **New beam pipes with wider aperture at HER injection point**
  - For improvement of injection efficiency
    - New beam pipes with wider aperture
    - New BPM for precise measurement of injected beam.

Pantheon, Rome

two thousand years ago ...

Ordinary people don't think like that.

The dome has a central oculus as the main source of natural light.

The oculus at the top of the dome allows rainfall on the floor.
The floor is equipped with drains and built with an incline of about 30 cm (12 in) to promote water runoff.

Light from the oculus moves on the floor in a reverse sundial effect to make time with light.

New ideas to overcome many challenges are welcome.

Appendix

Luminosity and Reduction in the Nano-Beam Scheme

(a) $$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma_x^* \sigma_y^*} R_L(\phi_x, \beta_y^*, \sigma_z, \sigma_x^*)$$

$\sigma_x^* = 18\ \mu m$ $\quad \varepsilon_x = 4\ nm$ $\quad \beta_x^* = 80\ mm$

$\sigma_z = 6\ mm$

(b) $$L = \frac{N_+ N_- n_b f_0}{4\pi \phi_x \sigma_z \sigma_y^*} R_L(0, \beta_y^*, \tilde{\sigma}_z, \tilde{\sigma}_x^*)$$

$$= \frac{N_+ N_- n_b f_0}{4\pi \phi_x \sigma_z \sigma_y^*} R_L(0, \beta_y^*, \sigma_x^*/\phi_x)$$

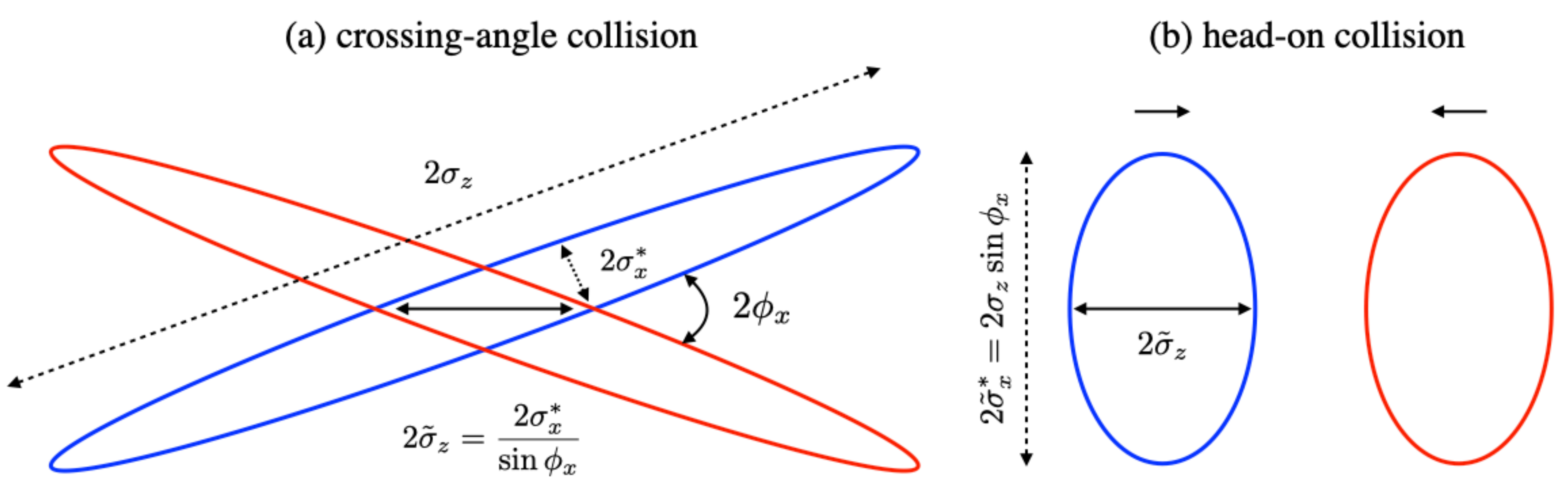
The dependence of σ_x^* is included in R_L.

$\phi_x \sigma_z = 250\ \mu m$

The σ_z is replaced with the effective $\tilde{\sigma}_z$.

The σ_x^* is replaced with the effective $\tilde{\sigma}_x^*$.

(a) and (b) give the same luminosity.
Large Piwinski angle is required.



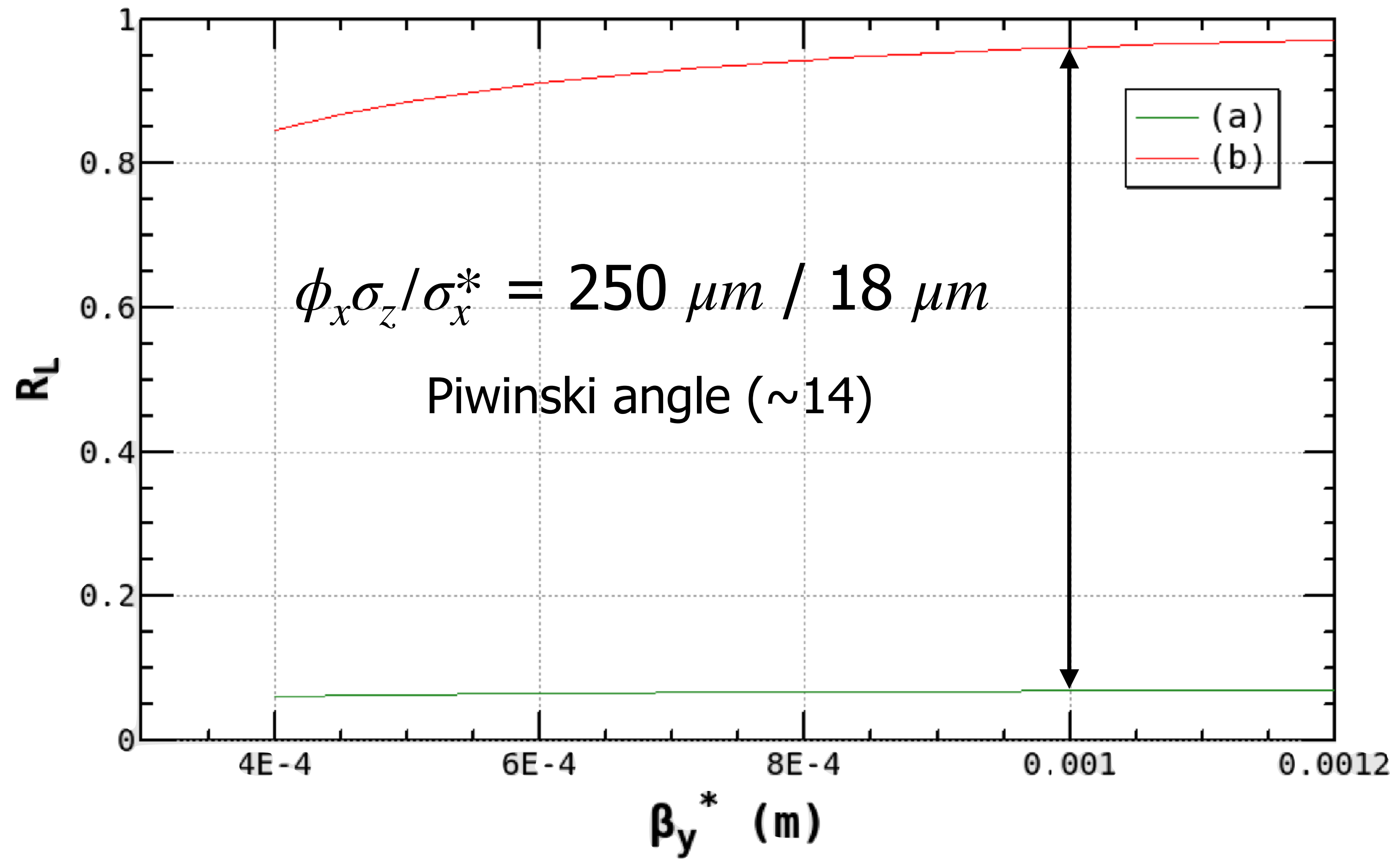
Luminosity reduction

$$R_L(\phi_x, \beta_y^*, \sigma_z, \sigma_x^*) = \frac{a}{\sqrt{\pi}} e^b K_0(b)$$

$$a = \frac{\beta_y^*}{\sigma_z}$$

$$b = \frac{a^2}{2}\left\{1 + \left(\frac{\sigma_z}{\sigma_x^*}\tan\phi_x\right)^2\right\}$$

Piwinski angle

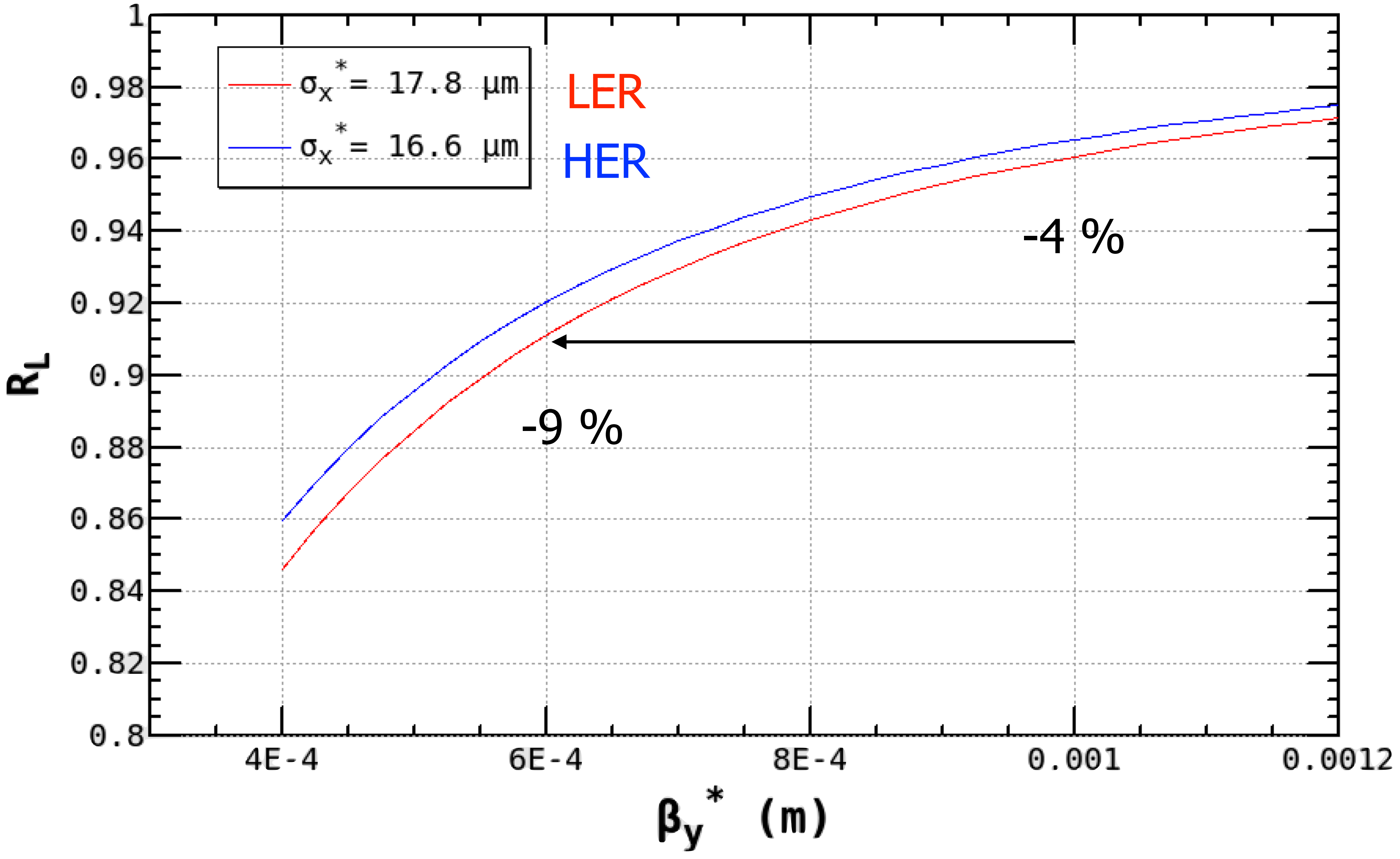


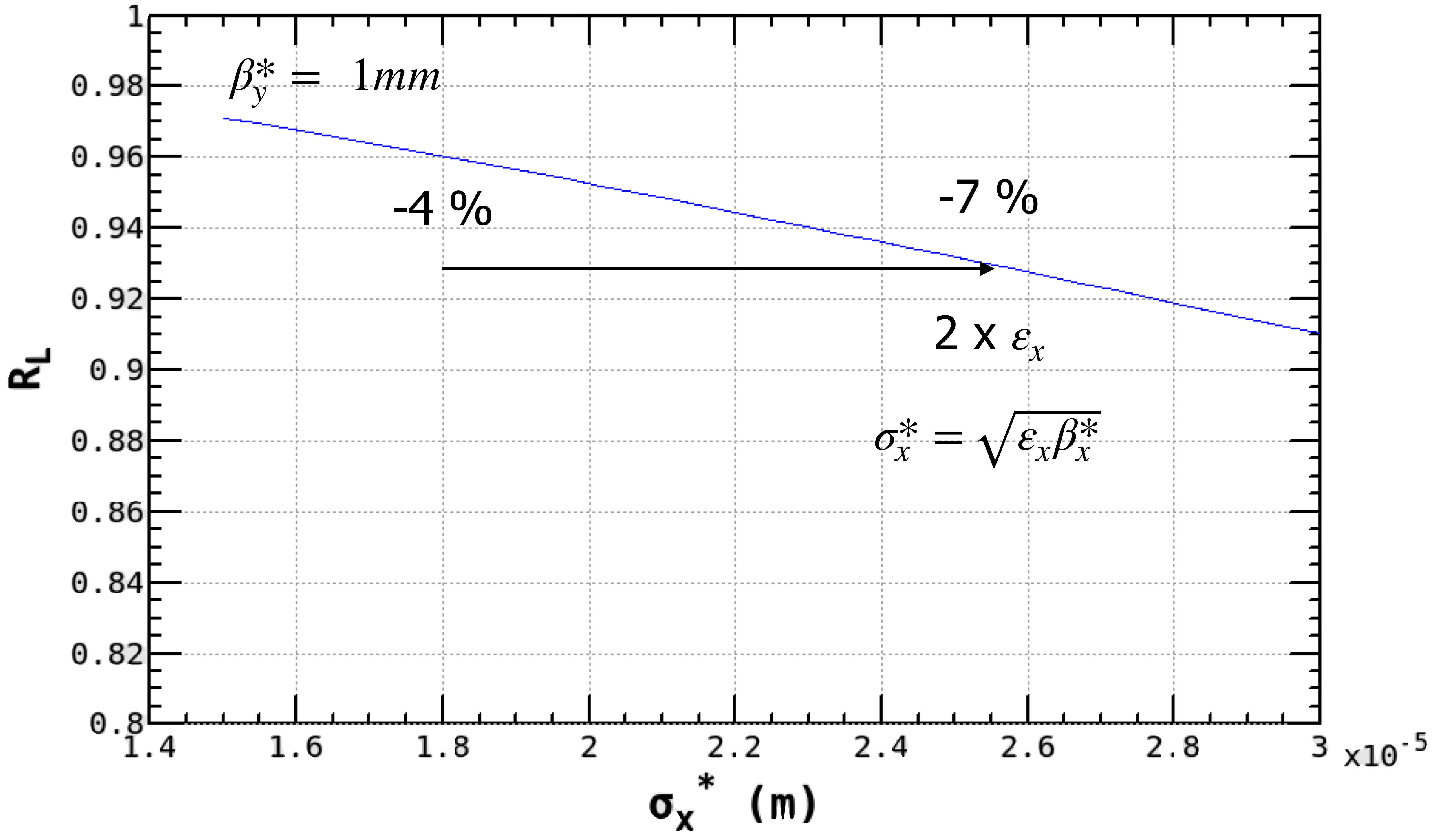
Handbook of Accelerator Physics and Engineering

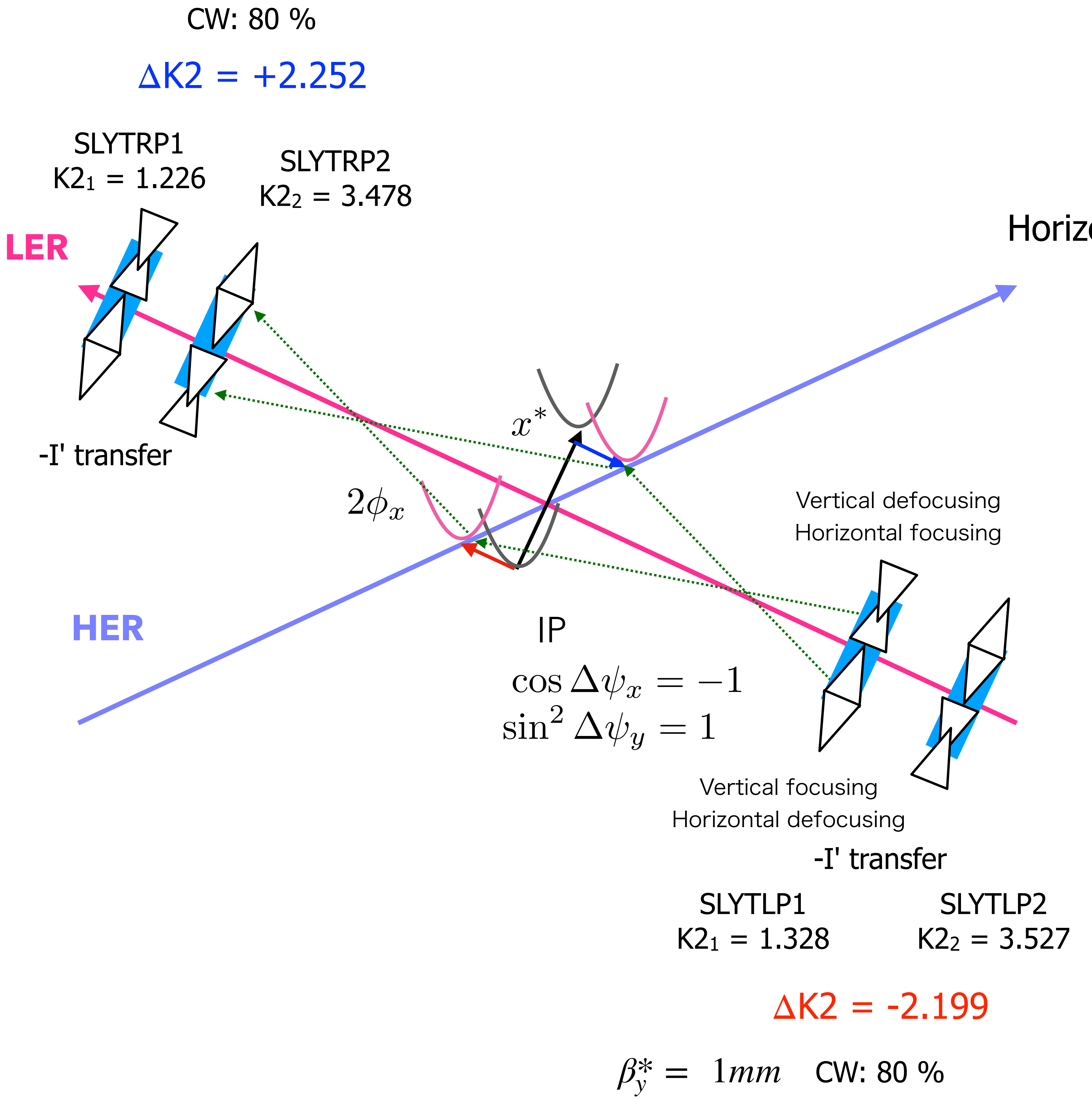
In the case of β_y^* is 1 mm, the luminosity loss is 4 %.

The σ_x^* becomes larger, the R_L becomes smaller. The low emittance is required.

When β_y^* is squeezed down to 0.6 mm, the luminosity loss is 9 %.







Large crossing angle can make a crab waist.

$$H_{cw} = -\frac{1}{2\tan 2\phi_x} x^* p_y^{*2}$$

Horizontal orbit deviation (particles in a bunch) at sextupole makes beta beat (waist shift) due to quadrupole field element.

$$\frac{1}{p_y^*}\frac{dy^*}{ds} = -\frac{x^*}{\tan 2\phi_x}$$

The waist shift is proportional to the horizontal orbit deviation.

$$\Delta s = -\frac{x^*}{\tan 2\phi_x} \quad \text{x } cw\ ratio$$

The crab waist reduces not only geometrical luminosity loss but also can suppress betatron and synchro-beta resonances due to beam-beam interaction.

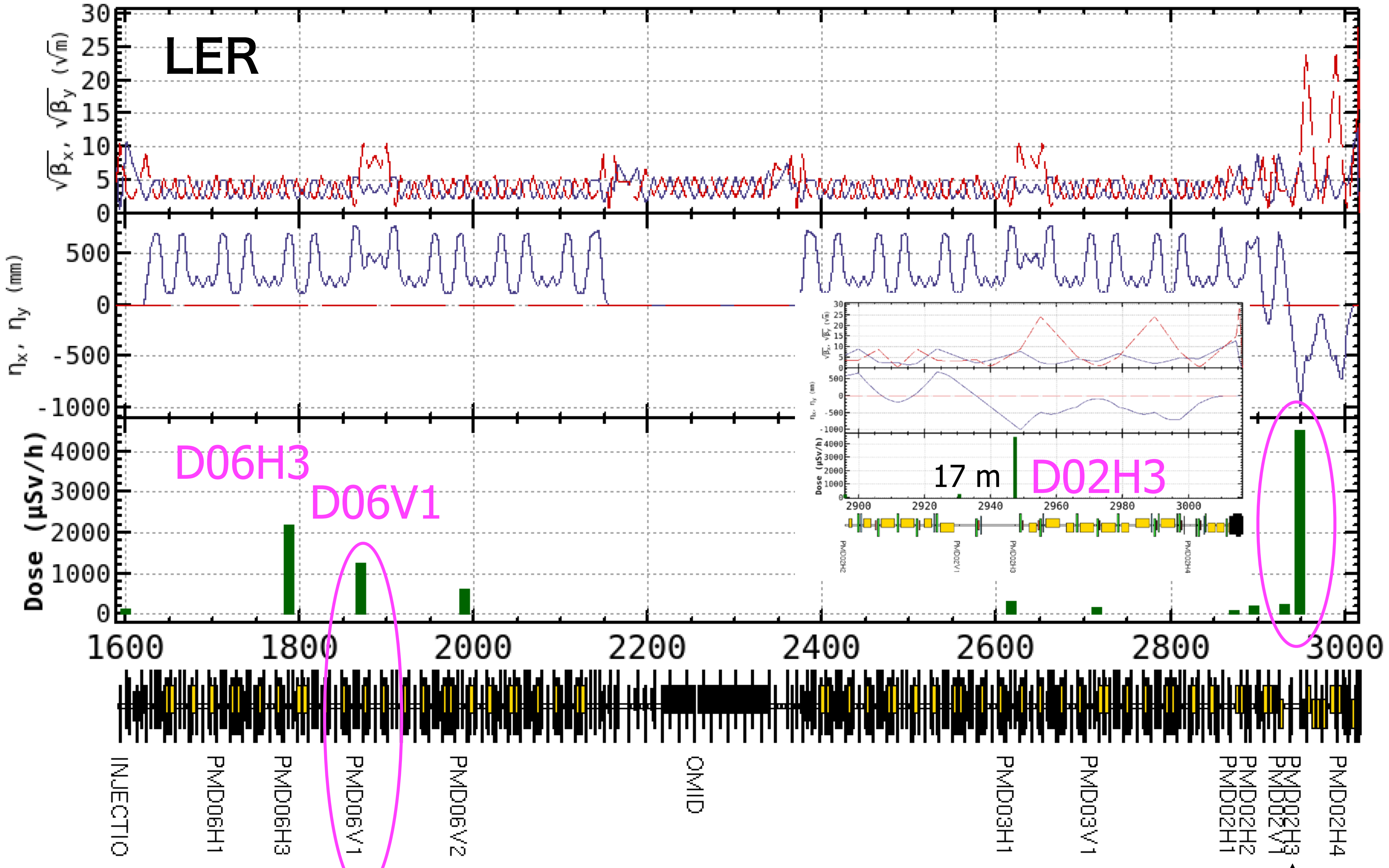
LER: CW ratio = 80 %
HER: CW ratio = 40 % → 60 % and above are available.

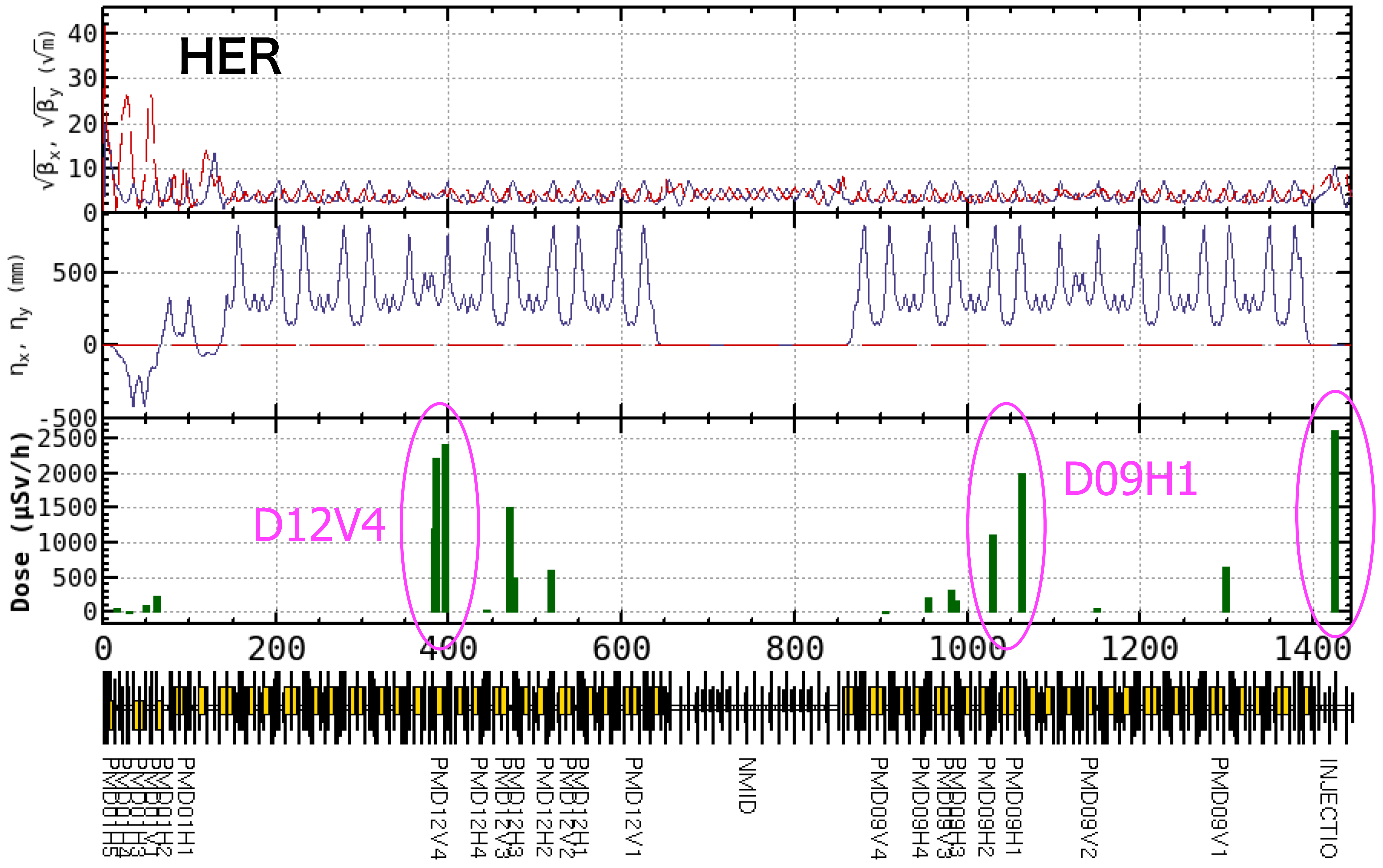
Location of Movable Collimators

Collimators and Radiation Dose (measured on June 22, 2022)

measured by Radiation Safety Group

"PM*" means movable collimator.





Injection Point

e^+ →

IP

← e^-

Injection Point

D06H3 damaged due to accidental fire of injection kicker on March 18

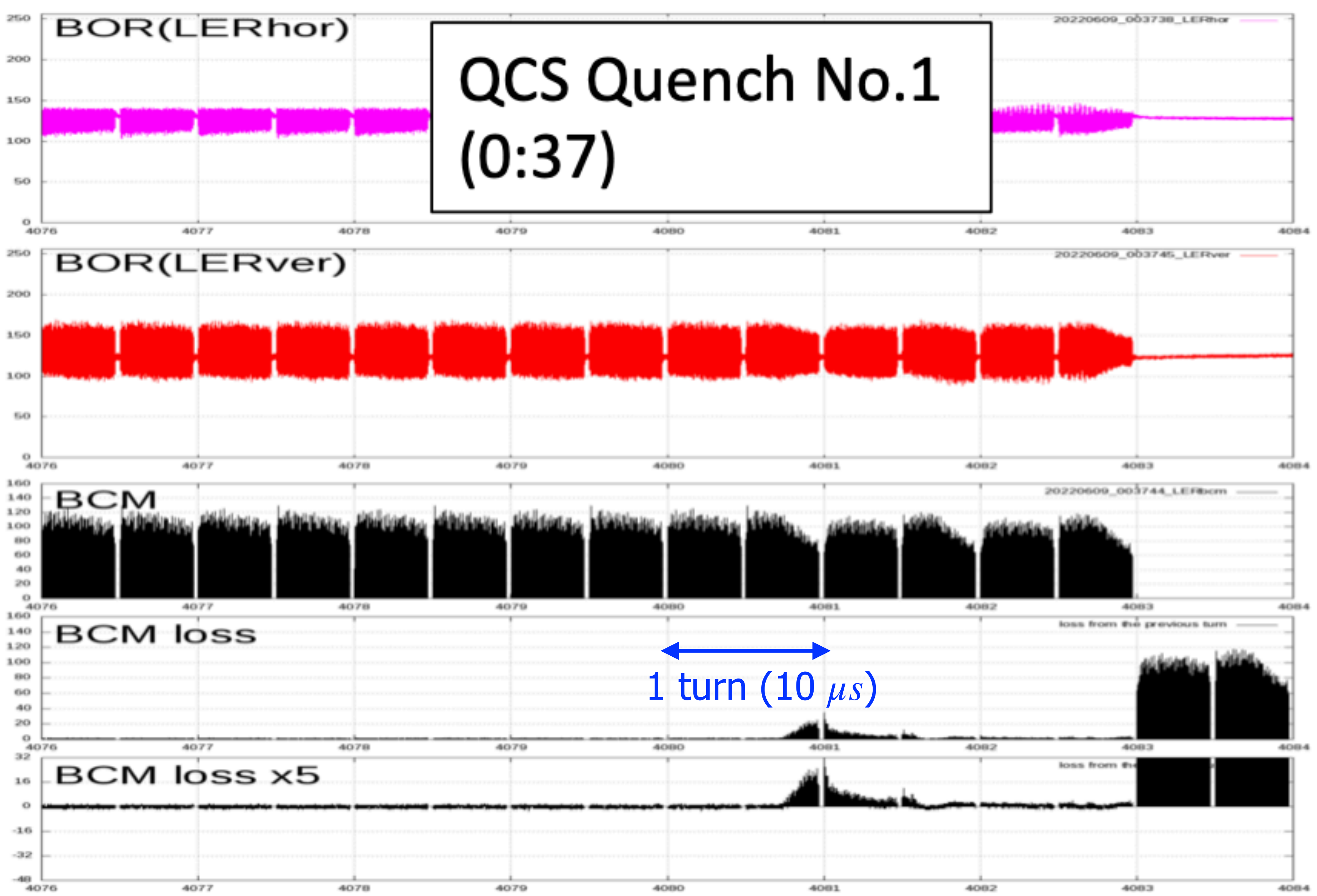
D02H3 is 17 m downstream of D02V1 which is damaged on March 11.

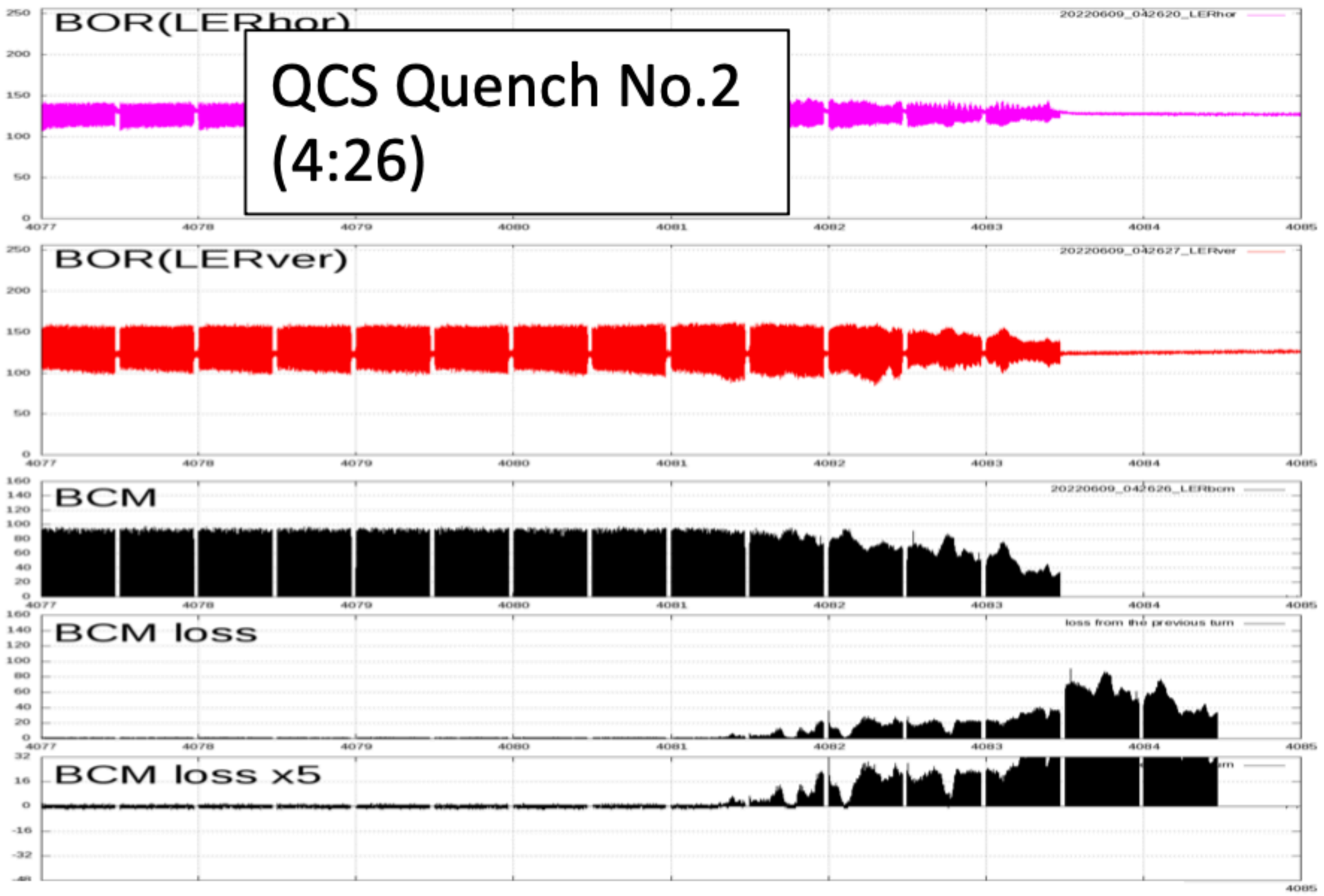
The radiation dose at the injection point is very high in HER.

The bottom jaw of D06V1 was opened from the usual setting due to damage of the collimator head. In stead of D06V1, D06V2 was used to protect D02V1 and QCS from mid. of June, 2022.

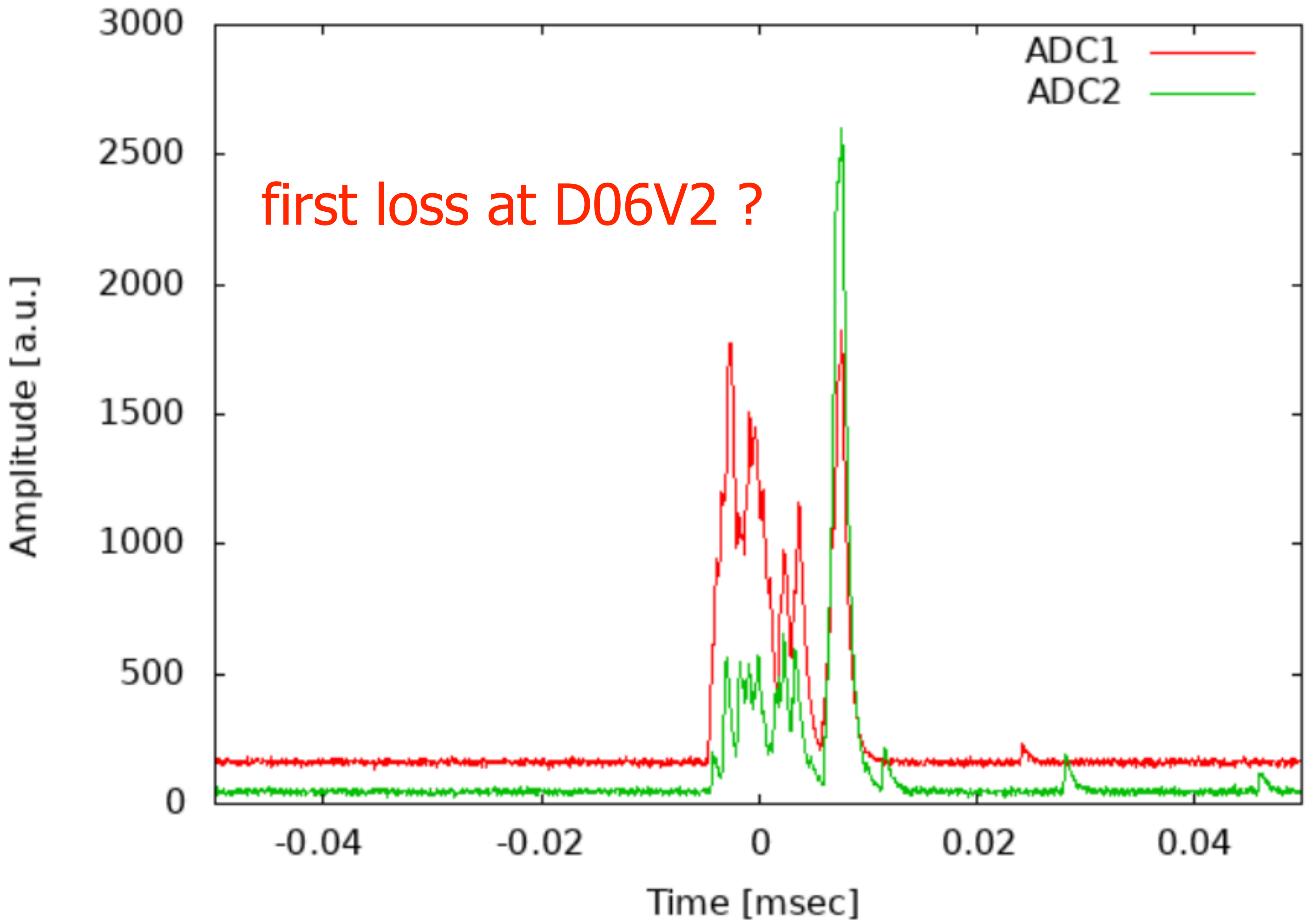
June 9, 2022

1 turn = 10 μs
2 trains, 2 abort gaps

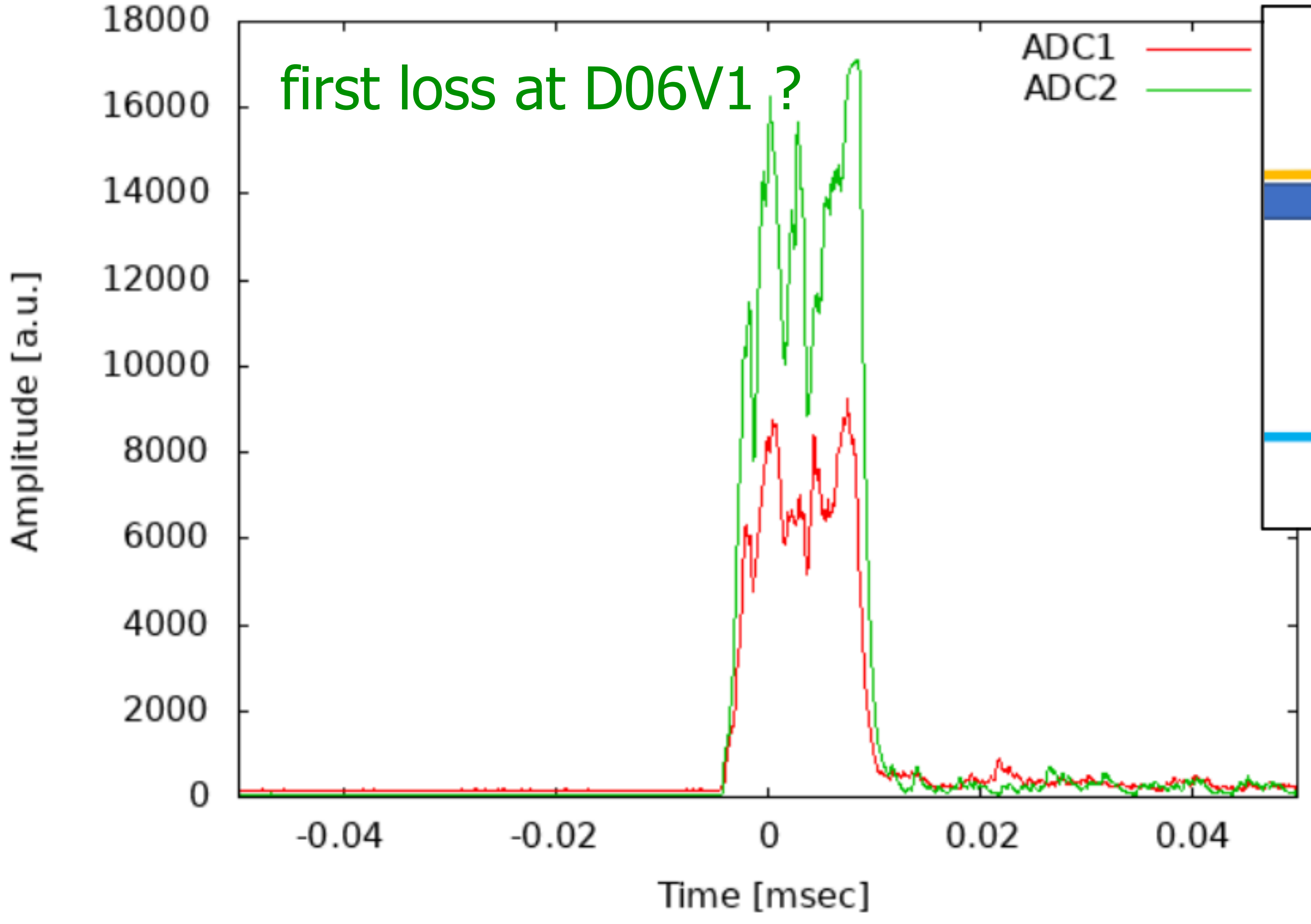


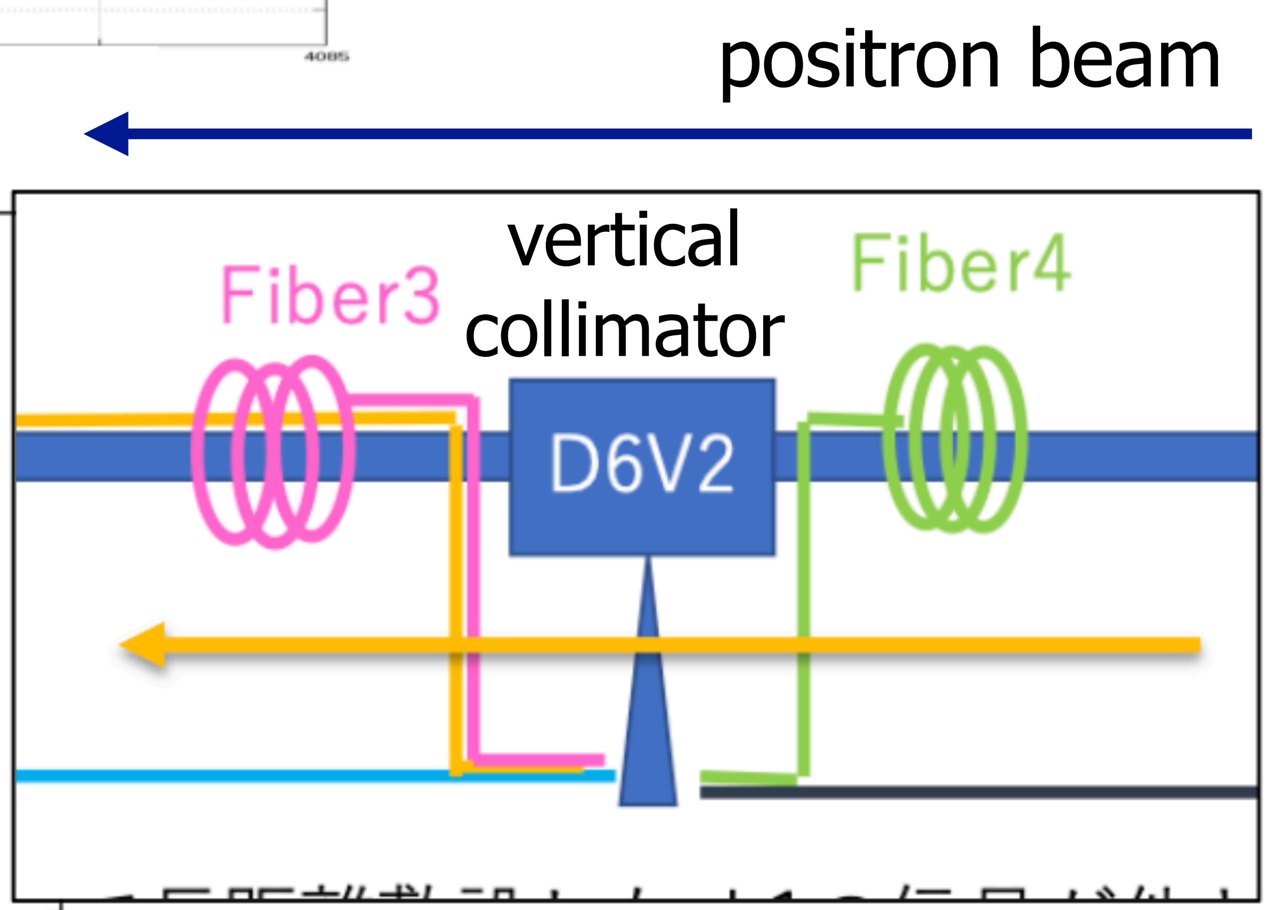


[D6 Opt.BLM] 2022-06-09_00:37:38.506358



[D6 Opt.BLM] 2022-06-09_04:26:20.629646





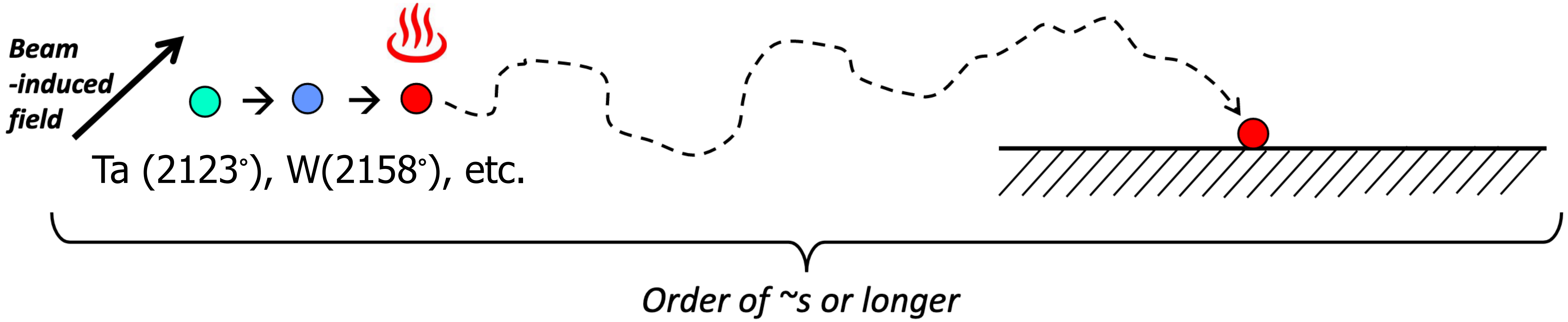
ADC1 = Fiber3

ADC2 = Fiber4

Physical process of the "Fireball" hypothesis, leading to fast beam loss

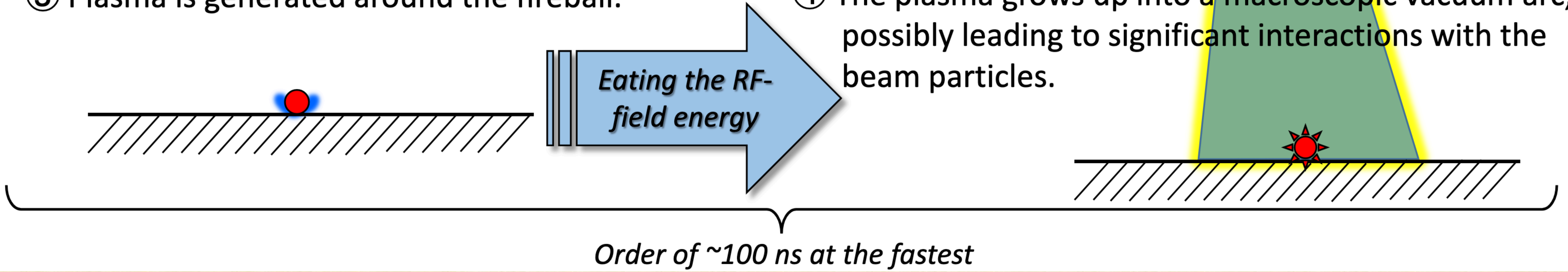
① A microparticle with a high sublimation point
is heated by the beam-induced field.
➔ **Fireball**

② The fireball touches some metal surface
with a low sublimation point (e.g. copper).



③ Plasma is generated around the fireball.

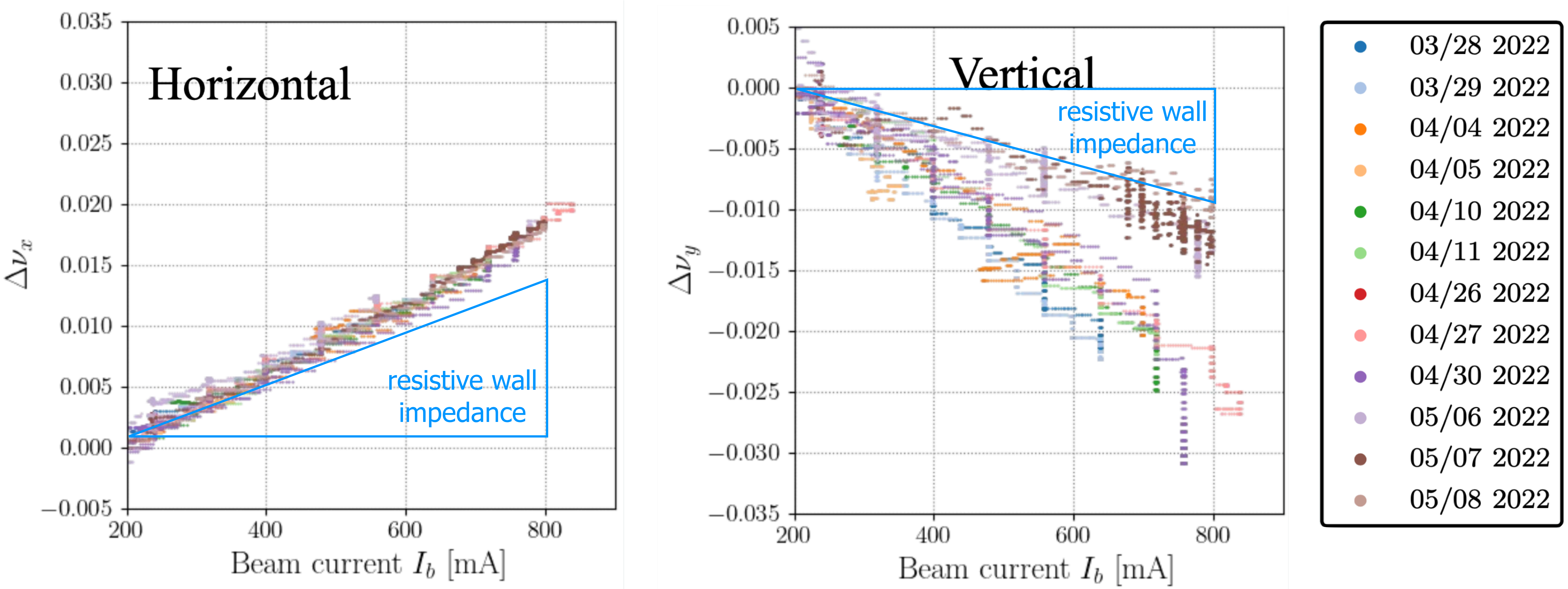
④ The plasma grows up into a macroscopic vacuum arc,
possibly leading to significant interactions with the
beam particles.



Optics Change with Beam Current

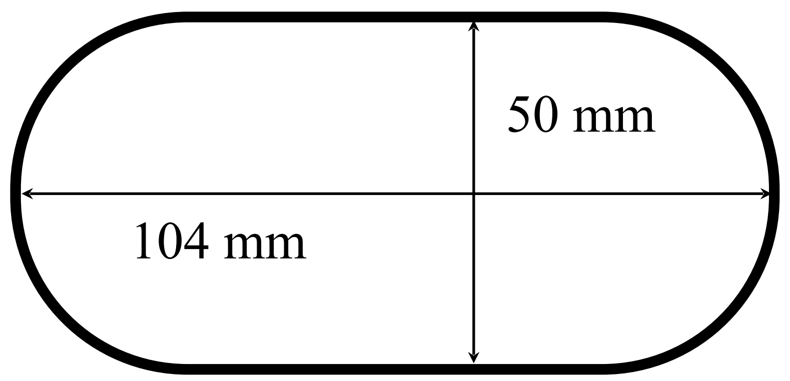
Daily variations in the vertical tune shift was observed. However, the horizontal tune shift was stable.
We assume that the vertical tune shift comes from horizontal orbit deviations at sextupoles in addition to the resistive wall.

HER



H. Sugimoto, 2022ab Summary Meeting

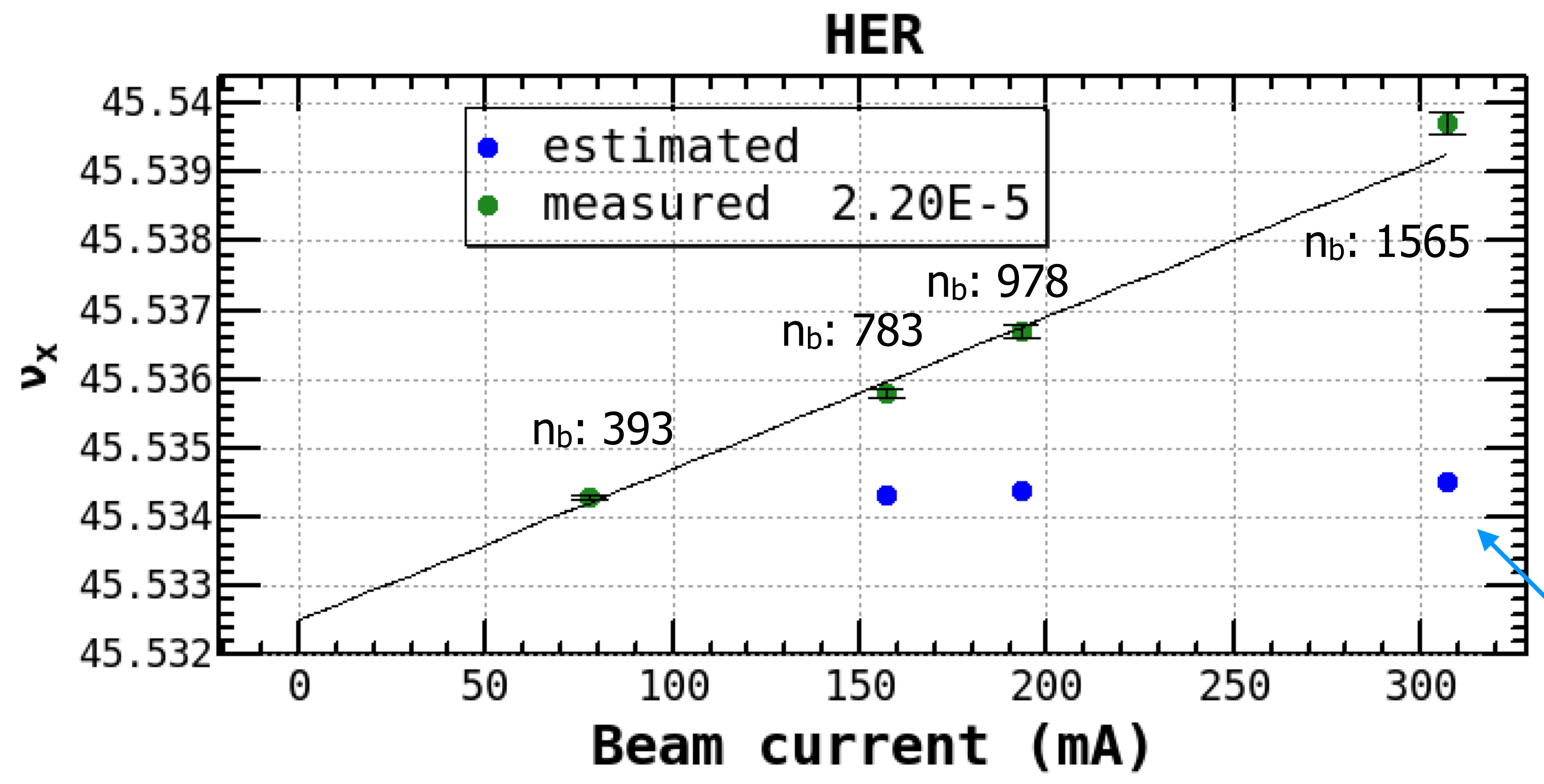
Cross section of HER chamber

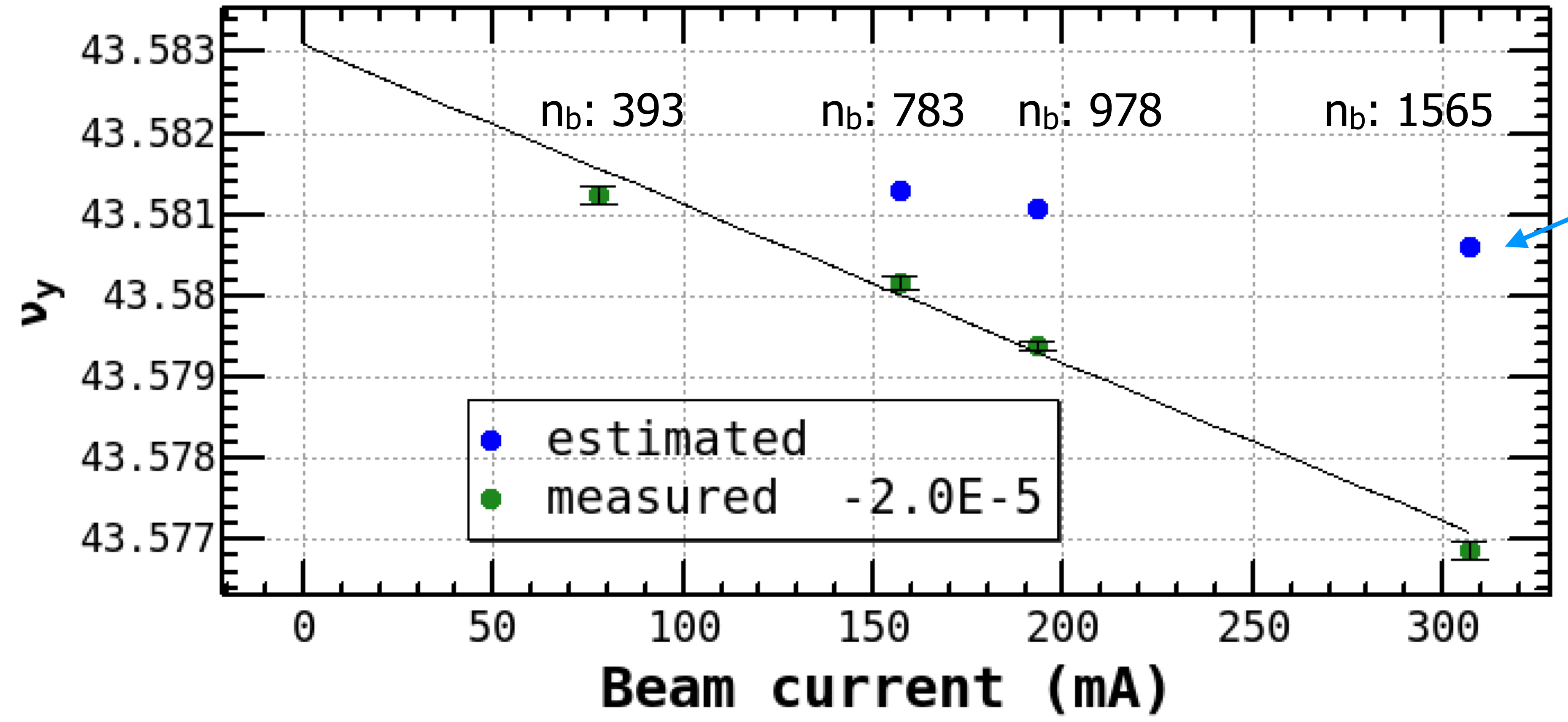


We always perform tune feedback with a pilot bunch (non collision).
Tune shift is estimated from amount of feedback.

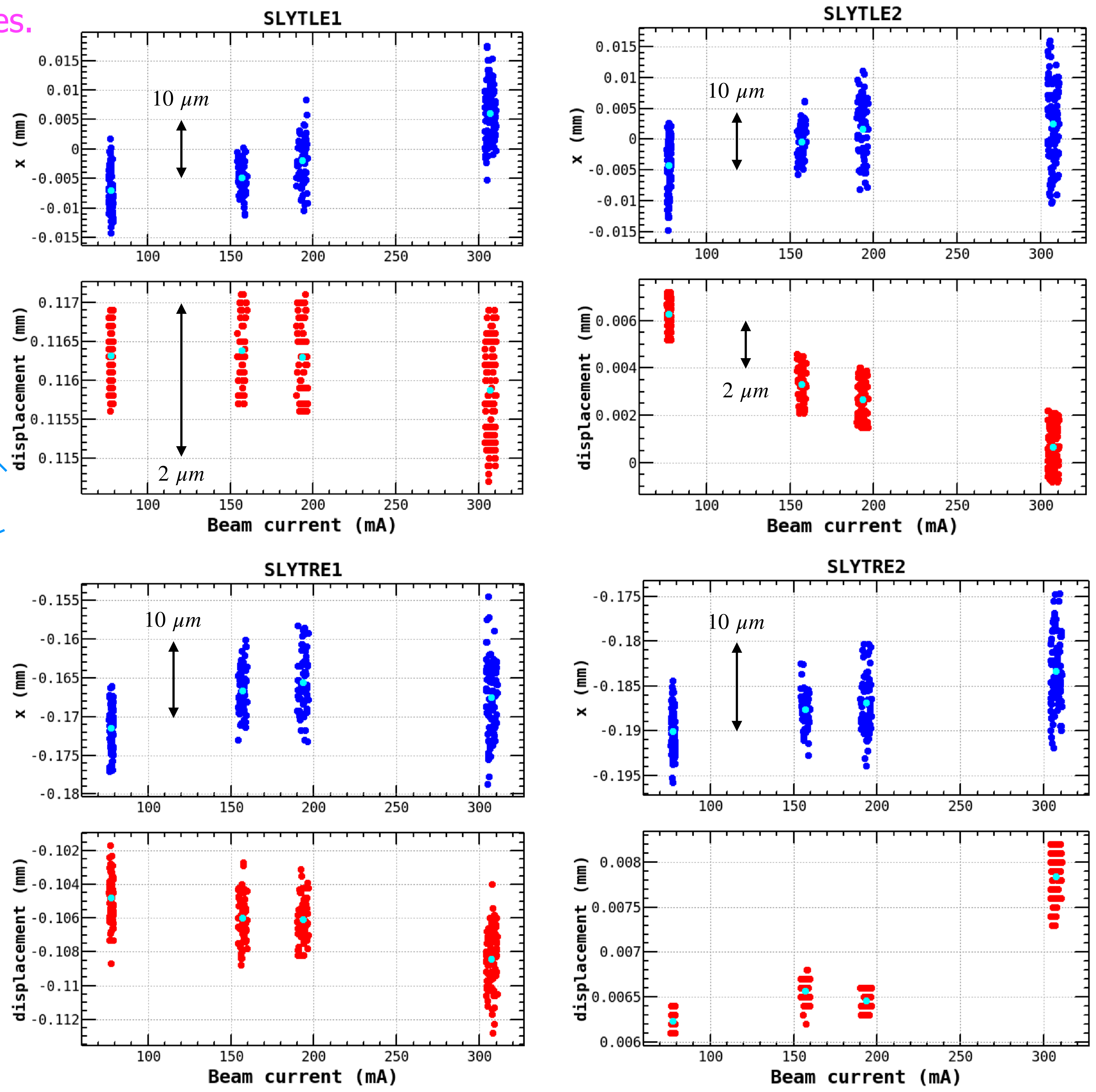
$\beta_x^*/\beta_y^* = 200\ mm/8\ mm$ (no crab waist)

The bunch current is fixed to be 0.2 mA with changing no. bunches.





HER



tune shift due to resistive wall impedance:

$$\Delta\nu_x/I = +2.2\times10^{-5}\ (1/mA)$$

$$\Delta\nu_y/I = -2.0\times10^{-5}\ (1/mA)$$

$$\rightarrow -1.64\times10^{-5}\ (1/mA)$$

corrected by orbit deviation

18:50 - 23:10, October 26, 2021

BPM Displacement Monitor (Gap Sensor)

BPM is fixed at quadrupole magnet and displacement monitor measures relative deviation (horizontal and vertical) between the BPM and the sextupole magnet. The measured offset is included in the final BPM measurement.

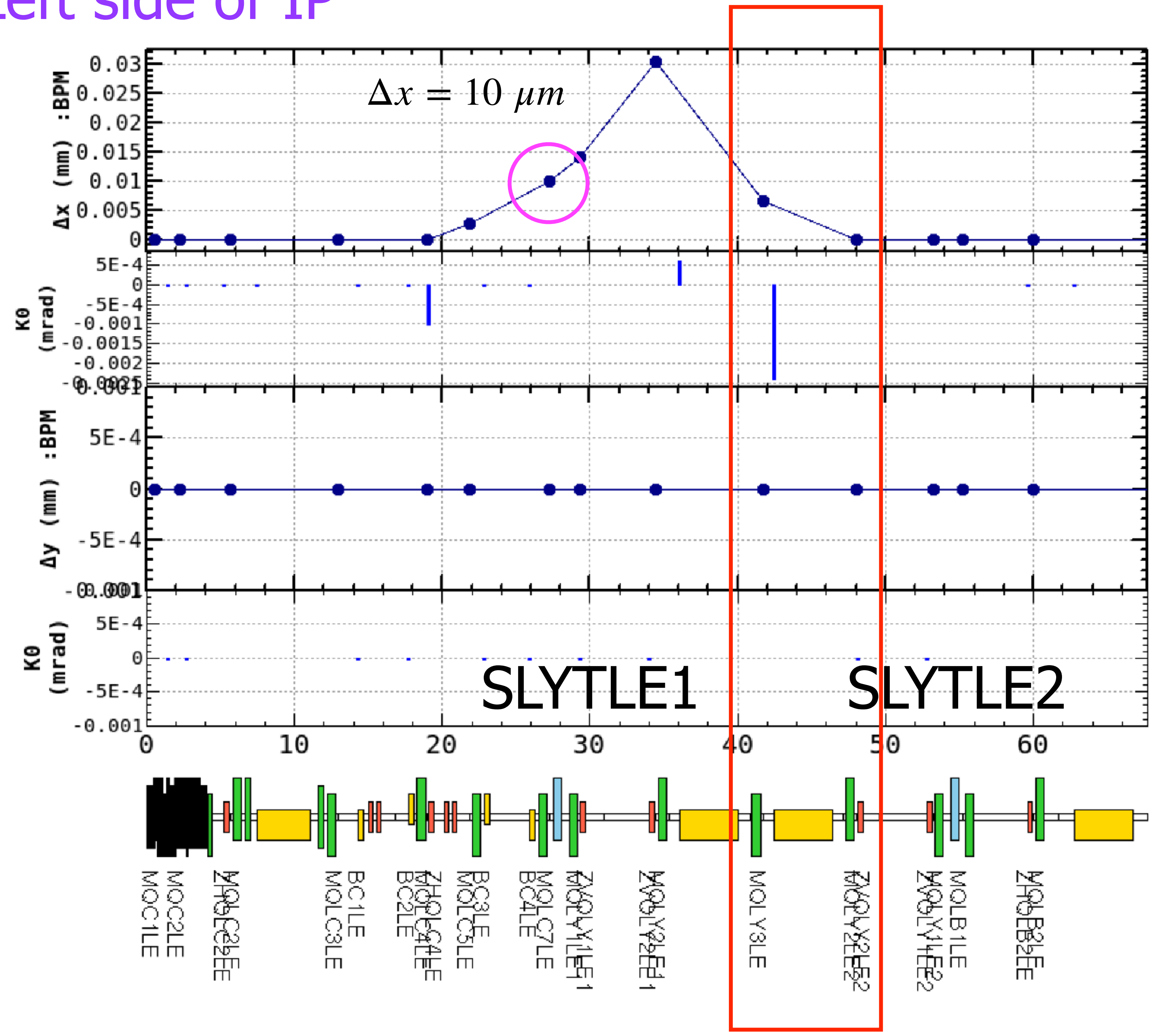
sextupole magnet (SD-type)

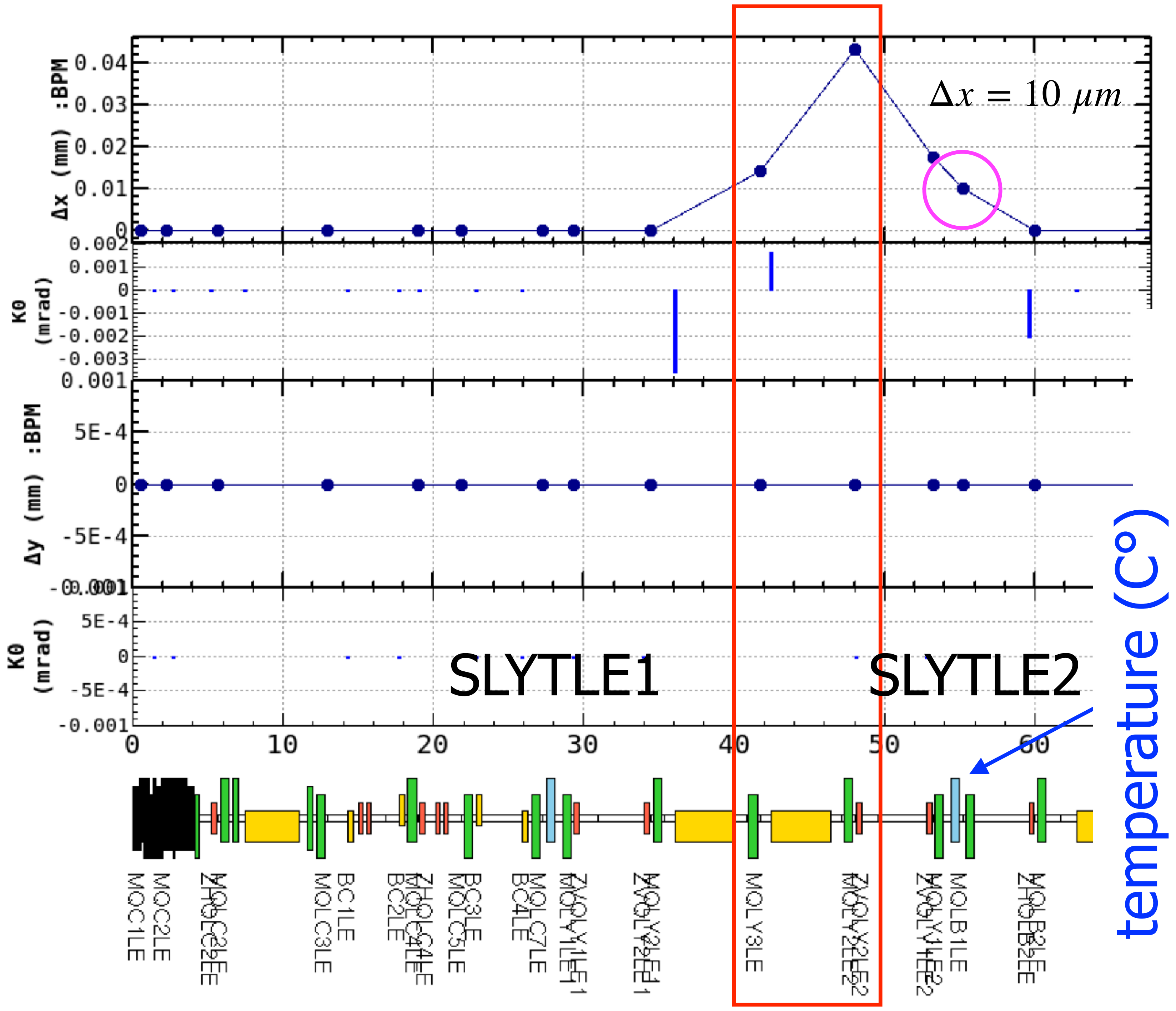
BPM

quadrupole magnet (QD-type)

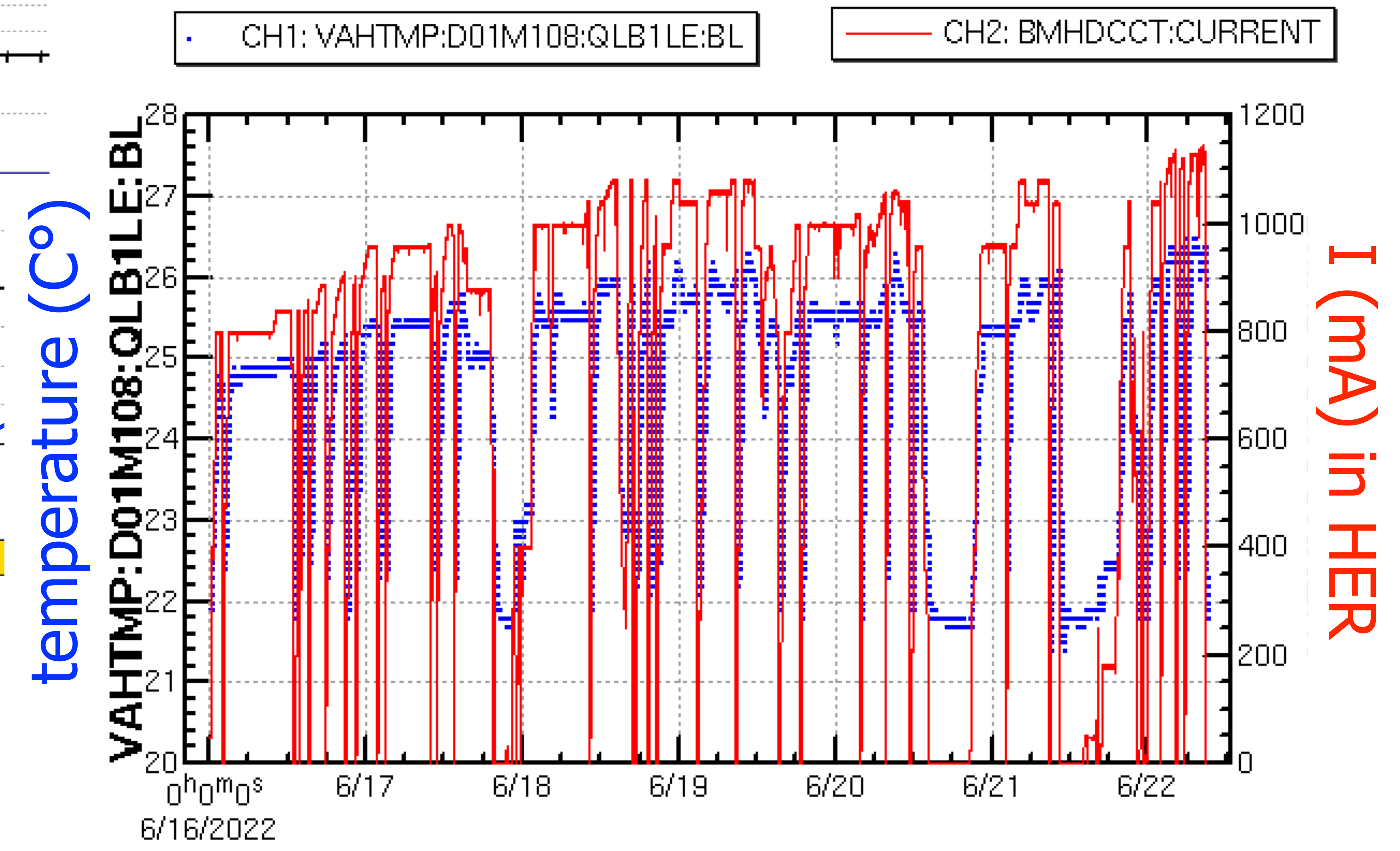
Local Orbit Correction at SLYTLE1 and SLYTLE2

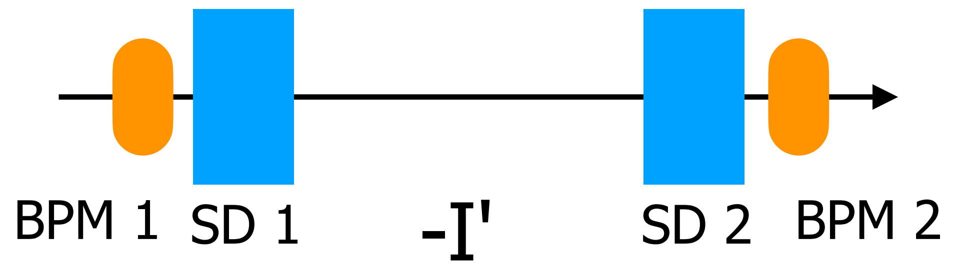
Left side of IP

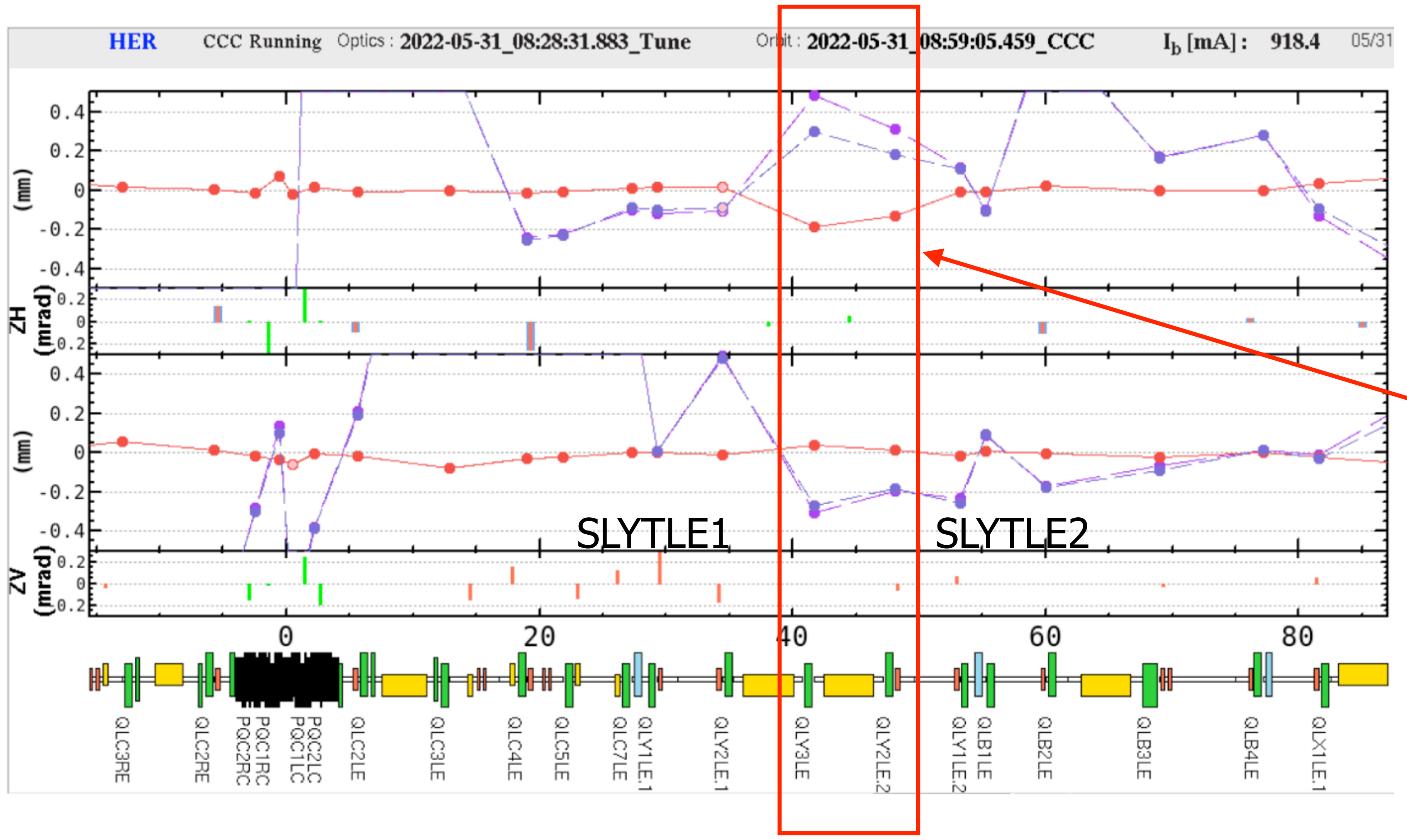




The local bumps correct the orbit at SLYTLE1 and SLYTLE2 (local chromaticity region;CW sextupoles).



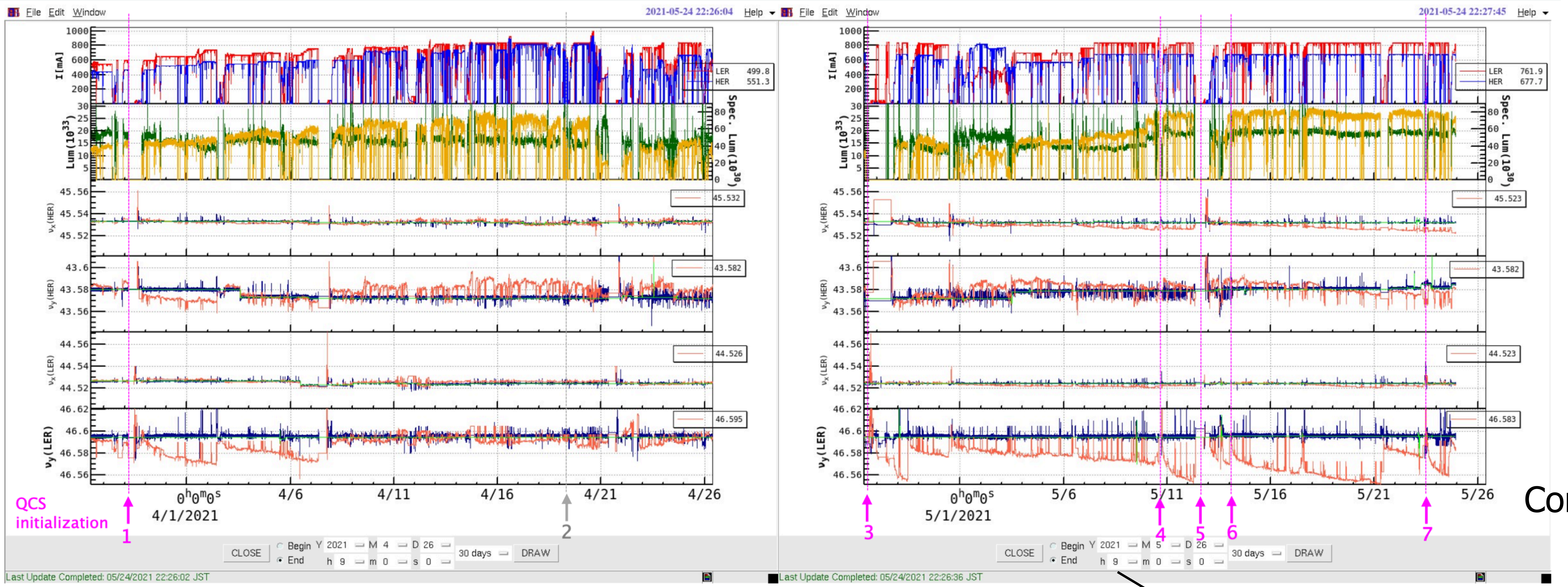




The horizontal orbit is distorted in the local chromaticity correction region (SLYTLE1 - SLYTLE2).

This region can not fit to the gold orbit when we correct the orbit at SLYs locally.

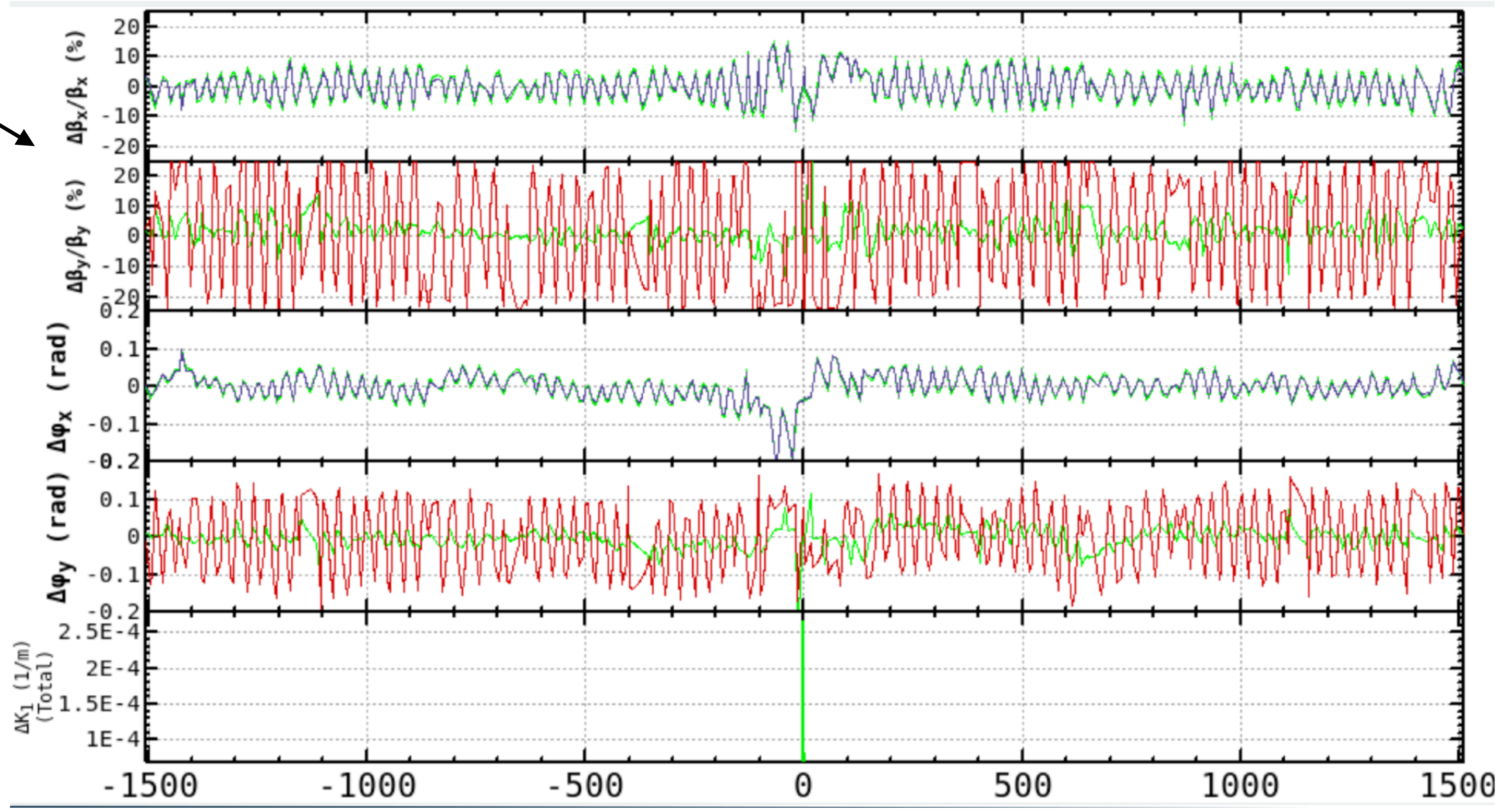
H. Koiso and H. Sugimoto



1. 3/28 Magnet PS QC1LE Charging Volt I/L Trouble
2. 4/19 QC1LE quench
   (4/21 On -> Off-resonance)
3. 4/26 Off -> On-resonance
4. 5/10 QC1RP & QC1LP quench
5. 5/12 Maintenance
6. 5/14 QC1RP quench
7. 5/23 QC1RP & QC1LP quench

Correction of beta-beat by only QCS

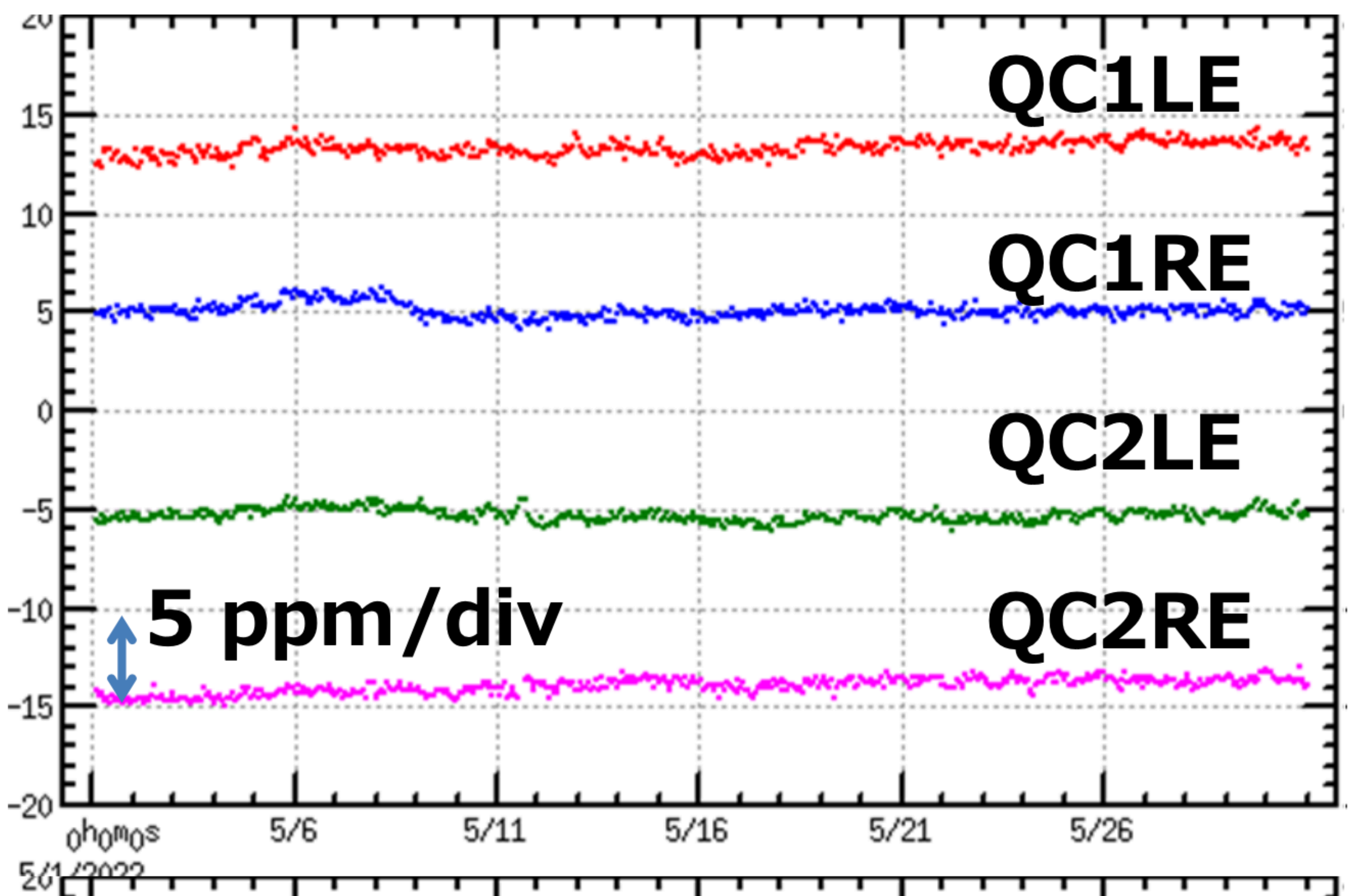
$\Delta K1$ = a few x 10^{-4} (1/m)

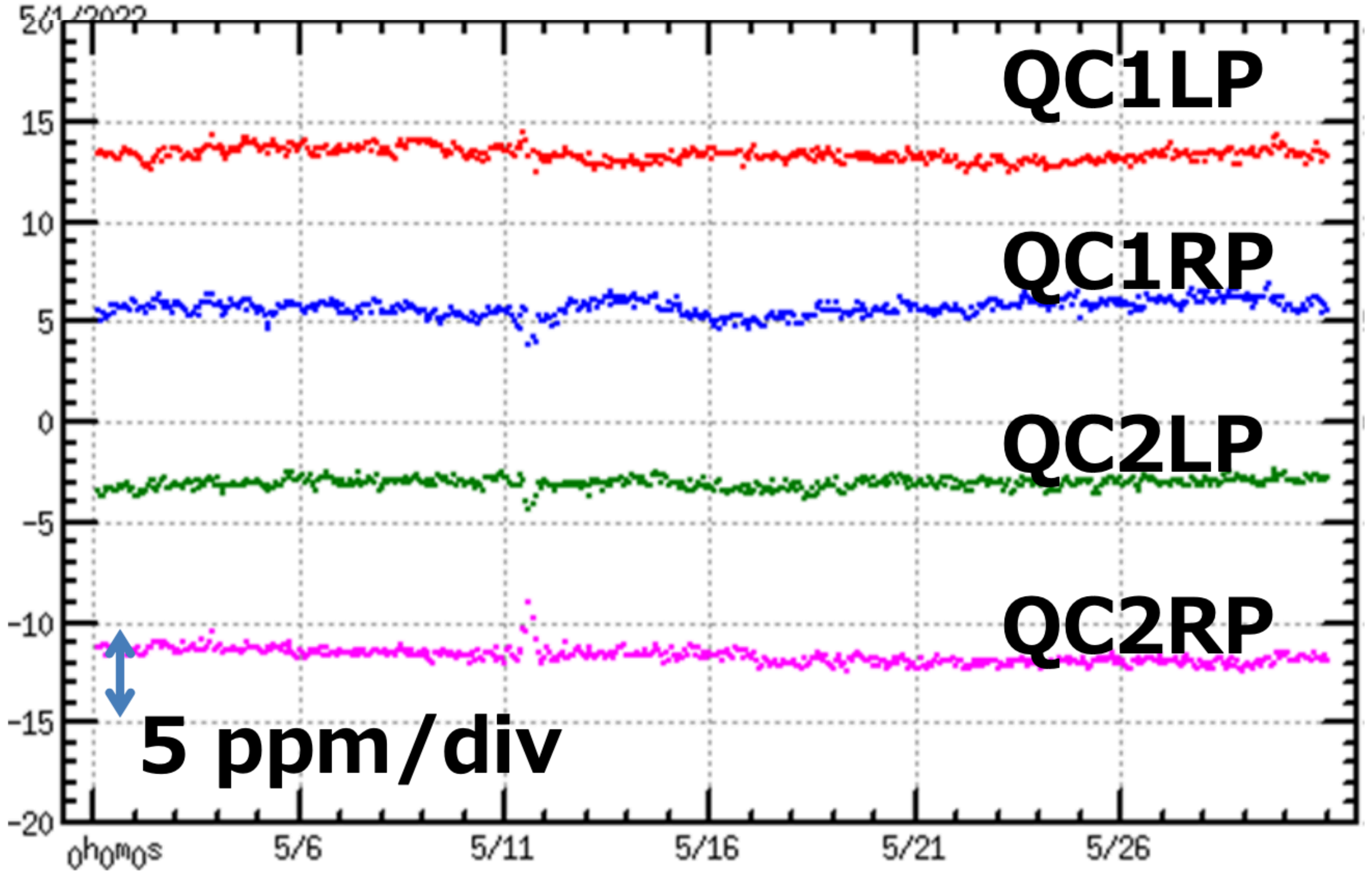


Drift of QCS magnetic field can be estimated by estimated tune shift.

Betatron tune (vertical) changes gradually after optics correction.
QCS initialization is performed before optics correction.
QCS initialization and optics correction is also performed after QCS quench.

Recently we modified the way of QCS initialization.
The drift of magnetic field is much reduced.





Main QCS coils: 2 ppm / 8 hours