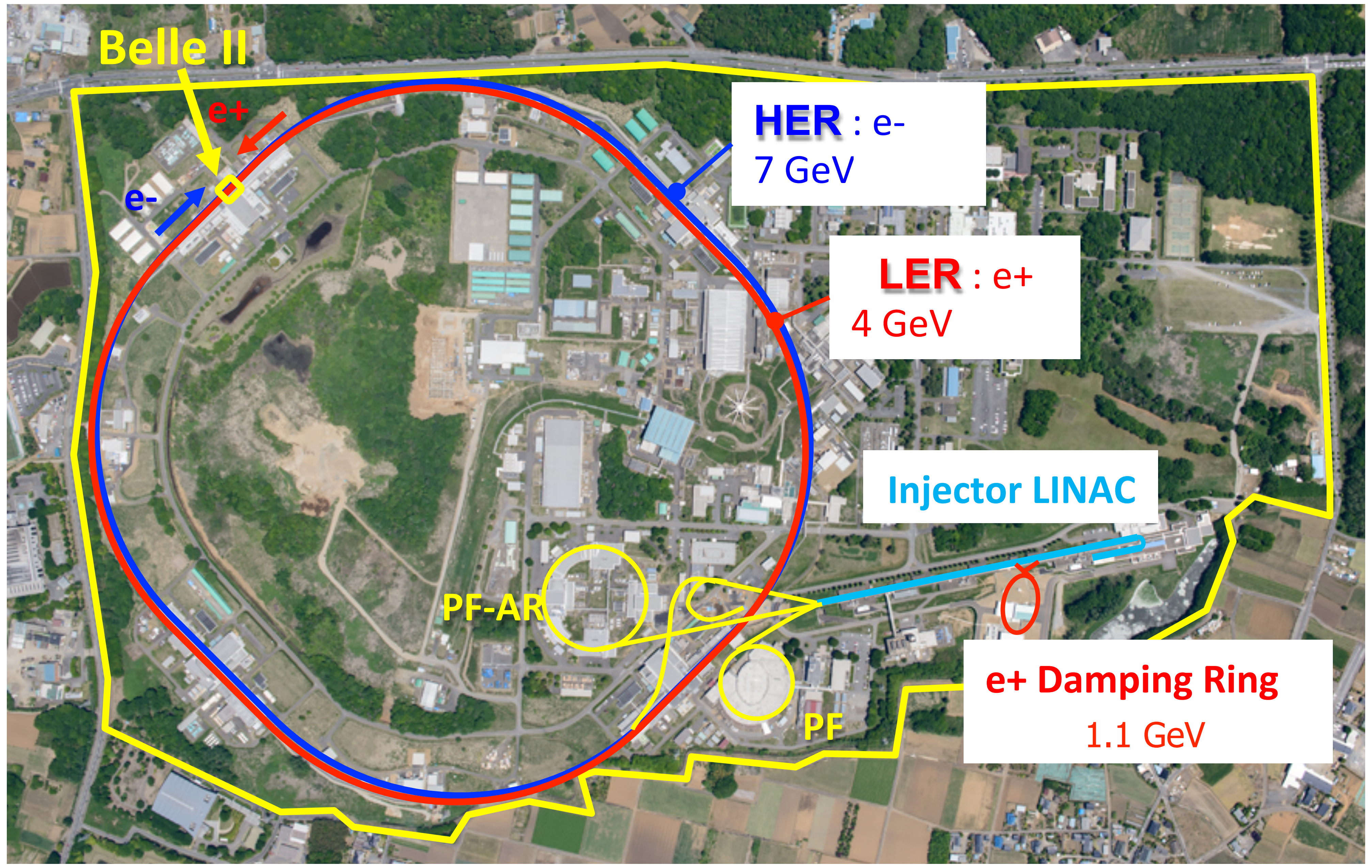
The SuperKEKB Operation

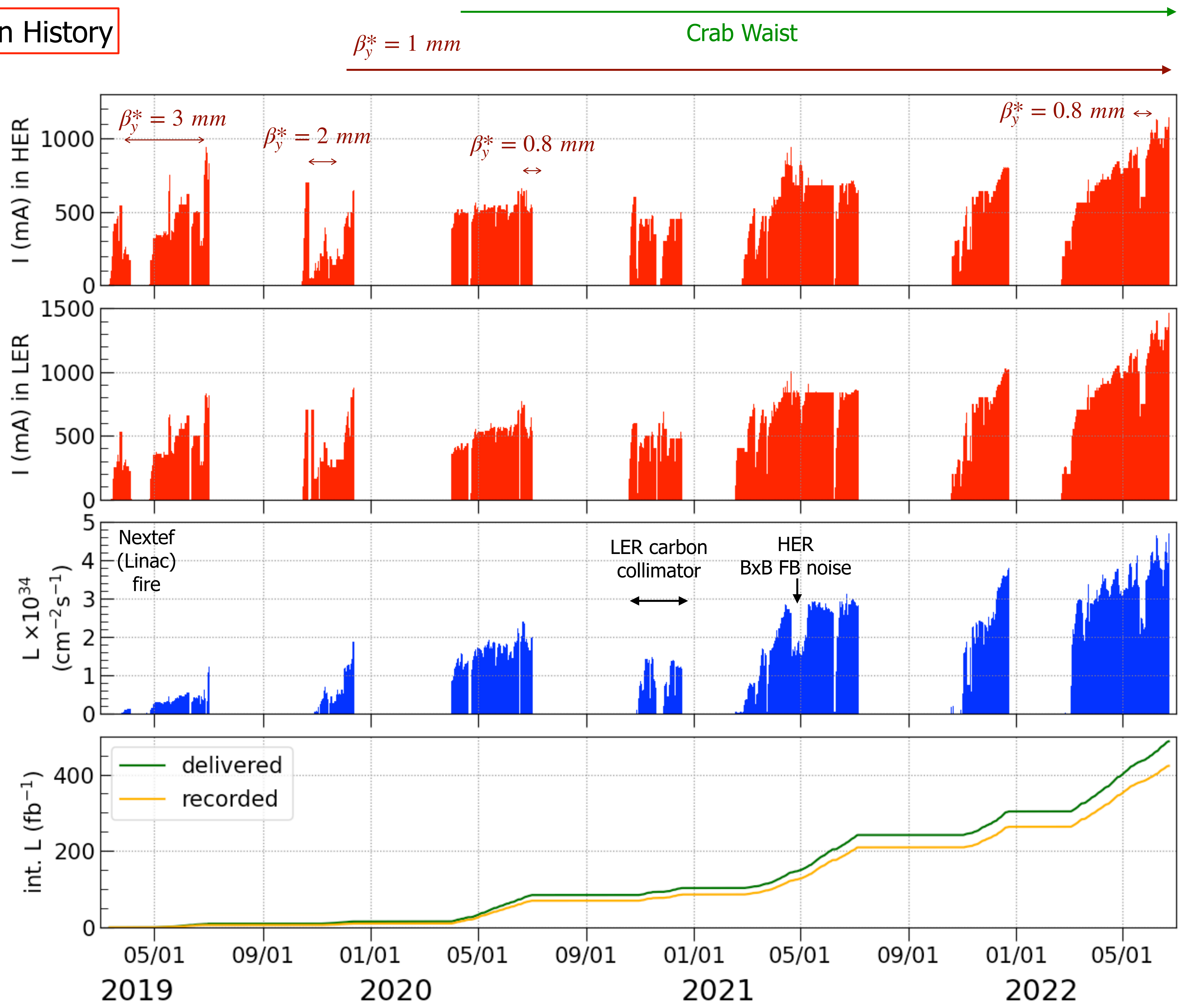
Y. Ohnishi (KEK)
on behalf of SuperKEKB and Belle II commissioning group

Super B-Factory Project at KEK, Japan



- Luminosity performance
- Beam tuning
- Obstacles to luminosity improvement
- Future plan and prospect

SuperKEKB Operation History



1st Long shutdown (LS1)

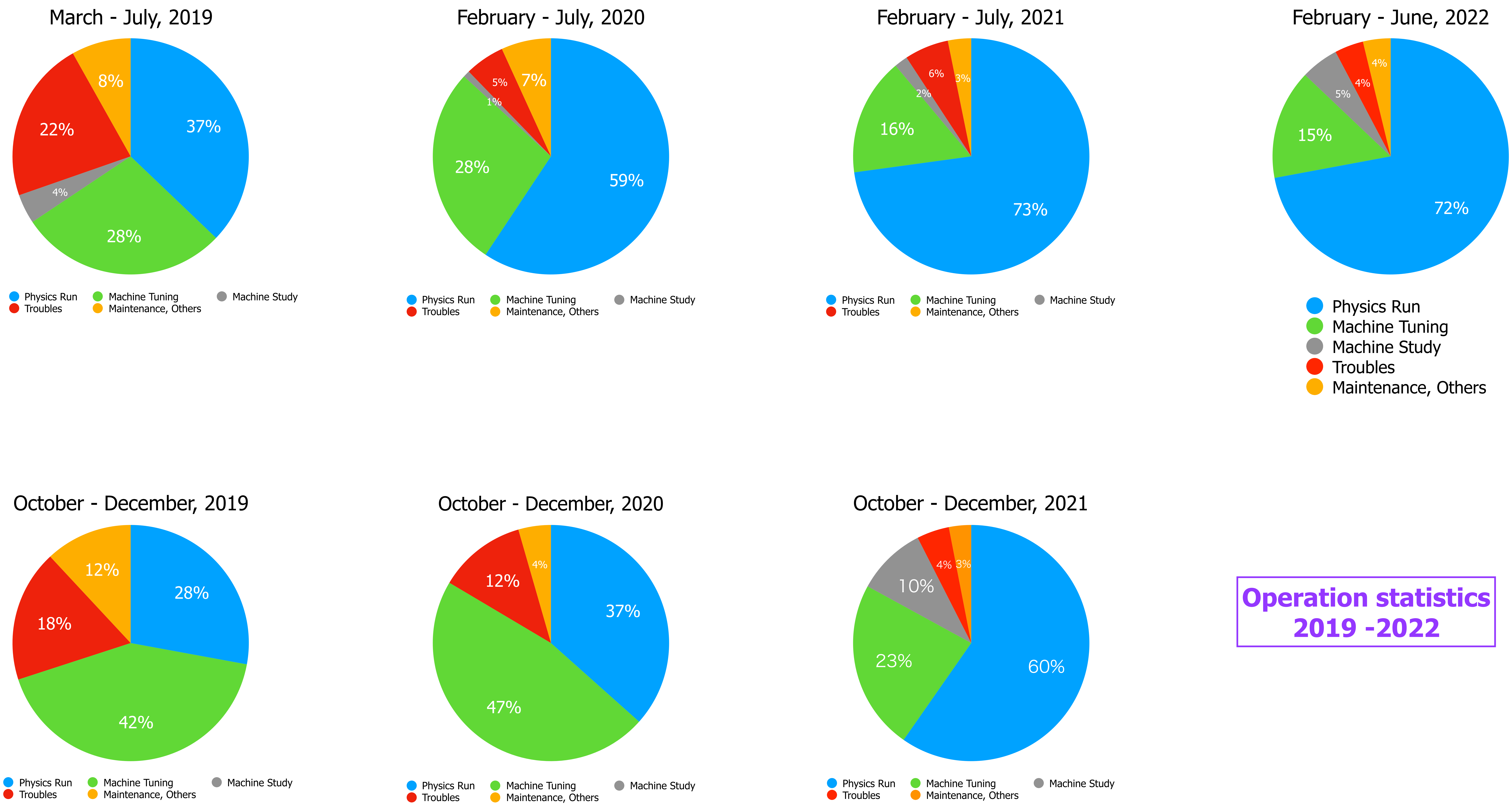
1145 mA

1460 mA

4.65×10^{34} cm^{-2}s^{-1}

(4.71×10^{34} cm^{-2}s^{-1})

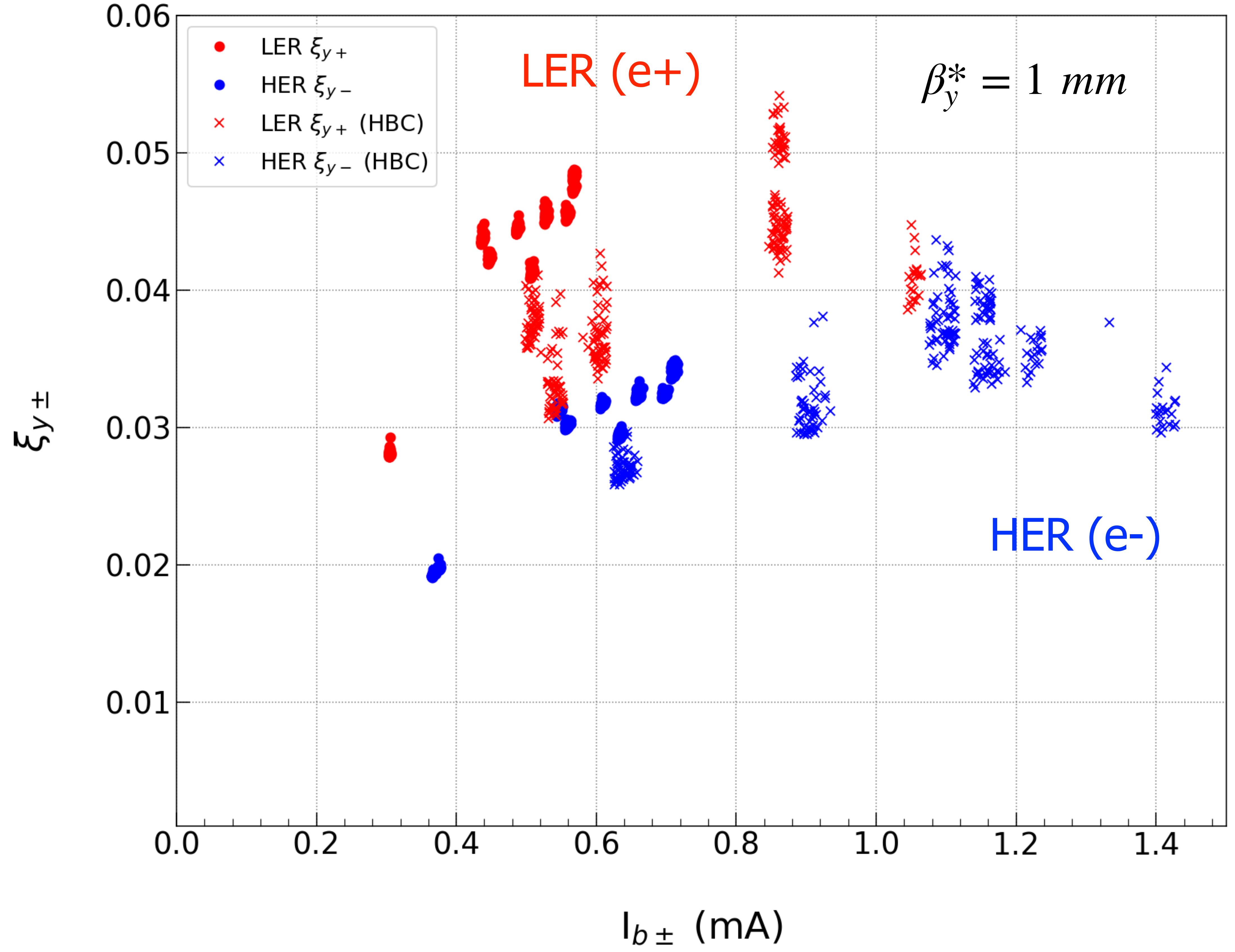
424 fb^{-1} / 491 fb^{-1}

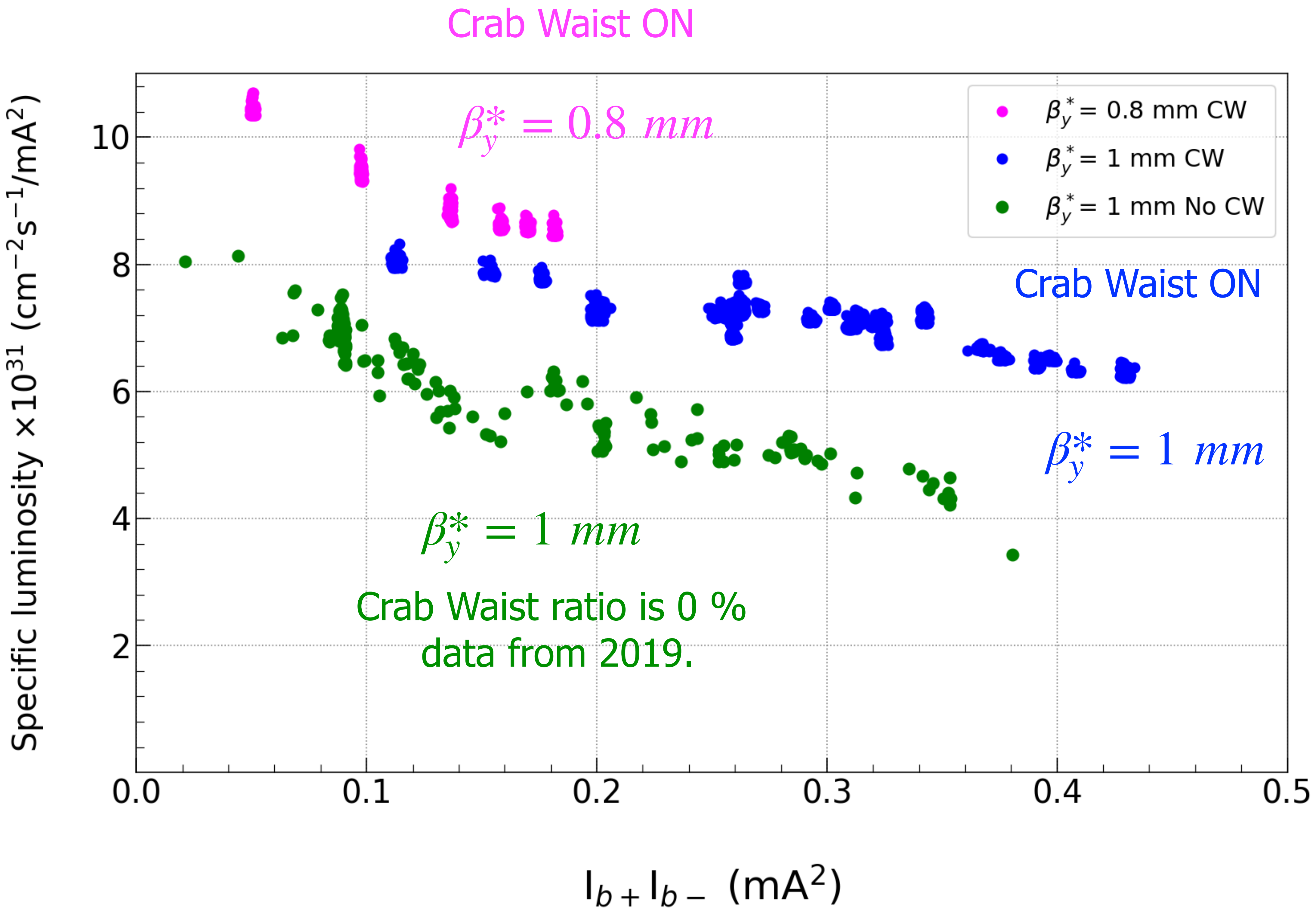

March - July, 2019
37%
28%
4%
22%
8%
Physics Run
Machine Tuning
Machine Study
Troubles
Maintenance, Others
February - July, 2020
59%
28%
1%
5%
7%
February - July, 2021
73%
16%
2%
6%
3%
February - June, 2022
72%
15%
5%
4%
4%
October - December, 2019
28%
42%
18%
12%
October - December, 2020
37%
47%
12%
4%
October - December, 2021
60%
23%
10%
4%
3%
Operation statistics
2019 -2022

Luminosity Performance

Beam-Beam Parameter and Specific Luminosity

●: physics run
×: HBC - High Bunch Current Study (393 bunches)





$$\xi_{y\pm} = 2er_e \frac{L\beta_y^*}{\gamma_\pm I\pm}$$

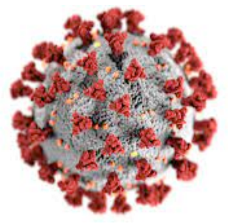
0.0565(LER) / 0.0434(HER)
at I_{b+} = 1.1 mA

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

The CW improved luminosity.
Data without CW was not the same period as CW data.
We will confirm the luminosity gain in the next operation.
Also the CW ratio will be optimized by lifetime and luminosity gain.

Machine Parameters

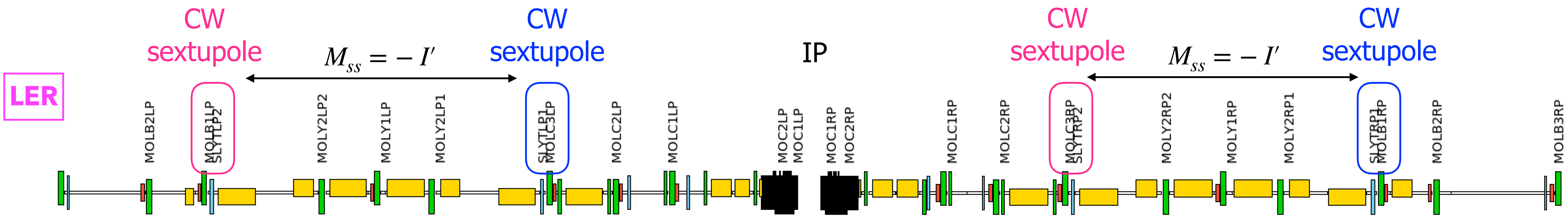
	May 22, 2022		June 8, 2022		June 22, 2022 *3		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	744	600	1321	1099	1363	1118	mA
Number of bunches	1565		2249		2249		
Bunch current	0.475	0.383	0.587	0.489	0.606	0.497	mA
Horizontal size σ_x*	17.6	16.6	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.250		0.303		0.315		μm *1
Vertical size σ_y*	0.177		0.215		0.223		μm *2
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.574	44.525 / 46.589	45.532 / 43.573	44.524 / 46.594	45.532 / 43.574	
β_x* / β_y*	80 / 0.8	60 / 0.8	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	40	80	40	%
Beam-Beam ξ_y	0.0309	0.0219	0.0407	0.0279	0.0398	0.0278	
Specific luminosity	8.74 x 10^{31}		7.21 x 10^{31}		6.95 x 10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.49 x 10^{34}		4.65 x 10^{34}		4.71 x 10^{34}		$cm^{-2}s^{-1}$

$\sigma_y^* \simeq 2 \times$  virus

*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by $\sqrt{2}$
*3) Belle II HV off

Beam Tuning

- Crab waist scheme
- Chromatic X-Y couplings at IP



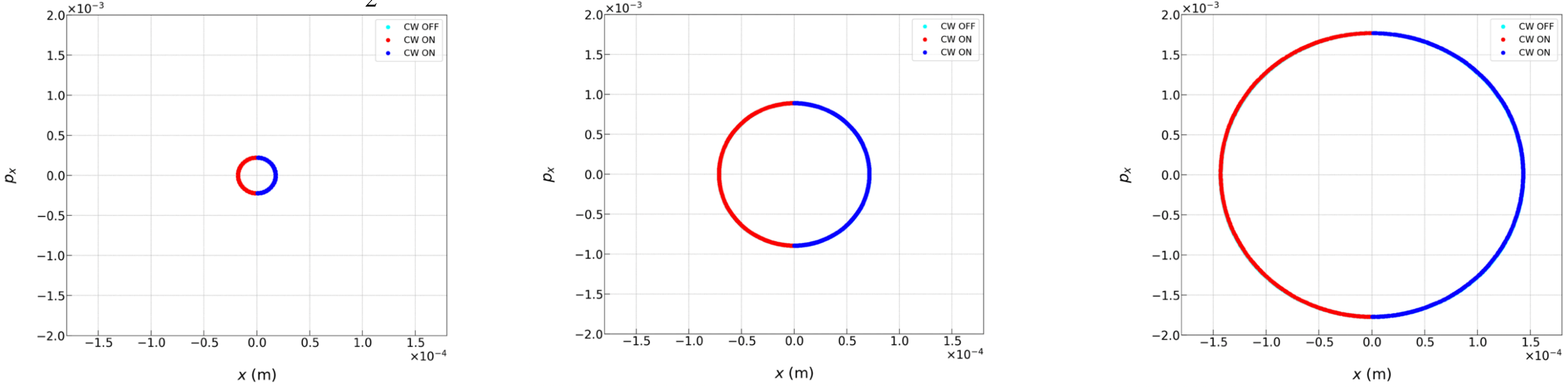
$$\Delta\psi_x = \psi_x^s - \psi_x^* \quad \sim \pi$$
$$\Delta\psi_y = \psi_y^s - \psi_y^* \quad \sim \frac{3}{2}\pi$$

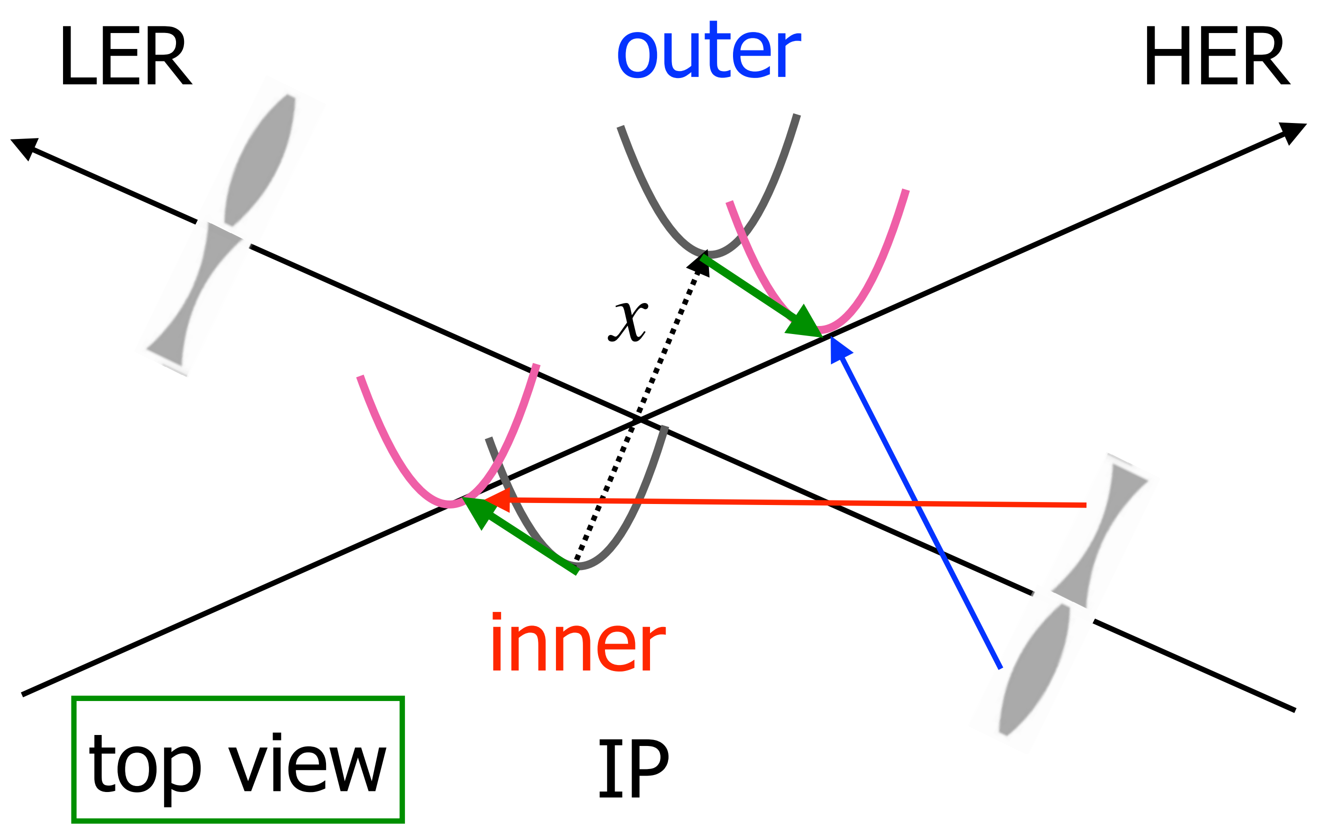
Crab Waist

Crab waist scheme creates α_y^* according to x at the IP. The sextupole makes vertical focusing and defocusing for outer and inner particles of the horizontal direction, respectively.

$$\Delta s = \beta_y^w \alpha_y^*$$

Horizontal

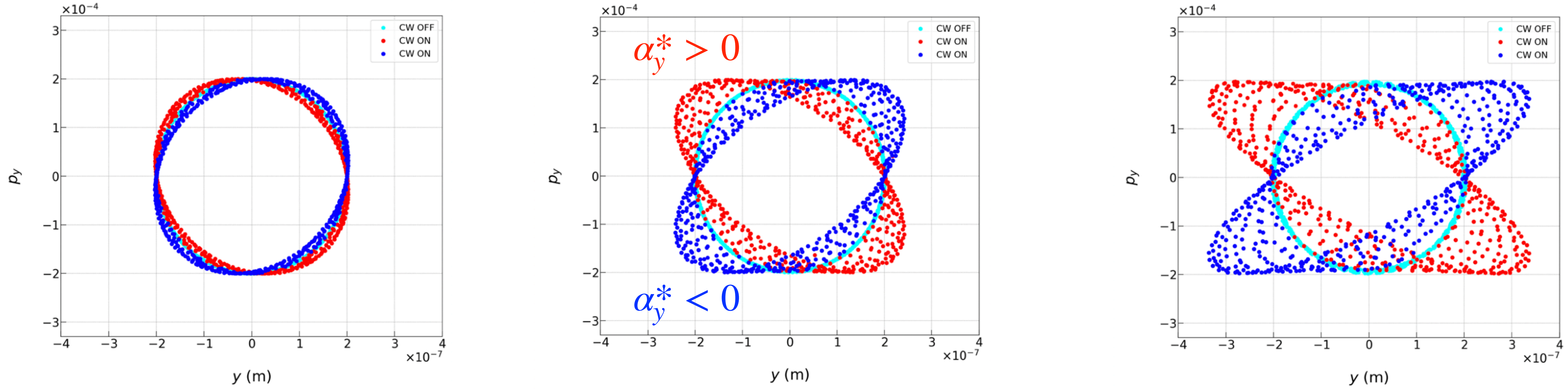




$$H_{CW} = -\frac{1}{2\tan 2\phi_x} x^* p_y^{*2}$$

Vertical

* multi-turn tracking of single particle



It is expected to reduce resonance lines and bean-tail due to beam-beam.

$$\sigma_y^{*2} = \mu^2 \varepsilon_y \left(\beta_y^* + \frac{\Delta s^2}{\beta_y^*} \right) + (\eta_y^* \sigma_\delta)^2 + \frac{\varepsilon_x}{\beta_x^*}(r_2^* + r_4^* \Delta s)^2 + \varepsilon_x \beta_x^* (r_1^* + r_3^* \Delta s)^2$$

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

if waist (Δs) is corrected to be zero.

vertical dispersion

X-Y couplings

Vertical emittance, vertical dispersion, coupling parameters r_1 and r_2 at the IP are fundamental parameters for luminosity performance.
Those parameters will be optimized so as to maximize luminosity.

Definition of X-Y couplings:

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} + \begin{pmatrix} \eta_u \\ \eta_{p_u} \\ \eta_v \\ \eta_{p_v} \end{pmatrix} \delta = \begin{pmatrix} \mu & 0 & -r_4 & r_2 \\ 0 & \mu & r_3 & -r_1 \\ r_1 & r_2 & \mu & 0 \\ r_3 & r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}$$

decoupled coordinate — **R** — physical coordinate

$$\mu^2 + \det \mathbf{R} = 1$$

Coupling matrix:

$$\begin{pmatrix} \gamma \mathbf{I} & \mathbf{C} \\ -\mathbf{C}^+ & \gamma \mathbf{I} \end{pmatrix} = \begin{pmatrix} \mu \mathbf{I} & -\mathbf{J}\mathbf{R}^\mathbf{T}\mathbf{J} \\ -\mathbf{R} & \mu \mathbf{I} \end{pmatrix}$$

$$\gamma^2 + \det \mathbf{C} = 1$$

There are 24 sextupole magnets on a supporting table in the LER and make them roll to induce skew sextupole field.

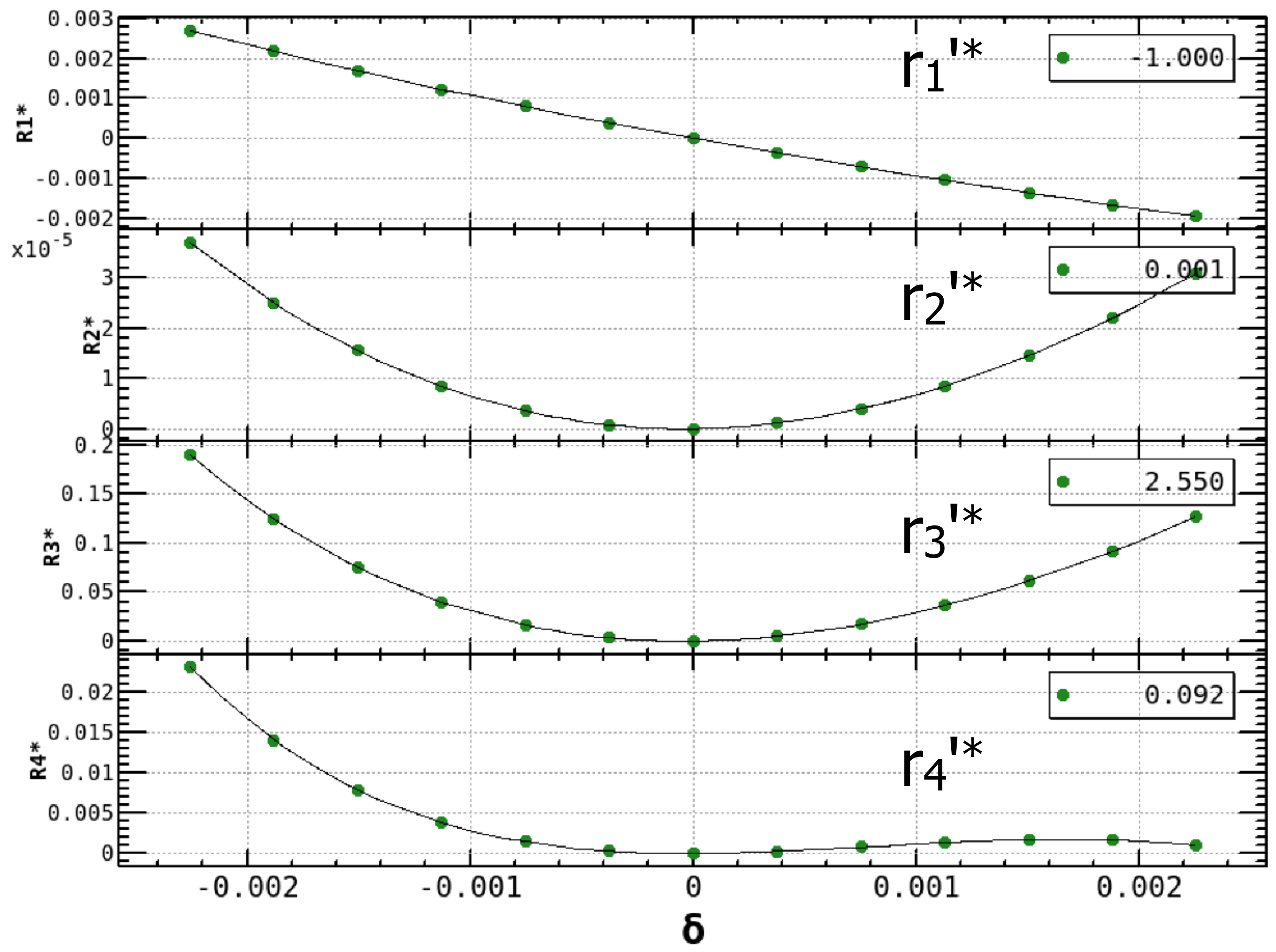
The 12 sextupoles are located at each side of the IP among 54 sextupoles in total.

Those sextupoles are used to make chromatic X-Y couplings at the IP by matching procedure with chromaticity correction.
The chromatic X-Y couplings of r_1^* and r_2^* are effective for luminosity.

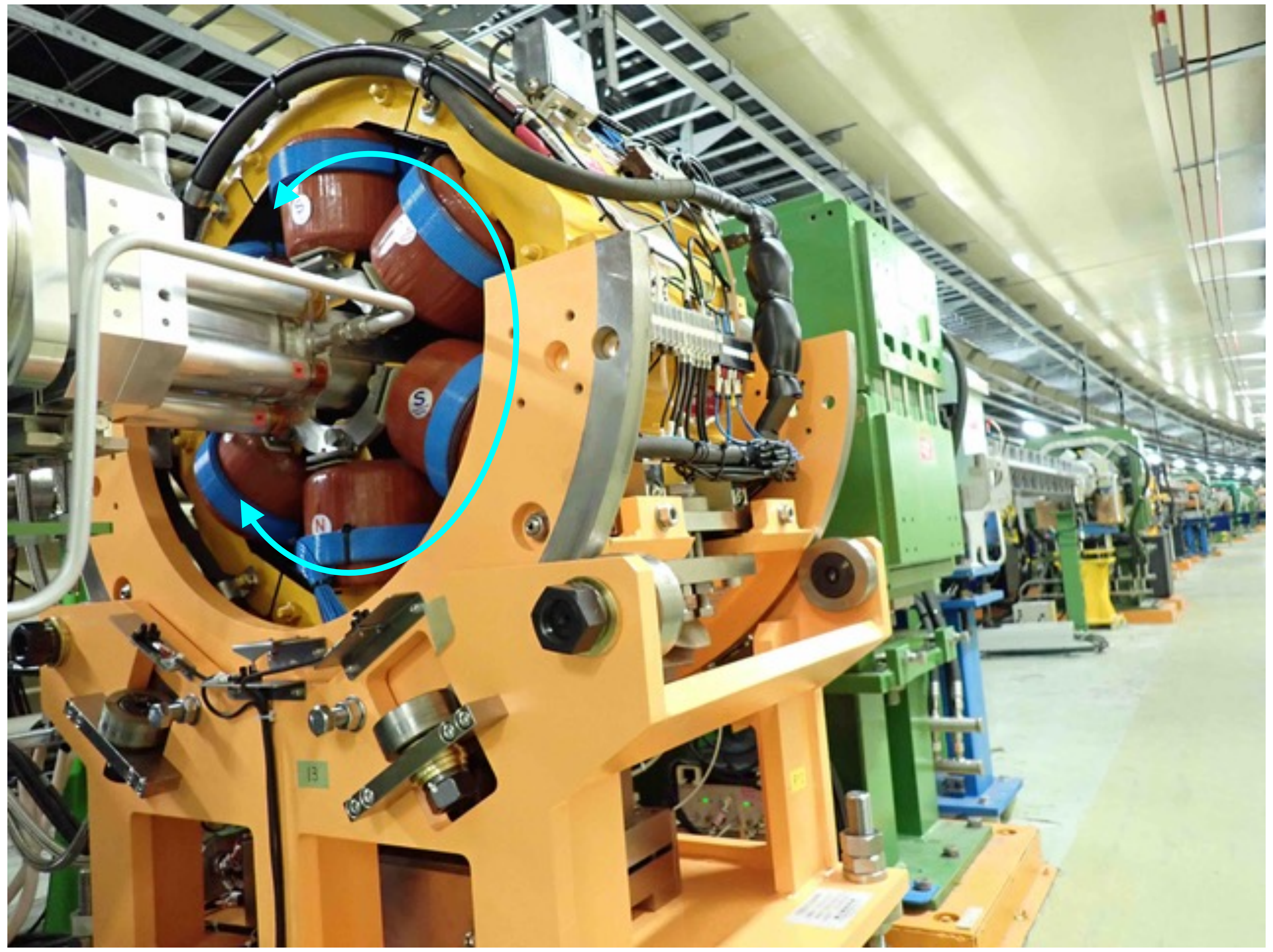
$$\frac{\partial r_1^*}{\partial \delta} = -1$$

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

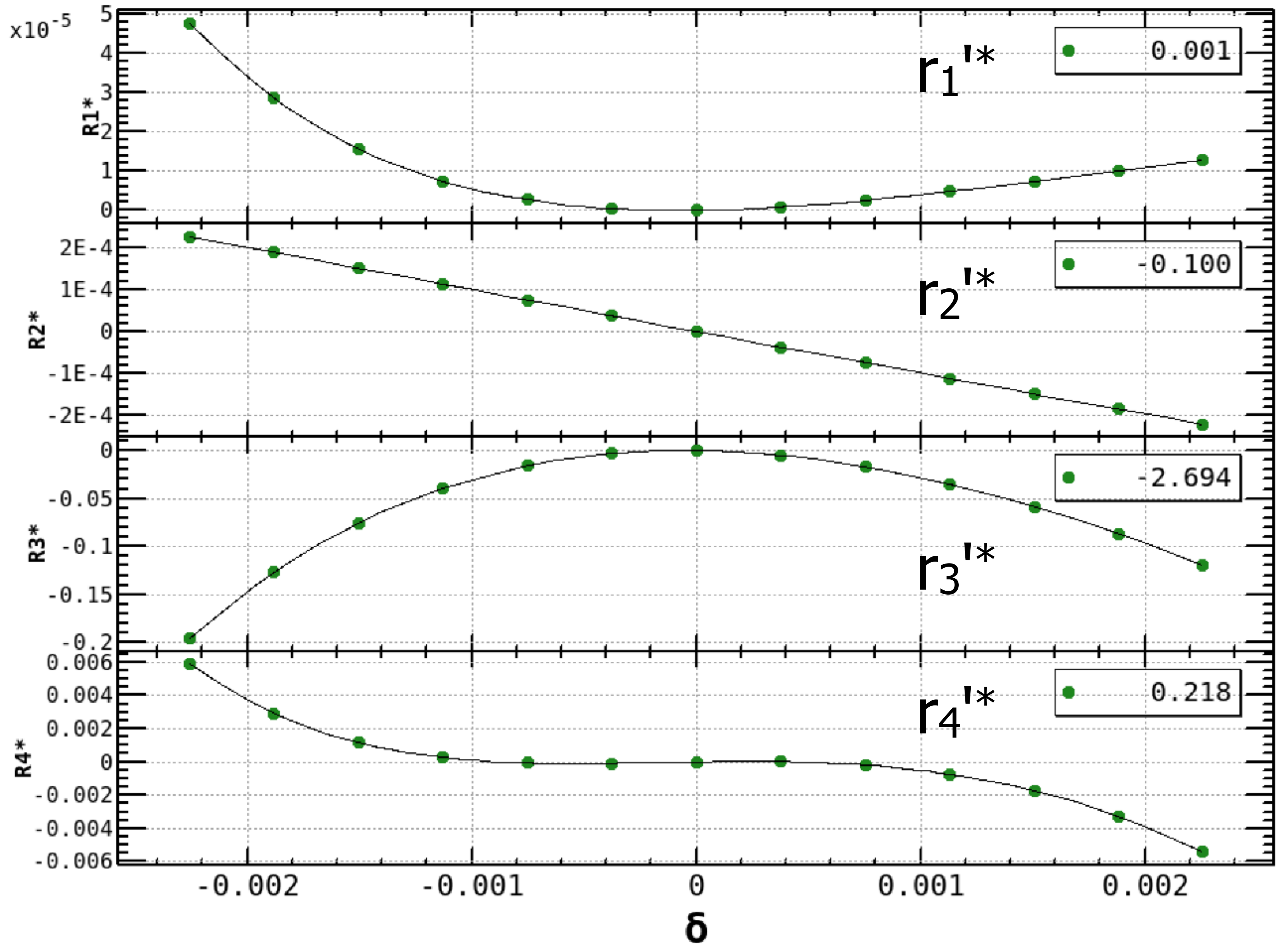
$$\frac{\partial r_2^*}{\partial \delta} = -0.1\ m$$



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



$$r_1 = C_{22} \qquad r_2 = -C_{12}$$

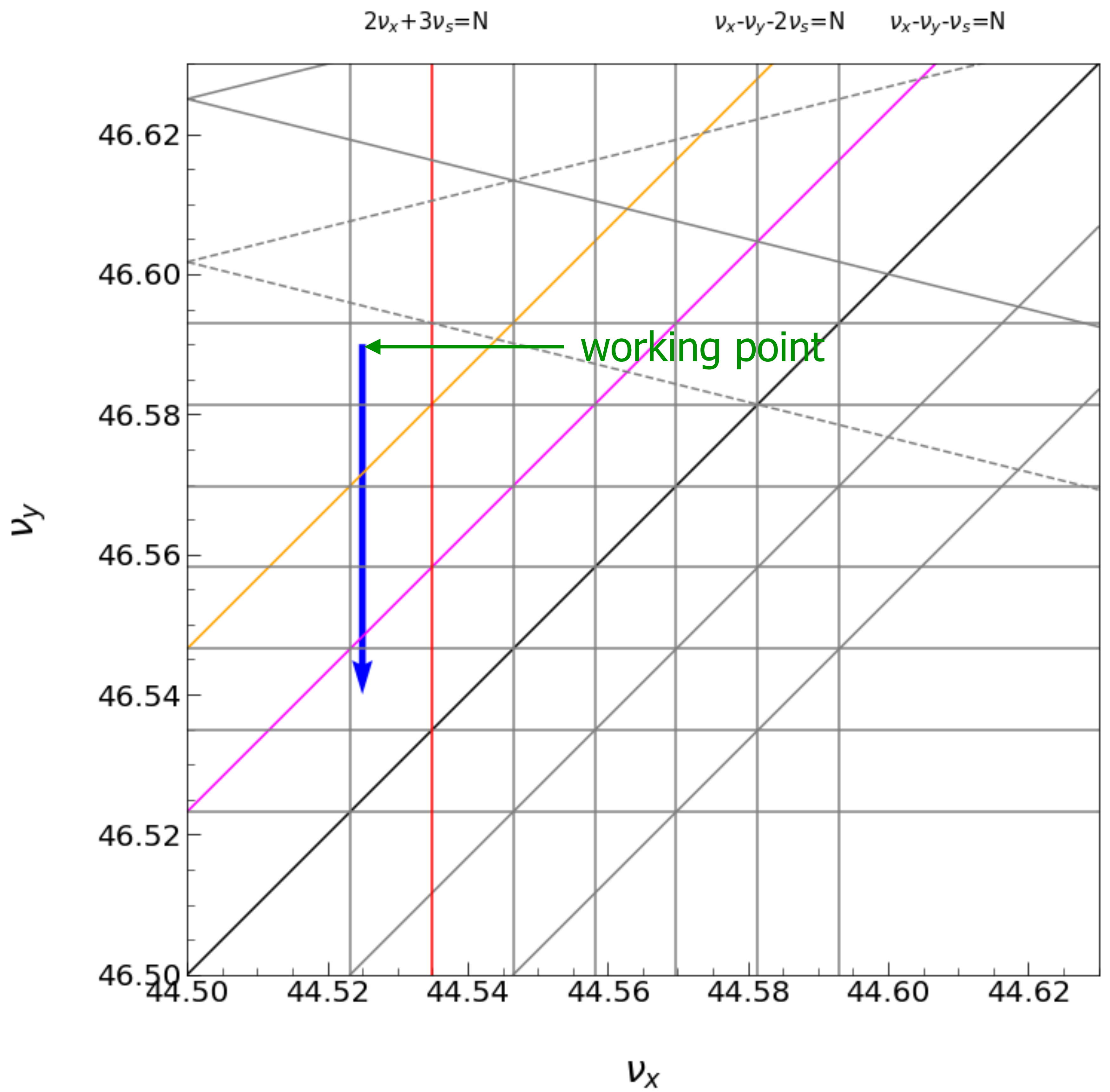


$$\frac{\Delta p}{p_0}$$

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

Chromatic X-Y Coupling Correction with Rotatable Sextupoles in LER

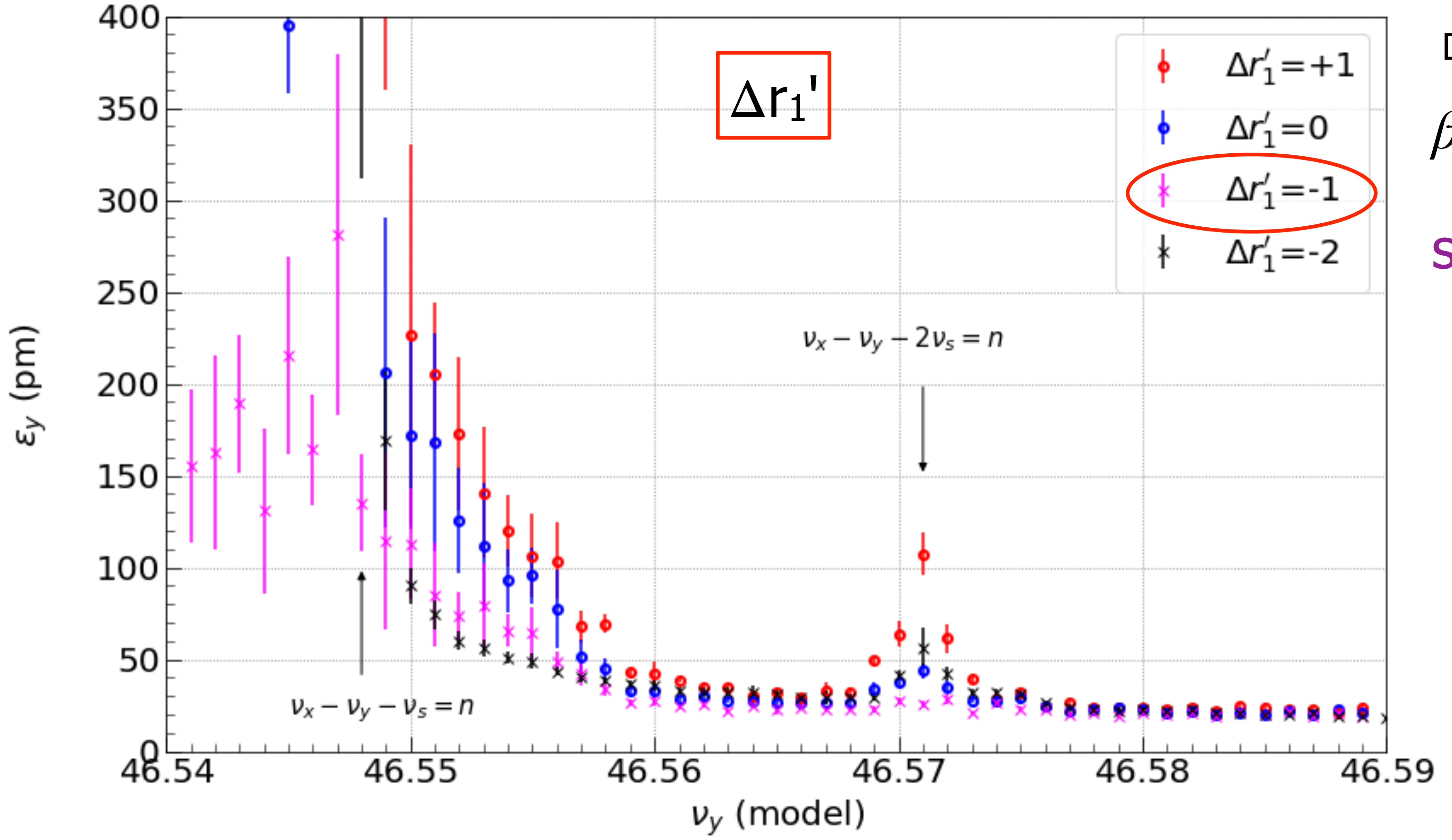
synchro-beta X-Y couplings



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

SLYTLPs and SLYTRPs were not used here.

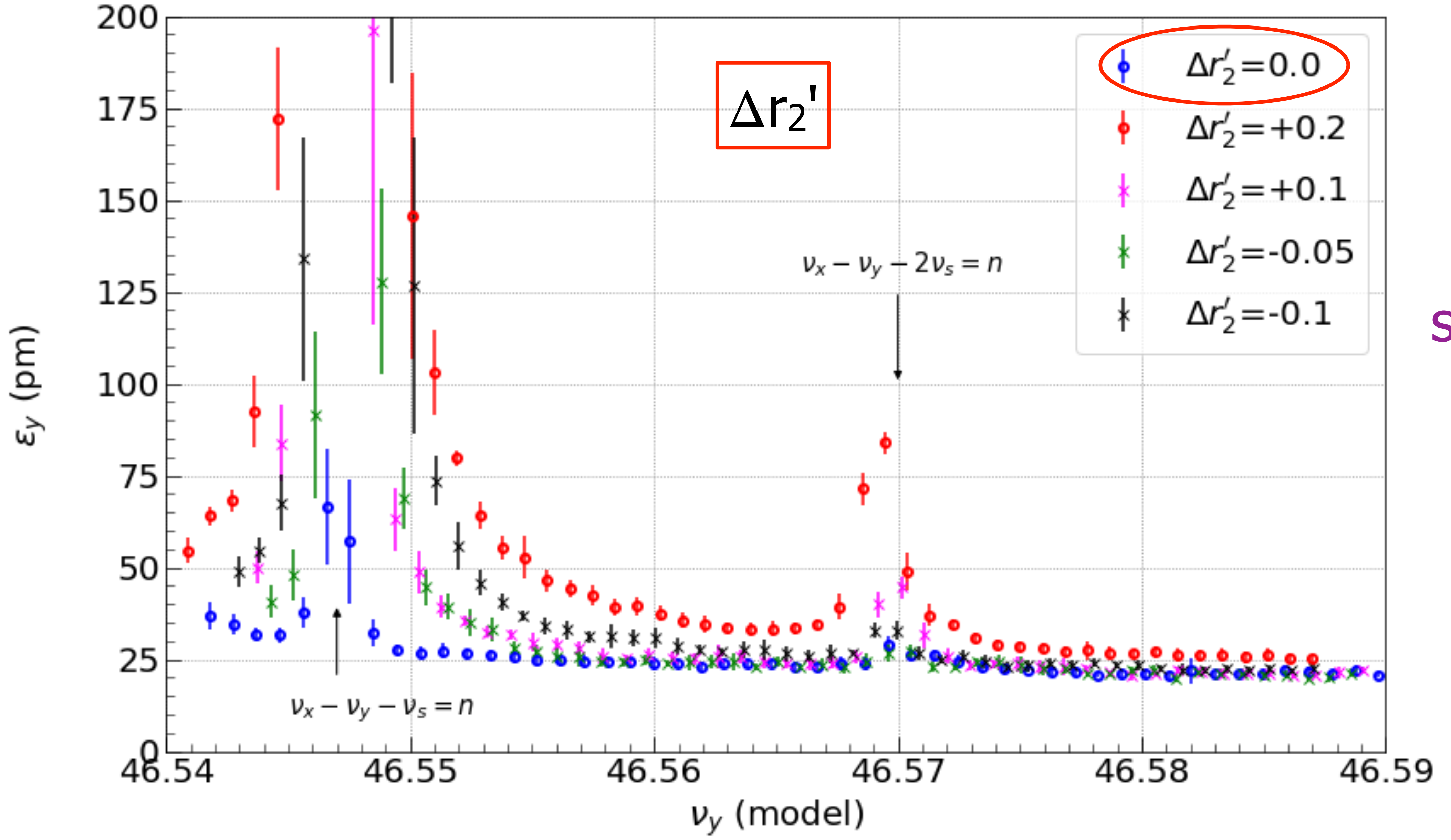
Rotatable sextupoles:
M. Masuzawa, T. Kawamoto et al.



Dec. 20, 2021

$\beta_y^* = 1\ mm$

single beam



March 14, 2022

$\beta_y^* = 1\ mm$

$\Delta r_1' = -1$

single beam

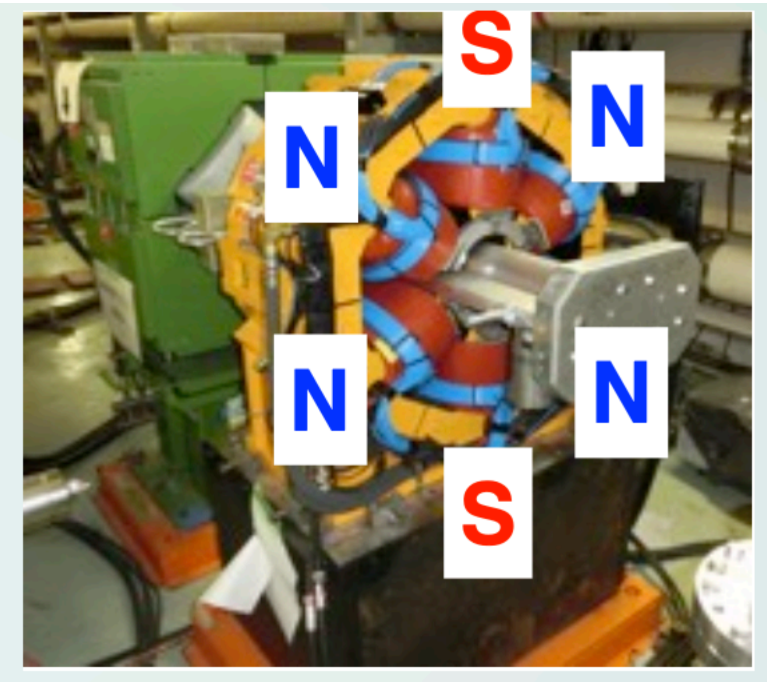
$\Delta r_2' = 0$
is optimal.

Optics Corrections

- The optics correction is performed at a low beam current. Typically, about 50 mA.
- Performance of optics corrections (beta, dispersions, X-Y couplings) for $\beta_y^* = 1\ mm$:

	LER	HER	unit
$(\Delta\beta_x/\beta_x)_{rms}$	5	5	%
$(\Delta\beta_y/\beta_y)_{rms}$	5	5	%
$(\Delta\eta_x)_{rms}$	10	30	mm
$(\Delta\eta_y)_{rms}$	5	5	mm
$(\Delta y)_{rms}/(\Delta x)_{rms}$	0.016	0.012	
ε_y	25	40	pm
$\varepsilon_y/\varepsilon_x$	0.63	0.87	%

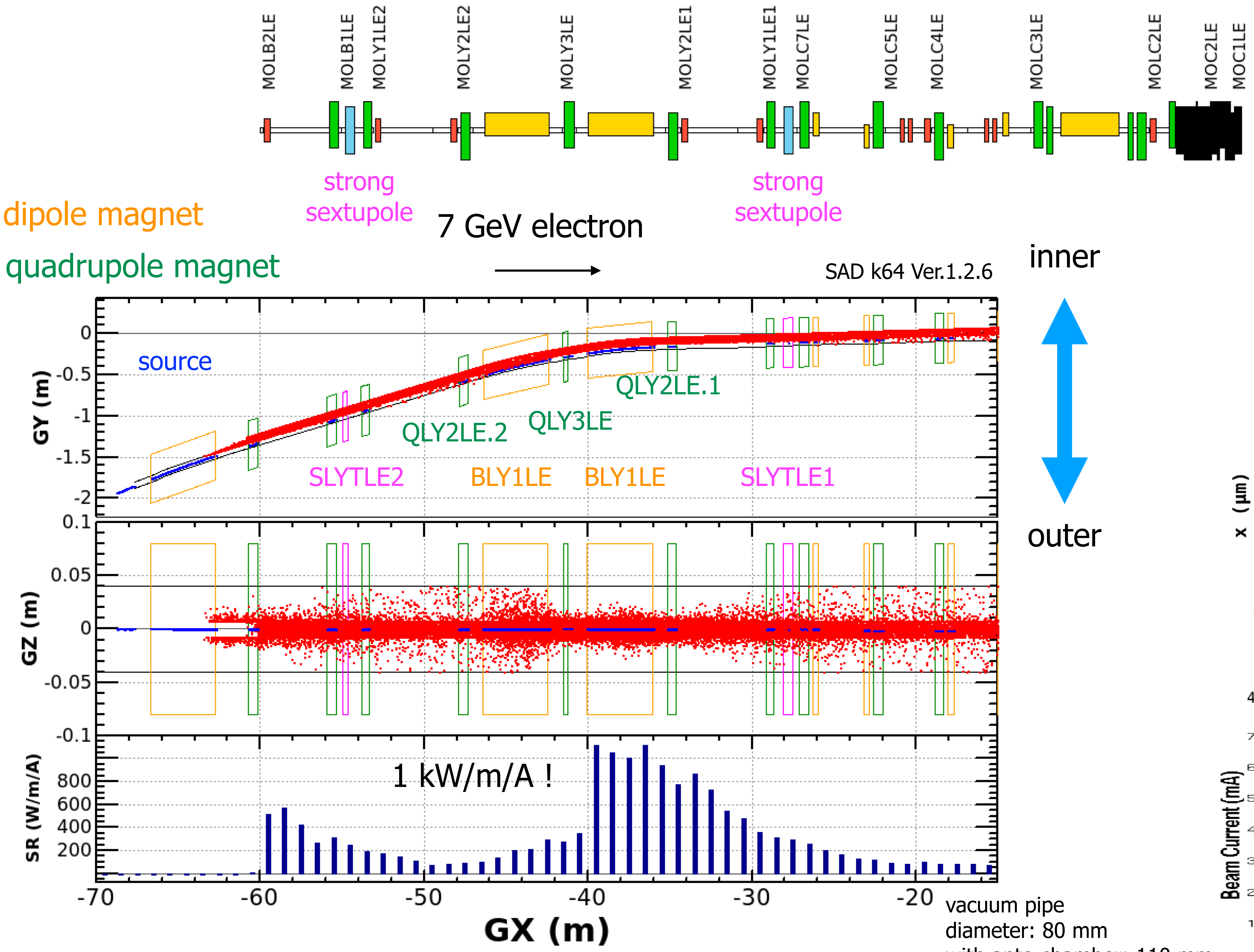
Vertical dispersions and X-Y couplings are corrected by using skew quad-like correctors.



- These results are obtained at low beam currents. The operation beam current is larger than 1 A.
- Beam pipe is deformed due to intense SR heating. BPM with beam pile is connected with a neighbor quadrupole magnet tightly. BPM can push the quadrupole magnet horizontally, horizontal kick is induced.
- Horizontal orbit at the strong sextupole creates large beta-beat.

H. Sugimoto et al., TUXAT0103, Proc. of eeFACT'22, Frascati, Italy, 2022

Synchrotron Radiation at Strong Sextupole Region in HER

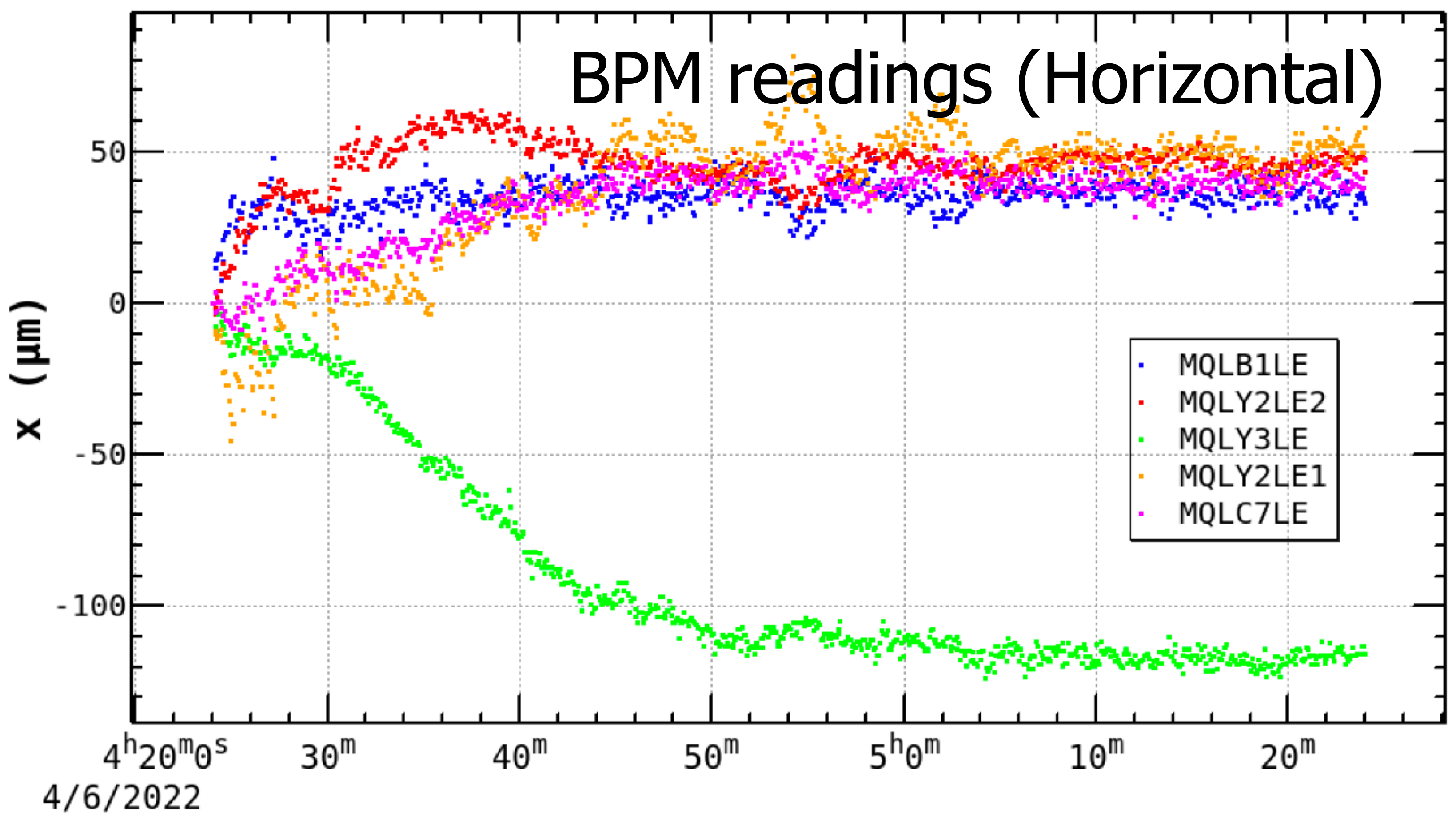


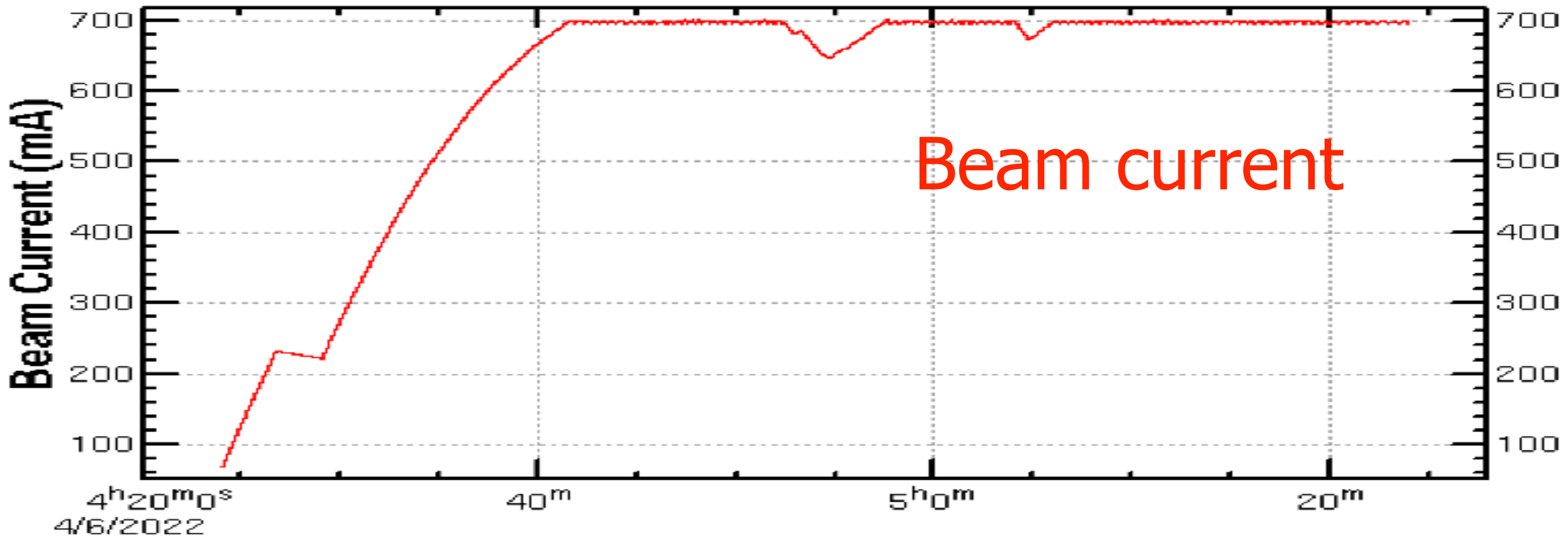
vacuum pipe
diameter: 80 mm
with ante-chamber: 110 mm
height: 14 mm (±7 mm)

The sextupole magnet does not touch the beam pipe.

So, the sextupole does not move due to the beam pipe deformation.

Beam pipe pushes quadrupoles with BPM, they move due to intense SR heating.

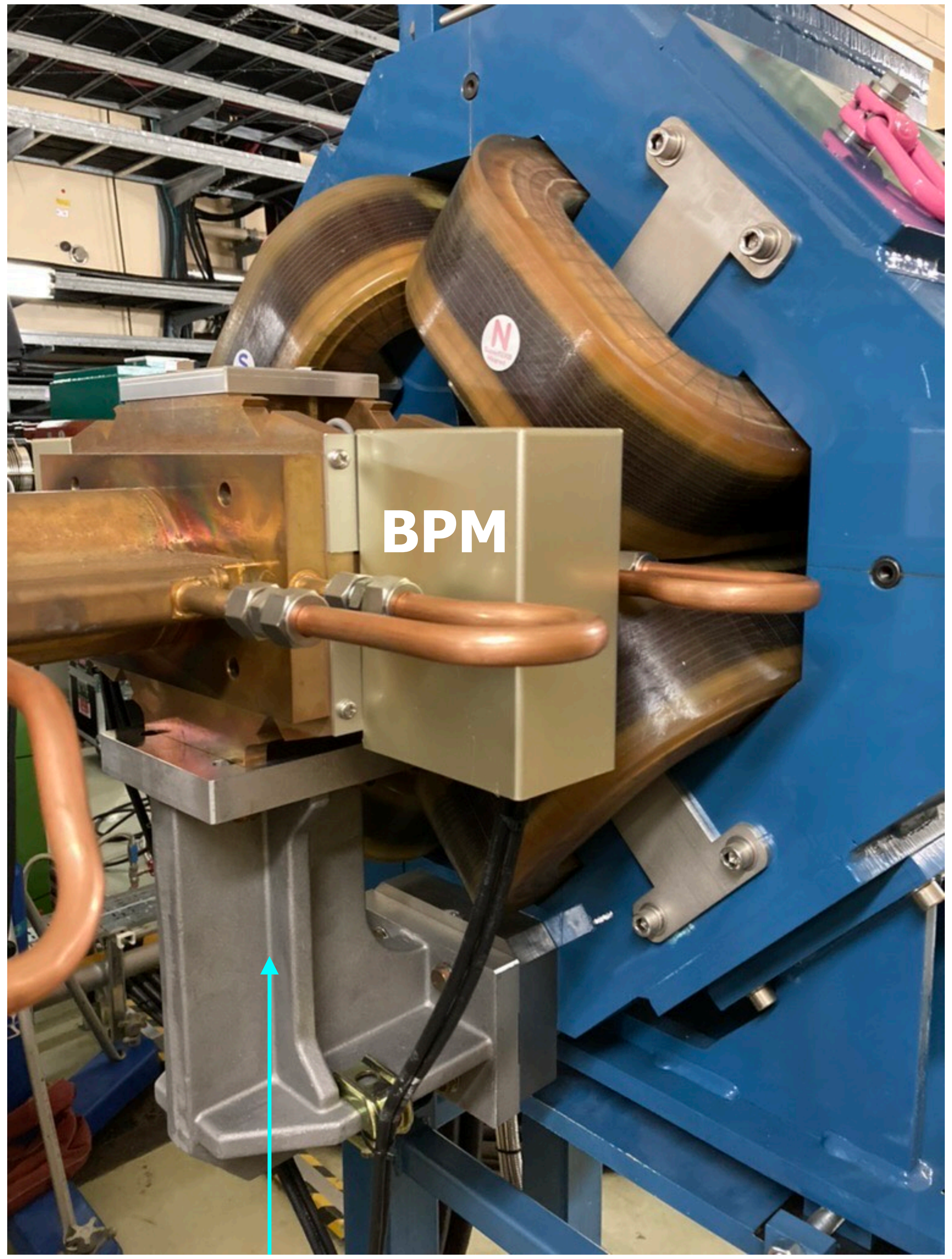




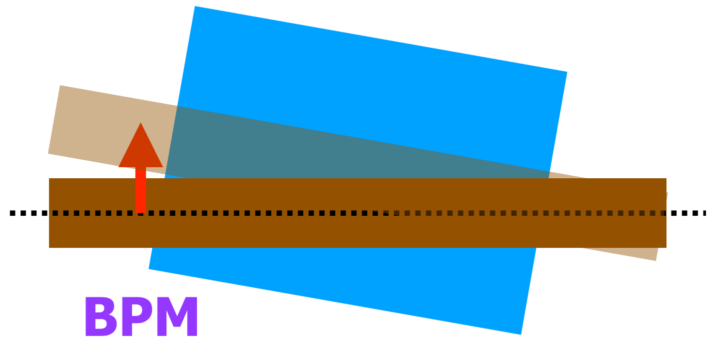
BPMs, Quadrupoles, and Sextupoles

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

BPM and Quadrupole Magnet

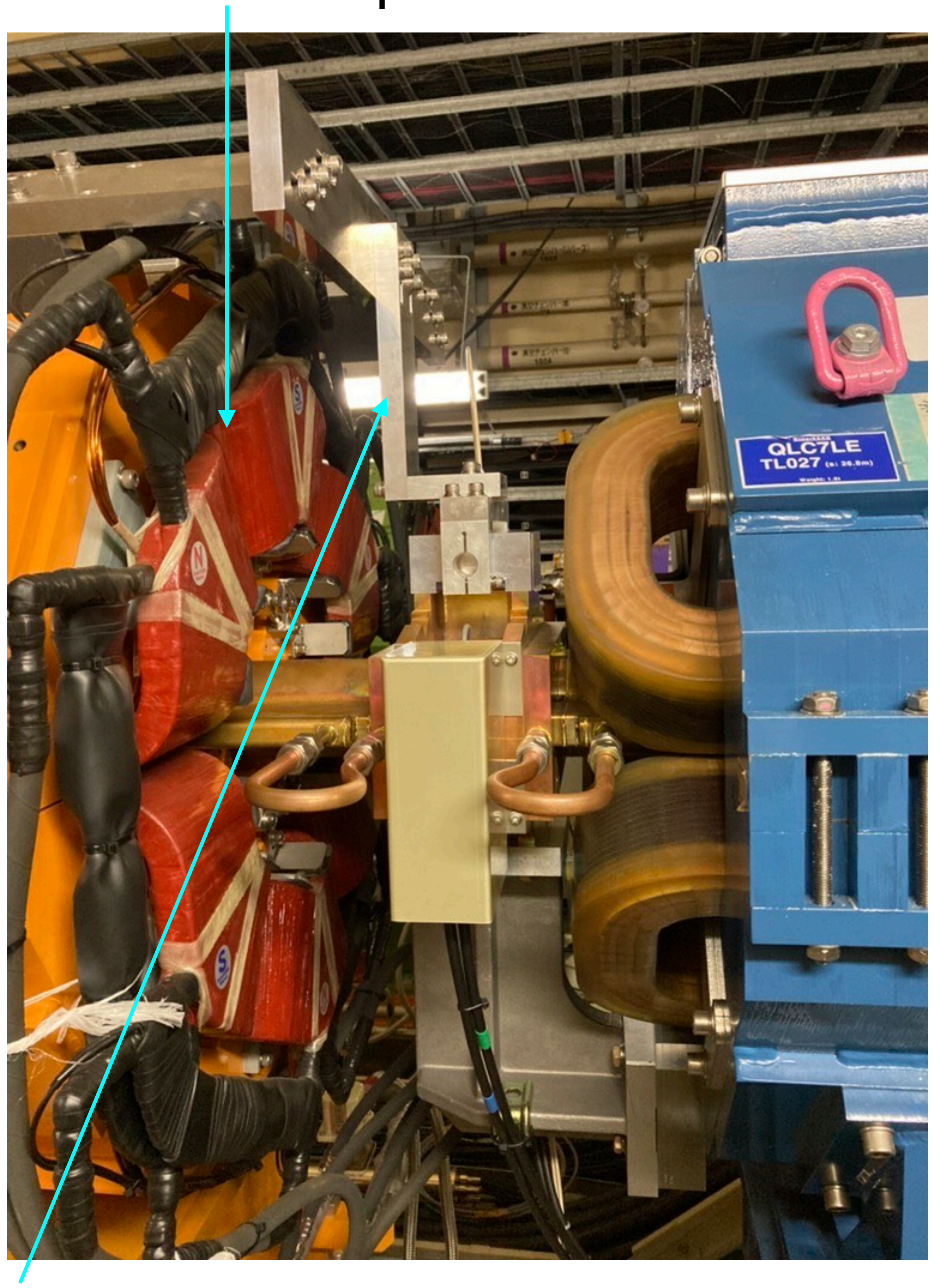


The beam pipe (BPM) is fixed to the quadrupole magnet.



Quad. moves like yaw and horizontal shift if BPM pushes quad.

Crab Sextupole in the HER



Gap sensor measures $(\Delta x, \Delta y)$ between BPM and sextupole.
Relation between BPM and quad. does not change. (see left fig.)

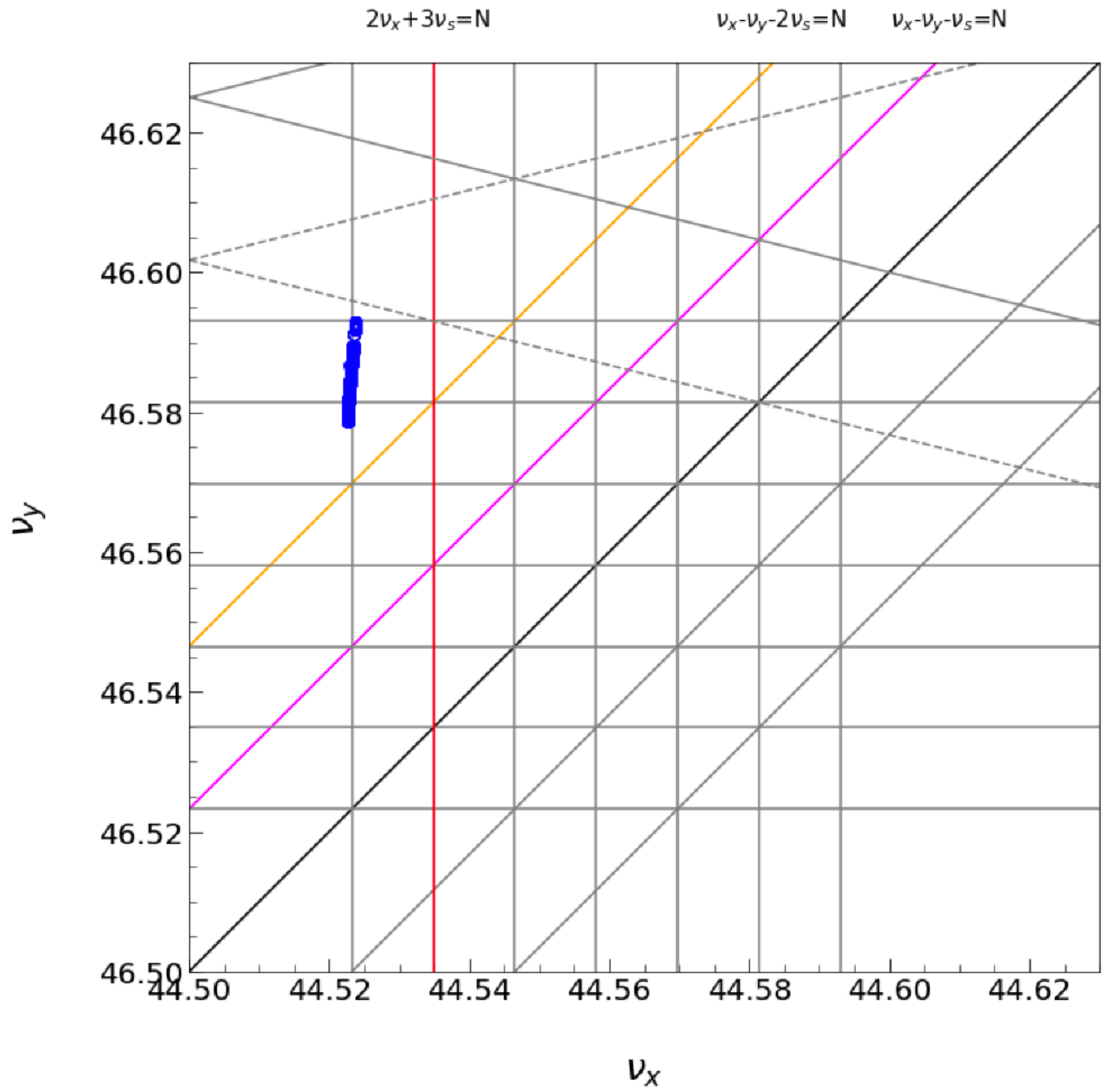
Deformation

Challenge of Optics Tuning at SuperKEKB

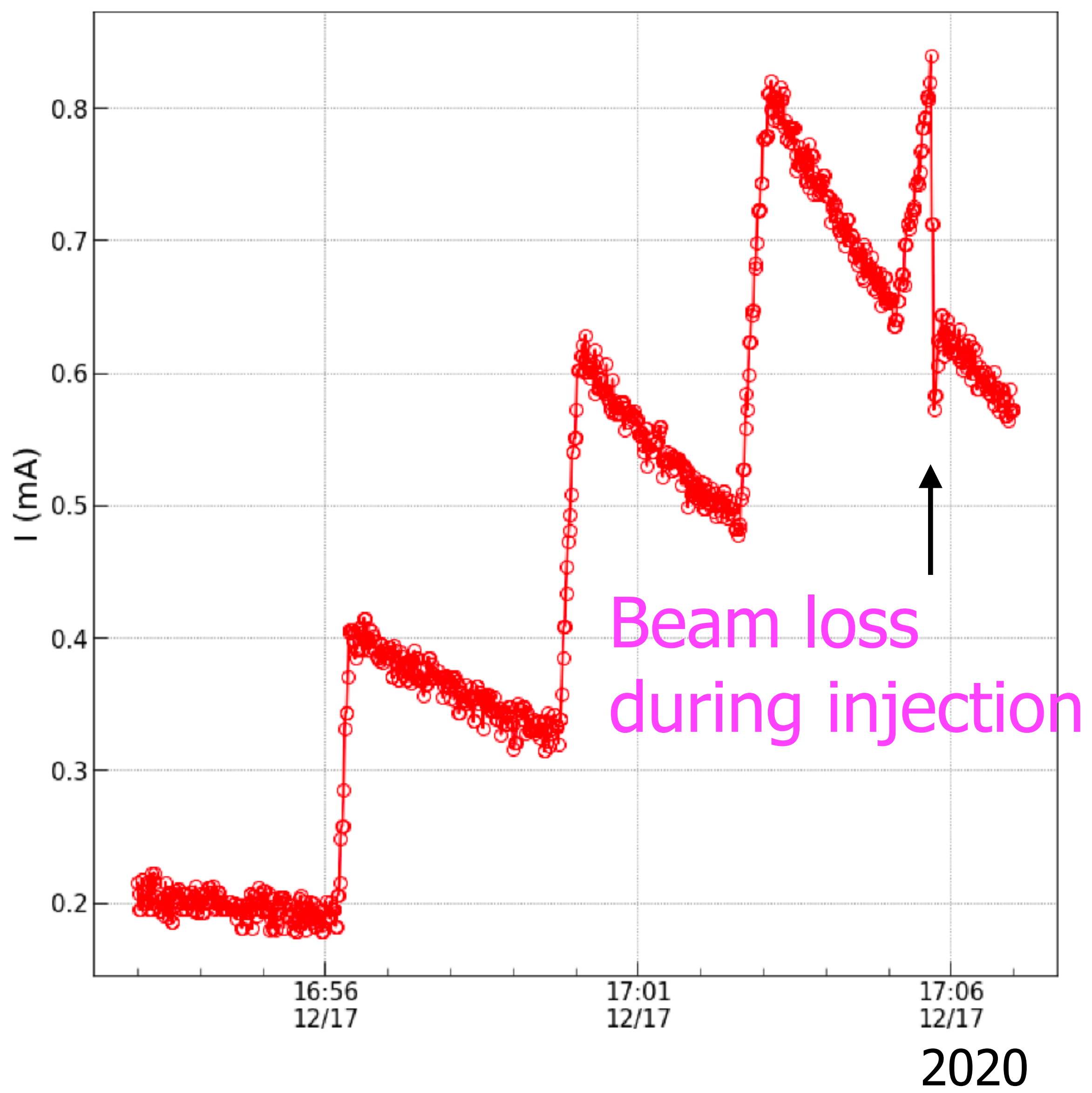
Obstacles to Luminosity Improvement

- Impedance of Collimators, TMCI and -1 mode instability
- Sudden Large Beam Loss

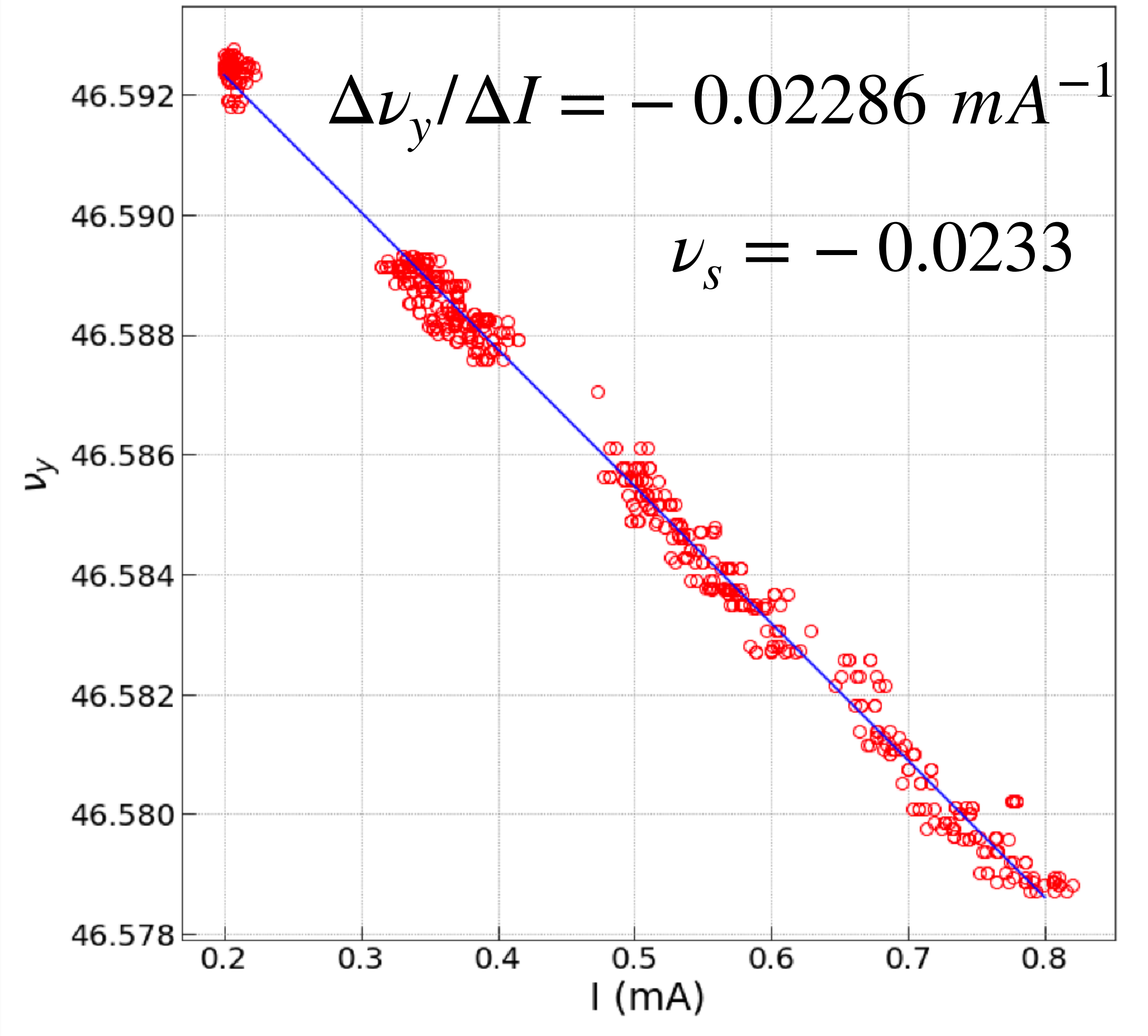
TMCI Observation at SuperKEKB

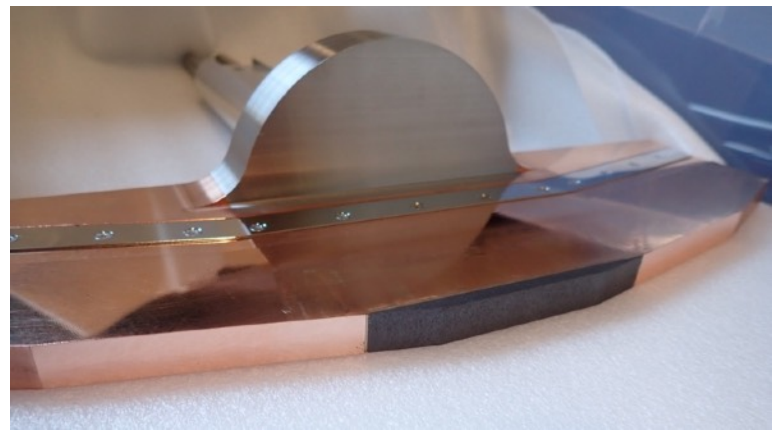


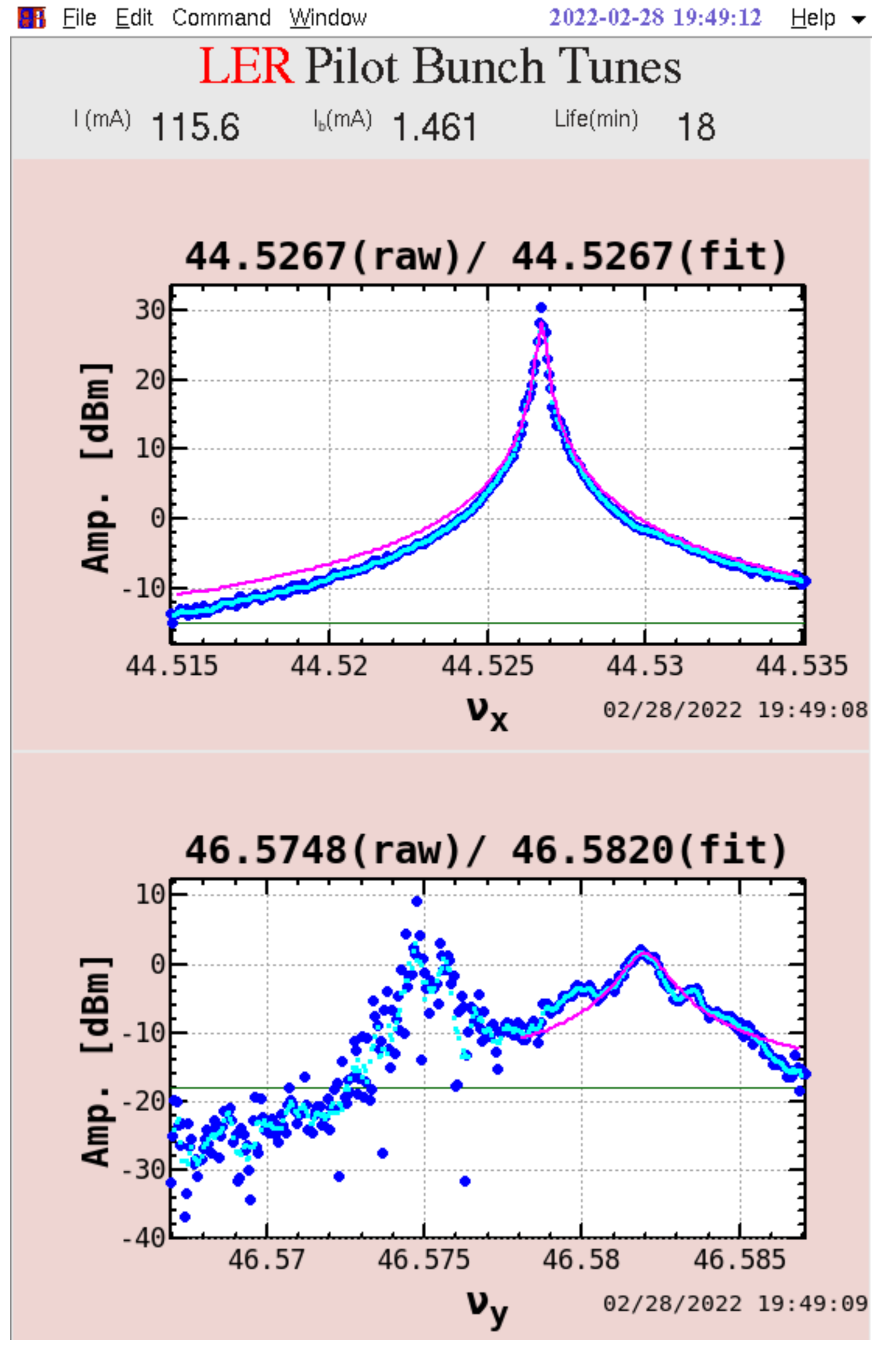
LER



single bunch operation

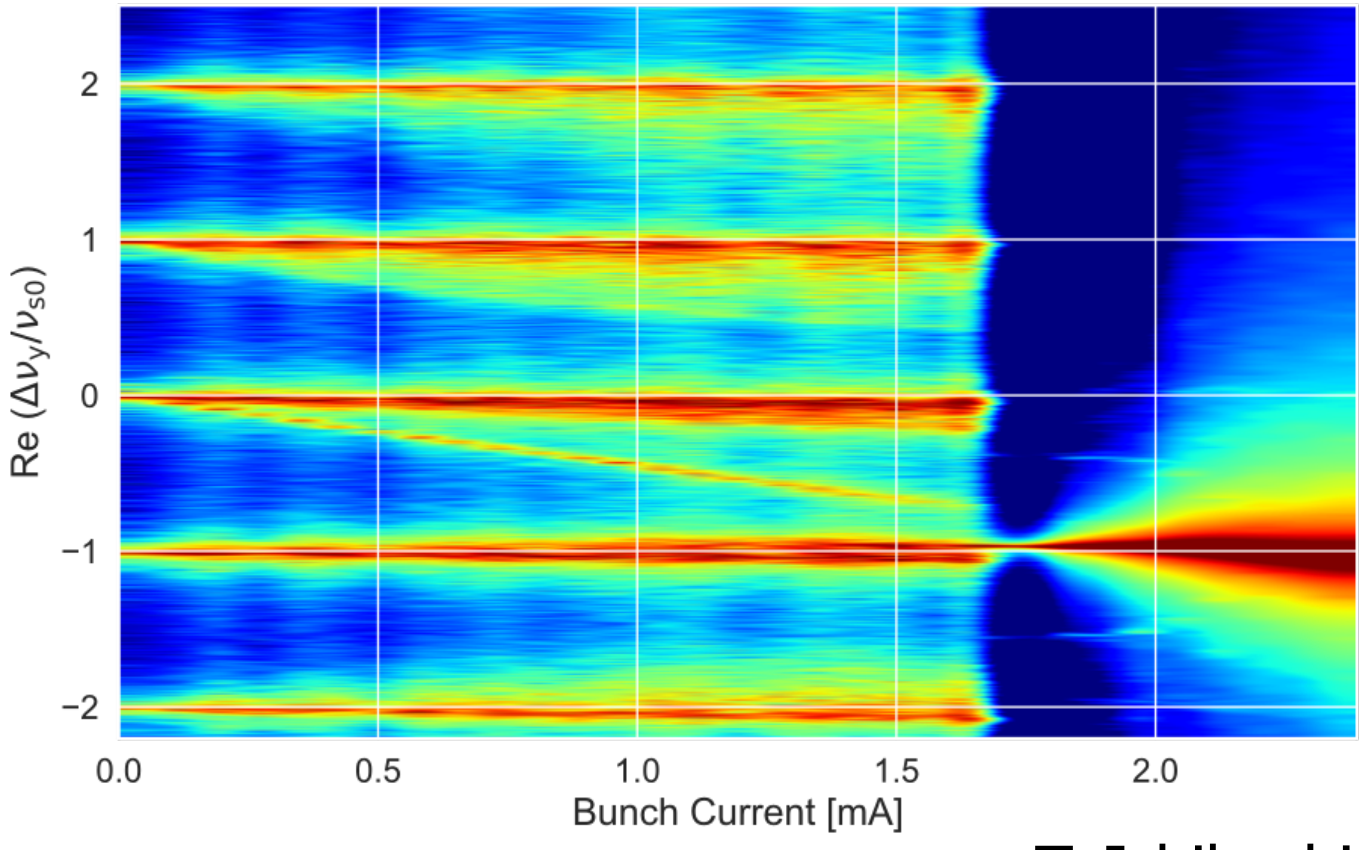






Tune measurement:
side band was observed
at high bunch current.

Simulation: PyHEADTAIL ($\Delta\nu_y/\Delta I \sim \nu_s/2$)



T. Ishibashi

We observed TMCI at SuperKEKB when we used a carbon head for one of the vertical collimators.
The tune shift was similar to the synchrotron tune and the threshold was 0.85 mA/bunch. (2020)

We control the vertical collimator aperture to keep the tune shift less than half of ν_s.
The TMCT threshold becomes 1.7 mA/bunch in the LER for the normal operation.

* We replaced the carbon head with tantalum after this experiment.

Single Bunch Tune Shift and Impedance

Tune shift is equivalent to impedance.

Larger circumference (larger T_0) makes larger tune shift.

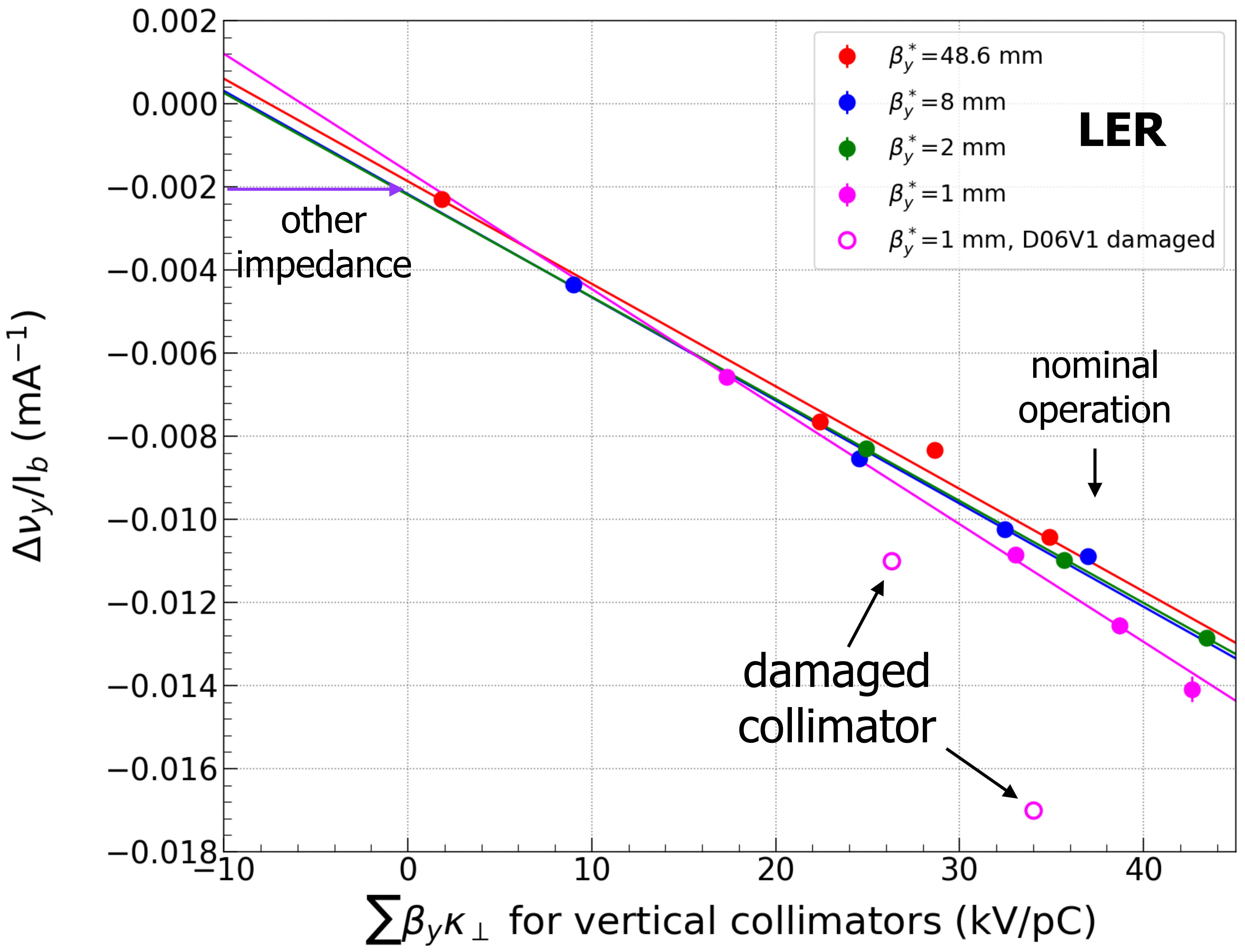
$$\frac{\Delta\nu_y}{I_b} = -\frac{T_0}{4\pi(E/e)}\sum_i \beta_{yi}\kappa_i(d)$$

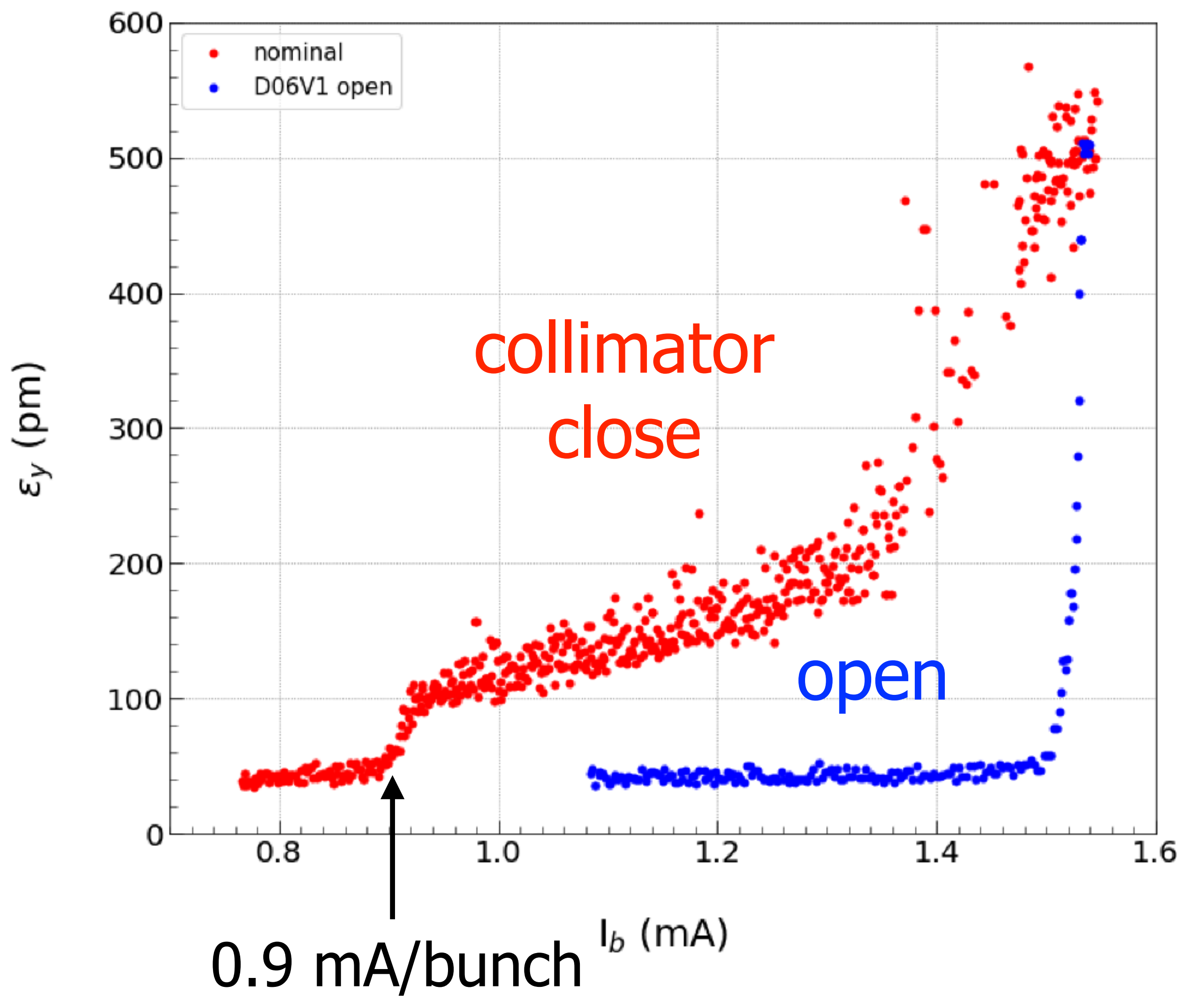
$$\rightarrow \frac{T_0}{4\pi(E/e)} = 0.2\ (ps/kV)$$ for SuperKEKB

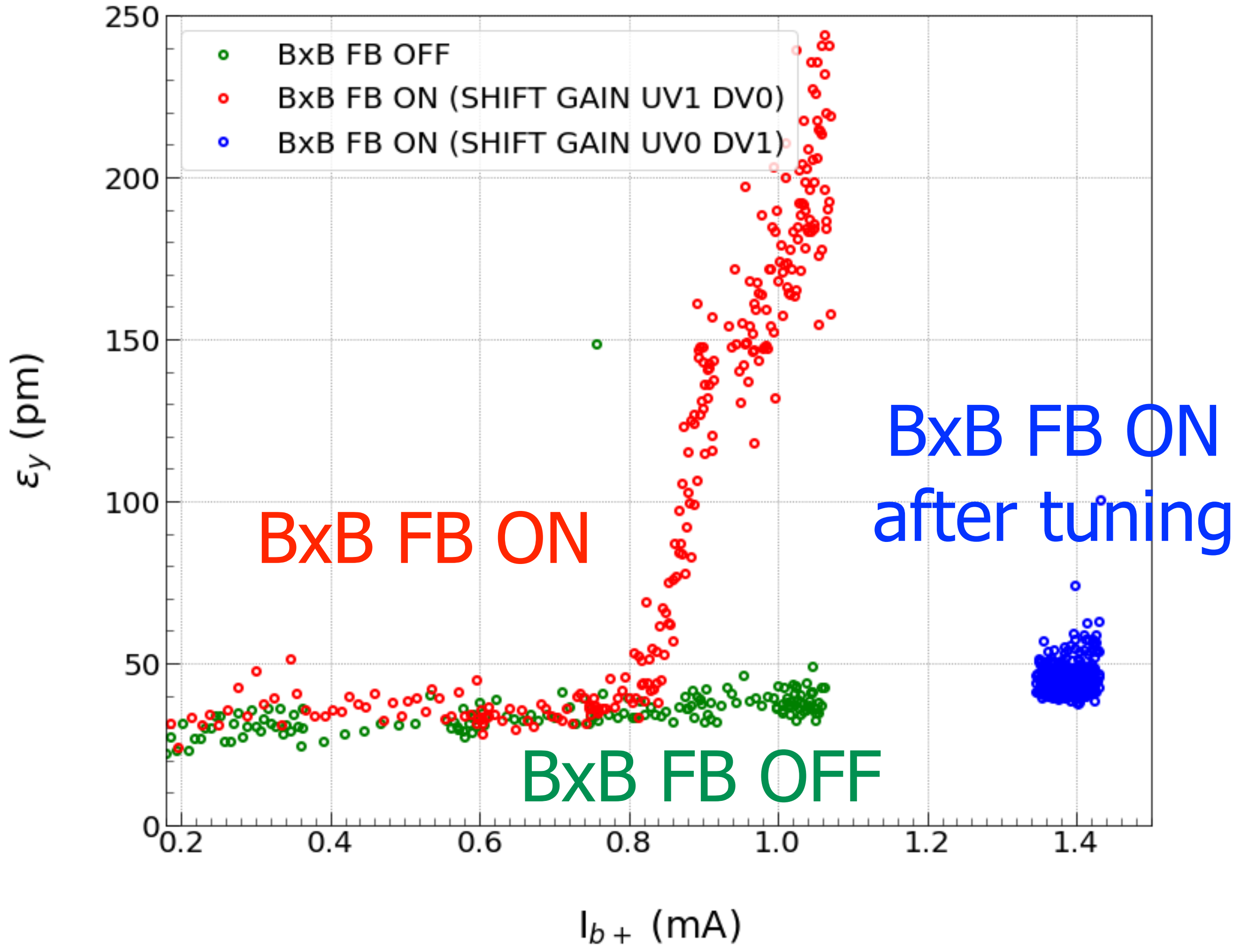
Kick factors of vertical collimators are calculated by GdfidL (and ECHO3D).

The vertical collimators contribute approximately 70 % of the total impedance.

Beam blowup was observed at much smaller than the TMCI threshold.
"-1 mode instability" ← impedance and BxB FB tuning







$$\sum\beta_y\kappa = 33.3\ (kV/pC)$$

Sudden Beam Loss (SBL)

Beam becomes unstable suddenly at high beam current.
Beam loss can lead to severe damage on collimators or final focus magnet (QCS) quench.

LER beam current : 1.4 A
number of bunches : 2249
luminosity : 4.58 x 10^{34} $cm^{-2}s^{-1}$

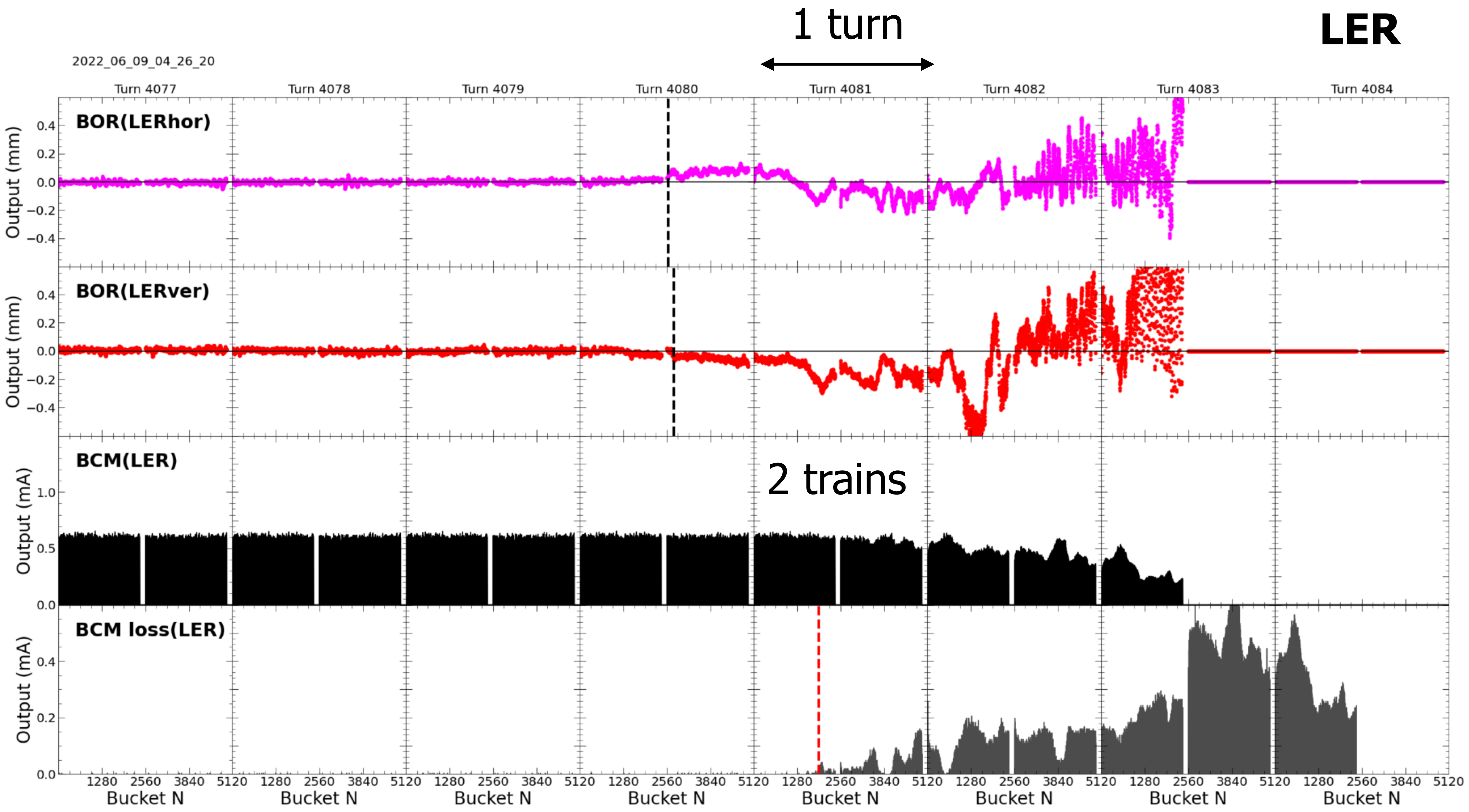
Beam loss within a few turns
without large oscillation before the loss.

Horizontal position

Vertical position

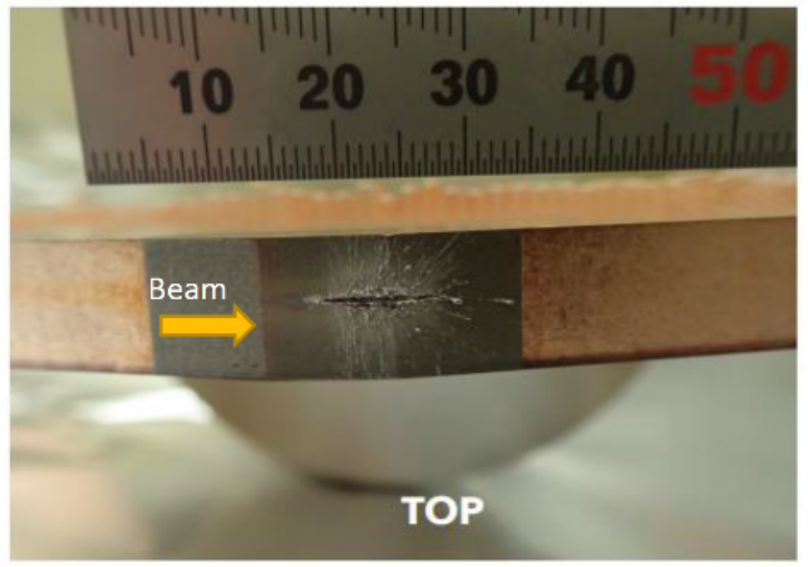
Bunch current

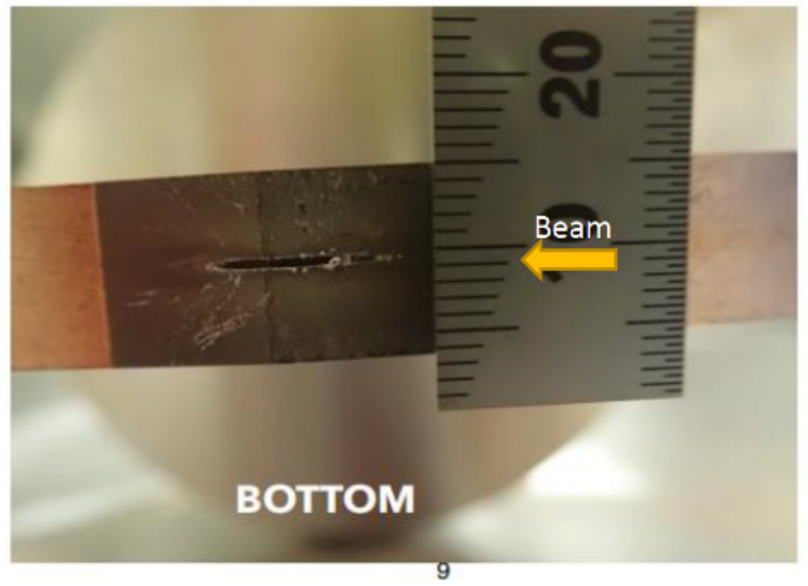
Amount of beam loss



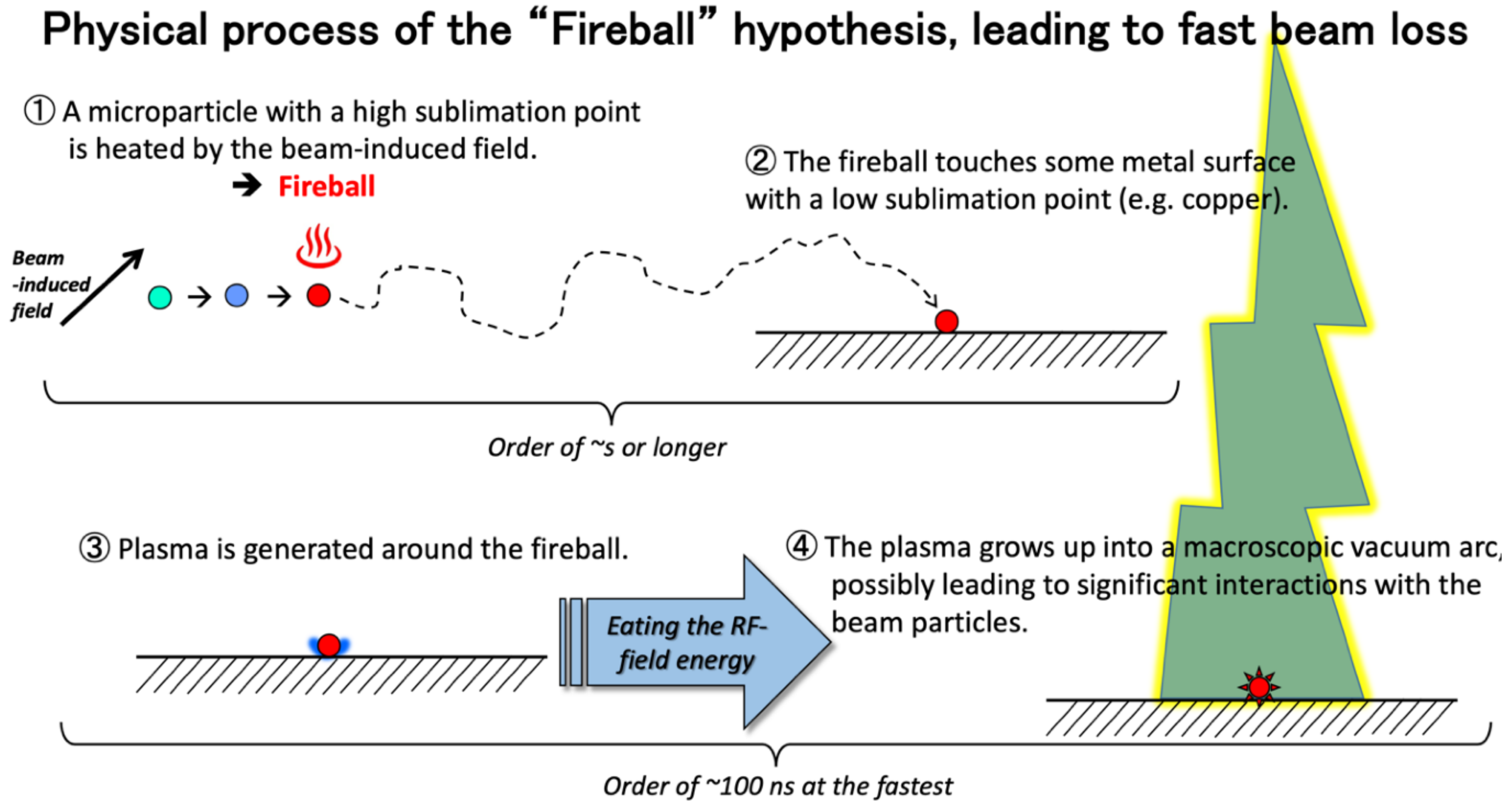
M. Aversano

Damage of collimator head





Fireball hypothesis



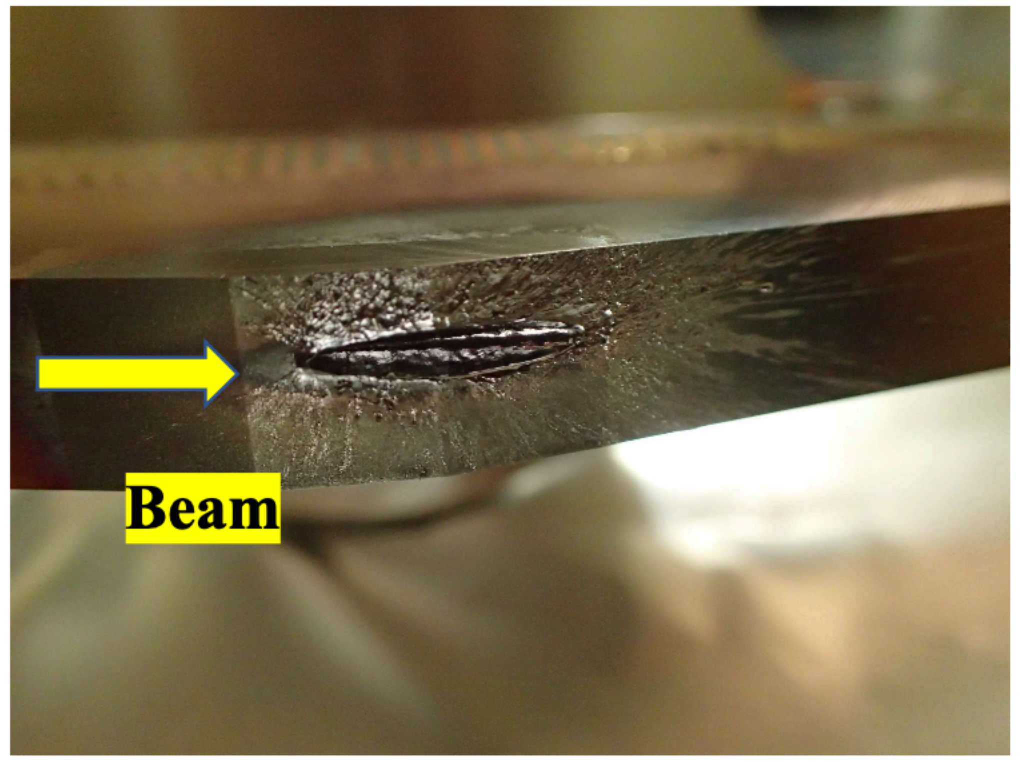
T. Abe at al., RF breakdown trigger, PR-AB 21, 122002, 2018.

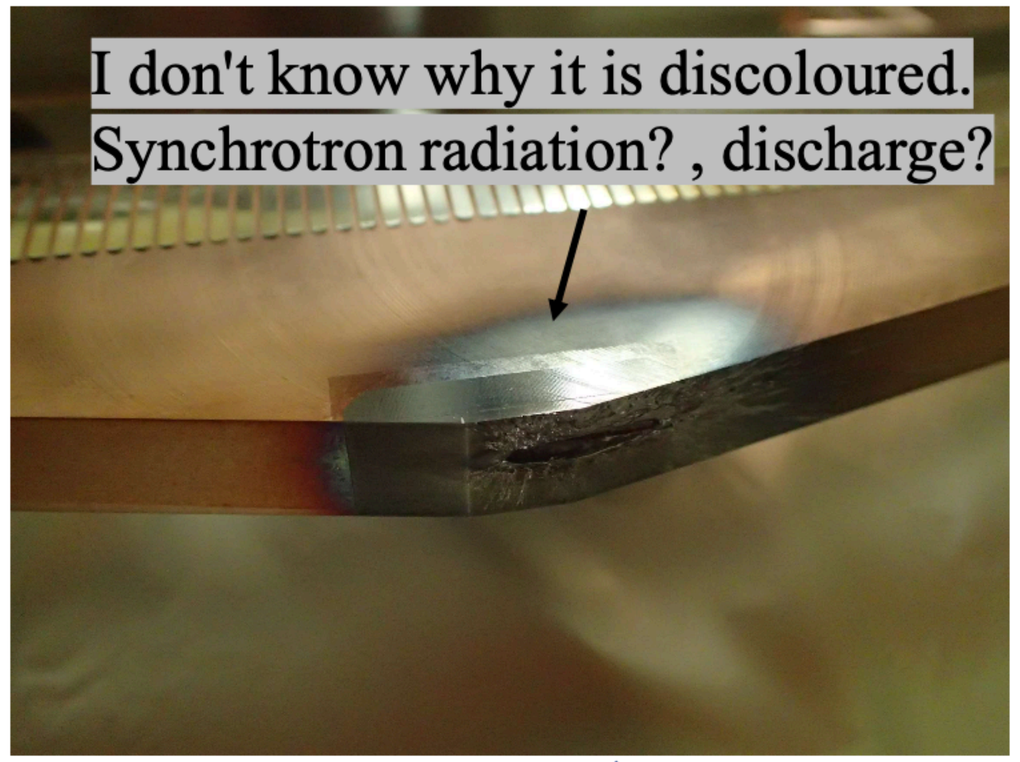
Trigger source can be collimator head.

Copper coating of collimator head will be effective if different sublimation point is problem.

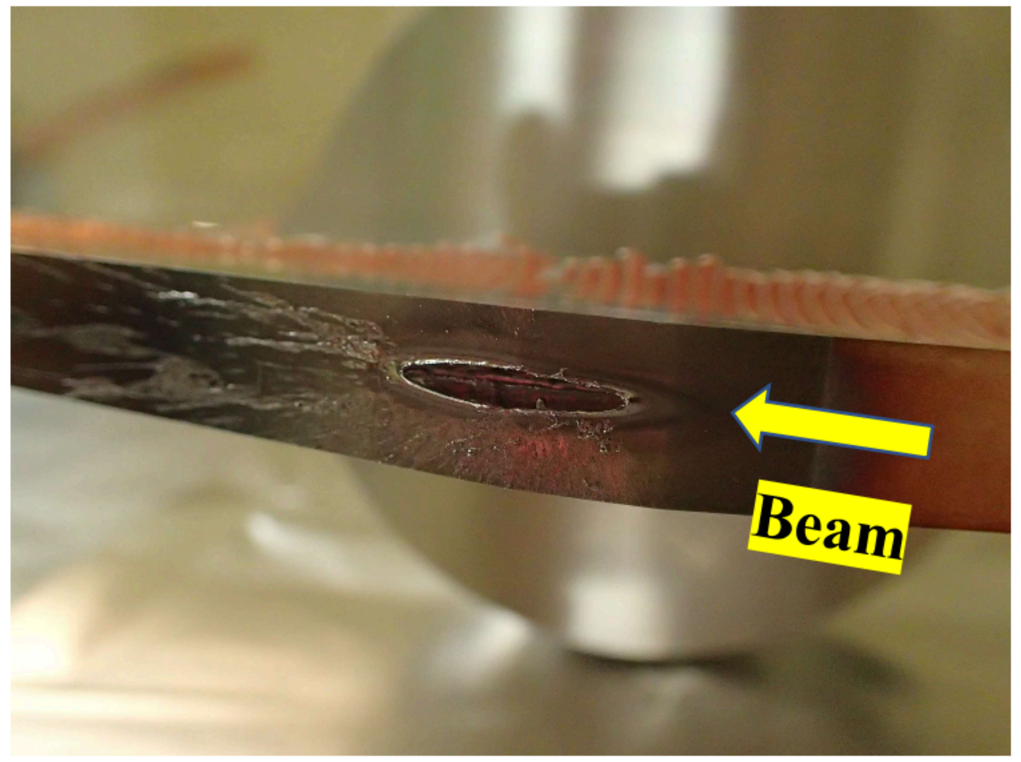
Vertical Collimator

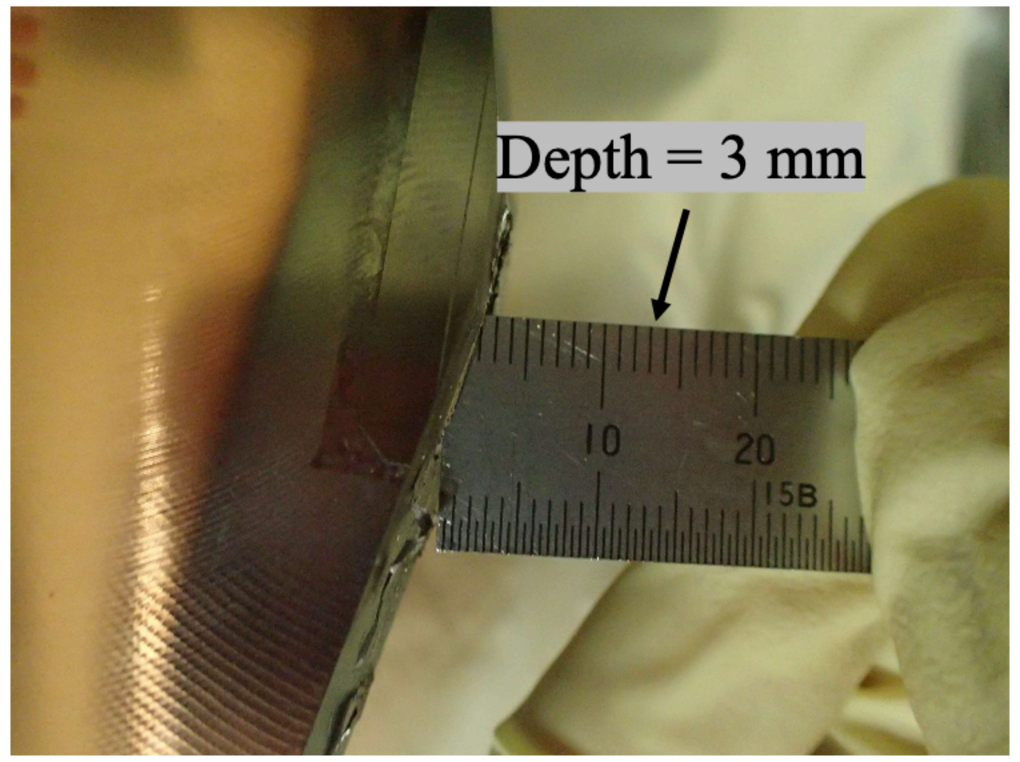
TOP side





BOTTOM side





I think the colours are similar.

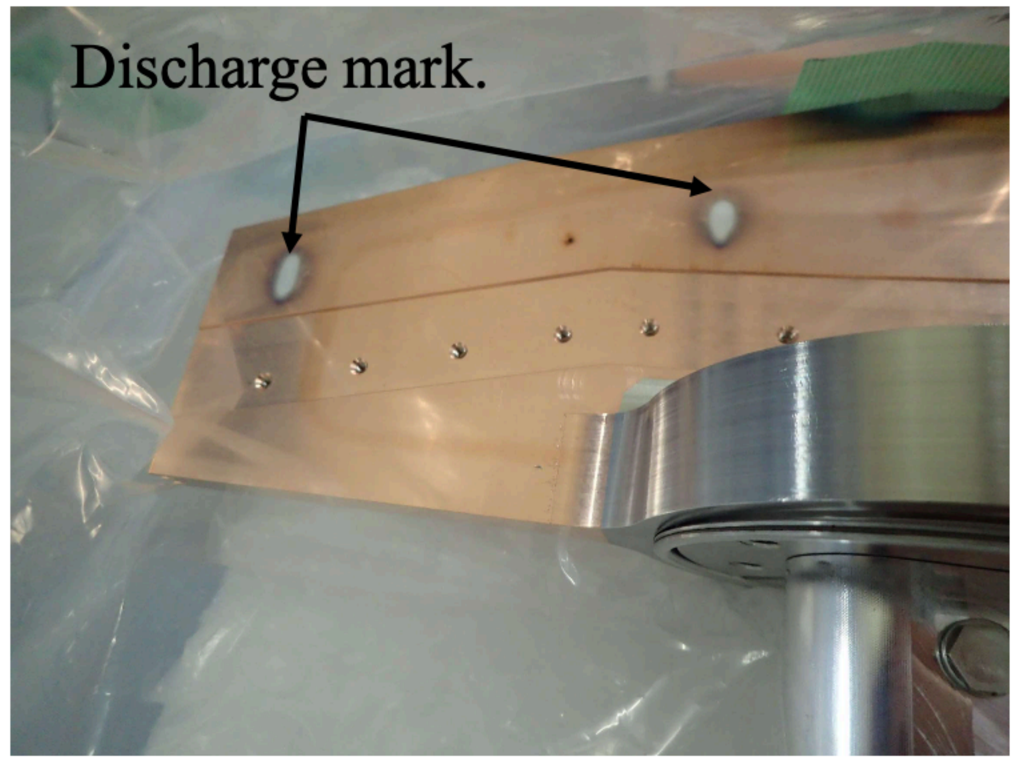
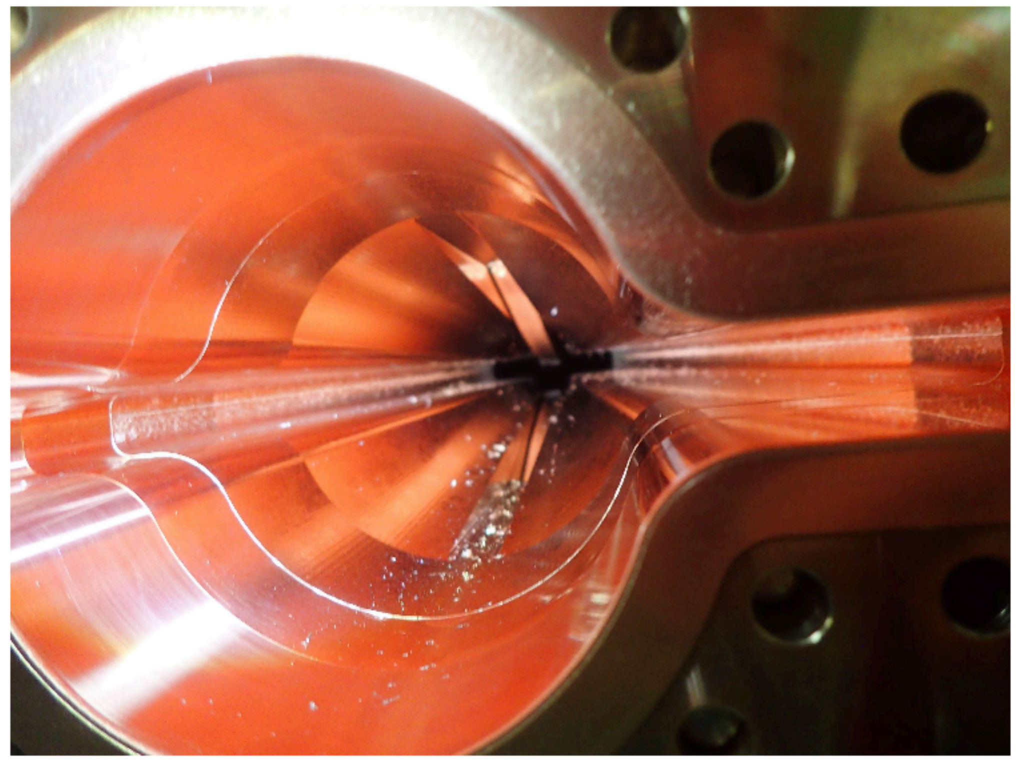
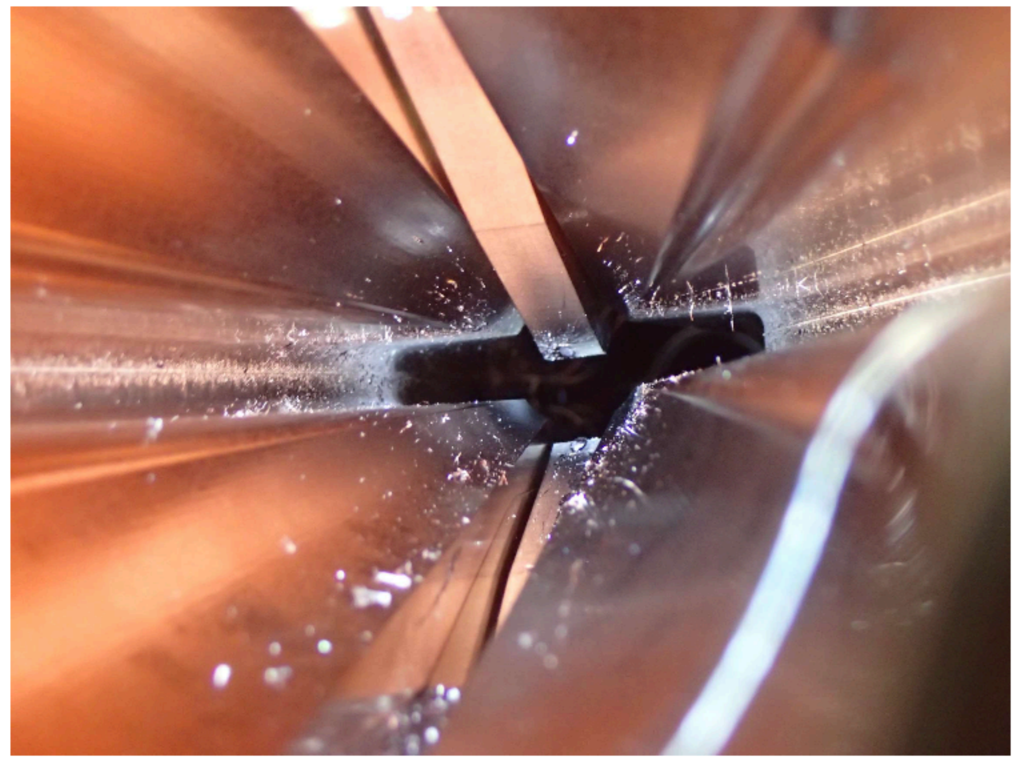


Photo from downstream.



top



bottom

We never expected the collimator damage before the commissioning.

There are many dusts.

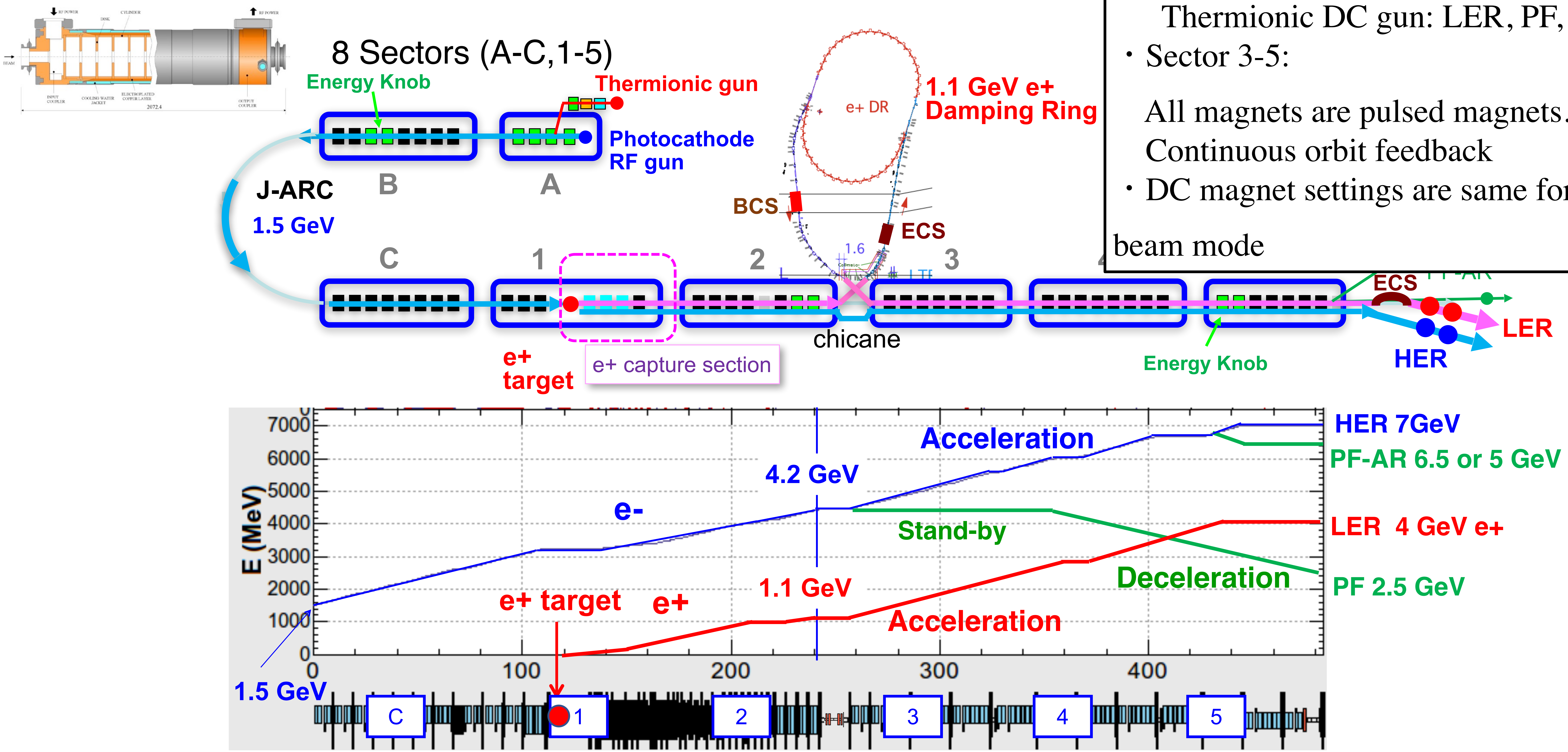
Injection System

Injector Linac Layout

M. Satoh

60 klystron units
240 accelerating structures (S-band 2-m-long)

- Two electron sources:
  RF gun: HER injection
  Thermionic DC gun: LER, PF, PF-AR
- Sector 3-5:
  All magnets are pulsed magnets.
  Continuous orbit feedback
- DC magnet settings are same for different beam mode

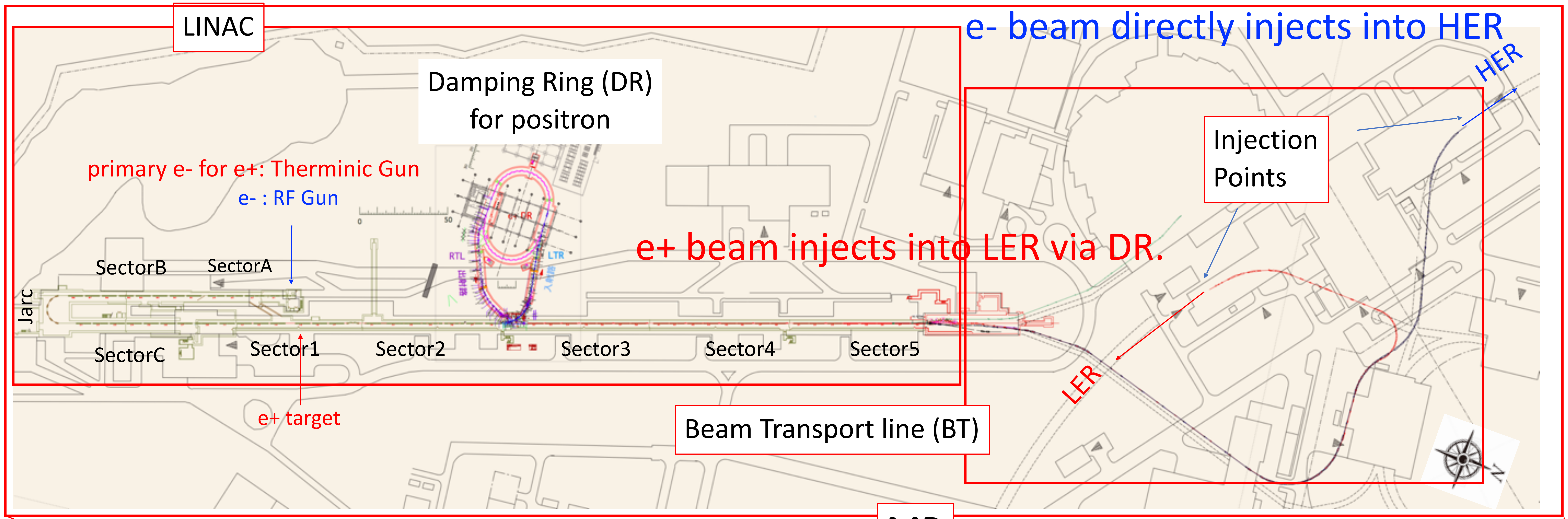


Beam energy variation for each beam mode along the beam line after J-ARC

N. Iida

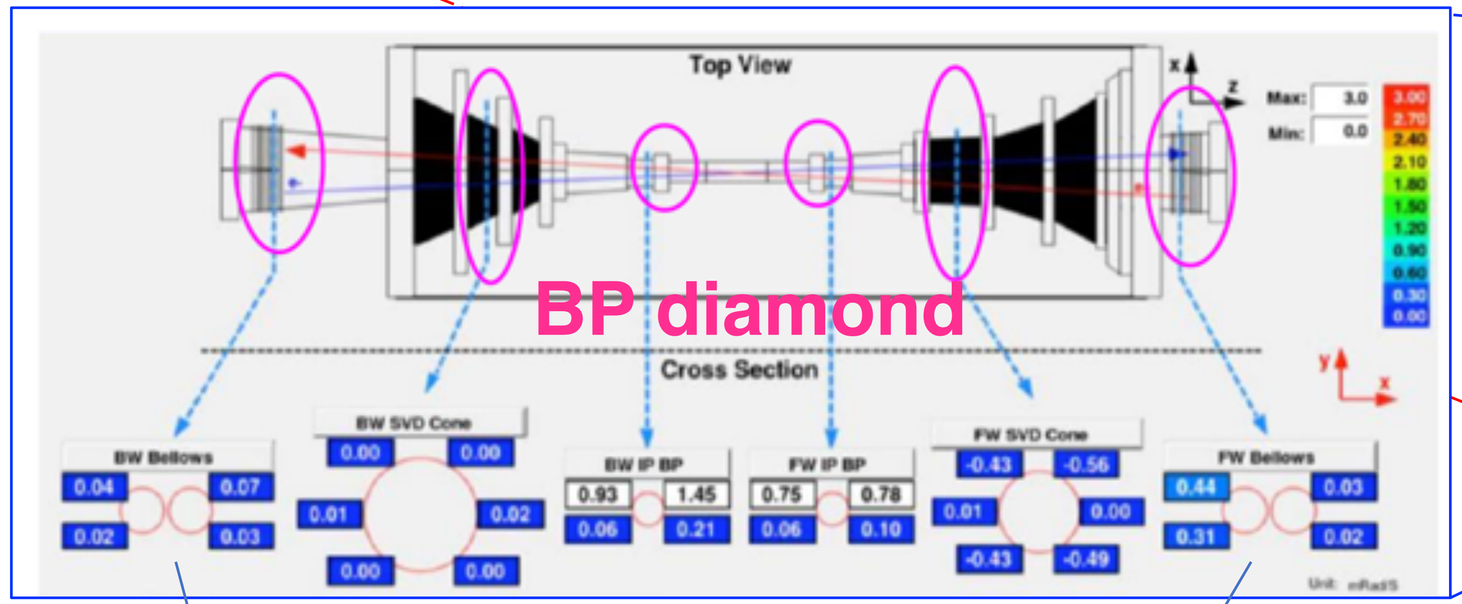
1. SuperKEKB injector complex

Layout of LINAC, BT, Background(BG) monitors in MR

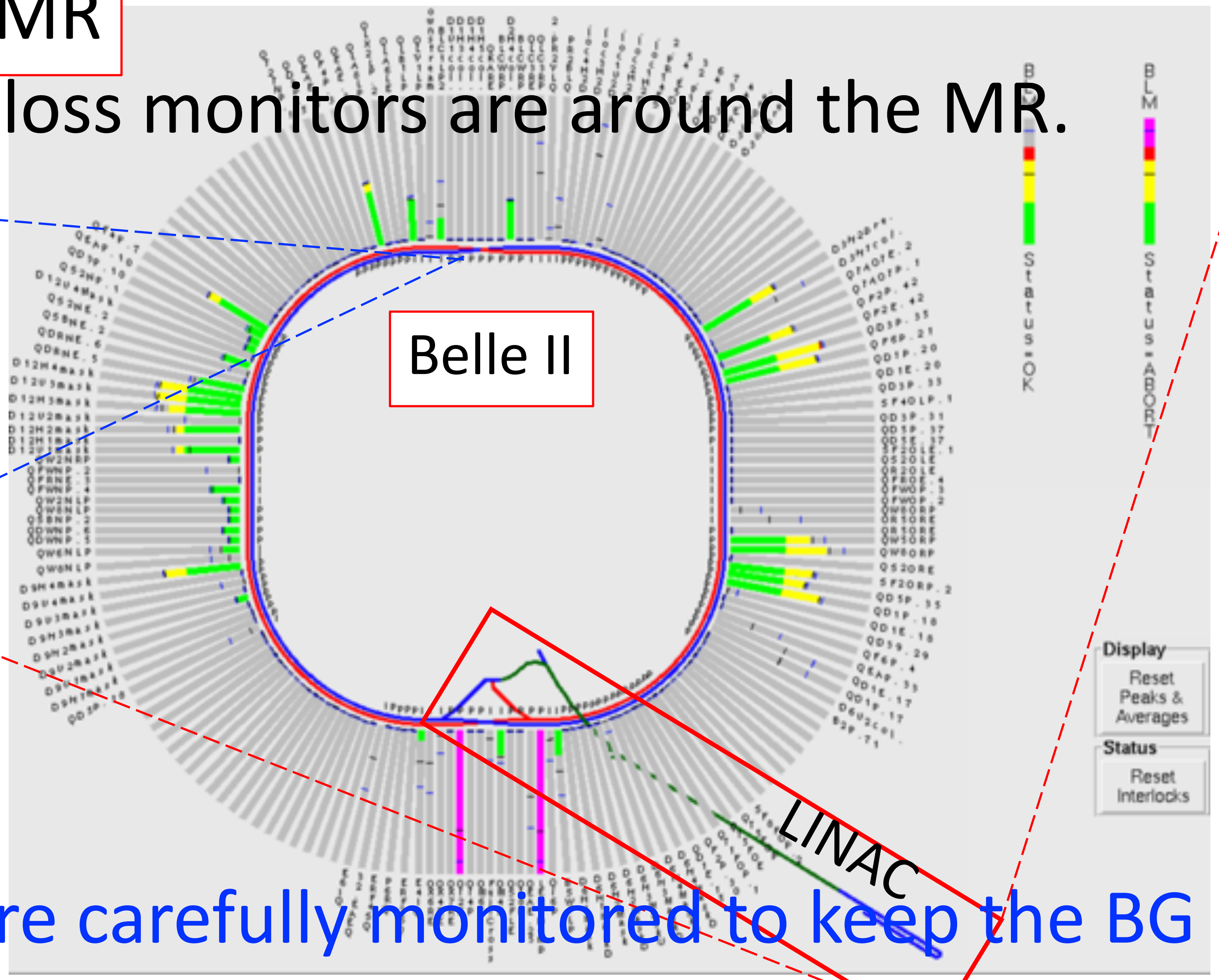


MR

Diamond detectors at QCS in Phase3



Many loss monitors are around the MR.



HER:
QCS(Diamond) BW135

LER:
QCS(Diamond) FW135

Most sensitive to the Background (BG) on Belle2.

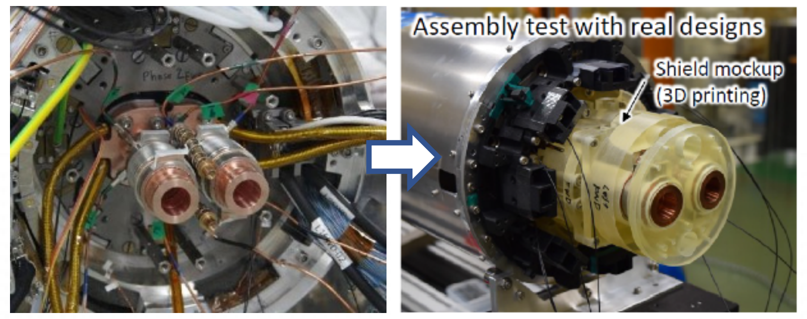
The signals from the Diamonds and the loss monitors are carefully monitored to keep the BG low.

Some aborts are avoided by stopping injection when the signals are high.

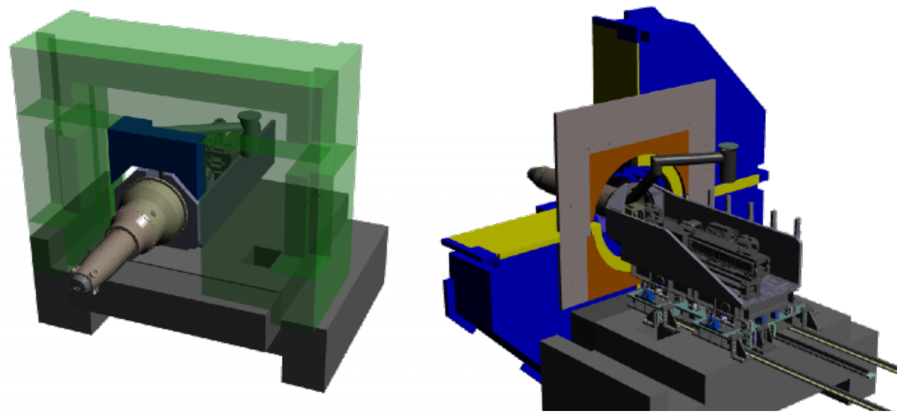
N. Iida

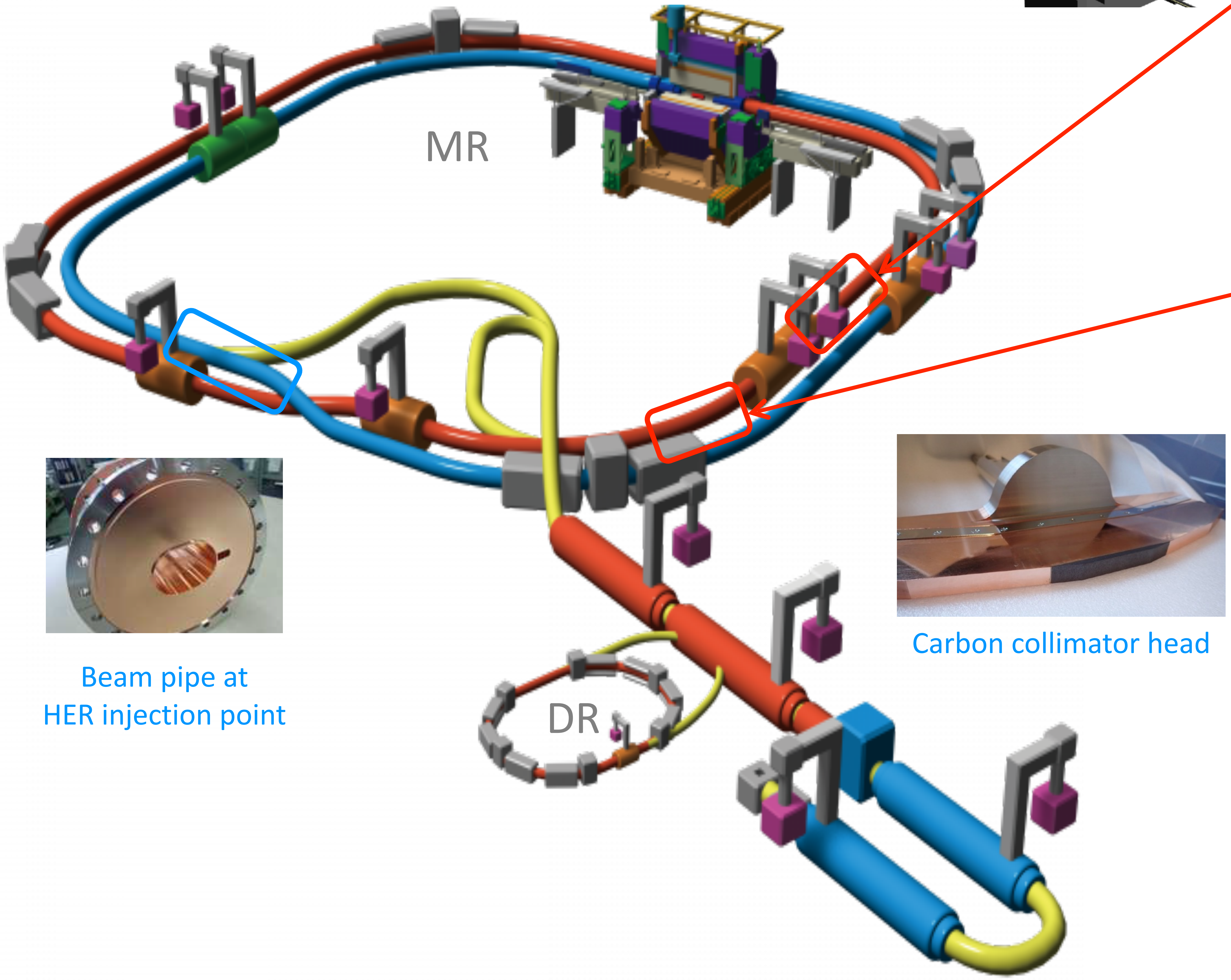
Future Plan and Prospect

Modification during the 1st Long Shutdown (LS1)



New heavy metal shield on IP bellows





Beam pipe at
HER injection point

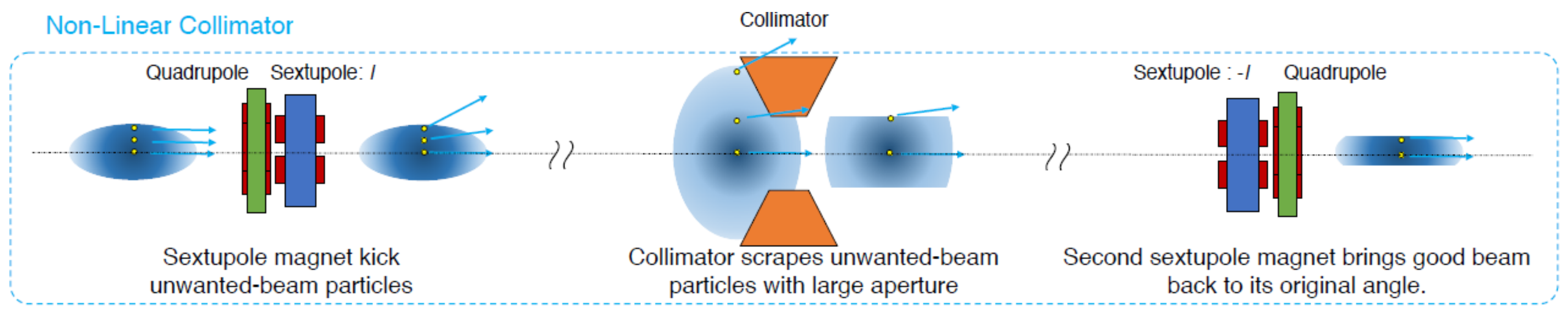
Carbon collimator head

- Nonlinear vertical collimator (LER)
  - reduction of impedance and backgrounds
- IR radiation shield modification
  - reduction of backgrounds
- Robust horizontal collimator head (LER)
  - replace with carbon-head for horizontal collimator.
- Copper-coated vertical collimator head
  - countermeasure for "fireball"
  - reduction of impedance
- New beam pipes with wider aperture a injection point (HER)
- RF cavity modification and replacement (LER)
  - stable operation and larger beam current

Ref. K. Shibata et al.

Reduction of Impedance: Nonlinear Collimator

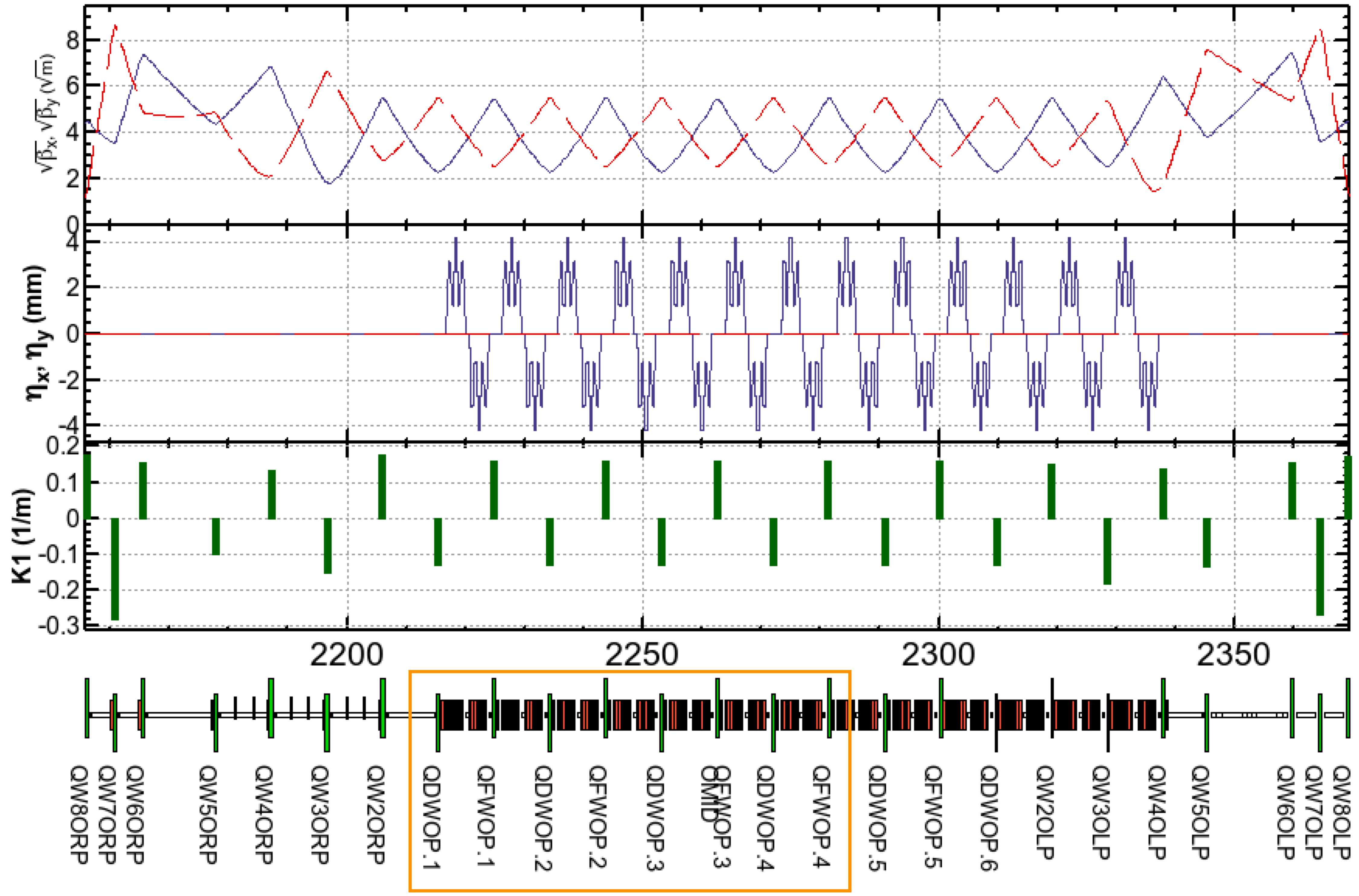
We install a nonlinear collimator (D05V1) to reduce impedance in the vertical direction.



$$\Delta p_y = \frac{SK_2}{2}\Delta y^2$$

OHO section

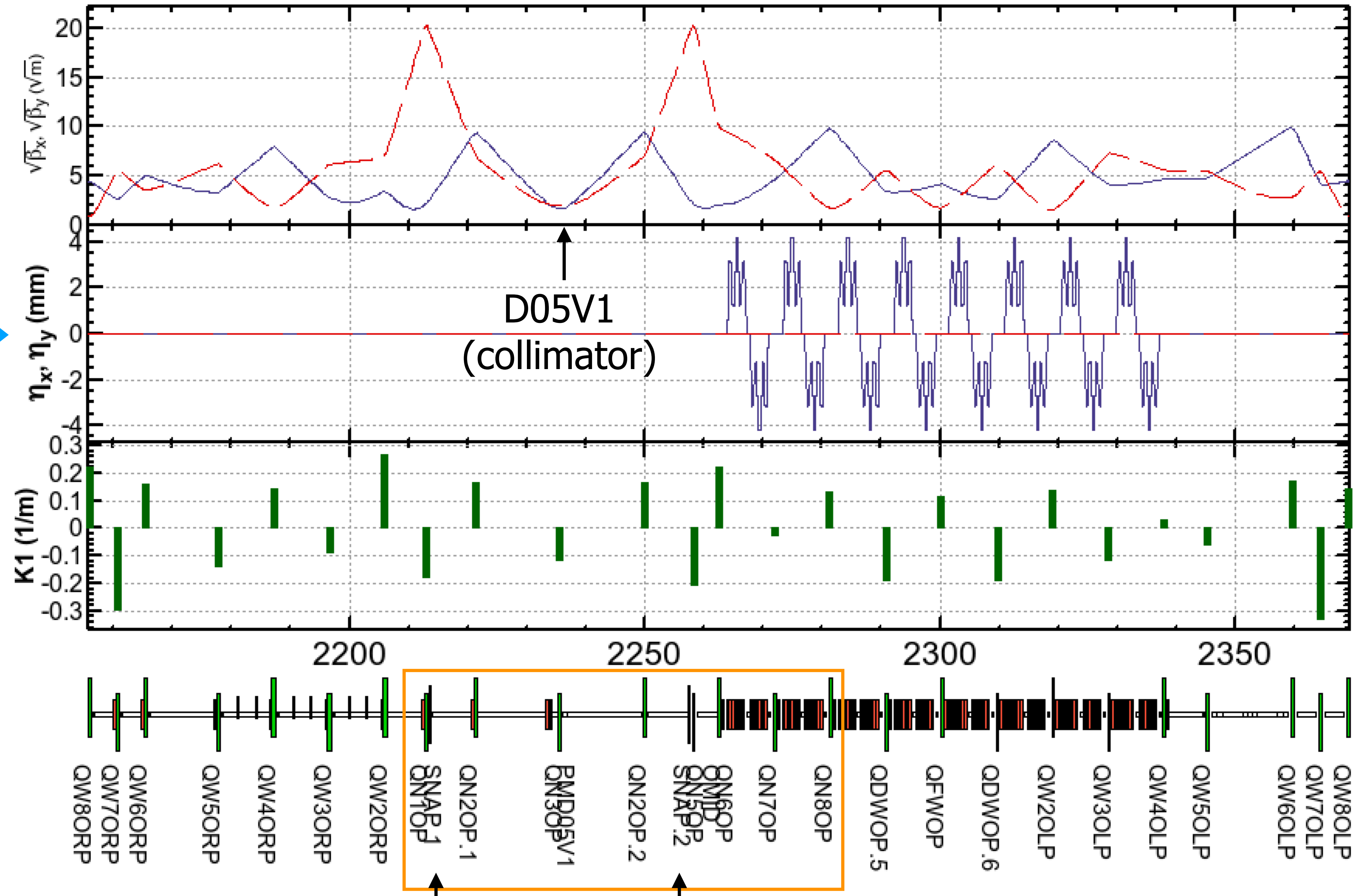
before LS1



wiggler section

positron →

after LS1



skew sextupole pair (SNAP)

$\Delta\psi_y = 2\pi$ to QC1RP

positron →

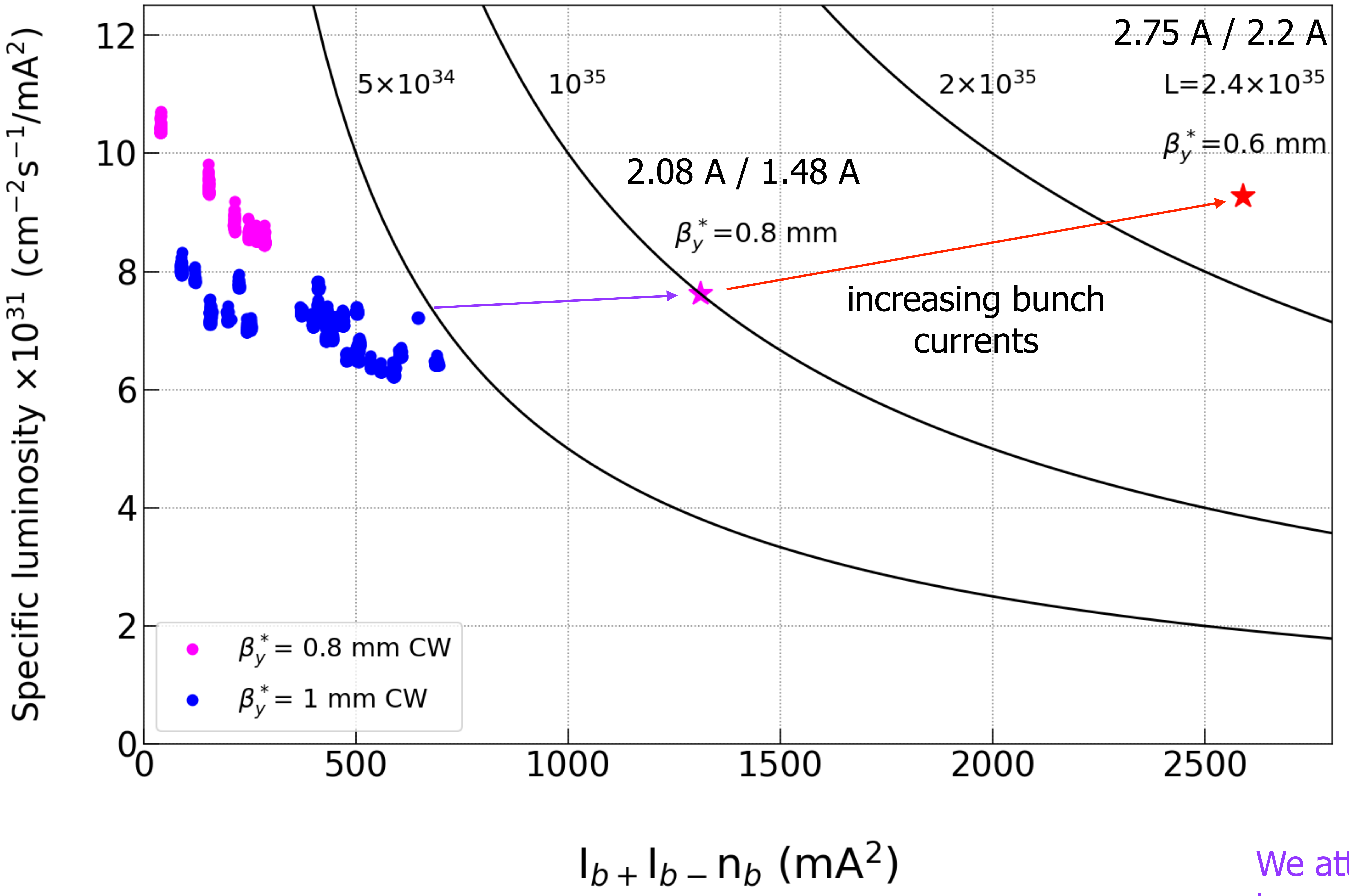
M = -I'

```
Damping time (msec):
X :   45.67757    Y :   45.68328    Z :   22.84954
```

```
Damping time (msec):
X :   52.99557    Y :   53.00312    Z :   26.50934
```

Toward 2.4 x 10^{35} $cm^{-2}s^{-1}$

The first milestone after LS1 is 10^{35} $cm^{-2}s^{-1}$.



$$L_{sp} = \frac{L}{I_{b+} I_{b-} n_b}$$

Unit of luminosity:

10^{34} $cm^{-2}s^{-1}$ = 1 KEKB

10^{35} $cm^{-2}s^{-1}$ = 1 SuperKEKB

We attempt to improve luminosity toward a new luminosity unit.

International Task Force (ITF) for SuperKEKB

61 researchers are joined to the ITF.
(26 researchers from foreign institutes ~43 %)

FCC-ee, CEPC, EIC, Super-Tau-Charm

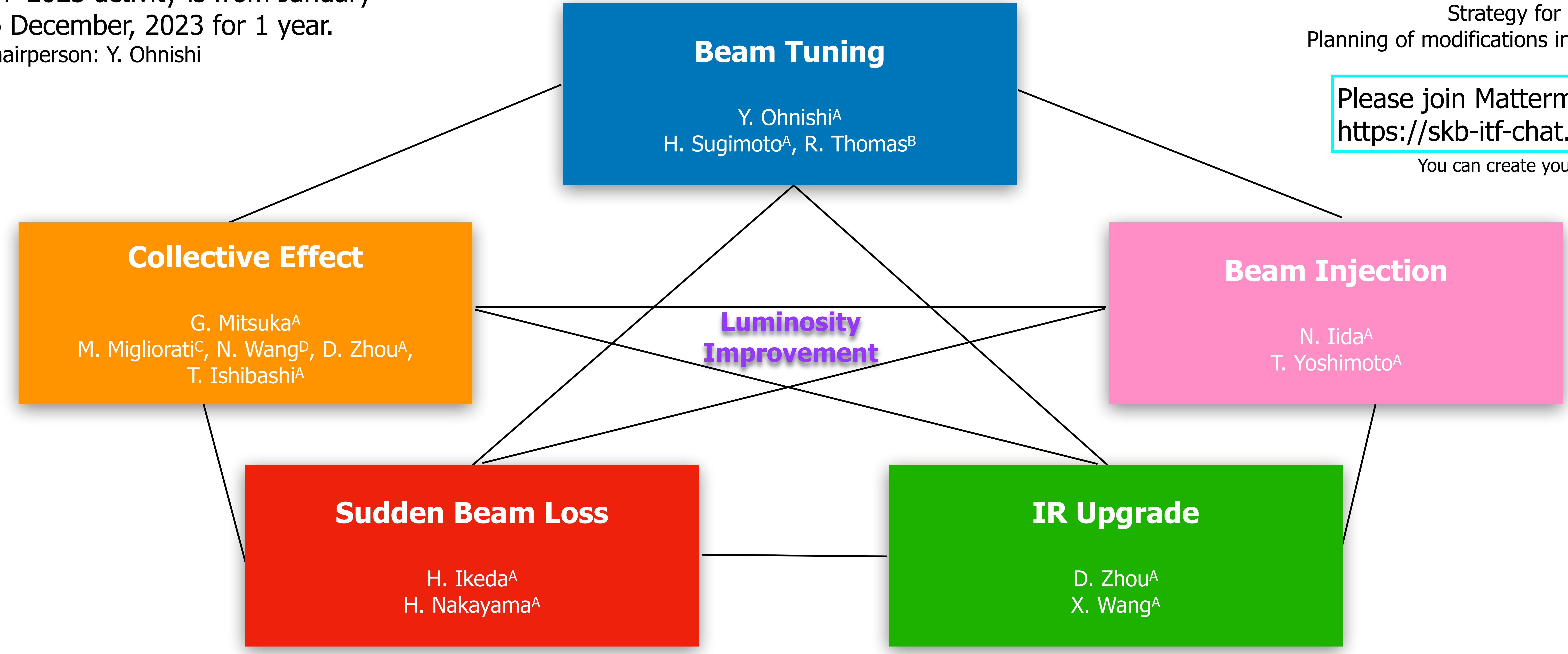
Find a realistic path to achieve 10^{35} $cm^{-2}s^{-1}$ in the post LS1 (1st long shutdown since mid. of 2022).
Find ideas to achieve $6x10^{35}$ $cm^{-2}s^{-1}$ after LS2 with a view to major modifications.

Investigation of factors inhibiting machine performance improvement
Analysis of data obtained from operation through summer 2022
Strategy for post-LS1
Planning of modifications in the LS2

ITF 2023 activity is from January to December, 2023 for 1 year.
Chairperson: Y. Ohnishi

Please join Mattermost:
https://skb-itf-chat.kek.jp

You can create your account.



ITF is organized under the B-Factory promotion office at KEK.

A) KEK, B) CERN, C) UNIROME1, D) IHEP

Summary

- Luminosity over 10^{35} $cm^{-2}s^{-1}$ is very challenge.
- In order to accomplish the target, we have to consider enormous issues;
  - Optics deterioration caused by beam-line deformation due to an intense synchrotron radiation
  - Impedance budget
  - Collimators and background reduction
  - Sudden beam loss
  - -1 mode instability in the LER
  - Dynamic aperture with crab waist and under the beam-beam interactions
  - Beam injection
  - ..., and so on
- ITF is important activity for us.
- Next beam operation will be started from December 2023.

Very challenging and slow improvements, ...

Recommendations and Comments

- Beam orbit is very important because the beam optics is defined by a reference orbit.
  - Especially, orbit at strong sextupoles. How to keep "Gold orbit" stable for long time ?
- Consider deformation of beam chamber due to intense synchrotron radiation.
  - Simulations of SR is important, and also in the vicinity of IP.
- To make sure orbit stability, a careful design of cooling water system is necessary. And ground motion too.
- BPMs at the final focus magnets are very important. However, the design and the alignment are very difficult due to lack of space.
- Beam collimation system is difficult to predict its feasibility and performance.
  - Can you find a compromise between beam background reduction and beam lifetime ?
- Skew sextupole magnet to correct chromatic X-Y couplings at IP (third order effect)
- Polarization at damping ring is a good idea.
- If machine error is constant, the correction is much easier. Many people simulates machine error with some assumption. But those studies help to write CDR or TDR only. No meaning once the commissioning would be started. Unexpected machine error will be found.

step 1

Analytic Calculation

step 2

Particle Tracking Simulation

These are necessary to write CDR or TDR ...

step 3

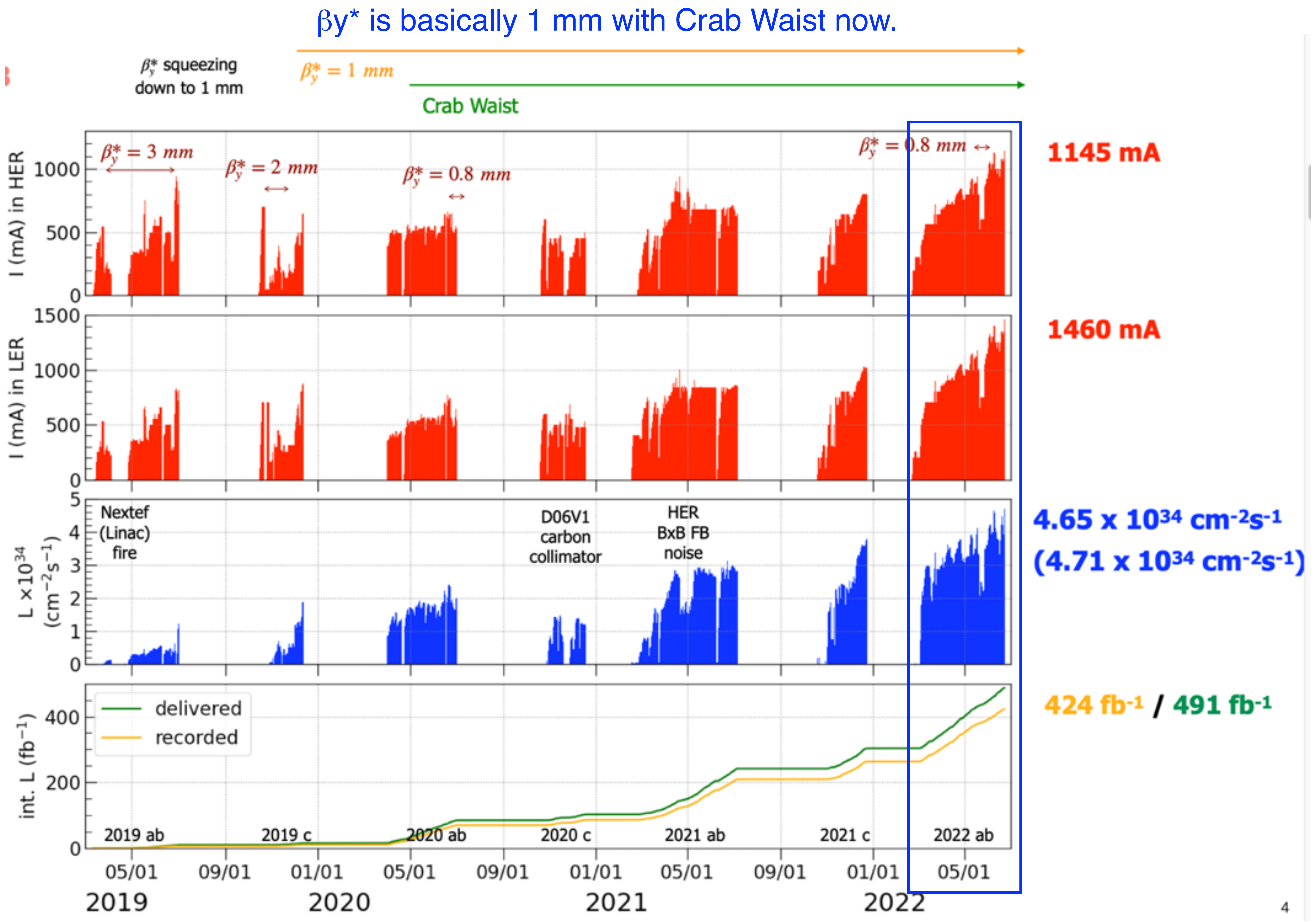
Experiment at Real Machine such as SuperKEKB

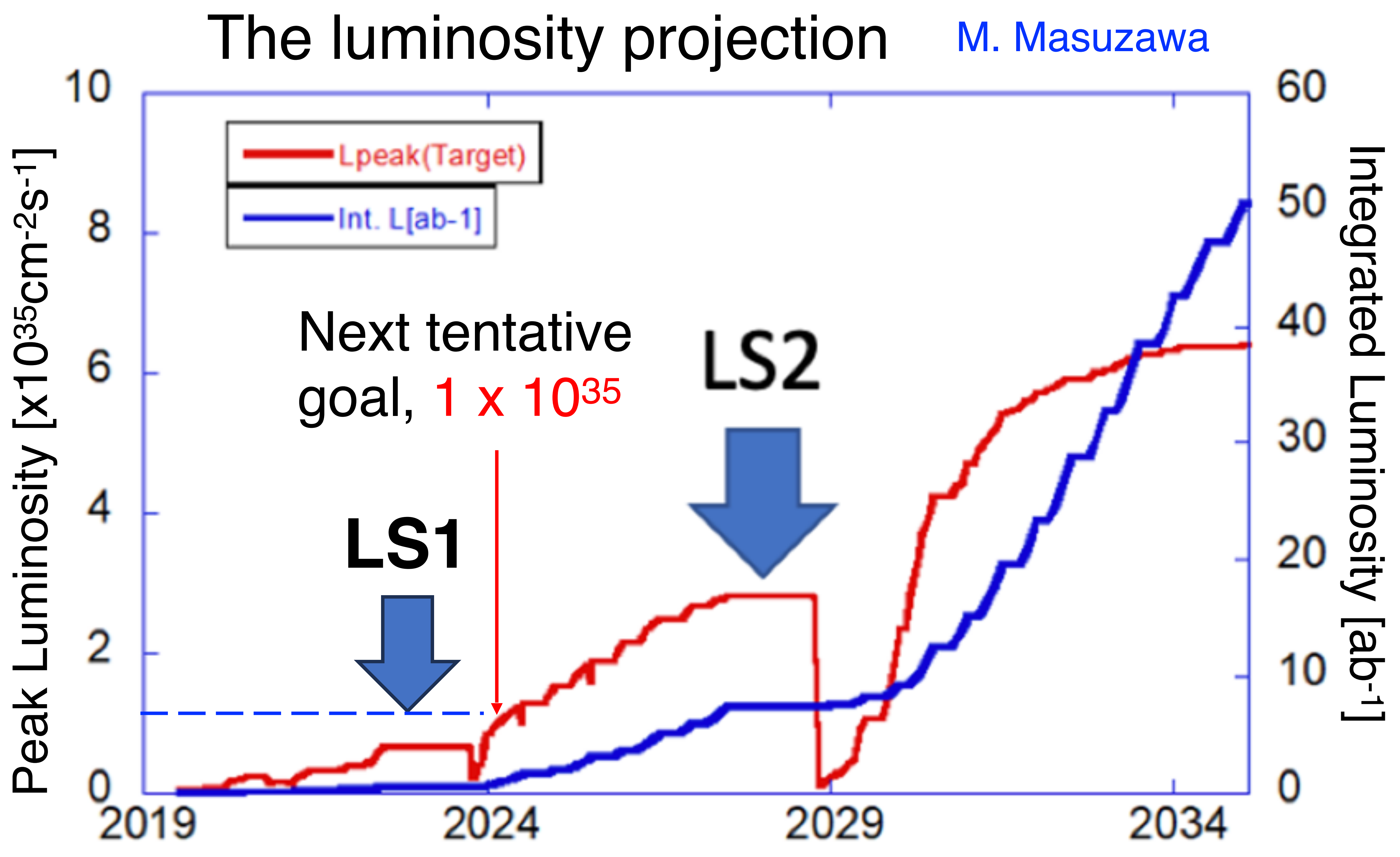
Some simulations are similar to experiments, but a lot of different things from our expectations ...

Appendix

Luminosity goal of SuperKEKB

Luminosity history by 2022 operation





- Now we are in long shutdown 1 (LS1) for Belle II detector upgrade, during which a nonlinear collimator (NLC) is installed.
- We need another long shutdown 2 (LS2) to improve the machine performance beyond 2.4×10^35 $cm^{-2}s^{-1}$ and toward the target peak luminosity of 6× 10^35 $cm^{-2}s^{-1}$.
- It probably requires a modification of the IR and, also an upgrade of the injection complex→ more than one year long shutdown.