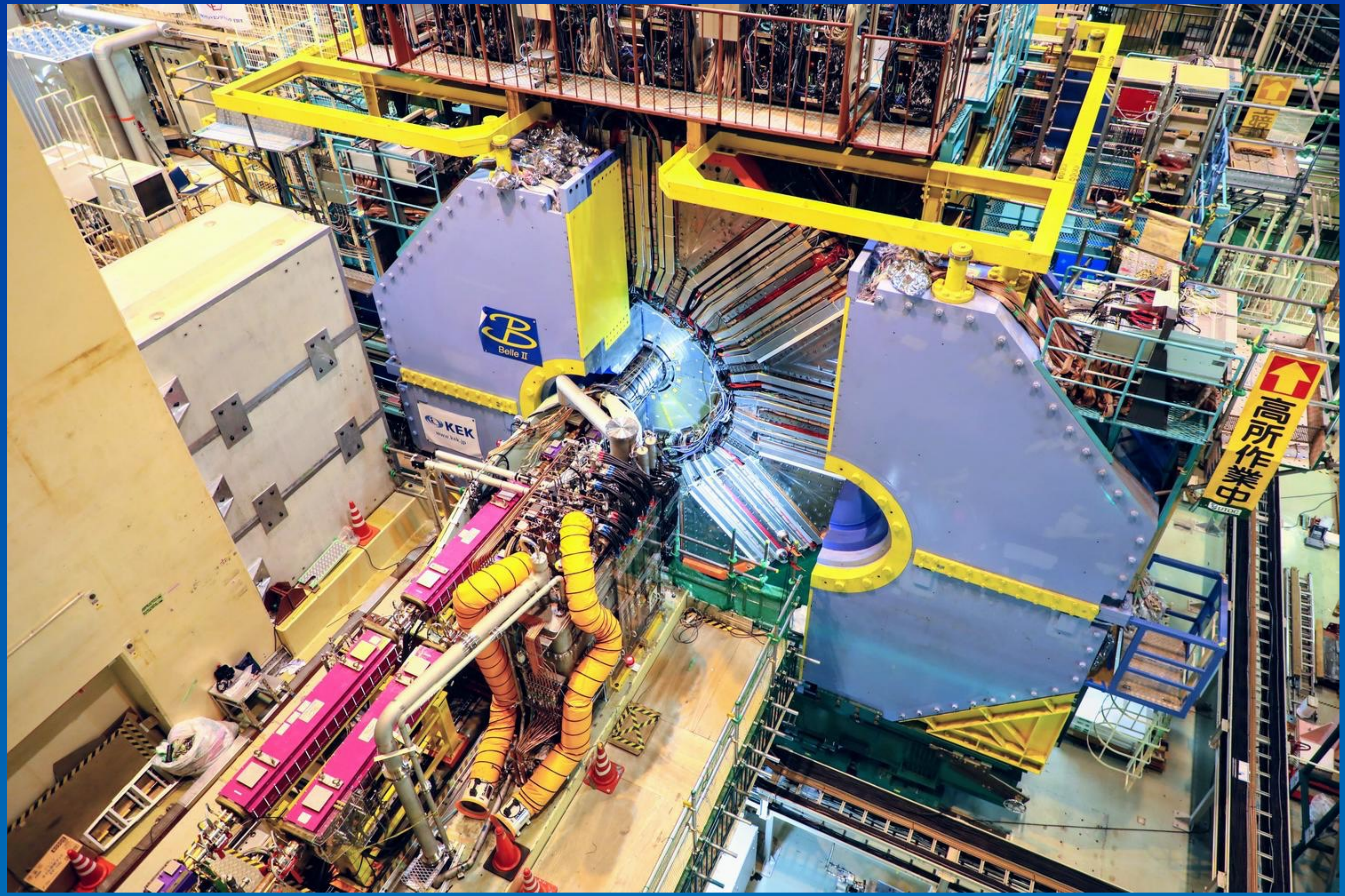
Highlights from SuperKEKB Phase 2 Commissioning



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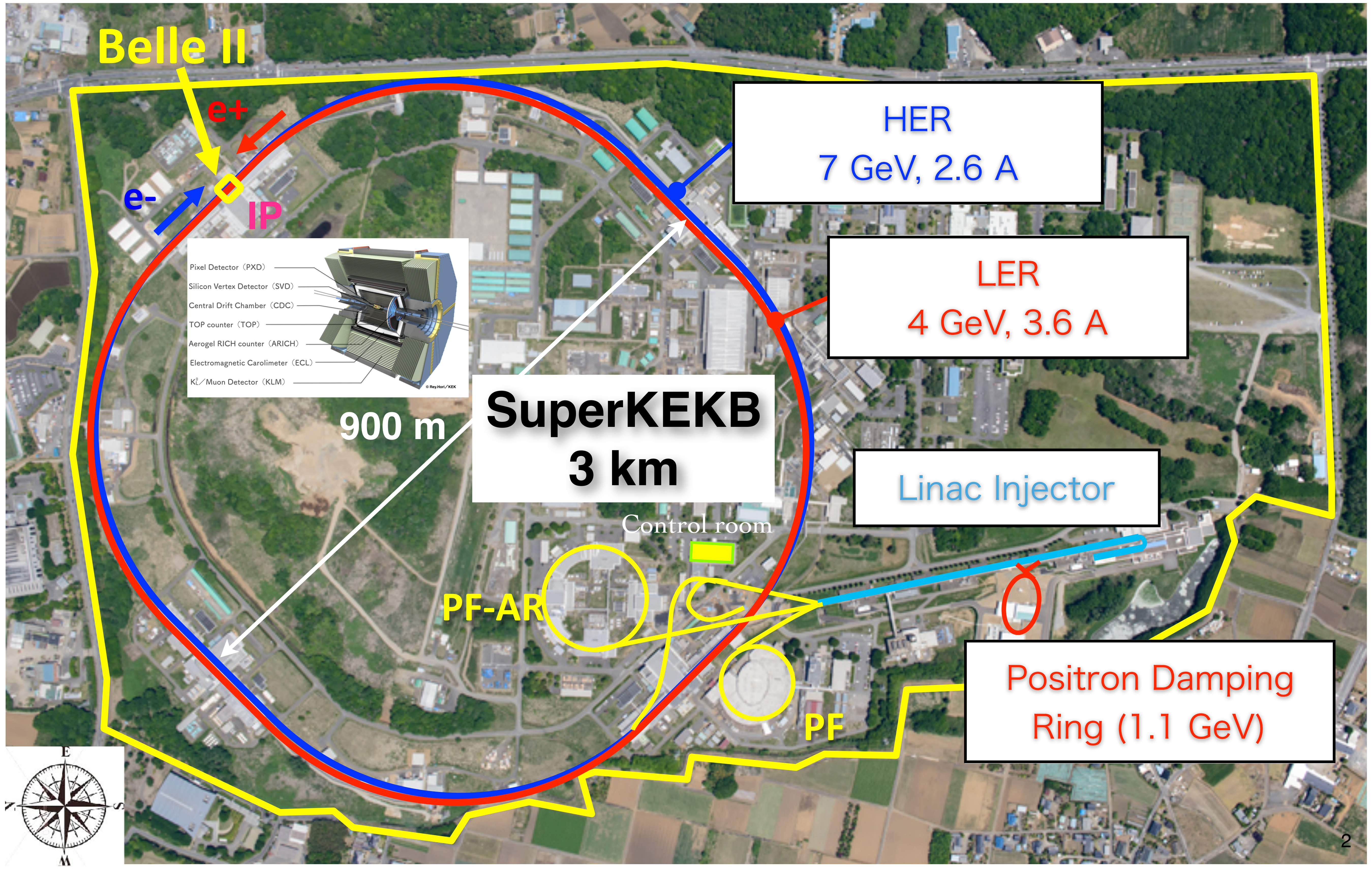
on behalf of the SuperKEKB commissioning group

MOXAA02

Final Target

Target Luminosity: 8 x 10^{35} cm^{-2} s^{-1}

40 times luminosity as high as KEKB

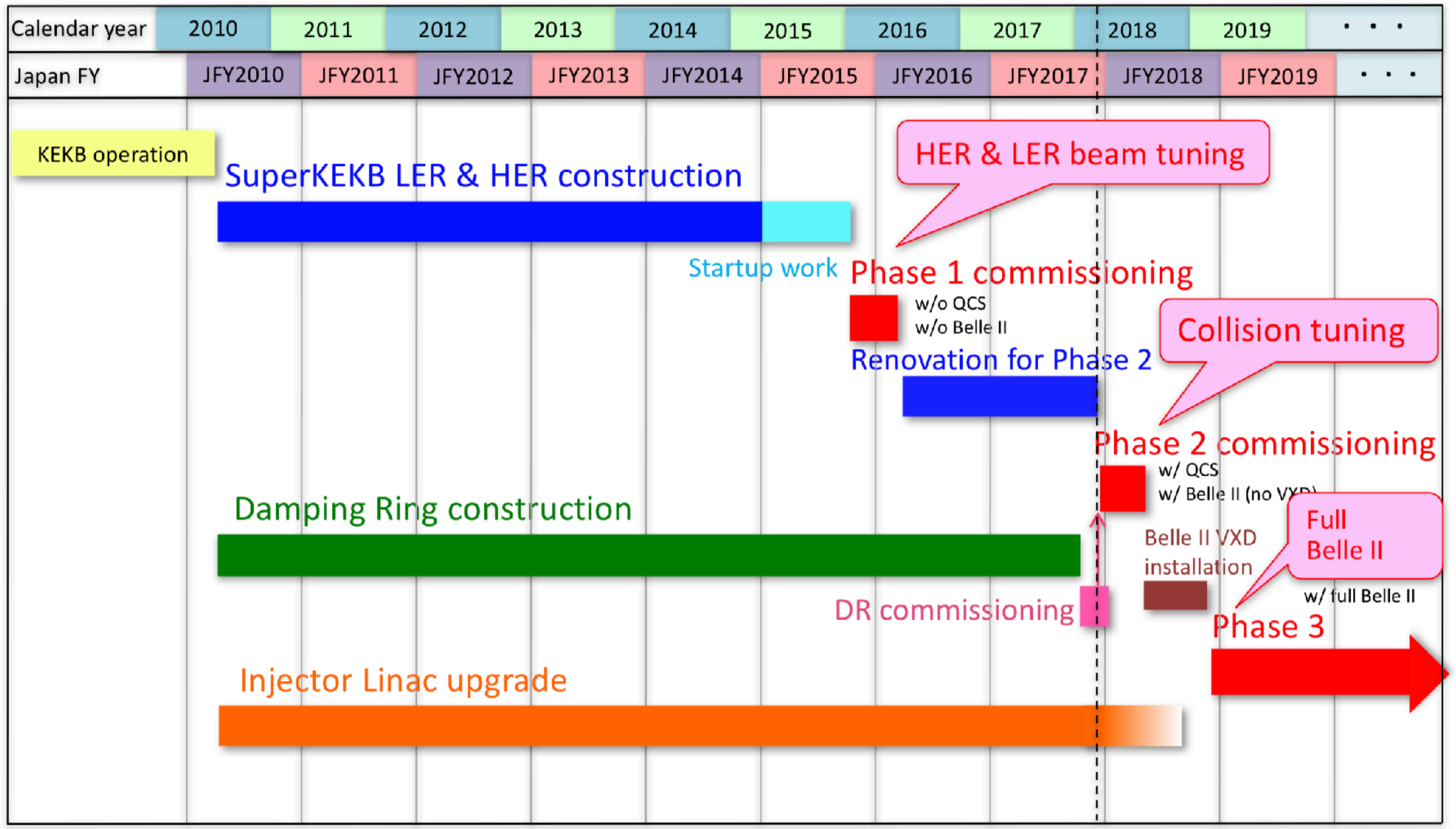


SuperKEKB project

Phase 1 : Feb. 8 - June 28, 2016

Phase 2 : March 19 - July 17, 2018

Phase 3 : March 11, 2019？ - ?



K. Akai

Beam-Beam Parameter

$$\xi_{y\pm} = \frac{r_e N_\mp}{2\pi\gamma_\pm(\sigma^*_{x,eff})}\sqrt{\frac{\beta^*_y}{\varepsilon_y}}$$

$\beta^*_y \to \text{small}$ ➡ $\xi_y \to \text{small}$ ➡ $L \to \text{large}$

Luminosity

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

Final Target $I_\pm \to \times 2$ $\beta^*_y \to \times 1/20$ $\xi_y \to \times 1$ ➡ $L \to \times 40$

Beam-Beam Parameter

$$\xi_{y\pm} = \frac{r_e N_{\mp}}{2\pi\gamma_{\pm}(\sigma^*_{x,eff})}\sqrt{\frac{\beta^*_y}{\varepsilon_y}}$$

$\beta^*_y \rightarrow$ small ⇒ $\xi_y \rightarrow$ small ⇒ $L \rightarrow$ large

Luminosity

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

Final Target $I_\pm \rightarrow \times 2$ $\beta^*_y \rightarrow \times 1/20$ $\xi_y \rightarrow \times 1$ ⇒ $L \rightarrow \times 40$

Beam-Beam Parameter

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$$\beta^*_y \rightarrow \text{small} \Rightarrow \xi_y \rightarrow \text{small} \Rightarrow L \rightarrow \text{large}$$

Luminosity

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e} \frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

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Final Target $I_{\pm} \rightarrow \times 2$ $\quad \beta^*_y \rightarrow \times 1/20$ $\quad \xi_y \rightarrow \times 1$ $\Rightarrow$ $L \rightarrow \times 40$

Luminosity in Nano-Beam Scheme

Beam-Beam Parameter

$$\xi_{y\pm} = \frac{r_e N_{\mp}}{2\pi\gamma_{\pm}(\sigma^*_{x,eff})}\sqrt{\frac{\beta^*_y}{\varepsilon_y}}$$

$$\beta^*_y \rightarrow \text{small} \Rightarrow \xi_y \rightarrow \text{small} \Rightarrow L \rightarrow \text{large}$$

Luminosity

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

$$\varepsilon_y \rightarrow \text{small}$$

Final Target $I_\pm \rightarrow \times 2$ $\beta^*_y \rightarrow \times 1/20$ $\xi_y \rightarrow \times 1$ $\Rightarrow$ $L \rightarrow \times 40$

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$$\xi_{y\pm} = \frac{r_e N_\mp}{2\pi\gamma_\pm(\sigma^*_{x,eff})}\sqrt{\frac{\beta^*_y}{\varepsilon_y}}$$

$$\beta^*_y \rightarrow \text{small} \;\Rightarrow\; \xi_y \rightarrow \text{small} \;\Rightarrow\; L \rightarrow \text{large}$$

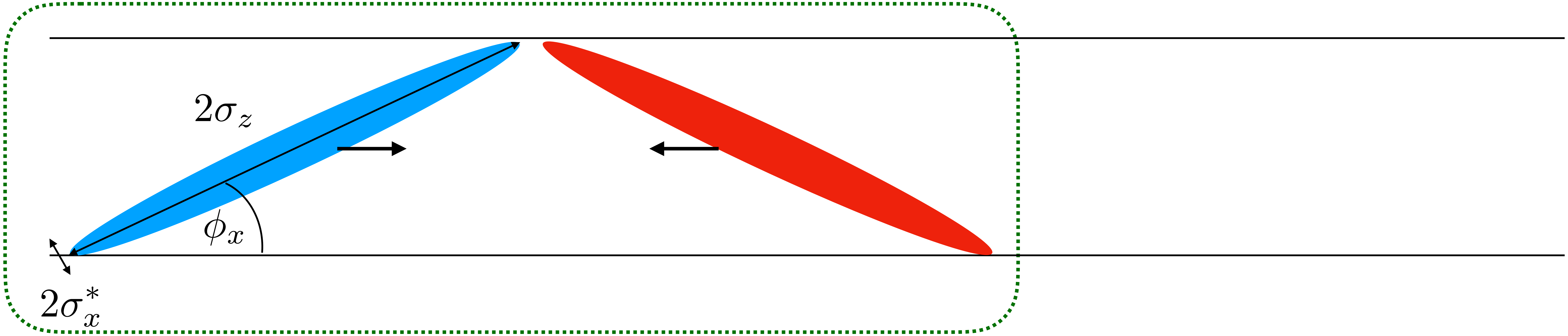
Luminosity

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

$$\varepsilon_y \rightarrow \text{small}$$

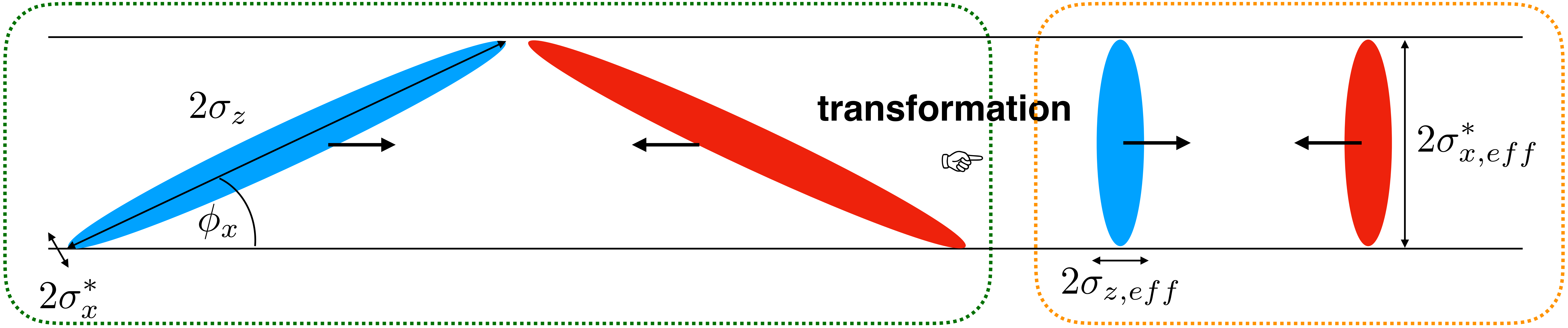
Final Target $I_\pm \rightarrow \times 2$ $\quad \beta^*_y \rightarrow \times 1/20$ $\quad \xi_y \rightarrow \times 1$ $\;\Rightarrow\;$ $L \rightarrow \times 40$

How to squeeze β_y^* smaller than σ_z ?



How to squeeze β_y^* smaller than σ_z ?

Same luminosity between them.

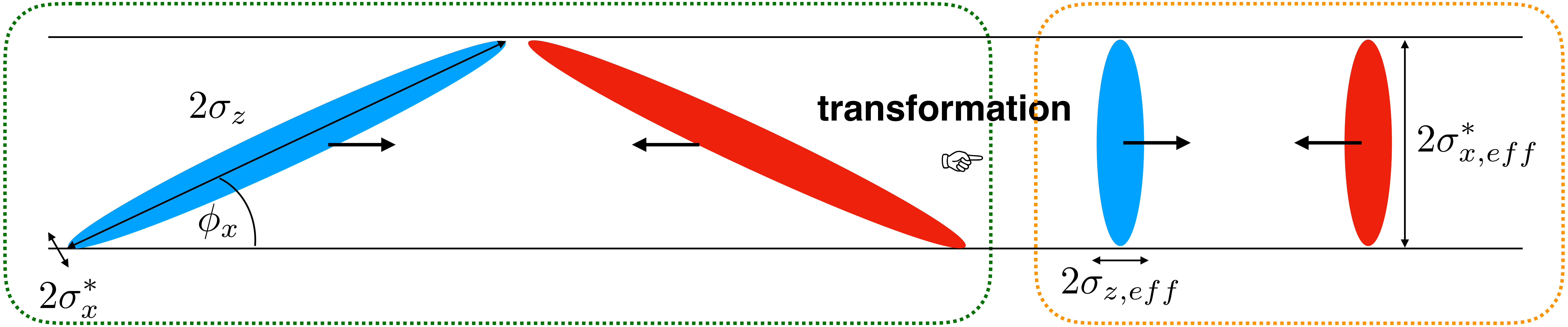


effective beam

$$\sigma_{z,eff} = \frac{\sigma_x^*}{\phi_x} \qquad \sigma_{x,eff}^* = \sigma_z \phi_x$$

How to squeeze β_y^* smaller than σ_z ?

Same luminosity between them.



effective beam

Piwinski angle $\Phi = \frac{\sigma^*_{x,eff}}{\sigma_x^*}$

$$\sigma_{z,eff} = \frac{\sigma_x^*}{\phi_x} \quad \sigma^*_{x,eff} = \sigma_z \phi_x$$

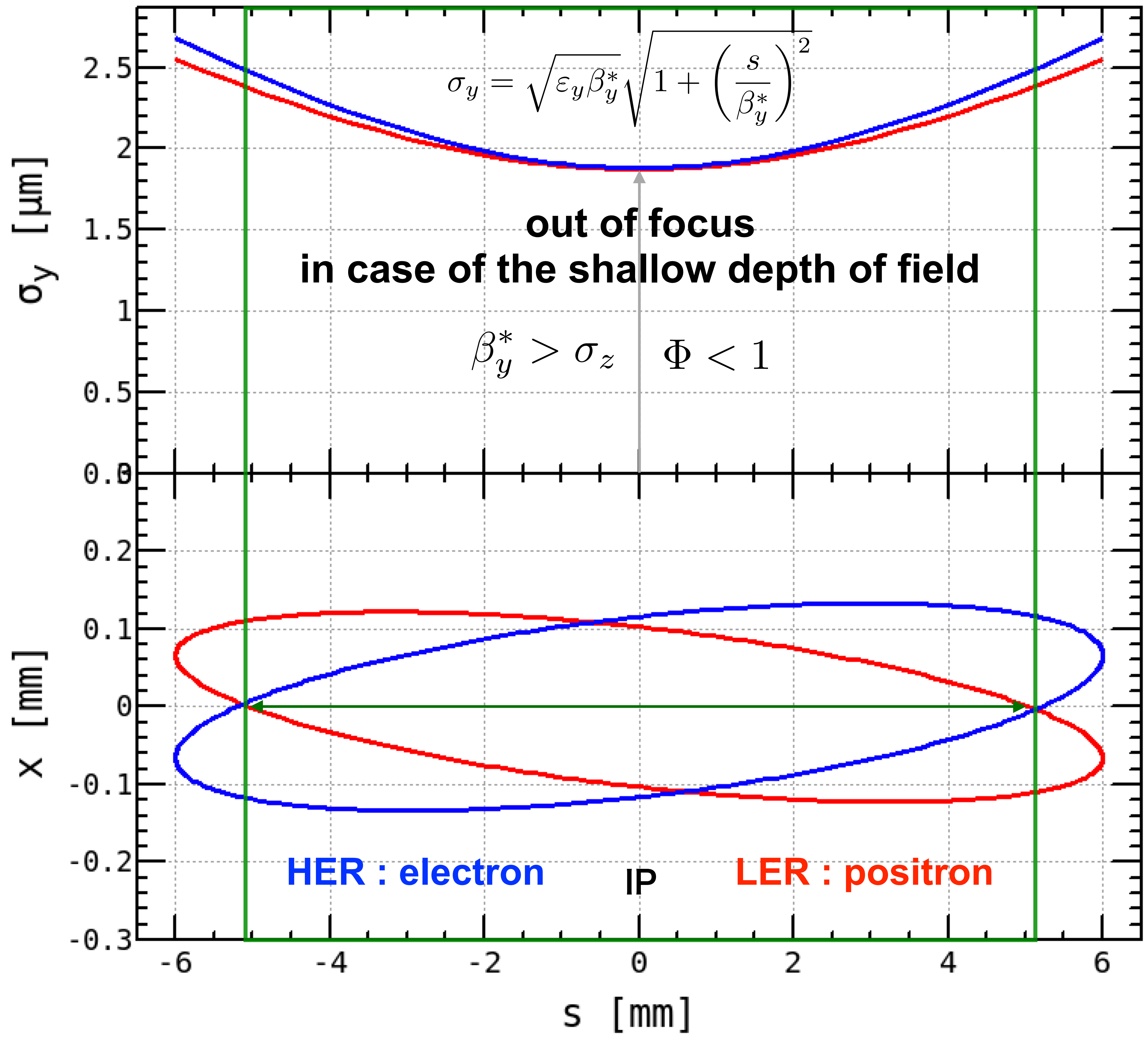
Hourglass effect $\beta_y^* > \sigma_{z,eff} = \frac{\sigma_z}{\Phi}$

Φ > 10 -20 in the nano-beam scheme

cf. Φ < 1 for ordinary schemes

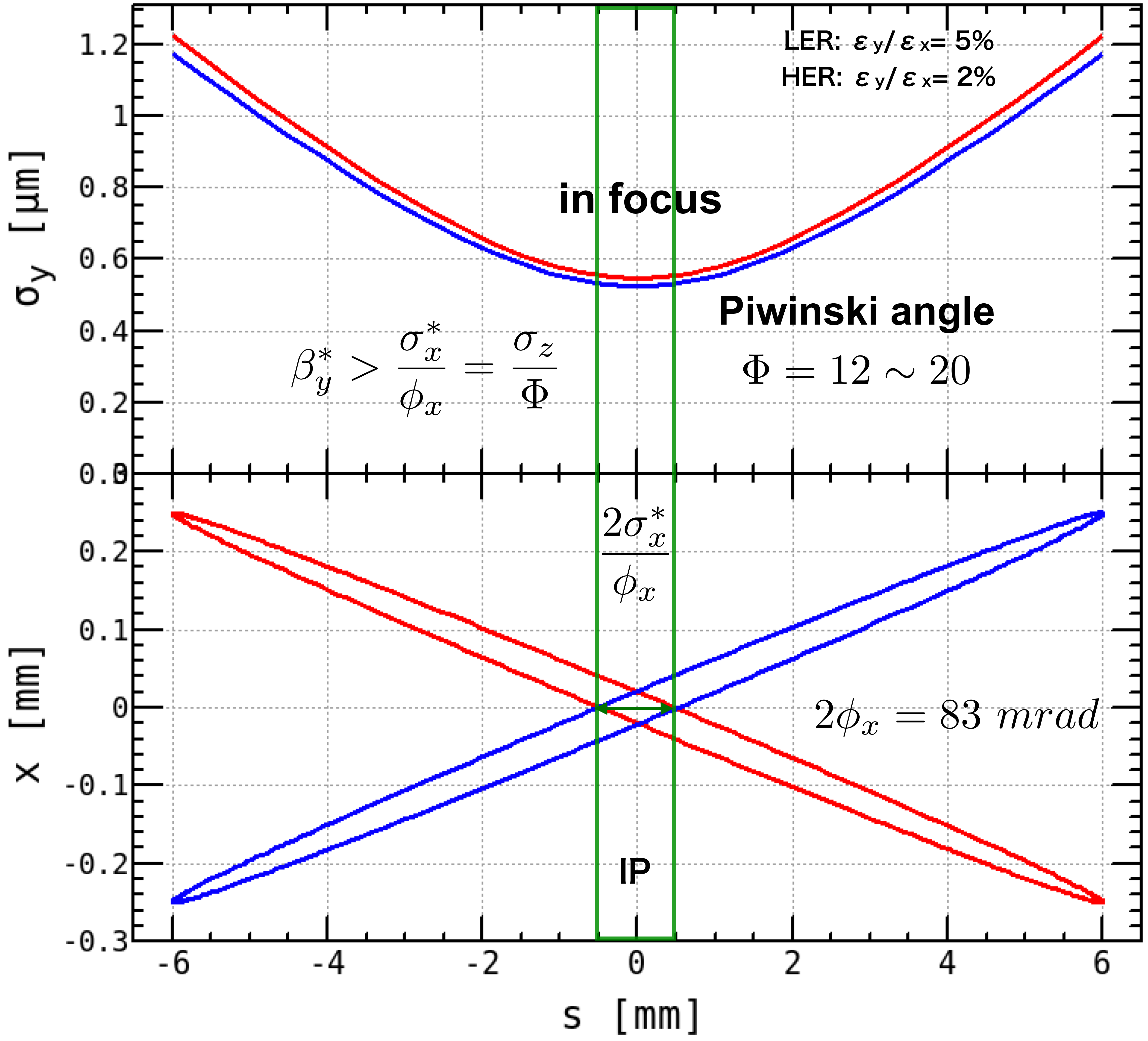
$$\sigma_z = 6\ mm, \quad \Phi = 20 \ \rightarrow \ \sigma_{z,eff} = 300\ \mu m$$

Ordinary collision (KEKB)



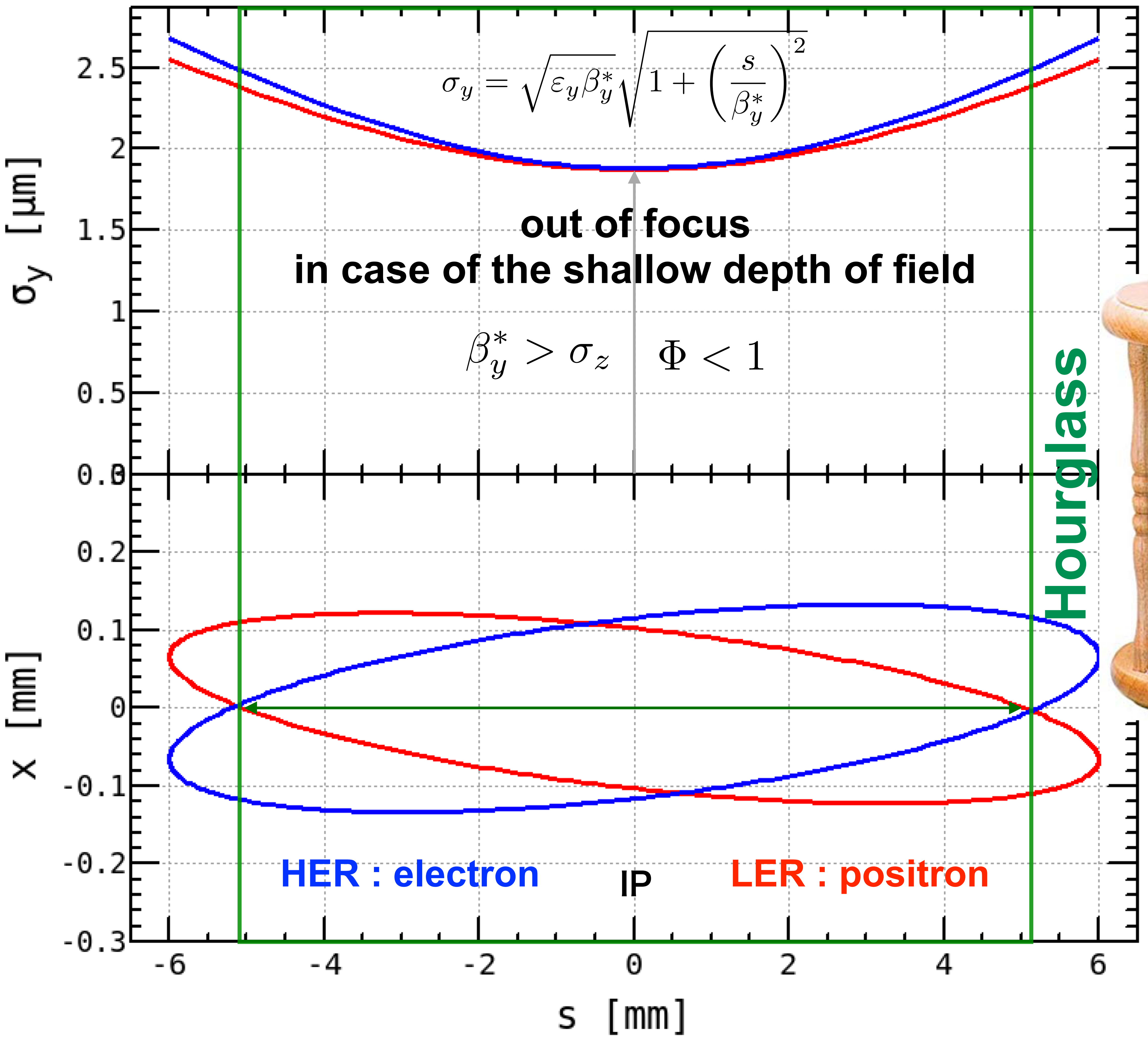
Large overlap region

Nano-Beam (SuperKEKB Phase 2)

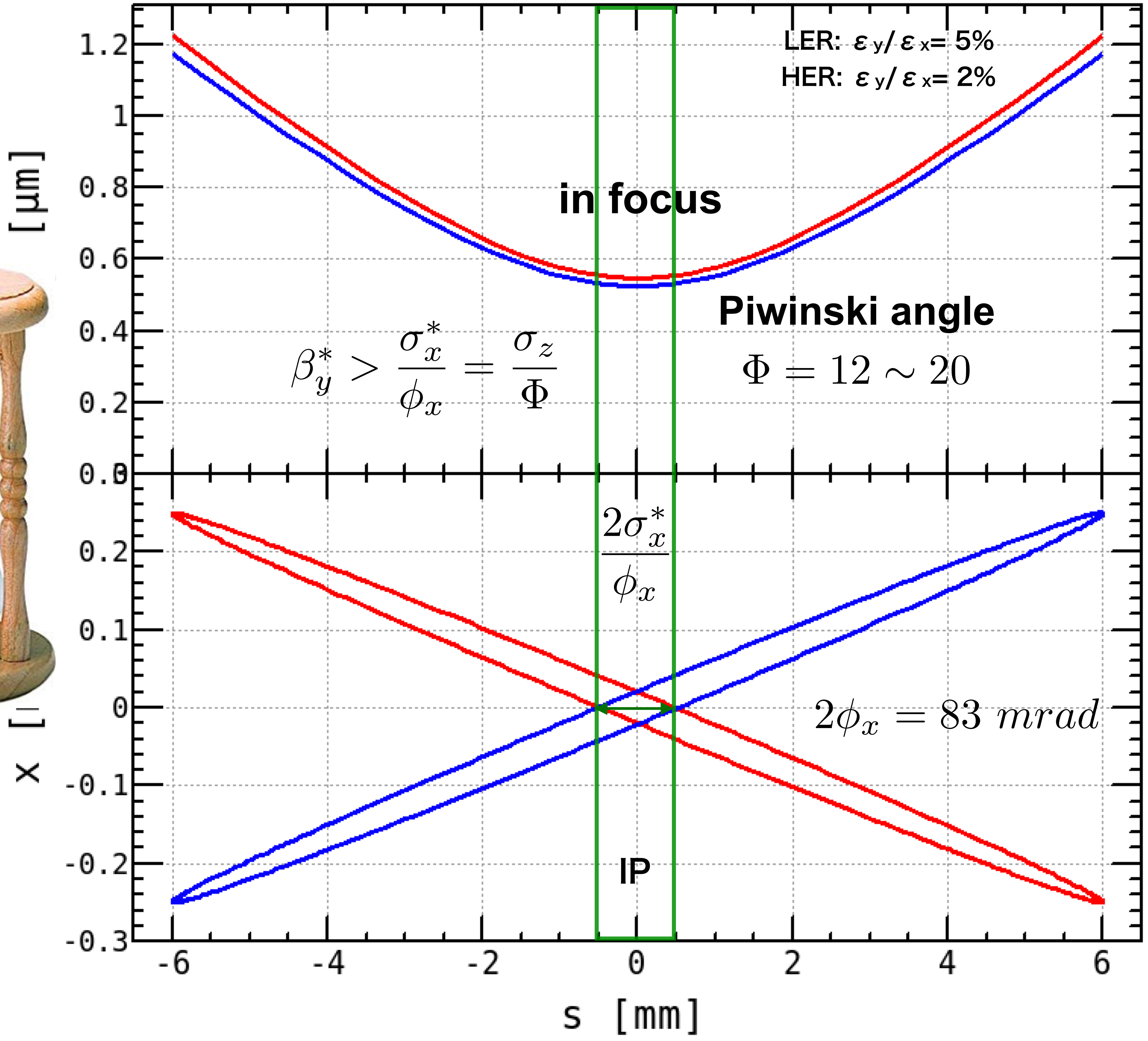


Small overlap region

Ordinary collision (KEKB)



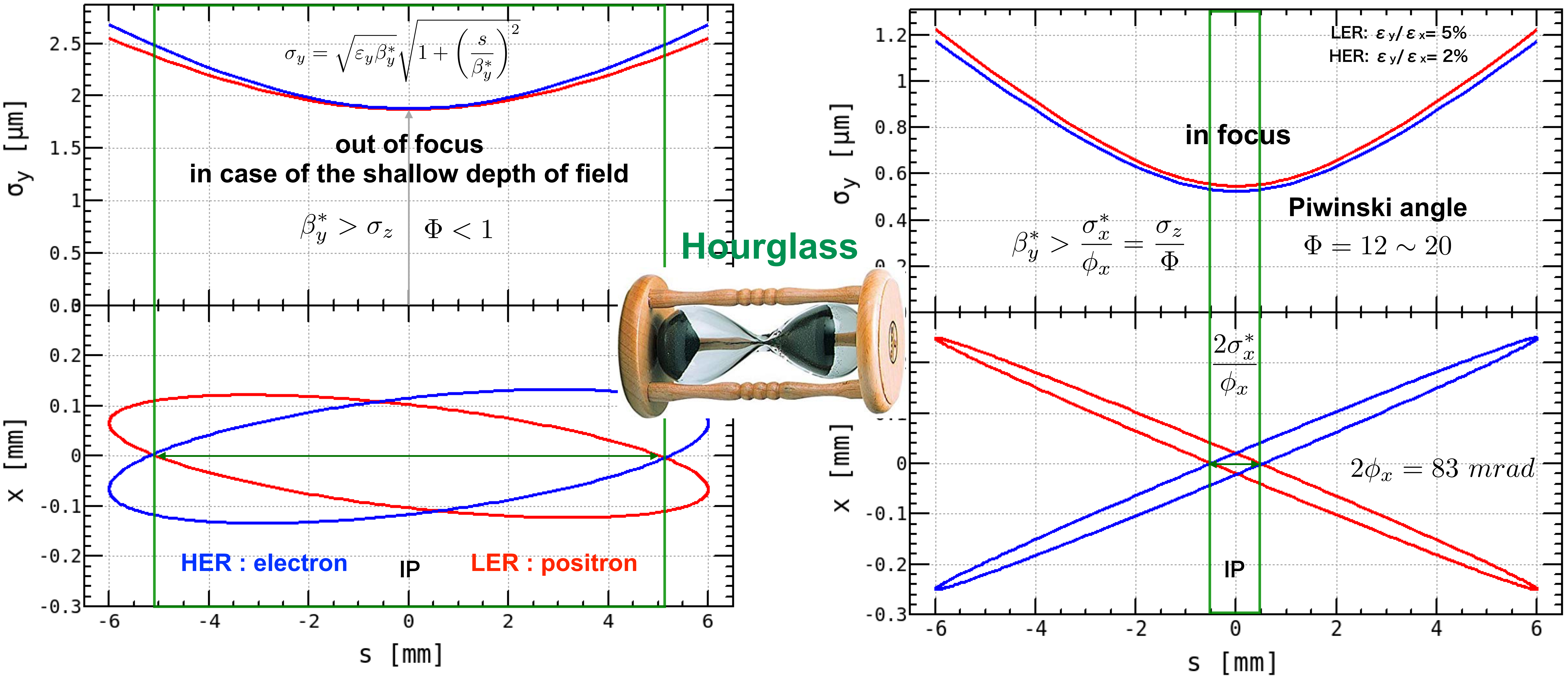
Nano-Beam (SuperKEKB Phase 2)



Large overlap region

Small overlap region

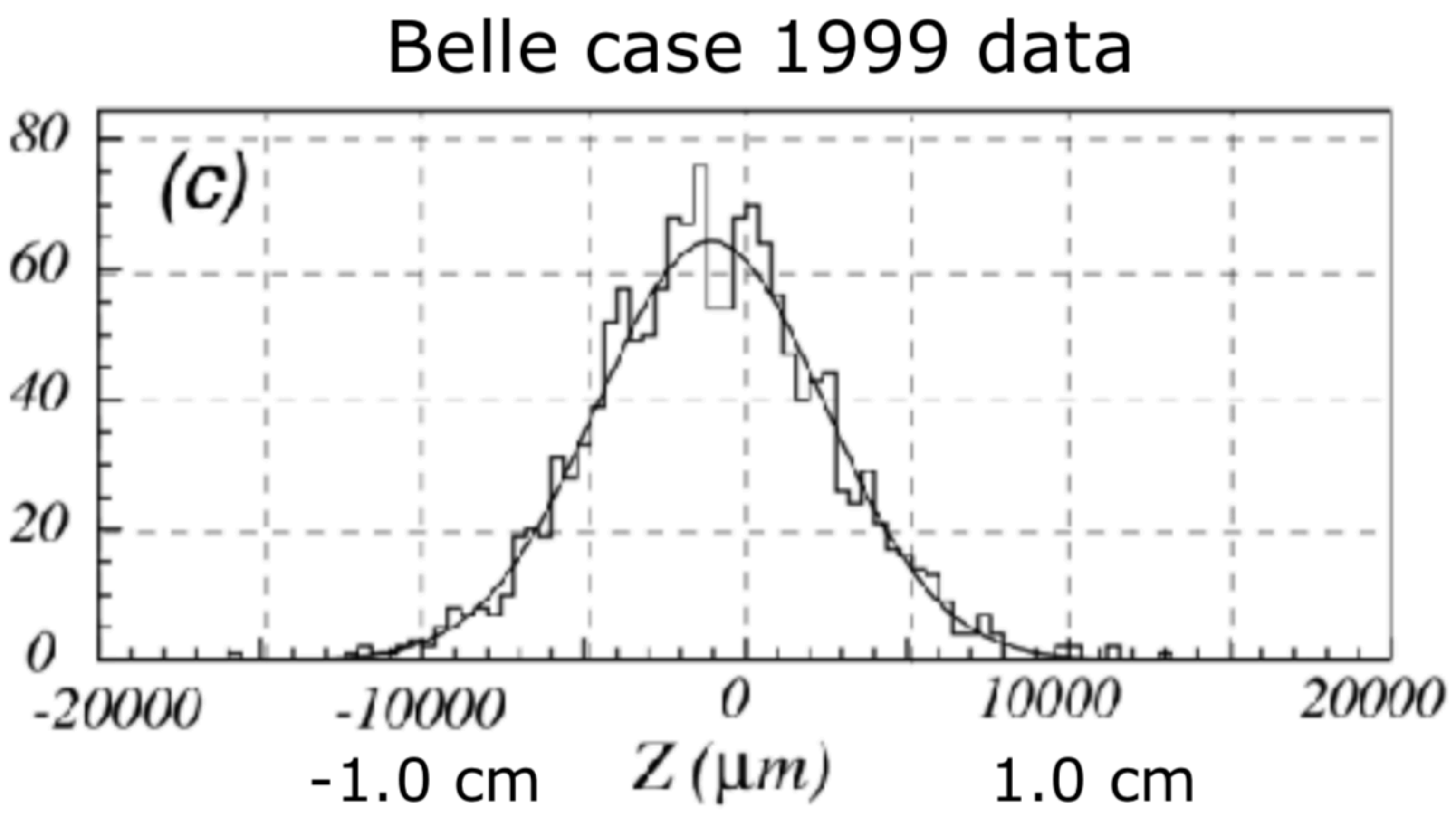
Ordinary collision (KEKB) | **Nano-Beam (SuperKEKB Phase 2)**



Large overlap region | **Small overlap region**

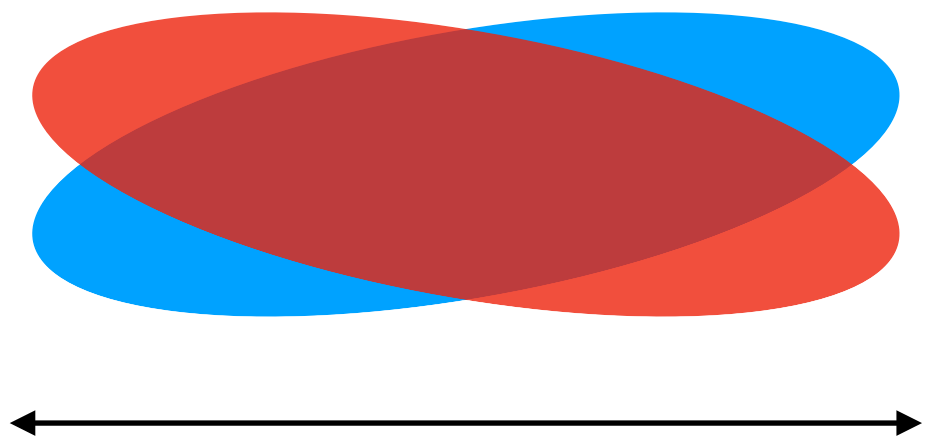
Overlap Region at IP

Ordinary collision (KEKB)



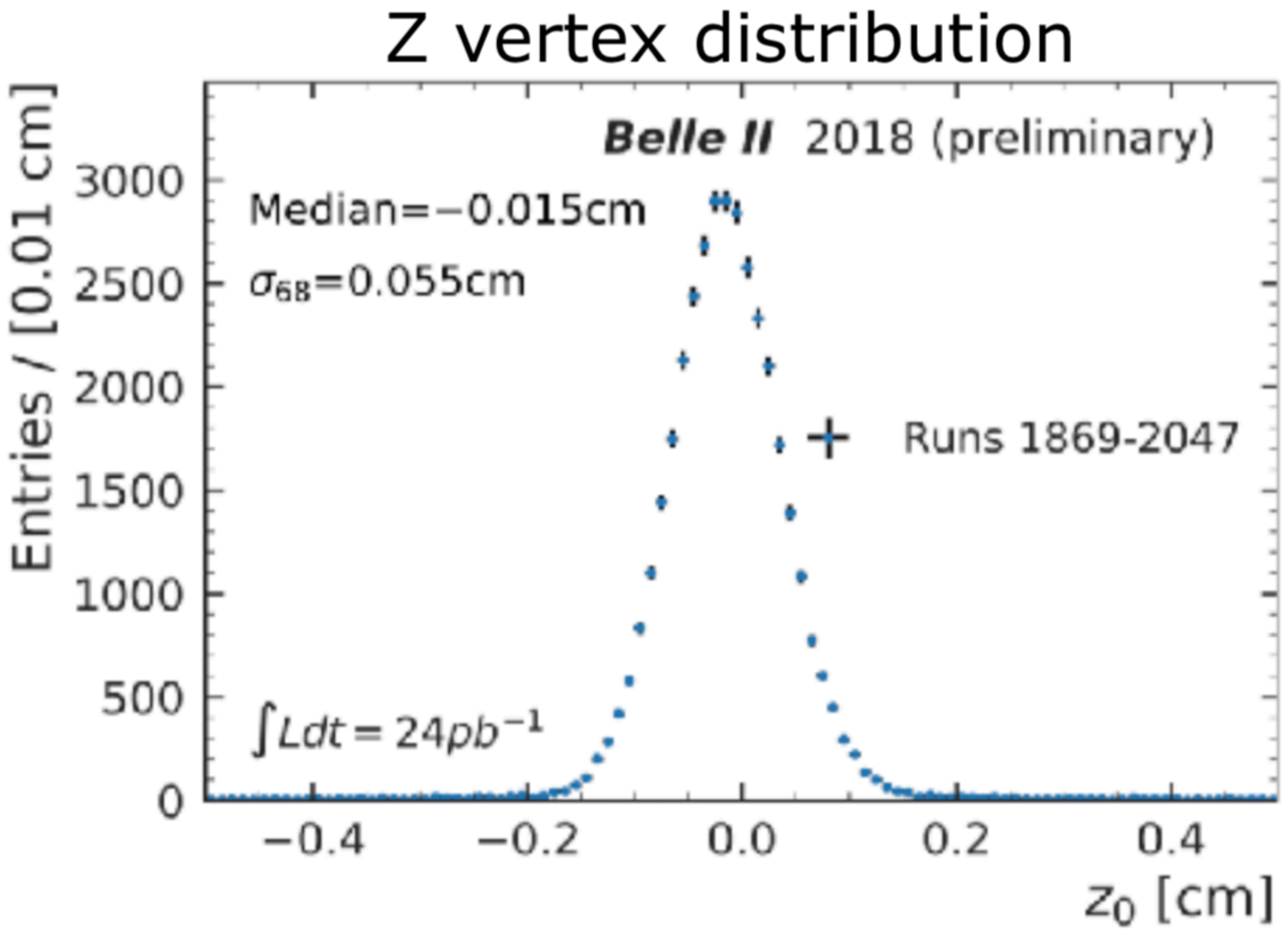
σ = 4.5 mm

measurement at Belle



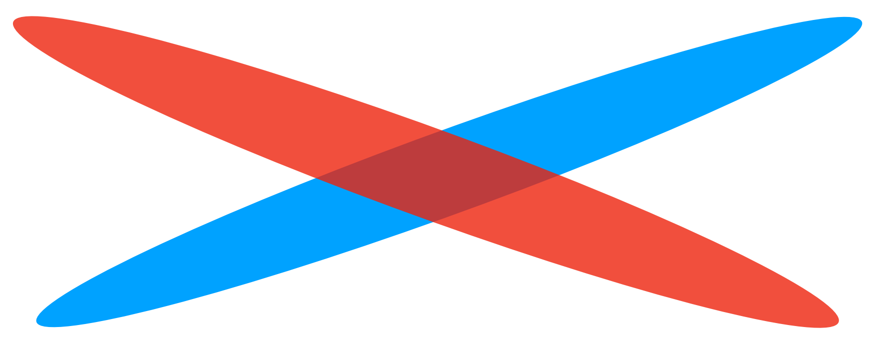
bunch length x 2

Nano-Beam (SuperKEKB Phase2)



σ = 550 μm

measurement at Belle II



The vertex distribution is constrained in the nano-beam scheme.

I. Adachi, T. Iijima

1. Verification of nano-beam scheme
   - Large crossing-angle, low emittance, and low beta at the IP
   - Luminosity increases even though β_y^* is smaller than σ_z.
   - Beam-Beam parameter, $\xi_y > 0.03$
   - $L = 10^{34}\ cm^{-2}s^{-1}$ at 1 [A] beam current in the LER
2. Understanding and reduction of Belle II backgrounds
3. Establishment of the injection system

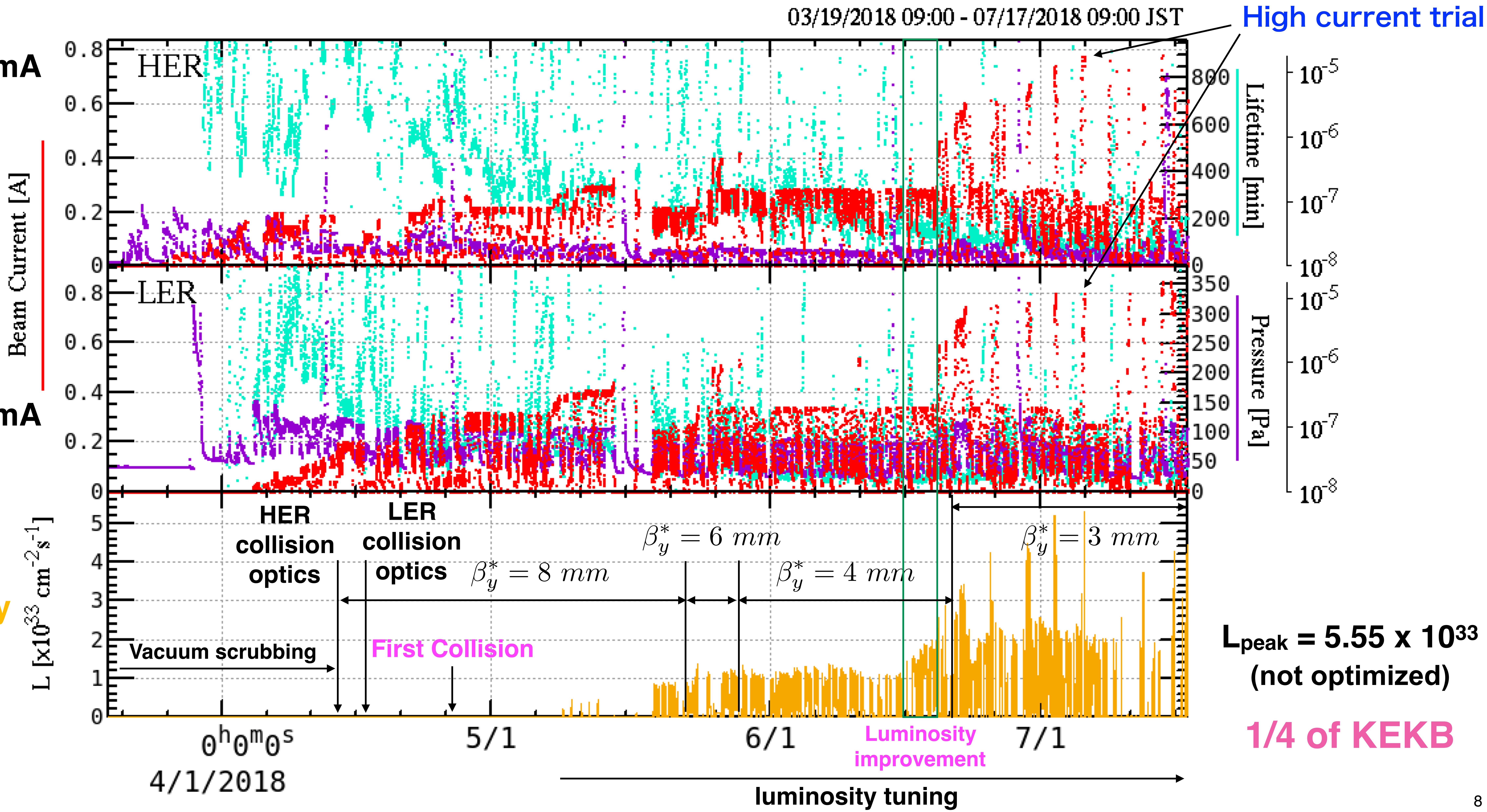
History of Phase 2 Commissioning

Max 800 mA (HER)

Beam Current

Max 860 mA (LER)

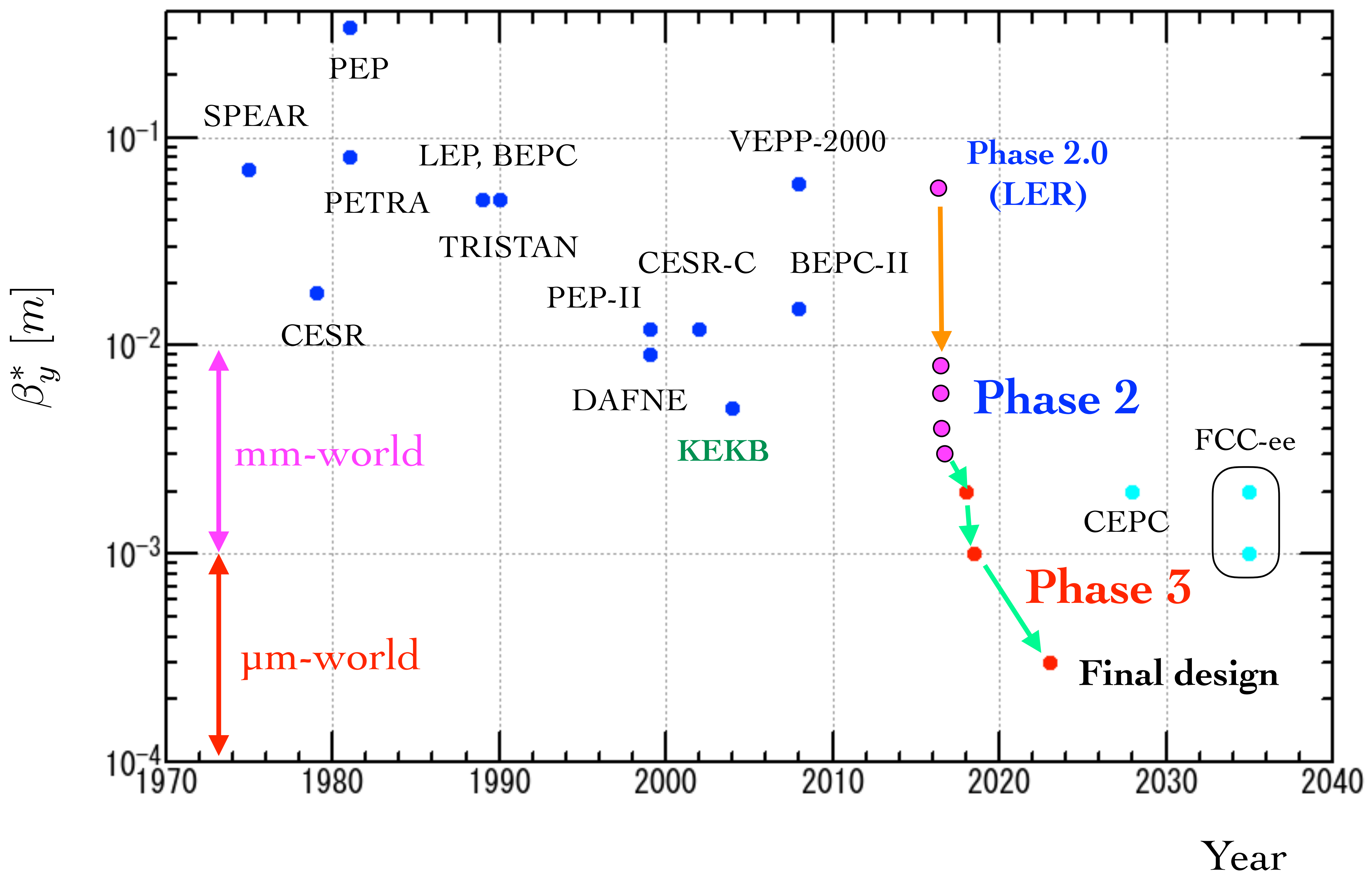
Luminosity



L_{peak} = 5.55 x 10^{33}
(not optimized)

1/4 of KEKB

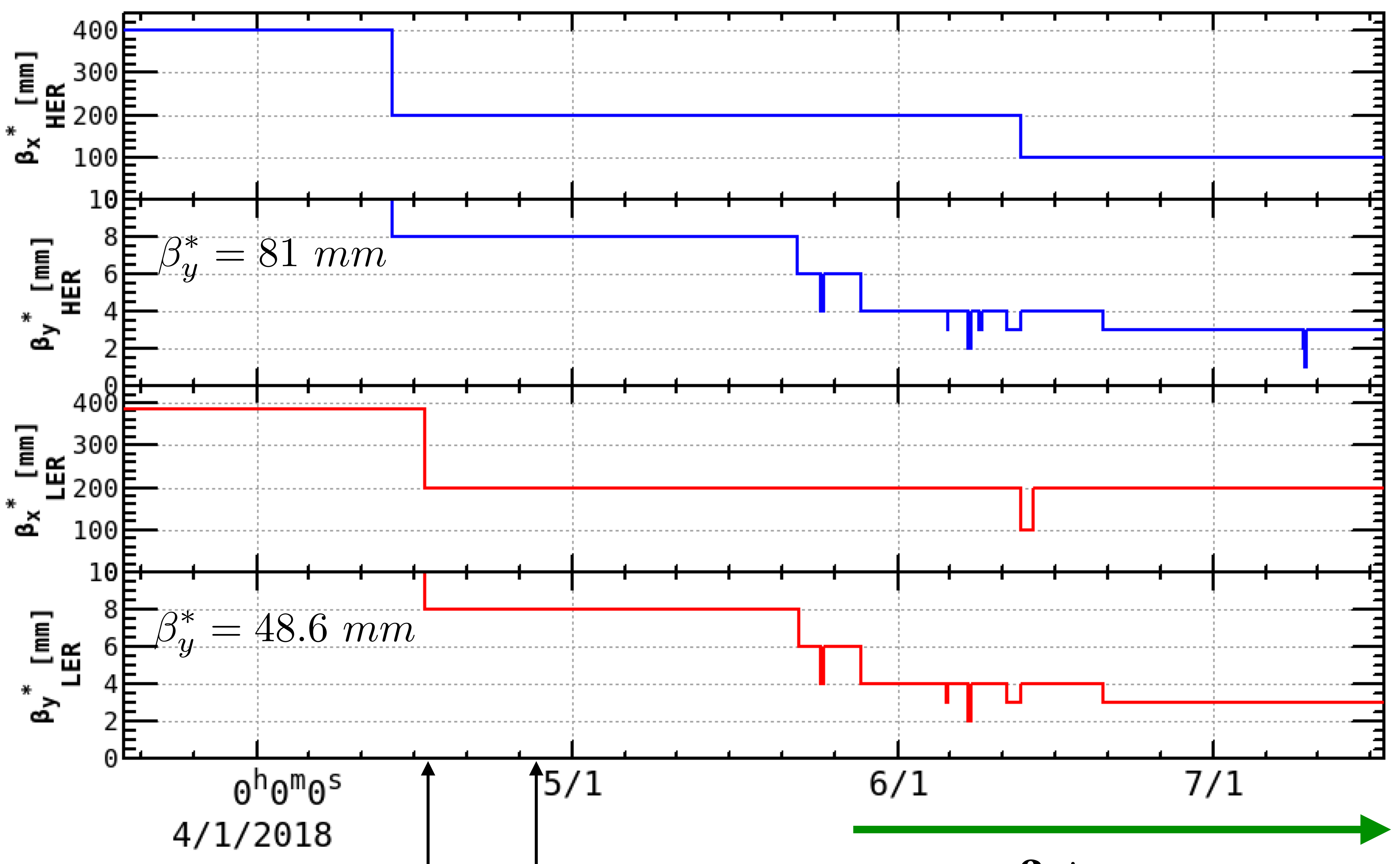
Strategy of beta squeezing for Phase 2 and Phase 3



β_y^* from mm to μm-world in Phase 3

The smallest β_y^* in the world !

Phase 2.0 detuned



First collision

Start collision tuning

$\beta_y^* < \sigma_z$

Test of Nano-Beam

Summary of Beta Squeezing at IP

Phase	β_x^* [mm]		β_y^* [mm]		comment	L_{peak} x10^{33} [$cm^{-2}s^{-1}$]	I_{LER} / I_{HER} , n_b [mA]	Start Date
	LER	HER	LER	HER				
2.1.0	200		8		Luminosity Run	0.93	250 / 220, 600	April 16
2.1.1	200		6		Luminosity Run	1.37	340 / 285, 789	May 22
2.1.2	200		4		Luminosity Run	1.36 no improve	340 / 285, 789	May 28
2.1.3	200		4	3	Luminosity Run	1.32	340 / 285, 789	June 8
2.1.4	200		3		Luminosity Run	1.05	320 / 265, 789	June 11
2.1.5	100		4		Luminosity Run	1.09	340 / 285, 789	June 12
2.1.6	200	100	4		Luminosity Run	2.04 improve !	350 / 295, 789	June 13
2.1.7	200	100	3		Luminosity Run	2.6	340 / 285, 789	June 20
2.2.0	200		2		Optics correction 50 mA	N/A	50 / 50, 1576	June 7
2.3.1	-	100	-	1.5	Optics correction 50 mA	N/A	- / 50, 1576	July 9

Machine Parameters

	Phase 2 (high bunch current)		Phase 2 (high current)		Phase 3 (final)		
	LER	HER	LER	HER	LER	HER	Unit
I @ L_{peak}	**265**	**217**	**788**	**778**	**3600**	**2600**	mA
n_b	395		1576		2500		
I/n_b	0.670	0.549	0.500	0.494	1.44	1.04	mA/bunch
ε_x	1.8	4.6	1.7	4.6	3.2	4.6	nm
β_x^*	200	100	200	100	32	25	mm
β_y^*	**3**	**3**	**3**	**3**	**0.27**	**0.3**	mm
α_c	2.9×10^{-4}	4.5×10^{-4}	2.9×10^{-4}	4.5×10^{-4}	3.2×10^{-4}	4.5×10^{-4}	
σ_δ	7.58×10^{-4}	6.31×10^{-4}	7.58×10^{-4}	6.31×10^{-4}	8.10×10^{-4}	6.37×10^{-4}	
U_0	1.76	2.43	1.76	2.43	1.76	2.43	NeV
V_c	8.4	12.8	8.4	12.8	9.4	15.0	MV
ν_s	-0.0220	-0.0258	-0.0220	-0.0258	-0.0244	-0.0280	
ν_x	44.562	45.542	44.561	45.545	44.53	45.53	
ν_y	46.617	43.609	46.614	43.612	46.57	43.57	
σ_y^* (X-ray)	883	652	1285*	528	48	62	nm
ξ_y ($\Sigma_y/\sqrt{2}$)	**0.030**	**0.021**	**0.0244**	**0.0141**	**0.088**	**0.081**	
L	**2.29×10^{33}**		5.55×10^{33}		8×10^{35}		$cm^{-2}s^{-1}$

*ε_y enhancement in LER

Preliminary

Machine Parameters (cont'd)

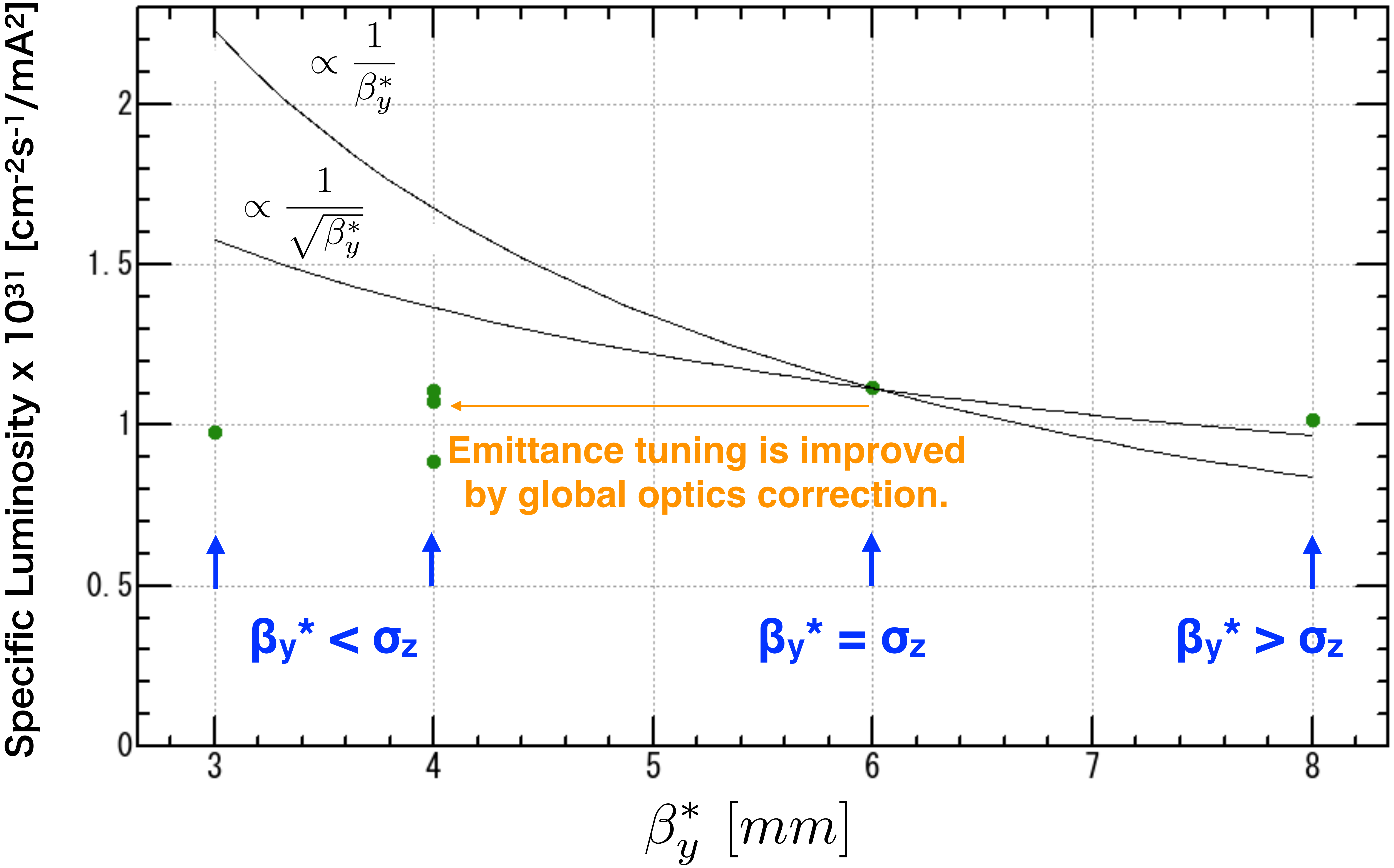
	Phase 2 (high bunch current)		Phase 2 (reference)		Phase 3 (final)		
	LER	HER	LER	HER	LER	HER	Unit
I @ L_{peak}	**265**	**217**	**327**	**279**	**3600**	**2600**	mA
n_b	395		789		2500		
I/n_b	0.670	0.549	0.414	0.353	1.44	1.04	mA/bunch
ε_x	1.8	4.6	1.7	4.6	3.2	4.6	nm
β_x^*	200	100	200	100	32	25	mm
β_y^*	**3**	**3**	**3**	**3**	**0.27**	**0.3**	mm
α_c	2.9×10^{-4}	4.5×10^{-4}	2.9×10^{-4}	4.5×10^{-4}	3.2×10^{-4}	4.5×10^{-4}	
σ_δ	7.58×10^{-4}	6.31×10^{-4}	7.58×10^{-4}	6.31×10^{-4}	8.10×10^{-4}	6.37×10^{-4}	
U_0	1.76	2.43	1.76	2.43	1.76	2.43	NeV
V_c	8.4	12.8	8.4	12.8	9.4	15.0	MV
ν_s	-0.0220	-0.0258	-0.0220	-0.0258	-0.0244	-0.0280	
ν_x	44.562	45.542	44.558	45.541	44.53	45.53	
ν_y	46.617	43.609	46.615	43.610	46.57	43.57	
σ_y^* (X-ray)	883	652	692	486	48	62	nm
ξ_y ($\Sigma_y/\sqrt{2}$)	**0.030**	**0.021**	**0.0277**	**0.0186**	**0.088**	**0.081**	
L	**2.29×10^{33}**		2.62×10^{33}		8×10^{35}		$cm^{-2}s^{-1}$

typical physics run

Preliminary

Verification of Nano-Beam Scheme

$$L \propto \frac{1}{\sqrt{\varepsilon_y \beta_y^*}} \quad \text{or} \quad L \propto \frac{\xi_y}{\beta_y^*} \qquad \xi_y \propto \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$



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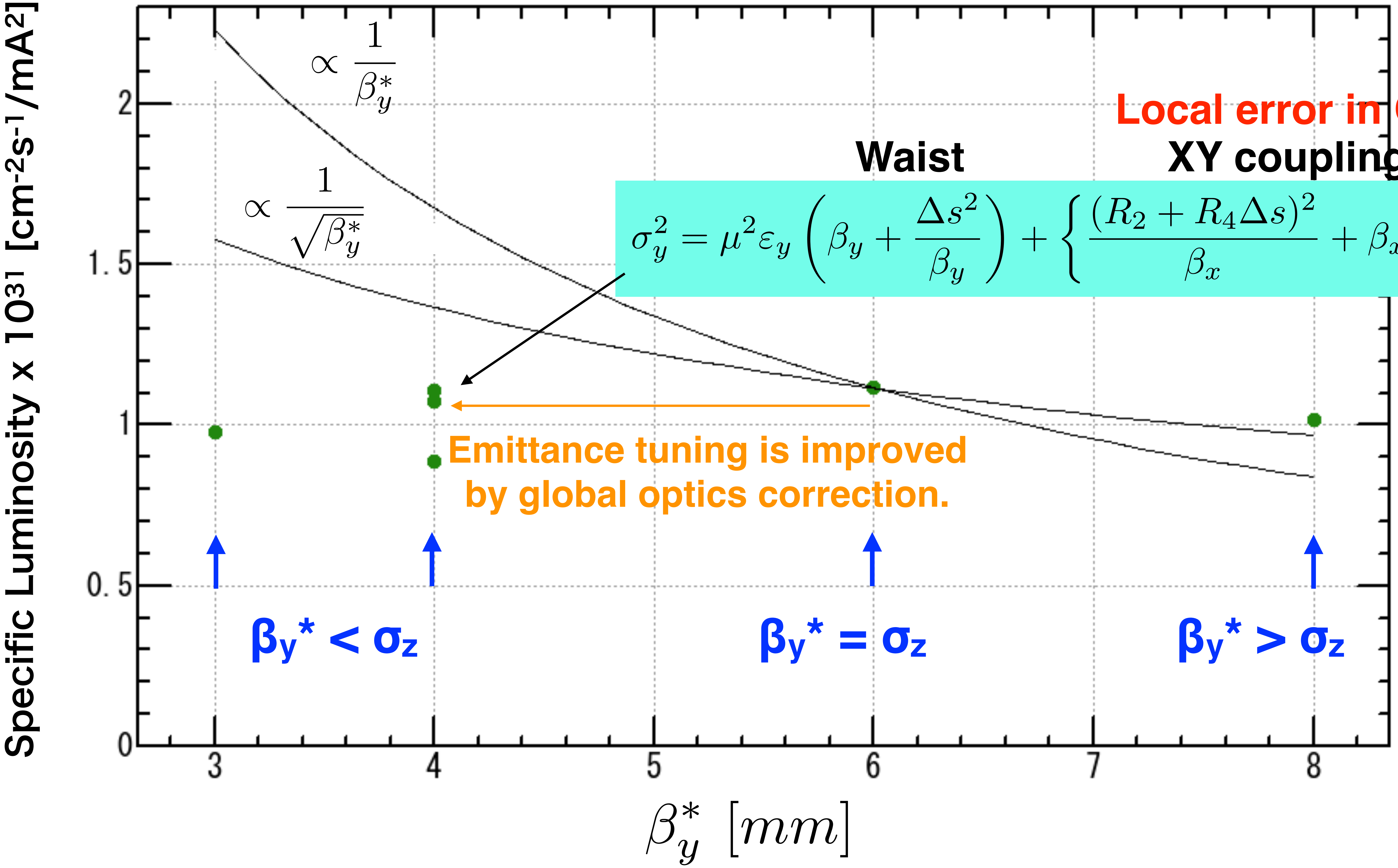
Waist — XY coupling (Local error in QCS) — YZ coupling

$$\sigma_y^2 = \mu^2 \varepsilon_y \left(\beta_y + \frac{\Delta s^2}{\beta_y}\right) + \left\{\frac{(R_2 + R_4 \Delta s)^2}{\beta_x} + \beta_x (R_1 + R_3 \Delta s)^2\right\} + (\eta_y \sigma_\delta)^2$$



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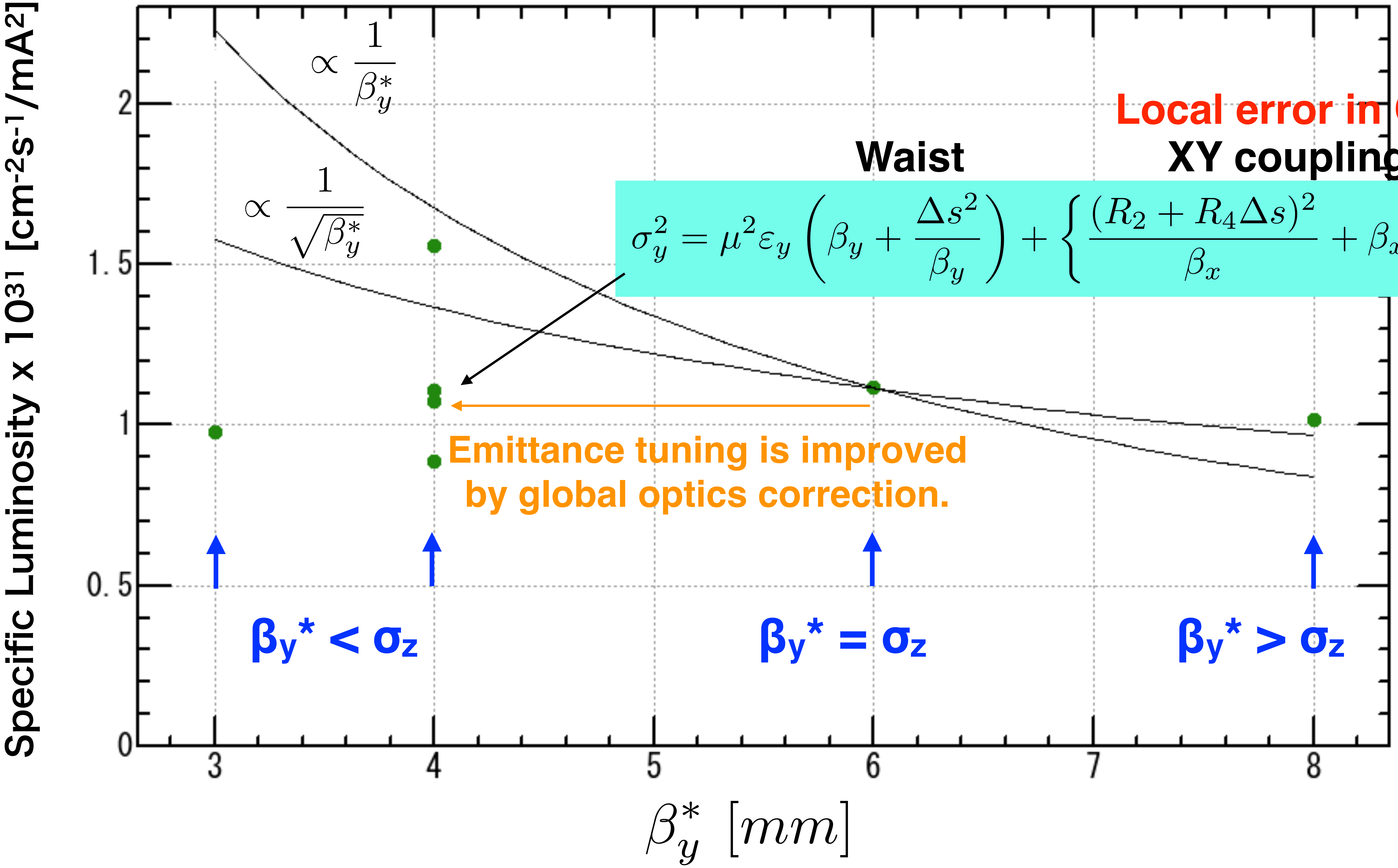

Local error in QCS

Waist | XY coupling | YZ coupling

$$\sigma_y^2 = \mu^2 \varepsilon_y \left(\beta_y + \frac{\Delta s^2}{\beta_y} \right) + \left\{ \frac{(R_2 + R_4 \Delta s)^2}{\beta_x} + \beta_x (R_1 + R_3 \Delta s)^2 \right\} + (\eta_y \sigma_\delta)^2$$

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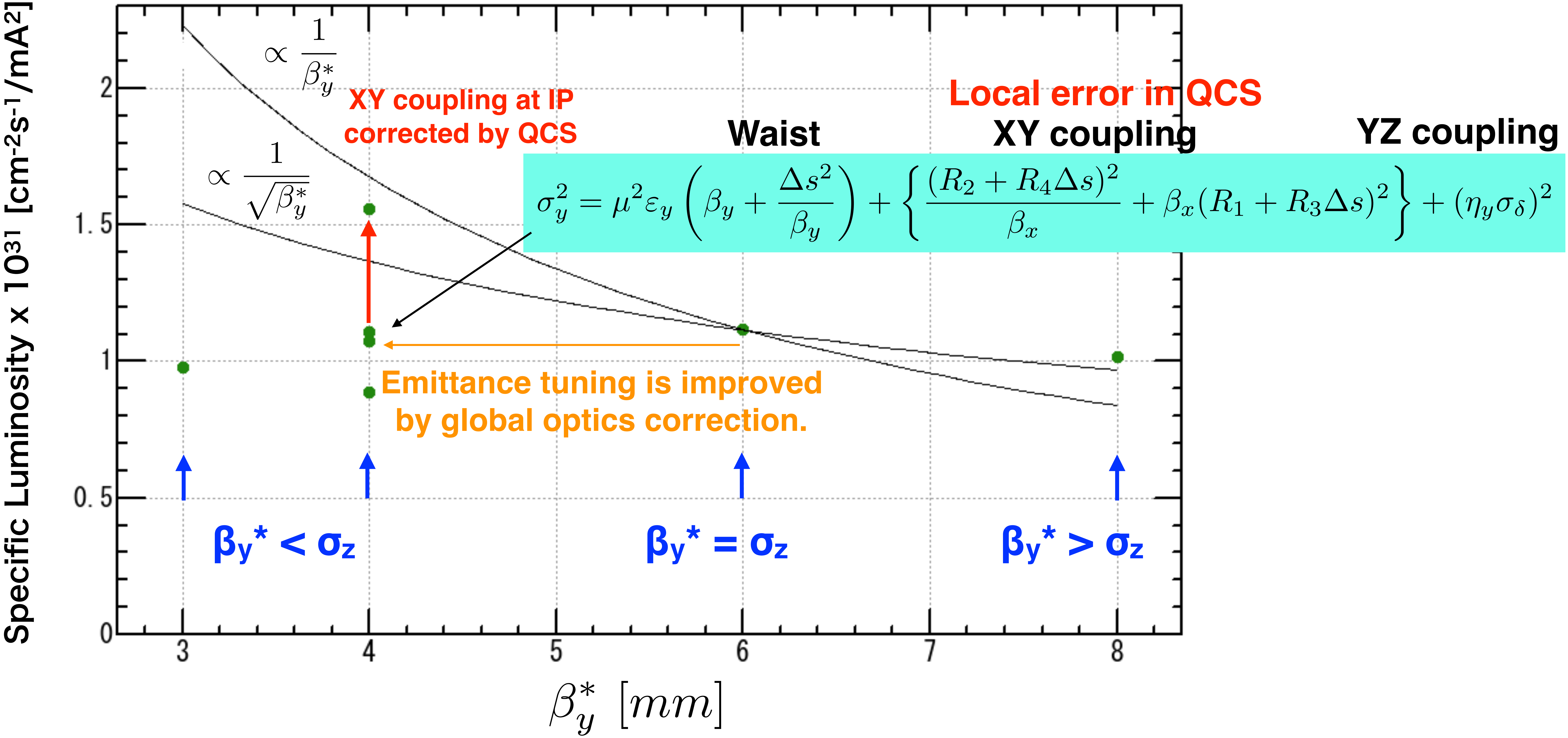

Verification of Nano-Beam Scheme

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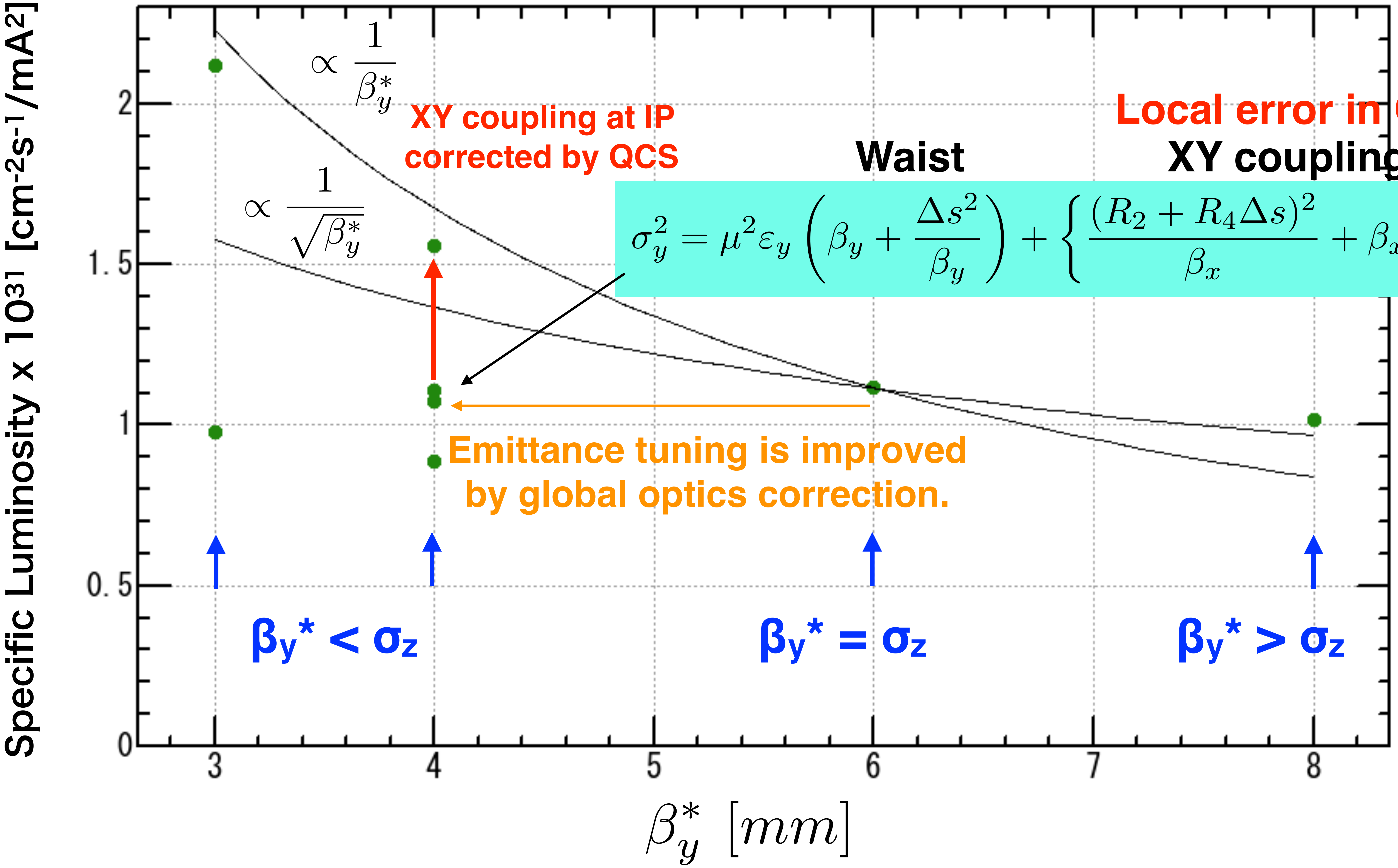

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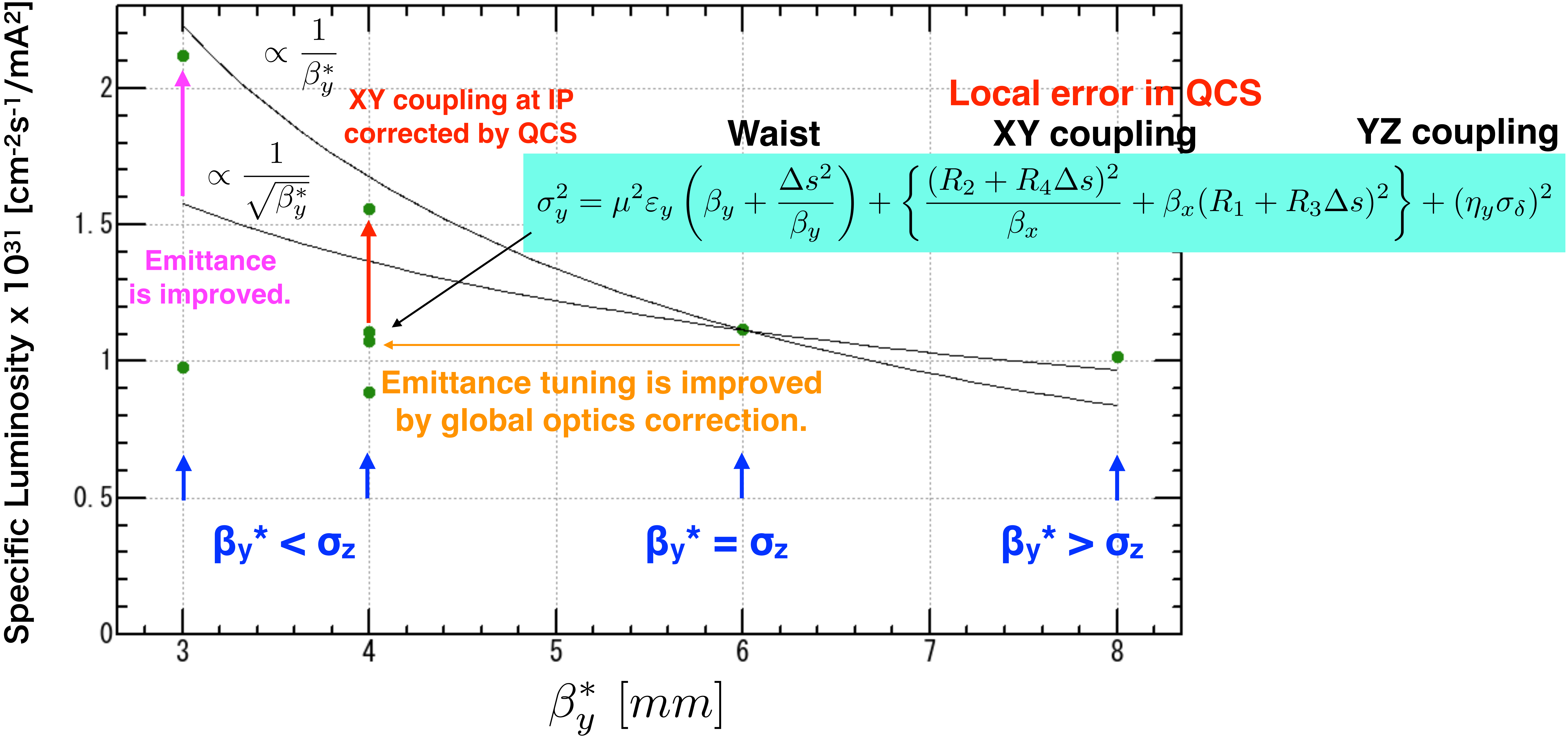
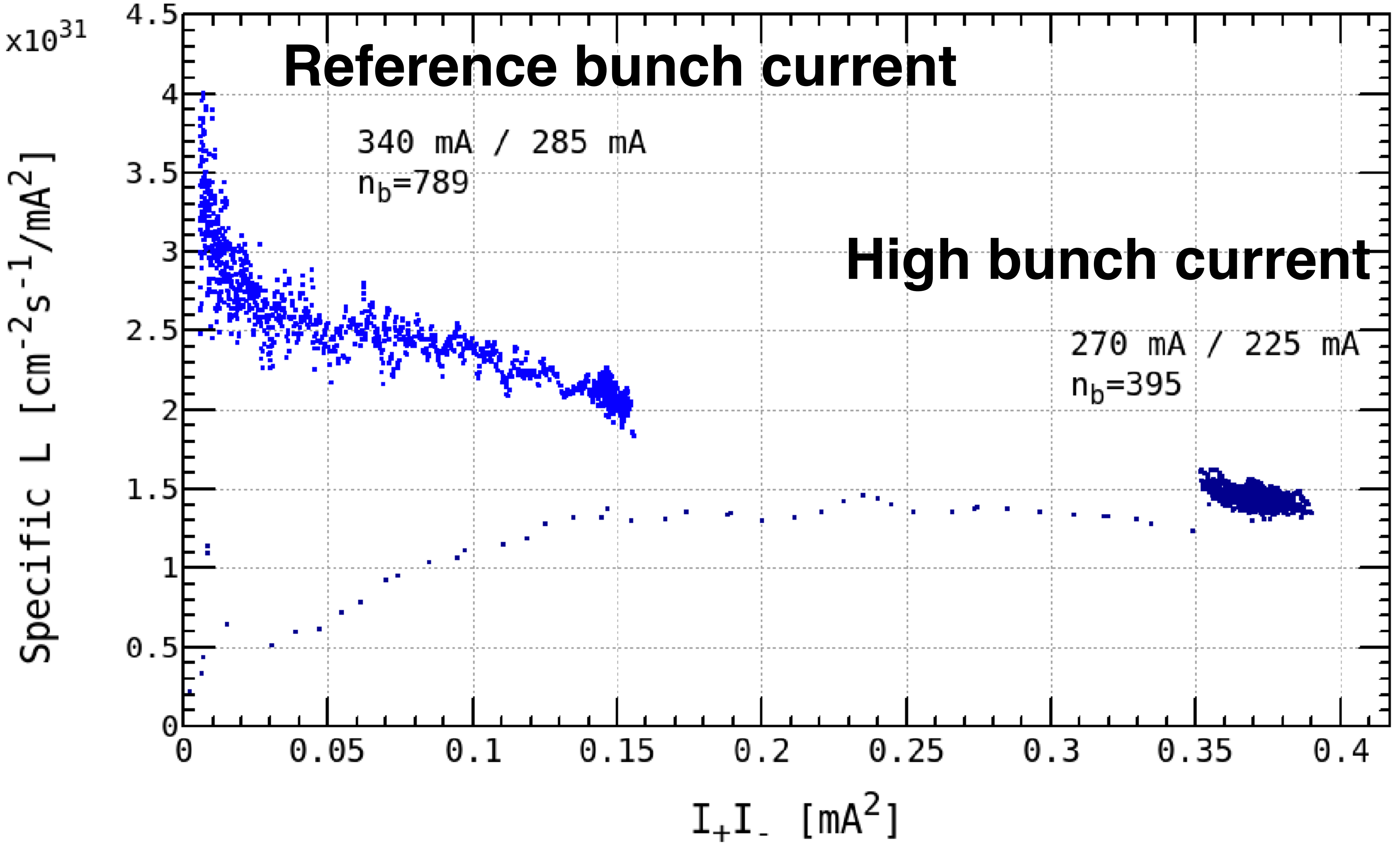
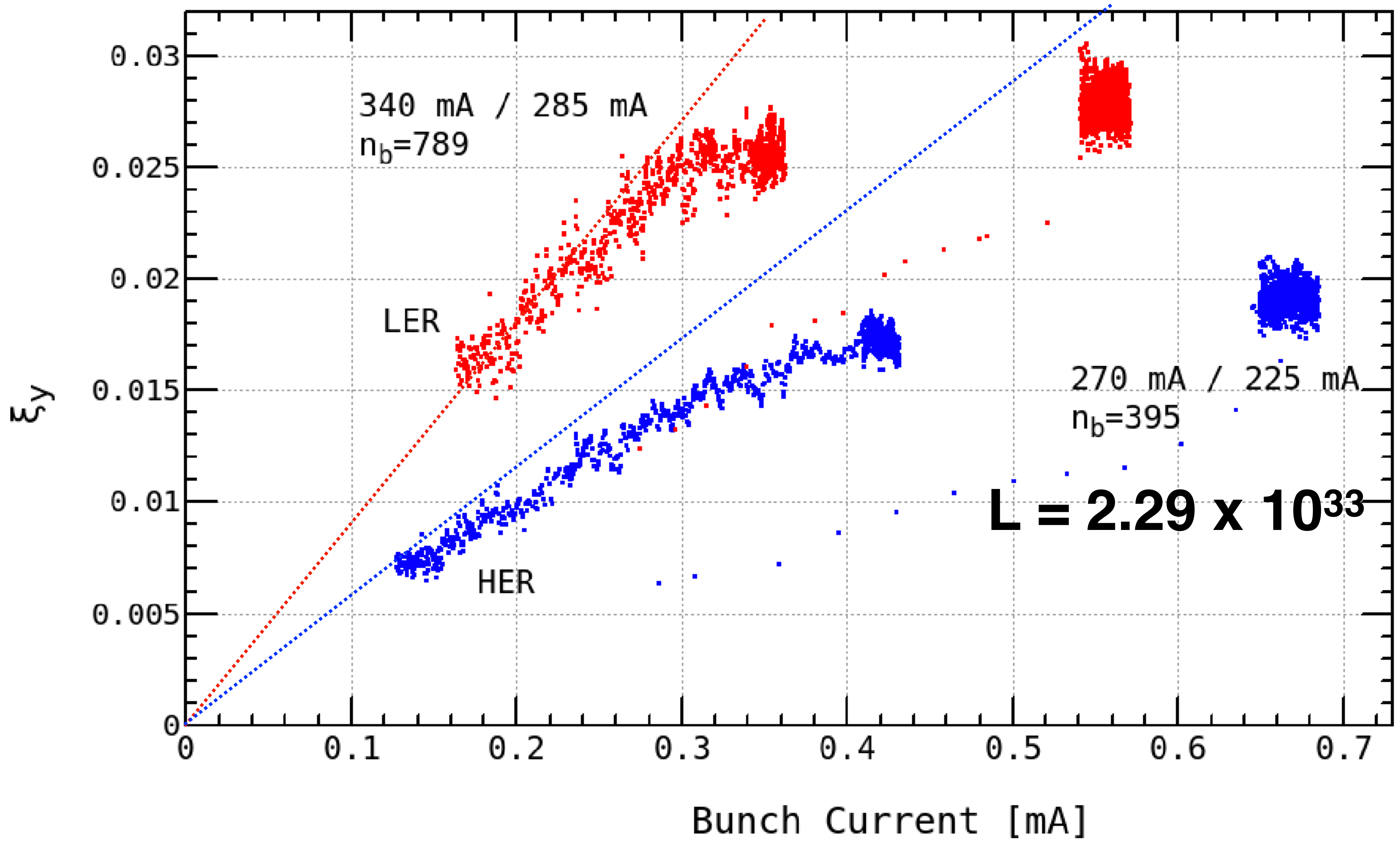


Specific Luminosity and Beam-Beam Parameter





The beam-beam parameter is 0.02.

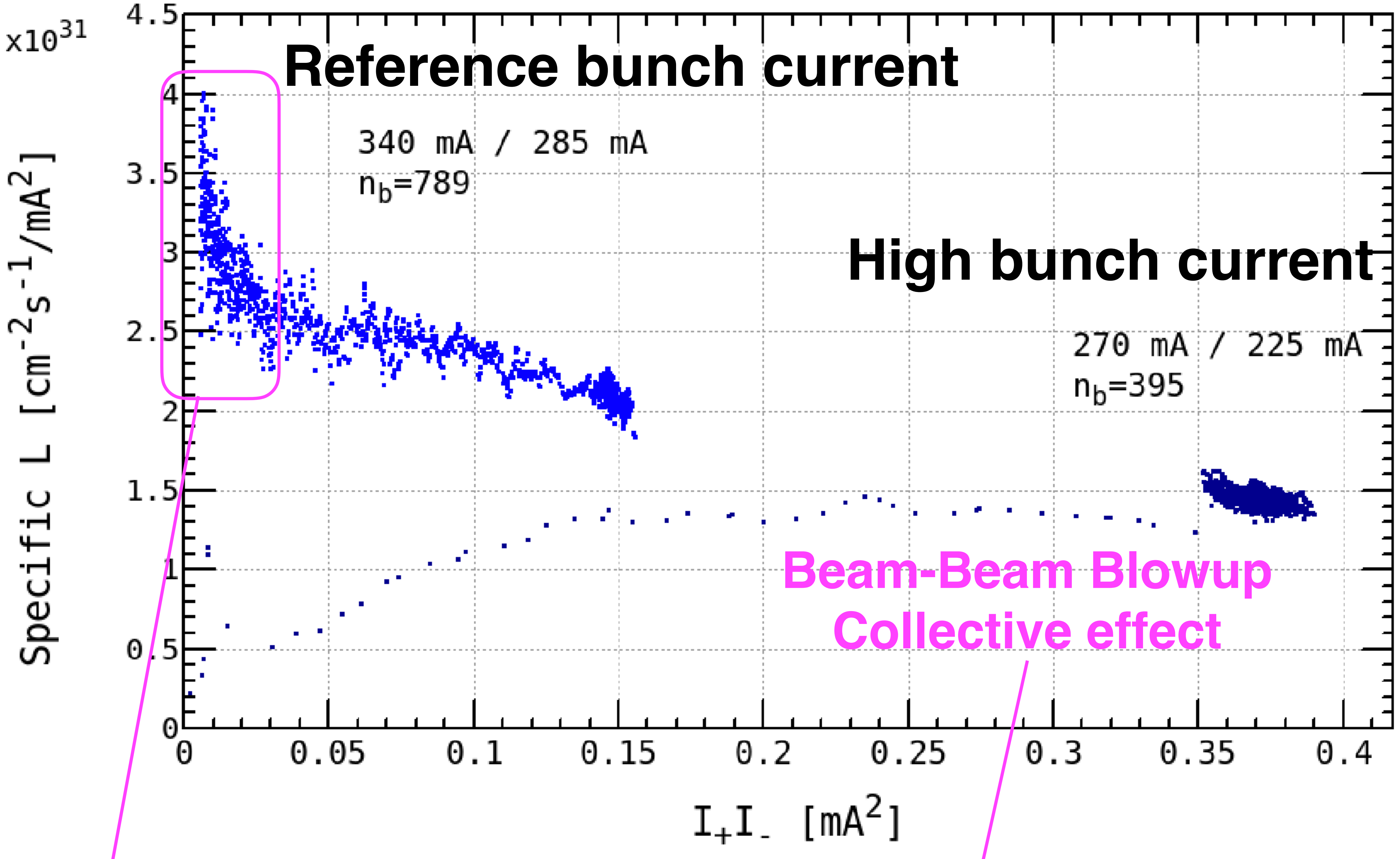
$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi(\sigma_z \phi_x)e^2 f_0 \sigma_y^*} = \frac{1.25 \times 10^{25}}{\sigma_y^*} \; [cm^{-2}s^{-1}/mA^2]$$

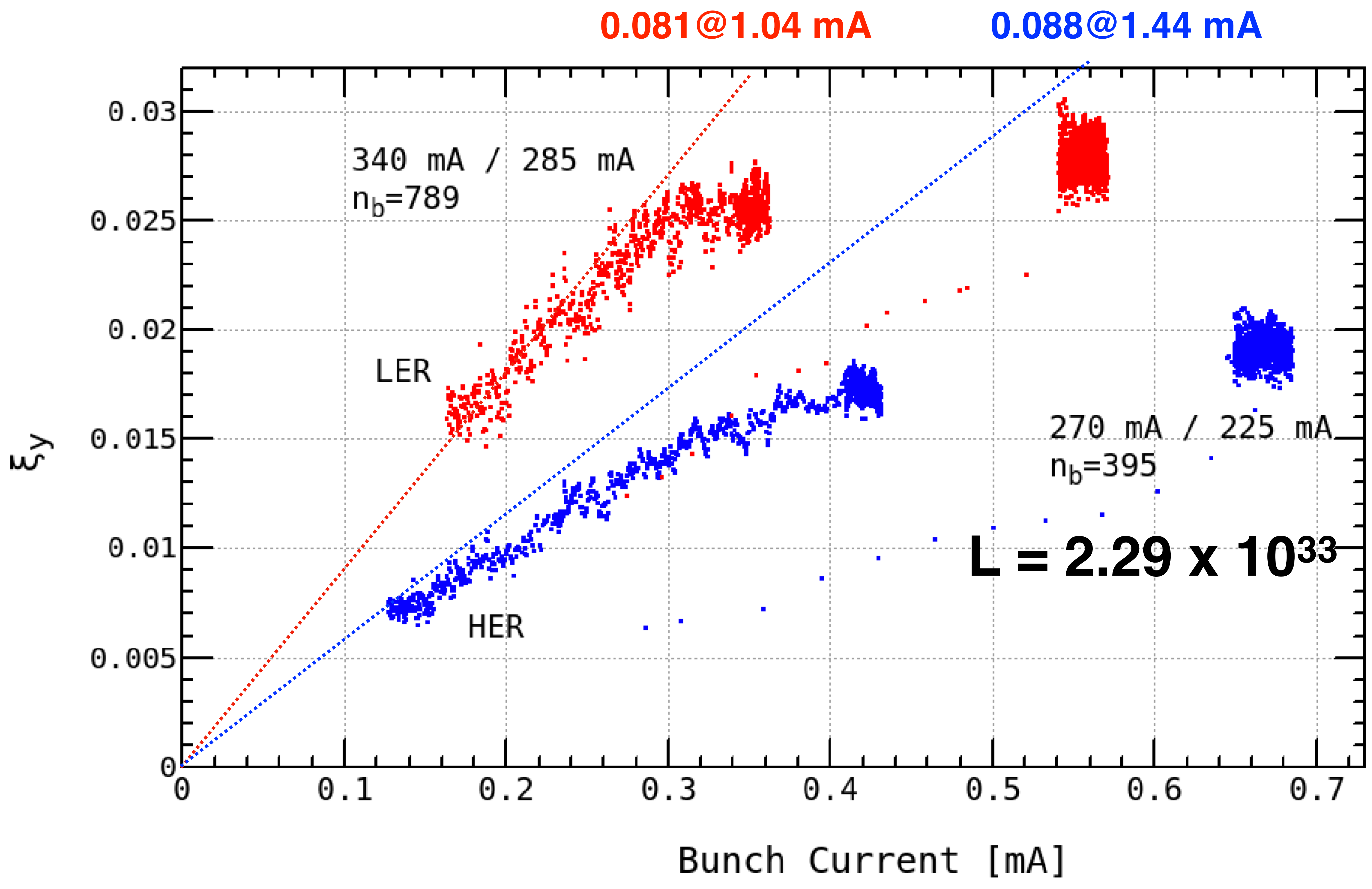
The beam size from L_{sp} is consistent with that of no beam-beam.

$L_{sp} = 4\text{x}10^{31} \rightarrow \sigma_y^* = 300$ nm ($\varepsilon_y = 30$ pm)

$\leftrightarrow \varepsilon_y = 23$ pm for single beam in LER

Specific Luminosity and Beam-Beam Parameter





Luminosity drop at low current. ☞ **issue in Phase 3**

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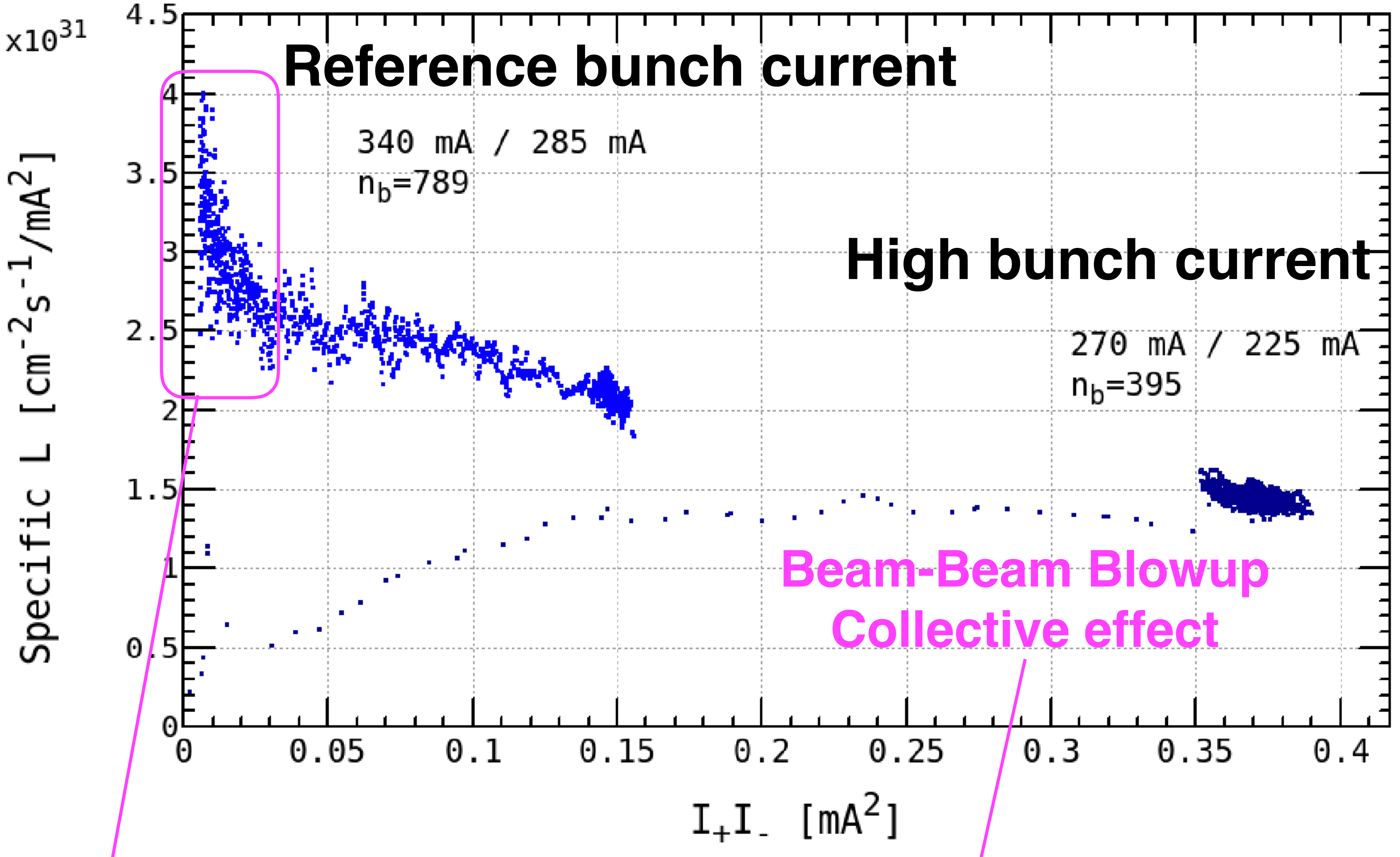
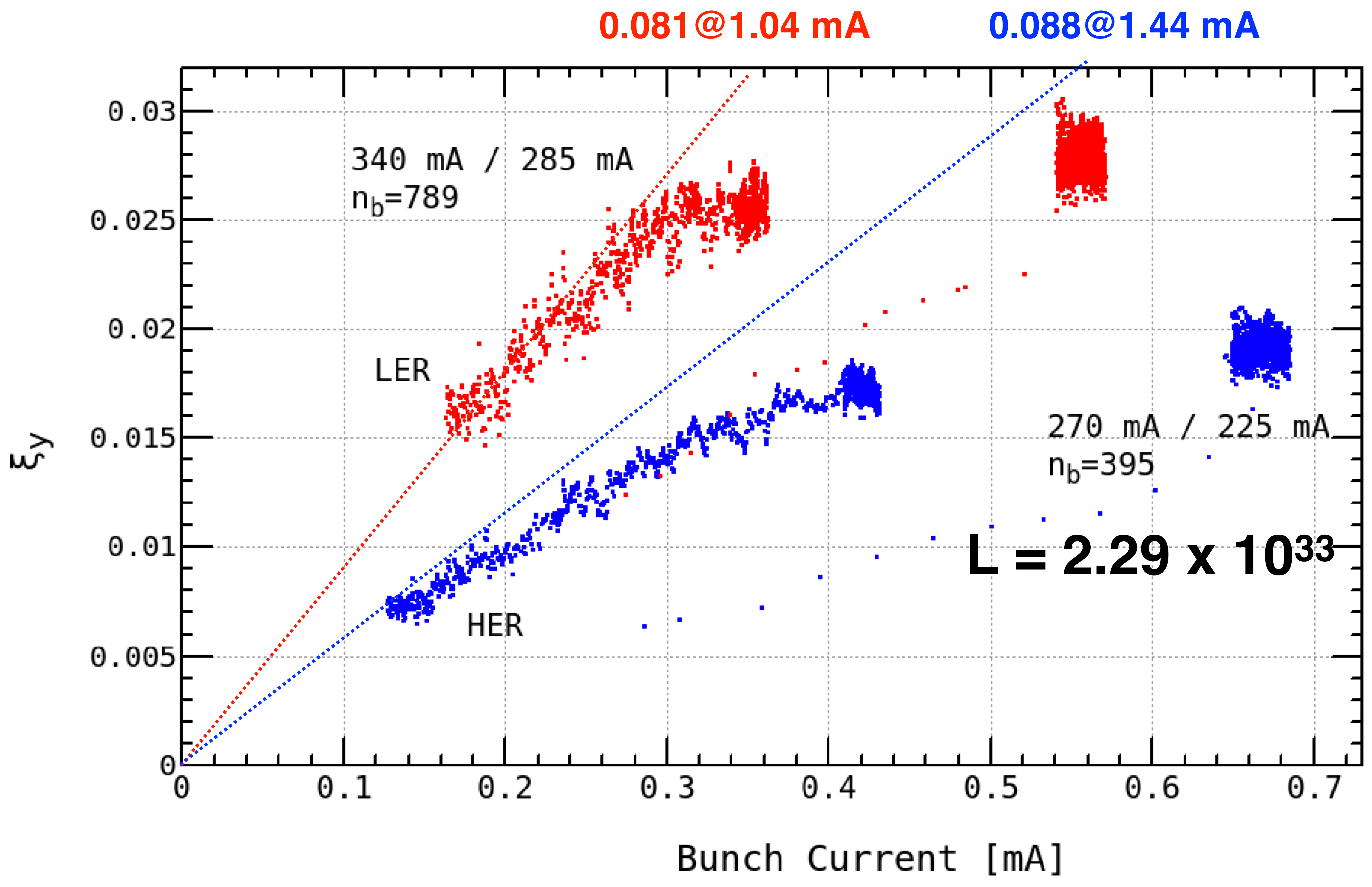
Specific Luminosity and Beam-Beam Parameter





Luminosity drop at low current. ☞ **issue in Phase 3**

$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi(\sigma_z \phi_x) e^2 f_0 \sigma_y^*} = \frac{1.25 \times 10^{25}}{\sigma_y^*} \; [cm^{-2}s^{-1}/mA^2]$$

The beam size from L_{sp} is consistent with that of no beam-beam.

L_{sp} = 4x10^{31} → σ_y^* = 300 nm (ε_y = 30 pm)

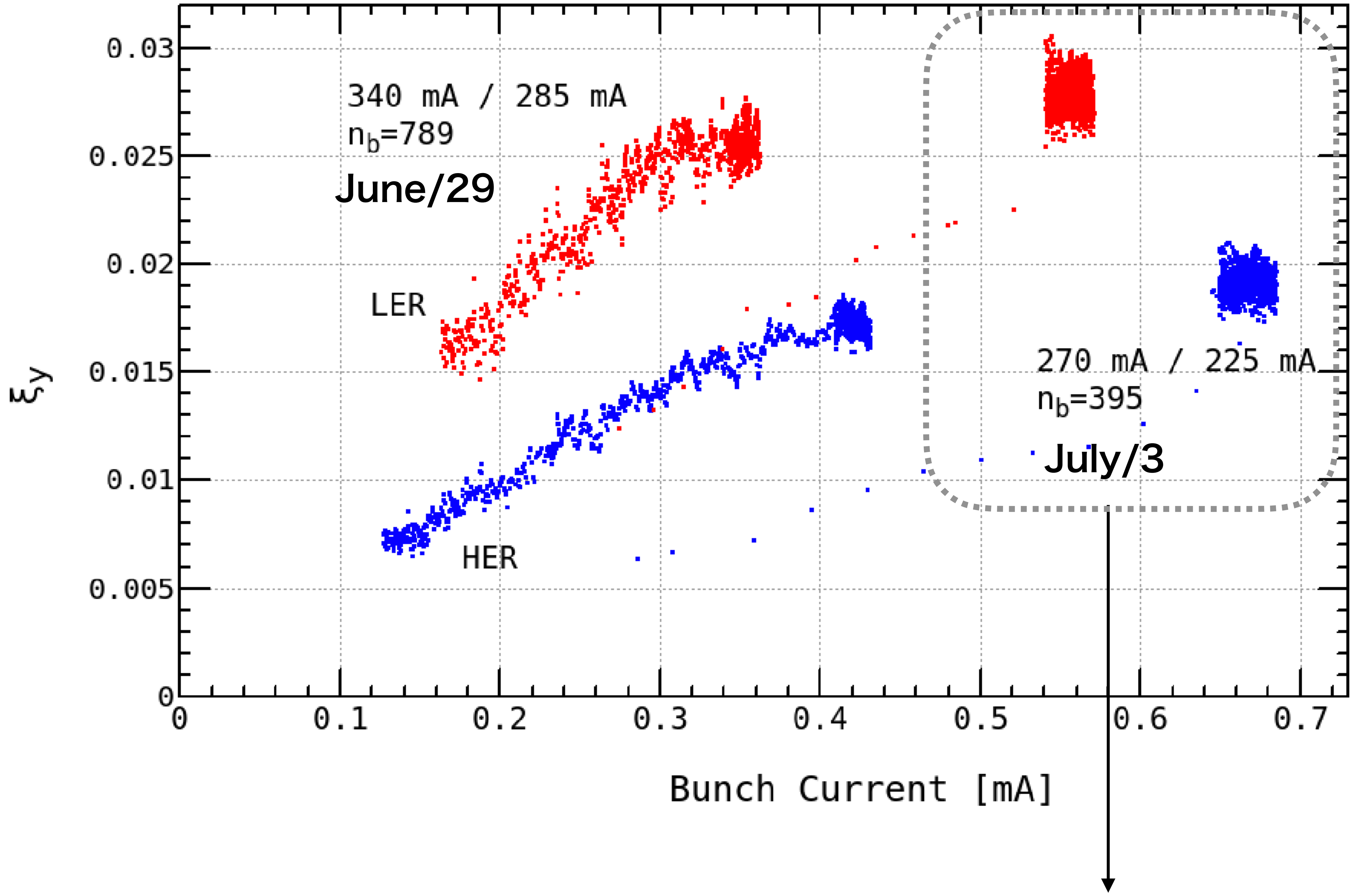
↔ ε_y = 23 pm for single beam in LER

The beam-beam parameter is 0.02.

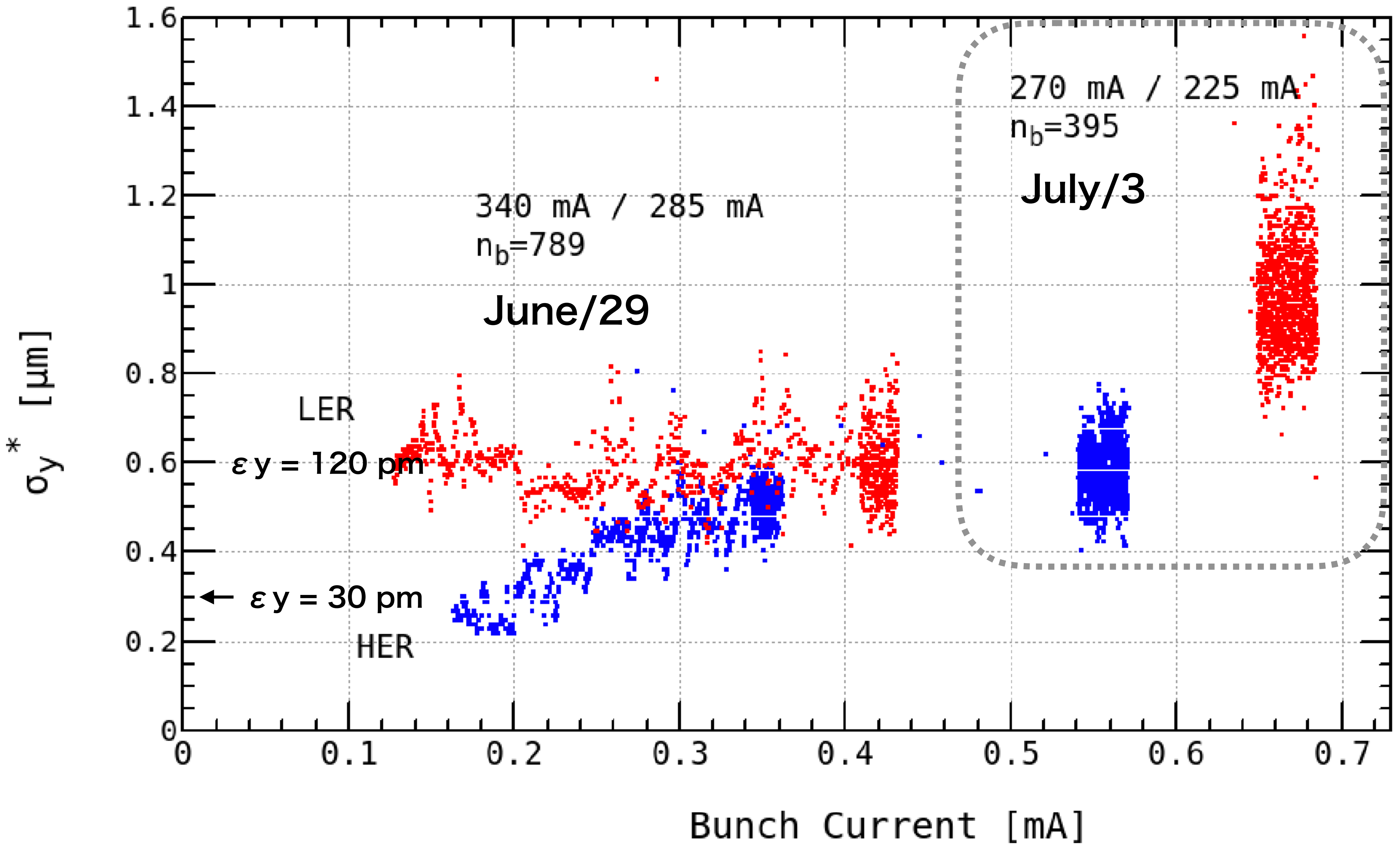
The beam-beam parameter is saturated at high bunch current. ☞ **issue in Phase 3**

$\beta_y^* = 3\ mm$ LER: $\beta_x^* = 200\ mm$ HER: $\beta_x^* = 100\ mm$

Assumption: $\sigma_{y-}^* = \sigma_{y+}^*$



Beam size at IP estimated from X-Ray Monitor

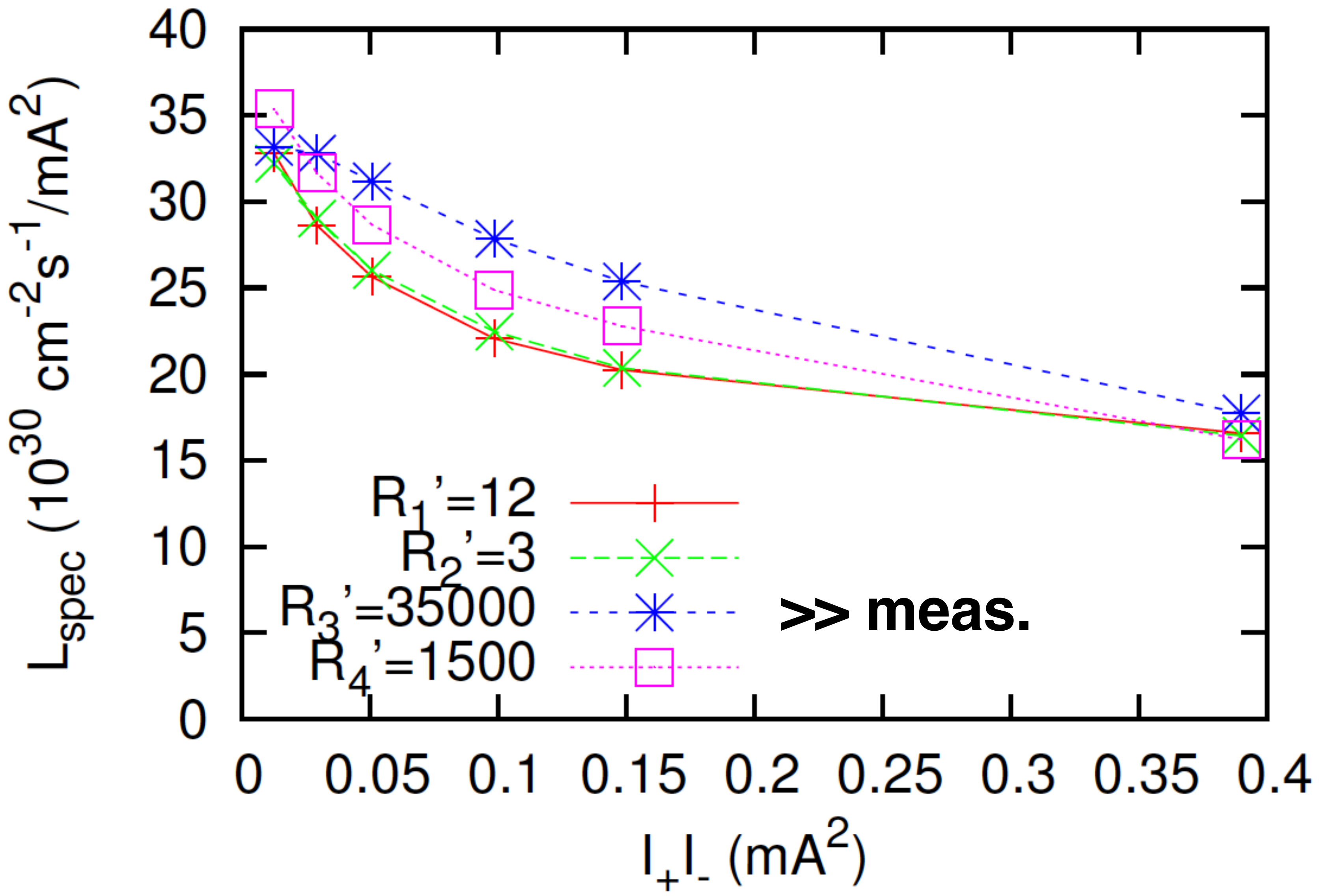


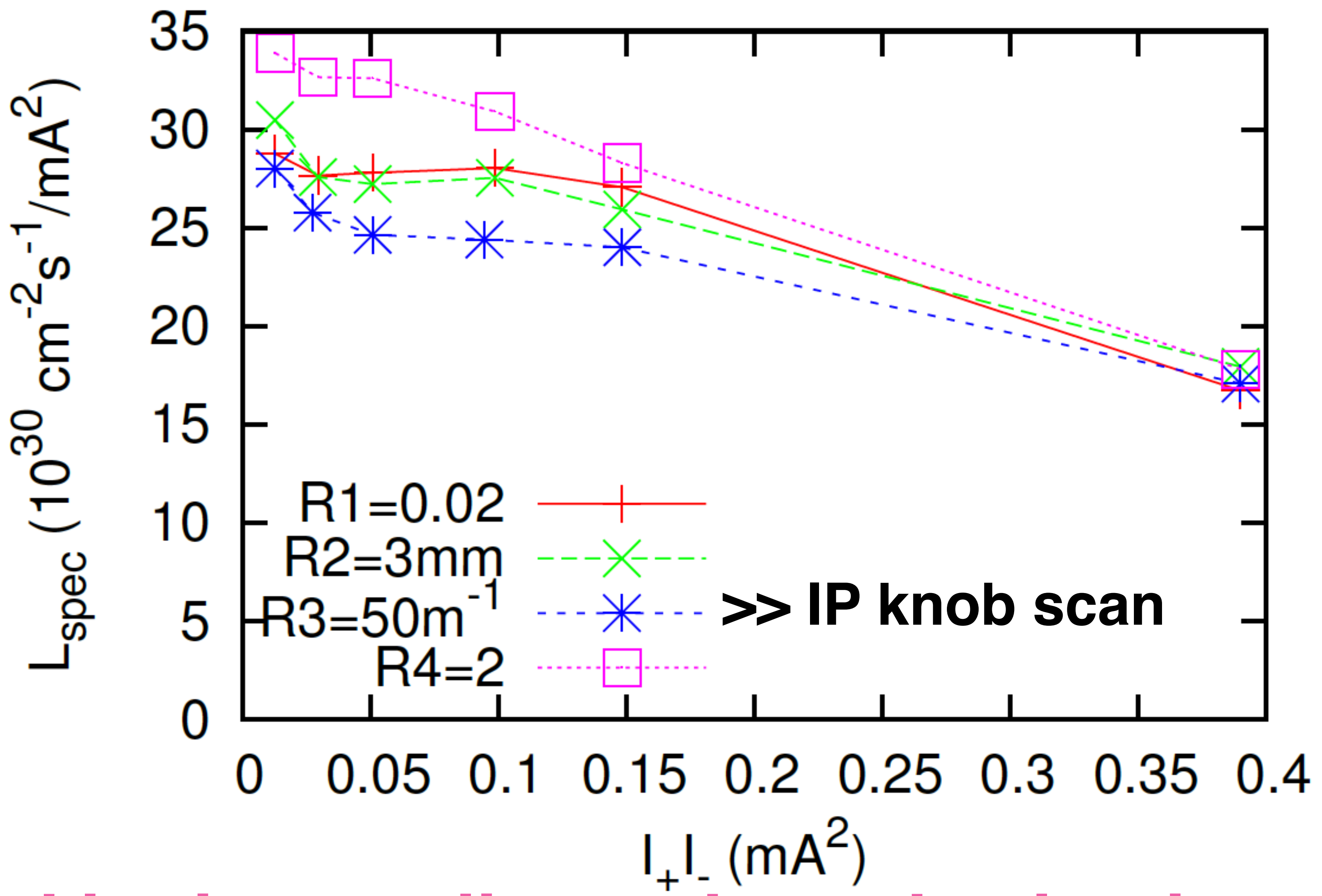
$$\Sigma_y = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad \Sigma_y/\sqrt{2} = 800\ \mu m$$

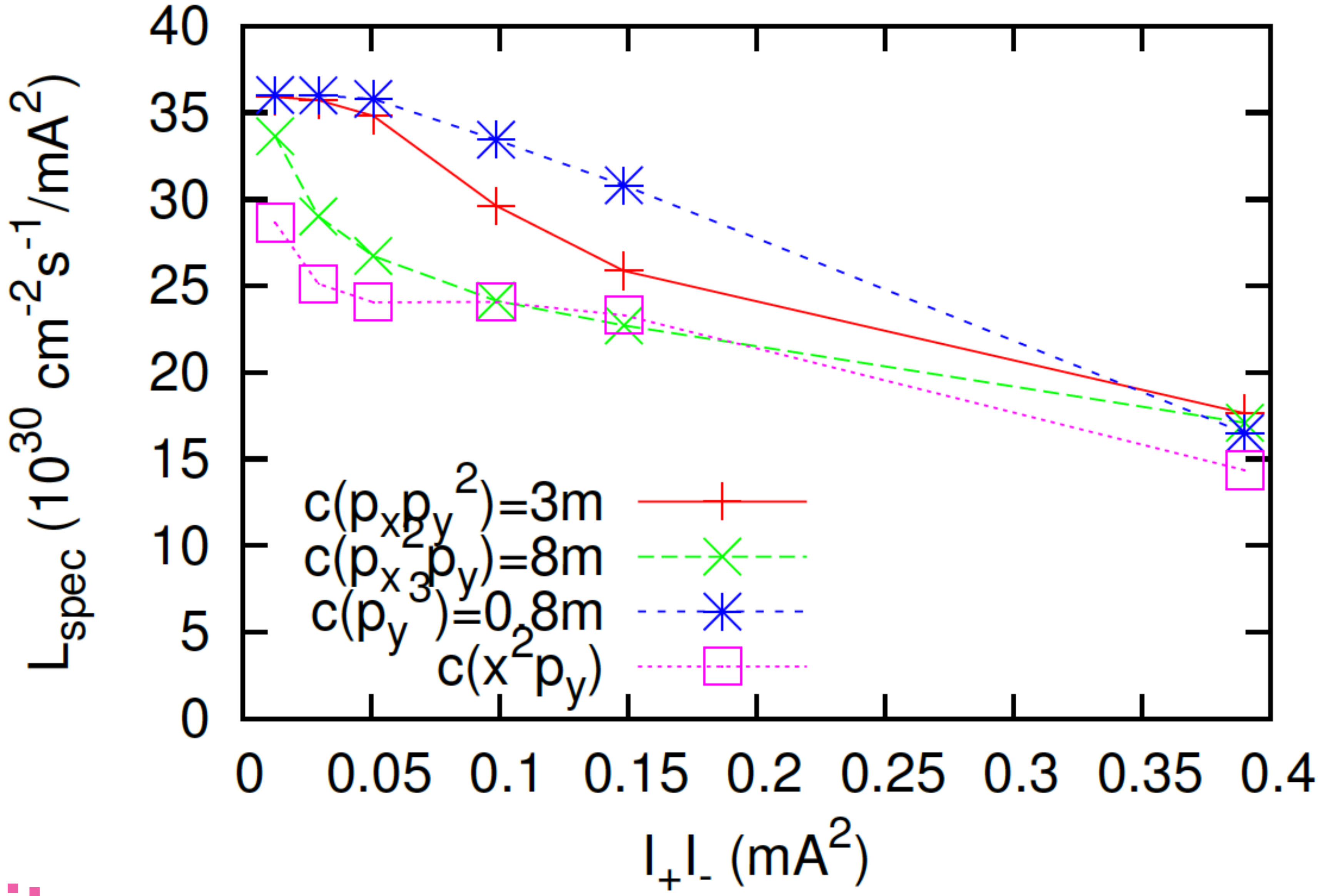
Beam size is large at the low bunch current in LER.
Blowup is also significant at high bunch current.

Beam-Beam simulations with machine error (W-S)

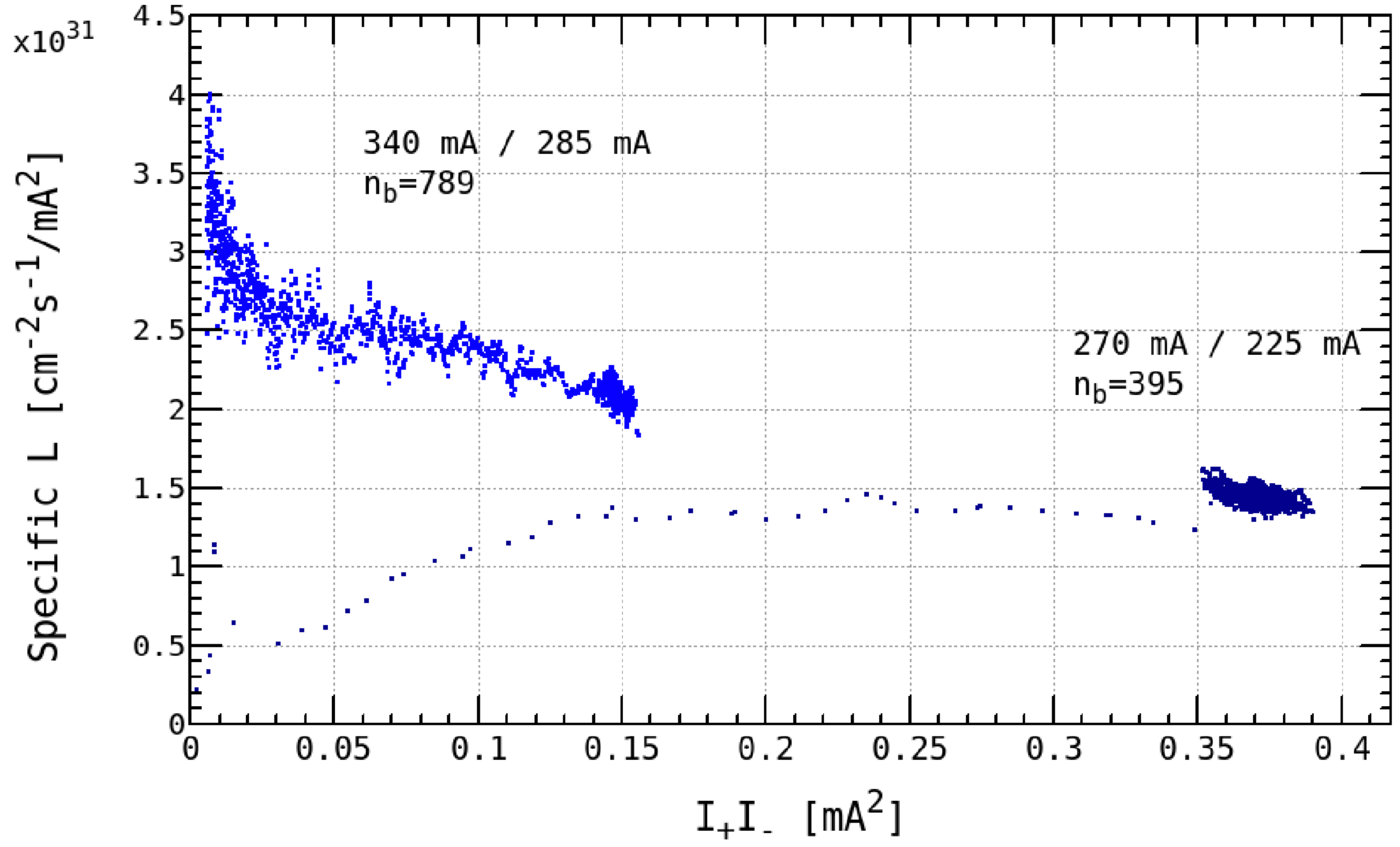
K. Ohmi





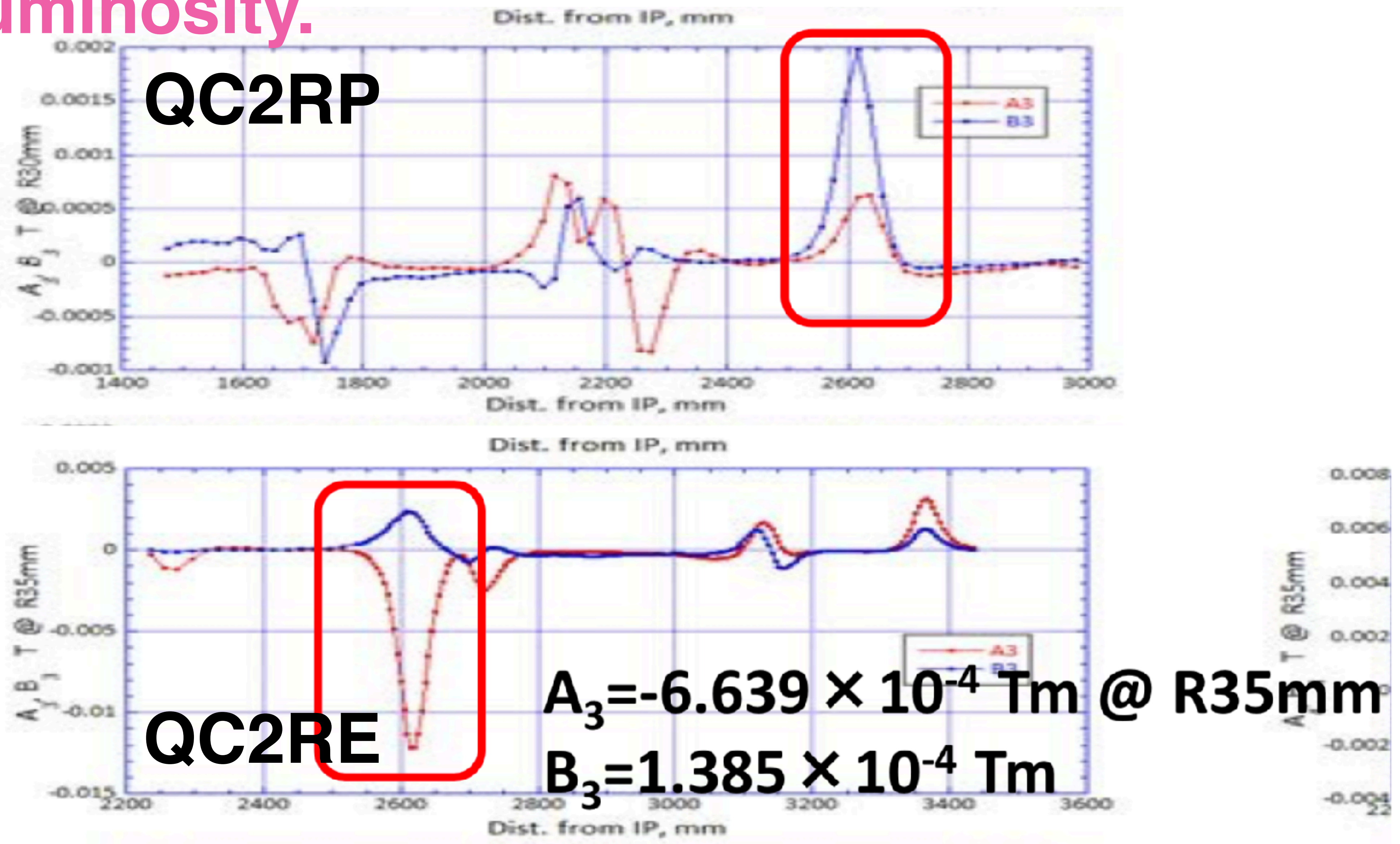


Interference of Beam-Beam and lattice nonlinear degrades luminosity.



measured magnetic field along beam axis (N. Ohuchi)

Error field:
sextupole
skew sextupole
in QCS



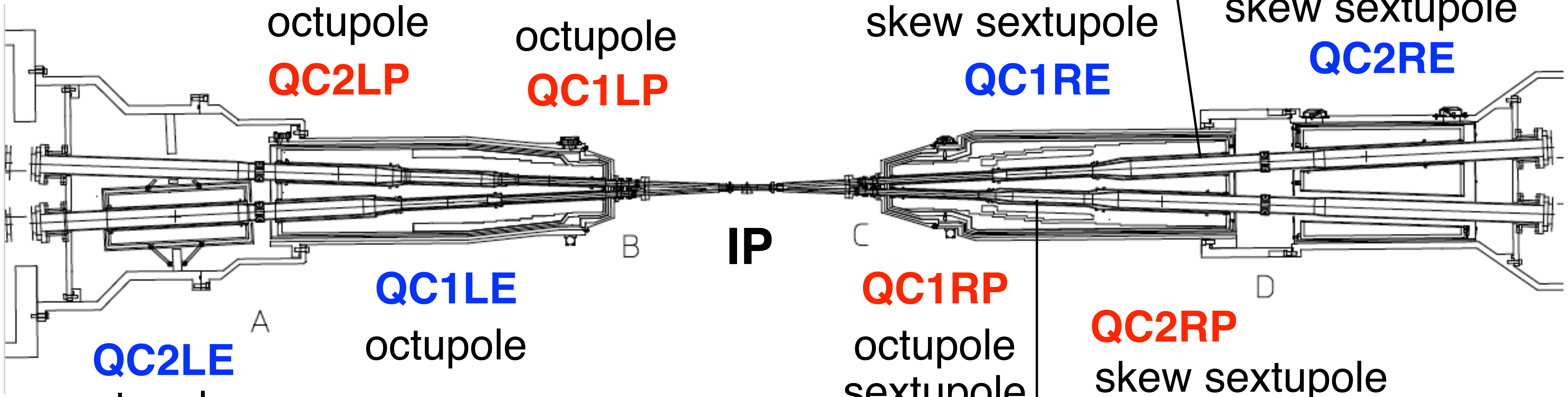
Skew quadrupole corrector coils in QCS (for each main quads.)

Rotatable sextupoles in LER

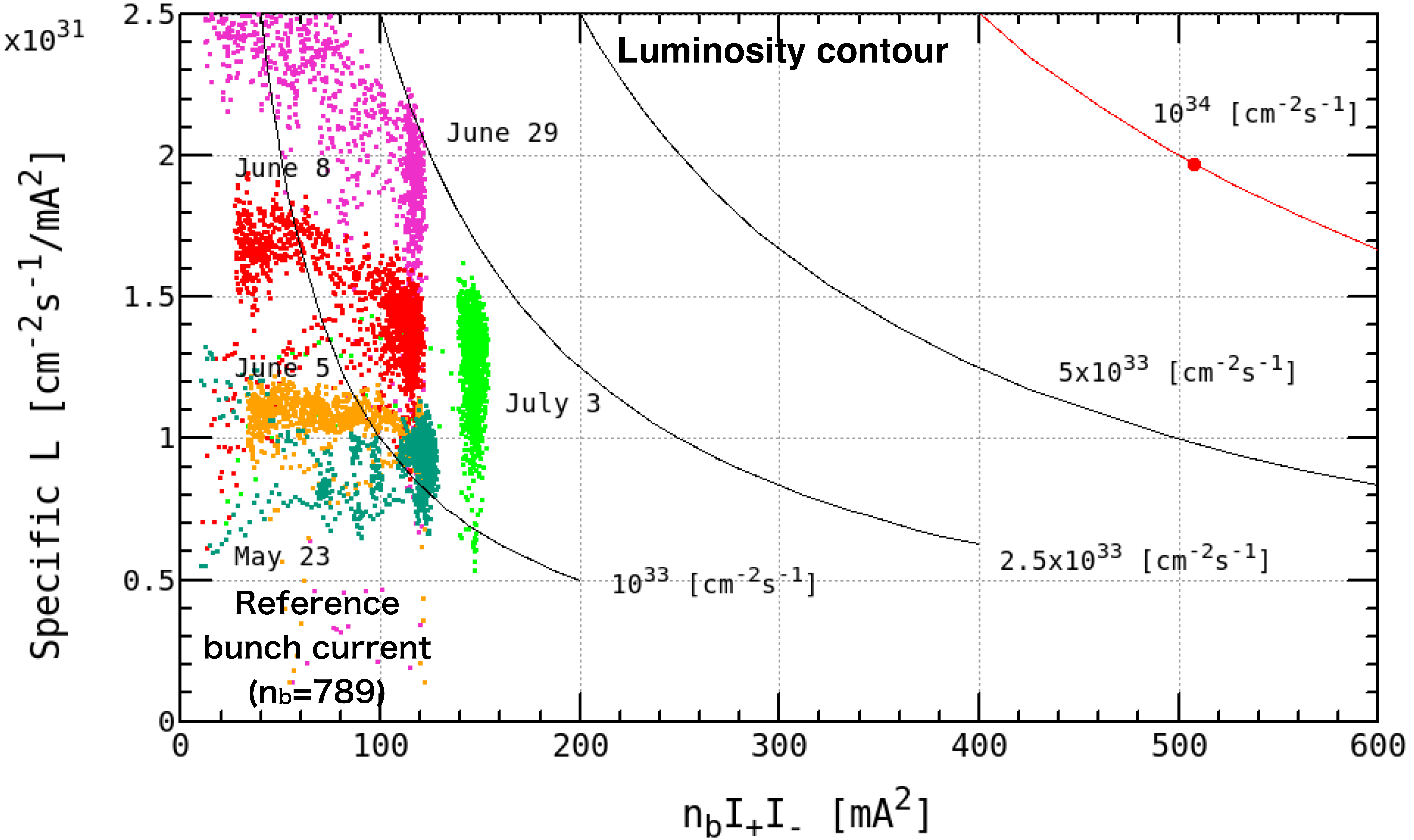
Sextupole corrector coils in QCS

Skew sextupole corrector coils in QCS

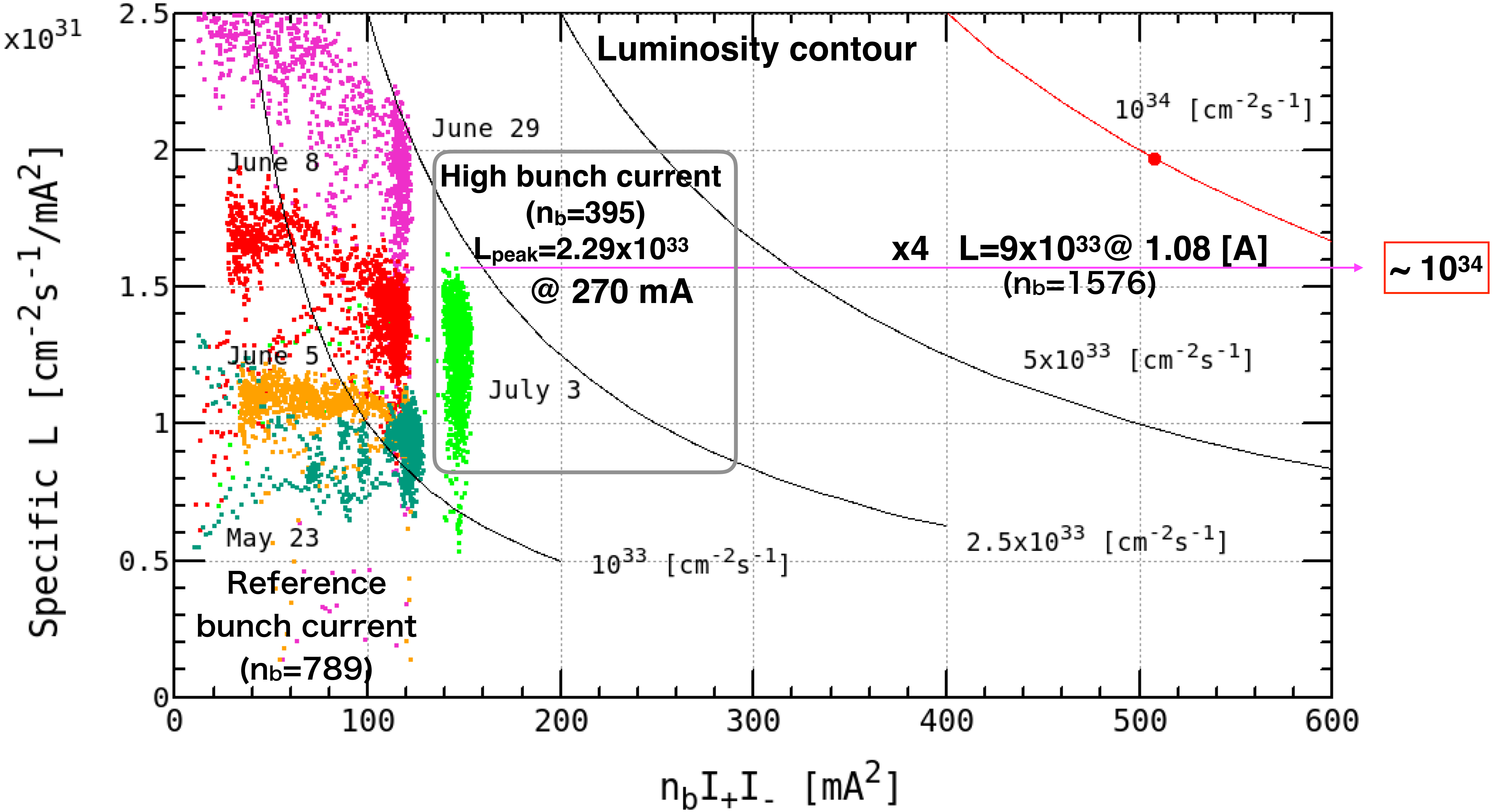
Octupole corrector coils in QCS



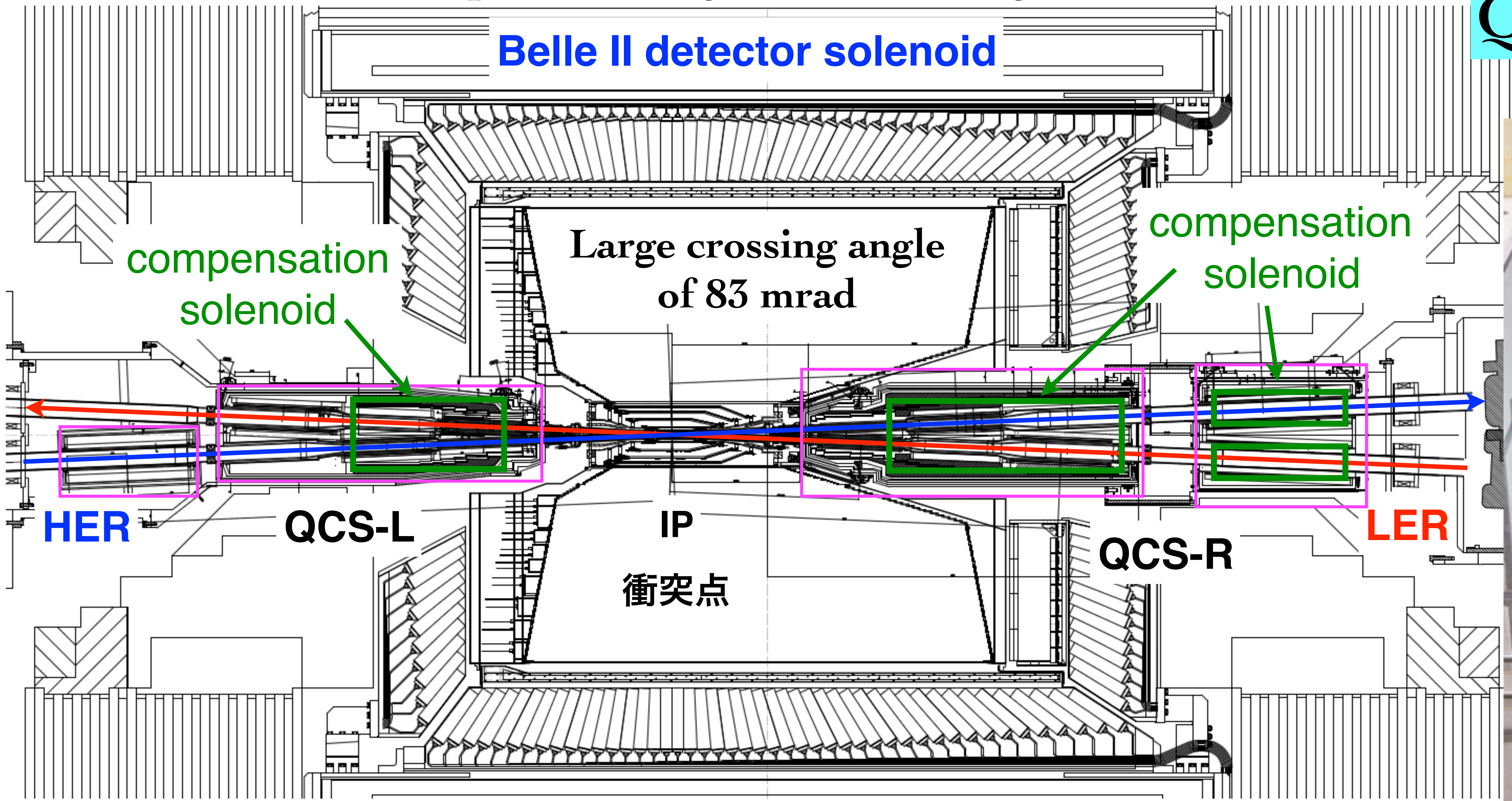
Specific Luminosity is improving day by day.



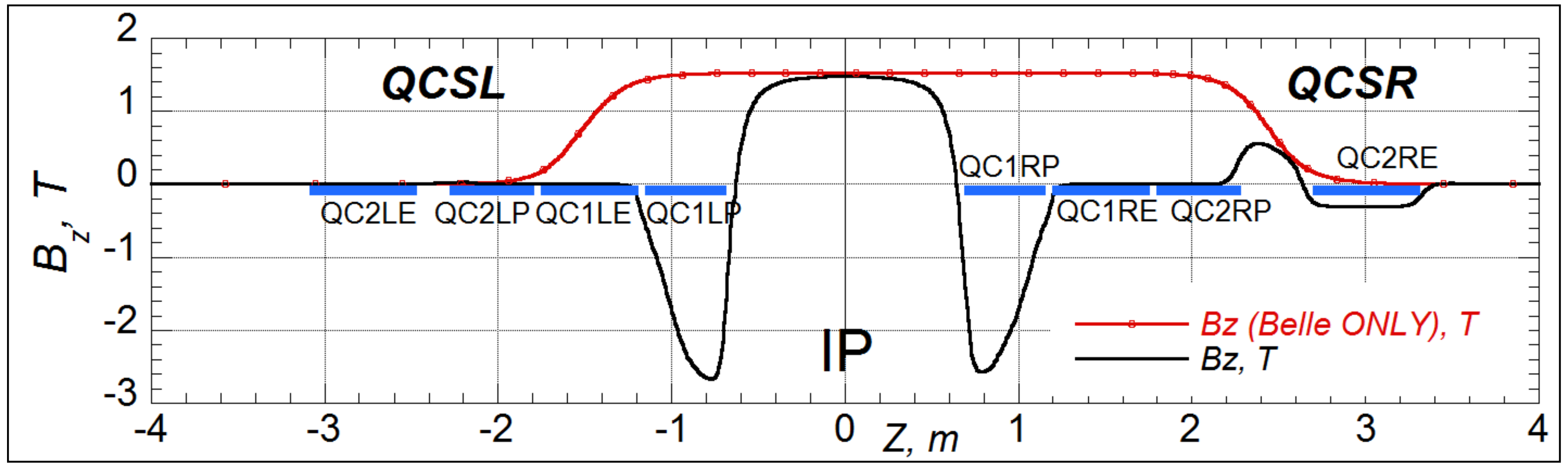
Specific Luminosity is improving day by day.



Superconducting Final Focus Magnets

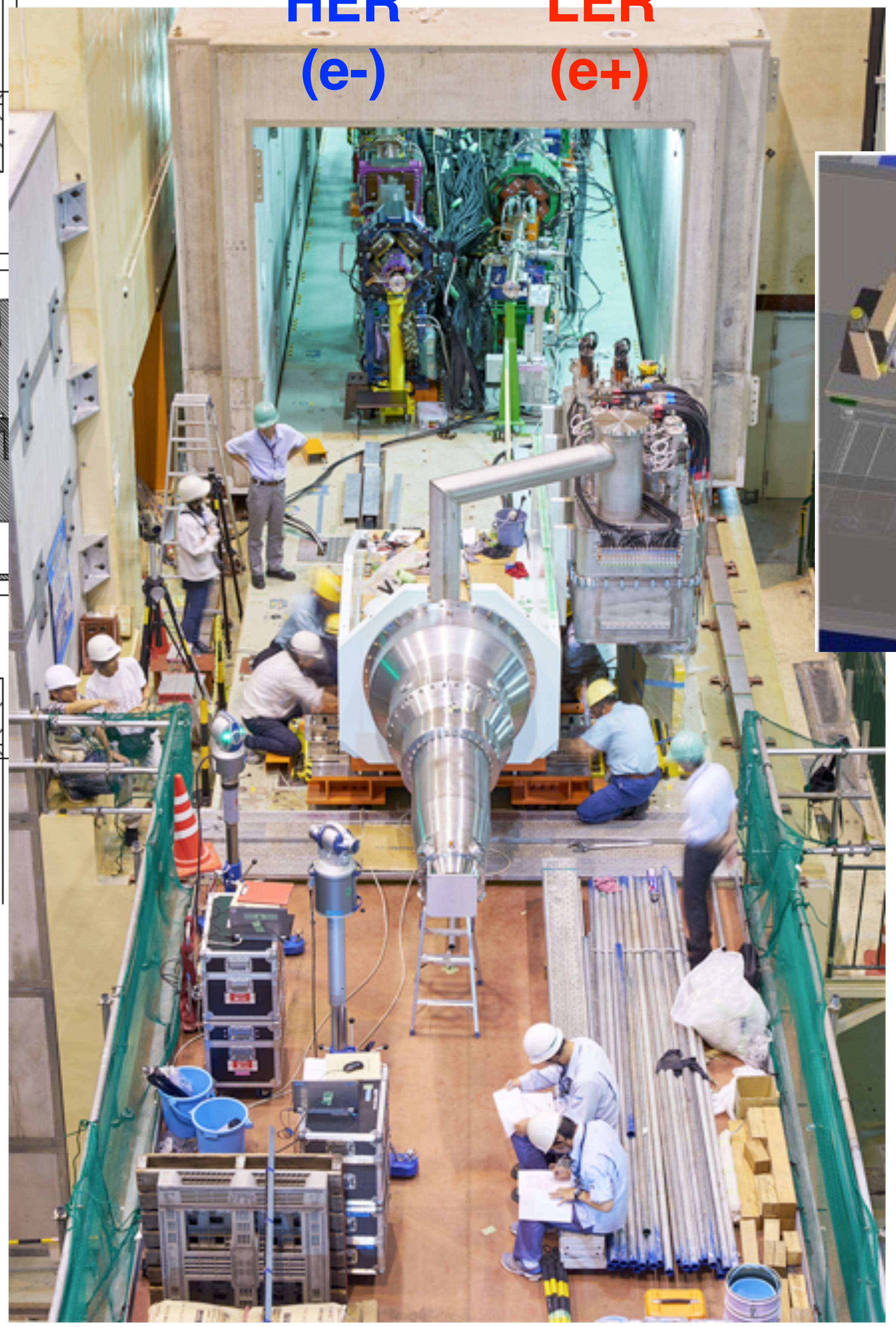


Belle II + compensation solenoid

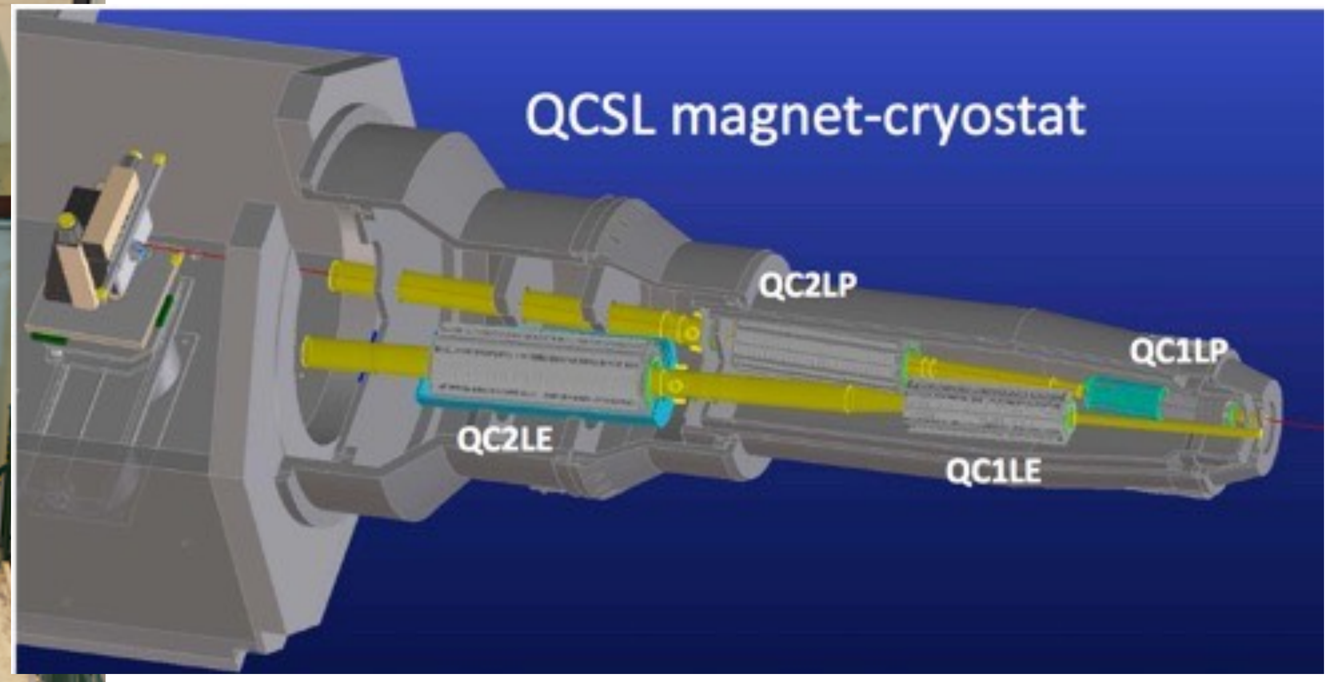


Quadrupoles and Compensation Solenoids (QCS)

HER (e-) LER (e+)



BROOKHAVEN NATIONAL LABORATORY



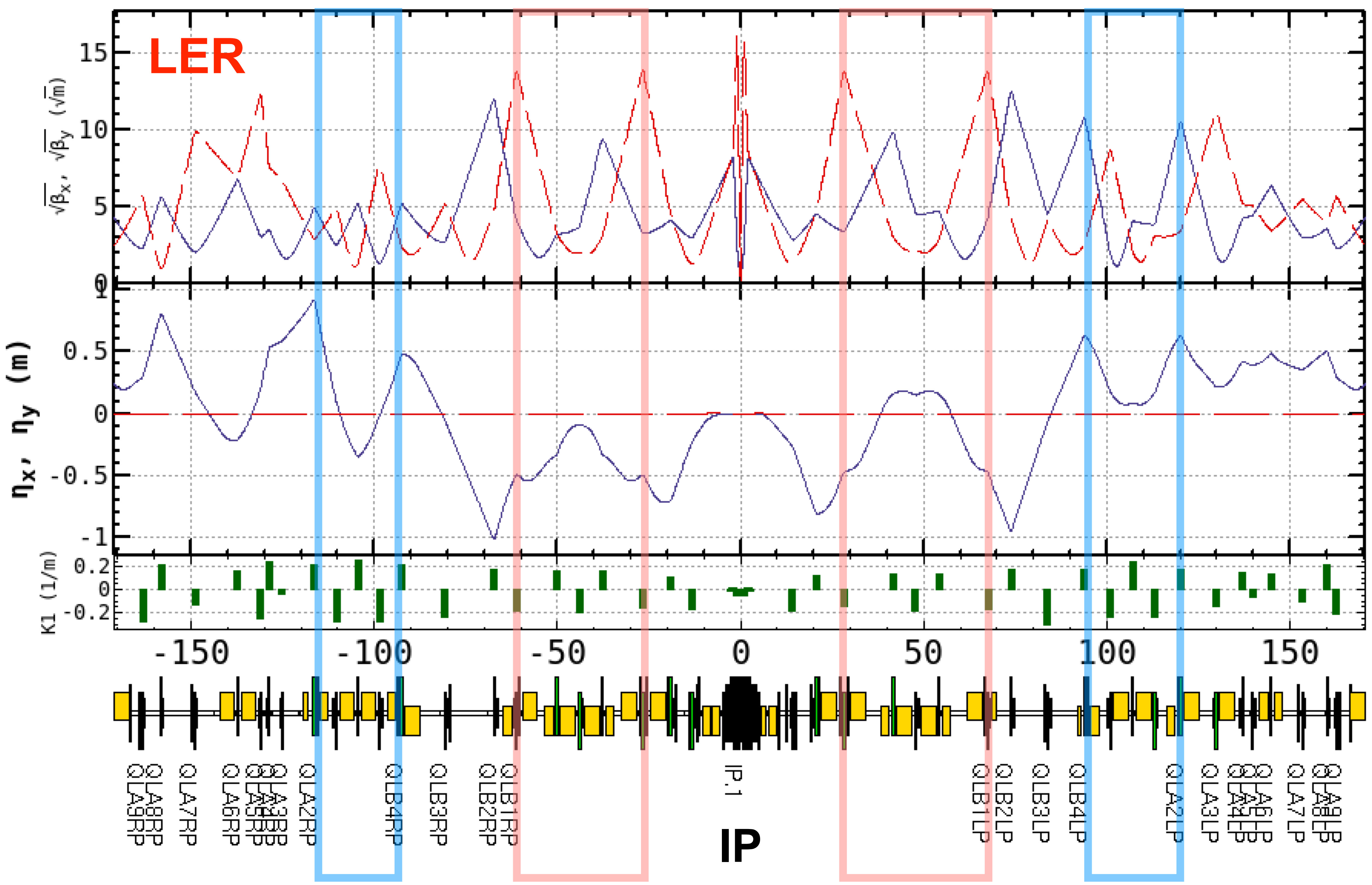
4 quadrupoles (QC1s, QC2s)
8 dipole corrector coils
4 skew quad. corrector coils
2 octupole coils
2 skew sextupole, etc for each ring.

Number of coils is 55 !

No dispersions and XY couplings in the IP although there is the solenoid field.

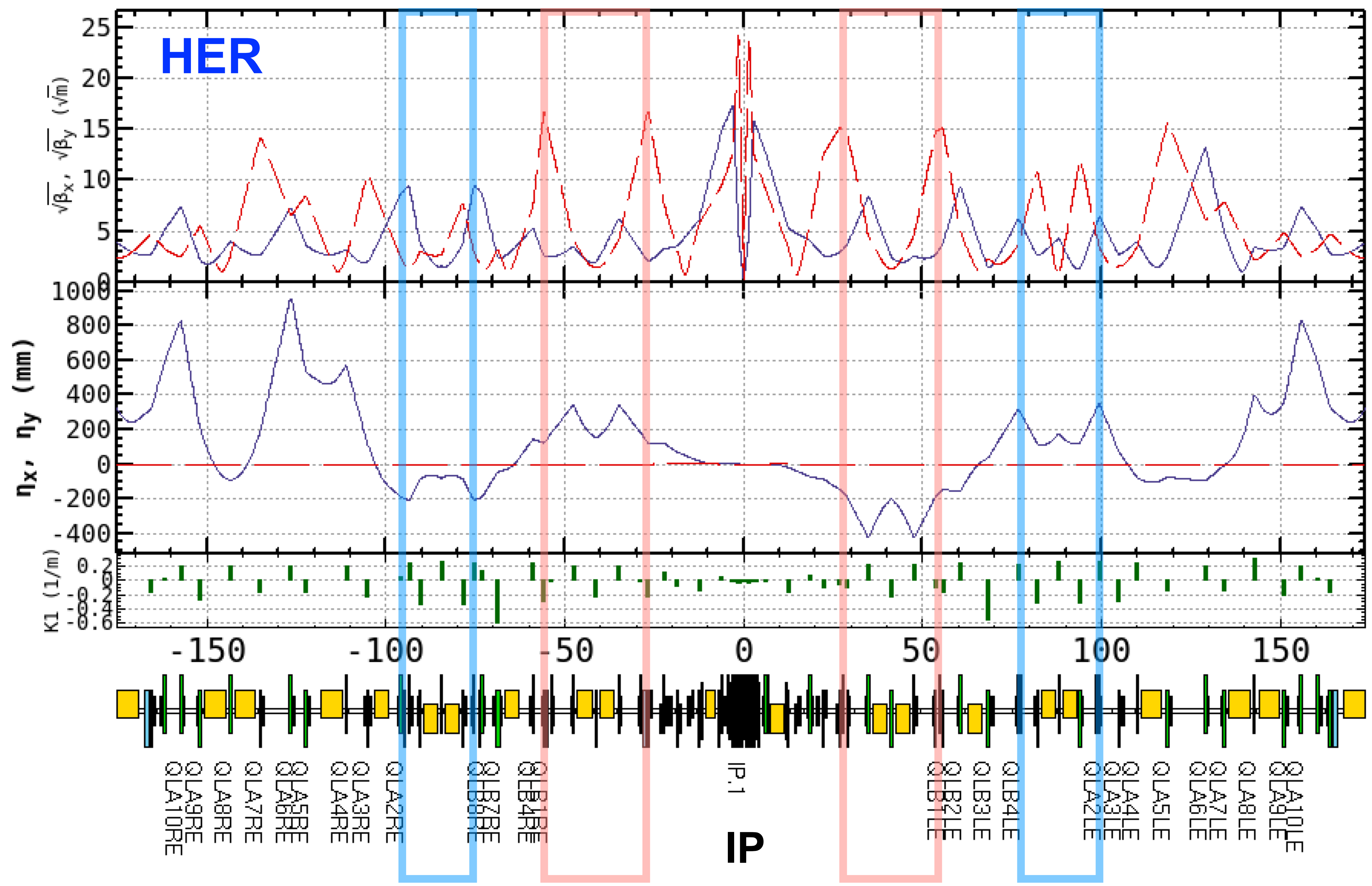
Typical optics in Phase 2

$\beta_x^* = 200\ mm \quad \beta_y^* = 3\ mm$



X-LCC Y-LCC Y-LCC X-LCC

$\beta_x^* = 100\ mm \quad \beta_y^* = 3\ mm$



X-LCC Y-LCC Y-LCC X-LCC

Natural Chromaticity
LER : ξ_x = -69 / ξ_y = -146
HER : ξ_x = -97 / ξ_y = -168

QC2:ξ_x = -8 / QC1:ξ_y = -67
QC2:ξ_x = -25 / QC1:ξ_y = -100

Local chromaticity correction (X-LCC, Y-LCC)
QC1 - Y-LCC: $\Delta\Psi_y = \pi$
QC2 - X-LCC: $\Delta\Psi_x = 2\pi$

strong sextupoles

Optics Correction and Collision Tuning

Global Optics Correction

<u>Optics correction based on COD</u>

Skew quads @sextupole pairs

H. bump@sextupole pairs

Correction of PS for each quad. family

The value is rms for all BPMs

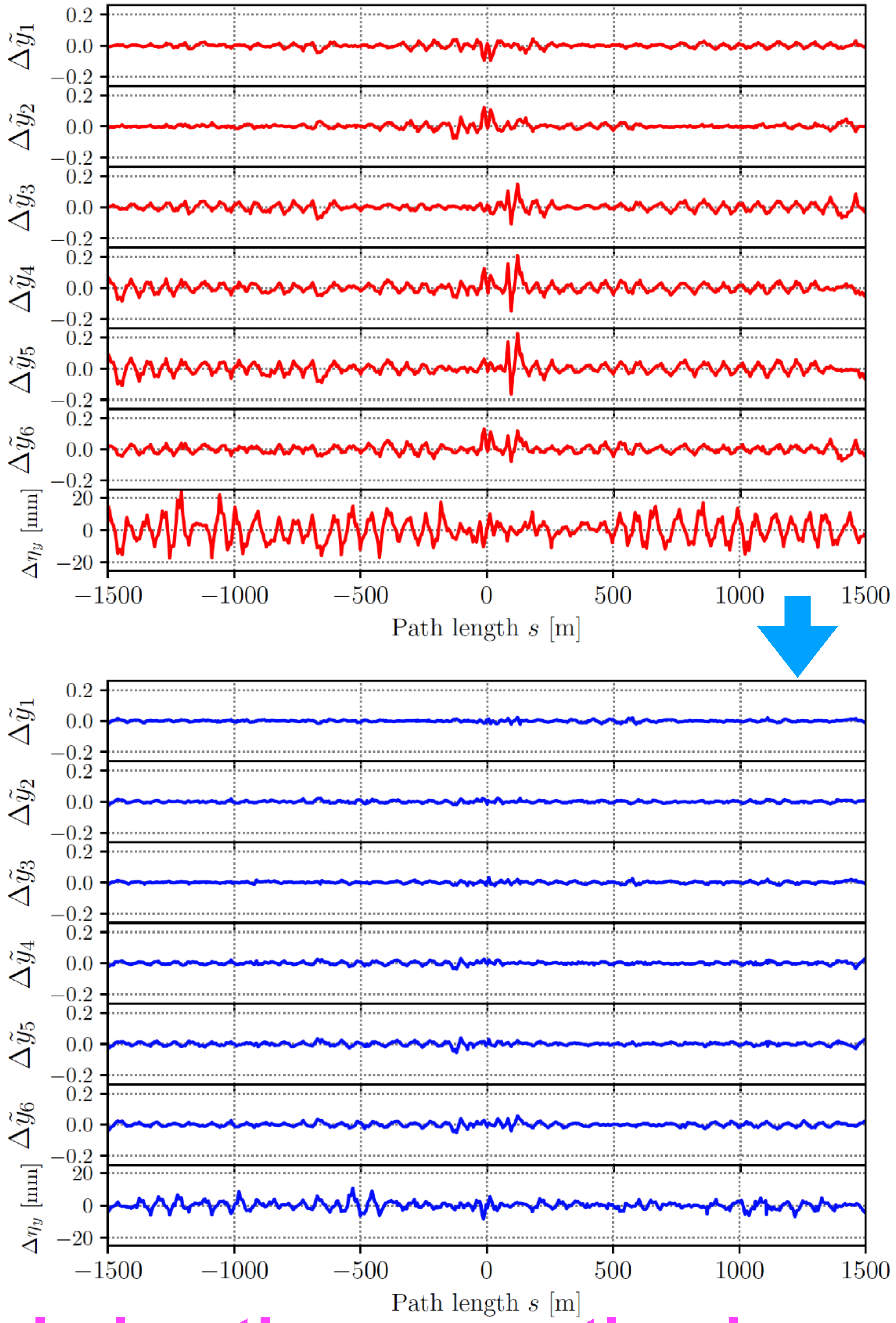
	LER	HER	unit
$\Delta\beta_x/\beta_x$	2	3	%
$\Delta\beta_y/\beta_y$	4	3	%
$\Delta y/\Delta x$ XY coup.	0.014	0.008	
$\Delta\eta_x$	10	9	mm
$\Delta\eta_y$	4	3	mm

Measured beam size by X-Ray Monitor

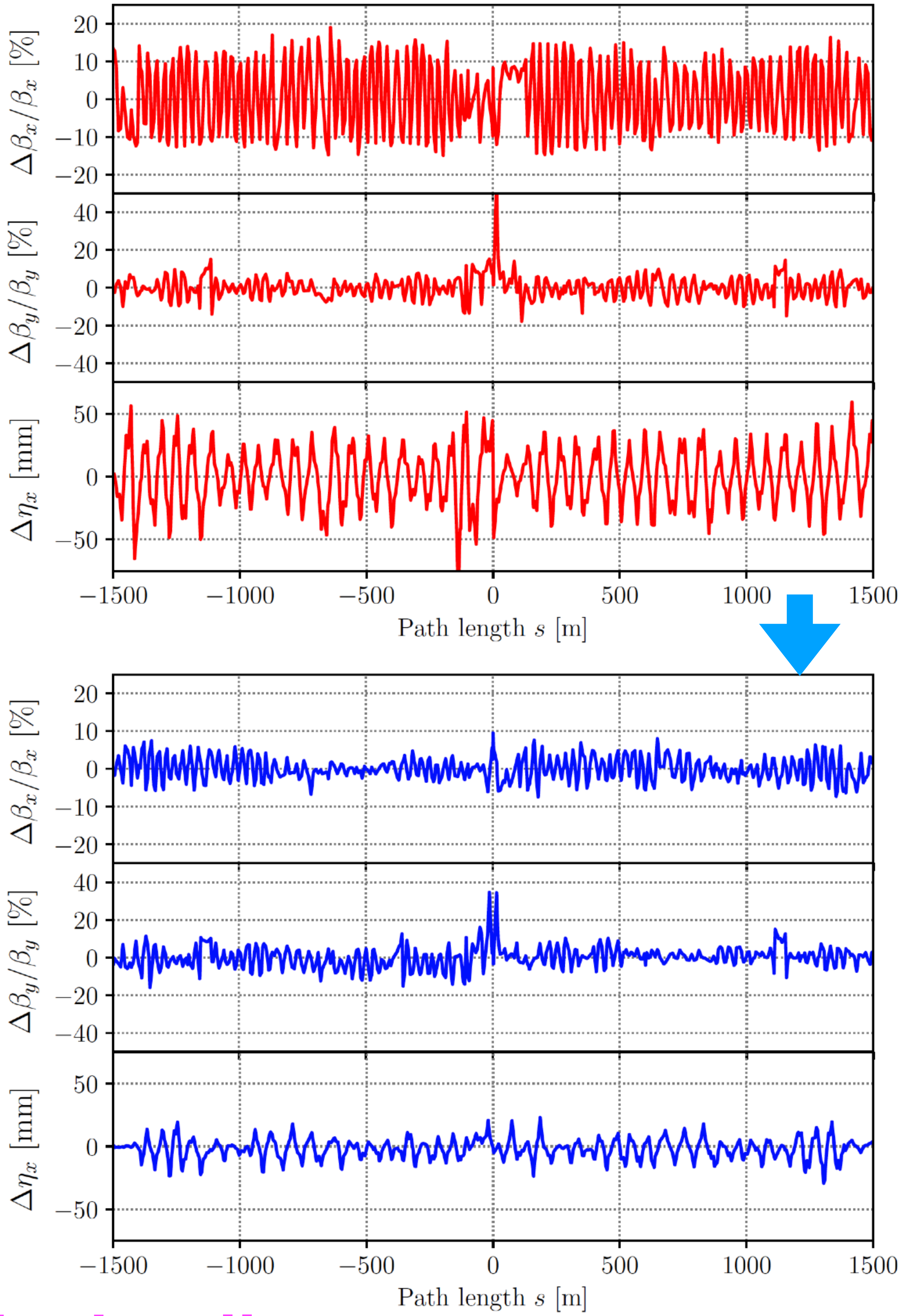
LER : 13 pm ($\varepsilon_y/\varepsilon_x$ = 0.8 %)

HER : 19 pm ($\varepsilon_y/\varepsilon_x$ = 0.4 %)

XY coupling: before and after



Beta and dispersion: before and after



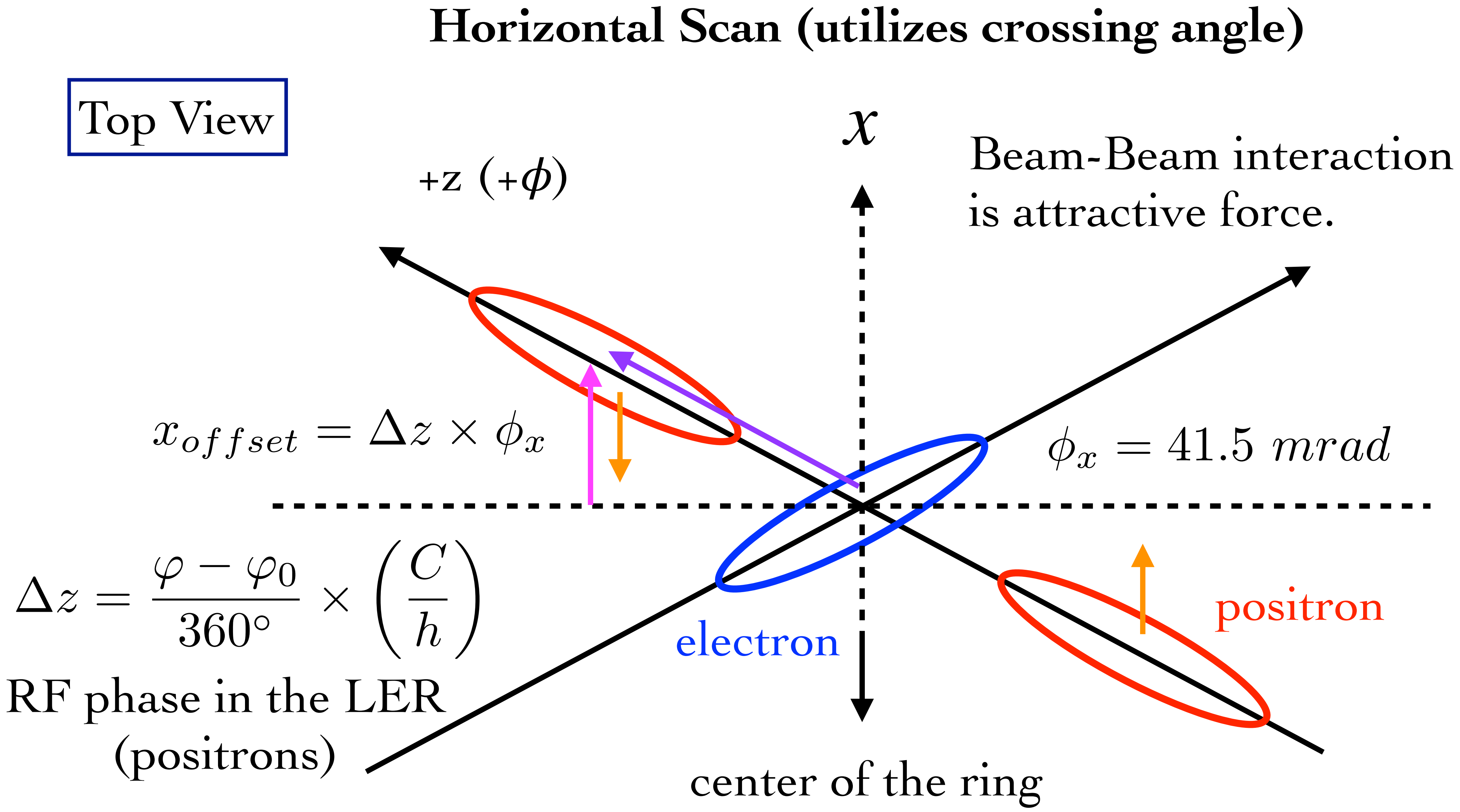
Global optics correction has worked well.

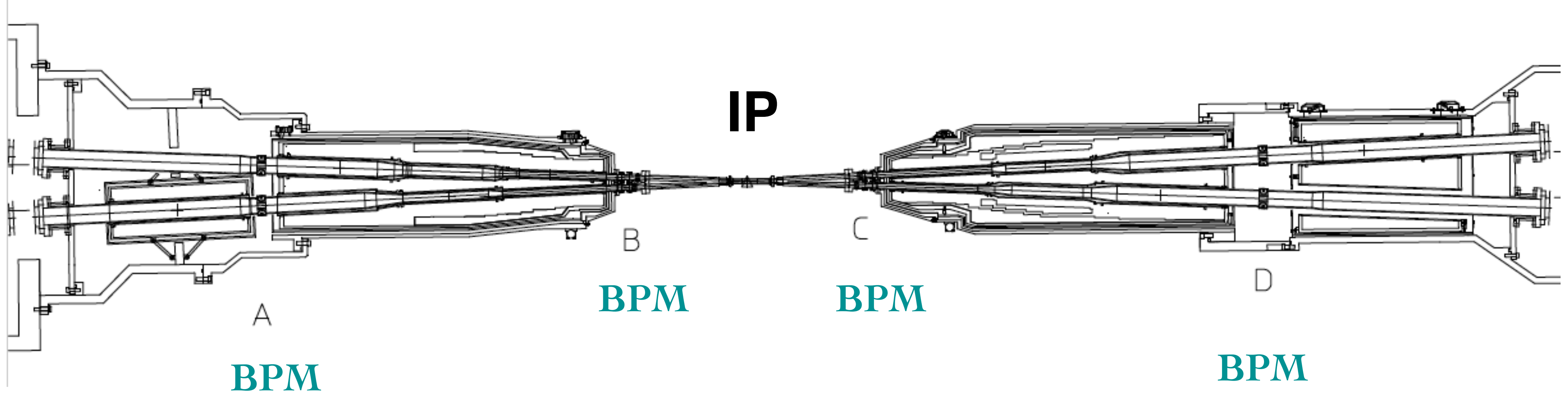
H. Sugimoto

Collision Timing: RF Phase Scan in LER

collision timing → offset due to crossing-angle → beam-beam kick

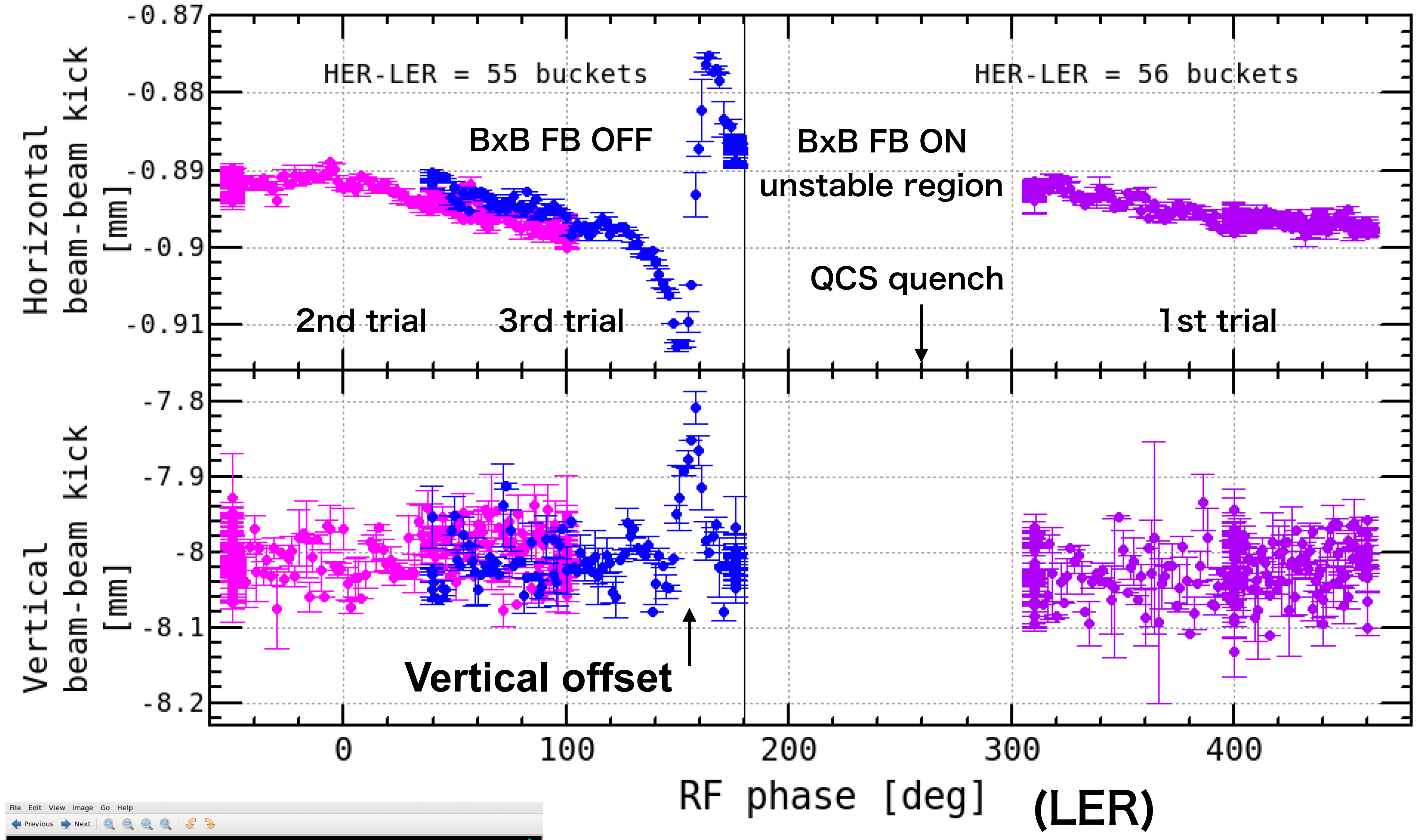
Try to find appropriate collision timing

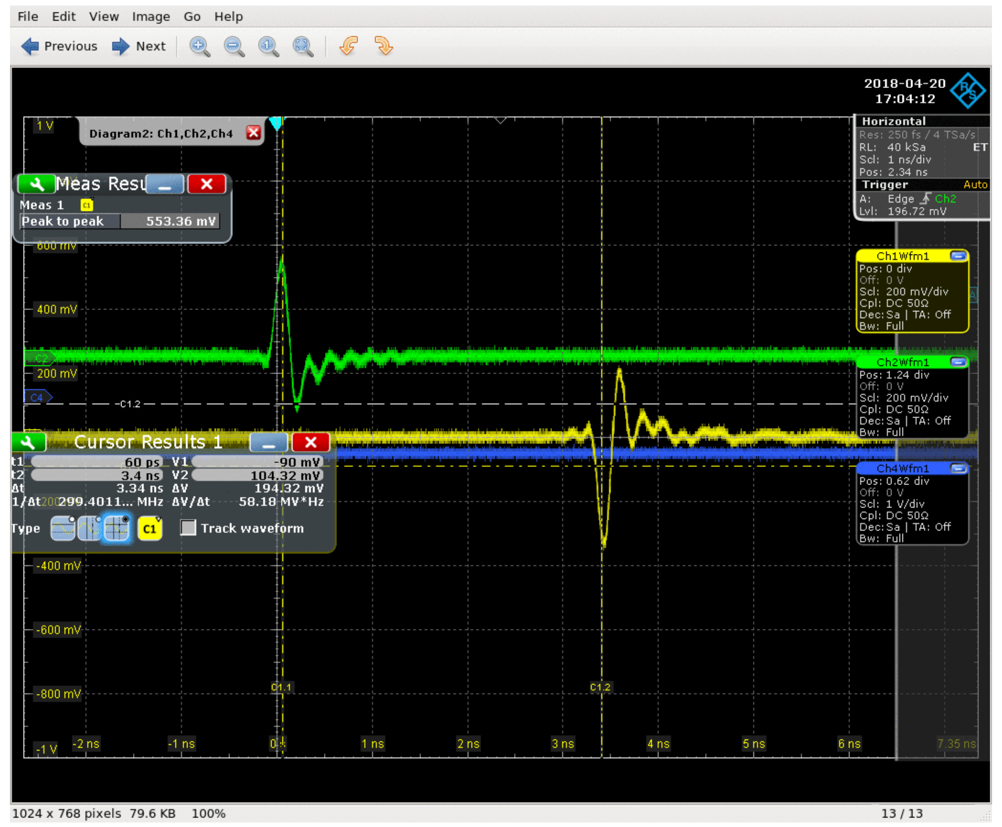




C = 3016.3 [m]
h = 5120

$$x_{offset} = \frac{\phi - \phi_0}{360} \times 0.6\ (m) \times 0.0415\ (rad)$$

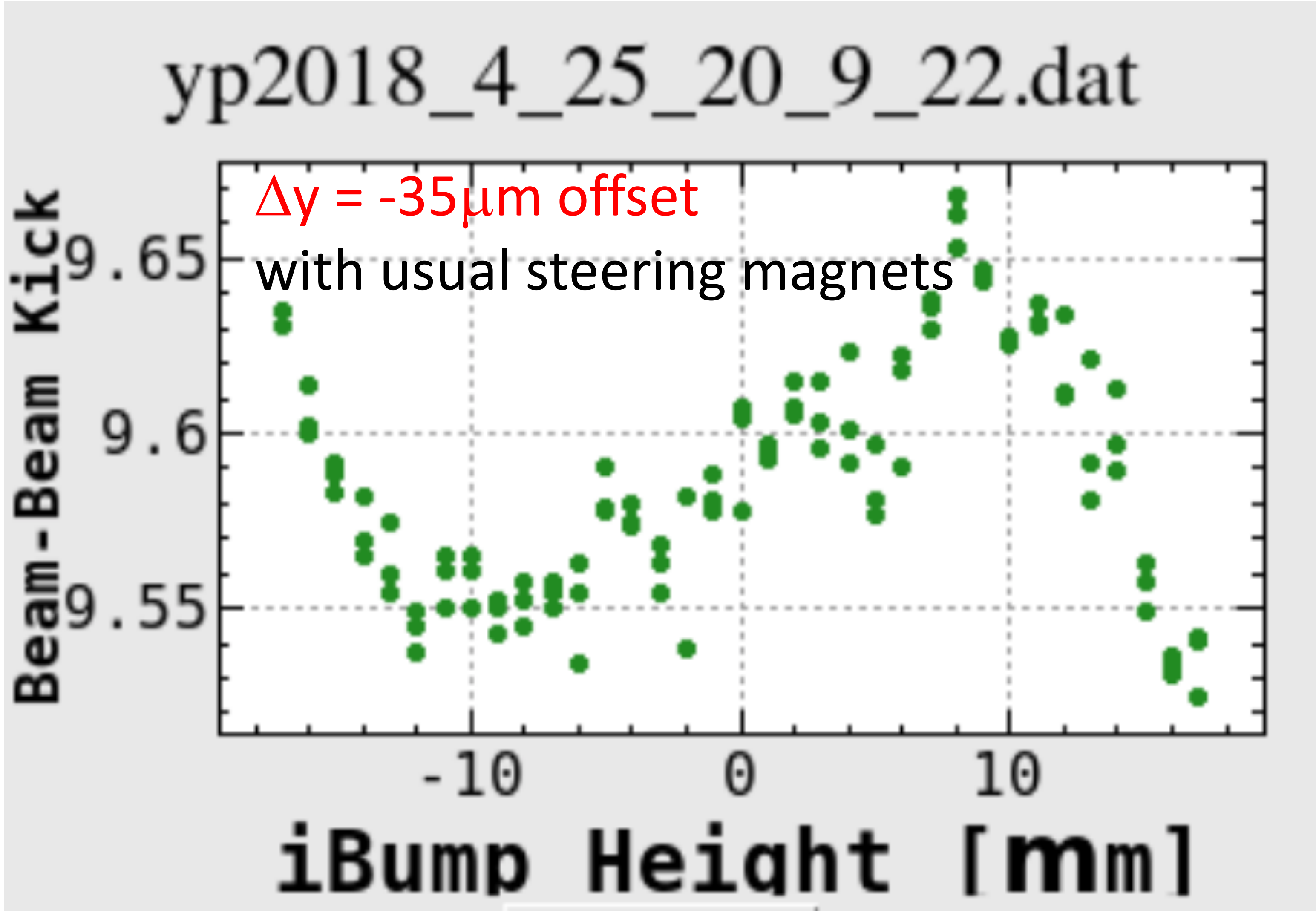




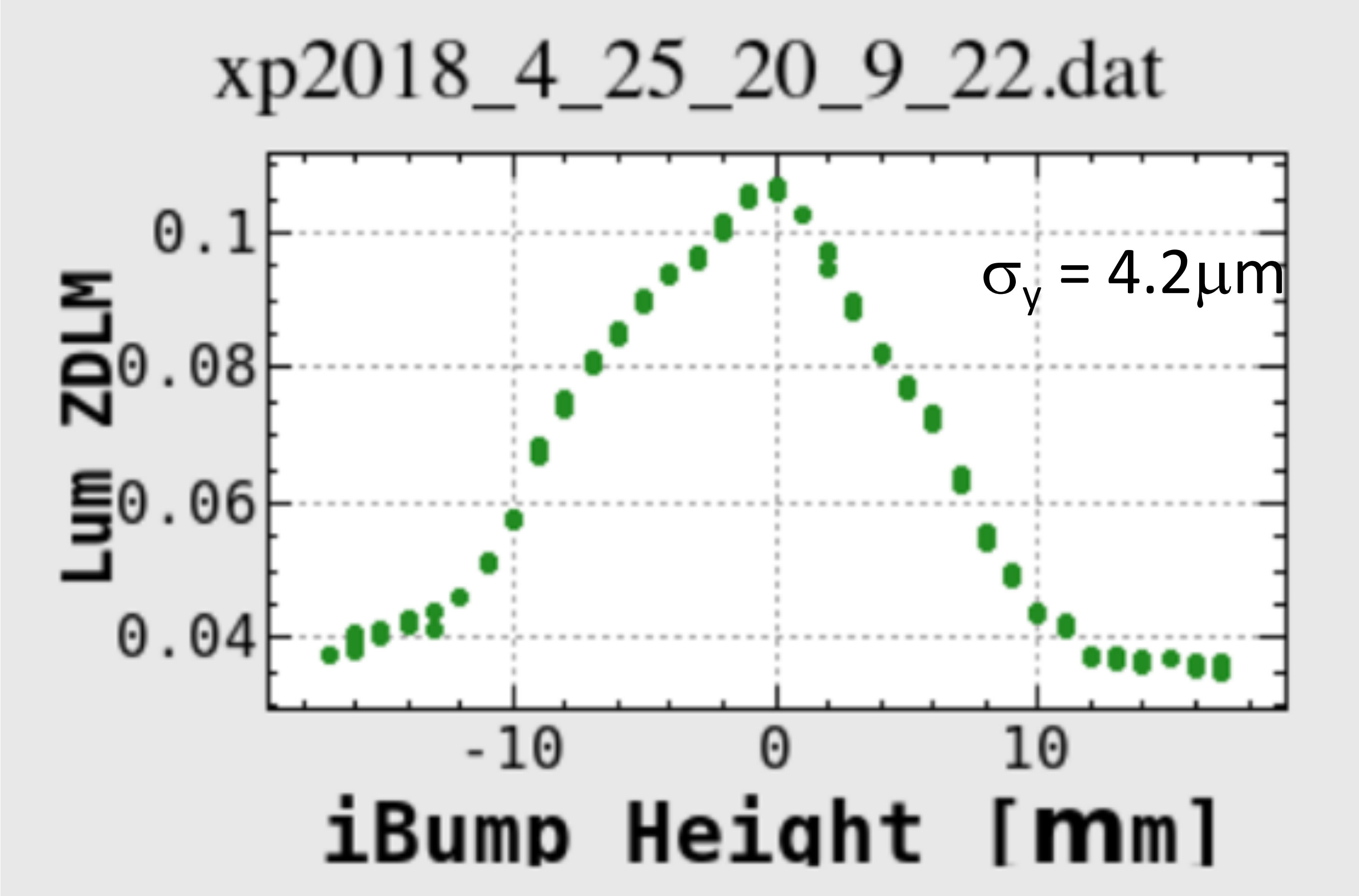
time difference measured by BPM

~2 nsec for 360 deg.

Vertical Beam-Beam Kick measured by Local Bump Orbit



Vertical beam-beam deflection
Higher bunch currents
LER: ~52mA (200bunches)
HER: ~38mA (200 bunches)

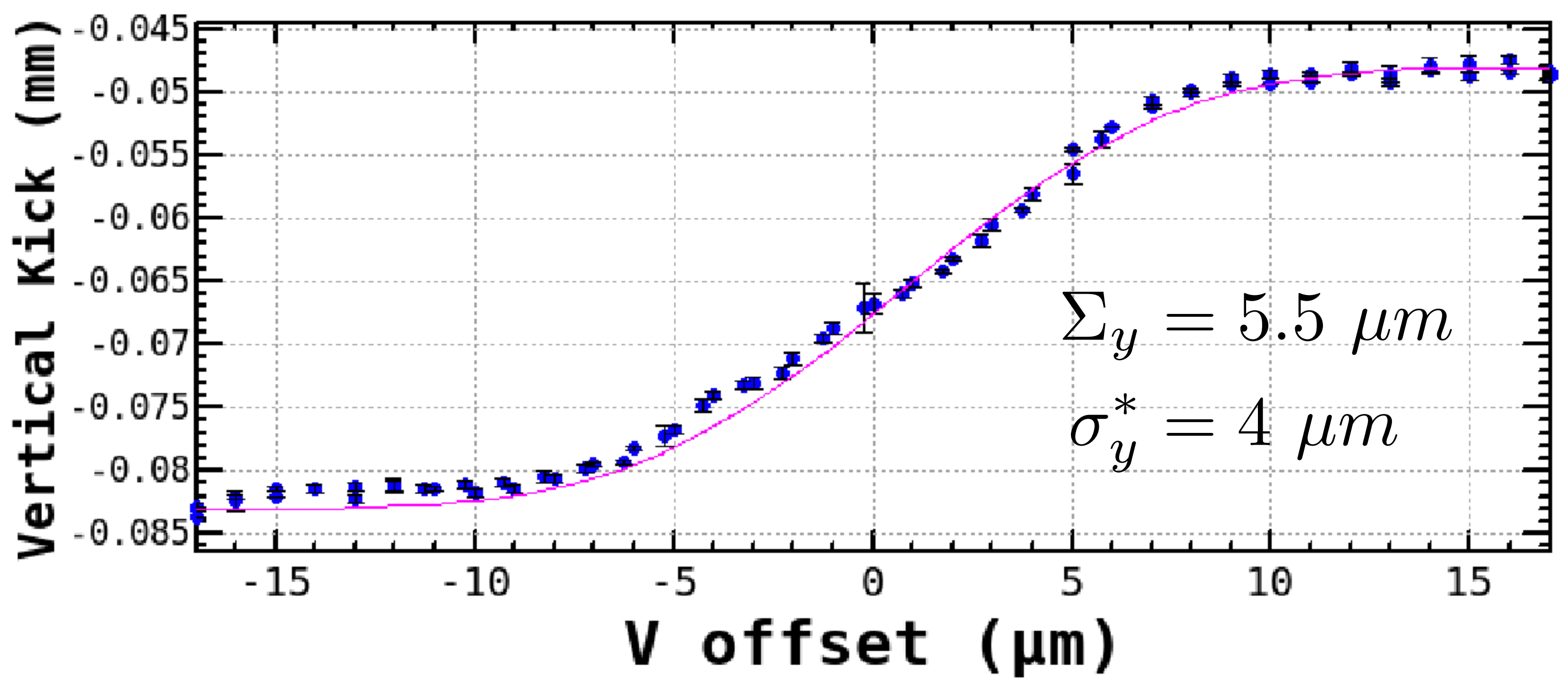


Vertical-orbit scan by using HER correctors

$LER: \quad \nu_x/\nu_y = 44.58/46.61$

$HER: \quad \nu_x/\nu_y = 45.57/43.61$

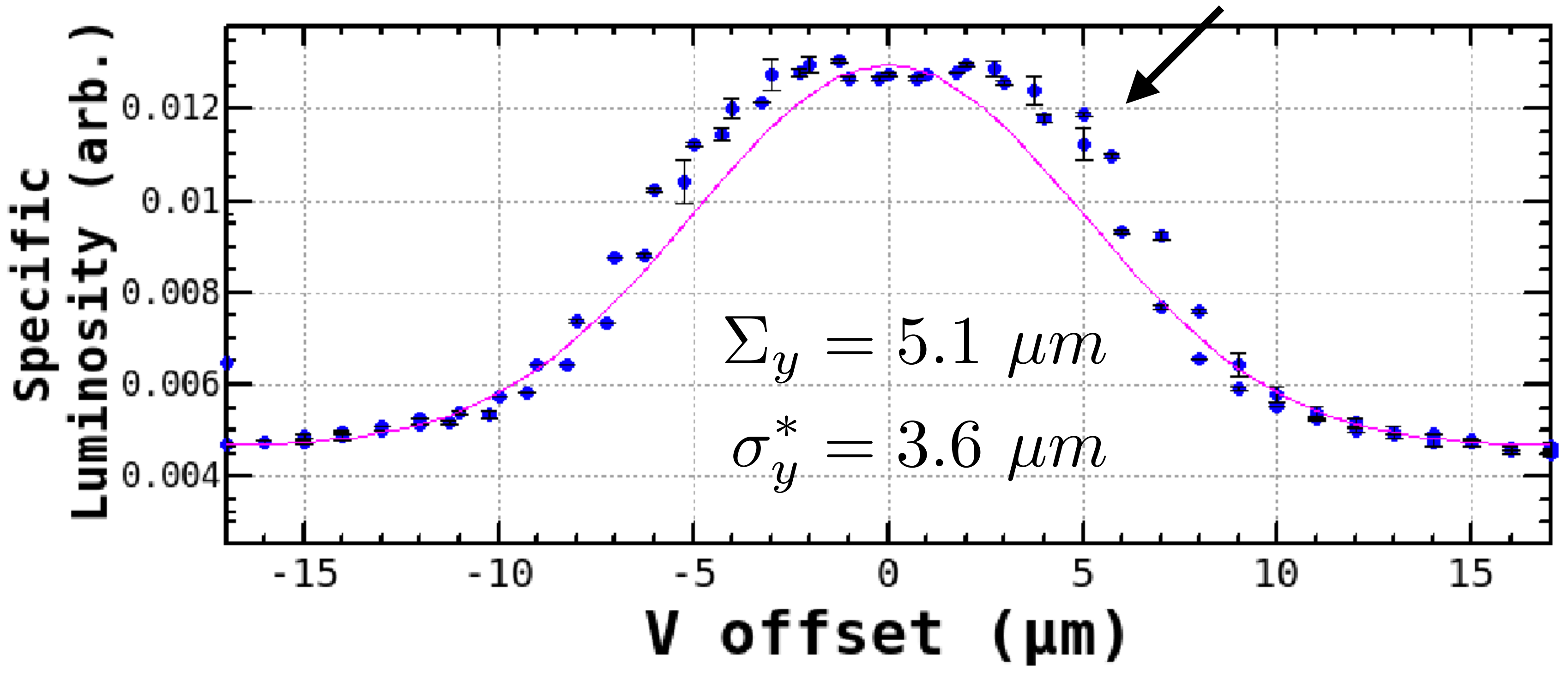
B-B Kick



subtract orbit offset

Sp. Luminosity

Double peak due to vertical angle of HER orbit.



Vertical beam size was still very large due to poor adjustment.

The collision point was moved ~1 cm along the beam axis.

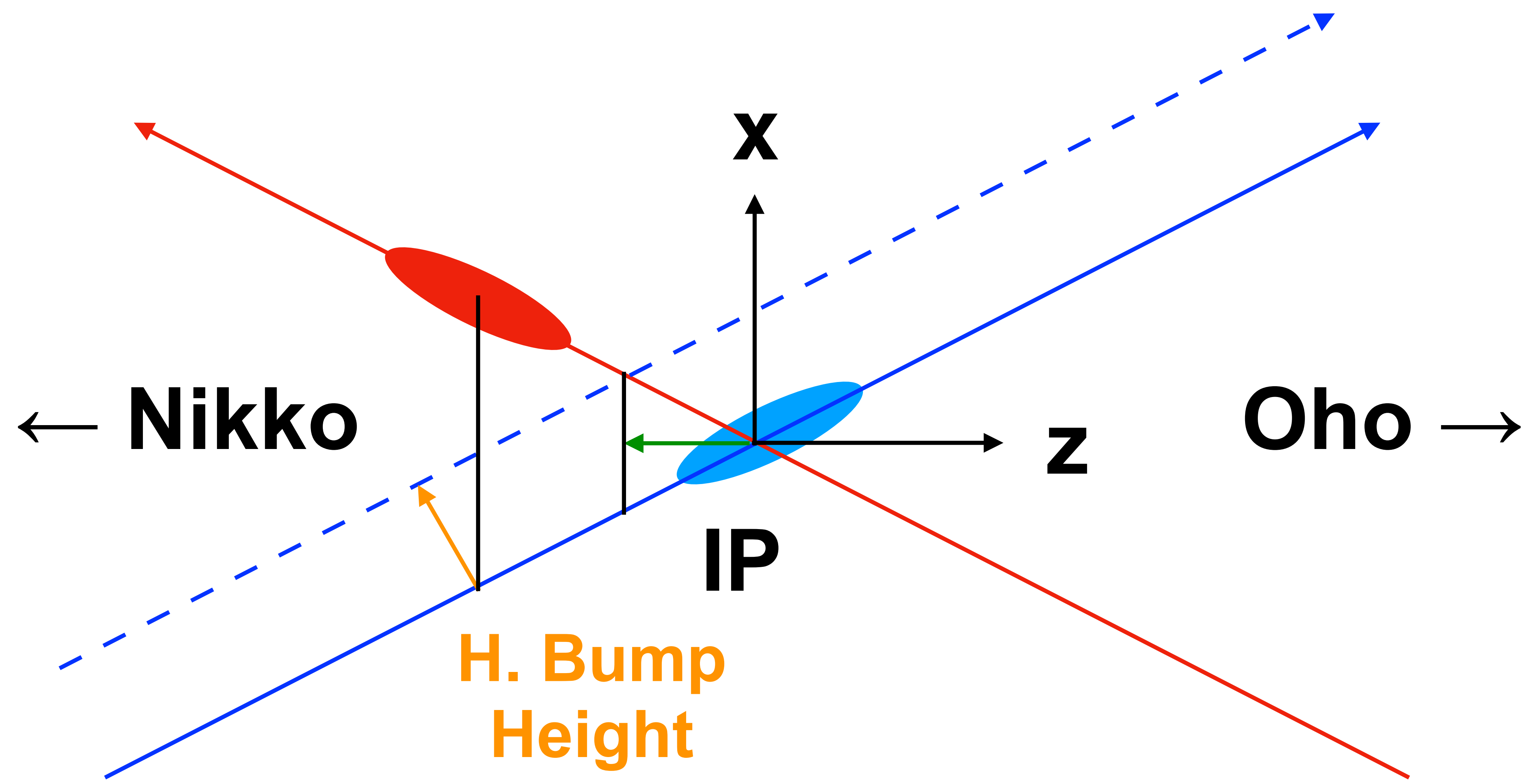
☞ **figured out by Belle II vertex data and corrected in the early May**

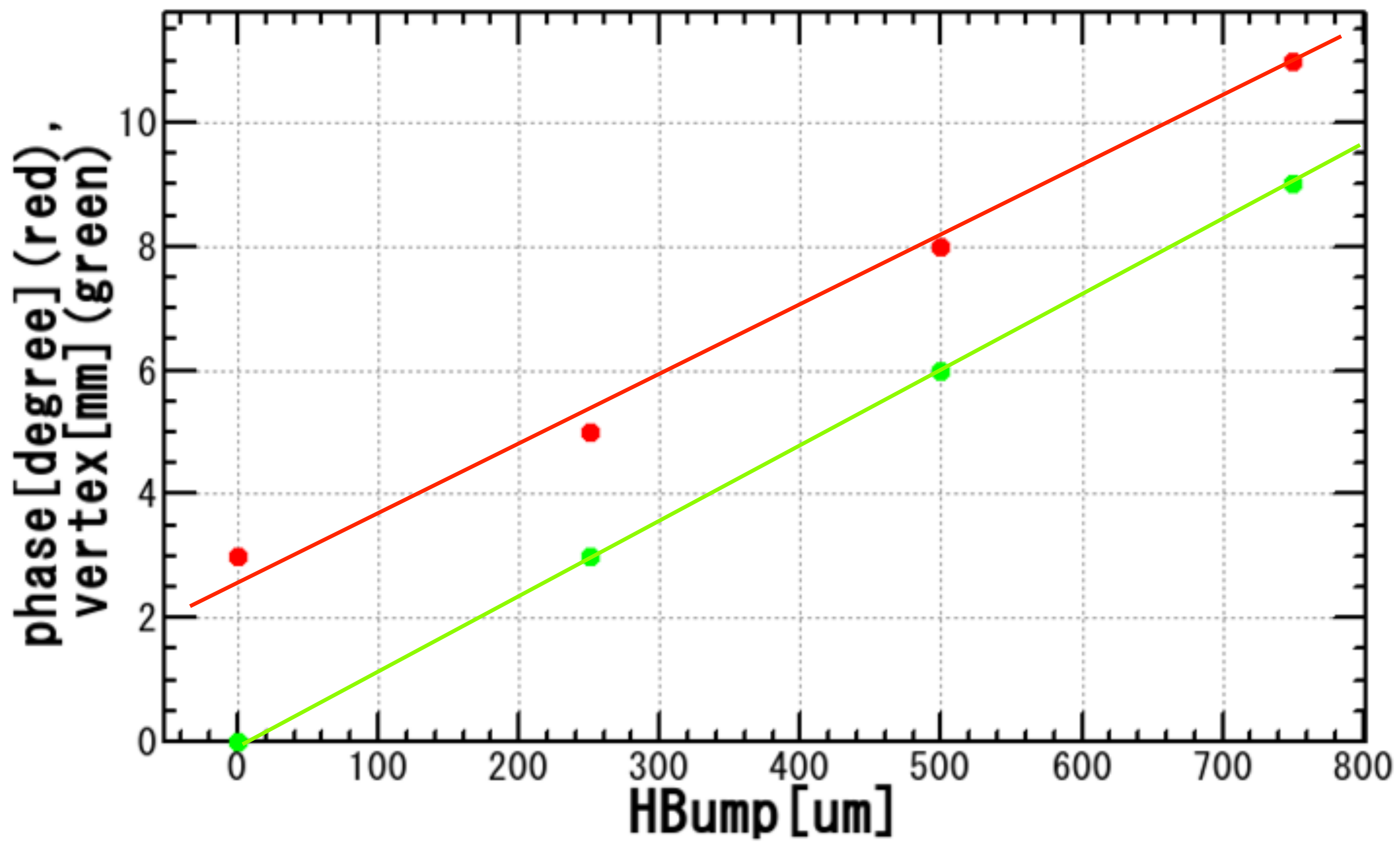
Adjustment of Vertex Position along z-coordinate

Day shift, May 4, 2018

HER H. Bump Height (μm)	Vertex position ΔZ(mm)	RF Phase (deg.)	σ_y^* fit $\Sigma_y/\sqrt{2}$ (mm)	Luminosity (LumiBelle 2)
0	0	3	2.8	0.12
250	3	5	2.5	0.13
500	6	8	2.2	0.16
750	9	11	1.8	0.20

Luminosity is much improved.



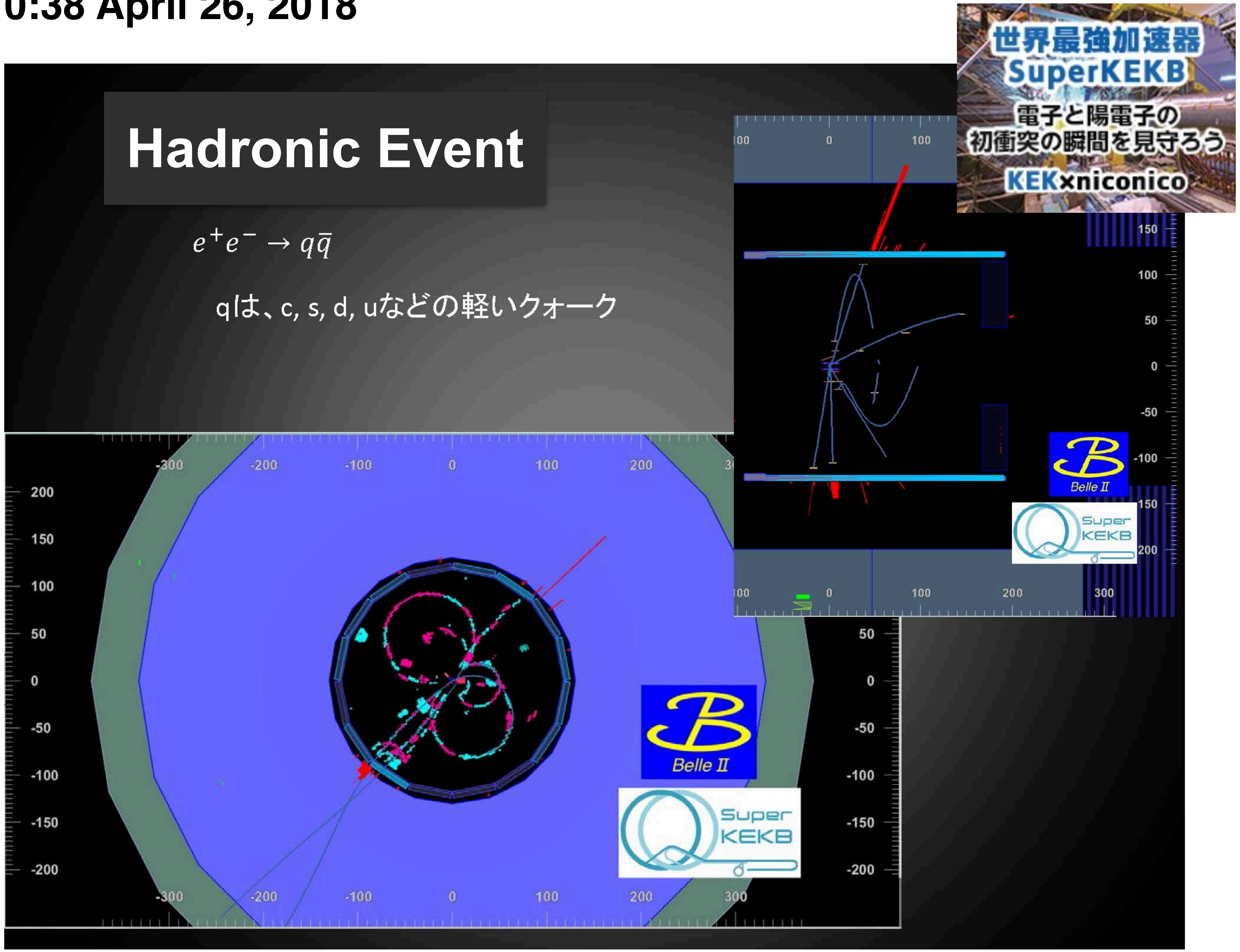


First Hadronic Event

Accelerator control room

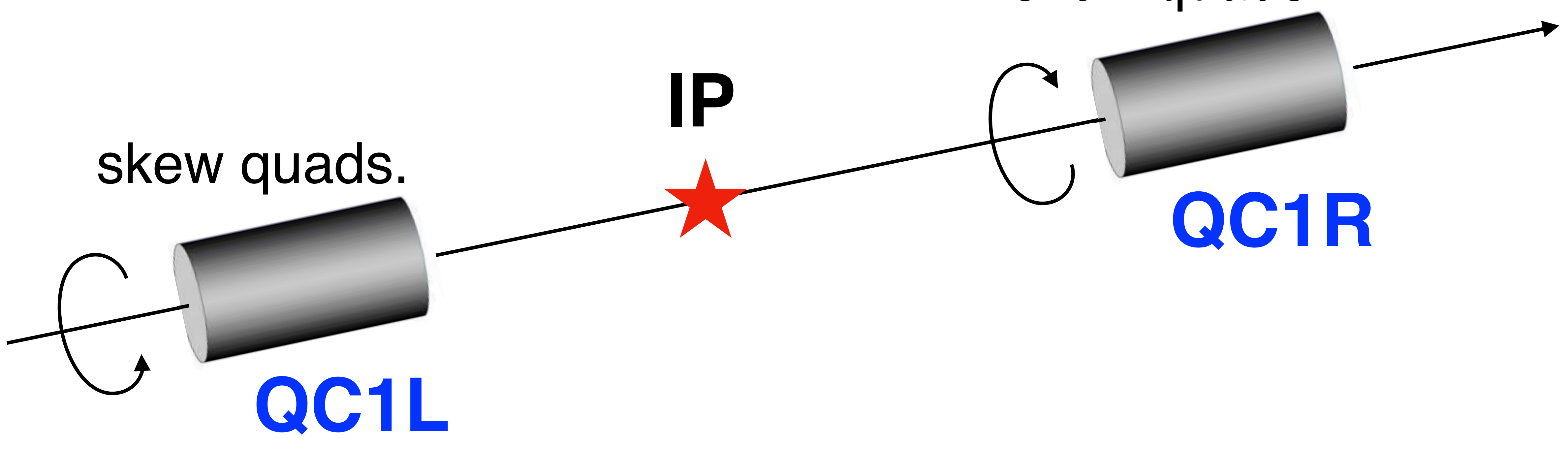
Belle II control room

0:38 April 26, 2018



Accelerator control room

Belle II control room

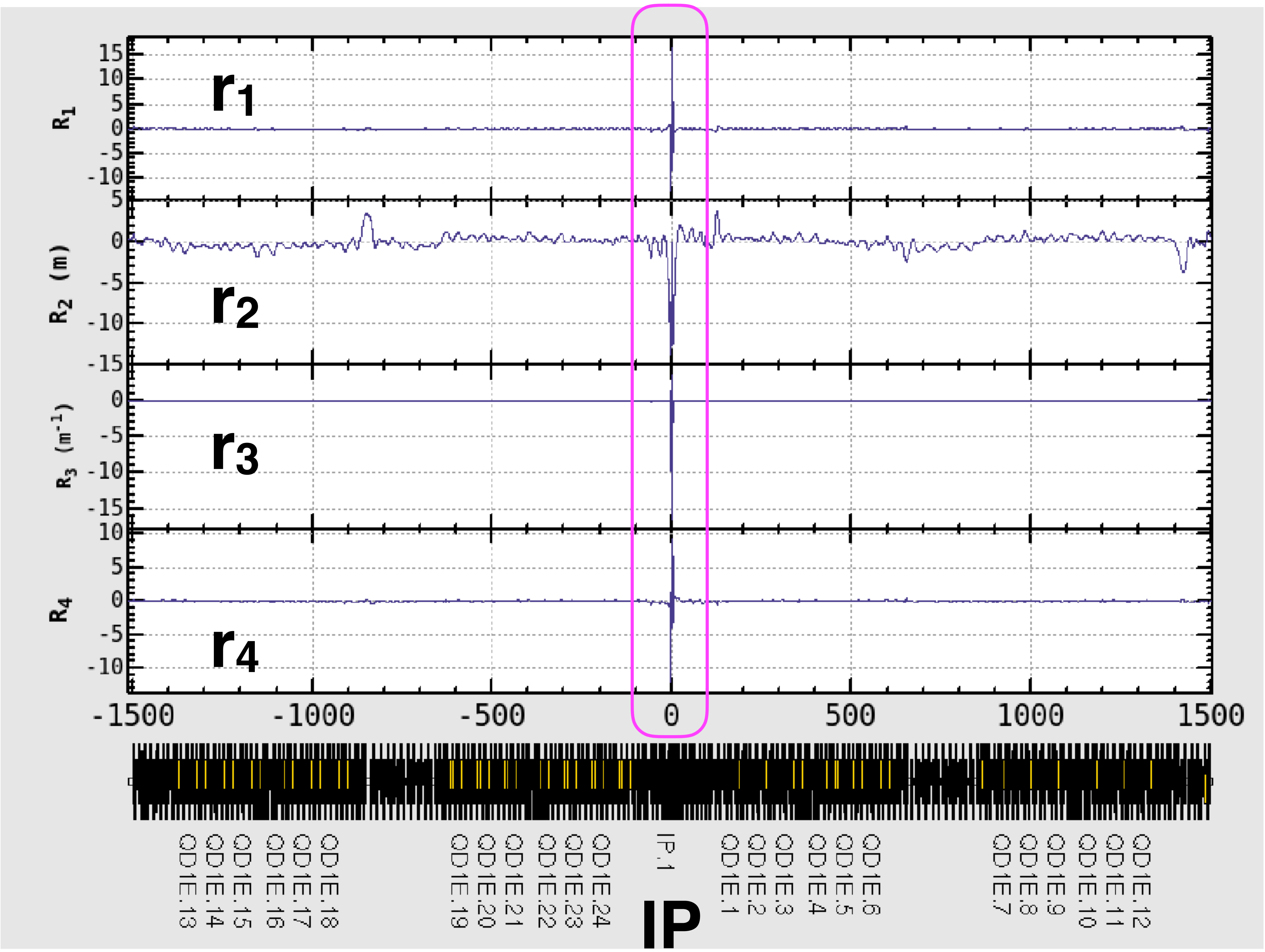


The same amount of rotation does not affect arc sections.

The global correction of XY couplings can not correct XY coupling at the IR completely.

XY coupling at IP remains locally.

XY couplings



Skew quads in QCS can be used to correct the local XY couplings.

Adjustment of XY Coupling with QC1 Skew Quadrupoles

$$\beta_x^* = 200\ mm \quad \beta_y^* = 4\ mm$$

Extremely low bunch current
15.8 mA/1576 bunches
to avoid beam-beam blowup as much as possible
and to get geometrical luminosity.

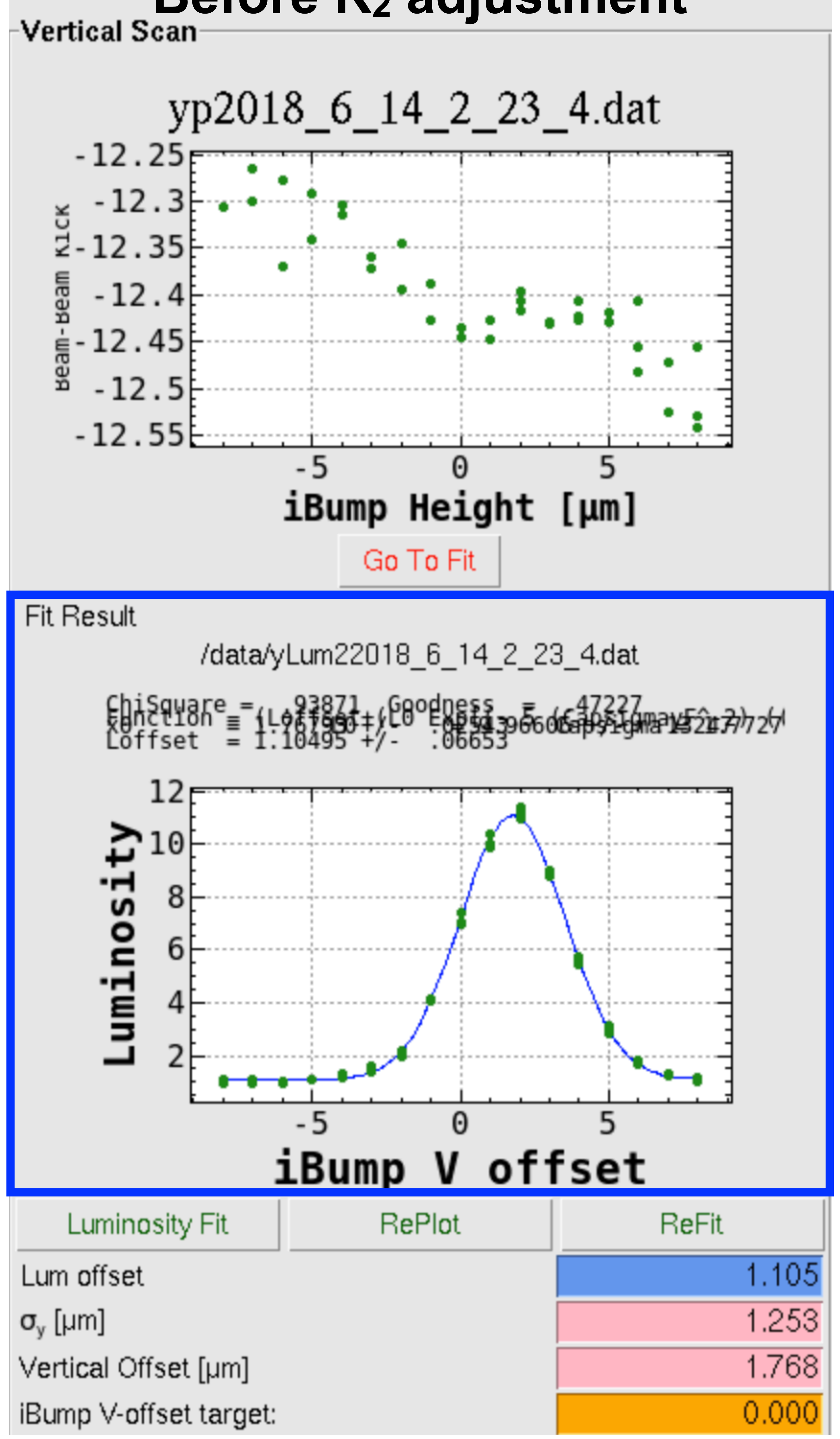
0.1 mA/bunch

$$\Sigma_y = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad \sigma_y^* = \Sigma_y / \sqrt{2}$$

LumiBelle2 is good performance !

Very large beam size ! →

Before R_2 adjustment



Y. Funakoshi

Adjustment of XY Coupling with QC1 Skew Quadrupoles

$$\beta_x^* = 200\ mm \quad \beta_y^* = 4\ mm$$

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15.8 mA/1576 bunches
to avoid beam-beam blowup as much as possible and to get geometrical luminosity.

0.1 mA/bunch

$$\Sigma_y = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad \sigma_y^* = \Sigma_y/\sqrt{2}$$

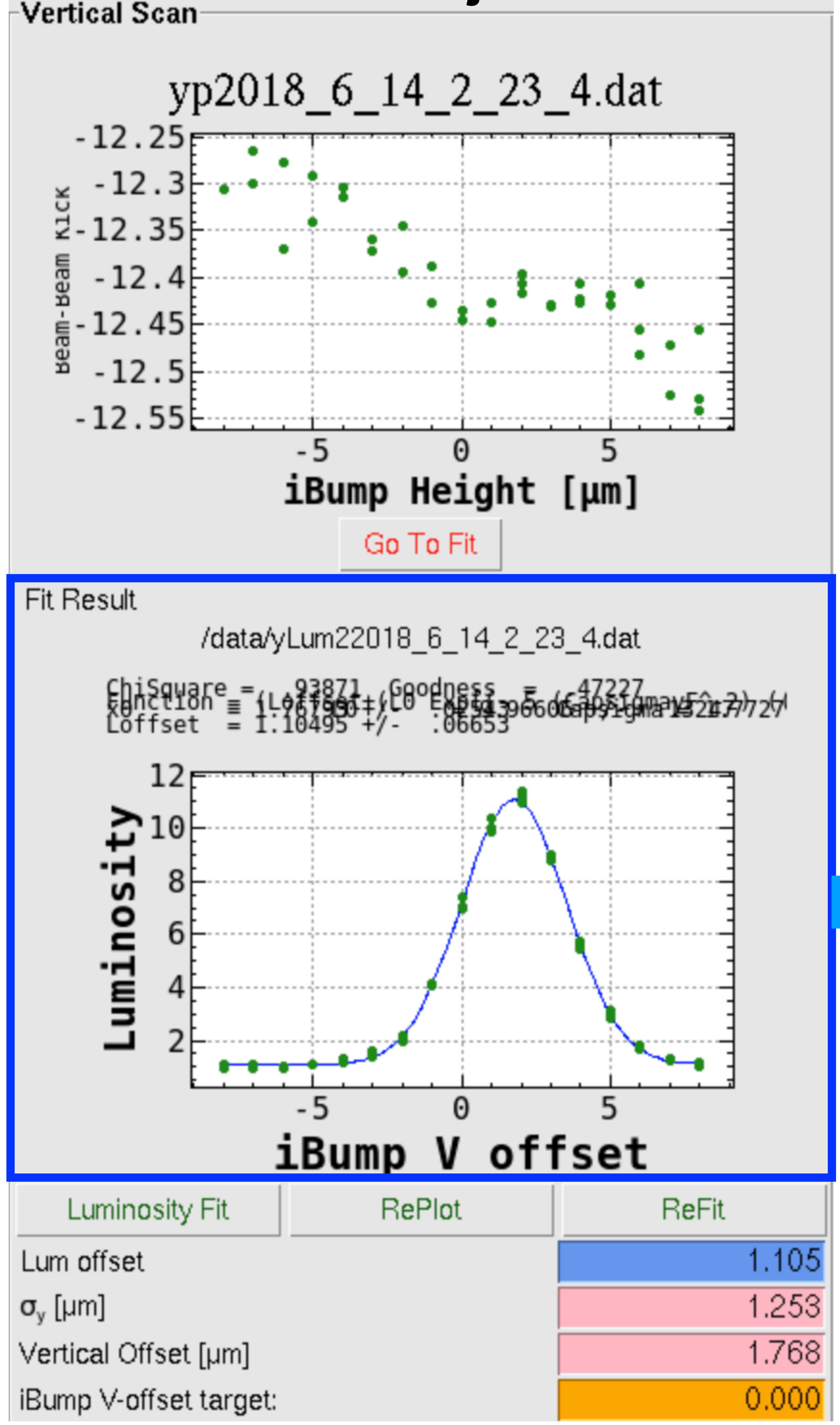
LumiBelle2 is good performance !

Very large beam size ! →

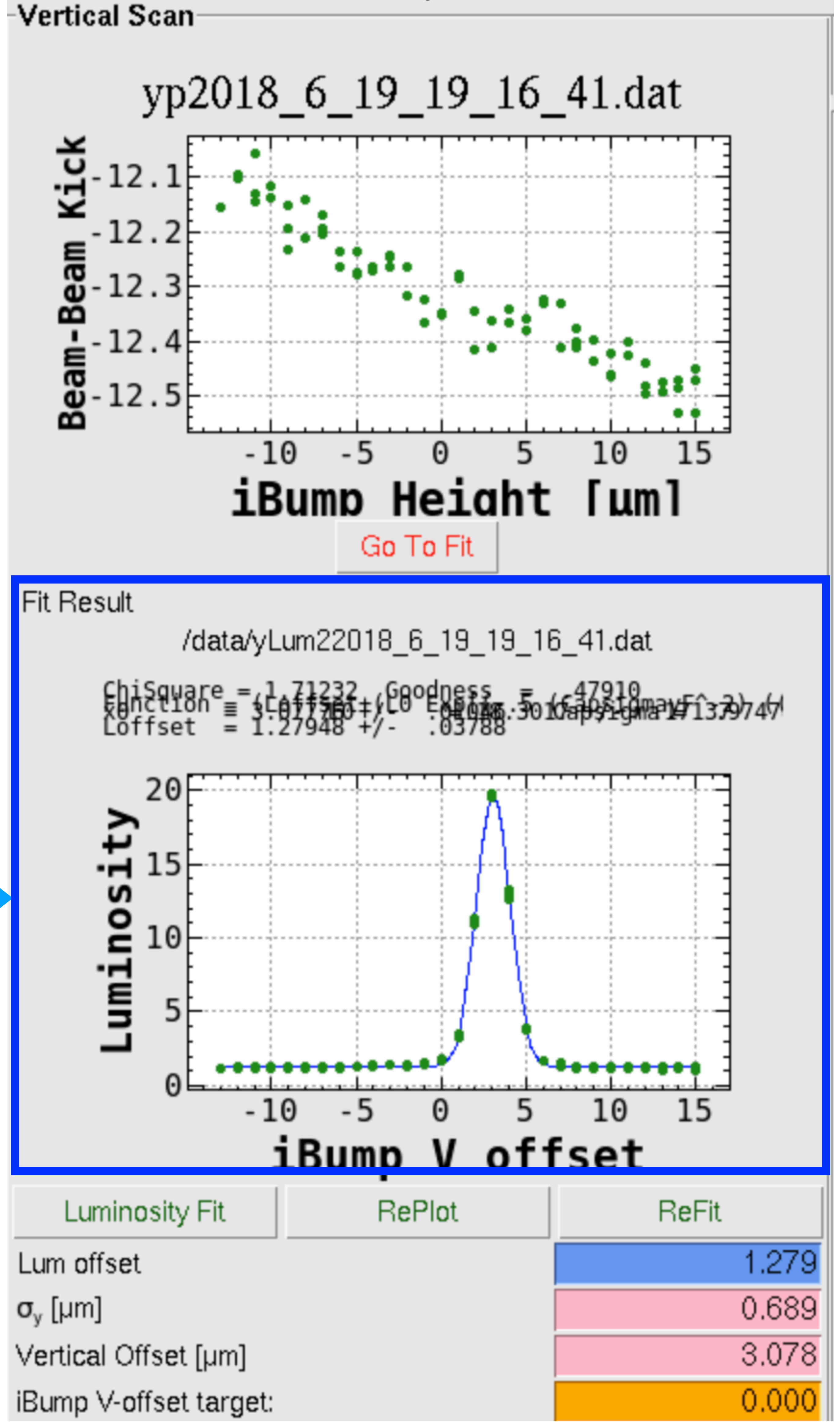
Estimation from X-Ray Monitor:
σ_y^* = 0.4 μm (LER), 0.5 μm (HER)
No change after adjustment of X-Y coupling(R_2) at IP

Measurement by beam-beam scan:
σ_y^* = 1.253 μm → 0.689 μm
Very small !

Before R_2 adjustment



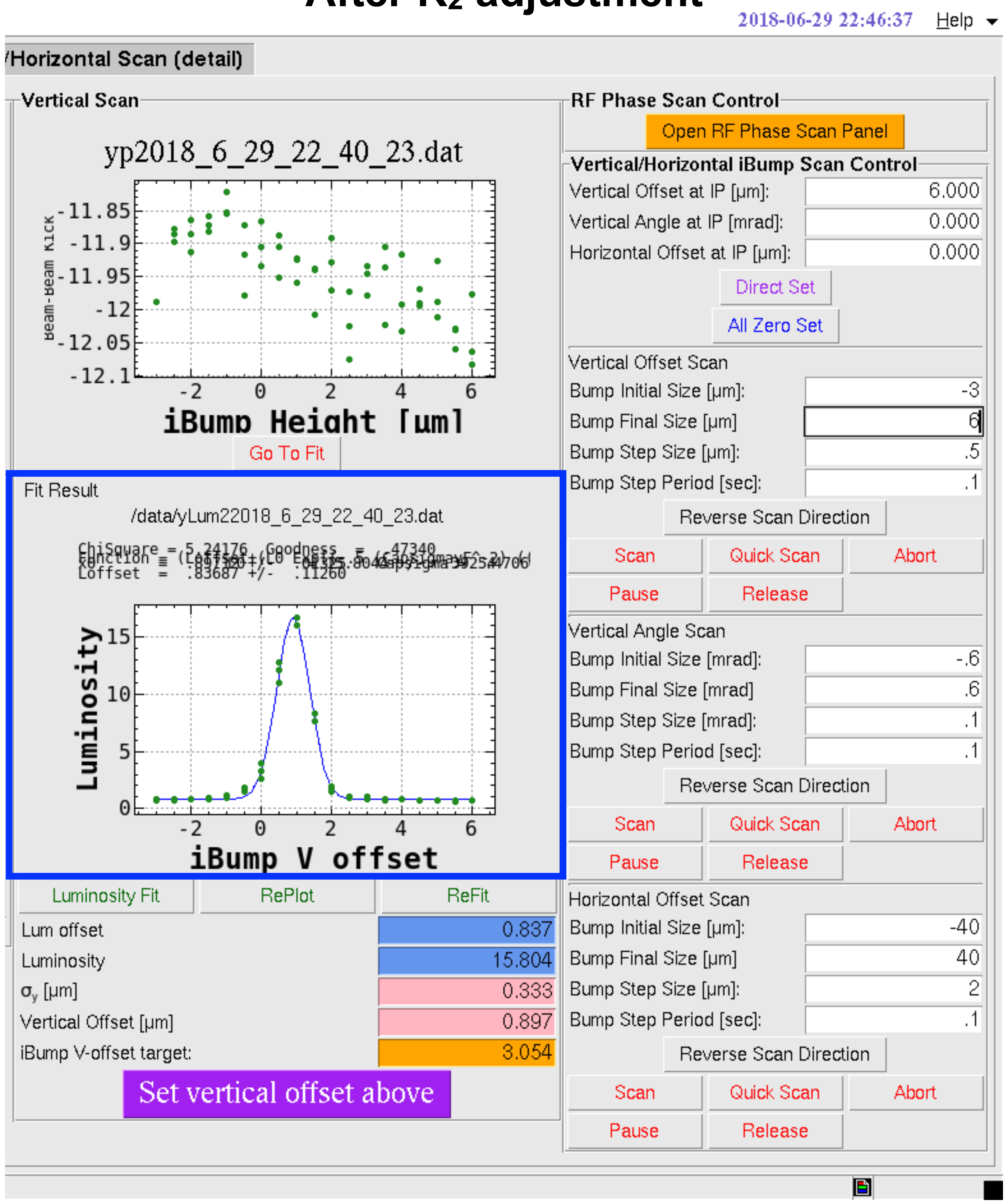
After R_2 adjustment



Y. Funakoshi

Smallest Beam Size measured from Beam-Beam Scan

After R_2 adjustment



$$\beta_x^* = 200\ mm \quad \beta_y^* = 3\ mm$$

Extremely low bunch current

15.8 mA/1576 bunches

to avoid beam-beam blowup as much as possible and to get geometrical luminosity.

0.1 mA/bunch

$$\Sigma_y = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad \sigma_y^* = \Sigma_y / \sqrt{2}$$

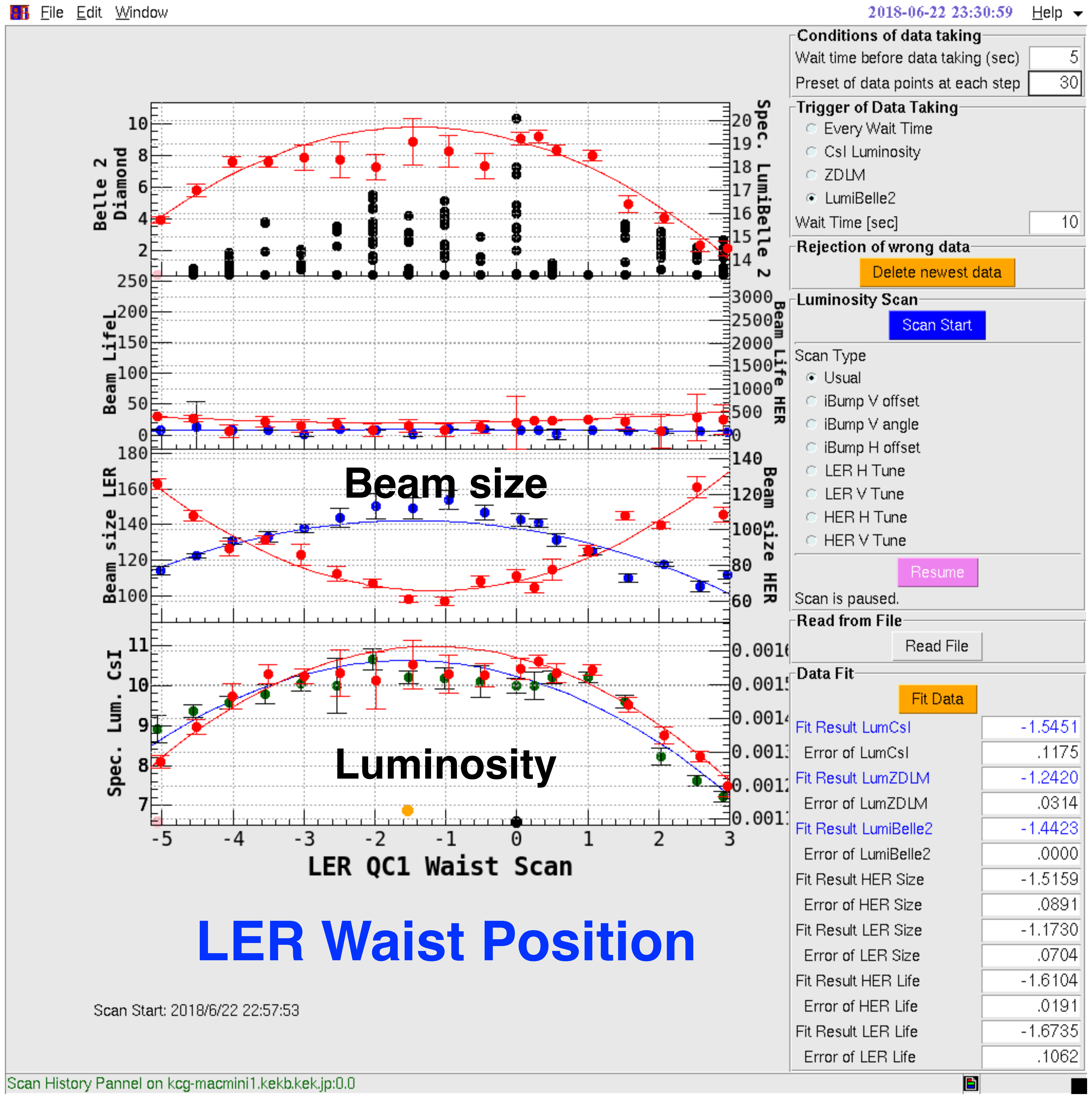
σ_y^* = 0.333 μm

Y. Funakoshi

Waist Scan by using QC1

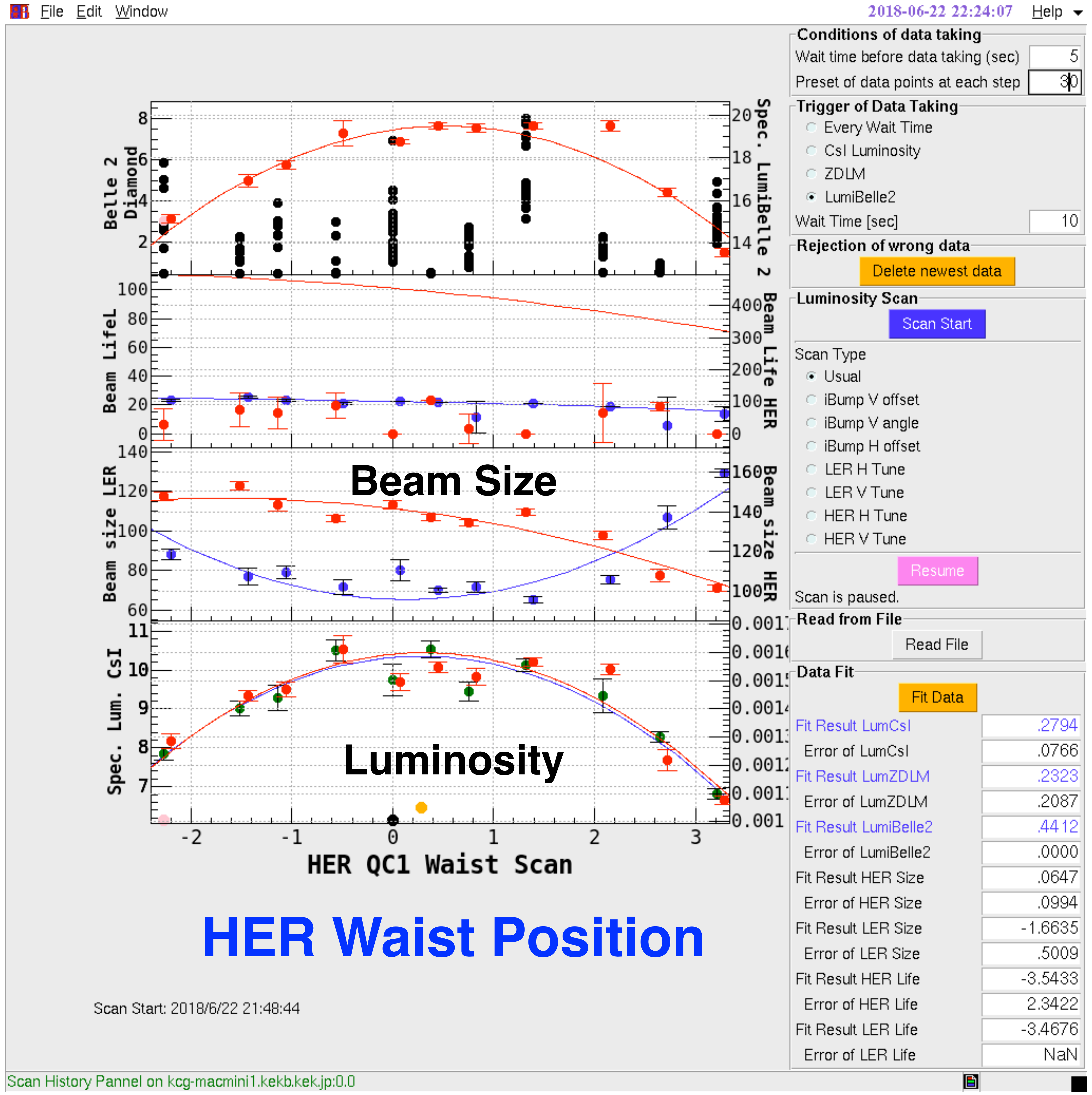
LER

Δs = -1.14 mm



HER

Δs = +0.4 mm

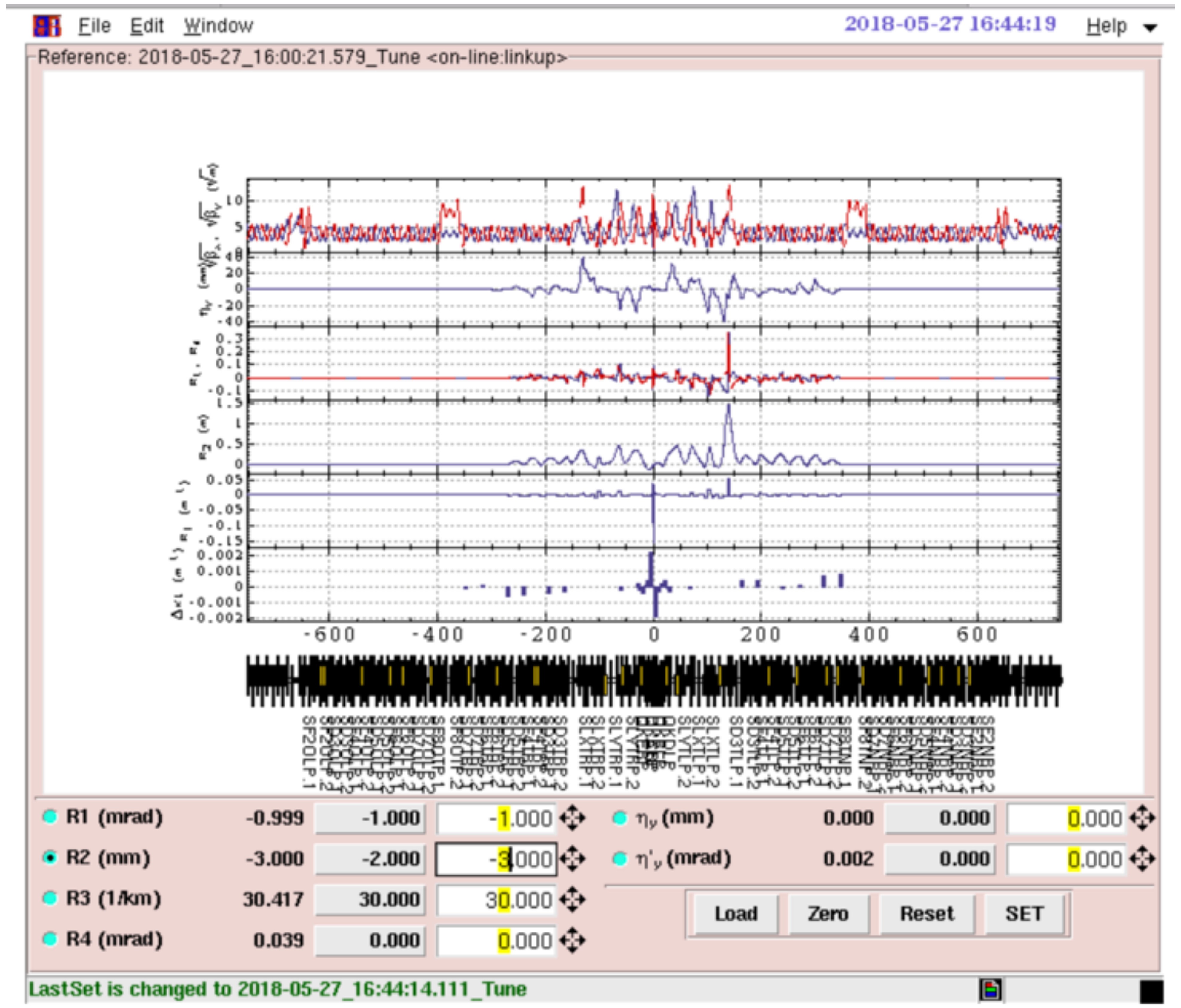


Collision Tuning with IP Knobs

A. Morita, Y. Funakoshi

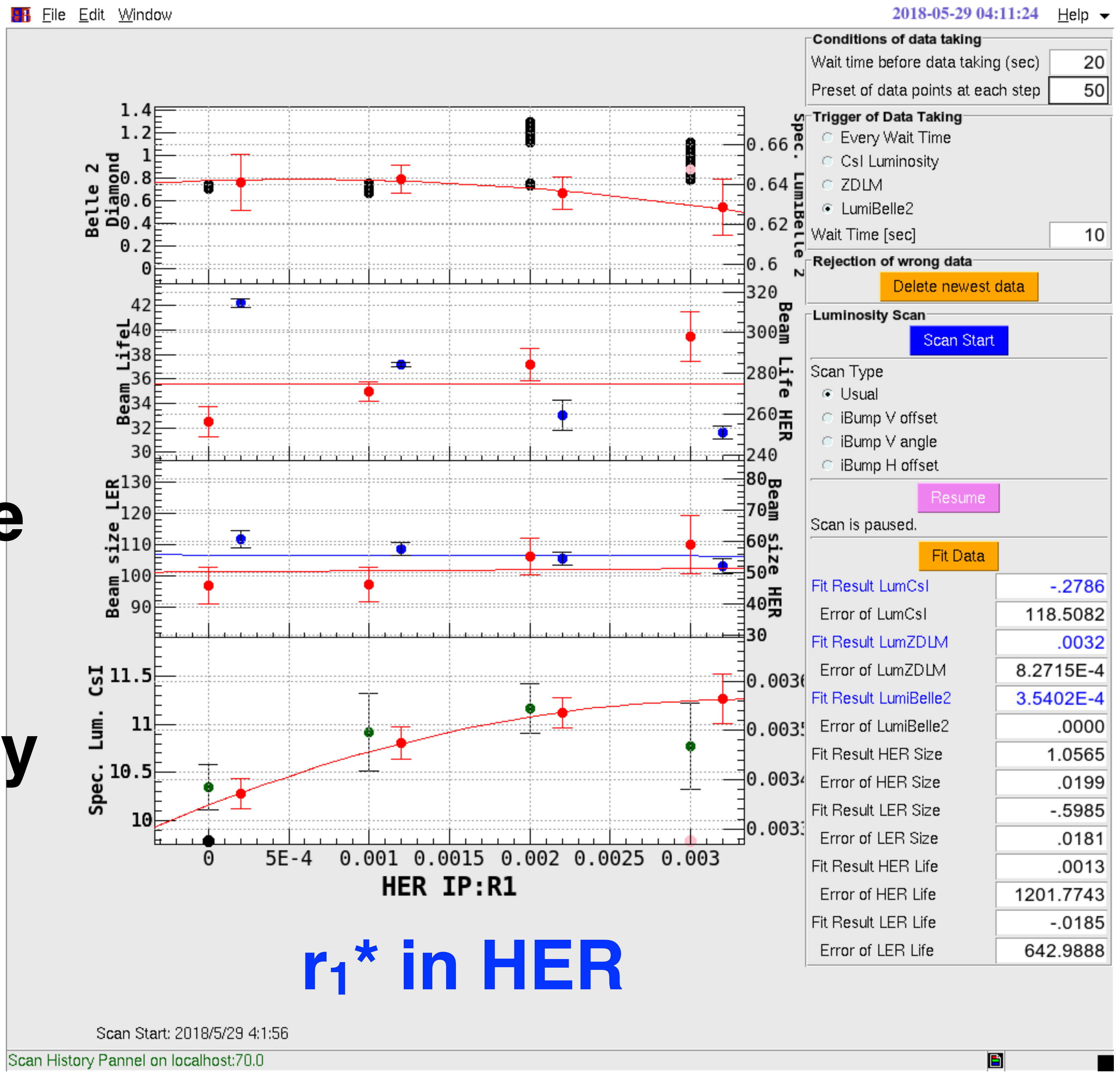
IP XY coupling knob and dispersion knob

Skew quadrupole coils at sextupoles are utilized.



Beam size (XRM)

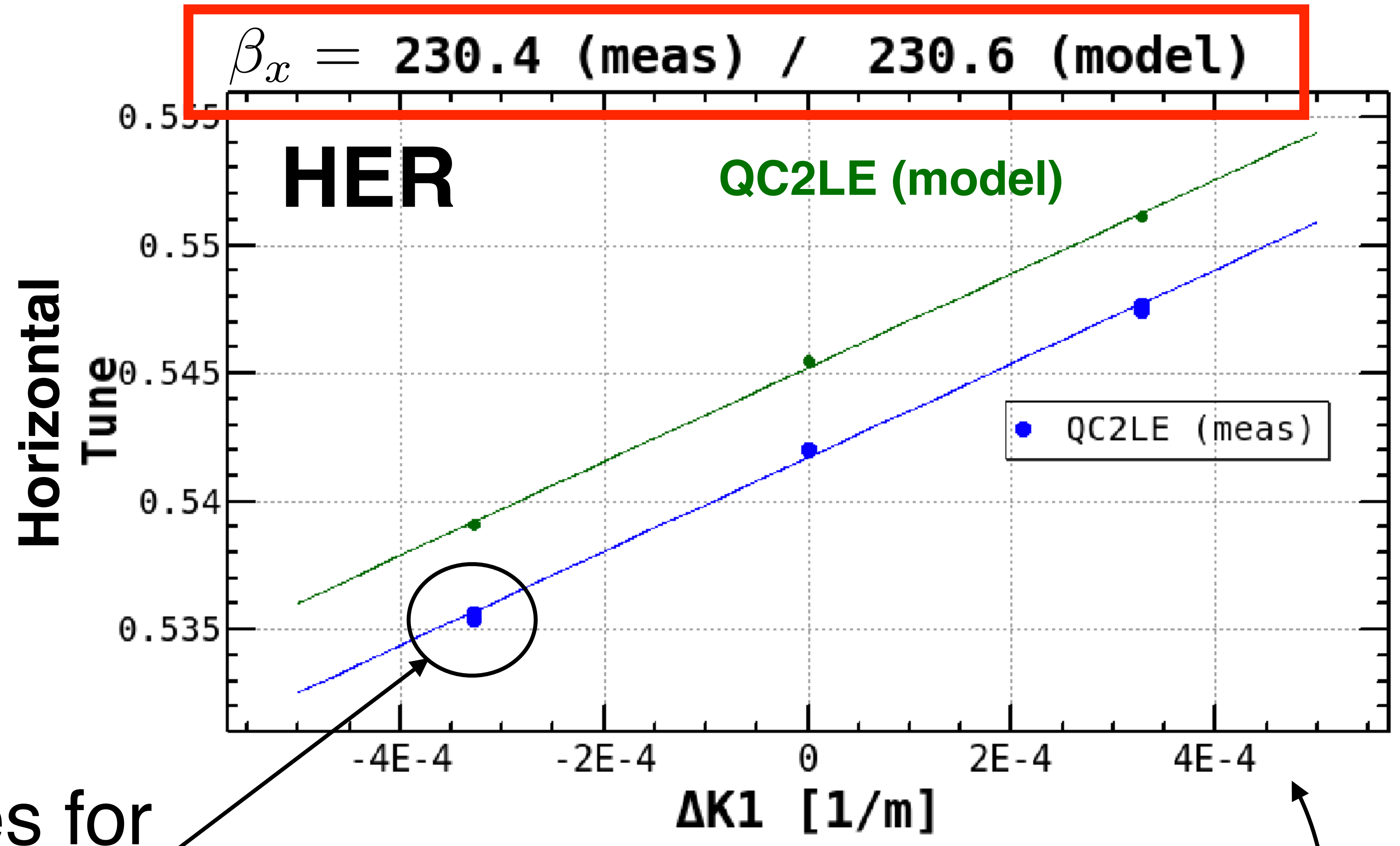
Luminosity

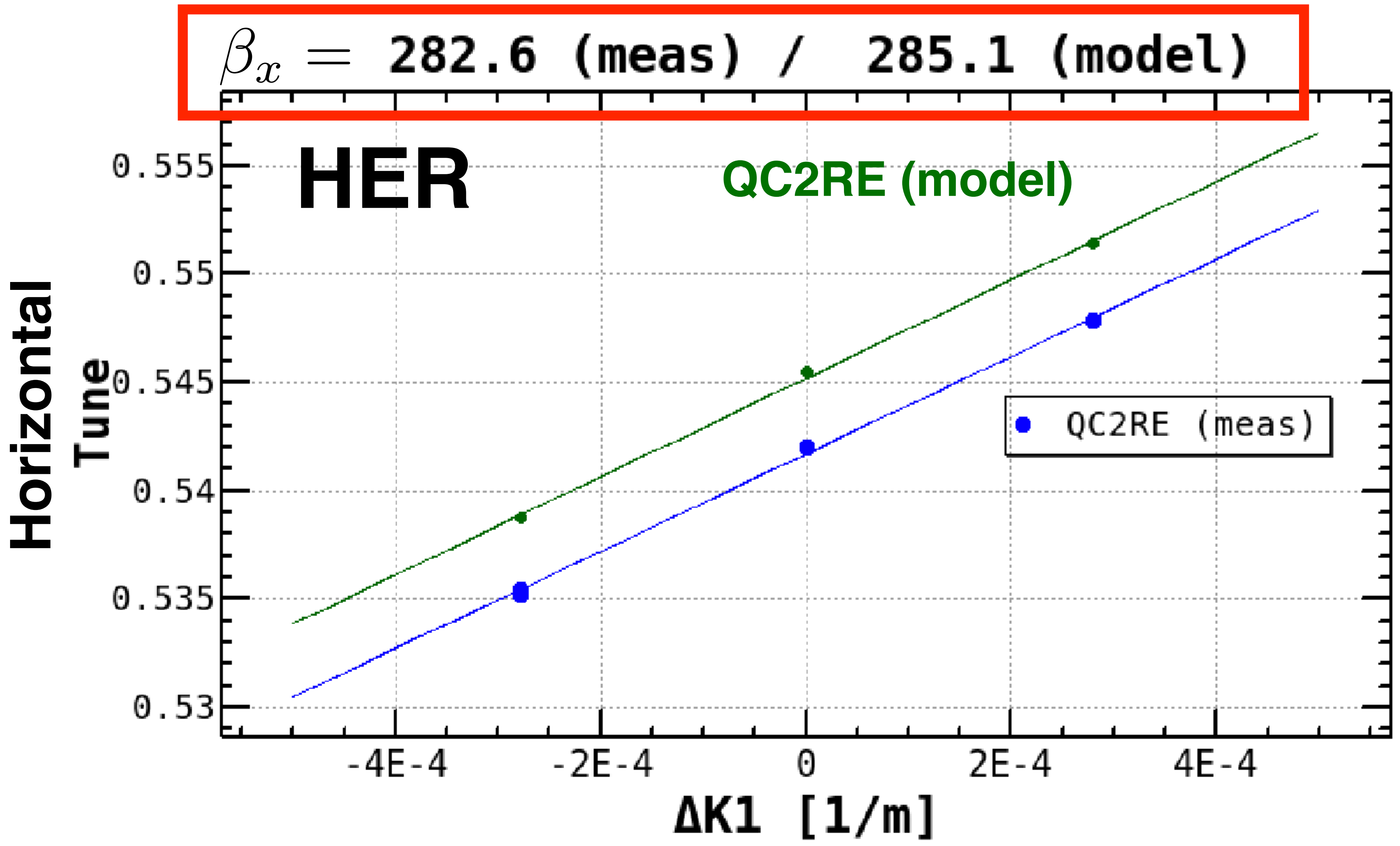


r_1^* in HER

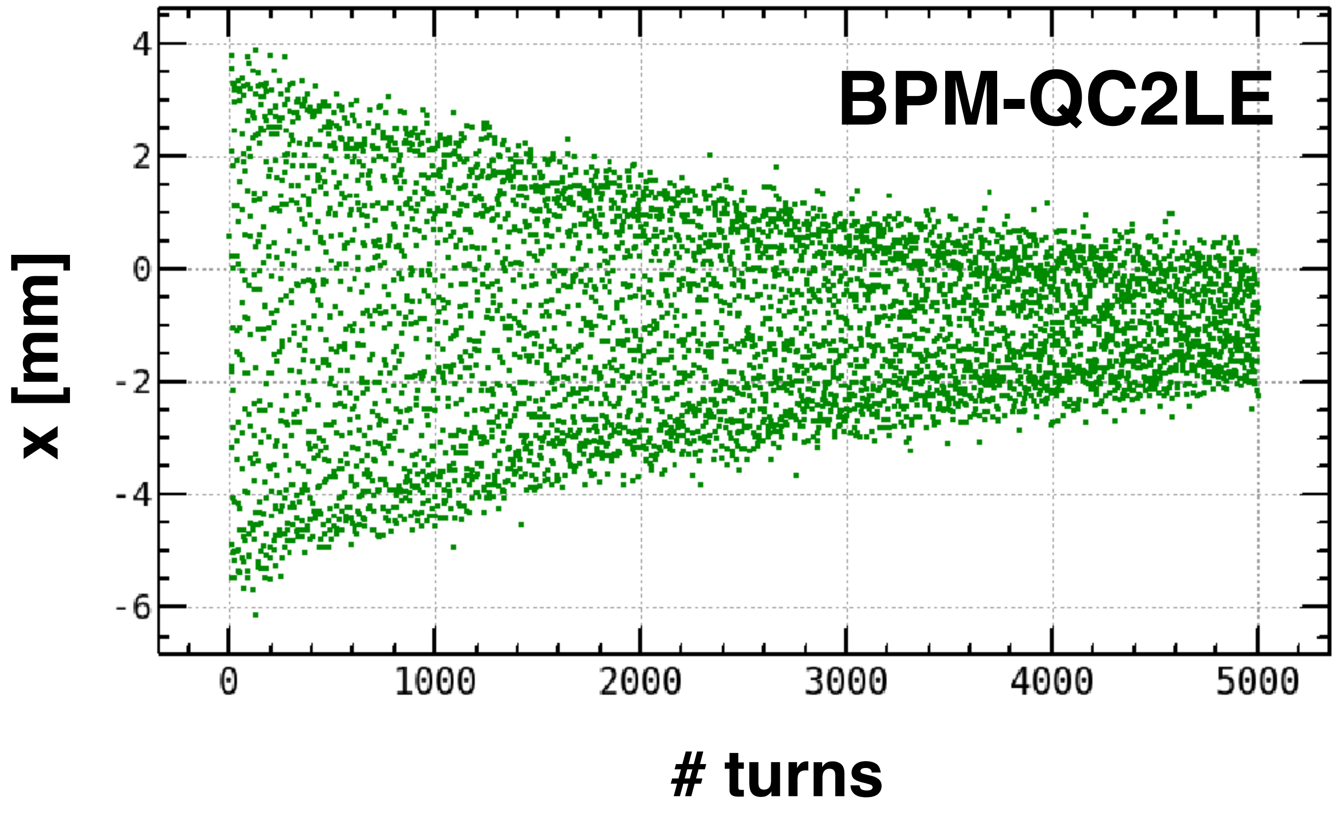
Quadrupole Excitation

Horizontal tune is obtained from TbT data. The beam is shacked by the injection kicker.





3 samples for each point

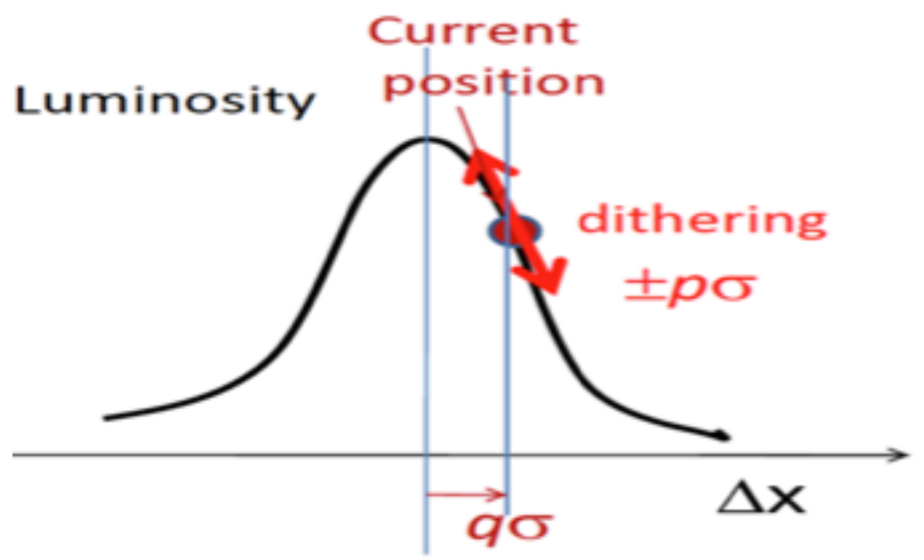


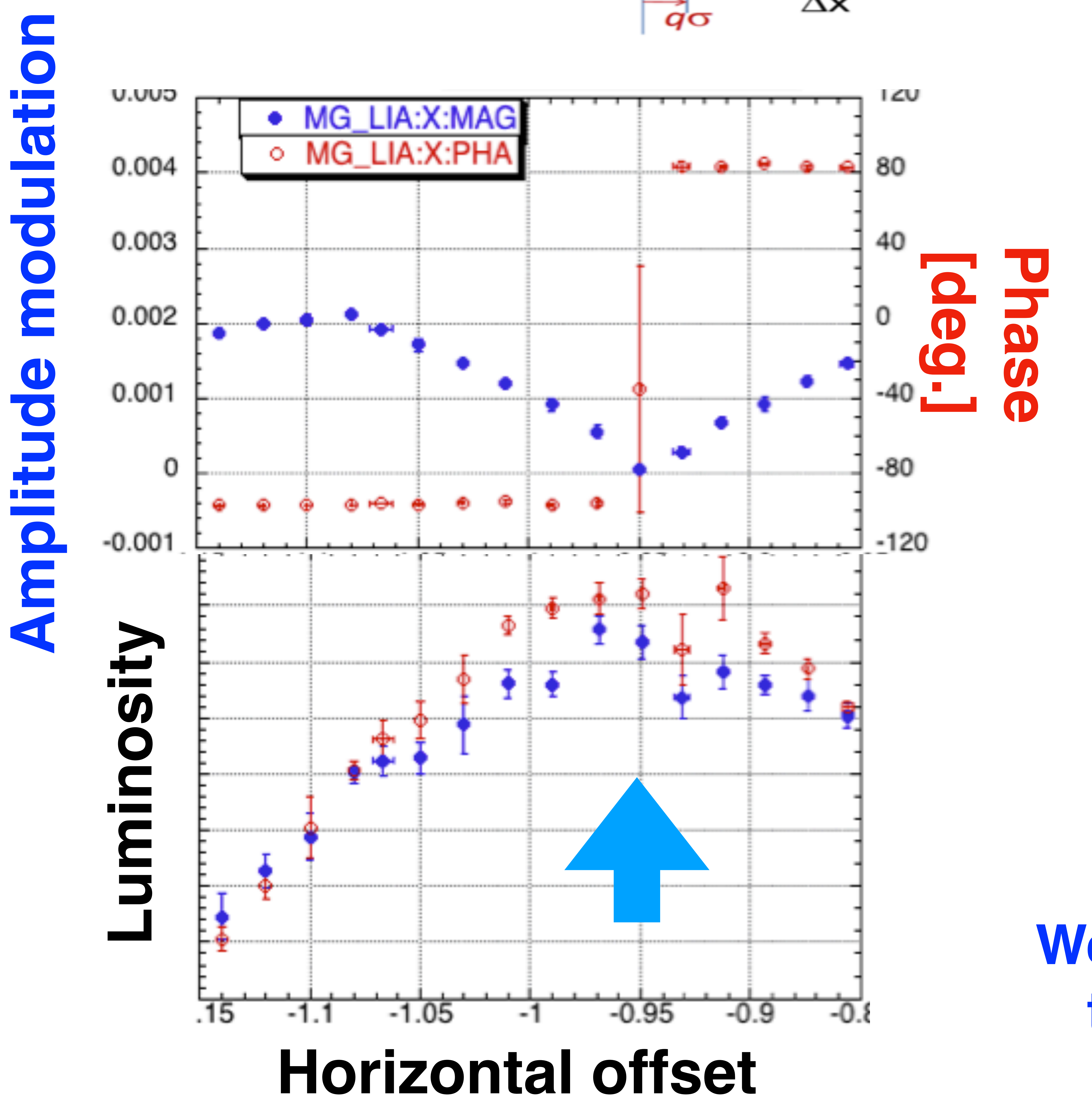
$$\beta_x = 4\pi \frac{\Delta \nu_x}{\Delta K_1}$$

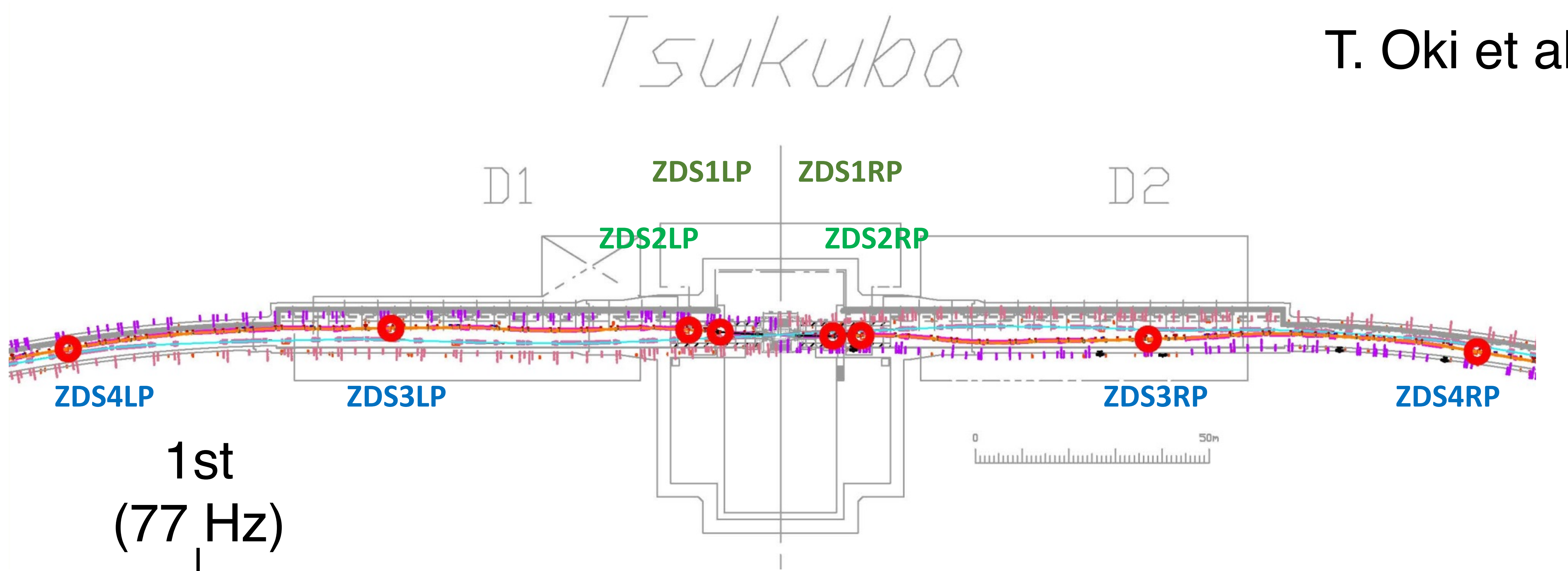
PLL is also available to give oscillations

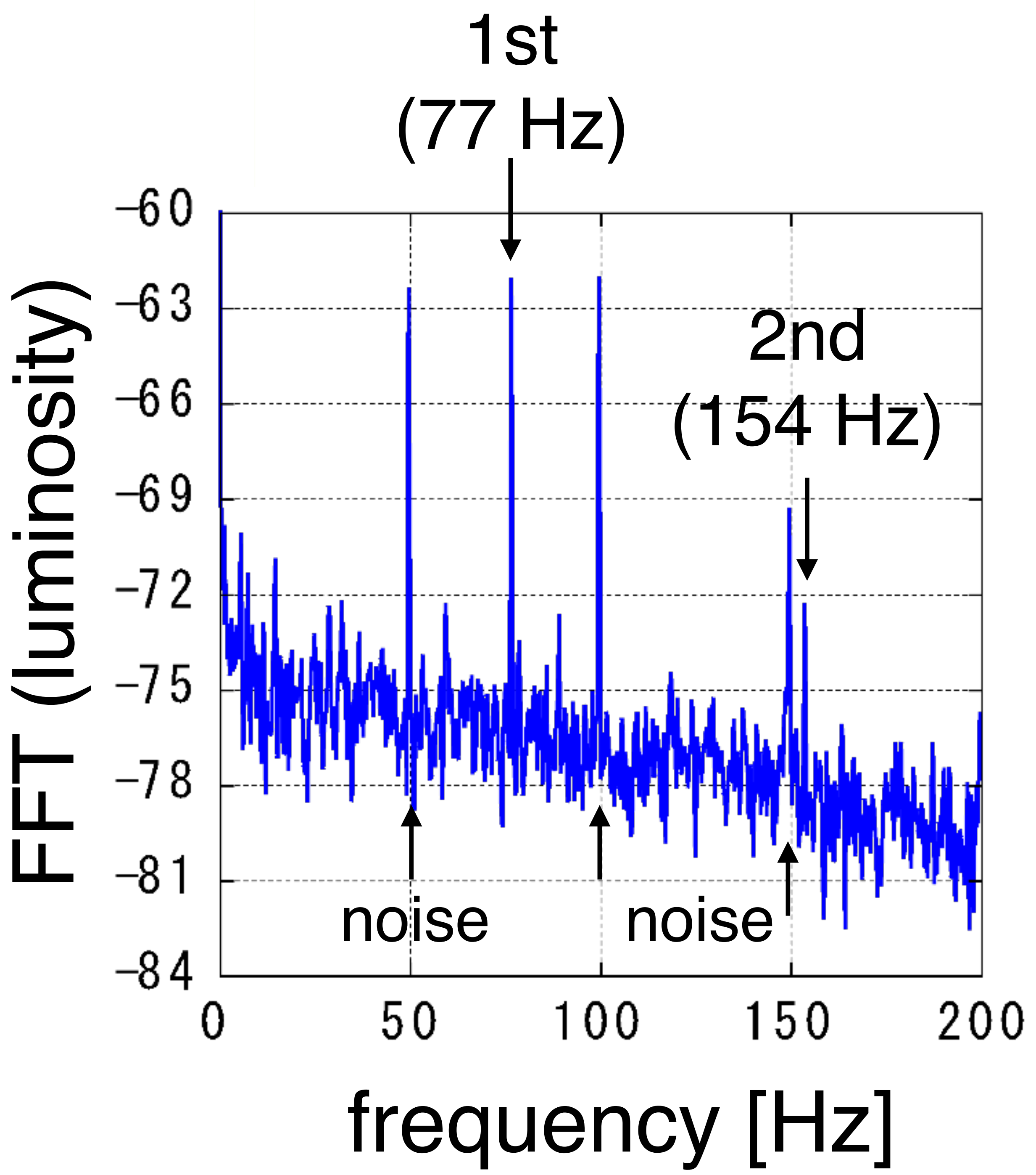
Measured beta is good agreement with the model.

T. Oki et al.

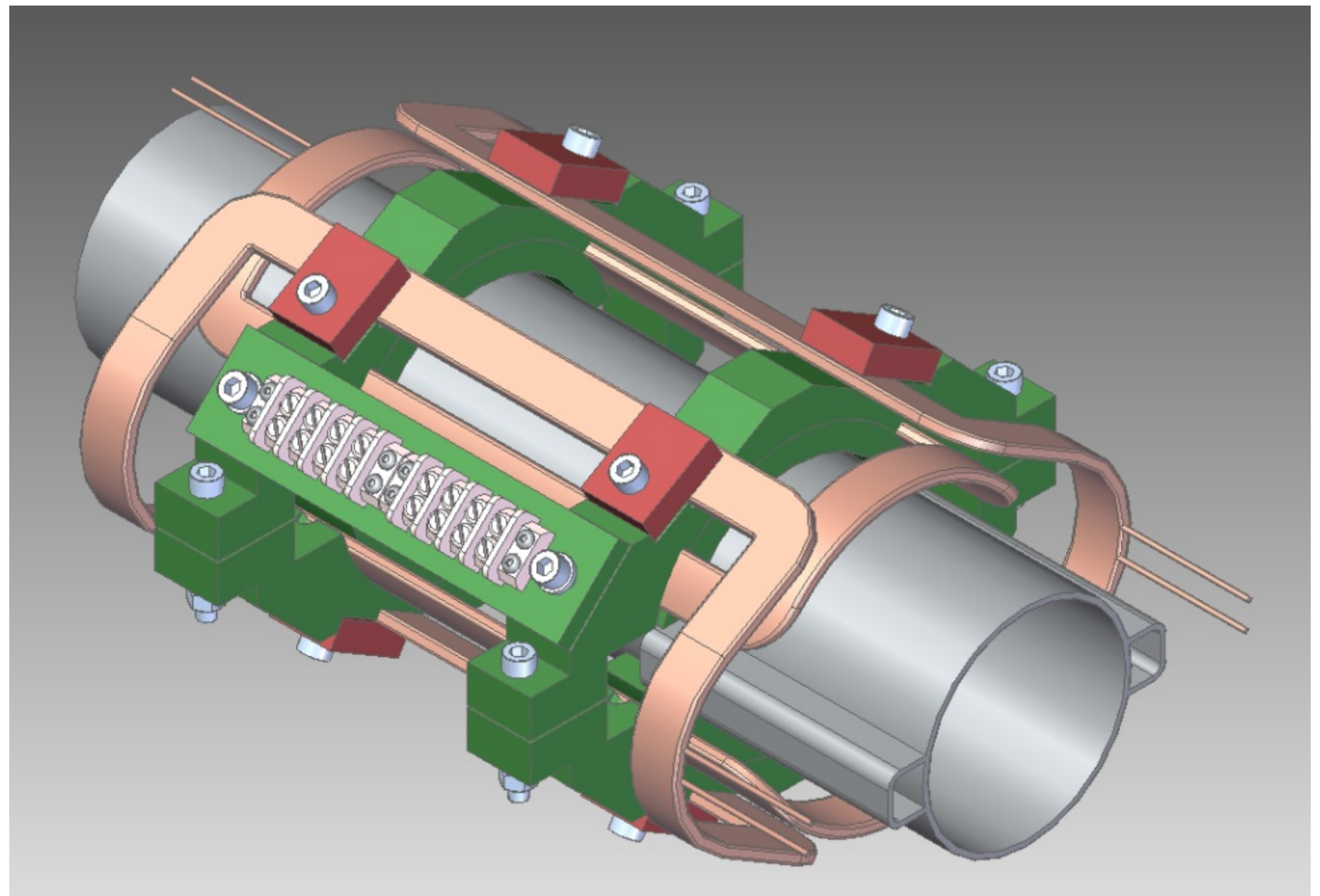








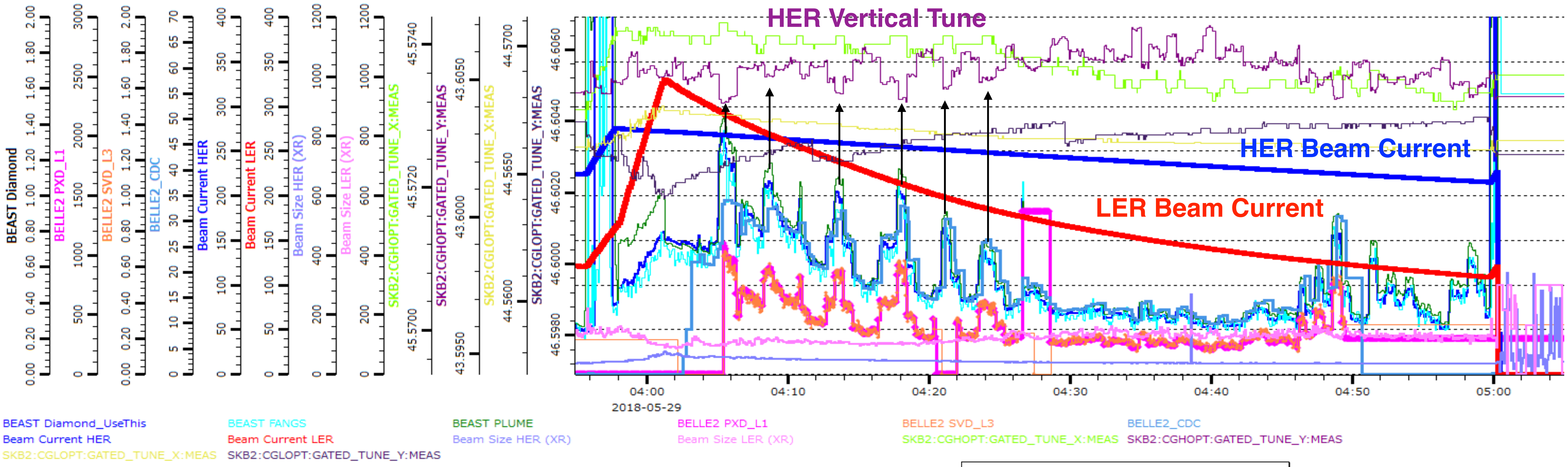
dithering coil



We confirmed that the luminosity peak is consistent with the minimum amplitude modulation and flip of phase.

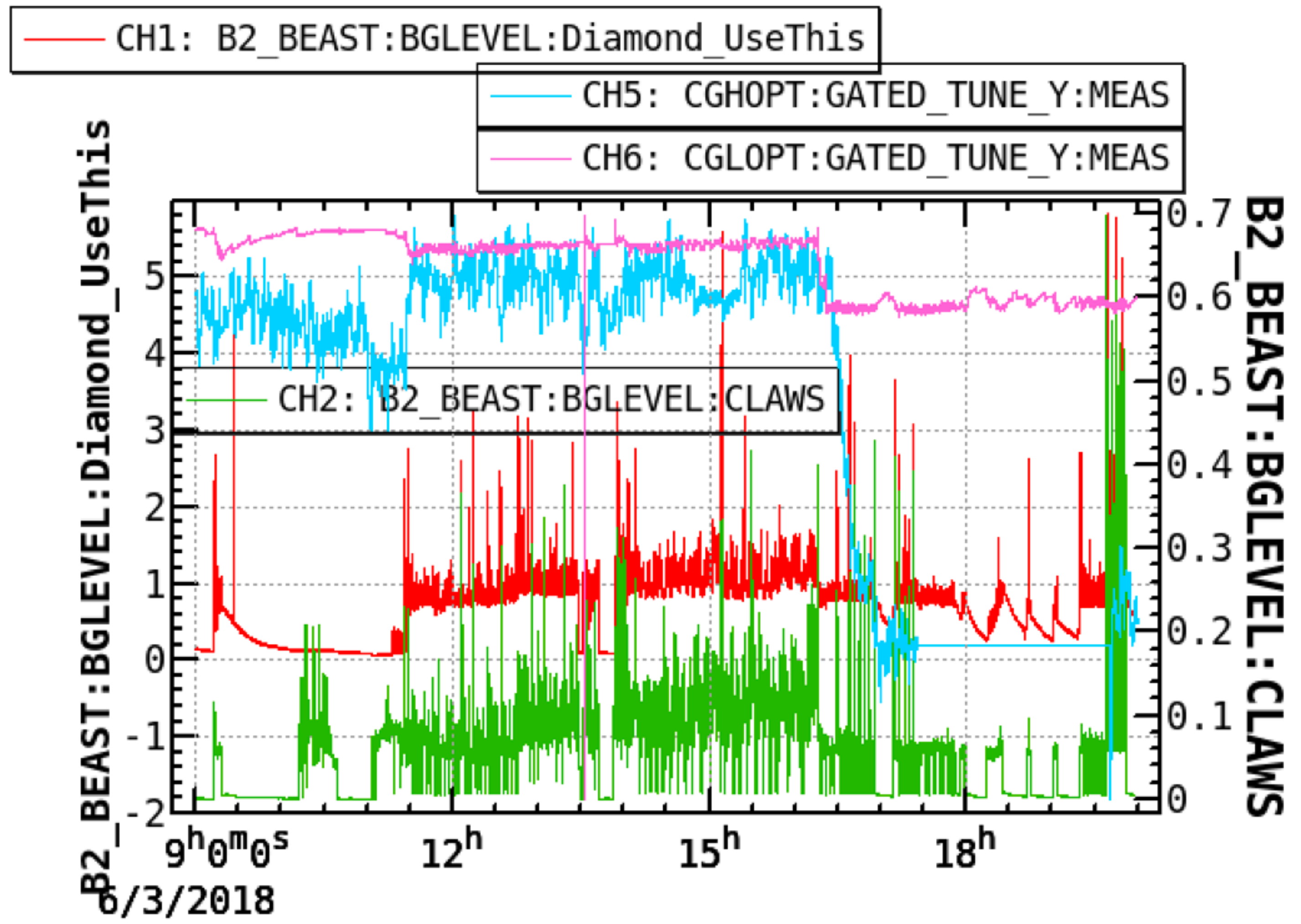
Luminosity run, May 29, 2018

H. Nakayama
slide from Phase 2 summary meeting



HER tune clearly affects the beam background.

We have to find better a working point and necessary to keep tunes.

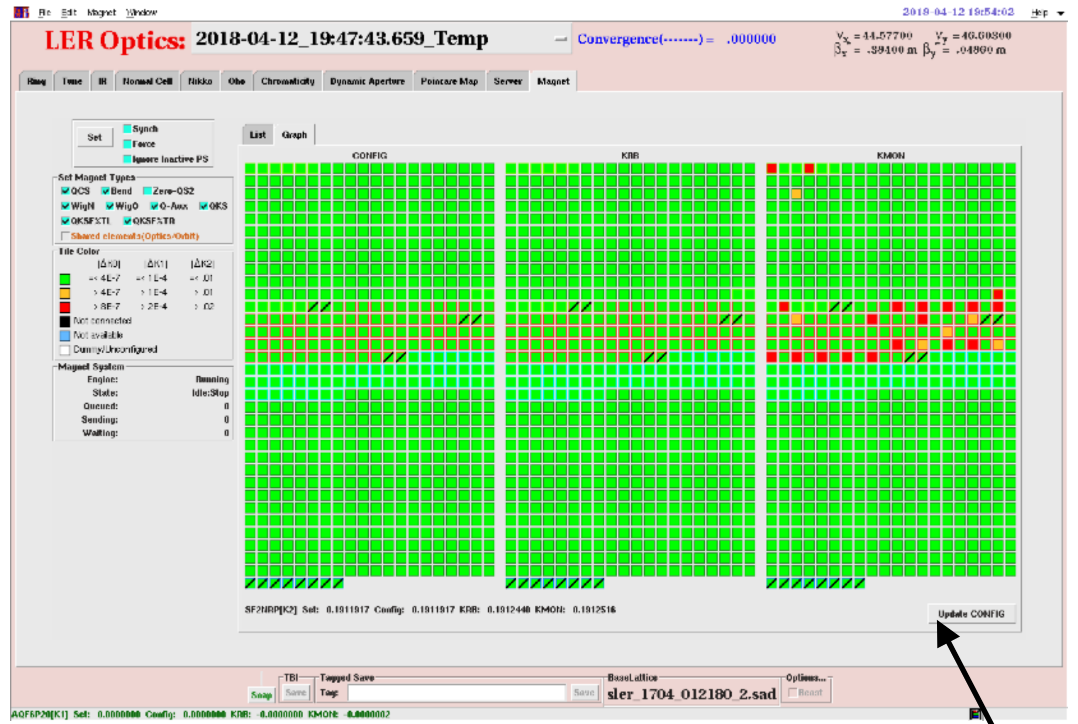


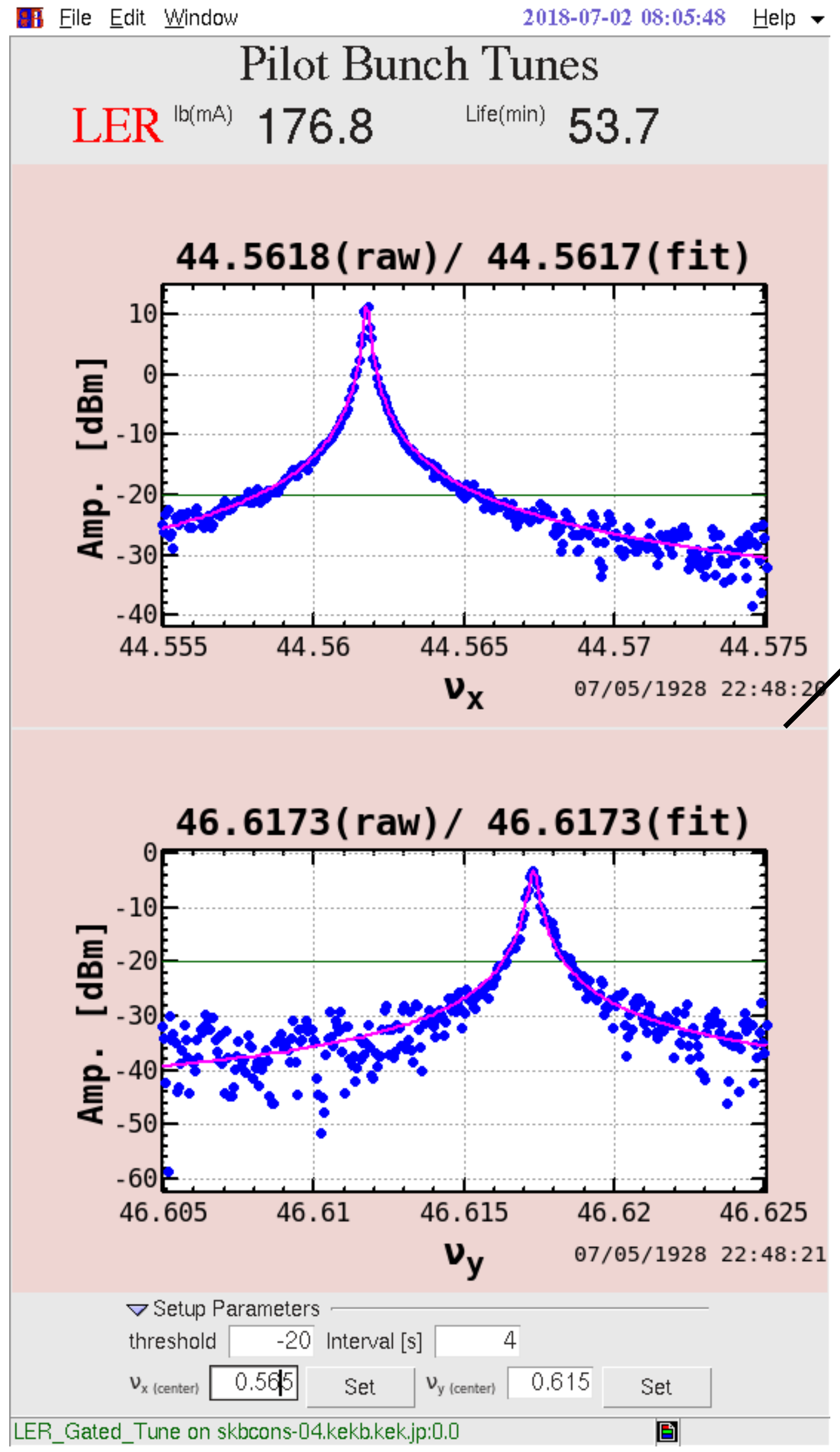
We have applied tune feedback system for the last week of Phase 2.

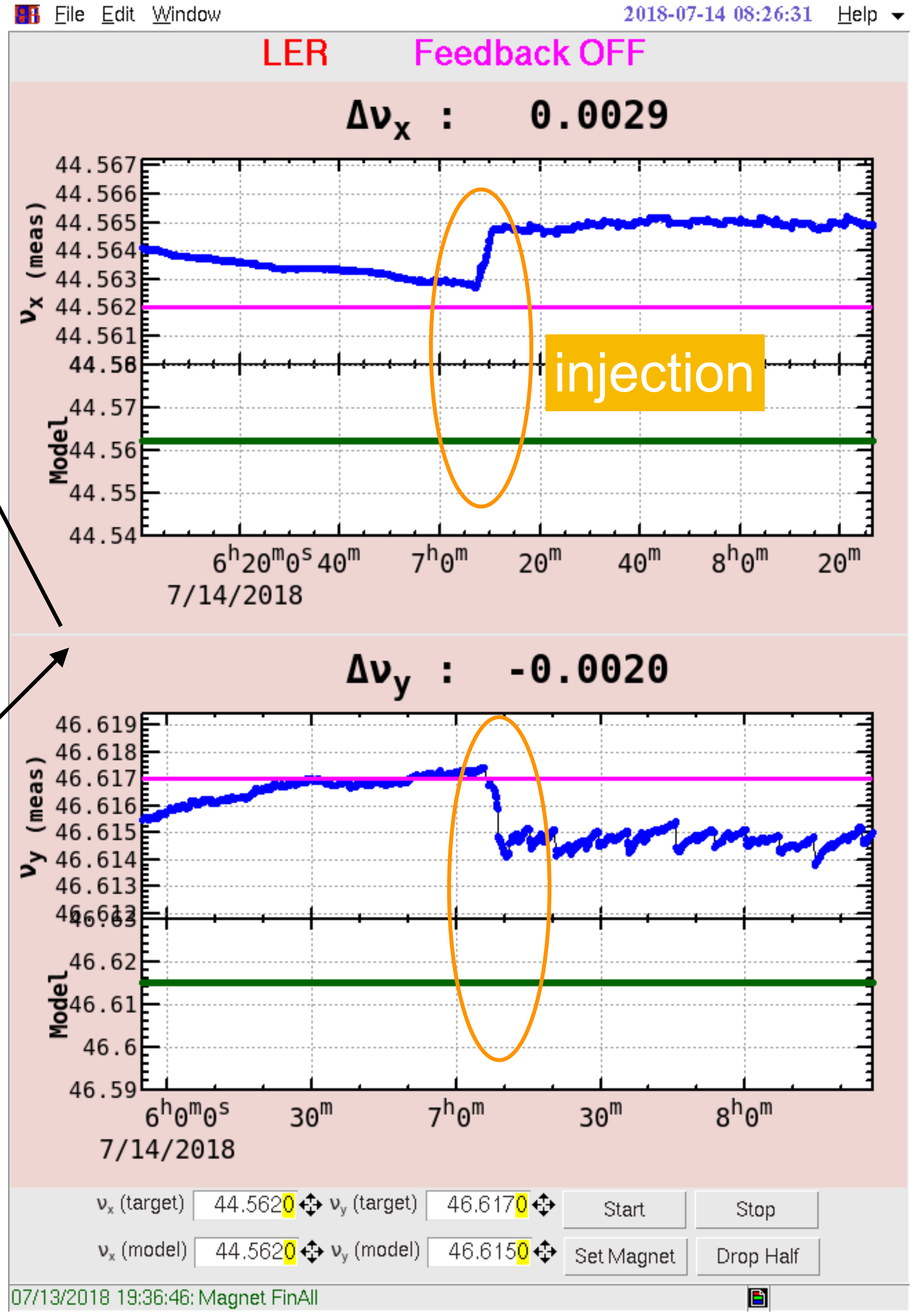
Tune shift due to resistive wall is compensated.

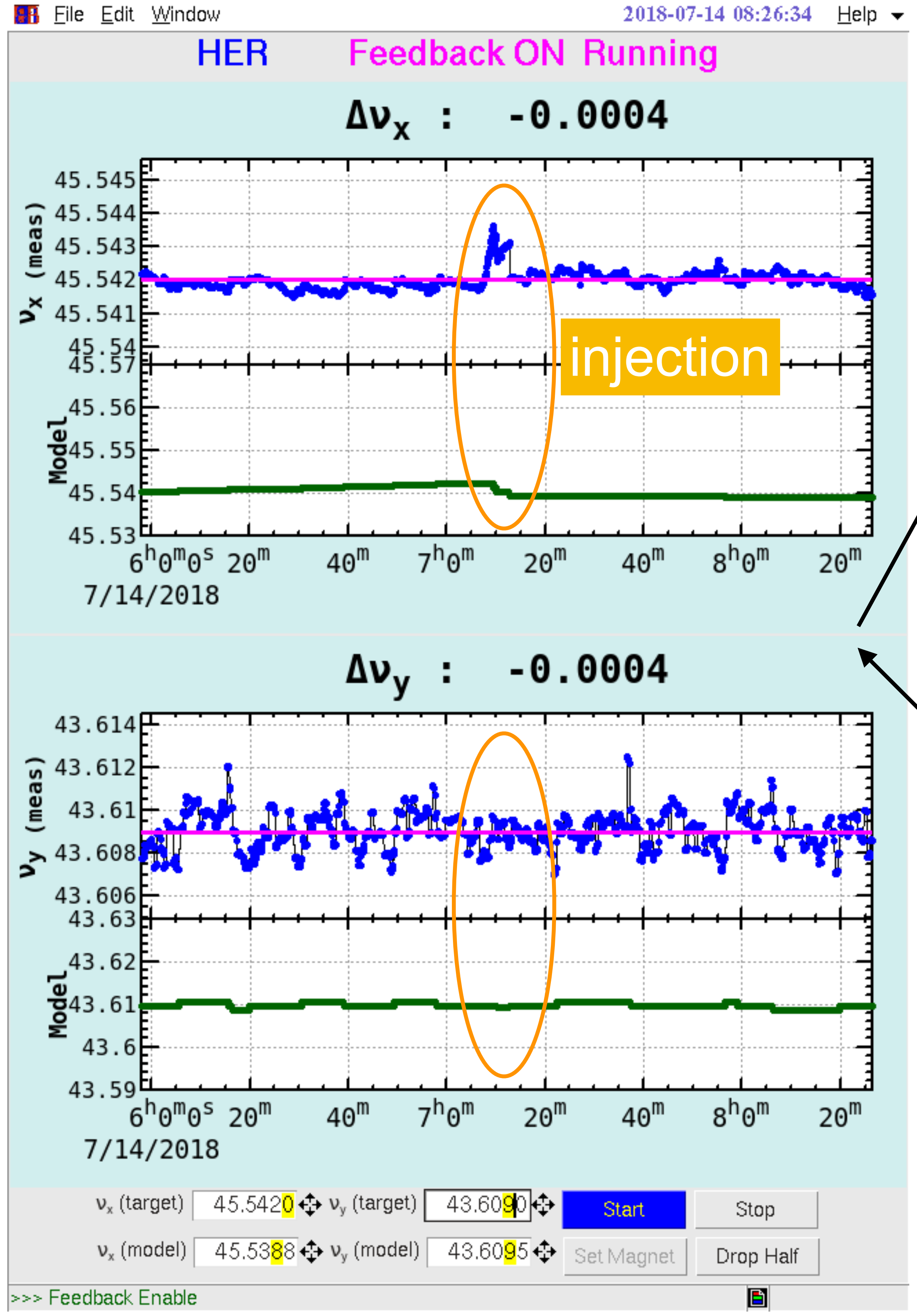
(dependent on the beam current)

optics server

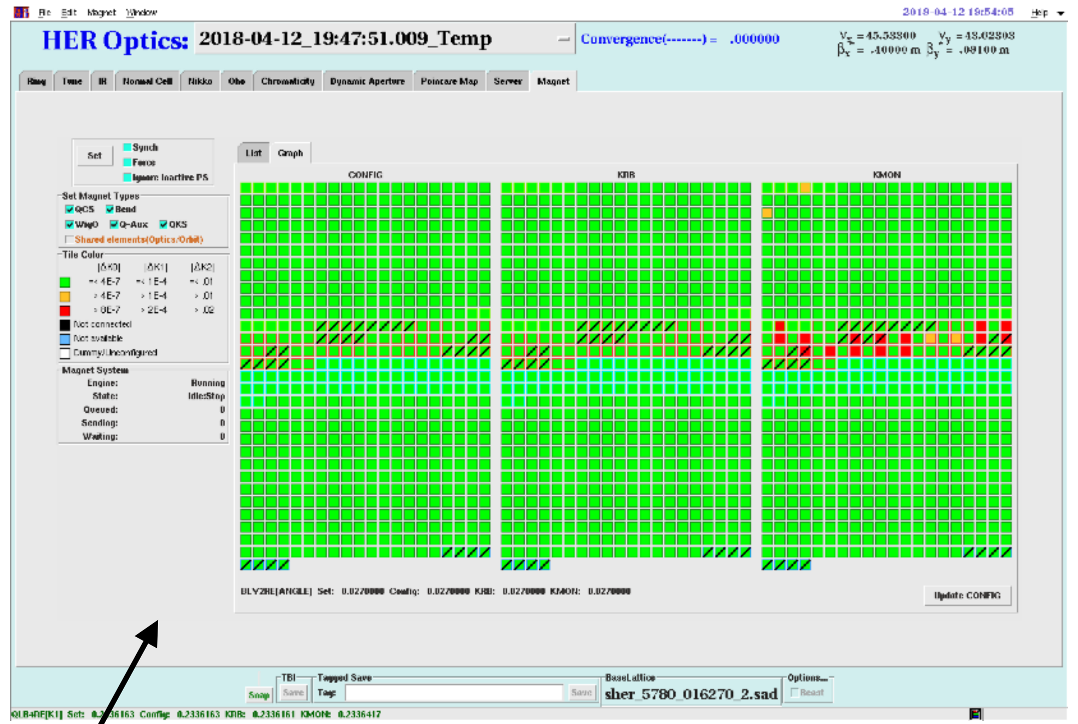


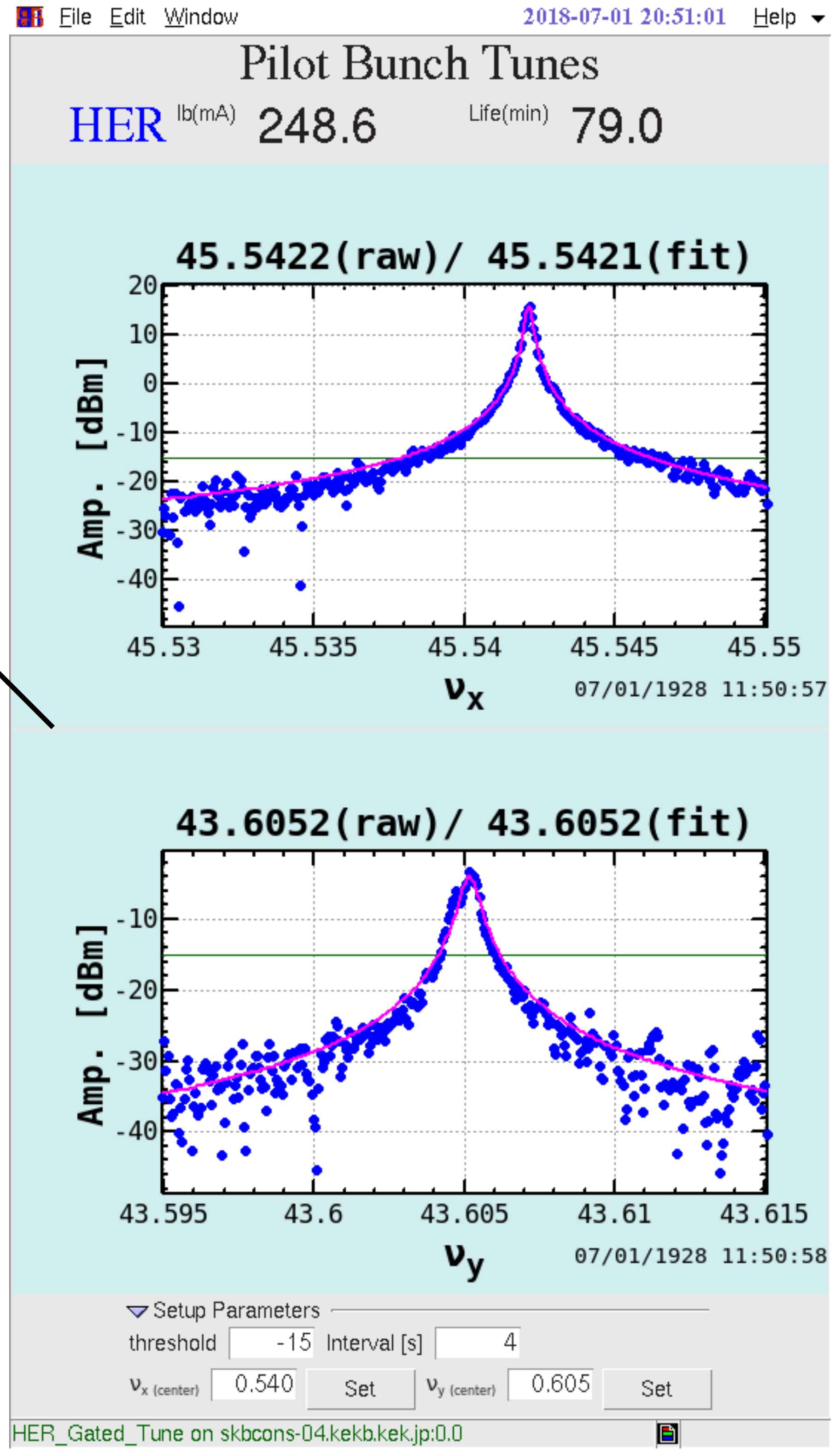






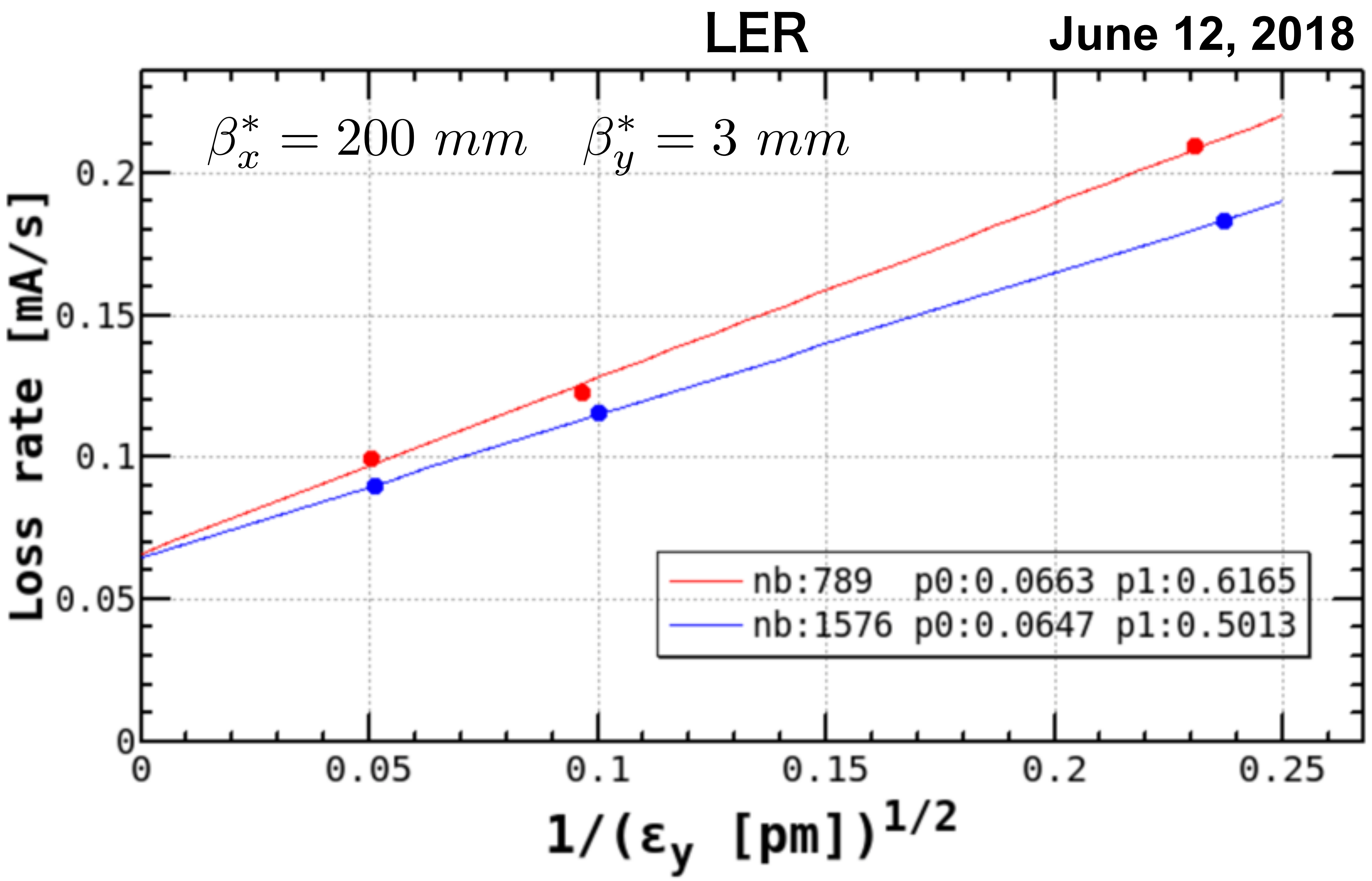
optics server

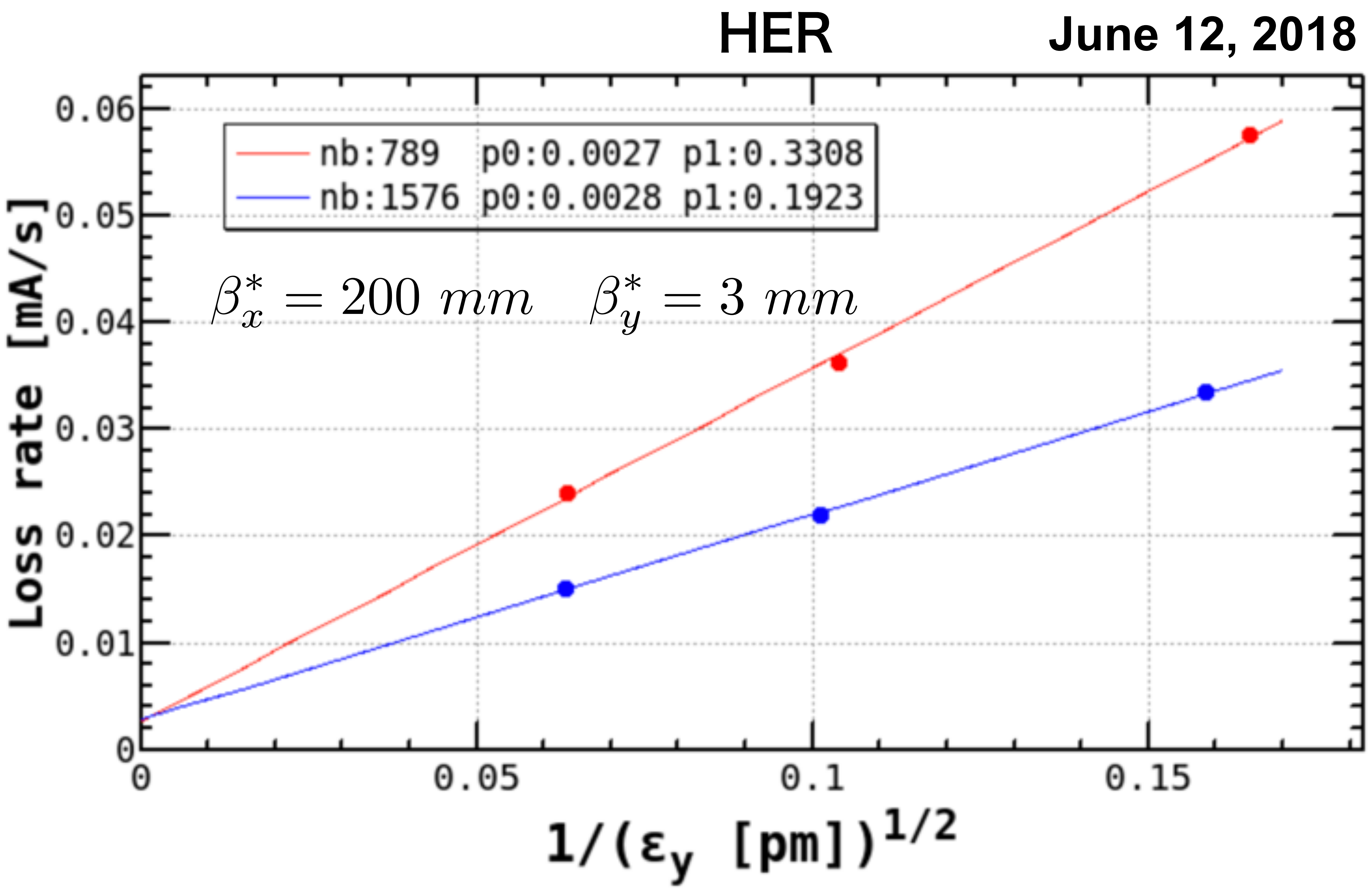




matching and send "set magnet" to optics server

Beam Lifetime





LER current: 320 mA
Touschek lifetime: 35 min (n_b: 789)
lifetime (others): 80 min

HER current: 285 mA
Touschek lifetime: 86 min (n_b: 789)
lifetime (others): 28 hours

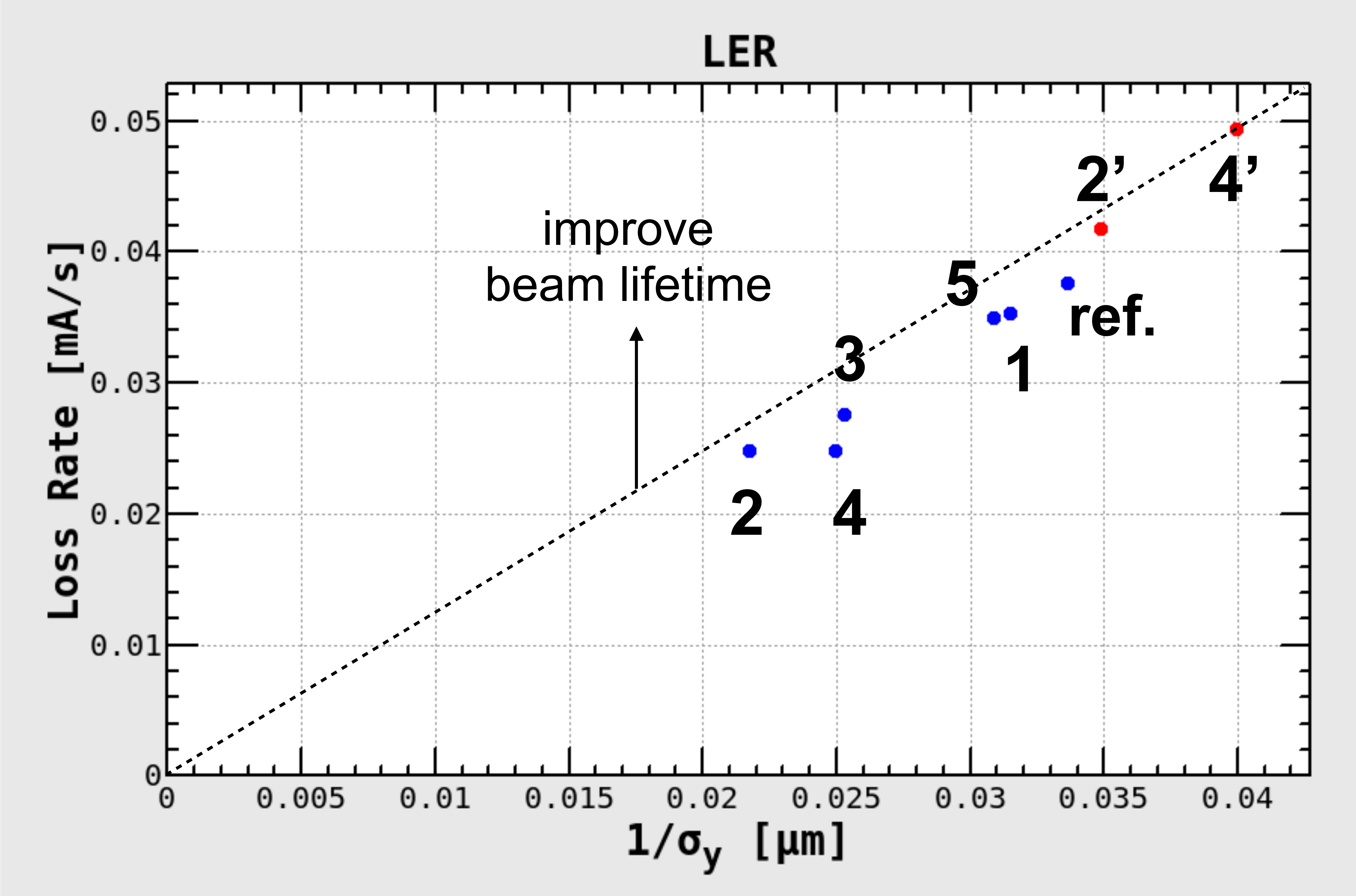
Physical aperture limits the beam lifetime.

Movable collimators to reduce background and avoid QCS quench

ε_y is controlled by vertical dispersions.

ID number specifies a different set of sextupole combination.

5 sets of sextupole settings



June 27, 2018

2' : with optics correction
4' : with optics correction

σ_y measured by XRM

← Beam size larger **Beam size smaller →**

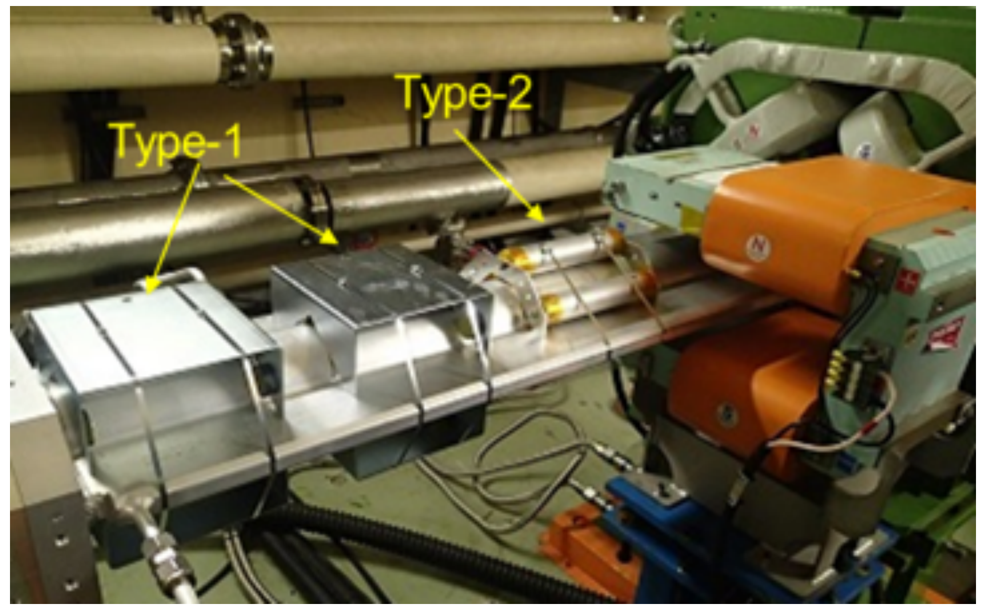
Sextupole tuning could not improve the beam lifetime in the LER.

Physical aperture limits the beam lifetime. (Tracking simulation supports this.)

Electron Cloud in LER

Additional permanent magnets

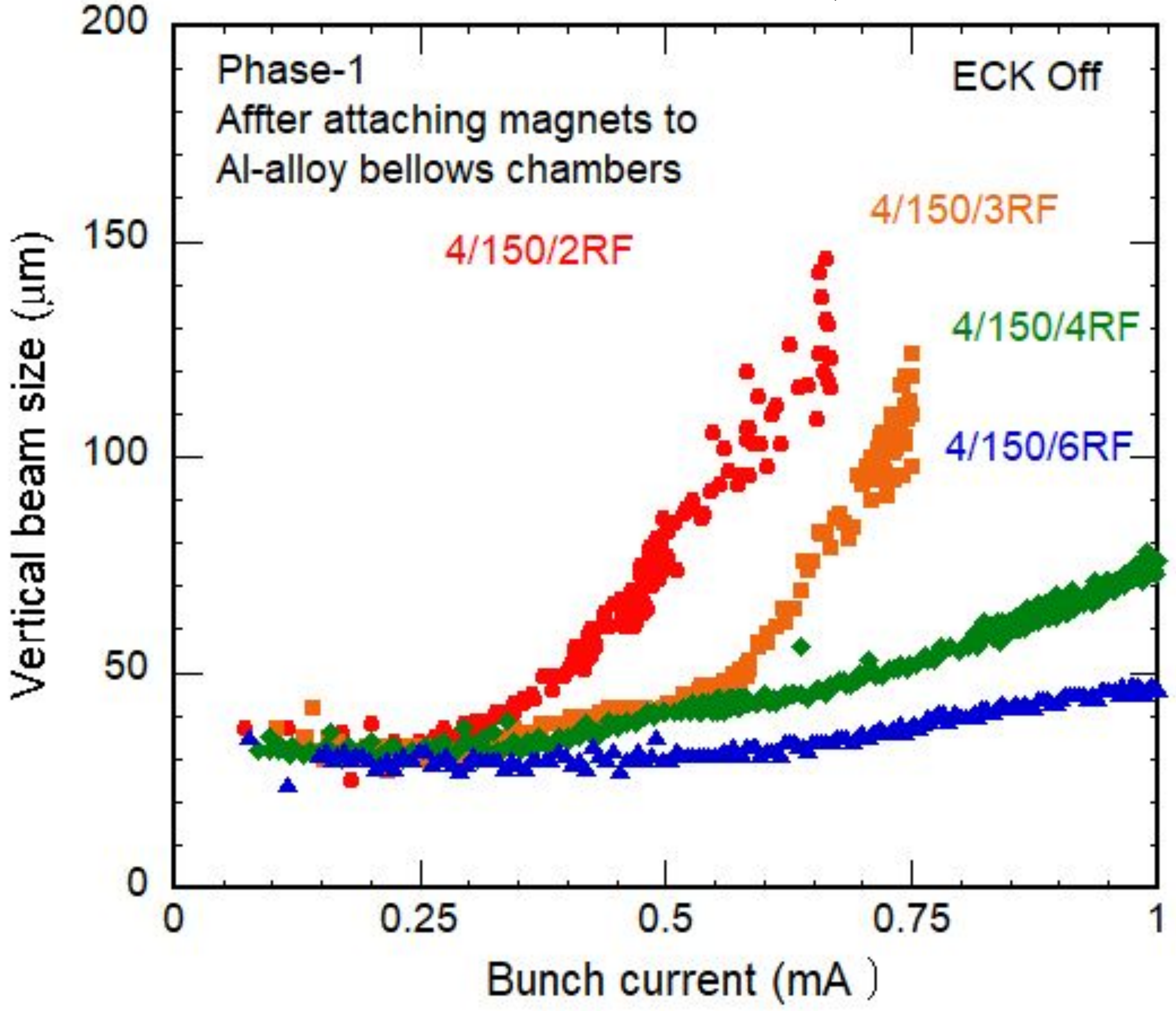
Y. Suetsugu et al.



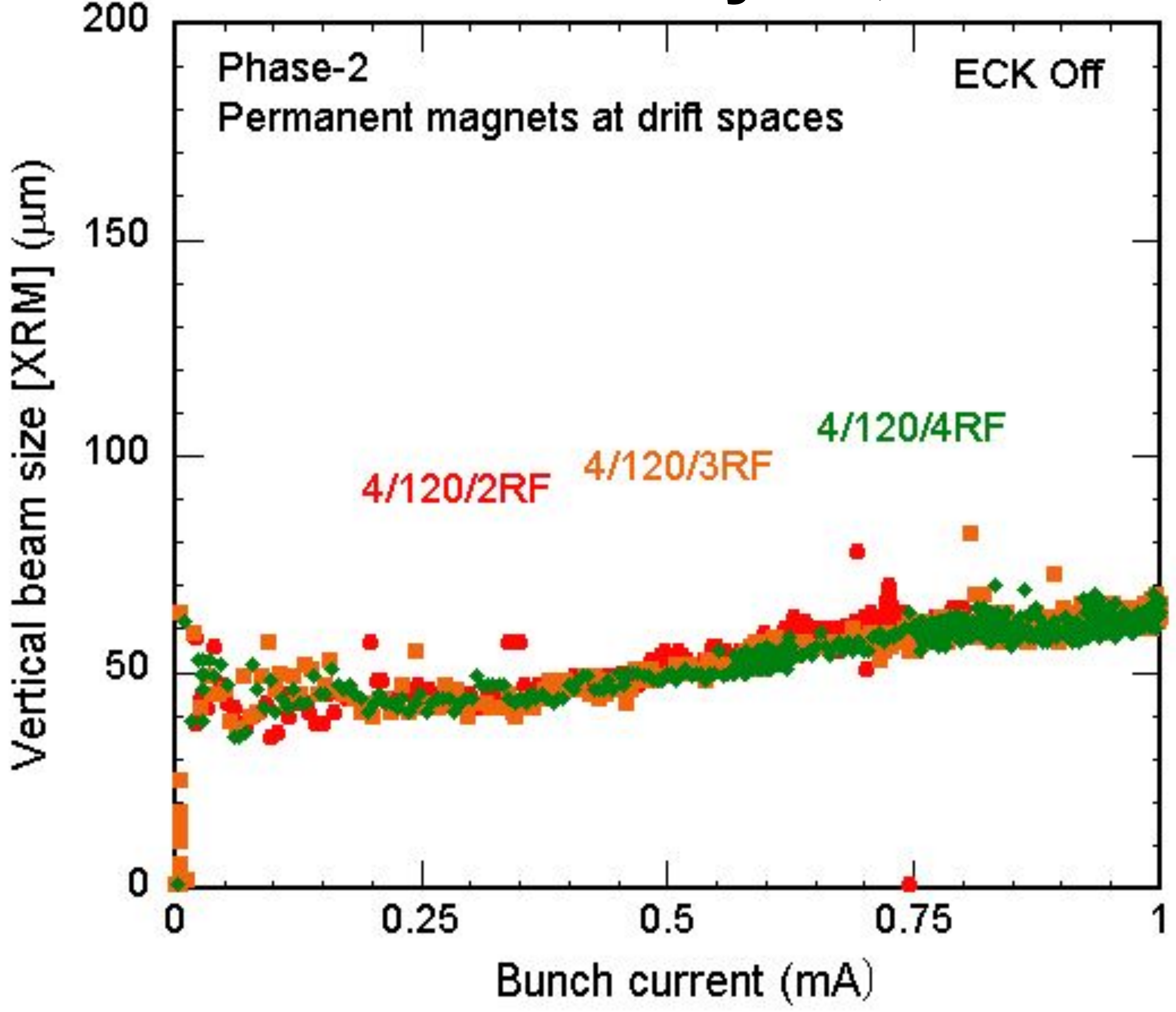
Threshold is much improved.
more than twice of 0.2 mA/bunch/RF bucket

Mode of CBI changes and the growth rate is reduced.

Phase 1: June 9, 2016



Phase 2: July 12, 2019

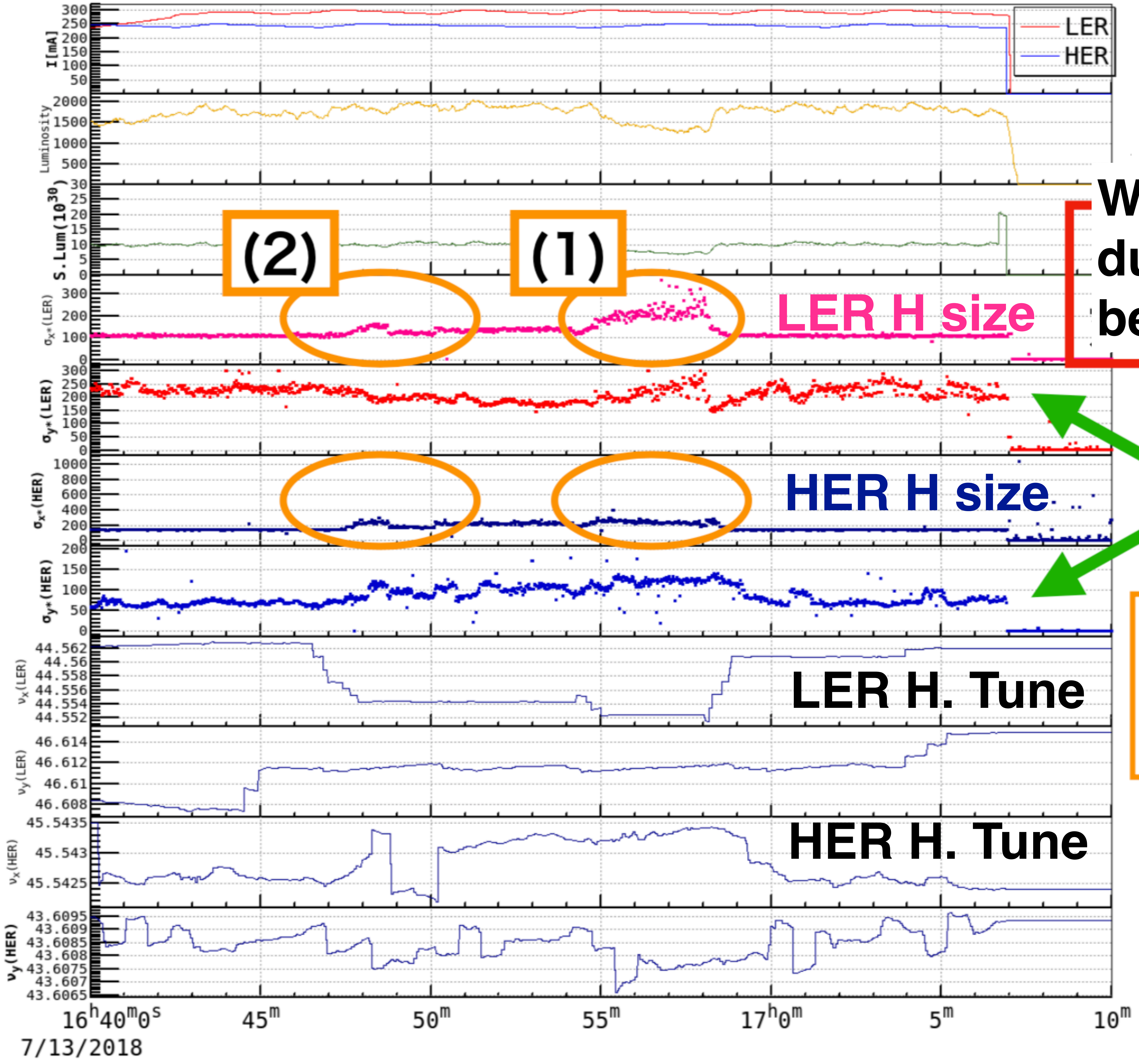


no blowup

Horizontal Coherent Beam-Beam Instability

K. Hirosawa, K. Ohmi

Horizontal tune dependence



We observed beam blowup due to horizontal beam-beam instability

Vertical beam size

Beam Blowup (1)

$$\nu_x(LER) = .552$$
$$\nu_x(HER) = .543$$

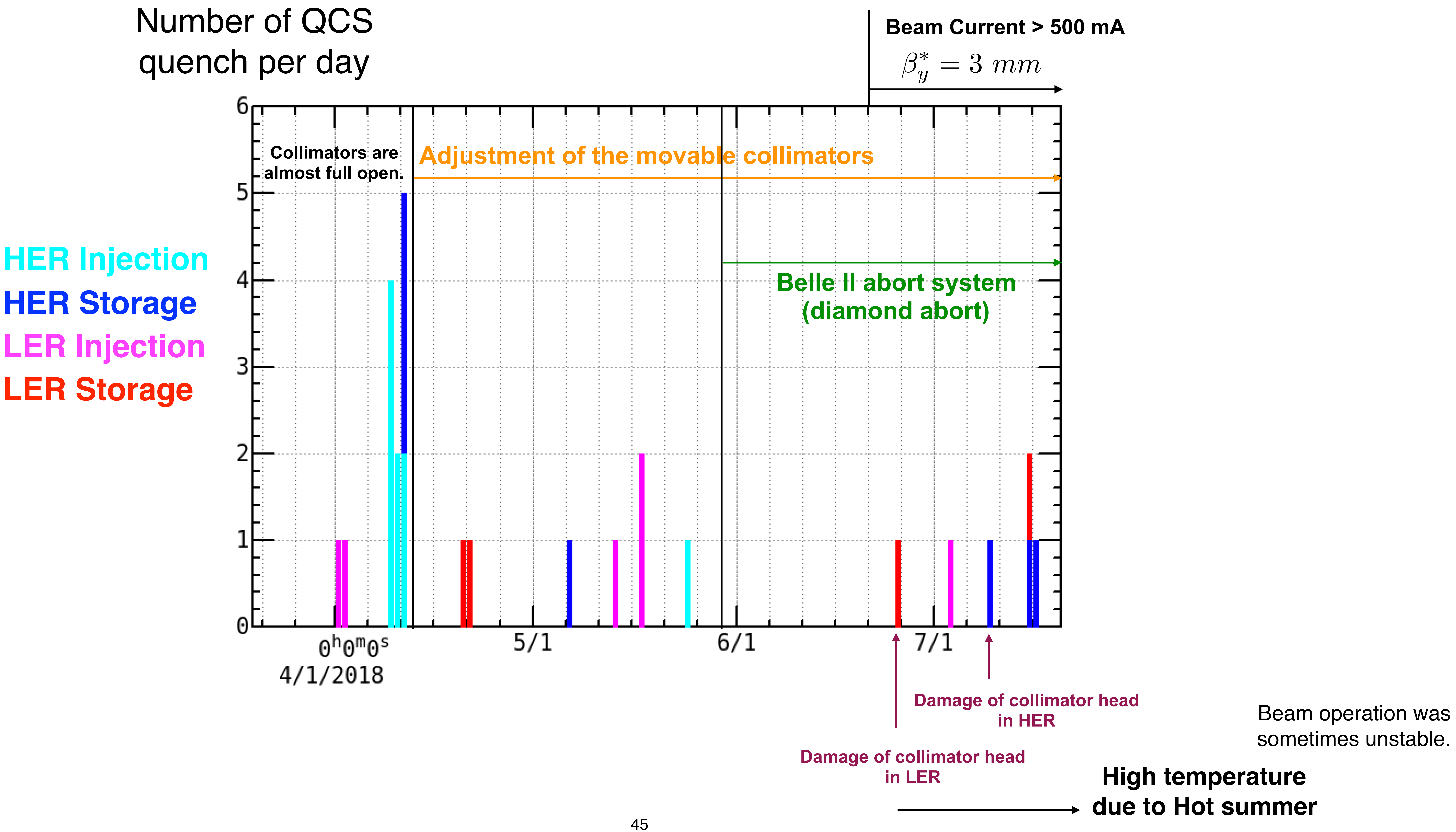
synchrotron tune is

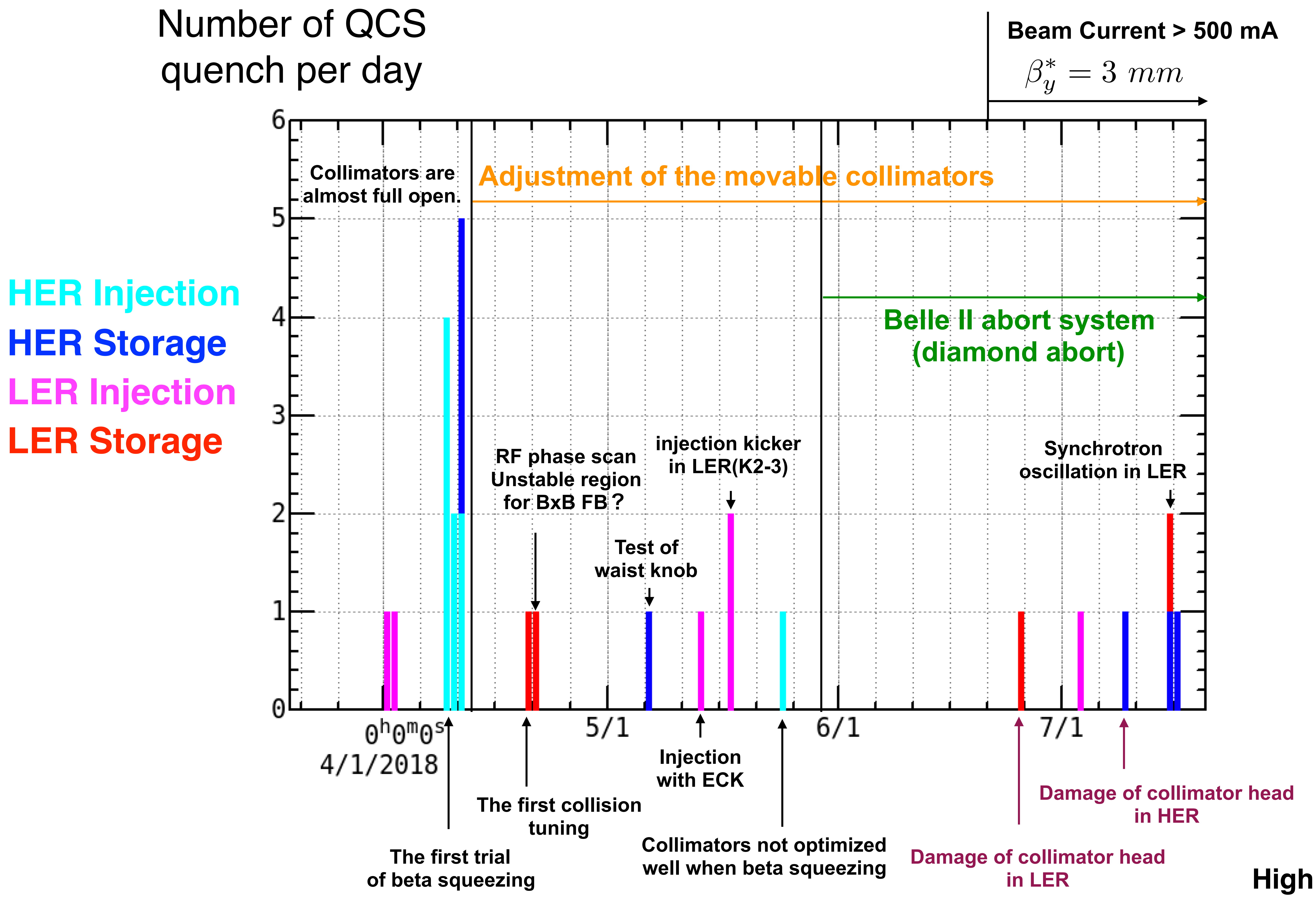
$$\nu_s(LER) = 0.0213$$
$$\nu_s(HER) = 0.0261$$

$$\nu_x(HER) + 2\nu_s(LER) = \text{int.}$$
$$\nu_x(LER) + 2\nu_s(HER) = \text{int.}$$

Unexpected Events

- QCS quench
  - QCS quench during beam injection
    - Beam loss in the vertical direction due to XY coupling before optics corrections. QCS is the smallest physical aperture.
    - Movable collimators and Belle II fast diamond abort system could avoid QCS quenches.
  - QCS quench during beam storage
    - Movable collimators can avoid most of QCS quenches.
    - There are few unknown events.
      - Hit collimator head due to longitudinal instability, dust trapping, … ?
      - Large orbit change when the beam is aborted ?


Number of QCS
quench per day
Beam Current > 500 mA
$\beta_y^* = 3\ mm$
HER Injection
HER Storage
LER Injection
LER Storage
Collimators are
almost full open.
Adjustment of the movable collimators
Belle II abort system
(diamond abort)
6
5
4
3
2
1
0
0h0m0s
4/1/2018
5/1
6/1
7/1
Damage of collimator head
in HER
Damage of collimator head
in LER
Beam operation was
sometimes unstable.
High temperature
due to Hot summer



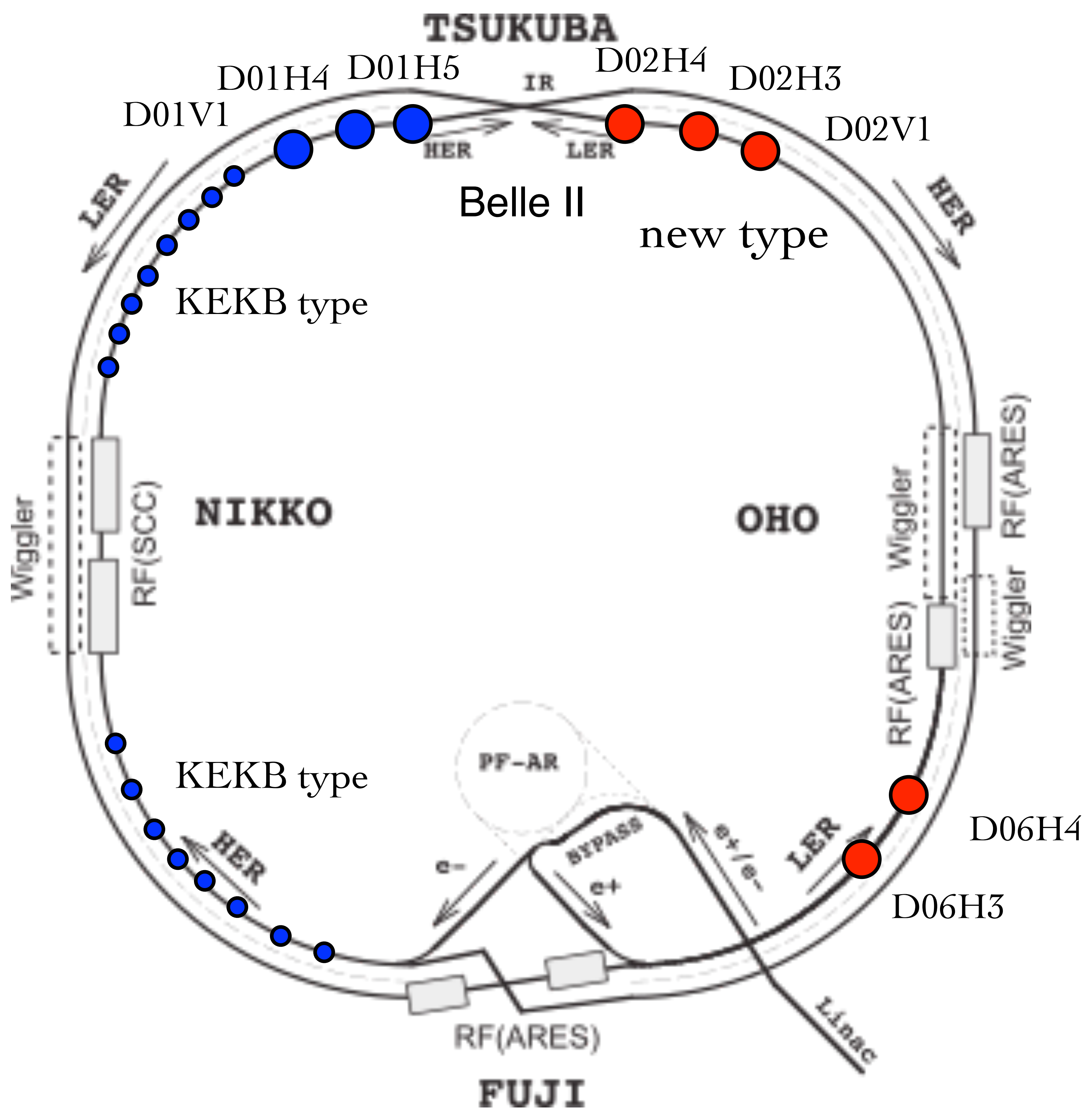
Beam operation was
sometimes unstable.

High temperature due to Hot summer

Damage of Movable Collimator (Head)

Reduce beam background

Compromise lifetime, injection, and detector background.

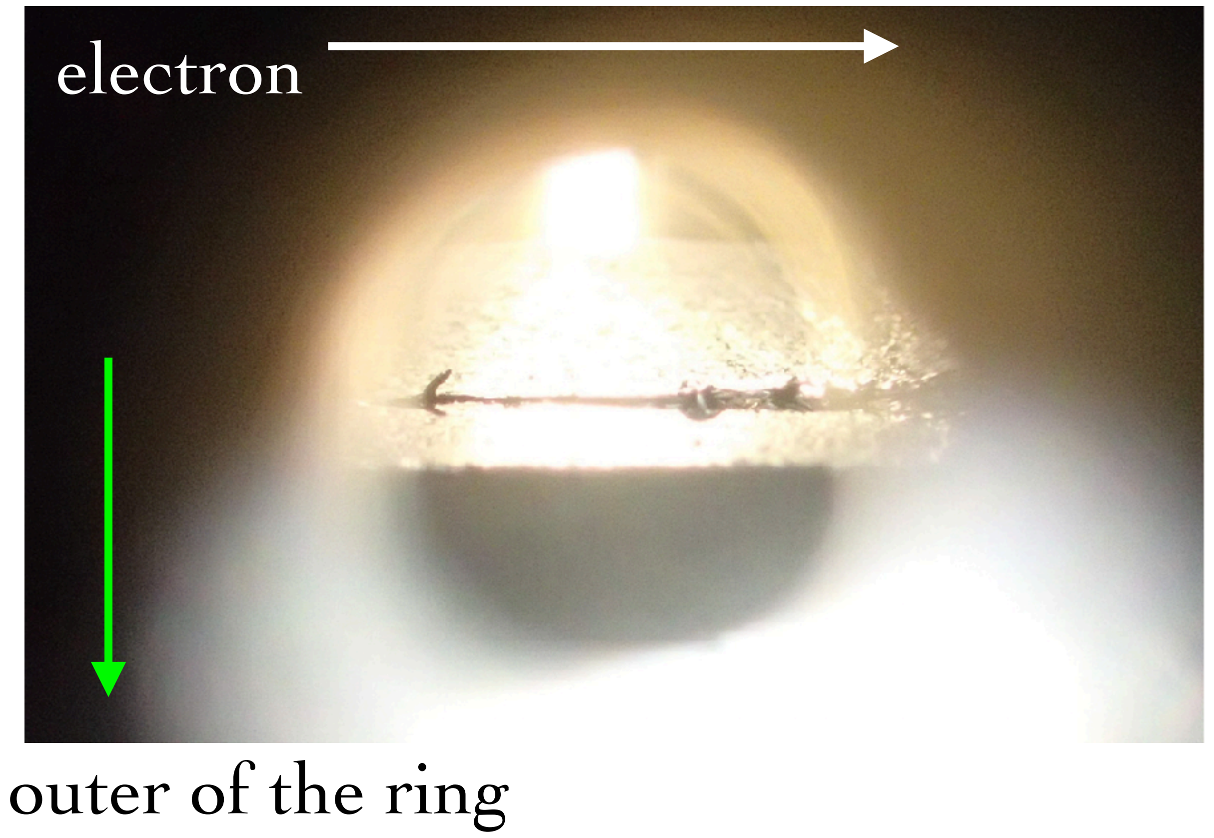


Number of movable collimators is small in LER. Especially, only one in the vertical.

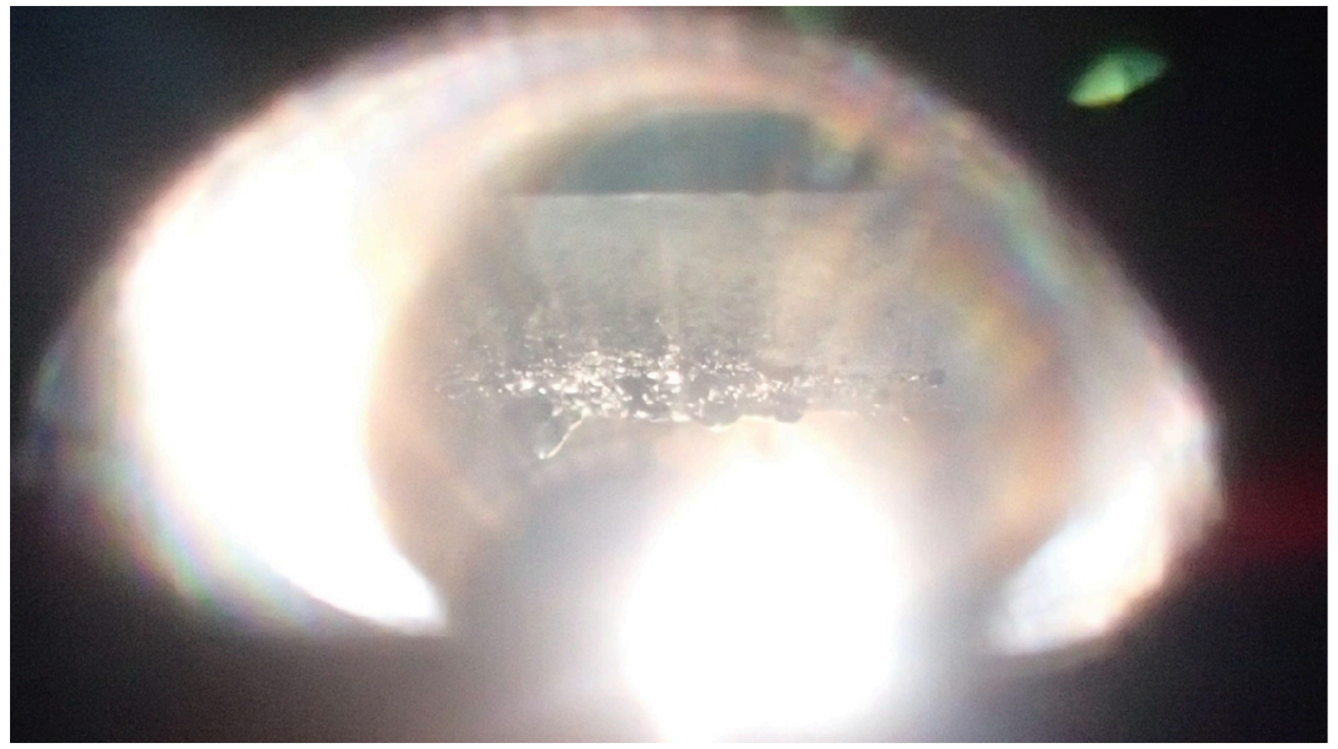
Vertical Collimator

LER

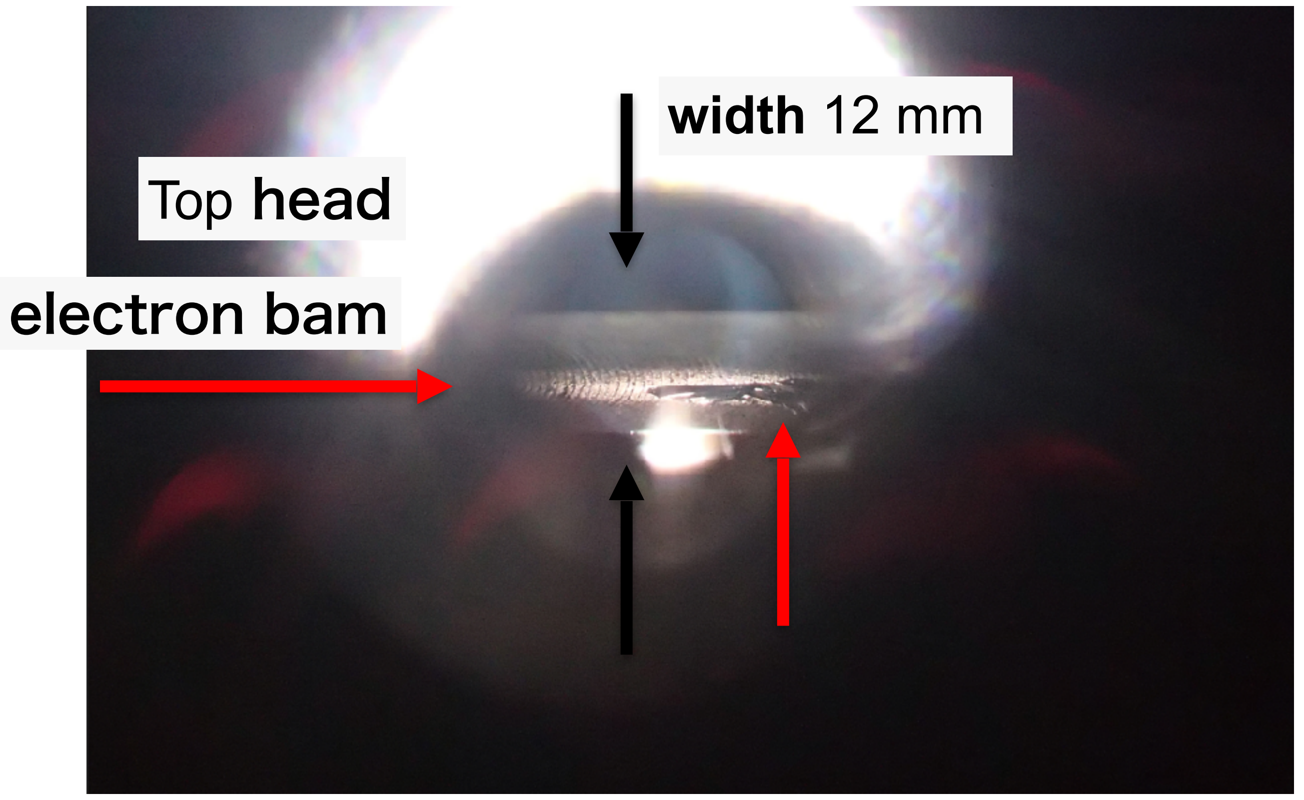
Bottom



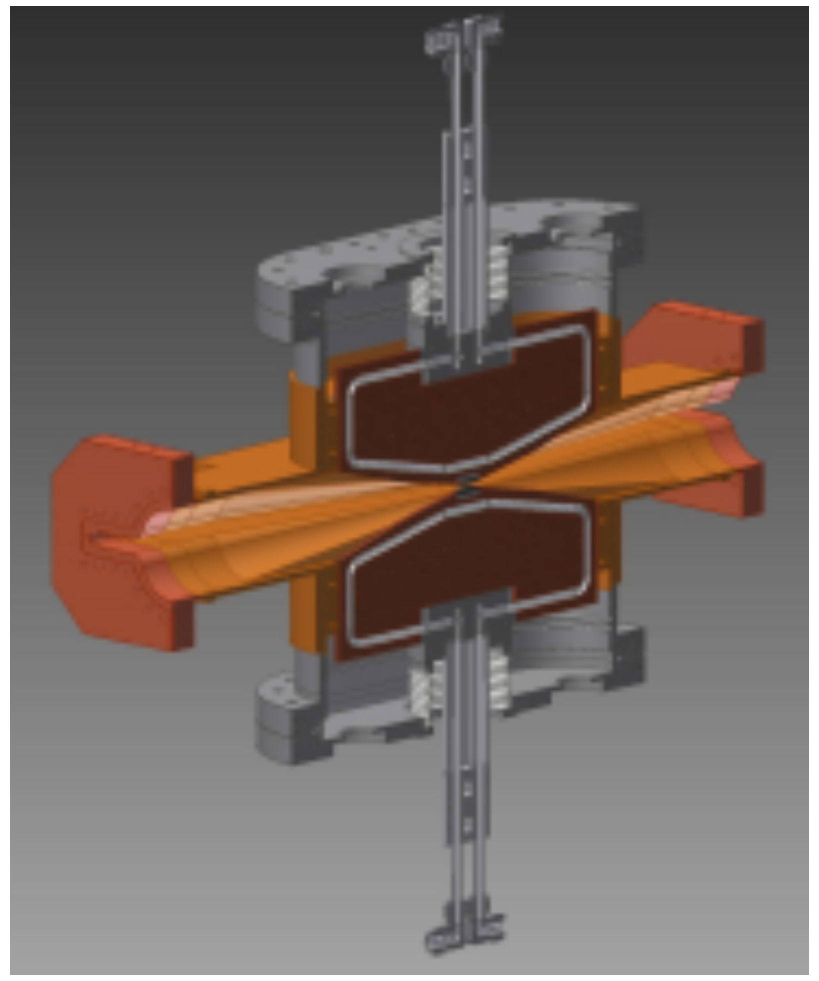
Top



HER

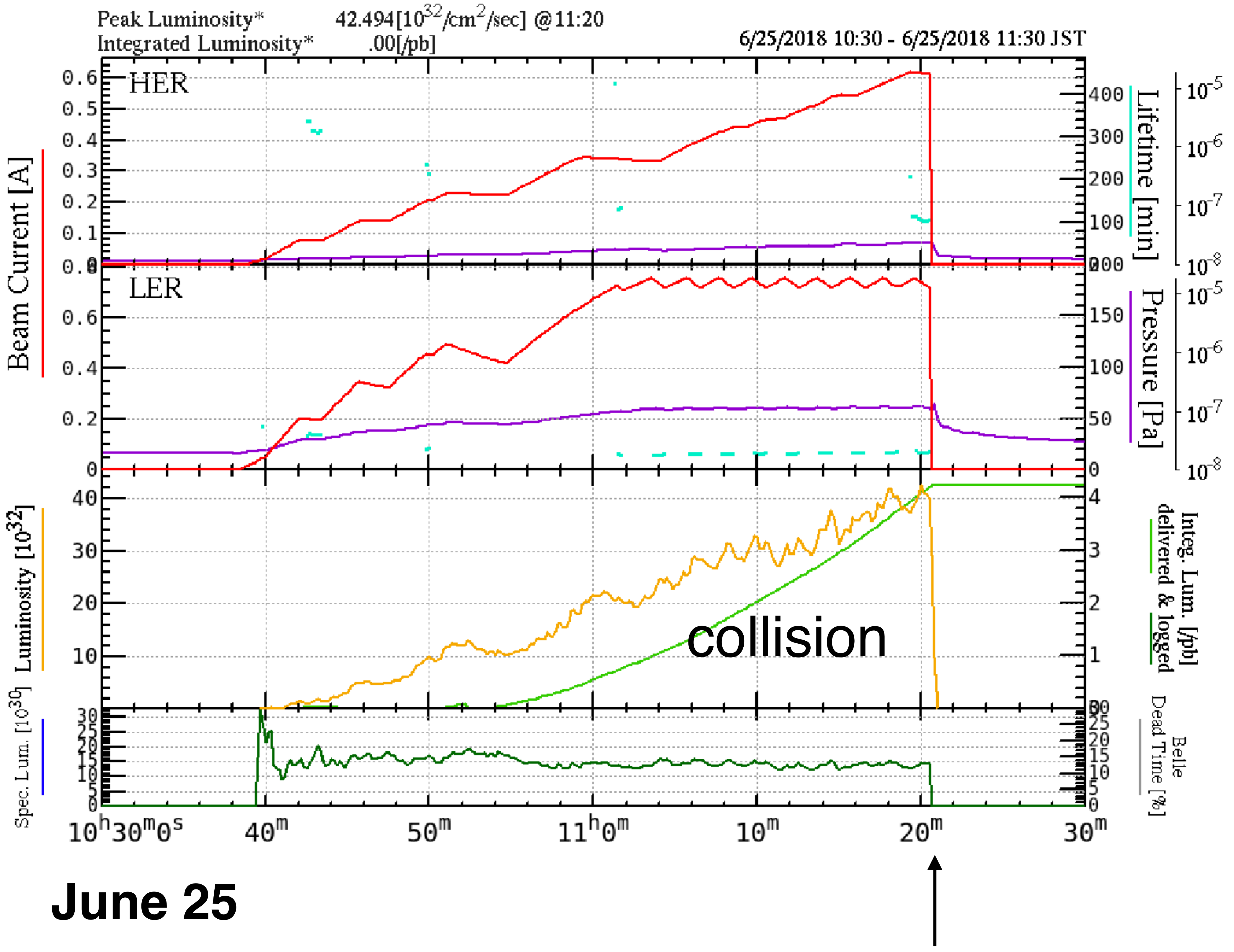


New collimator (SLAC type)



Y. Suetsugu, T. Ishibashi, S. Terui

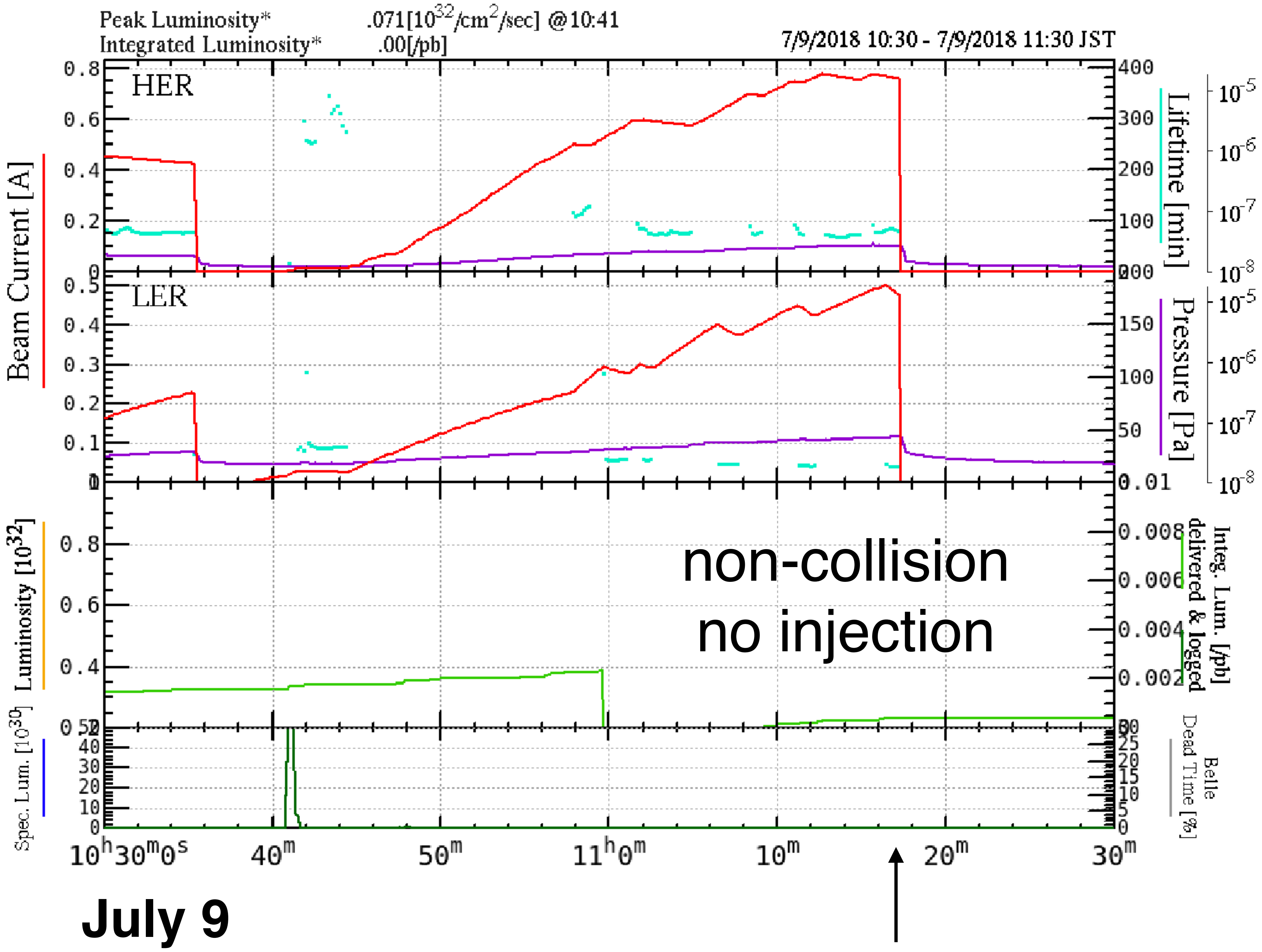
Collimator Damage



June 25

QCS quench (LER and HER)

LER vertical collimator has damage.
Vacuum pressure rise was observed in the vicinity of the collimator.



July 9

QCS quench (HER)

HER vertical collimator has damage.
Vacuum pressure rise was observed in the vicinity of the collimator.
No bunch oscillation with beam loss

H. Nakayama

Additional LER V mask at phase3 start

- Possible location: D06V1/2, D03V1/2
- D06 is favored than D03
  - showers from D03V1/V2 might reach IR
  - betatron tunes on D06 collimators can be adjusted upon request, by changing straight section optics
- D06V1 or D06V2? → D06V2 is favored
  - nu_y(D06V2) – nu_y(D02V1) is closer to ~0.25
    → D06V2 can more effectively stop injection BG from various phases, while D06V1 can reduce D02V1 loss
  - D06V2 beta_y is smaller than D06V1
    → "nominal width" is smaller, but no problem at beta_y*=3mm or 1mm. It might be a problem at 0.27mm (d=1.1mm), but we cannot close >=2 collimators anyway at 0.27mm, due to TMC instability

beta_y*=3mm

Phase2.1.7	beta_y	nu_y	Δnu	d[mm]
PMD06V1	61.43	28.90	+0.04	6.7
PMD06V2	19.24	30.54	+0.18	3.7
PMD03V1	16.96	41.47	+0.11	3.5
PMD03V2	16.96	42.63	+0.27	3.5
PMD02V1	**21.57**	**44.93**	+0.07	4.0
QC1RP995	**260.7**	**46.36**	+0	13.5

beta_y*=0.27mm

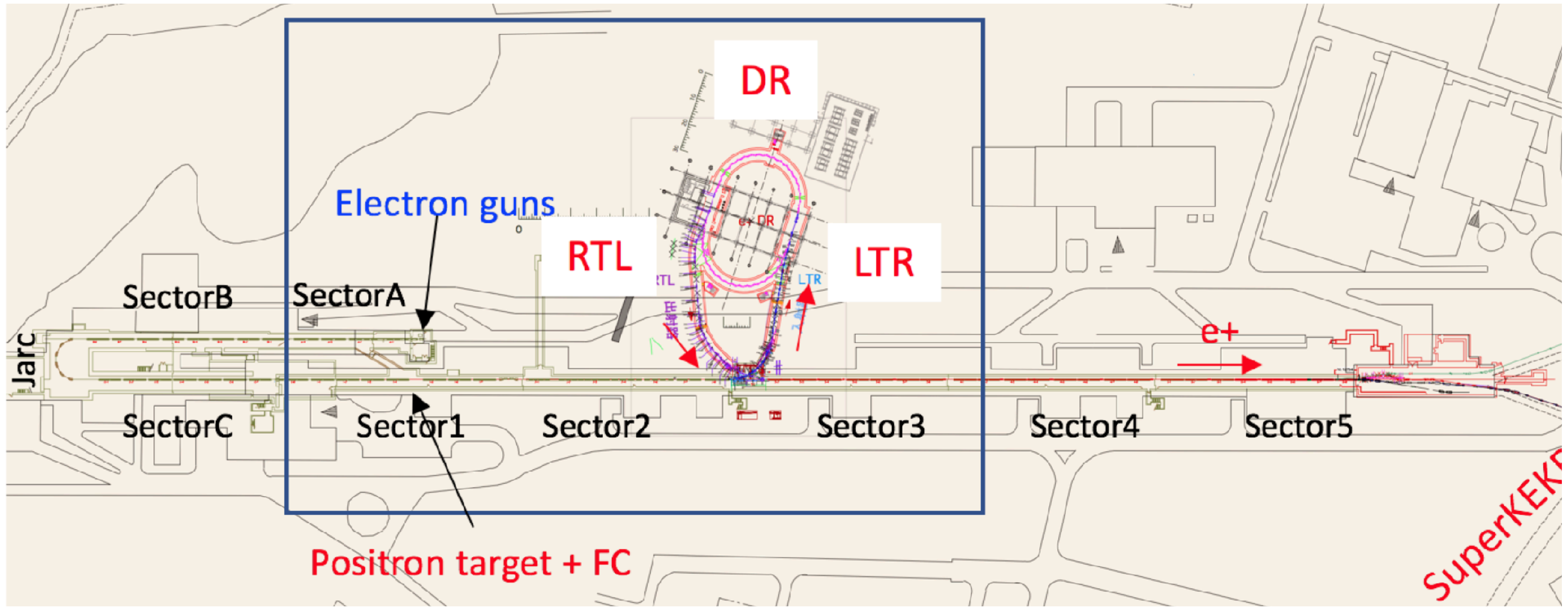
Phase3	beta_y	nu_y	Δnu	d[mm]
PMD06V1	61.43	28.92	+0.10	2.0
PMD06V2	19.24	30.56	+0.24	1.1
PMD03V1	16.96	41.49	+0.17	1.1
PMD03V2	16.96	42.66	+0.34	1.1
PMD02V1	**111.75**	**44.83**	+0.01	2.7
QC1RP995	**2794.00**	**46.32**	+0	13.5

LER: D02H1, D02H2, D03H1, D06V2, D06H4→D06H1

HER: D01H3

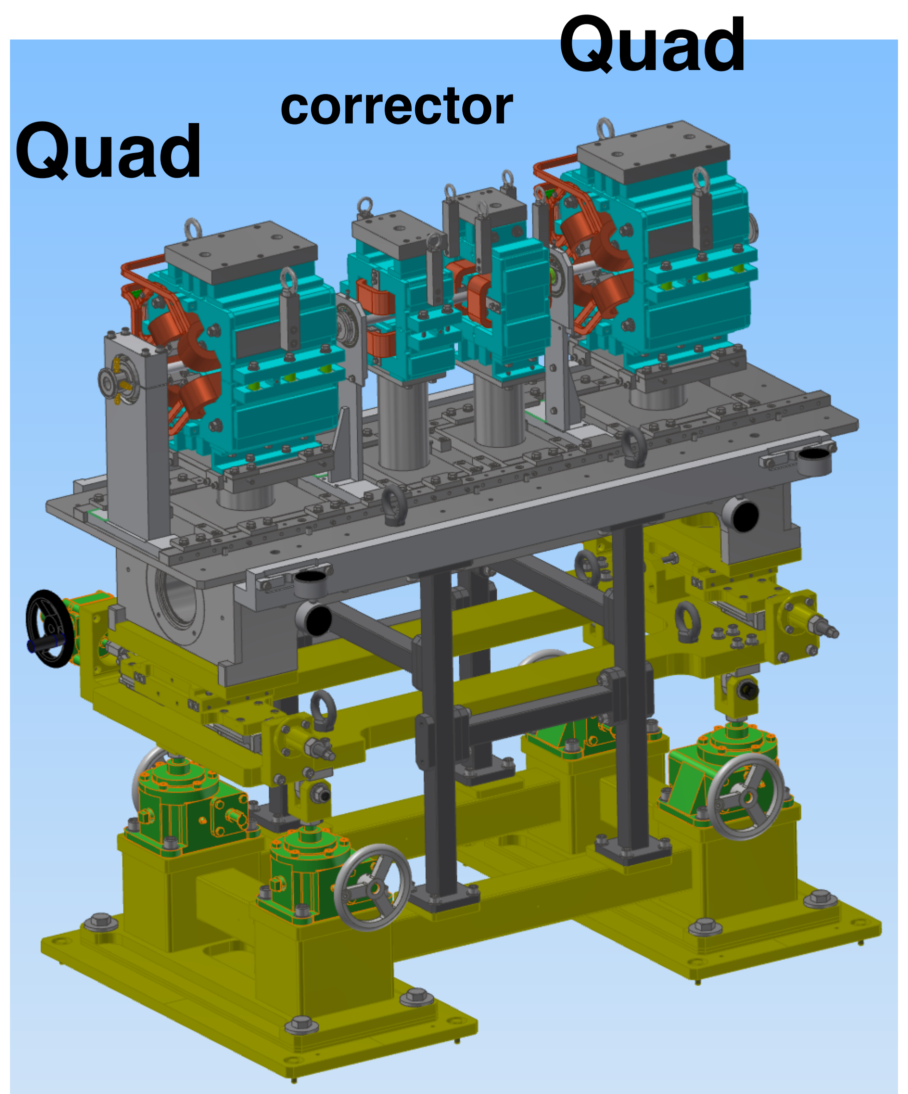
Beam loss control becomes more flexible.

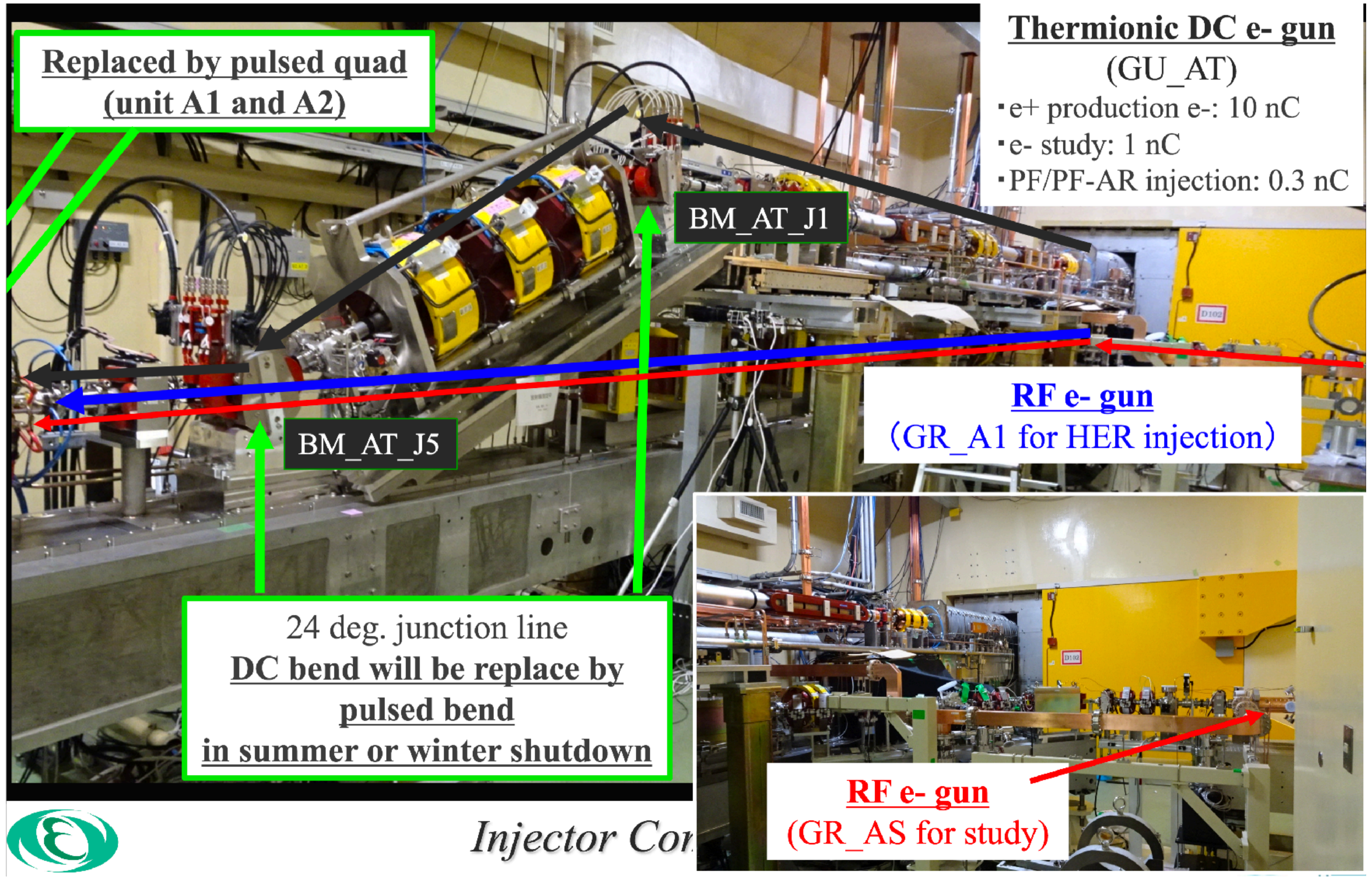
Injection System



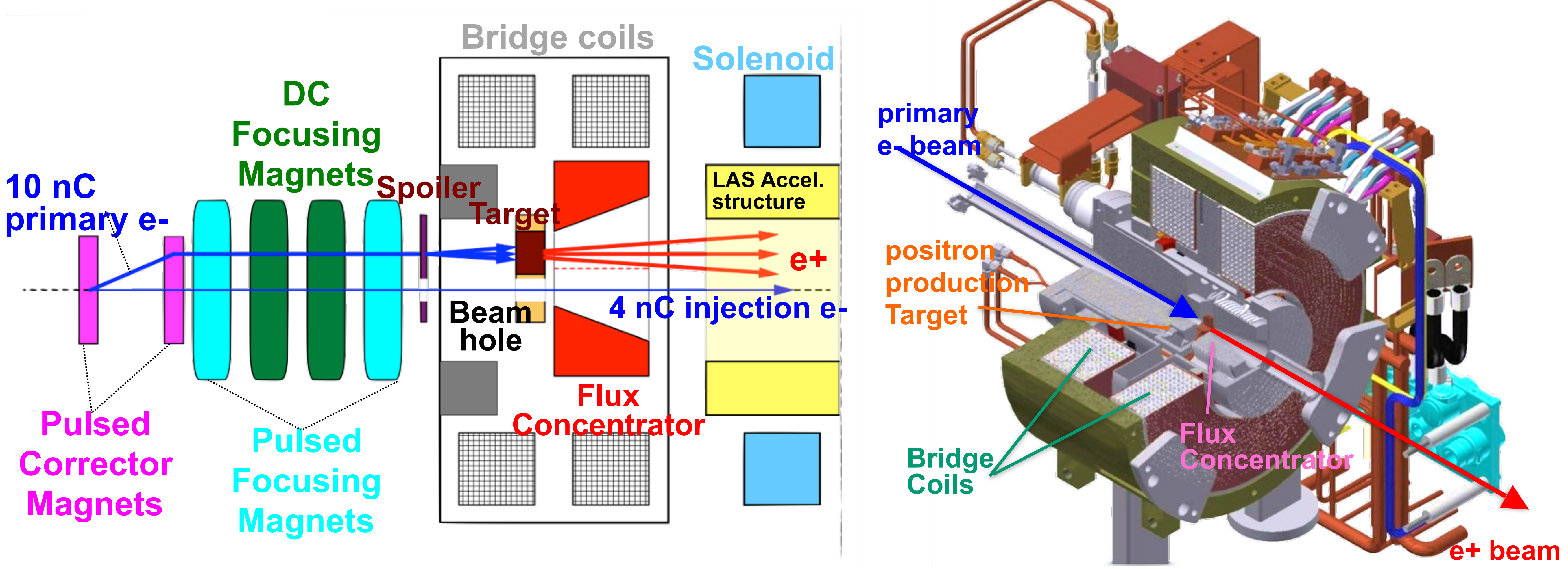
PF 2.5 GeV e-
PF-AR 6.5 GeV e-
LER 4 GeV e+
HER 7 GeV e-

Pulse magnets
(3 - 5 sector)





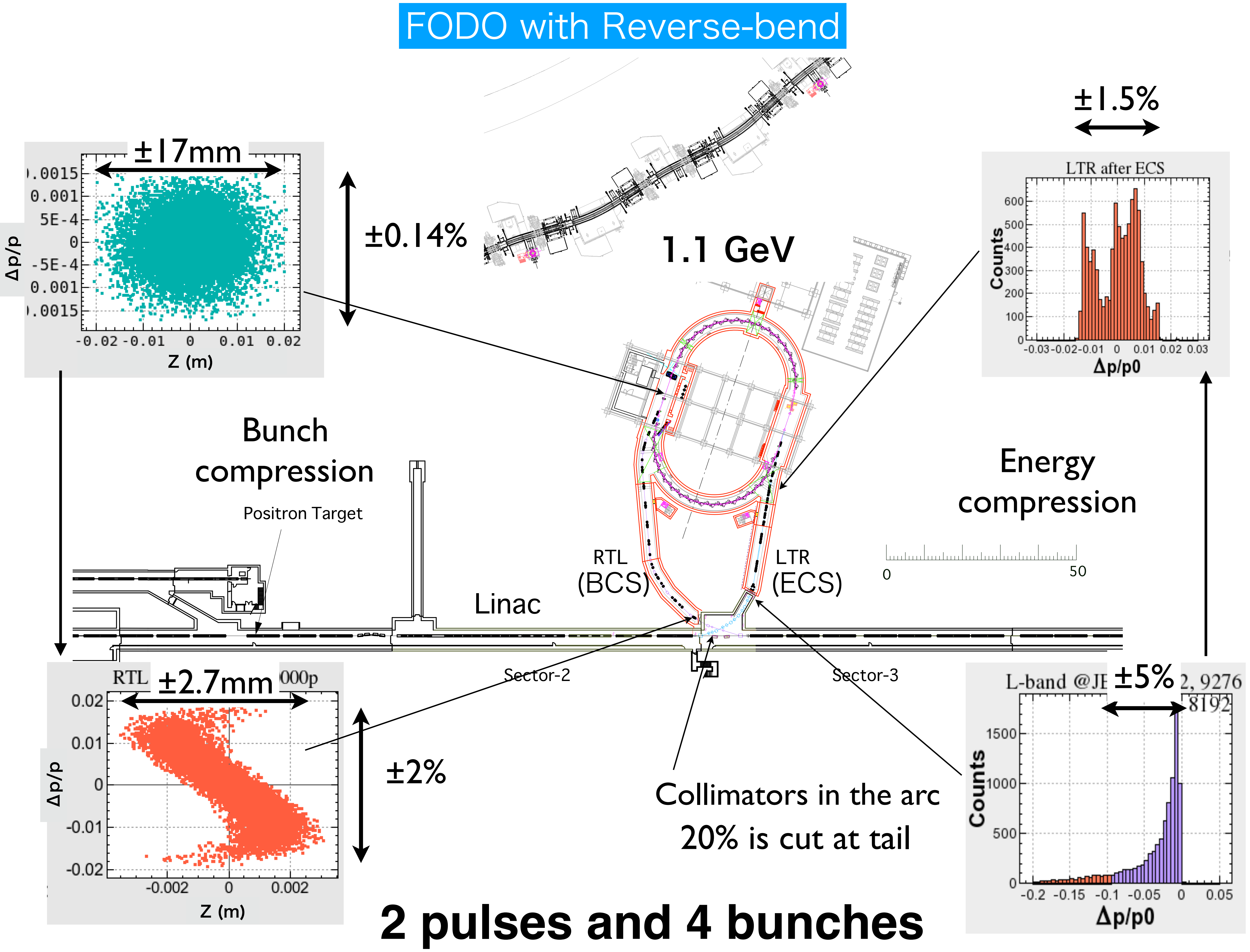
Positron generator

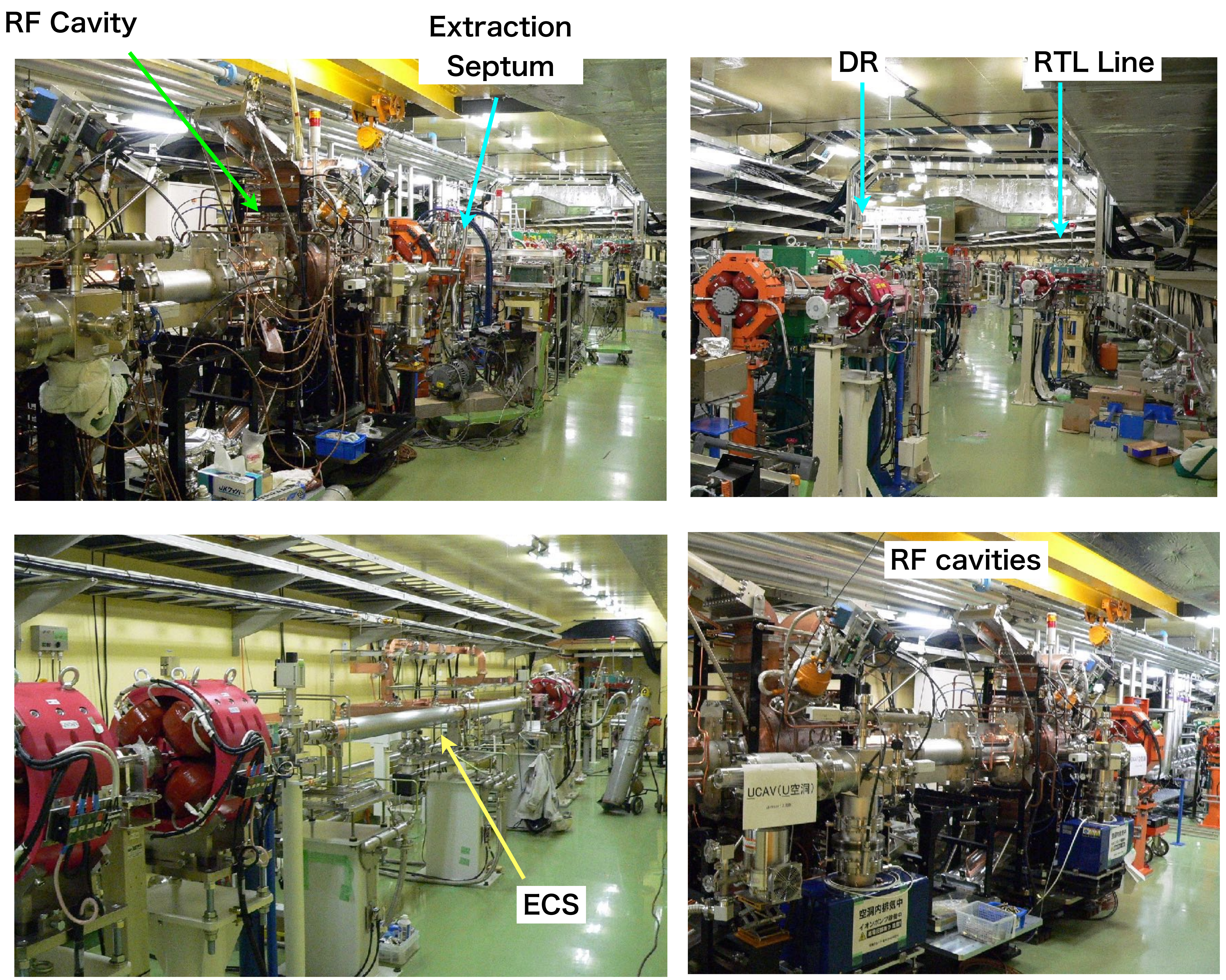


There is a hole where electrons passing through.

Positron Damping Ring

The commissioning was started on February 8.





M. Kikuchi et al.

2 pulses and 4 bunches

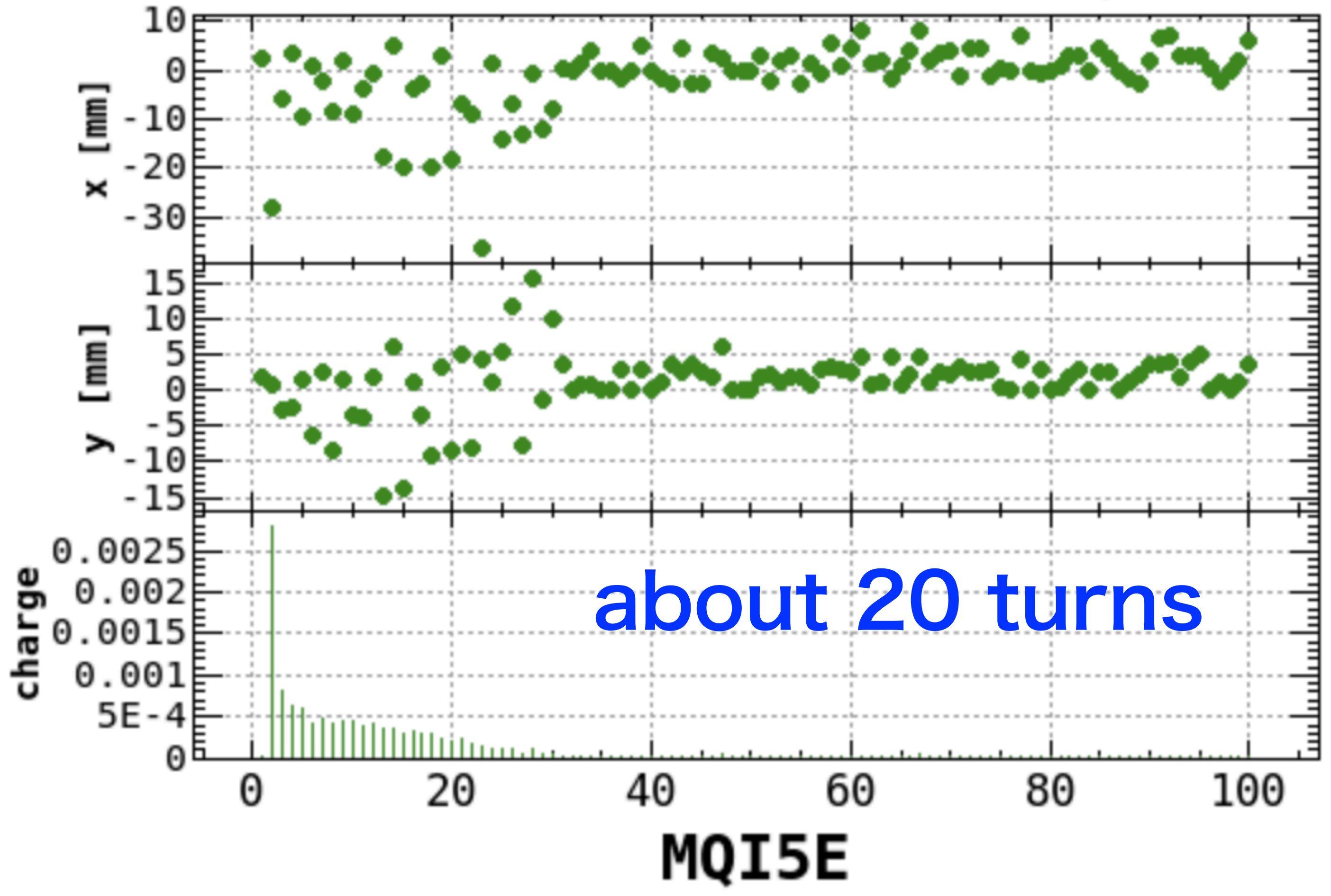
ε_x 30 nm ← 1300 nm

τ_x/τ_s 11.5 msec/5.9 msec

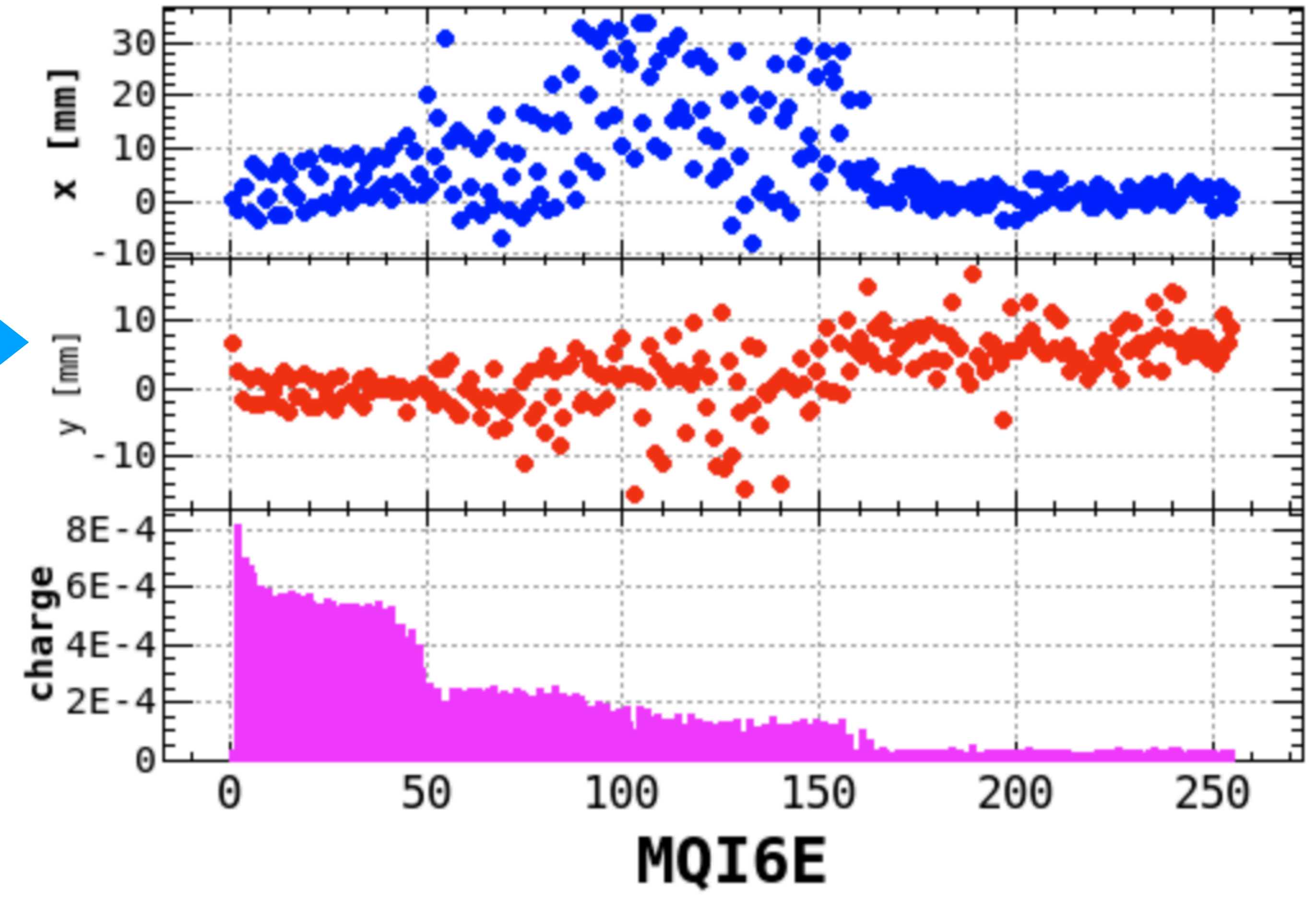
σ_z 6.7 mm

First Beam Storage in HER

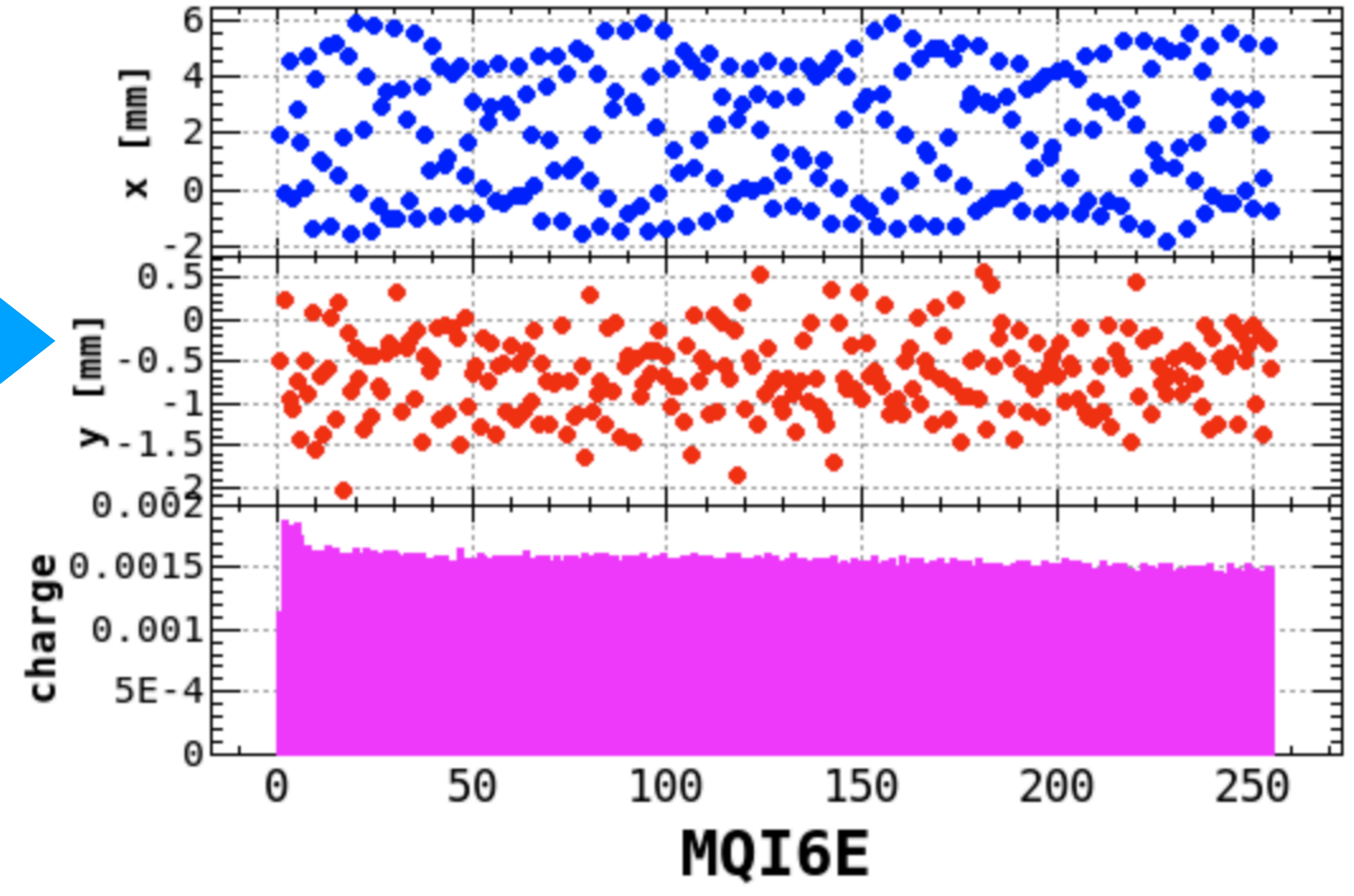
RF cavity OFF 3/19 23:47

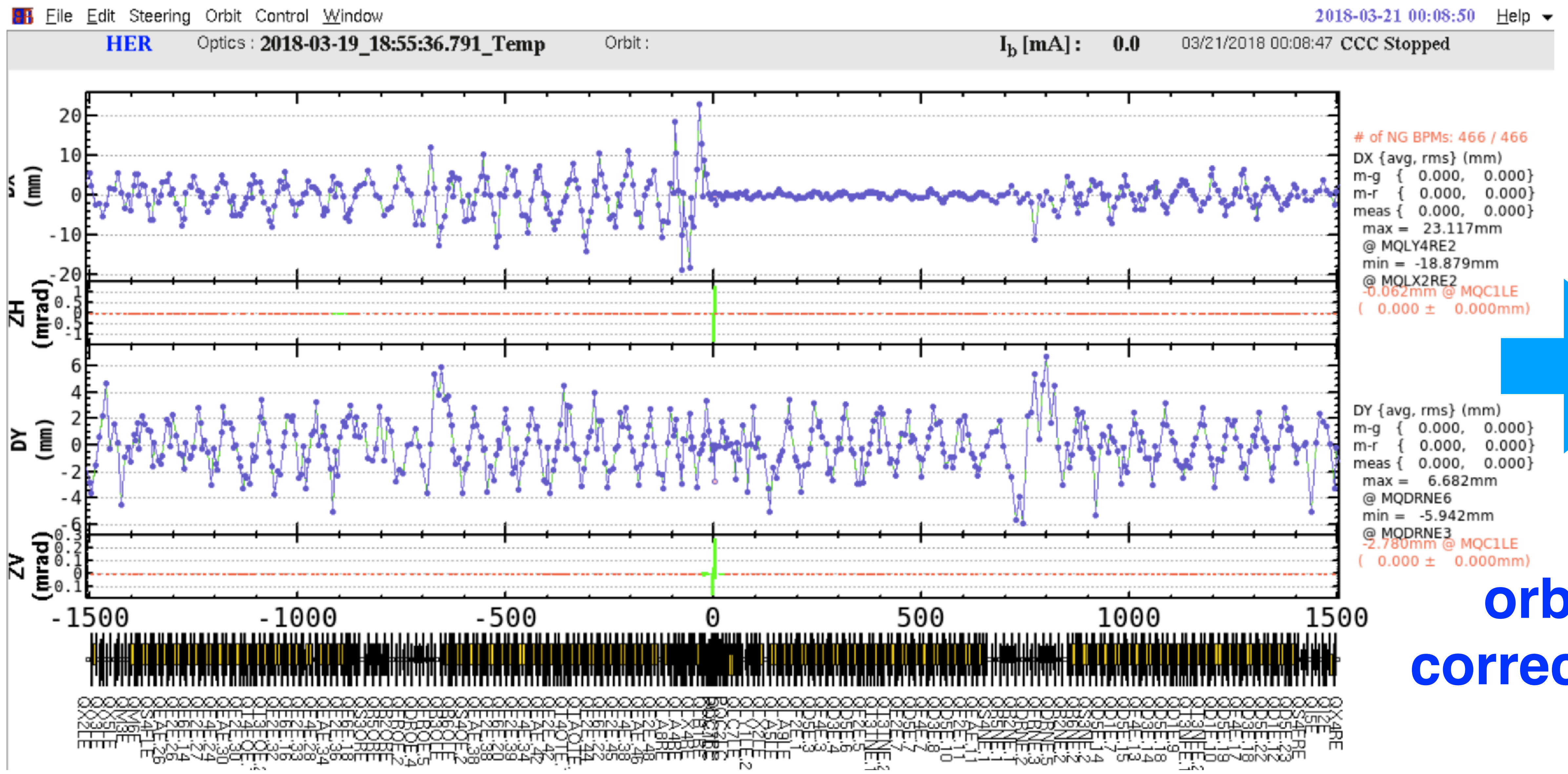


RF cavity ON 3/21 00:08

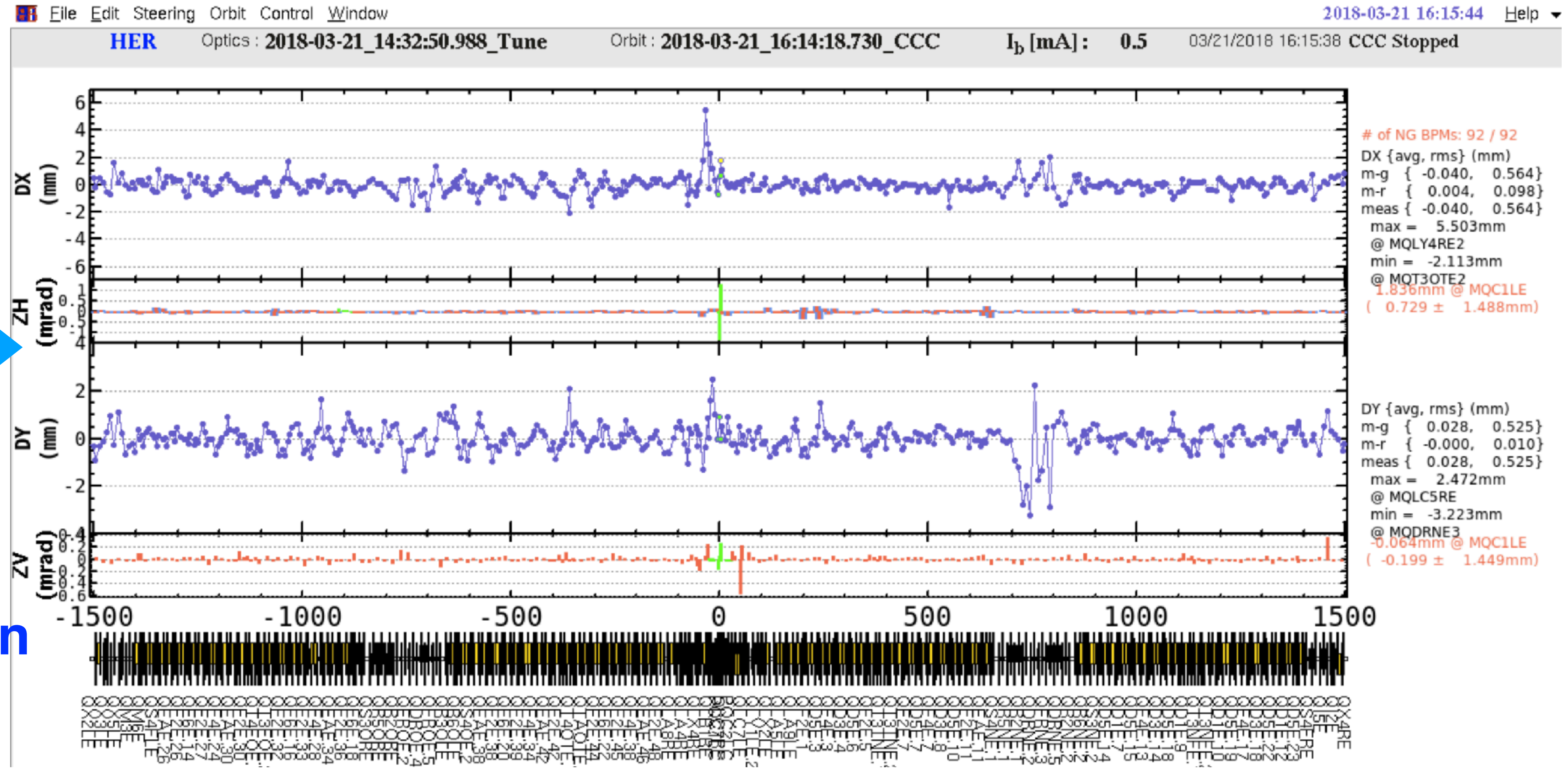


TbT BPM near injection point





orbit correction

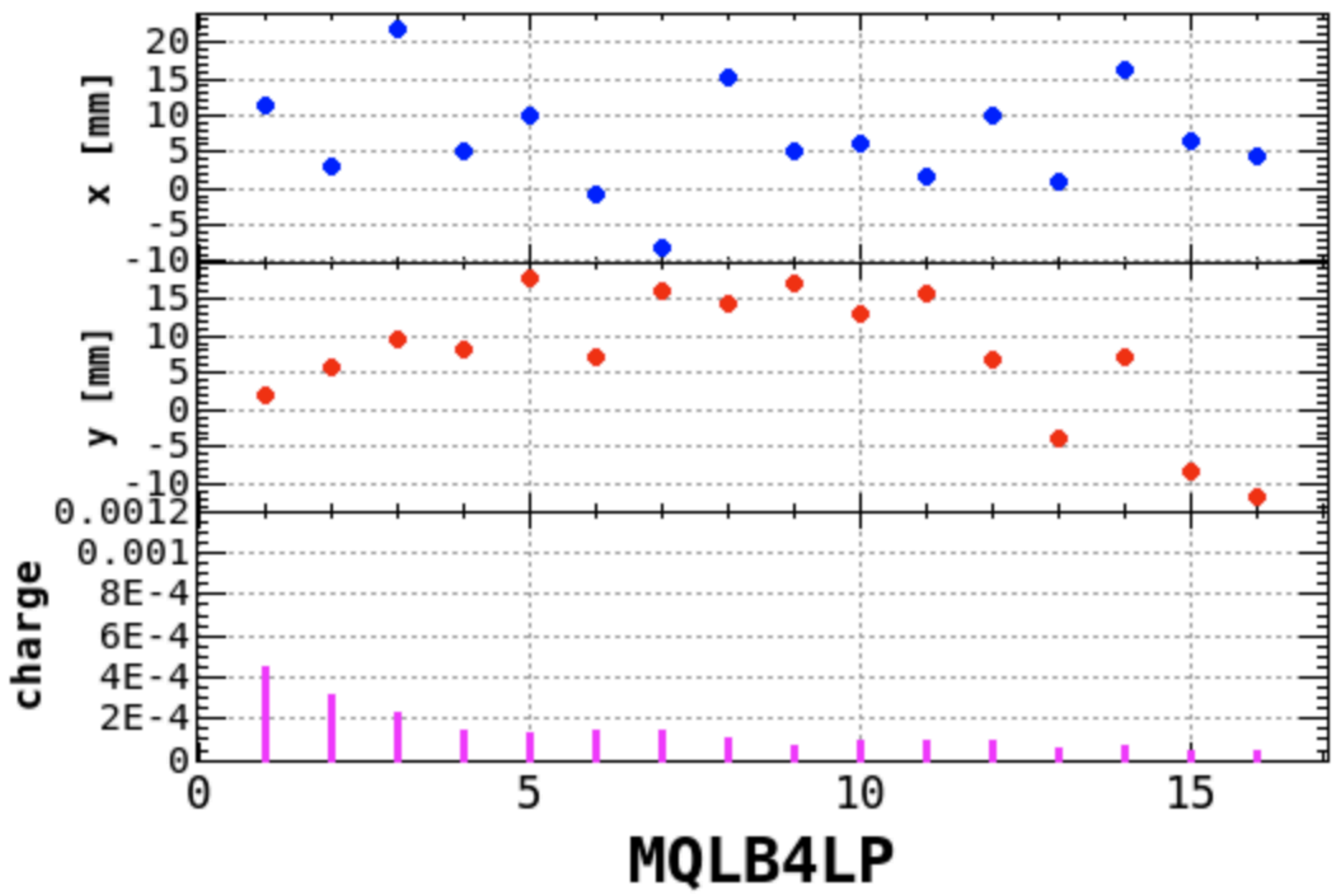


Only one of six kickers worked in the initial injection tuning in HER.

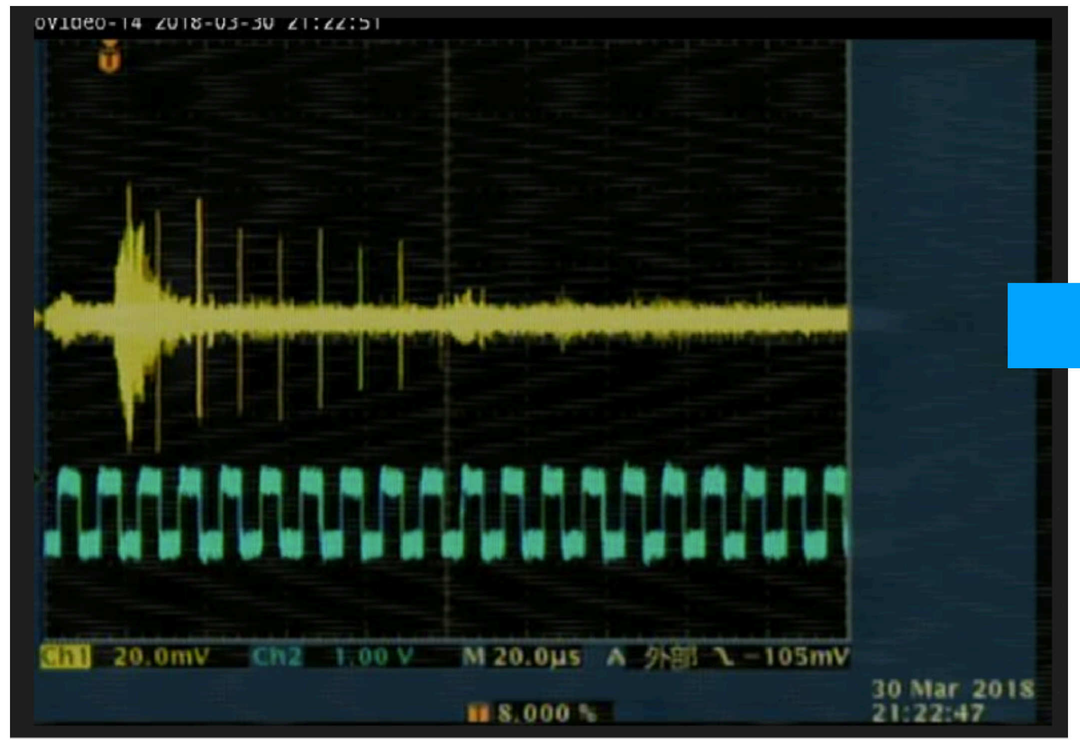
Polarities of vertical corrector in QCS were wrong.

First Beam Storage in LER

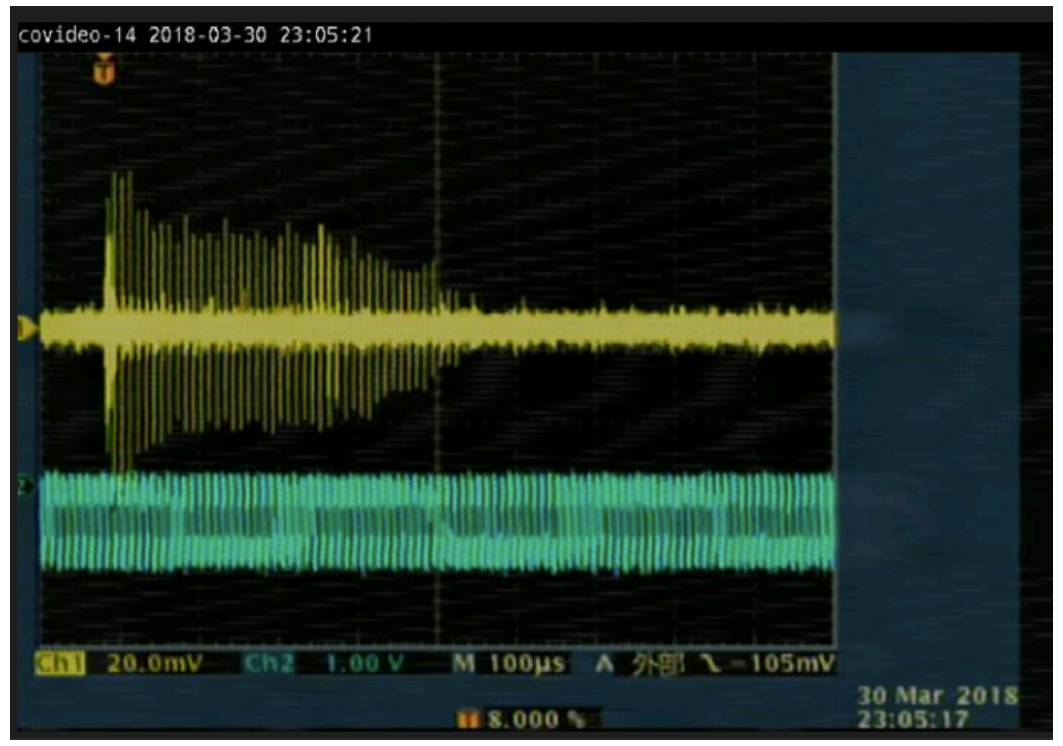
RF cavity OFF 3/30 21:26

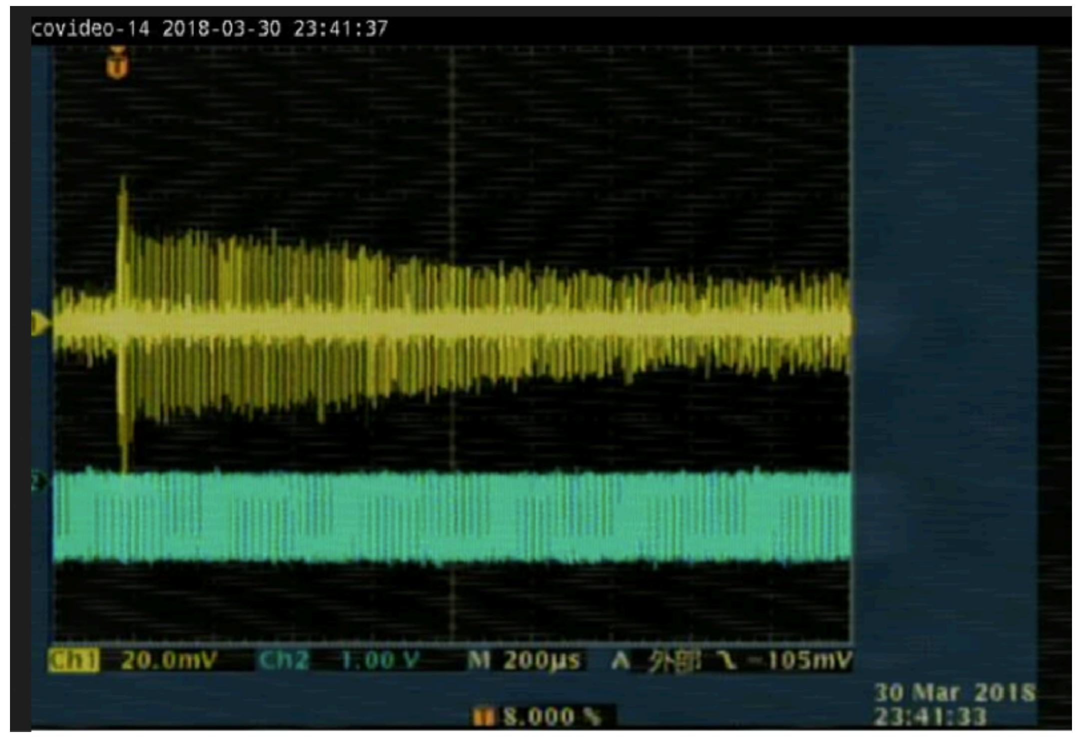


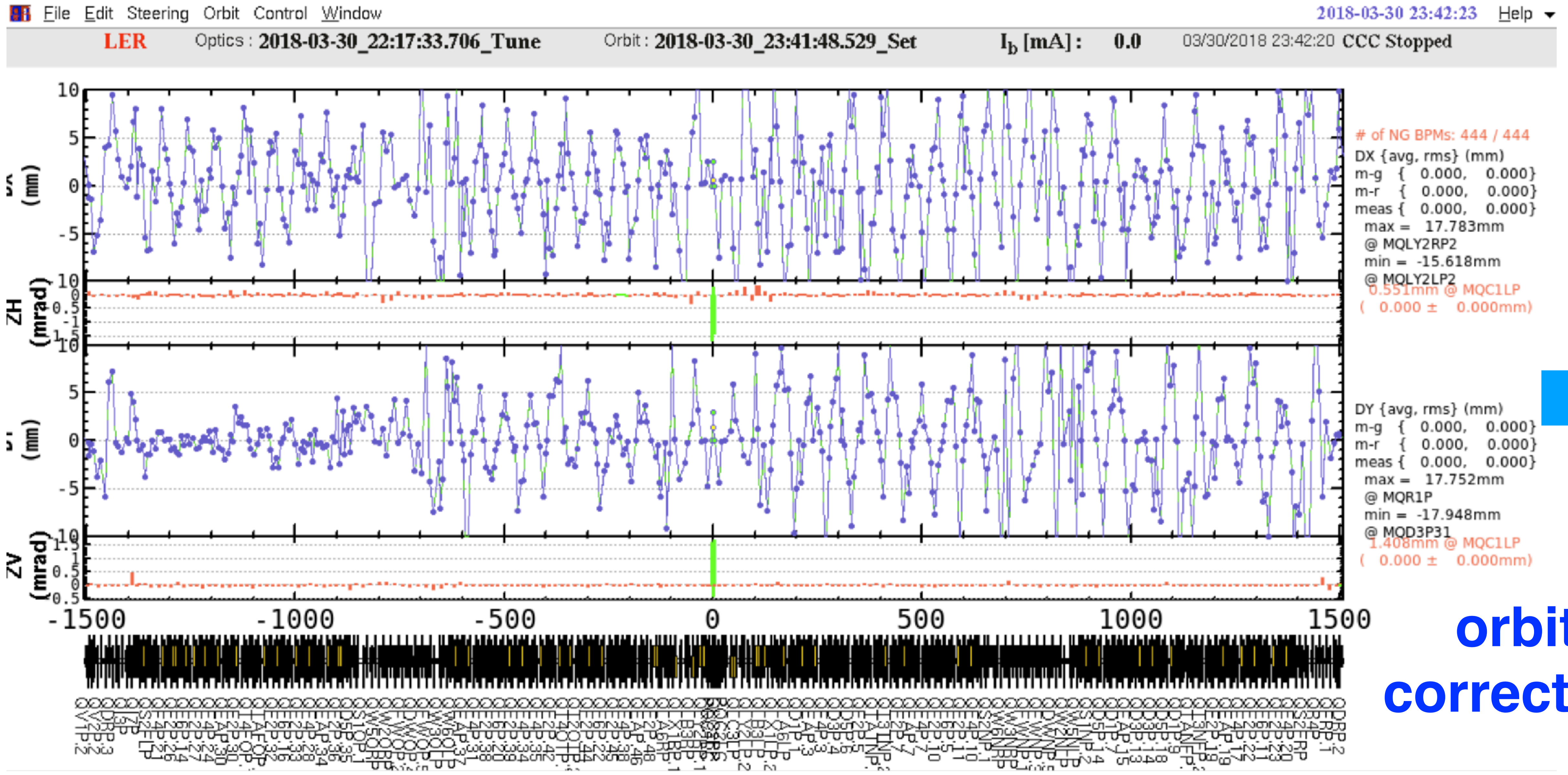
CT



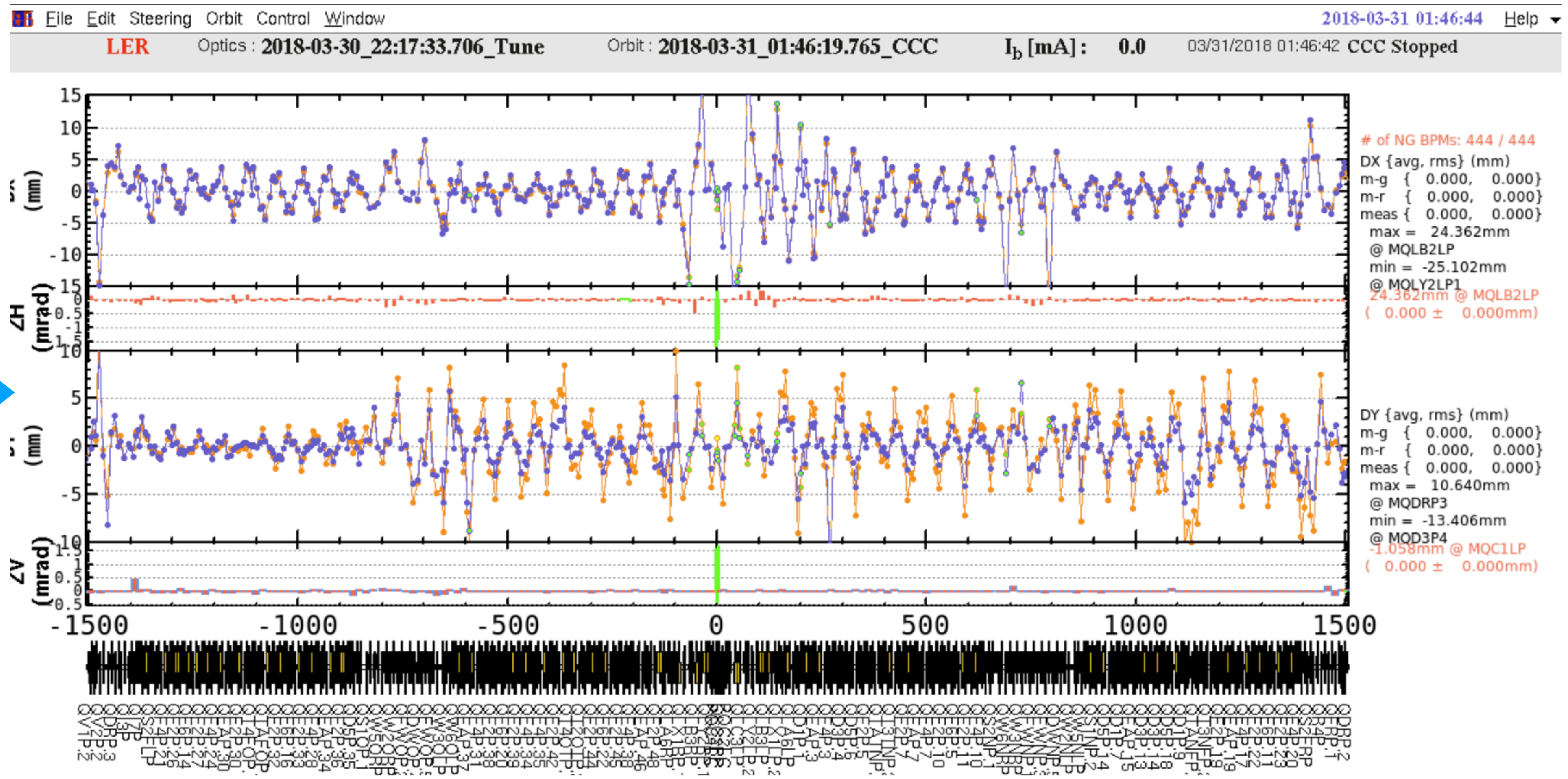
RF cavity ON 3/30 23:41







orbit correction



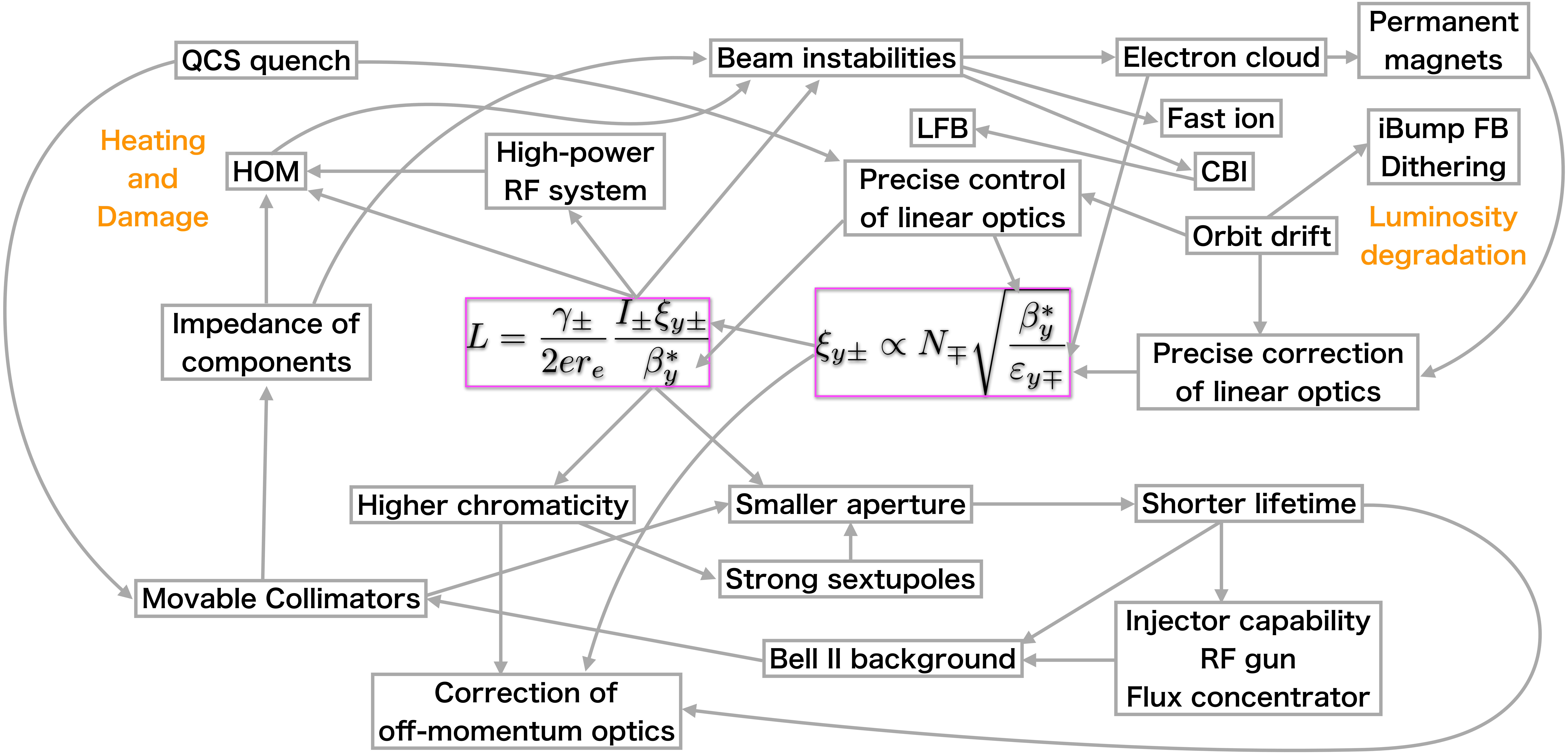
Wiring between skew quads(QC2RP) and horizontal corrector(QC2LP) in LER was swapped.

Summary of Phase 2 Commissioning

Spaghetti Diagram

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

$$\xi_{y\pm} \propto N_{\mp}\sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}$$



QCS quench
Beam instabilities
Electron cloud
Permanent magnets
Fast ion
LFB
iBump FB Dithering
CBI
Heating and Damage
HOM
High-power RF system
Precise control of linear optics
Orbit drift
Luminosity degradation
Impedance of components
$L = \frac{\gamma_\pm}{2er_e} \frac{I_\pm \xi_{y\pm}}{\beta_y^*}$
$\xi_{y\pm} \propto N_\mp \sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}$
Precise correction of linear optics
Higher chromaticity
Smaller aperture
Shorter lifetime
Strong sextupoles
Movable Collimators
Injector capability
RF gun
Flux concentrator
Bell II background
Correction of off-momentum optics

Summary

- Verification of nano-beam scheme
    - luminosity tuning at β_y^*=3 mm (x10 final value)
    - 2.26 x 10^{33} $cm^{-2}s^{-1}$ at I_{LER} = 270 mA (n_b=395) → 10^{34} $cm^{-2}s^{-1}$ at I_{LER} = 1080 mA (n_b = 1576)
    - Beam-beam parameter reaches 0.02.
    - Peak luminosity is 5.55 x 10^{33} $cm^{-2}s^{-1}$ (LER: 790 mA).
- Max beam current is 860 mA, 800 mA in HER.

Verification of nano-beam ☺

Beta squeezing 😀

Luminosity performance 🙁

I_{LER} < 1 [A] 🙁

- QCS quench issue (unexpected). Movable collimators can avoid most of quenches.
- We will install additional collimators until Phase 3 operation to control beam loss and/or background.
- We will fight interference of beam-beam and lattice nonlinear to improve luminosity performance in Phase 3.

Appendix

Luminosity performance and β_y^* squeezing

Geometrical luminosity is low before beam-beam blowup occurs.

Global optics correction is good and measured vertical beam size is enough small from X-Ray Monitor.

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

Waist position Δs and vertical dispersion affect vertical beam size at IP.

In case of $\Delta s = 0$, r_1 and r_2, η_y make beam size large.

QCS error is localized. **<u>Rotation error</u>**

Physical Coordinate XY coupling Normal coordinate

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

$$M_4 = R M_{2\times2} R^{-1} \qquad M_{2\times2} = \begin{pmatrix} M_u & 0 \\ 0 & M_v \end{pmatrix}$$

$$\mu^2 + (r_1 r_4 - r_2 r_3) = 1$$

Luminosity performance and β_y^* squeezing

Geometrical luminosity is low before beam-beam blowup occurs.

Global optics correction is good and measured vertical beam size is enough small from X-Ray Monitor.

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

Waist position Δs and vertical dispersion affect vertical beam size at IP.

In case of $\Delta s = 0$, r_1 and r_2, η_y make beam size large.

QCS error is localized. **Rotation error** **→ r_1 and r_2 shoudl be zero. QCS can make it.**

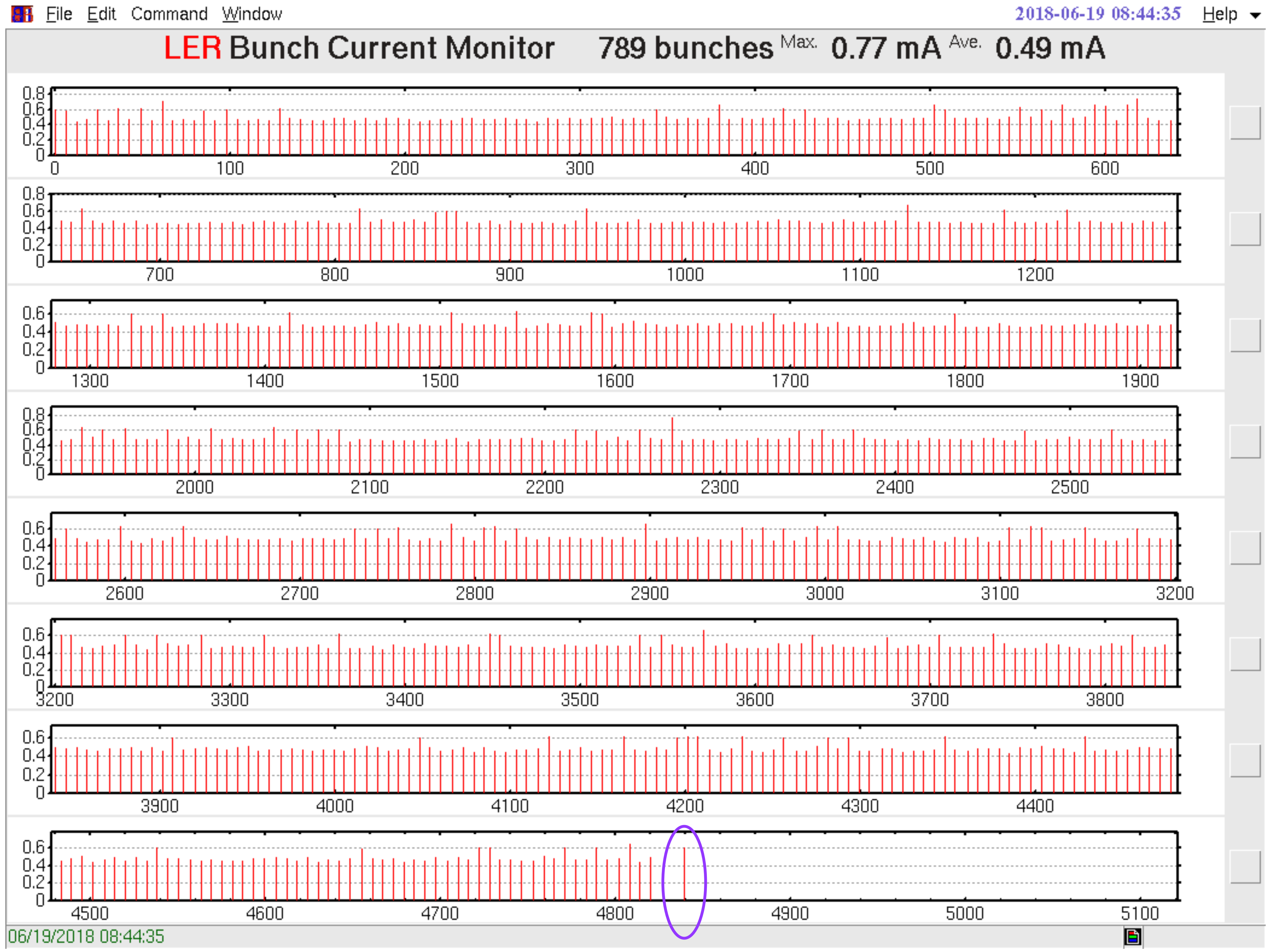
Physical Coordinate XY coupling Normal coordinate

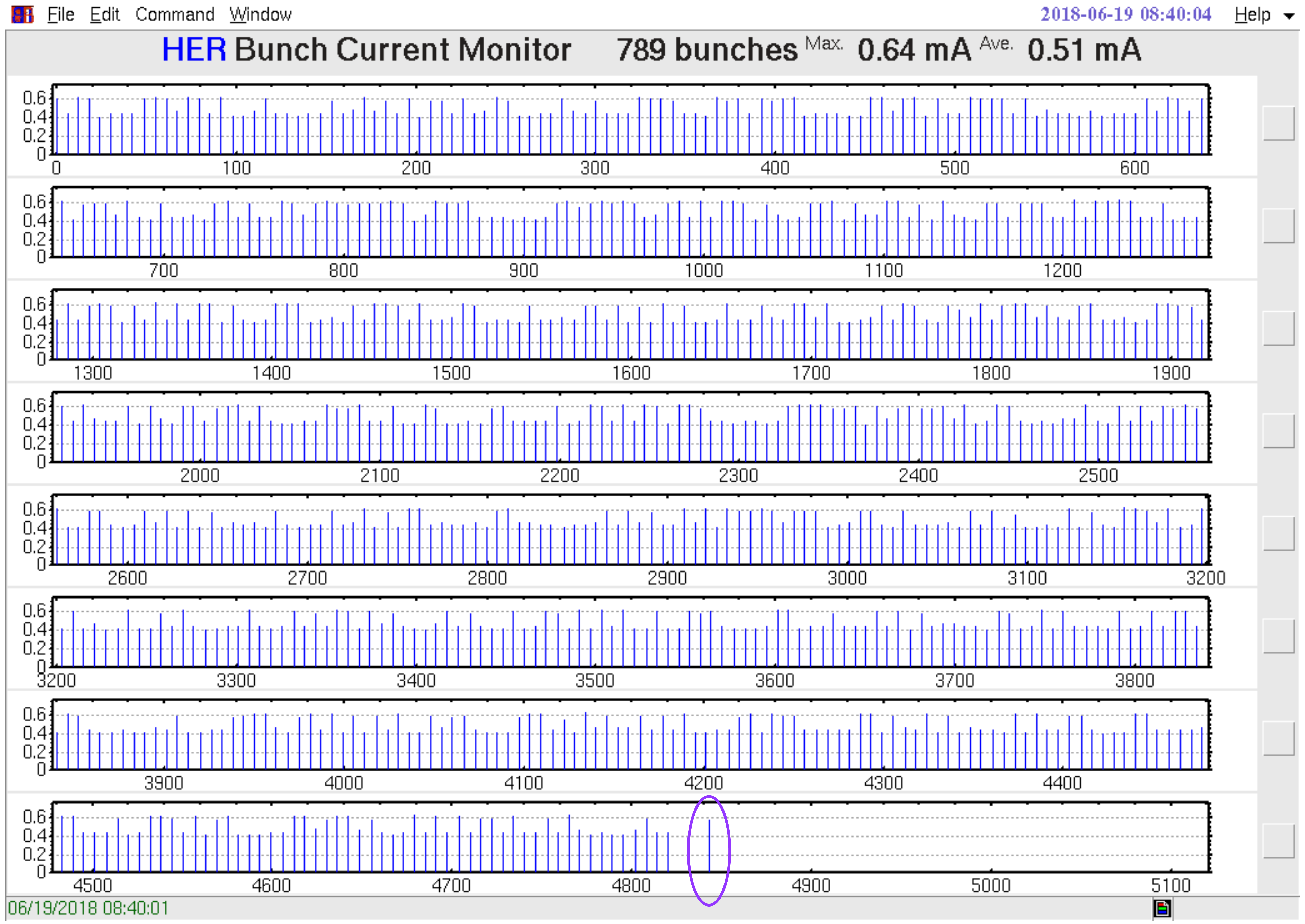
$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} = \begin{pmatrix} \mu & 0 & r_4 & -r_2 \\ 0 & \mu & -r_3 & r_1 \\ -r_1 & -r_2 & \mu & 0 \\ -r_3 & -r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix}$$

$$M_4 = R M_{2\times 2} R^{-1} \qquad M_{2\times 2} = \begin{pmatrix} M_u & 0 \\ 0 & M_v \end{pmatrix}$$

$$\mu^2 + (r_1 r_4 - r_2 r_3) = 1$$

Bunch Current Monitor





Pilot bunch (non-collision)

Pilot bunch (non-collision)

Tunes are measured by gated tune meter.