Phase 2 Achievements

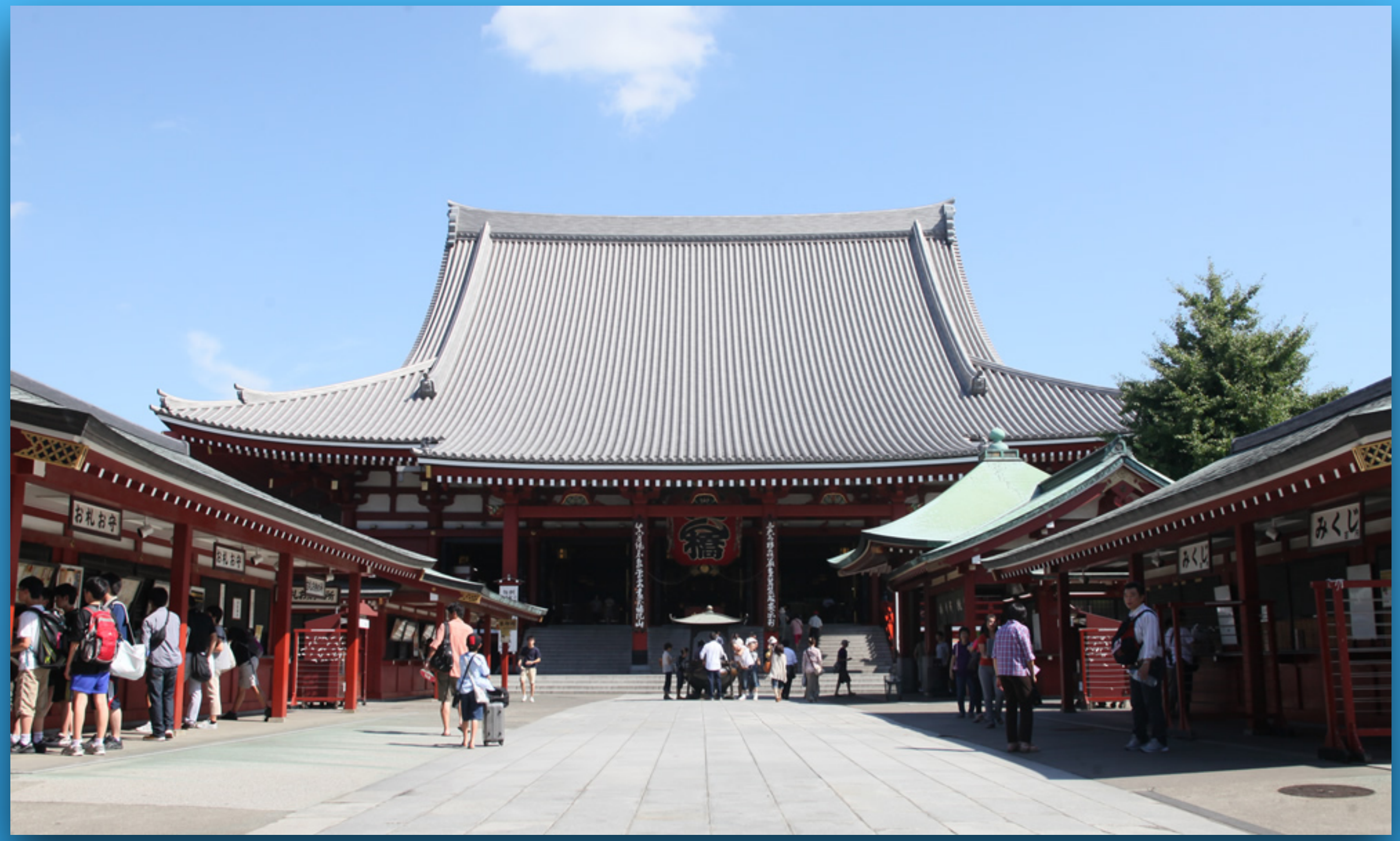
March 19 - July 17, 2018

Y. Ohnishi

Before starting Phase 2

Kaminari-mon Gate

Senso-ji (Buddhist temple), Tokyo



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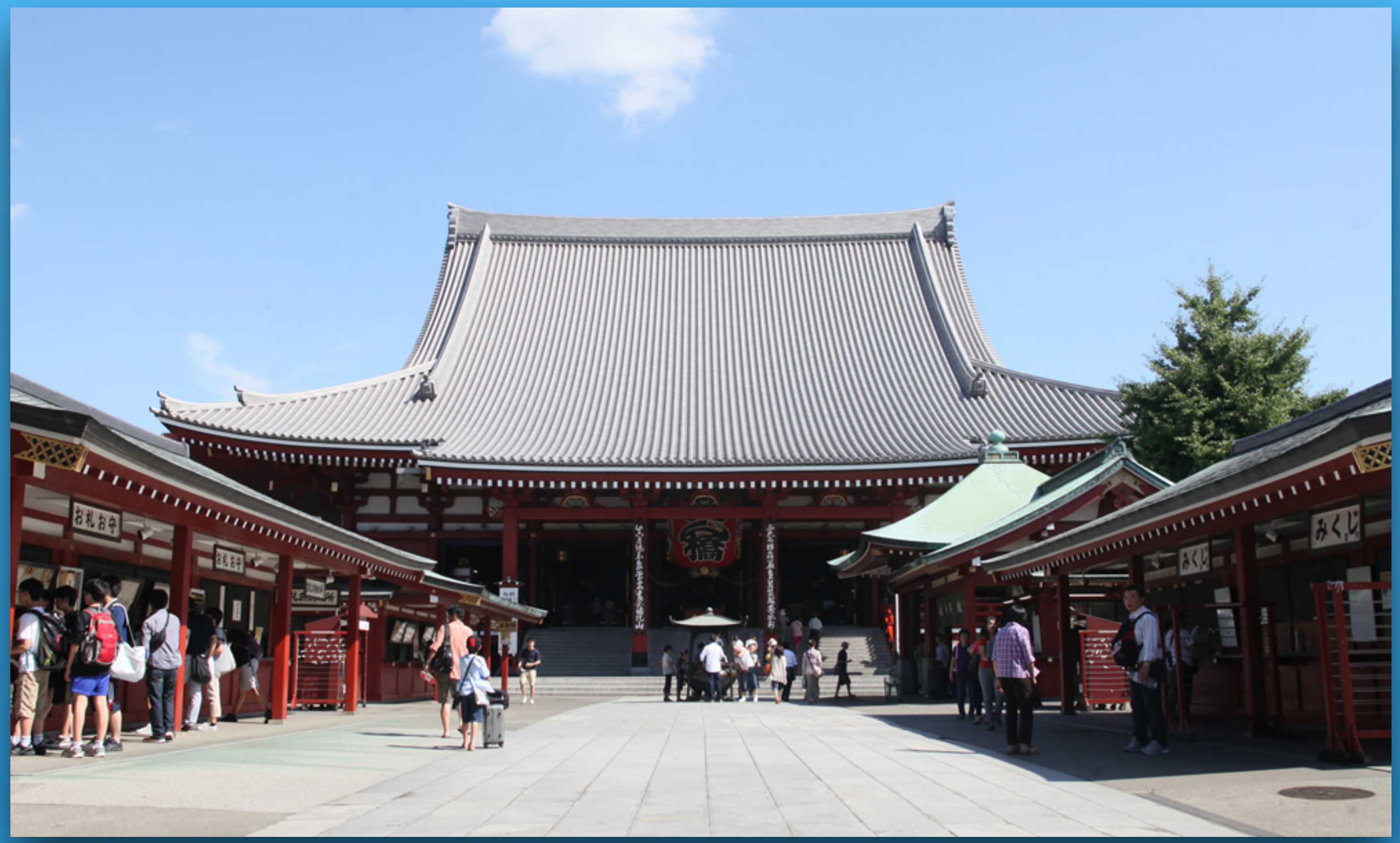
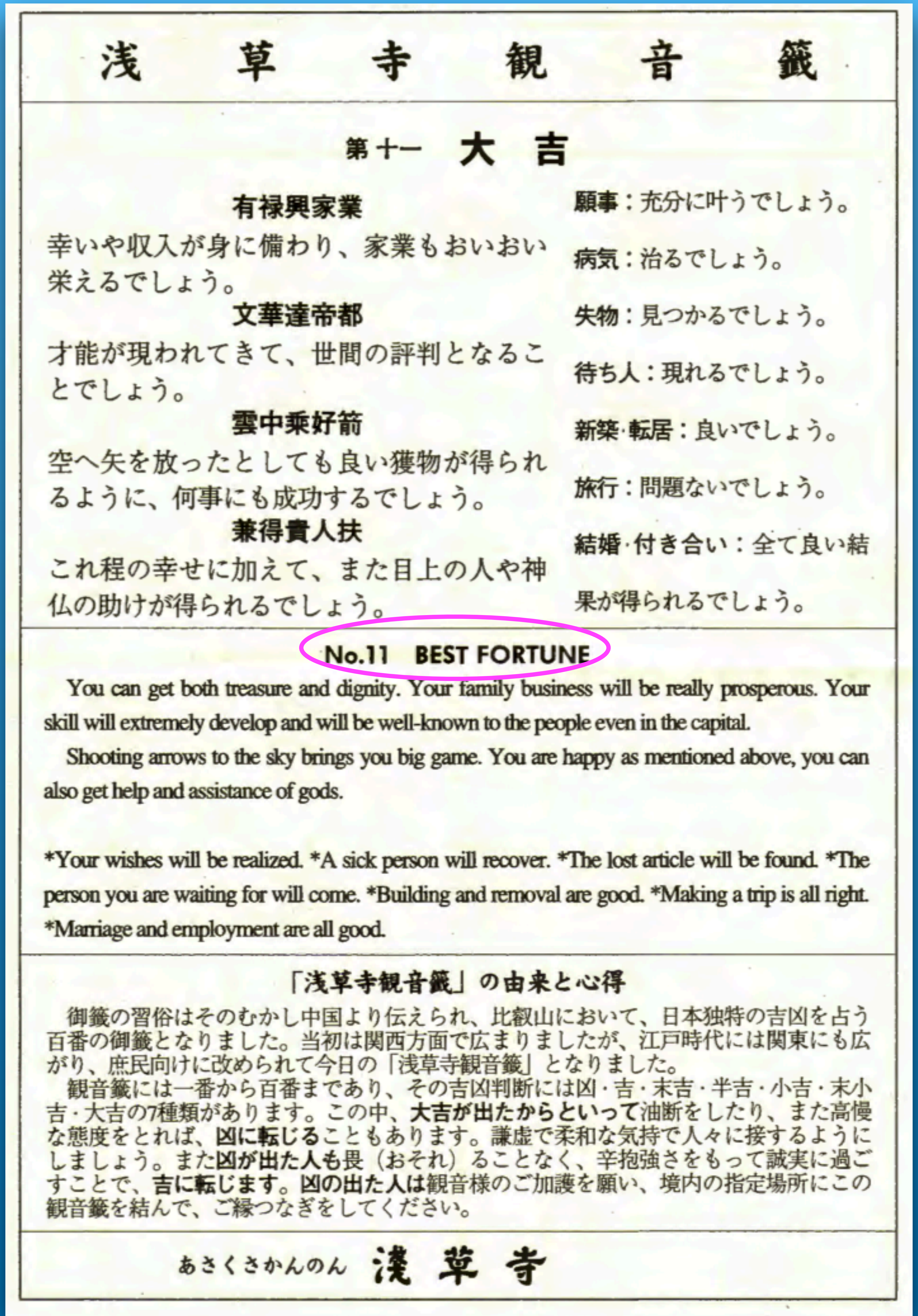




浅　草　寺　観　音　籤

第十一　大　吉

有禄興家業
幸いや収入が身に備わり、家業もおいおい栄えるでしょう。

文華達帝都
才能が現われてきて、世間の評判となることでしょう。

雲中乗好箭
空へ矢を放ったとしても良い獲物が得られるように、何事にも成功するでしょう。

兼得貴人扶
これ程の幸せに加えて、また目上の人や神仏の助けが得られるでしょう。

願事：充分に叶うでしょう。
病気：治るでしょう。
失物：見つかるでしょう。
待ち人：現れるでしょう。
新築·転居：良いでしょう。
旅行：問題ないでしょう。
結婚·付き合い：全て良い結果が得られるでしょう。

No.11　BEST FORTUNE

You can get both treasure and dignity. Your family business will be really prosperous. Your skill will extremely develop and will be well-known to the people even in the capital.
Shooting arrows to the sky brings you big game. You are happy as mentioned above, you can also get help and assistance of gods.

*Your wishes will be realized. *A sick person will recover. *The lost article will be found. *The person you are waiting for will come. *Building and removal are good. *Making a trip is all right. *Marriage and employment are all good.

「浅草寺観音籤」の由来と心得

御籤の習俗はそのむかし中国より伝えられ、比叡山において、日本独特の吉凶を占う百番の御籤となりました。当初は関西方面で広まりましたが、江戸時代には関東にも広がり、庶民向けに改められて今日の「浅草寺観音籤」となりました。
観音籤には一番から百番まであり、その吉凶判断には凶·吉·末吉·半吉·小吉·末小吉·大吉の7種類があります。この中、**大吉が出たからといって**油断をしたり、また高慢な態度をとれば、**凶に転じる**こともあります。謙虚で柔和な気持で人々に接するようにしましょう。また凶が出た人も畏（おそれ）ることなく、辛抱強さをもって誠実に過ごすことで、**吉に転じます**。**凶の出た人は**観音様のご加護を願い、境内の指定場所にこの観音籤を結んで、ご縁つなぎをしてください。

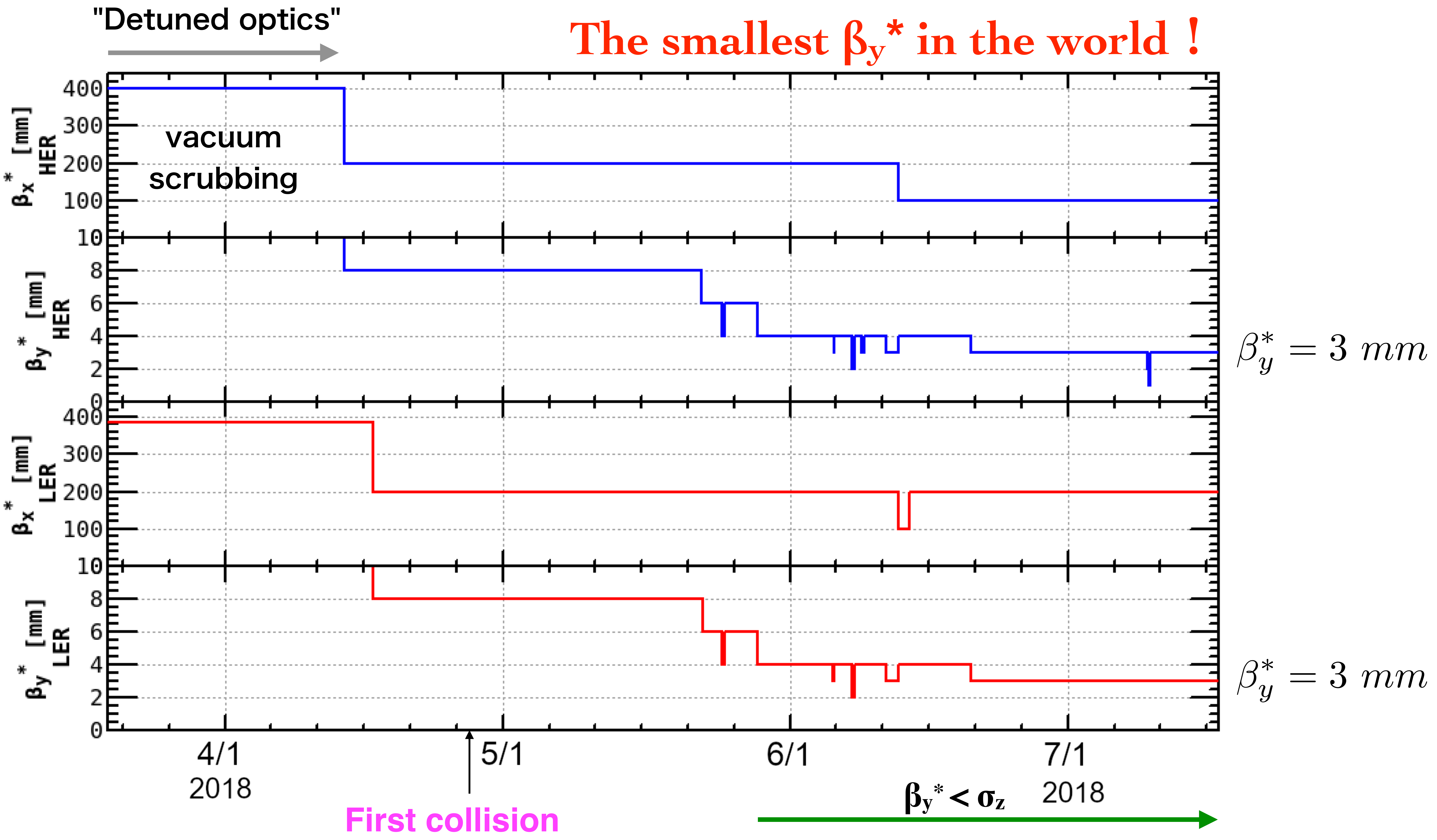
あさくさかんのん　浅　草　寺

1. Verification of nano-beam scheme
   - Squeezing β_y^* down to a few mm < σ_z.
   - 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

Verification of Nano-Beam Scheme

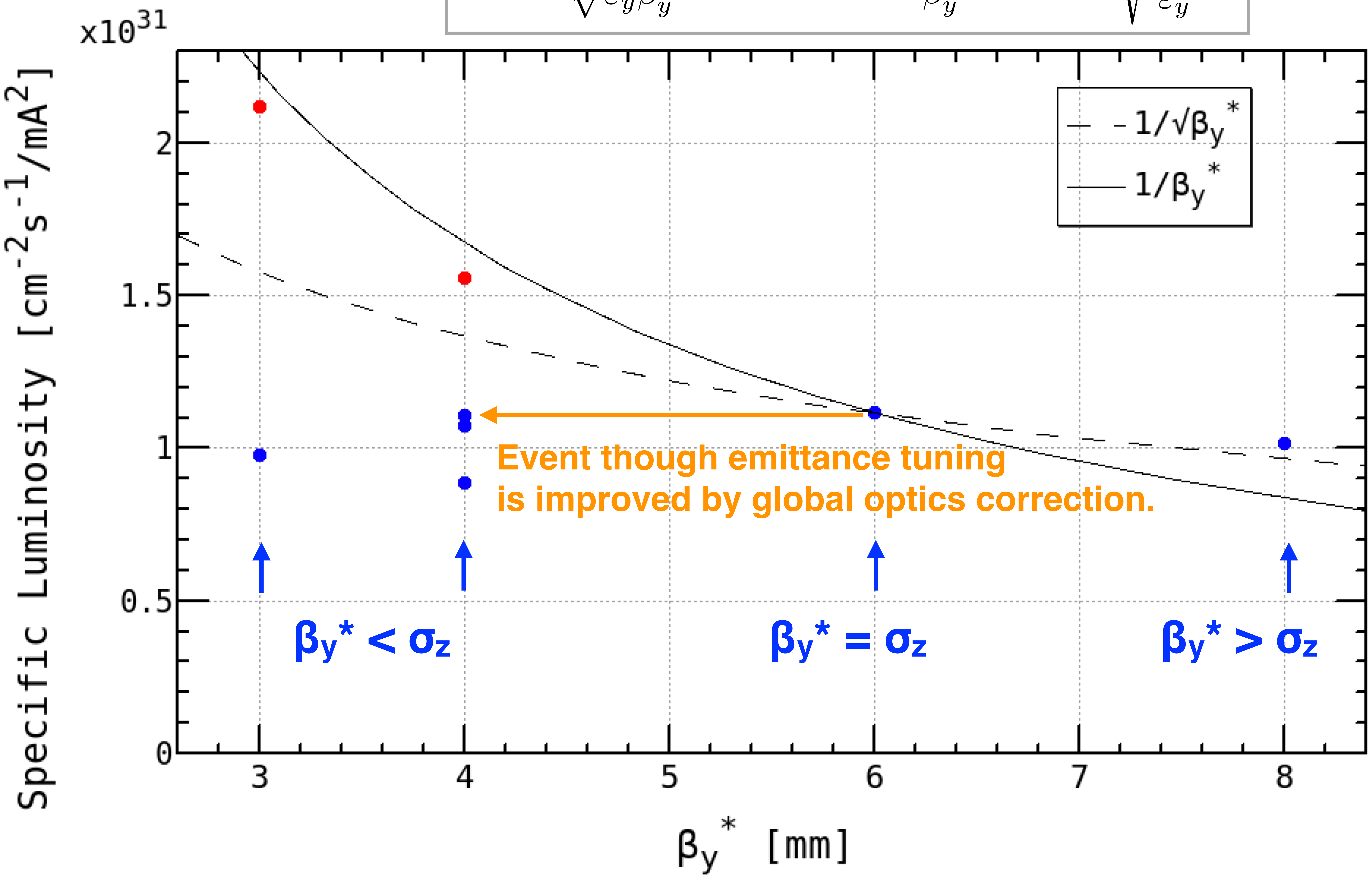
Target	Achievements	Remark
Squeezing β_y^* down to 2 mm	β_y^* = 3 mm	β_y^* = 2 mm is tested for machine study
Luminosity increases even though $\beta_y^* < \sigma_z$.	confirmed	XY coupling at the IP is adjusted by QC1.
Beam-Beam Parameter, $\xi_y > 0.03$	$\xi_{y-} = 0.021$ at I_{b+} = 0.67 mA	$\xi_{y+} = 0.030$ at I_{b-} = 0.55 mA
L = 10^{34} $cm^{-2}s^{-1}$ at 1 [A] in LER	L = 2.29 x 10^{33} $cm^{-2}s^{-1}$ at 0.265 [A] in LER	L = 9x10^{33} $cm^{-2}s^{-1}$ at 1 [A] in LER extrapolation by a factor 4

Beta Squeezing at IP



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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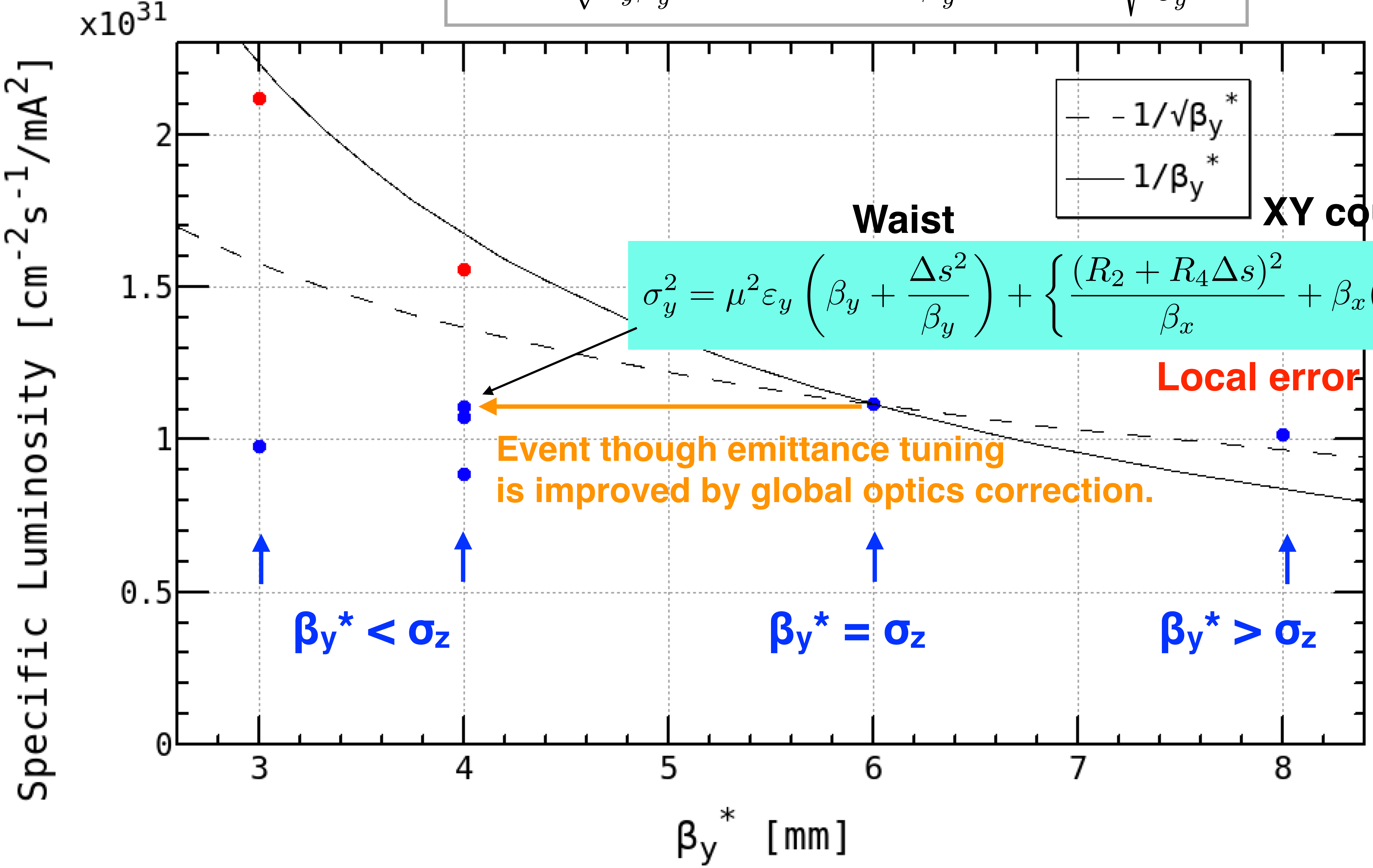


Waist

XY coupling

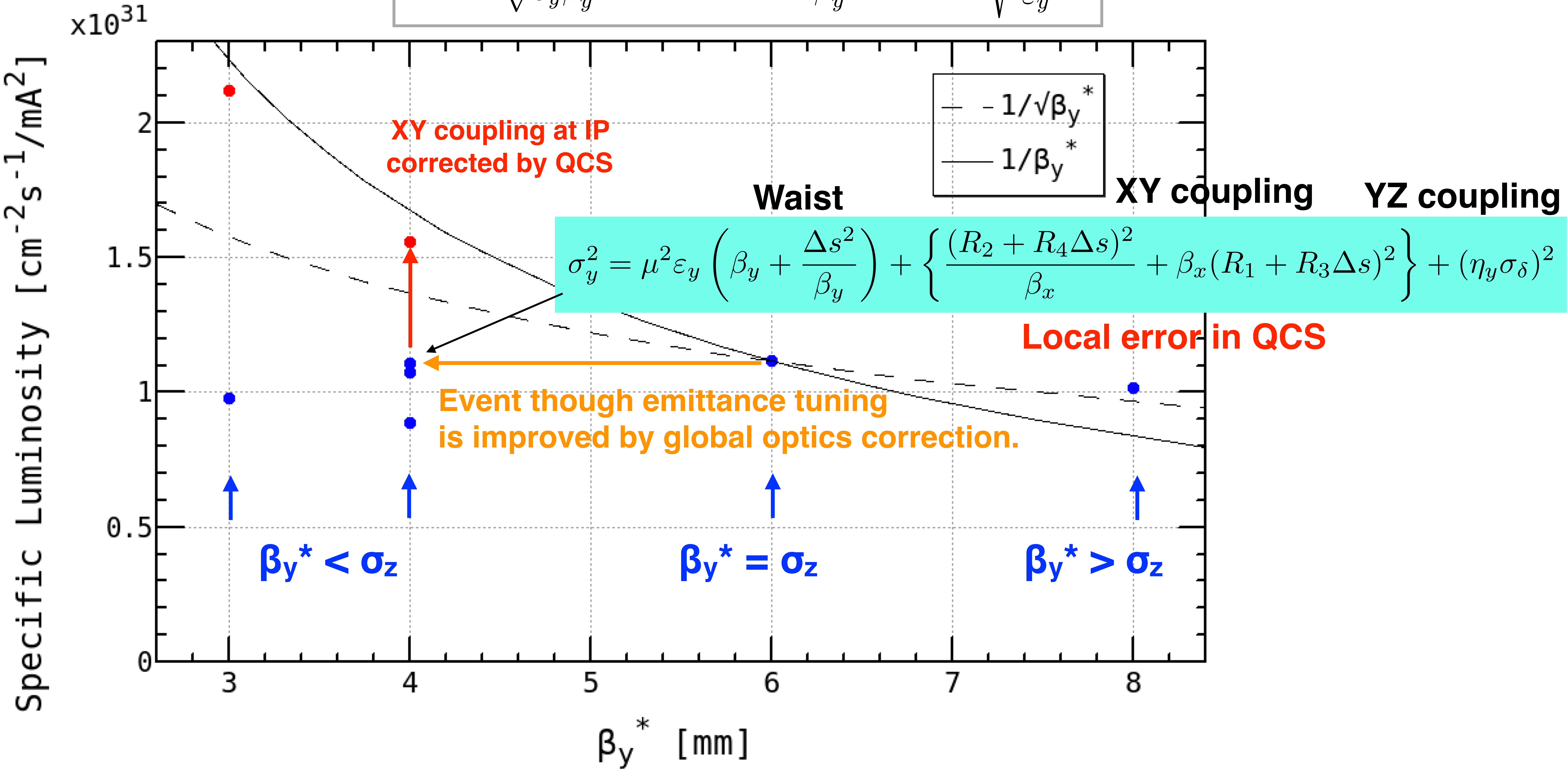
YZ coupling

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

Local error in QCS

Verification of Nano-Beam Scheme

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



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

Verification of Nano-Beam Scheme

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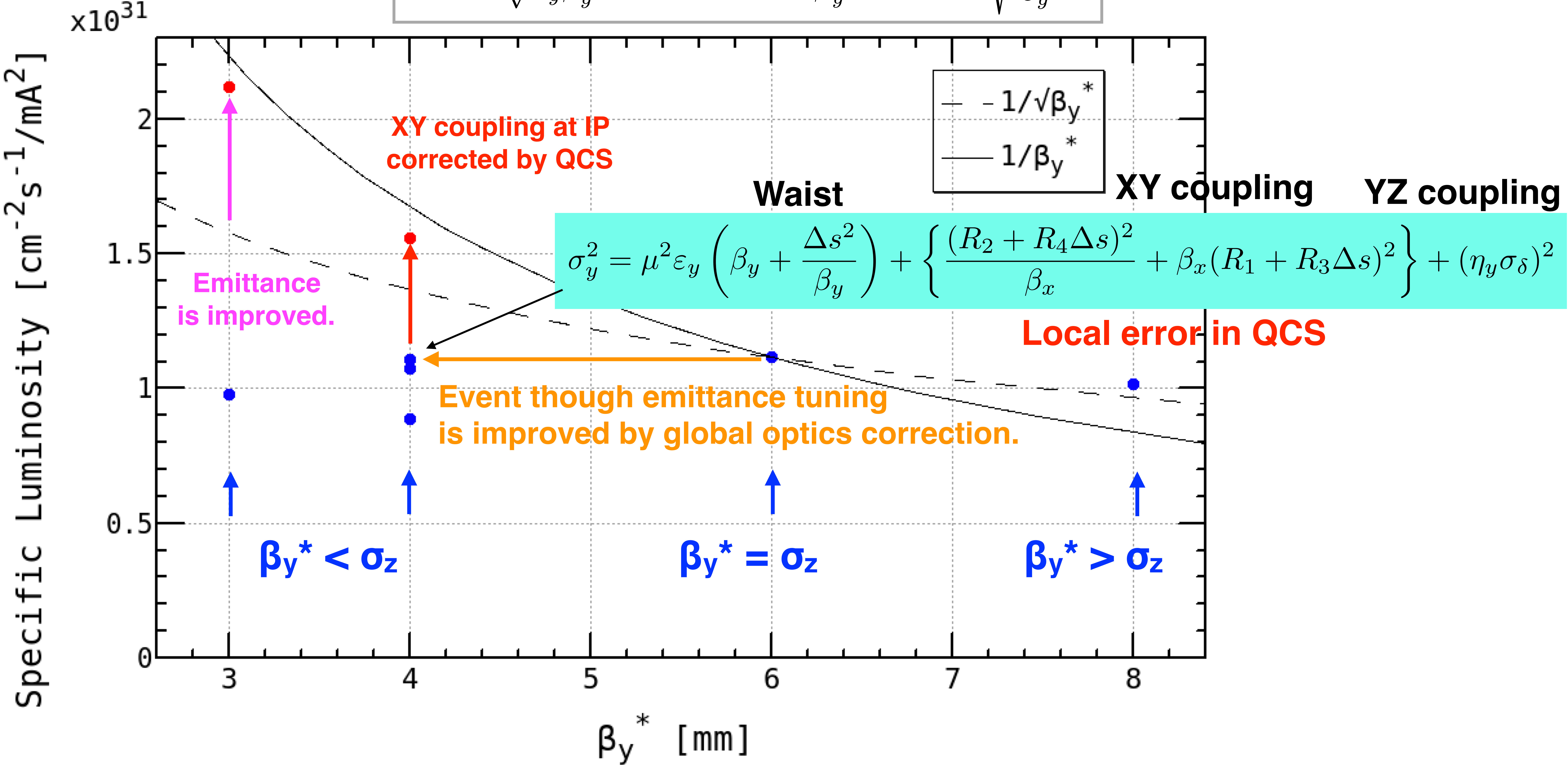


$$\sigma_y^2 = \mu^2 \varepsilon_y \left(\beta_y + \frac{\Delta s^2}{\beta_y}\right) + \left\{ \frac{(R_2 + R_4 \Delta s)^2}{\beta_x} + \beta_x (R_1 + R_3 \Delta s)^2 \right\} + (\eta_y \sigma_\delta)^2$$

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.

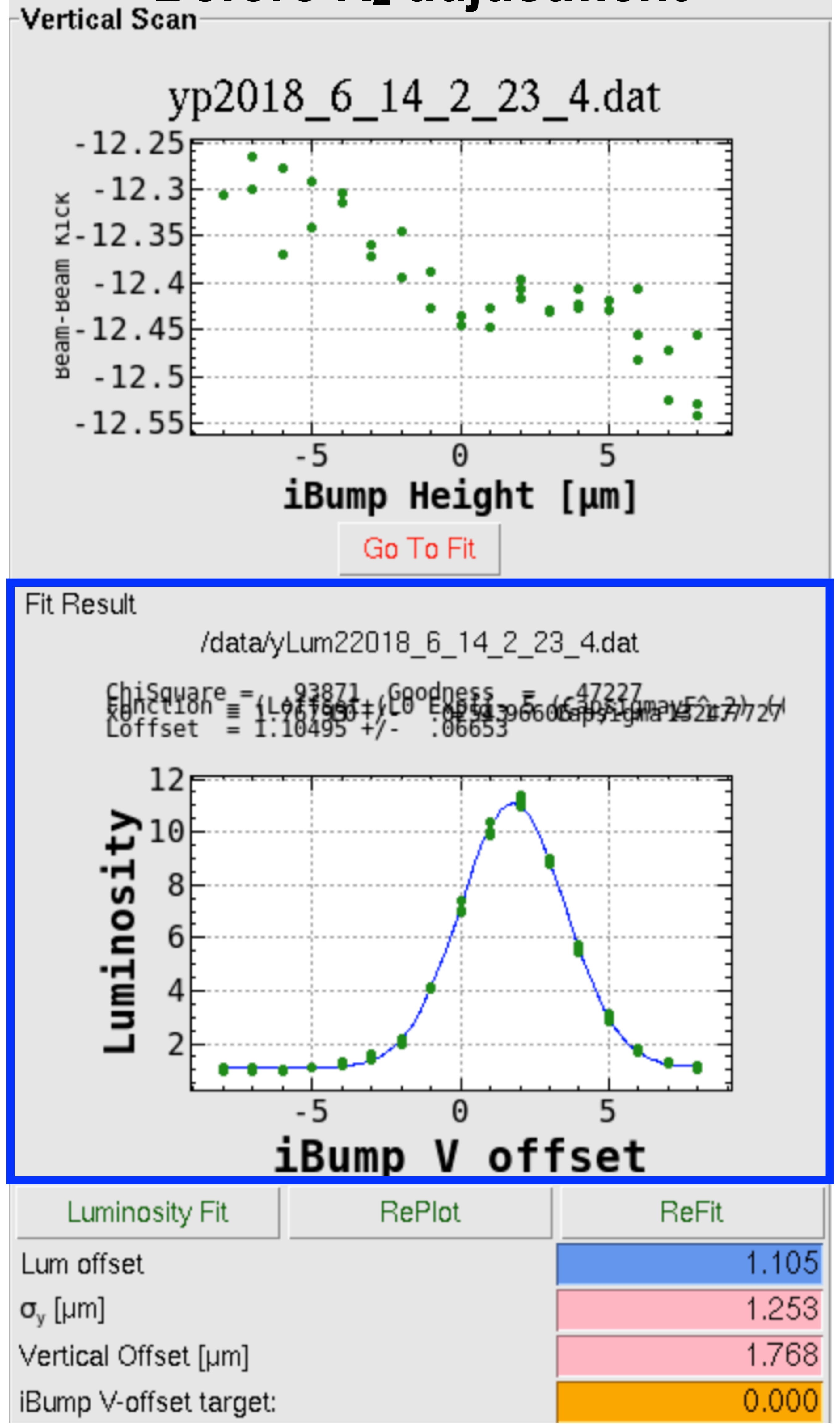
0.1 mA/bunch

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

LumiBelle2 is good performance !

Very large beam size ! →

Before R_2 adjustment



Y. Funakoshi

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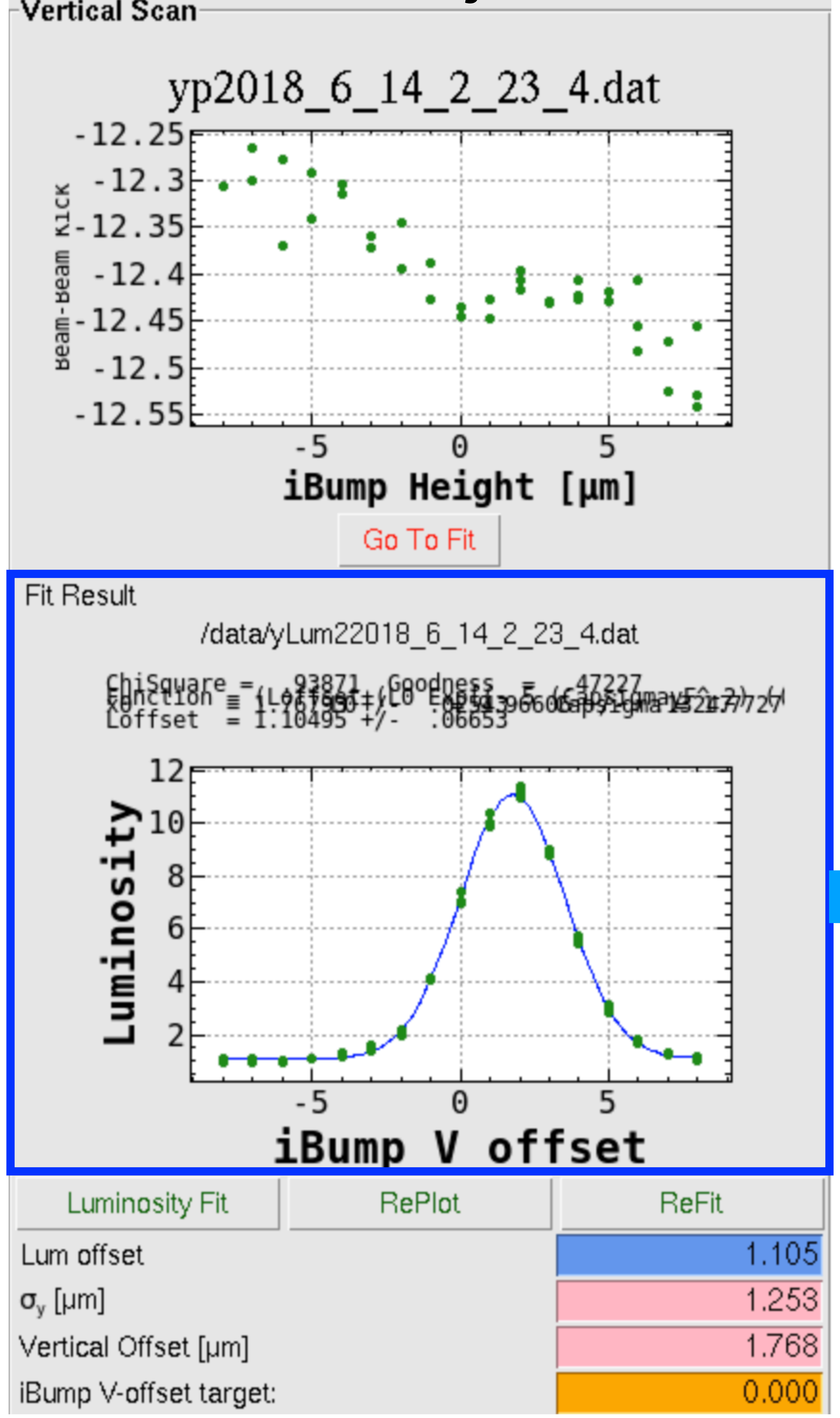
LumiBelle2 is good performance !

Very large beam size ! →

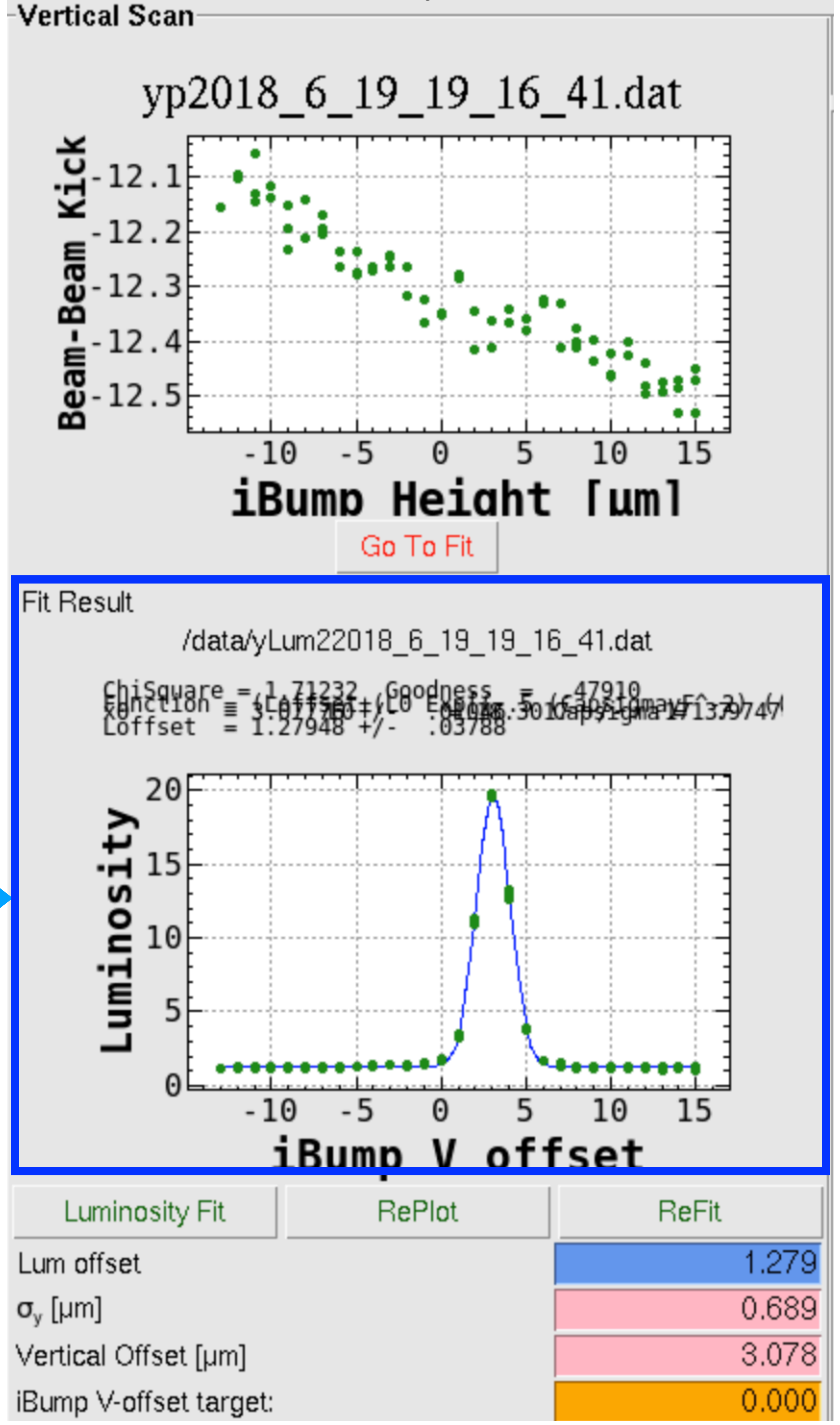
Estimation from X-Ray Monitor:
σ_y^* = 400 nm (LER), 500 nm (HER)
No change after adjustment of X-Y coupling(R_2) at IP

Measurement by beam-beam scan:
σ_y^* = 1253 nm → 689 nm
Beam size becomes small !

Before R_2 adjustment



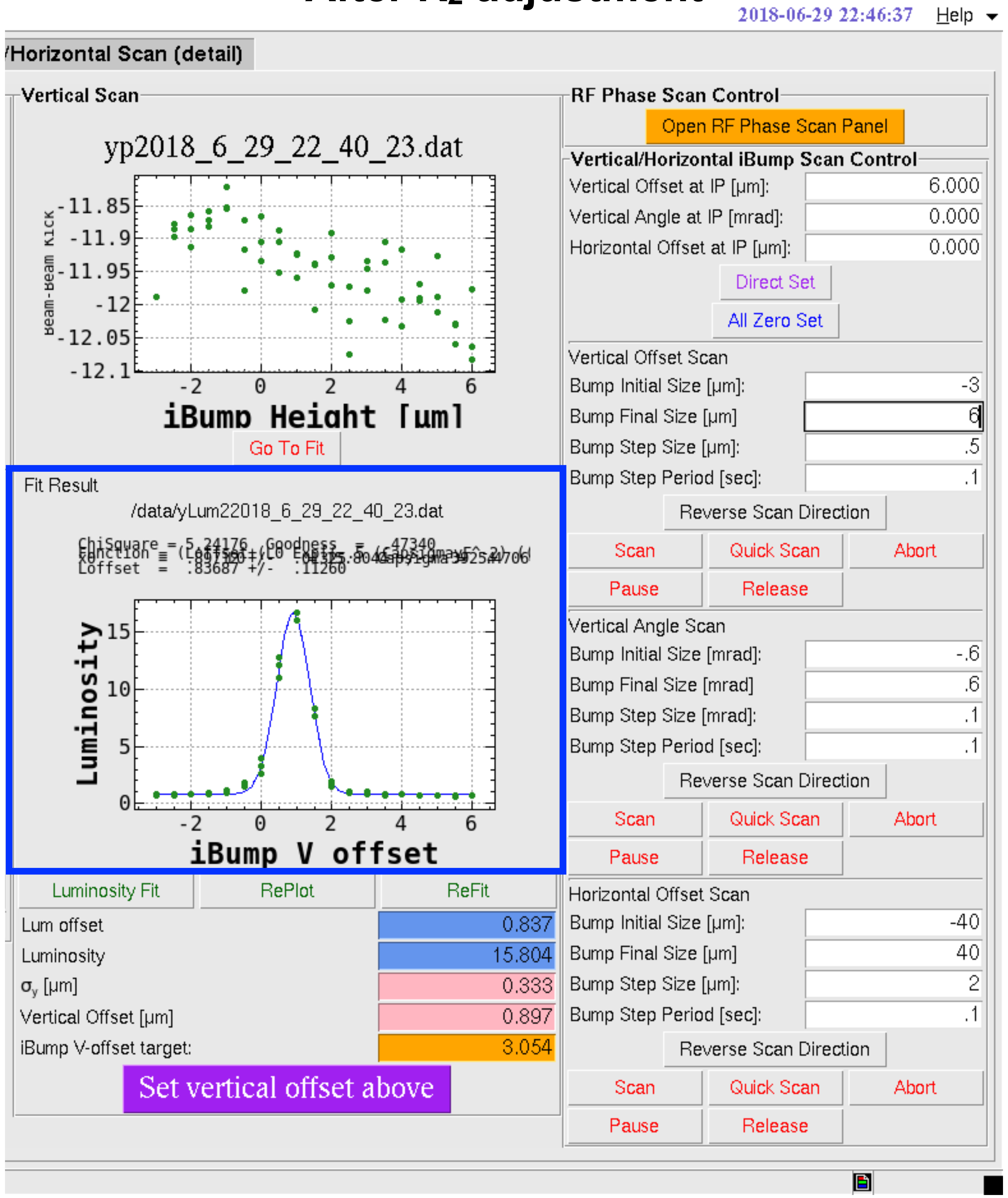
After R_2 adjustment



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.

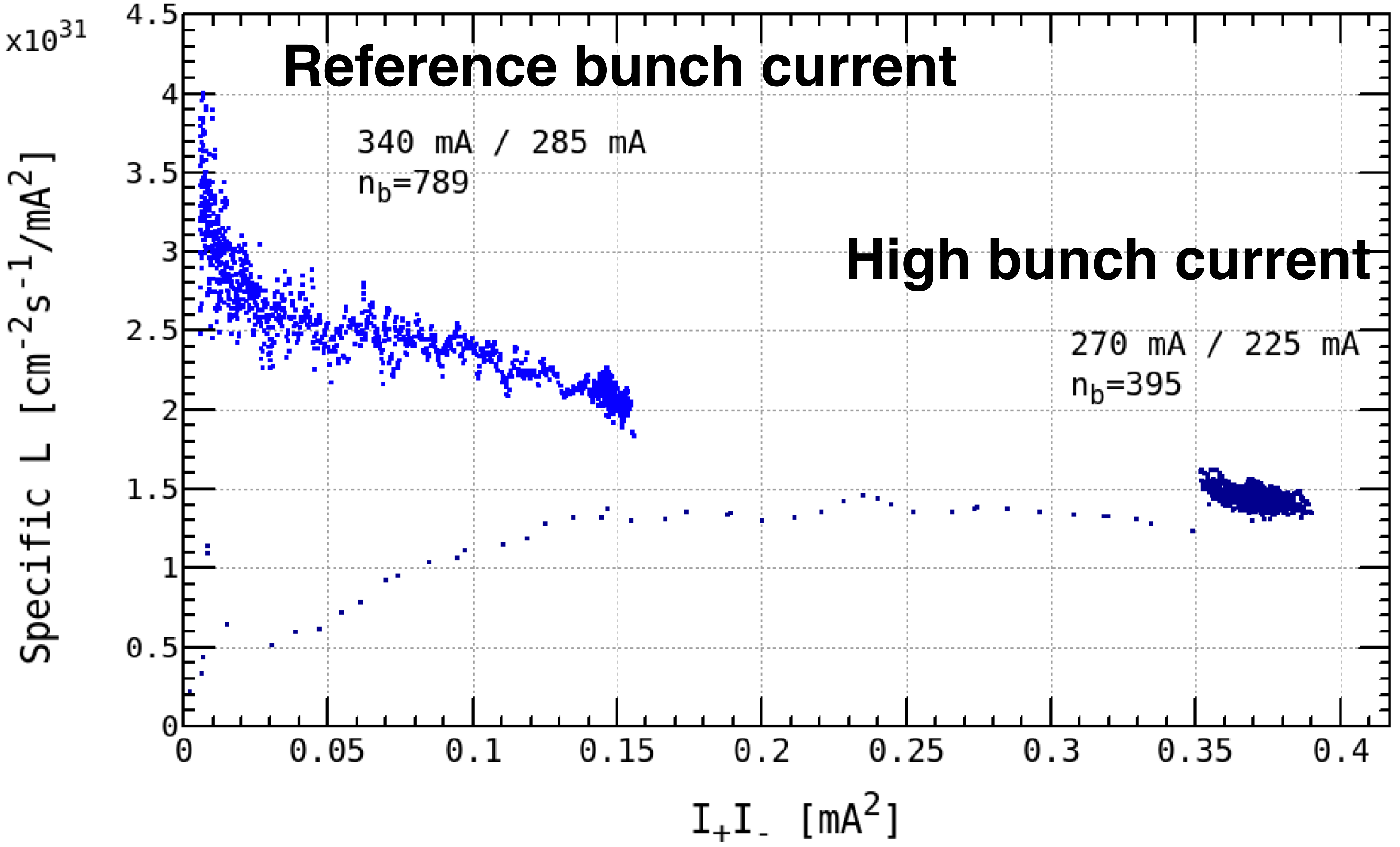
0.1 mA/bunch

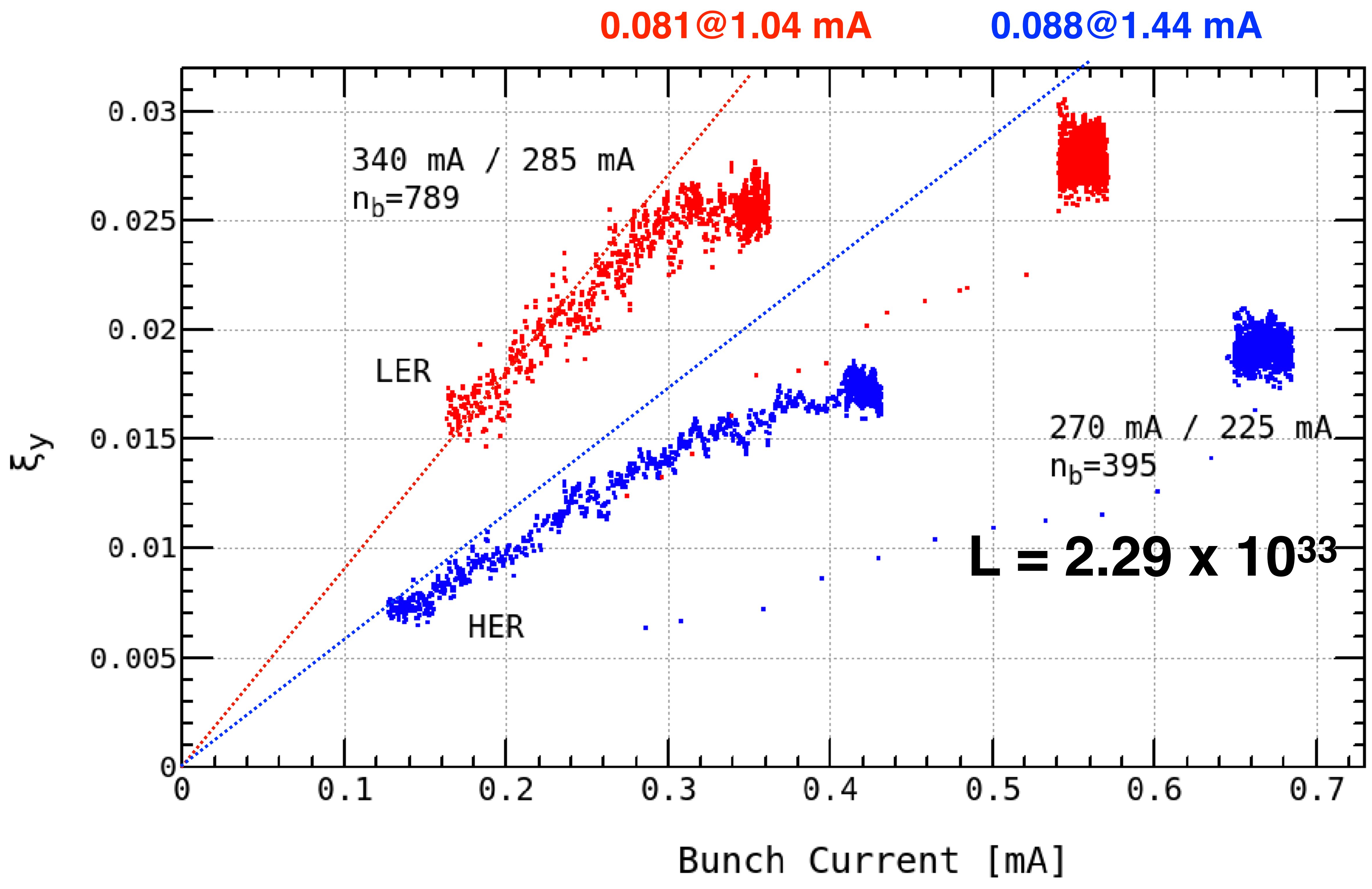
$$\Sigma_y^* = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad \sigma_y^* = \Sigma_y^*/\sqrt{2}$$

σ_y^* = 333 nm

Y. Funakoshi

Specific Luminosity and Beam-Beam Parameter





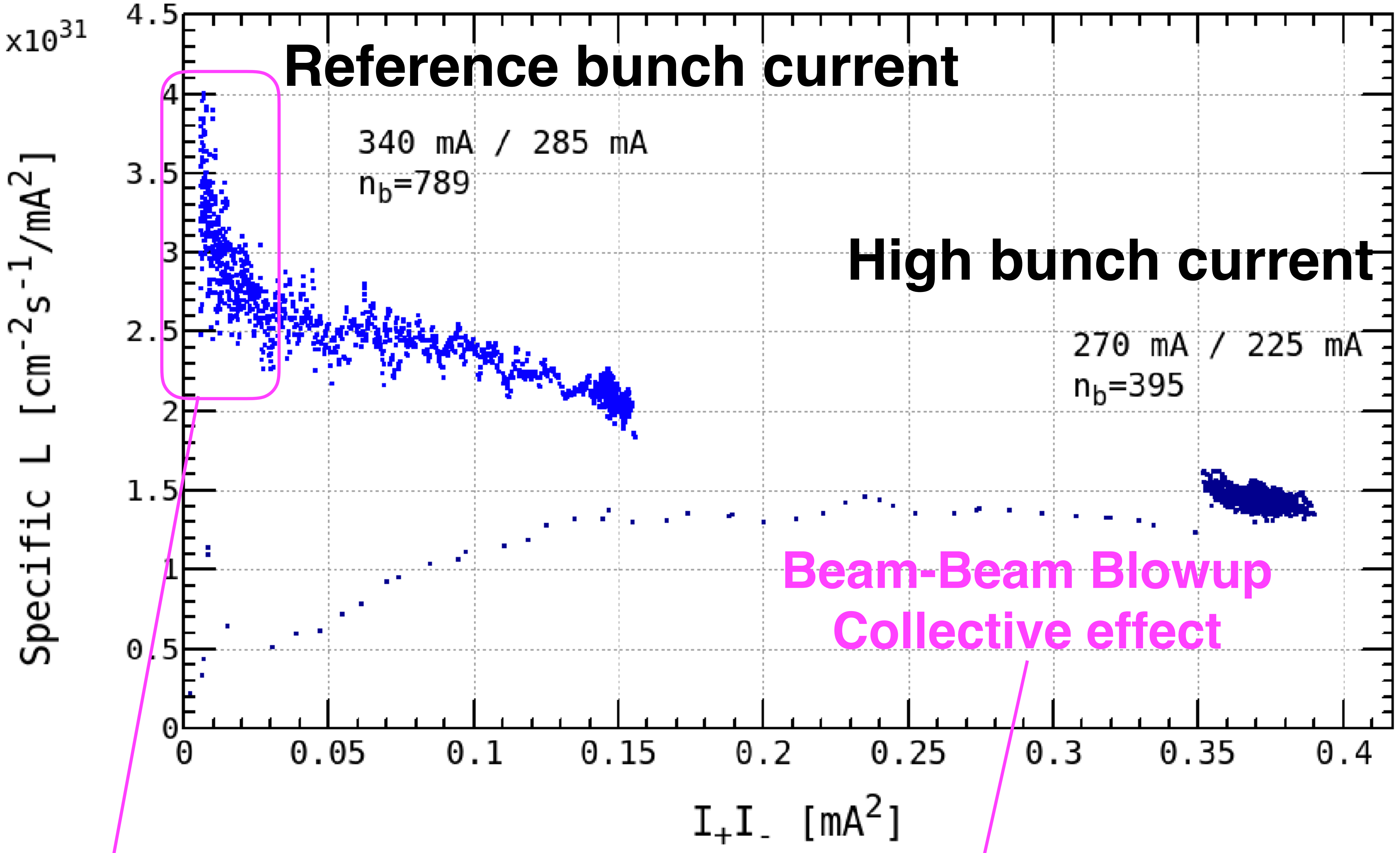
$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi(\sigma_z \phi_x)e^2 f_0 \sigma_y^*} = \frac{1.25 \times 10^{25}}{\sigma_y^*} \; [cm^{-2}s^{-1}/mA^2]$$

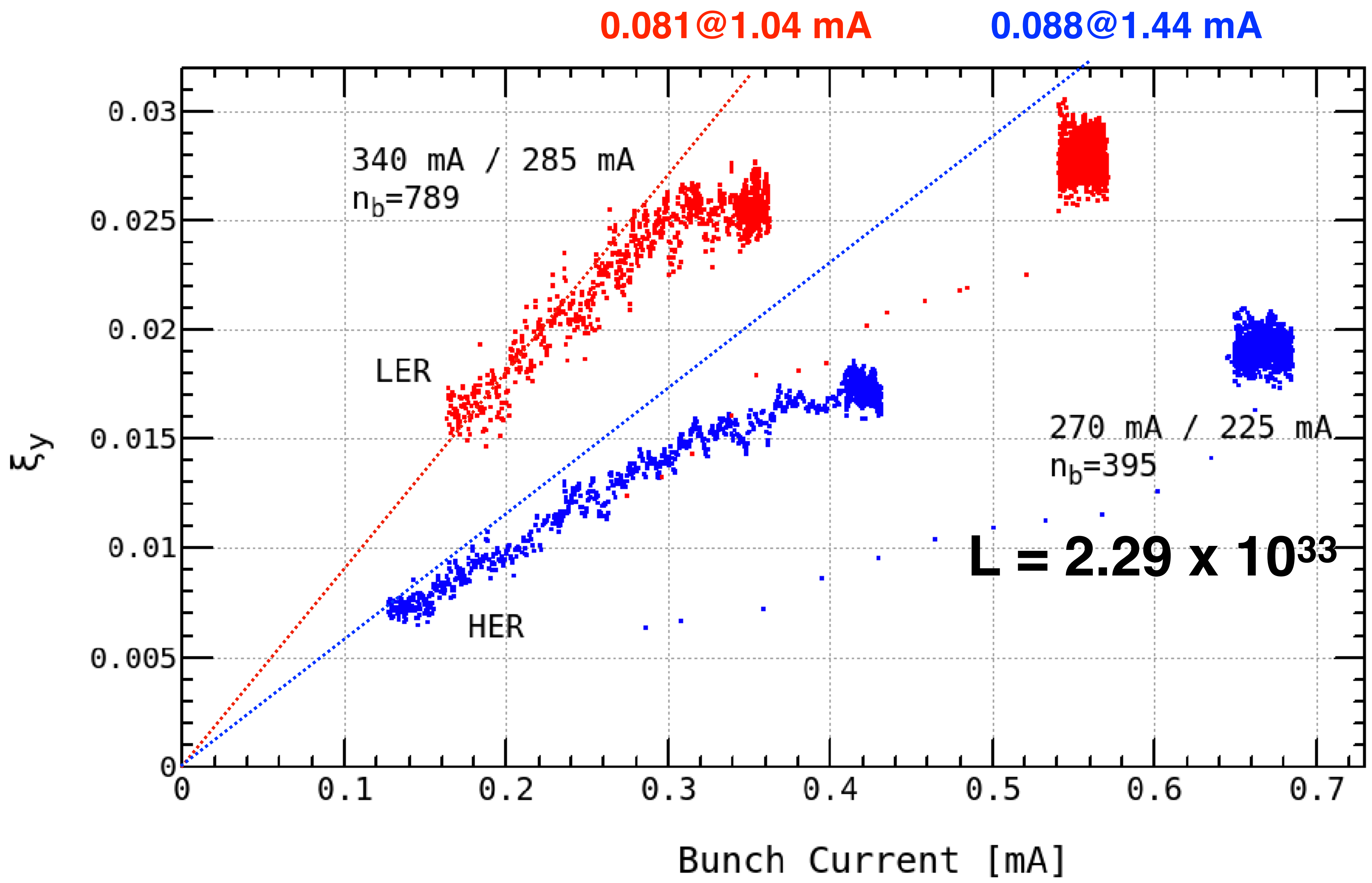
The beam-beam parameter is 0.02.

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

L_{sp} = 4×10^{31} → σ_y^* = 300 nm (ε_y = 30 pm)

↔ ε_y = 23 pm for single beam in LER





Luminosity drop at low current. ☞ issue in Phase 3

$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi(\sigma_z\phi_x)e^2 f_0 \sigma_y^*} = \frac{1.25\times10^{25}}{\sigma_y^*}\ [cm^{-2}s^{-1}/mA^2]$$

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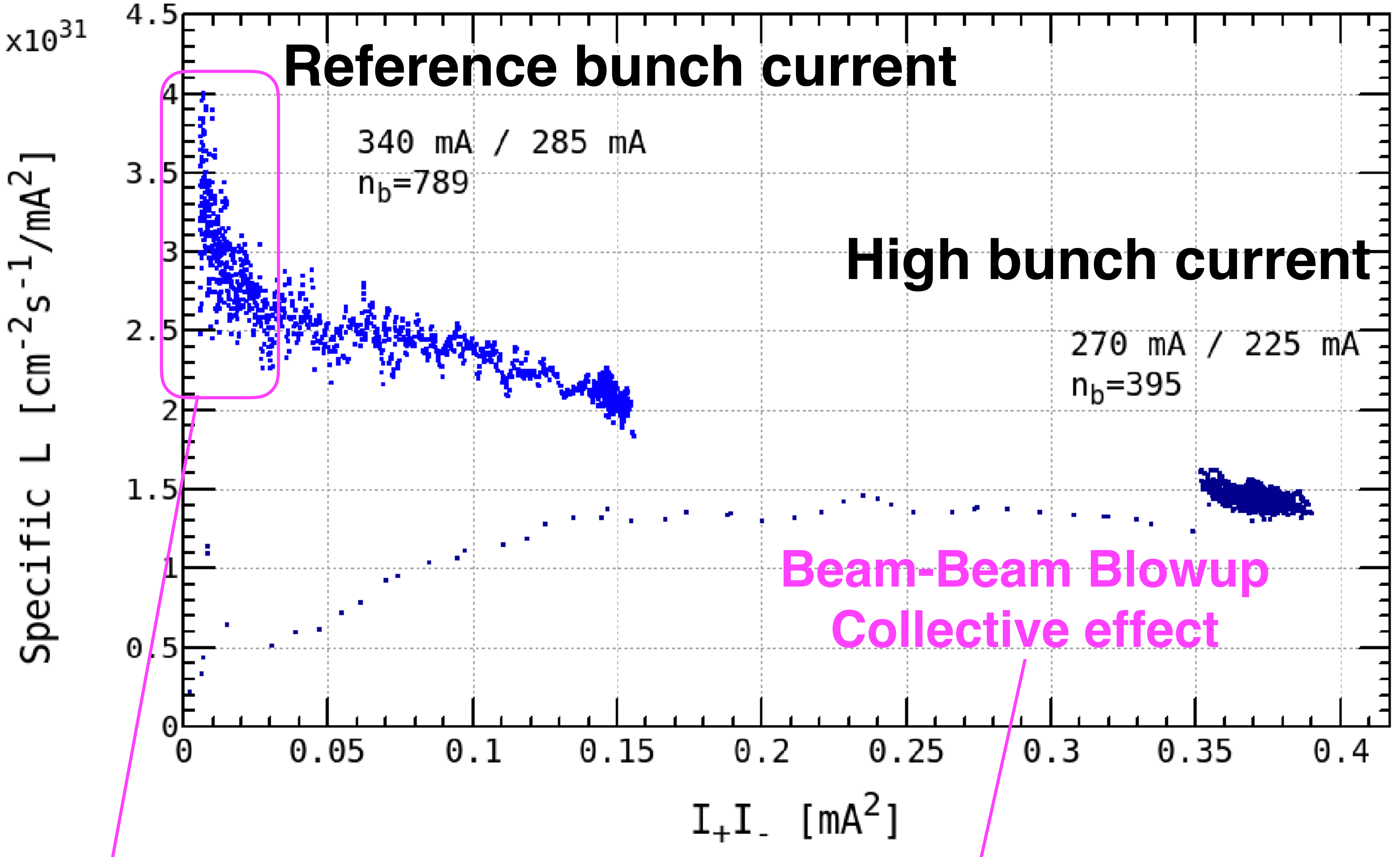
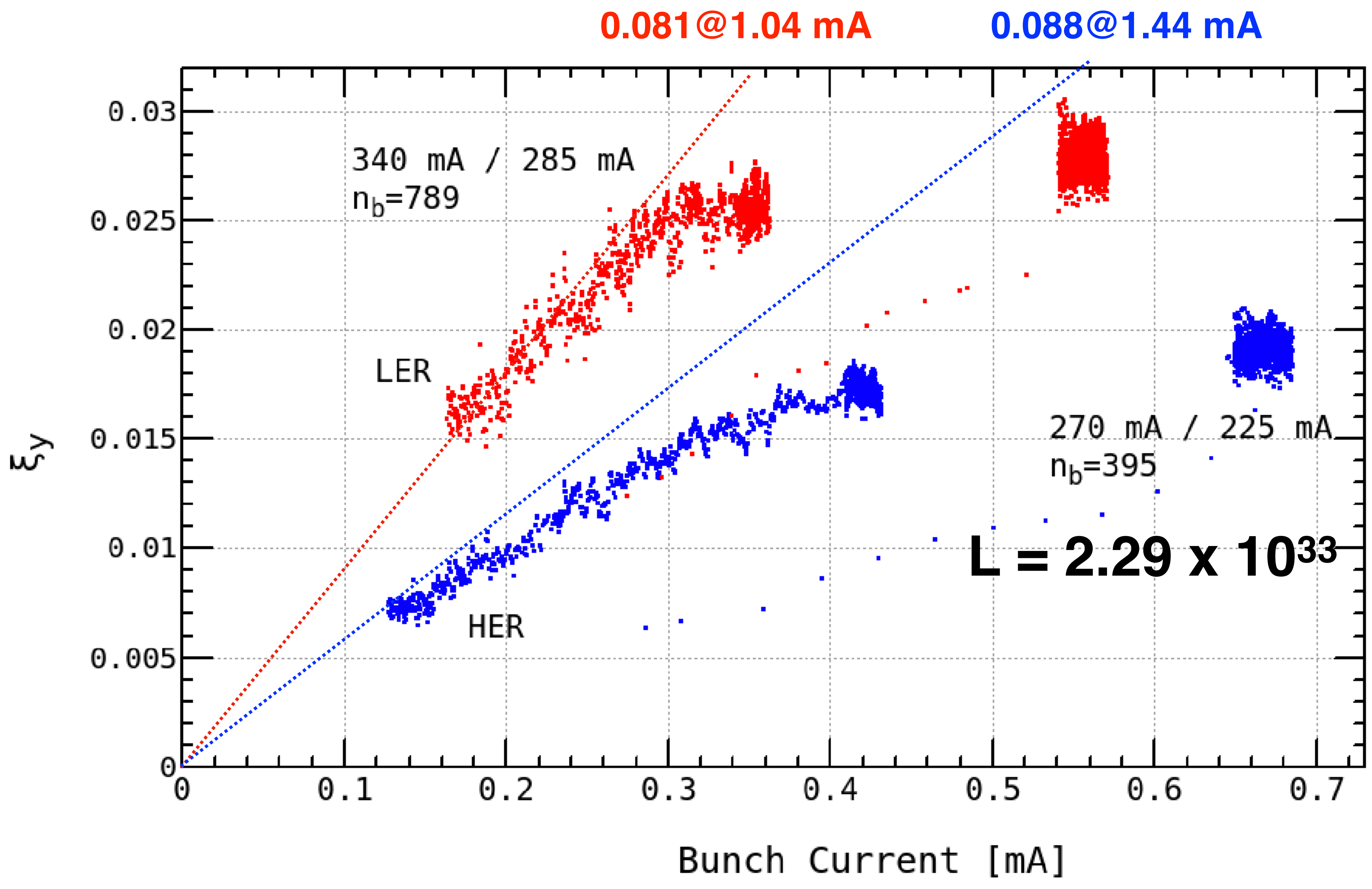
Specific Luminosity and Beam-Beam Parameter





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

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

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L_{sp} = 4×10^{31} → σ_y^* = 300 nm (ε_y = 30 pm)

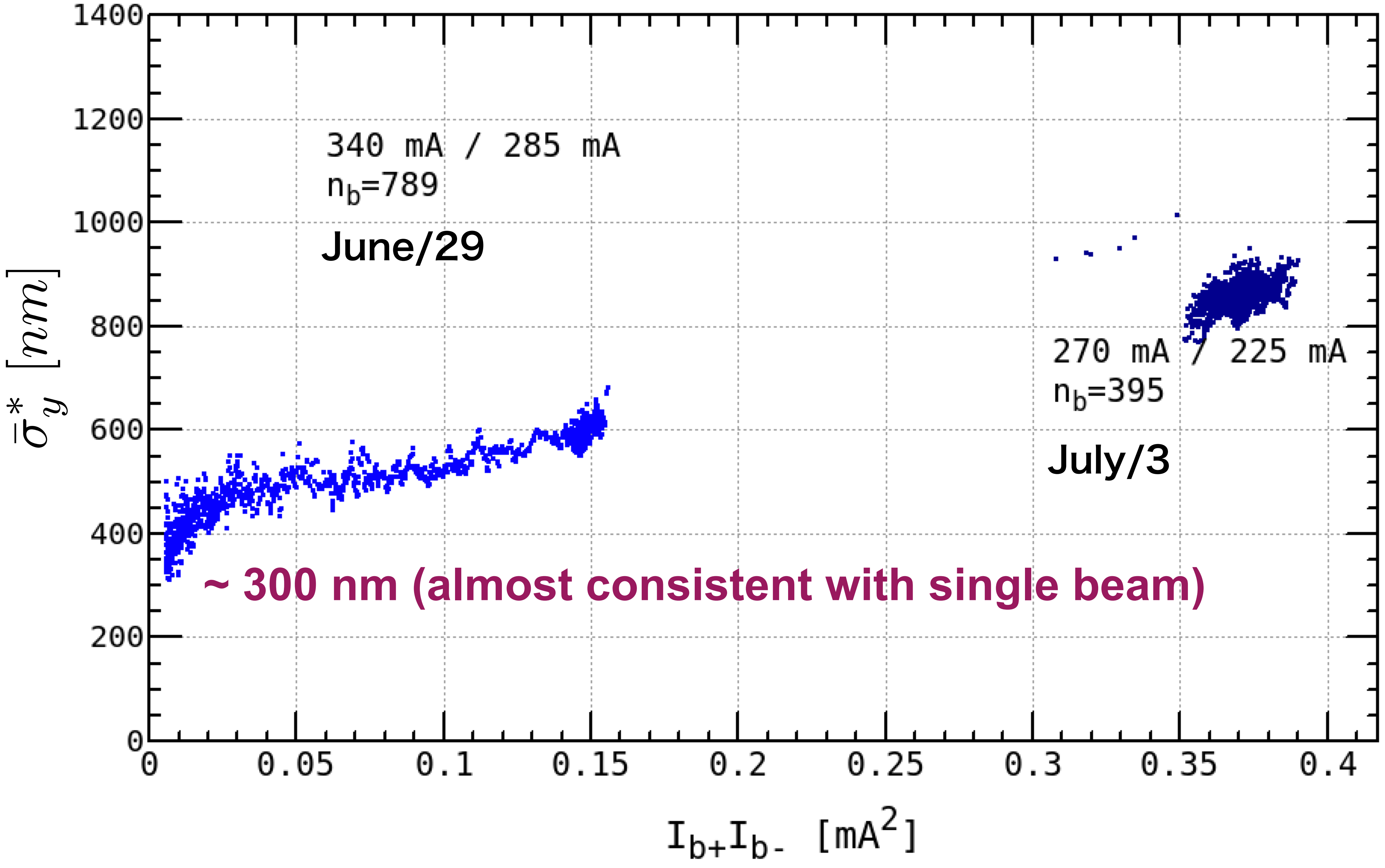
↔ ε_y = 23 pm for single beam in LER

The beam-beam parameter is 0.02.

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

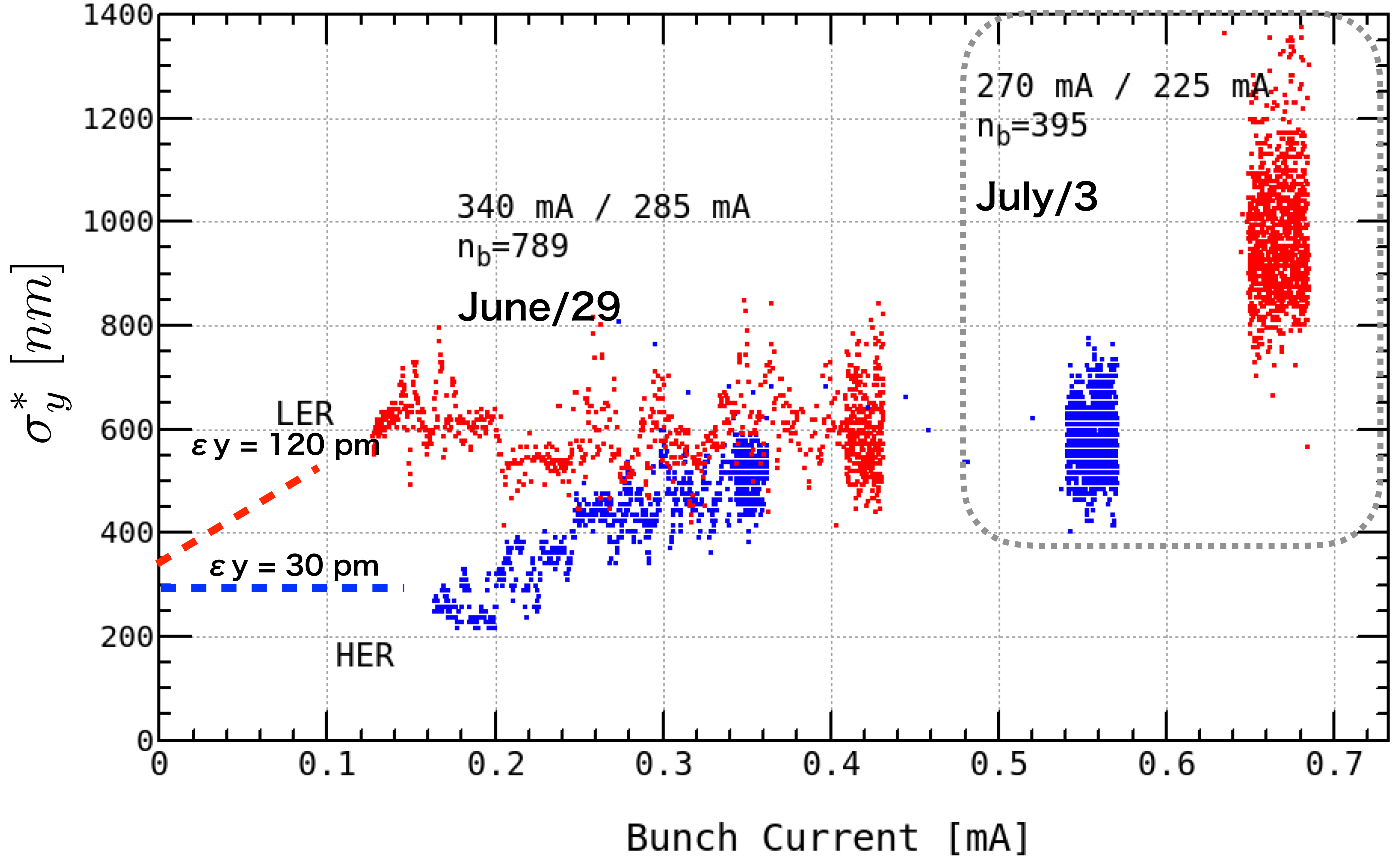
$\beta_y^* = 3\ mm$ LER: $\beta_x^* = 200\ mm$ HER: $\beta_x^* = 100\ mm$

Beam size at IP estimated from luminosity



$$\bar{\sigma}_y^* = \frac{\Sigma_y^*}{\sqrt{2}} \qquad \Sigma_y^* = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}} \qquad L = \frac{N_+ H_- f_{col}}{2\sqrt{2}\pi\sigma_x^* \Sigma_y^*}$$

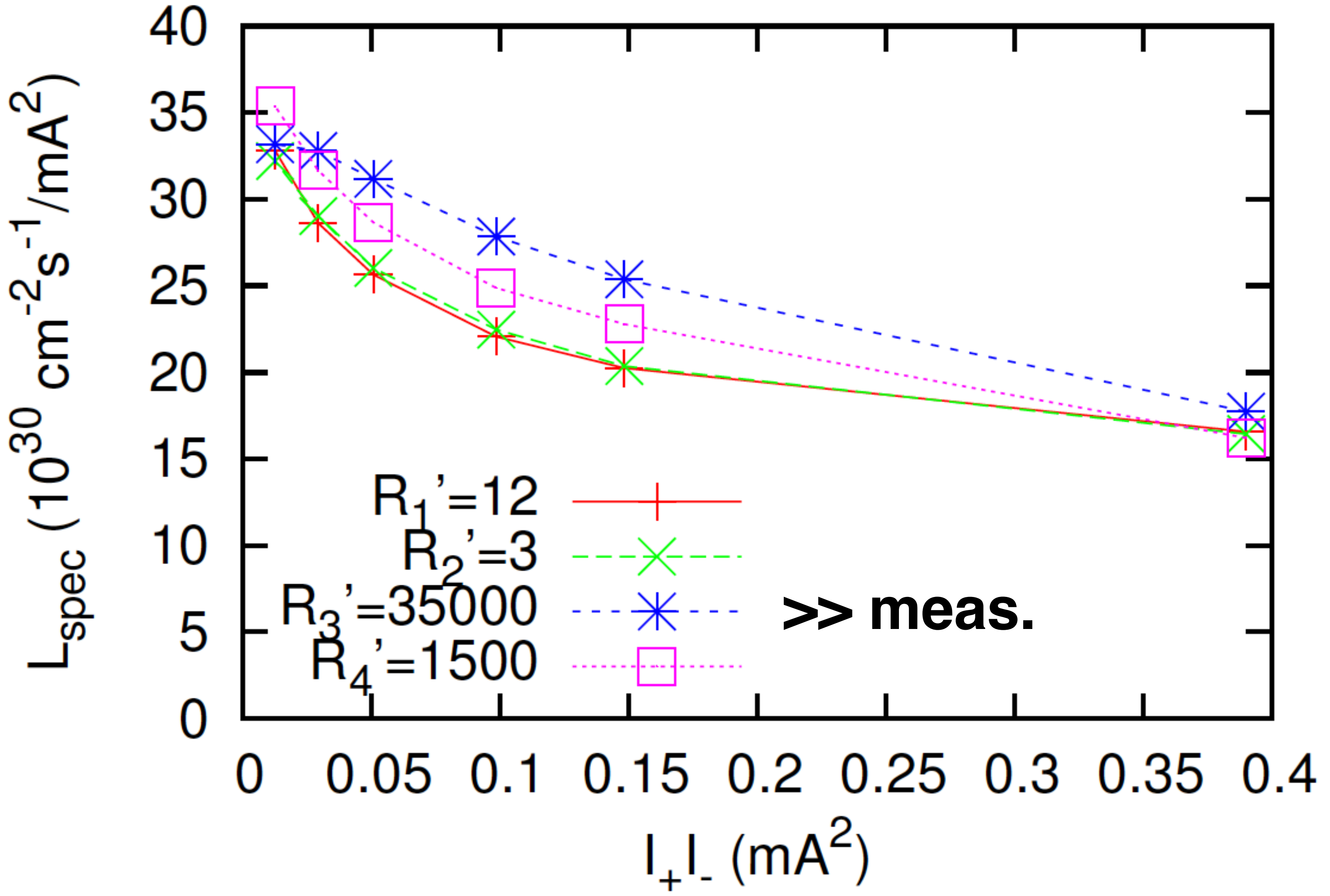
Beam size at IP estimated from X-Ray Monitor

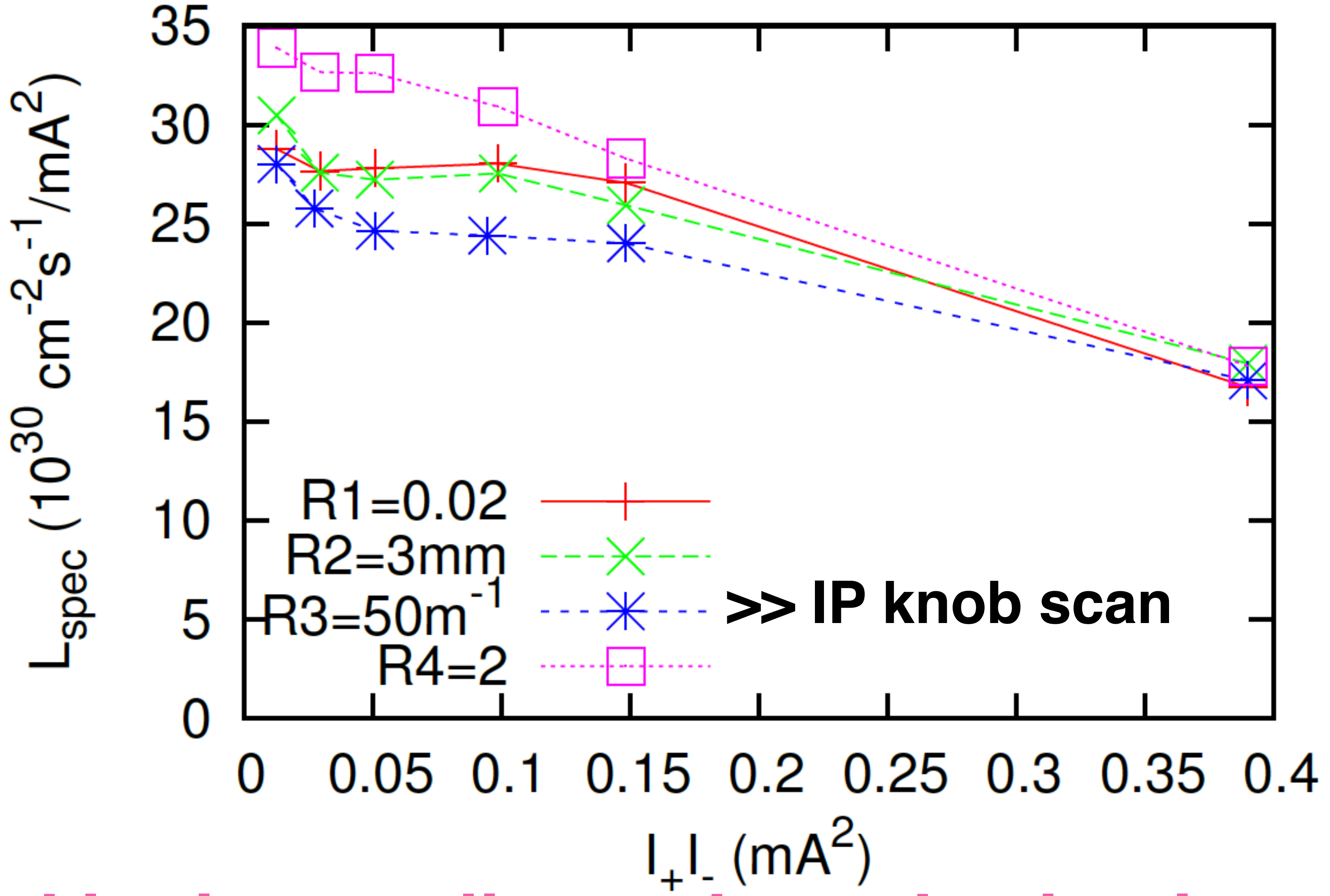


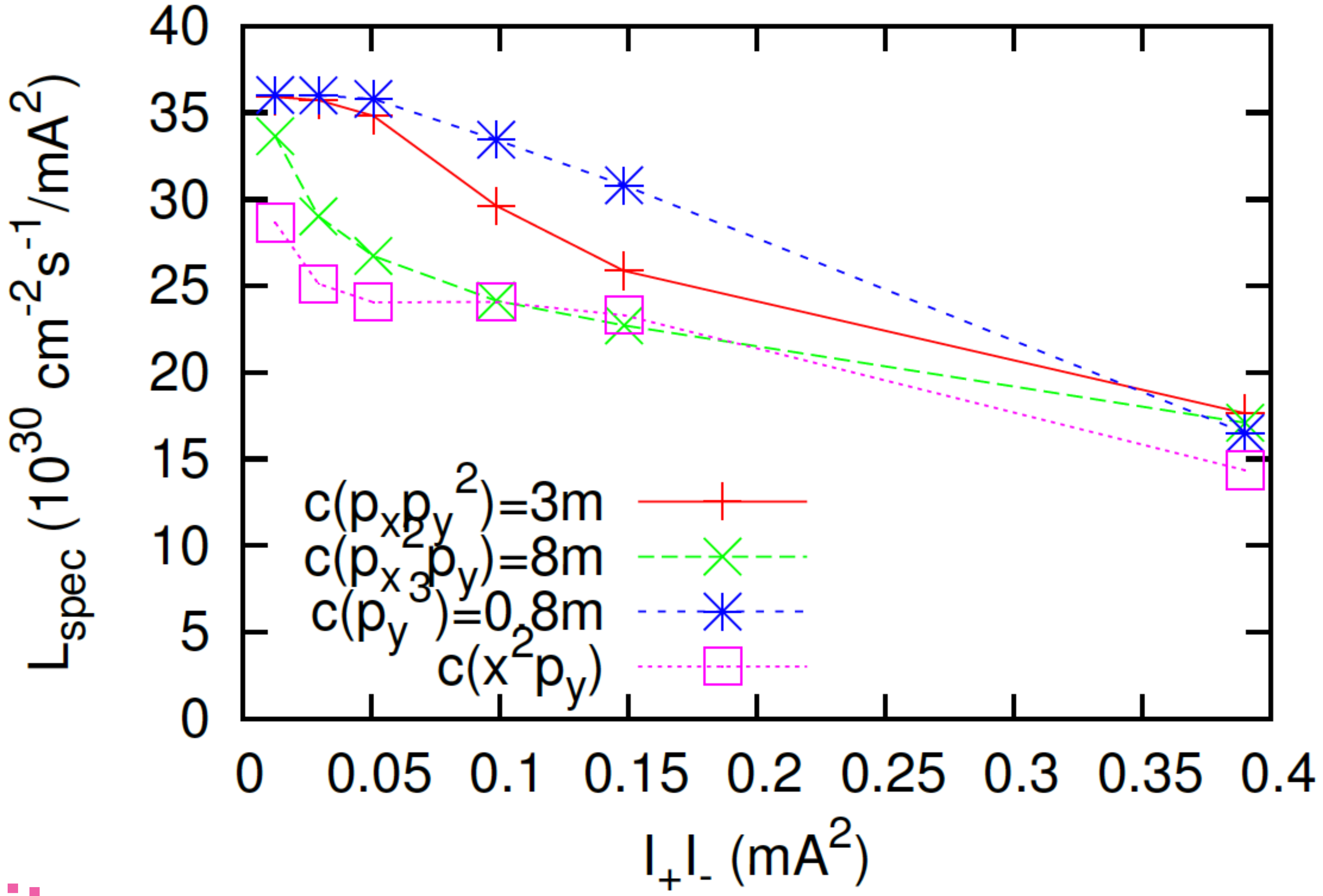
Beam size is large at the low bunch current in LER.
Blowup is also significant at high bunch current.

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

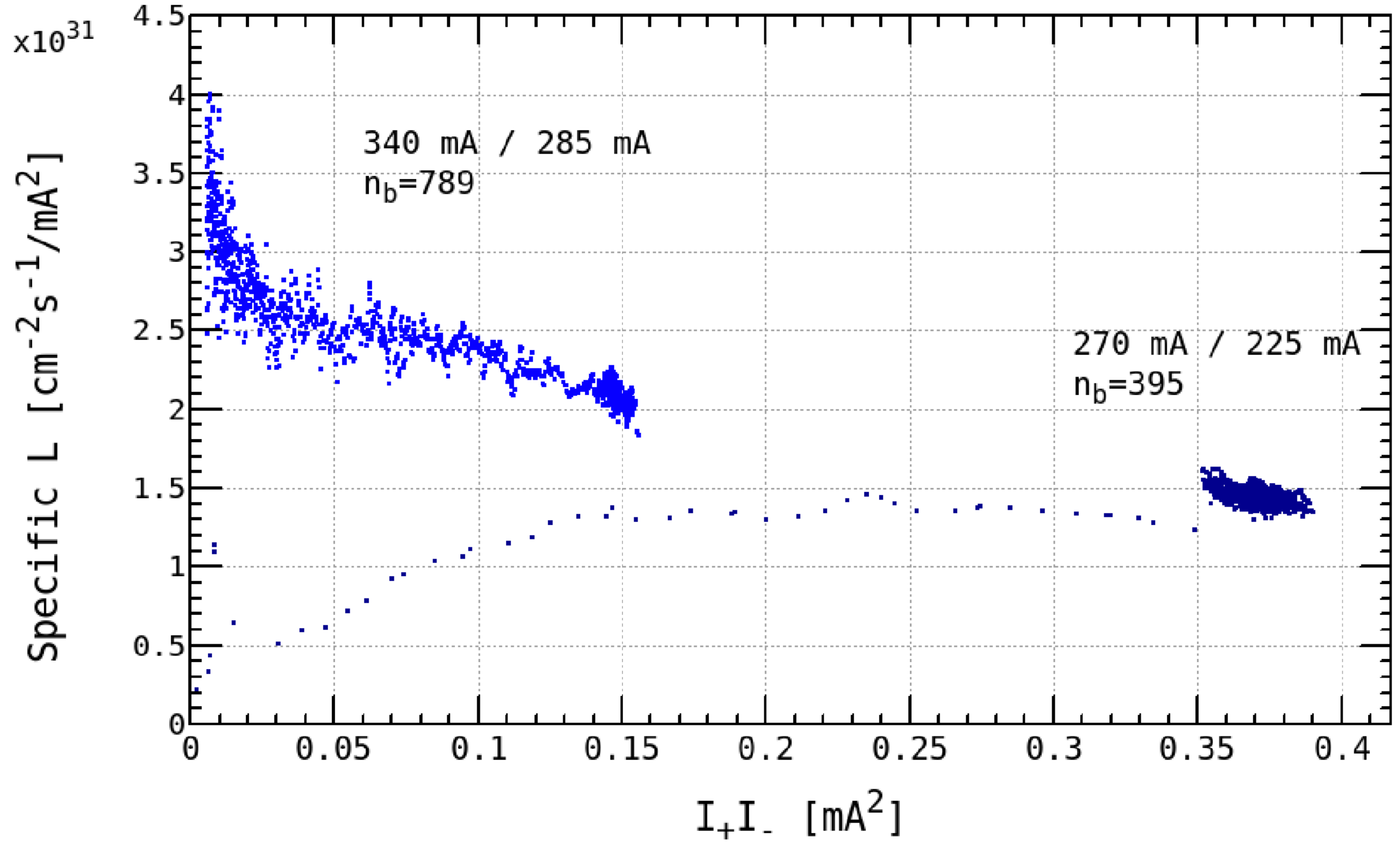
K. Ohmi





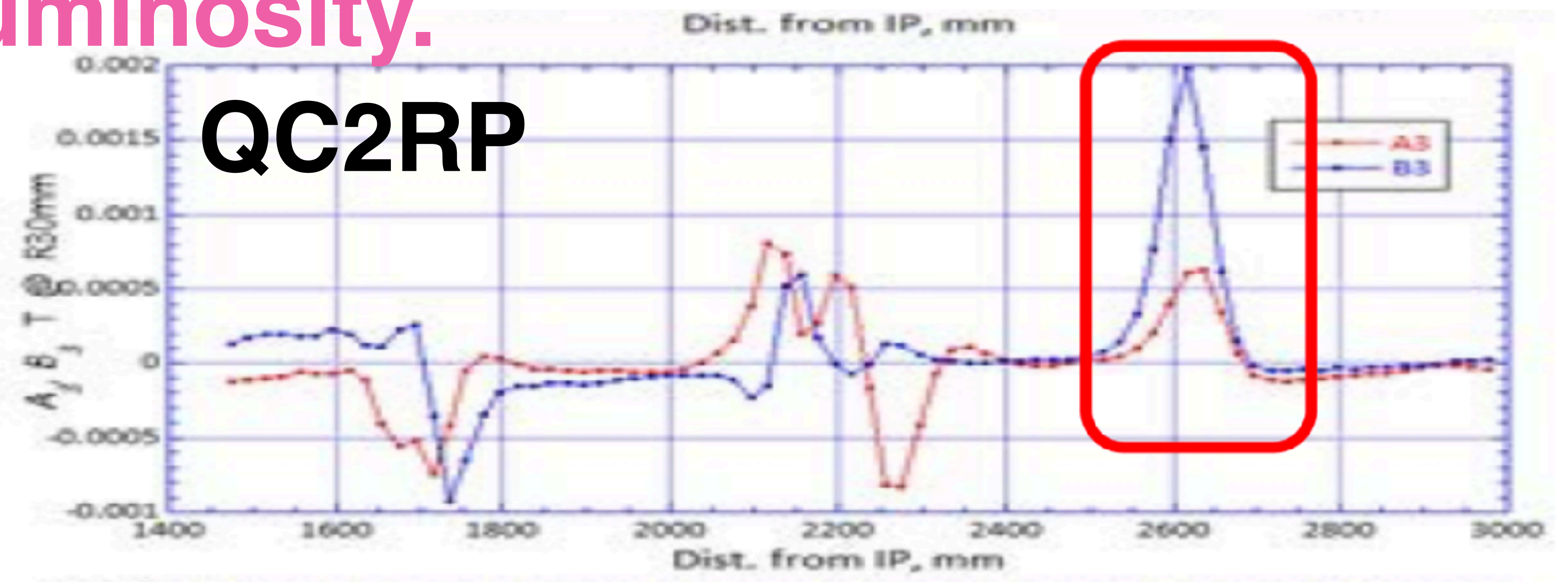


Interference of Beam-Beam and lattice nonlinear degrades luminosity.



measured magnetic field along beam axis (N. Ohuchi)

Error field:
sextupole
skew sextupole
in QCS



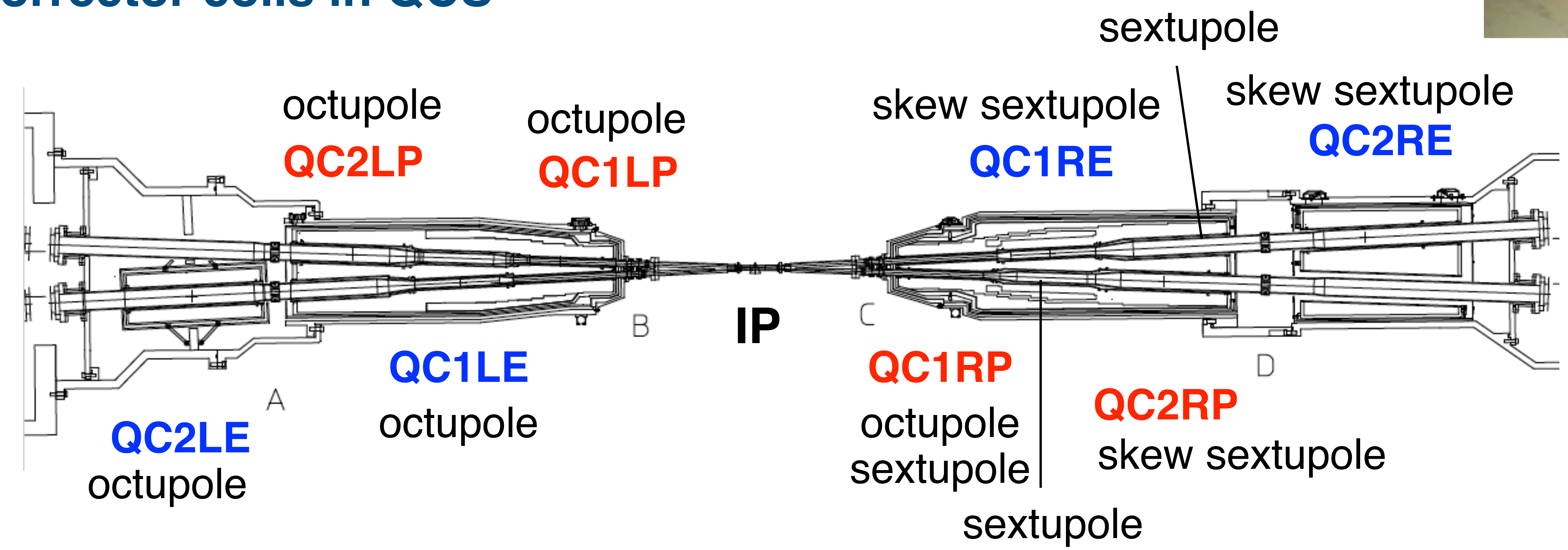
Skew quadrupole corrector coils in QCS (for each main quads.)

Rotatable sextupoles in LER

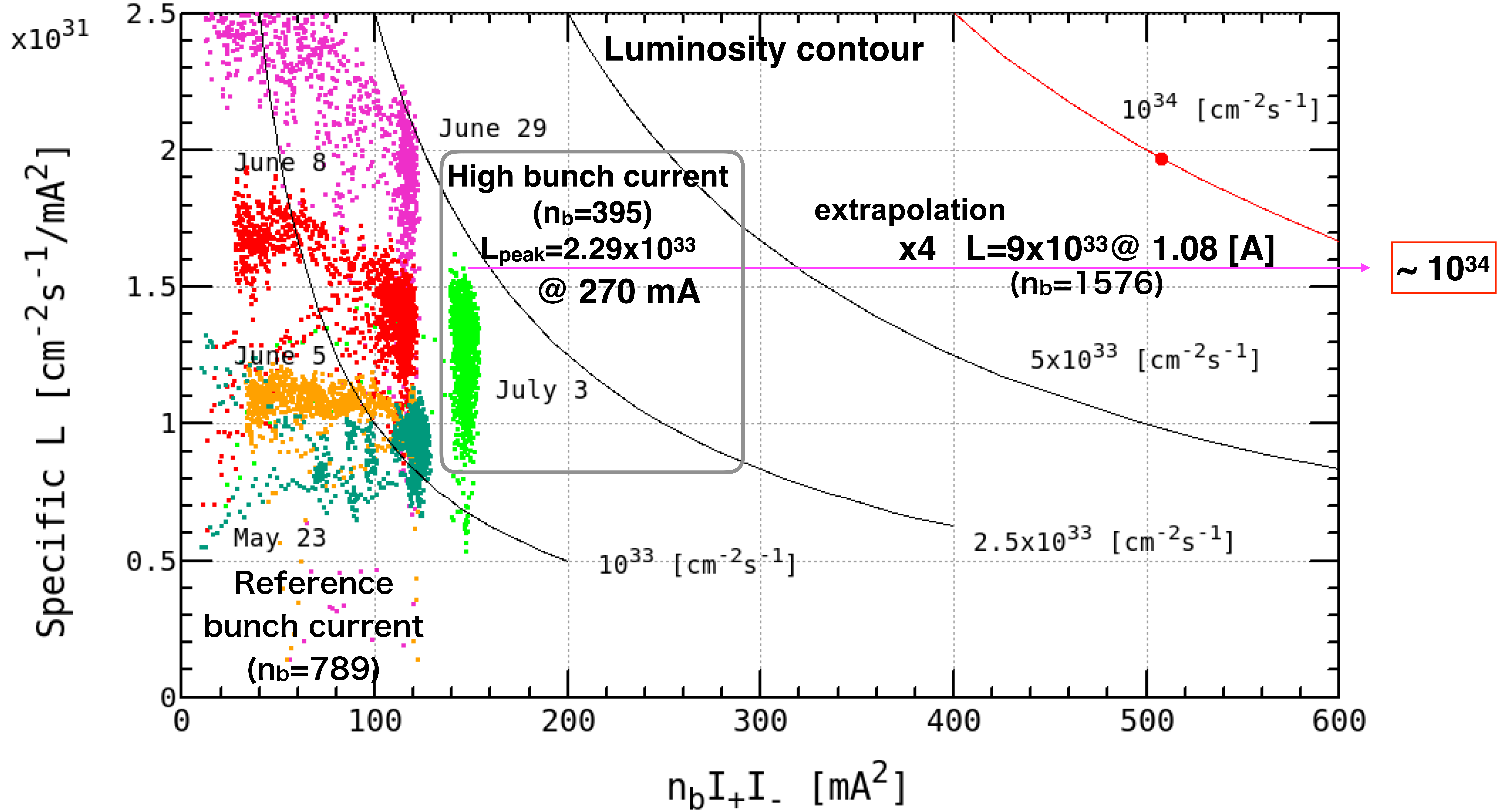
Sextupole corrector coils in QCS

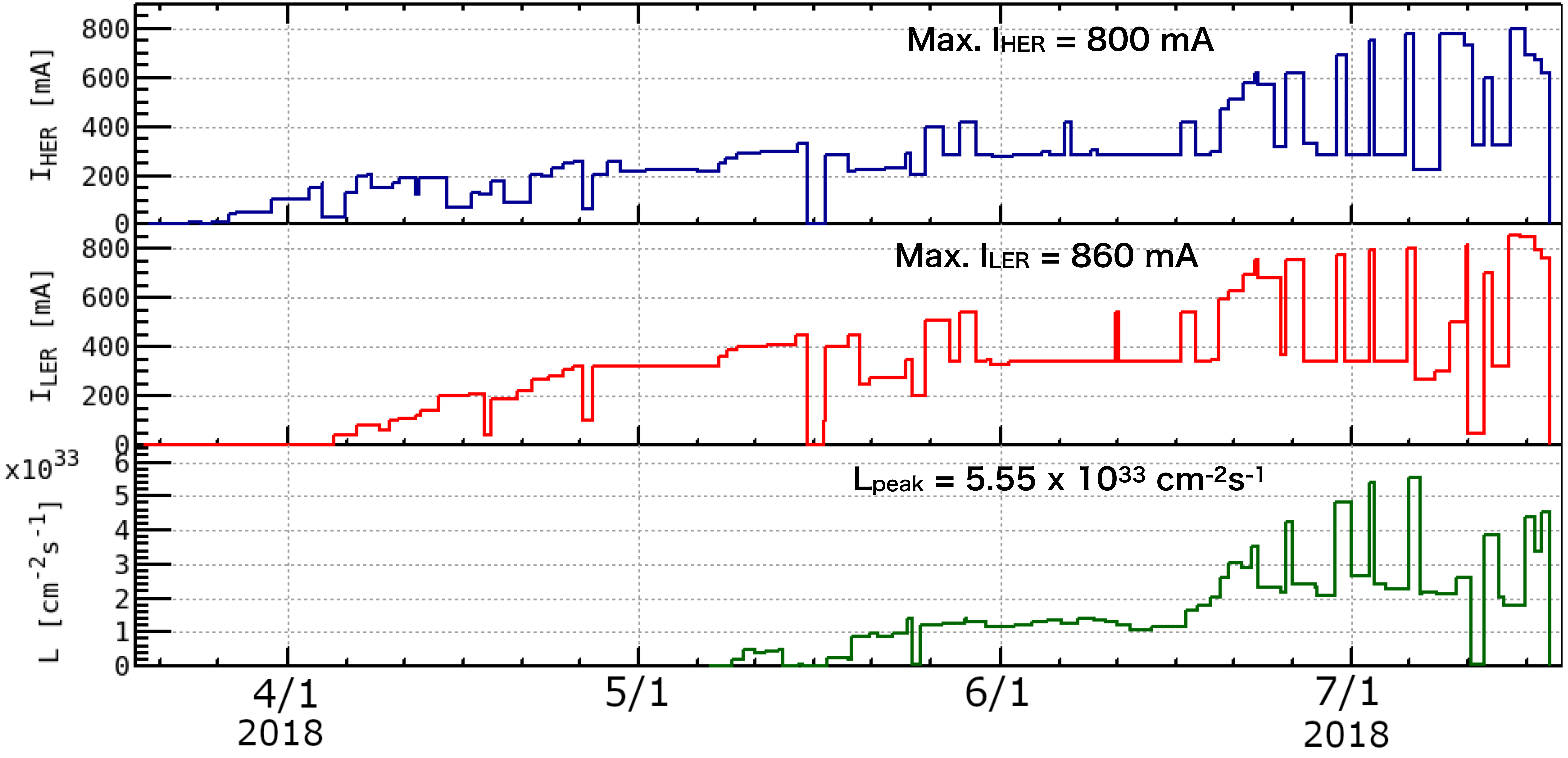
Skew sextupole corrector coils in QCS

Octupole corrector coils in QCS



Specific Luminosity is improving day by day.




Max. IHER = 800 mA
Max. ILER = 860 mA
Lpeak = 5.55 x 1033 cm-2s-1
IHER [mA]
ILER [mA]
L [cm-2s-1]
x1033
0
200
400
600
800
0
1
2
3
4
5
6
4/1
2018
5/1
6/1
7/1
2018

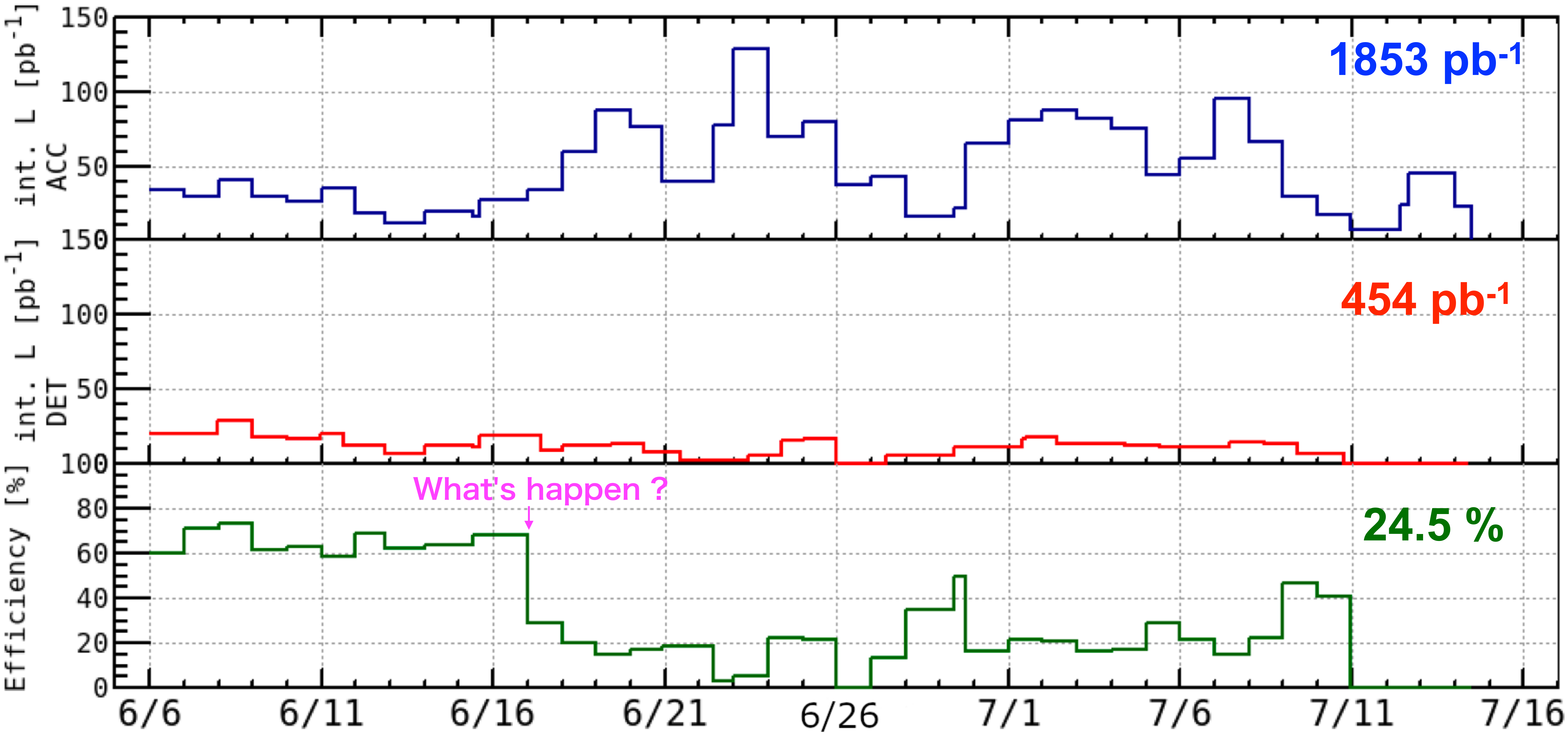
Machine Parameters in Phase 2

	High bunch current		Reference		High current		
	LER	HER	LER	HER	LER	HER	Unit
I @ L_{peak}	**265**	**217**	**327**	**279**	**788**	**778**	mA
n_b	395		789		1576		
I/n_b	0.670	0.549	0.414	0.353	0.500	0.494	mA/bunch
ε_x	1.8	4.6	1.7	4.6	1.7	4.6	nm
β_x^*	200	100	200	100	200	100	mm
β_y^*	**3**	**3**	**3**	**3**	**3**	**3**	mm
ν_x	44.562	45.542	44.558	45.541	44.561	45.545	
ν_y	46.617	43.609	46.615	43.610	46.614	43.612	
σ_y^* (XRM)	883	652	692	486	1285*	528	nm
$\bar{\sigma}_y^* = \Sigma_y^*/\sqrt{2}$	**797**		**552**		**879**		nm
ξ_y	**0.030**	**0.021**	**0.0277**	**0.0186**	**0.0244**	**0.0141**	
L	**2.29 x 10^{33}**		2.62 x 10^{33}		5.55 x 10^{33}		$cm^{-2}s^{-1}$

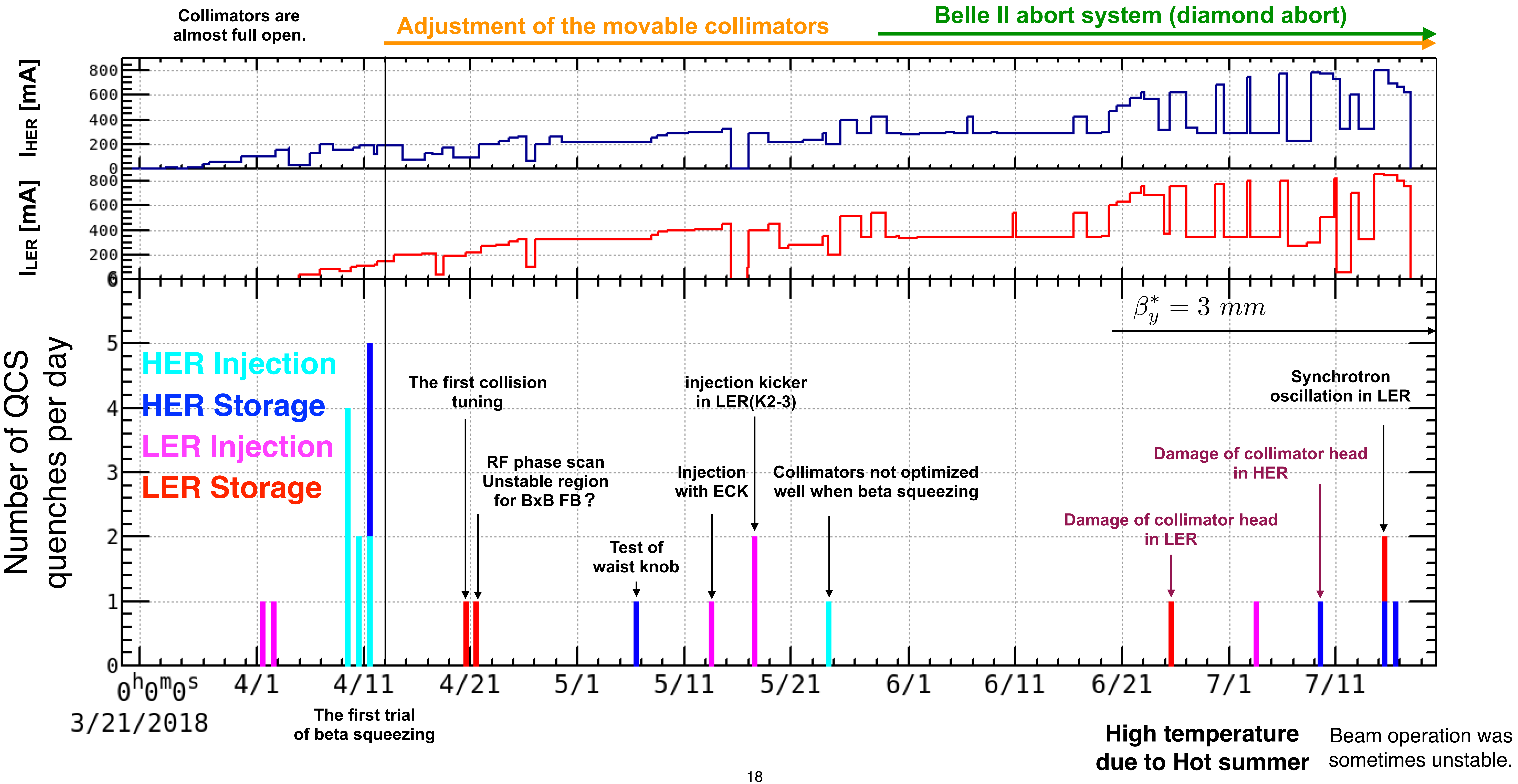
test of luminosity performance — typical physics run — *ε_y enhancement in LER

Daily Integrated Luminosity in Phase 2 (0 - 9am for 40 days)

ONLINE Data

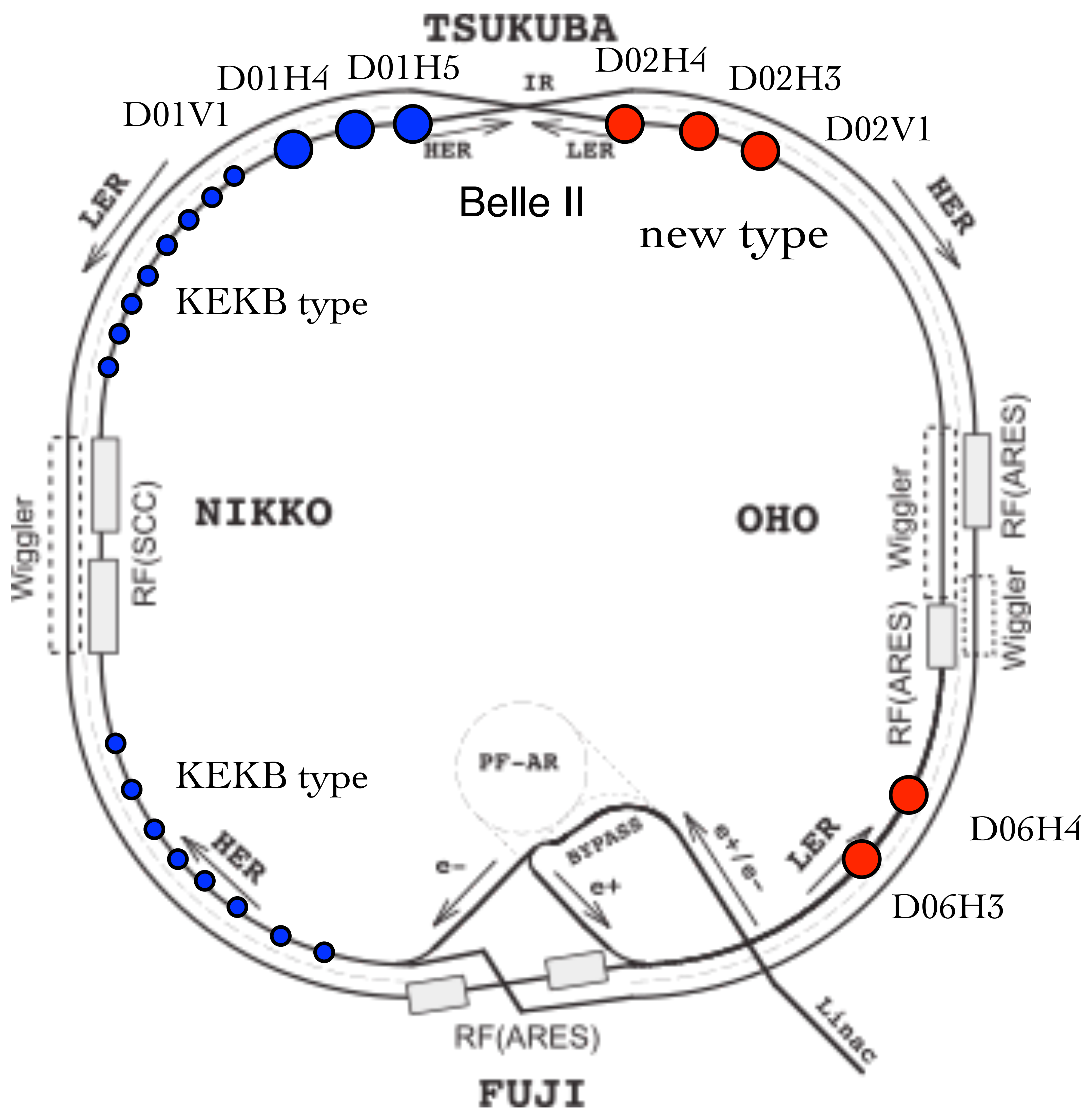


Issues in Phase 2


Collimators are almost full open.
Adjustment of the movable collimators
Belle II abort system (diamond abort)
I_HER [mA]
I_LER [mA]
Number of QCS quenches per day
HER Injection
HER Storage
LER Injection
LER Storage
$\beta_y^* = 3\ mm$
The first collision tuning
RF phase scan Unstable region for BxB FB ?
Test of waist knob
Injection with ECK
injection kicker in LER(K2-3)
Collimators not optimized well when beta squeezing
Damage of collimator head in LER
Damage of collimator head in HER
Synchrotron oscillation in LER
0h0m0s 3/21/2018
4/1
4/11
4/21
5/1
5/11
5/21
6/1
6/11
6/21
7/1
7/11
The first trial of beta squeezing
High temperature due to Hot summer
Beam operation was sometimes unstable.

Damage of Movable Collimator (Head)

Compromise lifetime, injection, and detector background.

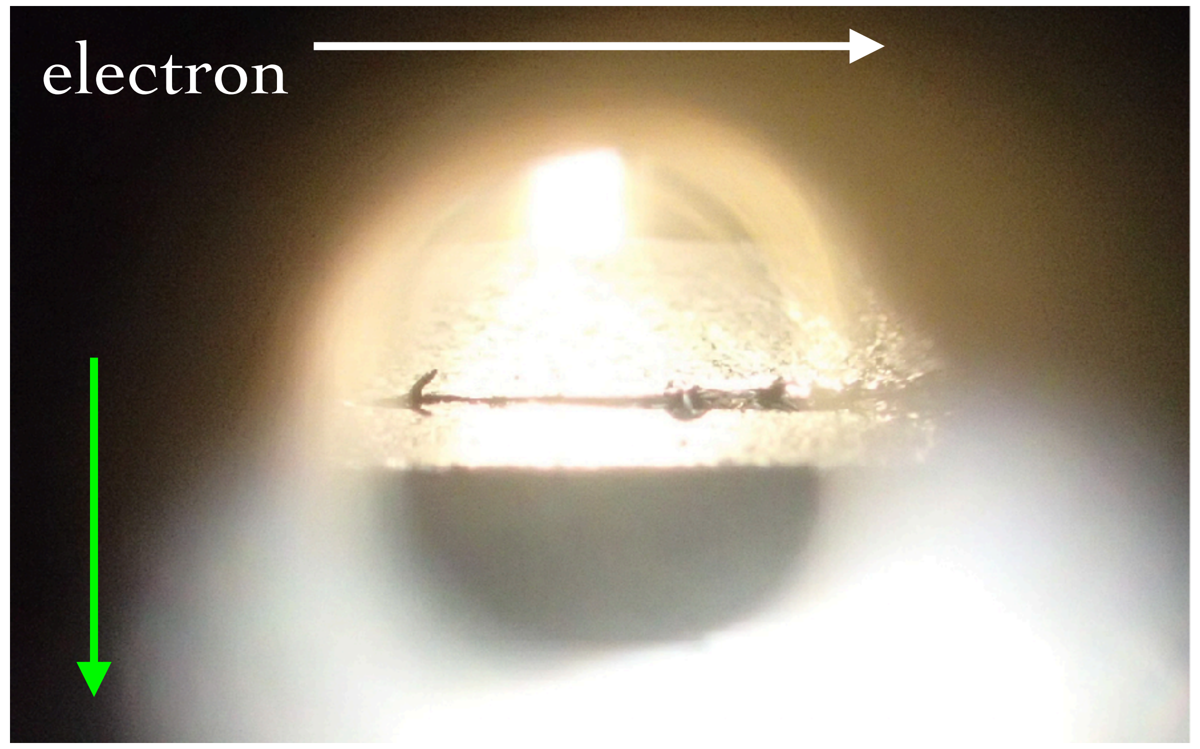


Number of movable collimators is small in LER.
Especially, only one in the vertical.

Vertical Collimator

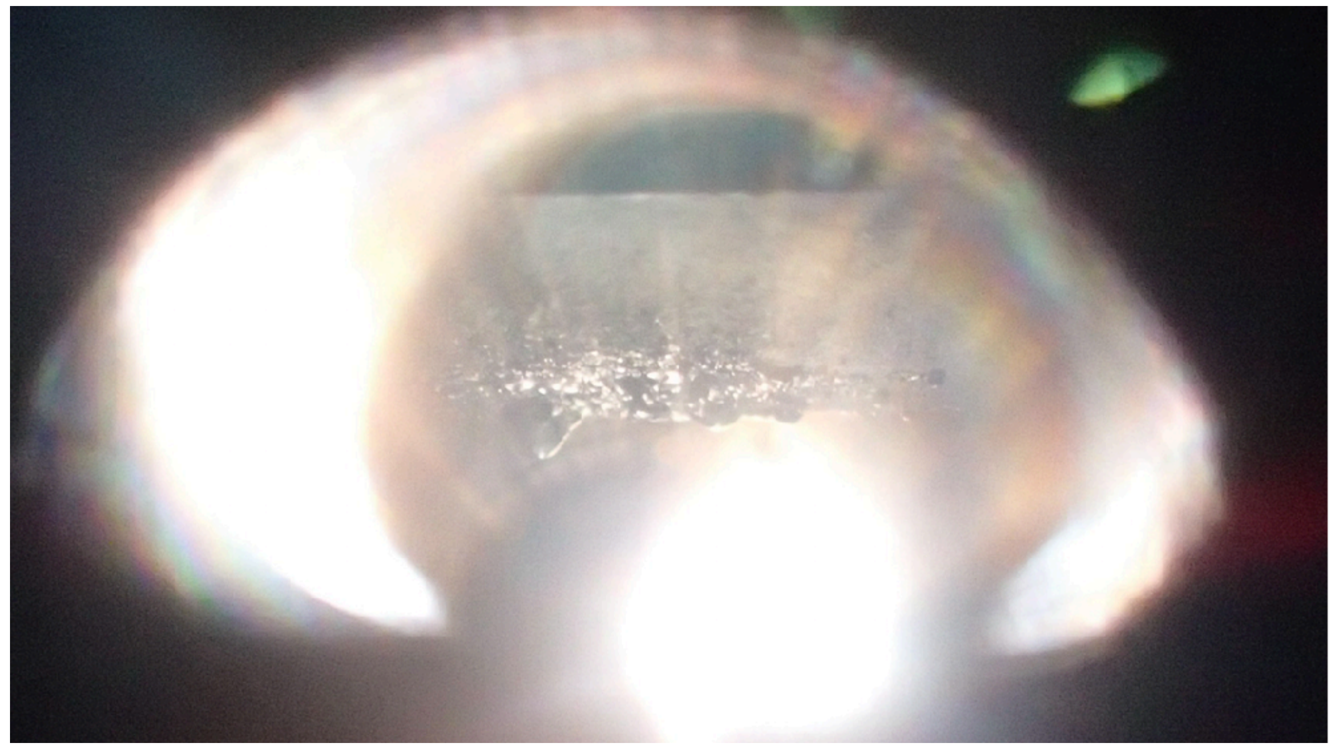
LER

Bottom

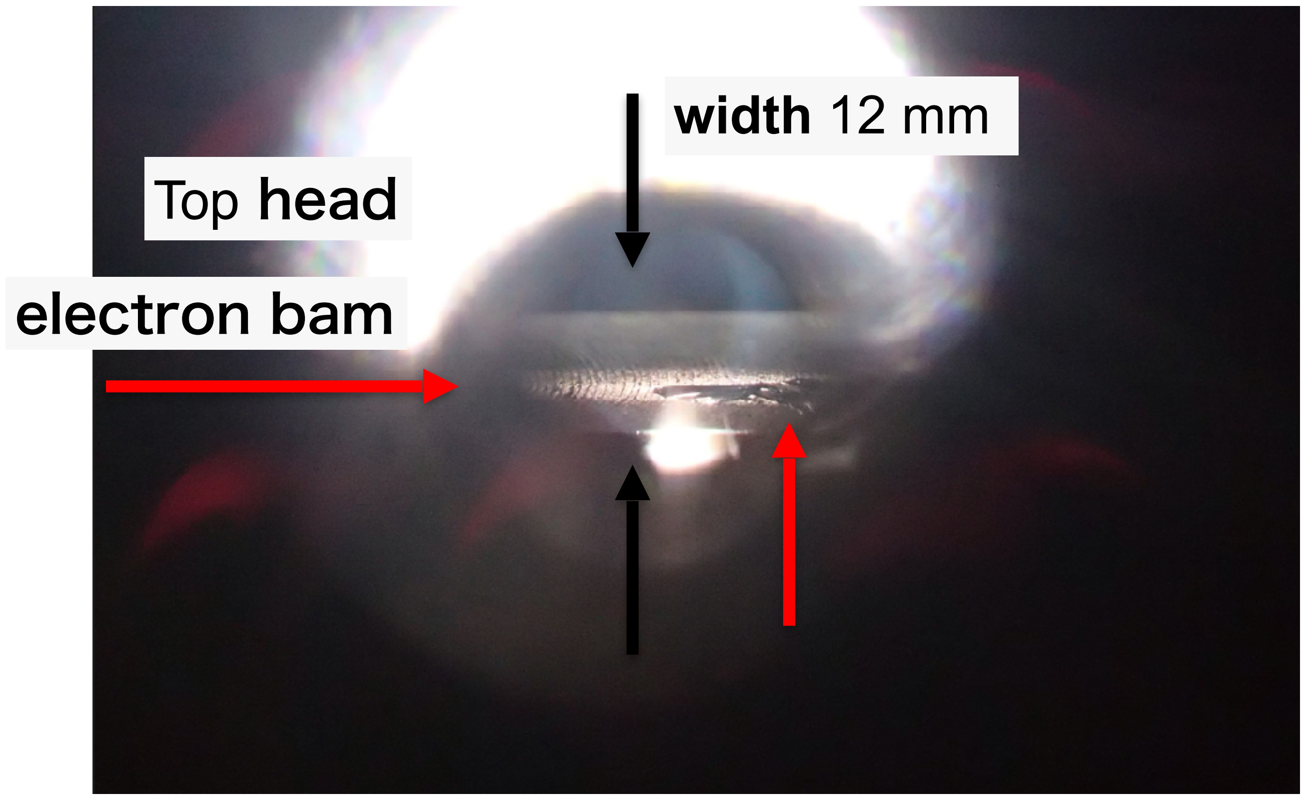


outer of the ring

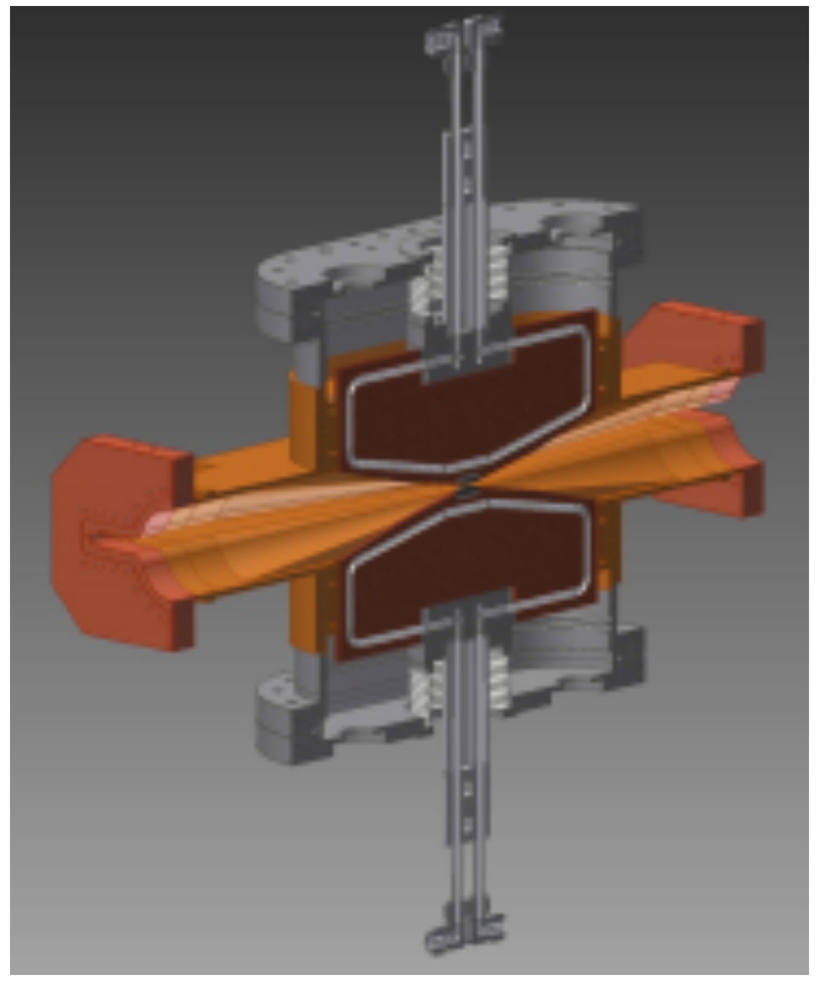
Top



HER

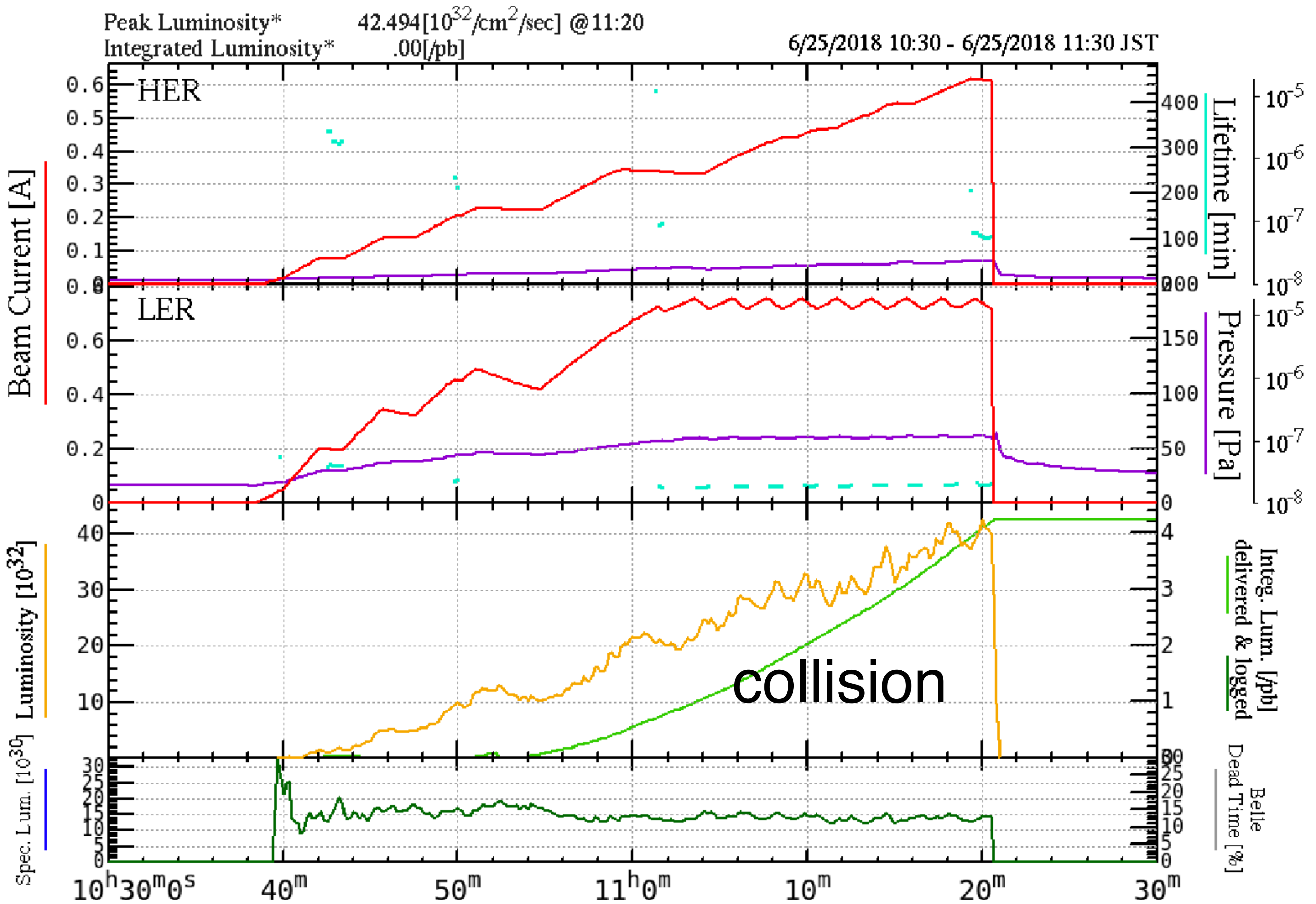


New collimator (SLAC type)



Y. Suetsugu, T. Ishibashi, S. Terui

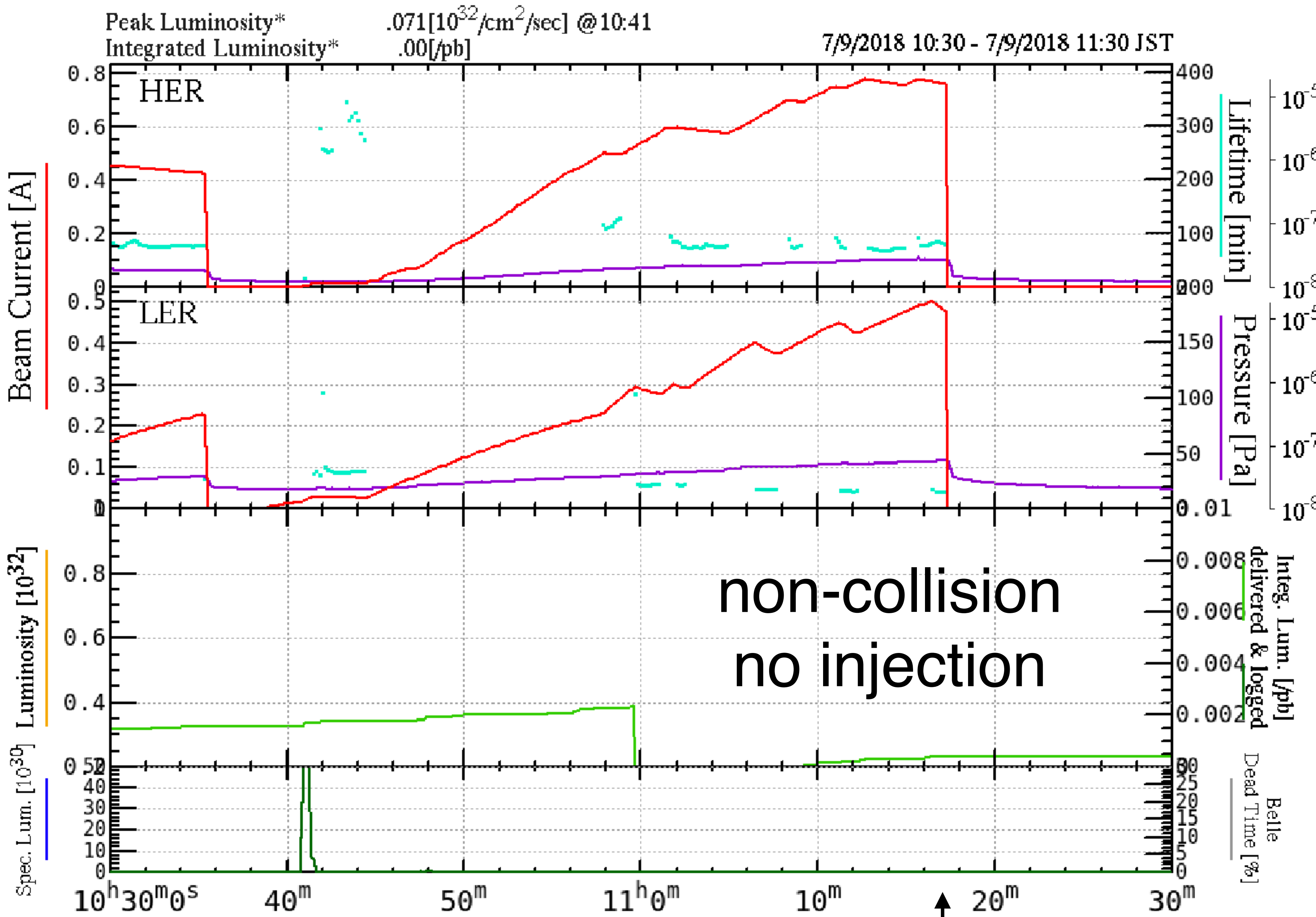
Incident of Collimator Damage



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

Summary

Beckoning cat (Fortune cat)

It is believed to draw happiness and customers.
"luminosity"

... To be continued in Phase 3

Appendix

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 ➡ (However) $L \rightarrow$ 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

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

However

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

Luminosity

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

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

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

However

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

Luminosity

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

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

Beam-Beam Parameter

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

However

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

Luminosity

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

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

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

However

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

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

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

Beam-Beam Parameter

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

However

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

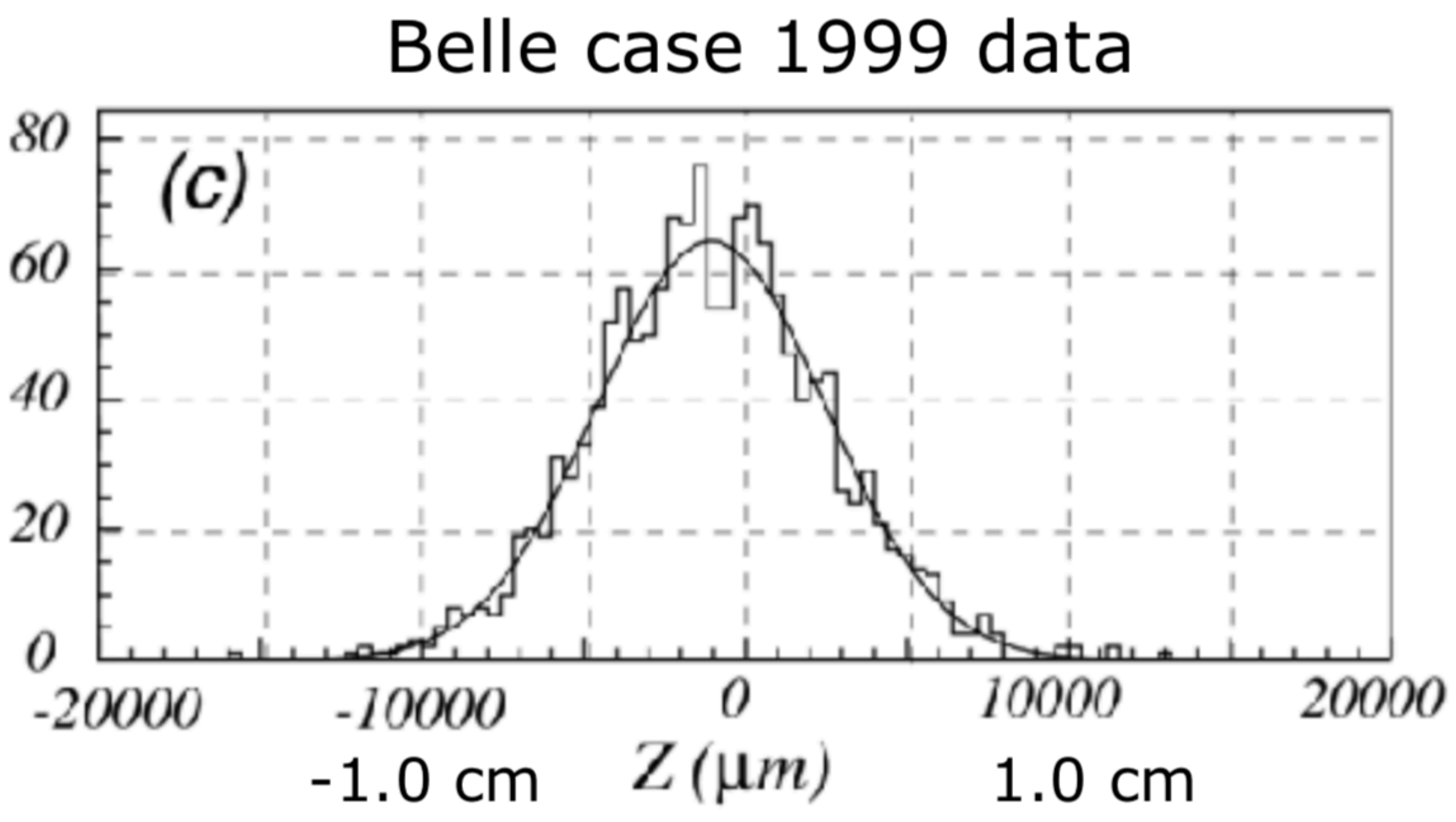
Luminosity

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

$\varepsilon_y \rightarrow$ small

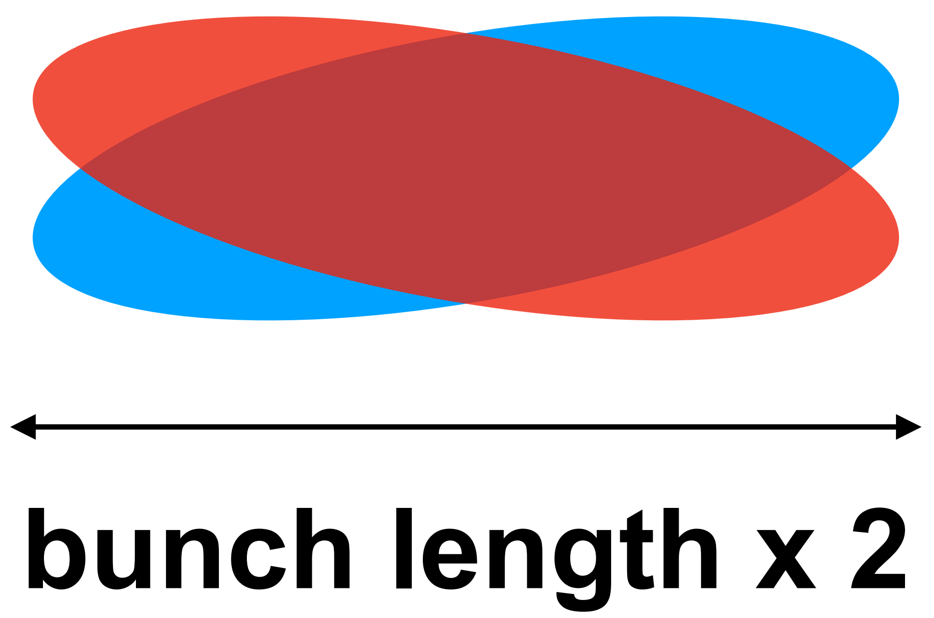
Final Target $I_\pm \rightarrow \times 2$ $\beta^*_y \rightarrow \times 1/20$ $\xi_y \rightarrow \times 1$ ⇒ $L \rightarrow \times 40$

Ordinary collision (KEKB)

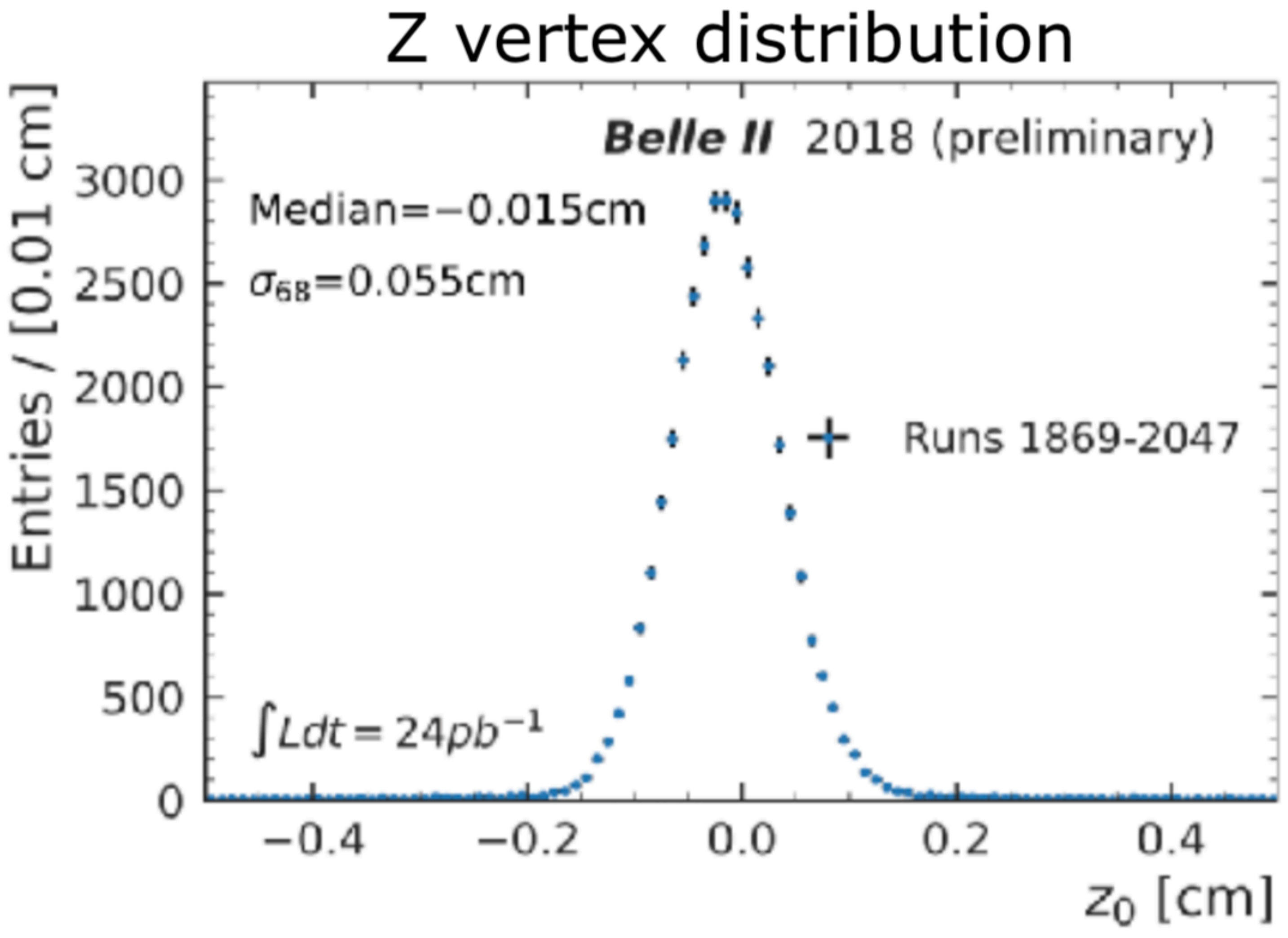


σ = 4.5 mm

measurement at Belle

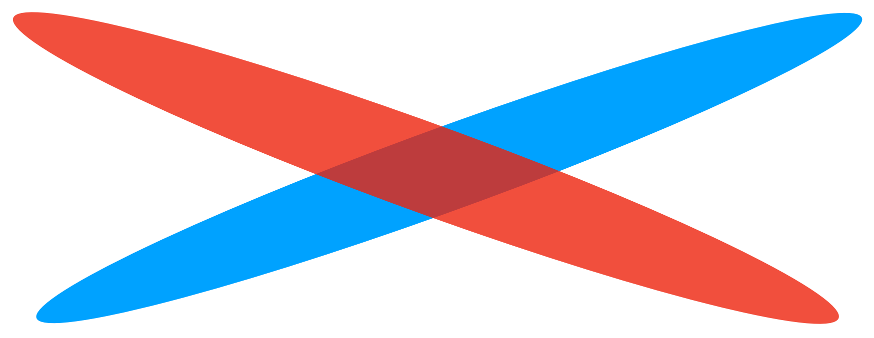


Nano-Beam (SuperKEKB Phase2)



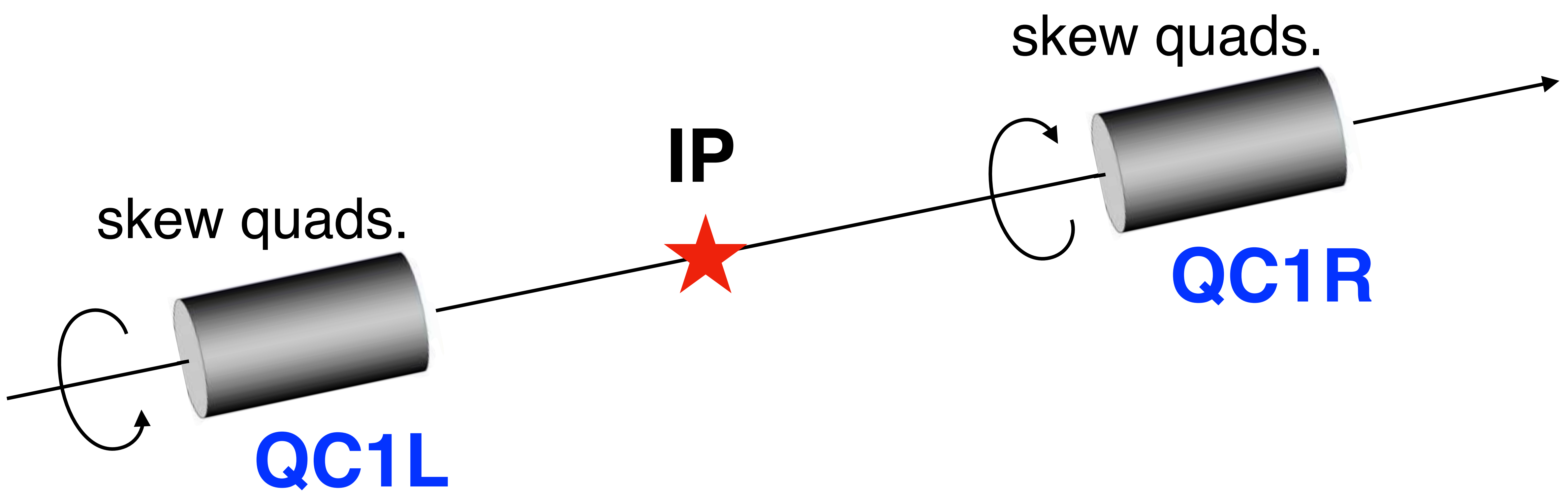
σ = 550 μm

measurement at Belle II



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

I. Adachi, T. Iijima

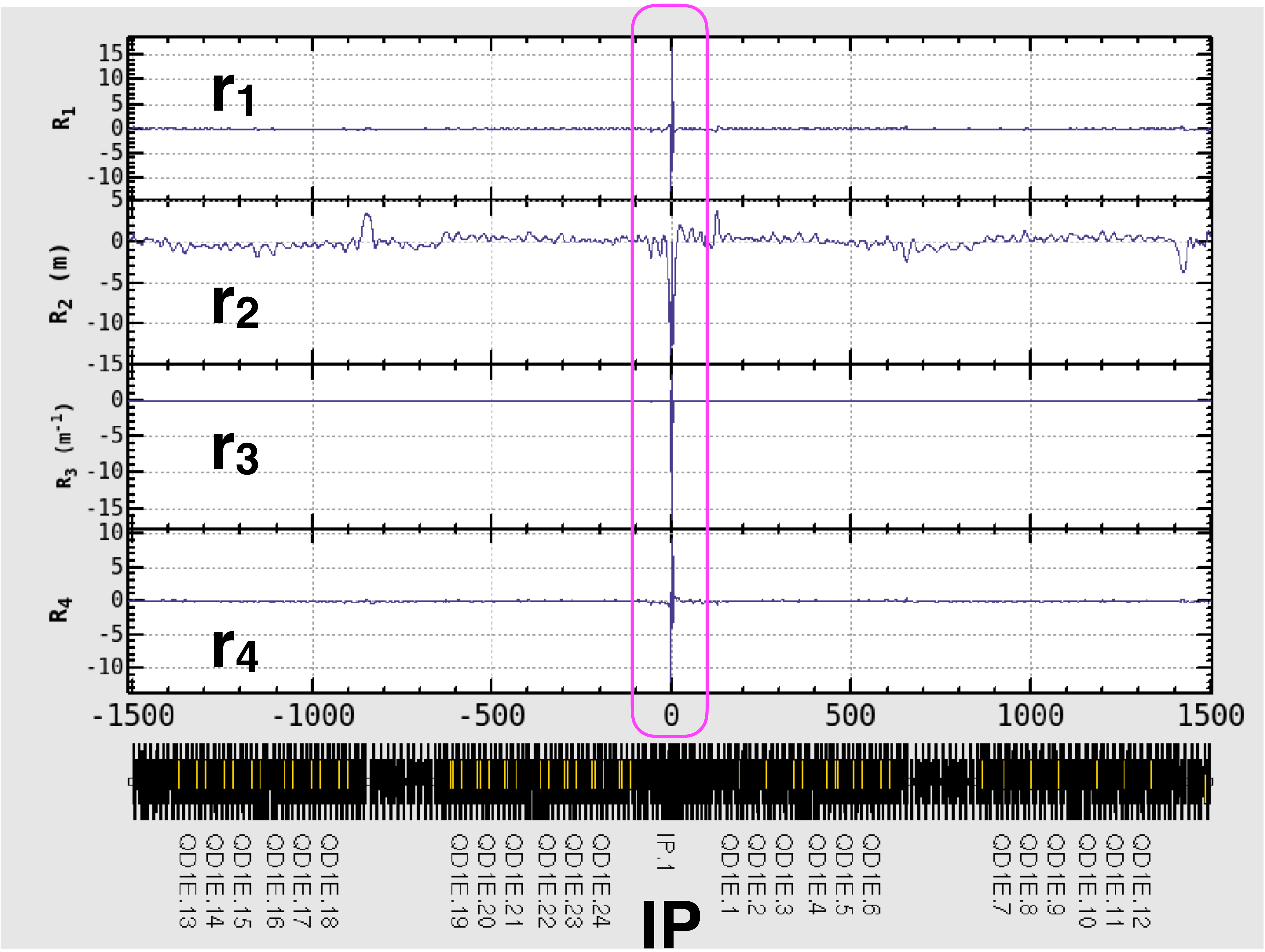


The same amount of rotation does not affect arc sections.

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

XY coupling at IP remains locally.

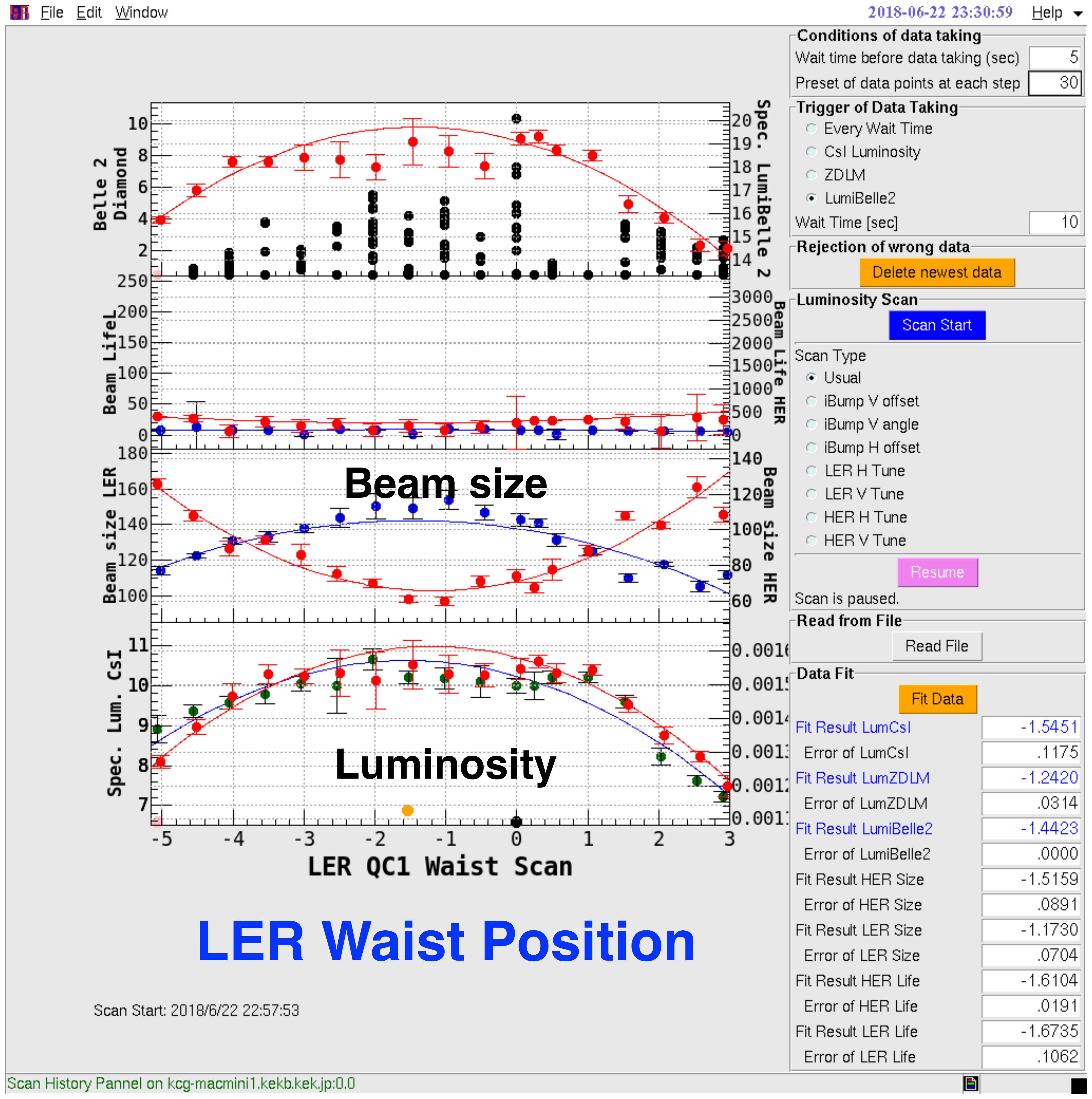
XY couplings



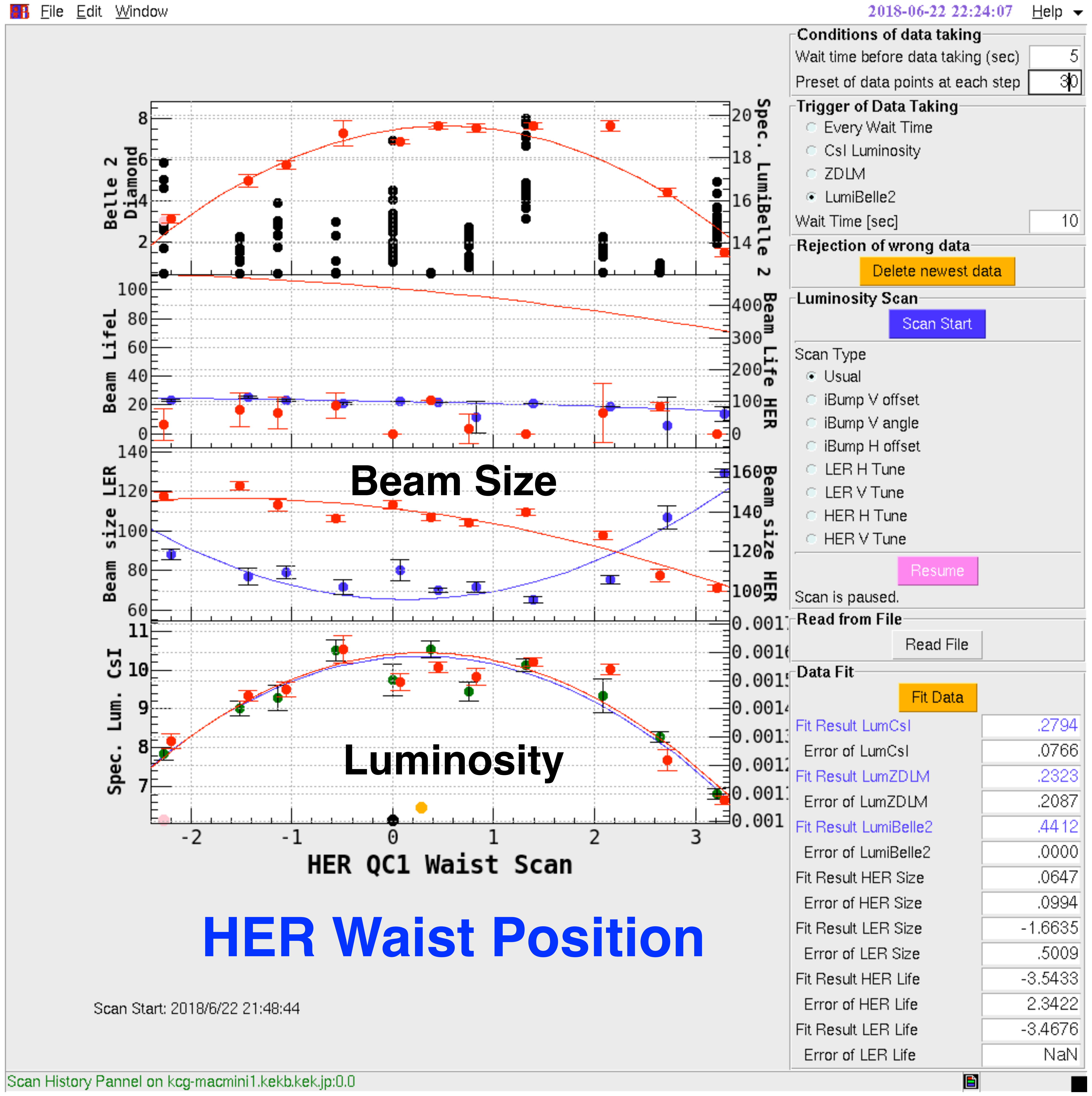
Skew quads in QCS can be used to correct the local XY couplings.

Waist Scan by using QC1

LER Δs = -1.14 mm



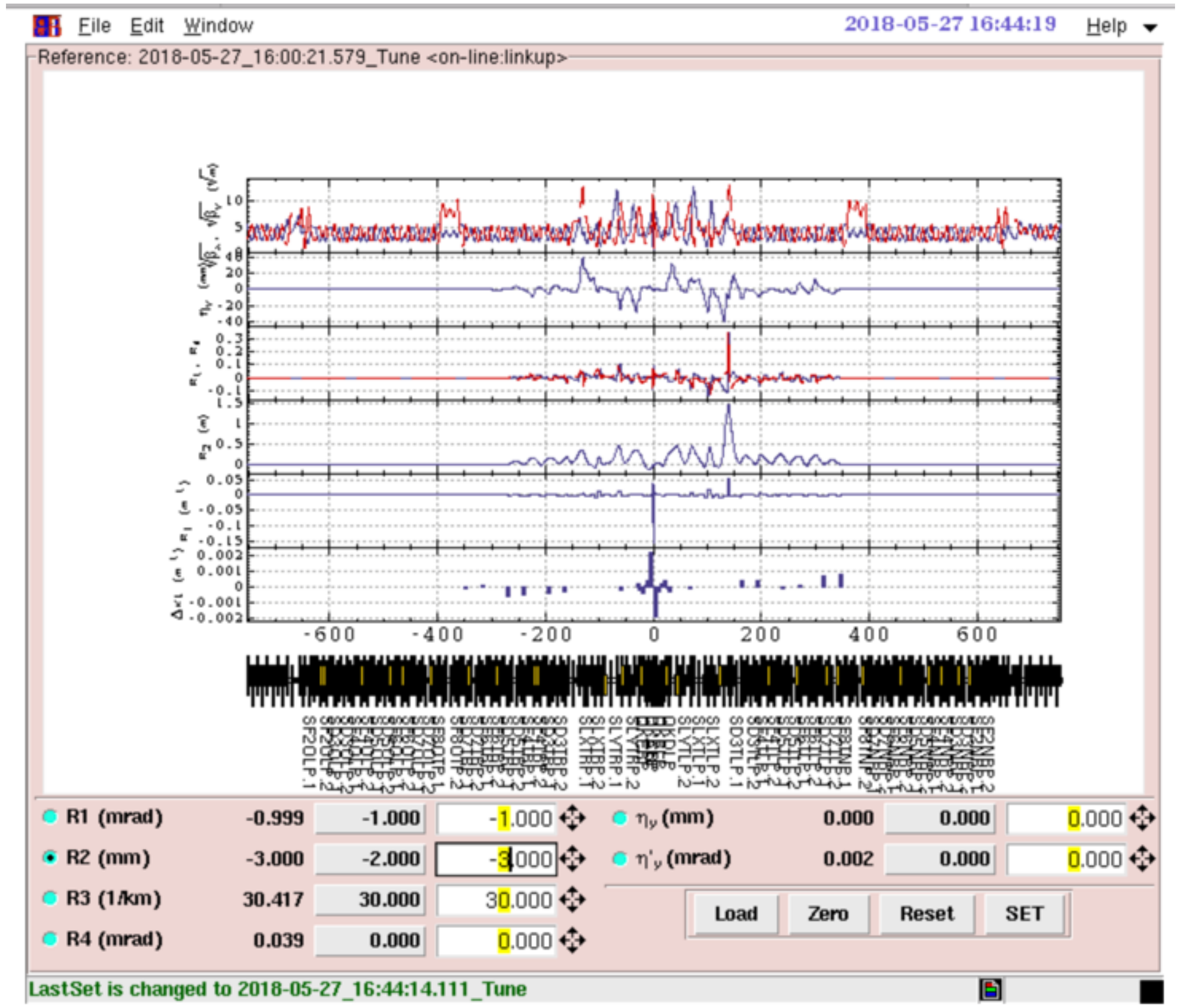
HER Δs = +0.4 mm



A. Morita, Y. Funakoshi

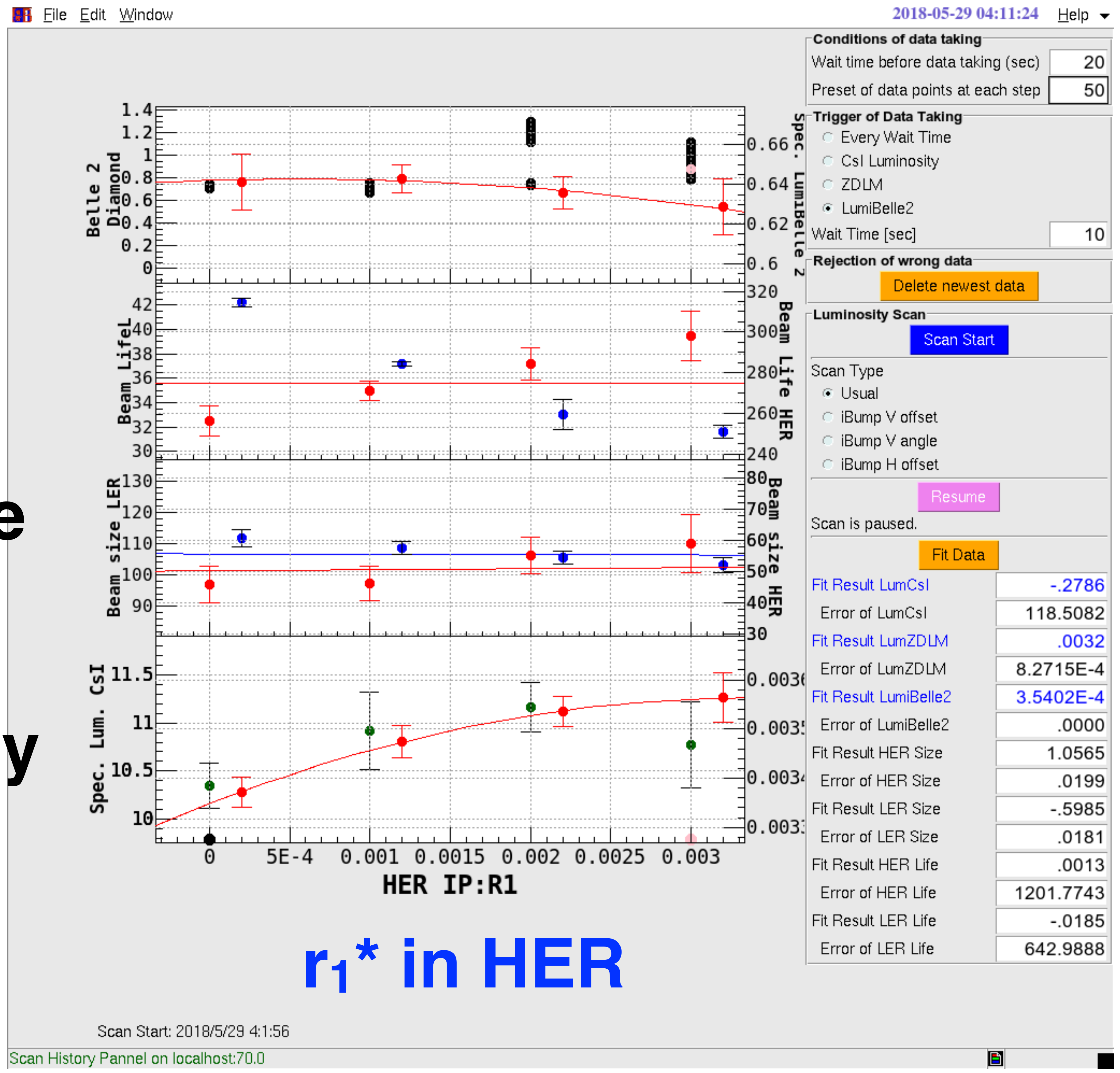
IP XY coupling knob and dispersion knob

Skew quadrupole coils at sextupoles are utilized.



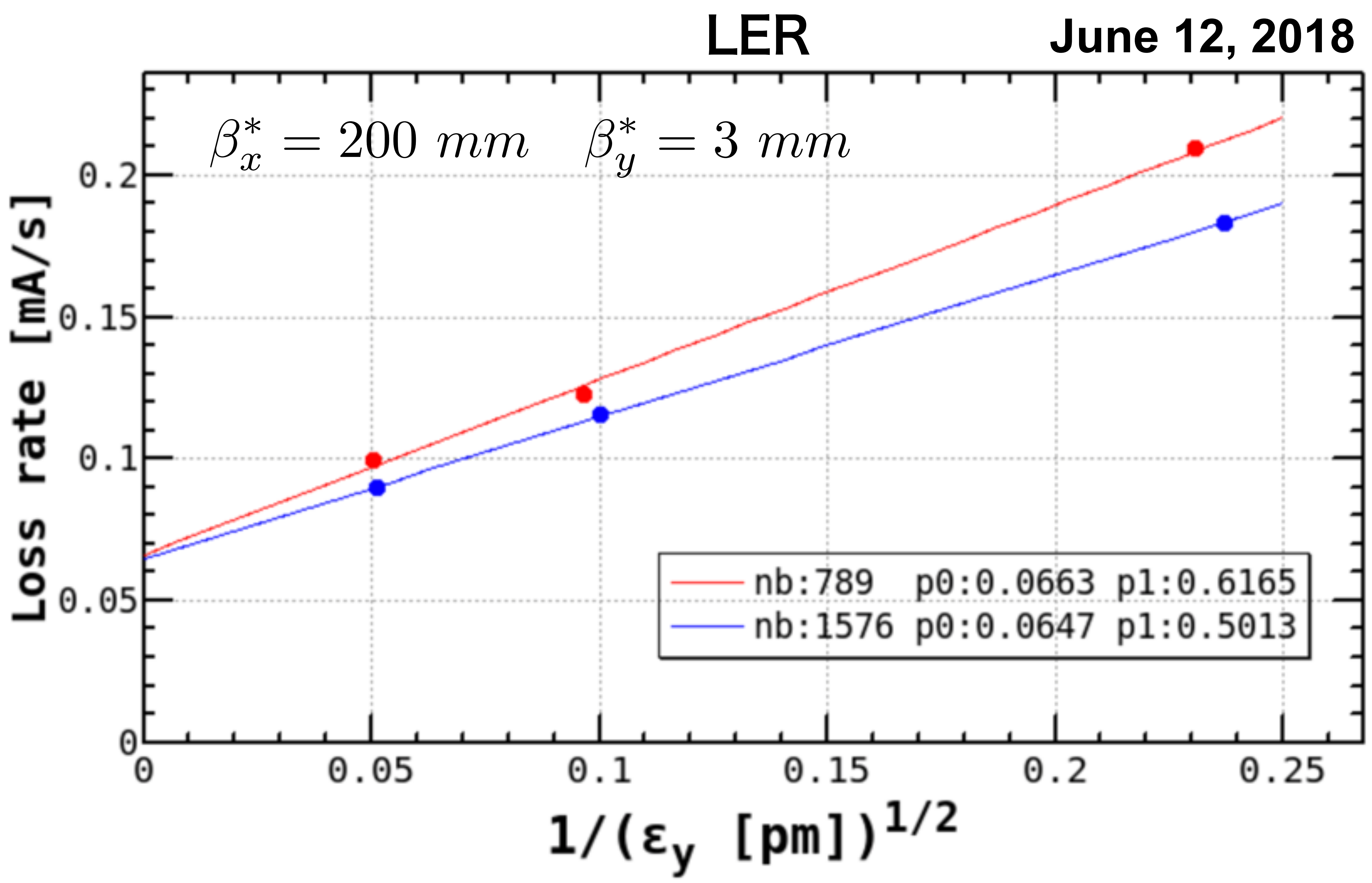
Beam size (XRM)

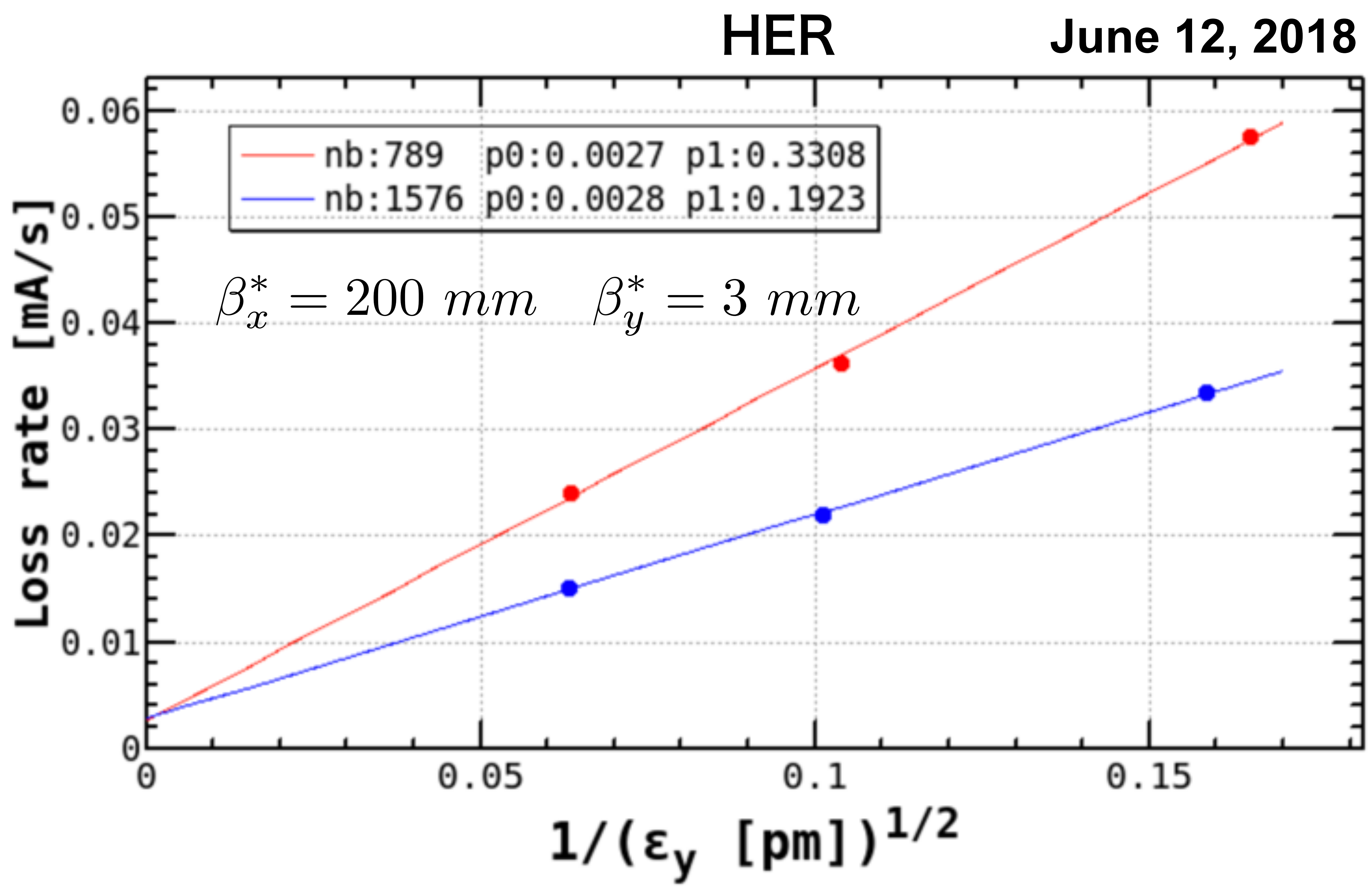
Luminosity



r_1* in HER

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.

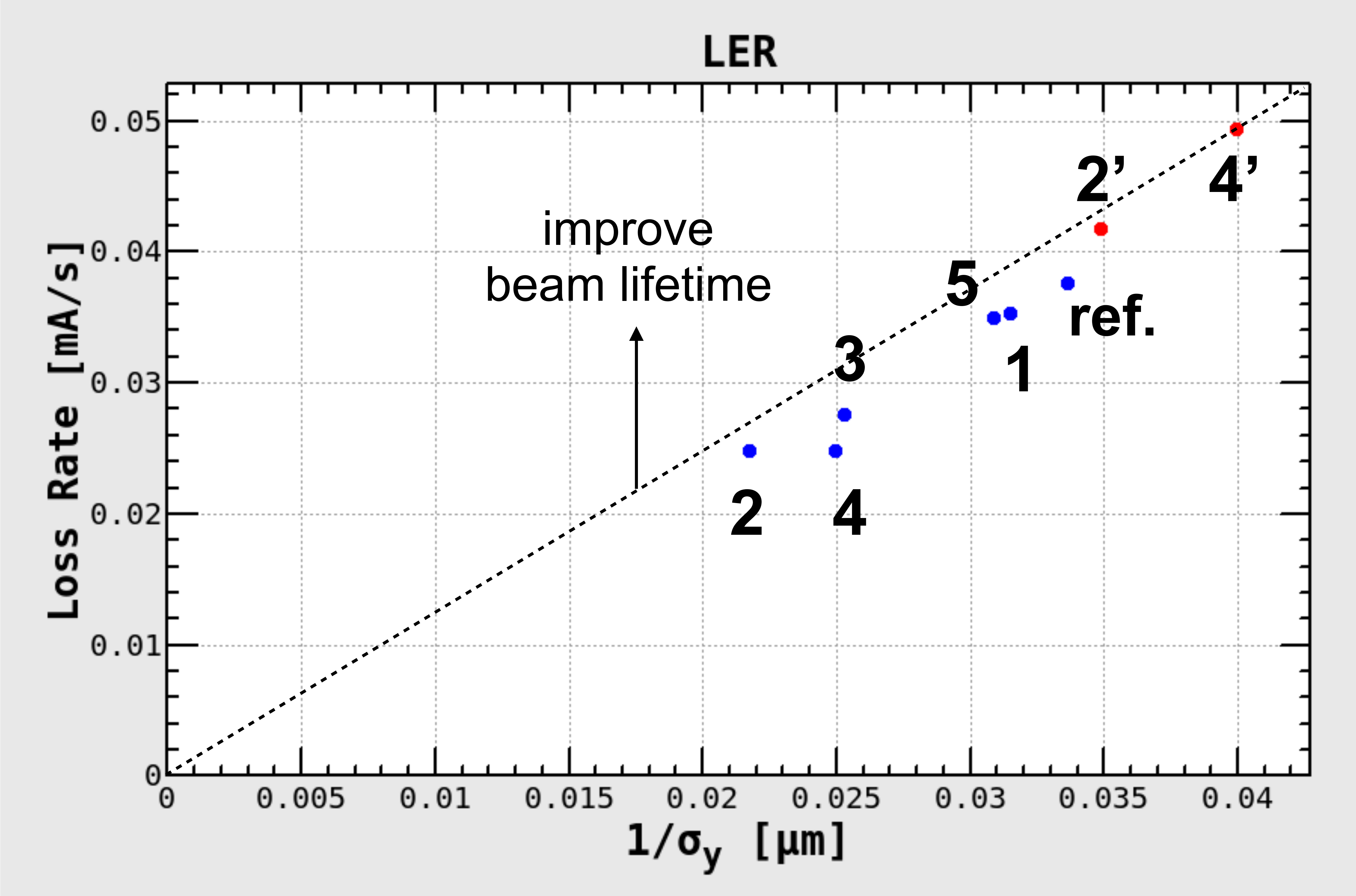
Movable collimators to reduce background and avoid QCS quench

ε_y is controlled by vertical dispersions.

Sextupole Tuning and Beam Lifetime

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

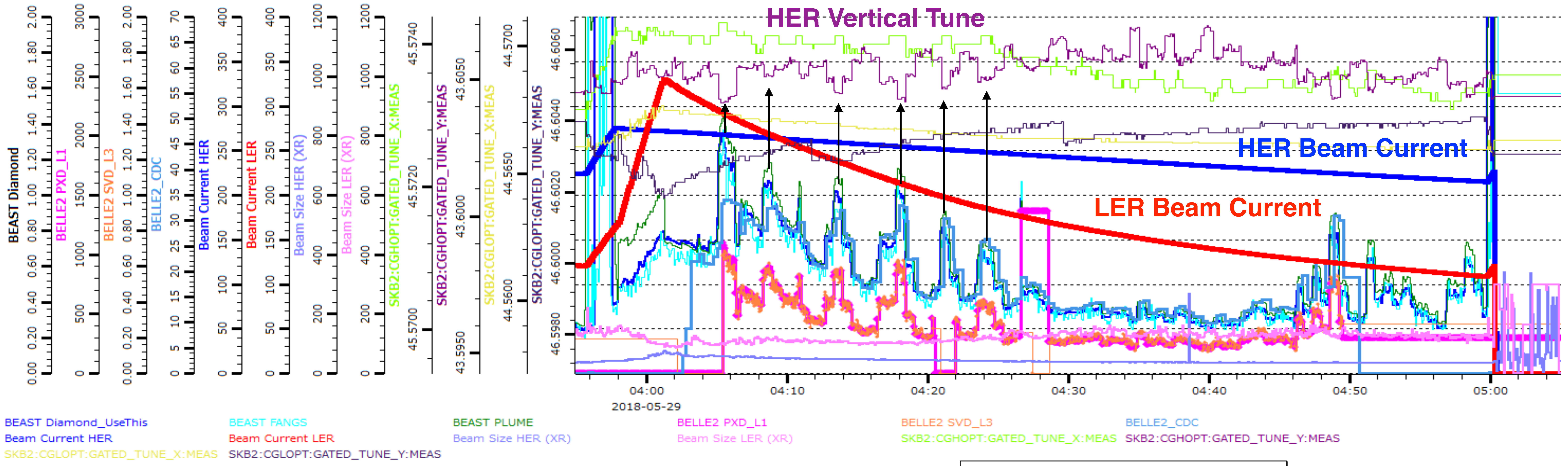
← Beam size larger **Beam size smaller →**

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

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

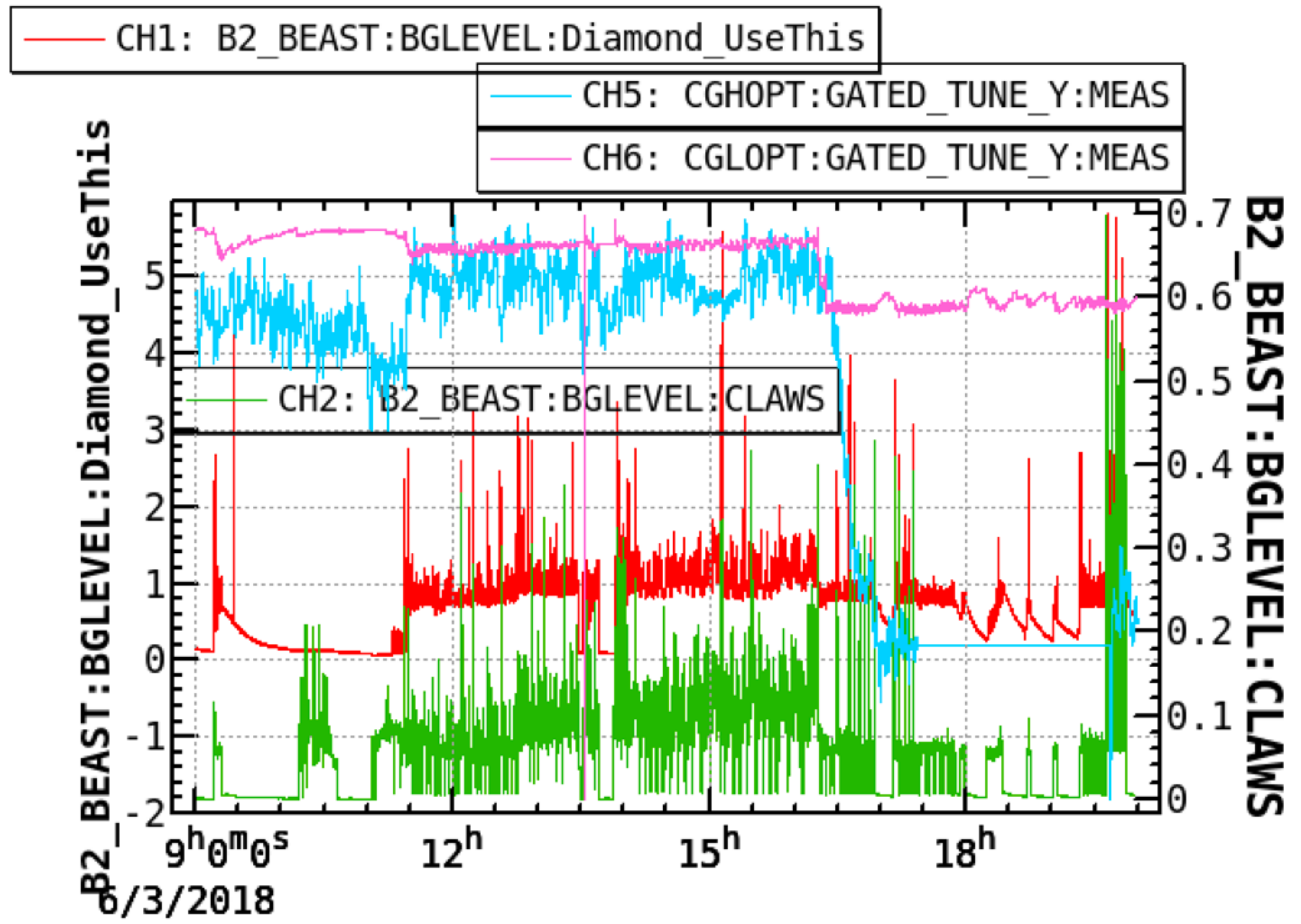
Luminosity run, May 29, 2018

H. Nakayama
slide from Phase 2 summary meeting

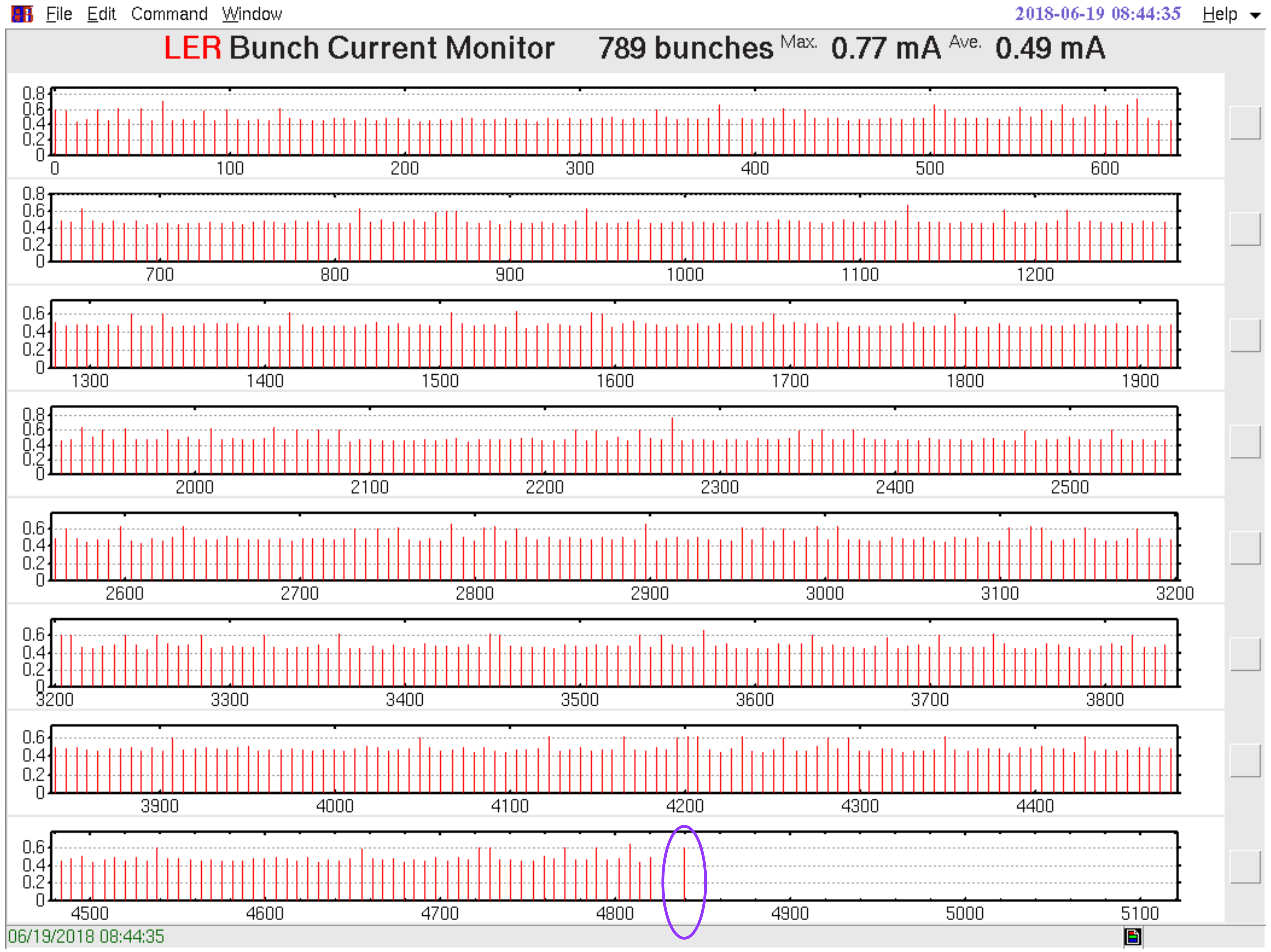


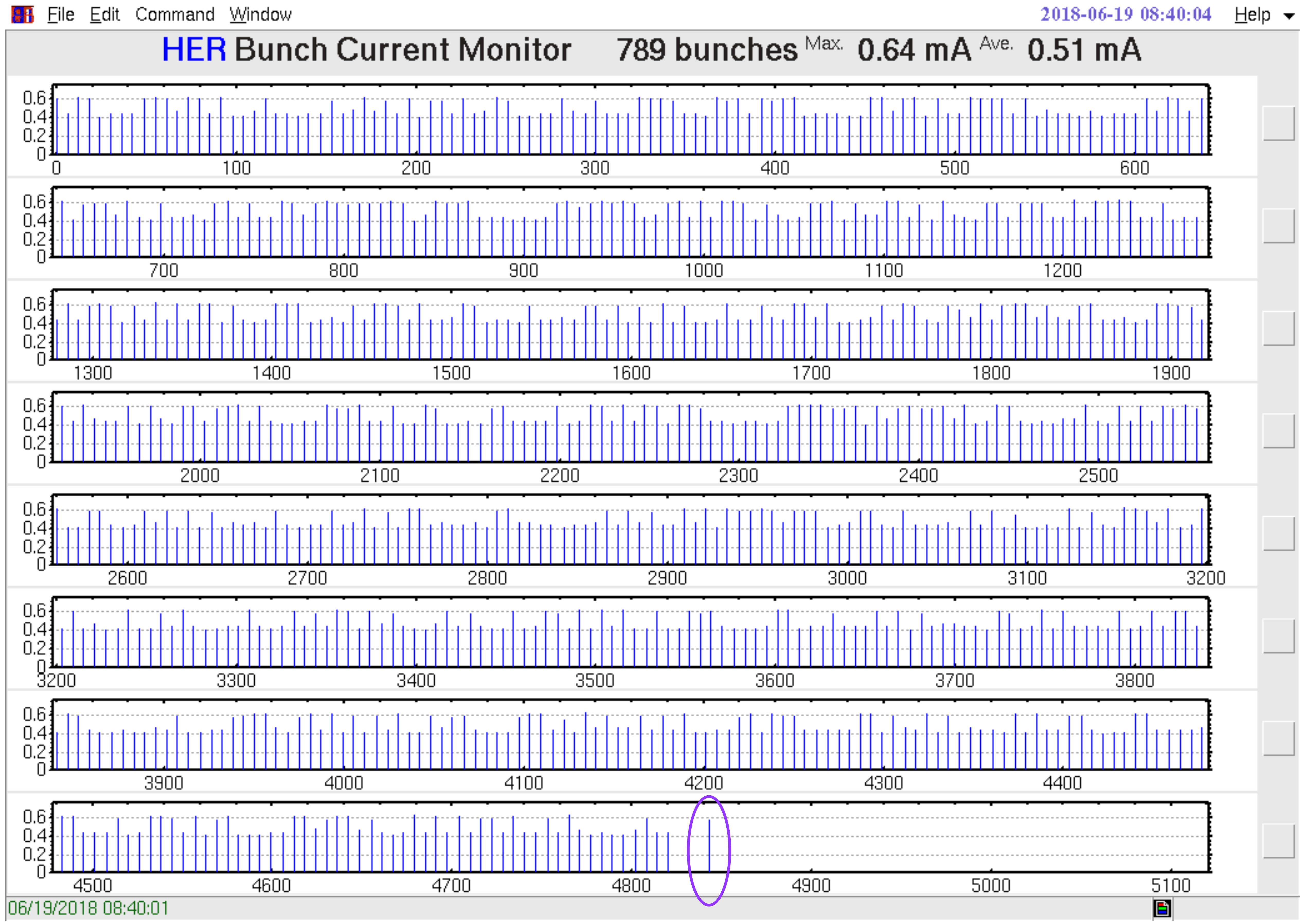
HER tune clearly affects the beam background.

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



Bunch Current Monitor





Pilot bunch (non-collision)

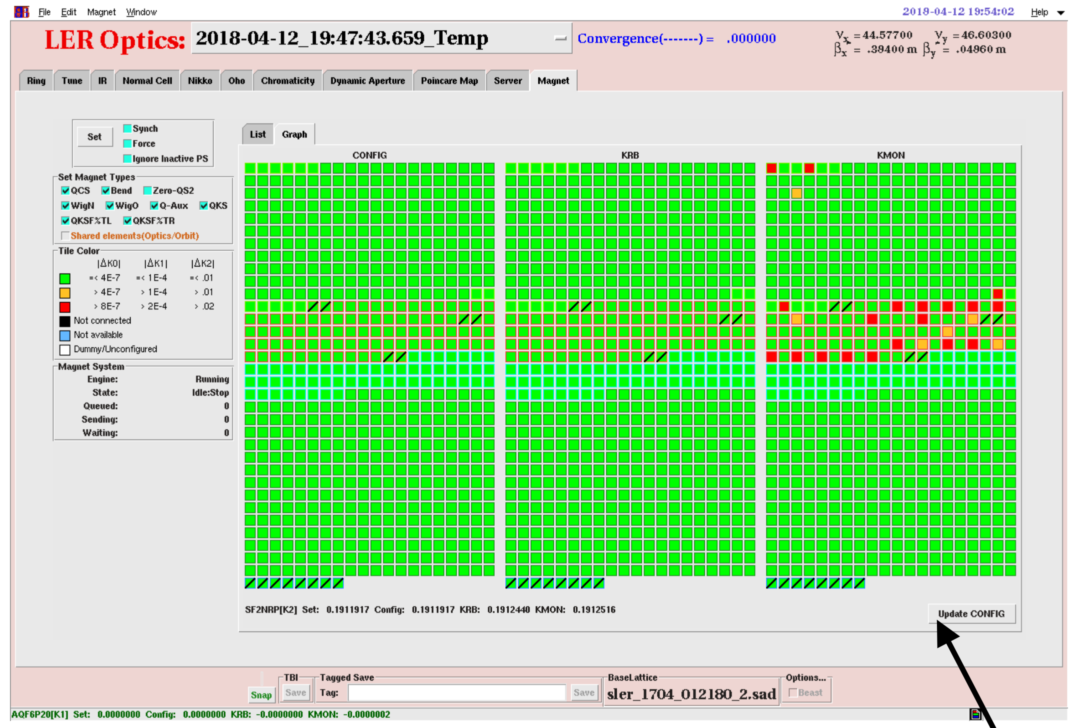
Pilot bunch (non-collision)

Tunes are measured by gated tune meter.

Betatron Tune Feedback

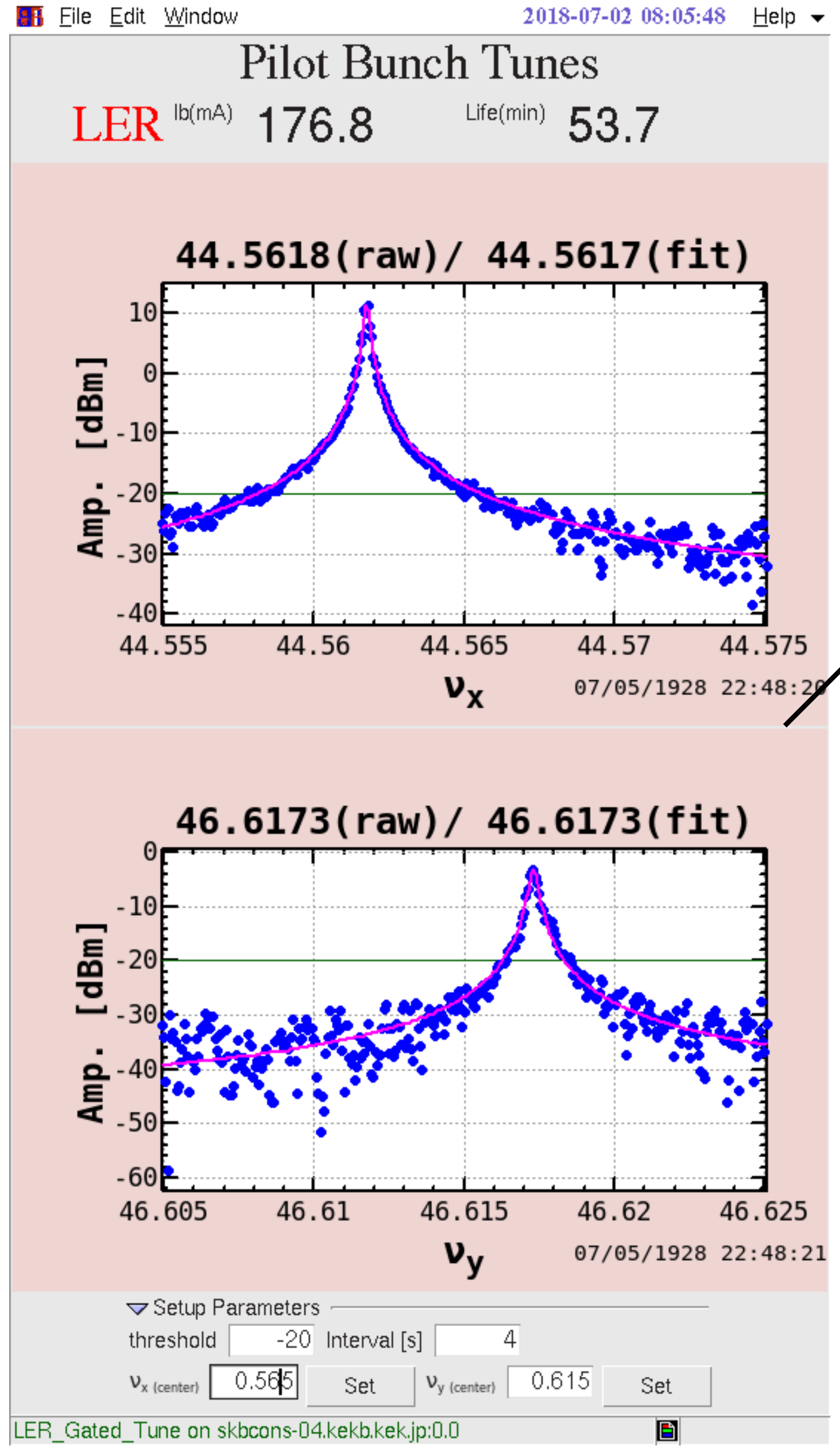
We have applied tune feedback system for the last week of Phase 2.

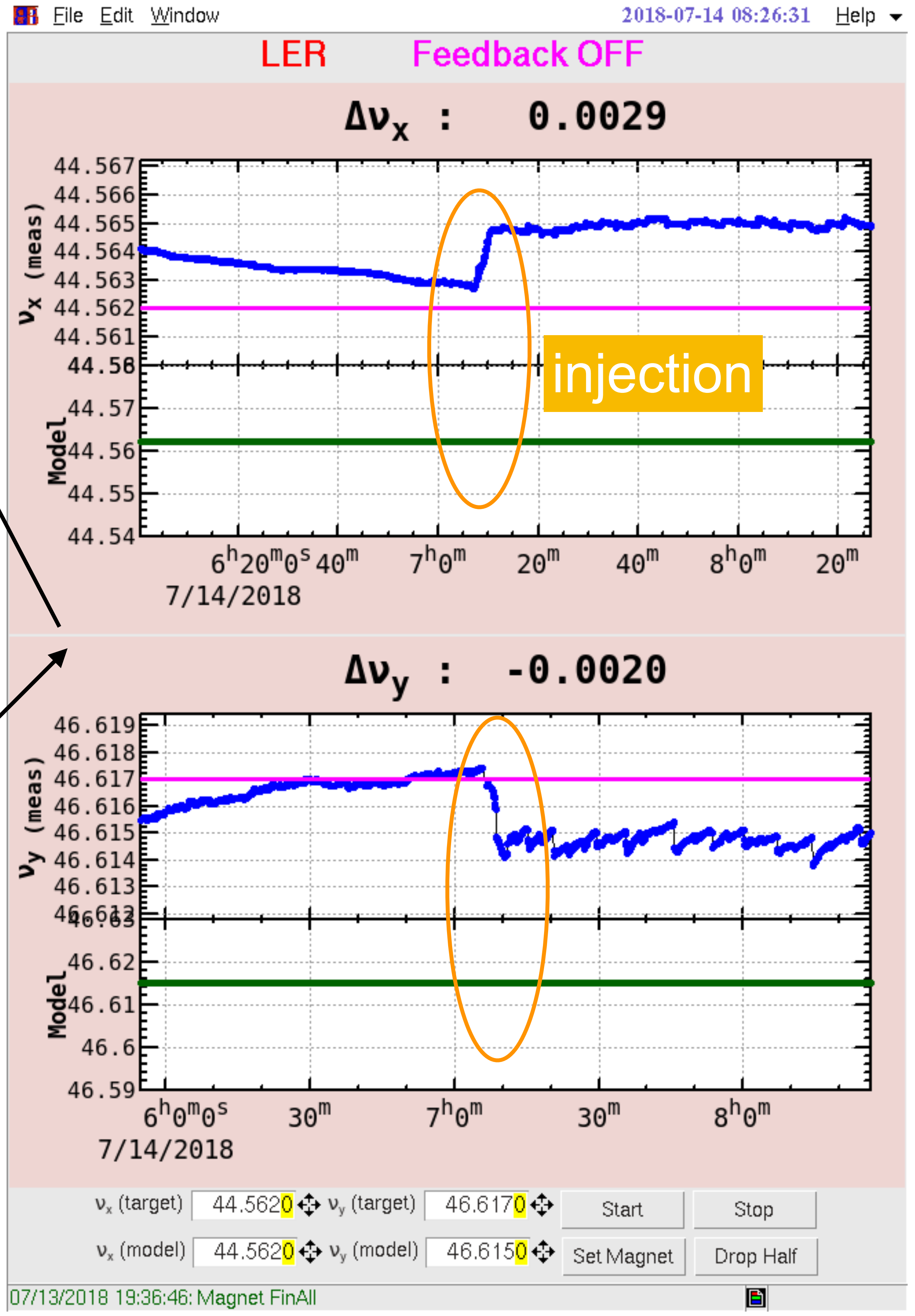
optics server

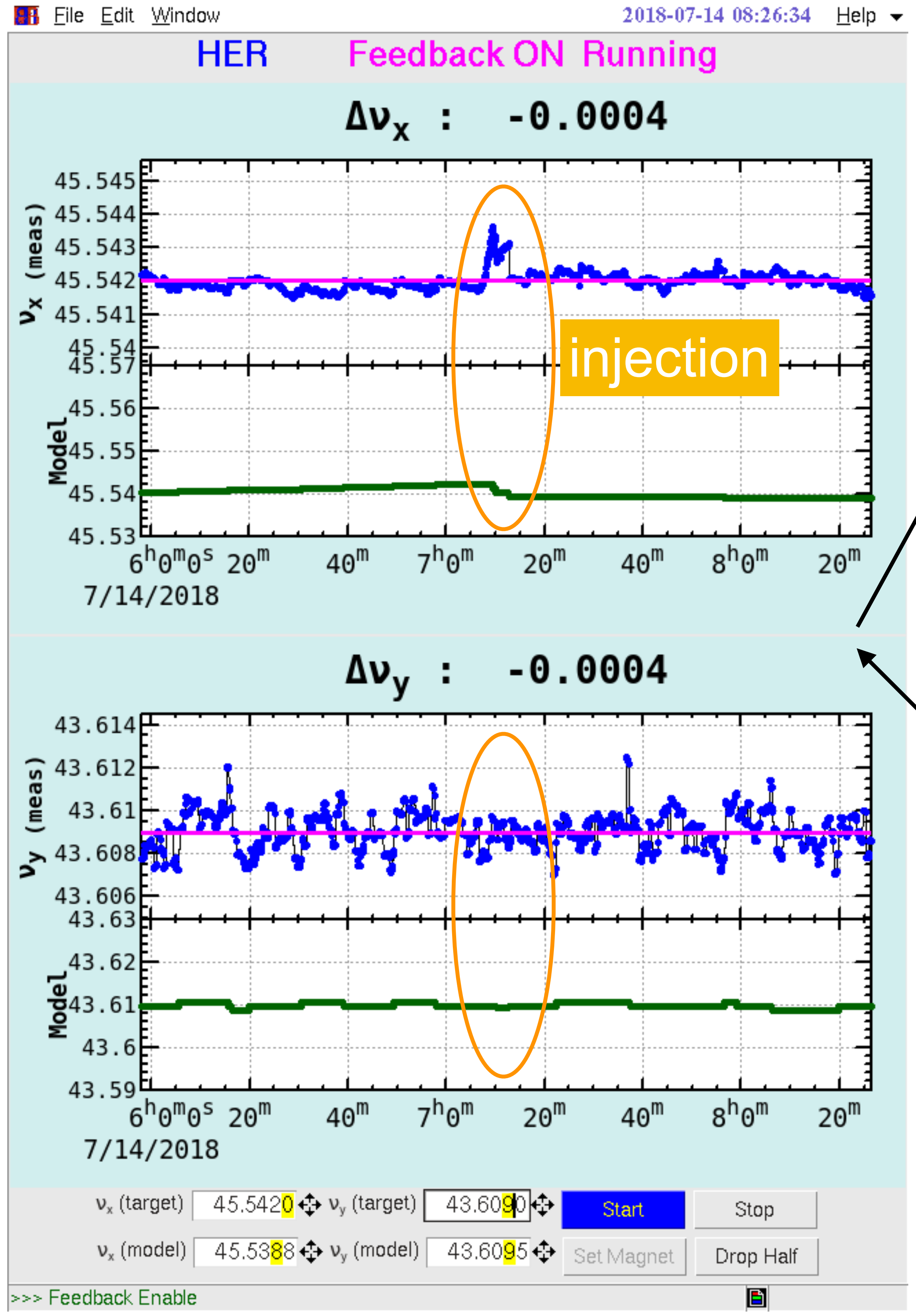


Tune shift due to resistive wall is compensated.

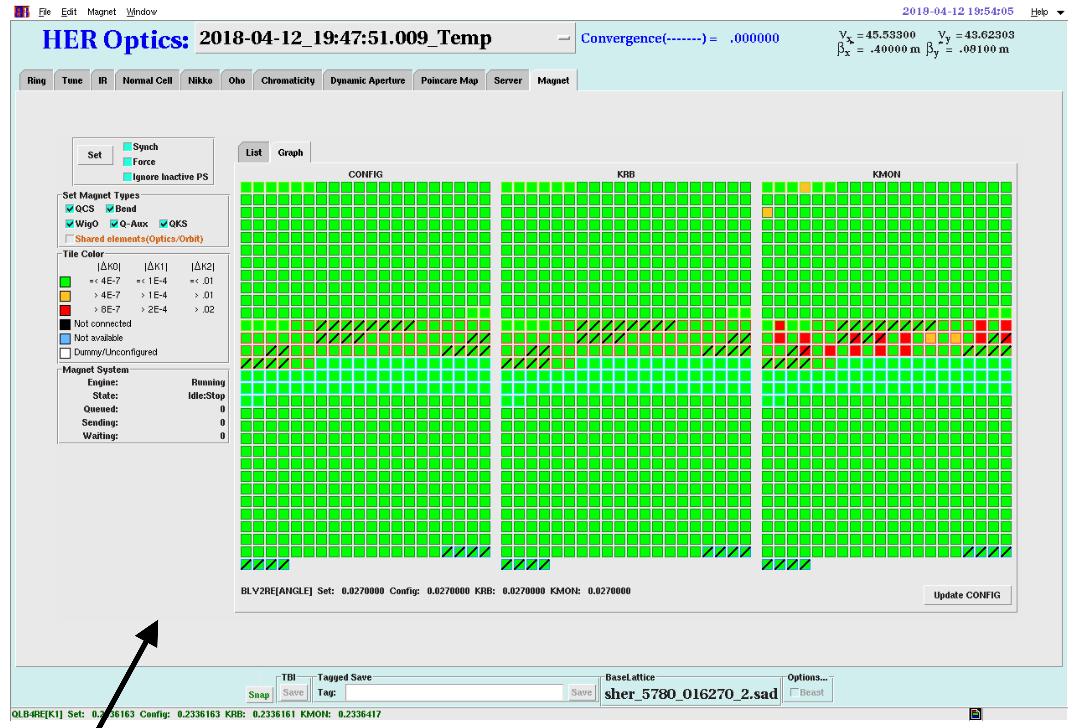
(dependent on the beam current)

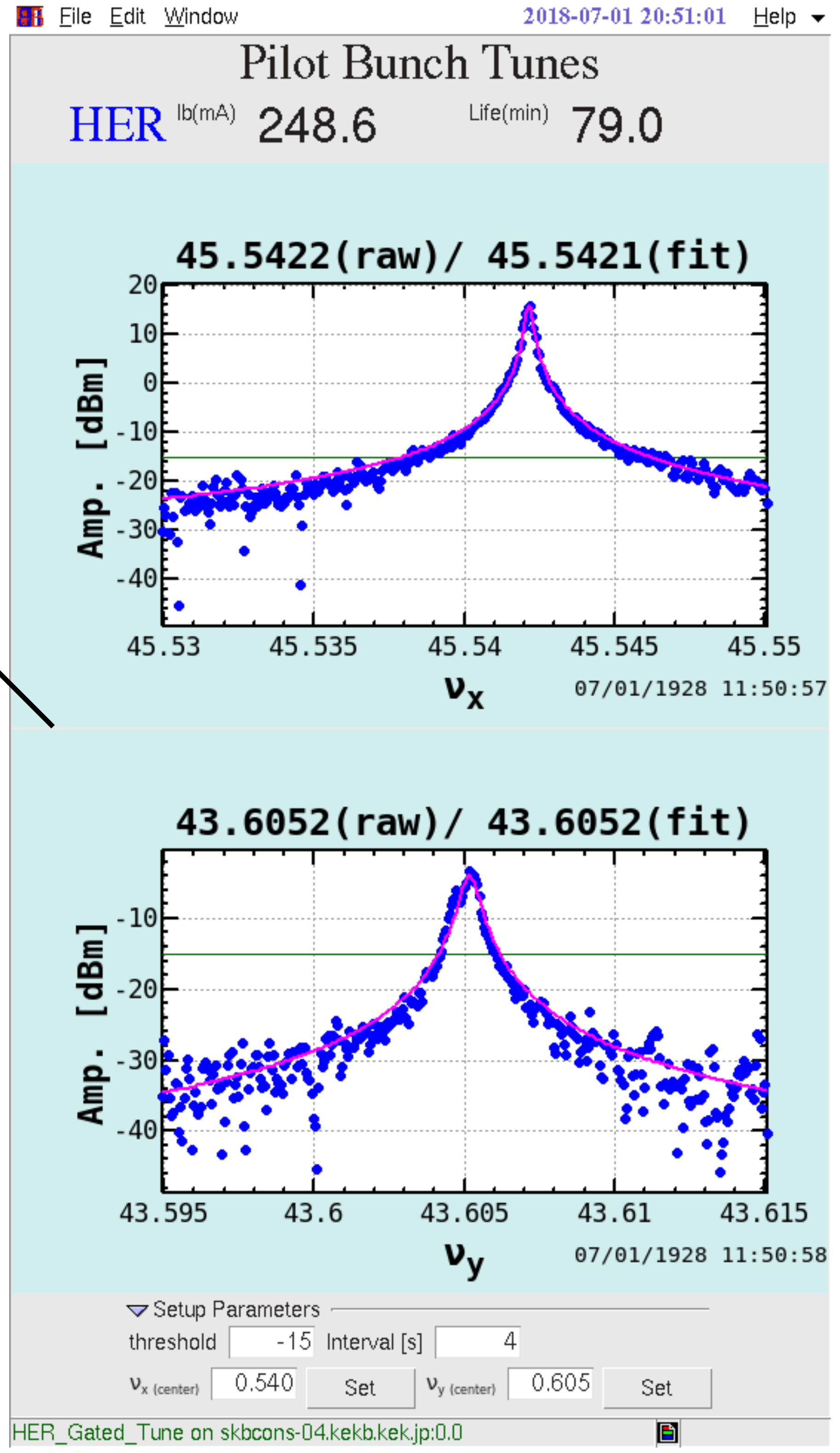






optics server

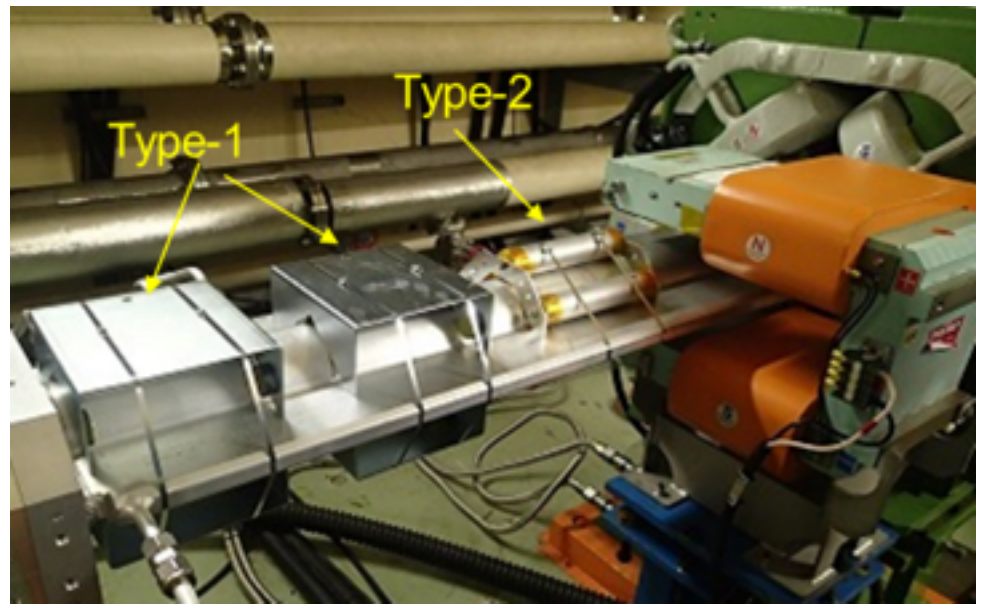




matching and send "set magnet" to optics server

Additional permanent magnets

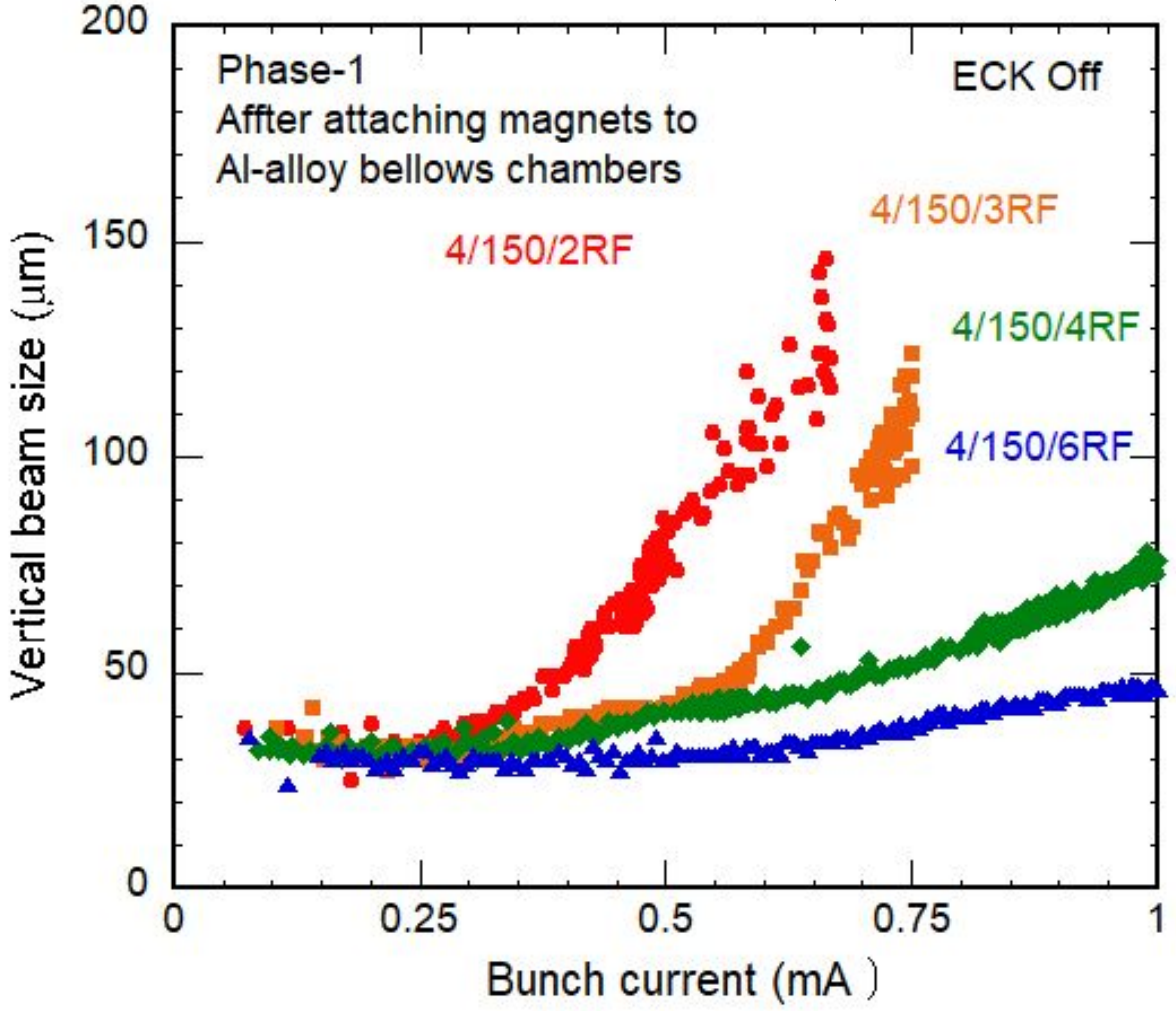
Y. Suetsugu et al.



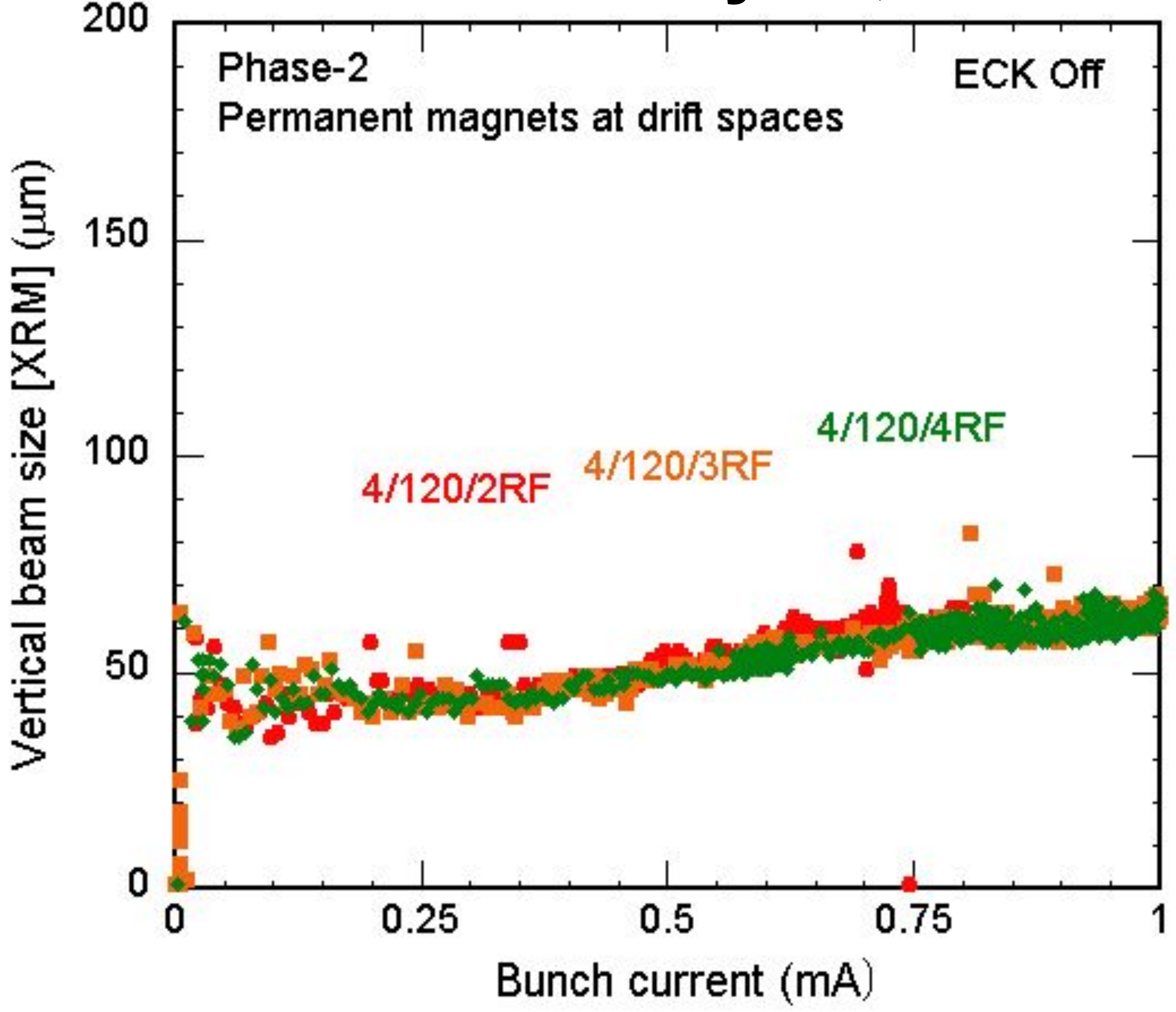
Threshold is much improved.
more than twice of 0.2 mA/bunch/RF bucket

Mode of CBI changes and the growth rate is reduced.

Phase 1: June 9, 2016



Phase 2: July 12, 2019



no blowup