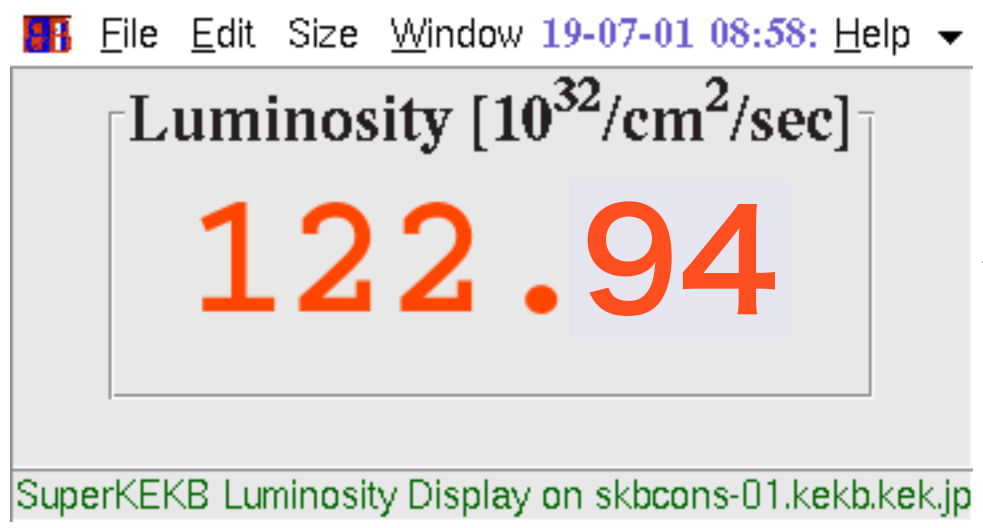
July 8, 2019

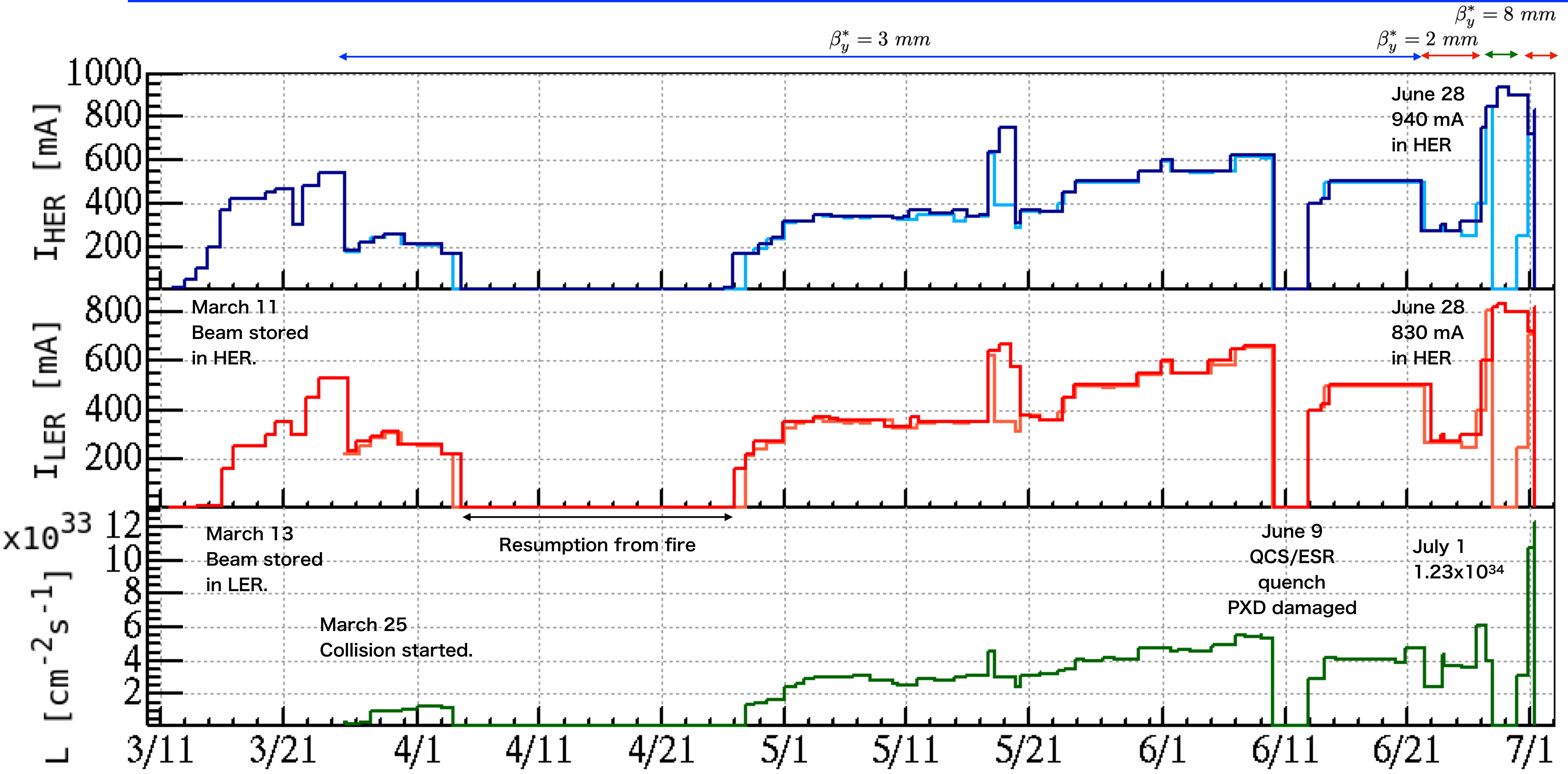
Present Performance and Plans

Y. Ohnishi



Peak luminosity at Phase 3
Spring Run 2019

Phase 3 Spring Run 2019



	July 1 08:58	July 1 1:48	July 1 1:26	June 20 19:10
β_x^* (mm)	**80**	**80**	**80**	200 / 100
β_y^* (mm)	**2**	**2**	**2**	3
I_{LER} / I_{HER} (mA)	799.7 / 821.5	398 / 401	265 / 268	494.7 / 496.1
n_b	1576	789	395	1576
$I_{b\,LER}$ / $I_{b\,HER}$ (mA)	0.507 / 0.521	0.504 / 0.508	0.671 / 0.678	0.314 / 0.317
$\xi_{y\,LER}$ / $\xi_{y\,HER}$	0.0355 / 0.0197	0.0375 / 0.0213	0.0389 / 0.0220	0.0335 / 0.0189
L_{sp} x10^{30}	29.5	32.0	24.8	30.7
L x10^{32}	**122.94**	64.58	44.66	47.85

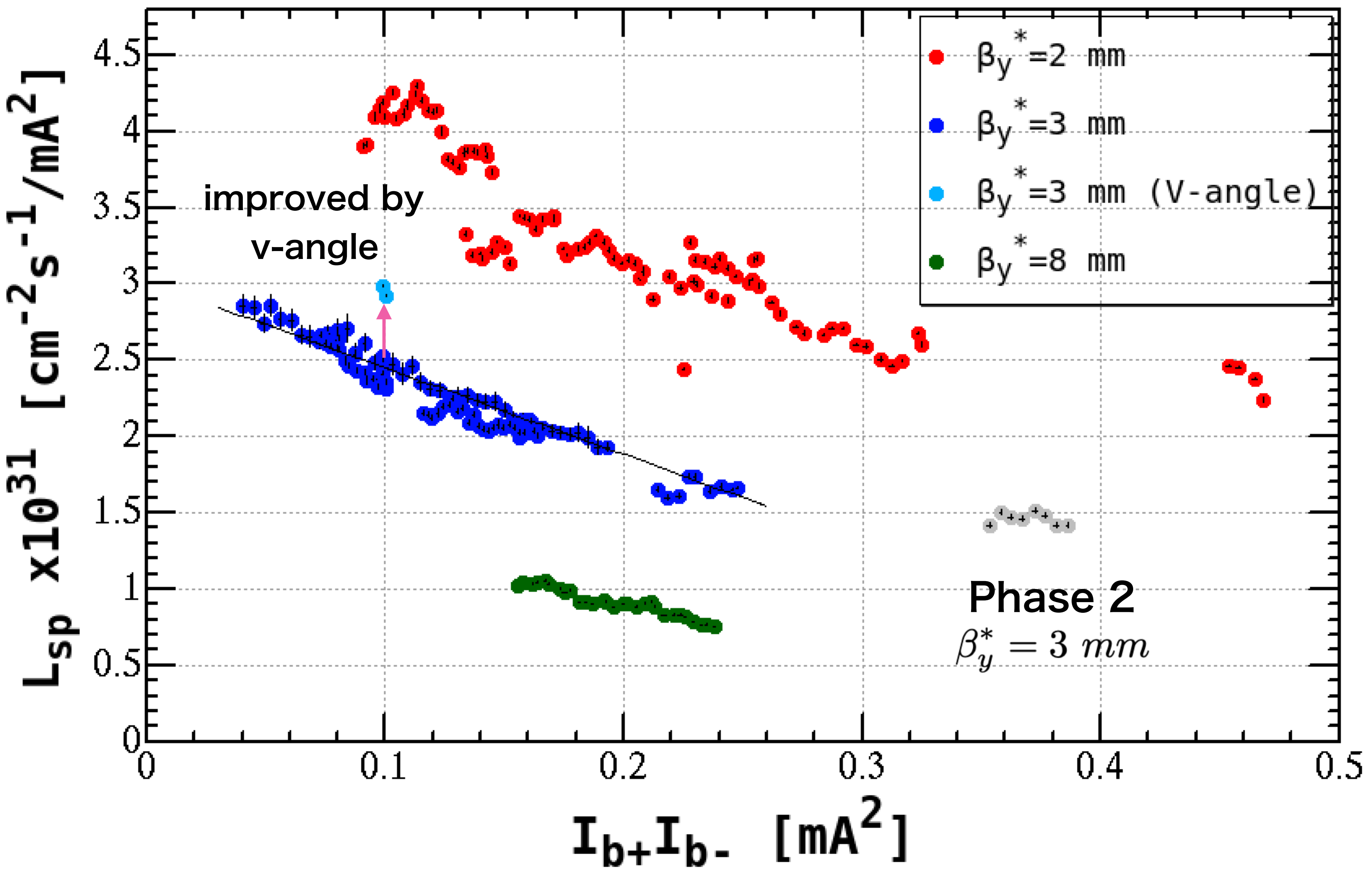
Definition of beam-beam parameter: $L = \frac{\gamma_\pm}{2er_e}\frac{\xi_{y\pm}I_\pm}{\beta_y^*}$

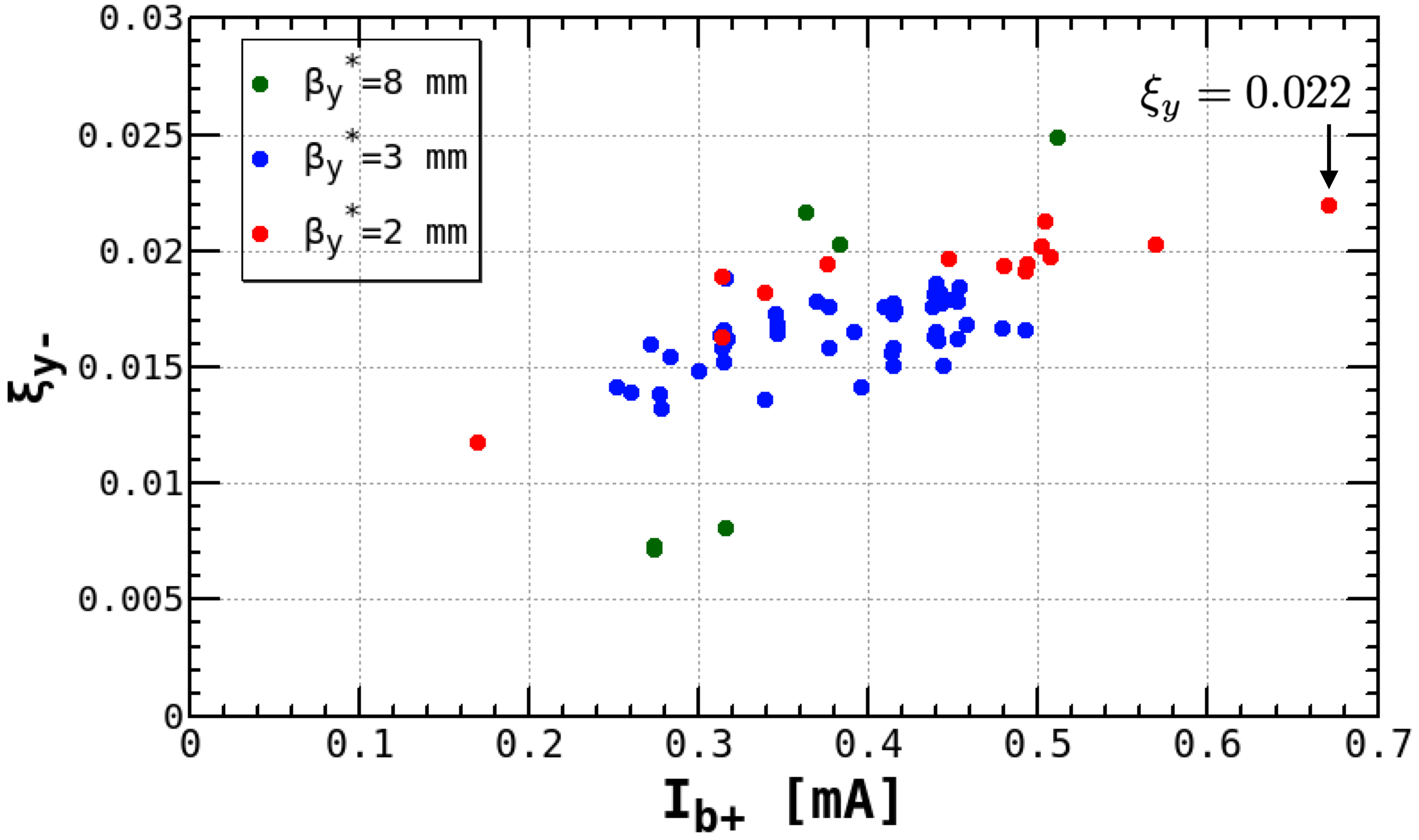
Definition of L_{sp}: $L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} = \frac{1}{2\pi e^2 f_0 \phi_x \Sigma_z \Sigma_y^*}$

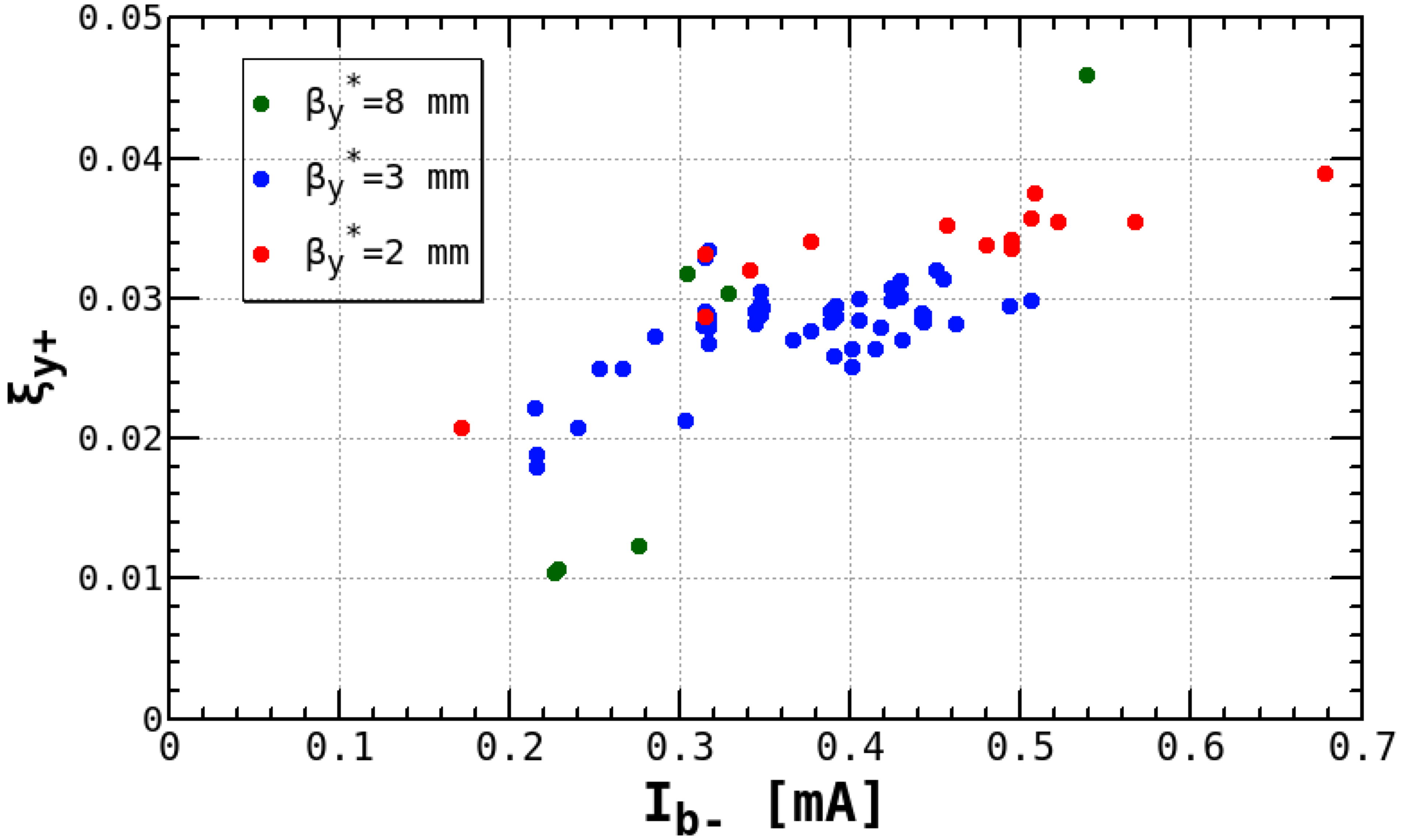
Contents

- Key issues limiting the current performance
- Strategy to reach the design luminosity
  - β* squeezing
  - beam-beam parameters → detailed talk by Ohmi-san
  - stored beam currents
  - detector background → Nakayama-san's talk, Iisda-san's talk for injection
  - QCS quench, fast beam abort → Ohuchi-san's talk, Ikeda-san's talk

Specific Luminosity and Beam-Beam Parameter







The specific luminosity is improved by squeezing the vertical beta function at IP.

The beam-beam parameter can be kept even though we squeeze the beta at IP.

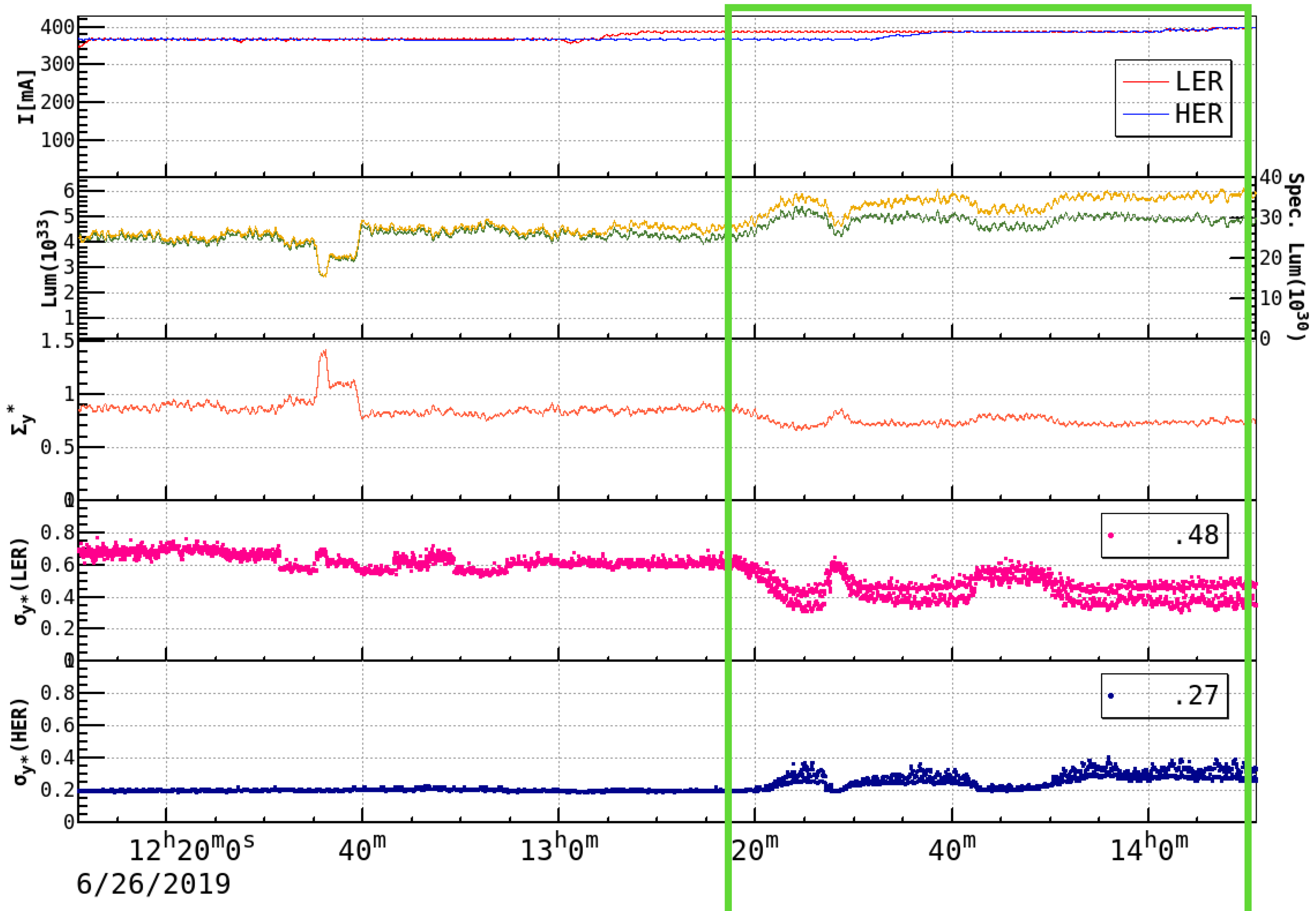
almost constant !

$$\xi_{y\pm} = \frac{r_e N_\mp}{2\pi\gamma_\pm \phi_x \sigma_{z\mp}} \boxed{\sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}}$$

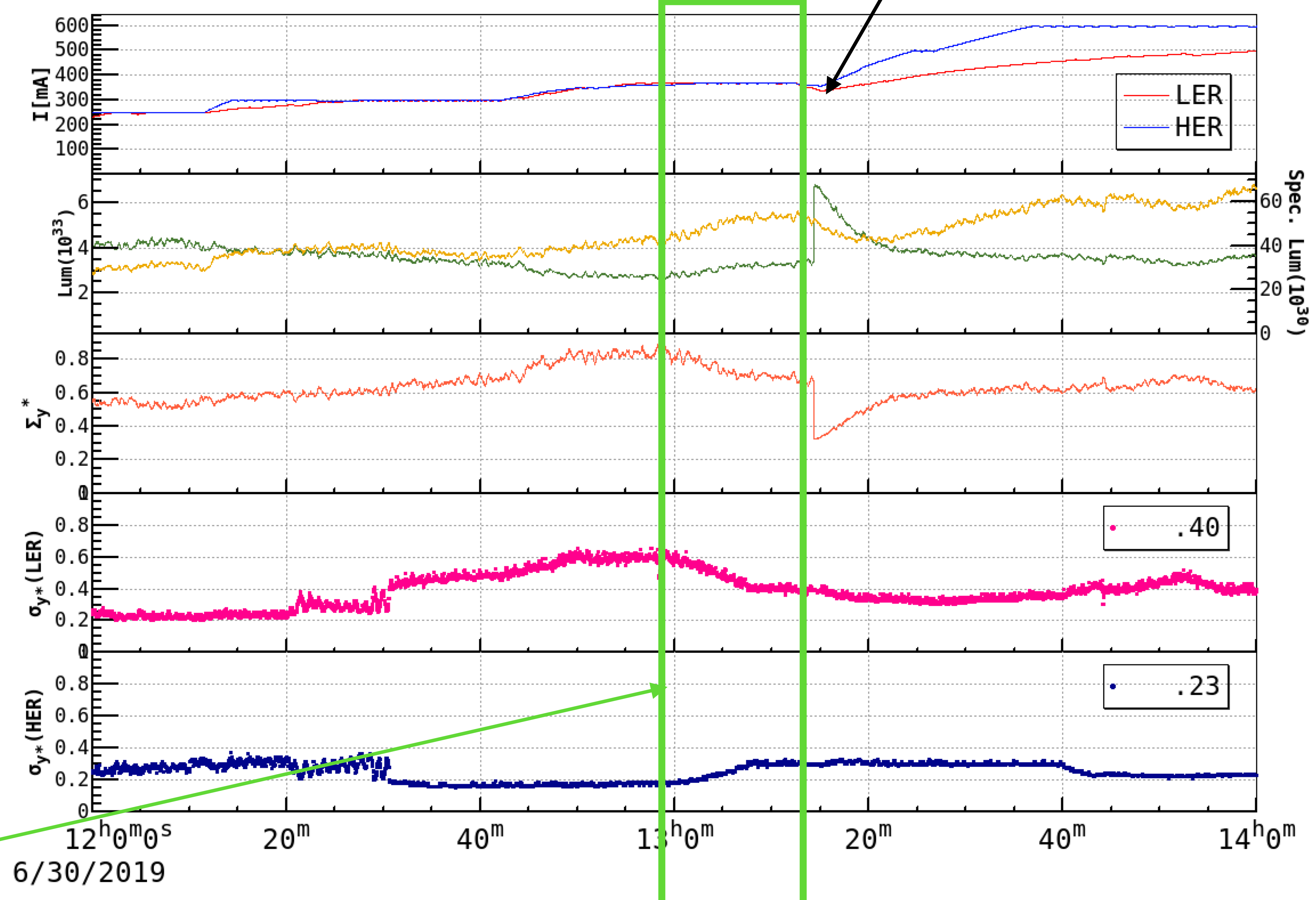
However, the final design is ξ_{y-} = 0.08 at I_{b+} = 1.4 mA.

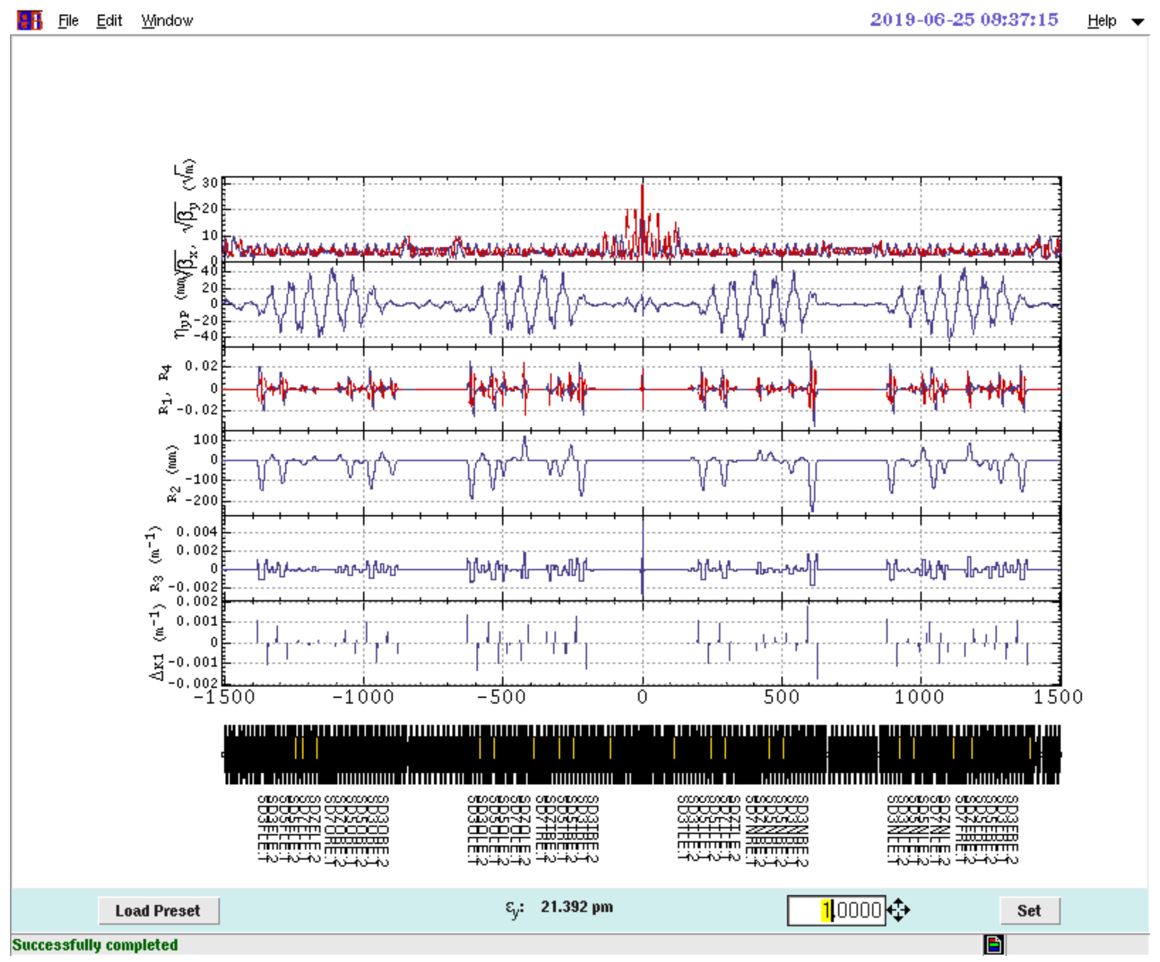
We need ξ_{y-} = 0.04 at I_{b+} = 0.7 mA. ↔ ξ_{y-} = 0.022

Continuous Injection Mode (CIM)



change fill pattern from #789 to #1576





Luminosity is improved by increasing ver. emittance in HER

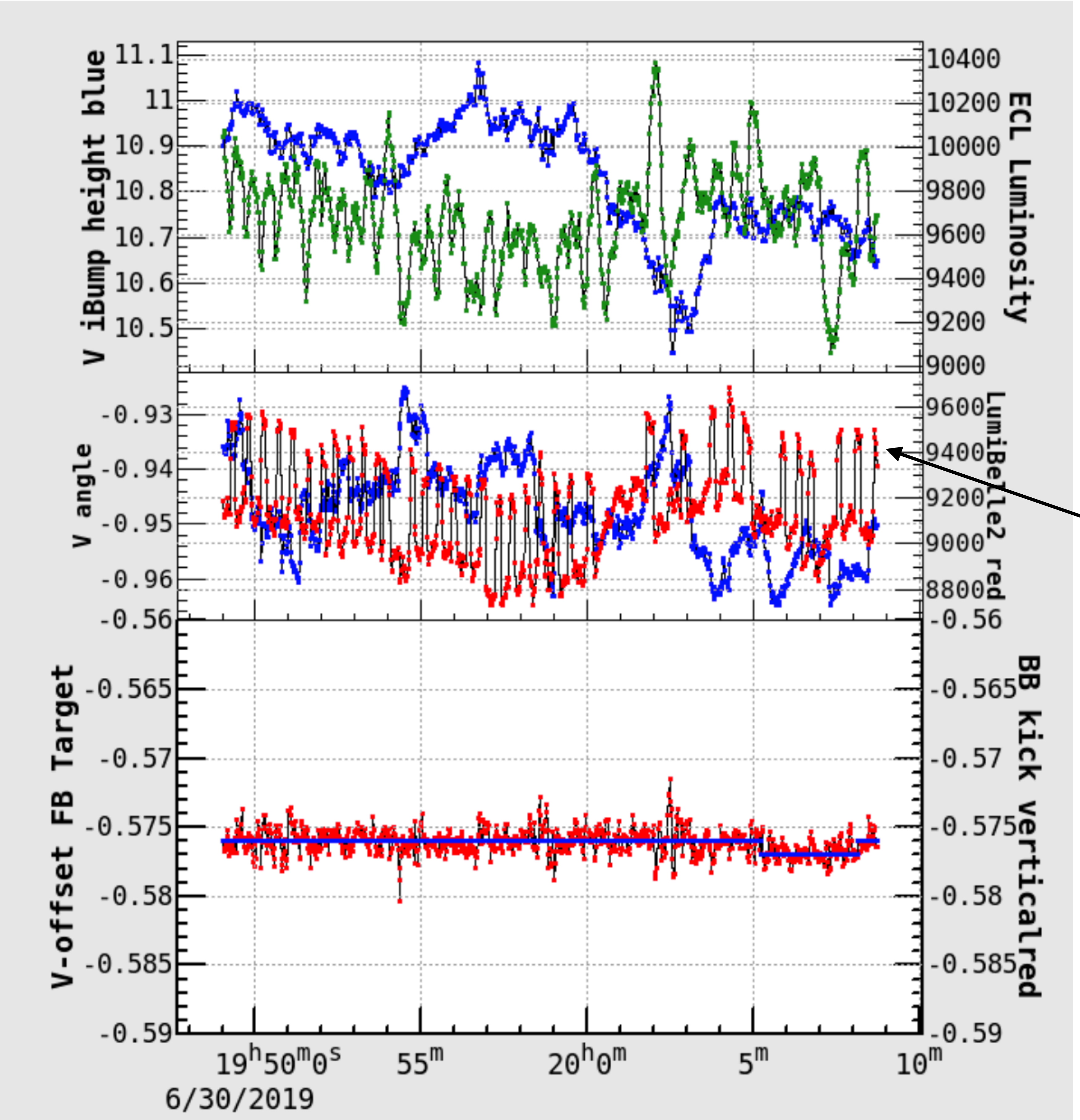
Beam size is unstable.
Flip-flop ?

The flip-flop became mild after optics corrections on June 29th.

However, we always observed the oscillation(fast) of the ver. beam-size with X-ray monitor.

<u>The emittance is one of the tuning parameters.</u>

$$\beta_x^* = 80\ mm \quad \beta_y^* = 2\ mm$$



ECL luminosity monitor provides moving average for 20 sec.

The peak-to-peak is 5 % ~ 10 % fluctuation

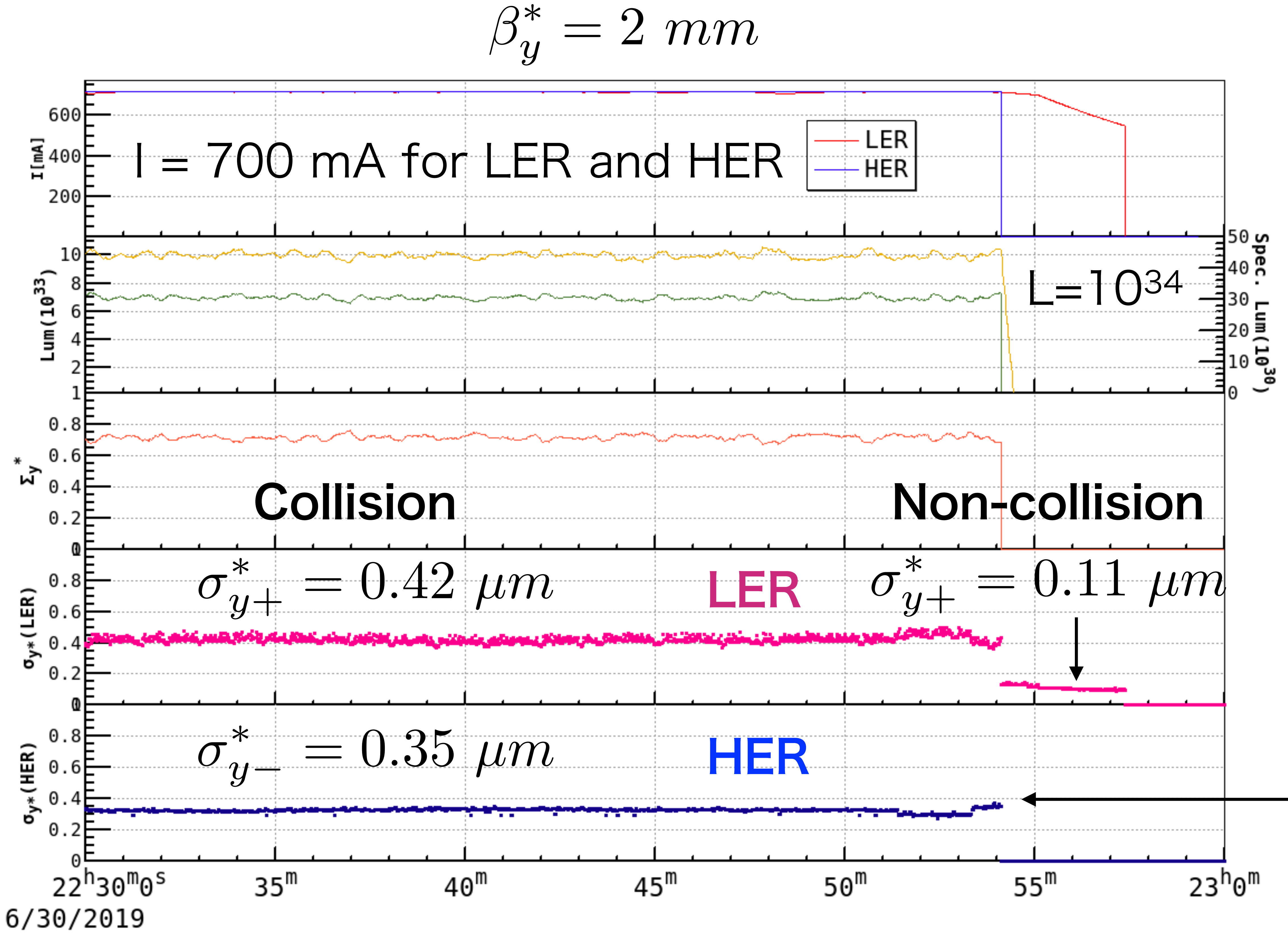
LumiBelle2 is a fast luminosity monitor.

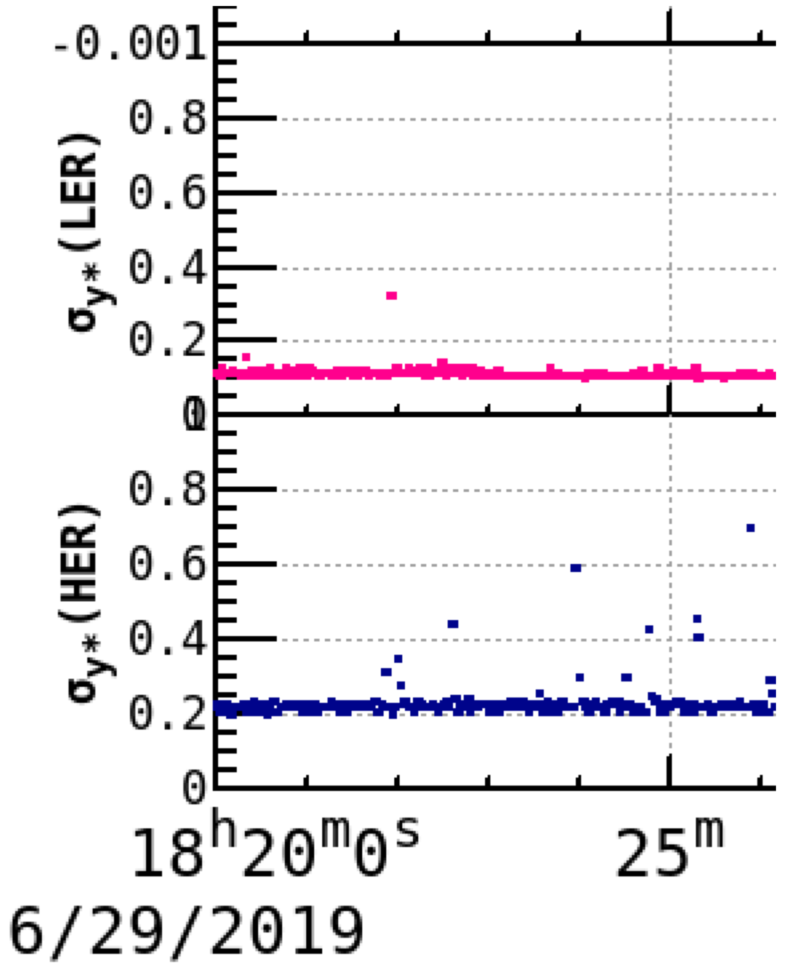
The luminosity spikes are not coincident with the injection.

Vertical orbit offset feedback (slow control)

by using ver. beam-beam kick (canonical)

Beam-Beam Blow-up





Ver. beam size measured by X-ray monitor.

HER

Non-collision

$\sigma_{y-}^* = 0.2\ \mu m$

The blow-up in the LER is significantly larger than the HER.

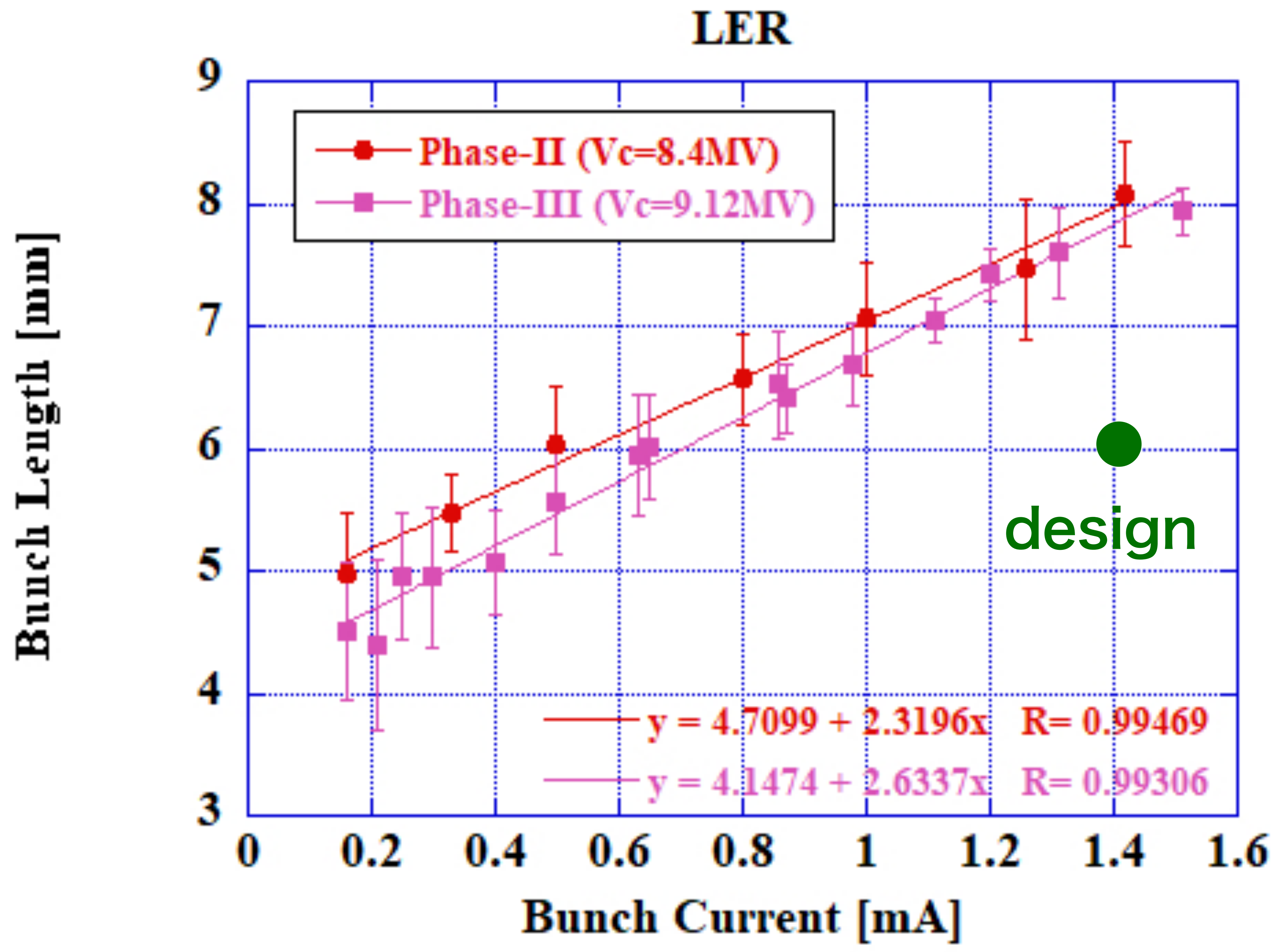
The HER vertical beam size is adjusted by using HER emittance control knob (ver. dispersion) in order to equalize the beam size as much as possible.

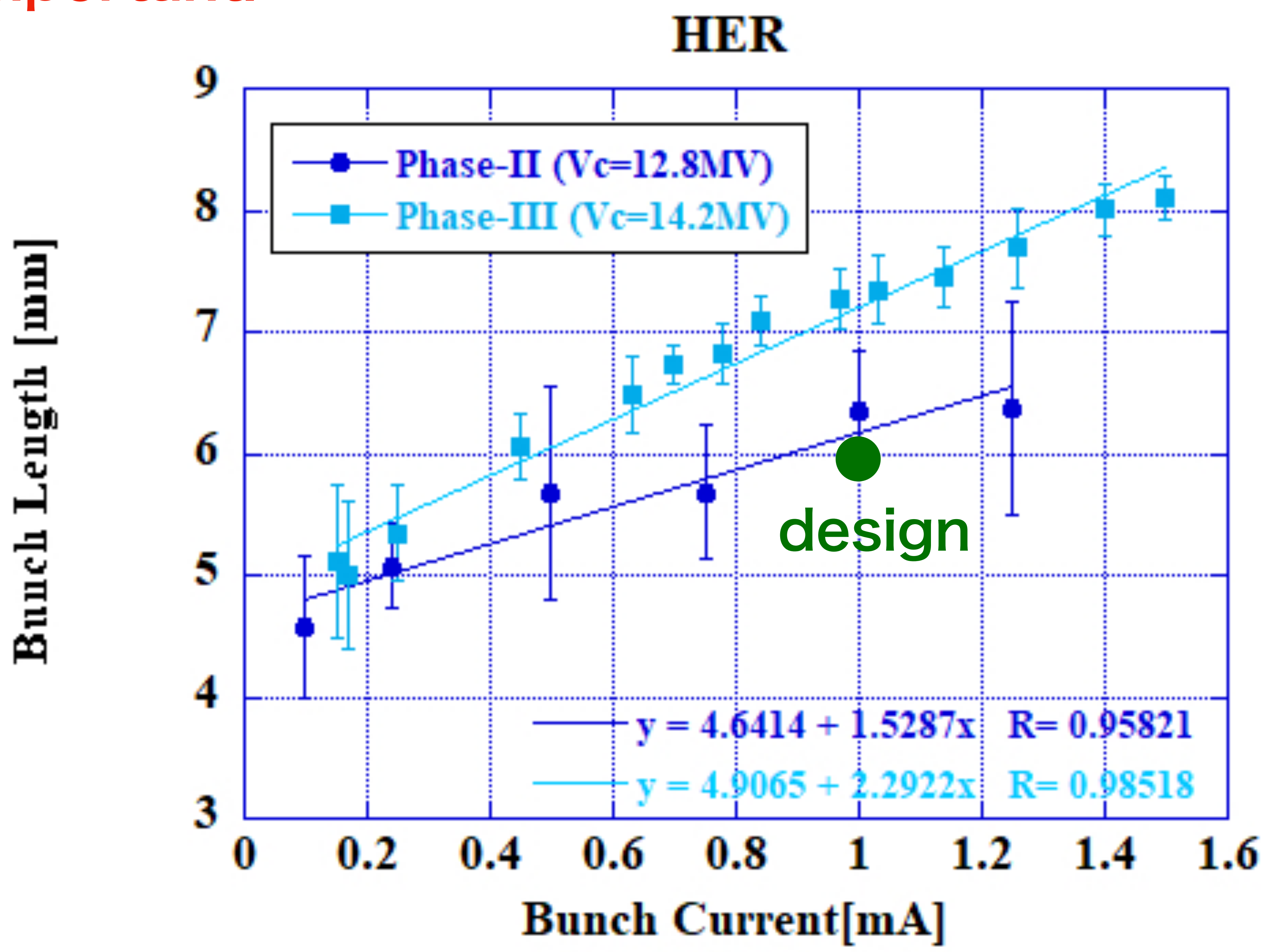
Emittance (non-collision)		Emittance (collision)		Final design: ε_y
LER: 6.1 pm	x14	LER: 88 pm	(4.4 %)	LER: 8.6 pm
HER: 20 pm	x3	HER: 61 pm	(1.6 %)	HER: 13 pm
			$(\varepsilon_y / \varepsilon_x)$	

H. Ikeda

$$L = \frac{N_- N_+ n_b f_0}{2\pi \phi_x \Sigma_z \Sigma_y^*} \quad \Sigma_z = \sqrt{\sigma_{z-}^2 + \sigma_{z+}^2} \quad \Sigma_y^* = \sqrt{\sigma_{y-}^{*2} + \sigma_{y+}^{*2}}$$

Bunch length is important.



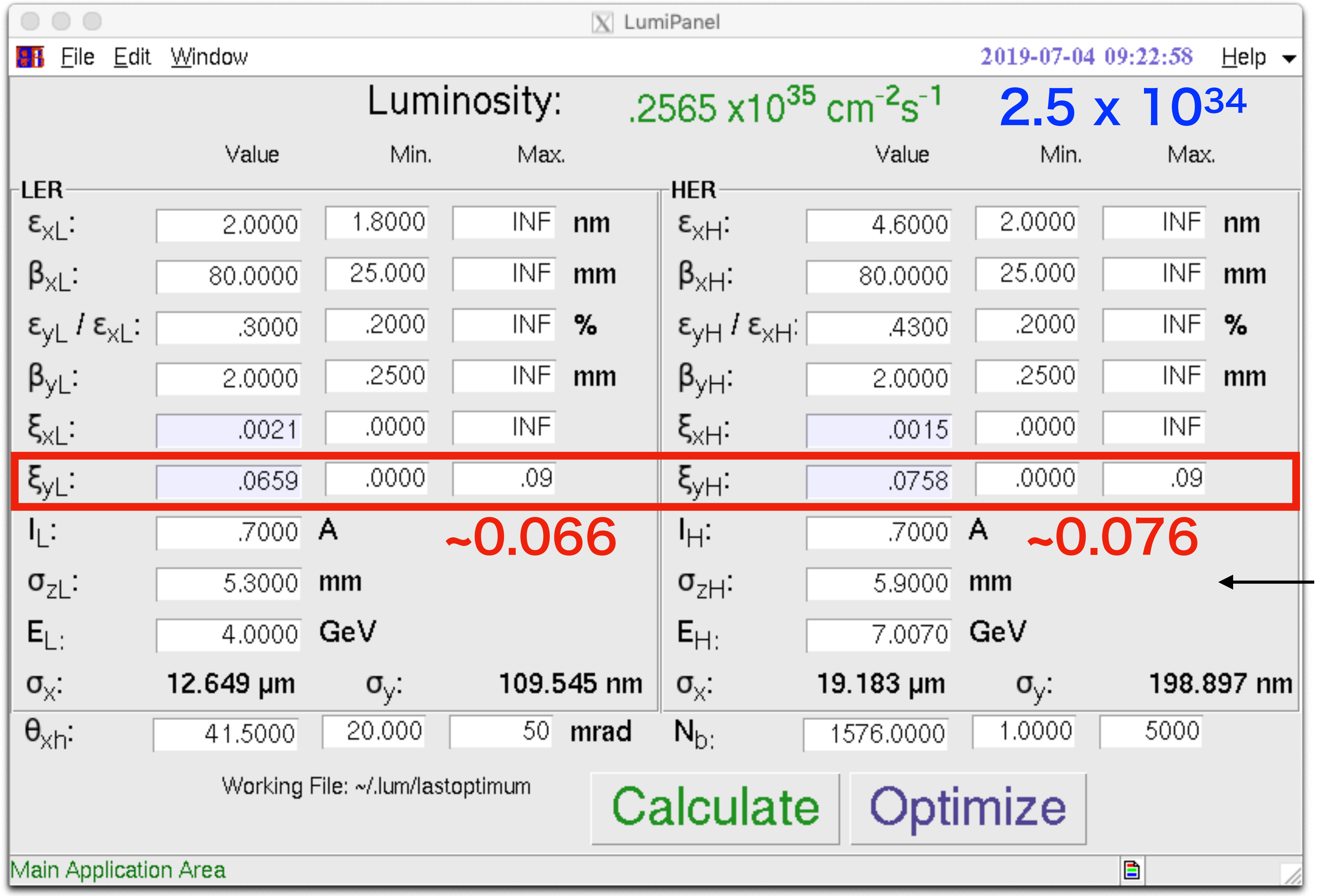


5.3 mm @ 700 mA (#1576)

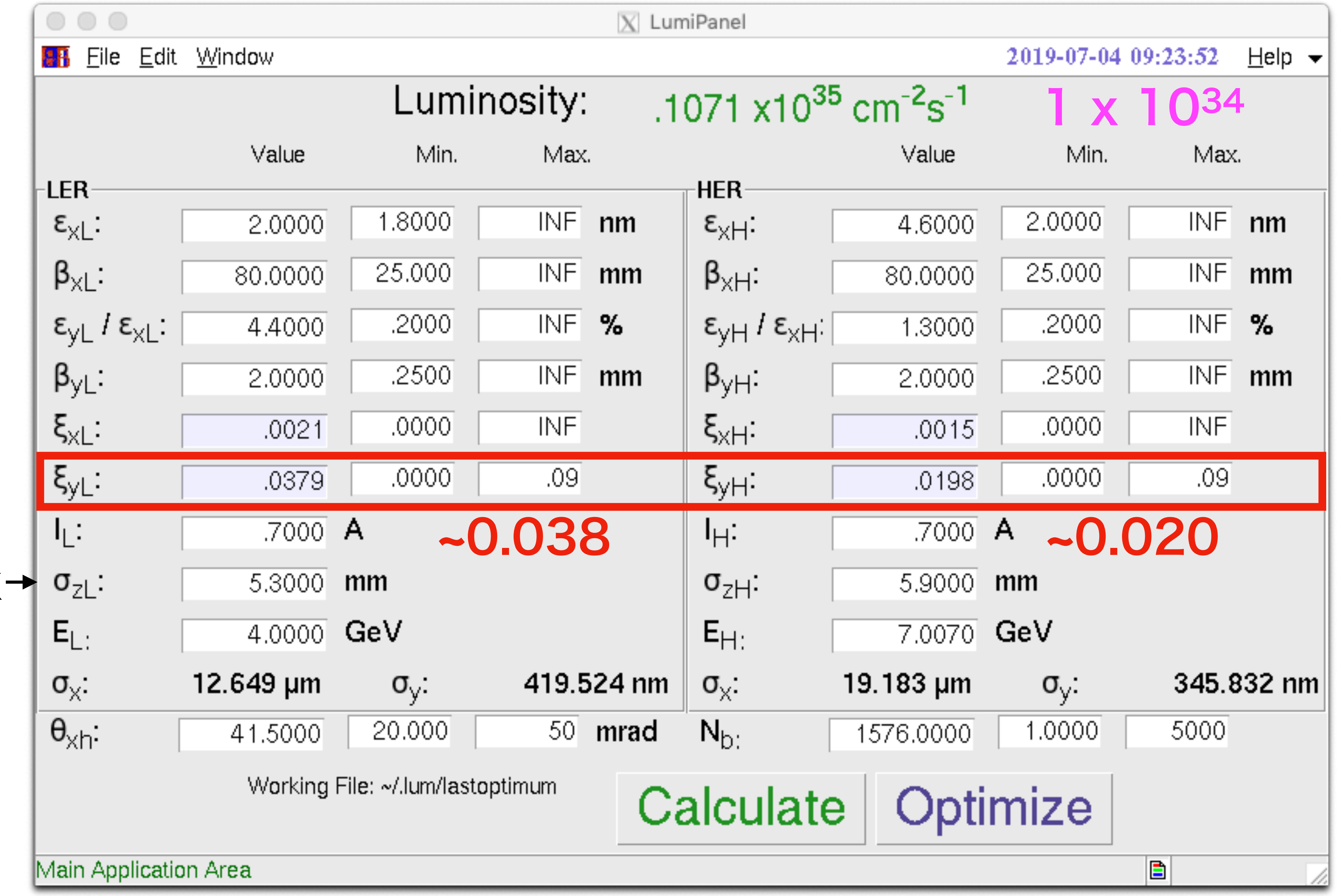
5.9 mm @ 700 mA (#1576)

Beam-Beam Parameter

LER: ε_y = 6.1 pm HER: ε_y = 20 pm ← XRM → LER: ε_y = 88 pm HER: ε_y = 61 pm



← Streak →



if there is no beam blow-up....

Consistent with the observation.

ξ_y = 0.076 for I_b = 0.44 mA is too large ?

Improvement and Understanding of Luminosity Performance

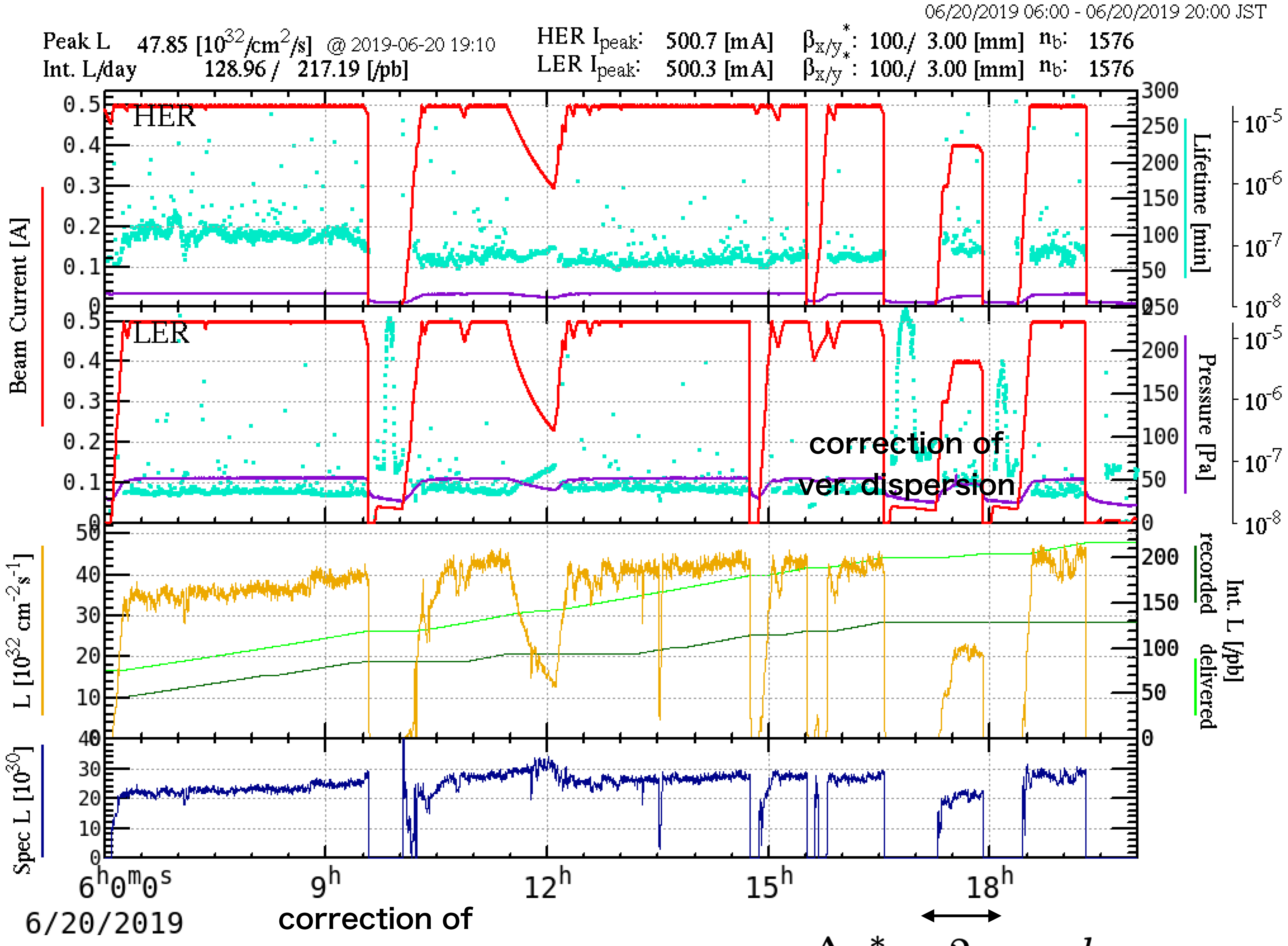
- **Linear optical parameters :**
  - X-Y couplings at IP → adiabatic luminosity scan: OK, r_2^* is corrected by the skew quad. coils at QC1s.
  - Ver. dispersions at IP → adiabatic luminosity scan: OK
  - Ver. waist → adiabatic luminosity scan: OK
  - Orbit at IP (H-angle and V-angle) → need more precise optimization (0.1 mrad step, see Ohmi-san's talk)
  - Betatron tunes → adiabatic luminosity and background scan, however need more survey (ref. D. Zhou-san)
- **Nonlinear optical parameters :**
  - Chromatic X-Y couplings at IP → adiabatic luminosity scan in HER : OK for ($R_3^{*\prime}$,$R_4^{*\prime}$), but not yet done in LER
  - Chromatic Beta at IP → adiabatic luminosity scan : no strong response
  - Skew sextupole correctors at QCS → adiabatic luminosity scan in HER: OK, but not yet done in LER
  - Sextupole and octupole correctors at QCS → not yet done
- **Cap sigma measurements at low bunch currents with Beam-Beam scan**
  - to check geometrical luminosity, vertical crossing-angle, off-momentum behavior, and cap bunch length

Vertical Angle at IP in LER

We made the vertical orbit bump to make the ver. angle at IP in LER.

Luminosity is increases by 20 % with $\Delta p_y^* = 1,\ 0.5\ mrad$

Beam background is also reduced.

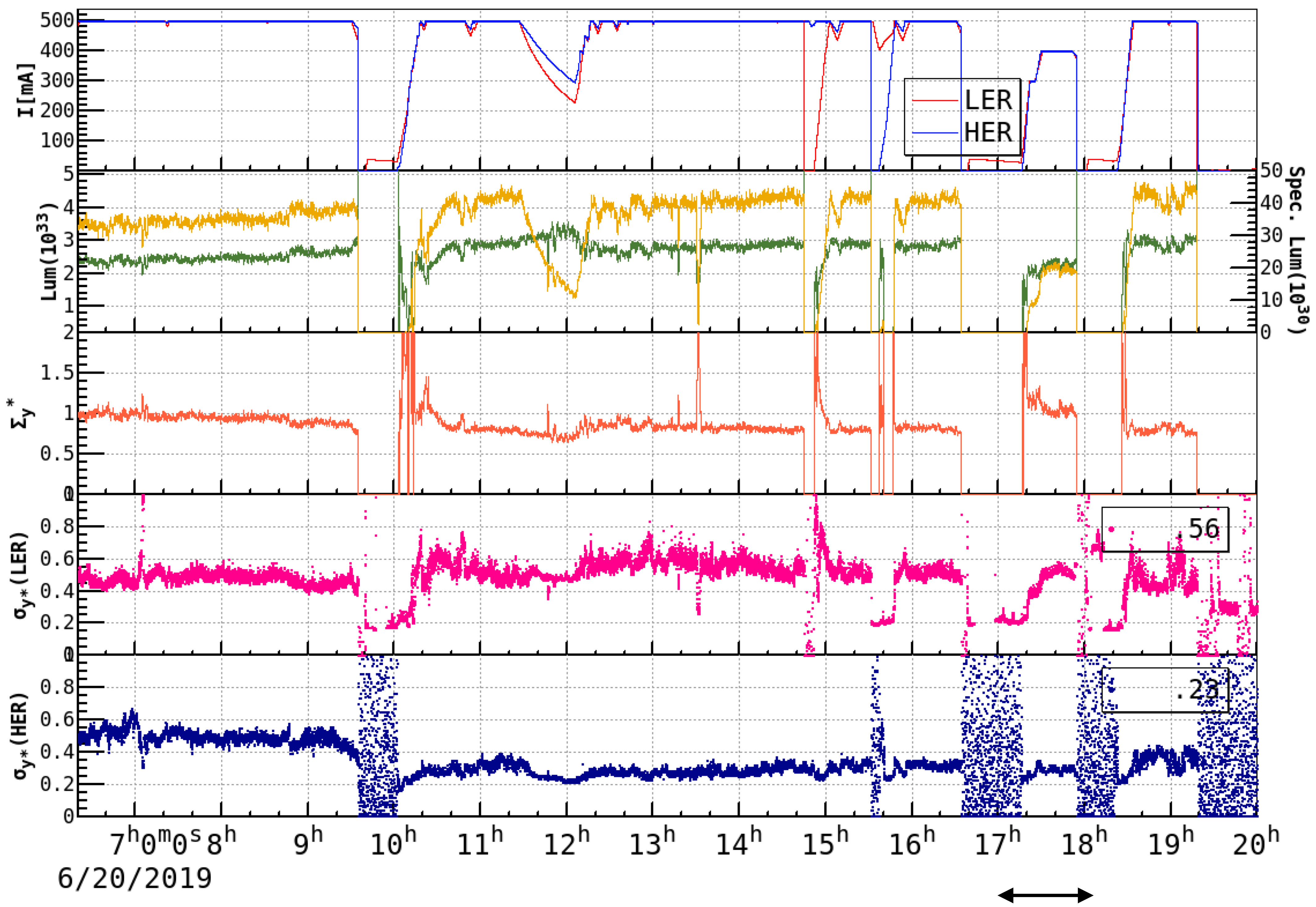


correction of ver. dispersion

$\Delta p_y^* = 2\ mrad$

$\Delta p_y^* = 0\ mrad$ $\Delta p_y^* = 1\ mrad$ $\Delta p_y^* = 0.5\ mrad$

L_{sp} is bad for 2 mrad



$\Delta p_y^* = 2\ mrad$

$\Delta p_y^* = 0\ mrad$ $\Delta p_y^* = 1\ mrad$ $\Delta p_y^* = 0.5\ mrad$

H. Koiso

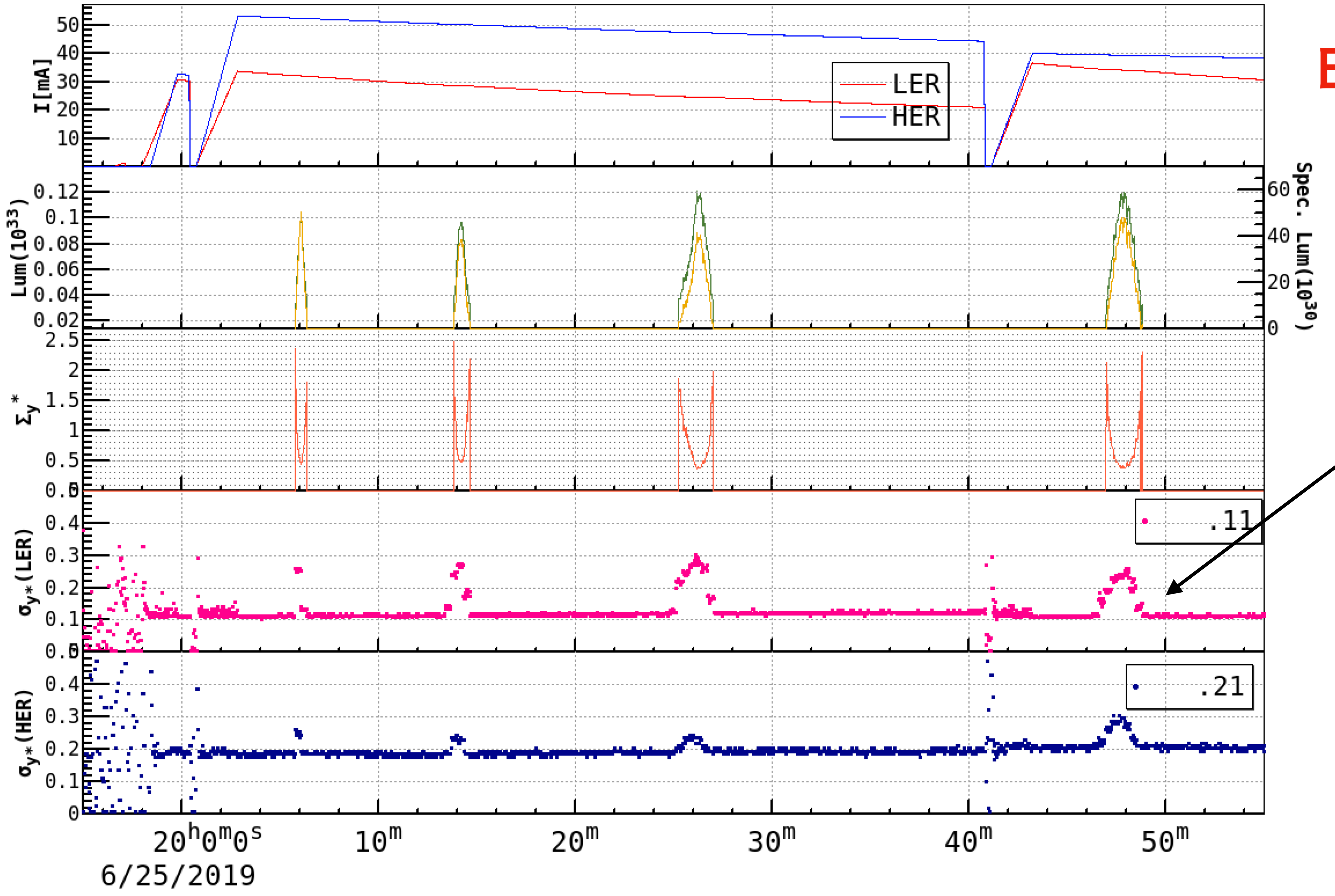
Cap Sigma Measurements with Beam-Beam Scan

Y. Funakoshi, Y. Ohnishi, A. Morita, H. Koiso
June 25, 2019

We used one-cycle injection (Kaji-san);
the injection is one time for each bucket.
In case of 789 bunches, it takes about 2 min for 6.25 Hz rep. to fill all buckets.
The bunch current is adjusted by linac beam with RF-gun and FC STB to make a small bunch current.
Beam profile is measured by LumiBelle2 (fast luminosity monitor) with ver. bump height or RF room phase scan.

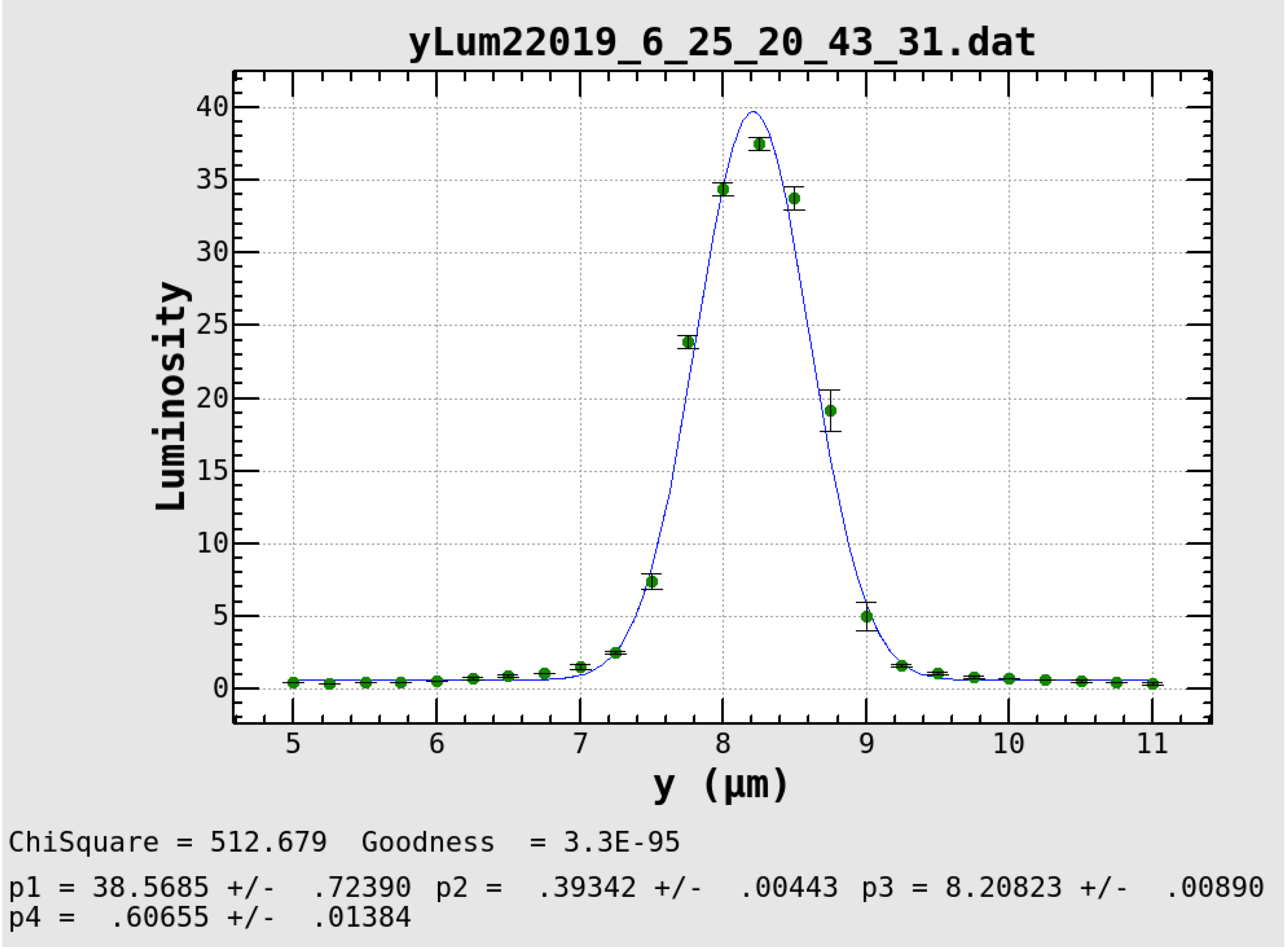
The bunch current is less than 0.04 mA/bunch

$$\beta_x^* = 80\ mm \quad \beta_y^* = 2\ mm$$



Beam-Beam blow-up was observed even though 0.04 mA/bunch.

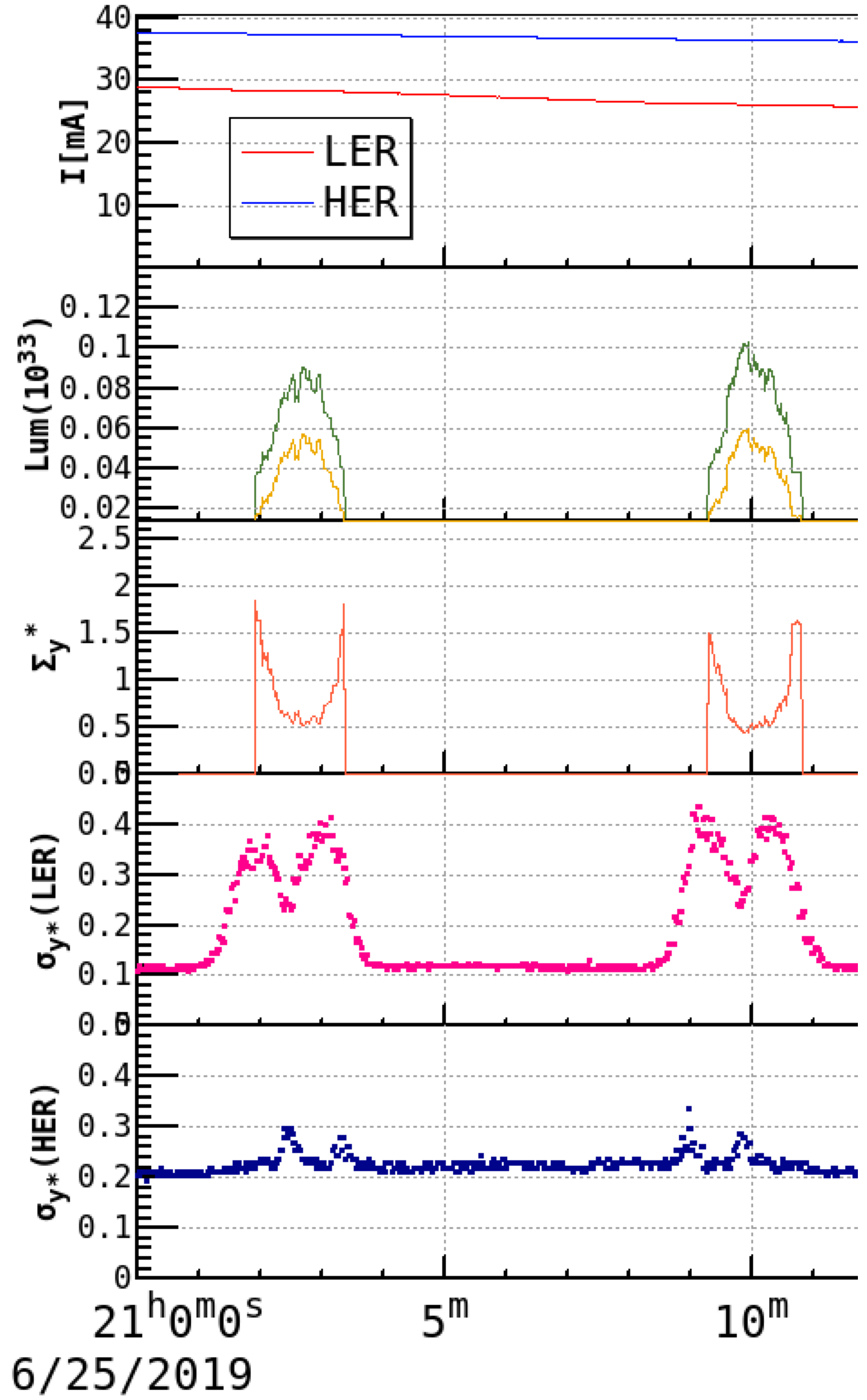
Σ_y^* measured by ver. offset scan



Σ_y^* (BB scan)	Σ_y^* (Lum)	Σ_y^* (XRM)	σ_{y+}^* (XRM)	σ_{y-}^* (XRM)
0.393 μm	0.38 μm	0.378 μm	0.234 μm	0.297 μm

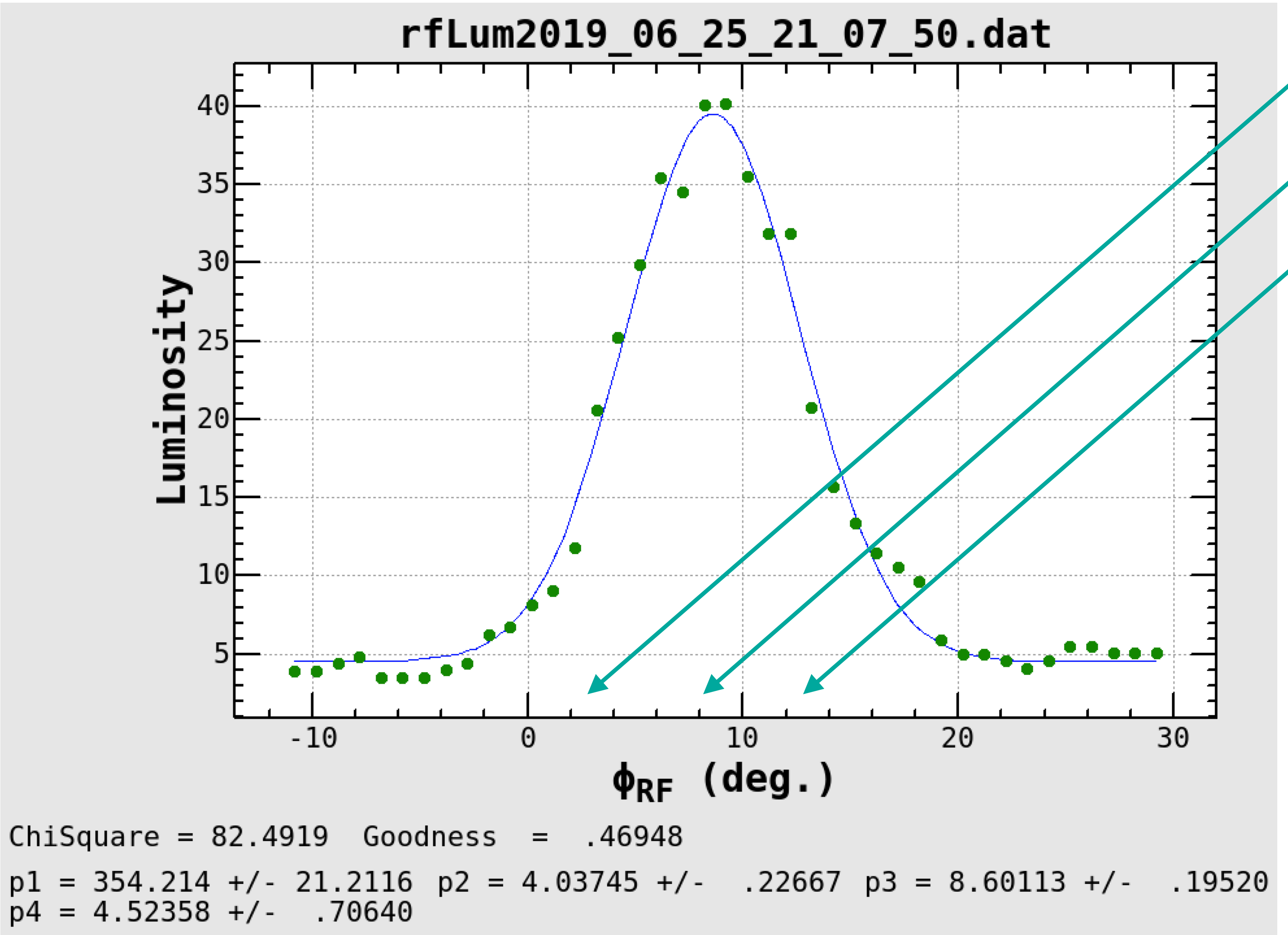
consistent with each other

Cap Sigma Measurements with Beam-Beam Scan (cont'd)



Bunch length measurement

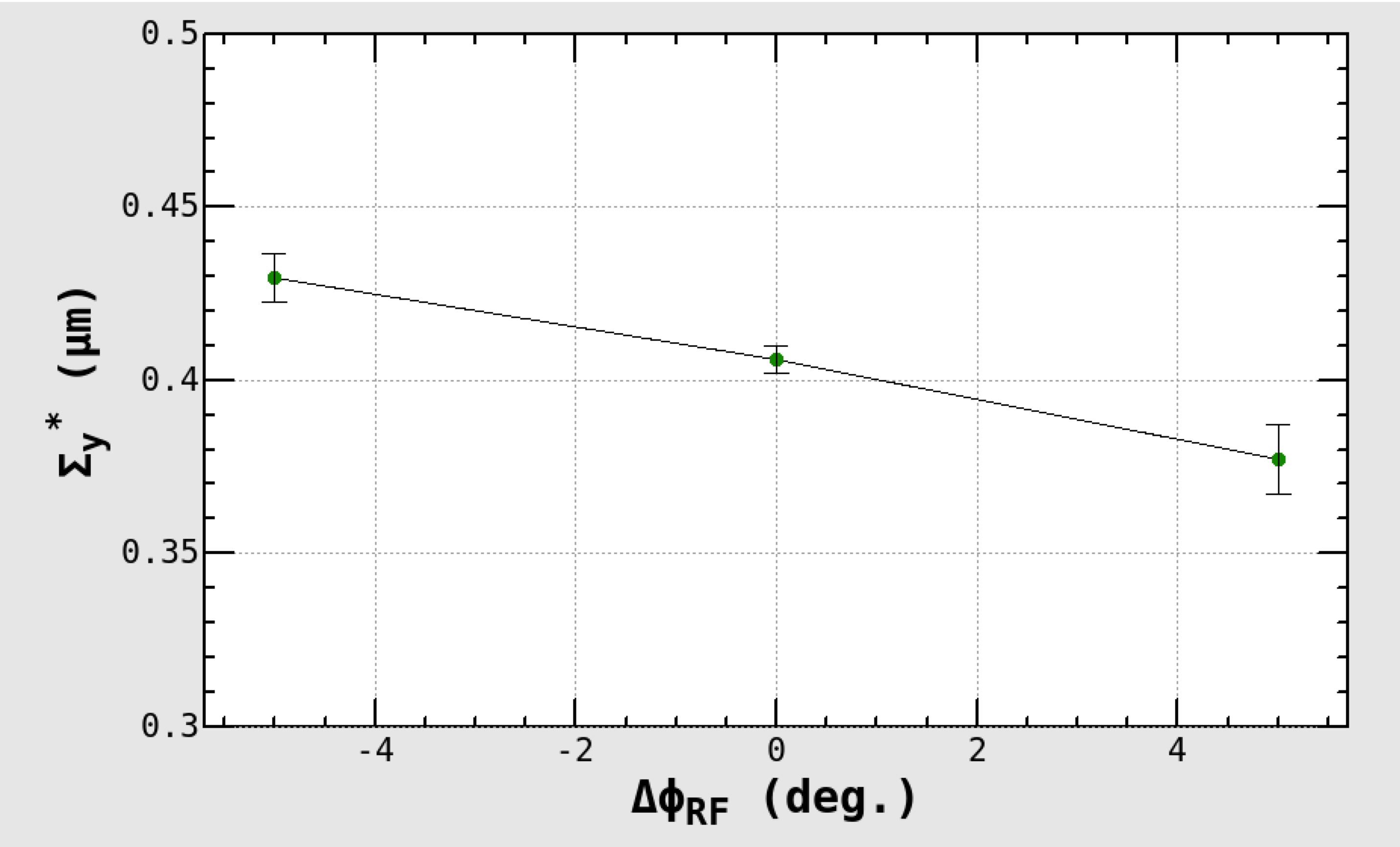
Σ_z measured by RF phase scan

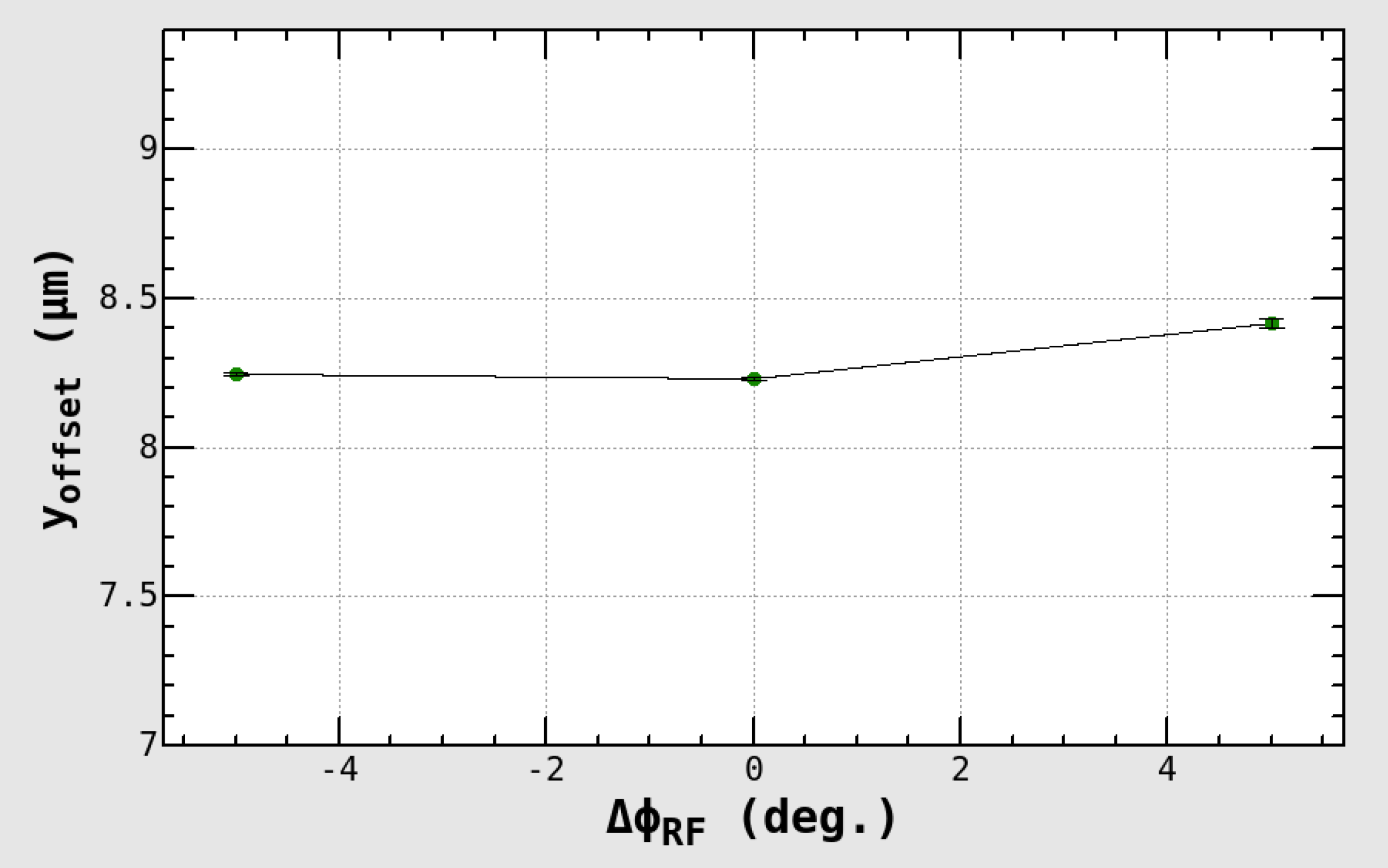


consistent with each other

In order to check vertical beam size/offset difference along z-coordinate

Σ_y^* measured by ver. offset scan at RF phase of $\Delta\phi$ = -5 deg., 0 deg., +5 deg.





deviation between RF phase offset is small

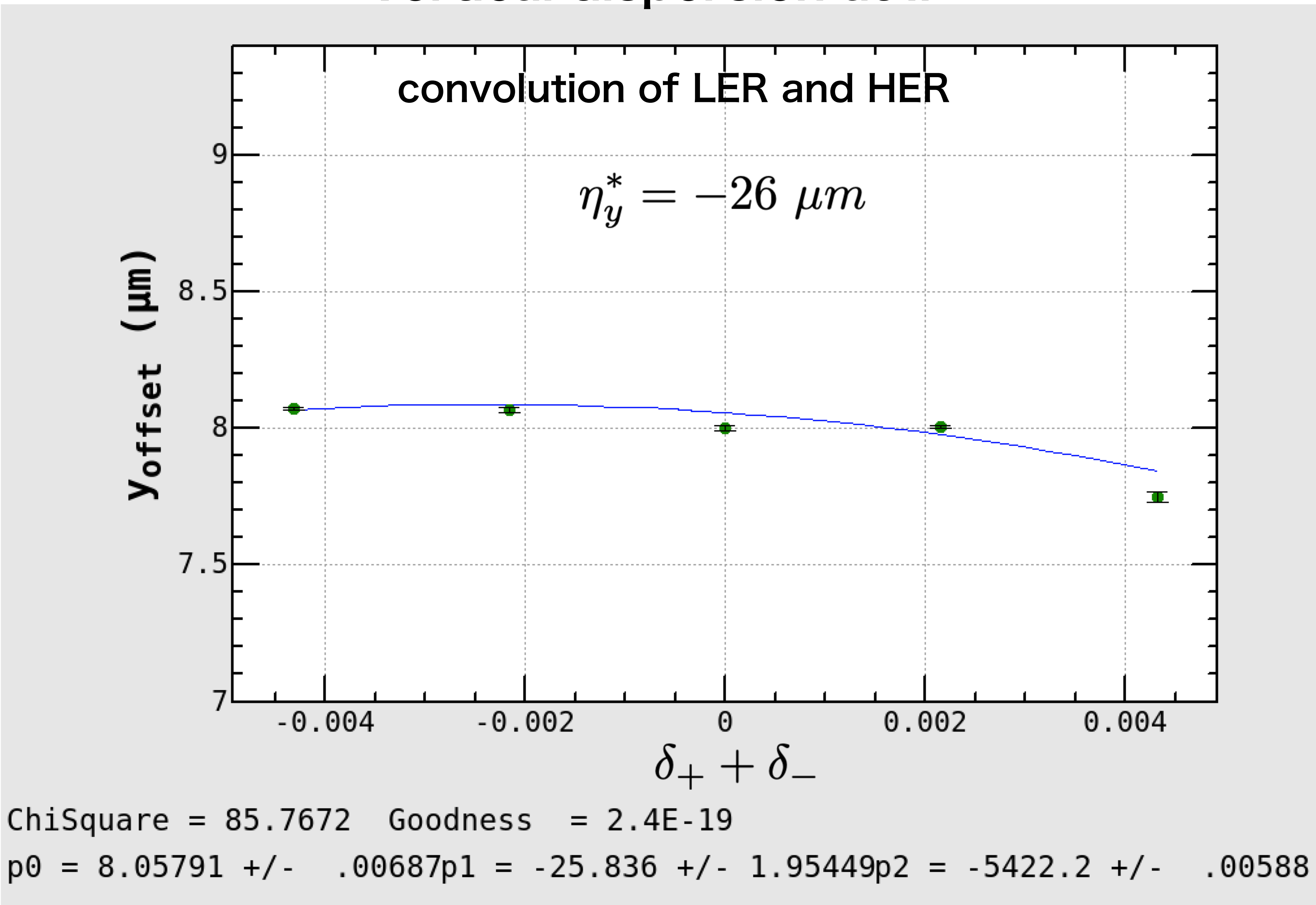
I_{b+} / I_{b-} = 0.038 mA / 0.0507 mA

Σ_z (BB scan)	Σ_z (Streak)	σ_{z+} (Streak)	σ_{z-} (Streak)
6.61 mm	6.58 mm	4.25 mm	5.02 mm

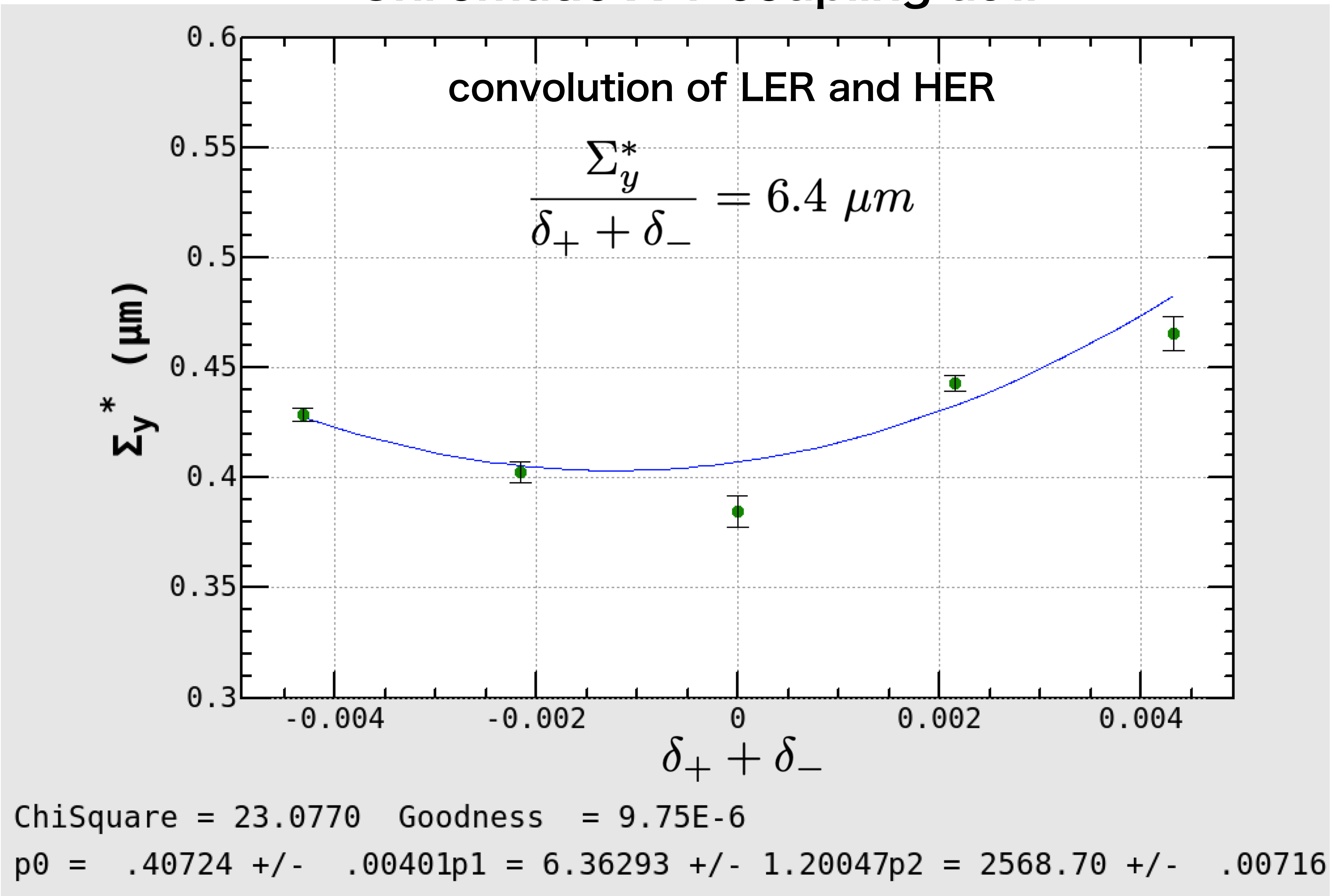
Cap Sigma Measurements with Beam-Beam Scan (cont'd)

Vertical offset scan with frequency shift (-400 Hz, -200 Hz, 0 Hz, +200 Hz, +400 Hz)

Vertical dispersion at IP



Chromatic X-Y coupling at IP



$$\sigma_{\delta+} = 7.53 \times 10^{-4}$$

$$\sigma_{\delta-} = 6.30 \times 10^{-4}$$

$$\sigma_\delta = \sqrt{\sigma_{\delta+}^2 + \sigma_{\delta-}^2}$$

$$\Delta\Sigma_y^* = \eta_y^* \sigma_\delta = 0.026\ \mu m < 0.1 \times \Sigma_y^*$$

The dispersion at IP is well corrected.

How about the second-order dispersion ?

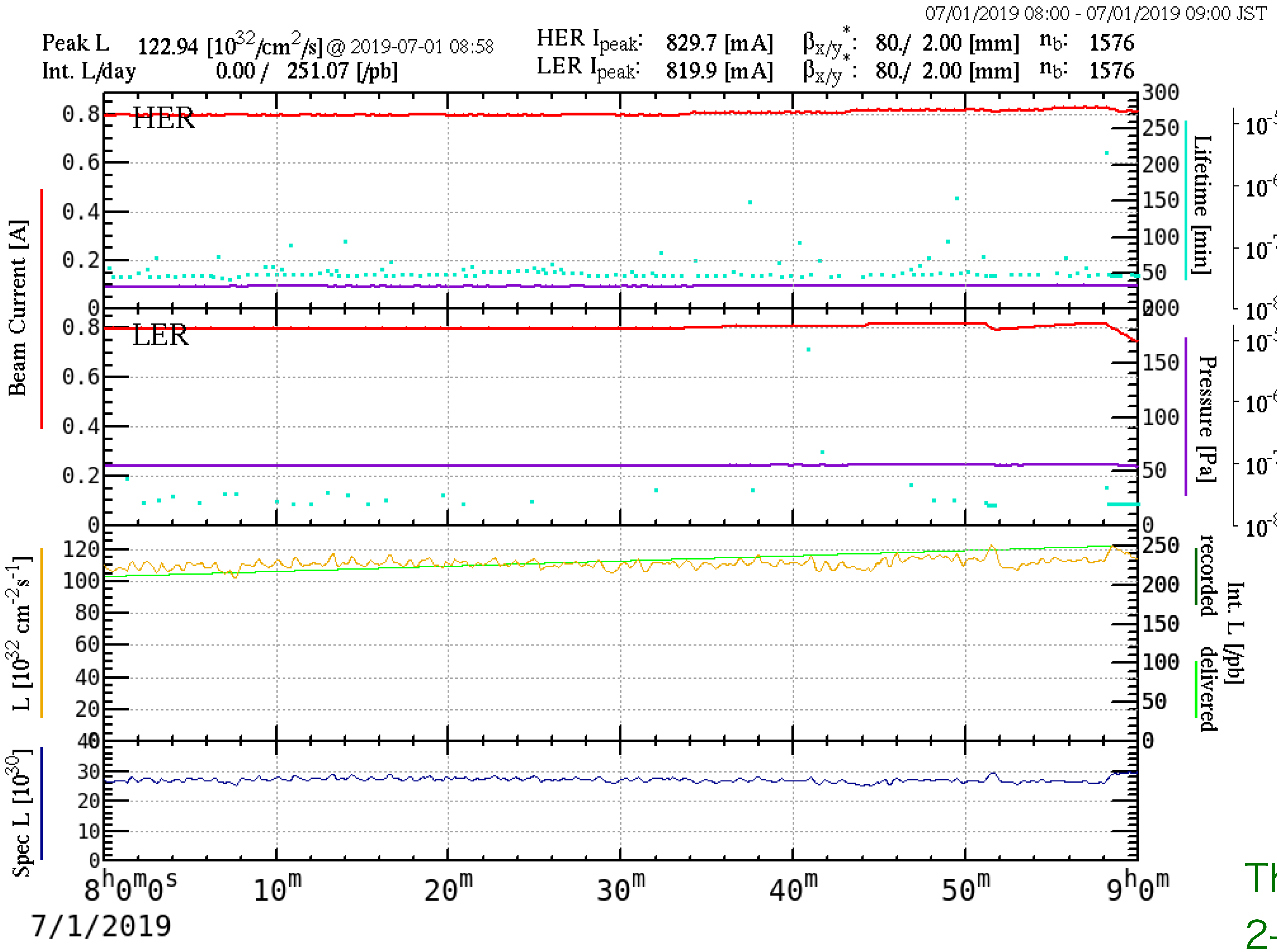
The chromatic X-Y coupling at IP is not so large.

$$\Delta\Sigma_y^*(\sigma_\delta) = 0.009\ \mu m \quad < \quad \Delta\Sigma_y^*(\sigma_\delta, r_1' = 12\ rad) = 0.18\ \mu m$$

$$\Delta\Sigma_y^*(\sigma_\delta, r_2' = 3\ m) = 0.58\ \mu m$$

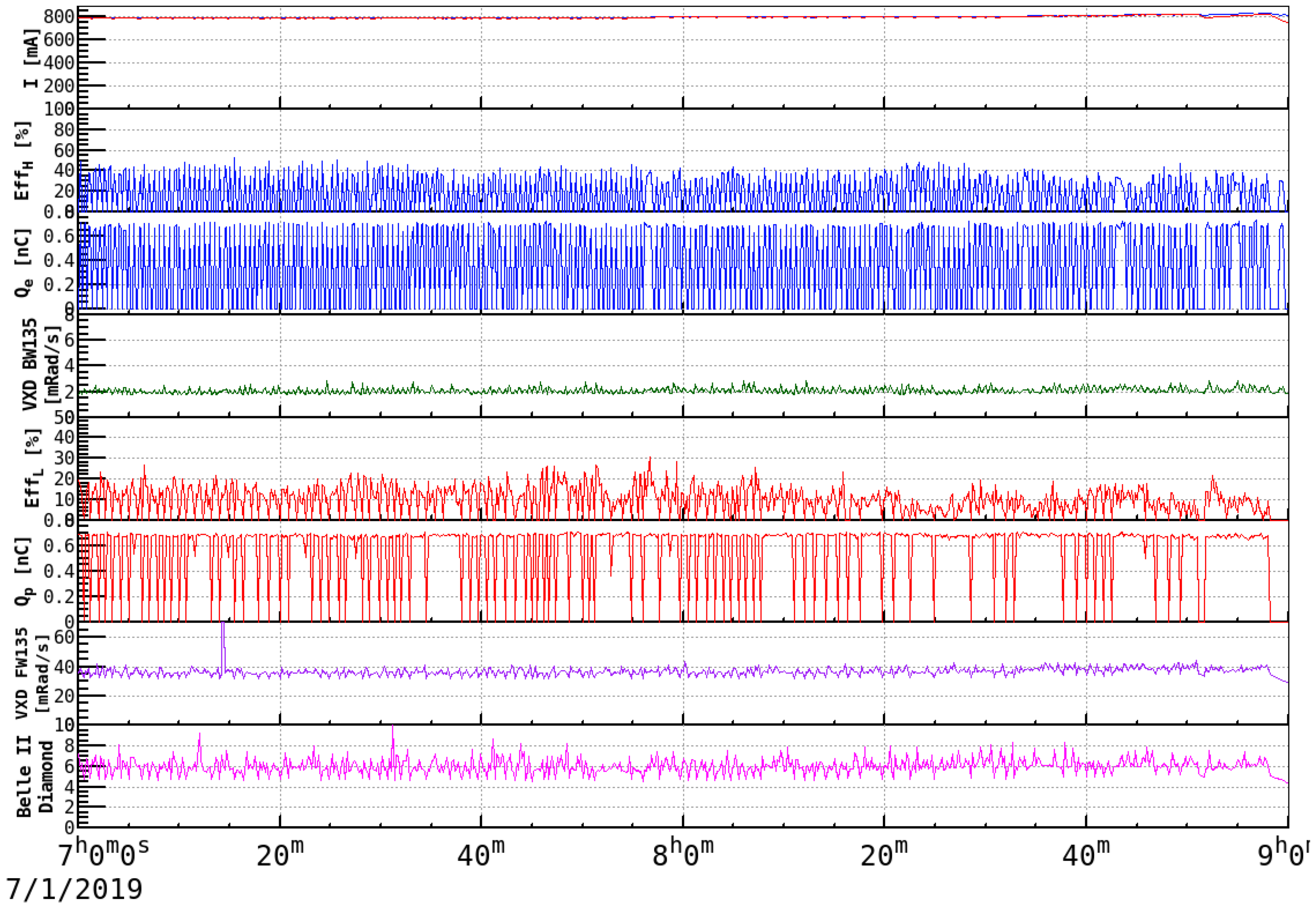
ref. Ohmi-san's talk for critical r_1' and r_2'

Max. Beam currents: LER ~ 800 mA and HER ~ 850 mA



LER lifetime ~ 20 min / HER lifetime ~50 min

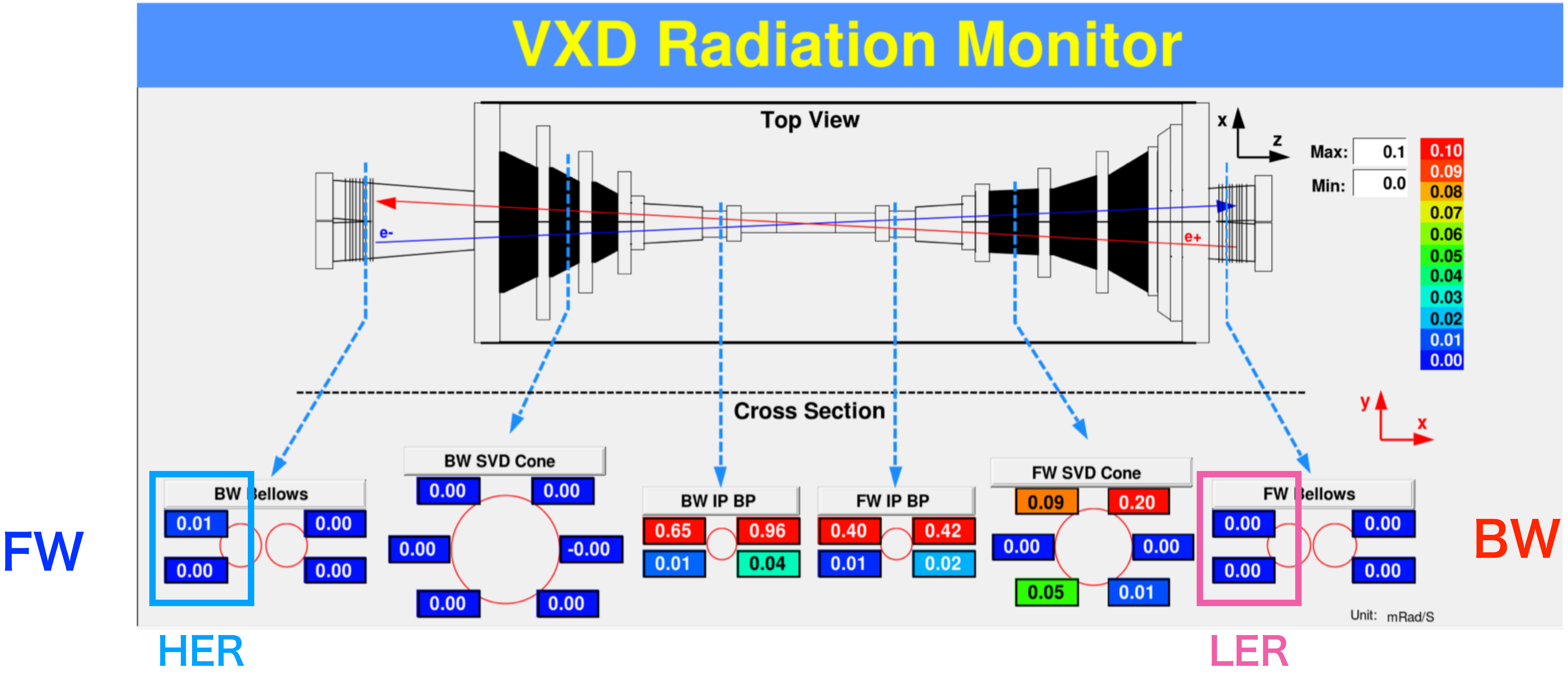
The lifetime restricts the max. beam currents.



The injector capability limits the max. beam current in LER. 2-bunch injection and/or ~25 Hz rep. are necessary to increase larger beam current.

Belle II - VXD Beam Abort: tests

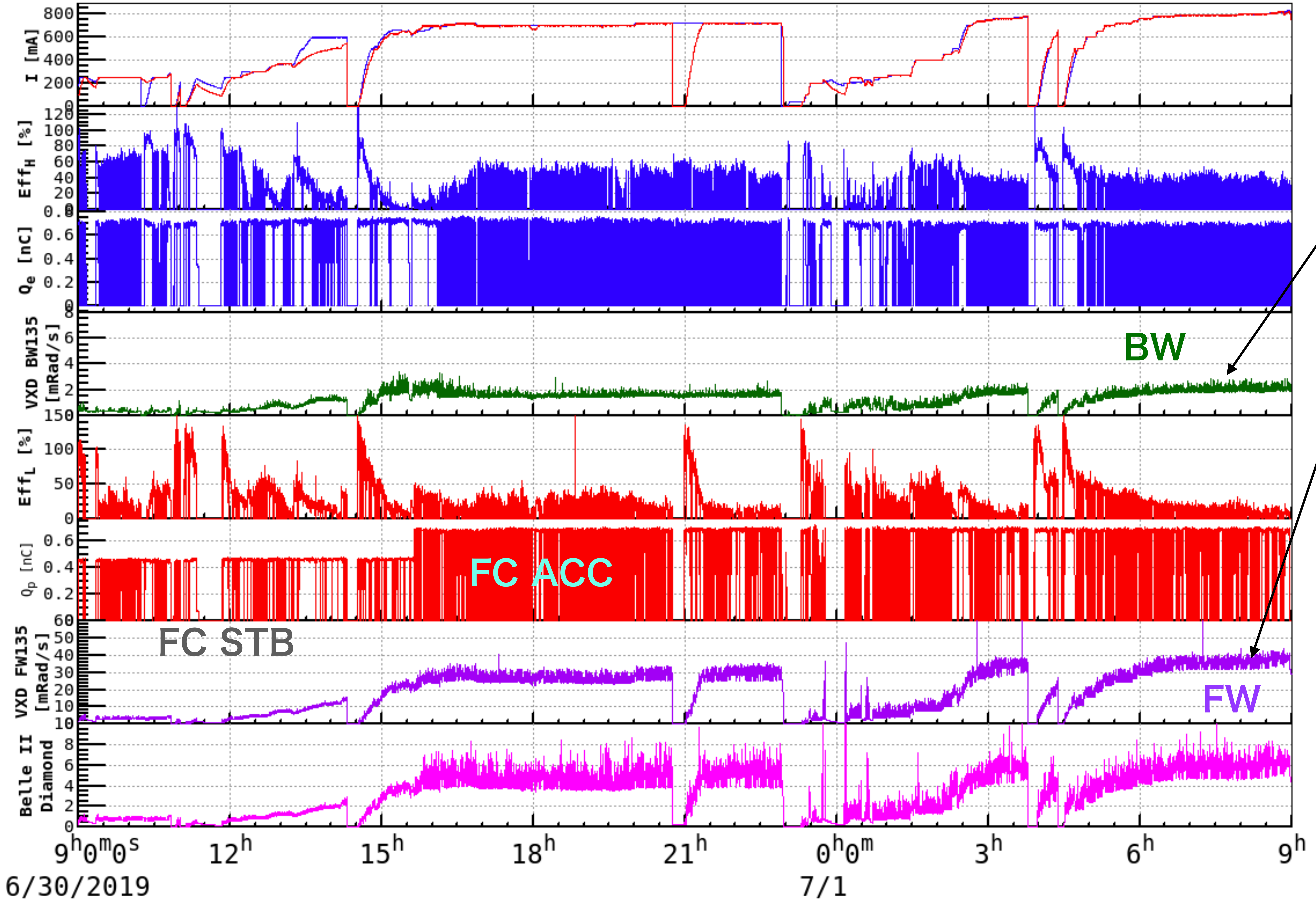
L.Lanceri – INFN & Univ.Trieste for the VXD monitoring group / SuperKEKB meeting 14/03/2019



28 diamond sensors

4 dedicated to beam abort requests, similar to Phase 2

20 dedicated to monitoring (initially!)
4 not read out yet (SVD BW, off-horizontal plane)



QCS Diamond Sensor

In order to tune on CDC HV, sum of BW and FW should be less than 12 mRad/s.

Tanaka's rule

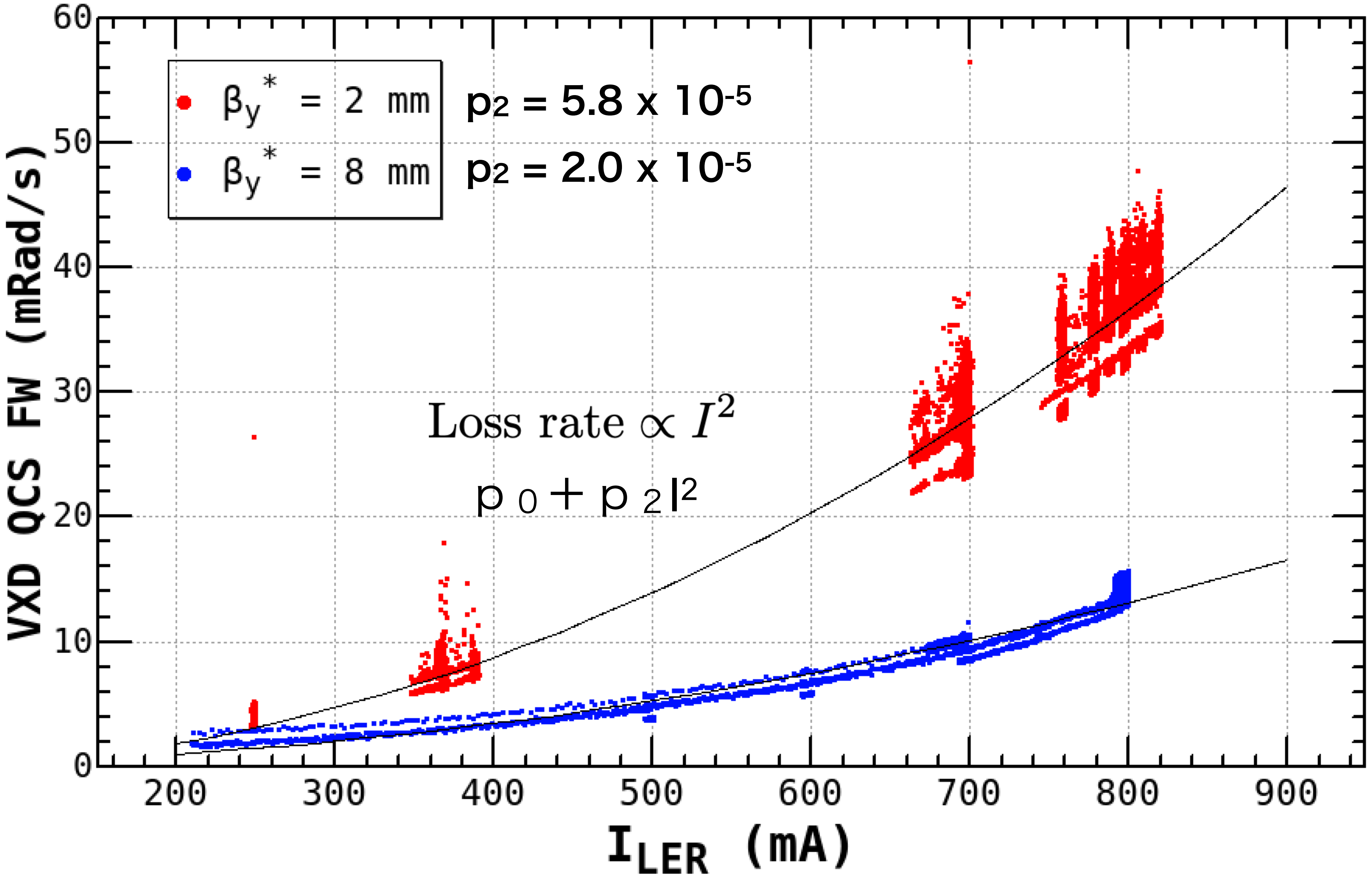
HER injection background depends on the horizontal tune.

LER injection background also depends on the horizontal tune.

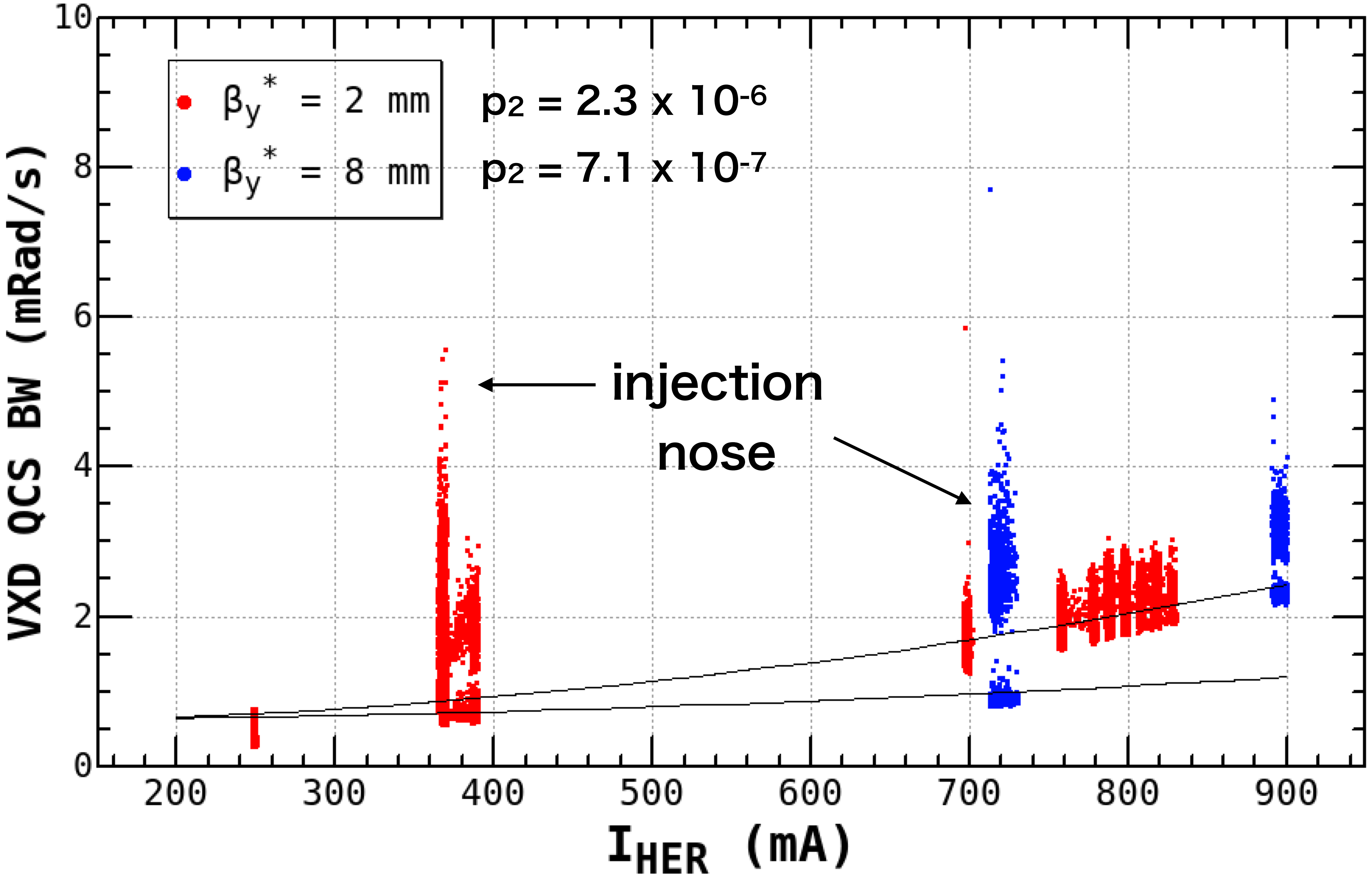
Storage background becomes very high as increasing the LER beam current.

Beam Background in LER and HER

LER storaged beam is dominant.



HER injection depends on the horizontal betatron tune.



LER + HER < 12 mRad/s requires LER < 700 mA for β_y^* = 8 mm and LER < 400 mA for β_y^* = 2 mm.

This rule comes from our experience to turn on the CDC HV. so-called "Tanaka's rule"

$L_p = 2.5\times10^{33}$

$L_p = 6\times10^{33}$

Beam Background due to Residual Beam Gas in LER

Loss Rate: $$\frac{N}{\tau} = Ncn_g \frac{4\pi r_e^2 Z^2}{\gamma} \left\langle \frac{1}{\theta_c^2} \right\rangle$$

Loss rate becomes larger
as increasing of the beta product
at QC1 and other places in the ring.

When we squeeze the beta*,
the loss rate increases
as the result of the beta product
increases even though the same
beam current.

$$L \propto \frac{I\xi_y}{\beta_y^*} \qquad \xi_y \propto \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

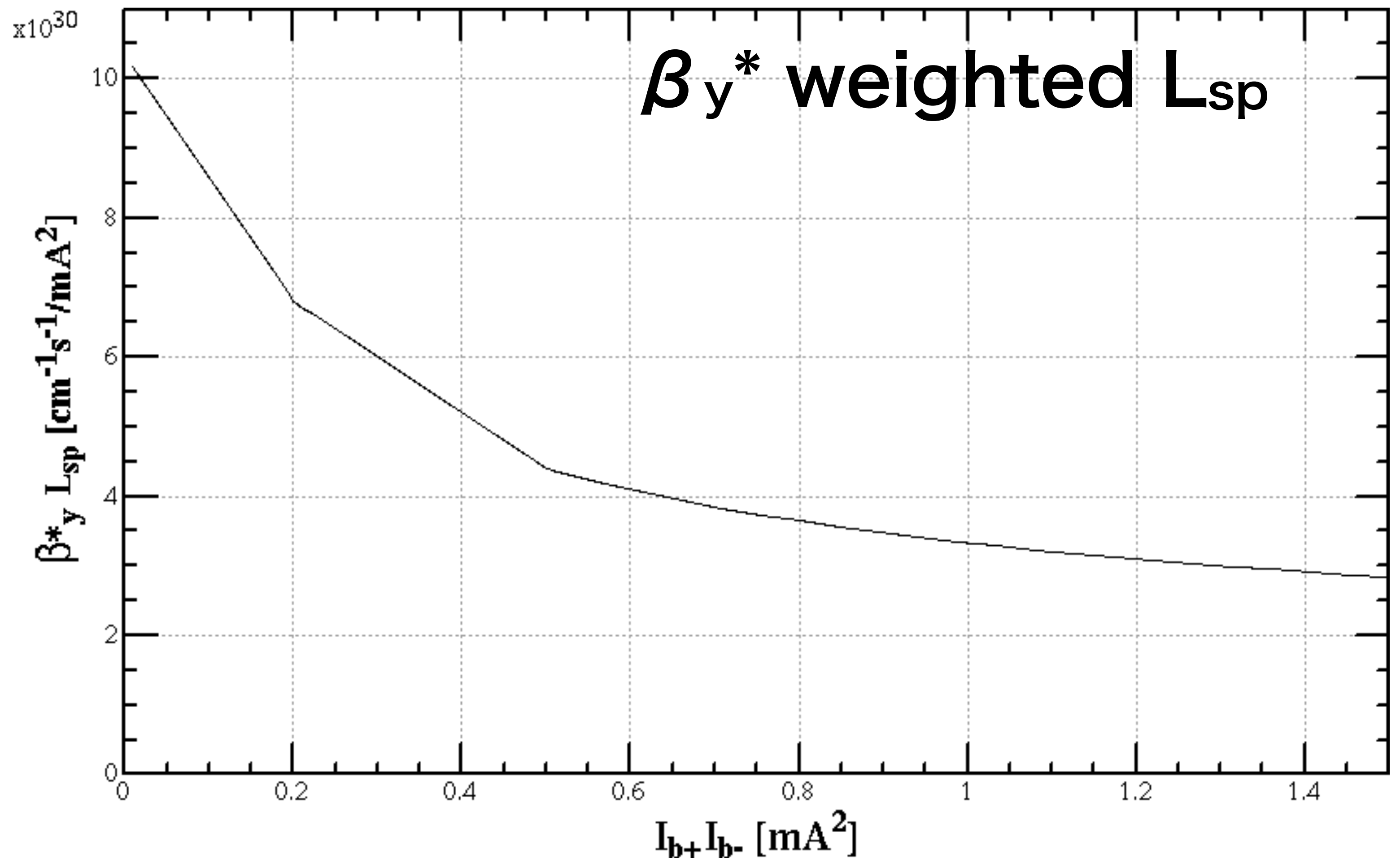
In order to achieve 10^{34},
I_{LER} = 340 ~ 470 mA at β_y^* = 1 mm

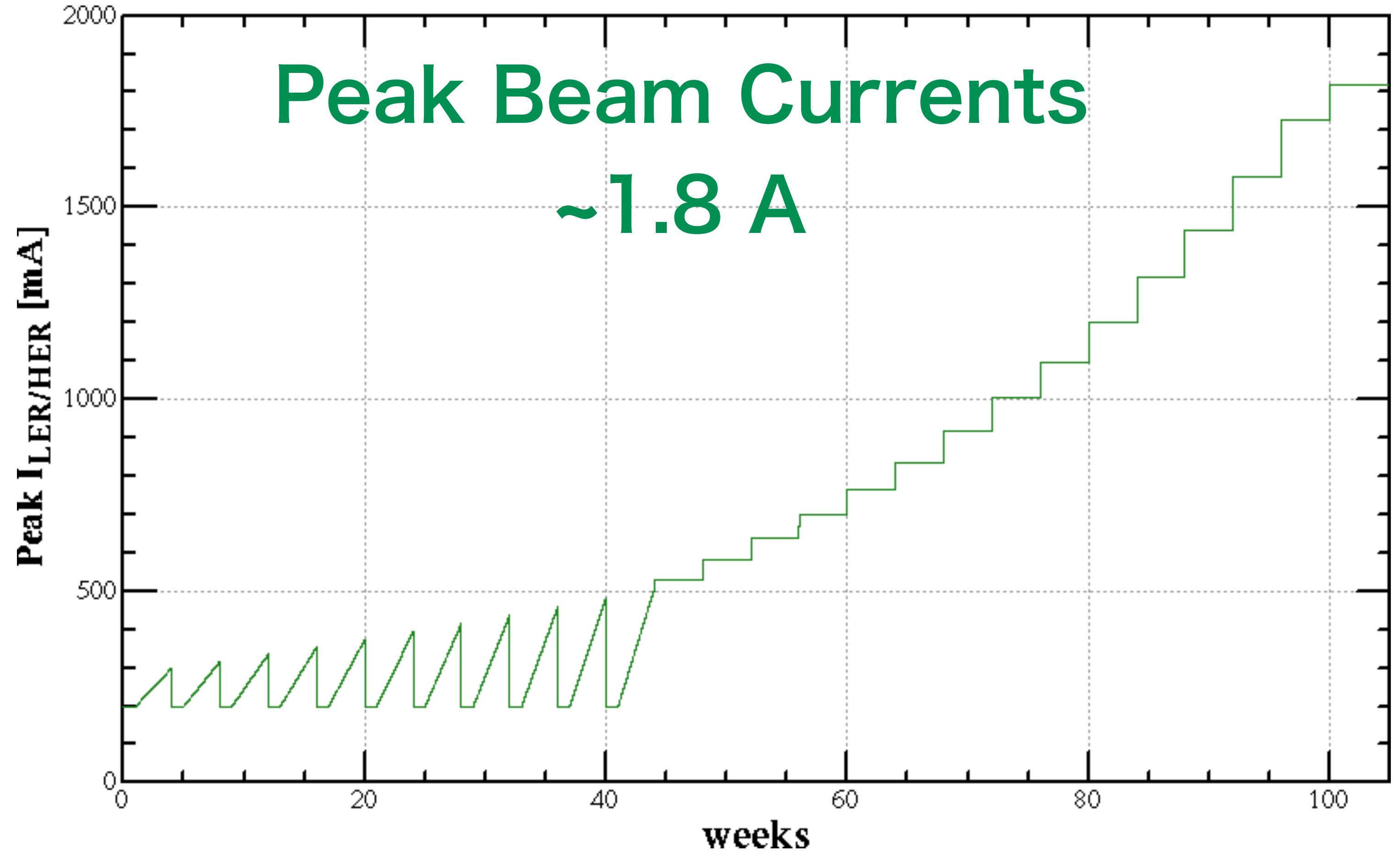
VXD BW+FW < 12 mRad/s ?

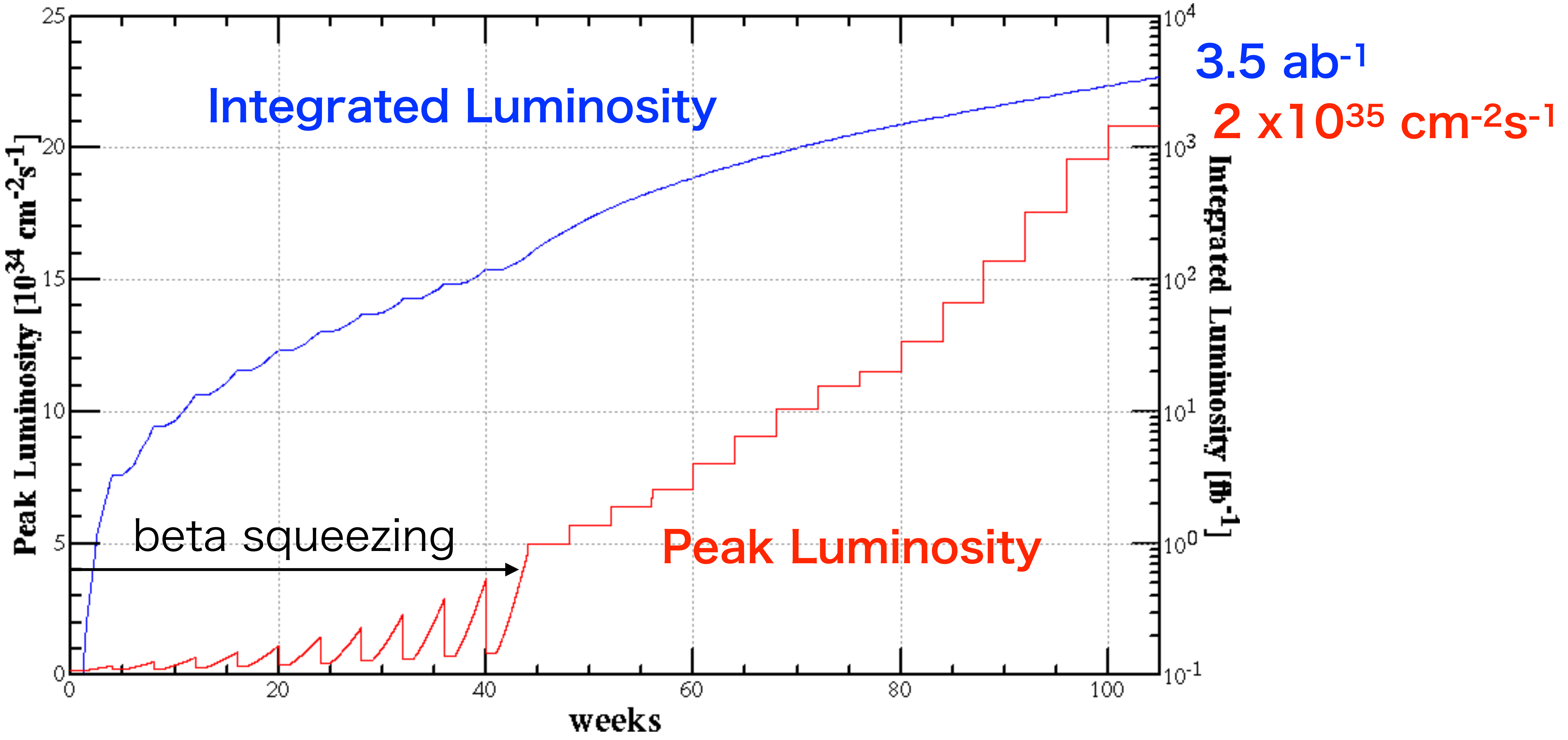
β_y^*	2	8	mm
$\beta_{y,QC1}$	370.6	95.8	m
$\beta_{y,D2V1}$	17.0	27.3	m
d_{QC1}	13.5		mm
d_{D2V1} (calc)	2.1	2.7	mm
d_{D2V1} (TOP)	2.3	4.5	mm
d_{D2V1} (BTM)	-2.0	-4.5	mm
I_{LER} (VXD BW+FW < 12)	400	700	mA
L (VXD BW+FW < 12)	6×10^{33}	2.5×10^{33}	$cm^{-2}s^{-1}$

L seems to be scaled by $1/\beta_y^*$ here.

A. Morita







1 year (52 weeks) 2 year (104 weeks)

beta squeezing every month (~11 months to reach design beta*):

β^*_y squeezing: 1.5mm -> 1.2mm -> 1.0mm -> 860μm -> 740μm -> 635μm -> 550μm-> 470μm -> 405μm -> 350μm -> 300μm

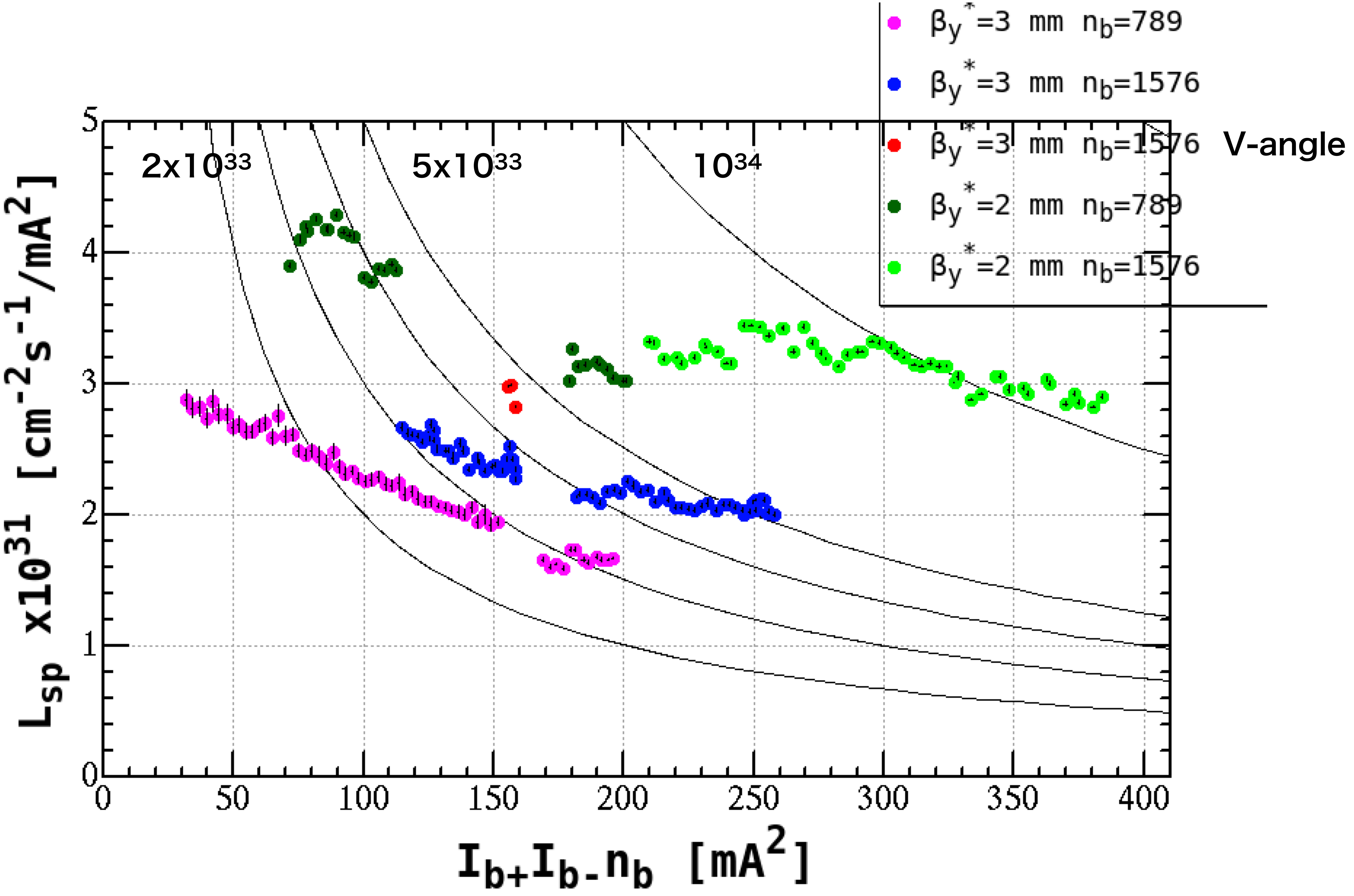
Assumption: the beam-beam parameter can be kept when the beta squeezing is performed,

Summary

- The beta at IP can be squeezed down to **2 mm** in the vertical and **80 mm** in the horizontal direction.
- The specific luminosity is improved as decreasing the beta at IP.
- The vertical beam-beam parameter can be kept to be ~0.02 at 0.67 mA bunch current even though the beta squeezing is performed. The target is ~0.04 to accomplish 0.08 for 1.4 mA bunch current.
- The peak luminosity is **1.23 x10^{34} cm^{-2}s^{-1}** at 800 mA / 820 mA (LER/HER).
- Beam-Beam blow-up is observed, and also flip-flop phenomena. The vertical emittance without collision is enough small when $\Sigma_y{}^*$ measurement and X-ray monitor are compared.
- In order to find machine error to degrade luminosity performance, we measure $\Sigma_y{}^*$ and Σ_z by using beam-beam scan at small bunch currents. No big error is not found so far.
- Linear optical parameters are almost optimized. X-Y coupling, dispersions at IP, waist, ...
- It is necessary to check nonlinear optical parameters, some of them are checked.

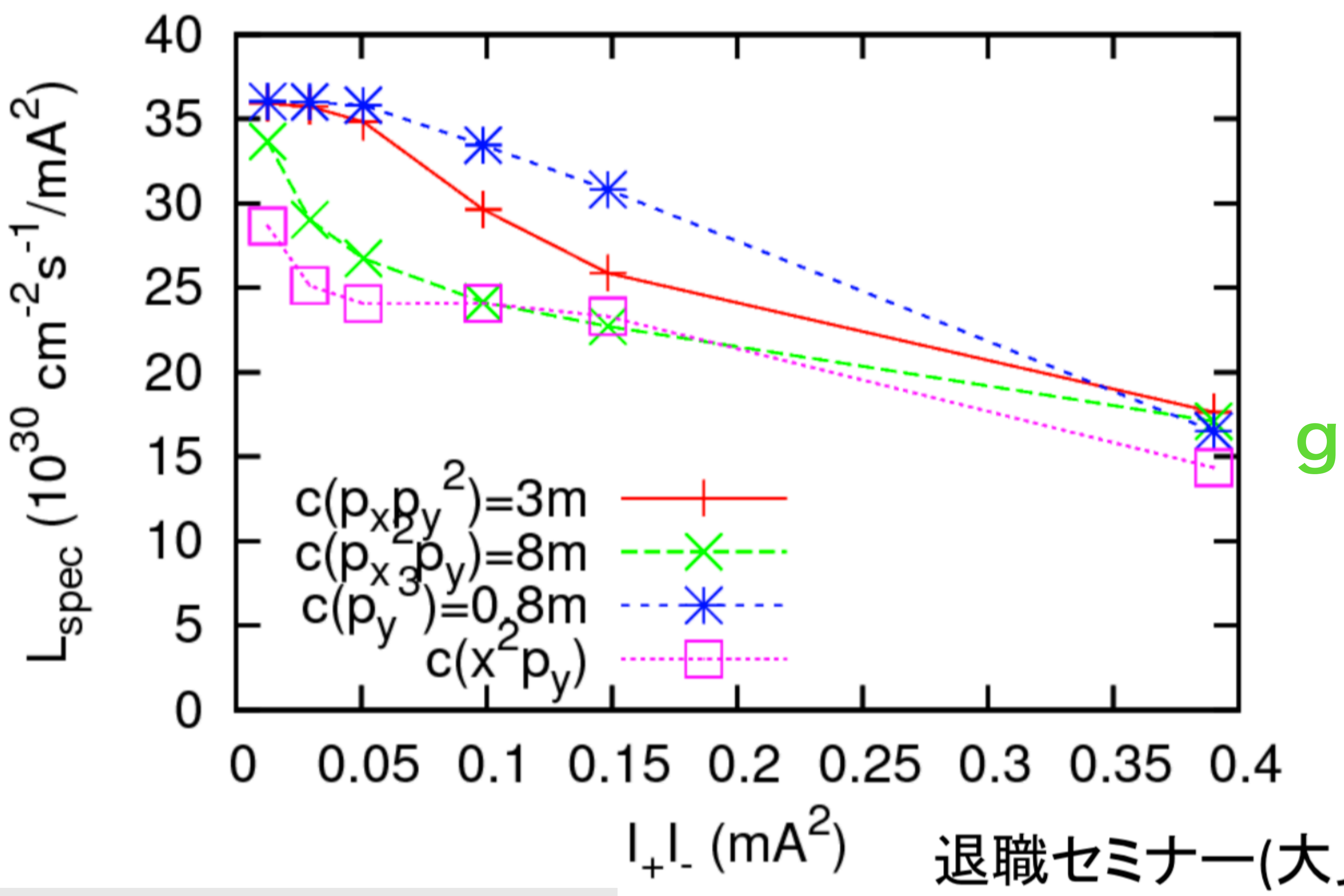
Appendix

Improvement of Specific Luminosity



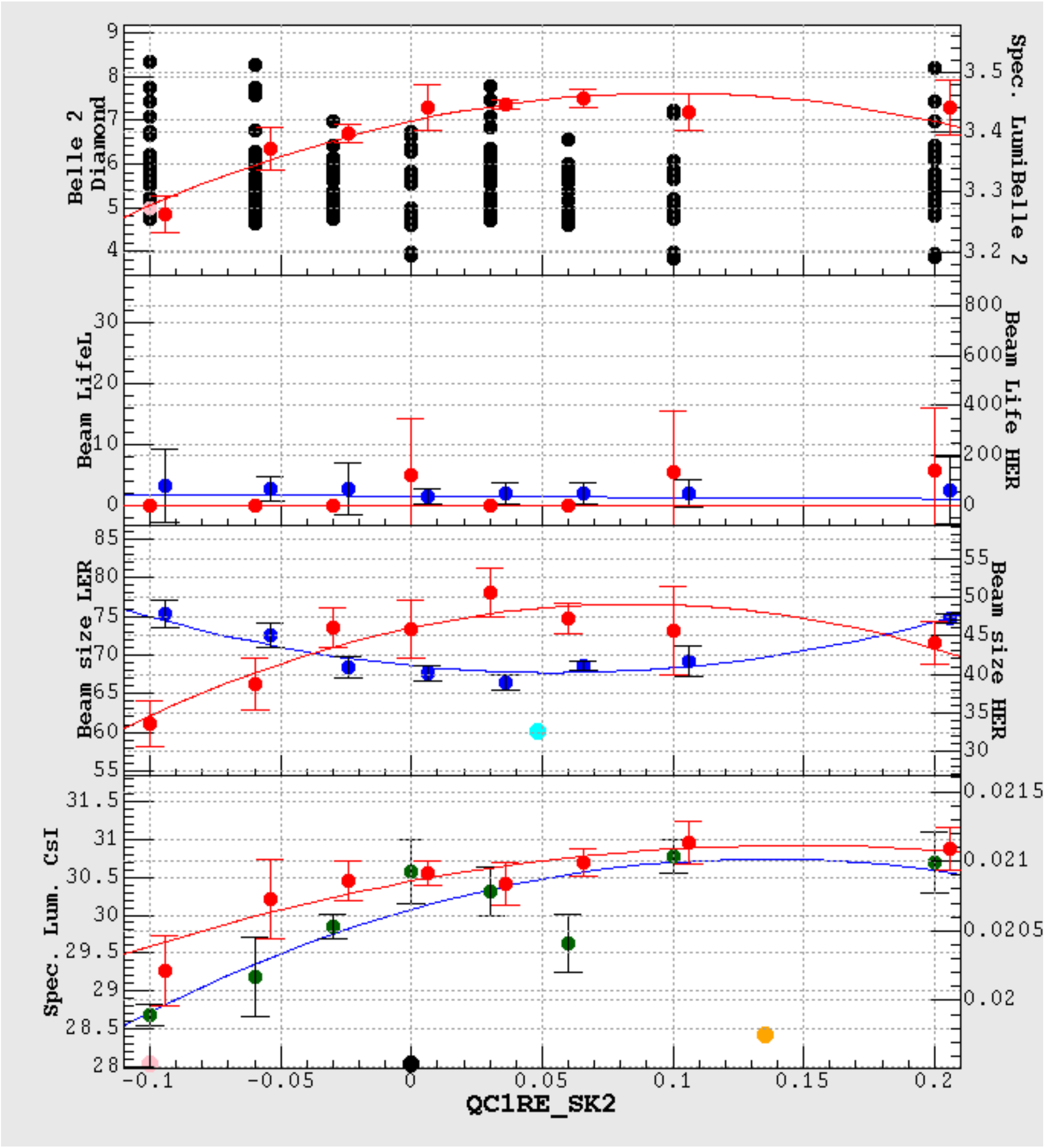
Nonlinear Aberrations and Chromatic X-Y Couplings

Nonlinear aberrations



退職セミナー(大見) Mar. 25, 2019

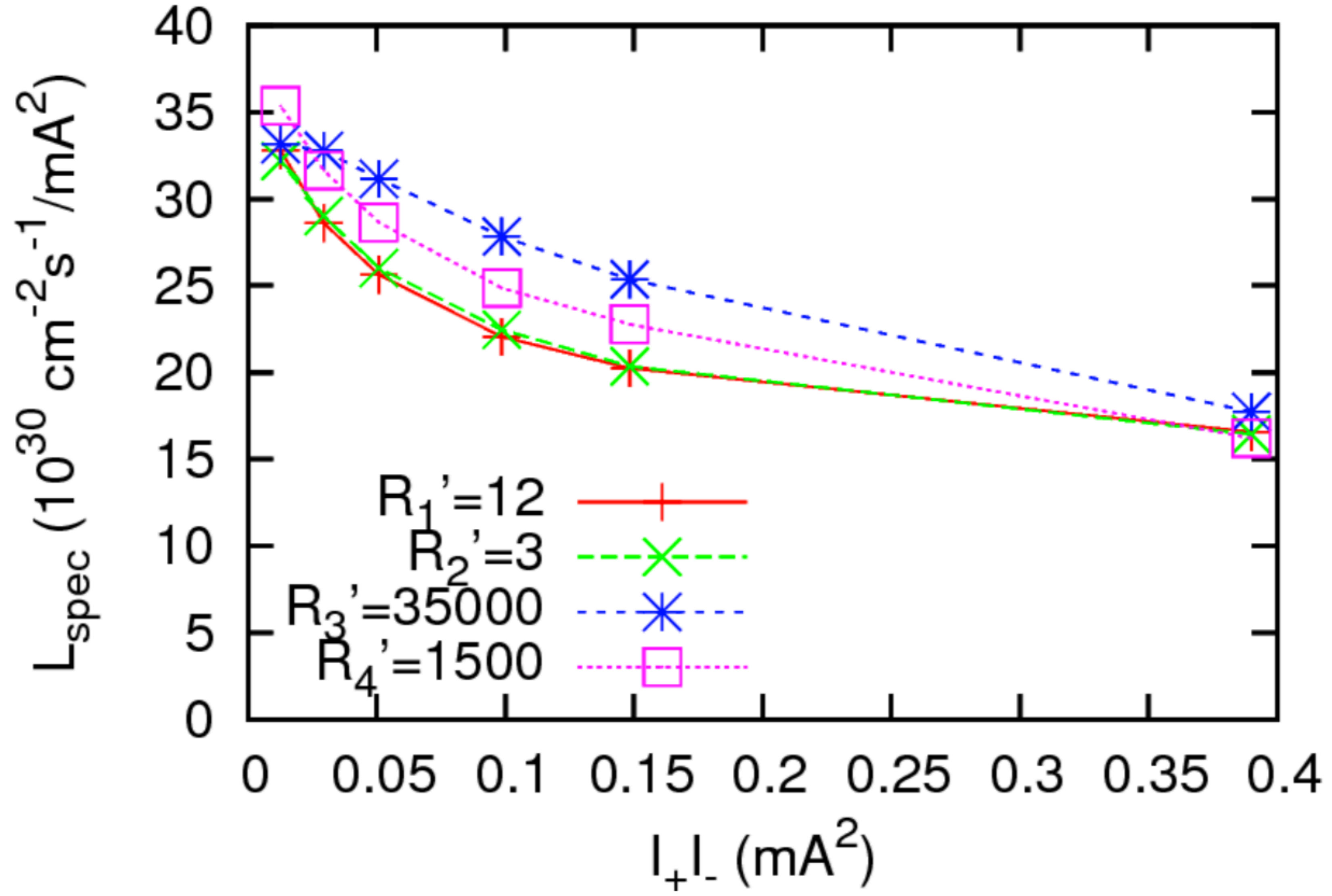
green: $p_x^2 p_y$



$P_x^2 P_y$ term is small
in the design ($c(p_x^2 p_y)$ = 0.07 m)

- R1’=12rad
- R2’=3m
- $C(p_x^2 p_y)$=8m

Chromatic X-Y couplings



退職セミナー(大見) Mar. 25, 2019

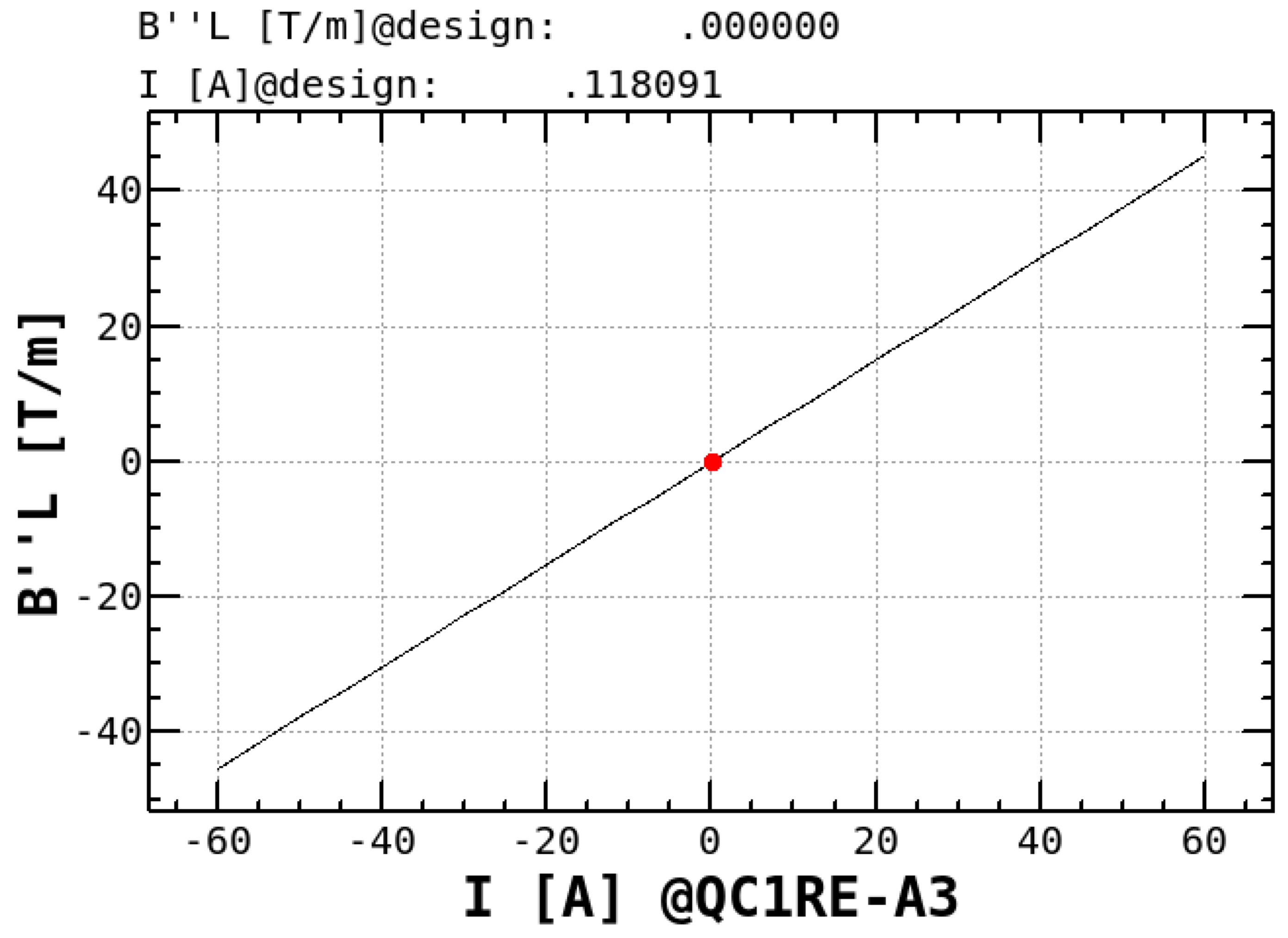
r_3' and r_4' are measured by TbT
and enough small. (r_3' = 300 m^{-1} r_4' = 20)

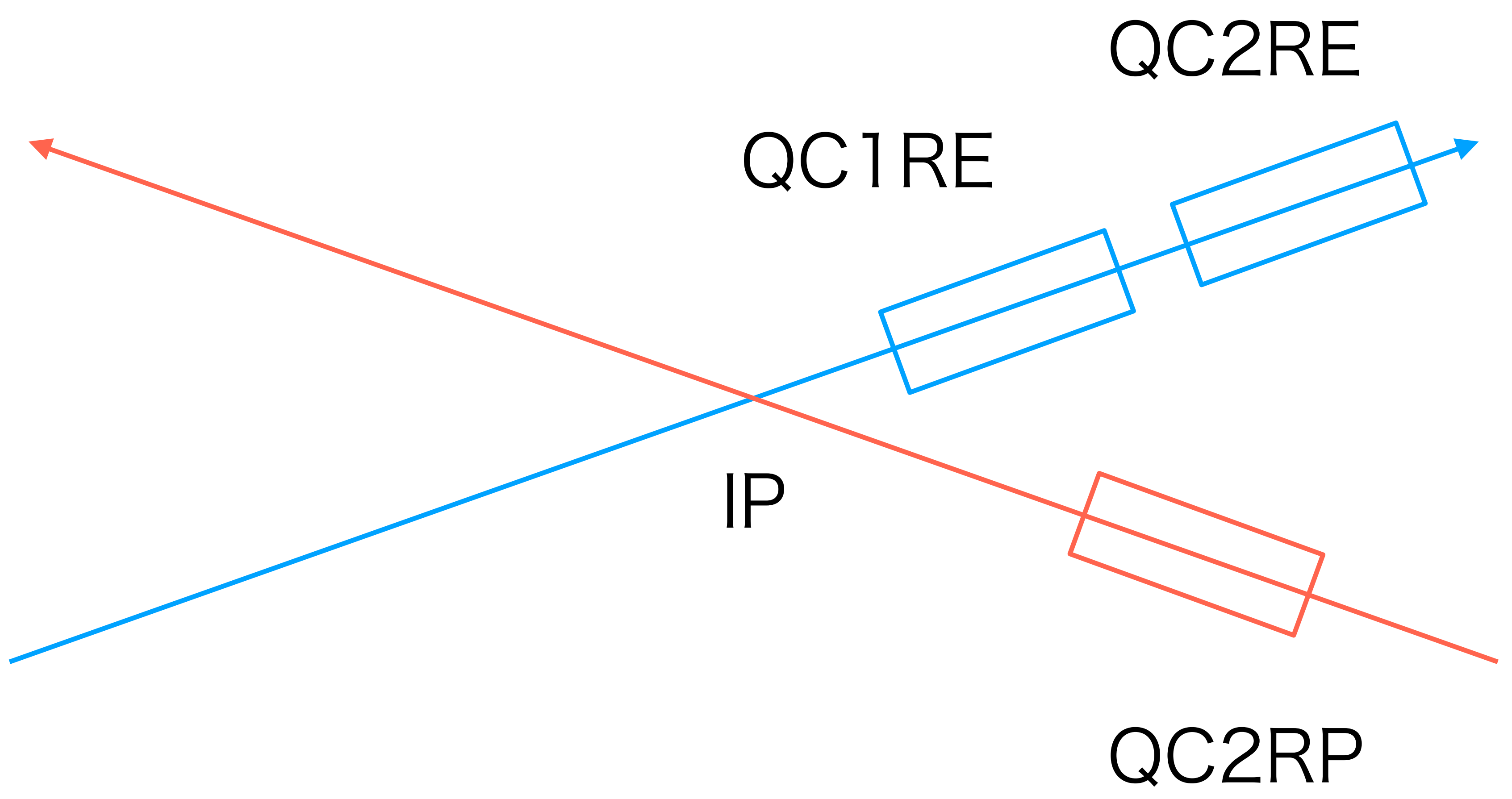
r_1' and r_2' are difficult to measure by TbT.

$$\Delta\sigma_y^{*2} = \sqrt{\varepsilon_x\left(\frac{r_2^{*2}}{\beta_x^*} + \beta_x^* r_1^{*2}\right)}$$

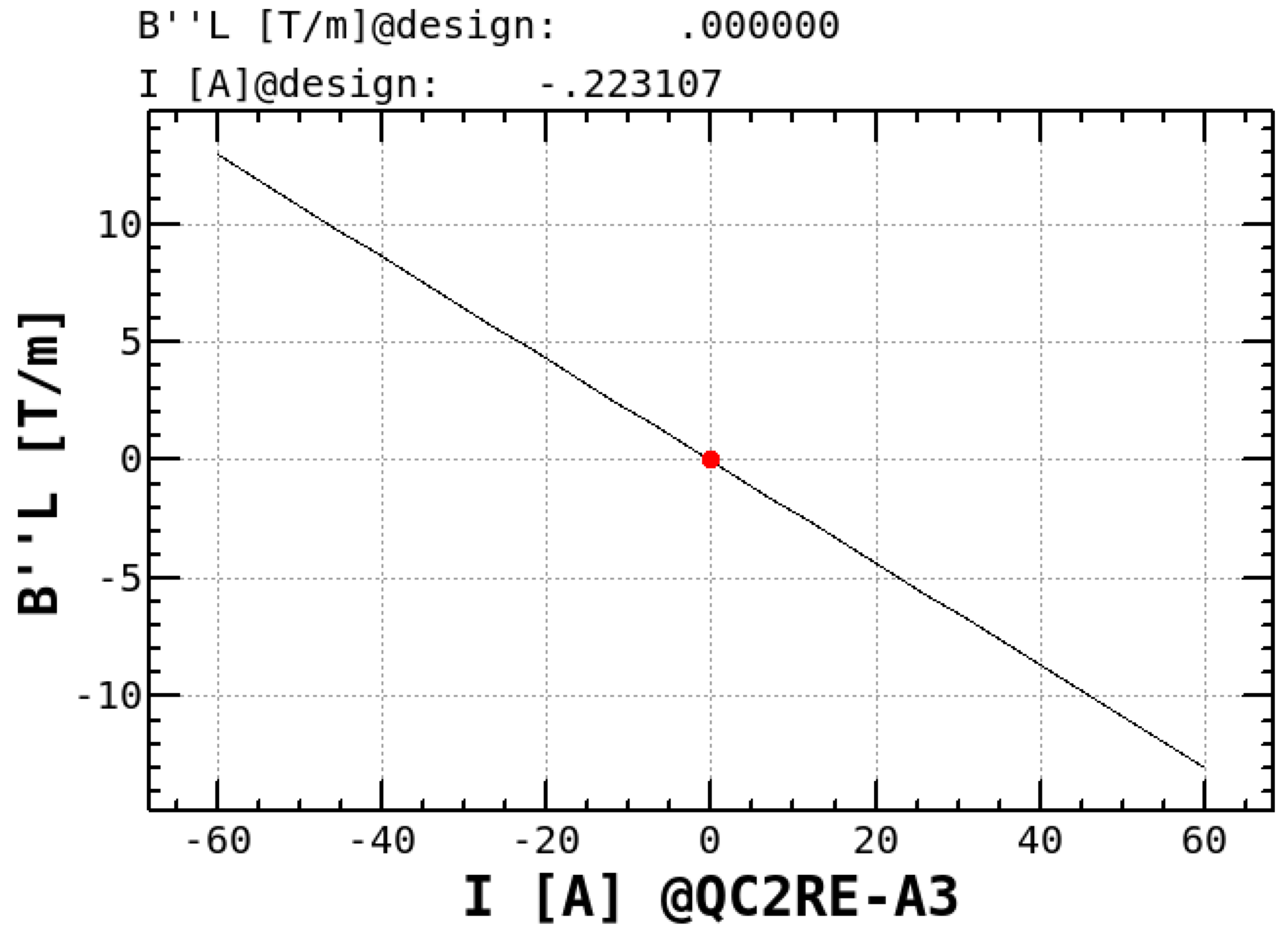
Skew Sextupole at QCS

40 T/m -> K2 = 1.7 m^{-2}

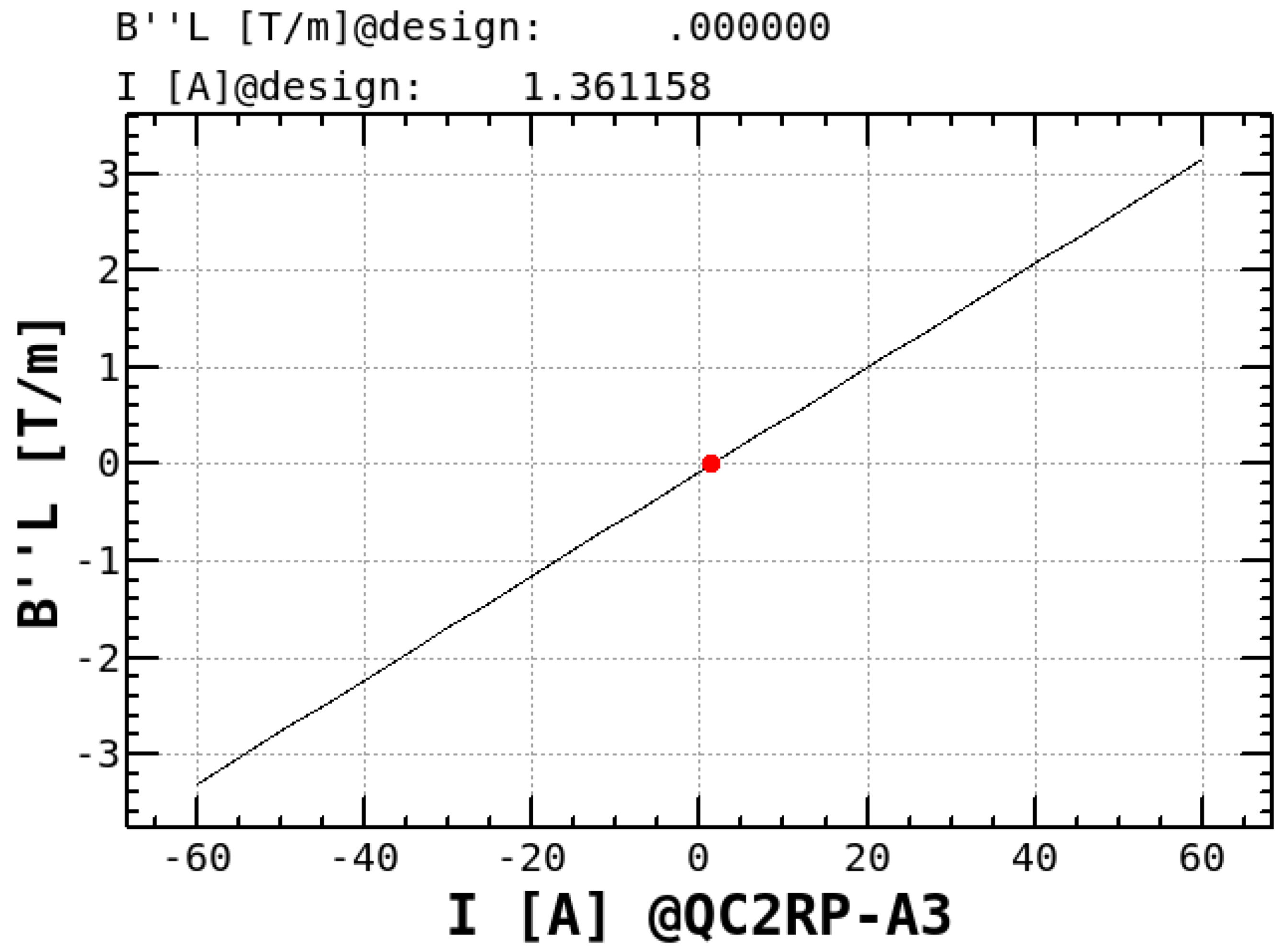




10 T/m -> K2 = 0.4 m^{-2}



2.5 T/m -> K2 = 0.1 m^{-2}



Hamiltonian of Skew Sextupole

$$H = \frac{e}{p} A_s = \frac{K_2}{6}(y^3 - 3x^2 y)$$

$$A_s = \frac{g_2}{6}(y^3 - 3x^2 y) \qquad g_2 = (B\rho)K_2$$

$$\vec{x} = M\vec{x^*}$$

IP -> QC2RP

```
{{  2.734260, -3.480206,  0.022371, -0.018732},
 { -0.787774,  1.368435, -0.013255,  0.009202},
 {  0.015129, -0.011311, -0.568849, -0.494743},
 { -0.013307,  0.007144,  1.730980, -0.252531}}
```

IP -> QC1RE

```
{{   1.079588,   -1.501248,   -0.000489,    0.000202},
 {  -0.615786,    1.782576,    0.001152,   -0.000382},
 {  -0.000980,    0.000937,    0.921587,   -1.320881},
 {   0.000412,   -0.000346,    0.574725,    0.261349}}
```

IP -> QC2RE

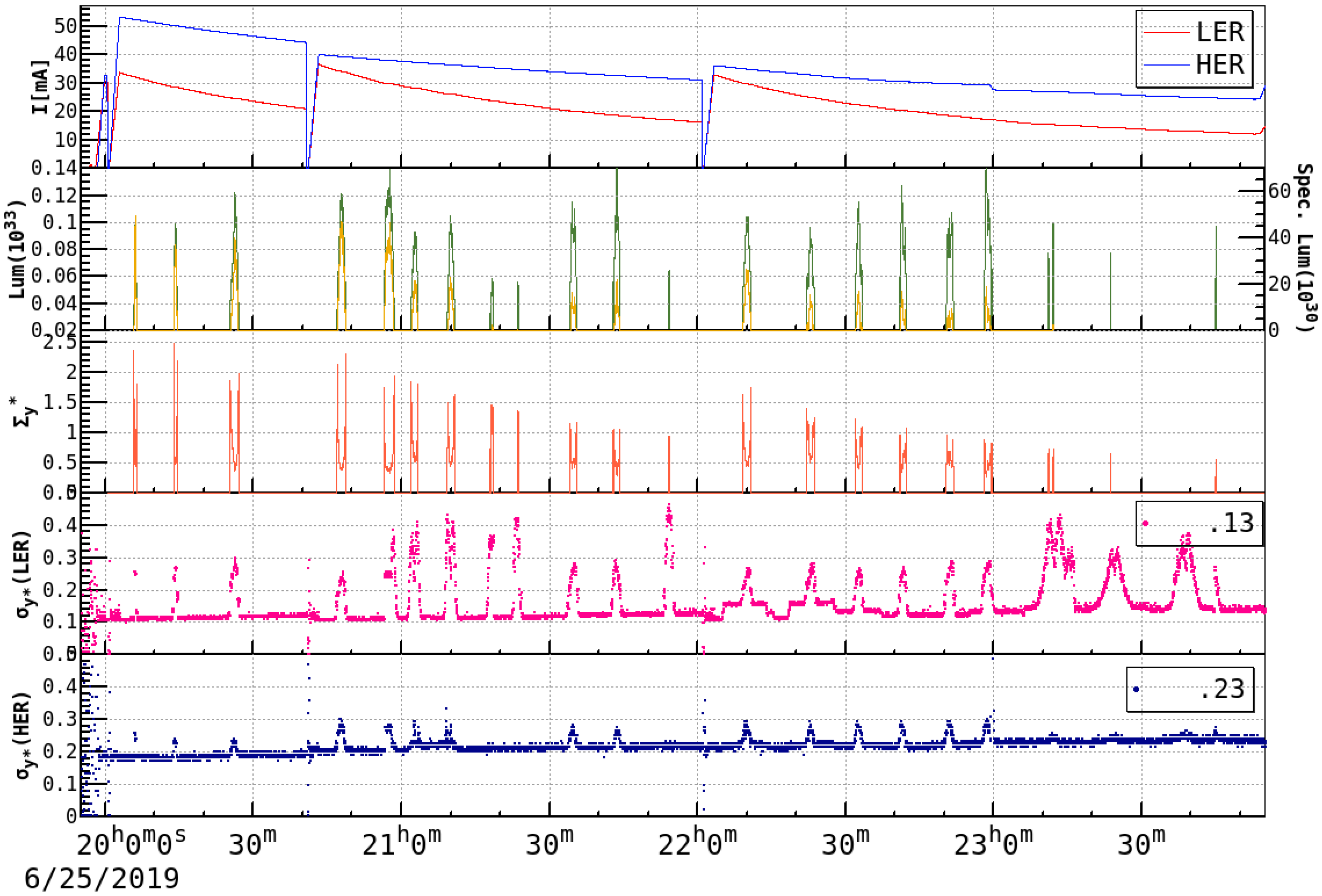
```
{{   2.822264,   -5.352622,   -0.003650,   -0.001791},
 {  -0.500603,    1.303750,    0.004173,   -0.001274},
 {  -0.009919,    0.018274,   -0.616102,   -0.718735},
 {   0.002742,   -0.006273,    1.173520,   -0.254078}}
```

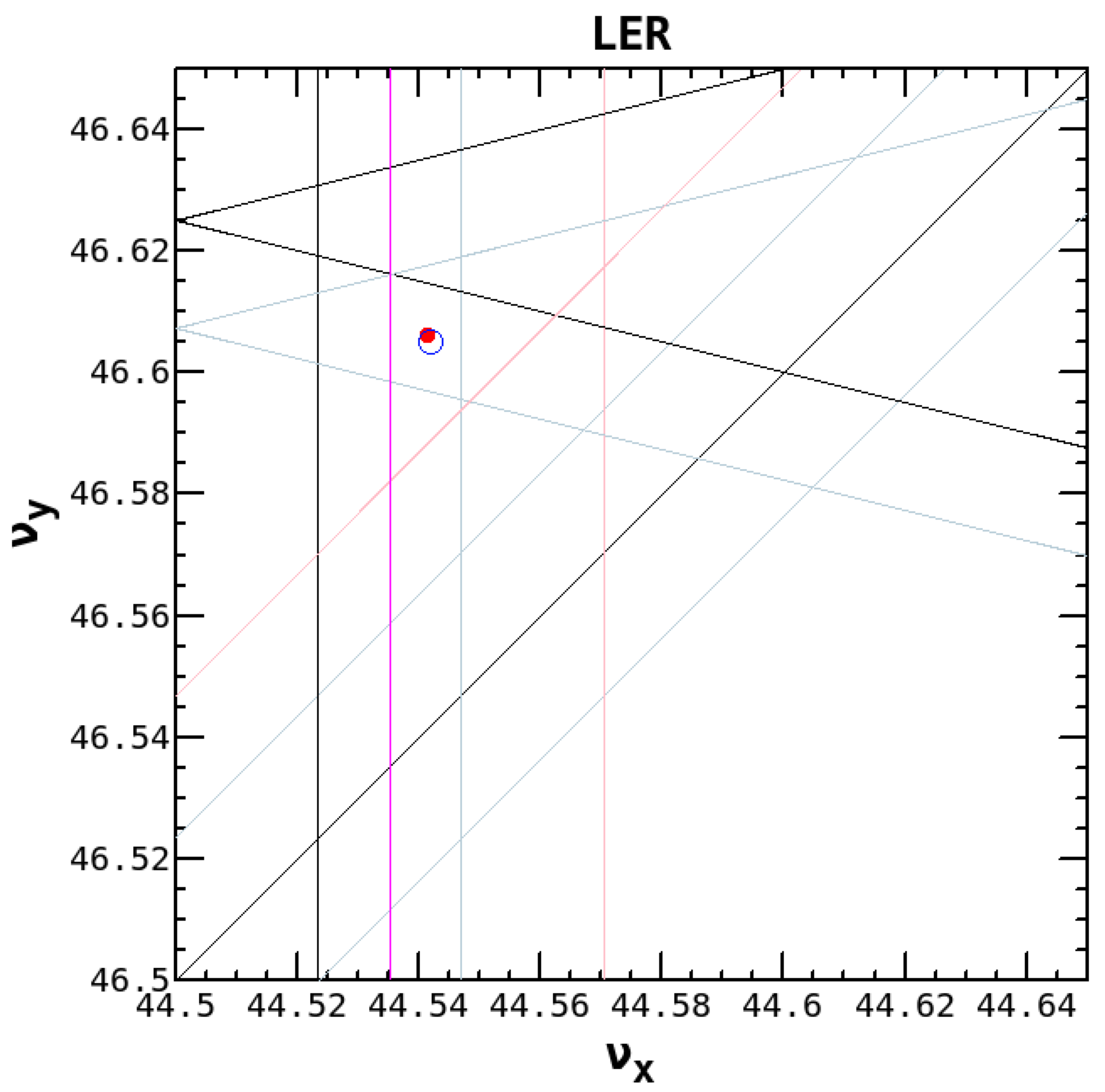
K2 = 1

	coefficient	coefficient
	QC1RE	
p_y^{*3}	-0.384096	
$p_x^{*2} p_y^*$	1.488466	
$x^{*2} p_y^*$	0.76975	
	QC2RE	QC2RP
p_y^{*3}	-0.061881	-0.020183
$p_x^{*2} p_y^*$	10.296074	2.996124
$x^{*2} p_y^*$	2.862423	1.849394

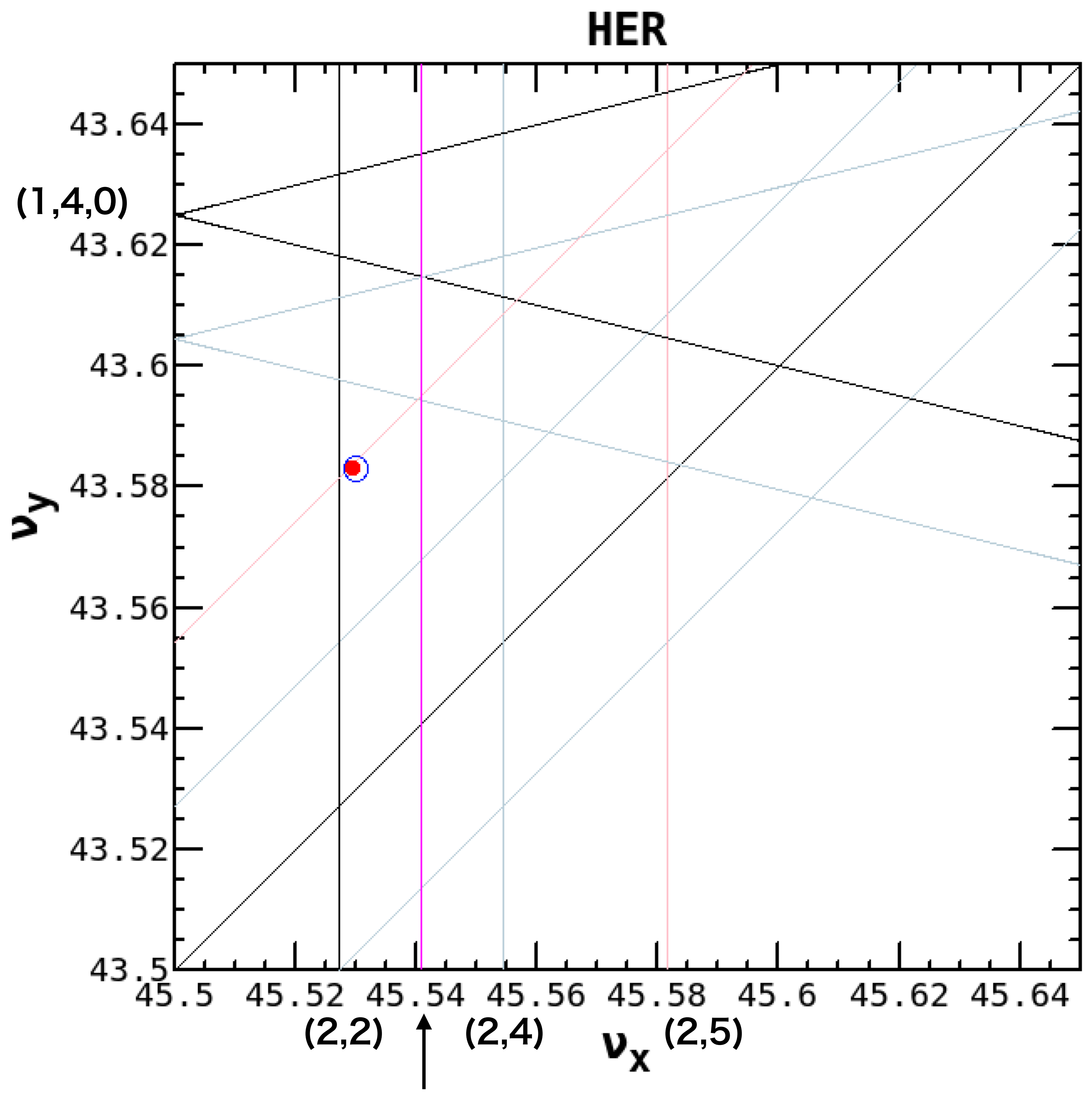
Dynamic aperture will be reduced by skew sextupole elements.

Cap Sigma Measurement





$\nu_s = -0.0235$



$2\nu_x + 3\nu_s = int.$

$\nu_s = -0.0272$

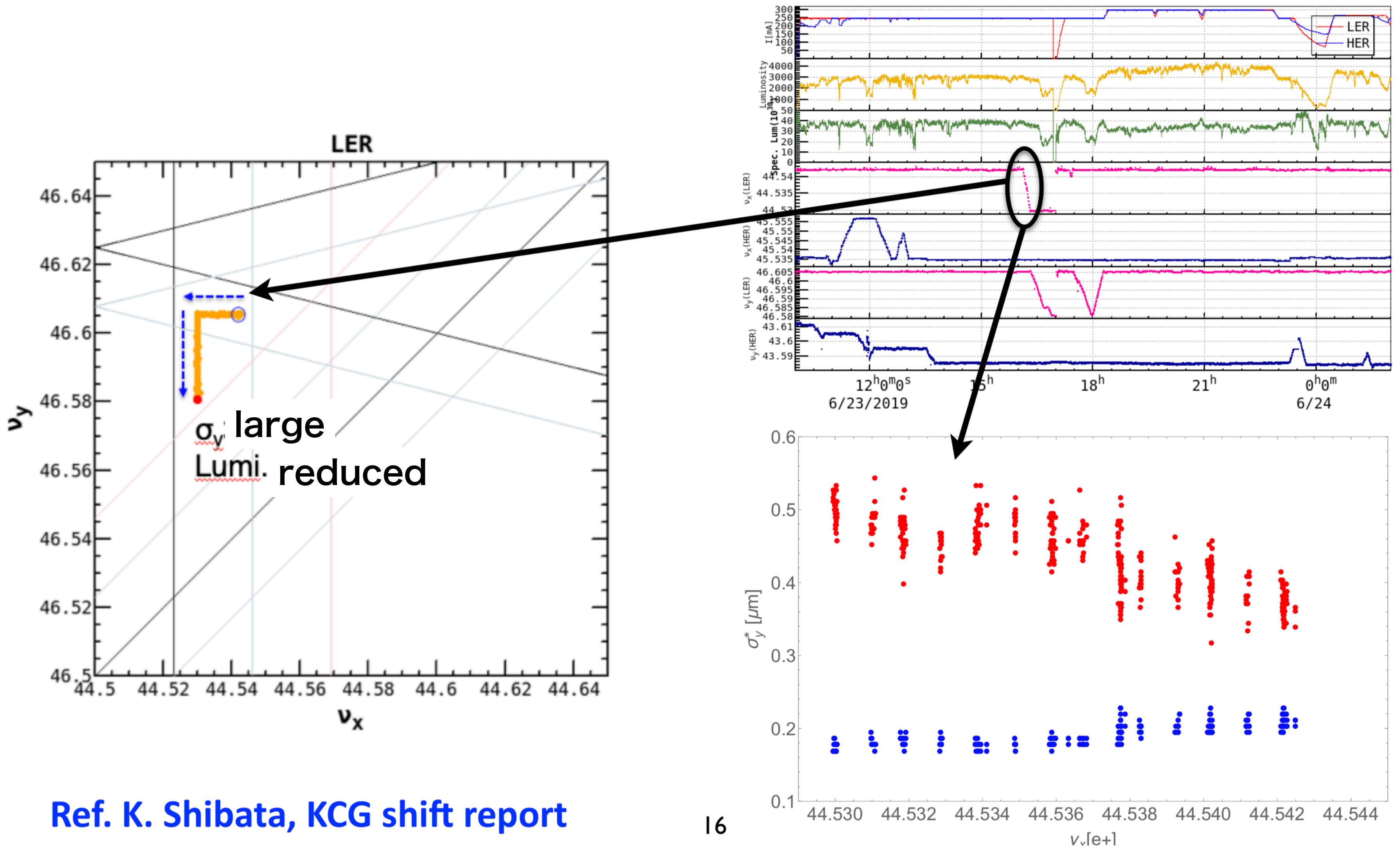
strong resonance line

Injection background is very high

Tune Scan

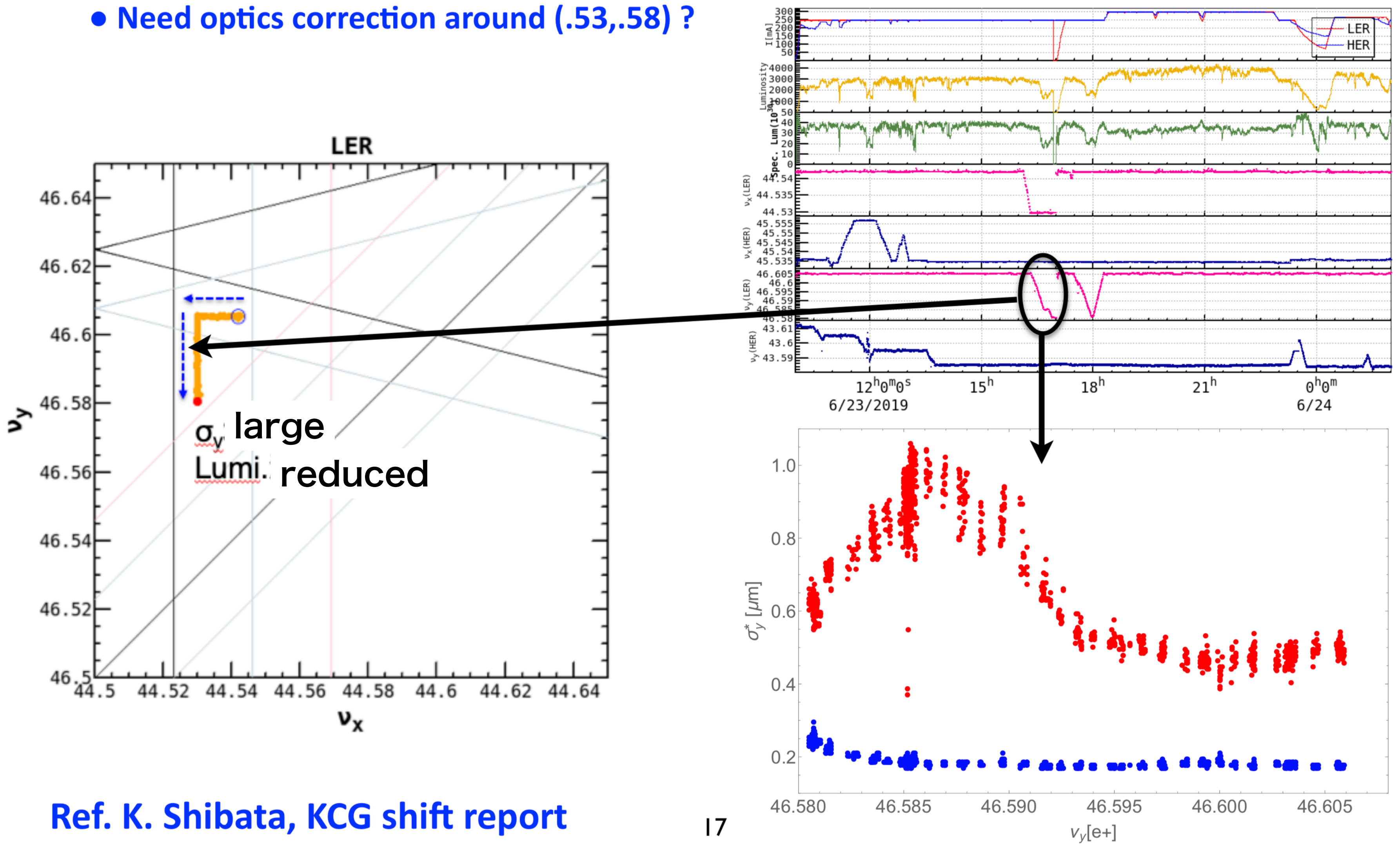
D. Zhou

- LER ν_x scan with ν_y = 46.606
  - No resonance around $2\nu_x + 3\nu_s$ = N.



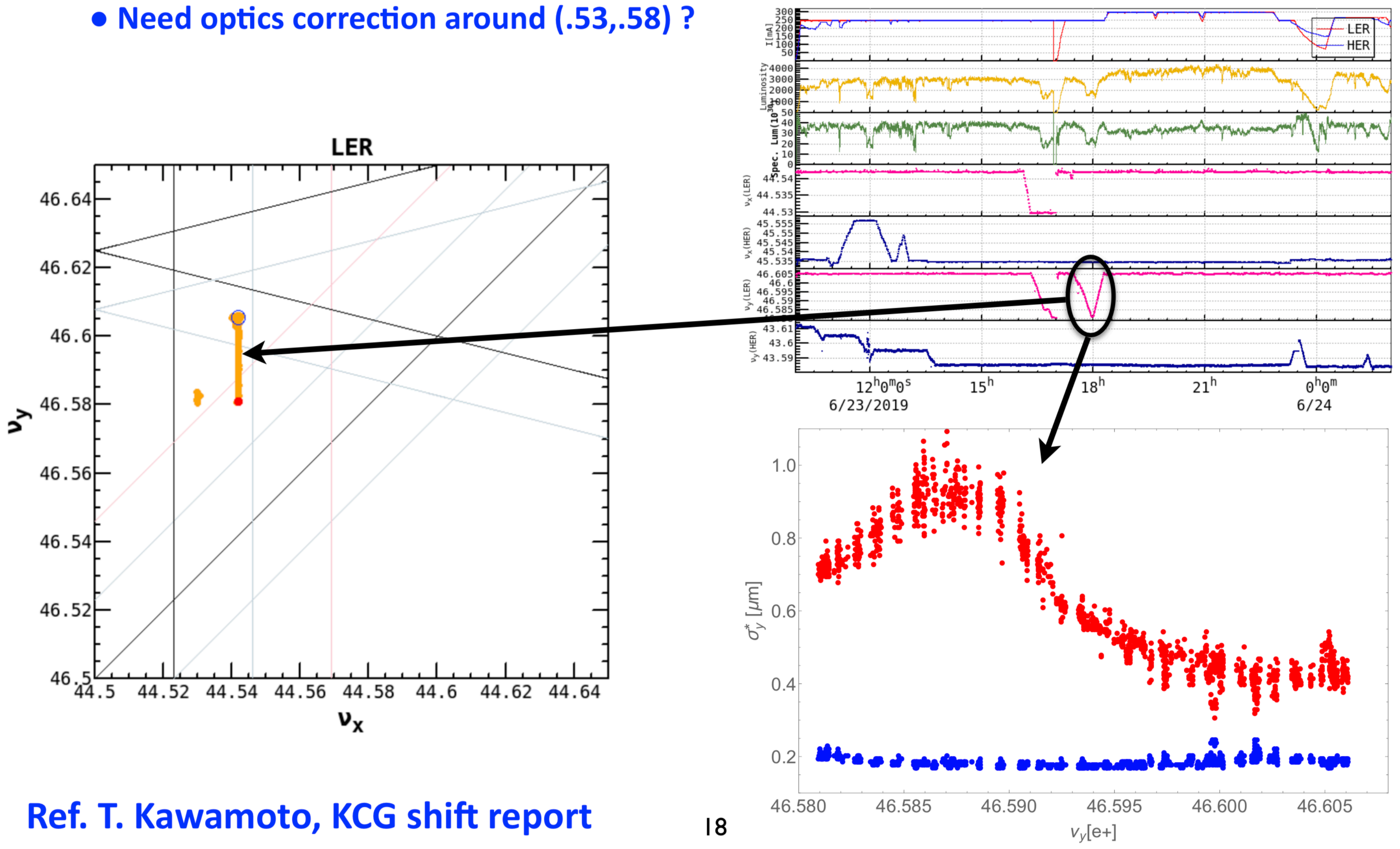
Ref. K. Shibata, KCG shift report

- LER ν_y scan with ν_x = 44.53
  - No resonance around ν_y = 44.586 ?! Unbelievable…
  - Need optics correction around (.53,.58) ?



Ref. K. Shibata, KCG shift report

- LER ν_y scan with ν_x = 44.542
  - No resonance around ν_y = 44.586 ?! Unbelievable…
  - Need optics correction around (.53,.58) ?

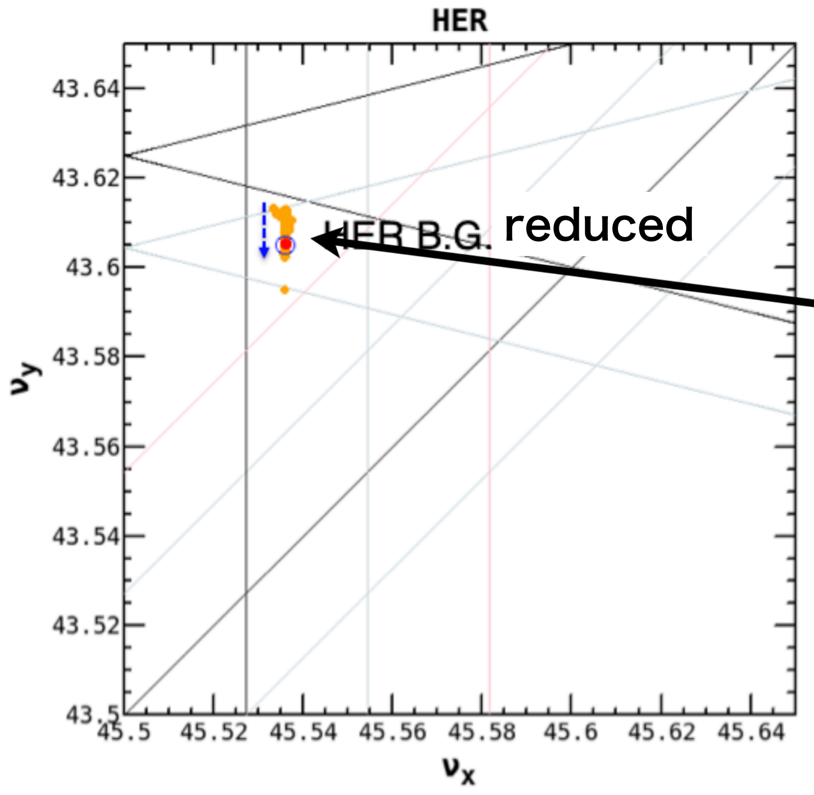


Ref. T. Kawamoto, KCG shift report

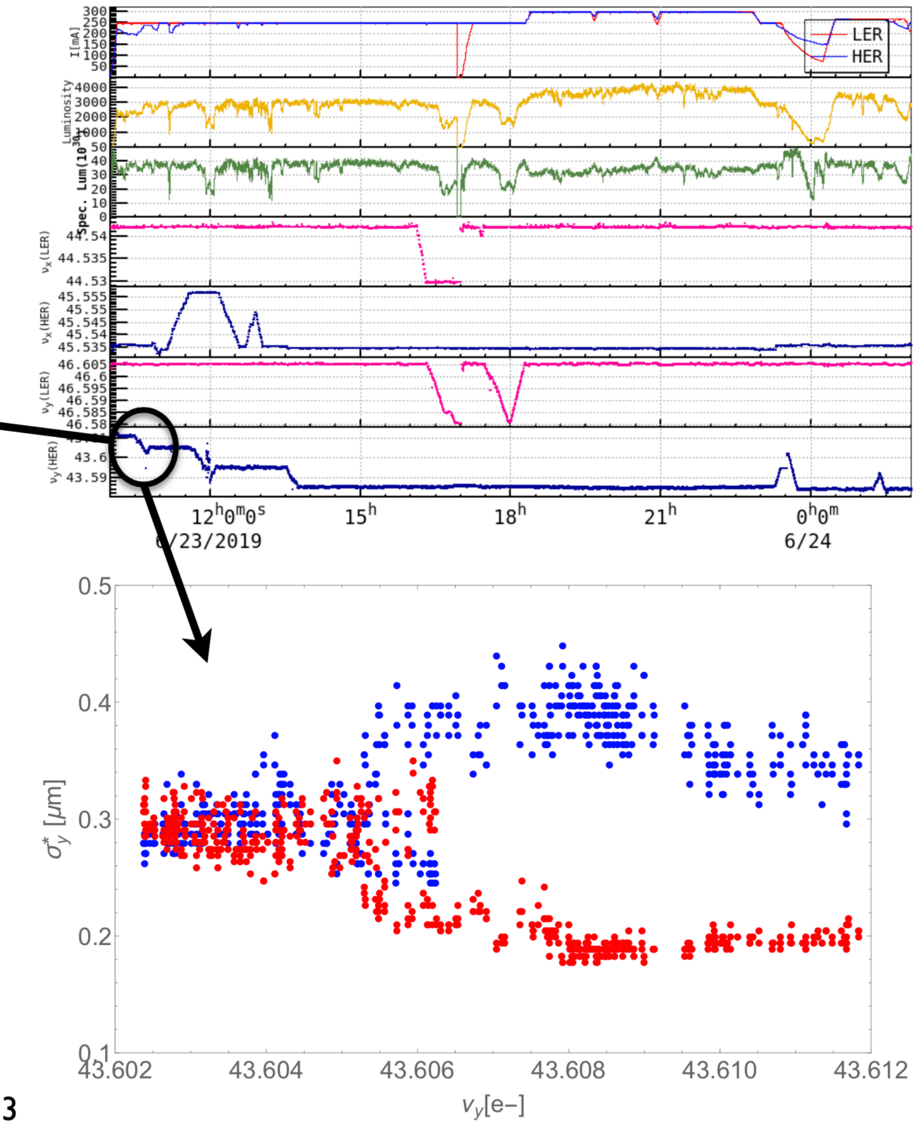
Tune Scan

➤ HER ν_y scan with ν_x = 45.536

- Note that HER beam current was not constant, so it's hard to draw conclusion from beam sizes



Ref. K. Shibata, KCG shift report



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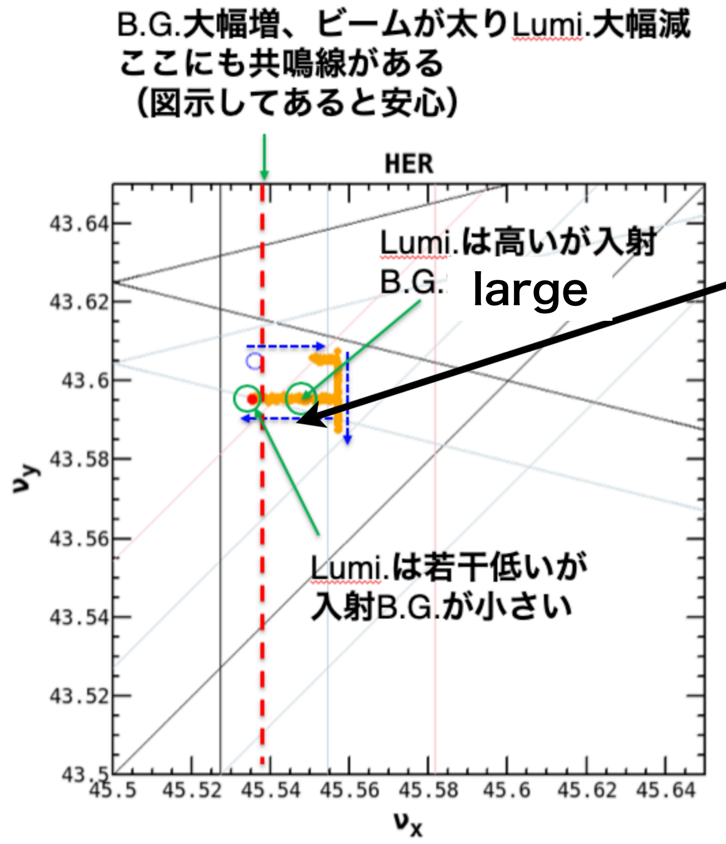
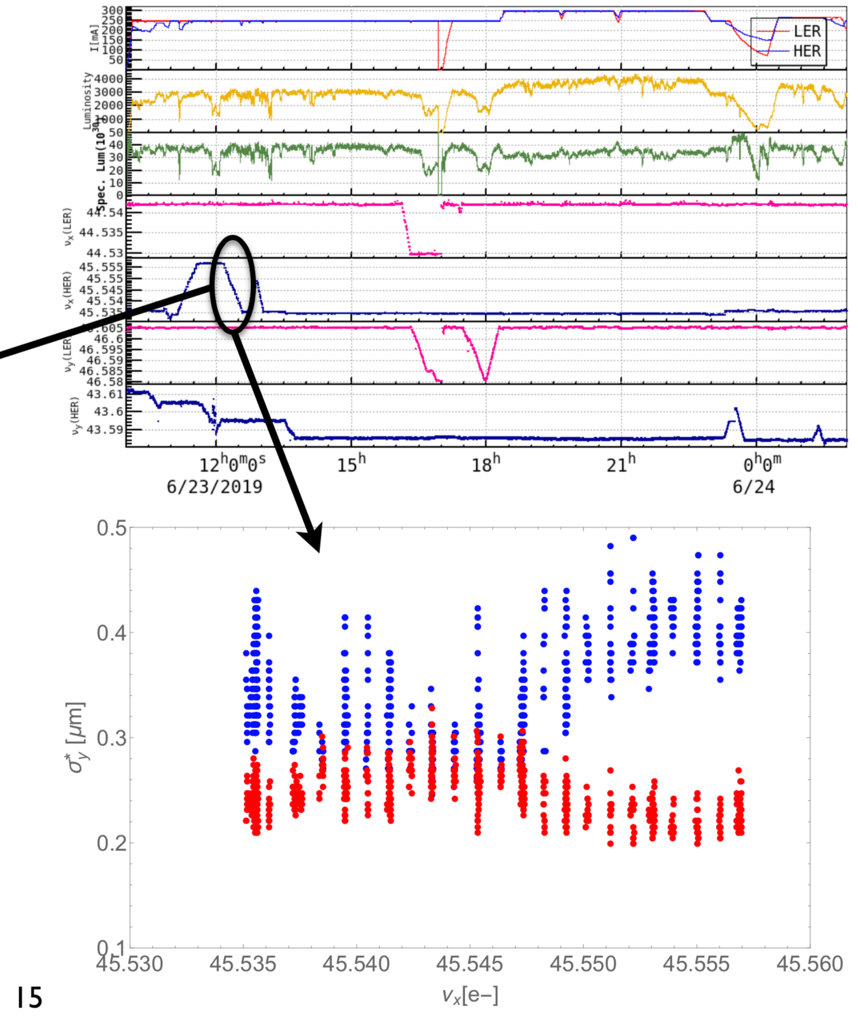
➤ HER ν_x scan with ν_y = 43.595

- Resonance around ν_x = 45.537 is not clear now.
- Flip-flop phenomenon?!



Ref. K. Shibata, KCG shift report



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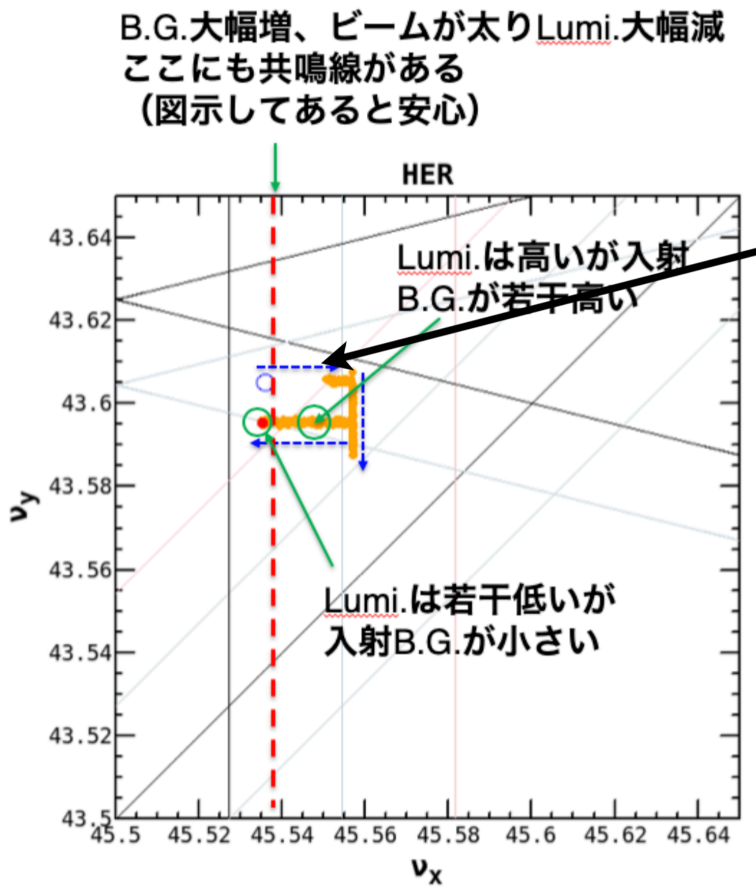
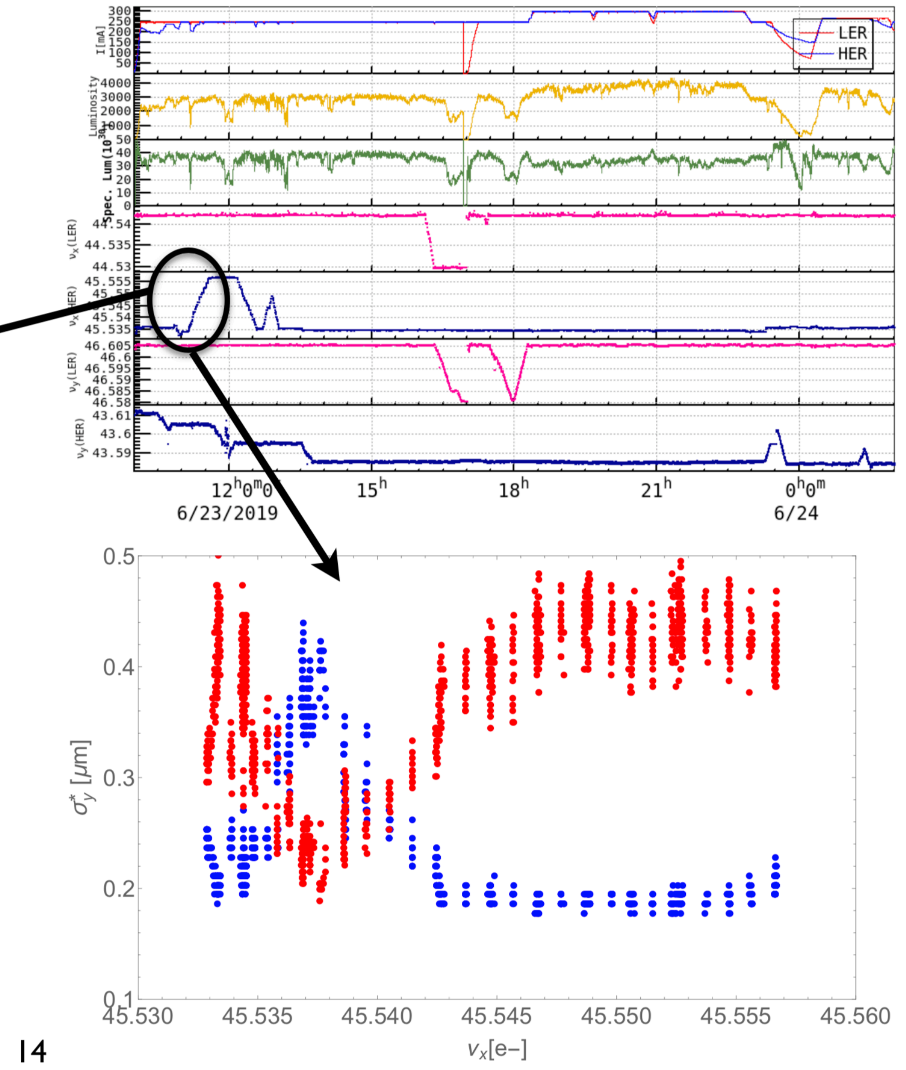
➤ HER ν_x scan with ν_y = 43.605

- Plausible resonance around ν_x = 45.537. How to explain it?



Ref. K. Shibata, KCG shift report



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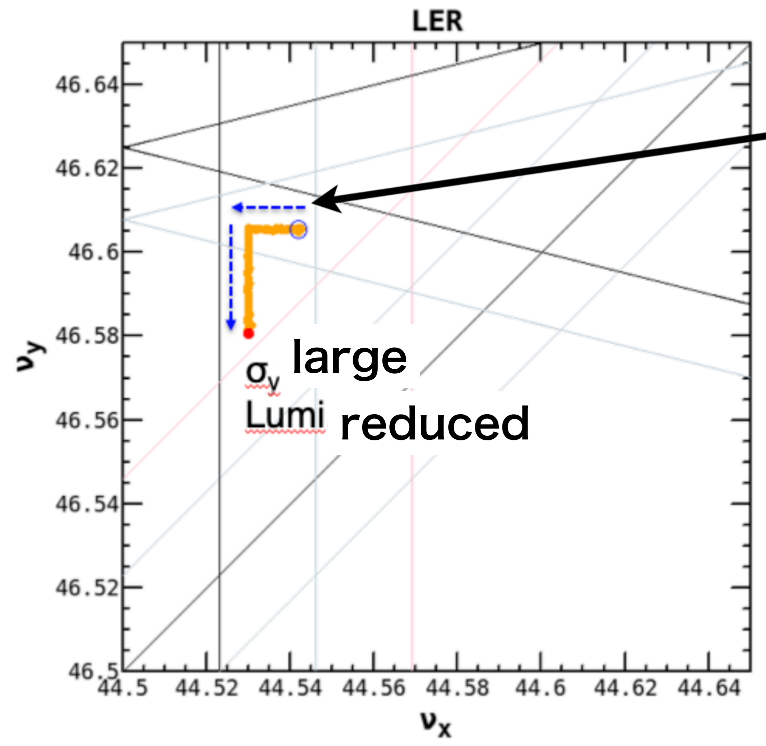
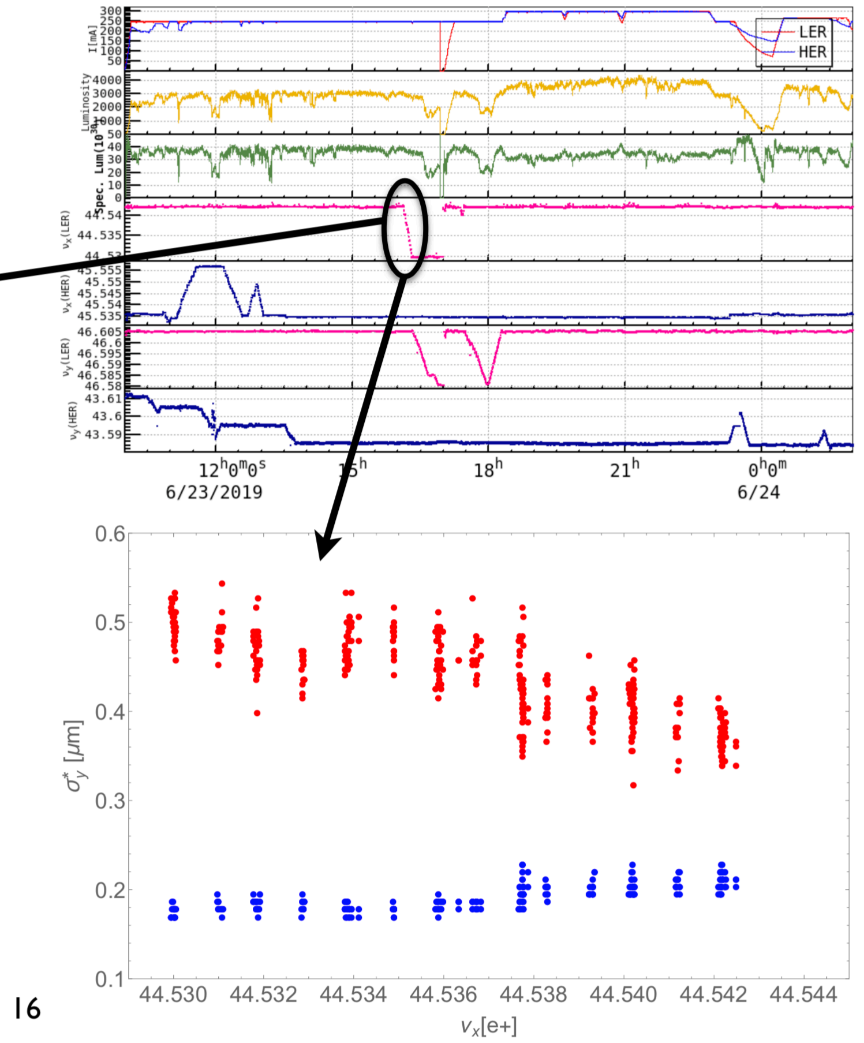
➤ LER ν_x scan with ν_y = 46.606

- No resonance around $2\nu_x + 3\nu_s$ = N.



Ref. K. Shibata, KCG shift report



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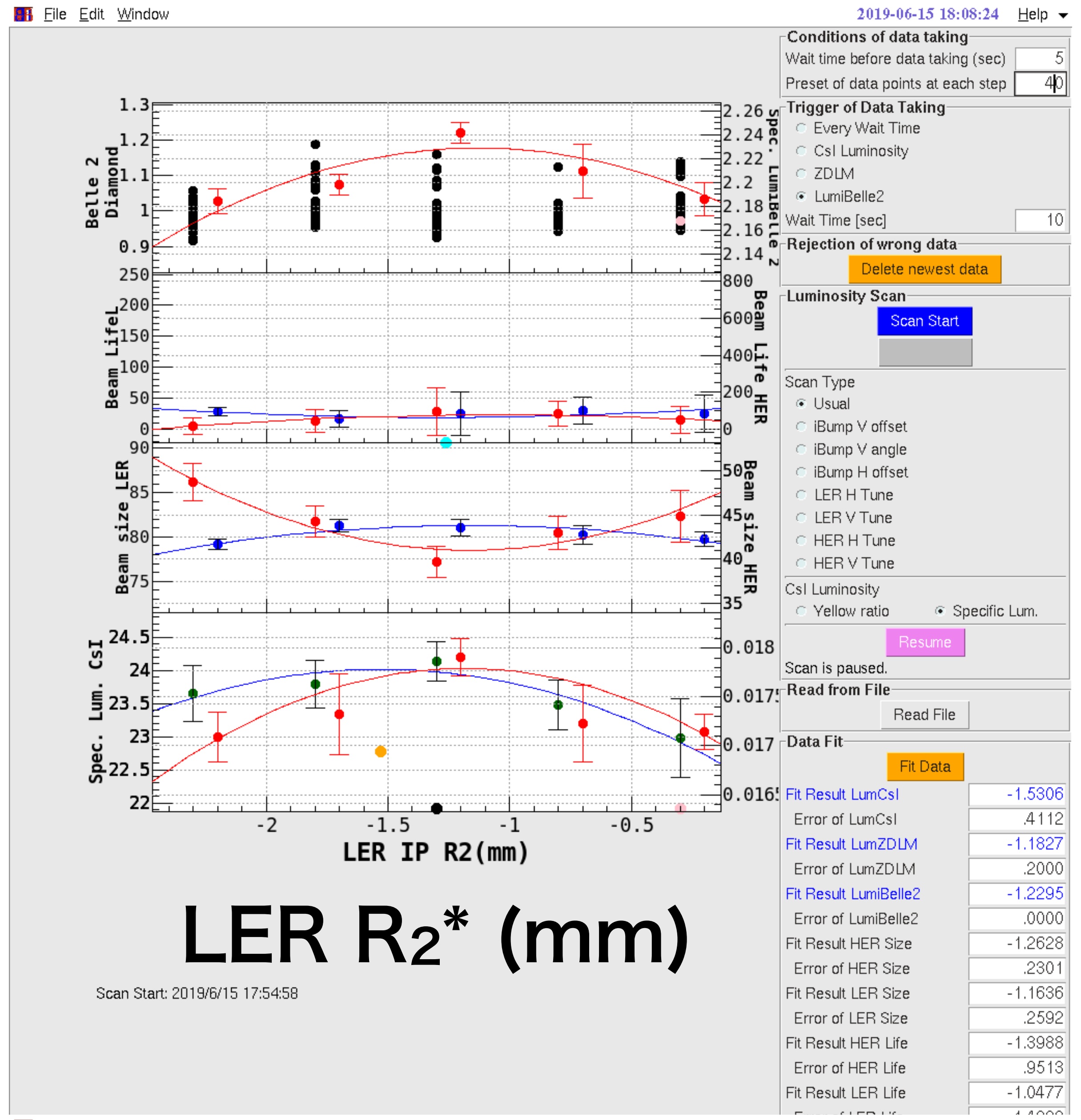
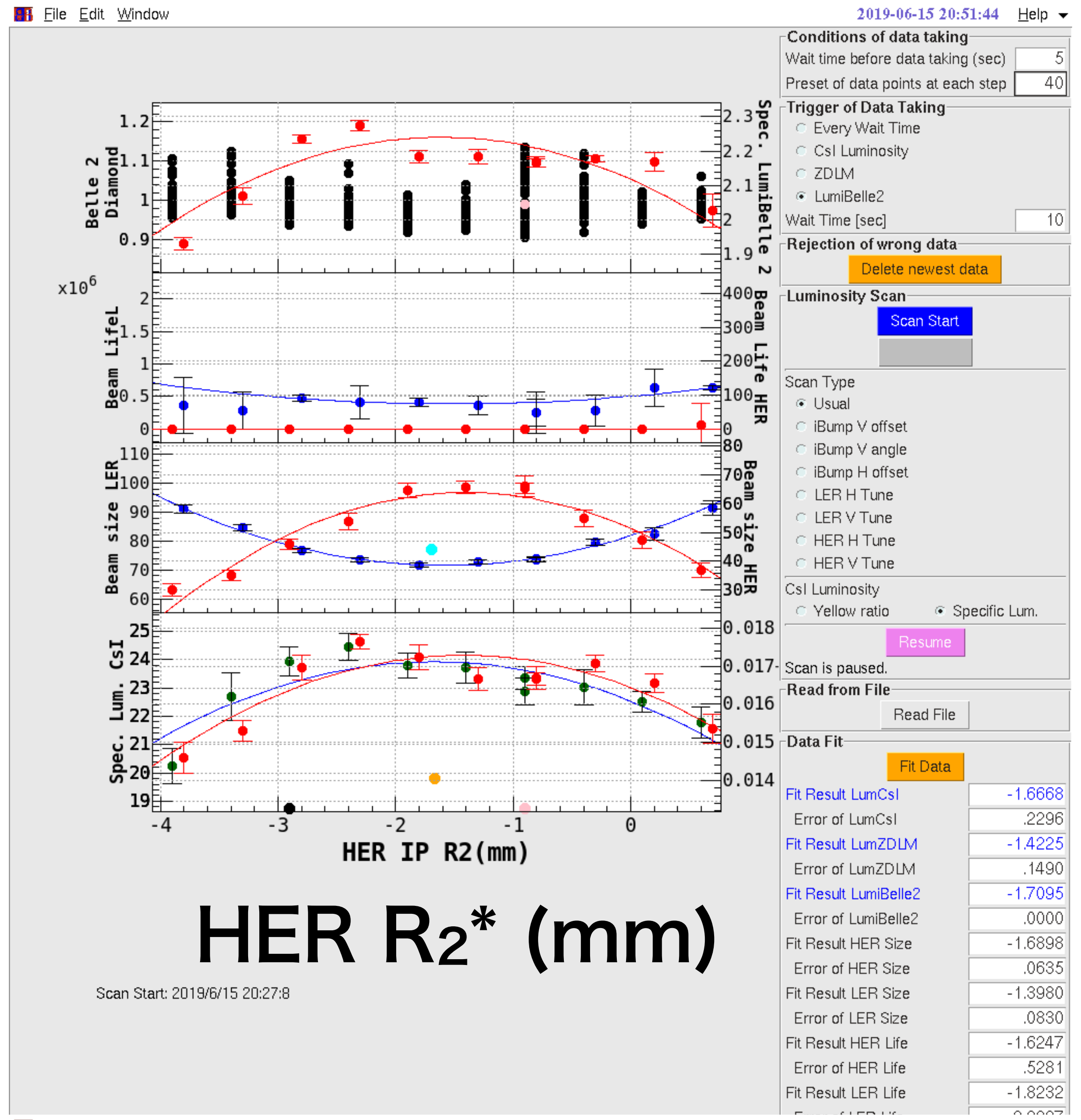
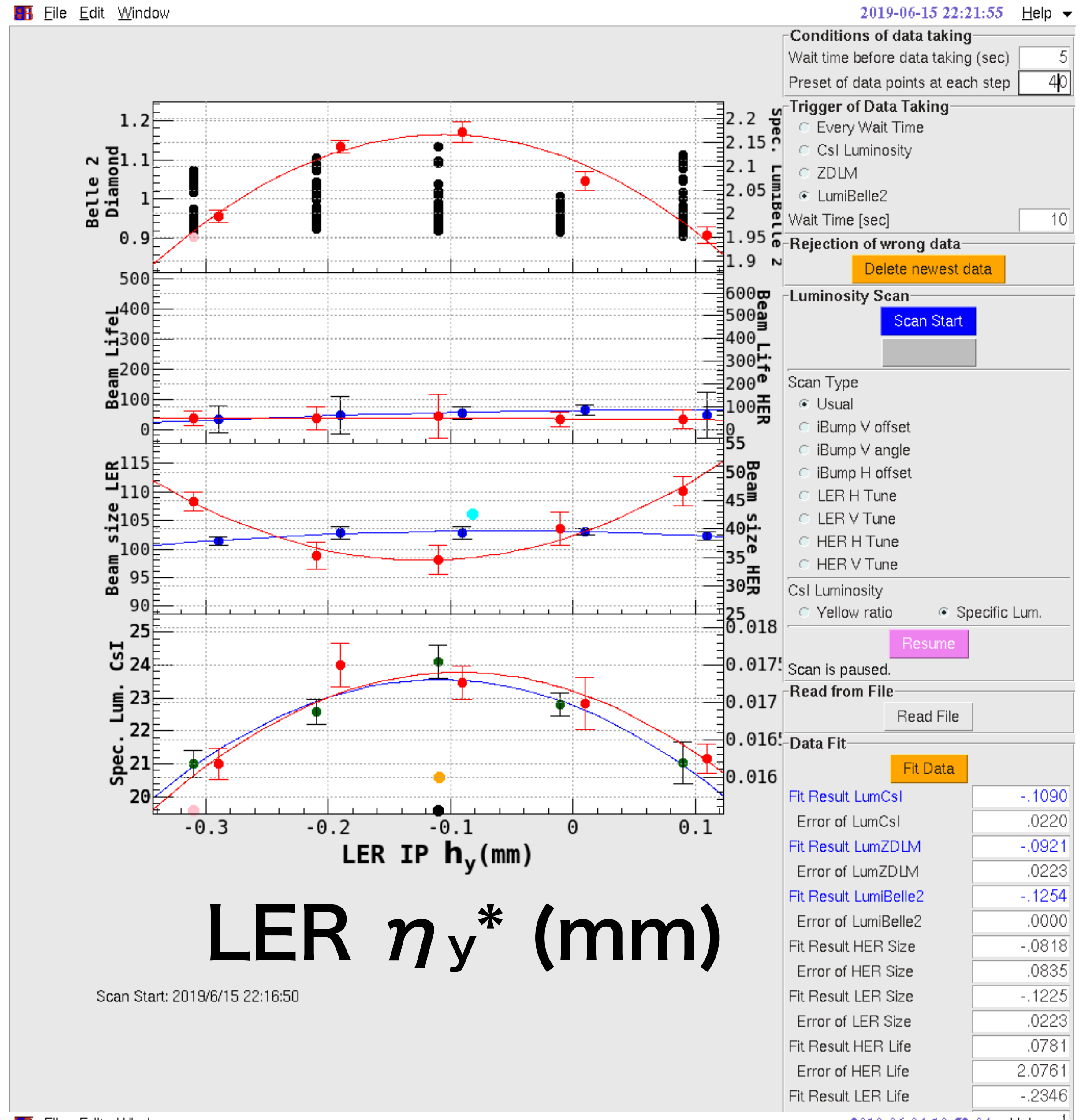
Linear Optics



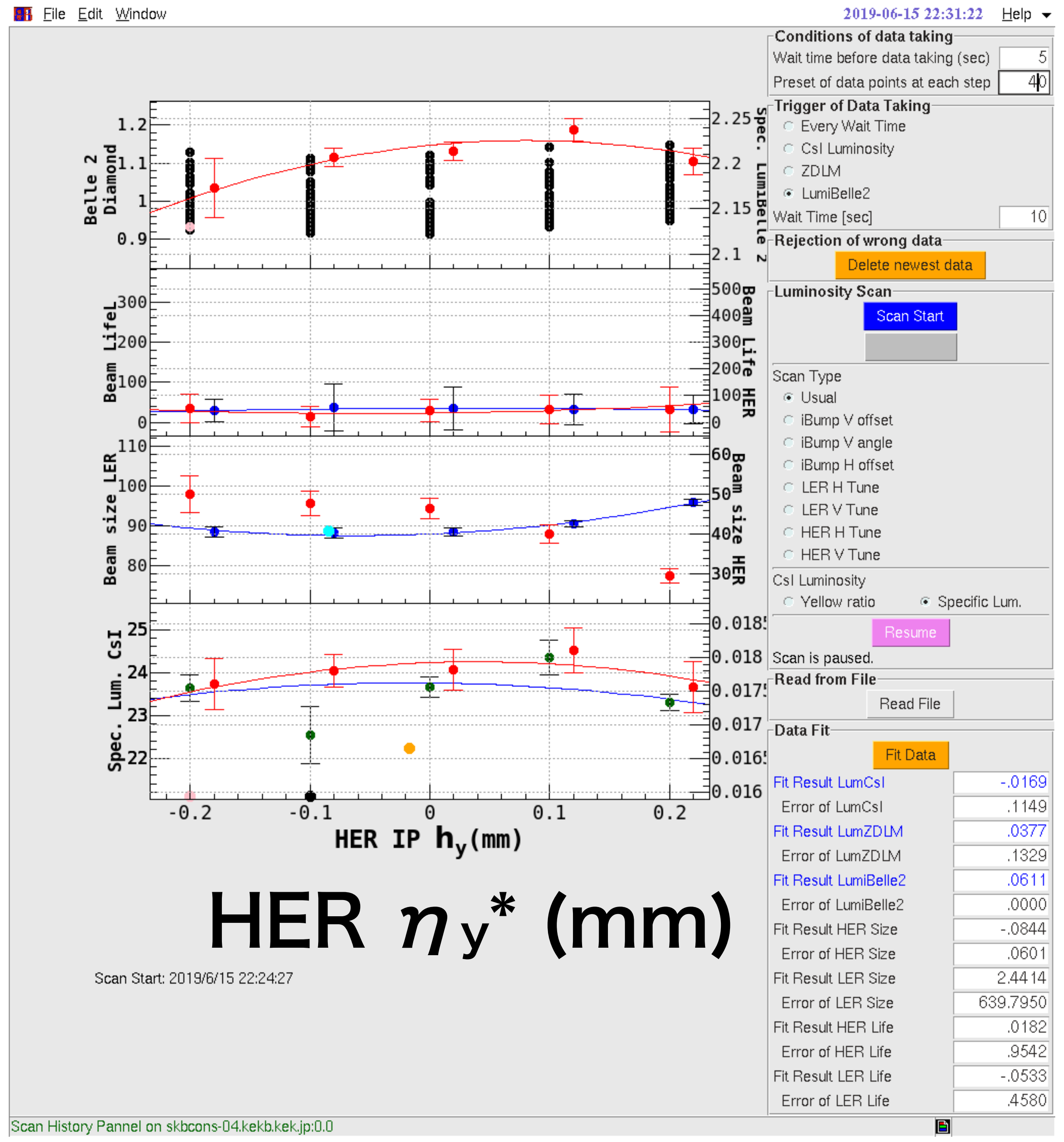
LER R_2^* (mm)



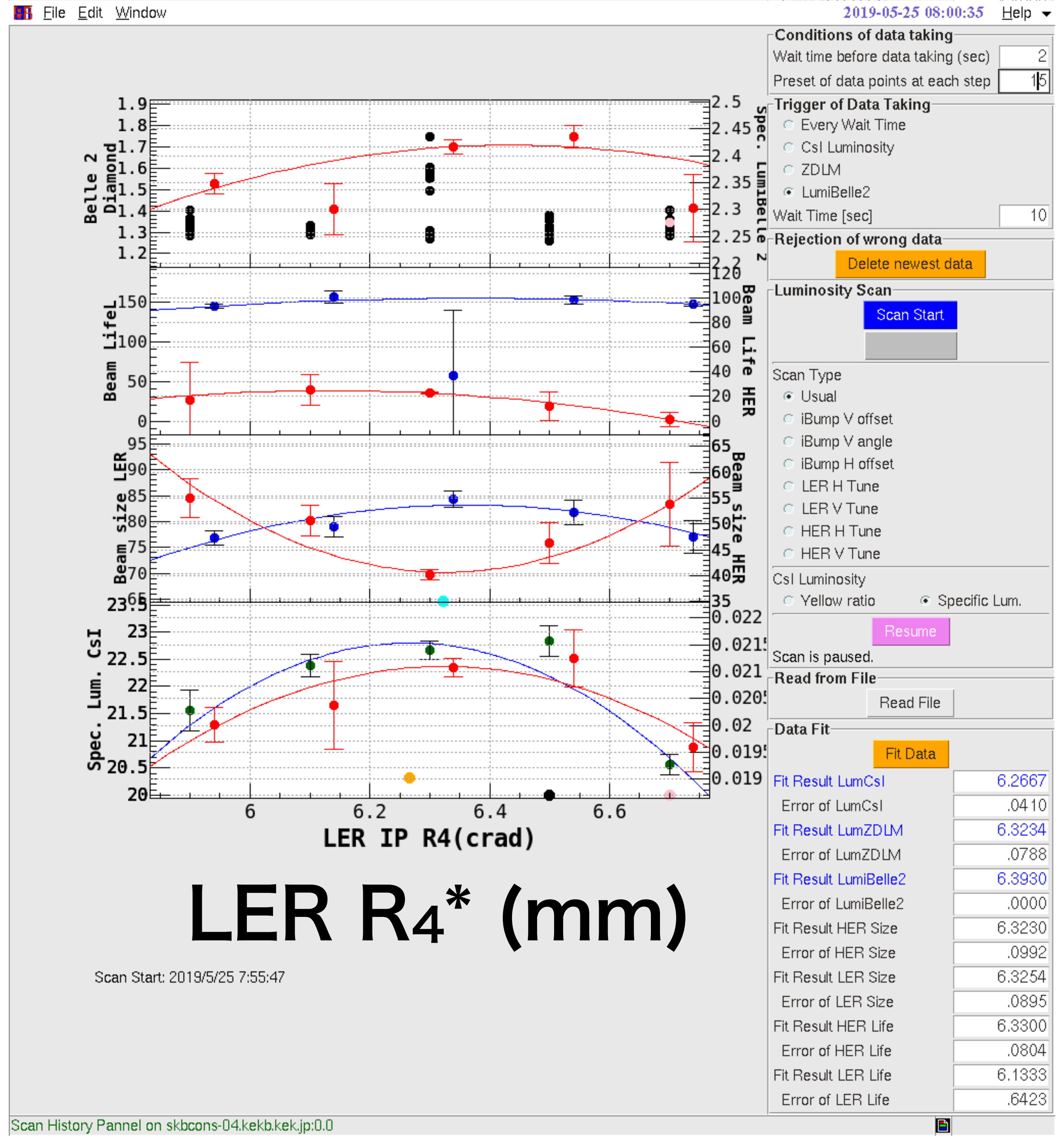
HER R_2^* (mm)



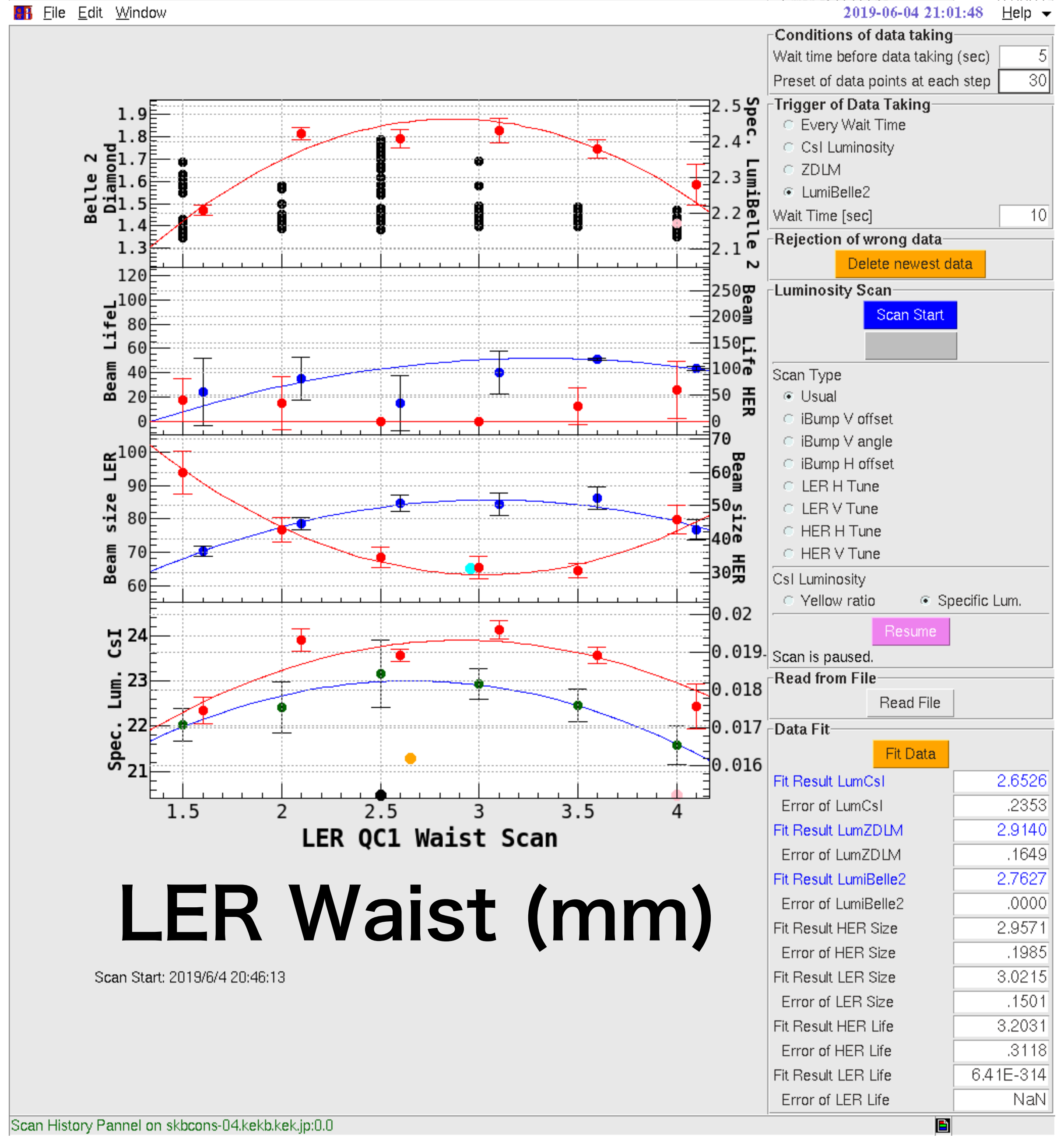
LER η_y^* (mm)



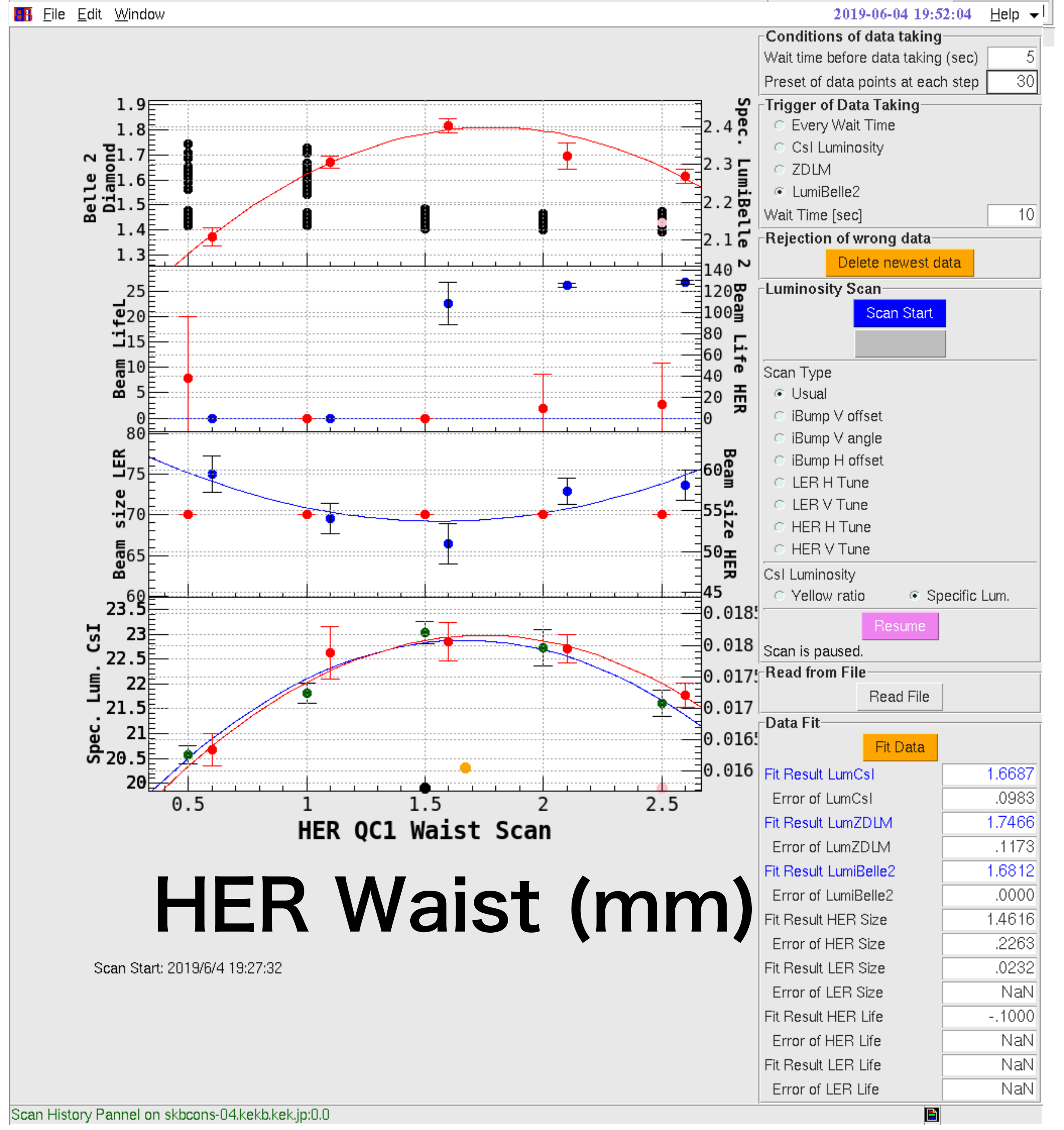
HER η_y^* (mm)



LER R_4^* (mm)



LER Waist (mm)



HER Waist (mm)

線形　＝　行列変換

Beta y*

Chromatic beta y* ?

L* : Kinematic term ? Nonlinear Maxwellian fringe ?

$$H \propto \left(1 - \frac{2}{3} k_1 L^{*2}\right) \frac{L^*}{\beta_y^{*2}} J_y^2$$

Squeezing/enlarge Beta_y* ?

L* ~ 0.76 m / 1.2 m (LER/HER)

Piwinski Angle

Coherent beam-beam instability

$$\sigma^*_{x,nano} = \sqrt{\sigma_x^{*2} + (\sigma_z \phi_x)^2} \simeq \sigma_z \phi_x \qquad \Phi = \frac{\sigma^*_{x,nano}}{\sigma^*_x} \simeq \frac{\sigma_z}{\sigma^*_x} \phi_x$$

Squeezing Beta_x*?

Φ ~ 15 in Phase 3(80 mm)

Hourglass effect

Crab-waist ?

Squeezing Beta_x*?

Large emittance ?