

# Status of SuperKEKB phase-2 commissioning

Akio Morita  
SuperKEKB Commissioning Group

ICHEP 2018

# What is SuperKEKB

- 3<sup>rd</sup> generation B-factory for Belle-II experiment
- Asymmetric energy e<sup>-</sup>-e<sup>+</sup> double ring collider

2017/September/1	LER	HER	unit	
E	4.000 e <sup>+</sup>	7.007 e <sup>-</sup>	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
E <sub>x</sub> /E <sub>y</sub>	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	() : zero current
Coupling	0.27	0.28		includes beam-beam
β <sub>x</sub> <sup>*</sup> /β <sub>y</sub> <sup>*</sup>	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α <sub>p</sub>	3.20x10 <sup>-4</sup>	4.55x10 <sup>-4</sup>		
σ <sub>δ</sub>	7.92(7.53)x10 <sup>-4</sup>	6.37(6.30)x10 <sup>-4</sup>		() : zero current
V <sub>c</sub>	9.4	15.0	MV	
σ <sub>z</sub>	6(4.7)	5(4.9)	mm	() : zero current
v <sub>s</sub>	-0.0245	-0.0280		
v <sub>x</sub> /v <sub>y</sub>	44.53/46.57	45.53/43.57		
U <sub>0</sub>	1.76	2.43	MeV	
T <sub>x,y</sub> /T <sub>s</sub>	45.7/22.8	58.0/29.0	msec	
ξ <sub>x</sub> /ξ <sub>y</sub>	0.0028/0.0881	0.0012/0.0807		
Luminosity	8x10 <sup>35</sup>		cm <sup>-2</sup> s <sup>-1</sup>	

Design for 40times luminosity of KEKB B-factory  
 - 1/20 β<sub>y</sub><sup>\*</sup>

- Double storage beam current

Using 'nano-beam' schem  
 (large Piwinski angle collision)

Design parameter table from  
<http://www-superkekb.kek.jp/>

# What is SuperKEKB Phase-2

- Configuration for beam collision test
- Major changes from Phase-1
  - Install Superconducting final focus quadrupole doublets(QCS)
  - Install Belle-II detector except near beam-pipe vertex detector
    - Beam background monitors are installed instead of missing detectors.
  - Introduction of damping ring for low emittance positron beam
    - Update LER injection system to match beam from damping ring

# Purpose of Phase-2 Commissioning

- Verification of 'nano-beam' scheme
  - Confirm luminosity increase by squeezing  $\beta_y^*$  even though  $\beta_y^*$  is smaller than bunch length  $\sigma_z$ .
    - Need squeezing  $\beta_y^*$  down to about 3mm(almost half of bunch length).
  - Achieve specific luminosity  $\sim 2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}/\text{mA}^2$
  - Achieve luminosity  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  (design value of KEKB B-factory)
- Beam background study for Belle-II detector
  - Understand background sources: coulomb, brems, Touschek, injection noise, ...
  - Control beam background by collimators and operation conditions.
- Stable operation
  - Keep stable beam collision.
  - Prevent QCS(superconducting final focus doublets) quench.

# Luminosity & $\beta_y^*$ dependency

Luminosity is defined as follows:

$$L = \frac{N_- N_+ n b f_{\text{rev}}}{2 \pi \sqrt{(\sigma_{x-}^{*2} + \sigma_{x+}^{*2})(\sigma_{y-}^{*2} + \sigma_{y+}^{*2})}}$$

$N_{\pm}$  is # of particles in bunch

$n b$  is # of bunches

$f_{\text{rev}}$  is revolution frequency

$\Phi_x$  is half crossing angle

Simplify with following assumptions:  $\sigma_{x-}^* = \sigma_{x+}^* \sim \sigma_z \phi_x$  ,  $\sigma_{y\pm}^* = \sqrt{\epsilon_{y\pm}} \beta_y^*$

$$L = \frac{f_{\text{rev}}}{2 \pi \sqrt{2} \sigma_z \phi_x} \frac{N_- N_+ n b}{\sqrt{(\epsilon_{y-} + \epsilon_{y+}) \beta_y^*}}$$

Beam-beam parameter is described as follows with assumption  $\sigma_{x\pm}^* \sim \sigma_z \phi_x \gg \sigma_{y\pm}^* = \sqrt{\epsilon_{y\pm}} \beta_y^*$

$$\xi_{\pm} \simeq \frac{r_e}{2 \pi \gamma_{\pm}} \frac{N_{\mp} \beta_{y\pm}^*}{\sigma_z \phi_x \sqrt{\epsilon_{y\mp} \beta_{y\mp}^*}} = \frac{r_e}{2 \pi \gamma_{\pm}} \frac{N_{\mp}}{\sigma_z \phi_x} \sqrt{\frac{\beta_y^*}{\epsilon_{y\mp}}} \quad \text{where } \beta_{y\pm}^* = \beta_y^*$$

If vertical emittance is conserved at squeezing  $\beta_y^*$ ,

- Luminosity is proportional to inverse of square-root of  $\beta_y^*$ .
- Beam-beam parameter becomes weaker as squeezing  $\beta_y^*$ .

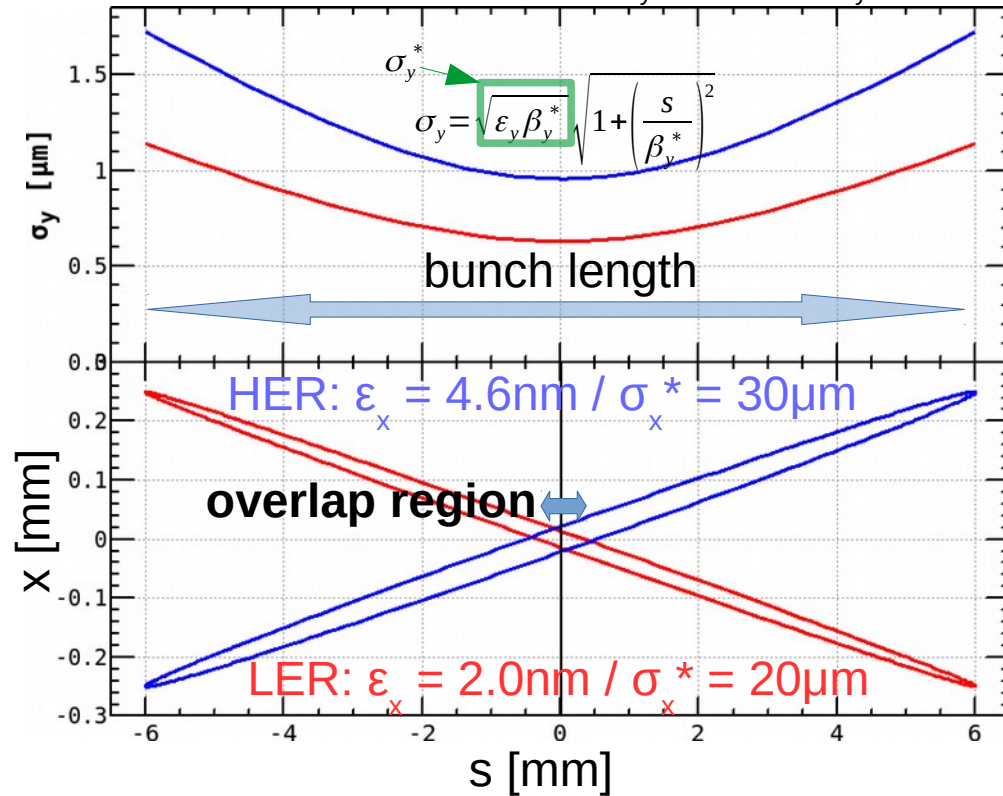
$$L \propto (\beta_y^*)^{-1/2}$$

$$\xi_{y\pm} \propto (\beta_y^*)^{+1/2}$$

**Luminosity SHOULD increase as squeezing  $\beta_y^*$ .**

# Bunch Profile & Hourglass Effect

Assumption:  $\beta_x^* = 200\text{mm}$ ,  $\beta_y^* = 4\text{mm}$ ,  $\varepsilon_y/\varepsilon_x = 5\%$



Vertical beam size far from IP is increased by hourglass effect.

In traditional collision scheme, average vertical beam size is blowing up in case of  $\beta_y^* \ll \sigma_z$ .

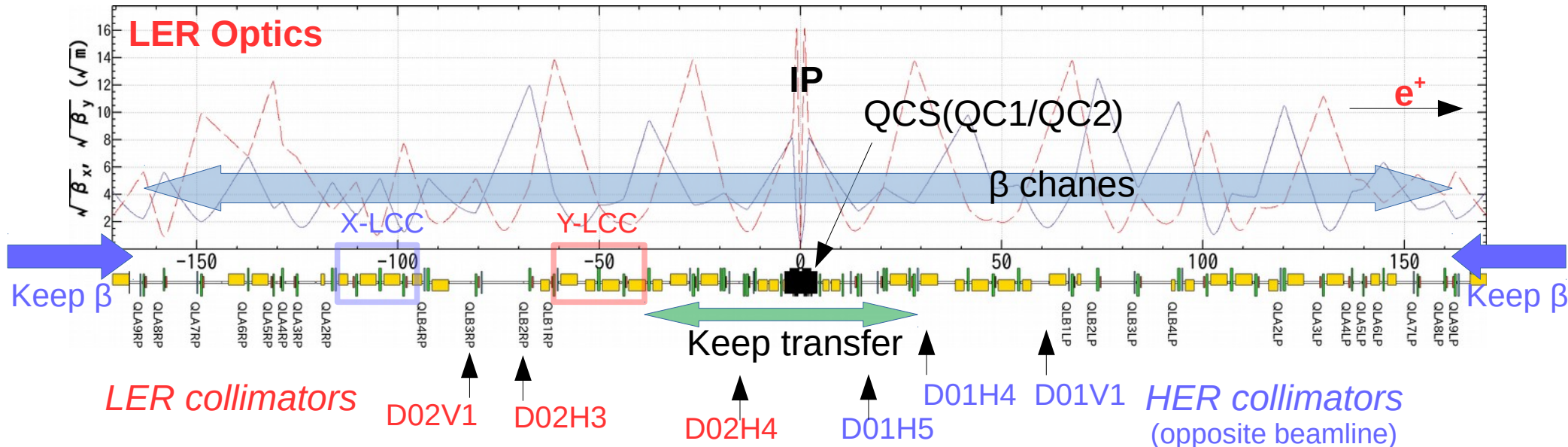
In 'nano-beam' scheme, longitudinal overlap region becomes shorter by reducing horizontal beam size and such short longitudinal overlap suppresses hourglass effect.

Effective interaction length:  $\sigma_z \rightarrow d = \frac{\sigma_x^*}{\sin(\phi_x)}$

$\phi_x$  is half crossing angle

# How to control beta-function

- We are detuning/squeezing  $\beta^*$  by using matching section quadrupoles: QLA & QLB.
  - Transfer matrix between IP and vertical local chromaticity corrector(Y-LCC) is not changed.
  - But, phase advance of IR section is changed by squeezing. (Need to rematch tune control section)



# Beta Squeezing

Phase	$\beta x^*$ [mm]		$\beta y^*$ [mm]		State	$L_{\text{peak}} \text{ cm}^{-2}\text{s}^{-1}$	$I_{\text{LER}}/I_{\text{HER}}$ , nb [mA]	Start
	LER	HER	LER	HER				
2.0	384	400	48.6	81	Detuned for Beam Capture			
2.1.0	200		8		Collision	$9.3 \times 10^{32}$	250/220, 600	04/16
2.1.1	200		6		Collision	$13.7 \times 10^{32}$	340/285, 789	05/22
2.1.2	200		4		Collision	$13.6 \times 10^{32}$	340/285, 789	05/28
2.1.3	200		4	3	Collision	$13.2 \times 10^{32}$	240/285, 789	06/08
2.1.4	200		3		Collision	$10.5 \times 10^{32}$	320/265, 789	06/11
2.1.5	100		4		Collision	$10.9 \times 10^{32}$	340/285, 789	06/12
2.1.6	200	100	4		Collision	$19.0 \times 10^{32}$	340/285, 789	06/13
2.1.7	200	100	3		Collision	$26.6 \times 10^{32}$	340/285, 789	06/20
2.2.0	200		2		Optics Correction			06/07
2.3.0	100		2		Not achieved			

# QCS Quenches in $\beta_y^*$ Squeezing

- We have many QCS quenches during early stage of  $\beta_y^*$  squeezing.
  - It blocks our study. (Typical recovery time 2 hours)
  - Quench is mainly occurred in QC1(vertical final focus quadrupole).
  - It would be caused by beam loss due to increased  $\beta_y$  at QC1.
- We make two workarounds.
  - Use beam collimator to protect QCS.
  - Link Belle-II diamond background detector to beam abort system for aborting beam before QCS quench by detecting beam loss near QCS.

**After applying workarounds, we squeeze  $\beta_y^*$  from 4mm to 2mm without QCS quenches.**

# Unscaled Luminosity at Squeezing

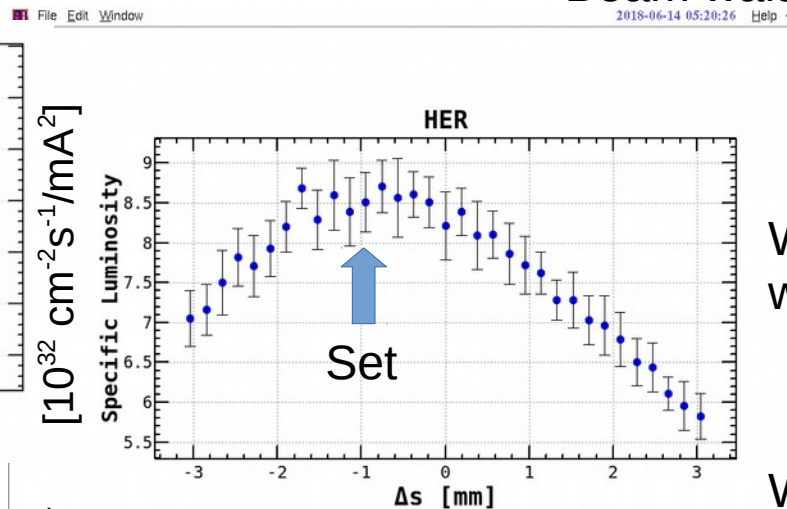
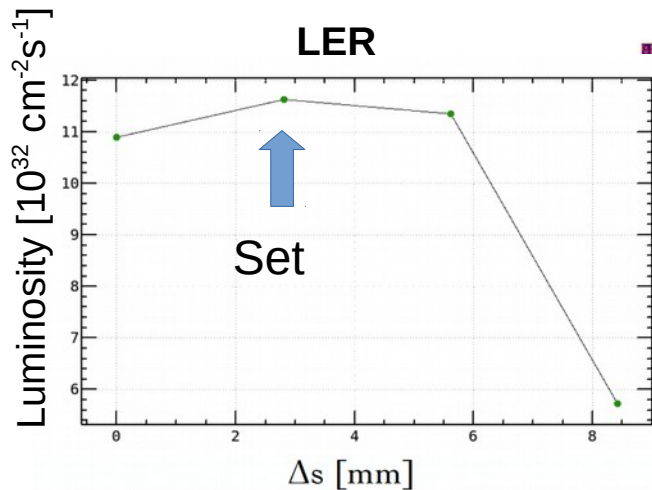
- Luminosity does not increase at squeezing  $\beta_y^*$  from 6mm to 4mm.
- Vertical beam size measured by X-ray monitor is shrunk as decaying beam current, however, specific luminosity does not increase.
  - While HER vertical beam size was shrinking by factor 3 due to beam current decay, specific luminosity was kept almost constant.
- We found discrepancy between vertical beam size of beam-beam scan and X-ray monitor measurements.
  - Beam-Beam scan size:  $\sigma_{y\text{ scan}}^* = 1.2\mu\text{m}$
  - X-ray monitor size:  $\sigma_y^* \sim 0.4/0.5\mu\text{m}(\text{LER/HER})$



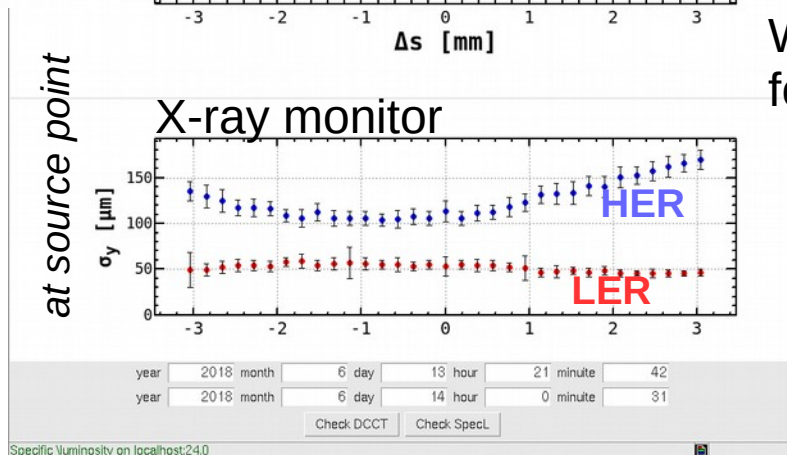
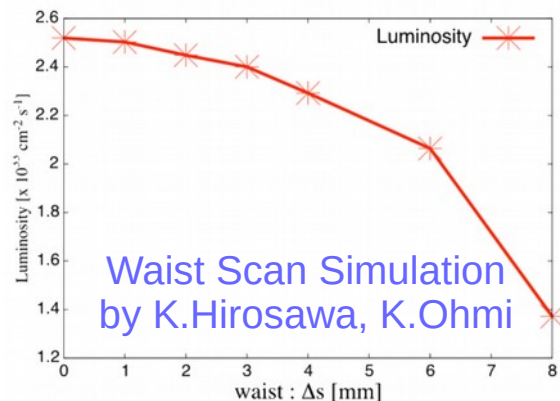
**Geometrical mismatch between two beams is suspected.**  
Need to check geometrical error at IP: waist,  $R1^*$ ,  $R2^*$ ,  $\eta_y^*$ , ...

# Waist Scan

Beam waist is scanned by using QC1  $\Delta K1$ .

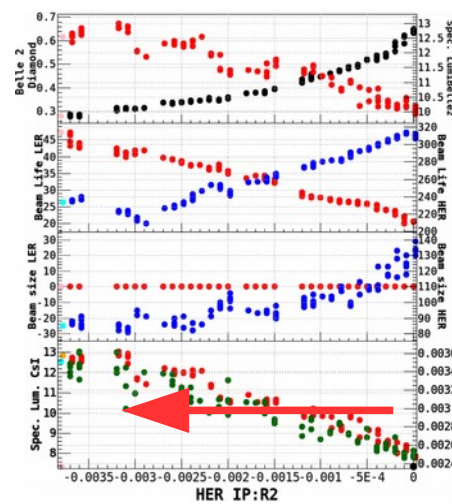
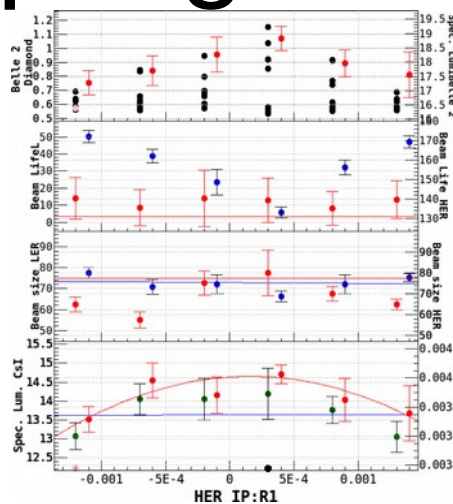
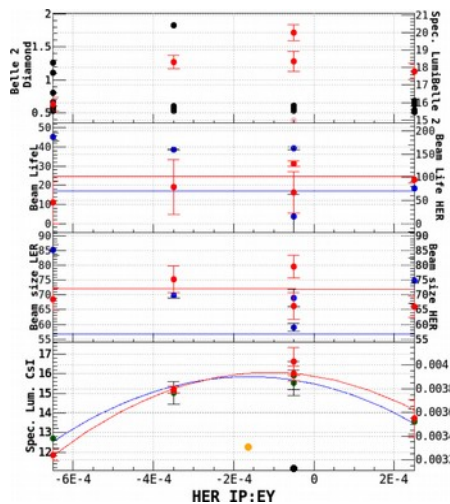


Waist scan results is consistent with simulation.



Waist shift is not large enough for geometrical beam mismatch.

# IP Coupling/Dispersion Knob Scan

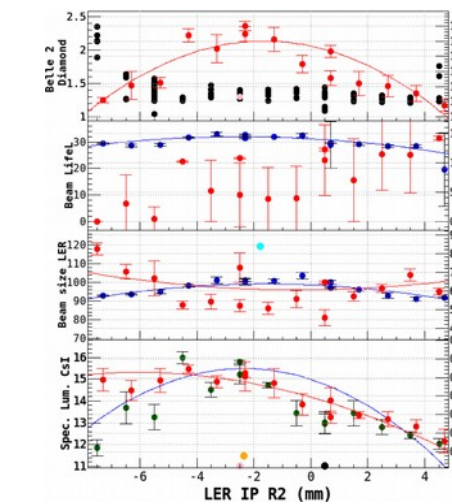
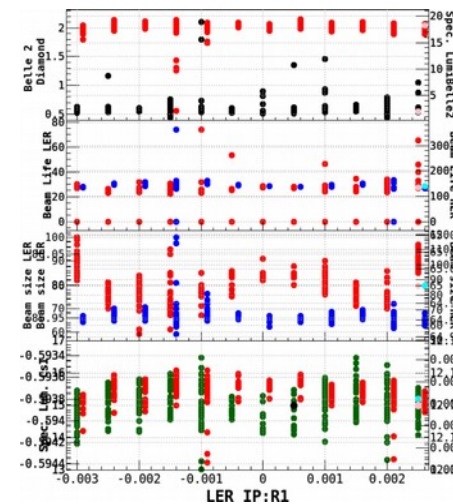
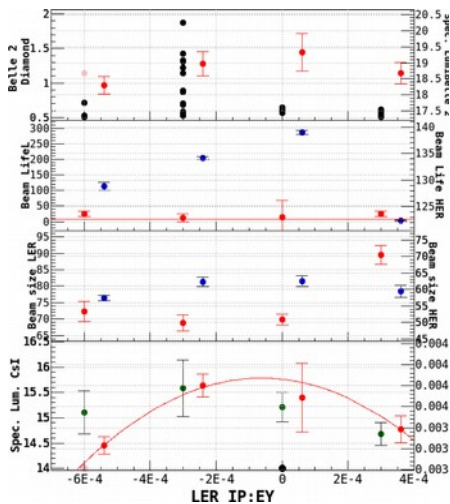


Big HER R2\* error is found.  
 $R2^* < -3$  mm

HER R2\* = 0  $\rightarrow$  -3mm

Where R2\* come from?

Why is not R2\* error found by global coupling measurement?



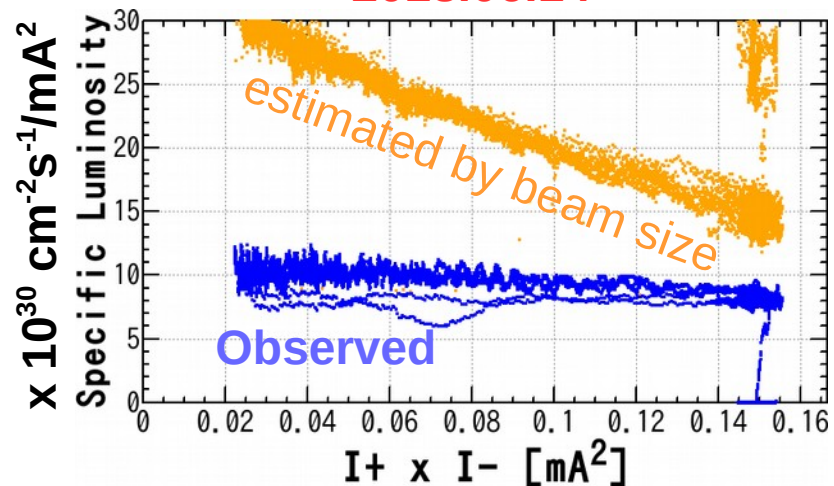
# HER R2\* Knob Issue

- Scan range is limited by power supply of skew quadrupole winding on arc sextupoles. ( $\pm 3\text{mm typ.}$ )
  - $\pm 3\text{mm}$  scan range is not enough to find luminosity peak.
- Knob height already exceeds perturbative region.
  - R2\* knob side effect makes vertical emittance growth.
- Another R2\* tunings:
  - Reintroduce orbit knob by using vertical orbit bump at arc sextupole pairs used in KEKB B-factory.
    - Vertical orbit bump for HER arc section is acceptable, because of old copper round vacuum chamber.
  - Correct R2\* by using QCS skew quadrupole corrector to avoid vertical dispersion generation by large skew quadrupole/orbit bump R2\* knobs.

# Specific Luminosity before & after IP coupling knob tuning

Phase 2.1.6:  $\beta_x^* = 200/100\text{mm(LER/HER)}$ ,  $\beta_y^* = 4\text{mm}$ ,  $I = 340/285\text{mA(LER/HER)}$ ,  $nb = 789$

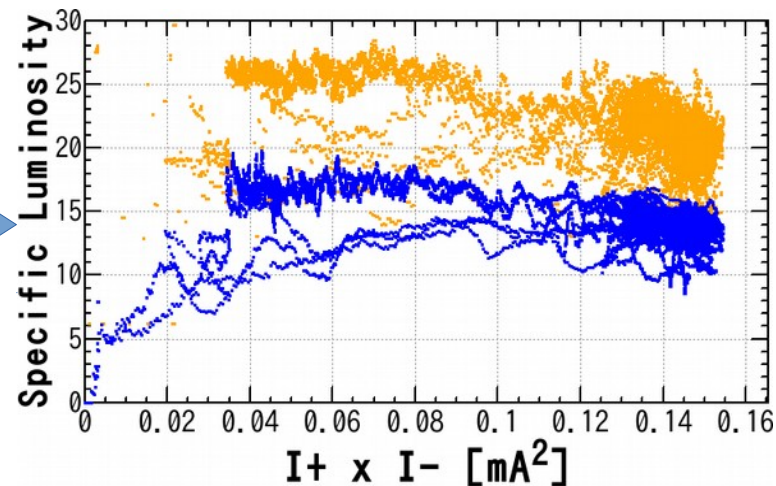
2018.06.14



IP knob tunings:  
R1\*, R2\*,  $\eta_y^*$ , ...

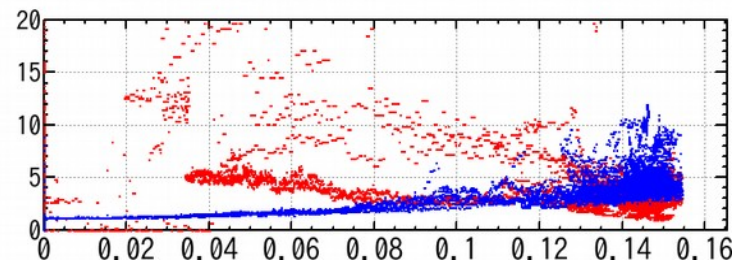
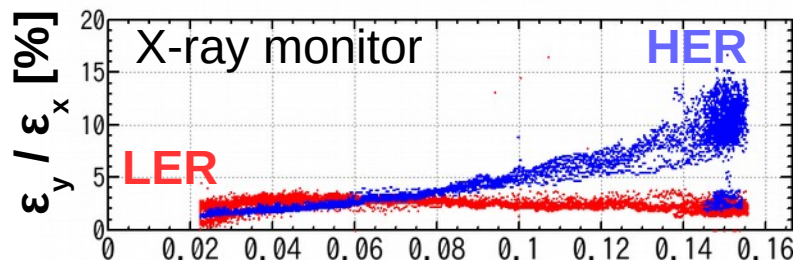


2018.06.17



$L_{\text{spec}}$  is improved.

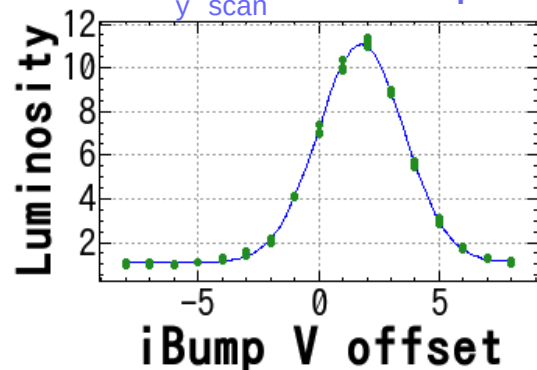
HER beam blowup is reduced.



# Beam-beam scan before & after IP coupling knob tuning

Phase 2.1.6:  $\beta_x^* = 200/100\text{mm}$ (LER/HER),  $\beta_y^* = 4\text{mm}$ ,  $I = 15/15\text{mA}$ (LER/HER),  $n_b = 1576$

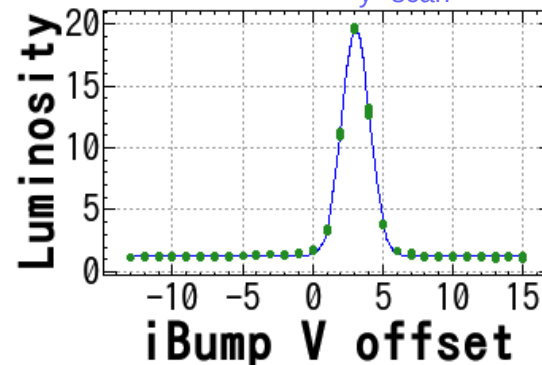
2018.06.14  $\sigma_{y \text{ scan}}^* = 1.253 \mu\text{m}$



$\sigma_{y \text{ scan}}^* : \quad \times 0.55$   
Luminosity:  $\times 1.84$

Improve consistency between  
B-B scan and X-ray monitor

2018.06.19  $\sigma_{y \text{ scan}}^* = 0.689 \mu\text{m}$



Luminosity Fit

RePlot

ReFit

Lum offset	1.105
Luminosity	9.966
$\sigma_y [\mu\text{m}]$	1.253

IP knob tunings:  
 $R1^*, R2^*, \eta_y^*, \dots$

Luminosity Fit

RePlot

ReFit

Lum offset	1.277
Luminosity	18.303
$\sigma_y [\mu\text{m}]$	0.689

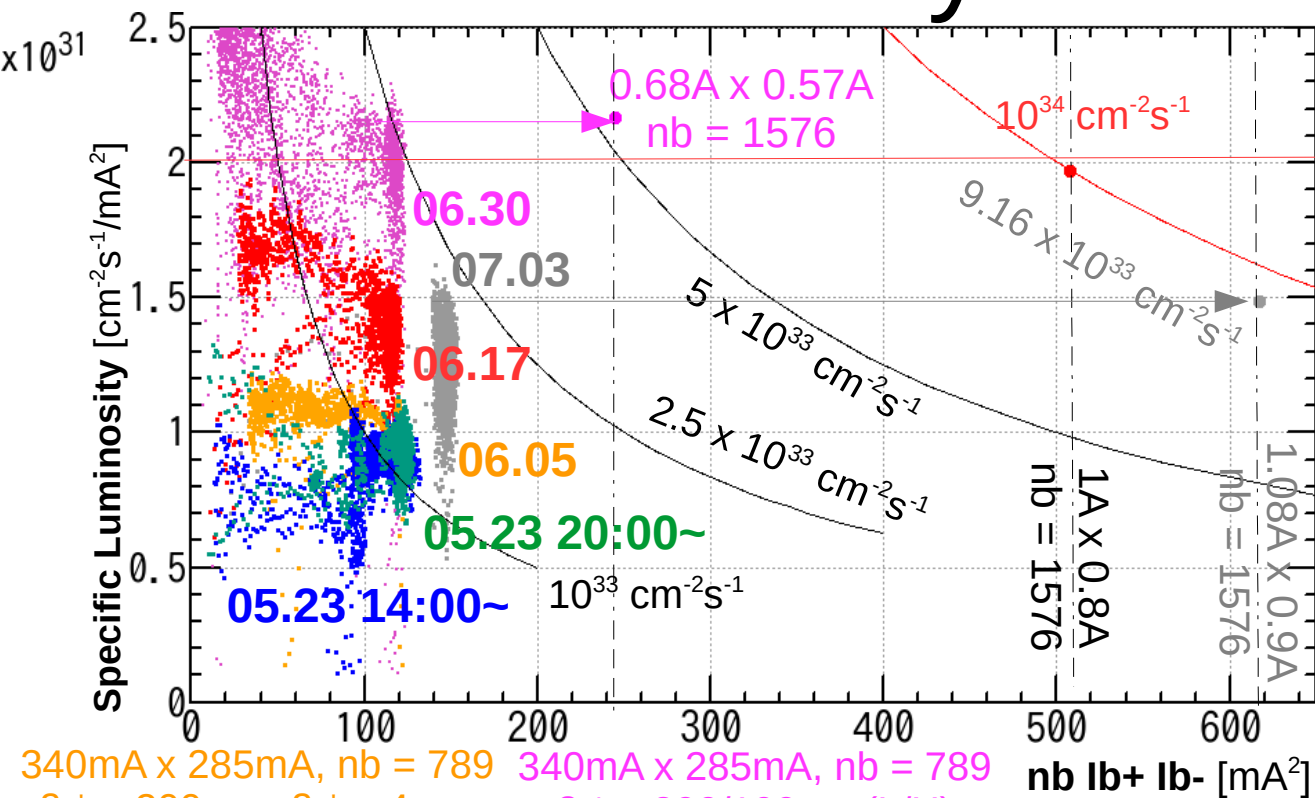
X-Ray monitor

$\sigma_{y \text{ x-ray}}^* \sim 0.4 / 0.5 \mu\text{m}$  (LER/HER)

X-Ray monitor

$\sigma_{y \text{ x-ray}}^* \sim 0.38 / 0.55 \mu\text{m}$  (LER/HER)

# Luminosity Performance



Specific luminosity increases by squeezing  $\beta_y^*$  after R2\* tuning.

06.30 22:00 ~ 07.01 10:00

340mA x 285mA, nb = 789

$L_{\text{peak}} = 2.6578 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

$L_{\text{sp}} = 2.2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} / \text{mA}^2$

nb x 2

679mA x 569mA, nb = 1576

$L_{\text{peak}} = 5.31 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

07.03 19:05 ~ 24:00

270mA x 225mA, nb = 394

$L_{\text{peak}} = 2.2906 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

$L_{\text{sp}} = 1.4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} / \text{mA}^2$

nb x 4

1080mA x 900mA, nb = 1576

$L_{\text{peak}} = 9.16 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

340mA x 285mA, nb = 789

$\beta_x^* = 200\text{mm}$ ,  $\beta_y^* = 4\text{mm}$

340mA x 285mA, nb = 789

$\beta_x^* = 200\text{mm}$ ,  $\beta_y^* = 6\text{mm}$

310mA x 252mA, nb = 600

$\beta_x^* = 200\text{mm}$ ,  $\beta_y^* = 6\text{mm}$

340mA x 285mA, nb = 789

$\beta_x^* = 200/100\text{mm}(L/H)$

$\beta_y^* = 3\text{mm}$

340mA x 285mA, nb = 789

$\beta_x^* = 200/100\text{mm}(L/H)$

$\beta_y^* = 4\text{mm}$

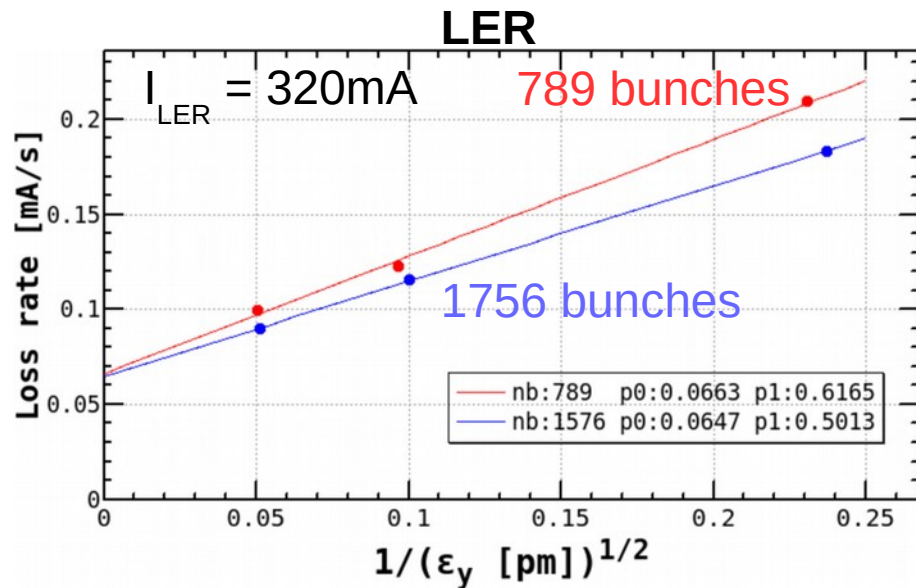
270mA x 225mA, nb = 394

$\beta_x^* = 200/100\text{mm}(L/H)$

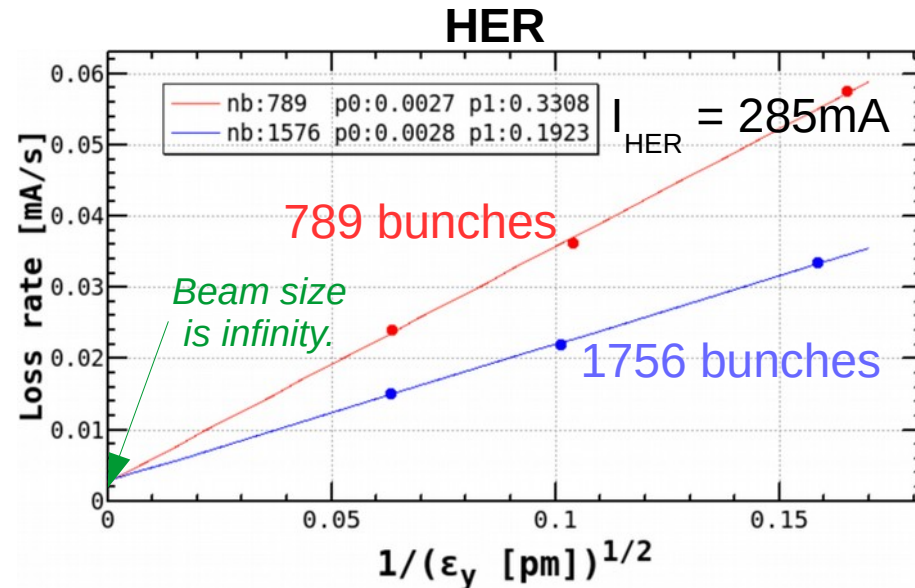
$\beta_y^* = 3\text{mm}$

# Beam Lifetime Measurement

Loss rate measurement with vertical emittance control knob by using dispersion.



Life(Touschek)  $\sim$  35 min  
Life(others)  $\sim$  80 min

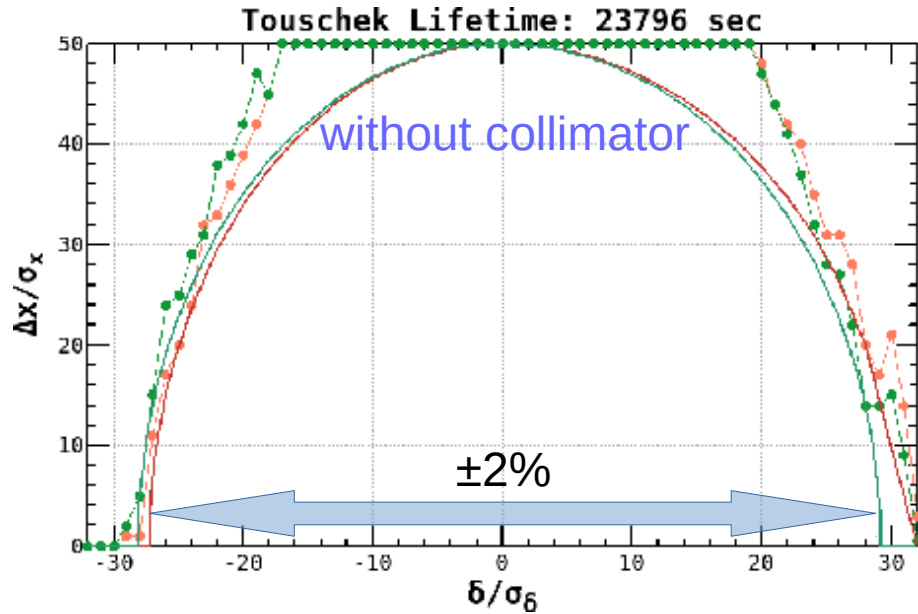


Life(Touschek)  $\sim$  86 min  
Life(others)  $\sim$  1680 min

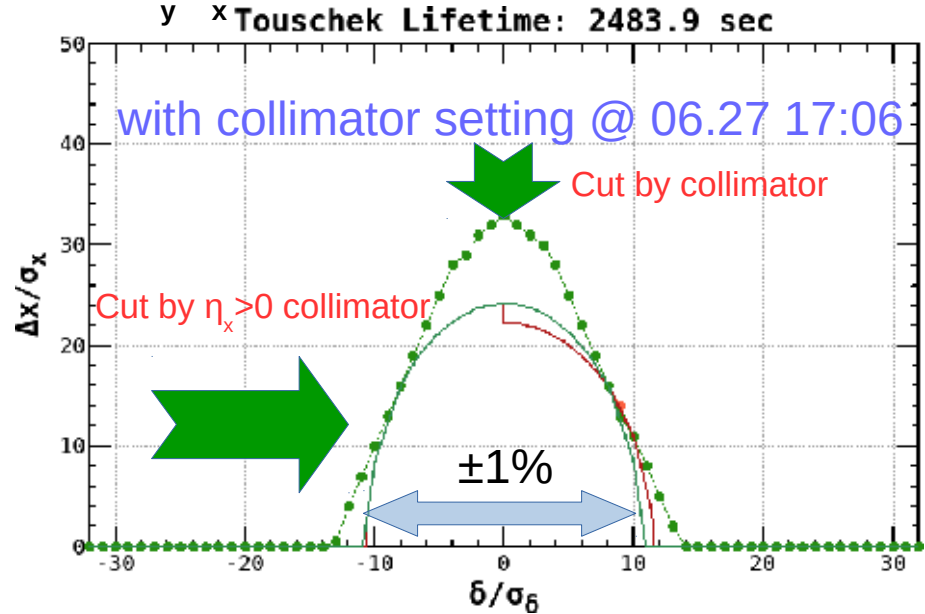
- LER lifetime(others) is too short if it is vacuum lifetime.

# LER Lifetime Simulation

100mA / 1576 bunches /  $\epsilon/\epsilon = 0.65\%$



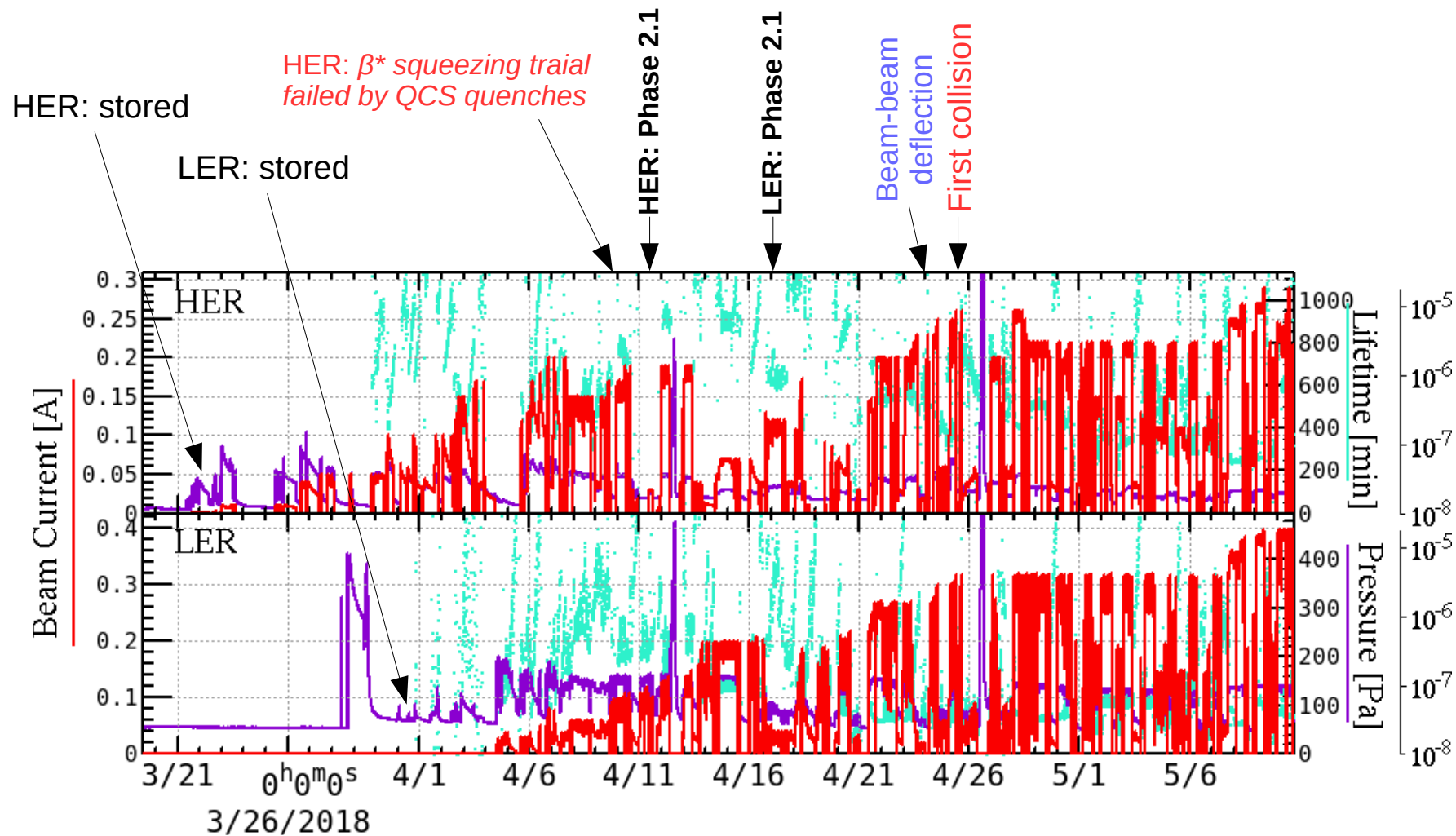
Touschek lifetime ~ 400min



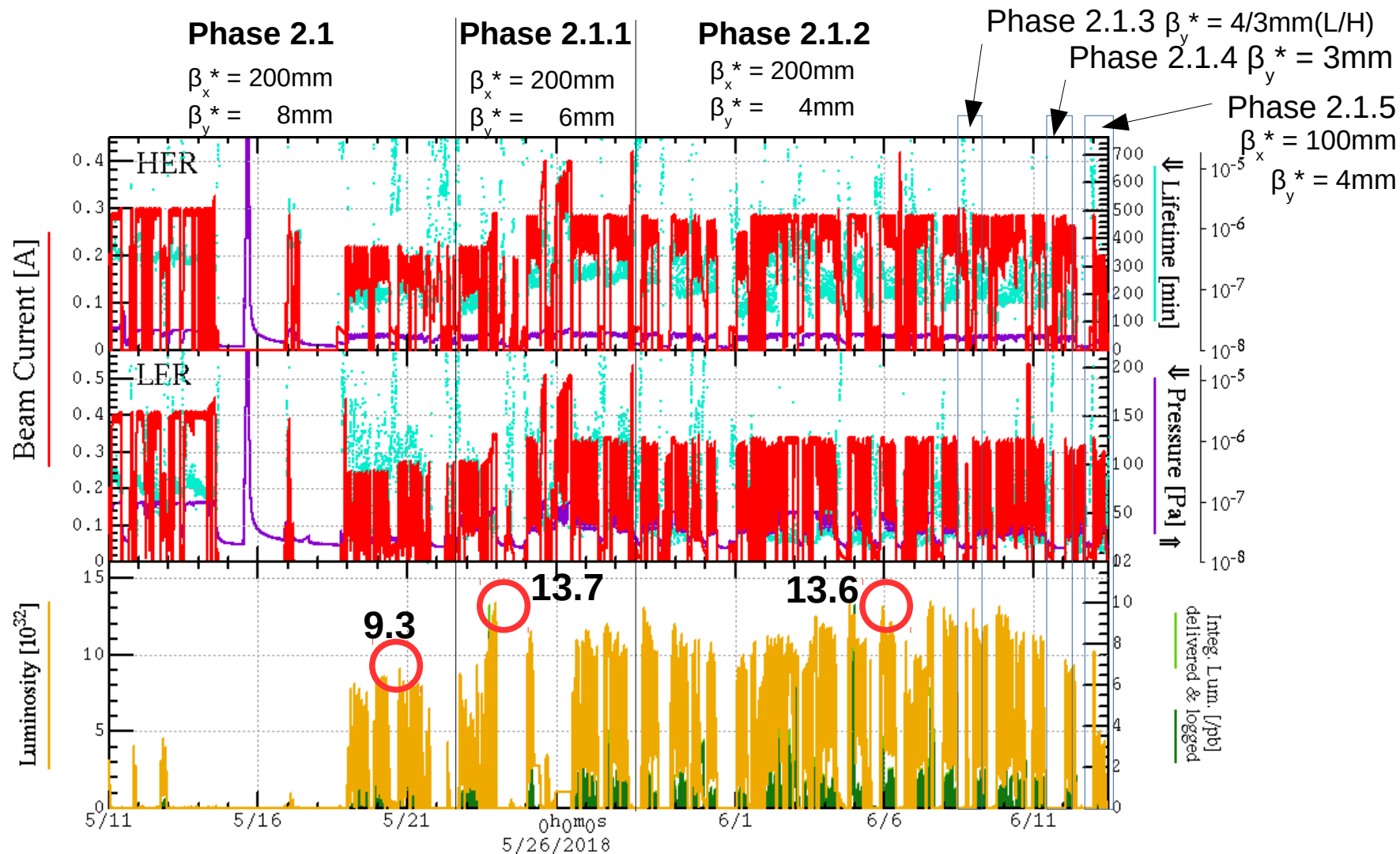
Touschek lifetime ~ 41min

- Simulation with collimator is consistent with measurements: loss rate measurement & momentum acceptance survey.

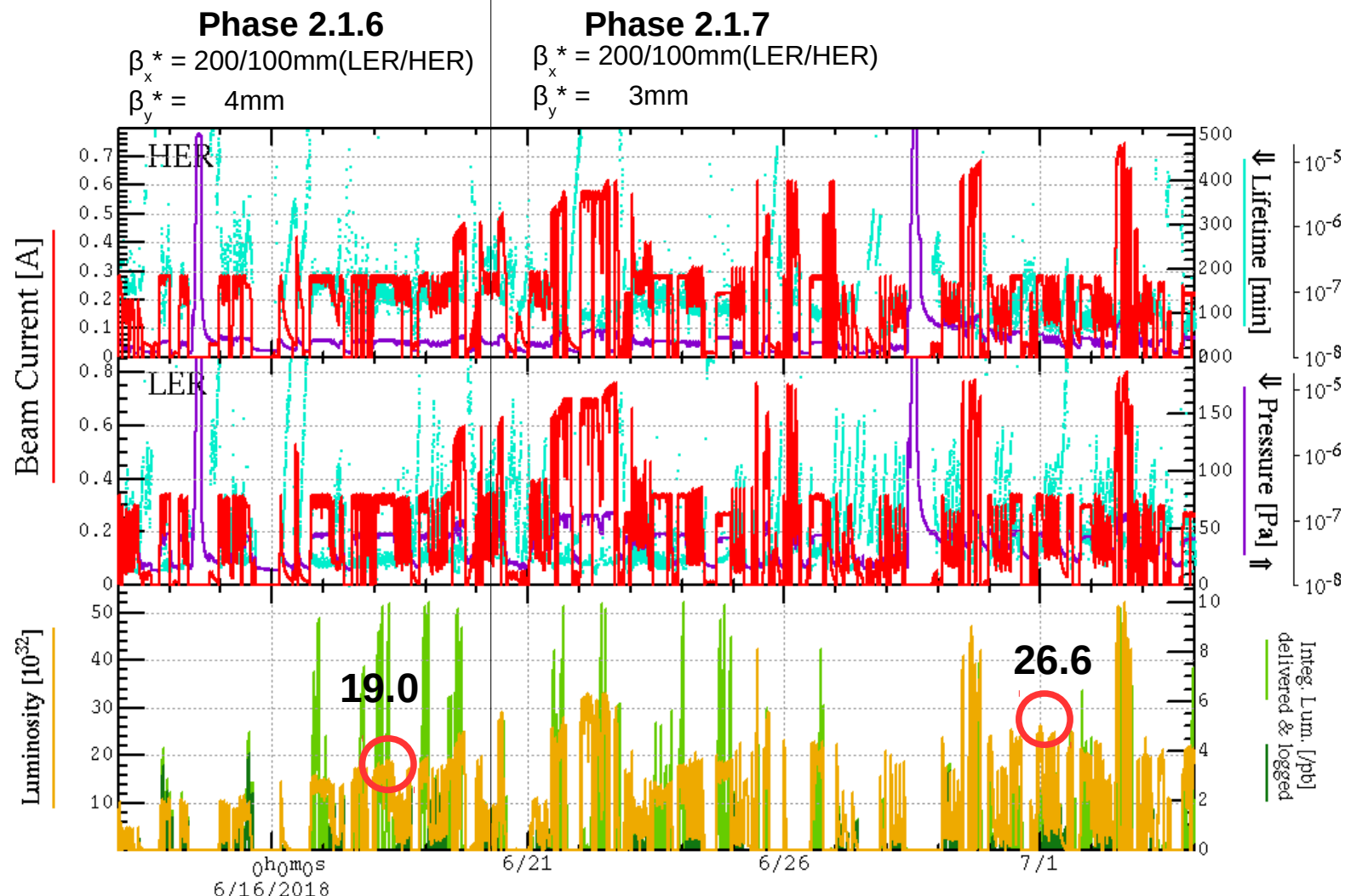
# Phase2: 03.19 ~ 05.11



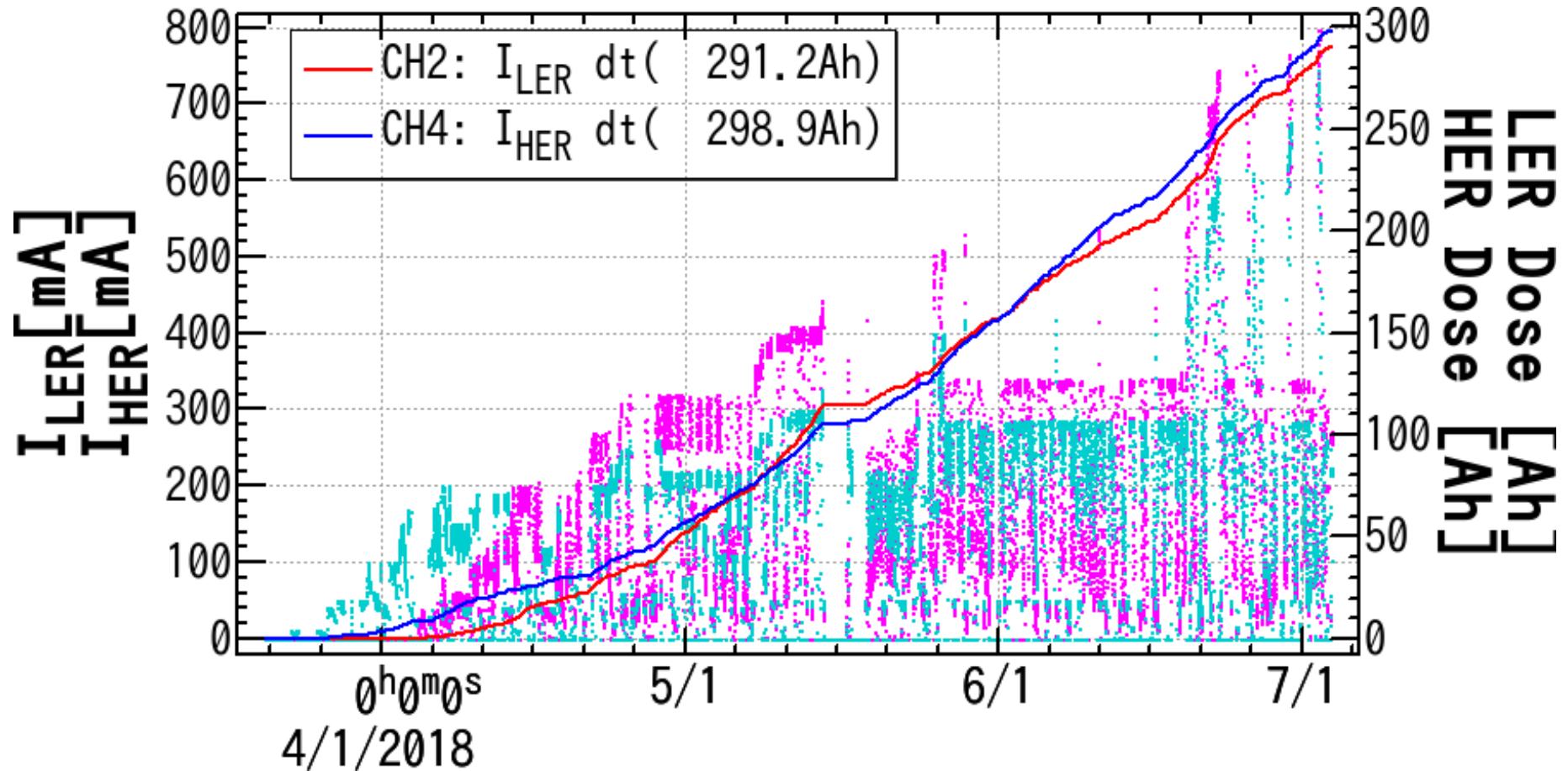
# Phase2: 05.11 ~ 06.13



# Phase2: 06.13 ~ 07.03



# Beam Currents and Beam Dose



# Achievements in Phase-2

- Maximum Stored Current: 788/745mA(LER/HER) with collision
- Beam Dose: 291/299Ah(LER/HER)
- Squeezing  $\beta_y^*$  down to 3mm(collision) / 2mm(single beam)
- $L_{\text{peak}} \sim 5.3886 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @ 2018.07.02 15:21 JST
  - $I \sim 788/745\text{mA(LER/HER)}$ ,  $nb = 1576$ ,  $\beta_x^* = 200/100\text{mm(LER/HER)}$ ,  $\beta_y^* = 3\text{mm}$
- $L_{\text{peak}} \sim 2.6678 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @ 2018.06.30 23:51 JST
  - $I \sim 340/285\text{mA(LER/HER)}$ ,  $nb = 789$ ,  $\beta_x^* = 200/100\text{mm(LER/HER)}$ ,  $\beta_y^* = 3\text{mm}$
- $L_{\text{spec}} \sim 2.2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}/\text{mA}^2$  @ 2018.06.30 22:40 JST
  - $I \sim 340/285\text{mA(LER/HER)}$ ,  $nb = 789$ ,  $\beta_x^* = 200/100\text{mm(LER/HER)}$ ,  $\beta_y^* = 3\text{mm}$
- $\sigma_{y \text{ scan}}^* \sim 0.333\mu\text{m}$  @ 2018.06.29 22:40
  - $I \sim 15/15\text{mA(LER/HER)}$ ,  $nb = 1576$ ,  $\beta_x^* = 200/100\text{mm(LER/HER)}$ ,  $\beta_y^* = 3\text{mm}$

# Summary

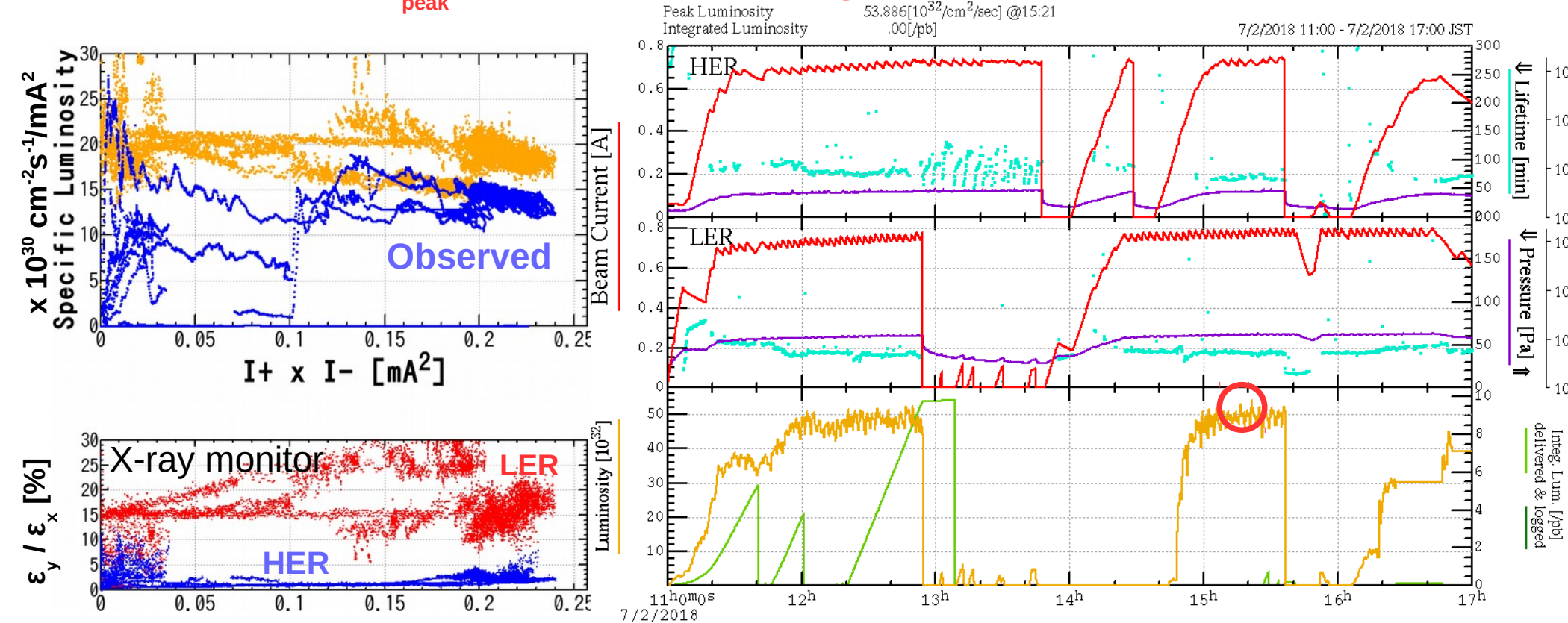
- Squeezing beta function issues
  - We have squeezed beta function at IP down to 2 mm for both rings. (optics correction)
  - We have achieved collision operation with  $\beta_y^* = 3\text{mm}$  and luminosity is not limited by hourglass effect at this  $\beta_y^*$ .
- Luminosity optimization issues
  - We found large R2 error at IP and it makes geometrical luminosity loss.
    - Trying to correct R2 error at IP by using QCS skew quadrupole, because it is too large to adjust by IP coupling/dispersion knob.
    - Need to identify error source and feedback to optics modeling.
  - Need to reduce beam-beam blowup.
  - Need more coupling/dispersion correction for reducing vertical emittance.
- Lifetime issues
  - We identify that short LER beam lifetime is caused by too tight horizontal collimator setting.
    - Need collimator optimization under trade-off between lifetime and Belle-II background.
    - Option: Introduce dispersion free horizontal collimator
  - Need sextupole parameter optimization for longer lifetime and weaker synchro-beta resonance lines.

Backup Slides

# Highest Luminosity

Phase 2.1.7:  $\beta x^* = 200/100\text{mm(LEP/HER)}$ ,  $\beta y^* = 3\text{mm}$ ,  $I = 788/745\text{mA(LEP/HER)}$ ,  $n_b = 1576$

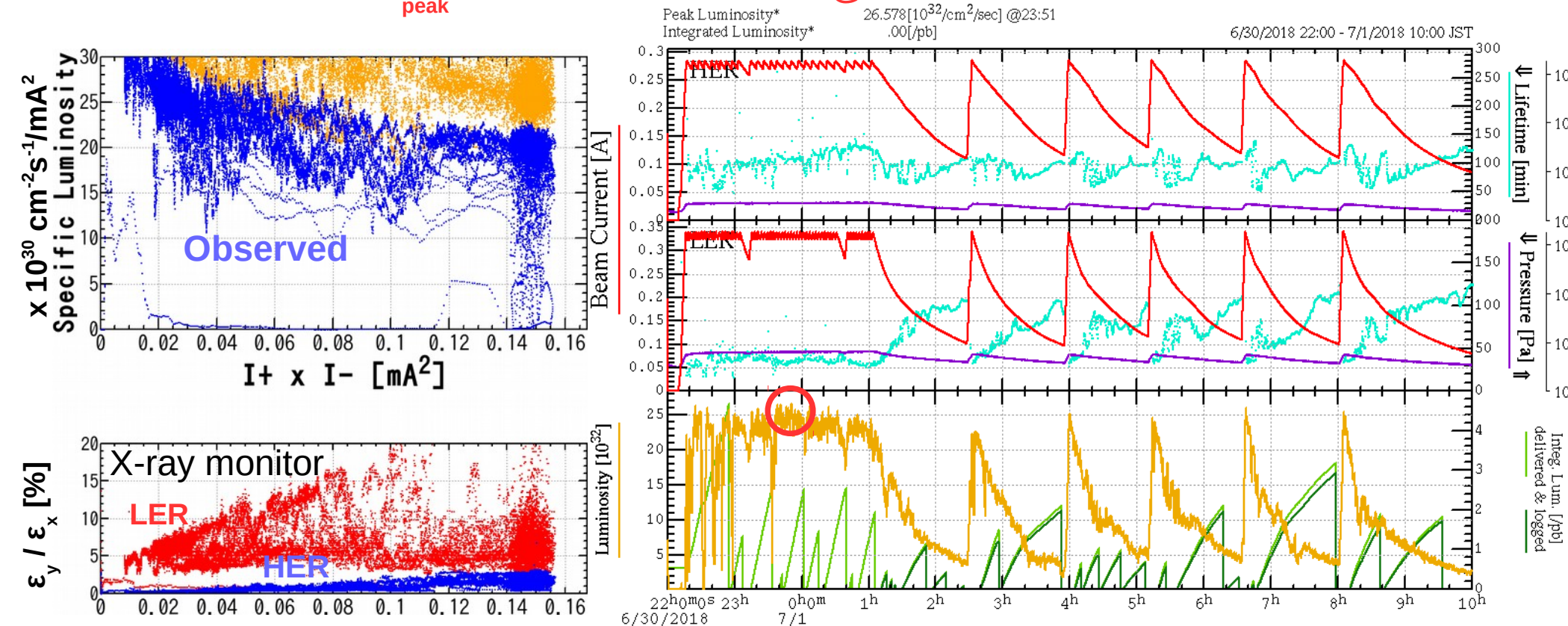
$L_{\text{peak}} = 5.3886 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} @ 2018.07.02 15:21 \text{ JST}$



# Best Luminosity (medium bunch current)

Phase 2.1.7:  $\beta x^* = 200/100\text{mm}$ (LER/HER),  $\beta y^* = 3\text{mm}$ ,  $I = 340/285\text{mA}$ (LER/HER),  $nb = 789$

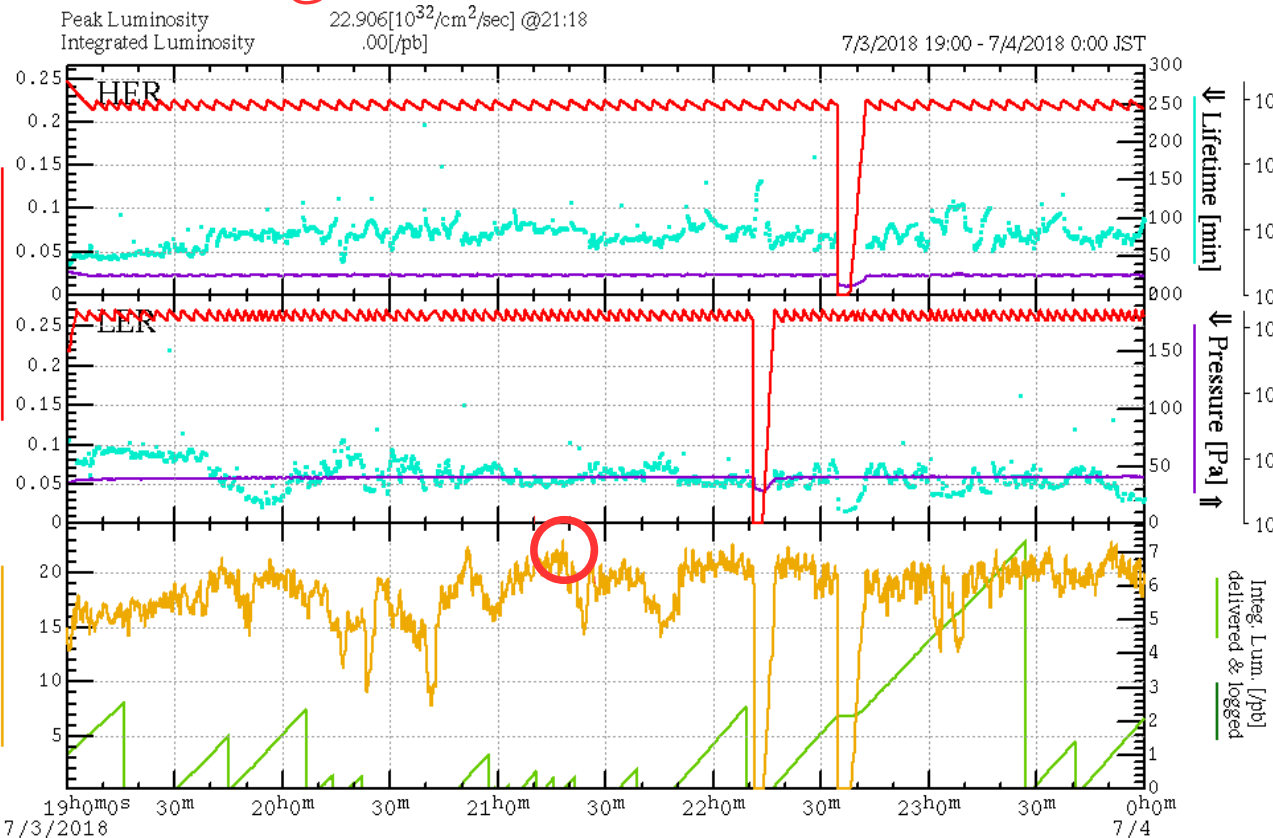
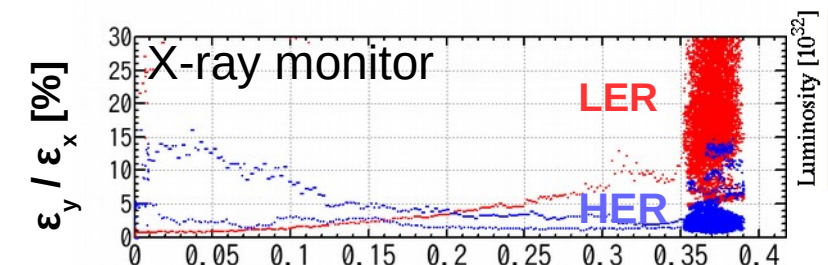
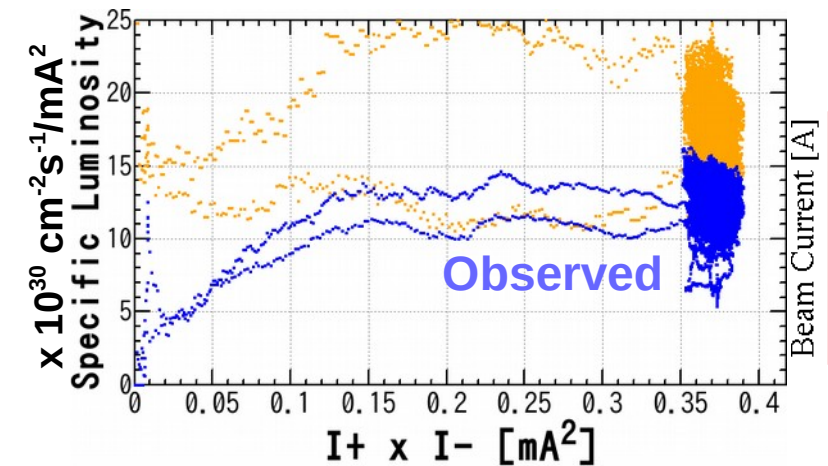
$L_{\text{peak}} = 2.6578 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @ 2018.06.30 23:51 JST



# Best Luminosity (high bunch current)

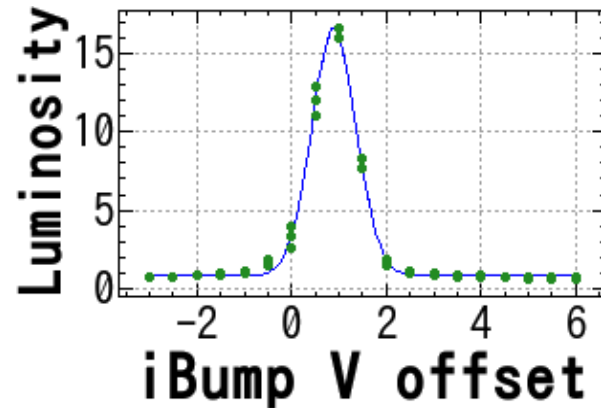
Phase 2.1.7:  $\beta x^* = 200/100\text{mm}$ (LER/HER),  $\beta y^* = 3\text{mm}$ ,  $I = 270/225\text{mA}$ (LER/HER),  $nb = 394$

**$L_{\text{peak}} = 2.2906 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @ 2018.07.03 21:18 JST**



# Smallest Beam-Beam Scan Size

Phase 2.1.7:  $\beta x^* = 200/100\text{mm}$ (LER/HER),  $\beta y^* = 3\text{mm}$ ,  $I = 15/15\text{mA}$ (LER/HER),  $n_b = 1576$   
measured at 2018.06.29 22:40 JST

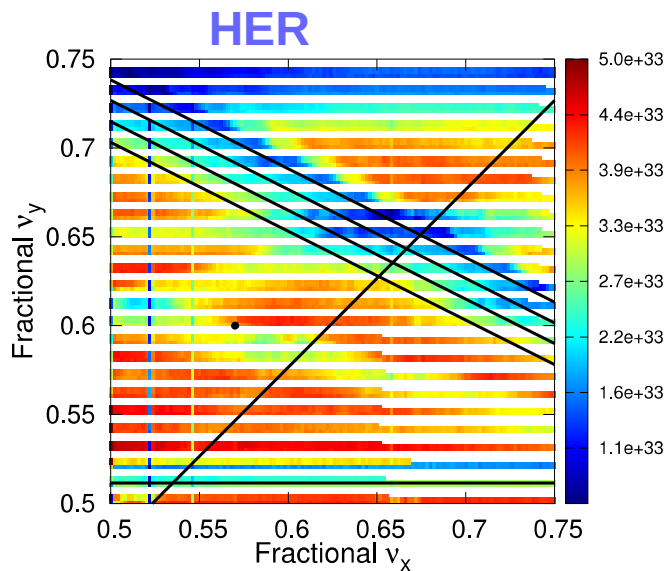
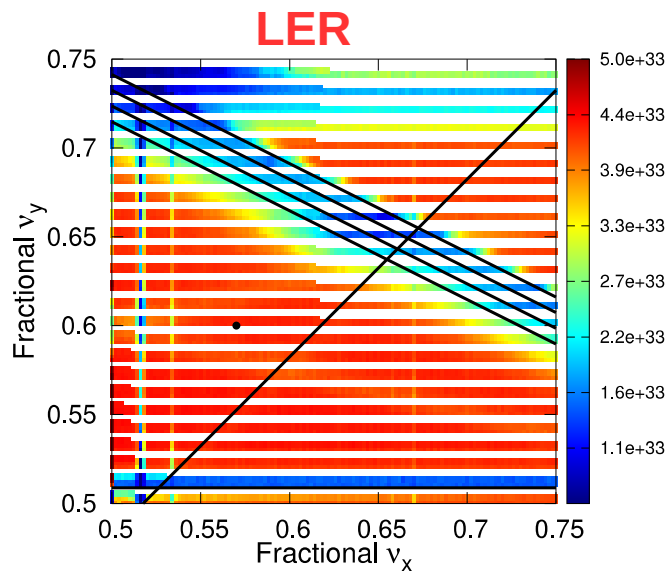


$$\sigma_y^* \text{ scan} = 0.333 \mu\text{m}$$

Luminosity Fit	RePlot	ReFit
Lum offset		0.827
Luminosity		15.811
$\sigma_y [\mu\text{m}]$		0.333

# Betatron Tune Working Point

- Stable region of betatron tune looks like smaller than current dependent tune shift.
- Many synchro-beta resonance lines are observed in operation and it affects beam size, lifetime, and luminosity.
- We need more tune survey and sextupole parameter survey for stable operation.
  - Tune feedback system is required to help operator.



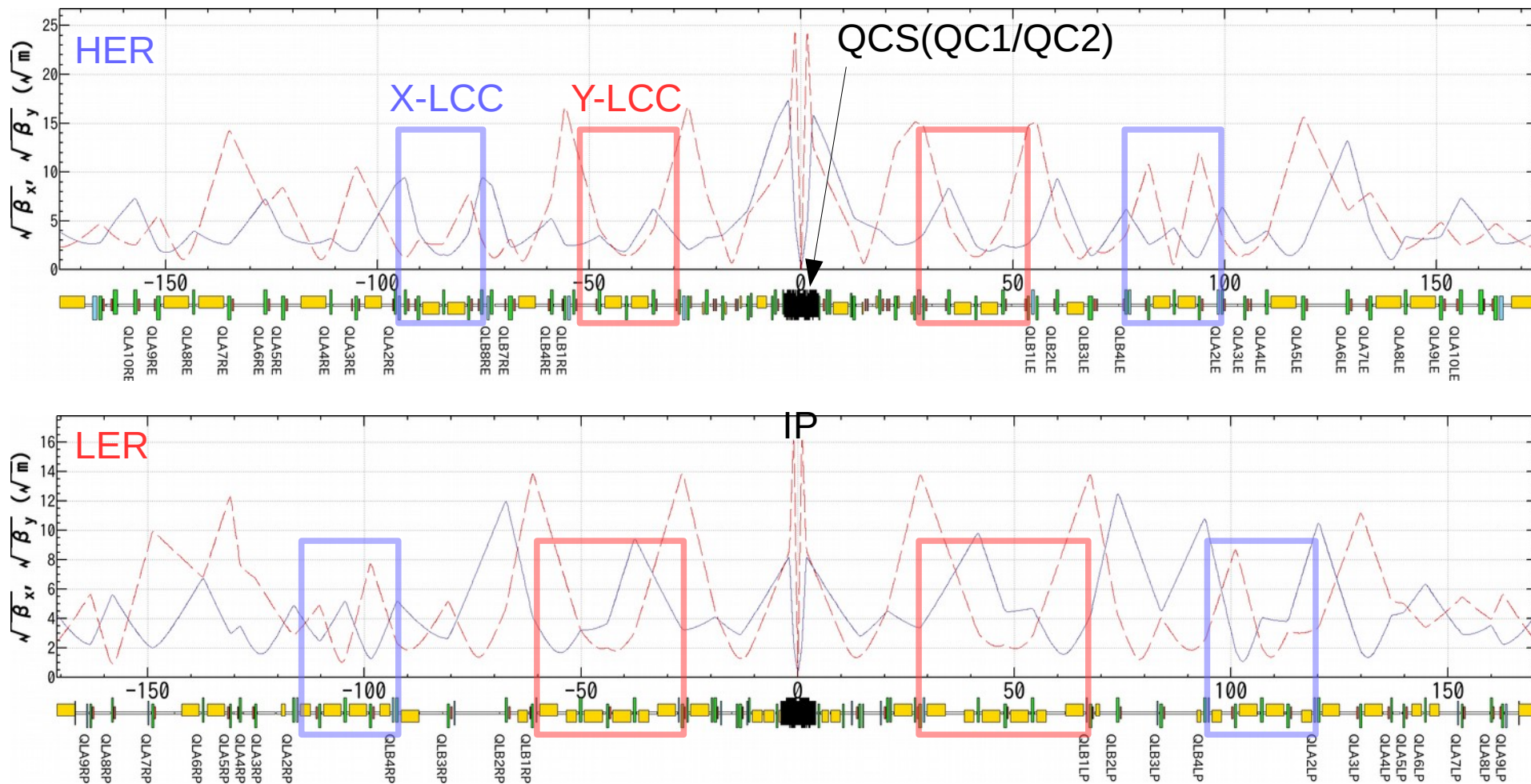
Luminosity simulation(ws)  
by D.zhou.

HER stable region looks like  
narrow compared with LER.

# Horizontal Waist(QC2 Waist)

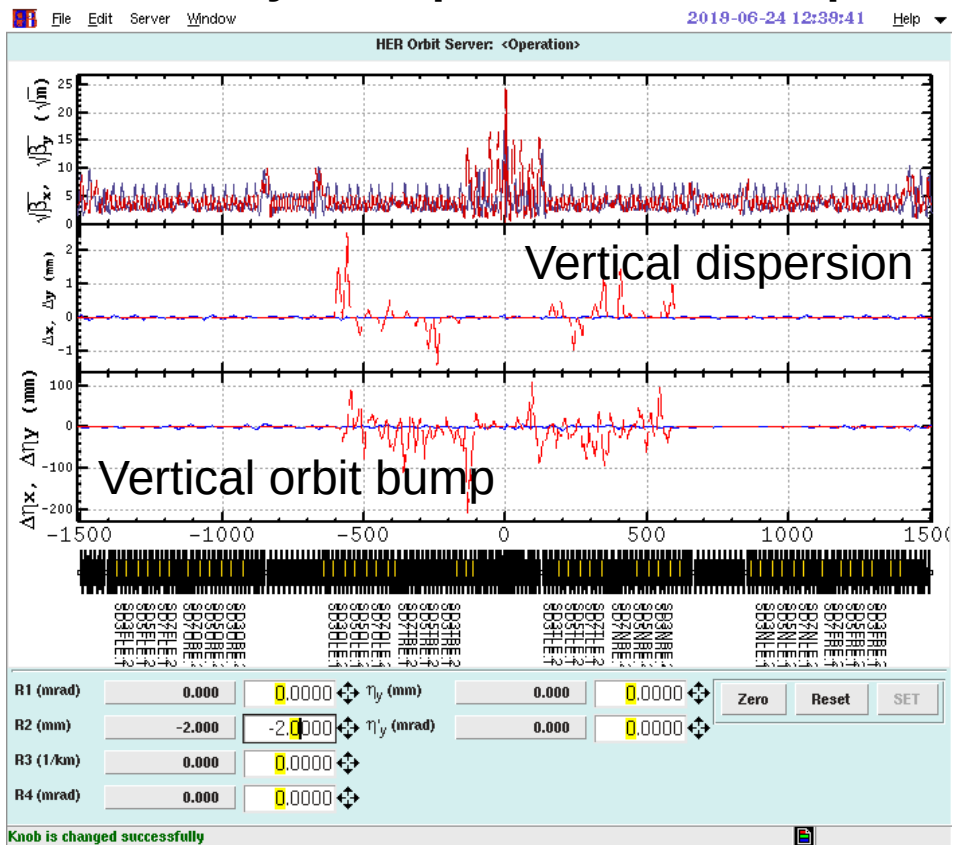
- Large ( $\sim 100\text{mm}$ ) HER  $\beta_x$  waist shift is predicted from analysis of  $\beta$ -function measurement results.
- Waist tuning by QC2 improves HER beam size, however, luminosity improvement is not clear.
  - It seems that LER beam becomes relatively weaker.
- Why is HER  $\beta_x$  waist shift larger than LER's one?
  - Is it depending with IR structure? (HER QC2 geometry is asymmetric.)
  - Does this waist shift affect Belle-II beam background?

# Phase 2.1.7 IR Optics

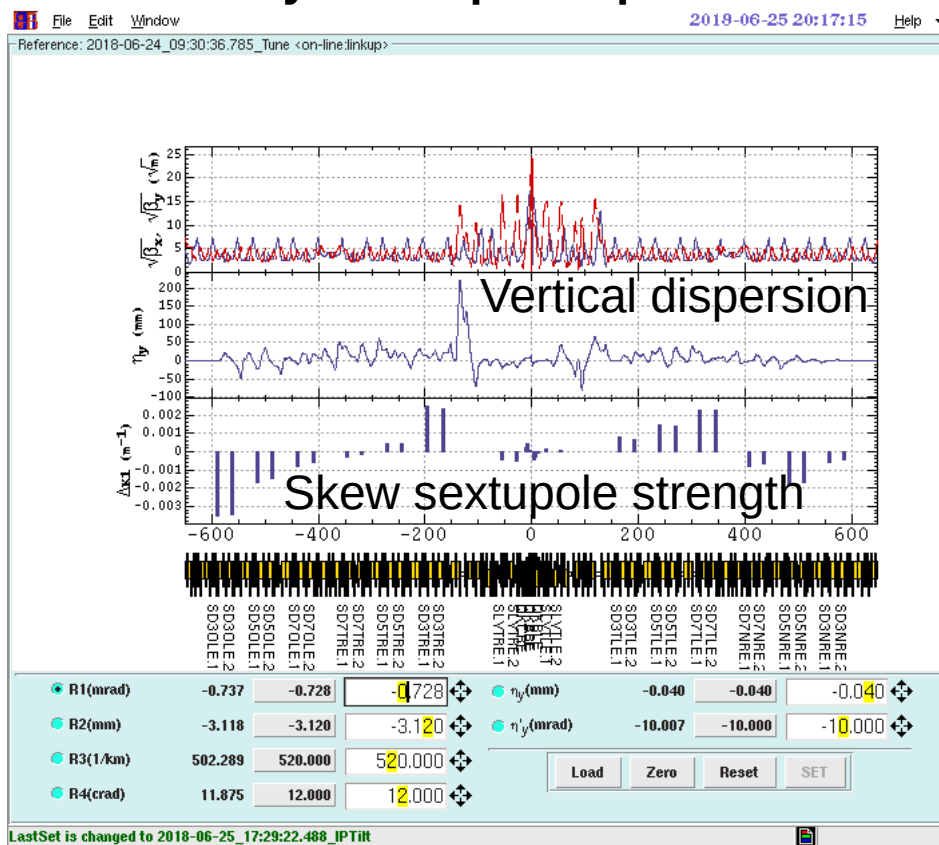


# HER IP Coupling/Dispersion Knob

**by sextupole vertical bump**



**by skew quadrupole**



- Injection background
  - The injection noise has been reduced with both of injection tuning and collimator tuning.
  - The optics changes frequently due to beta squeezing, so the tuning procedure is repeated when the optics changes.
- Synchrotron radiation
  - SR is observed by PXD which is larger than simulations.
- Vacuum
  - vacuum background decreases as increasing beam dose.
- Touschek effect
- Radiative Bhabha (not seen due to low luminosity)
- Beam tail
  - Hits at  $s = \sim 220$  mm cannot be beam tail because beam-stay-clear is  $110 \sigma$ .