Optics correction including IP local coupling at SuperKEKB

Akio Morita
SuperKEKB Commissioning Group

eeFACT 2018

This work was supported by JSPS KAKENHI Grant Number 17K05475.

Final Focus System Test

- Check both cable connection and operation software by using single kick and local orbit bump.
  - Fixed following connection errata.
    - Miss-connection between QC1LP and QC1RP BPMs.
    - Miss-connection between skew quadrupole and vertical dipole steering winding on QC2LP magnet.
    - Polarity inversion in HER vertical dipole steering.
  - Found hysteresis of superconducting dipole steering correctors.
    - It WOULD be caused by physical properties of superconducting wire.
    - Blocker for accurate IP local orbit control.
- Calibrate both electrode gain balance and position offset for final focus quadrupole(QC*) BPMs.
  - The QC* electrode gain error is larger than gain error of arc section BPMs.

Global Optics Correction

- Optics measurement & correction method is same as phase-1 commissioning.
  - It is based on closed orbit response measurement by using multi-turn BPMs(not TbT).
    - Cross talk of vertical orbit response by horizontal single steering kick(XY-Coupling)
    - Orbit response difference by shifting cavity frequency(Physical Dispersion)
    - Fitting $\sqrt{\beta}\cos\varphi$, $\sqrt{\beta}\sin\varphi$ to single steering kick response(Global Beta)
  - Correction by using linear model response with singular value decomposition(SVD)

Correction	Target function	Variables
XY-coupling	Δy(cross talk of horizontal single kick)	$\Delta SK1$
V-dispersion	$\Delta\eta y$	$\Delta SK1$
H-dispersion	$\Delta\eta x$	$\Delta K1$ & H-bump on sextupoles
Global beta	$\Delta\nu$, $\Delta\beta/\beta$, $\Delta\varphi$	$\Delta K1$

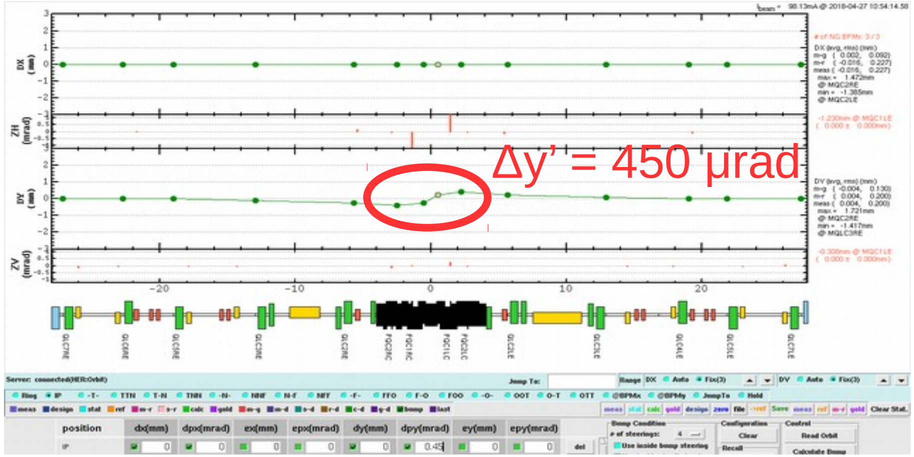
    - For skew quadrupole winding on sextupole pair, the orthogonal $\Delta SK1$ parameter sub-spaces are used for XY-coupling and vertical dispersion correction, respectively.

- Frequent optics measurement compared with phase-1 commissioning.
  - Phase-2 ~7.5 measurements/day (~900 measurements / 120days)
  - Phase-1 ~3.3 measurements/day (~500 measurements / 150days)

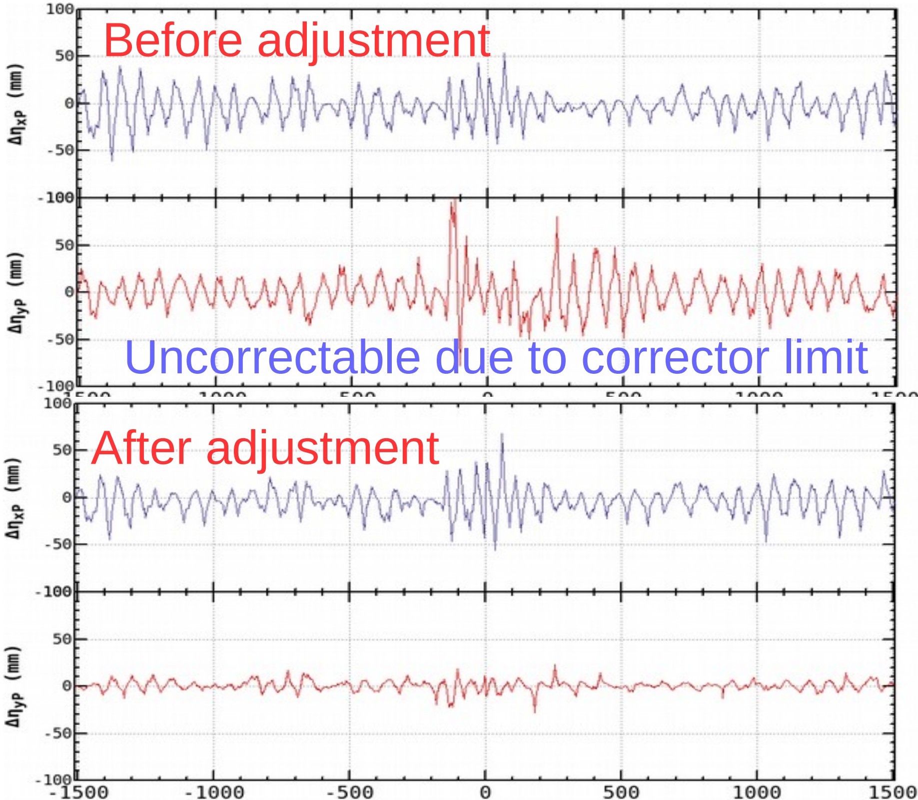
HER IR Orbit Issue

- In order to reduce temperature discrepancy between upper and lower side of HER downstream vacuum pipe, IR vertical angle of HER is adjusted.

Y. Suetsugu & H. Koiso, 2018-04-27



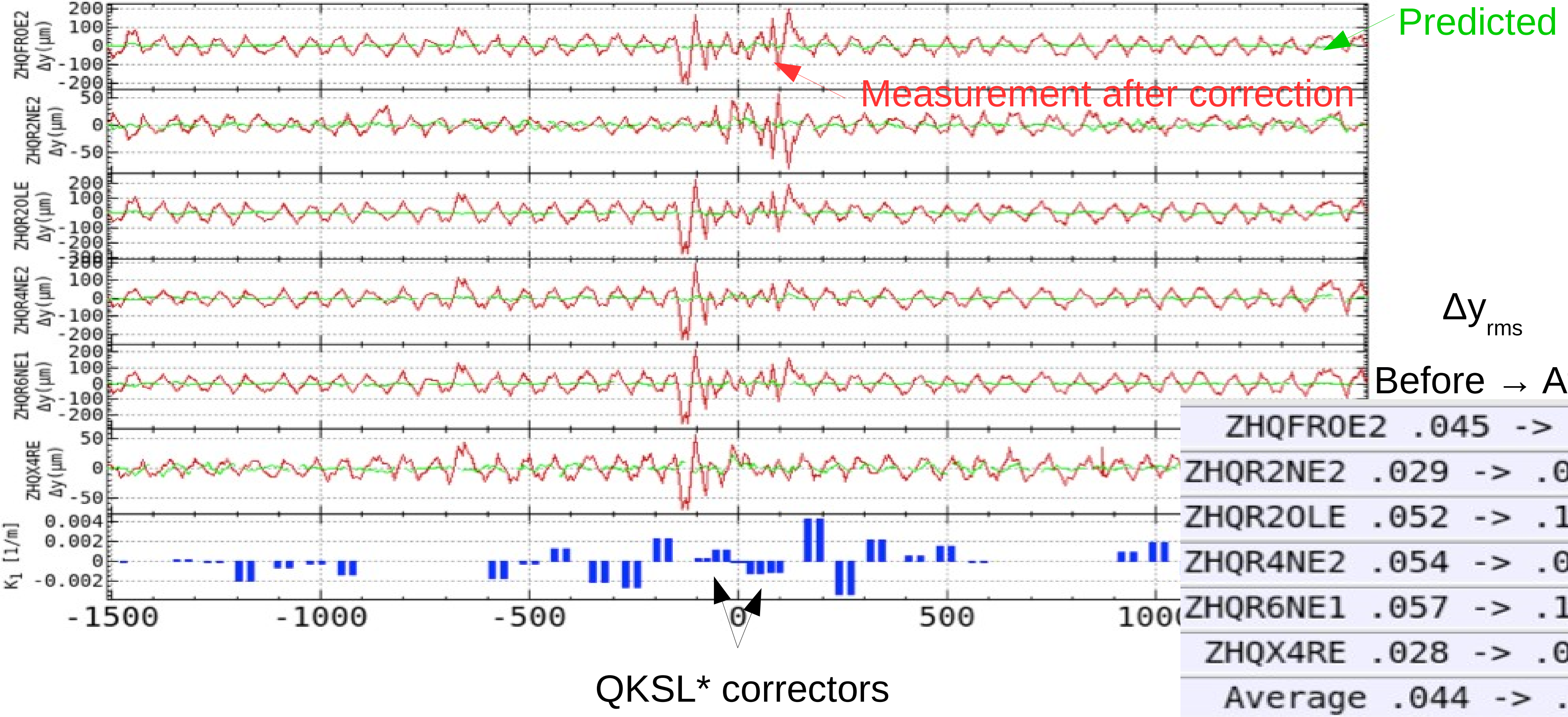
Measured HER physical dispersion error



- Vacuum pressure around heat spot is improved.
- Vertical dispersion correction is improved.

QKSL* Issue(1)

- The large discrepancy between prediction and measurement after correction is found in HER XY-coupling correction using QKSL* skew quadrupole winding on LCC sextupole magnet.



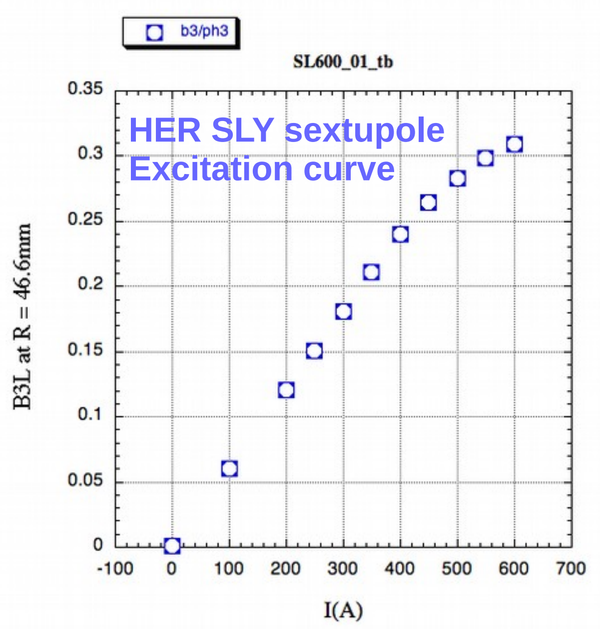
Δy_{rms}

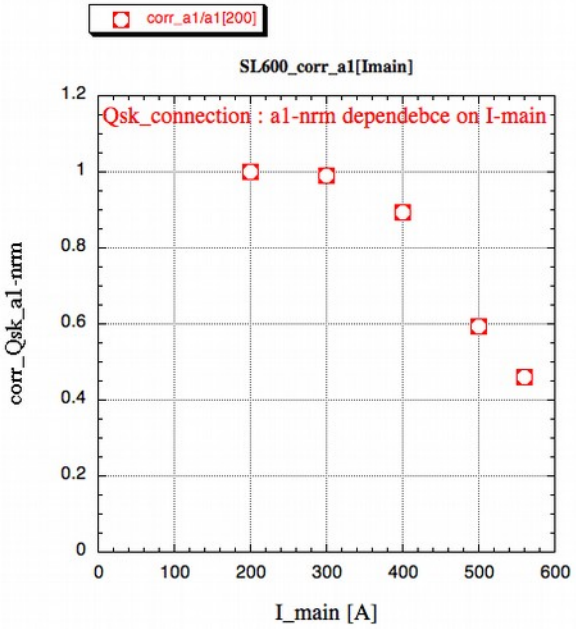
Before → After

ZHQFROE2	.045	->	.1
ZHQR2NE2	.029	->	.031
ZHQR2OLE	.052	->	.107
ZHQR4NE2	.054	->	.095
ZHQR6NE1	.057	->	.113
ZHQX4RE	.028	->	.036
Average	.044	->	.08

QKSL* Issue(2)

- Checking hardware, optics and etc...
  - It is caused by main sextupole current dependency of skew quadrupole excitation coefficient.
- Fixed by introducing calibration factor depending with main sextupole current into optics server software.(not EPICS IOC)



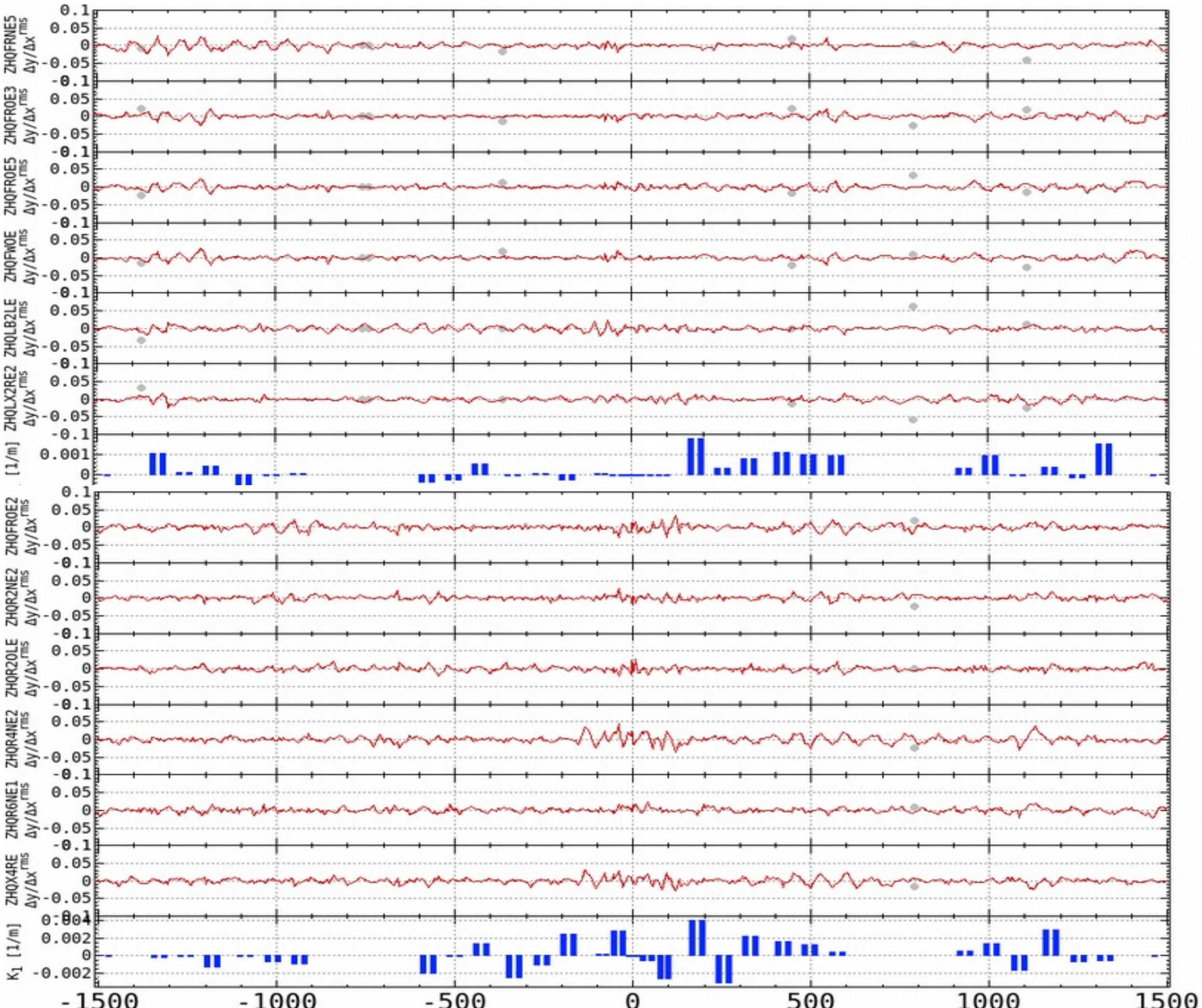


QKSLY skew quadruple winding Excitation coefficent depending with main sextupole current

HER XY-Coupling Correction

Phase-1

Phase-2



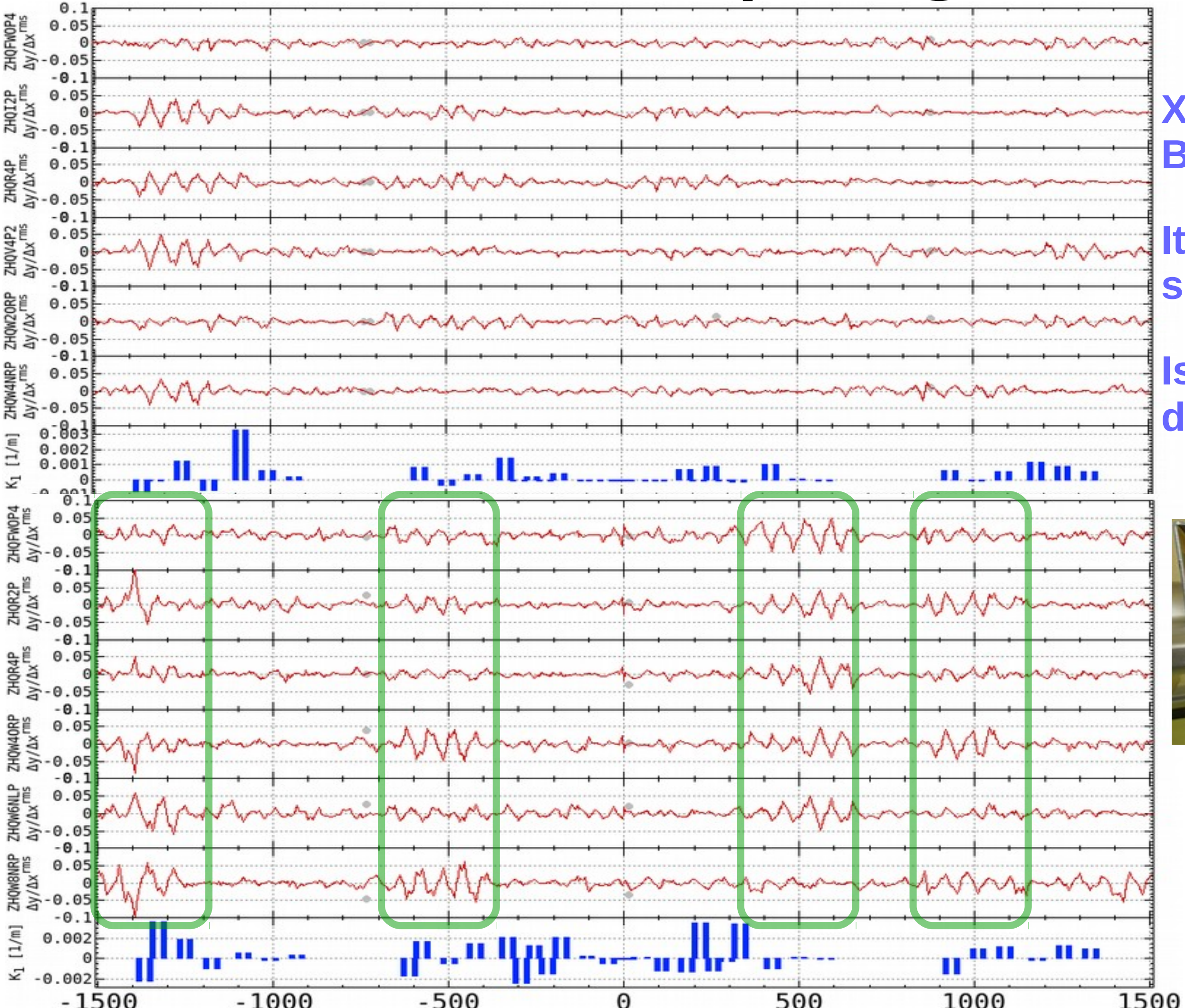
Almost same quality

CAUTION: Steering set is different.

LER XY-Coupling Correction

Phase-1

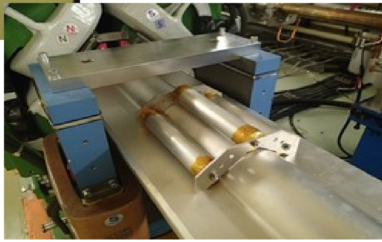
Phase-2



XY-coupling degradation is found.
But, IR section is not so bad.

It can not be explained by tunnel subsidence(sextupole alignment).

Is it caused by permanent magnet device for e^- cloud?



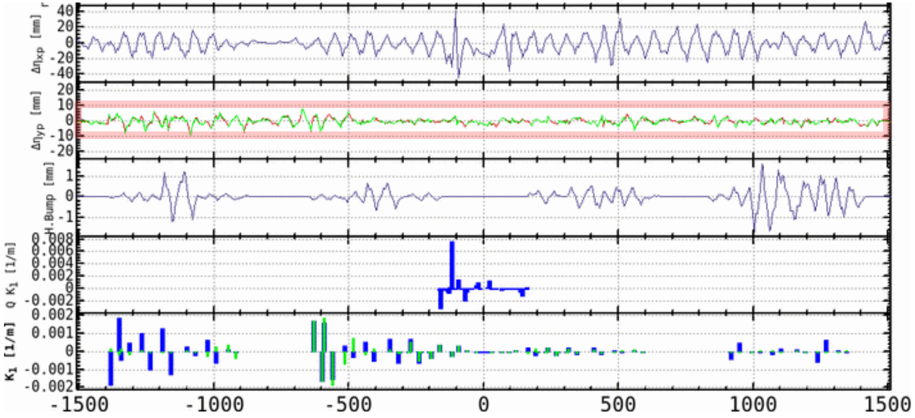
CAUTION: Steering set is different.

Dispersion Correction

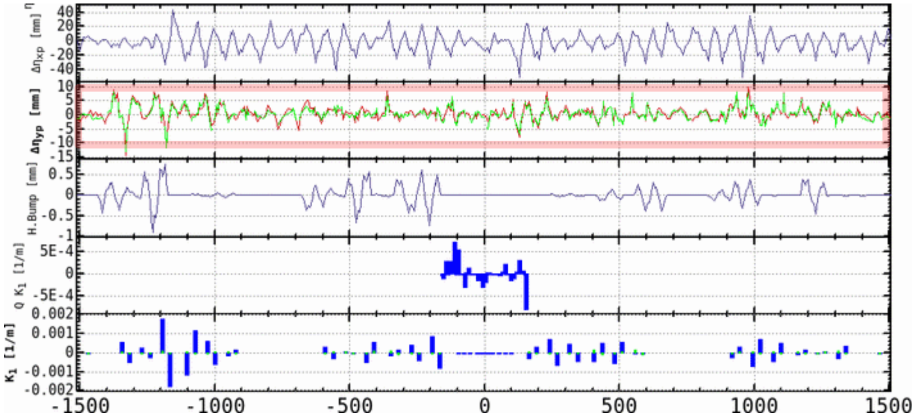
LER

HER

Δηy = 2.0mm(rms)

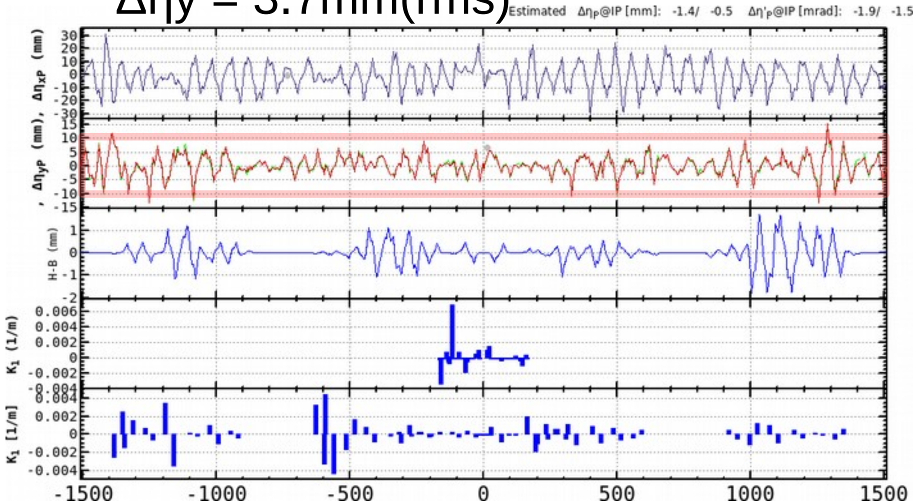


Δηy = 2.6mm(rms)

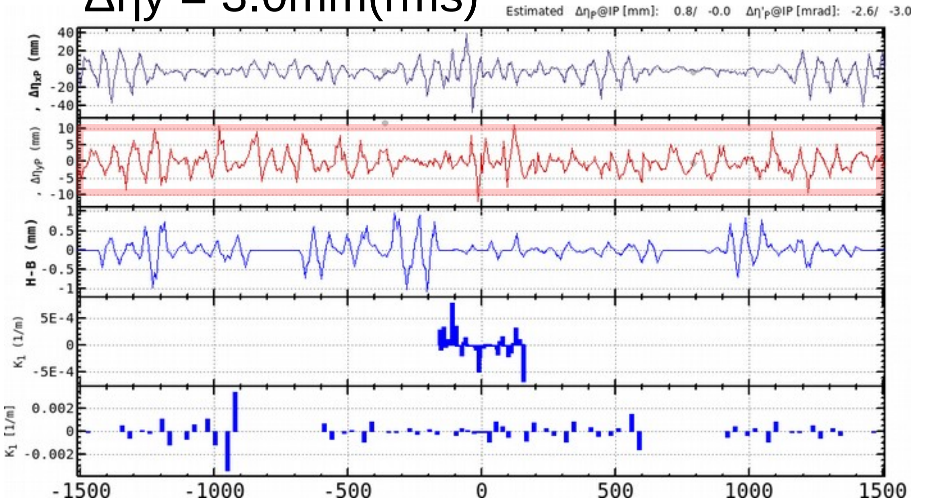


Phase-1

Δηy = 3.7mm(rms)



Δηy = 3.0mm(rms)

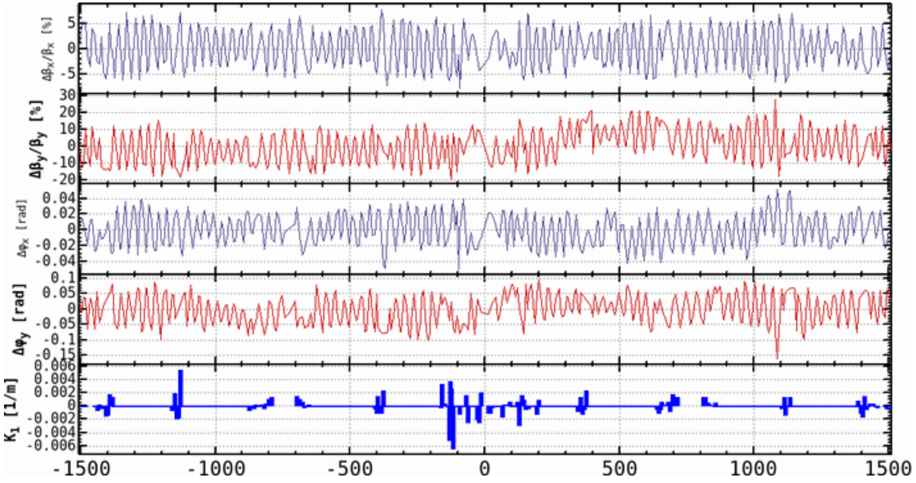


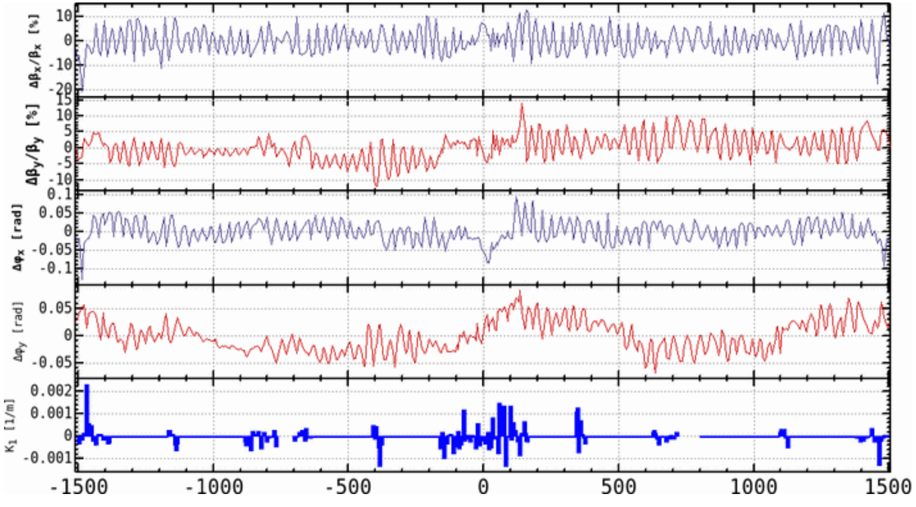
Phase-2

Global Beta Correction

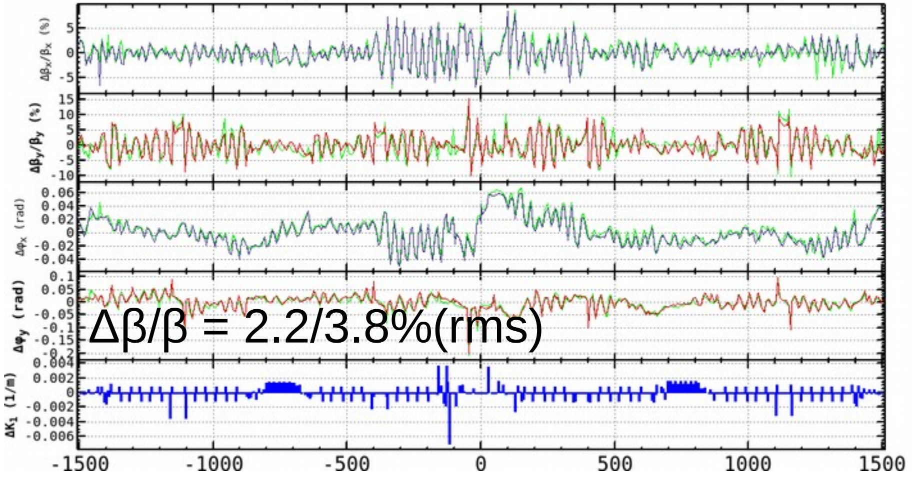
LER **HER**

Phase-1

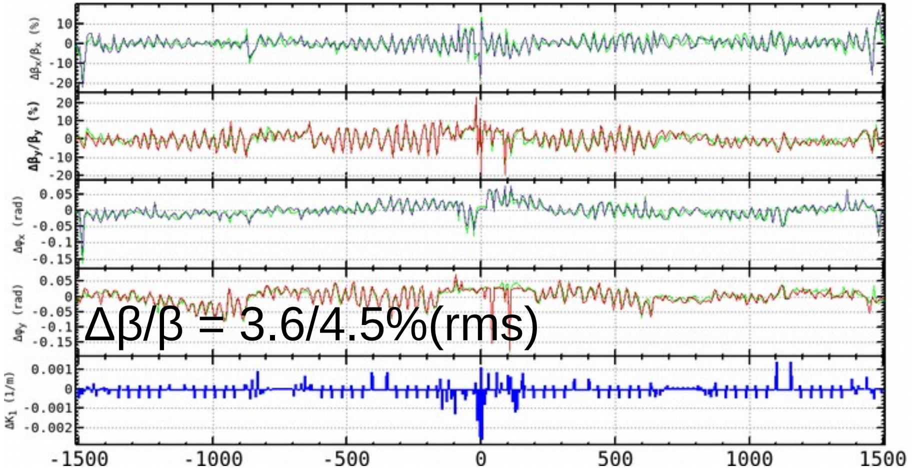




Phase-2



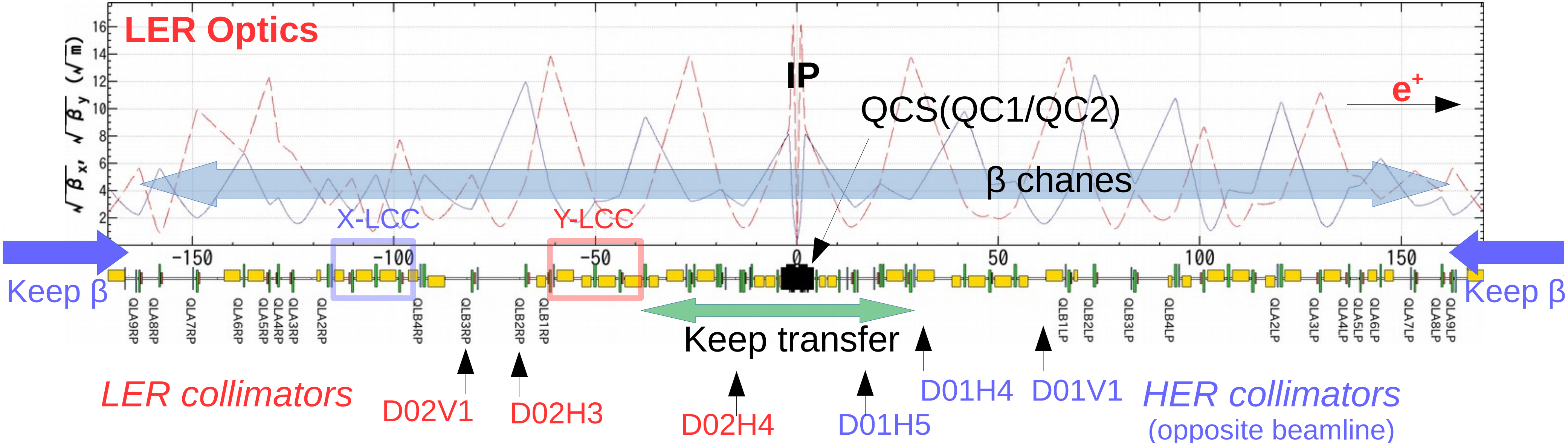
Δβ/β = 2.2/3.8%(rms)



Δβ/β = 3.6/4.5%(rms)

Beta Squeezing & Luminosity Scaling

- We are detuning/squeezing β* 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 section)
- Luminosity scaling law: $L = \frac{f_{rev}}{2\pi\sqrt{2}\sigma_z \phi_x} \frac{N_- N_+ nb}{\sqrt{(\epsilon_{y-} + \epsilon_{y+})\beta_y^*}}$
  - Luminosity is proportional to inversed square-root of β_y* if vertical emittance is kept.



Beta Squeezing Table

Phase	βx* [mm]		By* [mm]		State	L_{peak} $cm^{-2}s^{-1}$	I_{LER}/I_{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	9.3×10^{32}	250/220, 600	04/16
2.1.1	200		6		Collision	13.7×10^{32}	340/285, 789	05/22
2.1.2	200		4		Collision	13.6×10^{32}	340/285, 789	05/28
2.1.3	200		4	3	Collision	13.2×10^{32}	240/285, 789	06/08
2.1.4	200		3		Collision	10.5×10^{32}	320/265, 789	06/11
2.1.5	100		4		Collision	10.9×10^{32}	340/285, 789	06/12
2.1.6	200	100	4		Collision	19.0×10^{32}	340/285, 789	06/13
2.1.7	200	100	3		Collision	26.6×10^{32}	340/285, 789	06/20
2.2.0	200		2		**Optics Correction**			06/07
2.3.0	100		2		**Not achieved**			

@ 2018.07.03(not up-to date)

QCS Quenchs in β_y* Squeezing

- We have many QCS quenches during early stage of β_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 β_y at QC1 and degraded XY-coupling.
- Workaround
  - Use beam collimator to protect QCS.
  - Reduce step size of βy* squeezing.
  - Perform fine optics correction and injection tuning before next squeezing step.
  - Link Belle-II diamond background detector to beam abort system in order to abort beam before QCS quench by detecting beam loss near QCS.

After applying workarounds, we squeeze β_y* from 4mm to 2mm without QCS quenches.

Unscaled Luminosity at Squeezing

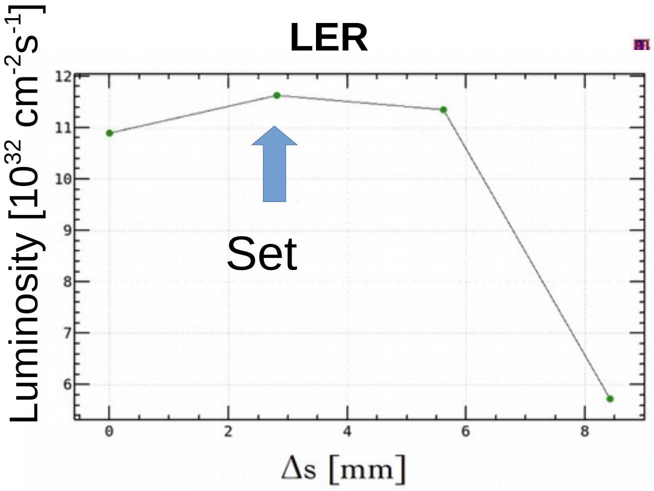
- Luminosity does not increase at squeezing β_y^* from 6mm to 4mm.
- Vertical beam size measured by X-ray monitor is shrinked as decaying beam current, however, specific luminosity does not increase.
  - While HER vertical beam size was shrinking by factor 3 due to beam current decay, specific luminosity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

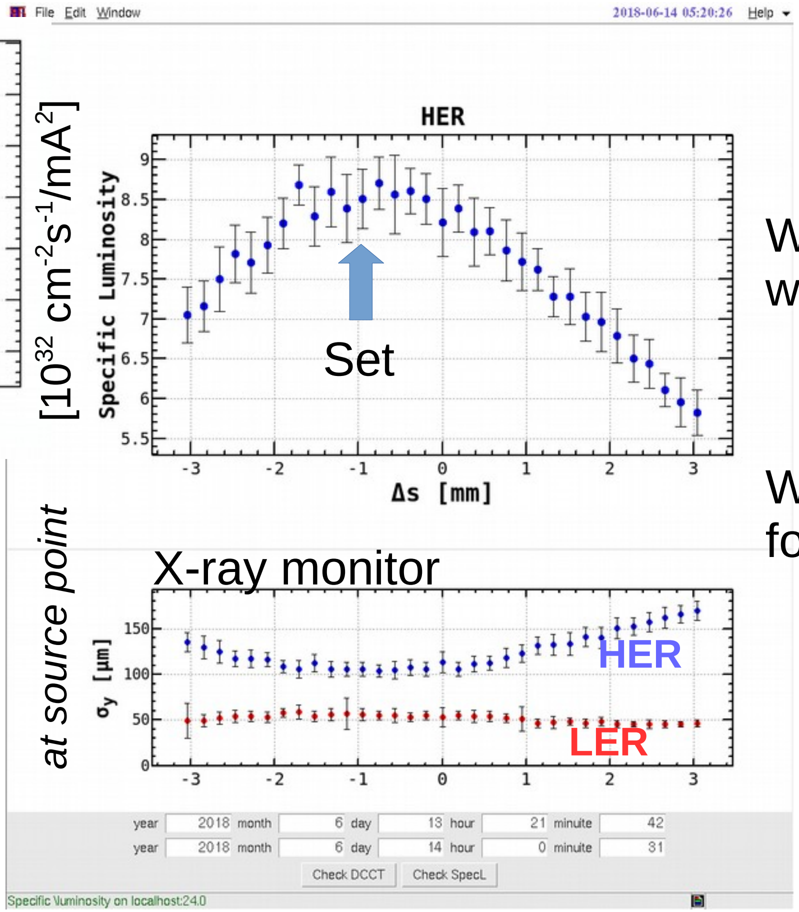
Geometrical mismatch between two beams is suspected.

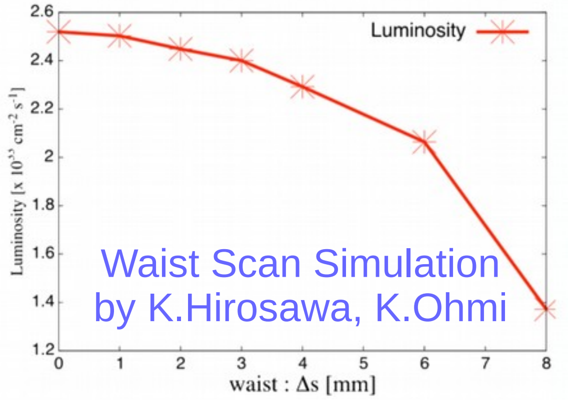
Need to check geometrical error at IP: waist, R1*, R2*, η_y^*, ...

Waist Scan

Vertical beam waist is scanned by using QC1 ΔK1.



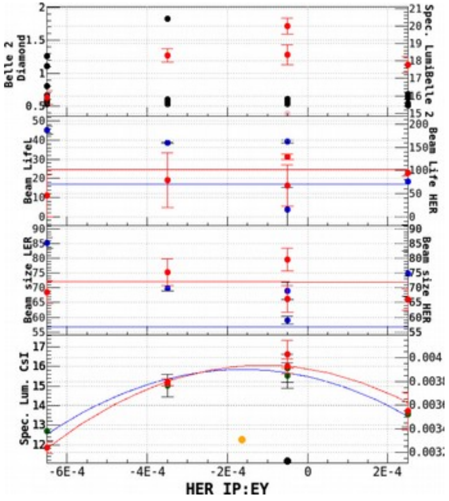


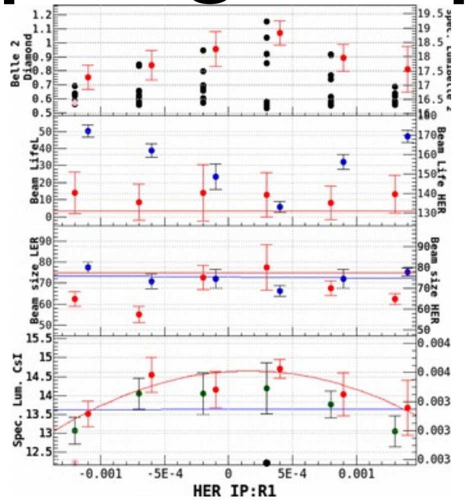


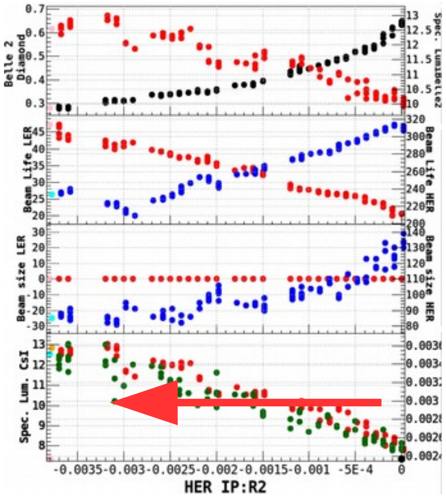
Waist scan results is consistent with simulation.

Waist shift is not large enough for geometrical beam mismatch.

IP Coupling/Dispersion Knob Scan

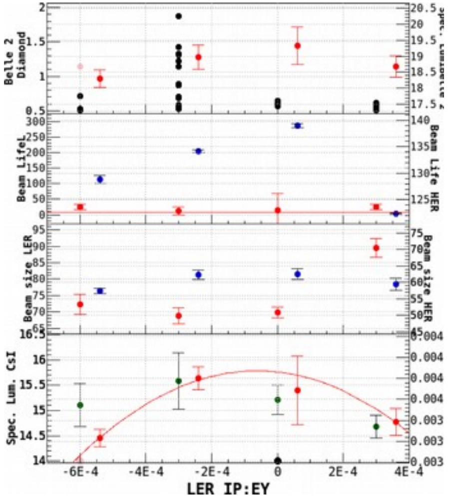


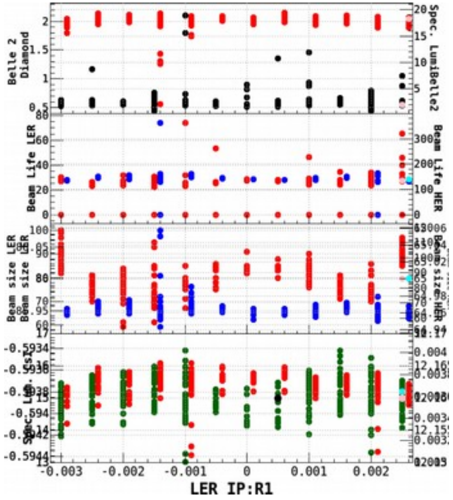


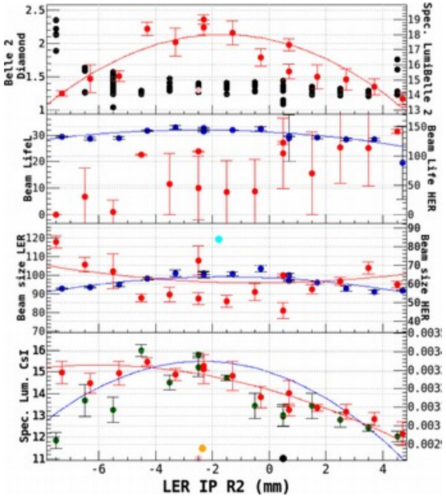


HER R2* = 0 → -3mm

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







Where R2* come from?

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

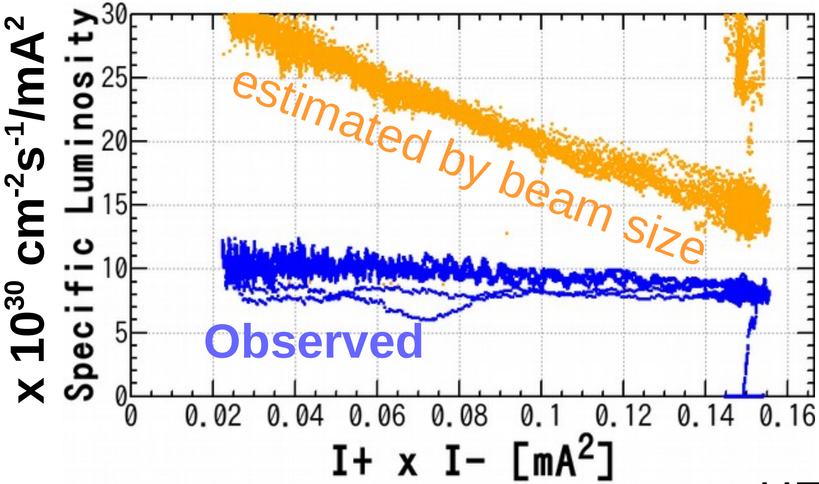
HER R2* Knob Issue

- Scan range is limited by power supply of skew quadrupole winding on arc sextupoles. (± 3mm typ.)
  - ±3mm scan range is not enough to find luminosity peak.
- 3mm R2* knob height already exceeds perturbative region.
  - R2* knob side effect makes vertical emittance growth.
- Another R2* tuning:
  - 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 coppor 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

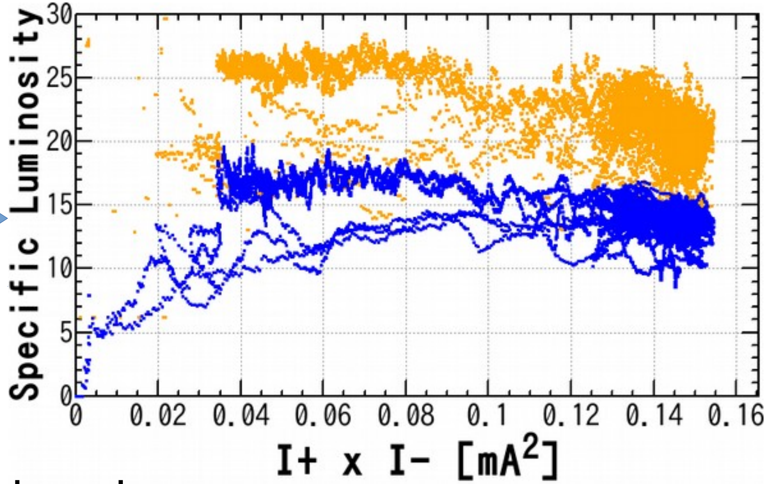
Phase 2.1.6: β_x^* = 200/100mm(LER/HER), β_y^* = 4mm, I = 340/285mA(LER/HER), nb = 789

2018.06.14



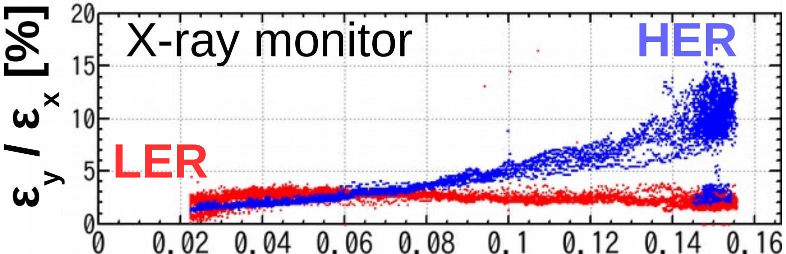
IP knob tunings:
R1*, R2*, η_y*,...

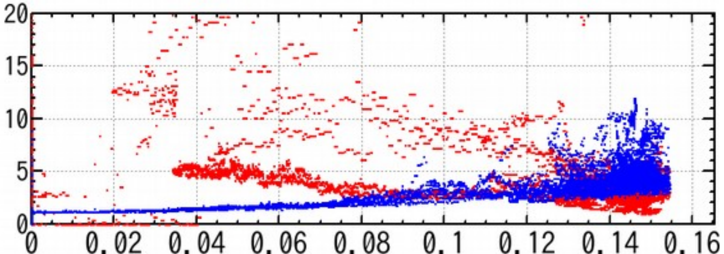
2018.06.17



L_{spec} is improved.

HER beam blowup is reduced.

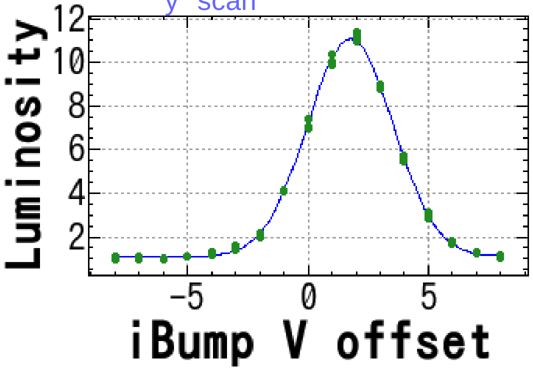




Beam-beam scan before & after IP coupling knob tuning

Phase 2.1.6: β_x^* = 200/100mm(LER/HER), β_y^* = 4mm, I = 15/15mA(LER/HER), nb = 1576

2018.06.14 $\sigma_{y\ scan}^*$ = 1.253 μm



Luminosity Fit	RePlot	ReFit
Lum offset		1.105
Luminosity		9.966
σ_y [μm]		1.253

X-Ray monitor

$\sigma_{y\ x\text{-}ray}^*$ ~ 0.4 / 0.5 μm (LER/HER)

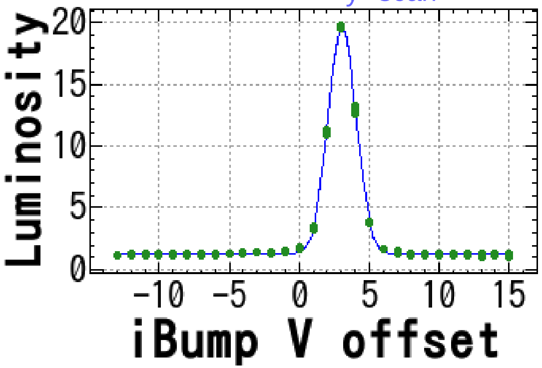
$\sigma_{y\ scan}^*$: x 0.55

Luminosity: x 1.84

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

IP knob tunings: R1*, R2*, η_y^*,...

2018.06.19 $\sigma_{y\ scan}^*$ = 0.689 μm



Luminosity Fit	RePlot	ReFit
Lum offset		1.277
Luminosity		18.303
σ_y [μm]		0.689

X-Ray monitor

$\sigma_{y\ x\text{-}ray}^*$ ~ 0.38 / 0.55 μm (LER/HER)

Summary

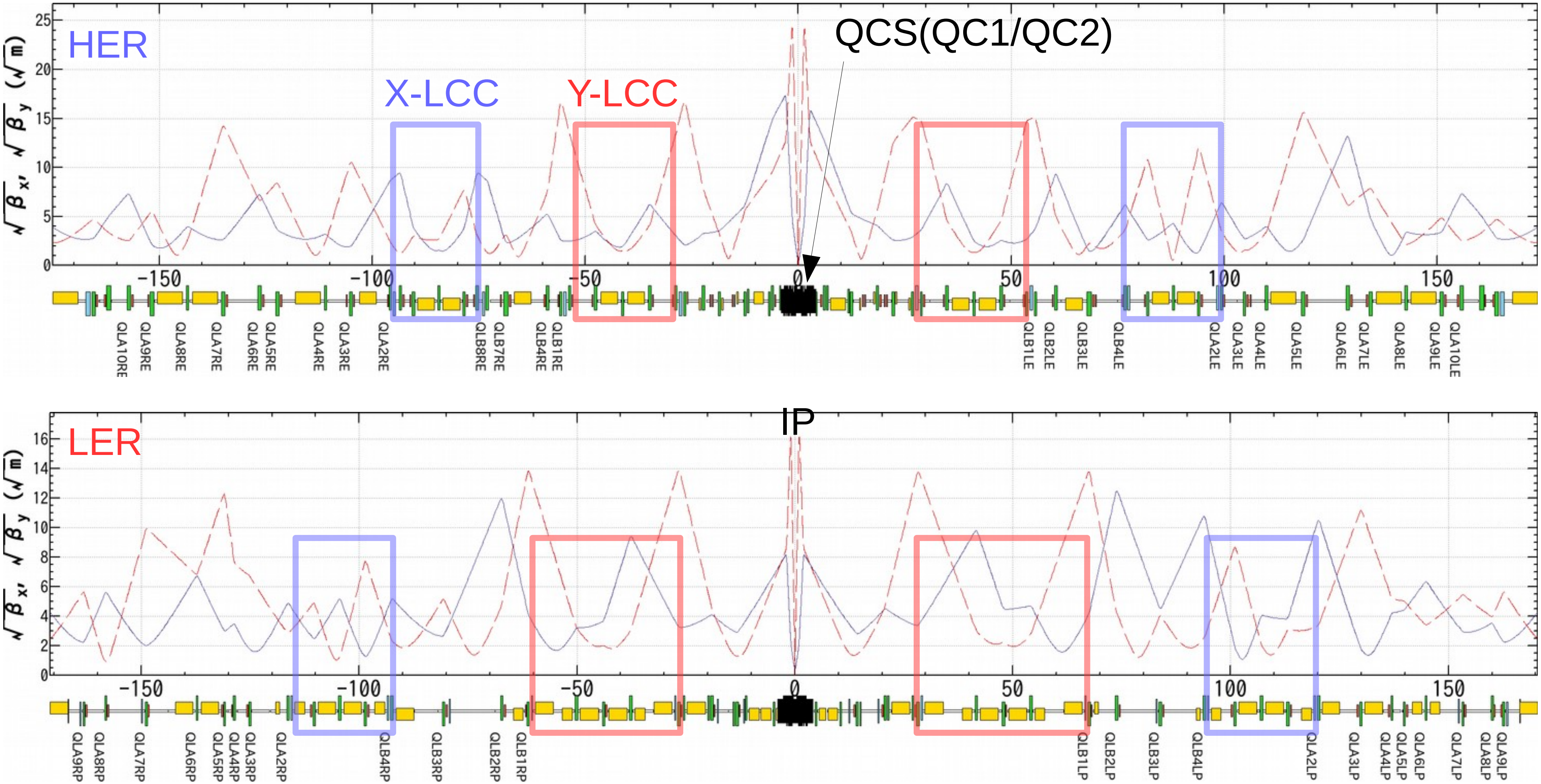
- β_y^* squeezing & Beam operation
  - β_y^* is squeezed down to 2 mm for both rings. (optics correction)
  - We have achieved collision operation with β_y^*= 3mm and luminosity is not limited by hourglass effect at this β_y^*.
- Optics correction
  - Global correction works fine, however, new XY-coupling error is found in LER arc section.
  - Large R2* error, which is a source of luminosity loss, is found by knob scan.
    - It is corrected by using QCS skew quadrupole, because it is too large to adjust by IP coupling/dispersion tuning knob.
    - HAVE TO identify error source and feedback to optics modeling.

Optics Issue for Phase-3

- Improve optics measurement accuracy in order to reach ultra low emittance operation for phase-3.
    - Large orbit displacement by either large single kick or large frequency shift makes beam loss at beam collimator.
    - Orbit response measurement by using high storage beam current for good BPM S/N has risk to destroy vacuum component.
- Introduce individual quadrupole corrector in arc cell for global beta correction.
    - Resolve offset accumulation of individual correctors.
    - Introduce individual -I cell correction.(How to prevent miscorrection?)
- Improve tuning knob software framework for daily tuning & study.
    - – Complete preliminary tuning knob software developed in phase-2 commissioning.
    - – Test & deploy synchronus magnet setting.
- Evaluate side effect of e-cloud countermeasure magnetic devices.

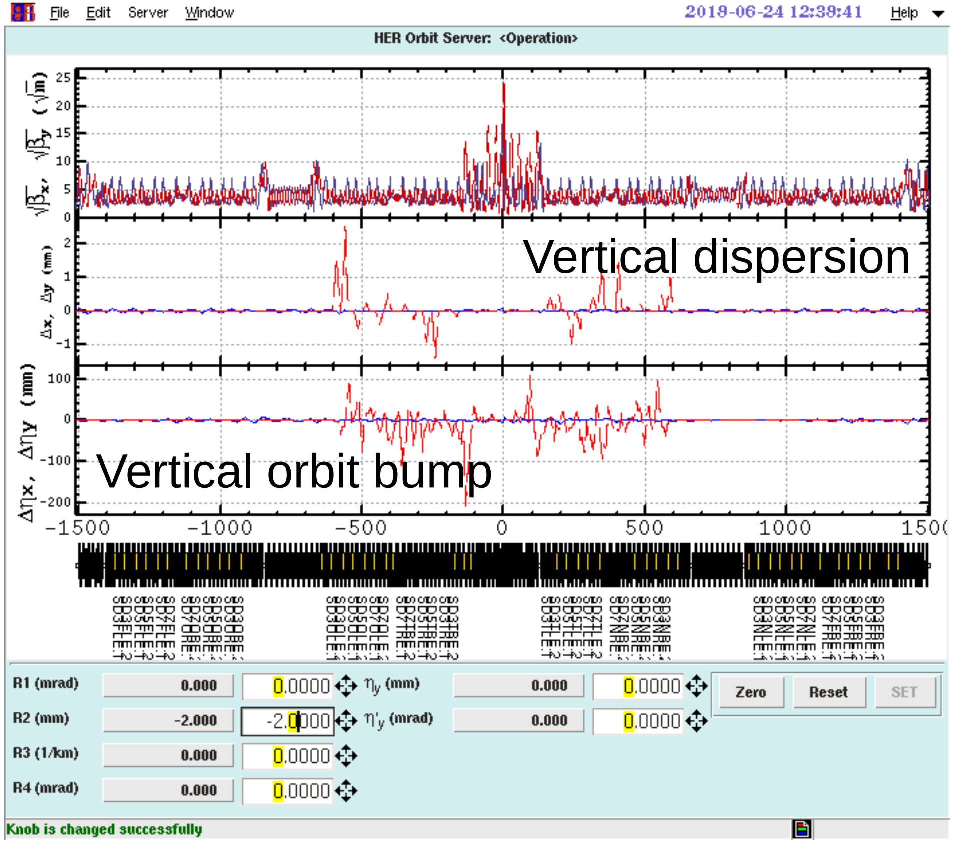
Backup Slides

Phase 2.1.7 IR Optics

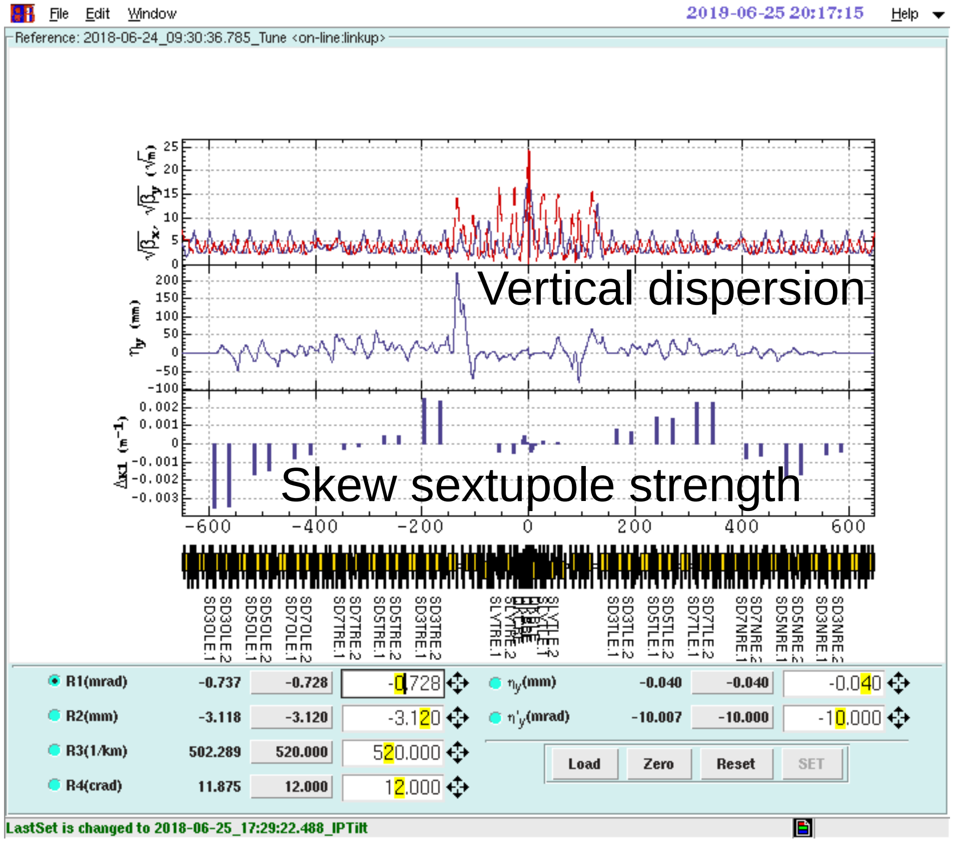


HER IP Coupling/Dispersion Knob

by sextupole vertical bump

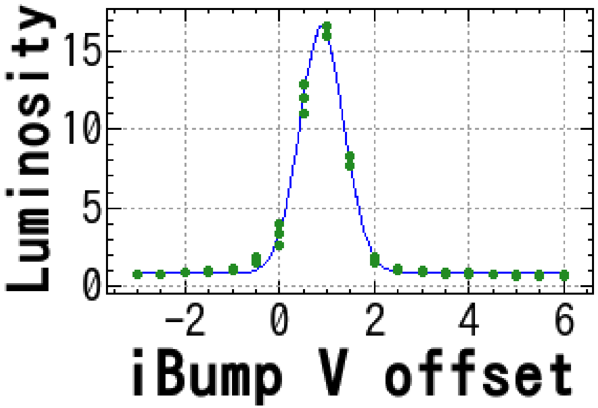


by skew quadrupole



Smallest Beam-Beam Scan Size

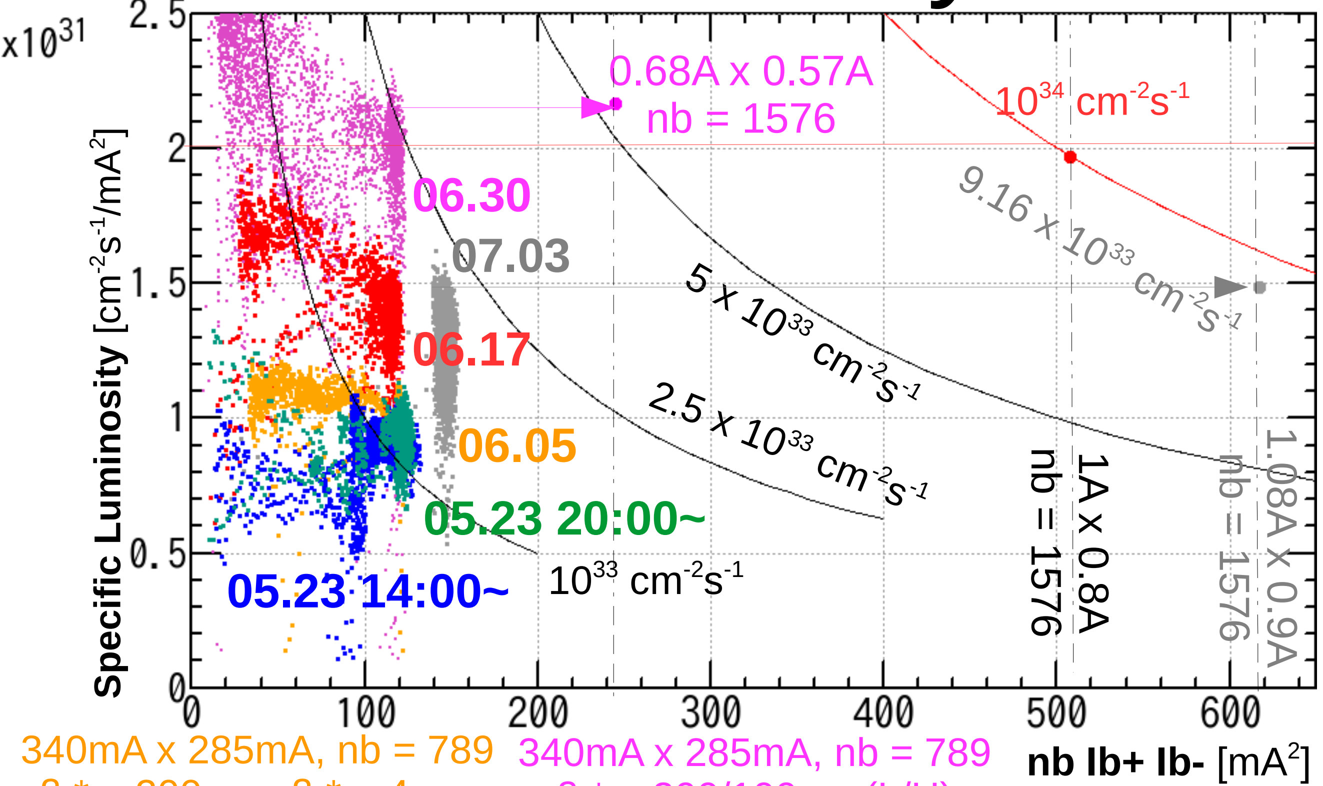
Phase 2.1.7: βx* = 200/100mm(LER/HER), βy* = 3mm, I = 15/15mA(LER/HER), nb = 1576
measured at 2018.06.29 22:40 JST



$\sigma_y^*{}_{scan}$ = 0.333 μm

Luminosity Fit	RePlot	ReFit
Lum offset		0.827
Luminosity		15.811
σ_y [μm]		0.333

Luminosity Performance



340mA x 285mA, nb = 789
β_x* = 200mm, β_y* = 4mm

340mA x 285mA, nb = 789
β_x* = 200mm, β_y* = 6mm

310mA x 252mA, nb = 600
β_x* = 200mm, β_y* = 6mm

340mA x 285mA, nb = 789
β_x* = 200/100mm(L/H)
β_y* = 3mm

340mA x 285mA, nb = 789
β_x* = 200/100mm(L/H)
β_y* = 4mm

270mA x 225mA, nb = 394
β_x* = 200/100mm(L/H)
β_y* = 3mm

Specific luminosity increases by squeezing βy* after R2* tuning.

06.30 22:00 ~ 07.01 10:00
340mA x 285mA, nb = 789
L_{peak} = 2.6578 x 10^{33} $cm^{-2}s^{-1}$
L_{sp} = 2.2 x 10^{31} $cm^{-2}s^{-1}/mA^2$

nb x 2

679mA x 569mA, nb = 1576
L_{peak} = 5.31 x 10^{33} $cm^{-2}s^{-1}$

07.03 19:05 ~ 24:00
270mA x 225mA, nb = 394
L_{peak} = 2.2906 x 10^{33} $cm^{-2}s^{-1}$
L_{sp} = 1.4 x 10^{31} $cm^{-2}s^{-1}/mA^2$

nb x 4

1080mA x 900mA, nb = 1576
L_{peak} = 9.16 x 10^{33} $cm^{-2}s^{-1}$