# Luminosity performance for Crab waist operation in SuperKEKB

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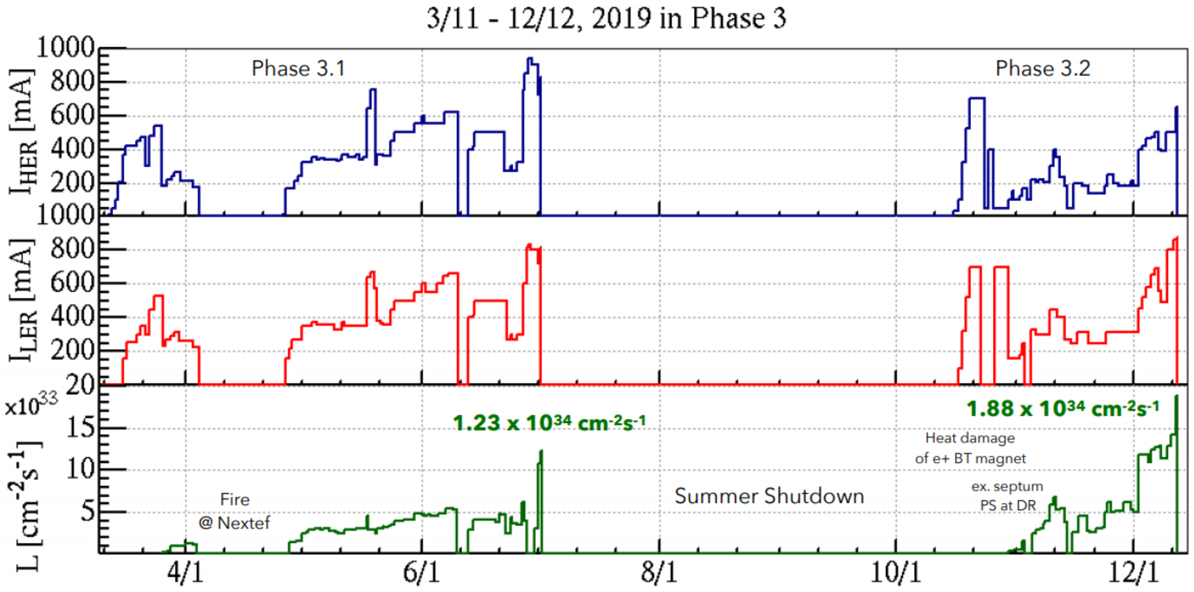
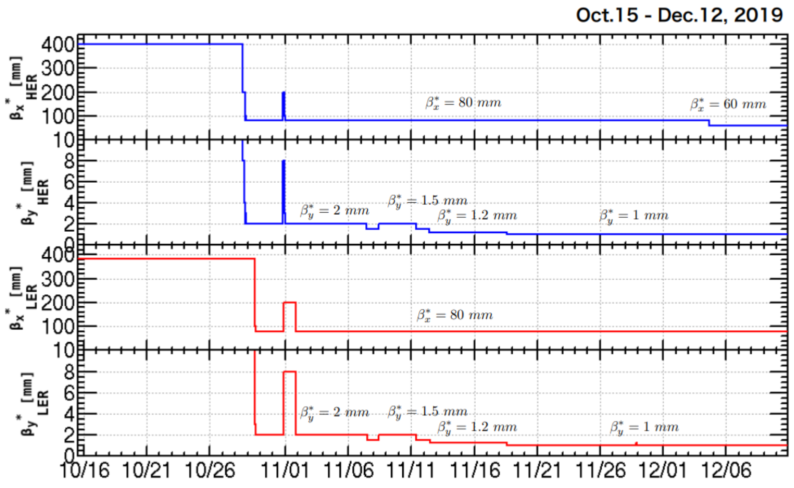
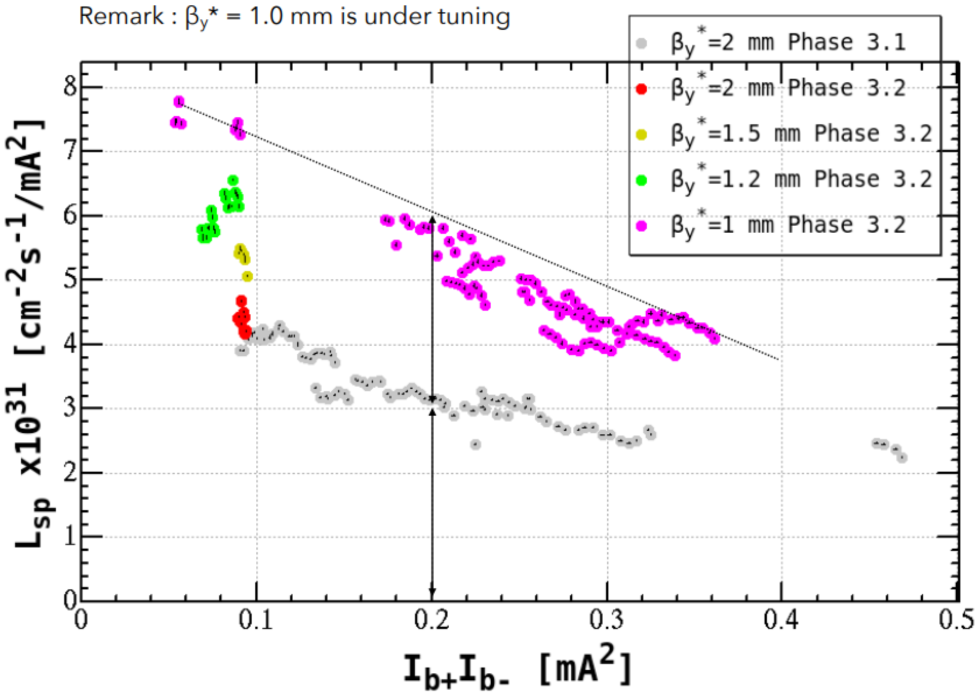
MAC2020

# SuperKEKB in 2019

Slide by Y. Ohnishi




$\beta_y^*$ is squeezed to 1mm in 2019.
Specific luminosity is lower than expected value (~9x$10^{31}$)at even low current.
The beam-beam parameter is limited at 0.02 (HER is lower, due to LER blowup).

# Try Crab waist in SuperKEKB

- Specific luminosity and beam-beam parameters were limited at lower values than expectation.
- Optics aberrations at IP (ex. Chromatic coupling) seems to degrade the luminosity performance, but the correction was not straightforward.
- $L_{sp} = 40 - 50 \times 10^{30}$ cm$^{-2}$s$^{-1}$mA$^{-2}$, while the geometrical value estimated by beam size measurement is $L_{sp} = 90 \times 10^{30}$.

- Then we decide to try the crab waist.
- Crab waist can be realized in both of LER and HER by detuning of SLY (non-interleaved local chromaticity correction) strength.
- We expect improvement of luminosity using the crab waist.

$$L_{sp} = \frac{1}{2\pi \Sigma_x \Sigma_y e^2 f_0}$$ $\Sigma_y = 0.2\mu$m, $L_{sp} = 89 \times 10^{30}$ cm$^{-2}$s$^{-1}$mA$^{-2}$

# Crab waist component

- $\theta_c$: half crossing angle, 41.5mrad.

$$H^* = \frac{1}{4\theta_c} x^* p_y^{*2} = 6.0 x^* p_y^{*2}$$

- Required crab waist term (80%)

$$H^* = 5 x^* p_y^{*2}$$

- The component can be created by local chromaticity correction sextupoles.

$$H_s = \frac{K_2}{6}\left(x^3 - 3xy^2\right)$$

$T^i$ is transfer matrix for IP to i-th sextupole.

$$x_i(x^*, p_x^*) = T_{11}^i x^* + T_{12}^i p_x^* \qquad y_i(y^*, p_y^*) = T_{33}^i y^* + T_{34}^i p_y^*$$

$$H^* = \frac{1}{4\theta_c} x^* p_y^{*2} = \sum_{i=1}^{N_L} \frac{K_{2,i}}{6}\left(x_i^3 - 3x_i y_i^2\right)$$

Betatron phase difference from IP is required nπ for x, (½+n) π for y to produce $xp_y^2$ term at IP.

# Betatron Phase variation
# Comparison between LER and HER

$\beta_x^*$=80mm, $\beta_y^*$=1mm

LER

| | AX | BX | NX | AY | BY | NY |
|---|---|---|---|---|---|---|
| SLYL1 | -0.57066 | 5.66431 | 0.47977 | 32.53525 | 524.96 | 0.75059 |
| SLYL2 | -0.75034 | 5.66431 | 0.97977 | -33.0733 | 524.96 | 1.25059 |
| SLXL1 | 12.54136 | 94.01306 | 1.1518 | -1.90277 | 11.46071 | 1.85521 |
| SLXL2 | -9.22825 | 94.01306 | 1.6518 | 0.71045 | 11.46071 | 2.35521 |
| | | | | | | |
| SLXR1 | 8.47988 | 65.82581 | -1.77001 | -3.644 | 19.2571 | -2.35147 |
| SLXR2 | -9.32224 | 65.82581 | -1.27001 | 3.75568 | 19.2571 | -1.85147 |
| SLYR1 | 0.65861 | 5.516 | -0.97574 | 38.76399 | 521.2173 | -1.24865 |
| SLYR2 | 0.66937 | 5.516 | -0.47574 | -39.2803 | 521.2173 | -0.74865 |
| IP | 0 | 0.08 | 44.53 | 0 | 0.001 | 46.5912 |

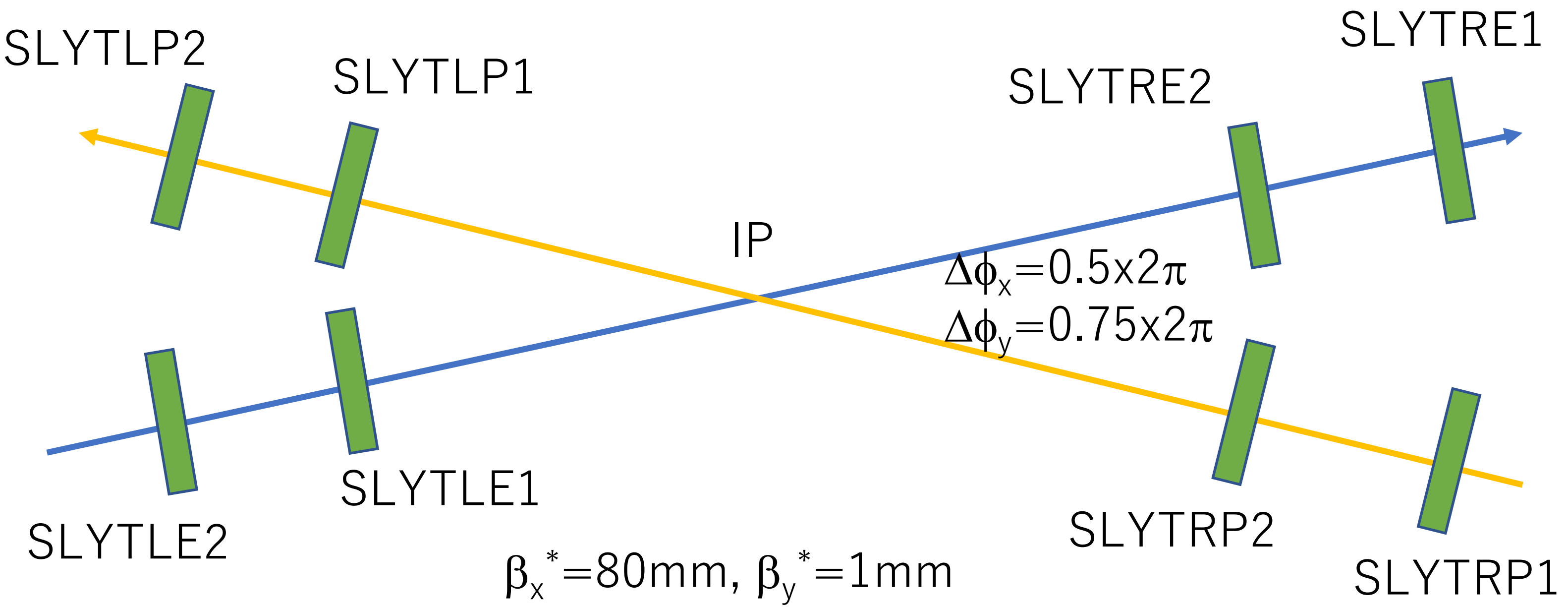
$\beta_x^*$=60mm, $\beta_y^*$=1mm

HER

| AX | BX | NX | AY | BY | NY |
|---|---|---|---|---|---|
| -0.60132 | 6.50764 | 0.46799 | 8.26539 | 675.0993 | 0.74989 |
| -0.96485 | 6.50764 | 0.96799 | -8.2618 | 675.0993 | 1.24989 |
| 7.86044 | 51.47830 | 1.28484 | -4.20090 | 16.84147 | 1.88390 |
| -7.86044 | 51.47830 | 1.78484 | 6.30734 | 16.84147 | 2.38390 |
| | | | | | |
| -5.29293 | 135.30740 | -1.74499 | 0.34348 | 1.13724 | -2.49426 |
| 5.24070 | 135.30740 | -1.24331 | 0.40252 | 1.13724 | -1.99426 |
| -0.01475 | 3.79083 | -0.98869 | 79.7672- | 701.63 | -1.25022 |
| 0.67384 | 3.79083 | -0.48869 | -79.767 | 701.63 | -0.75022 |
| -0.00011 | 0.06 | 45.53302 | -0.00209 | 0.001 | 43.57037 |

Crab waist (FCCee type, K. Oide et al., PRAB) can be tried using the local chromaticity correction sextuples in both of LER and HER, though the phase variation is not perfect especially in x.

# Magnet configuration




$\beta_x^*$=80mm, $\beta_y^*$=1mm

| | $K_2(m^{-2})$ | | $K_2(m^{-2})$ |
|---|---|---|---|
| SLYTLE.1 | 9.5213 | SLYTLP.1 | 1.4349 |
| SLYTLE.2 | 8.0697 | SLYTLP.2 | 3.7171 |

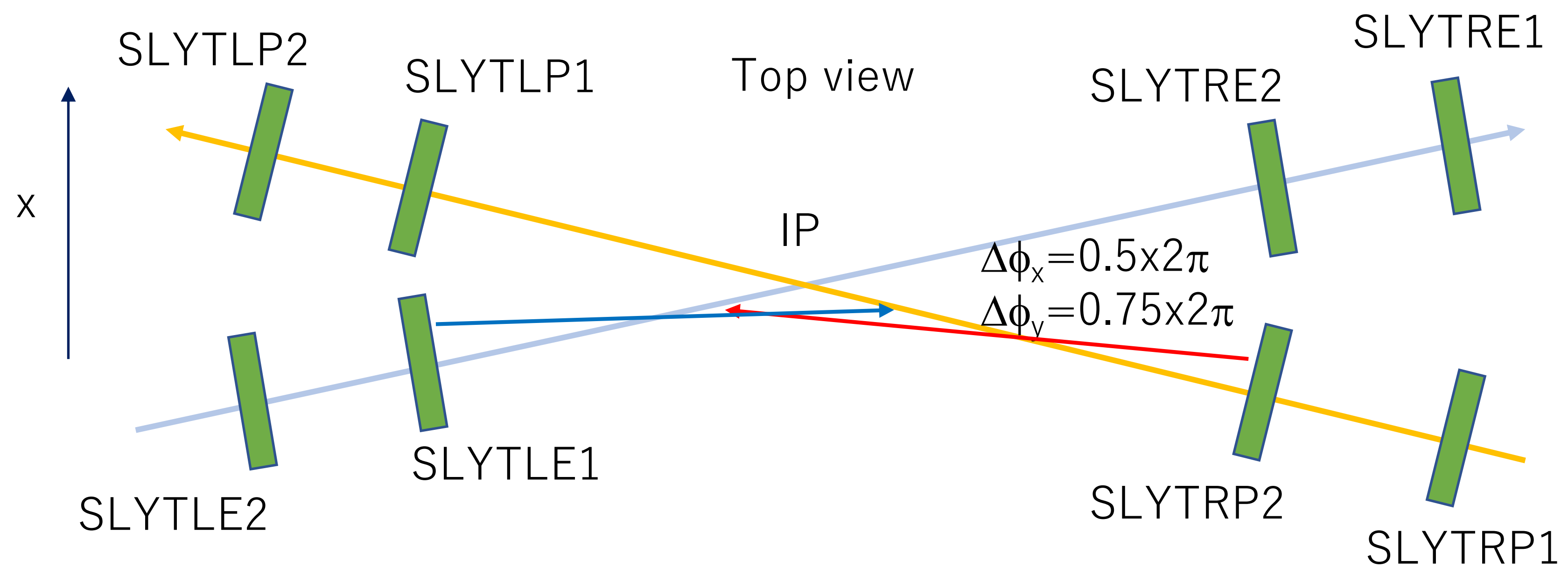
| | $K_2(m^{-2})$ | | $K_2(m^{-2})$ |
|---|---|---|---|
| SLYTRE.1 | -7.9251 | SLYTRP.1 | 0.9978 |
| SLYTRE.2 | -9.7211 | SLYTRP.2 | 3.3356 |

Design $\beta$

| | $K_2(m^{-2})$ | | $K_2(m^{-2})$ |
|---|---|---|---|
| SLYTLE.1 | 9.1304 | SLYTLP.1 | 1.341 |
| SLYTLE.2 | 7.6788 | SLYTLP.2 | 3.6239 |

| | $K_2(m^{-2})$ | | $K_2(m^{-2})$ |
|---|---|---|---|
| SLYTRE.1 | -8.1626 | SLYTRP.1 | 1.1294 |
| SLYTRE.2 | -9.9586 | SLYTRP.2 | 3.4679 |

# Polarity Check for the final hardware arrangement




- LER beam travels right to left.
  - For X>0, Sextupole SLYTRP2 with larger K2(>0), focus/defocus in x/y direction.
  - Phase of X changes 180 degree.
  - Y waist shifts away from IP.
- HER beam travels left to right
  - The same condition as LER.

# $3^{rd}$ order terms at IP in LER Crab waist

$\beta^*$=1mm

- Left

| | $K_2(m^{-2})$ | $xp_y^2$ | $p_xp_y^2$ | $xy^2$ | $p_xy^2$ | $xyp_y$ | $p_xyp_y$ |
|---|---|---|---|---|---|---|---|
| SLYTLP.1 | 1.4349 | 3.1435 | -0.0321 | 43.8484 | -0.4484 | -23.4807 | 0.2401 |
| SLYTLP.2 | 3.7171 | -8.1435 | 0.0833 | -113.594 | 1.1616 | 60.8292 | -0.622 |
| SLXTLP.1 | 0.6621 | -0.0469 | -0.0053 | -28368.2 | -3199.25 | 72.9414 | 8.226 |
| SLXTLP.2 | 0.6621 | 0.0469 | 0.0053 | 28368.17 | 3199.251 | -72.9414 | -8.226 |
| Sum | | -5 | 0.0512 | -69.7455 | 0.7132 | 37.3485 | -0.3819 |

- Right

| | $K_2(m^{-2})$ | $xp_y^2$ | $p_xp_y^2$ | $xy^2$ | $p_xy^2$ | $xyp_y$ | $p_xyp_y$ |
|---|---|---|---|---|---|---|---|
| SLXTRP.1 | 0.297 | -0.0066 | -0.0042 | -3644.36 | -2306.72 | -9.8402 | -6.2284 |
| SLXTRP.2 | 0.297 | 0.0066 | 0.0042 | 3644.363 | 2306.719 | 9.8402 | 6.2284 |
| SLYTRP.1 | 0.9978 | -2.134 | -0.0262 | -153.026 | -1.8809 | 36.1417 | 0.4442 |
| SLYTRP.2 | 3.3356 | 7.134 | 0.0877 | 511.5711 | 6.288 | -120.823 | -1.4851 |
| Sum | | 5 | 0.0615 | 358.5452 | 4.4071 | -84.6811 | -1.0409 |

- Uninvited parasitic terms appears due to imperfection of betatron phase, but their contributions are small (10% in normalized coordinates, $P_xP_y^2$.

# $3^{rd}$ order terms at IP in HER Crab waist

$\beta^*=(80,1)$mm

- Left

| | $K_2(m^{-2})$ | $xp_y^2$ | $p_xp_y^2$ | $xy^2$ | $p_xy^2$ | $xyp_y$ | $p_xyp_y$ |
|---|---|---|---|---|---|---|---|
| SLYTLE.1 | 9.5213 | 32.7962 | -0.4012 | 15.9549 | -0.1952 | 45.7498 | -0.5597 |
| SLYTLE.2 | 8.0697 | -27.7962 | 0.34 | -13.5225 | 0.1654 | -38.775 | 0.4744 |
| SLXTLE.1 | 2.8507 | 0.0568 | -0.0163 | 76893.09 | -22145.7 | -132.138 | 38.0567 |
| SLXTLE.2 | 2.8507 | -0.0568 | 0.0163 | -76893.1 | 22145.72 | 132.1384 | -38.0567 |
| sum | | 5 | -0.0612 | 2.4328 | -0.0292 | 6.9748 | -0.0853 |

- Right

| | $K_2(m^{-2})$ | $xp_y^2$ | $p_xp_y^2$ | $xy^2$ | $p_xy^2$ | $xyp_y$ | $p_xyp_y$ |
|---|---|---|---|---|---|---|---|
| SLXTRE.1 | -3.4726 | -3.86E-6 | 7.33E-6 | -2957.06 | 5610.141 | -0.2138 | 0.4056 |
| SLXTRE.2 | -3.4726 | 3.86E-6 | -7.33E-6 | 2957.06 | -5610.14 | 0.2138 | -0.4056 |
| SLYTRE.1 | -7.9251 | 22.0628 | 0.0942 | 10.74 | 0.0459 | -30.7866 | -0.1315 |
| SLYTRE.2 | -9.7211 | -27.0628 | -0.1156 | -13.174 | -0.0563 | 37.7637 | 0.1613 |
| Sum | | -5 | -0.0214 | -2.4341 | -0.0104 | 6.9771 | 0.0298 |

- Uninvited parasitic terms appears, but their contributions are small (10% in normalized coordinates, $P_xP_y^2$.

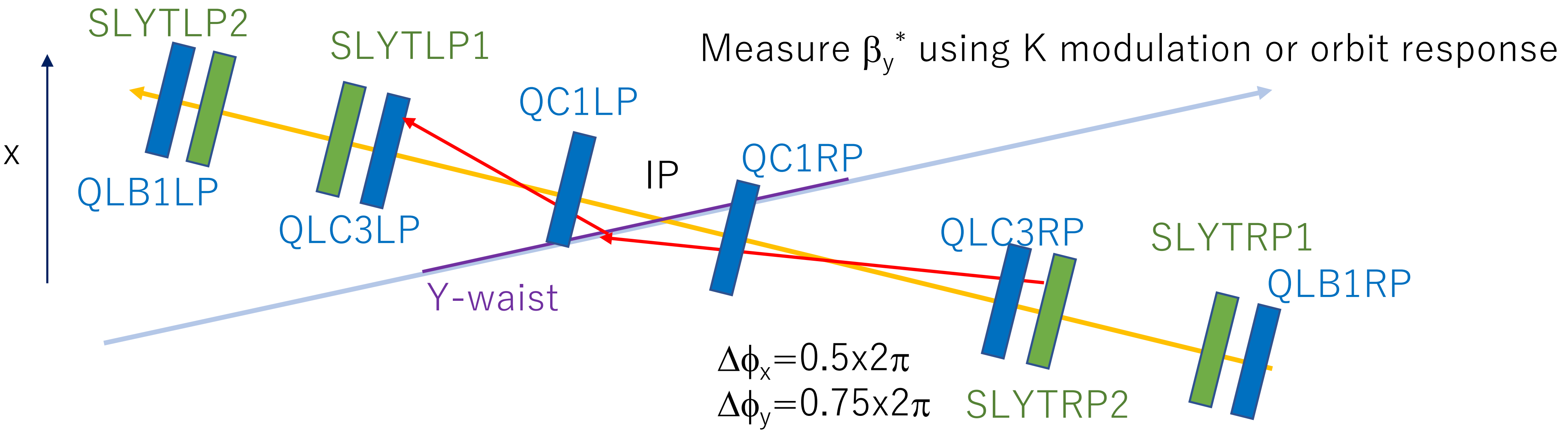
# Measurement of Crabbing waist

- Apply x orbit at SLYTLP1 and SLYTRP2.
- Measure vertical beta at QC1 using K modulation.
- Measure vertical beta using orbit response.
- Check IP waist shift.

$$\delta x_{SLY} = 1mm \ @\beta_{x,SLY} = 5.66m$$

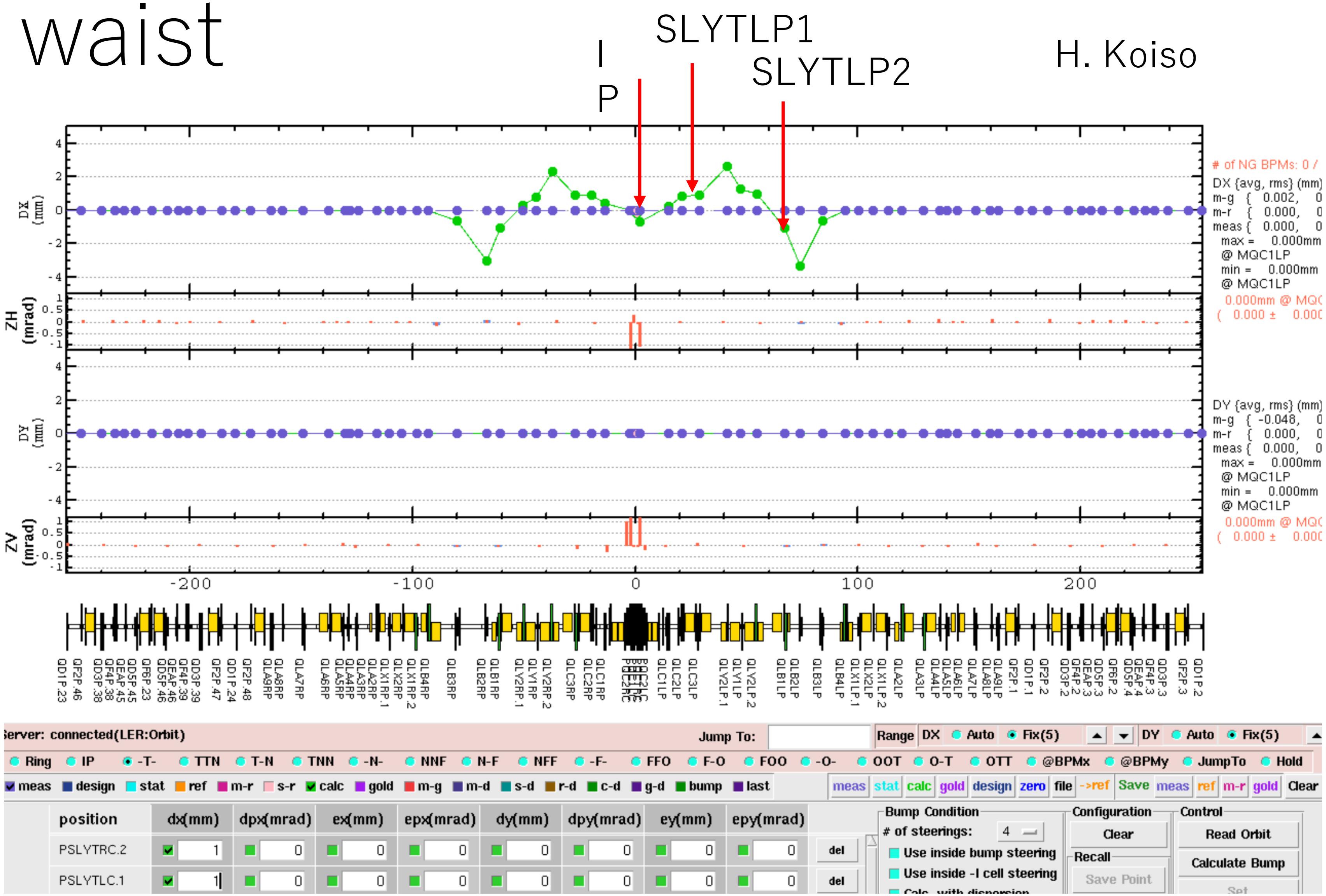
$$\delta x^* = 0.12mm \ @\beta_x^* = 0.08m$$

$$\delta s = \frac{\delta x^*}{2\theta_c} = 1.4mm$$



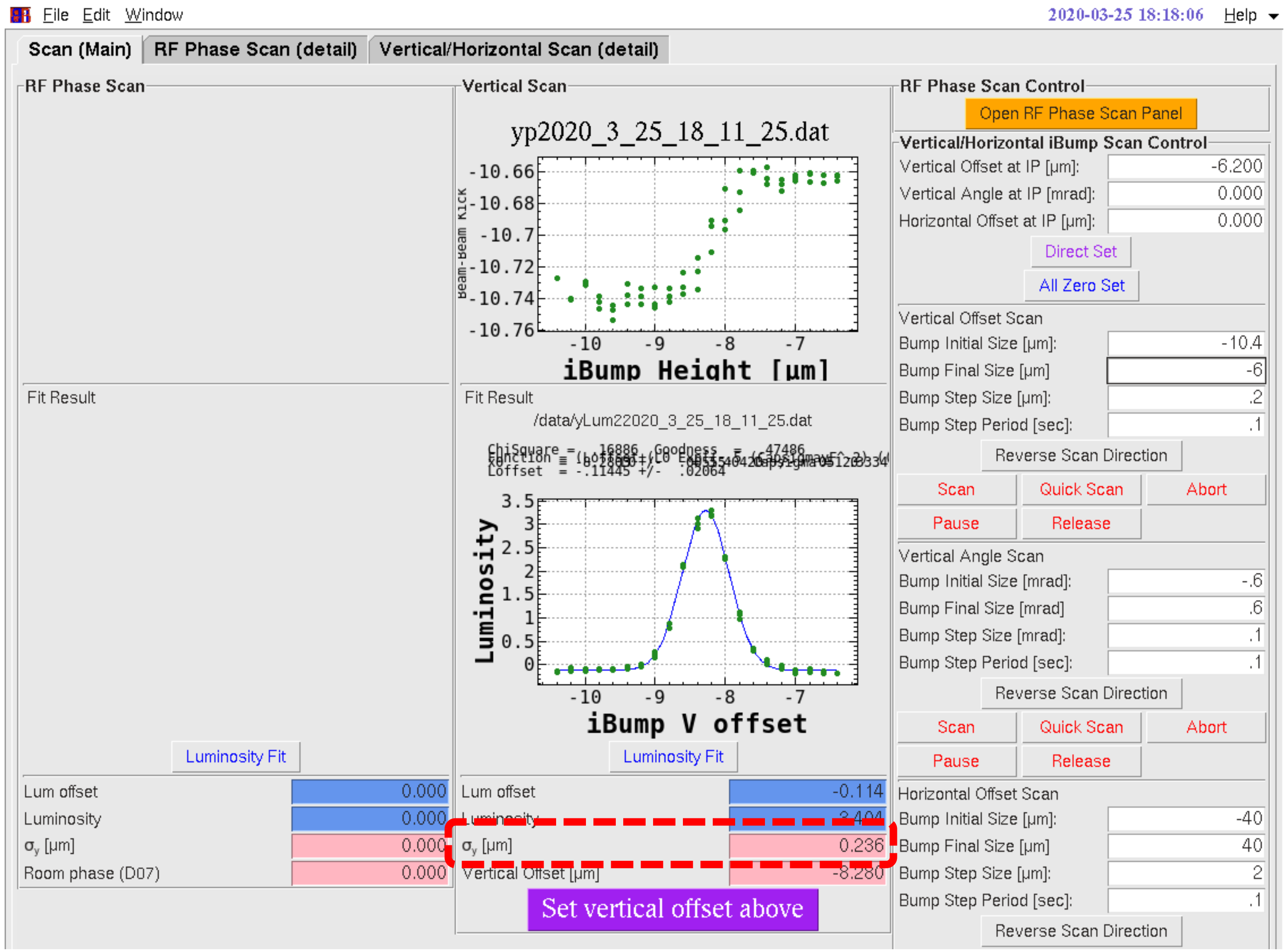
# Closed bump to create crabbing waist

H. Koiso

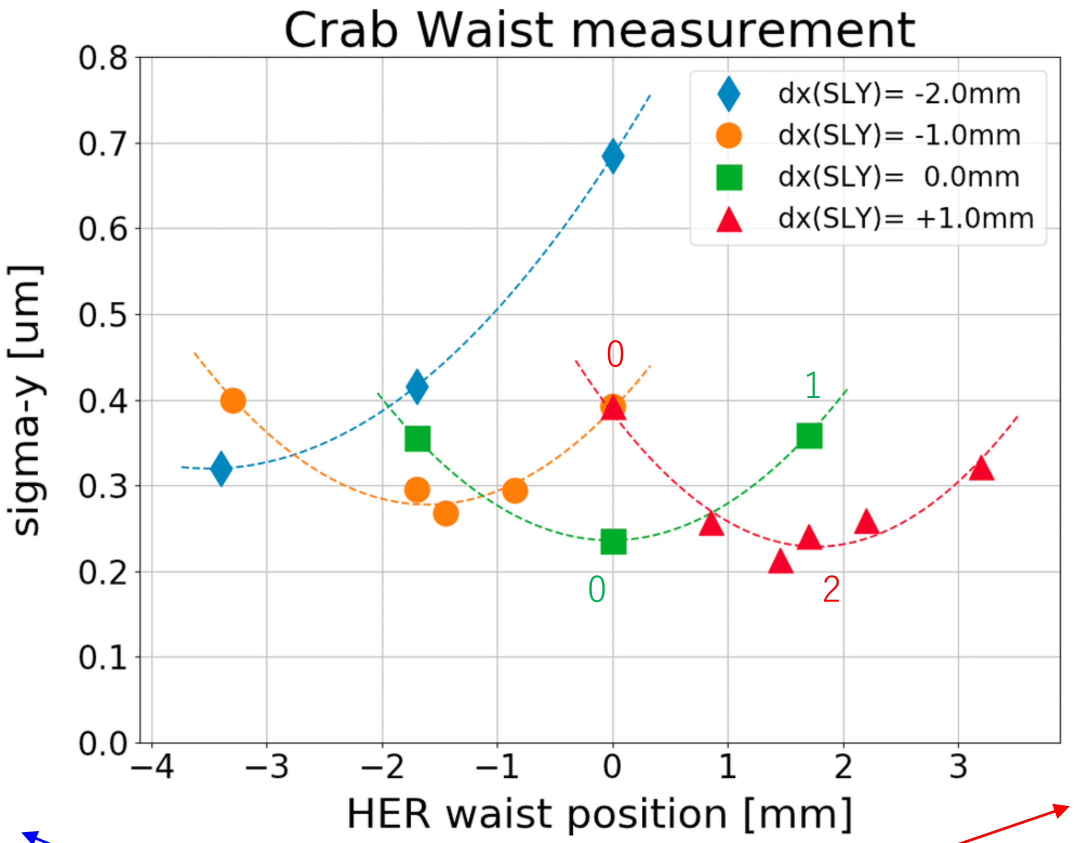


# V-offset scan

- Σy measured by V-offset scan.



# Crab Waist measurement

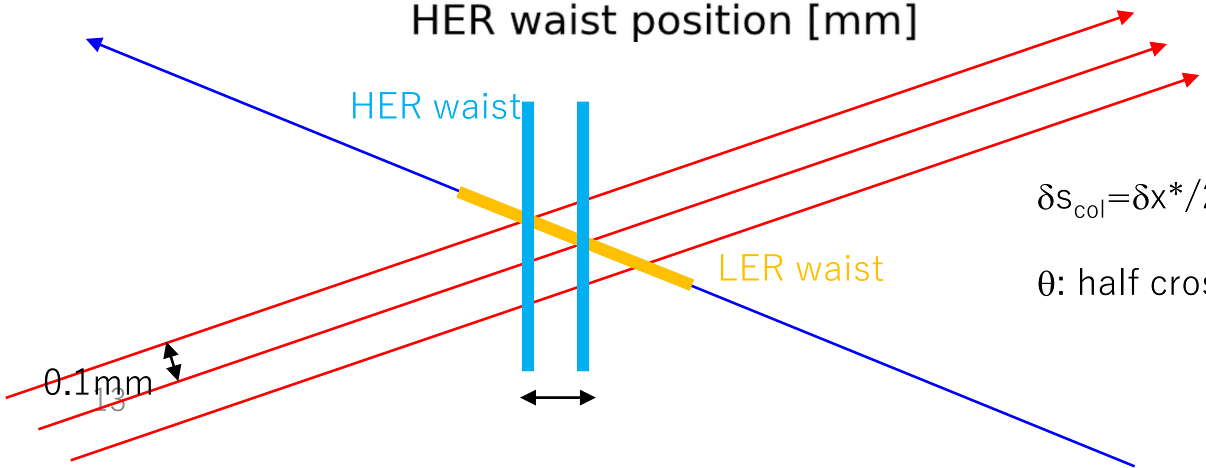



For different LER IP orbit offset dx(SLY), HER waist position changed and Σy/sqrt(2) measured.

LER crab waist
HER no crab waist

Waist scan changing HER waist, then search LER waist

- LER waist changes for LER IP orbit: crab waist




$\delta s_{col}=\delta x^*/2\theta=1.45$mm

$\theta$: half crossing angle

# K modulation

- QC1 s=L*=900mm, waist shift δs=1mm.

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \qquad \Delta\nu = \frac{\Delta K_1 \beta}{4\pi}$$

$$\beta(s+\delta s) - \beta(s-\delta s) = \frac{d\beta(s)}{ds} 2\delta s = \frac{4s\delta s}{\beta^*}$$

$$\frac{\beta(s+\delta s) - \beta(s-\delta s)}{\beta(s)} \cong \frac{4\delta s}{s} \qquad \frac{\beta(s+\delta s) - \beta(s)}{\beta(s)} \cong \frac{2\delta s}{s}$$

$$\beta_y(s = 900mm) = 745m \qquad \beta(s+\delta s) - \beta(s-\delta s) = 3.6\text{m}$$

$$\delta\Delta\nu = \frac{\Delta K_1 \delta\beta}{4\pi} \qquad \frac{\delta\Delta\nu}{\Delta\nu} = \frac{\delta\beta}{\beta} \qquad \frac{\Delta K_1}{K_1} = 2 \times 10^{-4}$$

$\Delta\nu = 0.01$ $\delta\Delta\nu = 0.5 \times 10^{-4}$ too small to be measured.

- It seems to be difficult to measure crab waist using K modulation.
- Beam-beam scan is only possible way now.

# Vertical orbit error in SLY

- Vertical orbit in SLYTLP/E induces R1* at IP

$$H^* = \frac{1}{4\theta_c} x^* p_y^{*2} \approx \sum_{i=1}^{N_L} \frac{K_{2,i}}{6} (x_i^3 - 3x_i y_i^2)$$

$$y_i(y^*, p_y^*) = T_{33}^i y^* + T_{34}^i p_y^* + y_{i,0} \quad y_{i,0} = T_{34}^i p_{y,0}^*$$

$$T_{kl}^{SLY1} = -T_{kl}^{SLY2} \qquad y_{SLY1,0} = -\, y_{SLY2,0}$$

$K_{2,SLY1} \neq K_{2,SLY2}$ crab waist

$$H_R^* = -\sum_{i=1}^{N_L} K_{2,i} y_{i,0} x_i y_i = -\Delta K_{2,SLY} y_{SLY1,0} x_i y_i$$

$$= -\Delta K_{2,SLY} y_{SLY1,0} \sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}} \sqrt{\beta_{y,SLY} \beta_y^*}\, x^* p_y^* = -R_1^* x^* p_y^*$$

$\beta_x$, $\beta_y$=(80,1)mm

$$R_1^* = \Delta K_{2,SLY} \sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}} \sqrt{\beta_{y,SLY} \beta_y^*}\; y_{SLY1,0} = 10.4\, y_{SLY1,0} = 10^{-3} \frac{y_{SLY1,0}}{\sigma_{y,SLY}}$$

$\sigma_{y,SLY} = 72.5\mu m$

# V Orbit at SLY - Fluctuation of R1

## HER

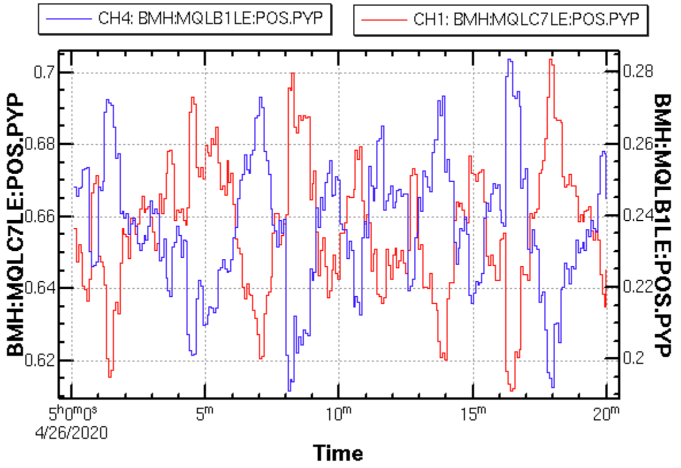
$$\delta R_1^* = \Delta K_{2,SLY}\,\delta y_{SLY1,0}\sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}}\sqrt{\beta_{y,SLY}\beta_y^*}$$

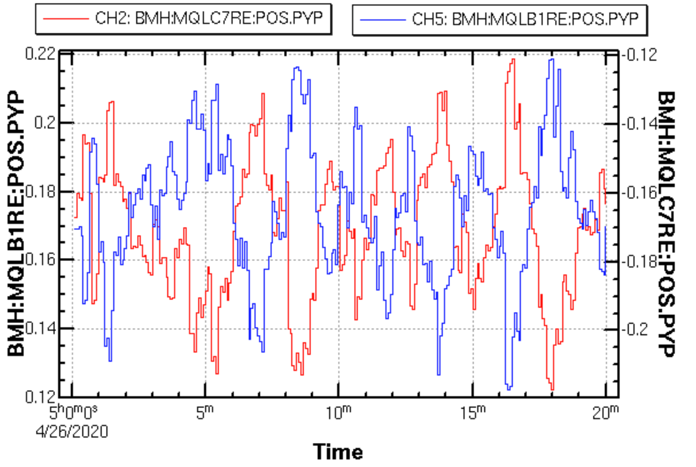
$$\delta y_{SLYE} = 0.08mm$$

CW40%

$$\Delta K_{2,SLYE}\sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}}\sqrt{\beta_{y,SLY}\beta_y^*} = 6$$

$$\delta R_{1,E}^* = 0.5mrad$$




## LER

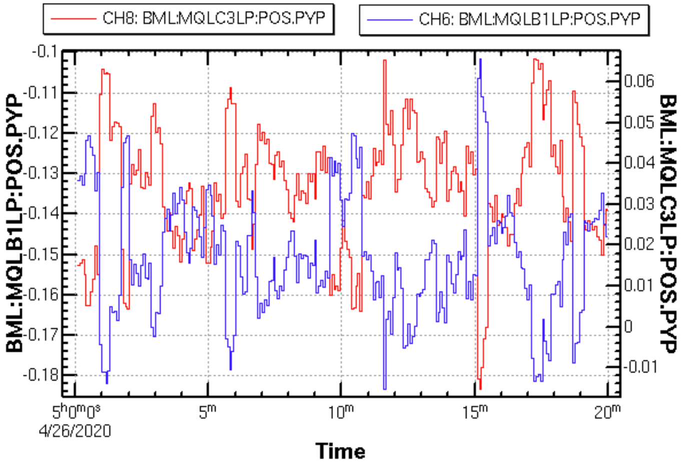
$$\delta y_{SLYP} = 0.09mm$$

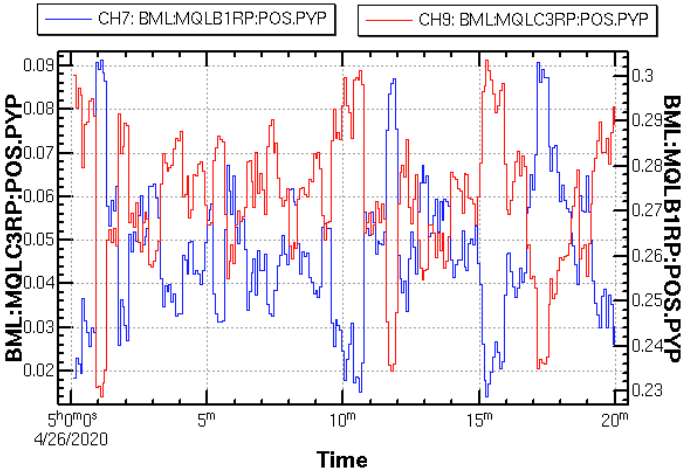
CW60%

$$\Delta K_{2,SLYP}\sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}}\sqrt{\beta_{y,SLY}\beta_y^*} = 10.4$$

$$\delta R_{1,P}^* = 0.9mrad$$

Not large but visible

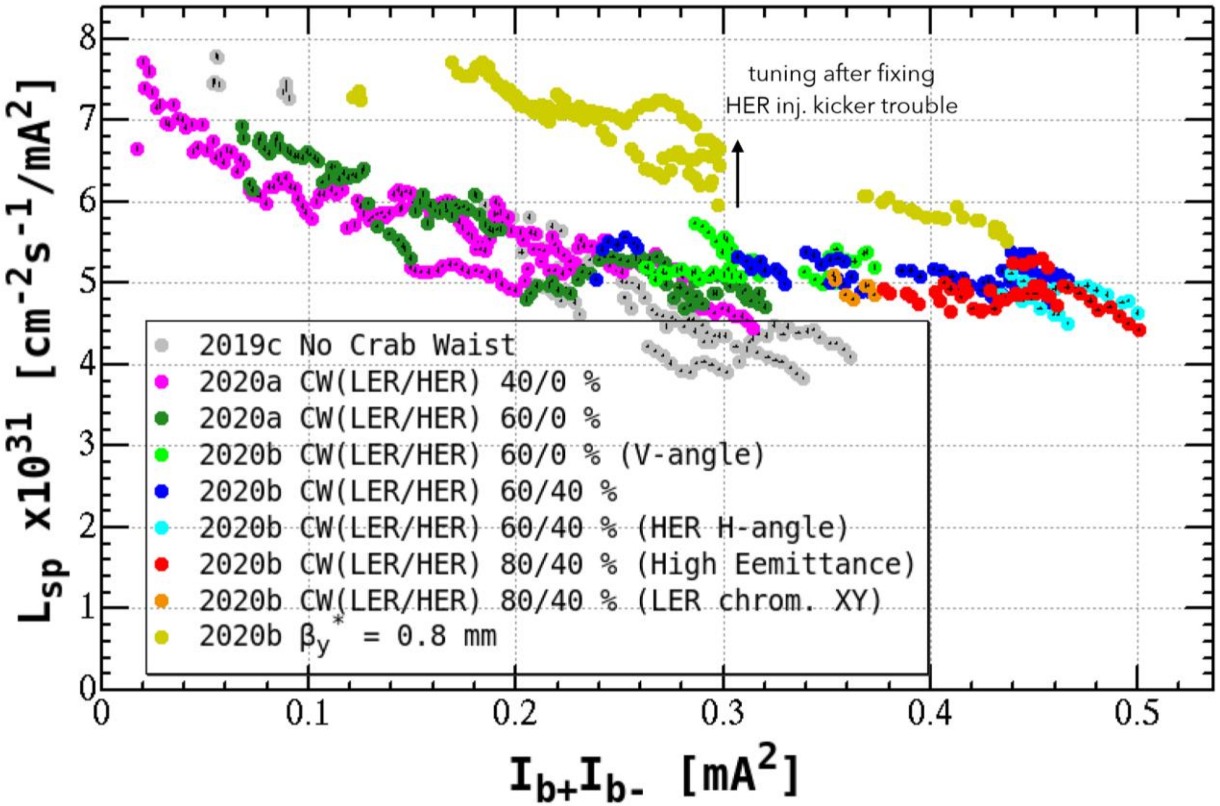


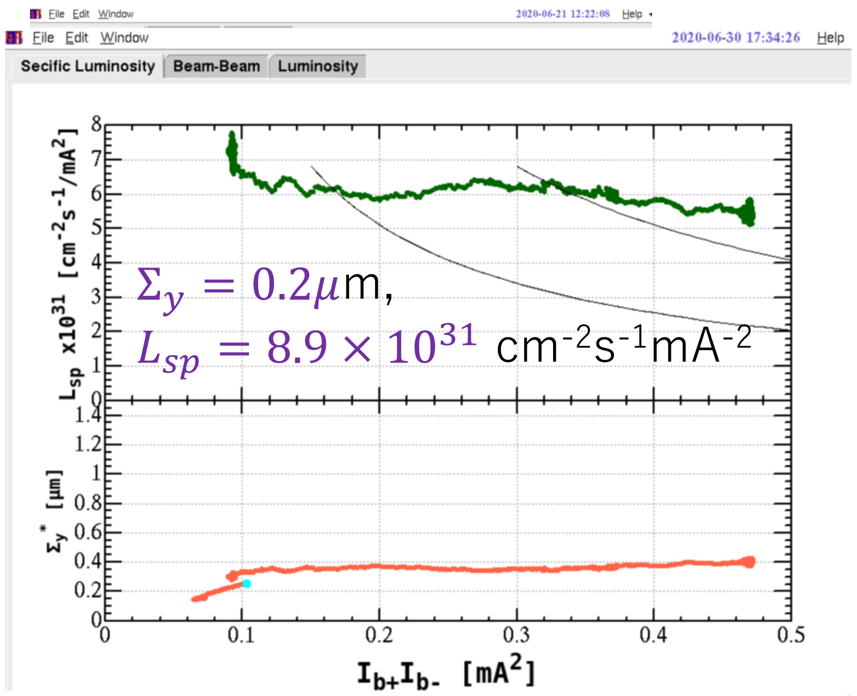
# Luminosity performance in the crab waist operation

- Specific luminosity is almost constant at higher current 0.03mA.
- Convoluted beam size in single beam is $\Sigma_y$=0.2μm ($\beta_y^*$=1mm), the corresponding $L_{sp}$=8.9x10$^{31}$ cm$^{-2}$s$^{-1}$mA$^{-2}$
- Specific luminosity degrade at very low current <0.03mA.

$$L_{sp} = \frac{1}{2\pi\Sigma_x\Sigma_y e^2 f_0}$$




2019

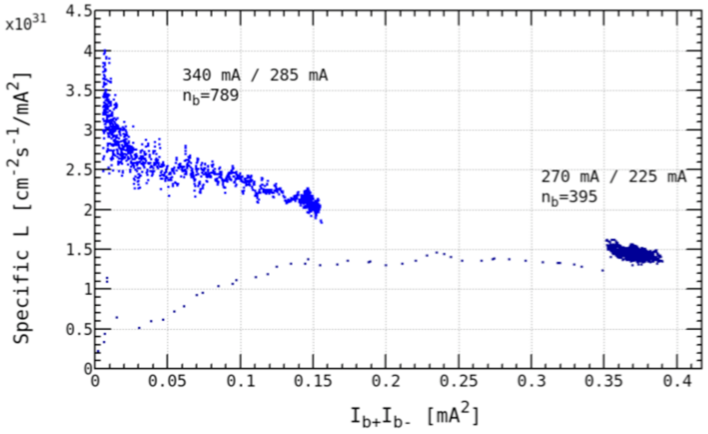


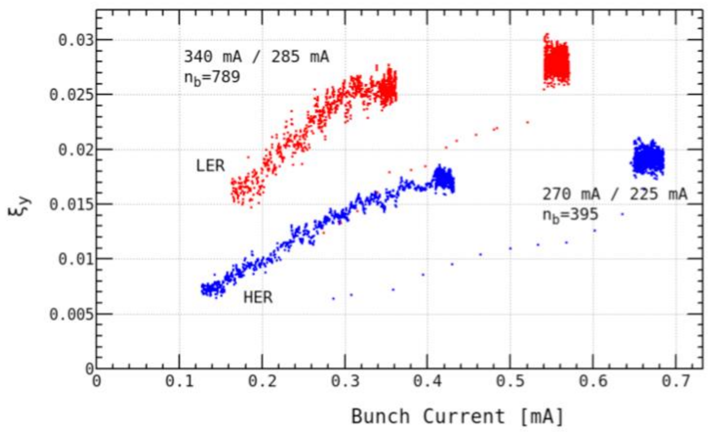
# Status of crab waist operation

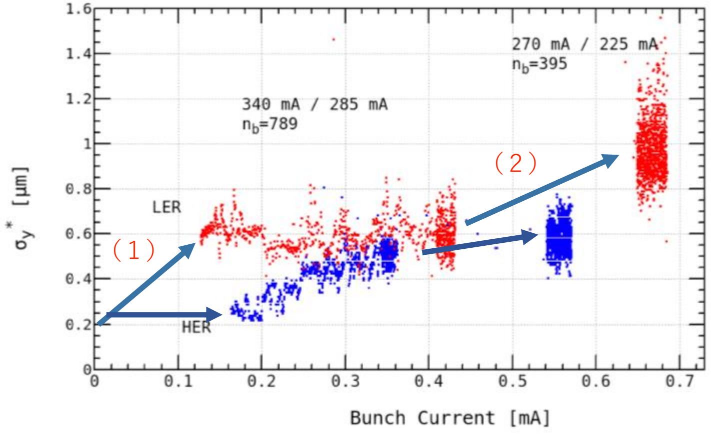
- Crab waist did not improve the luminosity performance drastically.
- Lsp degraded at low bunch current as the same as before.
- There were some improvement on the beam back ground and life time.
- At high bunch current, the gain seems to be clear.

# Beam size blowup at very low bunch current collision observed since the early stage of commissioning

- $\beta_y$=3mm
- Two stage blow-up of LER beam
  1. Very small bunch current, $I_+I_-$=0.01mA$^2$.
  2. High bunch current $I_+$>0.5 mA
- Single stage in HER
  - HER beam $I_-$>0.2mA.



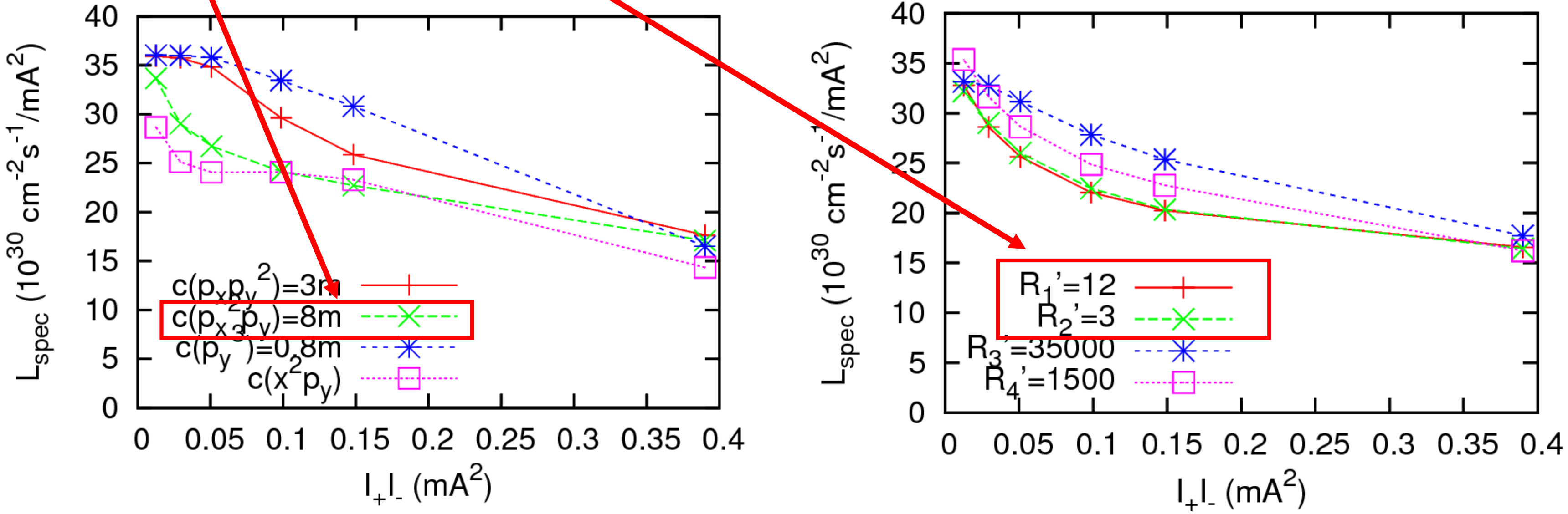
# Possible source of the beam size blow up at low current collision

K. Ohmi, retire seminar at Apr. 2019

- Chromatic, or nonlinear aberrations
- R1'=12rad
- R2'=3m
- $C(p_x^2 p_y)$=8m

100 times larger for the early estimation.

Weak strong simulation with nonlinear IP aberrations



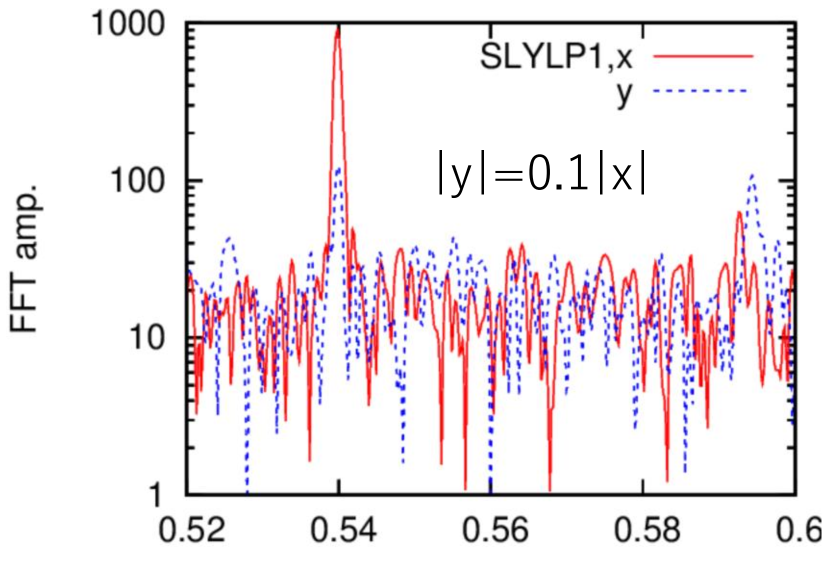

$\beta_y$=3mm

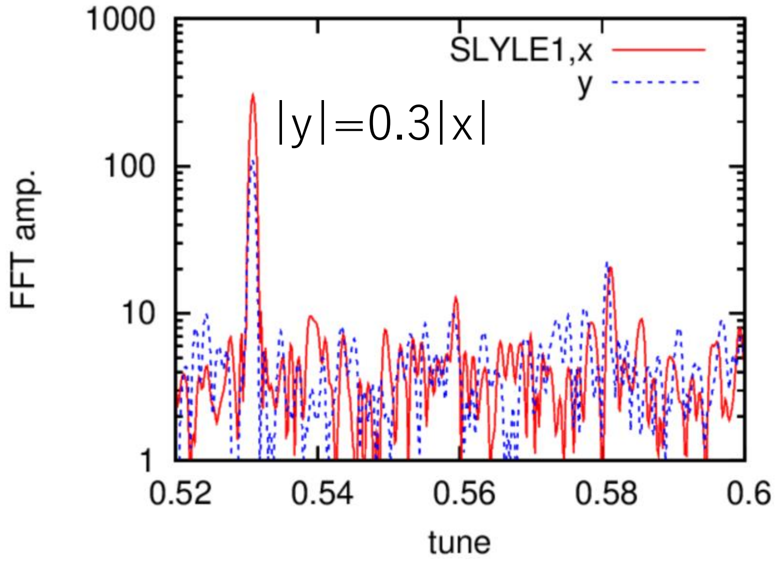
# TbT optics (coupling) measurement at IR

- Search for the optics aberrations which degrades the luminosity performance.

- Excite x mode using injection kicker.
- Measure y oscillation with $\nu_x$.
  - R1: y motion with in-phase of x motion.
  - R2: y motion with $\pi/2$ deviation of x motion.
  - Strong vertical signal (30% of x) was seen in some BPM's.

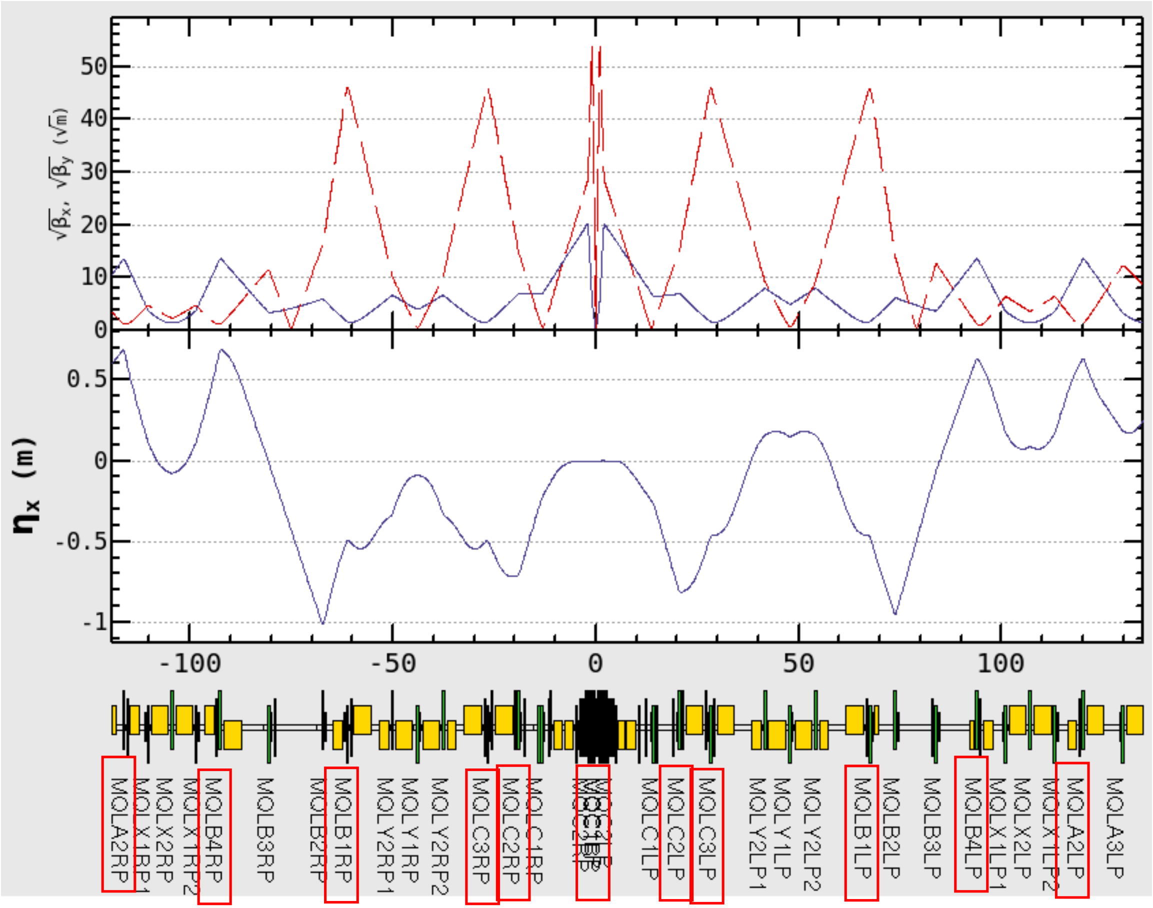
- IP coupling is interpolated from QC1L-R monitors



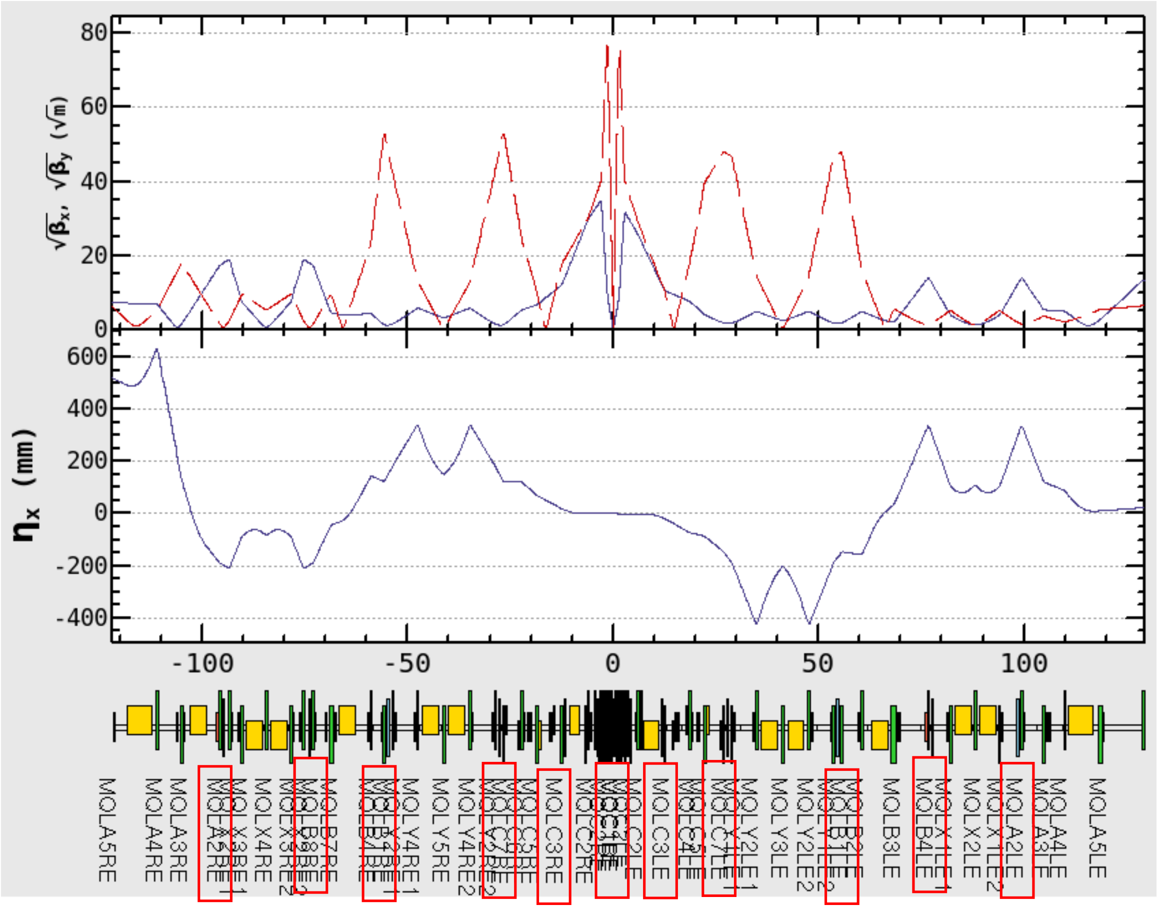



# IR optics and BPM's

LER



HER



COD, TbT

# x-y coupling TbT measurement

- y motion in X mode.

$$\boldsymbol{x} = RB\boldsymbol{X}$$

$$B = \begin{pmatrix} B_X & 0 \\ 0 & B_Y \end{pmatrix}$$

$$R = \begin{pmatrix} r_0 & 0 & r_4 & -r_2 \\ 0 & r_0 & -r_3 & r_1 \\ -r_1 & -r_2 & r_0 & 0 \\ -r_3 & -r_4 & 0 & r_0 \end{pmatrix}$$

$$B_X = \begin{pmatrix} \sqrt{\beta_X} & 0 \\ -\alpha_X/\sqrt{\beta_X} & 1/\sqrt{\beta_X} \end{pmatrix}$$

$$y = -r_1 x - r_2 p_x = -r_1 a \cos\phi(s) + r_2 \left[\frac{a}{\beta}\sin\phi(s) + \frac{\alpha}{\beta} a \cos\phi(s)\right]$$

$$= c\cos(2\pi n\nu_x + \phi_y)$$

$$\phi(s) = 2\pi n\nu_x + \phi_x$$

$$\frac{c}{a}\cos(\phi_y - \phi_x) = \left(-r_1 + r_2\frac{\alpha}{\beta}\right)$$

$$\frac{c}{a}\sin(\phi_y - \phi_x) = -\frac{r_2}{\beta}$$

$\frac{c}{a} = \frac{|Y|}{|X|}$ in the figure

$$p_y = -r_3 x - r_4 p_x = -r_3 a \cos\phi(s) + r_4 \left[\frac{a}{\beta}\sin\phi(s) + \frac{\alpha}{\beta} a \cos\phi(s)\right]$$

$$= d\cos(2\pi n\nu_x + \phi_q)$$

$$\beta = \beta_x$$

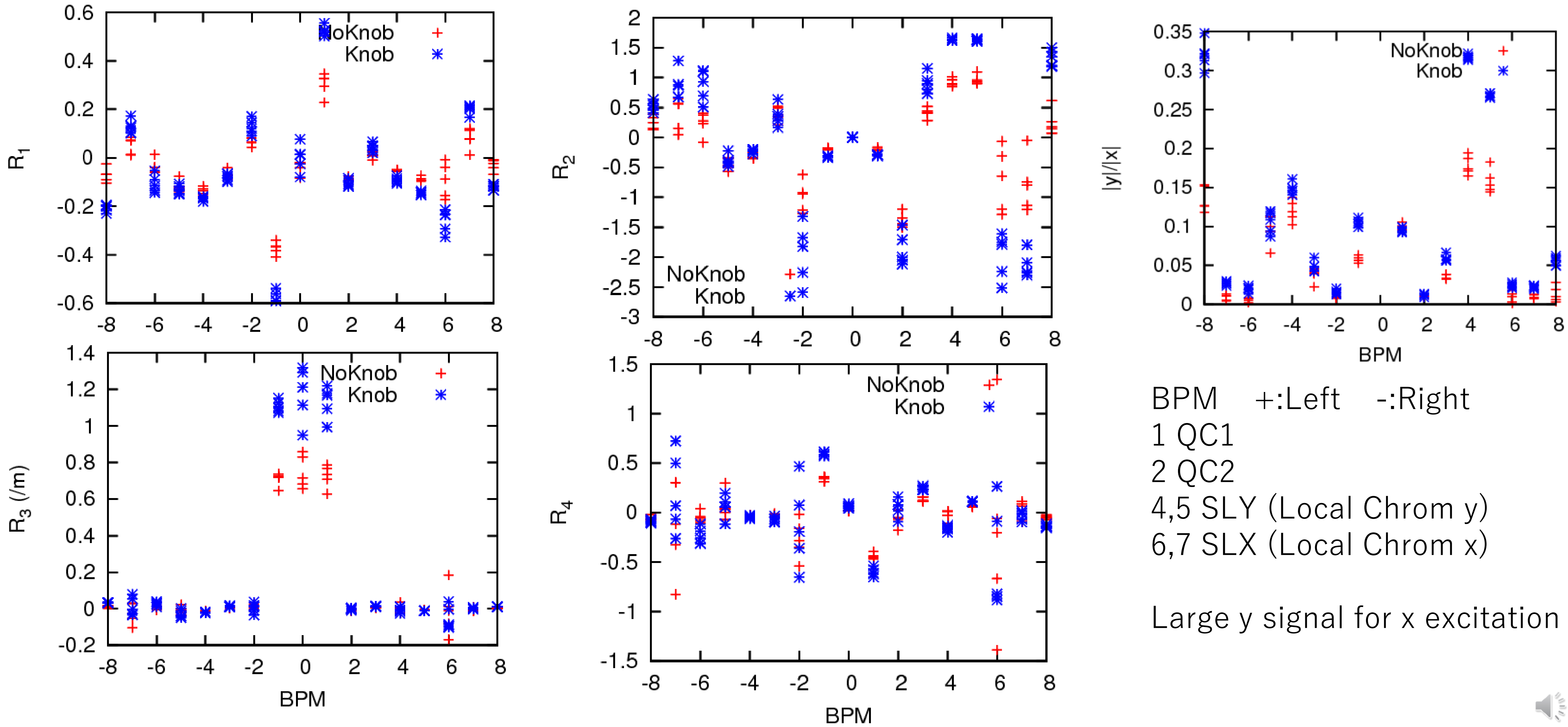
$$\alpha = \alpha_x$$

$$\frac{d}{a}\cos(\phi_q - \phi_x) = \left(-r_3 + r_4\frac{\alpha}{\beta}\right)$$

$$\frac{d}{a}\sin(\phi_q - \phi_x) = -\frac{r_4}{\beta}$$

# LER, Mar. 9, 2020

- Very large x-y coupling exists in IR.

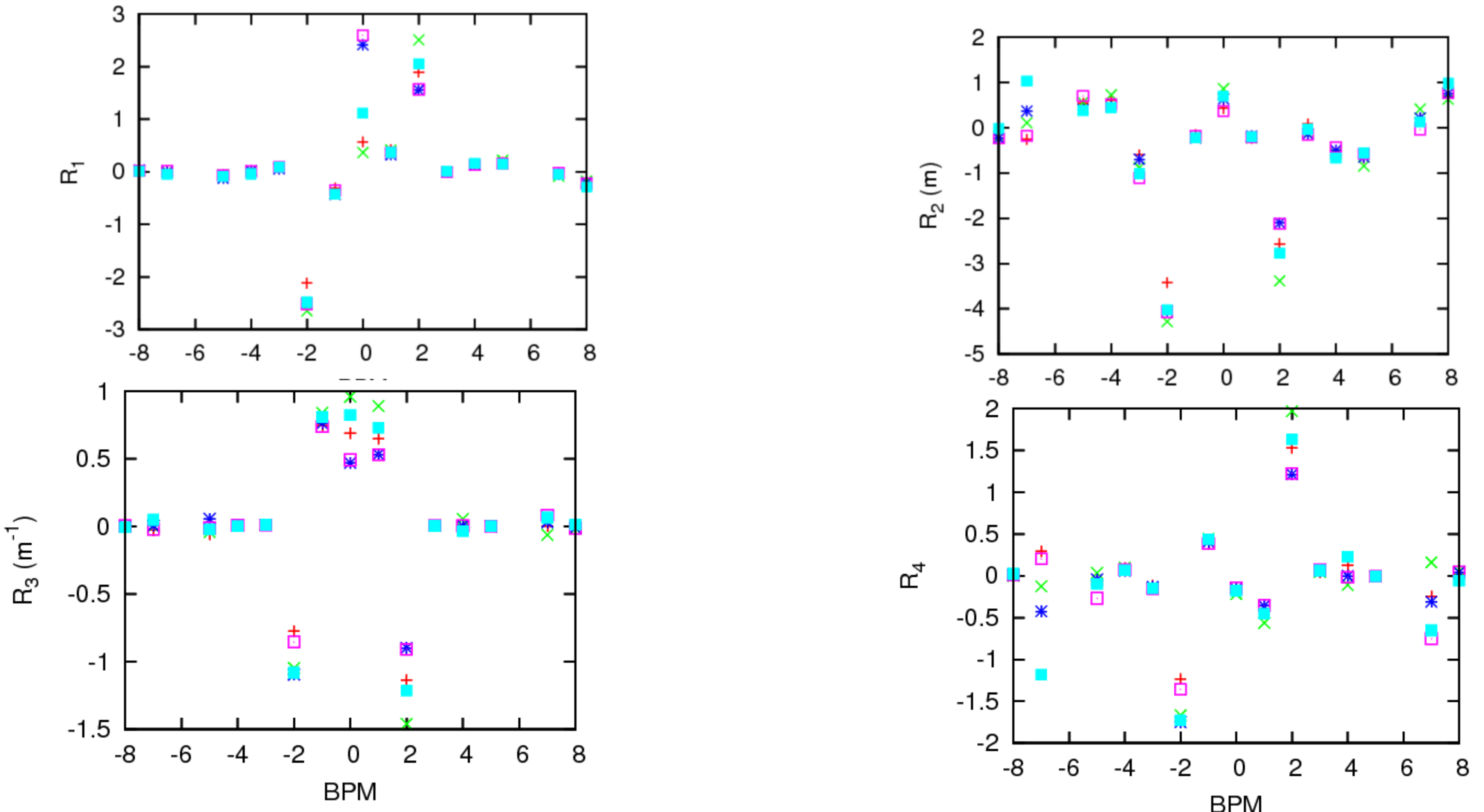



BPM +:Left -:Right
1 QC1
2 QC2
4,5 SLY (Local Chrom y)
6,7 SLX (Local Chrom x)

Large y signal for x excitation

# HER, Mar. 5, 2020

- Very large x-y coupling exists in IR.



# Beam-beam simulations considering the IR coupling at SLY

- Crab waist is realized by detuning of chromatic correction sextupole.
- X-y coupling at SLY may affect the crab waist.

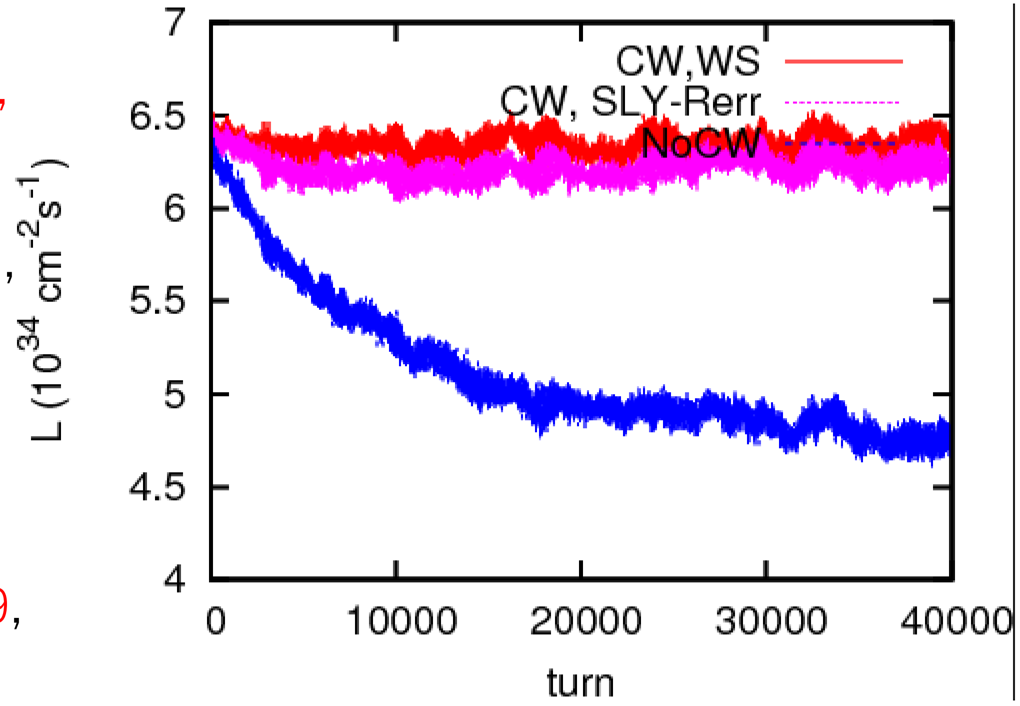
- Beam-beam simulation considering SLY coupling

- Chromatic coupling at IP induced in IR area is not considered.

# Weak-strong Simulation for the crab waist using detuned SLY w/o SLY coupling

- 1567 bunches, 0.9x1.1A, $\beta$=80, 1mm.
- Detuned SLY's.

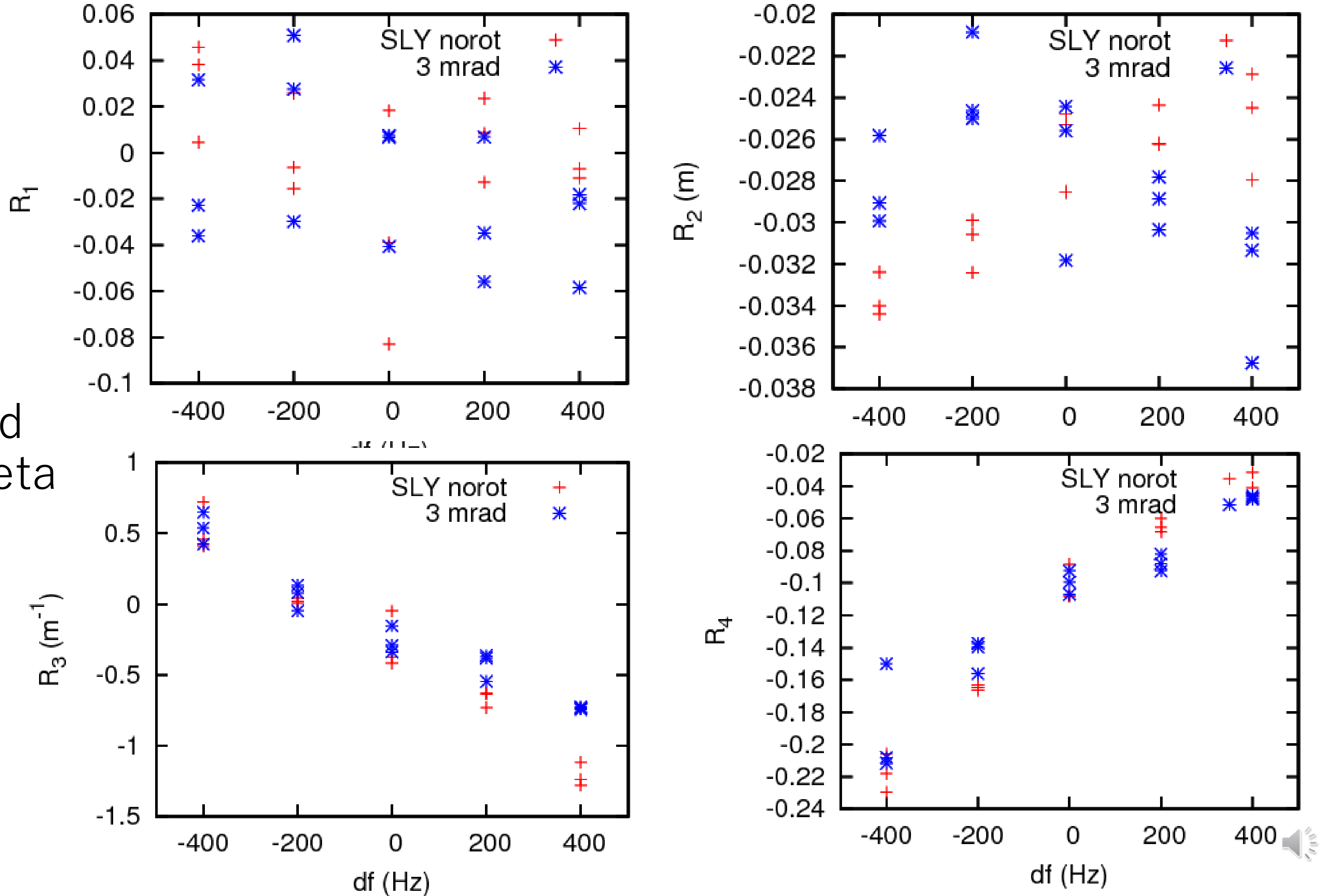
SLYR1 K2=0.9978
twiss= 0.65861, 5.51600,-0.97574, 38.76399, 521.21731,-1.24865,
R=0.0133, 0.0766, 0.0138, -0.219
SLYR2 K2=3.3356
twiss= 0.66937, 5.51600,-0.47574, -39.28025, 521.21731,-0.74865,
R= 0.0261, -0.123, 0.0051, -0.00087
SLYL1 K2=1.4349
twiss= -0.57066, 5.66431, 0.47977, 32.53525, 524.96002, 0.75059,
R=0.052, -0.698, 0.003, -0.0967
SLYL2 K2=3.7171
twiss= -0.75034, 5.66431, 0.97977, -33.07327, 524.96002, 1.25059,
R= 0.075, -0.822, 0.0059, -0.0665




Effect (on momentum) of linear coupling at SLY is negligible in the crab waist collision. Parasitic terms also does not affect.

# Chromatic coupling at IP in LER

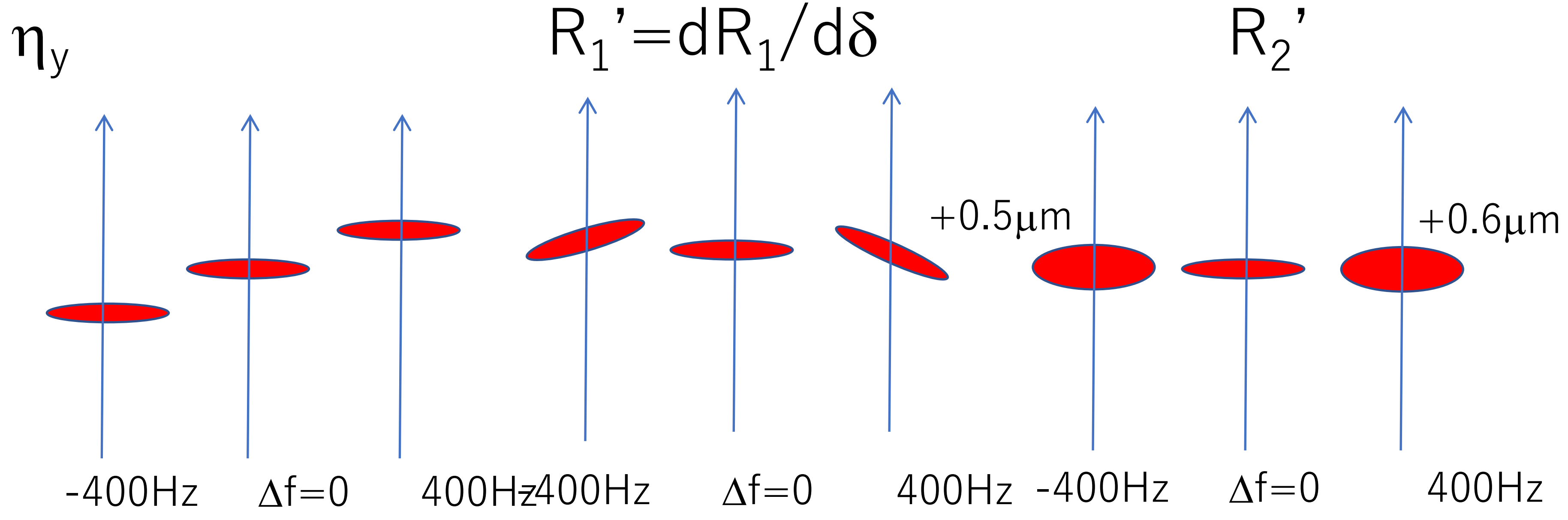
- SLY is rotated small angle as a test.
- Optics measurement W/O SLY rotation
- $R_1$ and $R_2$ are hard to measure, while $R_3$ and $R_4$ are easy, due to beta squeezing.



# Measurement of chromatic coupling for $R_1$ and $R_2$

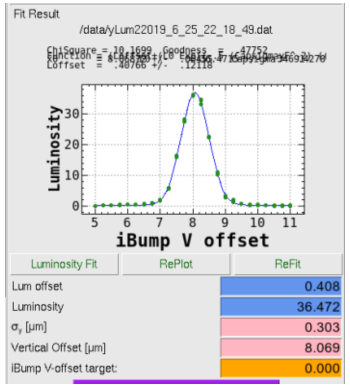
- If a chromatic beam size variation are seen, it can be source of luminosity degradation

$\Delta f = 400\text{Hz} \rightarrow \delta = 0.17\%$

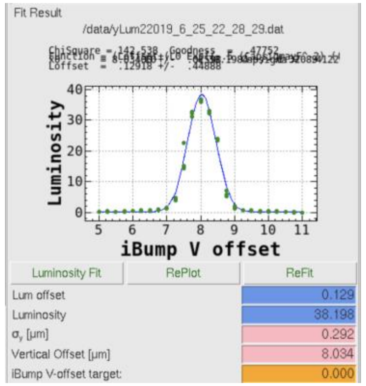



- Measure the beam size using beam-beam scan (Luminosity.)

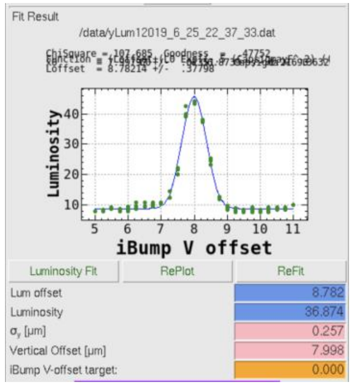
# Vertical offset scan with different RF frequency



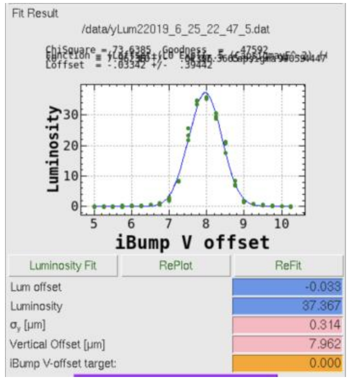

Δf = +400Hz



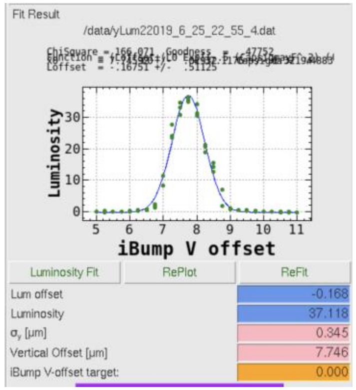

Δf = +200Hz




Δf = ±0Hz




Δf = -200Hz




Δf = -400Hz
beam loss at the scan

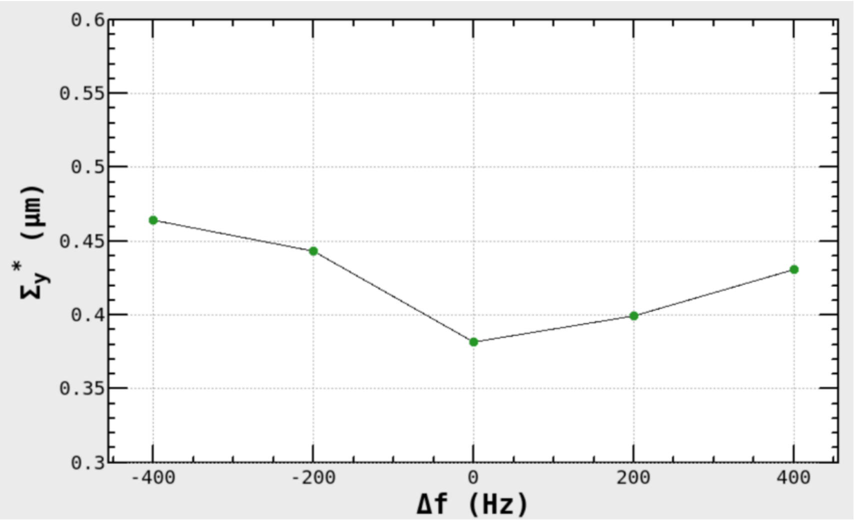
Y. Funakoshi
One cycle injection by Kaji.

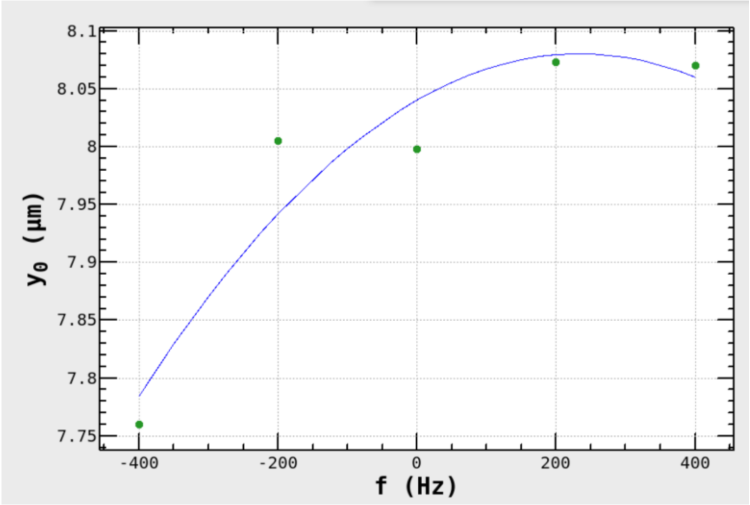
Vertical offset shift for frequency shift：IP vertical dispersion
Vertical size variation for frequency shift beam energy：IP chromatic coupling

# Latest data June 25,2019

Beam size variation for energy change was observed. Chromatic coupling exists at IP.

Nonlinear dispersion also exist at IP.



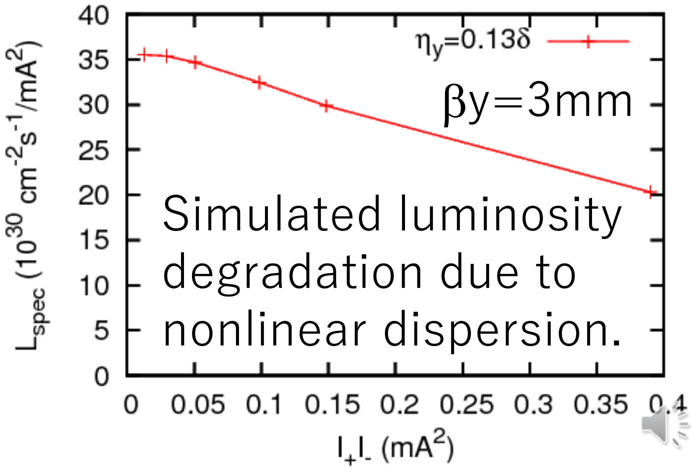

Chromatic beam size enlargement

$$\Delta\sigma_y = 0.28\ \mu$$

A half strength of the Chromatic coupling, which can degrade the luminosity, exists.

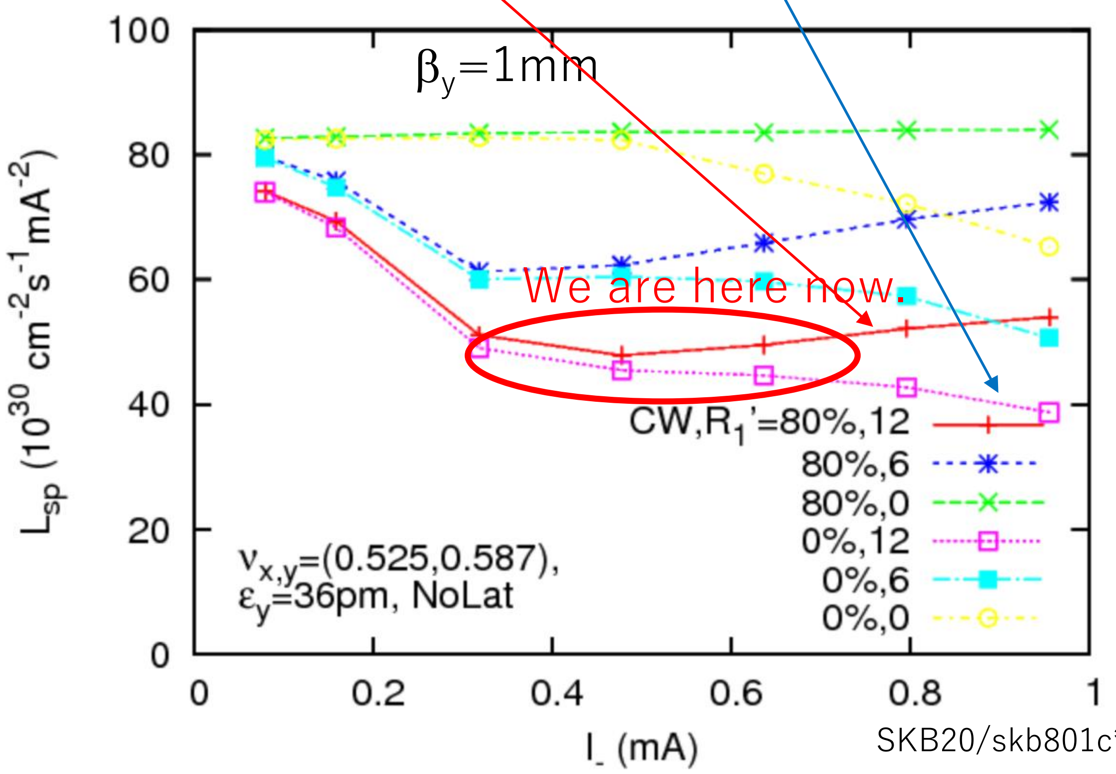
R1'=12rad $\Delta\sigma_y = R_1(\delta)\sigma_x = 0.50\ \mu m$

R2'=3m $\Delta\sigma_y = \dfrac{R_2(\delta)}{\beta_x}\sigma_x = 0.62\ \mu m$



# Weak-strong simulation for crab waist with chromatic coupling

- Lsp worsens in the low bunch current (<0.3mA) and then changes slowly for a large R1'=6, 12.
- Lsp somewhat increase/decrease for Crab waist ON/OFF for I>0.5mA.




SKB20/skb801c*,wc*

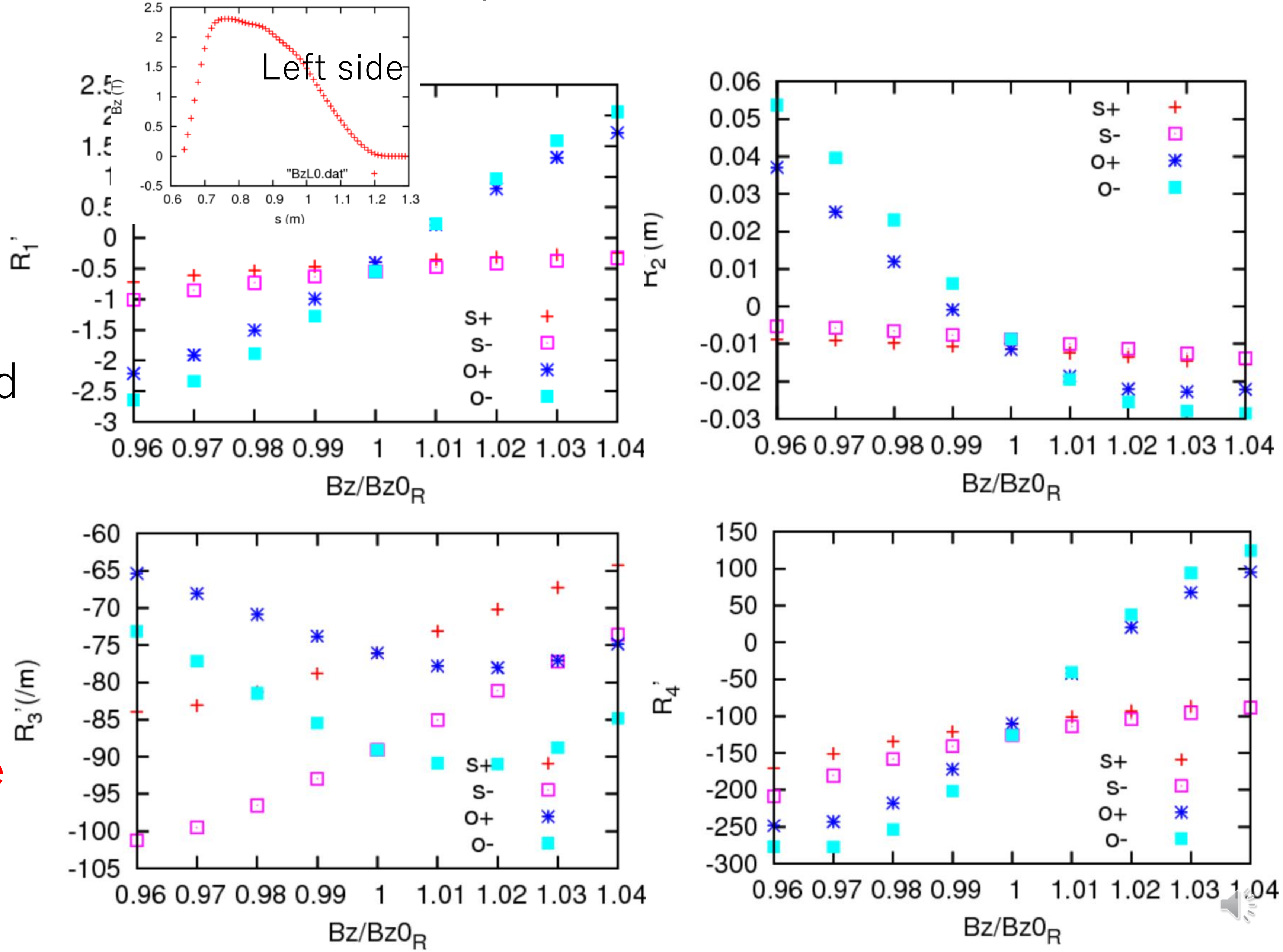
# $R_1$' correction using rotatable sextupoles

- SLY's contribute R1' dominantly. Target $R_1$'=+-12.
- 1st trial $R_1$'+=3, mainly using SLY in June 15, 2020.
  - Emittance increase in single beam.
  - Luminosity performance does not change remarkably, decrease 10%.
- 2nd trial $R_1$'+=0.5 using all sextupoles since June 18 (H, Koiso).
  - Luminosity performance does not change remarkably.

- There is no clear evidence, in which R1' affects luminosity performance, yet.

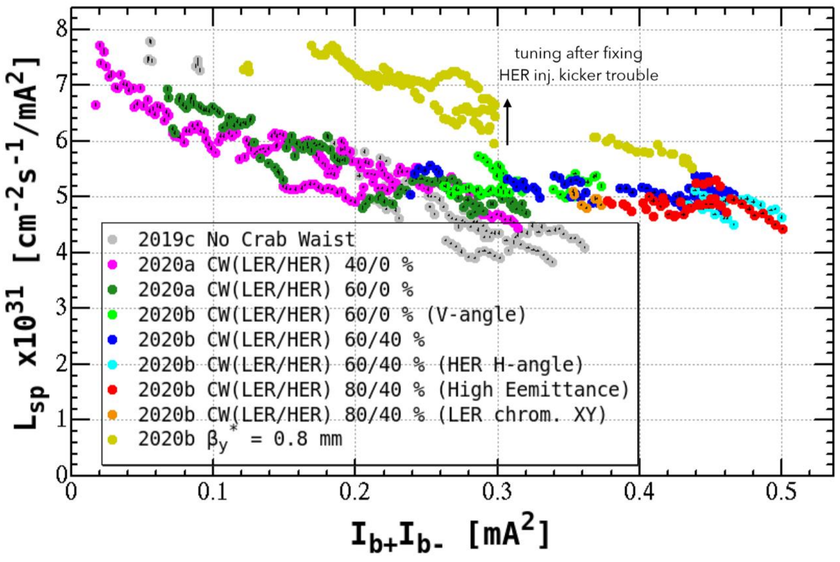
# Effects of imperfection of compensation solenoids

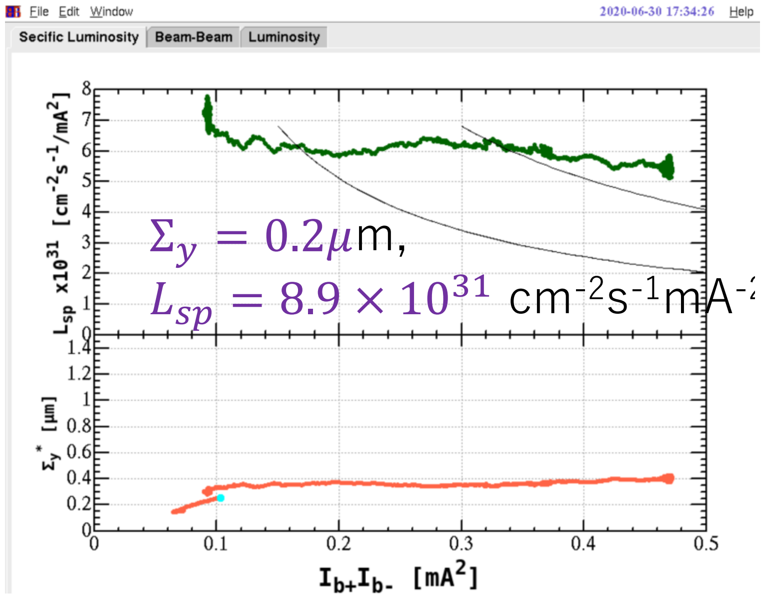
- R'=dR/dδ vs Bz(ESLR)
- Change Bz uniformly with a factor.
- S: ESL, ESR are changed the same value.
- O: Opposite value.
- dp=+-0.1%,
- No large chromatic coupling appears for the imperfection of 4%.

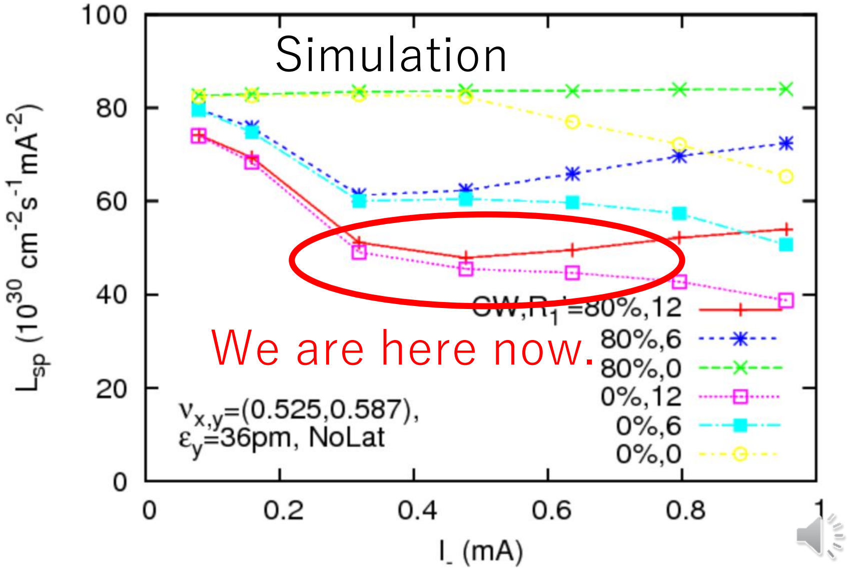


# How to continue the crab waist operation

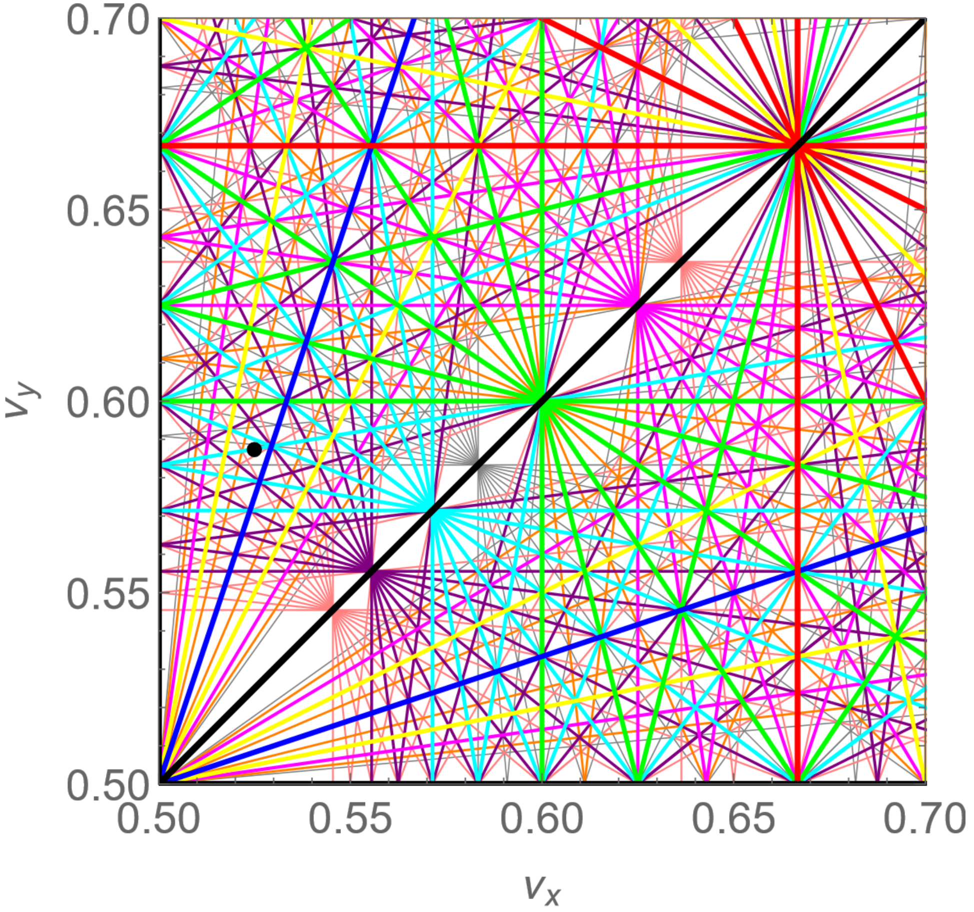
- Further high bunch current, squeezing further
  - Specific luminosity is almost constant at higher current 0.03mA.
  - Luminosity and beam-beam parameter increase if higher bunch current is available.
- Specific luminosity degradation at very low current.
  - Study of the degradation source, chromatic or nonlinear optics aberrations.
  - Correction of the aberrations
- For smaller beta, dynamic aperture may shrink due to IR nonlinearity.

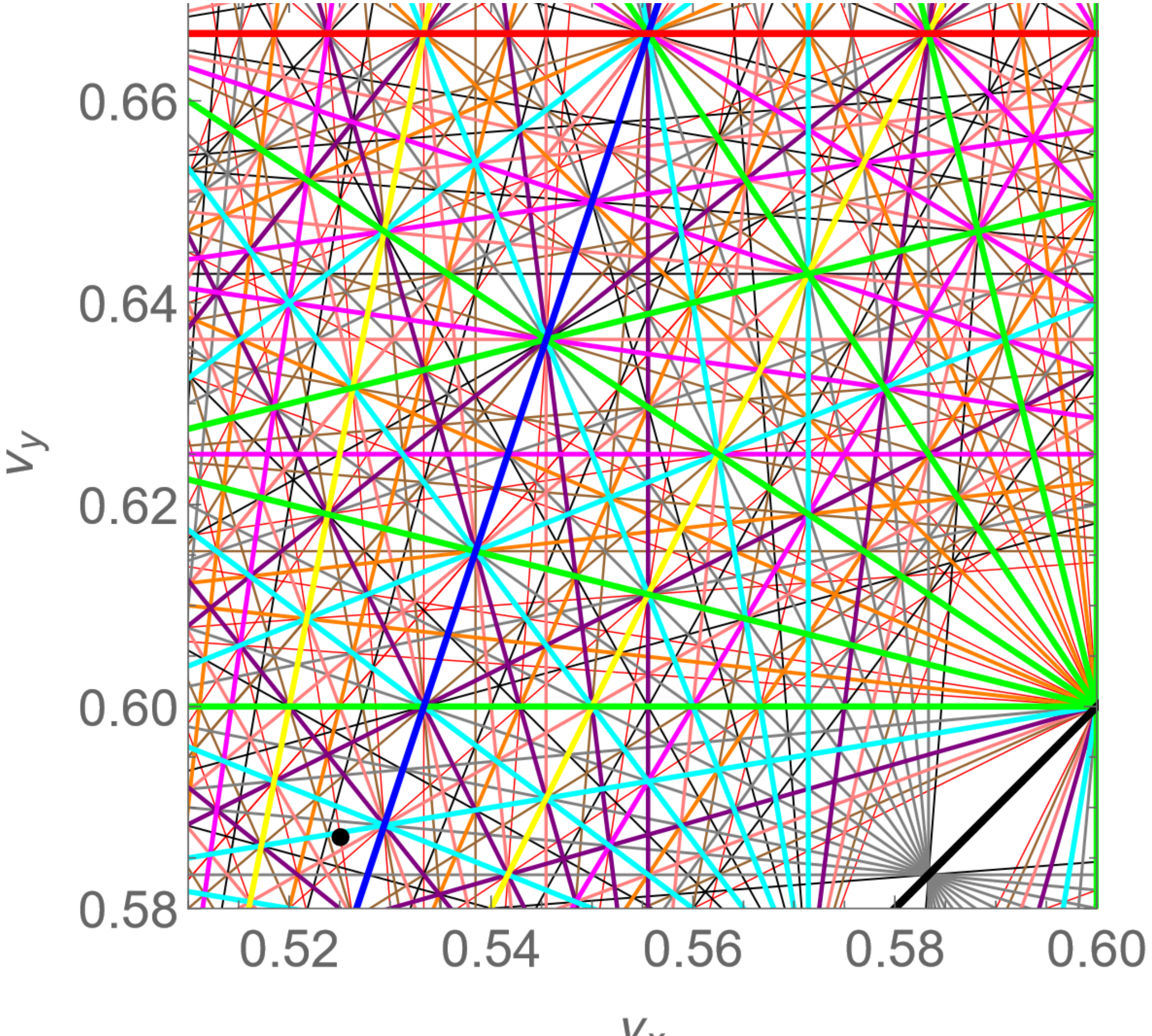


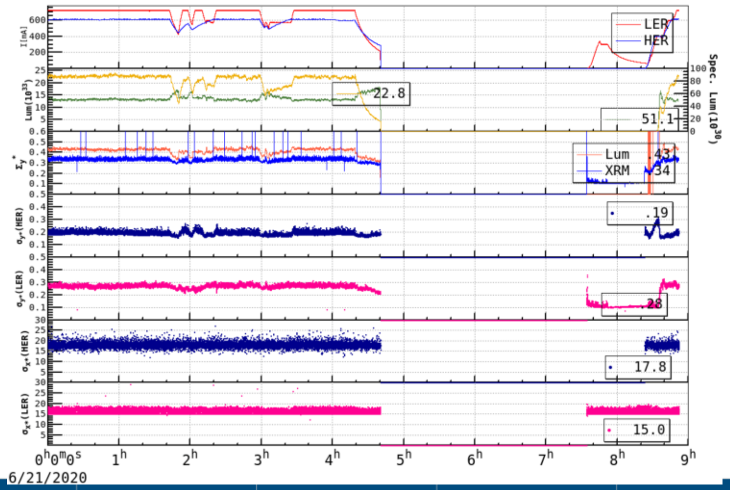



# Why beam-beam blowup in low bunch current collision

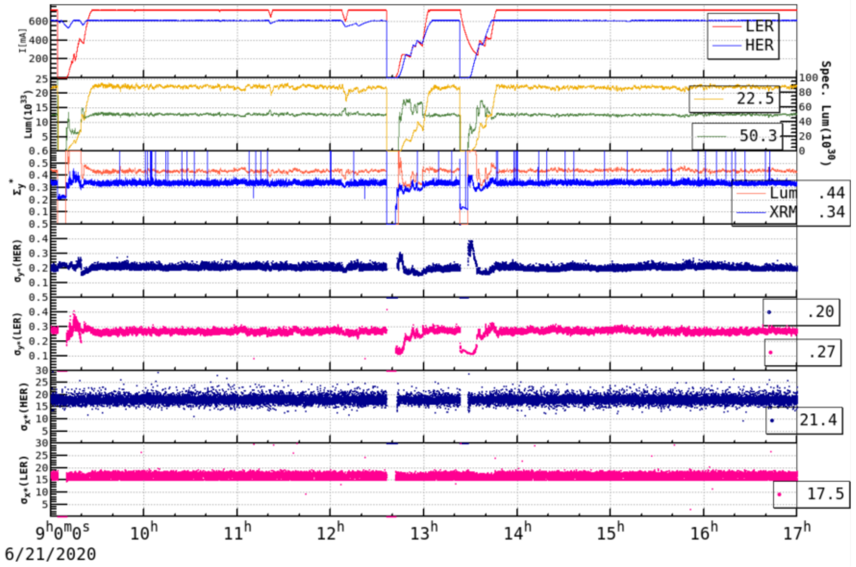


# Parameters and beam size at the best condition



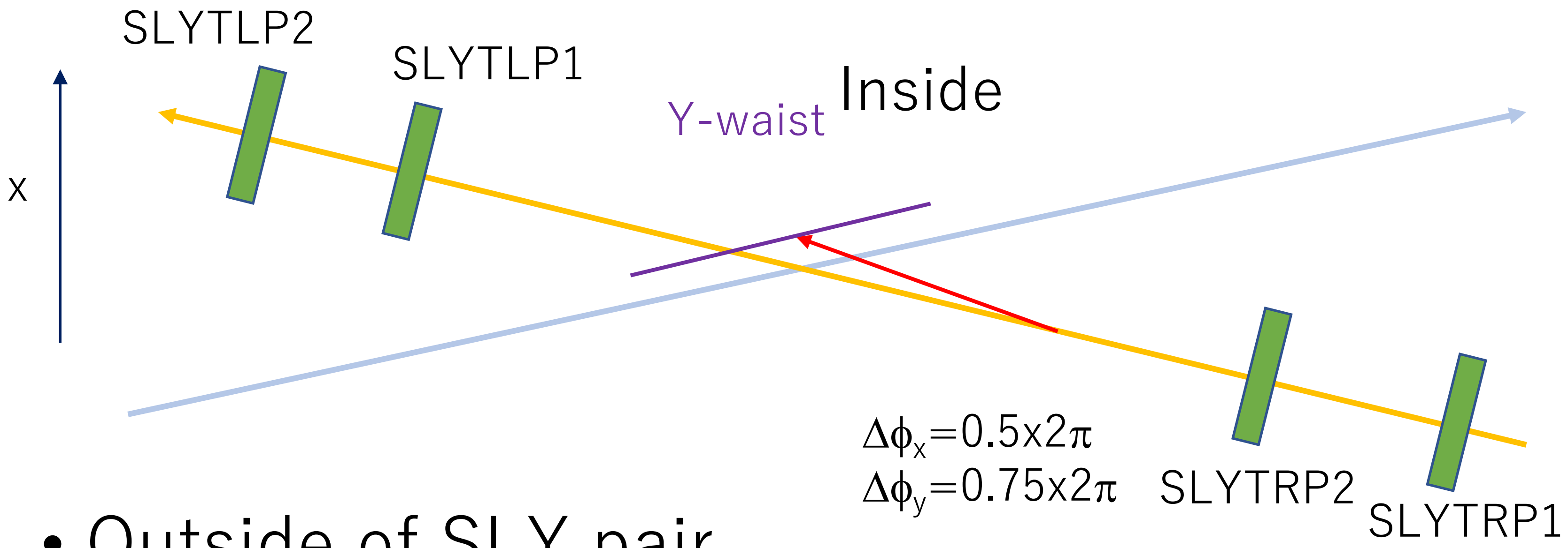

| June 21, 2020 | LER | HER | Unit | Remarks |
|---|---|---|---|---|
| Beam current | 712 | 607 | mA | |
| Bunch current | 0.728 | 0.621 | mA | |
| Vertical size $\sigma_y{}^*$ | 0.27 | 0.20 | $\mu$m | XRM measurement |
| Vertical cap sigma $\Sigma_y{}^*$ | 0.336 | | $\mu$m | XRM meaurement |
| $\Sigma_z$ | 8.24 | | mm | estimated by Luminosity |
| $\Sigma_z{}^*/\sqrt{2}$ | 5.8 | | mm | estimated by Luminosity |
| Bunch length $\sigma_z$ | 4.6 | 5.1 | mm | design (zero current) |
| $\Sigma_z$ | 6.9 | | mm | design (zero current) |



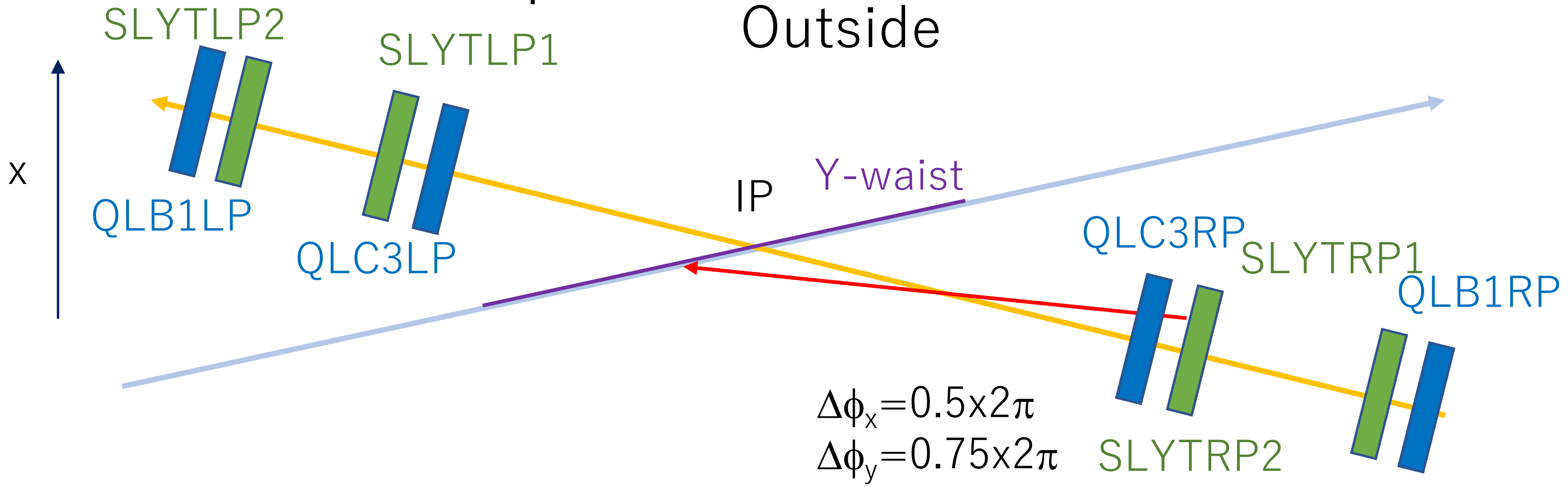

| | SuperKEKB : June 21, 2020 | | SuperKEKB : Dec. 8, 2019 | | Unit |
|---|---|---|---|---|---|
| Ring | LER | HER | LER | HER | |
| Emittance | 4.0 | 4.6 | 2.0 | 4.6 | nm |
| Beam Current | 712 | 607 | 467 | 388 | mA |
| Number of bunches | 978 | | 783 | | |
| Bunch current | 0.728 | 0.621 | 0.597 | 0.496 | mA |
| Horizontal size $\sigma_x{}^*$ | 17.9 | 16.6 | 12.6 | 16.6 | µm |
| Vertical cap sigma $\Sigma_y{}^*$ | 0.403 | | 0.445 | | µm*1 |
| Vertical size $\sigma_y{}^*$ | 0.285 | | 0.315 | | µm*2 |
| Betatron tunes $\nu_x$ / $\nu_y$ | 45.523 / 43.581 | 44.531 / 41.577 | 44.525 / 46.590 | 45.534 / 43.567 | |
| $\beta_x{}^*$ / $\beta_y{}^*$ | 80 / 1.0 | 60 / 1.0 | 80 / 1.0 | 60 / 1.0 | mm |
| Piwinski angle | 13 | 15 | 18 | 15 | |
| Crab Waist Ratio | 80 | 40 | 0 | 0 | % |
| Beam-Beam parameter $\xi_y$ | 0.0389 | 0.0261 | 0.0281 | 0.0193 | |
| Specific luminosity | 5.43 x $10^{31}$ | | 4.91 x $10^{31}$ | | $cm^{-2}s^{-1}/mA^2$ |
| Luminosity | 2.40 x $10^{34}$ | | 1.14 x $10^{34}$ | | $cm^{-2}s^{-1}$ |

# Horizontal orbit

- Inside of SLY pair

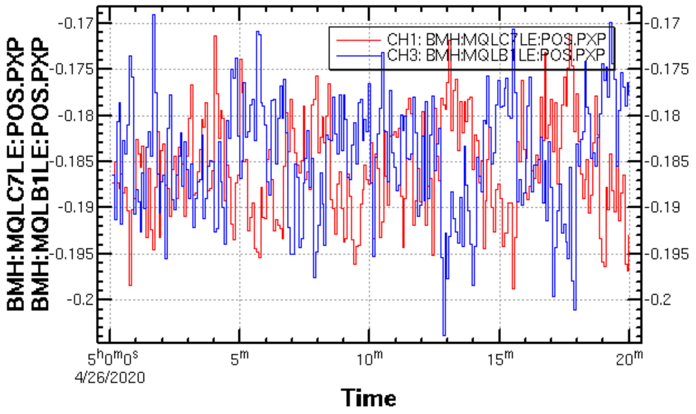


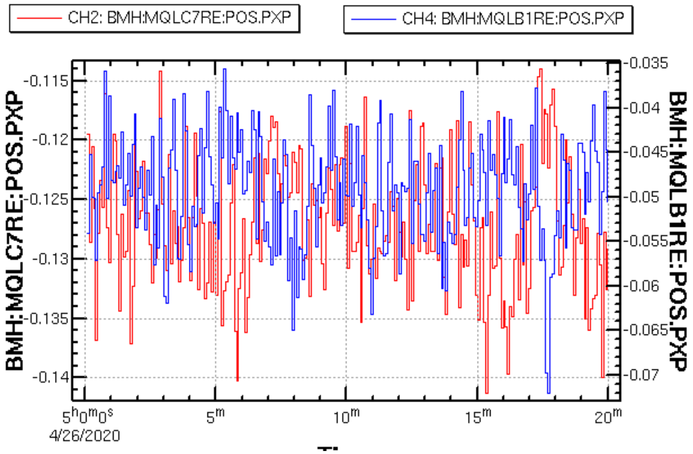

- Outside of SLY pair



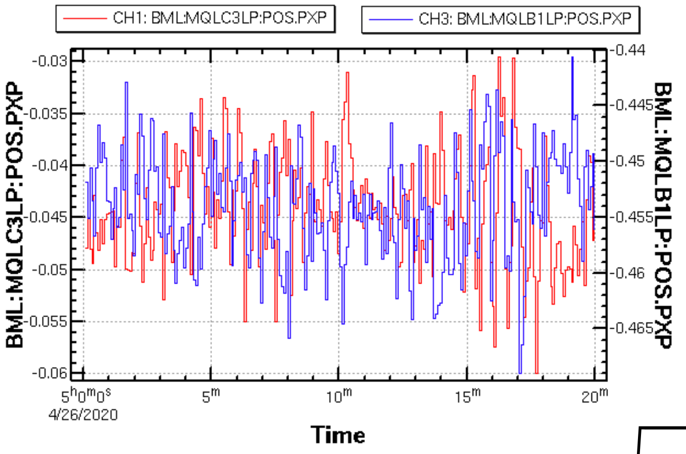
# Horizontal orbit fluctuation at SLY

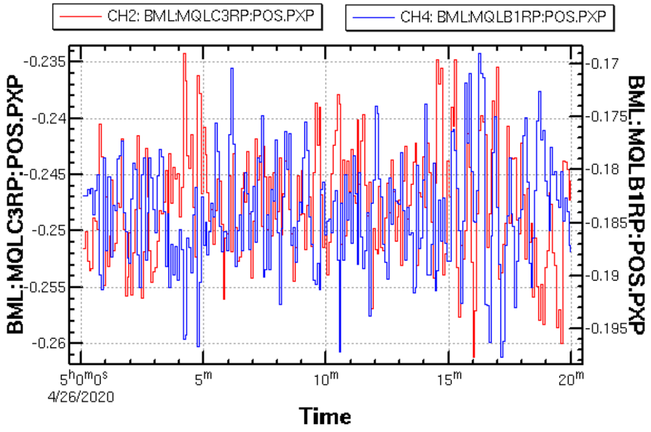
- HER




- LER




- Waist fluctuation

$$\delta x^* = \delta x_{SLY}\sqrt{\frac{\beta_x^*}{\beta_{x,SLY}}} \qquad \sqrt{\frac{\beta_x^*}{\beta_{x,SLY}}} \sim \frac{1}{3}$$

$$\delta x^* = 0.1\text{mm} \qquad \delta s = \frac{\delta x^*}{\theta_c} = 0.25\text{mm} < \beta_y^*$$

Not serious now