# Finite angle crossing, crab crossing and crab waist collision KEKB-SuperKEKB

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EIC workshop, Oct. 7-9, 2020

# Collision with a crossing angle

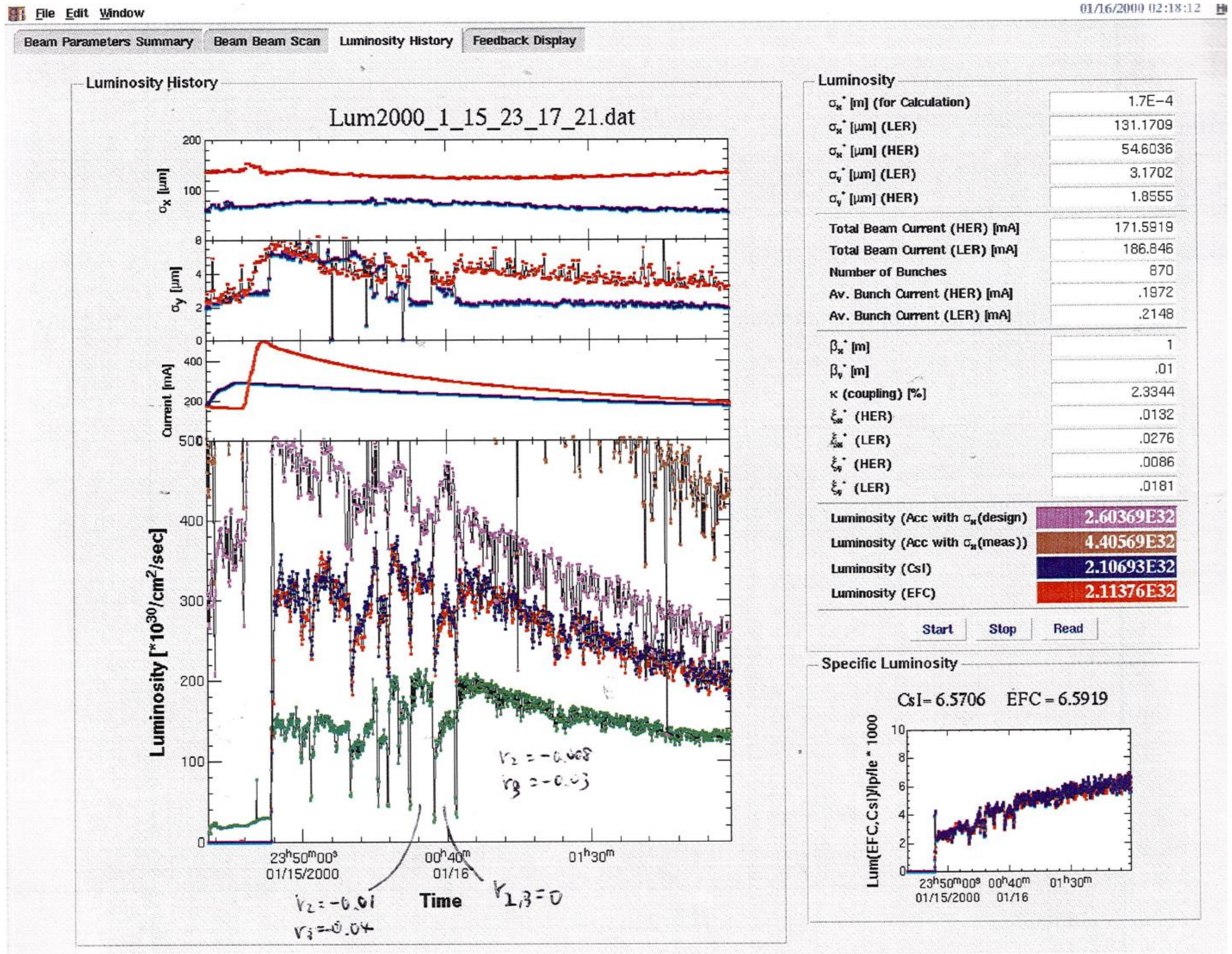
- KEKB $\theta_h$=11mrad, $\sigma_z\theta_h/\sigma_x$=0.75
- Main limitation source was x-y coupling at IP and electron cloud.
- Day-by-day tuning of IP coupling
- Winding weak-solenoids around whole beam chamber, luminosity increased.
- L=1.712x$10^{34}$ $cm^{-2}s^{-1}$
- $L_{sp}$=1.067 x$10^{31}$ $cm^{-2}s^{-1}/mA^2$
- $\xi_{n,\pm} = \frac{2r_e\beta_{y,\pm}L}{\gamma_\pm N_\pm f_{col}}$ =0.0883, 0.0435

e- tune shift is limited by e+ beam blow-up.

| | Nov. 2006 (w/o crab) | |
|---|---|---|
| | LER | HER |
| Circumference | 3016 | |
| Hor. Emittance (nm) | 18 | 24 |
| Beam current (mA) | 1662 | 1340 |
| # of bunches | 1388+1 | |
| RF frequency | 508.88 | |
| RF Voltage (MV) | 8.0 | 15.0 |
| $\nu_s$ | -0.0246 | -0.0226 |
| $\nu_x$ / $\nu_y$ | 45.505/43.534 | 44.509/41.565 |
| $\beta_x^*$ / $\beta_y^*$ (cm) | 59/0.65 | 56/0.59 |
| $\alpha$ (mom. compact.) | 3.31 x $10^{-4}$ | 3.38 x $10^{-4}$ |
| $\xi_{n,\pm} = \frac{2r_e\beta_{y,\pm}L}{\gamma_\pm N_\pm f_{col}}$ | 0.0883 | 0.0435 |
| Beam life (min@mA) | 110@1600 | 180@1340 |
| Lumi. ($10^{34}$ $cm^{-2}s^{-1}$) | 1.712 | |

# X-y coupling at IP

- First observation (tuning) of x-y coupling at IP. HER r2,r3.
- IP coupling and dispersion corrections were established as main tasks of commissioning shift after this time in KEKB.



# Beam-beam potential

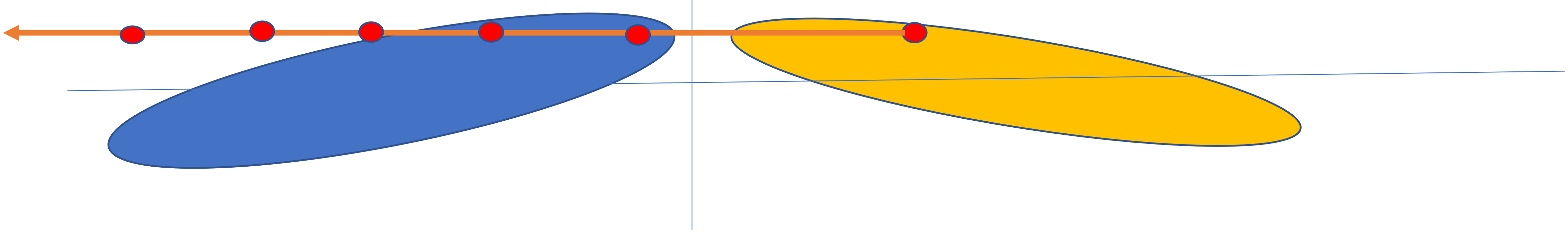
$$U_G(x,y) = \frac{r_p}{\gamma}\int_0^{\infty} \frac{1-\exp\left(-\frac{x^2}{2\sigma_x^2+u}-\frac{y^2}{2\sigma_y^2+u}\right)}{\sqrt{(2\sigma_x^2+u)(2\sigma_y^2+u)}}du$$

- Crossing angle

$$U_{bb} = \int \lambda(z')U_G(x+\theta_c(z-z'), y+p_y s; s)ds \qquad s=(z-z')/2$$

$$y = r_0 y^* - R_1 x^* - R_2 p_x^* \qquad p_y = p_y^* - R_3 x^* - R_4 p_x^*$$

Many x-y resonances appear in the beam-beam potential.



# Crab crossing

- Crossing angle is equivalent to x-z coupling at IP.
- Removing the x-z coupling and choosing the operating point $\nu_x=0.5+\varepsilon$, beam-beam tune shift can be increased drastically.

- Beam-beam simulation with Gaussian approximation can not predict beam-beam limit precisely.

$$U_{bb} = \int \lambda(z')U_G(x+\theta_c(z-z'), y+p_y s; s)ds$$

x-y resonances, $2m_x\nu_x+2m_y\nu_y=n$, appear.

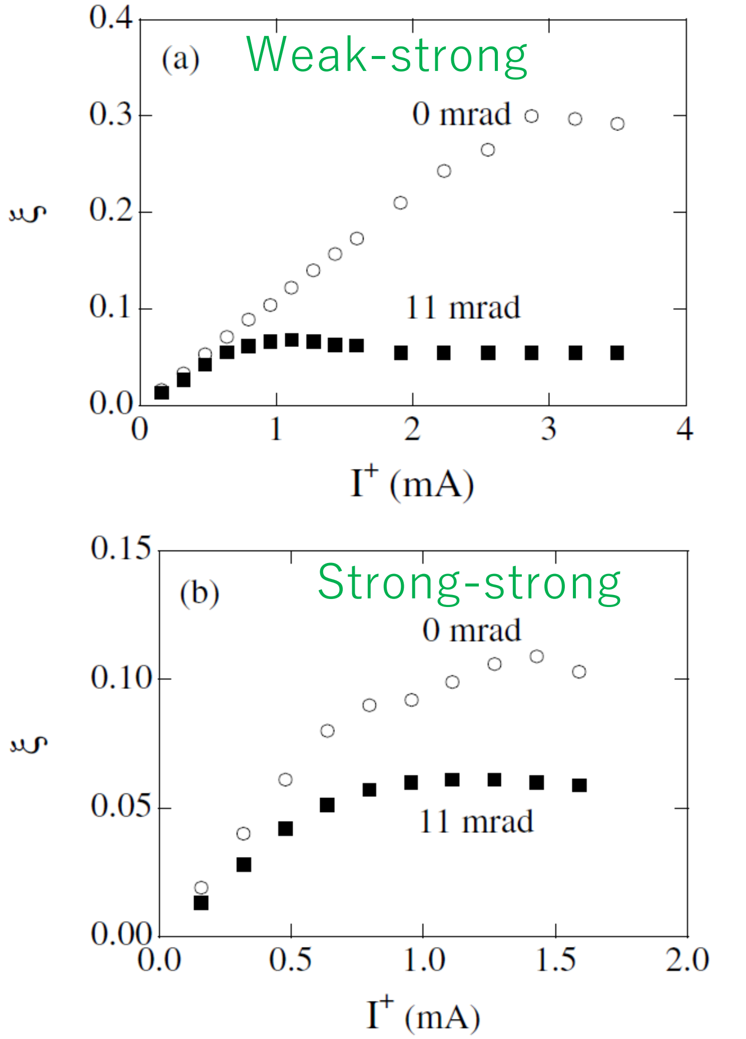



FIG. 3. Beam-beam parameters for crossing angle of 0 and 11 mrad as function of bunch current. (a),(b) were obtained by the weak-strong and strong-strong simulations, respectively.

# Performance of Crab crossing

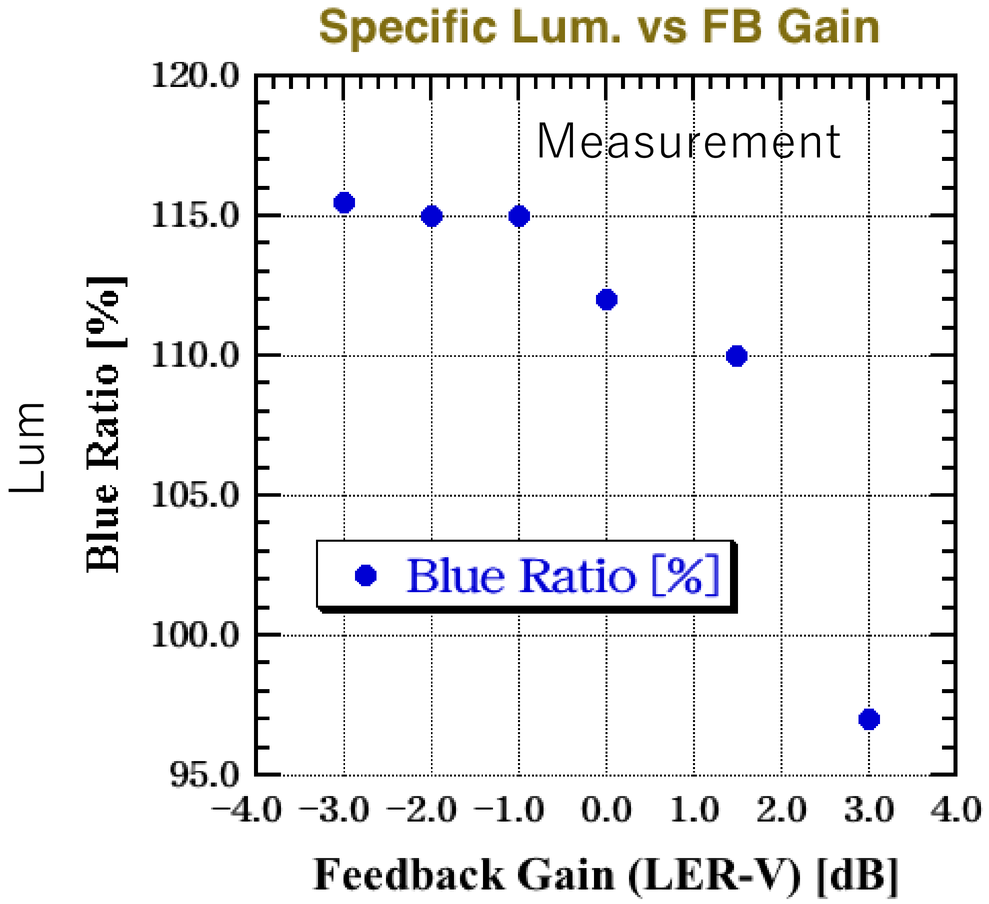
- Better beam-beam performance, but not very drastic.
- Chromatic coupling correction helps to increase the luminosity.
- $\beta_x^*$ could not squeezed due to the dynamic beta increase at crab cavity.
- $L=2.108\text{x}10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- $L_{sp}=1.718\ \text{x}10^{31}\ \text{cm}^{-2}\text{s}^{-1}/\text{mA}^2$
- $\xi_{n,\pm} = \frac{2r_e\beta_{y,\pm}L}{\gamma_\pm N_\pm f_{col}} =$ 0.1002, 0.0604

e- tune shift is limited by e+ beam blow-up.

| | June 2009 (w crab) | |
|---|---|---|
| | LER | HER |
| Circumference | 3016 | |
| Hor. emittance | 18 | 24 |
| Beam current | 1637 | 1188 |
| # of bunches | 1585 | |
| RF frequency | 508.88 | |
| RF Voltage | 8.0 | 15.0 |
| $\nu_s$ | -0.0246 | -0.0226 |
| $\nu_x / \nu_y$ | 45.506/43.561 | 44.512/41.621 |
| $\beta_x^* / \beta_y^*$ | 120/0.59 | 120/0.59 |
| $\alpha$ (mom. compact.) | $3.31 \times 10^{-4}$ | $3.38 \times 10^{-4}$ |
| $\xi_{n,\pm} = \frac{2r_e\beta_{y,\pm}L}{\gamma_\pm N_\pm f_{col}}$ | 0.1002 | 0.0604 |
| Luminosity ($10^{34}\ \text{cm}^{-2}\text{s}^{-1}$) | 2.108 | |

# Collision offset noise and luminosity

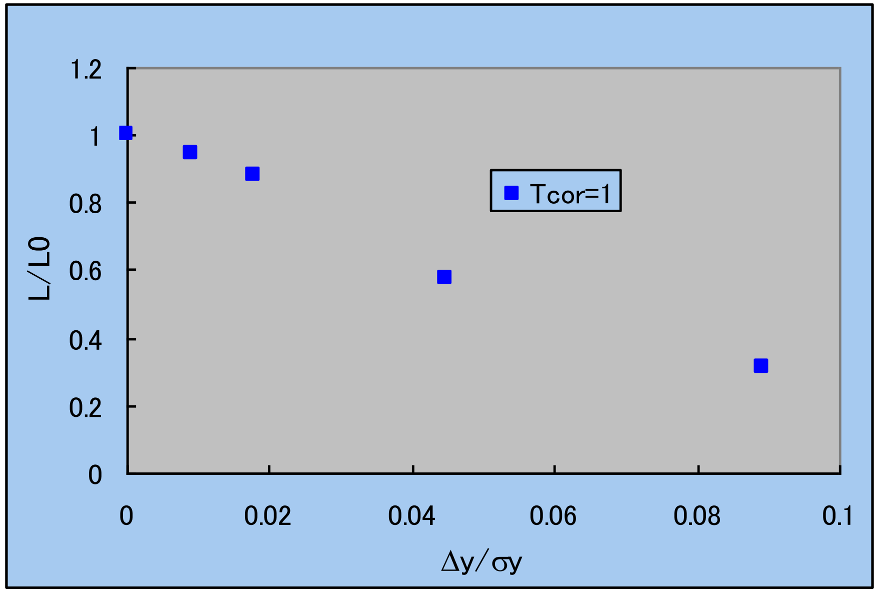
## Specific Luminosity vs FB Gain




Simulation with collision offset noise in vertical

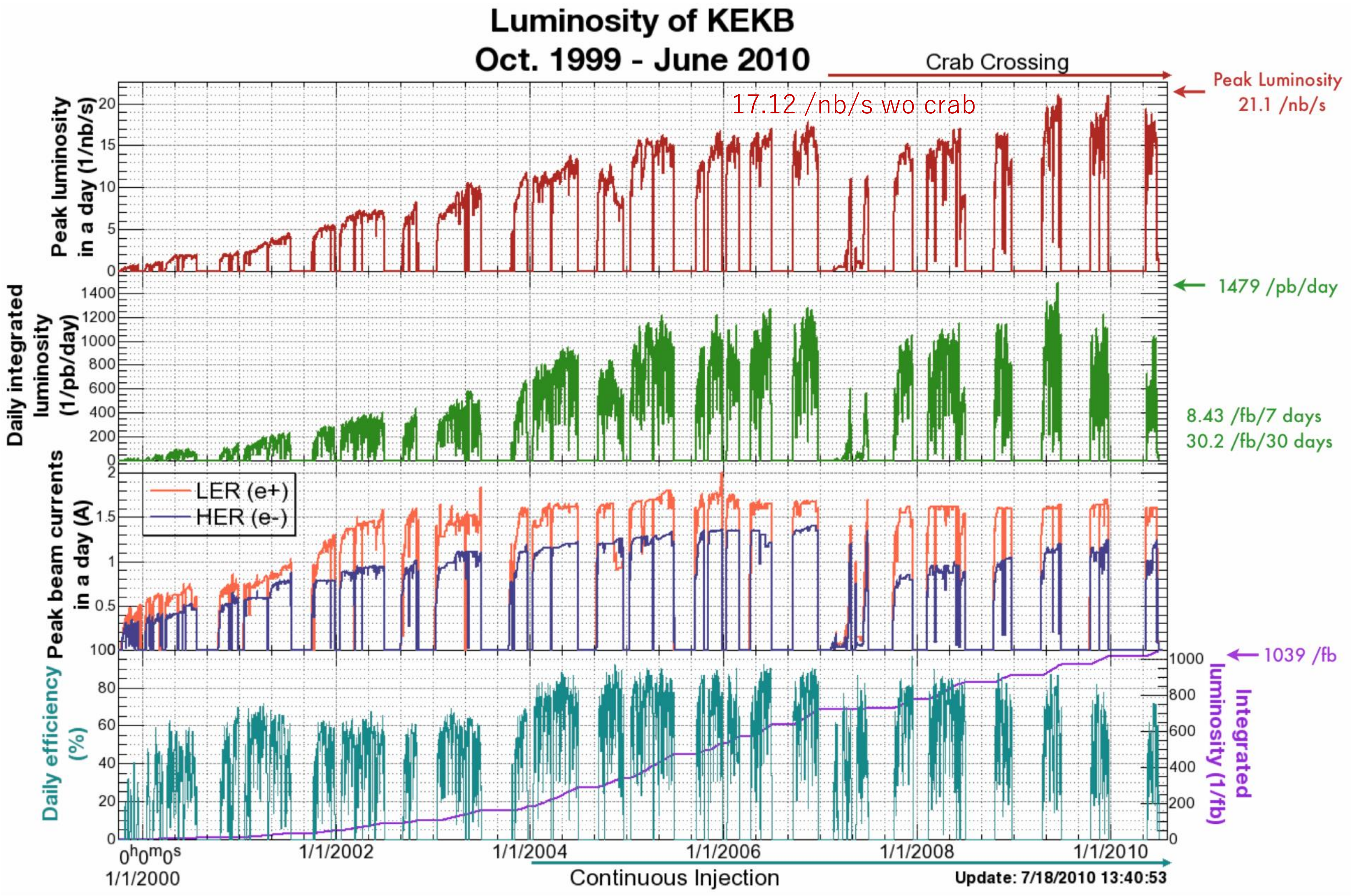
PAC2005

$$\langle \Delta y(t)\Delta y(t')\rangle = \Delta y^2 \delta(t-t')$$




Only 2% of noise degrades luminosity ~20%.

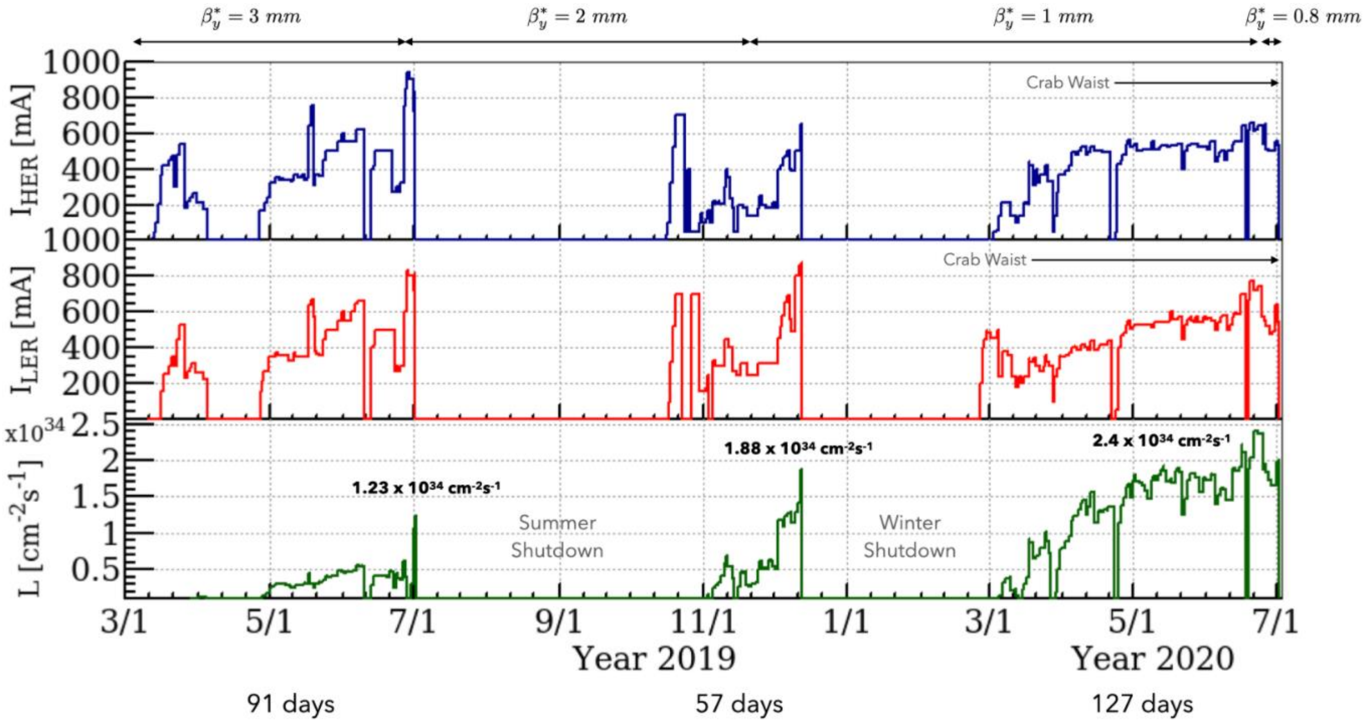
FB gain of the LER vertical affects the specific luminosity.
The other gains (LER H, HER H/V) have no effect.



Luminosity of KEKB
Oct. 1999 - June 2010
Crab Crossing
Peak Luminosity
21.1 /nb/s
17.12 /nb/s wo crab
1479 /pb/day
8.43 /fb/7 days
30.2 /fb/30 days
1039 /fb
Peak luminosity in a day (1/nb/s)
Daily integrated luminosity (1/pb/day)
Peak beam currents in a day (A)
LER (e+)
HER (e-)
Daily efficiency (%)
Integrated luminosity (1/fb)
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
Continuous Injection
Update: 7/18/2010 13:40:53

# SuperKEKB: Collision with a large crossing angle

- Small emittance, extremely small $\beta_{x,y}^*$,
- A large crossing (Piwinski) angle, $\sigma_z\theta_{c/2}/\sigma_x$~20.
- SuperKEKB (collision) started at 2019.
- Crab waist operation started at March 2020.
- $\beta_{x,y}^*$ was squeezed to (60,0.8)mm at July 2020.
- Luminosity 2.4x$10^{34}$ $cm^{-2}s^{-1}$ was recorded.

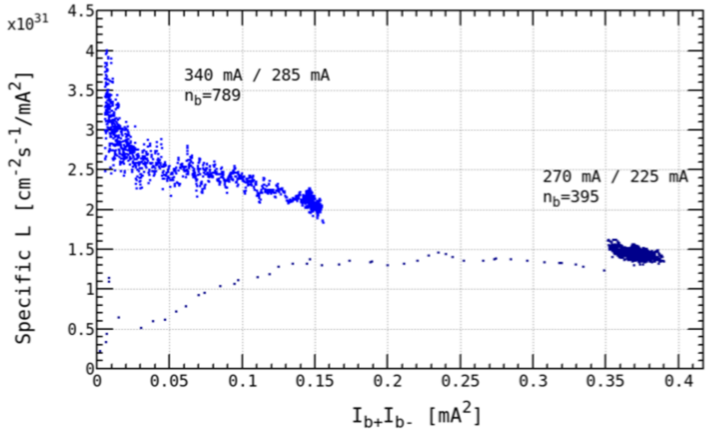


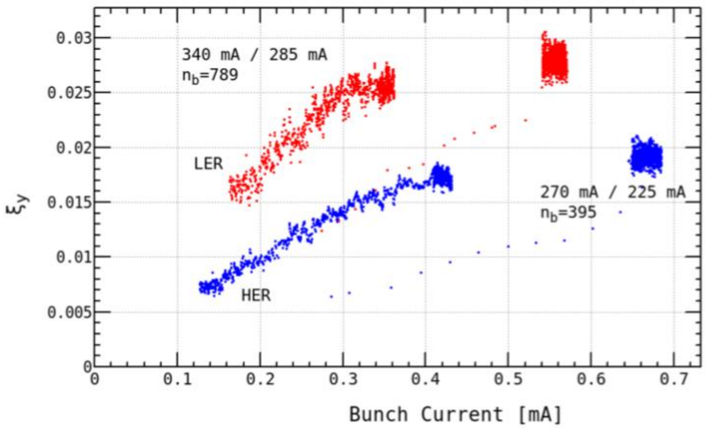

| | Dsign | |
|---|---|---|
| | LER | HER |
| Circumference | 3016 | |
| Hor. emittance | 3.2 | 4.6 |
| Beam current | 3600 | 2600 |
| # of bunches | 2500 | |
| RF frequency | 508.88 | |
| RF Voltage | 9.4 | 15.0 |
| $\nu_s$ | -0.0246 | -0.0280 |
| $\nu_x$ / $\nu_y$ | 44.525/44.585 | 45.525/43.585 |
| $\beta_x^*$ / $\beta_y^*$ (mm) | 32/0.27 | 25/0.30 |
| α (mom. compact.) | 3.25 x $10^{-4}$ | 4.55 x $10^{-4}$ |
| Half crossing angle | 41.5 mrad | |
| Lumi. ($10^{34}$ $cm^{-2}s^{-1}$) | 80 | |

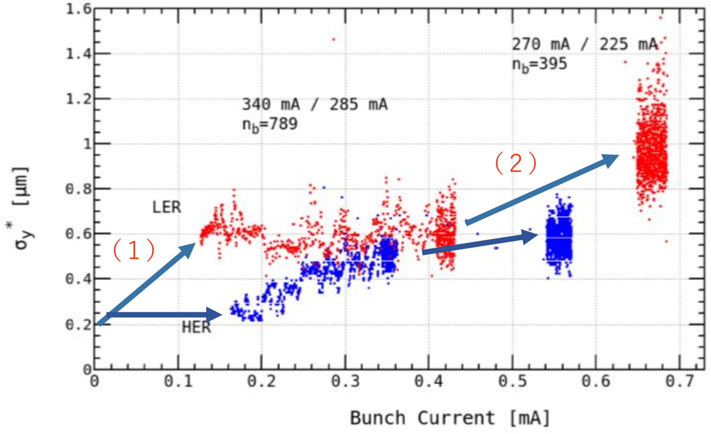
# Beam size blowup at very low bunch current collision observed since the early stage of commissioning

- $\beta_y$=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.

2019 Spring



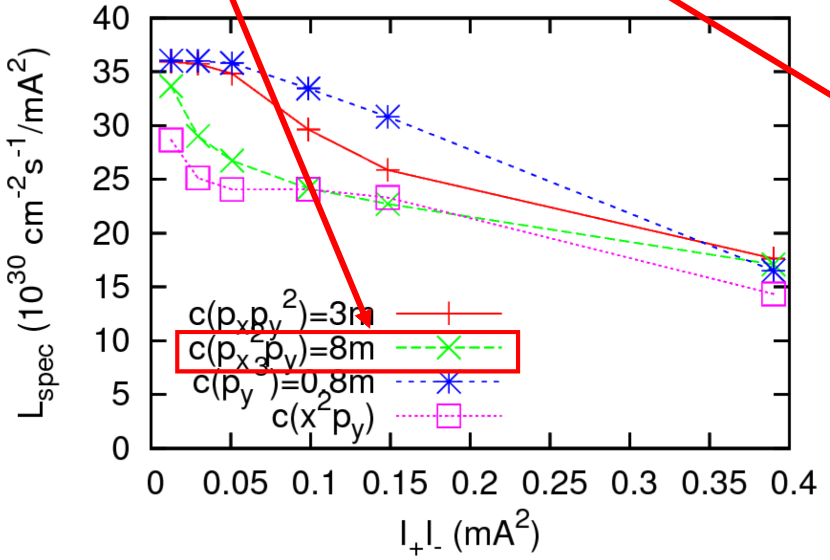
# Possible source of the beam size blow up at low current collision

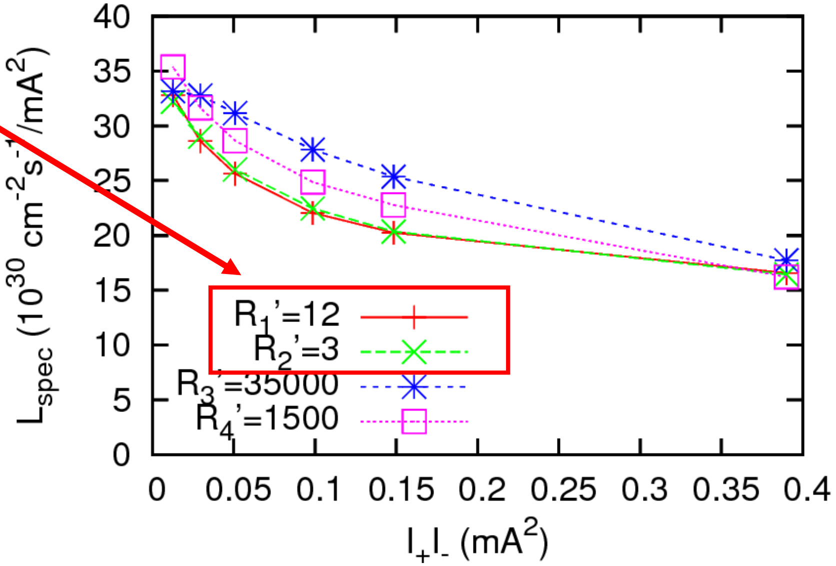
K. Ohmi, retire seminar at Apr. 2019

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

100 times larger for the early estimation by D. Zhou et al.

Weak strong simulation with nonlinear IP aberrations

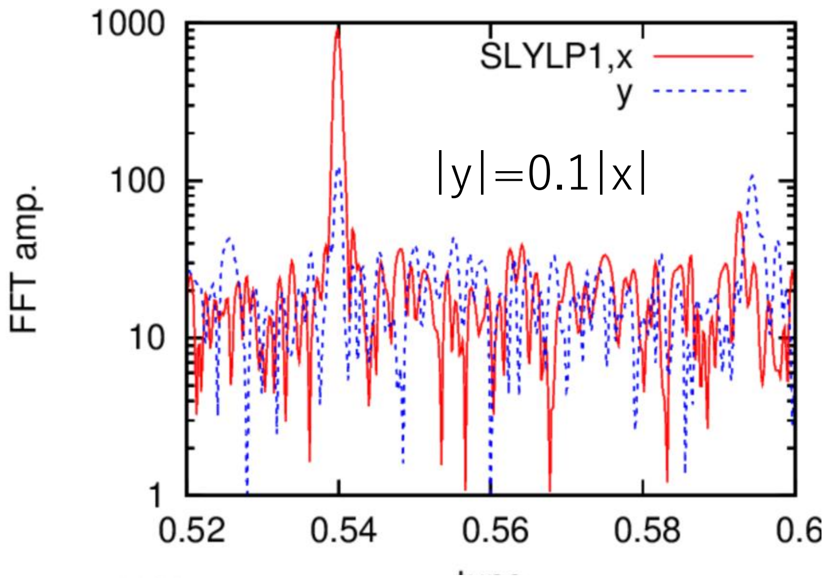


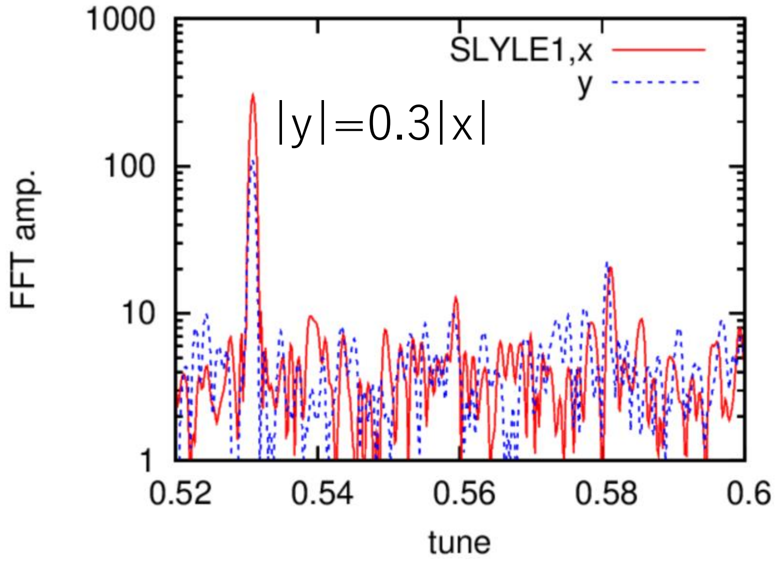




$\beta_y=3mm$

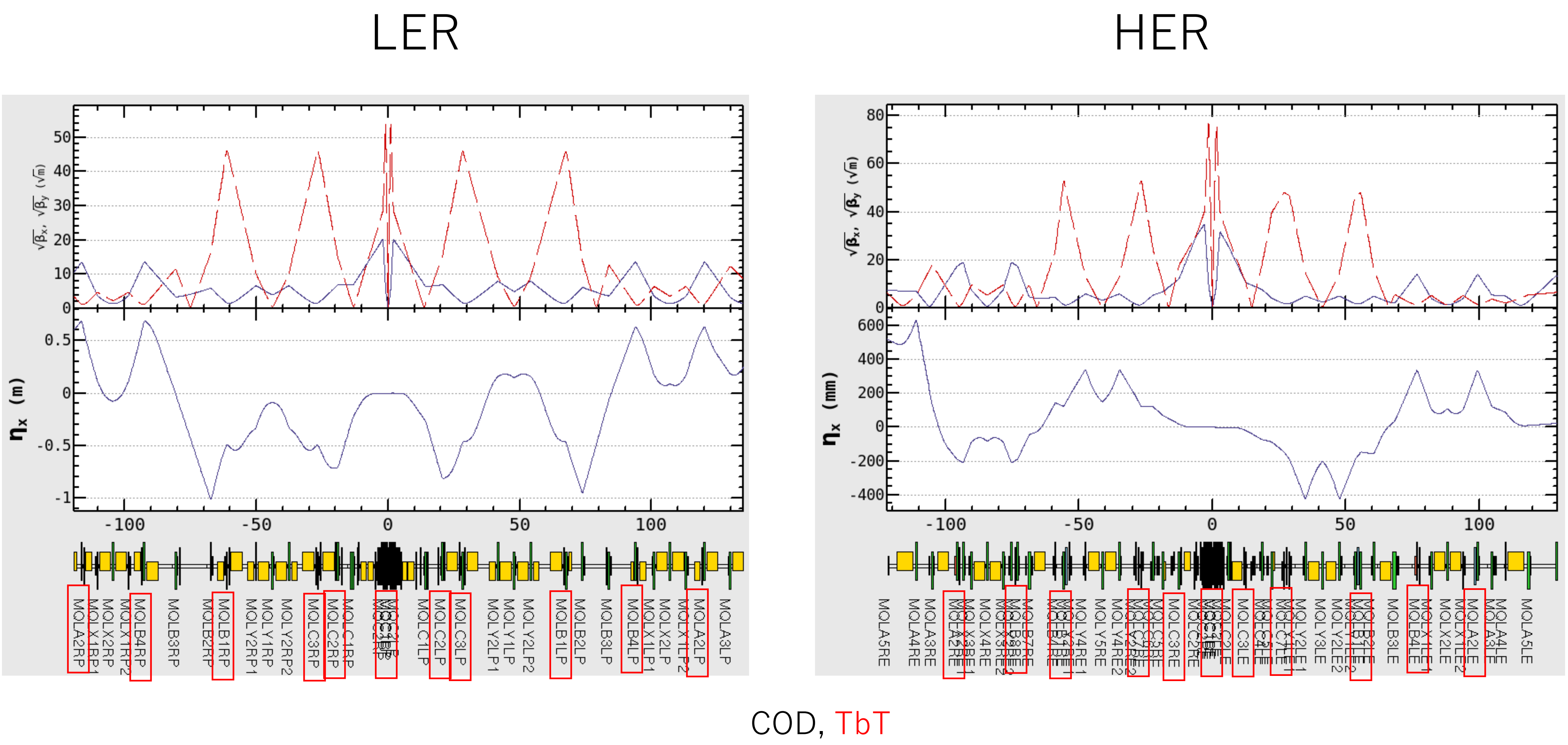
# TbT optics (coupling) measurement at IR

- 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



# x-y coupling TbT measurement

- y motion in X mode.

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

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

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

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

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

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

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

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

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

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

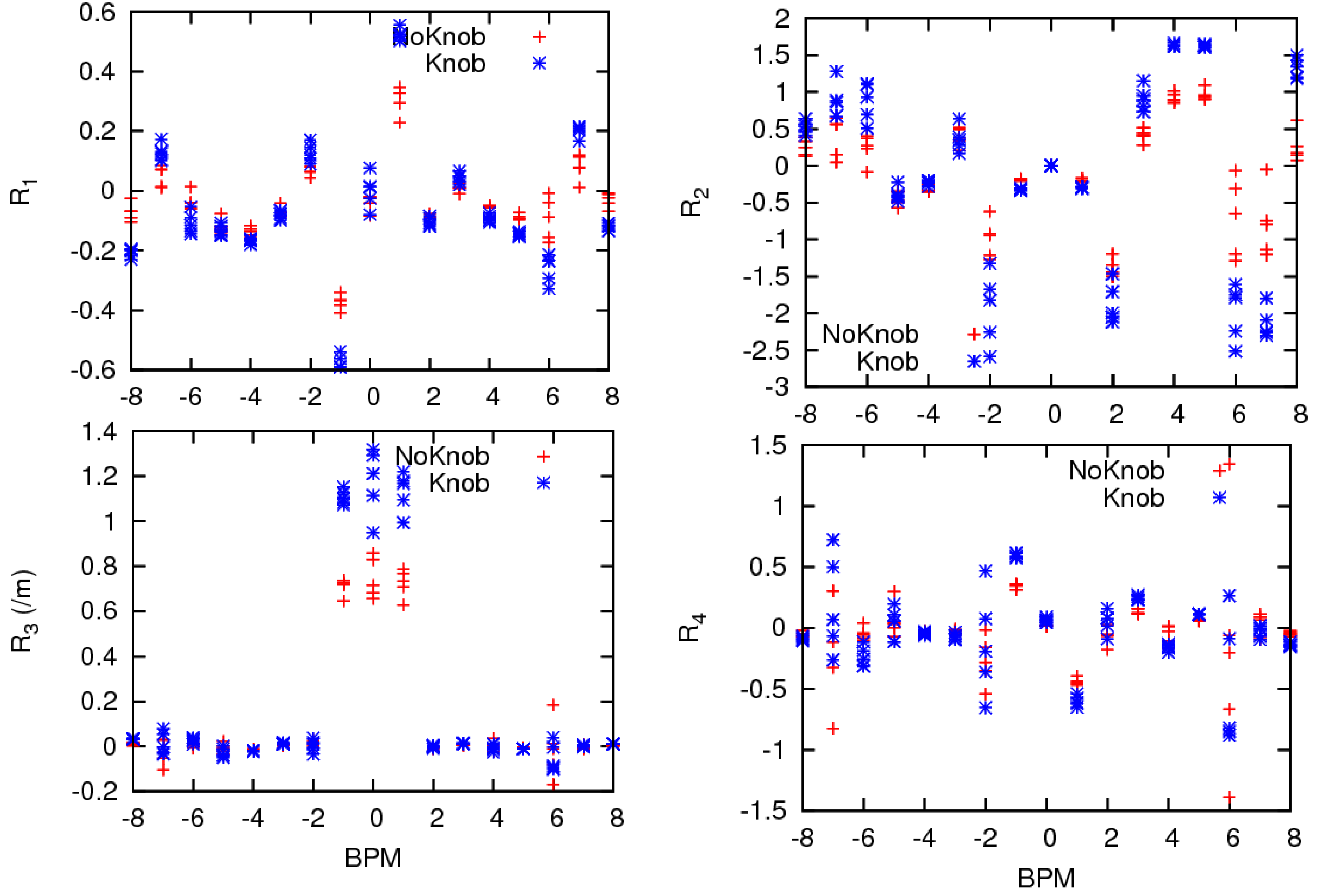
$$= d\cos(2\pi n\nu_x + \phi_q)$$

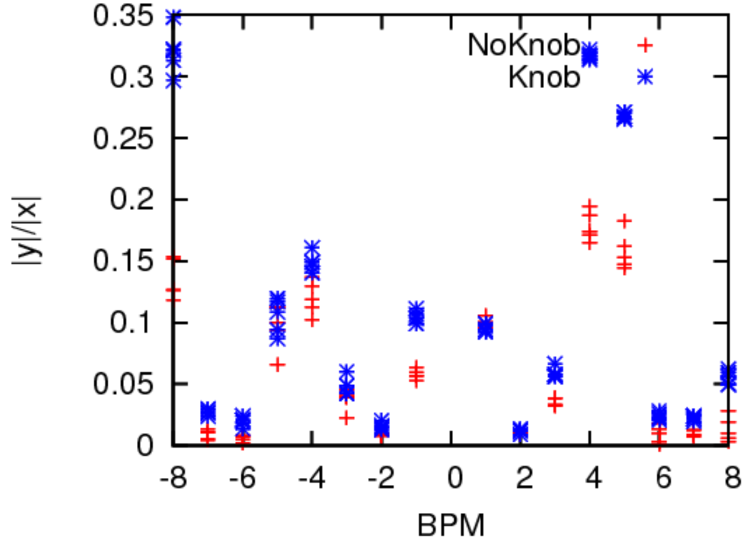
$$\beta = \beta_x$$
$$\alpha = \alpha_x$$

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

# LER, Mar. 9, 2020

- Very large x-y coupling exists in IR.



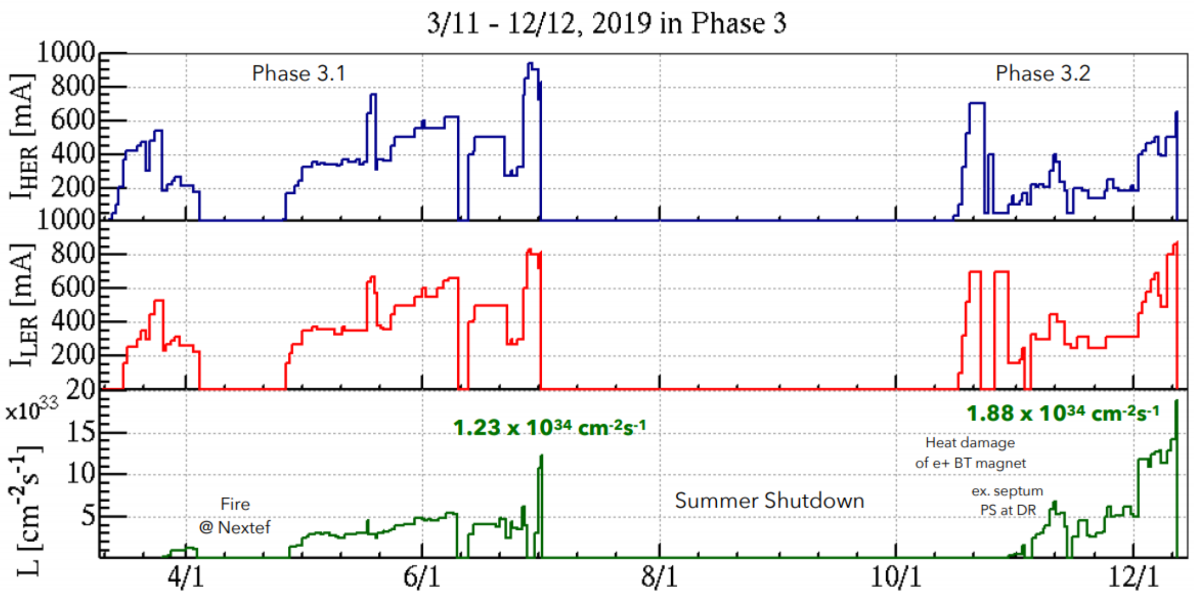



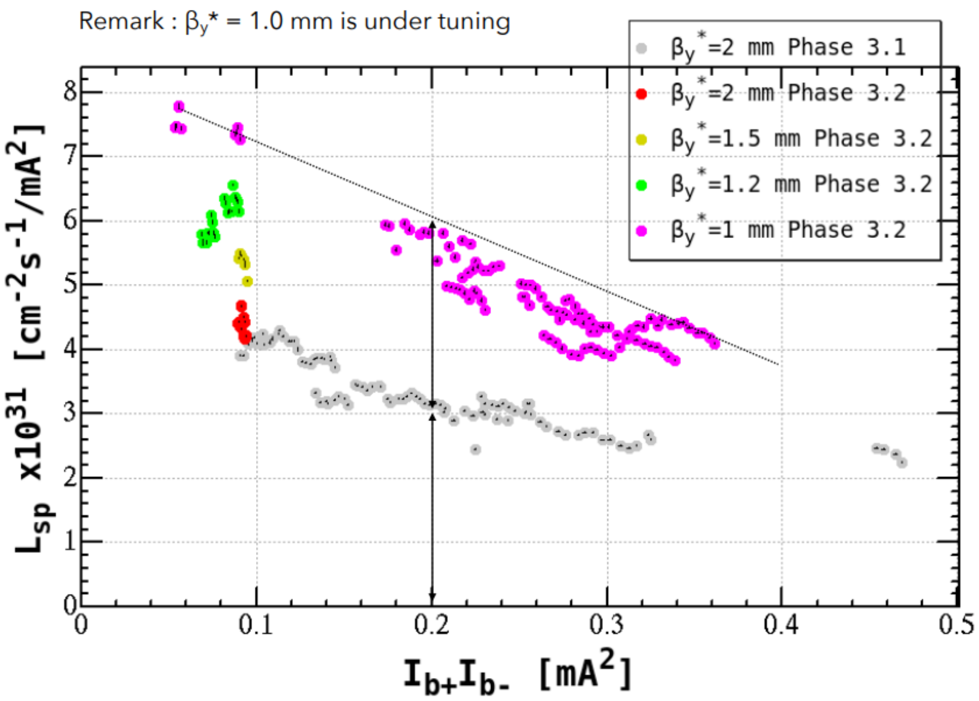

BPM +:Left -:Right
1 QC1
2 QC2
4,5 SLY (Local Chrom y)
6,7 SLX (Local Chrom x)

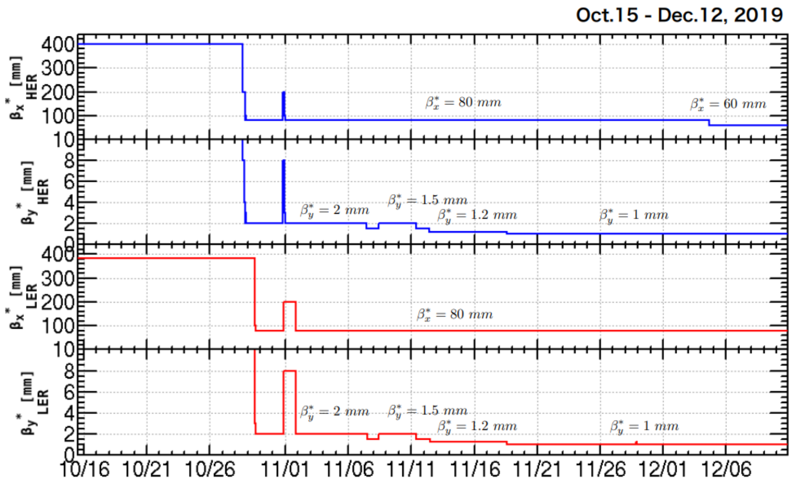
Large y signal for x excitation

# 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 in 2019.
- 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$^{-2}$

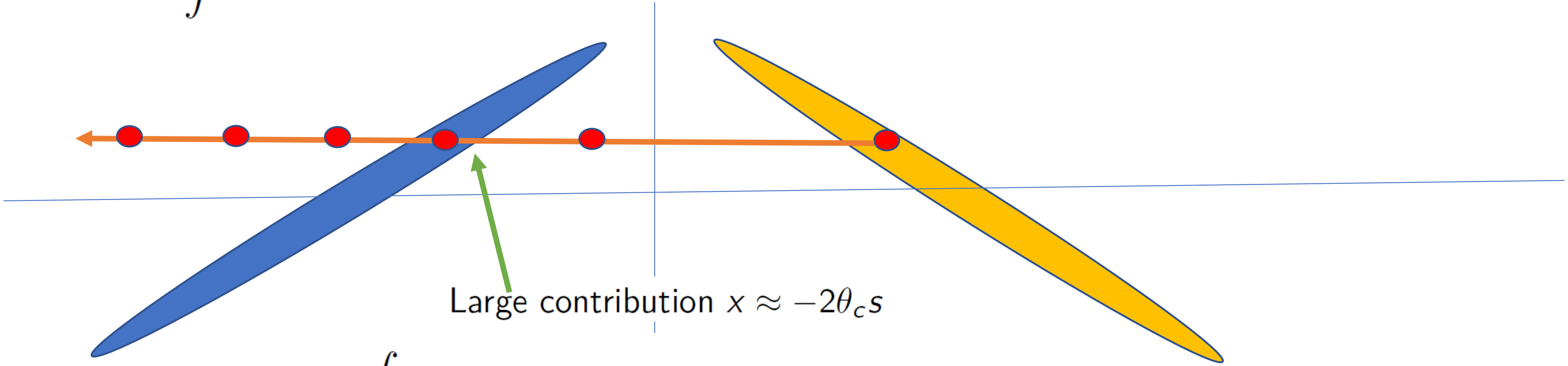
# Beam-beam potential

$$U_G(x,y) = \frac{r_p}{\gamma}\int_0^\infty \frac{1-\exp\left(-\frac{x^2}{2\sigma_x^2+u}-\frac{y^2}{2\sigma_y^2+u}\right)}{\sqrt{(2\sigma_x^2+u)(2\sigma_y^2+u)}}du$$

- Crossing angle

$$U_{bb} = \int \lambda(z')U_G(x+\theta_c(z-z'), y+p_y s; s)ds$$

$$s = (z-z')/2$$




$$U_{bb} \approx \int \lambda(z')U_G(x+2\theta_c s, y - xp_y/(2\theta_c); s)ds$$

Many x-y resonances appear.

# Crab waist

- Hamiltonian

$$H_{cw} = \frac{1}{4\theta_c} x^* p_y^{*2}$$

$$T_{rev} e^{-:H_{cw}(\boldsymbol{X}^*):} e^{-:U_{bb}(\boldsymbol{X}^*):} e^{:H_{cw}(\boldsymbol{X}^*):} = T_{rev} e^{-:U_{bb}(e^{-:H_{cw}(\boldsymbol{X}^*):}\boldsymbol{X}^*)}$$

- Crab waist transformation

$$y \to y + xp_y/(2\theta_c)$$

$$U_{bb} \approx \int \lambda(z') U_G(x + 2\theta_c s, y - xp_y/(2\theta_c); s) ds$$

$$\Rightarrow \int \lambda(z') U_G(x + 2\theta_c s, y; s) ds$$

x-y resonances induced by crossing angle disappear.

- X-y (chromatic) coupling

$$y \Rightarrow y - R_1 x - R_2 p_x$$

$$\Rightarrow \int \lambda(z') U_G(x + 2\theta_c s, y - R_1 x - R_2 p_x; s) ds$$

x-y resonances appear.

# Crab waist implementation

- $\theta_c$: 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.

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

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

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

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

$$= c_{w1} x^* p_y^{*2} + c_{w2} p_x^* p_y^{*2} + \cdots$$

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

See page 7-8

# 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 |

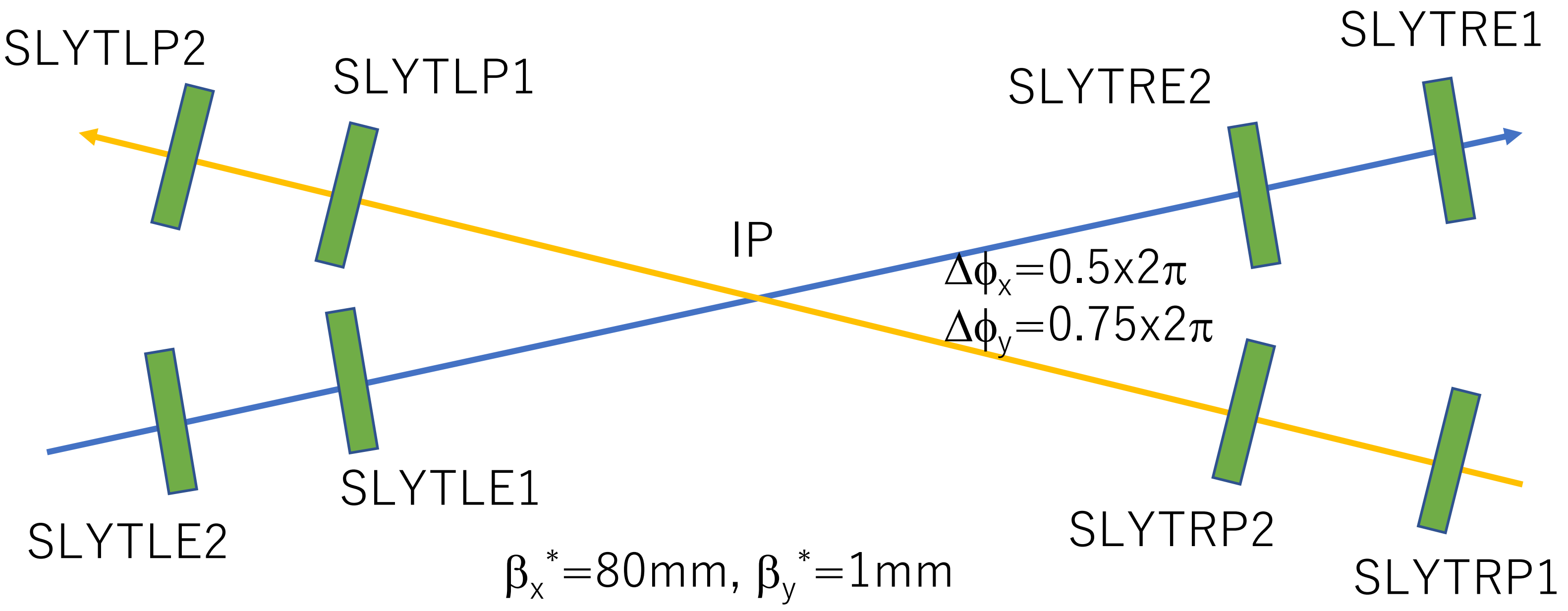
$\beta_x^*$=60mm, $\beta_y^*$=1mm

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




| | $K_2(m^{-2})$ | | $K_2(m^{-2})$ |
|---|---|---|---|
| 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 |

K2(SLY*1)=K2(SLY*2) in the design. Crab waist is realized by detuning the SLY's.

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

Design β

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

# 3rd order terms at IP in LER Crab waist

$\beta_y^*$=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, $P_xP_y^2$.

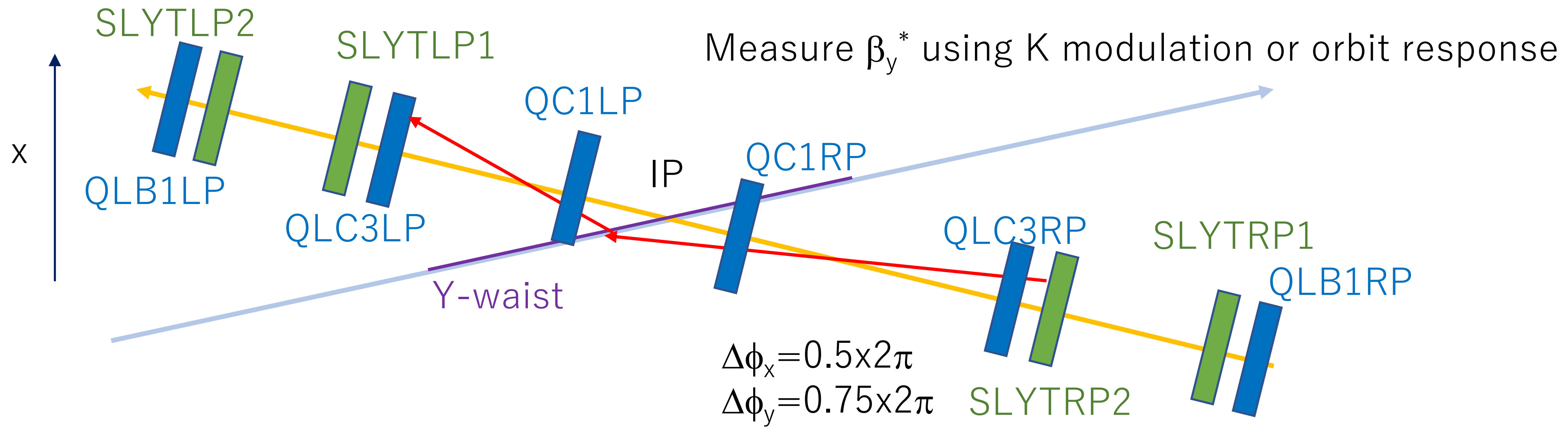
# Measurement of Crabbing waist

- 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.

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

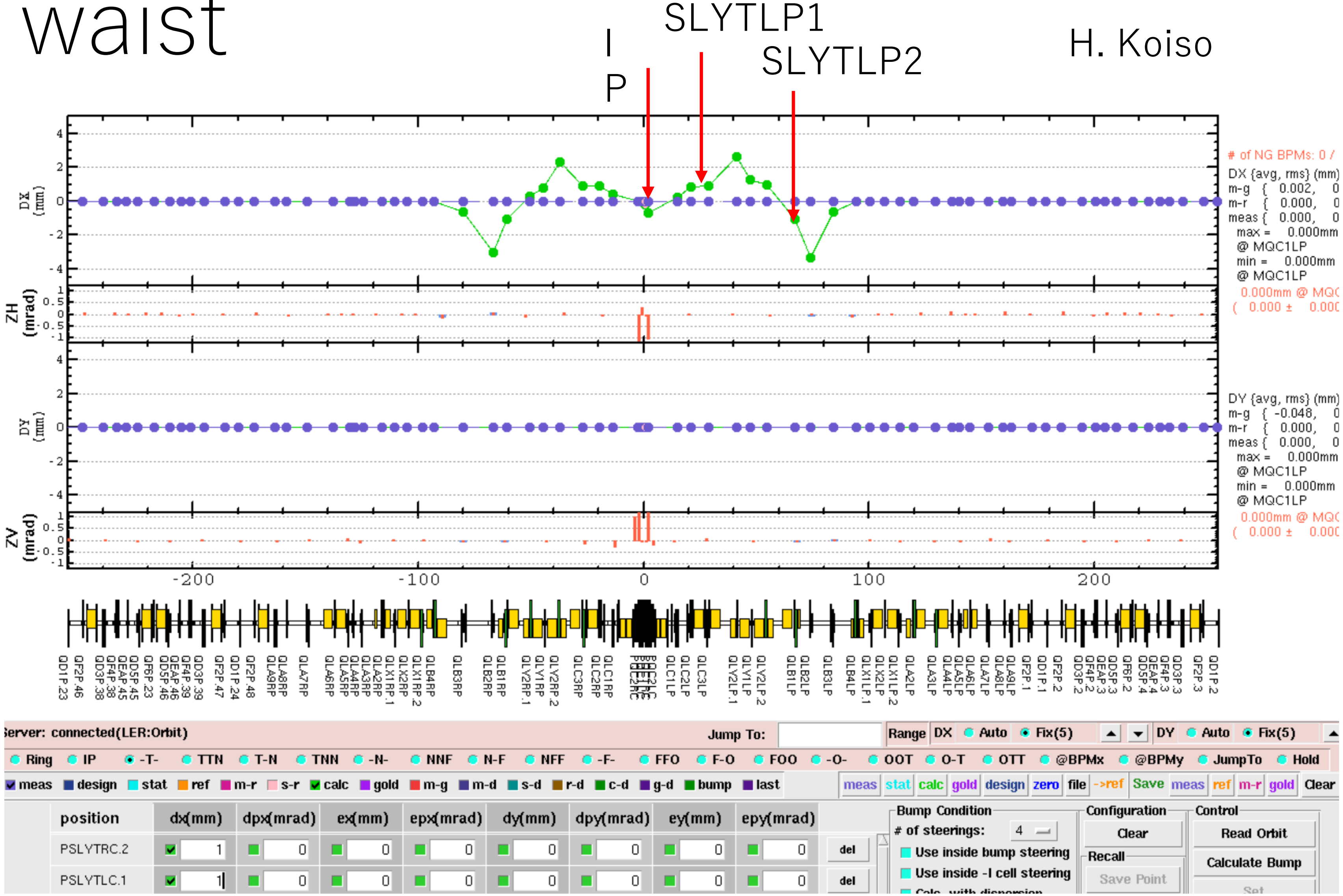
$$\delta x^* = 0.12mm \ @\beta_x^* = 0.08m$$

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



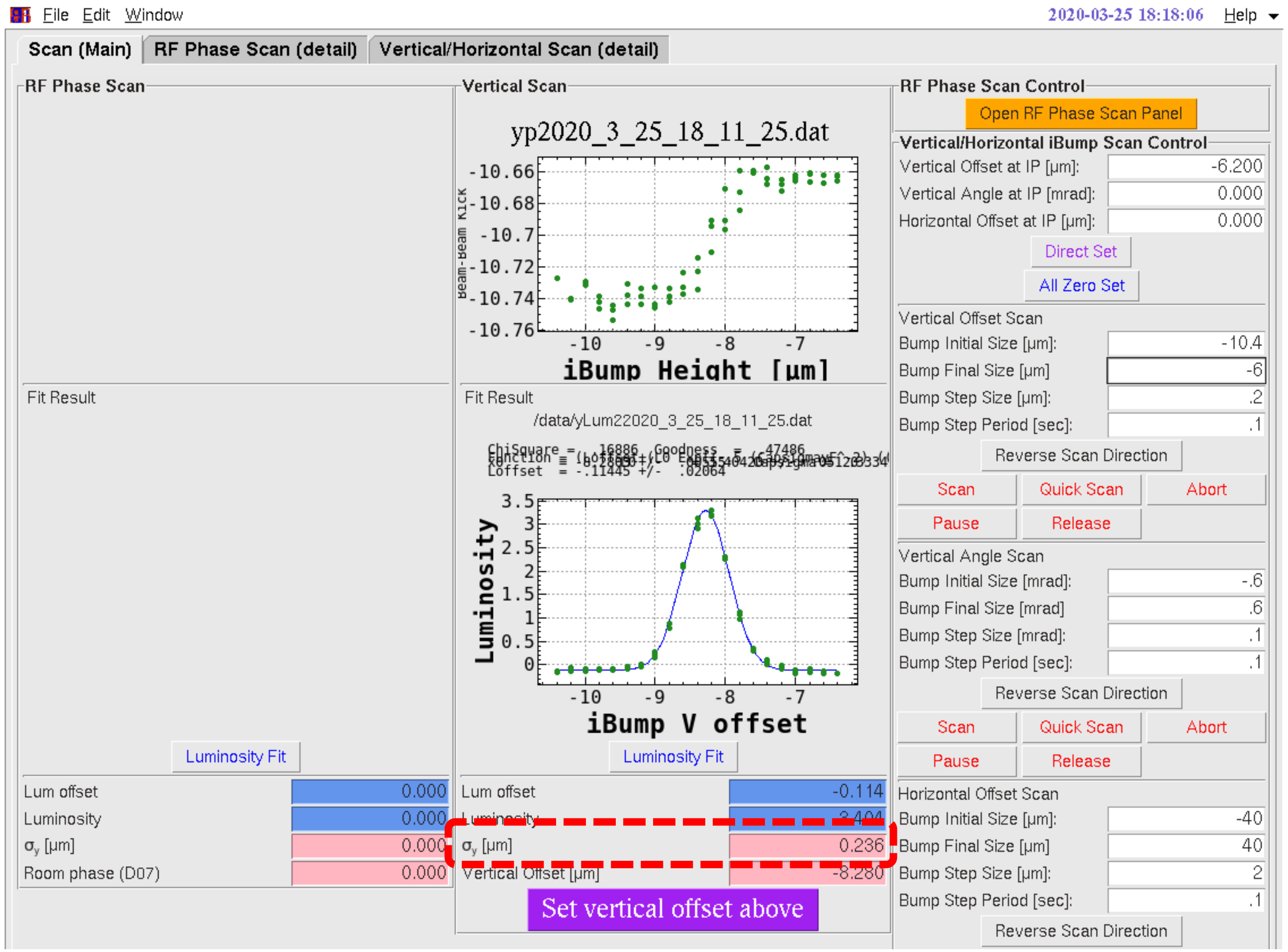
# Closed bump to create crabbing waist

H. Koiso

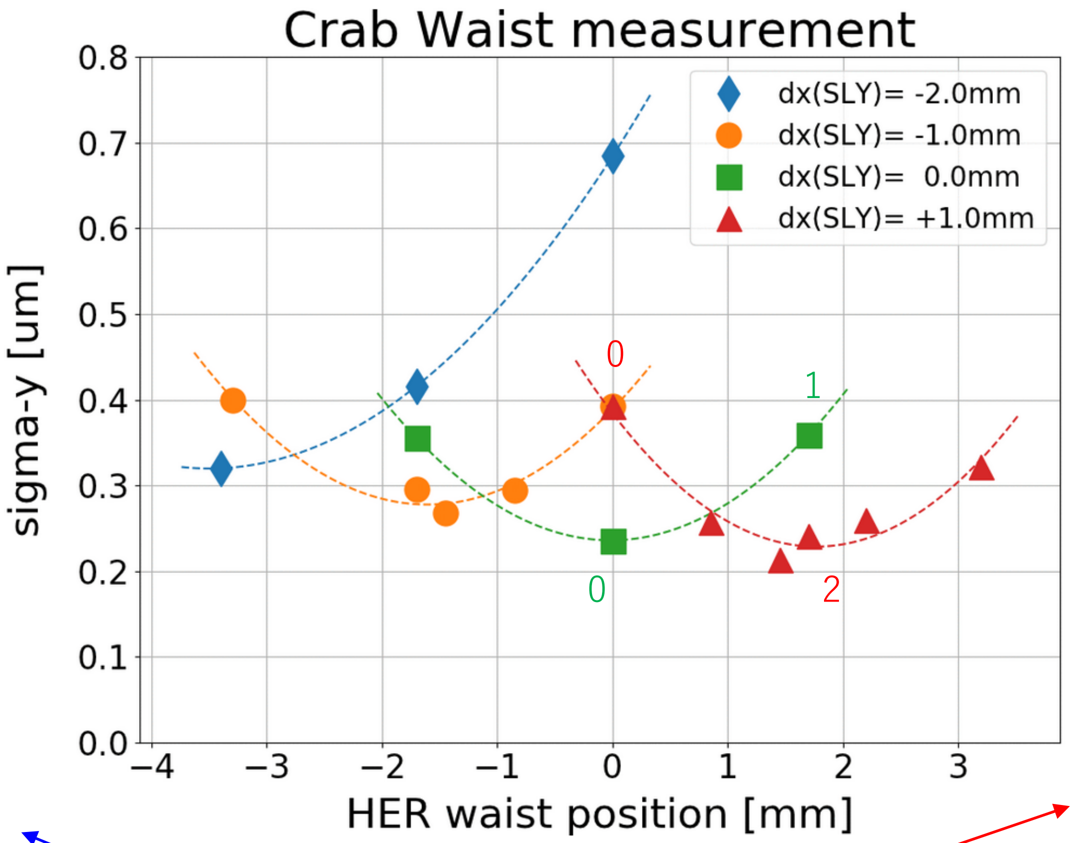


# V-offset scan

- Σy measured by V-offset scan.



# Crab Waist measurement

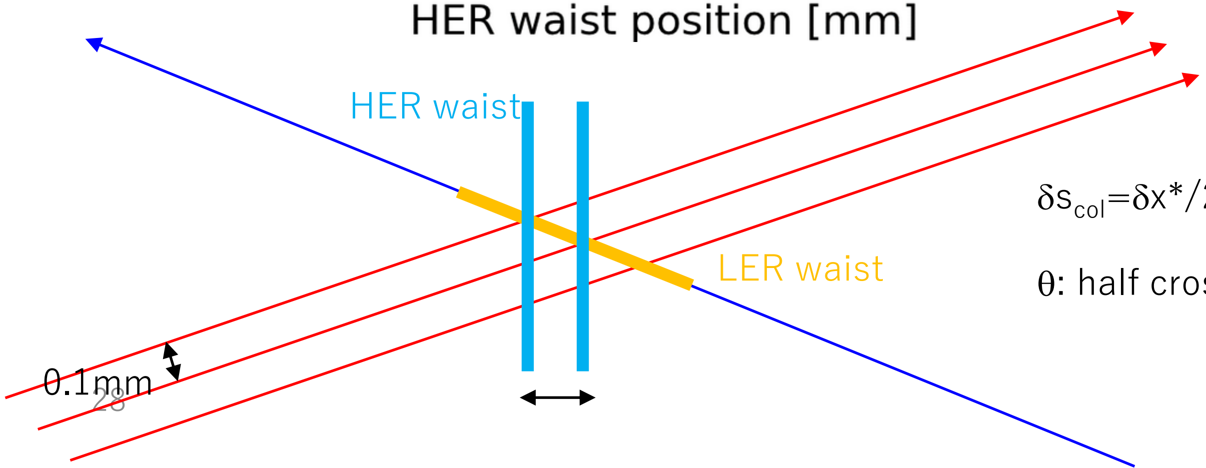



For different LER IP orbit offset dx(SLY), HER waist position changed and Σy/sqrt(2) measured.

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



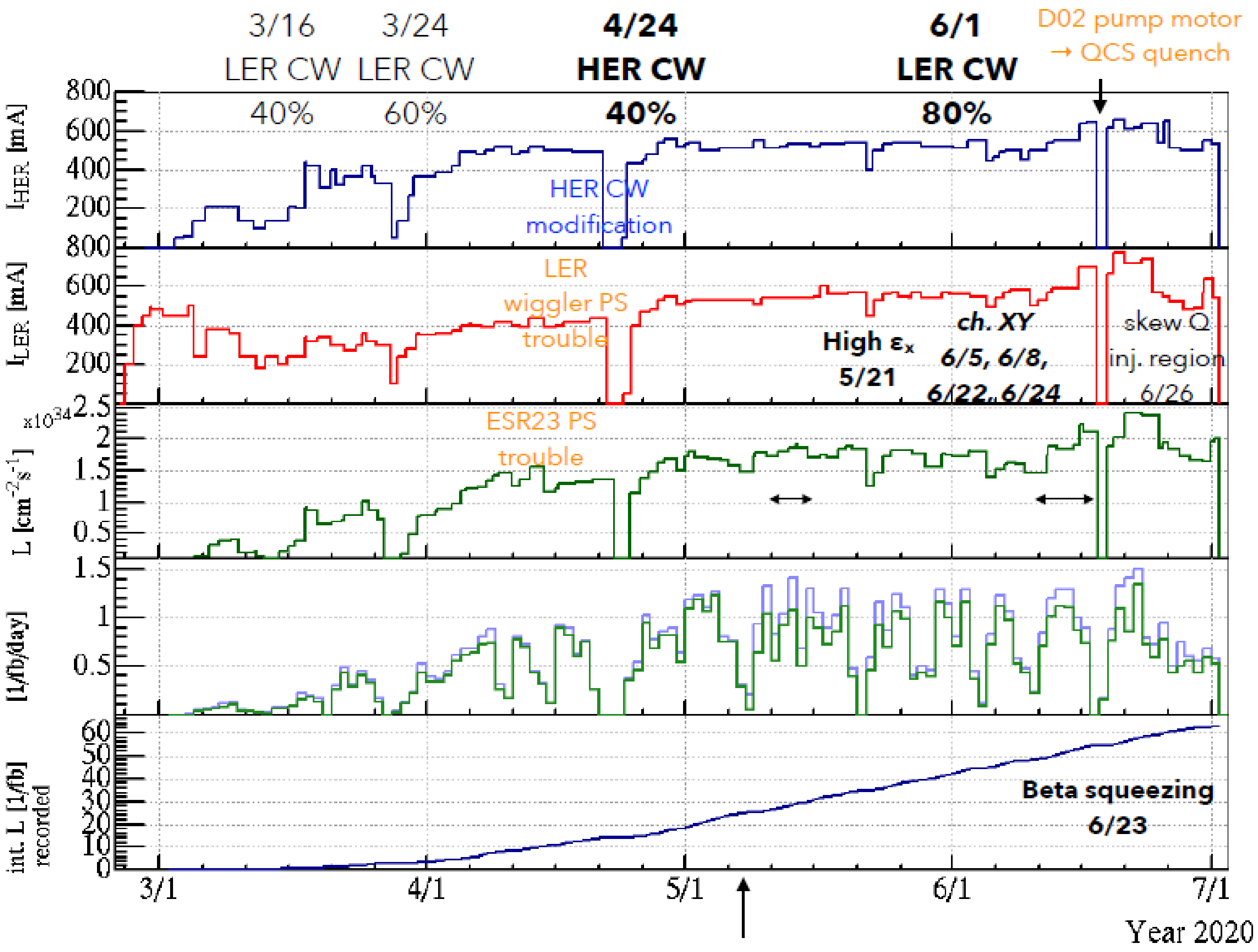

$\delta s_{col} = \delta x^*/2\theta = 1.45\text{mm}$

θ: half crossing angle

$$\sigma_x^* = 0.018mm$$

Y. Ohnishi, KEKB Rev. 2020

# Operation Summary




Remarks : ECL online luminosity does not include trigger veto dead time before May 7.

LER started on Feb. 25

HER started on March. 2

**Max. current**
**LER : 770 mA**
**HER : 660 mA**

**Peak luminosity : 2.4 x 10$^{34}$ cm$^{-2}$s$^{-1}$**

**Int. luminosity/day : 1.346 / 1.498 fb$^{-1}$**

5/11-5/14 off-resonance

6/10-6/17 off-resonance

**LER :**

$$\beta_x^*/\beta_y^* = 80\ mm/1\ mm$$
$$\rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

**HER :**

$$\beta_x^*/\beta_y^* = 60\ mm/1\ mm$$
$$\rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

# Machine Parameters (I)

| | 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 |
| **Lifetime** | 760 | 1270 | 522 | 1393 | sec |
| **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 $\nu_x$ / $\nu_y$** | 44.523 / 46.581 | 45.531 / 43.577 | 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** | 10.7 | 12.7 | 15.1 | 12.7 | |
| **Crab waist ratio** | 80 | 40 | 0 | 0 | % |
| **Beam-Beam parameter $\xi_y$** | 0.0389 | 0.0261 | 0.0281 | 0.0193 | |
| **Specific luminosity** | $5.43 \times 10^{31}$ | | $4.91 \times 10^{31}$ | | $cm^{-2}s^{-1}/mA^2$ |
| **Luminosity** | $2.40 \times 10^{34}$ | | $1.14 \times 10^{34}$ | | $cm^{-2}s^{-1}$ |

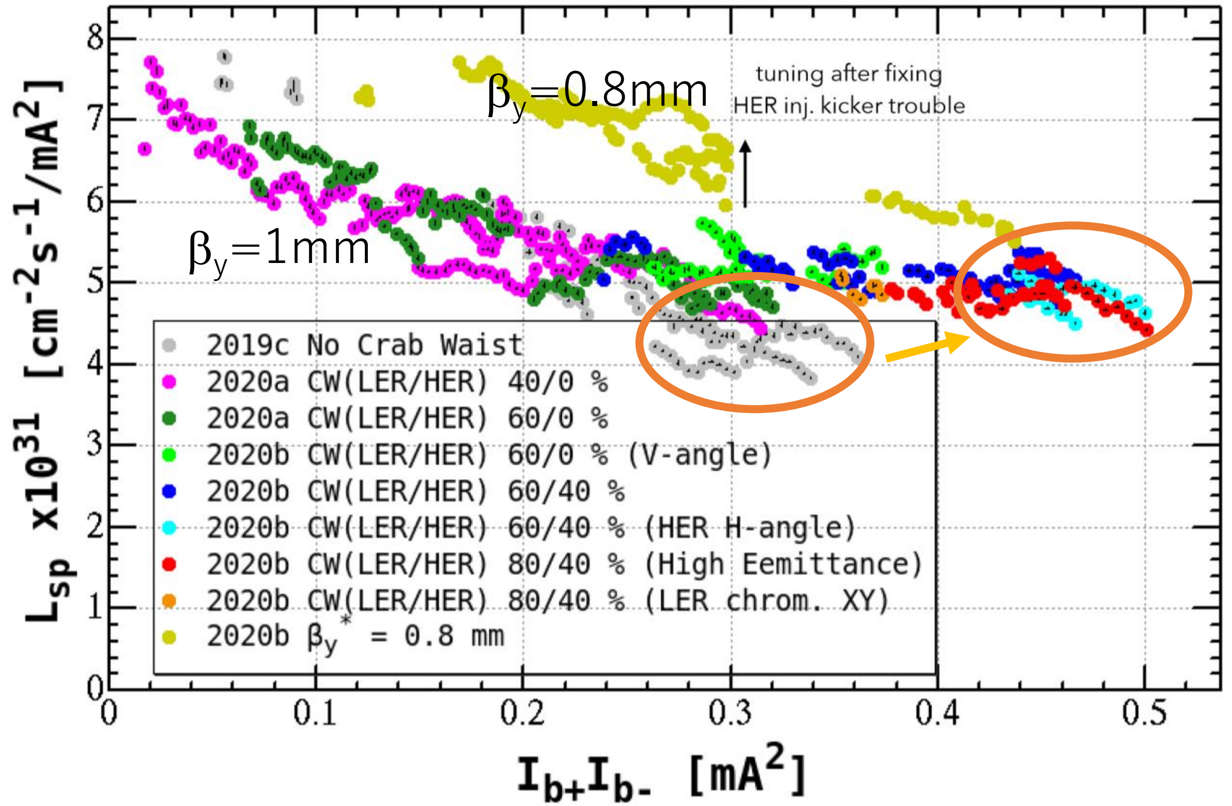
*1) estimated by luminosity with assuming design bunch length

*2) divide *1 by √2

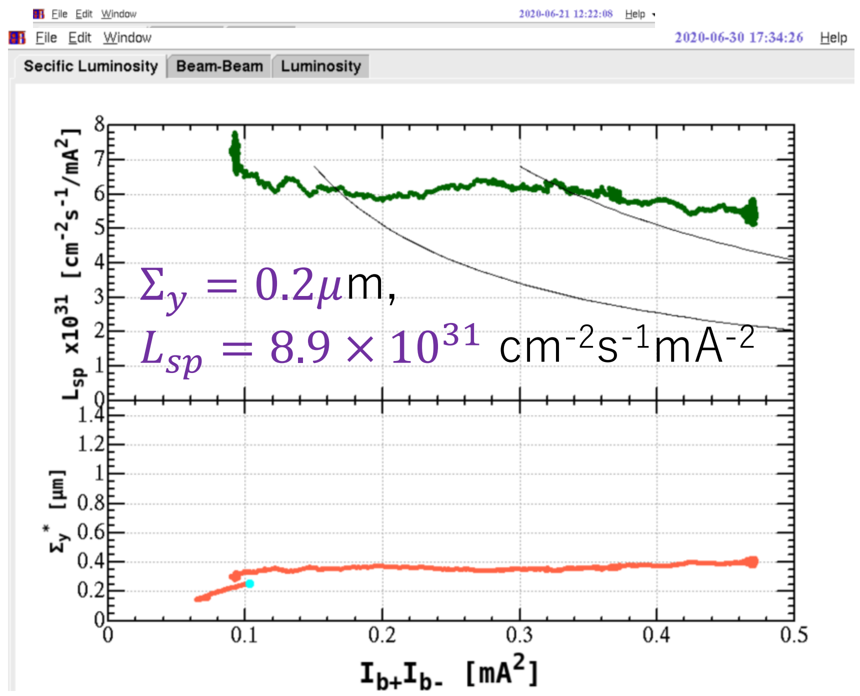
# Luminosity performance in the crab waist operation

- 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.

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

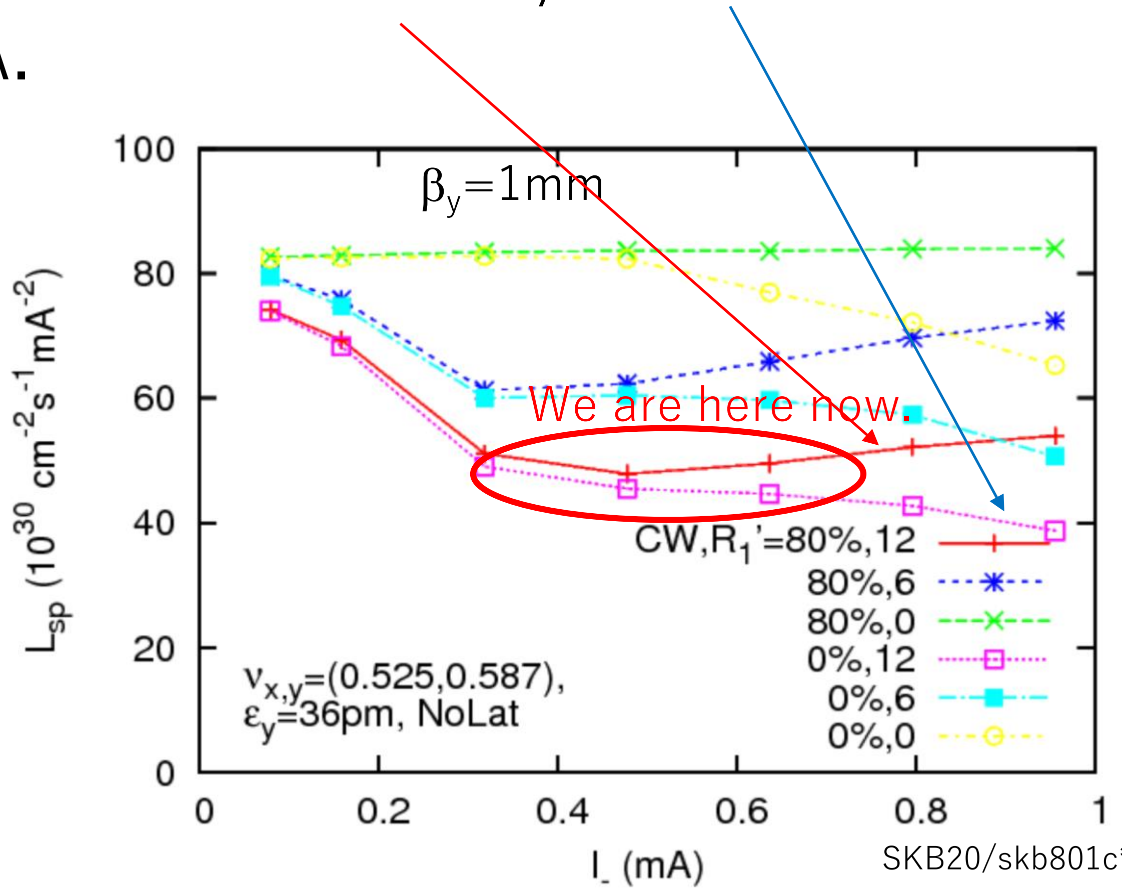



2019



# 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*

# Crab waist collision

- Crab waist gave good beam-beam performance, but not very drastic.
- More gain of crab waist should be given by higher bunch current.
- High current, higher bunch current and further $\beta^*$ squeeze are limited by detector background.
- $L=2.40\times10^{34}$ cm$^{-2}$s$^{-1}$
- $L_{sp}=5.43\times10^{31}$ cm$^{-2}$s$^{-1}$/mA$^2$
- $\xi_{n,\pm} = \frac{2r_e\beta_{y,\pm}L}{\gamma_\pm N_\pm f_{col}}$ = 0.0389, 0.0261

e- tune shift is limited by e+ beam blow-up.

Thank you for your attention

# K modulation

- QC1 s=L*=900mm, waist shift δs=1mm.

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

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

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

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

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

$$\Delta\nu = 0.01$$

$\delta\Delta\nu = 0.5 \times 10^{-4}$ 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

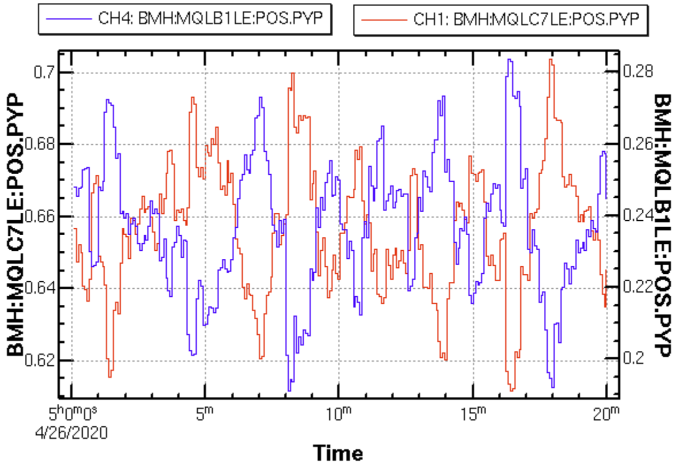
$$\delta R_1^* = \Delta K_{2,SLY}\,\delta y_{SLY1,0}\sqrt{\frac{\beta_{x,SLY}}{\beta_x^*}}\sqrt{\beta_{y,SLY}\beta_y^*}$$

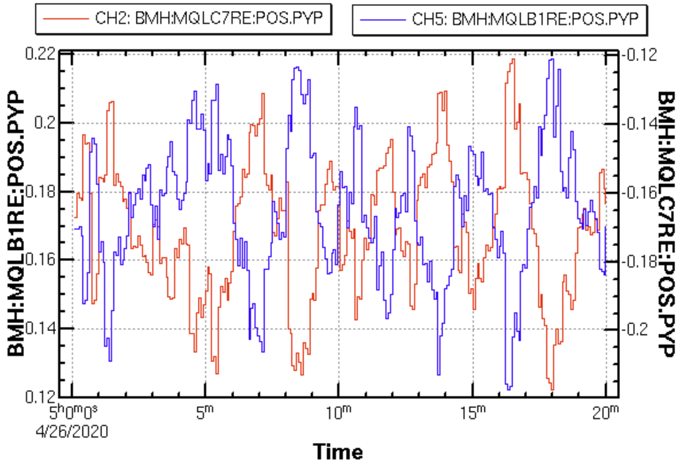
$$\delta y_{SLYE} = 0.08mm$$

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

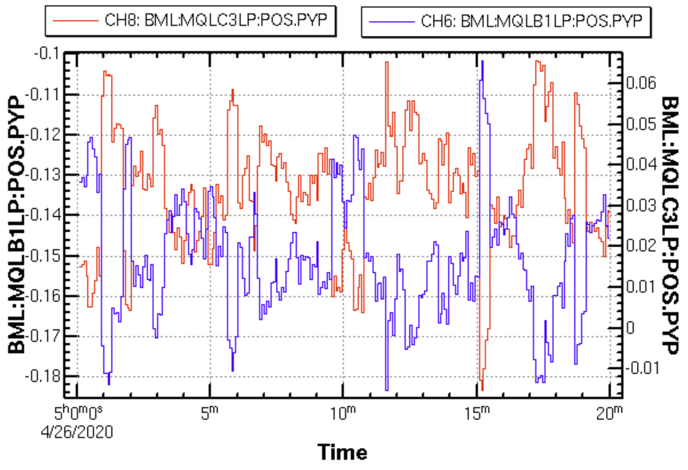
$$\delta y_{SLYP} = 0.09mm$$

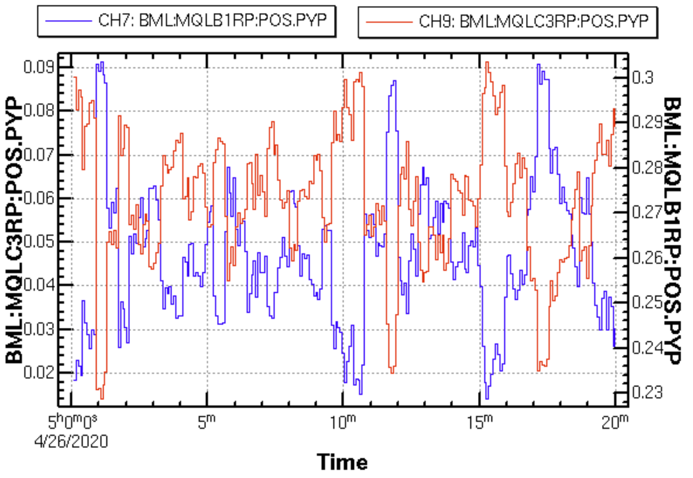
CW60%

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

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

Not large but visible



# Beam-beam potential with coupling and crab waist

- Crossing angle

$$U_{bb} = \int \lambda(z')U_G(x+\theta_c(z-z'), y+p_y s; s)ds \qquad s=(z-z')/2$$

$$e^{-:H_{cw}:}e^{-:R:}U_{bb}e^{:R:}e^{:H_{cw}:} \rightarrow$$

1. $y_w = y^* + x^* p_y^*/(2\theta_c) \qquad p_{xw} = p_x^* - p_y^{*2}/(4\theta_c)$
2. $y = r_0 y_w - R_1 x^* - R_2 p_{xw} \qquad p_y = p_y^* - R_3 x^* - R_4 p_{xw}$
3. $\int \lambda(z')U_G(x^* + 2\theta_c s, y + p_y s)ds$

$$y + p_y s = r_0\left(y^* + \frac{x^* p_y^*}{2\theta_c}\right) - R_1 x^* - R_2\left(p_x^* - \frac{p_y^{*2}}{4\theta_c}\right) + \left\{p_y^* - R_3 x^* - R_4\left(p_x^* - \frac{p_y^{*2}}{4\theta_c}\right)\right\}s$$

$$\frac{\partial x}{\partial J_x} = \frac{\partial x^*}{\partial J_x} \equiv x_J^* \qquad \frac{\partial y}{\partial J_x} = \frac{r_0}{2\theta_c}x_J^* p_y^* - (R_1 + R_3 s)x_J^* - (R_2 + R_4 s)p_{x,J}^* \qquad x_J^* = \frac{\partial x^*}{\partial J_x}$$

$$\frac{\partial x}{\partial J_y} = 0 \qquad \frac{\partial y}{\partial J_y} = r_0\frac{\partial y^*}{\partial J_y} + \frac{x^*}{2\theta_c}\frac{\partial p_y^*}{\partial J_y} \equiv r_0(y_J^* + p_{y,J}^* s) + \frac{x^*}{2\theta_c}p_{y,J}^* - \frac{R_2 + R_4 s}{2\theta_c}p_y^* p_{y,J}^*$$

# U differentials

$$\frac{\partial U_G}{\partial J_x} = \frac{\partial x}{\partial J_x}\frac{\partial U_G}{\partial x} + \frac{\partial y}{\partial J_x}\frac{\partial U_G}{\partial y}$$

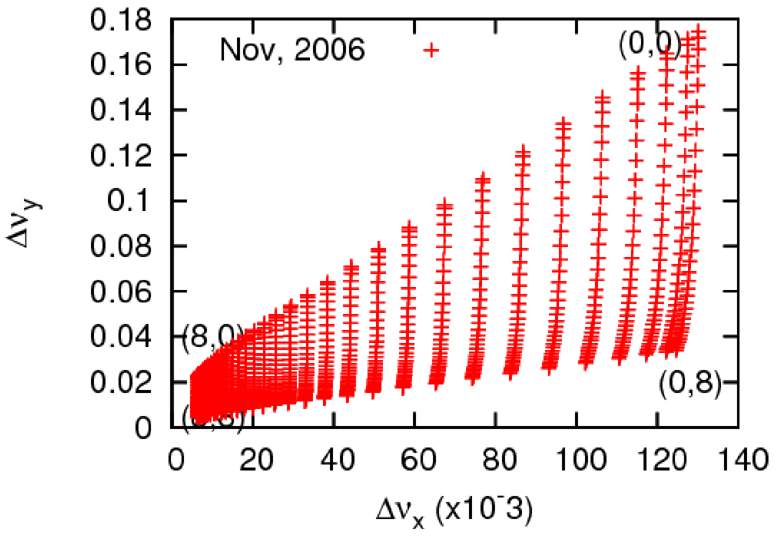
$$\frac{\partial U_G}{\partial J_y} = \frac{\partial x}{\partial J_y}\frac{\partial U_G}{\partial x} + \frac{\partial y}{\partial J_y}\frac{\partial U_G}{\partial y}$$

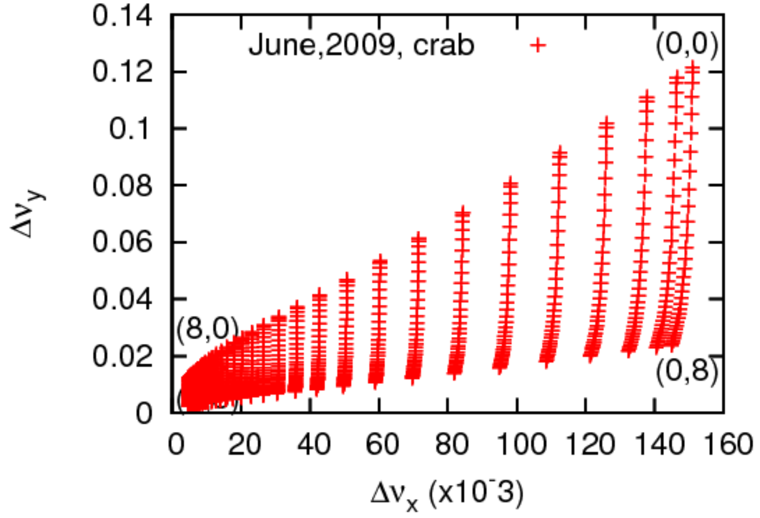
$$\frac{\partial^2 U_G}{\partial J_x^2} = \frac{\partial^2 x}{\partial J_x^2}\frac{\partial U_G}{\partial x} + \frac{\partial^2 y}{\partial J_x^2}\frac{\partial U_G}{\partial y} + \left(\frac{\partial x}{\partial J_x}\right)^2 \frac{\partial^2 U_G}{\partial x^2} + 2\frac{\partial x}{\partial J_x}\frac{\partial y}{\partial J_x}\frac{\partial^2 U_G}{\partial x \partial y} + \left(\frac{\partial y}{\partial J_x}\right)^2 \frac{\partial^2 U_G}{\partial y^2}$$

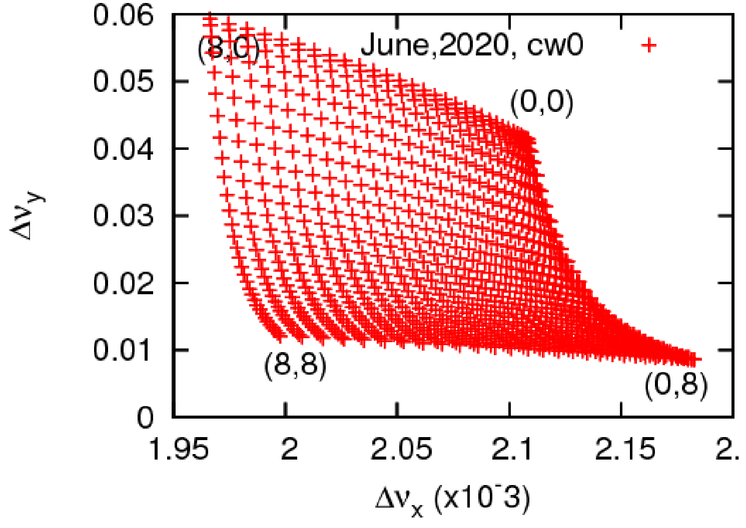
$$\frac{\partial^2 U_G}{\partial J_y^2} = \frac{\partial^2 x}{\partial J_y^2}\frac{\partial U_G}{\partial x} + \frac{\partial^2 y}{\partial J_y^2}\frac{\partial U_G}{\partial y} + \left(\frac{\partial x}{\partial J_y}\right)^2 \frac{\partial^2 U_G}{\partial x^2} + 2\frac{\partial x}{\partial J_y}\frac{\partial y}{\partial J_y}\frac{\partial^2 U_G}{\partial x \partial y} + \left(\frac{\partial y}{\partial J_y}\right)^2 \frac{\partial^2 U_G}{\partial y^2}$$

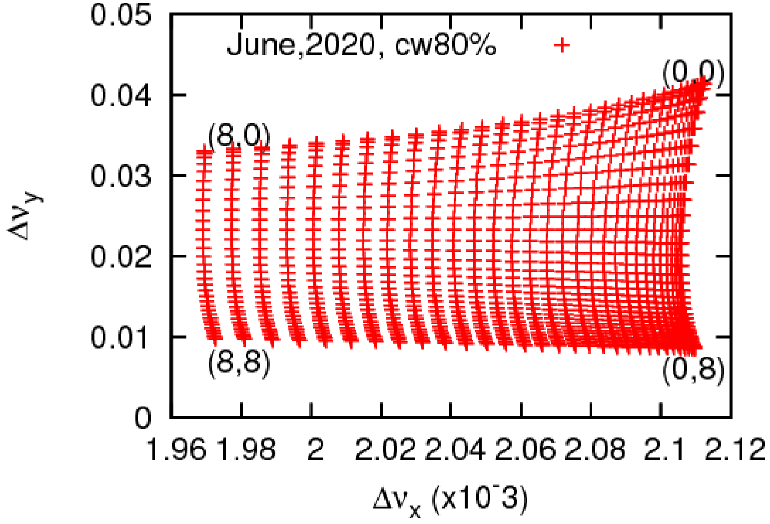
$$\frac{\partial^2 U_G}{\partial J_x \partial J_y} = \frac{\partial^2 y}{\partial J_x \partial J_x}\frac{\partial U_G}{\partial y} + \frac{\partial x}{\partial J_x}\frac{\partial y}{\partial J_y}\frac{\partial^2 U_G}{\partial x \partial y} + \frac{\partial y}{\partial J_x}\frac{\partial y}{\partial J_y}\frac{\partial^2 U_G}{\partial y^2}$$

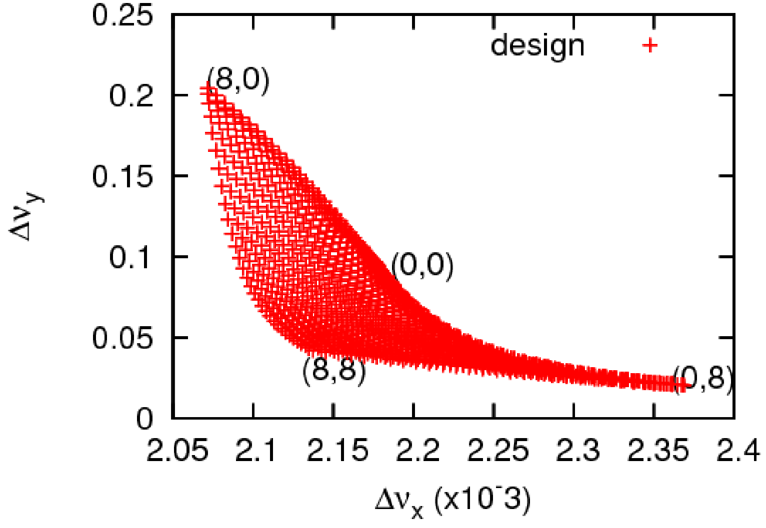
# Tune spread in KEKB and SuperKEKB



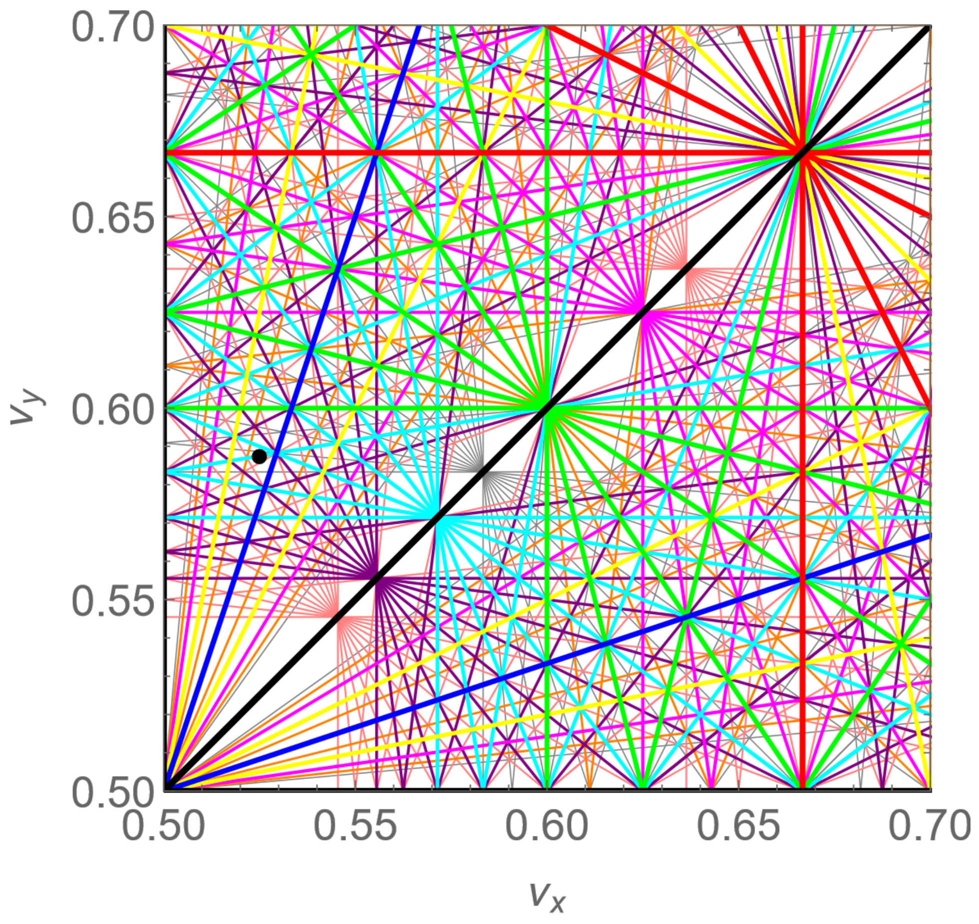



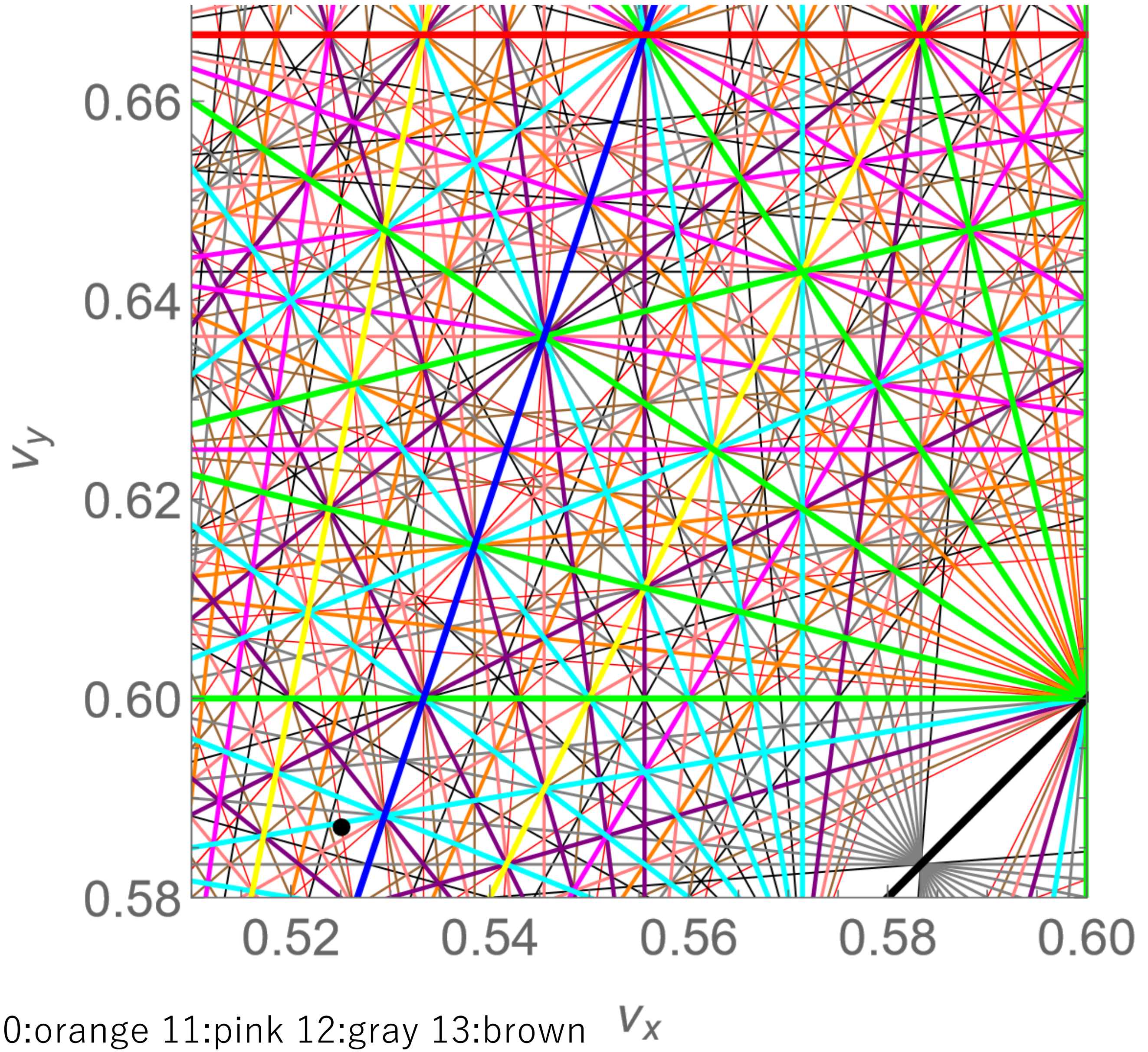



# Why beam-beam blowup in low bunch current collision




- 3:red 4:blue 5:green 6:yellow 7:cyan 8:magenta 9:purple 10:orange 11:pink 12:gray 13:brown

# Resonance width for $\nu_x + 4\nu_y = 3$ w/wo crab waist

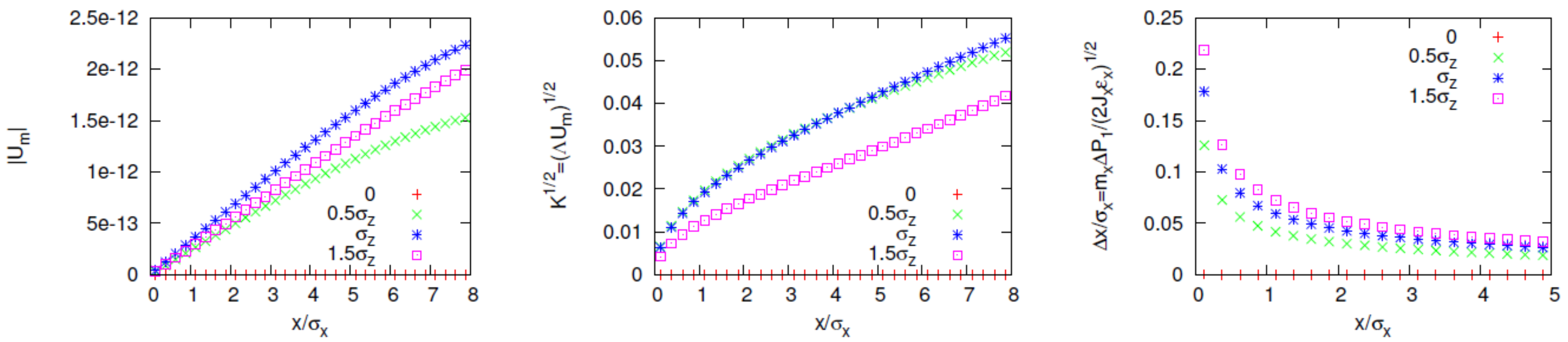


Figure: Resonance without crab waist.

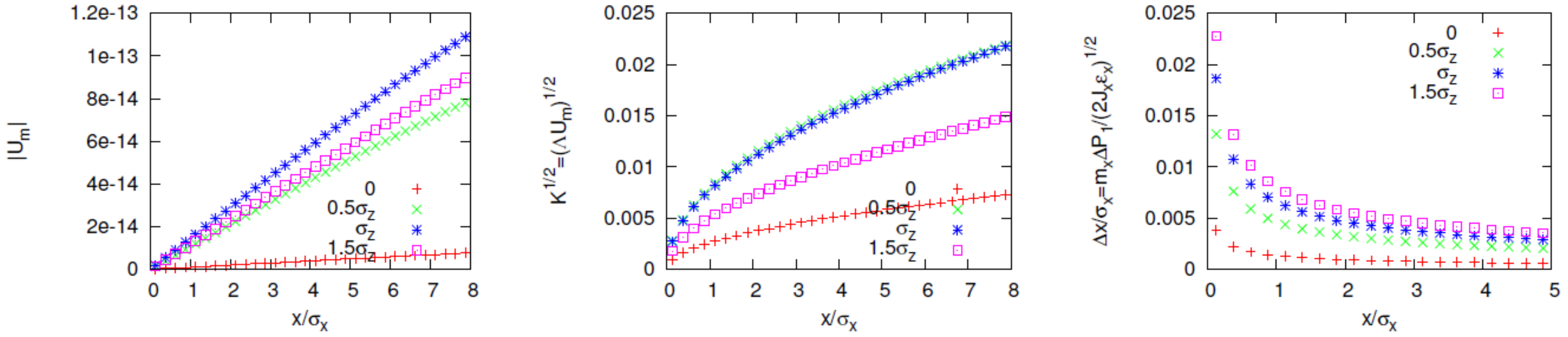
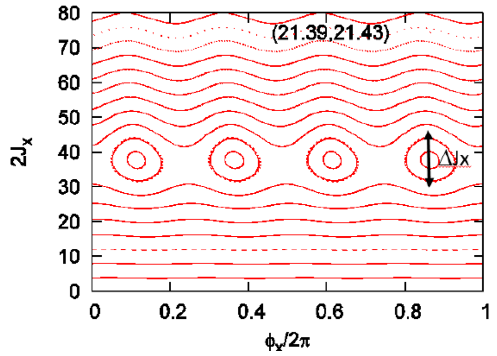


Figure: Resonance with crab waist.

Resonance width: Island width in phase space.




K. Ohmi, Joint Acc. School 2019, Dubna

The resonance width with crab waist is one order lower than that without crab waist.

# Beam-beam induced resonance in the presence of IP coupling

- X-y coupling resonances are induced.

$$T_{rev}e^{-:R:}e^{-:U_{bb}(\boldsymbol{X}):}e^{-:R:} = T_{rev}e^{-:U_{bb}(e^{-:R:}\boldsymbol{X}):}$$

$R(\boldsymbol{X}) = -R_1 x p_y - R_2 p_x p_y + R_3 xy + R_4 p_x y$ $\boldsymbol{X} = (x, p_x, y, p_y, z, \delta)$ at IP

$$e^{-:U_{bb}(e^{-:R:}\boldsymbol{X}):} = \int \lambda(z')U_G\big(x + 2\theta_c s, y - R_1 x - R_2 p_x + (p_y - R_3 x - R_4 p_x)s; s\big)ds$$

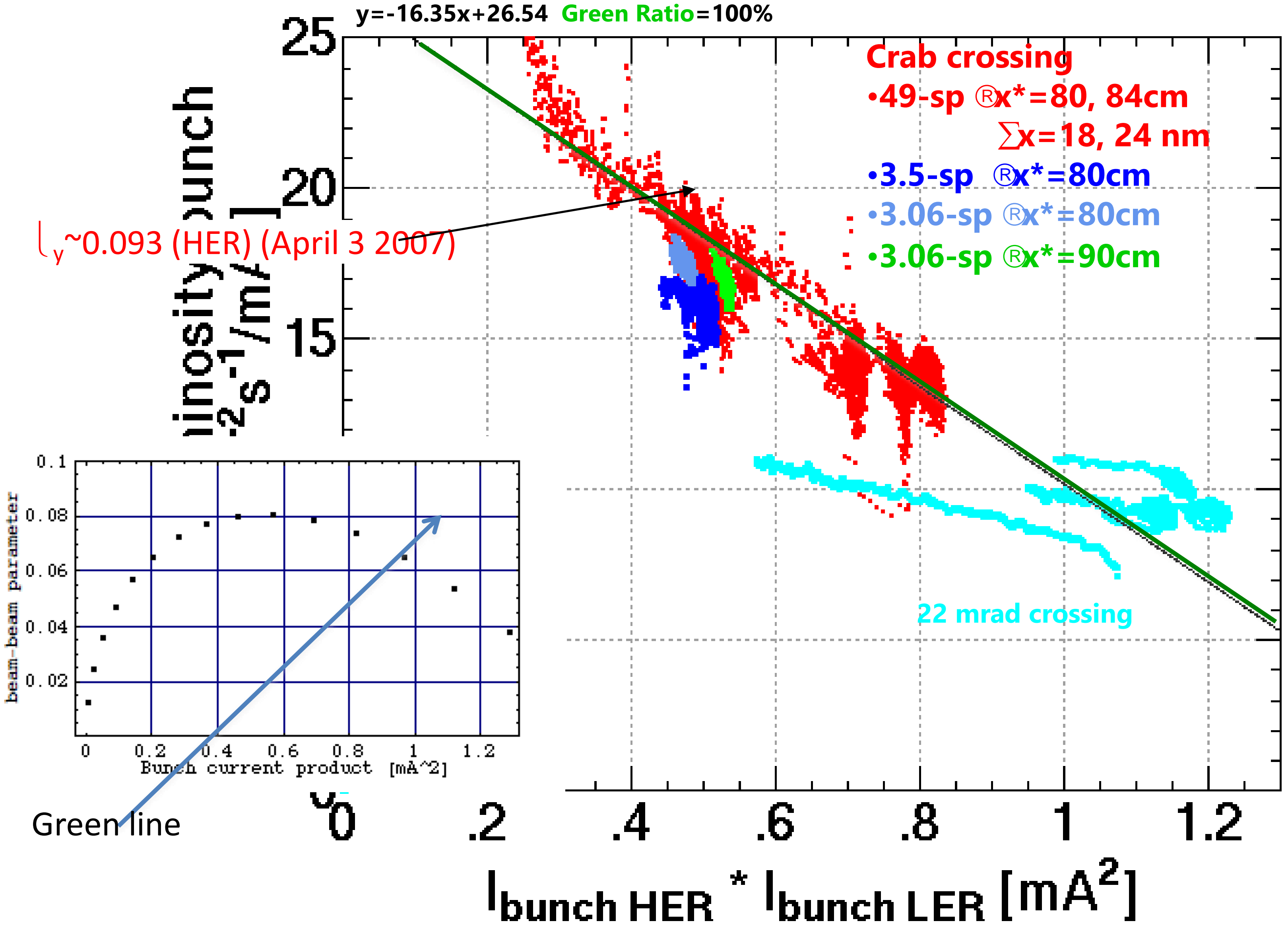
# Beam-beam simulations considering the IR coupling at SLY

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

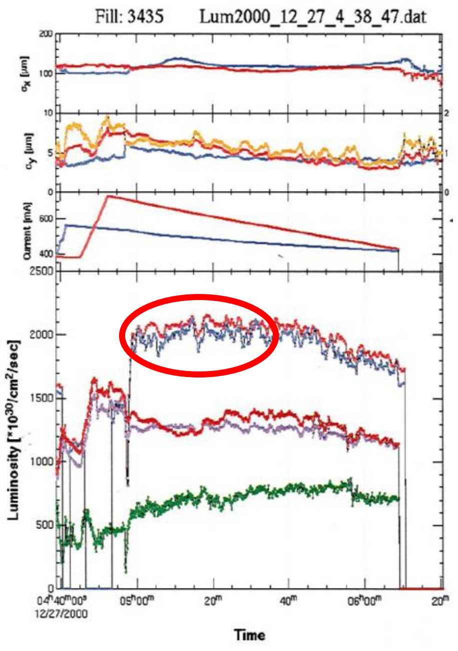
- Beam-beam simulation considering SLY coupling

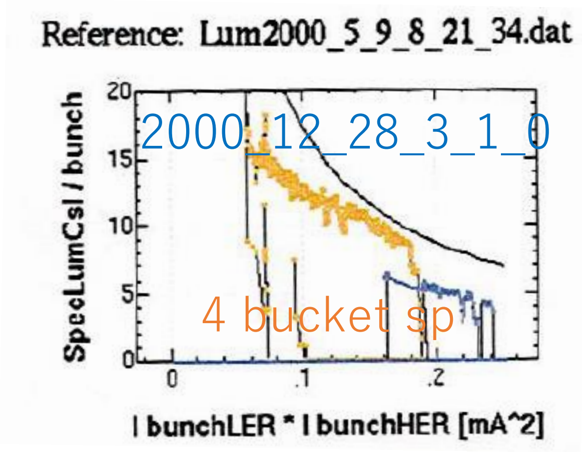
- Chromatic coupling at IP induced in IR area is not considered.

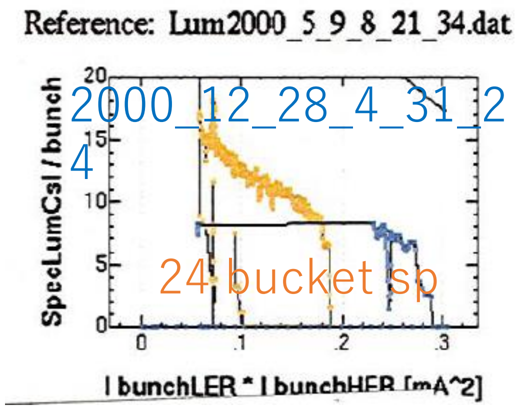
# Specific Luminosity and beam-beam parameter
# Before summer 2008

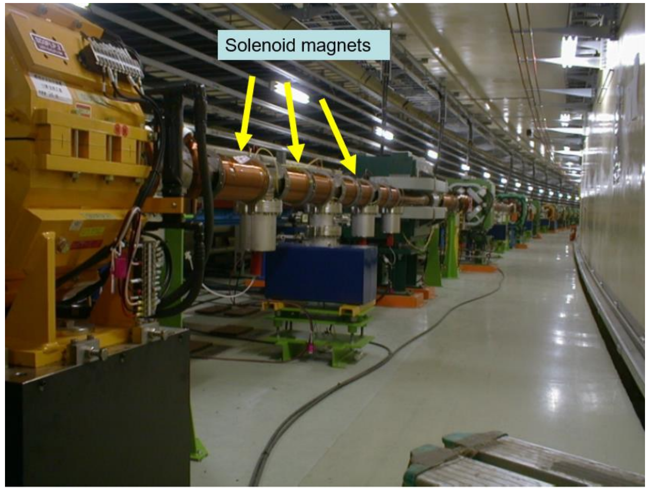


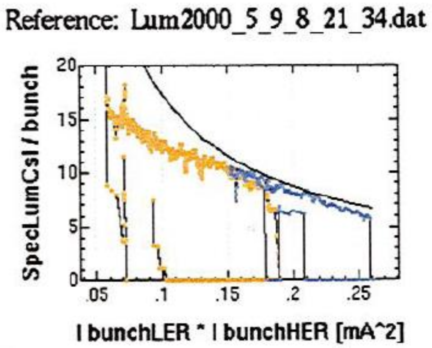
# Electron cloud

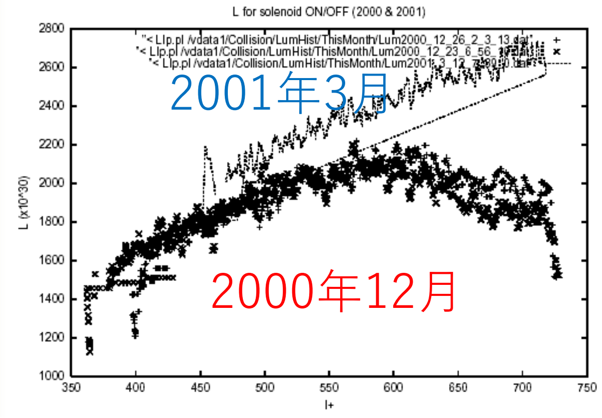


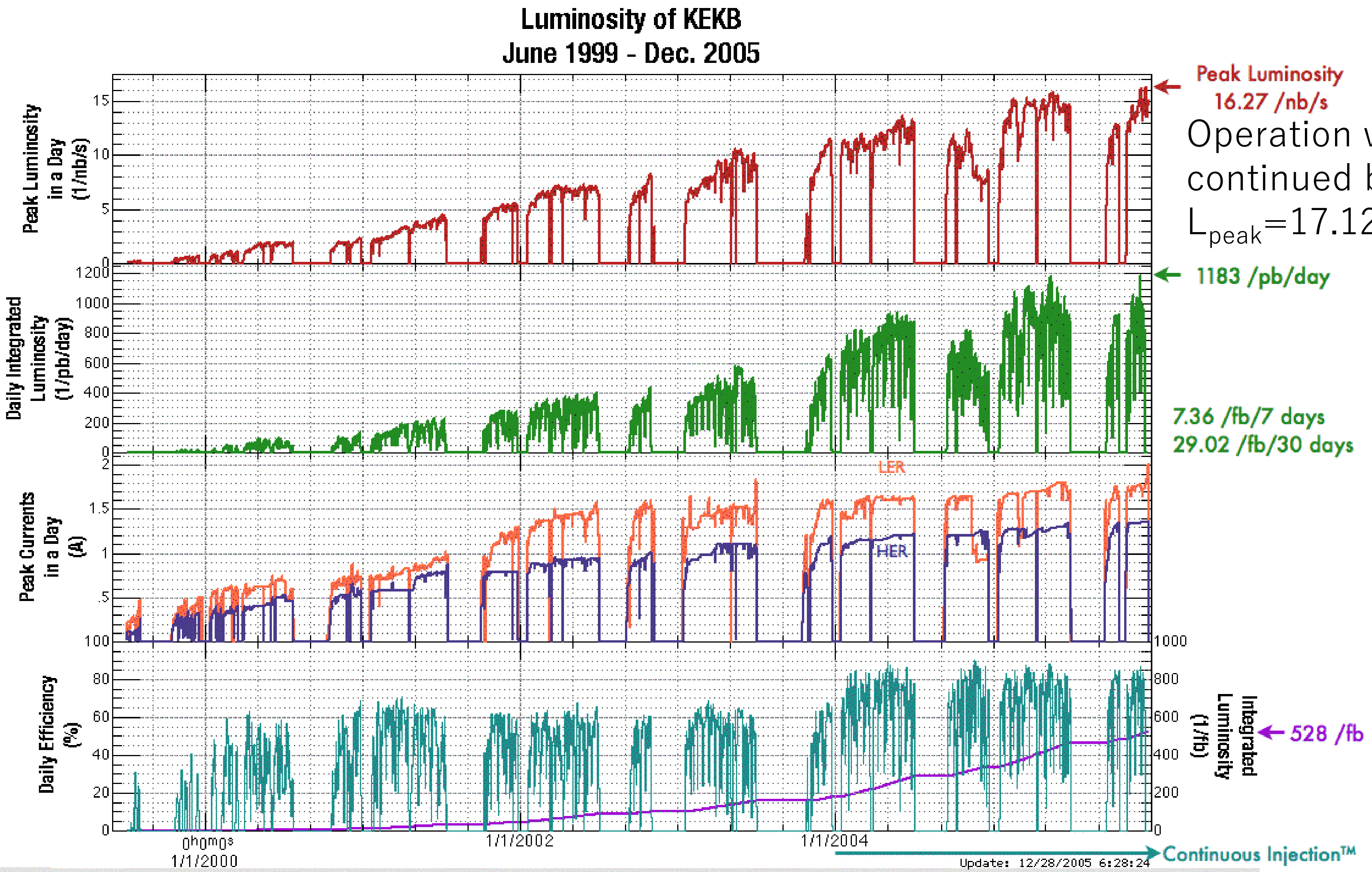




当時の代表的なLsp
Reference: yellow line
当該Fill: blue
2000年末時点では大電流でLumが飽和していた。

# Luminosity history of KEKB, collision with crossing angle 11mrad




Operation with crossing angle had been continued by 2006 June.
$L_{peak}$=17.12/nb/s