Beam-beam issues in SuperKEKB

K. Ohmi, D. Zhou

MAC2019

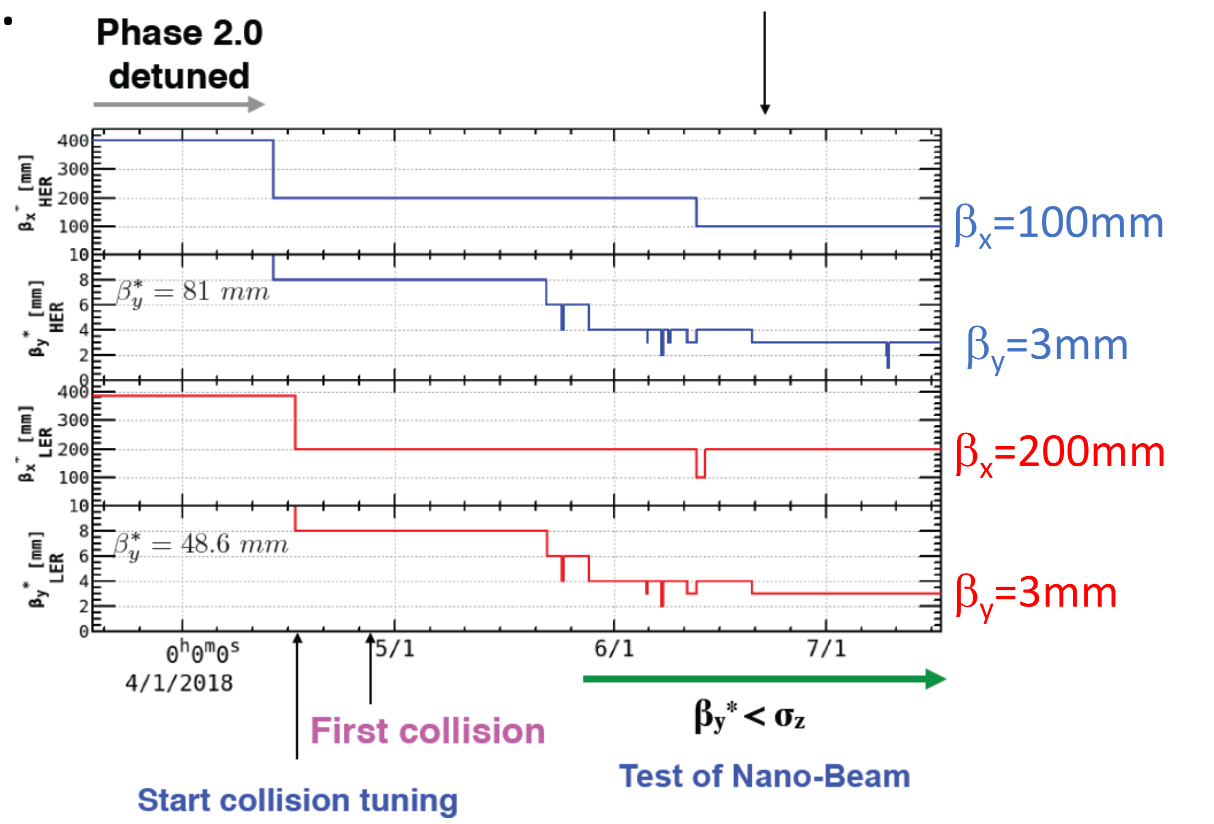
Thanks to Y. Funakoshi, A. Koval, H. Koiso, G. Mitsuka, A. Morita, Y. Ohnishi, H. Sugimoto, R. Yang…, for machine experiments in my(KO) absent, June 23-July 1.

Summary of Phase-2 & 3

- Collision with large Piwinski angle, $\frac{\sigma_z \theta_c}{\sigma_x^*} \geq 10$ has been performed in Phase 2 & 3.
- Squeeze β_y^* step-by-step.
- Beam-beam parameter was kept squeezing β_y^*.
- Squeezing beta contributed the luminosity increase following $L = \frac{\gamma I_\pm \xi_{y\pm}}{2 e r_e \beta_y^*}$.
- Luminosity 10^{34} $cm^{-2}s^{-1}$ was achieved at the end of Phase-3.
- Beam-beam parameter has been limited to be ξ_{y-} =0.02 for e- beam due to blow-up of e+ beam.
- Multi-bunch effect in luminosity was weak.

Commissioning of SuperKEKB

- Phase-2 (2018) Start collision installation of Belle 2 detector. Squeeze β_x=200-100, 200mm, β_y=8->6->4->3->2mm.
- Phase-3 (Mar. 2019-) Belle 2 data taking at β_x=100, 200mm, β_y=3mm.
- β_y=2mm, Jun.21.



Luminosity/bunch history in Phase-2

N_{bunch}=788 (398 in July 13)

$$\frac{\sigma_z \theta_c}{\sigma_x^*} = 10$$

$$\xi_L = \frac{2 e r_e \beta_y^*}{\gamma I} L$$

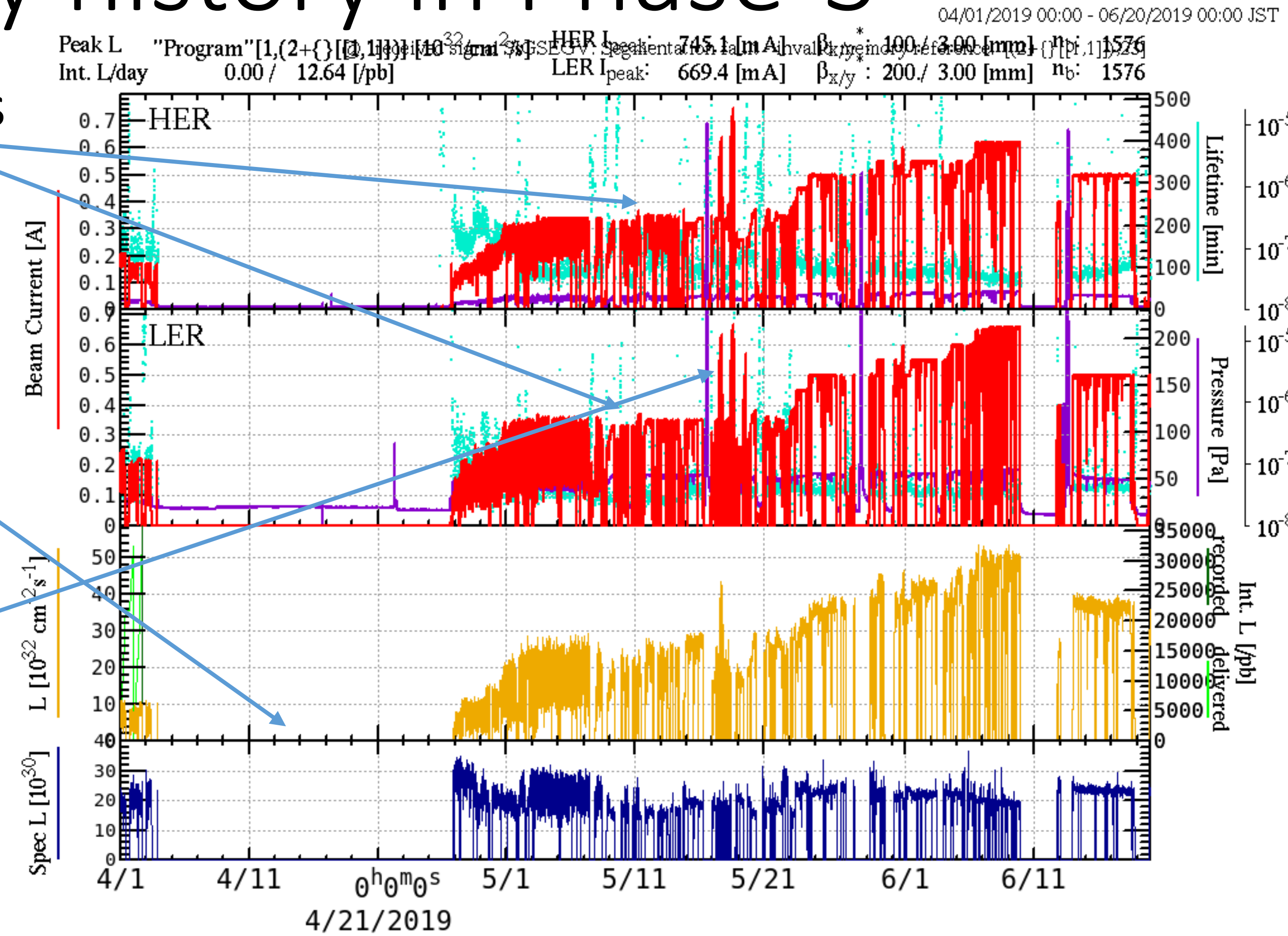
θ_c: half crossing angle

	β_x (mm)	β_y (mm)	L_b (10^{30})	I_b (mA)	ξ_L
Apr,16	200	8	1.55	0.417,0.367	0.0343,0.0223
May,22	200	6	1.73	0.431,0.362	0.0279,0.0190
May,28	200	4	1.73	0.431,0.362	0.0185,0.0126
Jun,8	200	4,3	1.68	0.431,0.362	0.0179,0.0092
Jun,11	200	3	1.33	0.406,0.336	0.0114,0.0078
Jun,12	100	4	1.38	0.431,0.362	0.0148,0.0101
Jun,13	200,100	4	2.59	0.444,0.374	0.0264,0.0179
Jun,20	200,100	3	3.30	0.431,0.362	0.0269,0.0182
July,13	200,100	3	5.78	0.669,0.548	0.0299,0.0209
2019					
Jun, 21	80,80	2			

R_2 correction

Luminosity history in Phase-3

- Increase currents
- Nb=1576.
- Fire trouble
- No collision



- Belle-2 data taking with β_x=100, 200mm, β_y=3mm.
- Peak Luminosity I=617, 644 mA. L=5.49x10^{33} $cm^{-2}s^{-1}$, ¼ of KEKB.
- The beam-beam parameter is 0.0176, 0.0295.
- Accumulate 6 fb^{-1}.

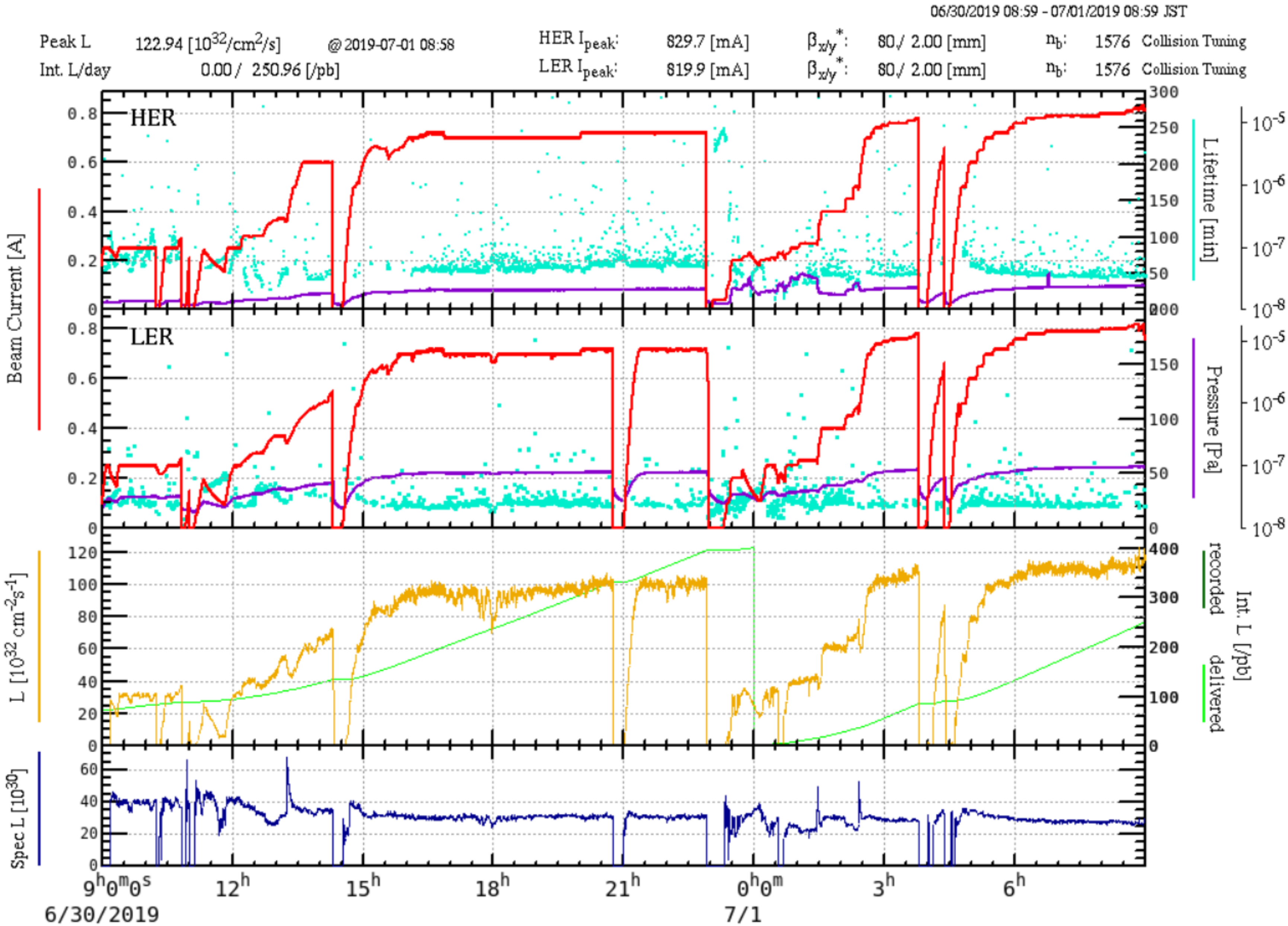
L(KEKB) =21.1x10^{33} $cm^{-2}s^{-1}$

Luminosity/bunch history in Phase-3

- N_{bunch}=1576 (788 in June,26)
- $\frac{\sigma_z \theta_c}{\sigma_x^*} = 10 \rightarrow 15$

2019	β_x (mm)	β_y (mm)	$L_t(10^{34})$	L_b (10^{30})	I_b (mA)	ξ_L	
June,7	200,100	3	0.549	3.48	0.408,0.391	0.0295,0.0176	QCS Vang
June,20	200,100	3	0.470	2.98	0.317,0.317	0.0325,0.0186	
June,26	80,80	2	0.613	7.78	0.508,0.508	0.0353,0.0202	
June,27	200,200	8	0.350	2.22	0.482,0.508	0.0425,0.0231	Study
June,27	200,200	8	0.400	2.54	0.514,0.539	0.0456,0.0248	
June,30	80,80	2	1.03	6.54	0.457,0.457	0.0329,0.0188	
July,1	80,80	2	1.23	7.81	0.520,0.526	0.0346,0.0195	
2018							
July,13	200,100	3	0.229	5.78	0.671,0.549	0.0299,0.0209	
Jun,20	200,100	3	0.260	3.30	0.431,0.362	0.0269,0.0182	

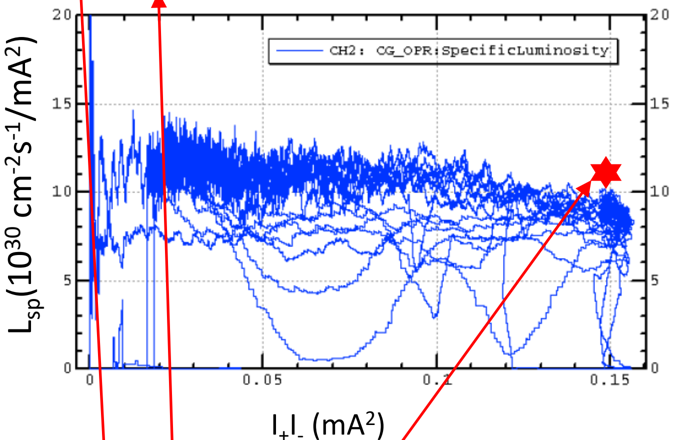
Luminosity on the last day



Linear X-Y coupling correction

- In early stage of Phase-2 commissioning, luminosity was lower than that estimated by emittance (XSRM) at low current.
- Disagreement between σ_y^* and $\sqrt{\varepsilon_y \beta_y^*}$

Before R2 corection

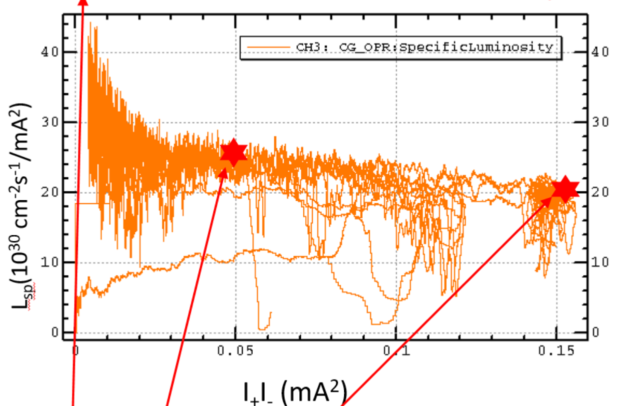


- 0mA, σ_{y0}=0.3μm, 0.4μm, L_{sp}=35
- 200x80mA, σ_{y0}=0.5μm, 0.6μm, L_{sp}=23
- 285x340mA, σ_{y0}=1.5μm, 0.6μm, L_{sp}=11

Lsp disagrees with geo value at low current

After R2 correction

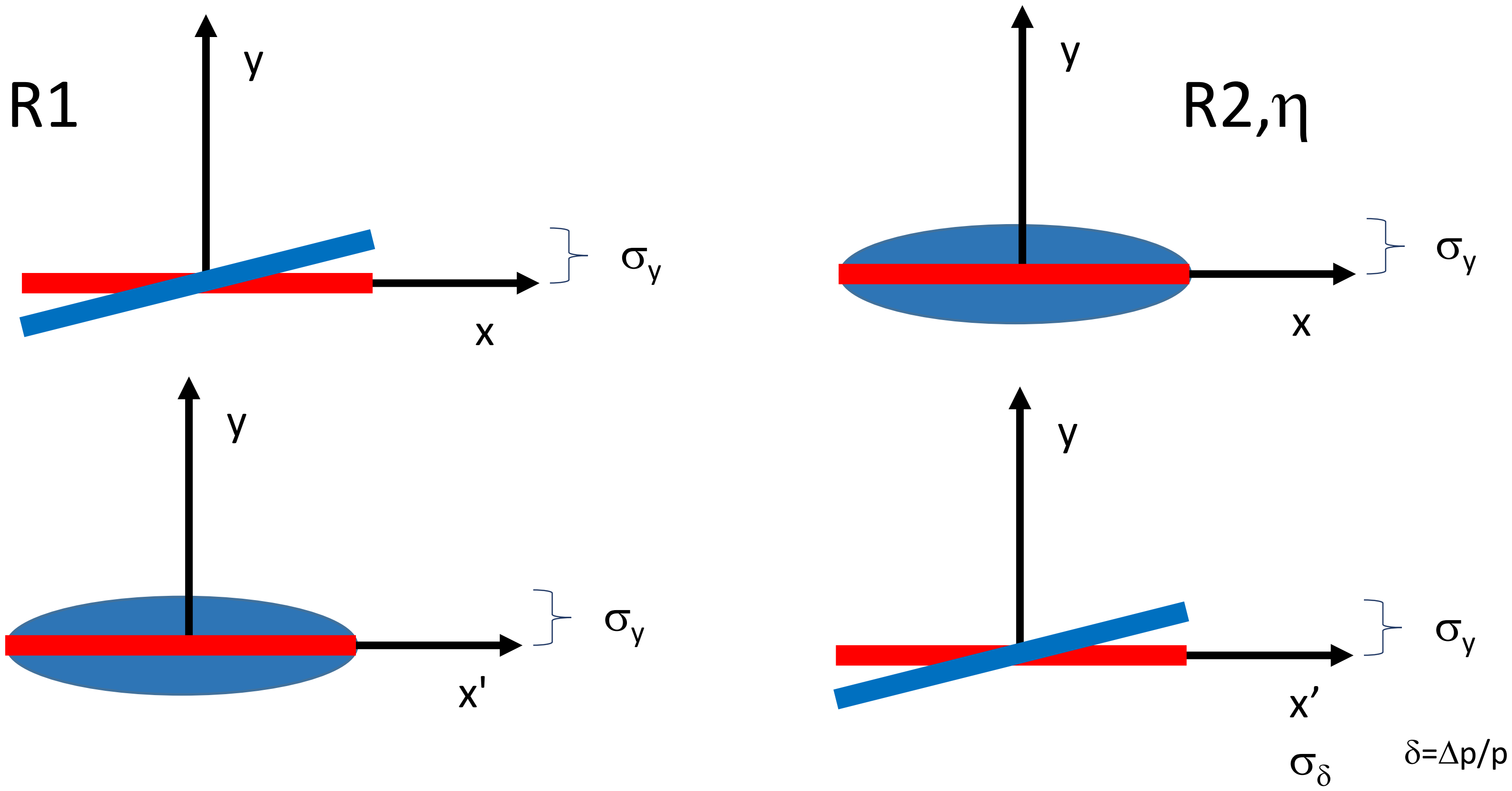
June 30, 2018



- 0mA, σ_{y0}=0.25μm, 0.25μm, Lsp=49
- 200x160mA, σ_{y0}=0.4μm, 0.6μm, Lsp=24.4
- 285x340mA, σ_{y0}=0.6μm, 0.6μm, Lsp=20.7

Lsp agrees with geo value at every current

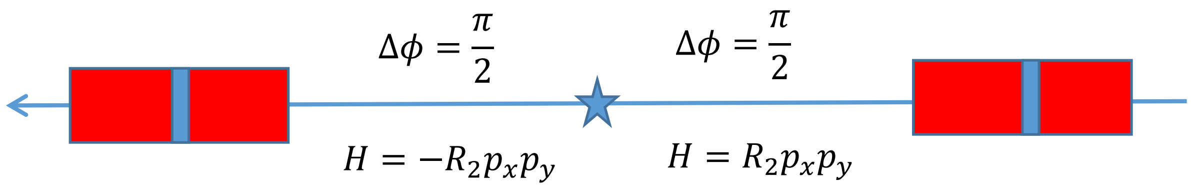
IP coupling and beam distribution at IP



$$\sigma_y^2 = \varepsilon_y \beta_y + \varepsilon_x \beta_x \left(\frac{r_2^2}{\beta_x^2} + r_1^2 \right) + (\eta_y \sigma_\delta)^2$$

Relation of R and skew strength of QC1 in a simple model

- Transformation of R2,



$H = \pm R_2 p_x p_y$ $\quad\quad$ $y = y \pm R_2 p_x$

- Assume π/2 for phase difference between IP to both QC1.

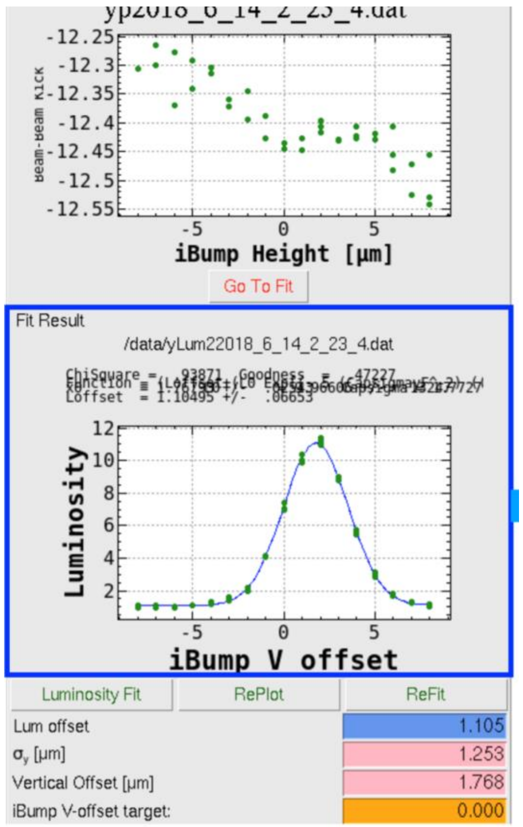
$$H = \pm \frac{R_2}{\sqrt{\beta_x^* \beta_{x,1}} \sqrt{\beta_y^* \beta_{y,1}}} xy \approx \pm R_2 xy$$

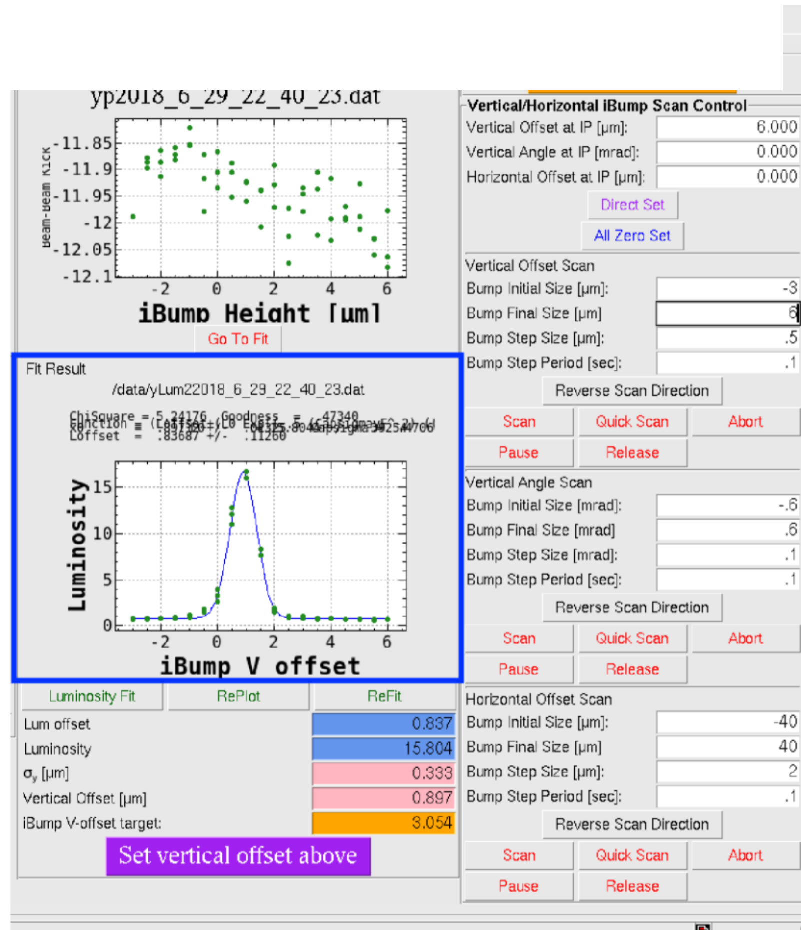
- Skew quad at QC1 is B'L/Bρ=R_2, which is independent of β*.
- Deviation from π/2 induces R3.
- Control of inside of π section is hard from outside. It should be corrected by both side of skew. (like waist correction)

$H = ds p_y^2$
waist shift

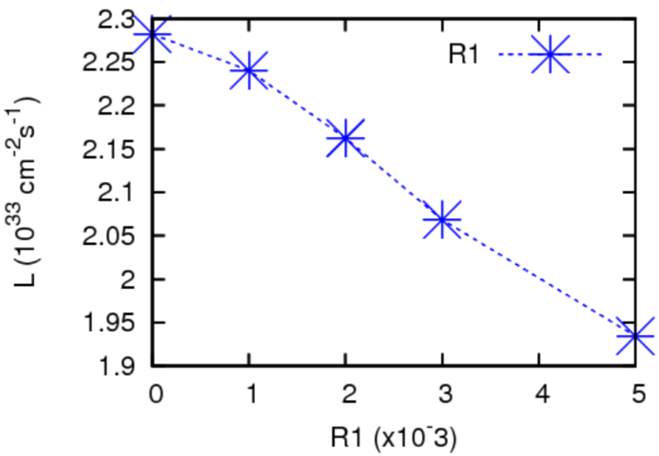
Vertical Beam size measurement using collision scan

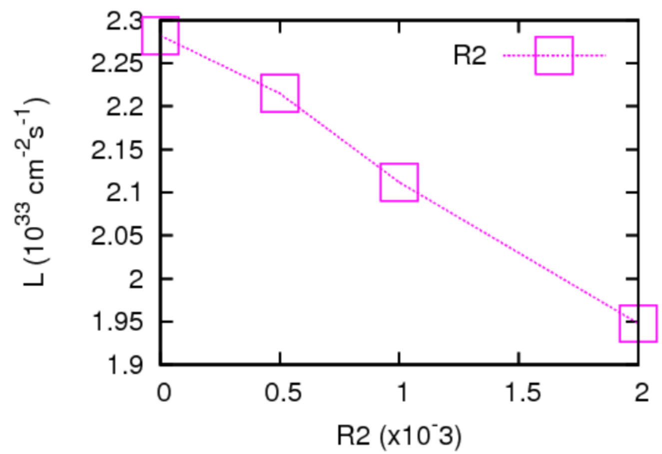
- Beam size is larger than $\sqrt{\varepsilon_y \beta_y^*}$ for existing R1, R2.
- After R2 correction, σ_y^*=1.25μm->0.33μm
- R1,R2 is measurable .



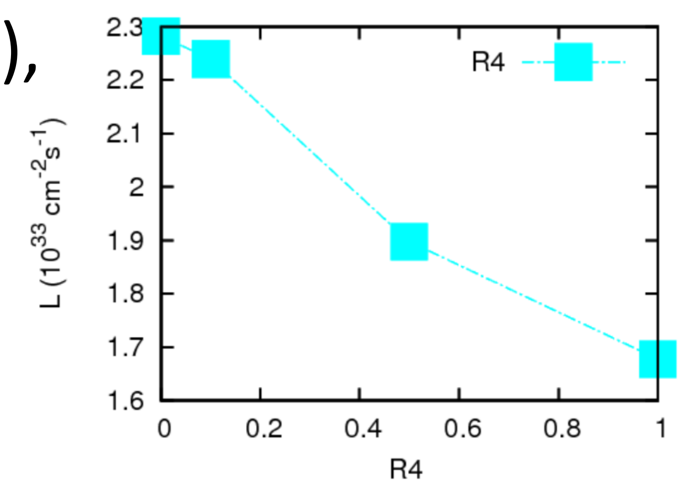


R scan in the simulation





- Required tuning range R1 O(mrad), R2 O(mm), R3 O(1m^{-1}),R4 O(0.1)



TbT measurement

$r_i = R_i$

- y motion in X mode.

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

$$\boldsymbol{x} = RB\boldsymbol{X} \qquad R = \begin{pmatrix} r_0 & 0 & r_4 & -r_2 \\ 0 & r_0 & -r_3 & r_1 \\ -r_1 & -r_2 & r_0 & 0 \\ -r_3 & -r_4 & 0 & r_0 \end{pmatrix}$$

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

r1: cos component of y for x betatron motion ,r2: sin component

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

$$= c\cos(2\pi n\nu_x + \phi_y) \qquad \phi(s) = 2\pi n\nu_x + \phi_x$$

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

r3: cos component of y for px betatron motion ,r4: sin component

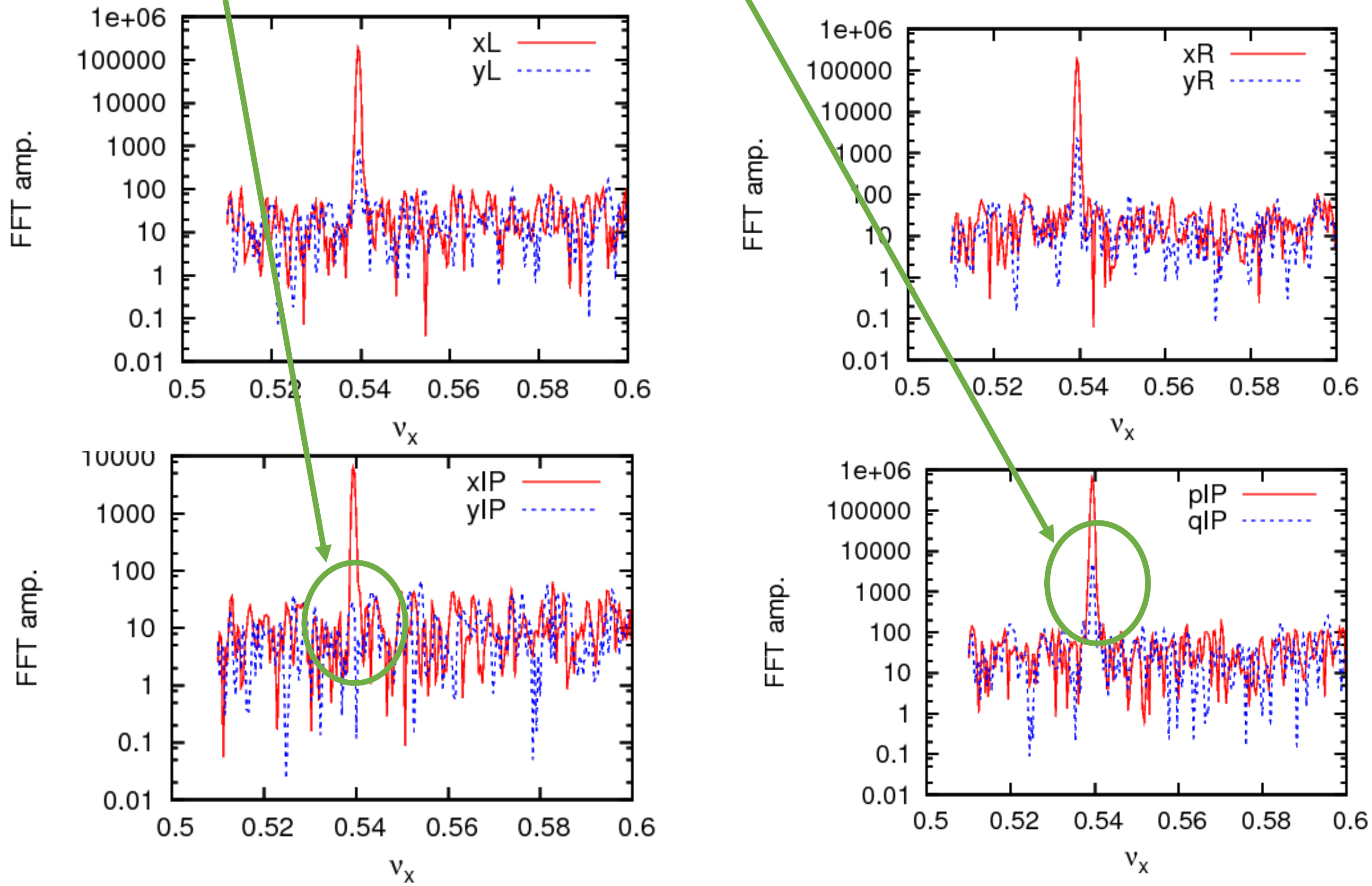
$$p_y = r_3 x - r_4 p_x = r_3 a \cos\phi(s) + r_4 \left[\frac{a}{\beta}\sin\phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos\phi(s)\right]$$

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

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

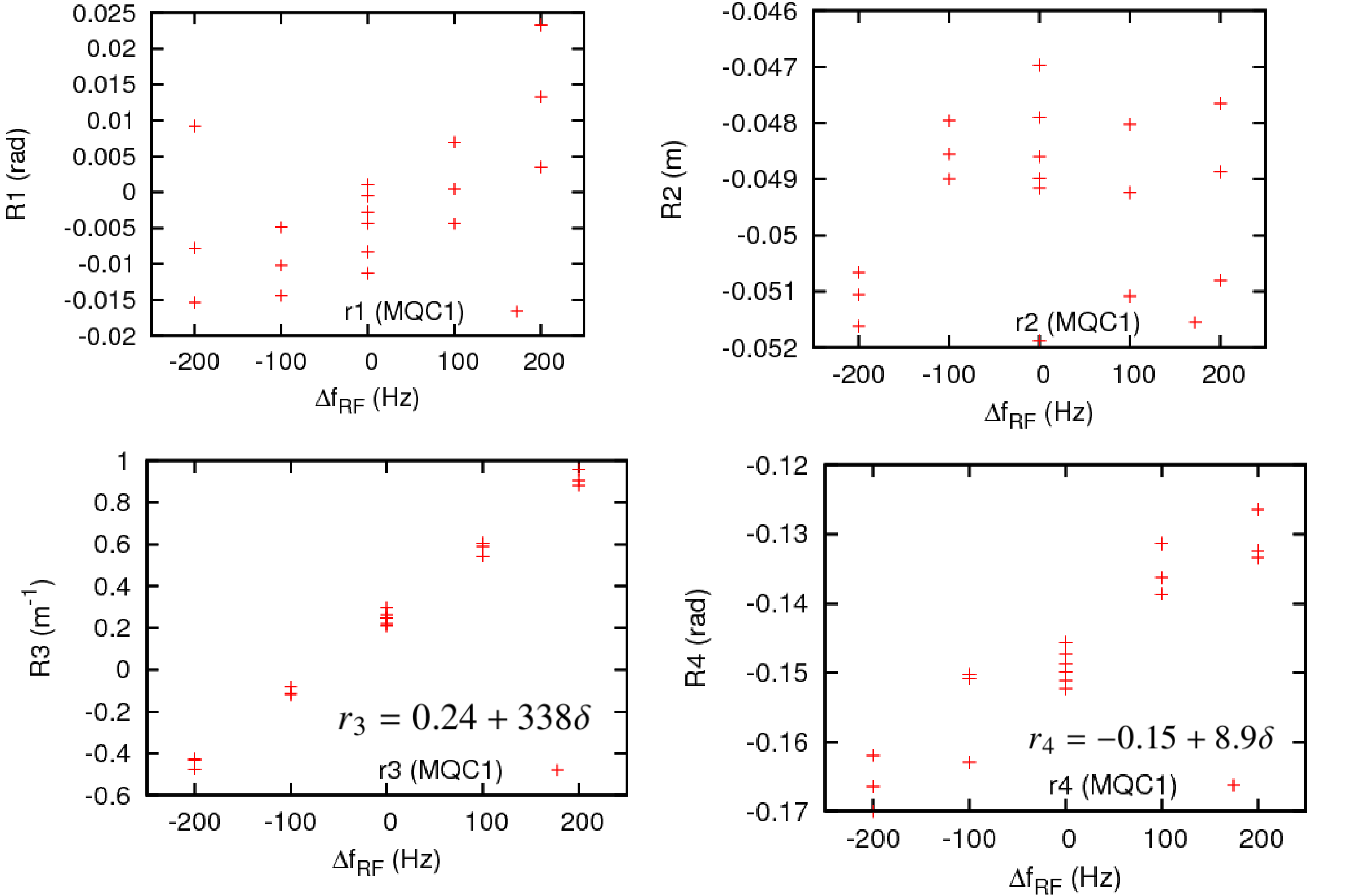
FFT of BPM data

- Small y_{IP}, but enough $p_{yIP}=q_{IP}$.
- R1,R2 are y for x and px. R3 and R4 are py for x and px.
- R1 and R2 are hard to be measured.



LER

- R1, R2 are ambiguos, but R3, R4 are well determined.



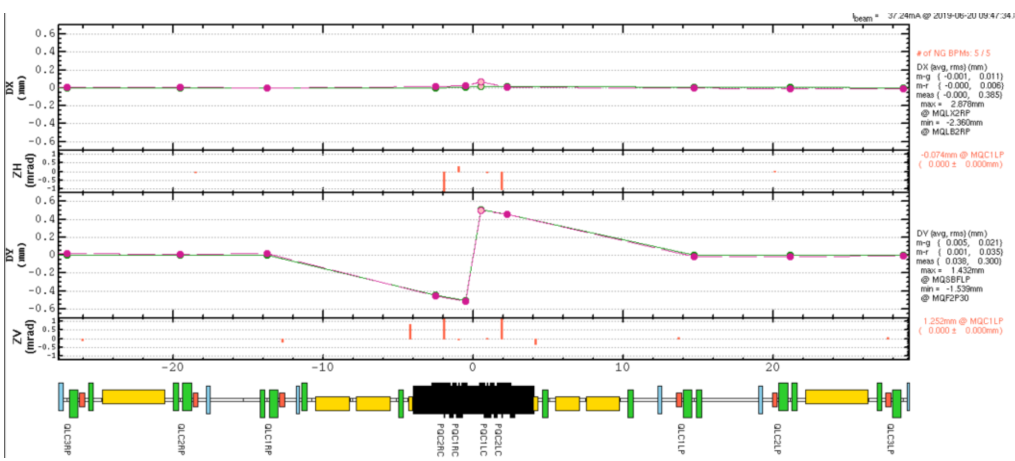
Lesson from linear x-y coupling correction

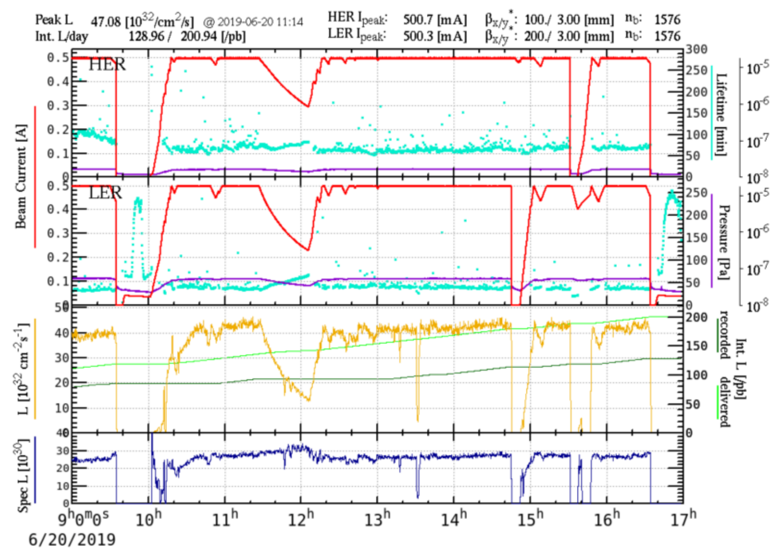
- We have to always confirm that the beam size at IP equal to $\sqrt{\varepsilon_y \beta_y^*}$ estimated by XSRM.
- R3,R4 are well determined by TbT measurement, but R1,R2 are not.
- R1,R2,ηy at IP can be measured by collision scan.
- R3,R4 are measurable. The tolerance for luminosity degradation in simulation is O(1). Insensitive for monitor rotation. R3,R4 are well managed.

- All linear coupling parameters are well managed.

Vertical angle at IP, June 20, 2019

- Vertical angle scan was limited due to heating on HER V angle change (done in KEK without problem).
- Change of LER V-angle vertical has induced vertical dispersion at IP.
- V angle scan with dispersion correction was done in 20, June 2019.

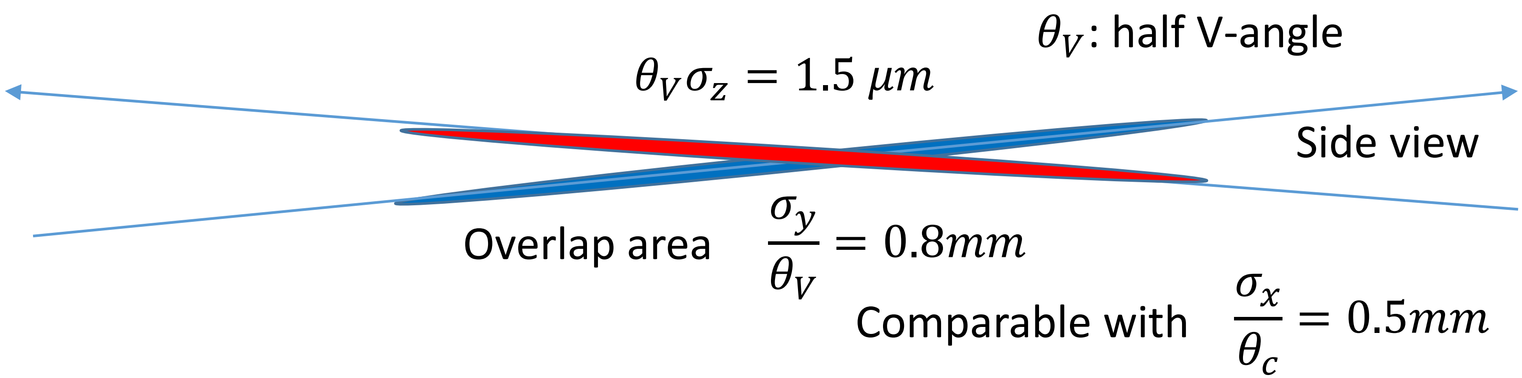


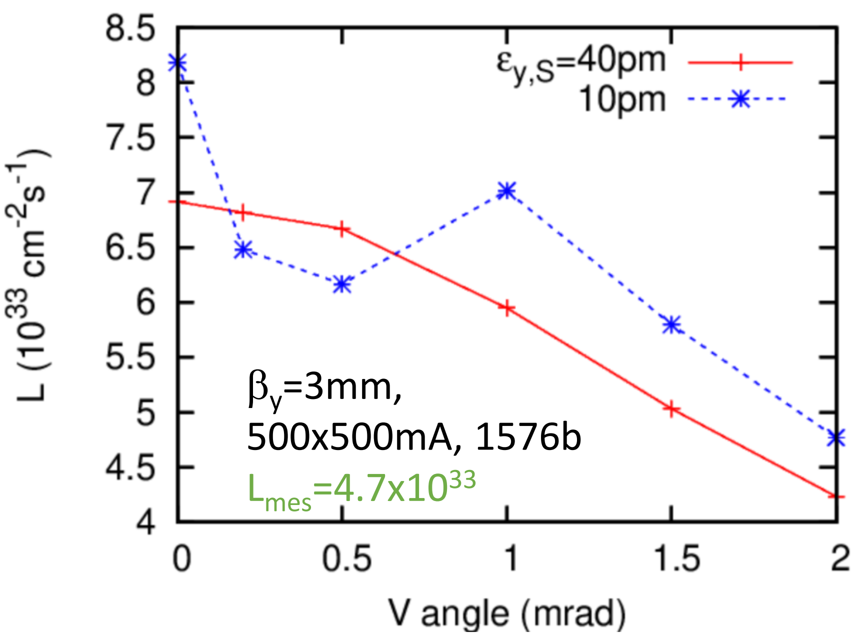


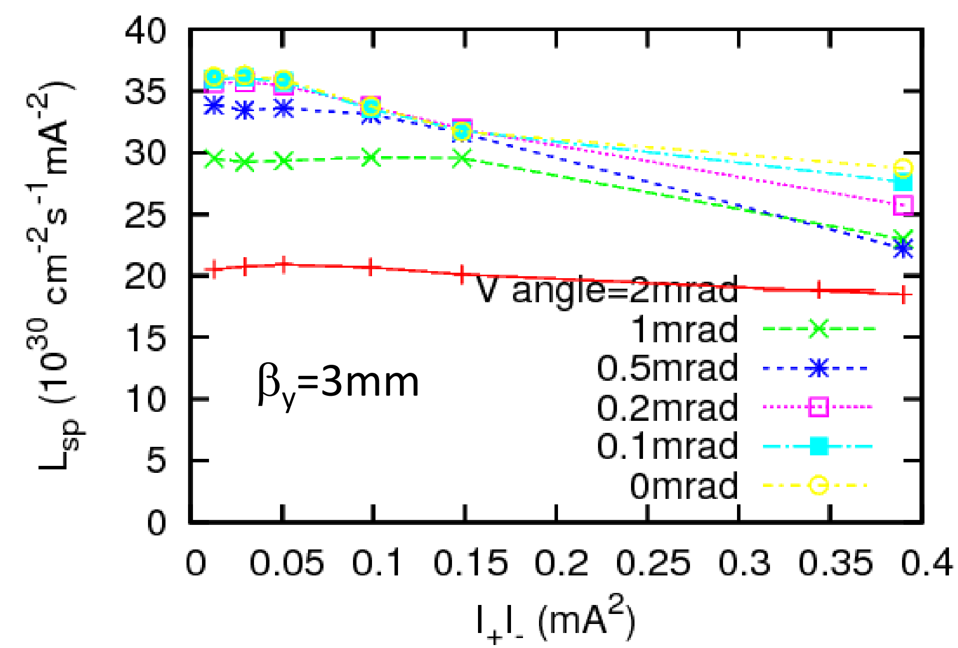
H.Koiso, Nakayama

Vertical crossing angle

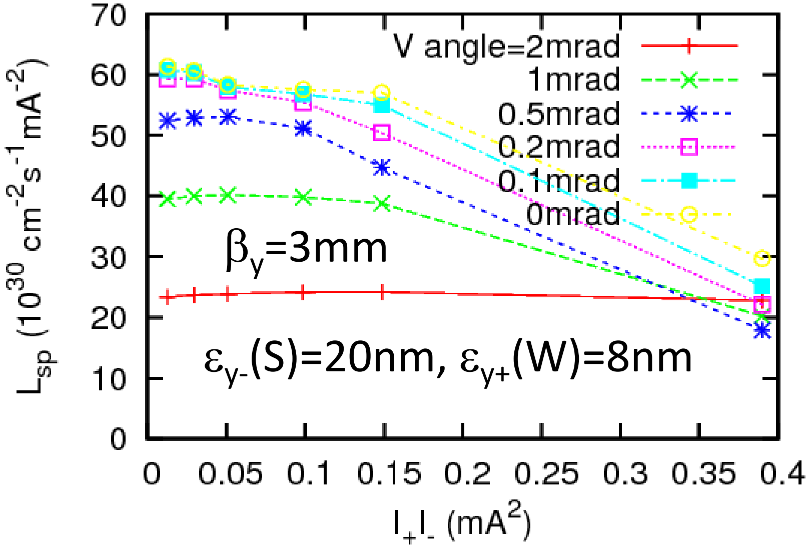
- Correction of full crossing angle $2\theta_V$=0.5mrad contributed 20% luminosity up (June 20, 2019).





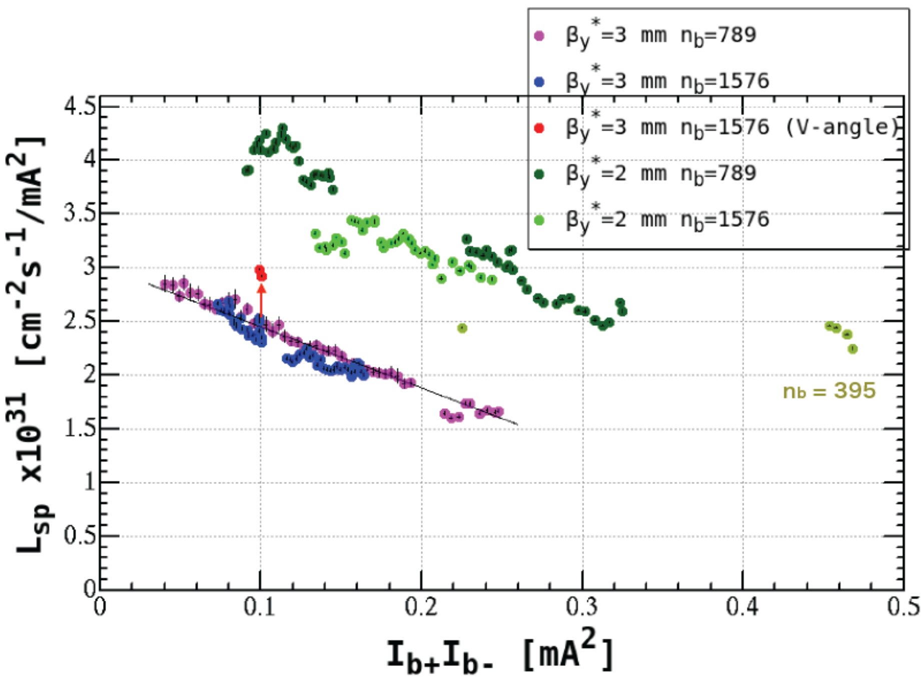


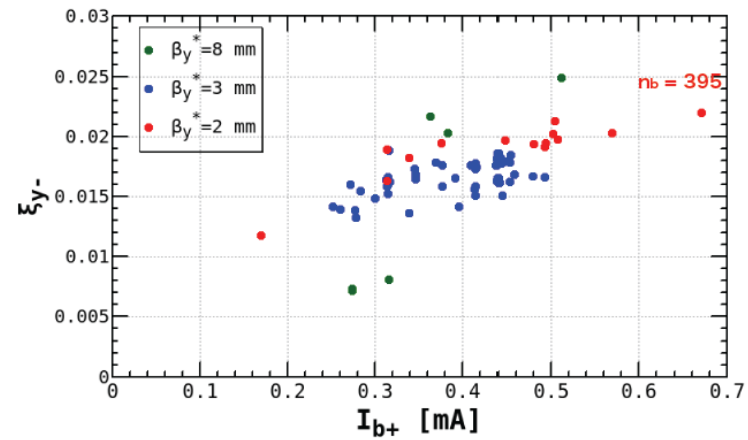
- For V angle 0.5mrad, luminosity loss is small for I_+I_- <0.2mA^2. It is 20% at I_+I_-=0.4mA^2. Initial condition ε_{y-}(S)=40nm, ε_{y+}(W)=40nm.
- For initial condition ε_{y-}(S)=20nm, ε_{y+}(W)=8nm, 20% lumi loss at I_+I_-=0.15mA^2, but Lsp is very high.
- Accuracy of vertical angle is ~0.1mrad at I_+I_-=0.4mA^2.

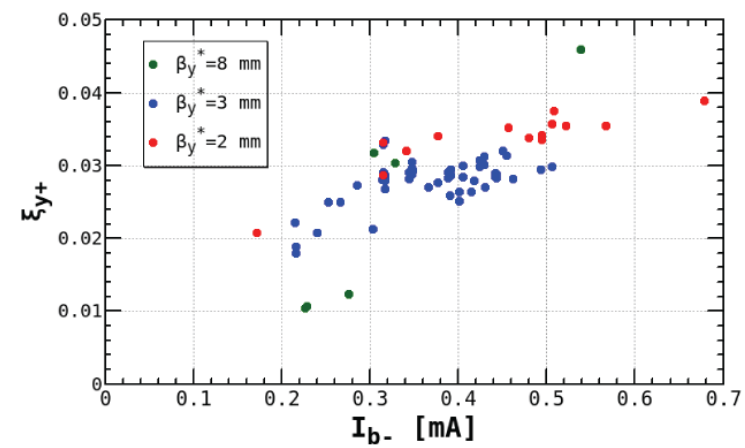


Present beam-beam performance

Specific Luminosity and Beam-Beam Parameter







Y. Ohnishi

IR magnets and their nonlinearity studied at early stage

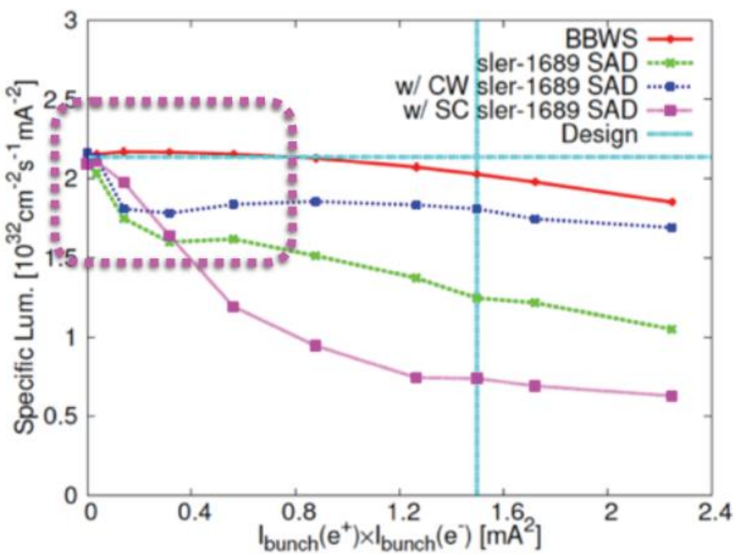
- There are many nonlinear field components in IR magnets.
- Chromatic coupling are induced at IR.

➤ **Realistic lattice: lum. drops at low beam currents**

➤ **Crab-waist:**

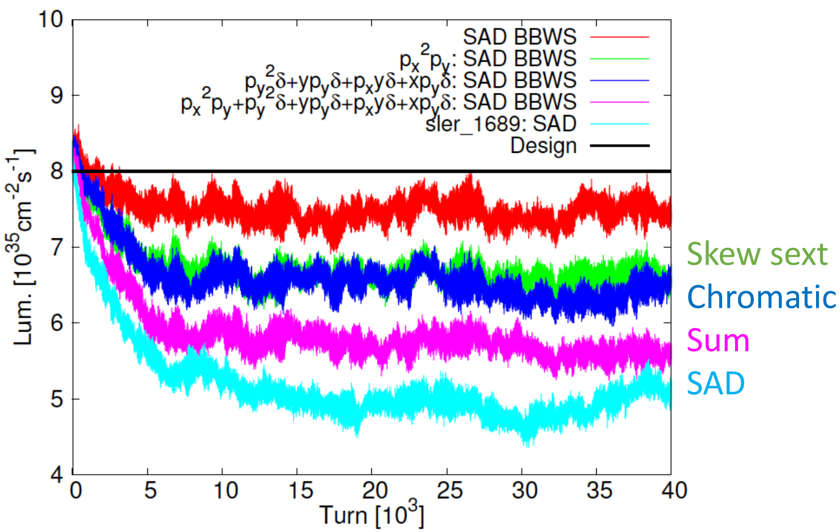
- **To cancel beam-beam driven resonances**
- **Work well at high currents, but not well at low currents**

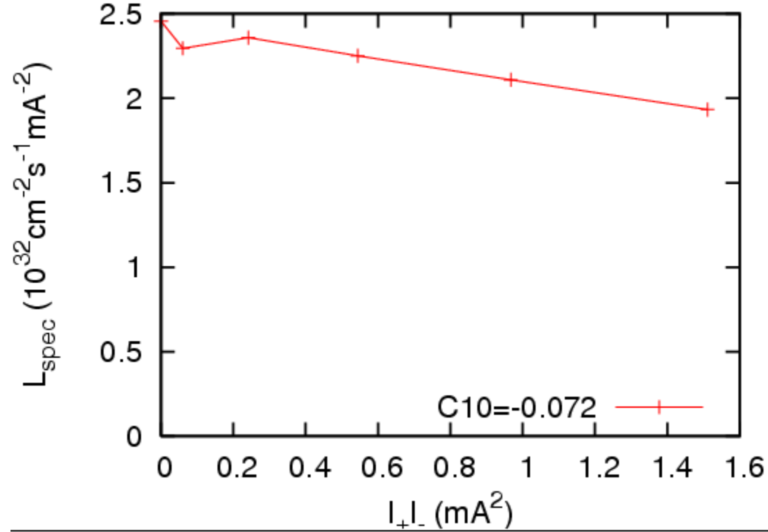
D. Zhou,
SKEKB MAC
2015

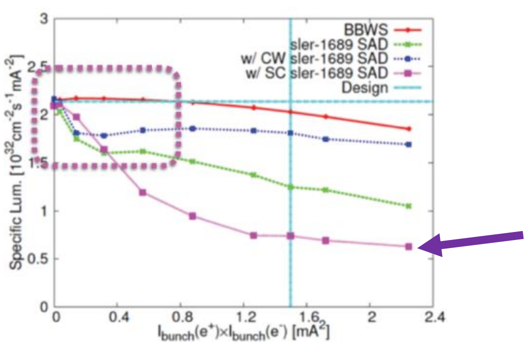


BBWS : arc expressed by simple transfer matrix
SAD: complex lattice structure

Luminosity for $H=c_{10}p_x^2p_y$ and chromatic Twiss, design parameter



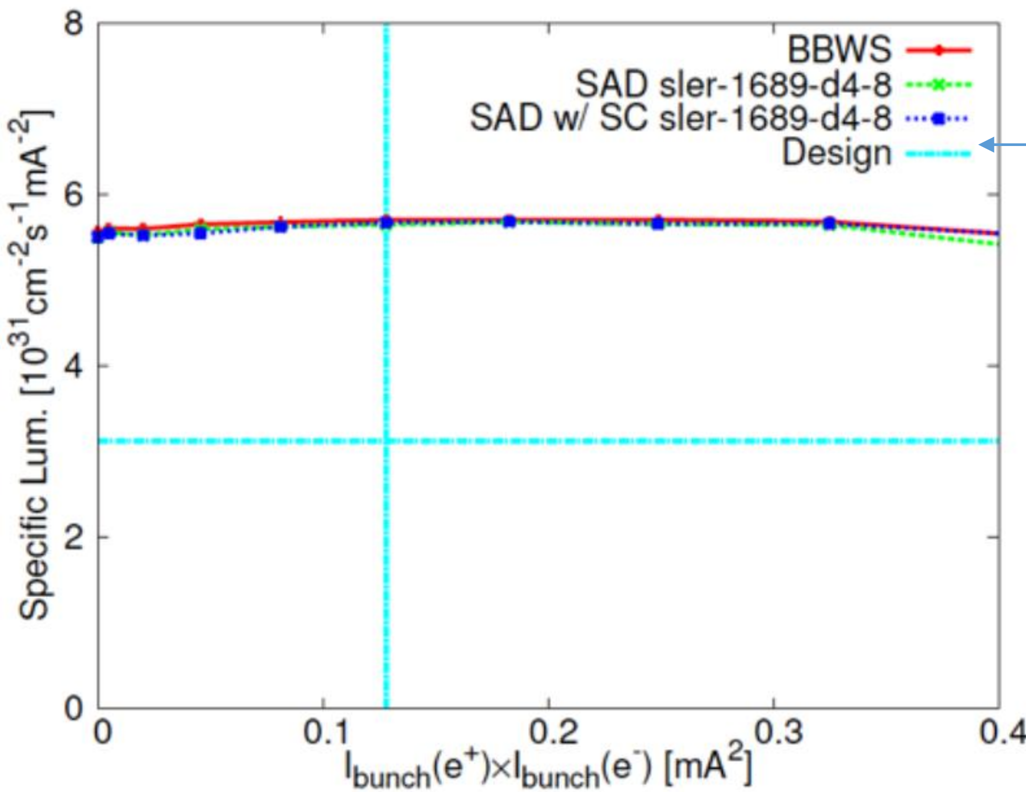




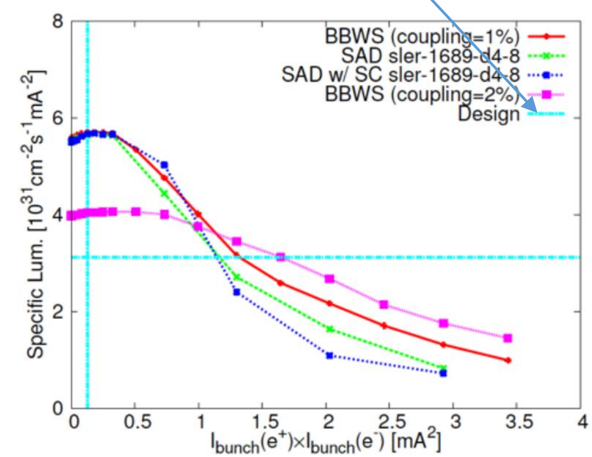
- The luminosity degradation due to Skew sext component and chromatic Twiss almost explains that of beam-beam simulation with SAD.
- The strength of p_x^2py term is 0.072.
- Study of Space charge force is next.

SAD simulation for detuned lattice : studied at early stage

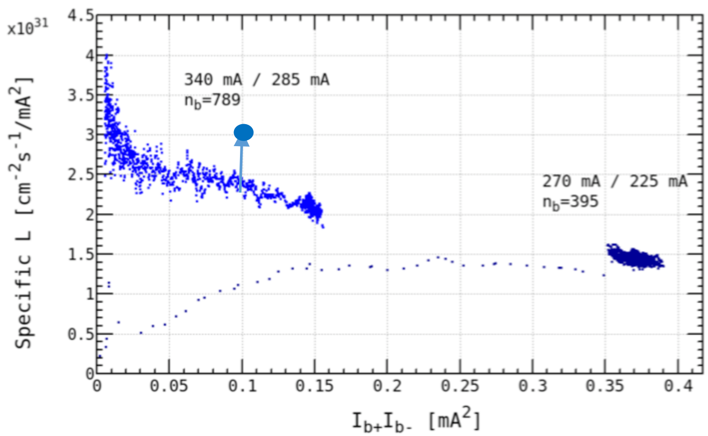
- βy=2.2, 2.4mm
- No difference between SAD and BBWS(simple arc+optics aberrations)

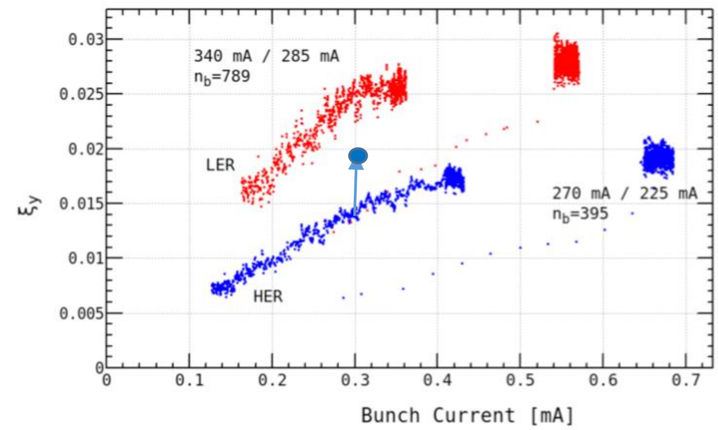


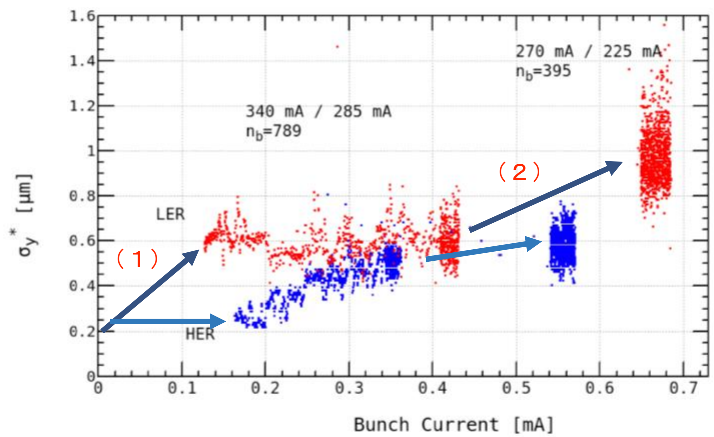
Temporal detuned design



Specific Luminosity and Beam-Beam (Phase 2)







2 stage blow-up of LER beam

（１） Very small bunch current, I_+I_- =0.01mA^2.

（２） High bunch current I_+>0.5 mA

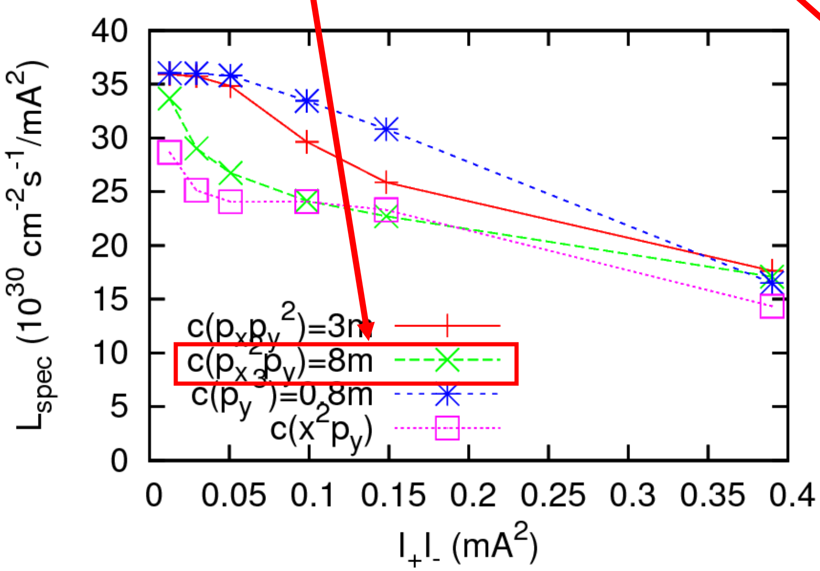
HER beam I_->0.2mA.

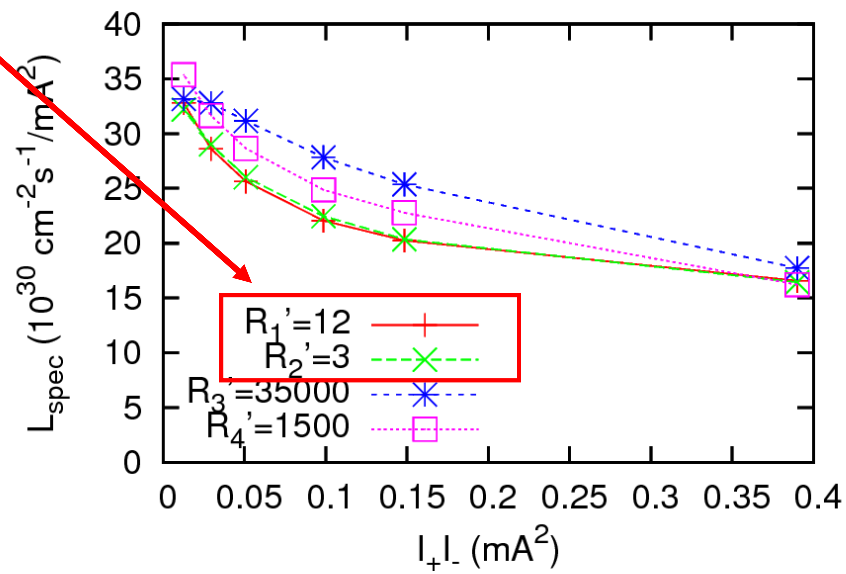
Chromatic, nonlinear aberrations

- Possible errors to explain measured luminosity
- R1'=12rad
- R2'=3m
- C($p_x^2 p_y$)=8m

100 times larger for the early estimation (page 22)

Weak strong simulation with nonlinear IP aberrations





Measurement of IP chromatic aberrations

- Effect on vertical beam size of the aberrations
- $\delta=\Delta p/p=0.17\%$.
- $R_1(\delta)$=20.4mrad
- $R_2(\delta)$=5.1mm
- $H = 8p_x^2 p_y$

ε_x=3 nm, $\varepsilon_y = 0.03$ nm $\quad \sigma_y = 0.3\mu m$

$\beta_x = 0.2\ m$

$$\Delta\sigma_y = R_1(\delta)\sigma_x = 0.50\ \mu m$$

$$\Delta\sigma_y = \frac{R_2(\delta)}{\beta_x}\sigma_x = 0.62\ \mu m$$

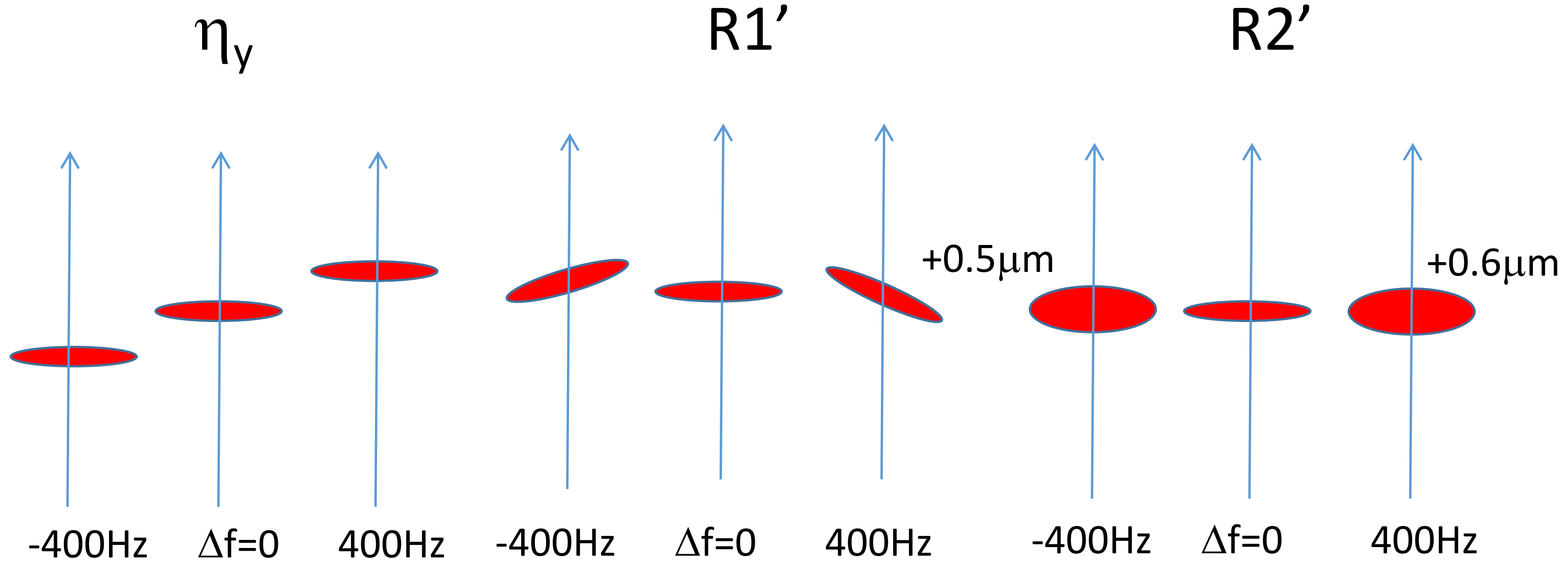
$$\Delta\sigma_y = 8\langle p_x^2\rangle = \frac{8\varepsilon_x}{\beta_x} = 0.12\mu m = 0.4\sigma_y$$

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

- Aberrations with clear vertical beam size increase as synchroton/betatron amplitude affect luminosity performance.
- Errors, which affect luminosity performance, are visible ones.
- Linear coupling, which gives 0.1-0.2σ_y, affect luminosity performance.

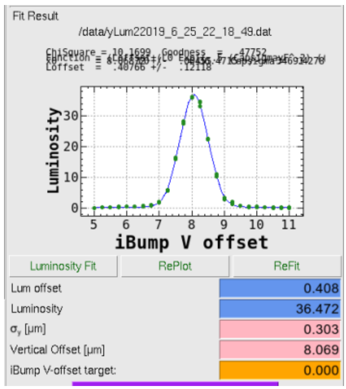
If a chromatic beam size variation are seen, it can be source of luminosity degradation

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

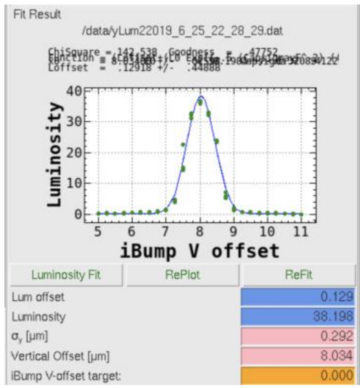


Measure the beam size using beam-beam scan (Luminosity.)

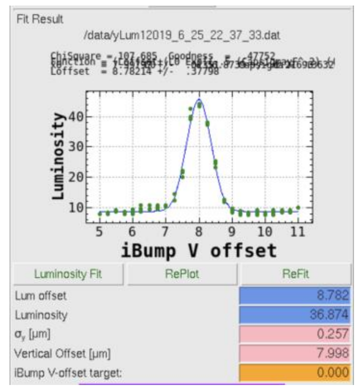
Vertical offset scan with different RF frequency



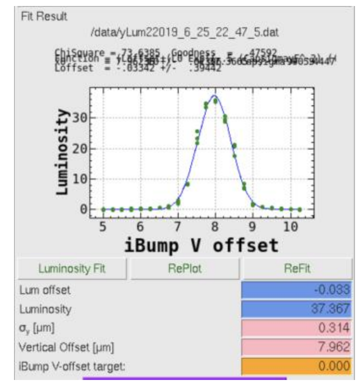
Δf = +400Hz



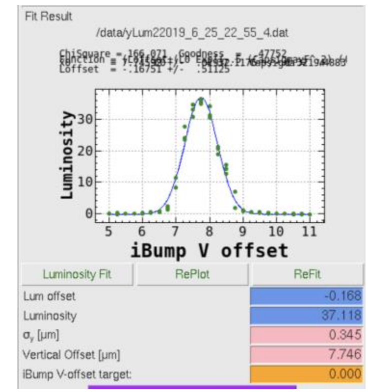
Δf = +200Hz



Δf = ±0Hz



Δf = -200Hz



Δf = -400Hz
beam loss at the scan

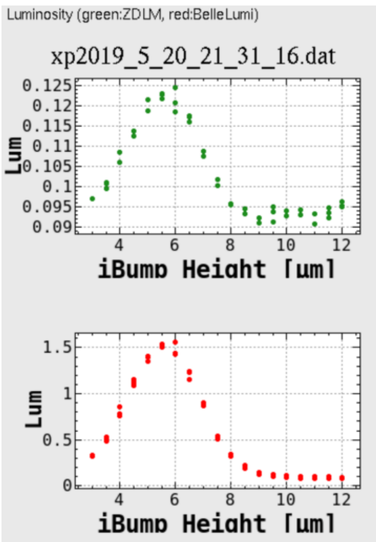
Y. Funakoshi
One cycle injection by Kaji.

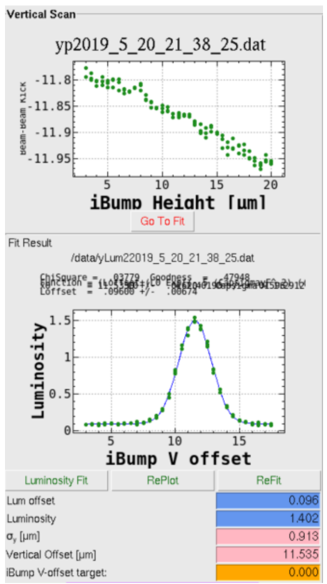
Vertical offset shift for frequency shift : IP vertical dispersion
Vertical size variation for frequency shift beam energy : IP chromatic coupling

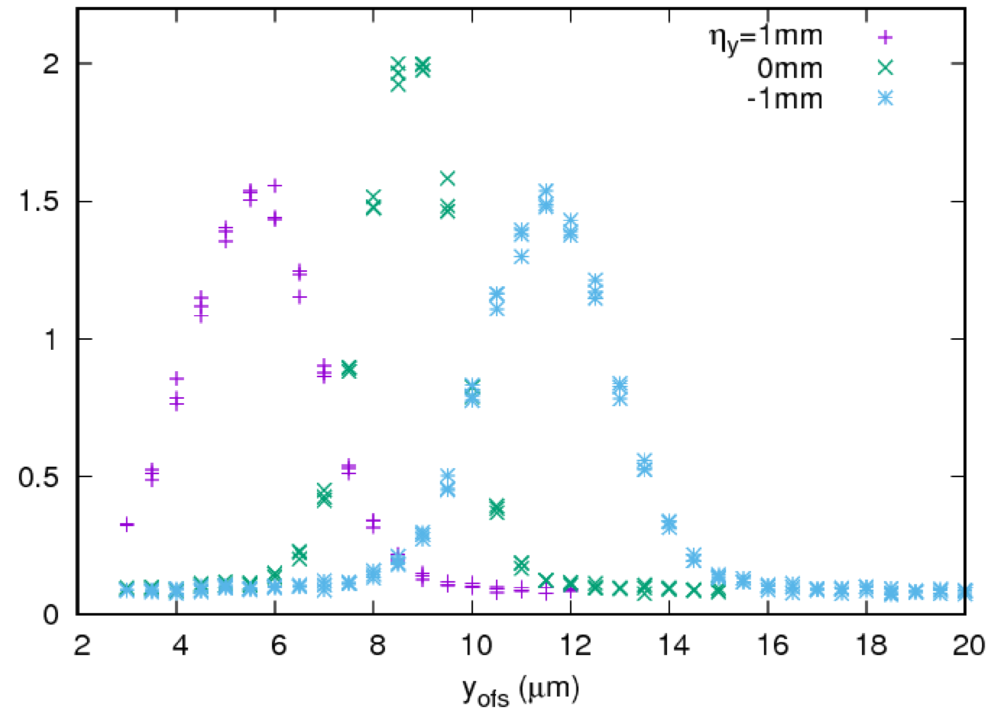
Dispersion at IP

- Δf=400Hz, IP Knob ON

η_y=+1mm η_y=-1mm



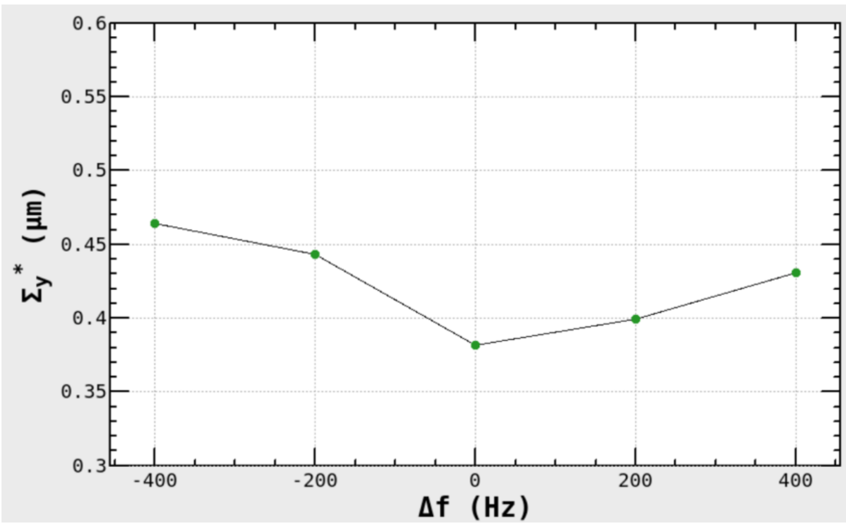


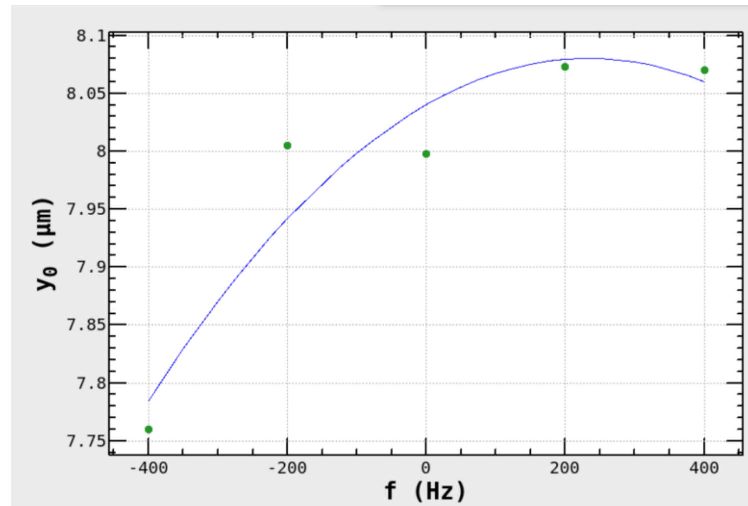


Y position shift and size increase due to dispersion are seen.

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

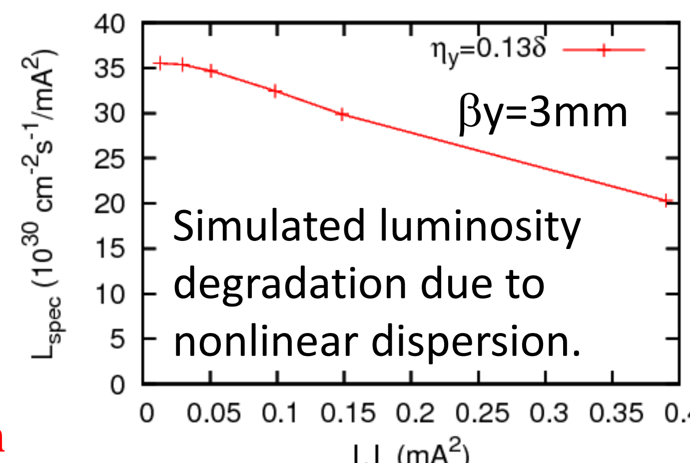
$$\Delta\sigma_y = 0.28\ \mu$$

A half strength of the Chromatic coupling can exist.

R1'=12rad
R2'=3m

$$\Delta\sigma_y = R_1(\delta)\sigma_x = 0.50\ \mu m$$

$$\Delta\sigma_y = \frac{R_2(\delta)}{\beta_x}\sigma_x = 0.62\ \mu m$$

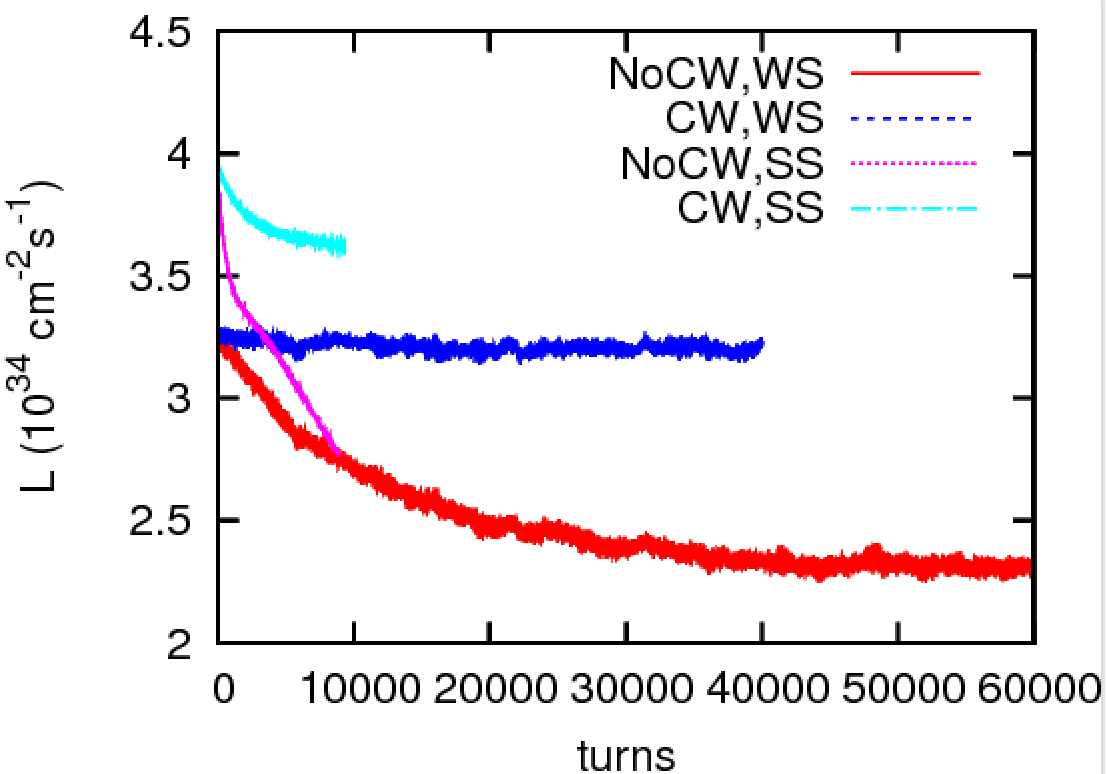


Chromatic and nonlinear coupling correction

- Chromatic coupling knob for HER was available. The tuning range was R1'~0.8rad (req.12rad), R2'~0.1m (3m).
- LER sextupole hardware rotation system is prepared, but not tried yet.
- Measurement showed no big aberrations, but 8-10 times wider range is desirable.
- Squeezing β_y^* further, wider range is required.
- Correction of Chromatic aberrations has started.
- Nonlinear coupling correction has started. It affects Dynamic aperture.

β_y=2mm

- $L_{mes.}$=1.24x10^{34} cm^{-2}s^{-1}, ξ_L=0.02 was achieved.
- ε_y=12, 18pm, ε_y=6mm.
- 820mAx820mA, 1576bunch
- Simulation shows 2 times higher luminosity, 2.3x10^{34} .

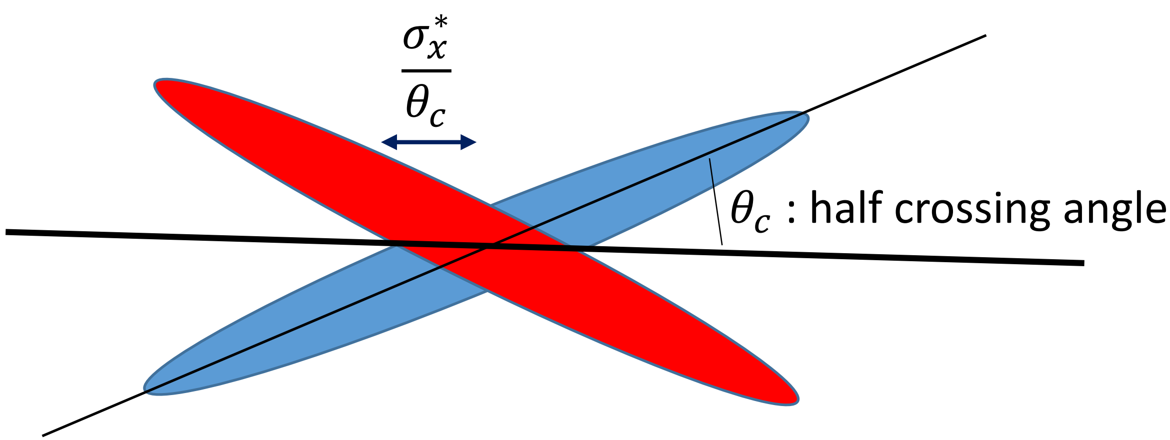


Beam-beam limit

- Beam-beam parameter has been limited to be ξ_{y-} =0.02 for e- beam due to blow-up of e+ beam.
- The tune shift limit 0.02 does not depend on β_y=4, 3, 2mm. The limit is somewhat high 0.025 at β_y=8mm.
- The low tune shift is caused by difficulty related to the large Piwinski angle, if the limit is independent of β_y?
- The tune shift limit at β_y=8mm

What determines the low beam-beam limit?

- Key parameters
  - β_y^*, chromatic effects
  - Piwinski angle $\frac{\sigma_z \theta_c}{\sigma_x^*}$ bunch length/overlap area
  - Hour glass effect $\frac{\sigma_x^*}{\theta_c \beta_y^*}$ ratio of overlap area and β_y^*



Choice of β_x, Hour glass effect

θ_c: Half crossing angle

- Key parameter $\sigma_x/(\theta_c\beta_y)$, characterize hour glass effect.
- Vertical tune shift increase as function of horizontal amplitude. (Crab waist effect).
- Synchro-beta resonance in head-on collision => x-y resonance in large crossing collision

- $\sigma_x/(\theta_c\beta_y)$=0.16 (2018-2019, βy=3mm, βx=100/200mm)
- =0.16-0.23 (βy=2mm, βx=80/80mm)
- $\sigma_x/(\theta_c\beta_y)$=0.9 (design βy=0.27/0.3mm, βx=32/25mm)

- Enough margin for the hour glass effect at present.

- If we see such Hour glass effect, crab waist must be necessary in SuperKEKB.

Summary

- Squeezing β_y was very successful. Luminosity increased twice, L=1.23x10^{34} cm^{-2}s^{-1}, in the last one week, 23 June - 1 July.
- Beam-beam parameter did not change for squeezing. Luminosity increases as $L = \frac{\gamma I_{\pm} \xi_{y\pm}}{2 e r_e \beta_y^*}$.
- This is fortunate result, because squeezing β_y makes sensitive for errors.

For beam-beam parameter and luminosity performance

- Beam-beam parameter increases for luminosity increasing due to e+ current up. Somewhat more beam-beam parameter may be possible.
- However in present condition, higher e^+ current than transparency condition was better. It seems e^+ beam has some problem.
- We have factor 2 discrepancy between simulation and achieved luminosity.
- The discrepancy was factor 2 in crab crossing.

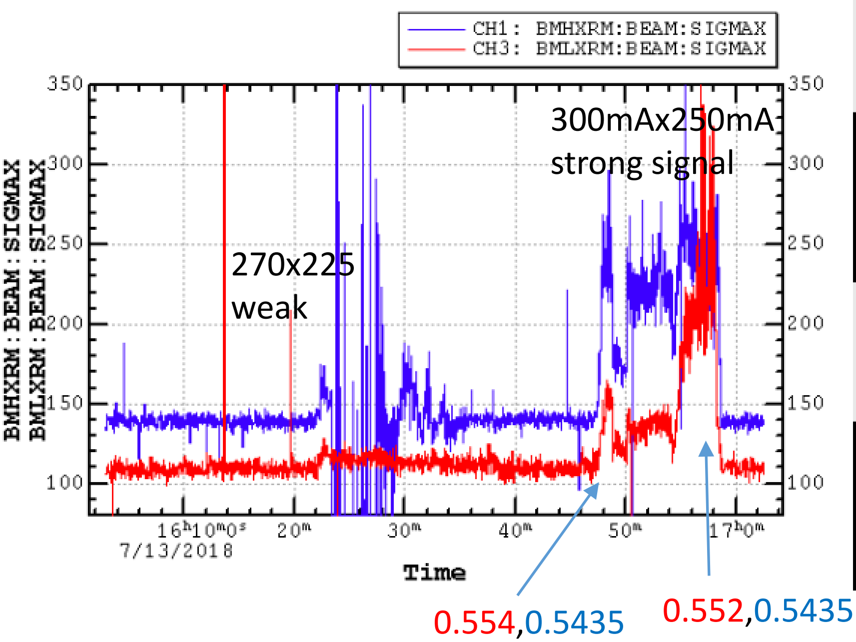
- Choice for near future
  1. We continue to search and correct error sources to explain the discrepancy.
  2. In parallel, we go crab waist. Not decided yet.

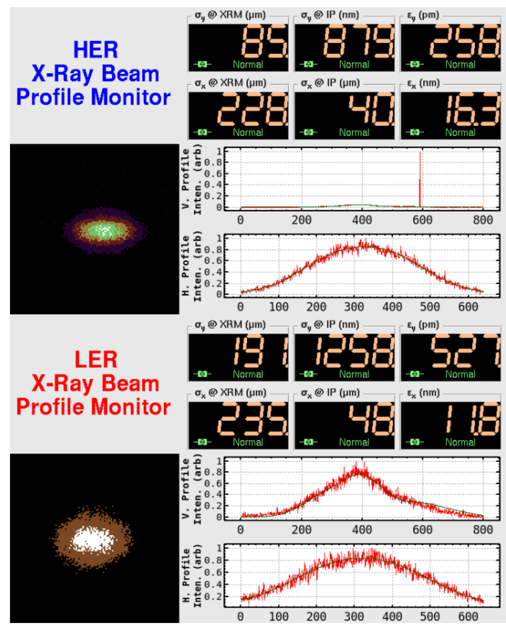
Coherent Beam-Beam-Head-Tail instability study in Phase II

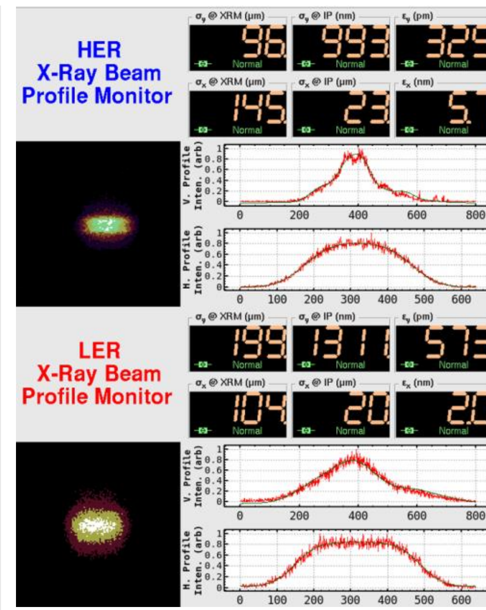
- Typical condition
- β_x=0.2m, 0.1m, β_y=3mm
- I_{tot}=270mA (e+)x 225mA (e-), Nb=395,
- I_b=0.68mAx0.57mA (design 1.44mAx1.04mA)
- Np=4.3×10^{10}, 3.6×10^{10}. (design 9.04×10^{10}x 6.53×10^{10})
- ν_s (e+)=0.022, ν_s (e-)=0.026

Horizontal beam size measurement

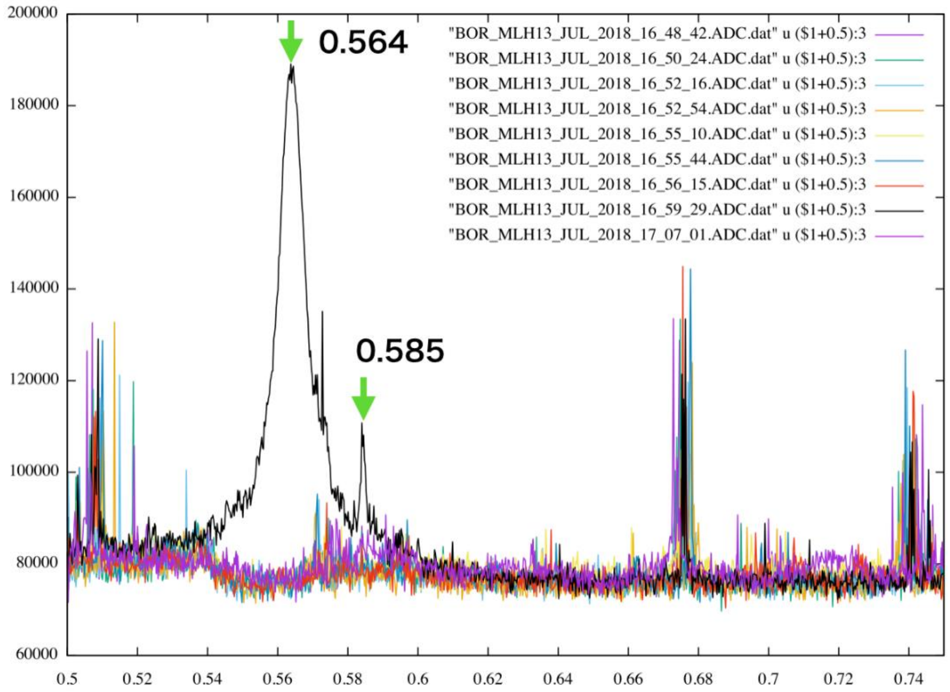
- 16:50 (instability start) & 16:57 (peak), data taking using streak camera x-z and BOR.
- Tune scn, ν_s (e+)=0.022, ν_s (e-)=0.026



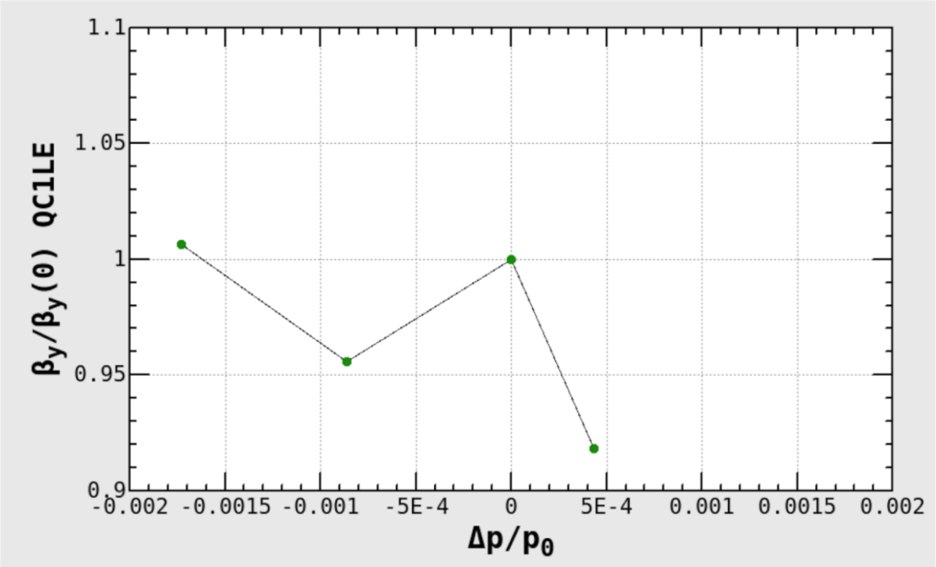


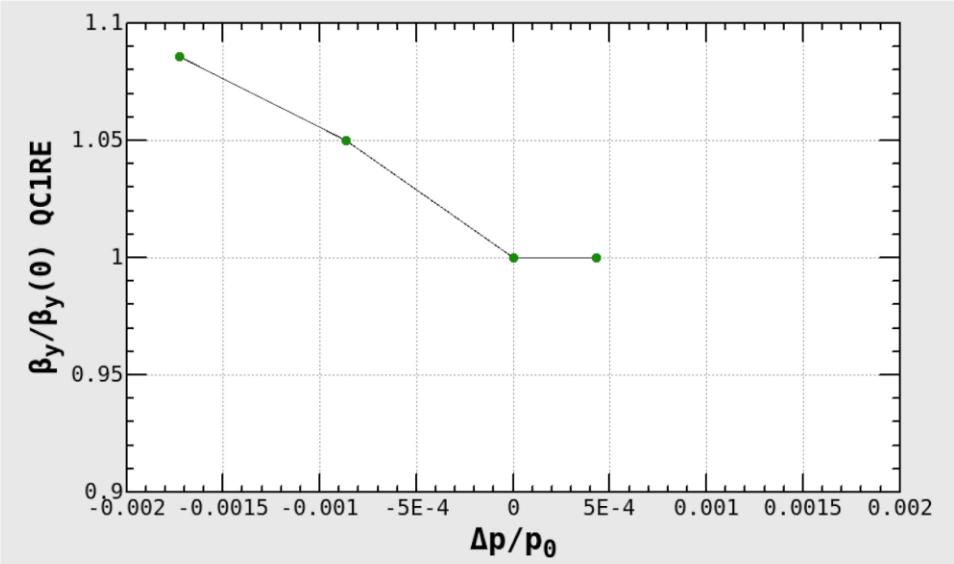


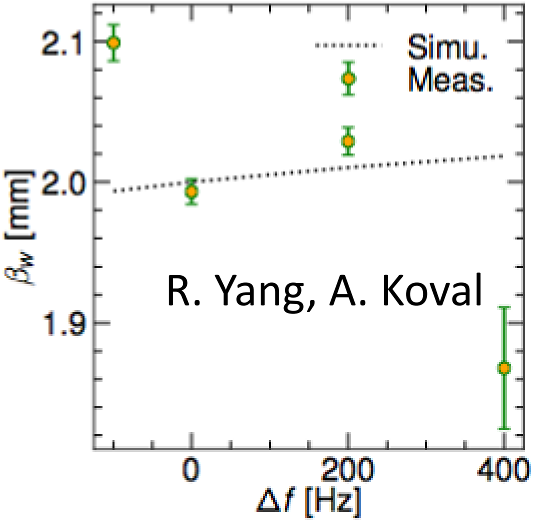
Beam oscillation at the horizontal size blowup



Backup

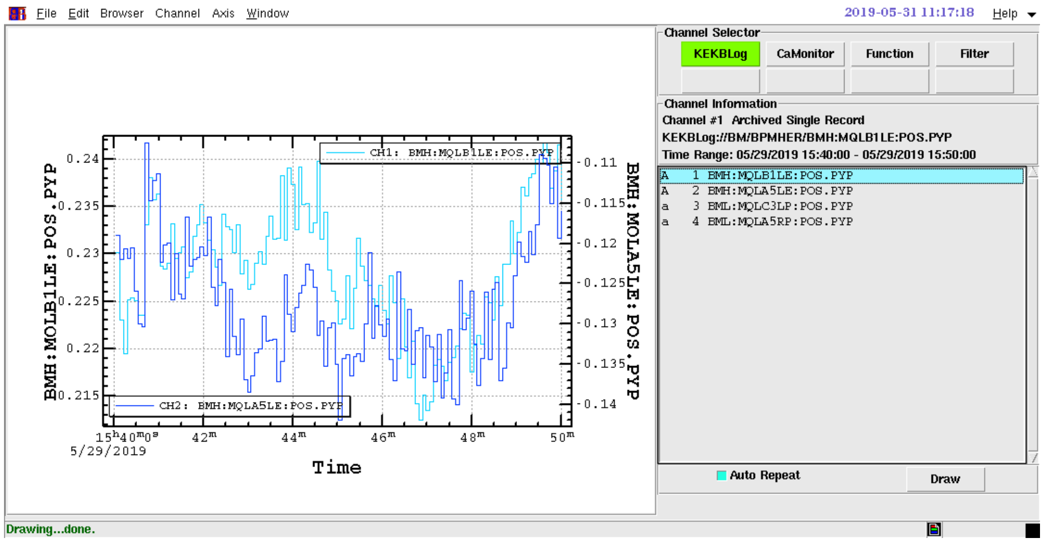

βy/βy(0) QC1LE
Δp/p0
1.1
1.05
1
0.95
0.9
-0.002
-0.0015
-0.001
-5E-4
0
5E-4
0.001
0.0015
0.002

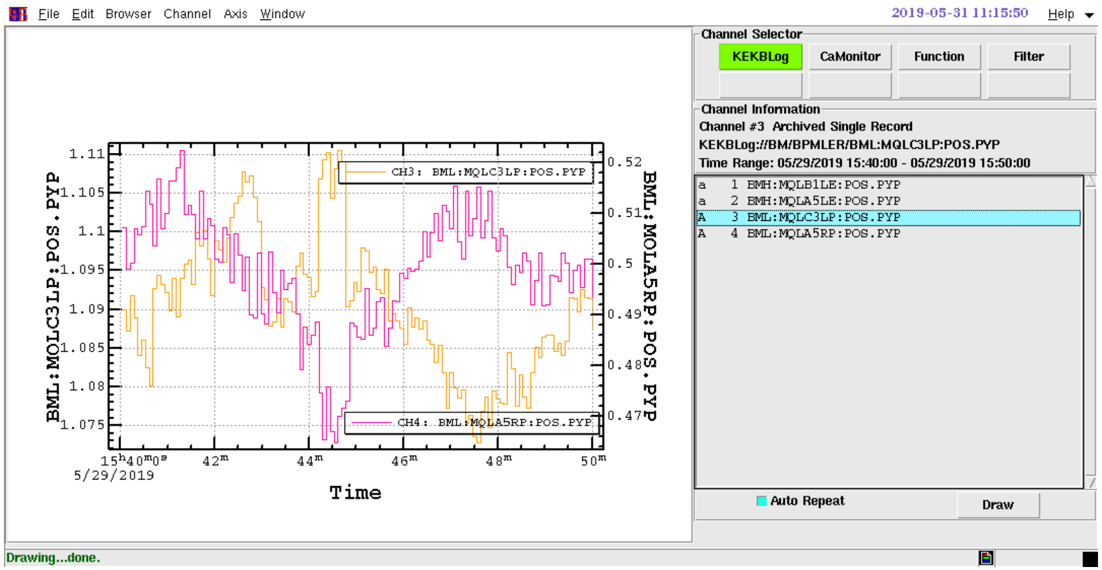

βy/βy(0) QC1RE
Δp/p0
1.1
1.05
1
0.95
0.9
-0.002
-0.0015
-0.001
-5E-4
0
5E-4
0.001
0.0015
0.002


βw [mm]
Δf [Hz]
2.1
2.0
1.9
0
200
400
Simu.
Meas.
R. Yang, A. Koval

Vertical offset noise, slow

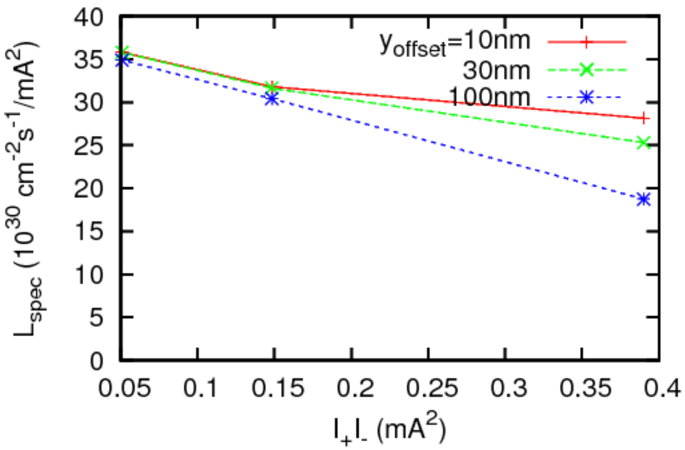
- ~Hz component

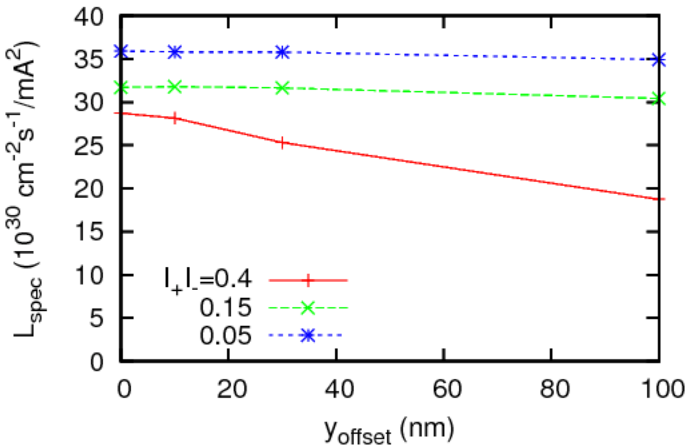


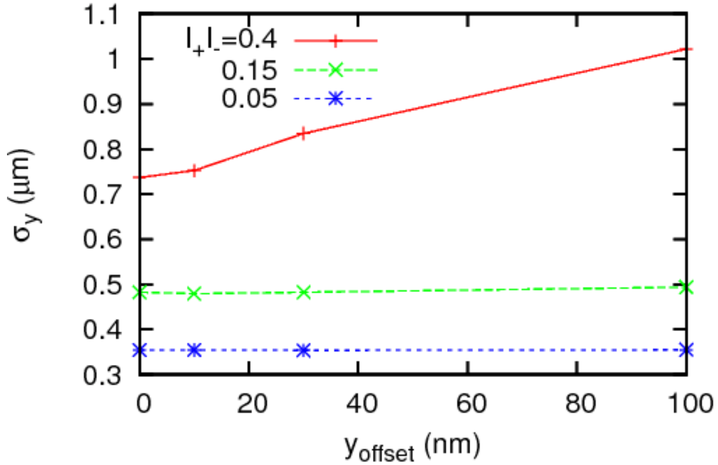


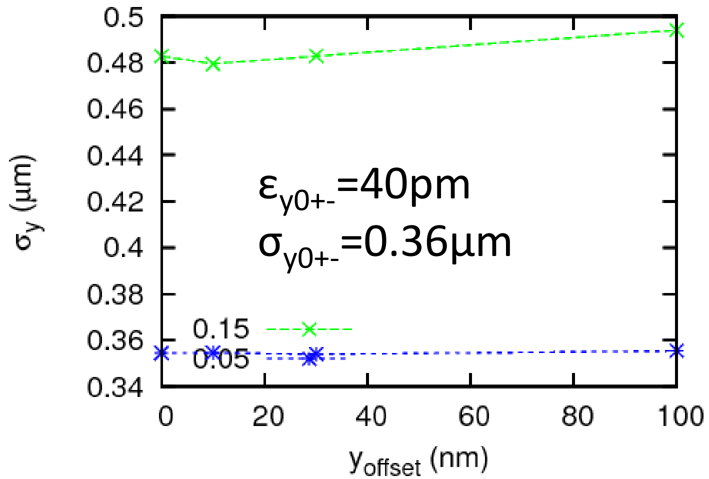
Luminosity degradation for Collision offset

- Luminosity vs y_{offset} (BBWS simulation)
  - L decreases for vertical offset at high bunch current.

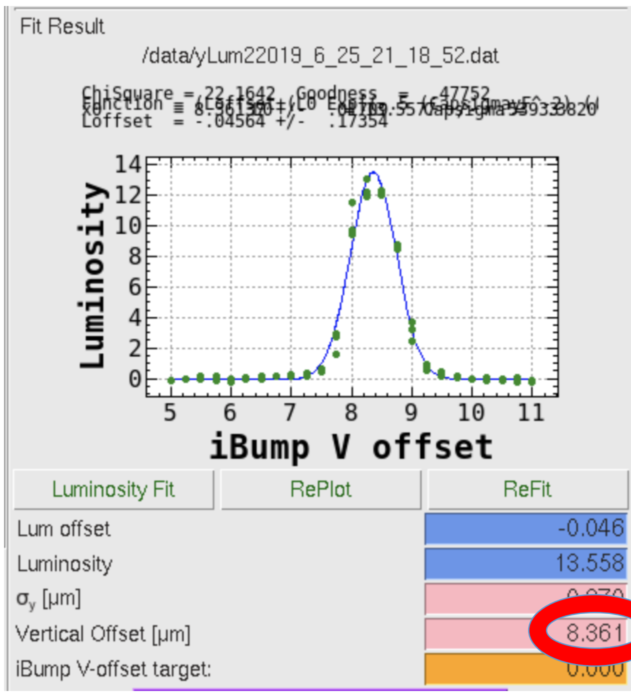


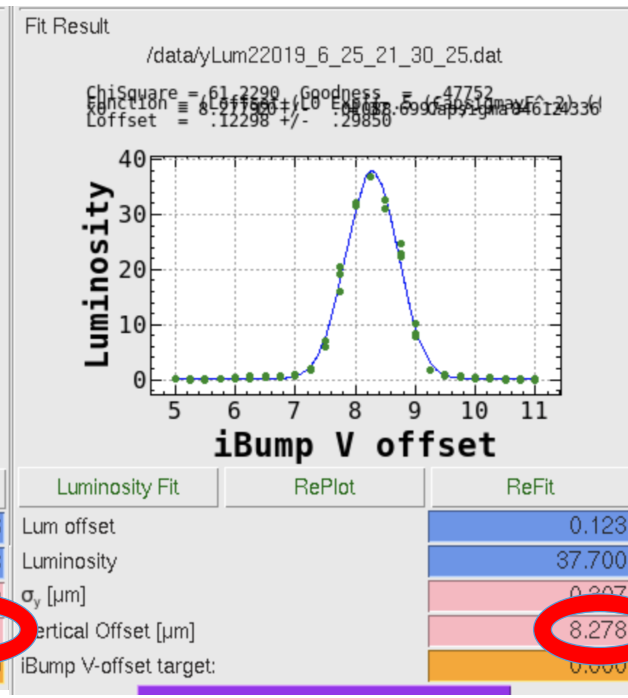


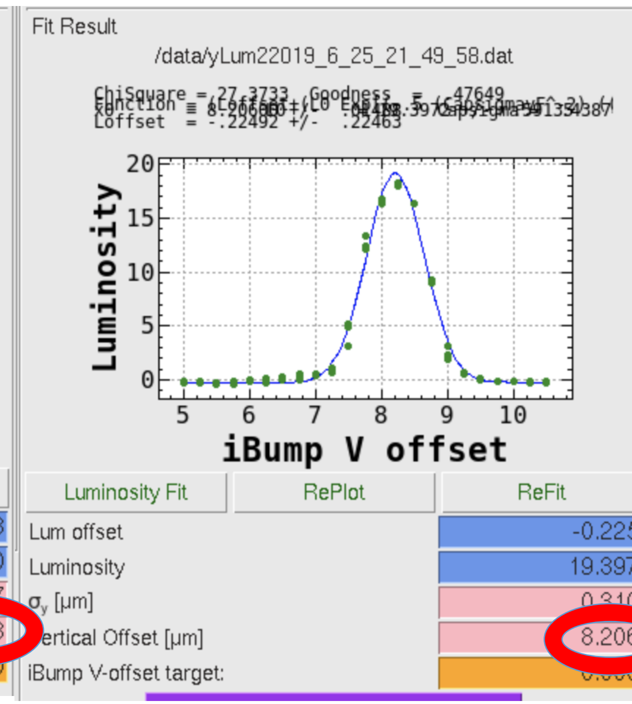




Vertical offset scan with RF phase offset



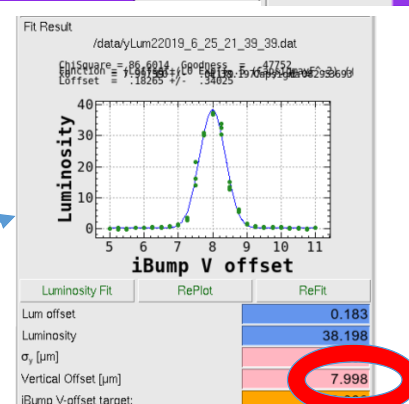




+5 degree (4.2mm offset)

0 degree

-5 degree (-4.2mm)



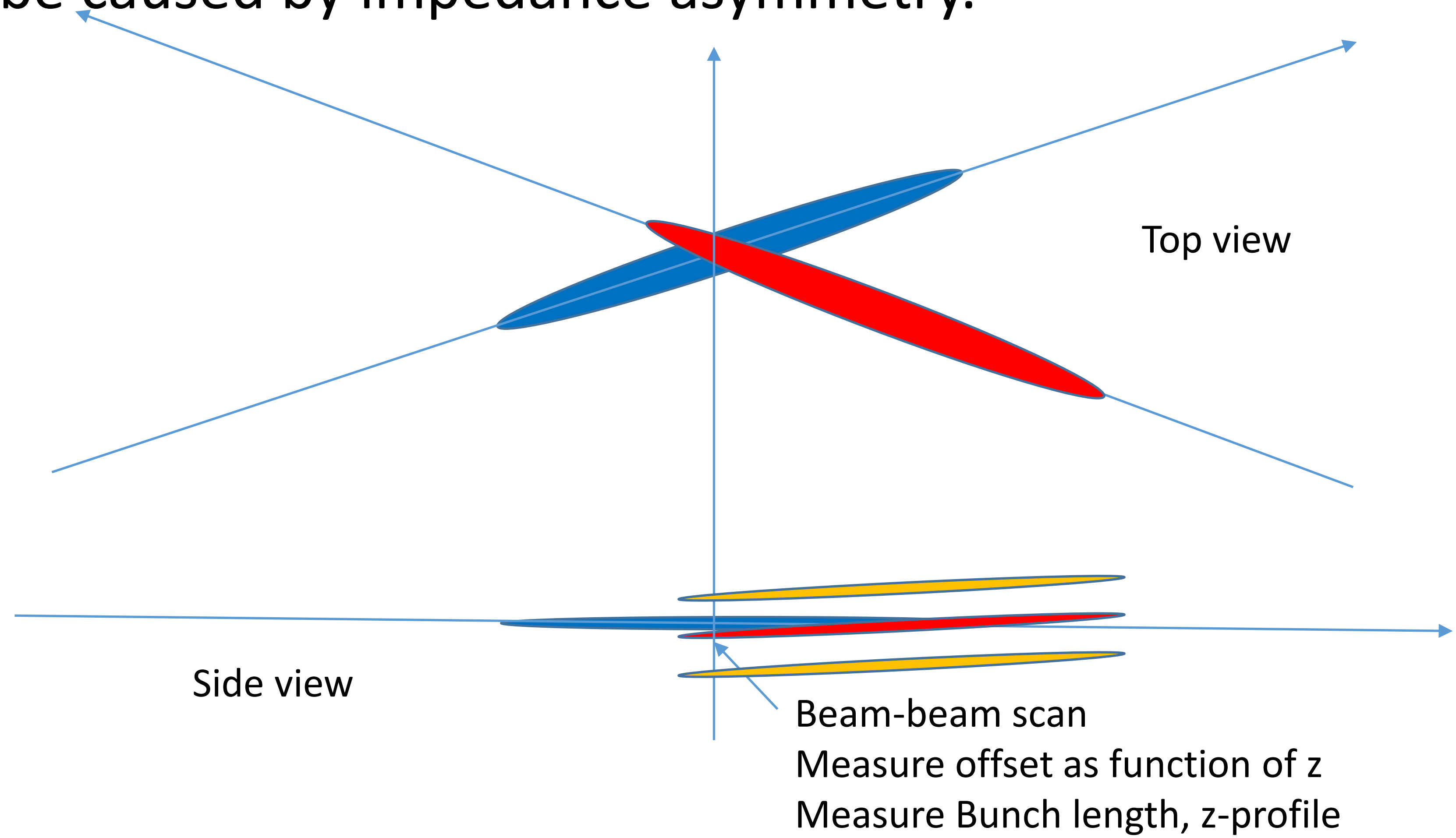
RF phase offsetによるvertical offsetの変化は小さい

逆方向にscan
11 -> 5 μm (他は5 ->11μm)

K. Ohmi

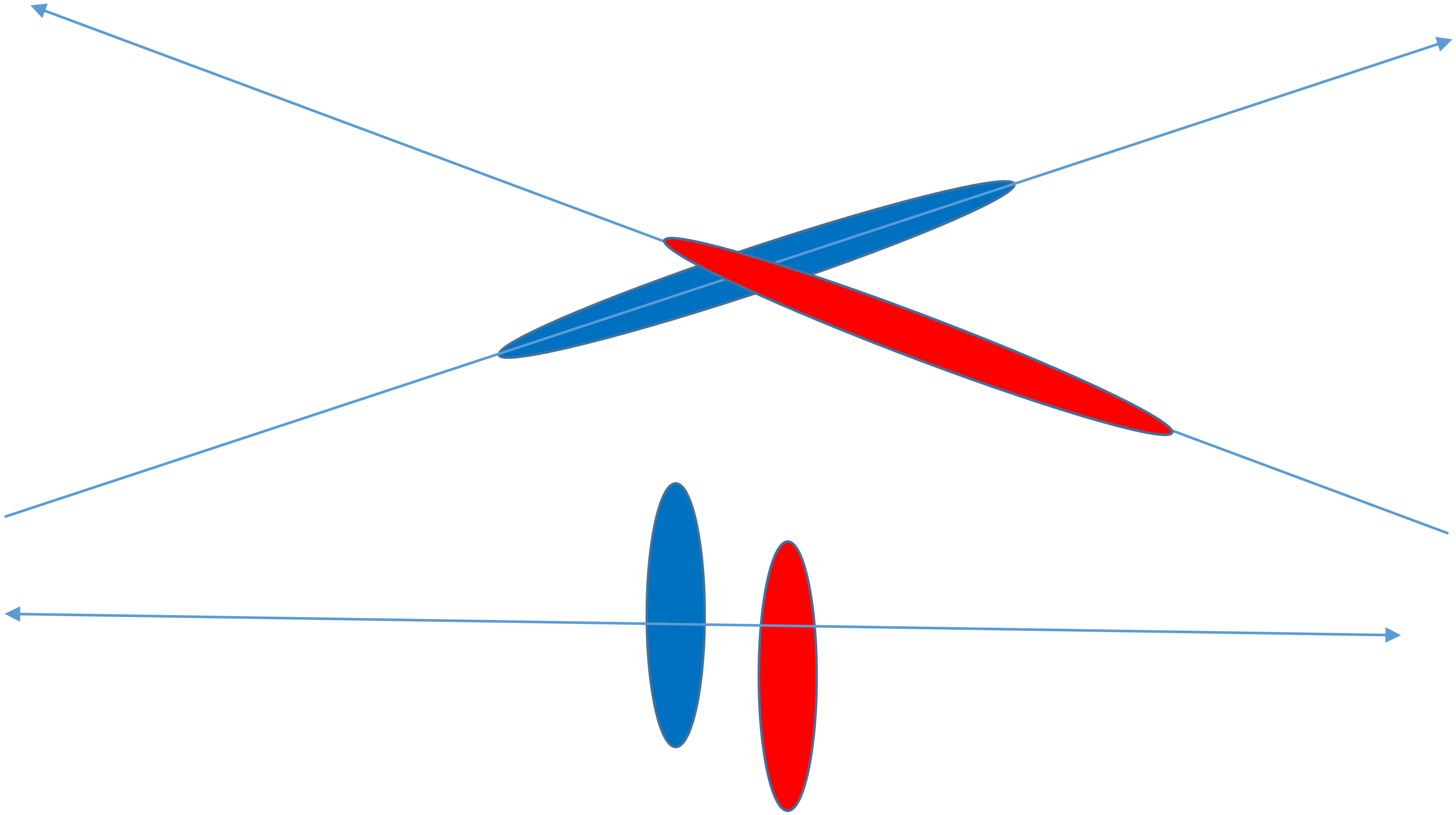
Vertical beam size/offset variation for z

- Low and high bunch current because beam tilt may be caused by impedance asymmetry.



Phase scan

- Equivalent to pan cake collision with projected longitudinal distribution



Luminosity integral

$$L = N_e N_p f_{col} \int_{-\infty}^{\infty} \rho_e(x,y,z_e;s)\rho_p(x,y,z_p;s)\delta\left(s - \frac{z_p - z_e}{2}\right) dx dy dz_e dz_p ds$$

$$\rho_e(x,y,z;s) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z} \exp\left(-\frac{(x-\theta_c z)^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)$$

$$\sigma_y(\mathrm{s}) = \sqrt{\varepsilon_y \beta_y(s)}$$

$$\frac{1}{2\pi\sigma_{x,e}\sigma_{x,p}} \int_{-\infty}^{\infty} \exp\left(-\frac{(x-\theta_c z_e)^2}{2\sigma_{x,e}^2} - \frac{\left(x-\theta_c z_p\right)^2}{2\sigma_{x,p}^2}\right) dx = \frac{\exp\left(-\frac{\left(z_e - z_p\right)^2 \theta_c^2}{2\Sigma_x^2}\right)}{\sqrt{4\pi\Sigma_x^2}}$$

$$\Sigma_x^2 = \sigma_{x,e}^2 + \sigma_{x,p}^2$$

$$\iint_{-\infty}^{\infty} \exp\left(-\frac{\left(z_e - z_p\right)^2 \theta_c^2}{2\Sigma_x^2} - \frac{z_e^2}{2\sigma_z^2} - \frac{z_p^2}{2\sigma_z^2}\right) dz_e dz_p = \frac{2\pi\Sigma_x\sigma_z}{\sqrt{\Sigma_x^2 + 2\sigma_z^2\theta_c^2}}$$

Luminosity in nano-beam collision

- Luminosity- collision is done in area $\sigma_x/\theta_c \ll \sigma_z$ at s*.

$$L = \frac{N_e N_p f_{col}}{\theta_c} \int_{-\infty}^{\infty} \rho_e(y,z;s^*)\rho_p(y,z;s^*)dy\,dz \qquad \frac{\sigma_x^*}{\theta_c} < \beta_y^*$$

- When e+ bunch shift in longitudinal

$$\rho_p(y,z) = \frac{1}{2\pi\sigma_{y,p}^*\sigma_{z,p}} \exp\left(-\frac{y^2}{2\sigma_{y,p}^{*2}} - \frac{(z-z_0)^2}{2\sigma_{z,p}^2}\right)$$

$$L(z_0) = \frac{N_e N_p f_{col}}{2\pi\theta_c} \frac{1}{\Sigma_y \Sigma_z} \exp\left(-\frac{z_0^2}{2\Sigma_z^2}\right)$$

Top view

Σ_z is measurable.

- Non-Gaussian longitudinal profile

$$L(z_0) \propto \int_{-\infty}^{\infty} \rho_e(z;s^*)\rho_p(z,z_0;s^*)dz$$

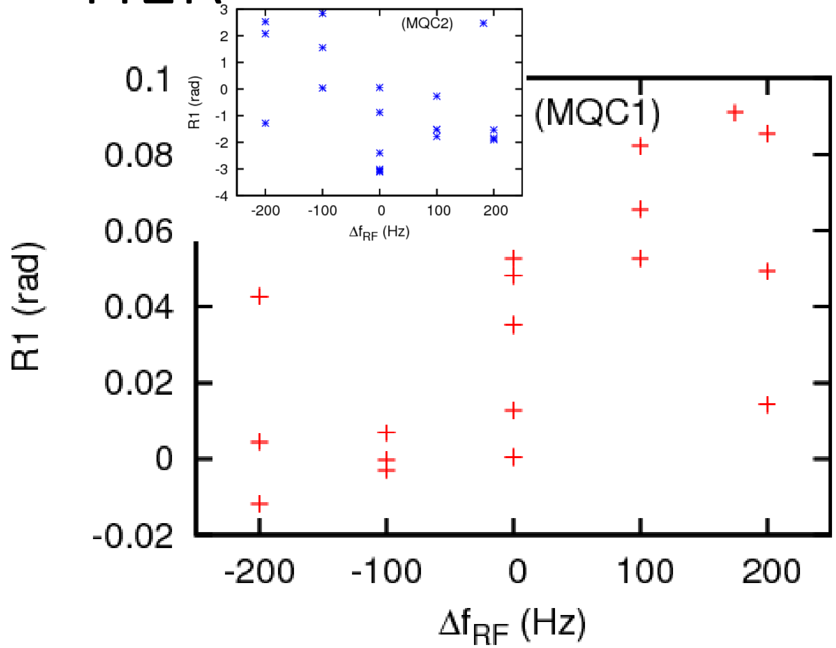
- Tilt beam in y-z

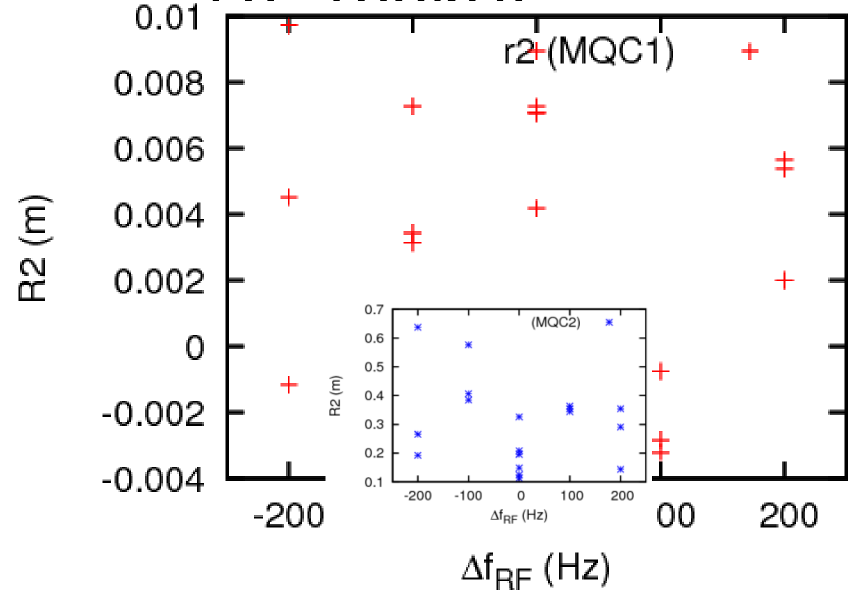
$$\rho_p(y,z) = \frac{1}{2\pi\sigma_{y,p}^*\sigma_{z,p}} \exp\left(-\frac{(y-az-b)^2}{2\sigma_{y,p}^{*2}} - \frac{(z-z_0)^2}{2\sigma_{z,p}^2}\right)$$

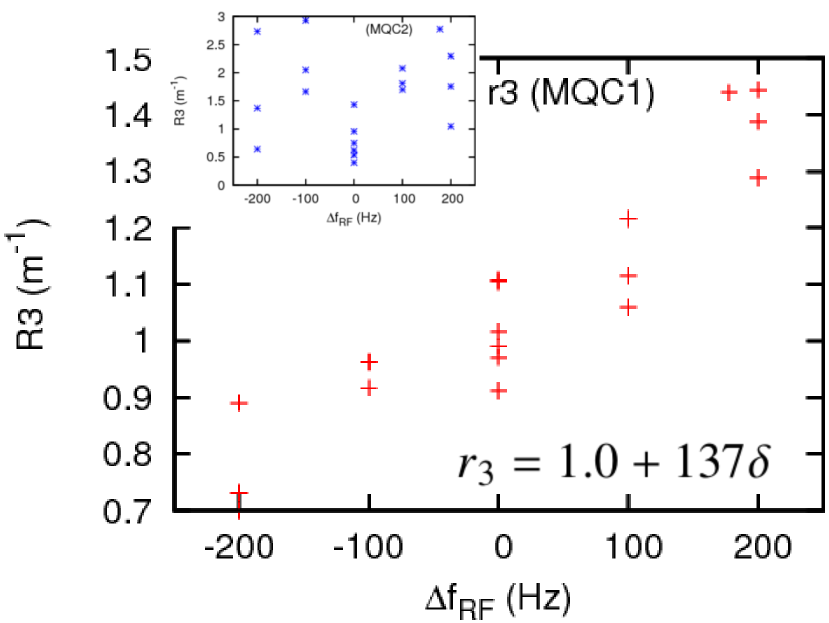
$$L(z_0,b) \propto \exp\left[-\frac{1}{2}\left(\frac{\Sigma_y^2 z_0^2 + \sigma_{z,p}^2 b^2 + \sigma_{z,e}^2(az_0+b)^2}{\Sigma_y^2\Sigma_z^2 + a^2\sigma_{z,e}^2\sigma_{z,p}^2}\right)\right]$$

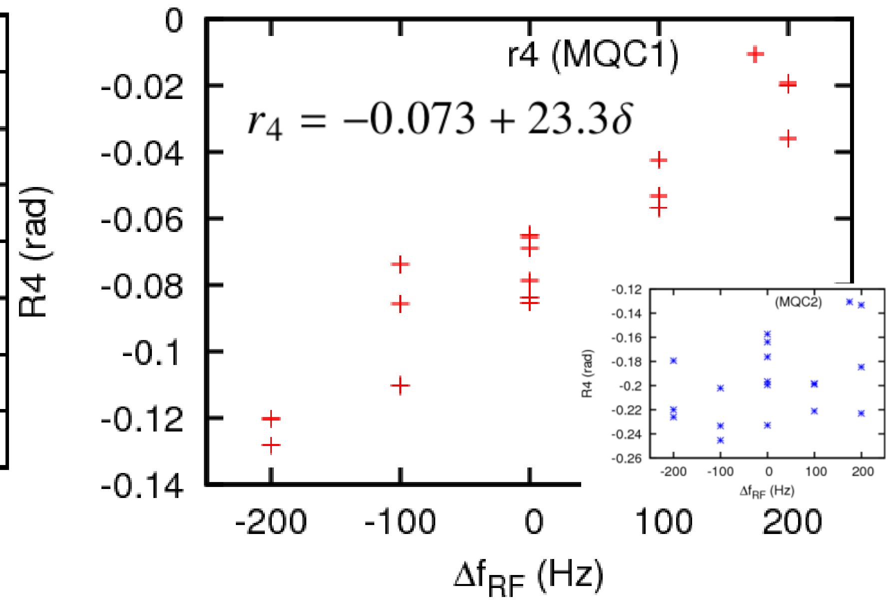
HER

- F0=100kHz







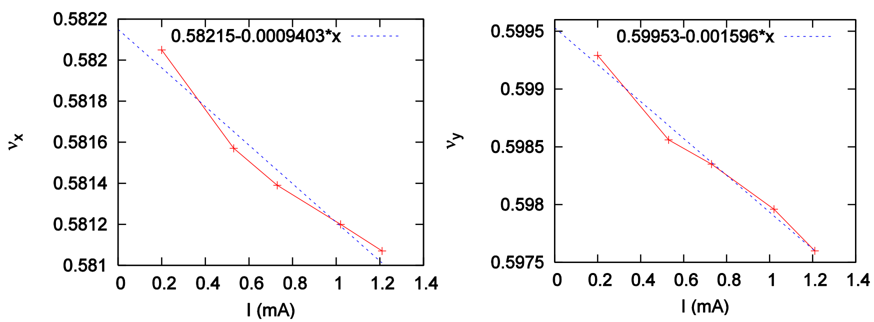


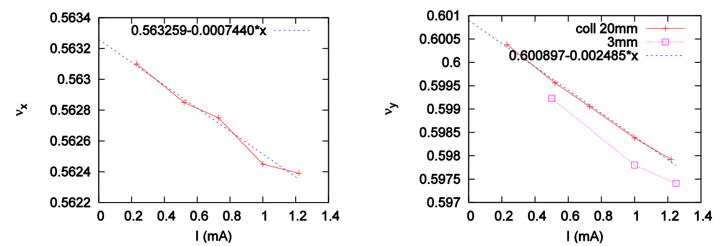
Impedance estimation- transverse

- Tune shift as function of bunch current

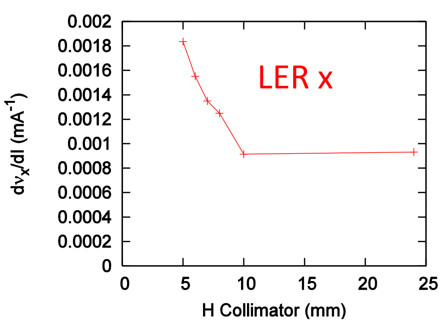
$$\Delta\nu_x = \frac{1}{4\pi^{3/2}}\frac{Nr_e}{\gamma}\frac{L}{\nu_x\sigma_z}\frac{iZ_{eff}}{Z_0}$$

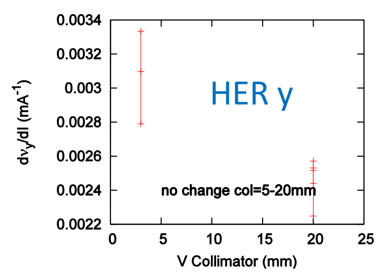
$$iZ_{eff}(k\Omega) = 33.3\frac{\Delta\nu_x}{I(mA)} \quad \text{LER} \qquad = 58.2\frac{\Delta\nu_x}{I(mA)} \quad \text{HER}$$





$iZ_{eff} = 31\ (x) \quad 53\ (y)\ k\Omega/m$ $\qquad iZ_{eff} = 43\ (x) \quad 145\ (y)\ k\Omega/m$





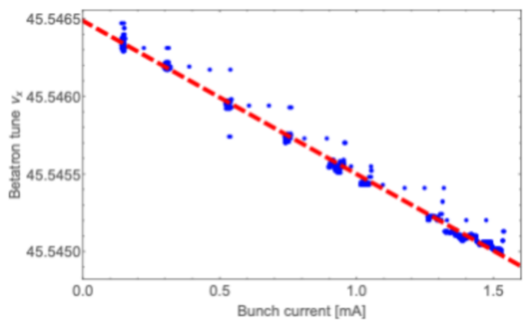
Collimator dependence

KEKB-LER: -0.0034mA^{-1}, 81kΩ/m
coll. open 33-46 kΩ/m T. Ieiri, EPAC00

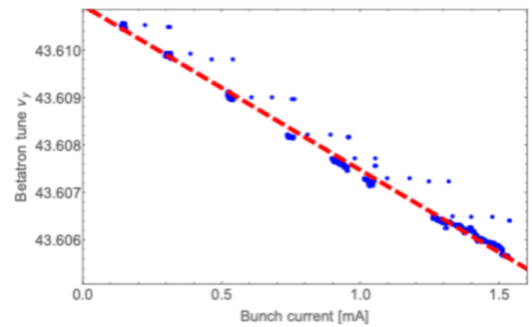
➤ Single-bunch betatron tune shift: HER

- Linear fitting model: f(x)=a+b*x
- $Zeff_x$ ~48.7 kΩ/m, $Zeff_y$ ~164 kΩ/m

Linear fitting:
f(I)=45.5465 - 0.000988*I[mA]



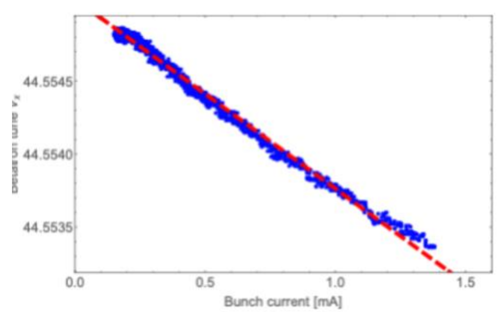
Linear fitting:
f(I)=43.6109 - 0.00347*I[mA]



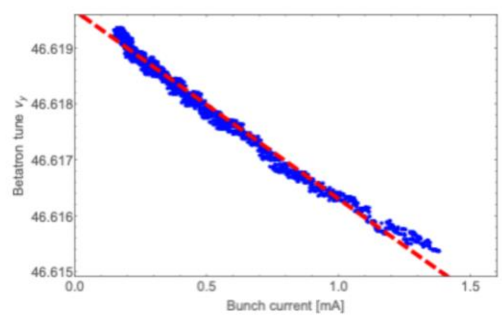
➤ Single-bunch betatron tune shift: LER

- Linear fitting model: f(x)=a+b*x
- Used natural decay of bunch current: Problematic because of changing machine conditions with time
- $Zeff_x$ ~32.2 kΩ/m, $Zeff_y$ ~87.4 kΩ/m

Linear fitting:
f(I)=44.5551 - 0.00130*I[mA]

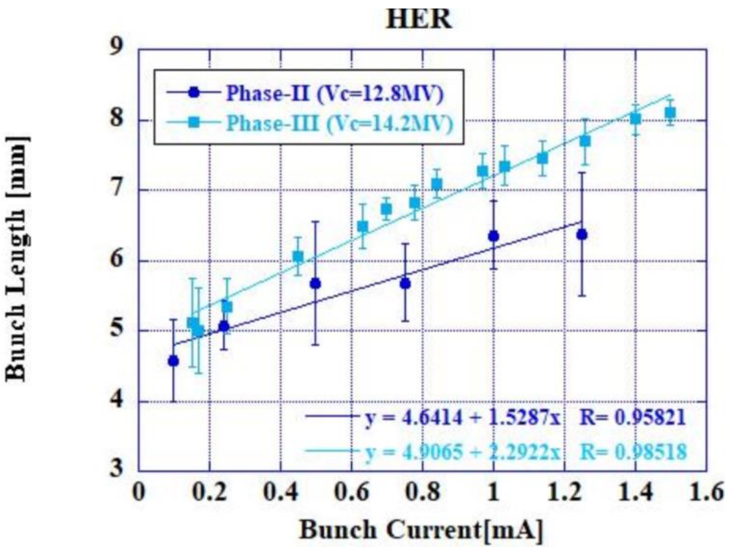


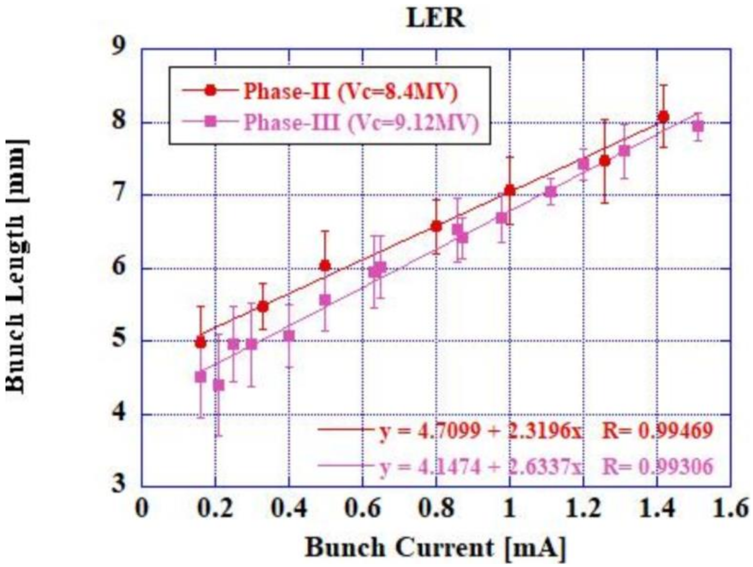
Linear fitting:
f(I)=46.6197 - 0.00337*I[mA]



Bunch length measurement

- H.Ikeda

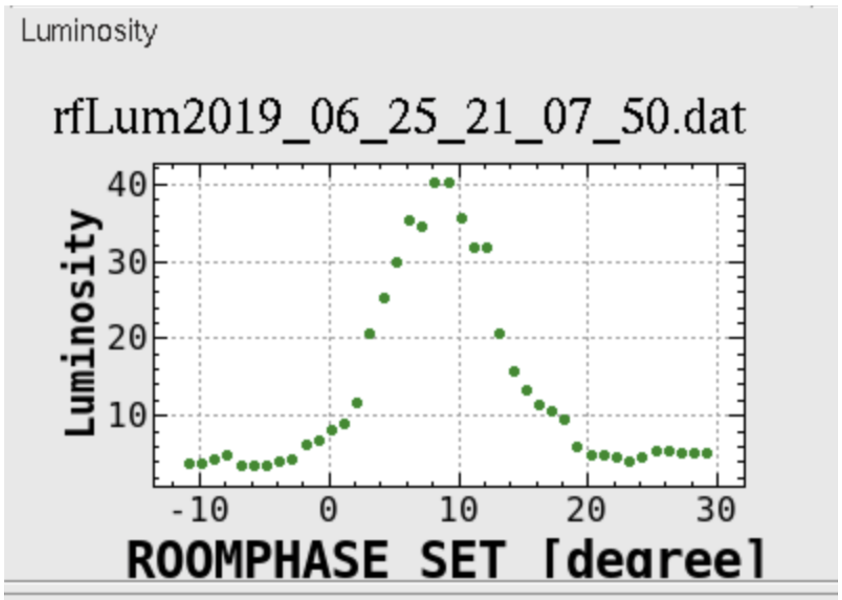


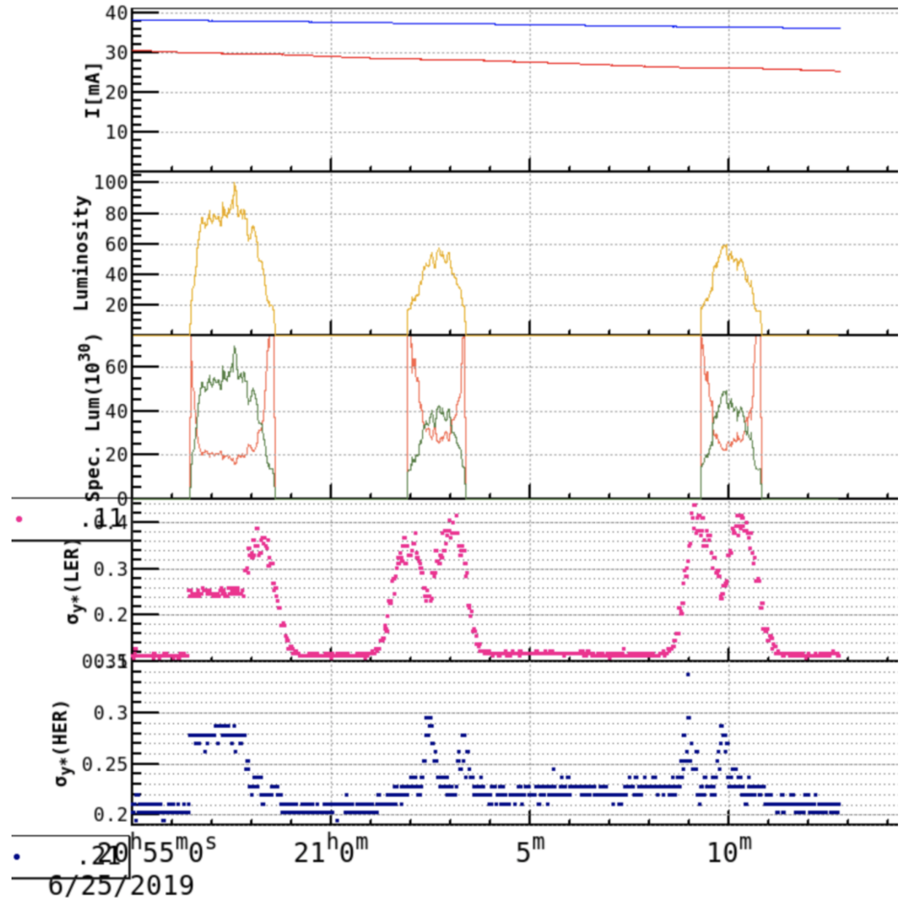


Measured by a Streak camera

The behaviors are similar as KEKB for both of LER and HER.
Bunch lengthening is stronger than that of simulation.

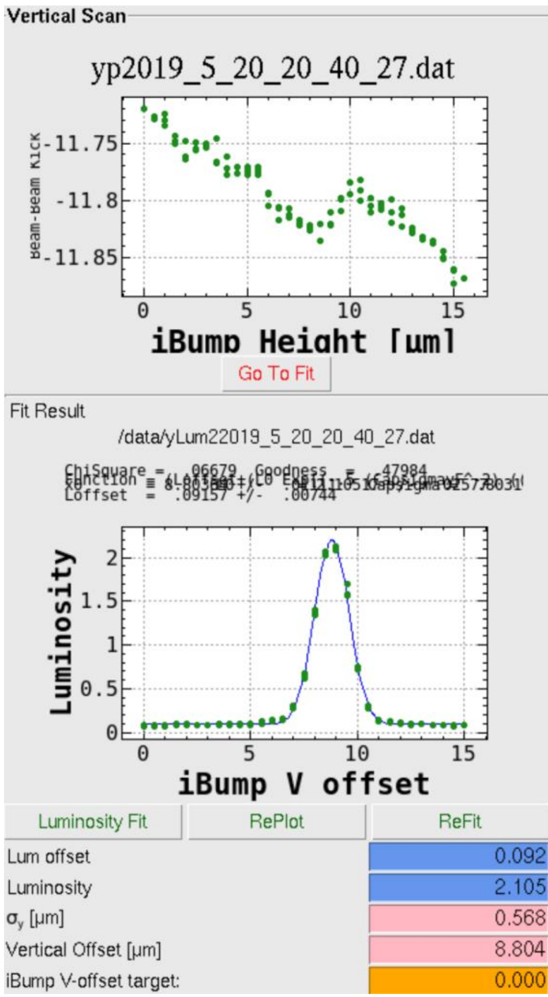
RF phase scan

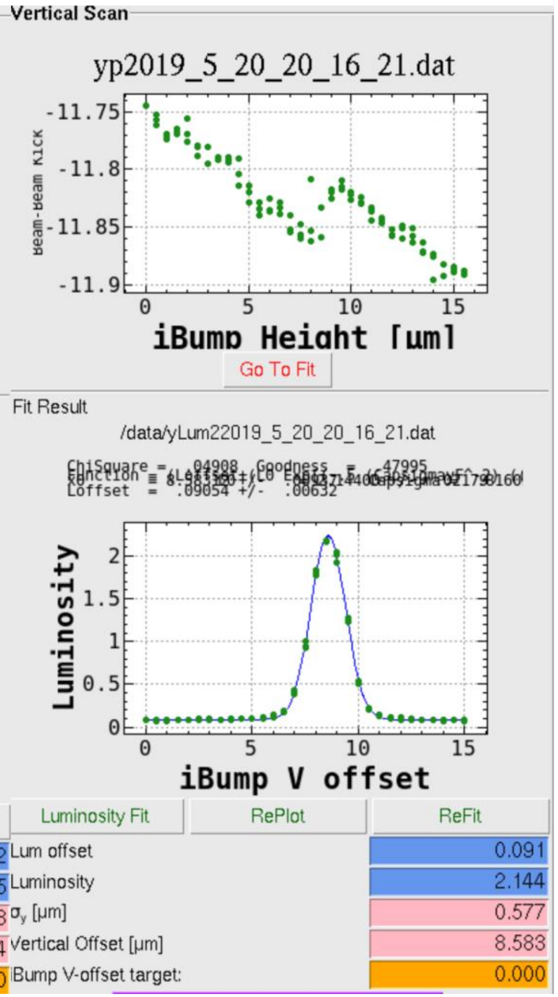


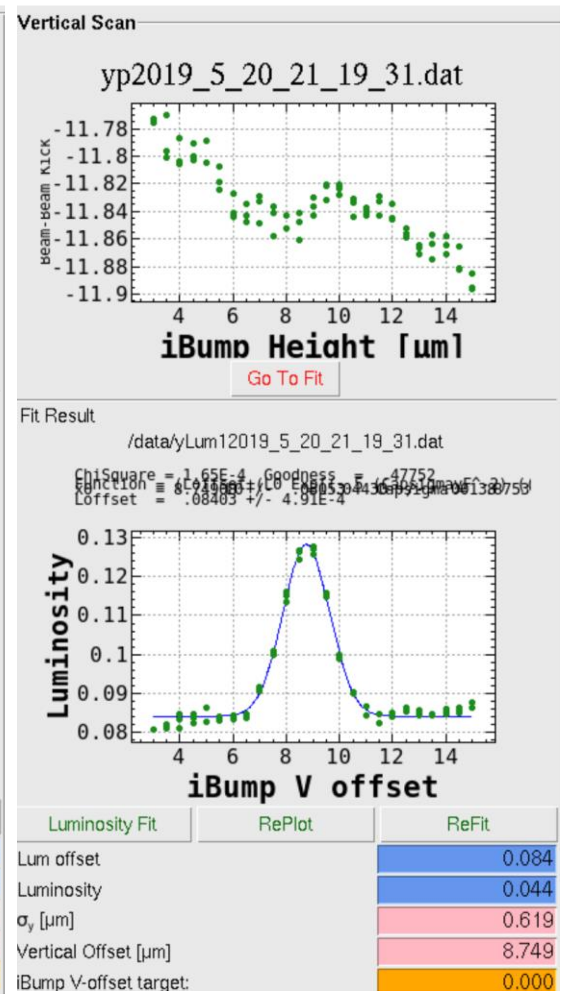


このデータからバンチ長を評価できるはず
->まだやってない

- set IP knob
- Δf=-400Hz 0Hz +400Hz

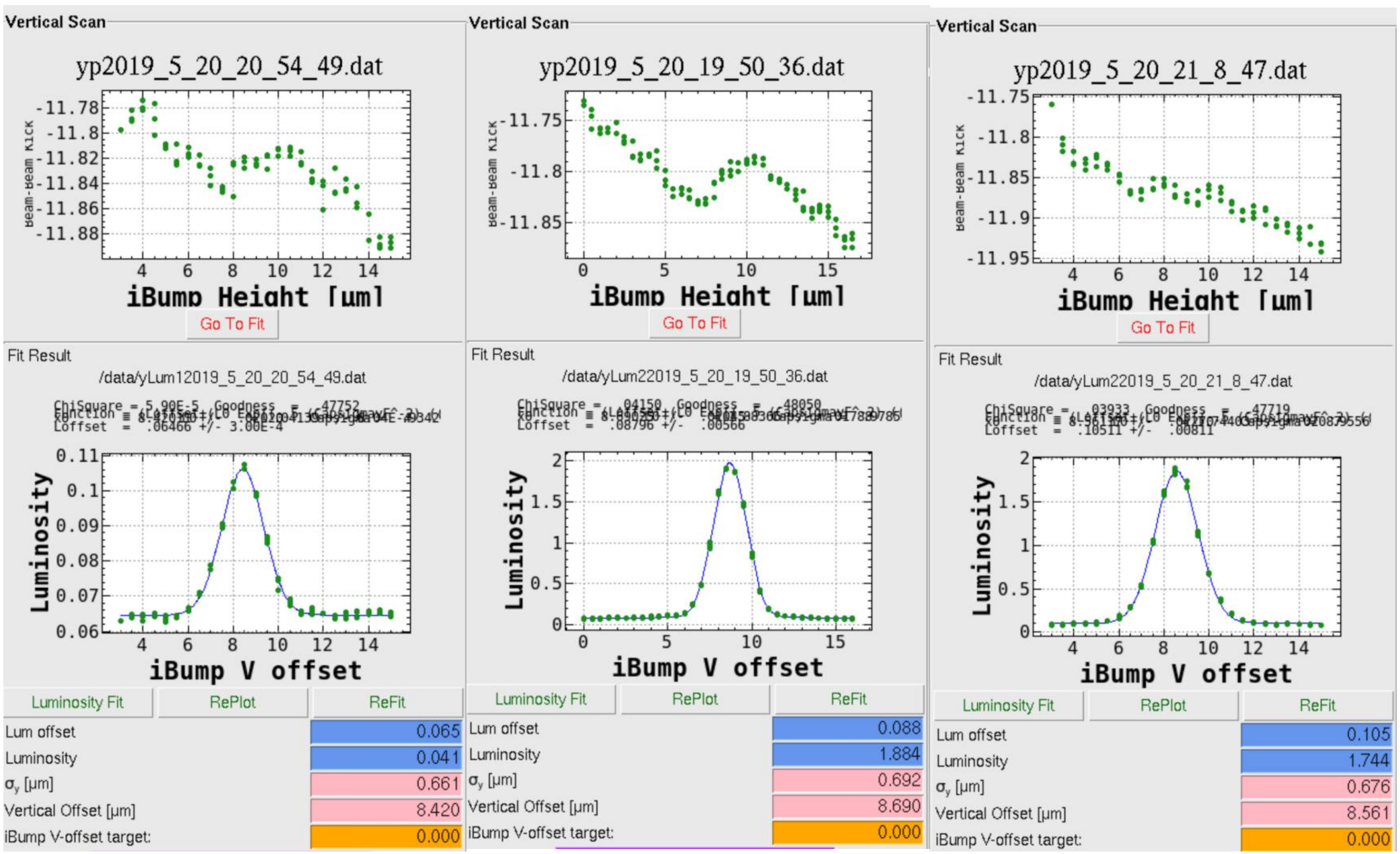






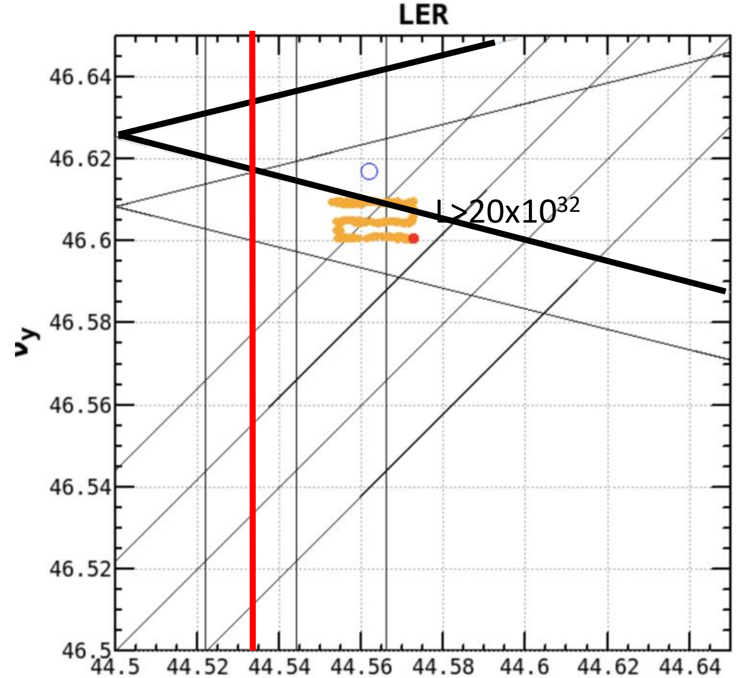
Beam-beam scan with Δf_{RF}

- IP knob off
- Δf=-400Hz 0Hz 400Hz



2018/7/6 Swing HBC tune scan

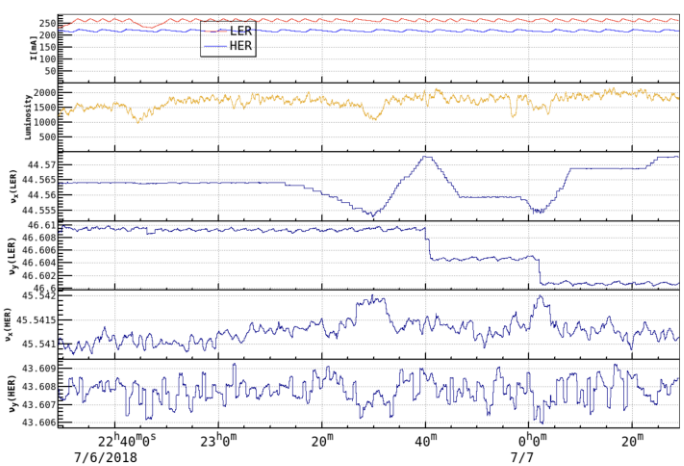
- One of the Crab waist effect
- Is resonance $\nu_x+4\nu_y=0$ seen?
- βx=200/100mm

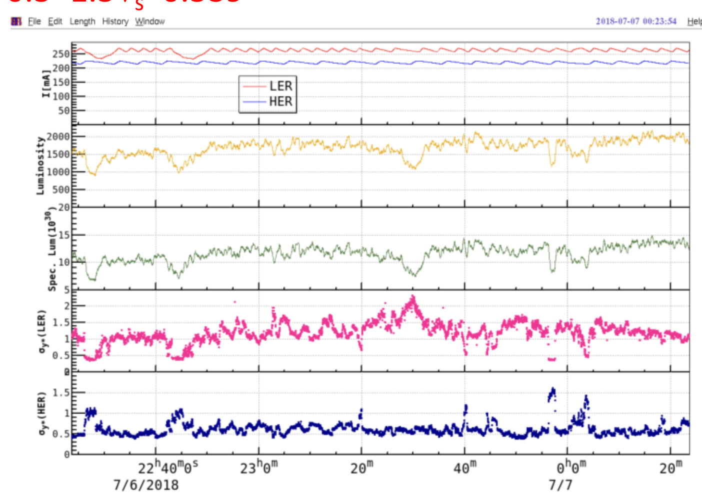


$\nu_x+4\nu_y=0$

Dangerous line
$\nu_x=0.5+1.5\nu_s=0.539$

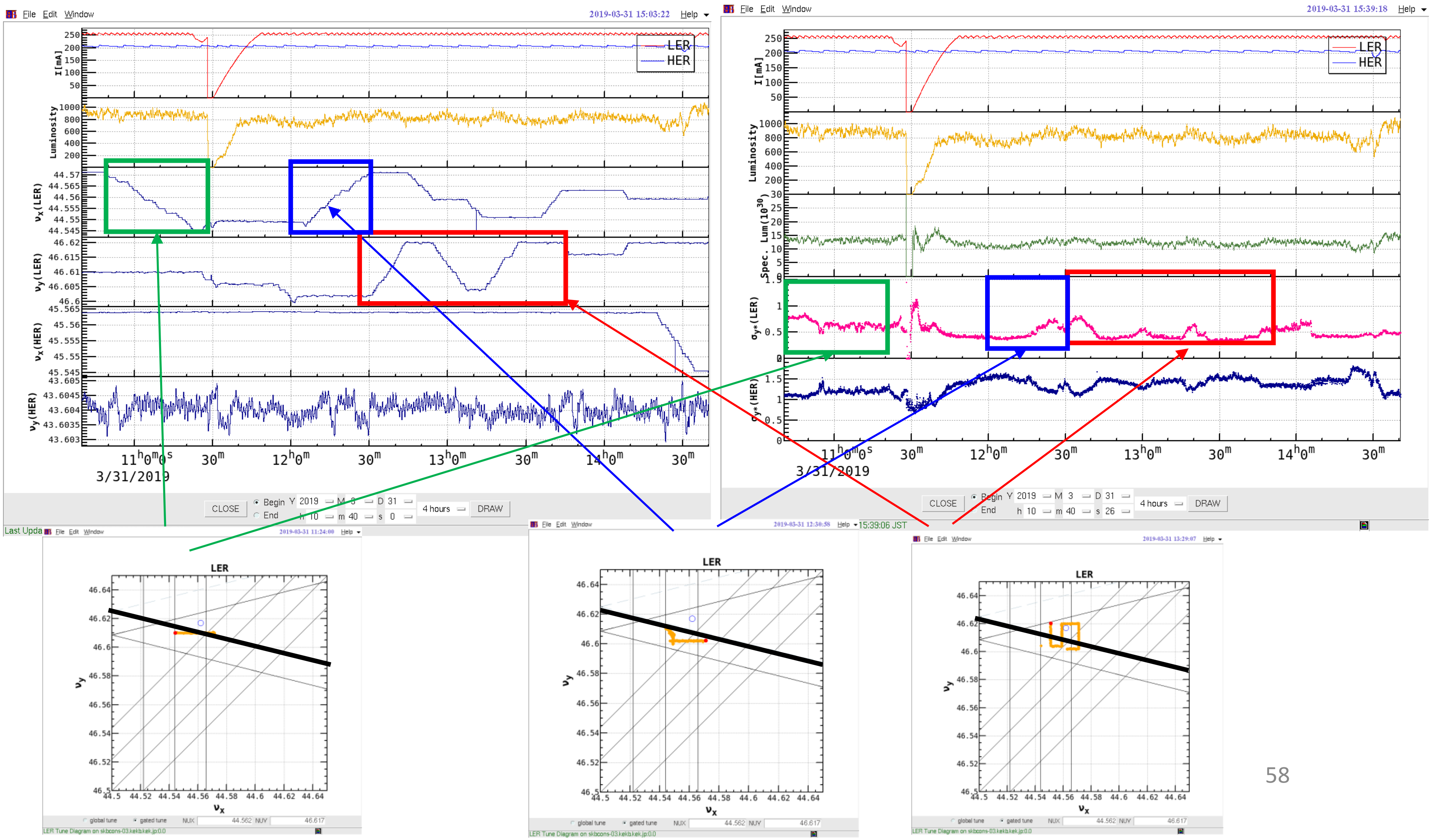
σ_x of both beam increases





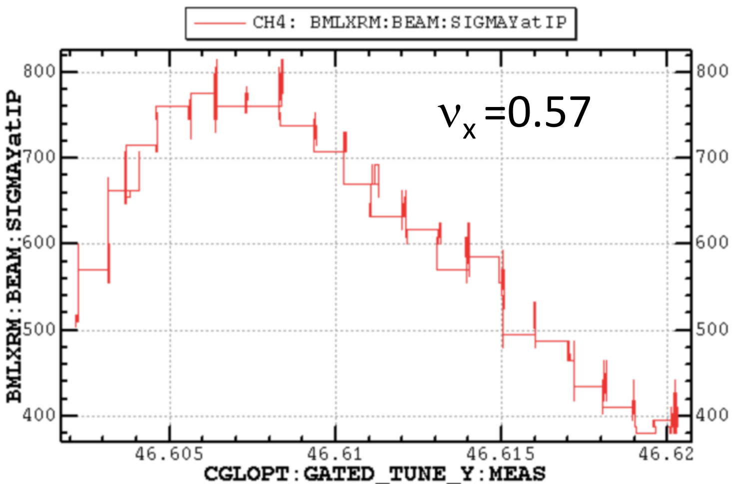
LER tune scan 2019/3/31

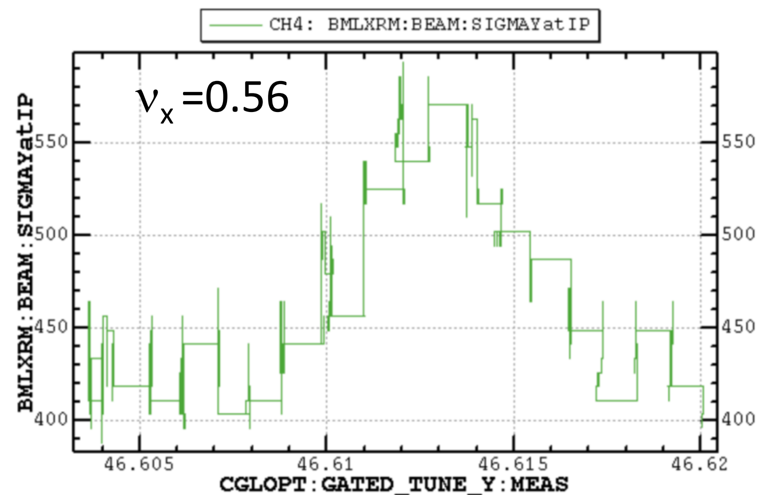
- nx+4ny=int is seen. βx=200/200mm

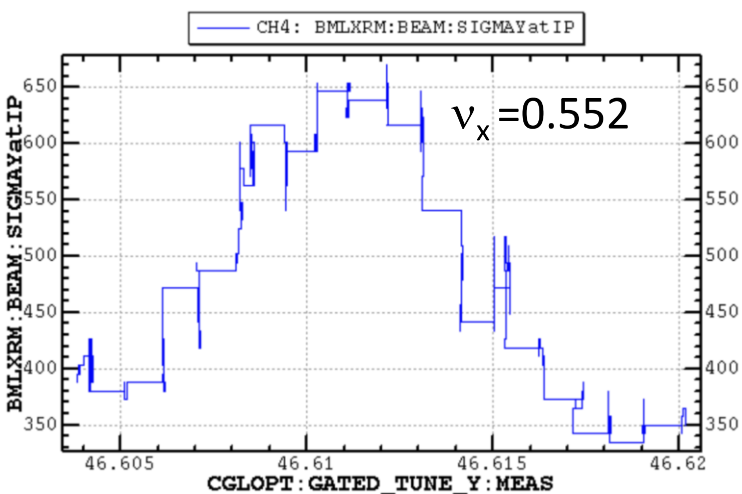


LER tune scan 2019/3/31

- Shift of σ_y peak for ν_x.





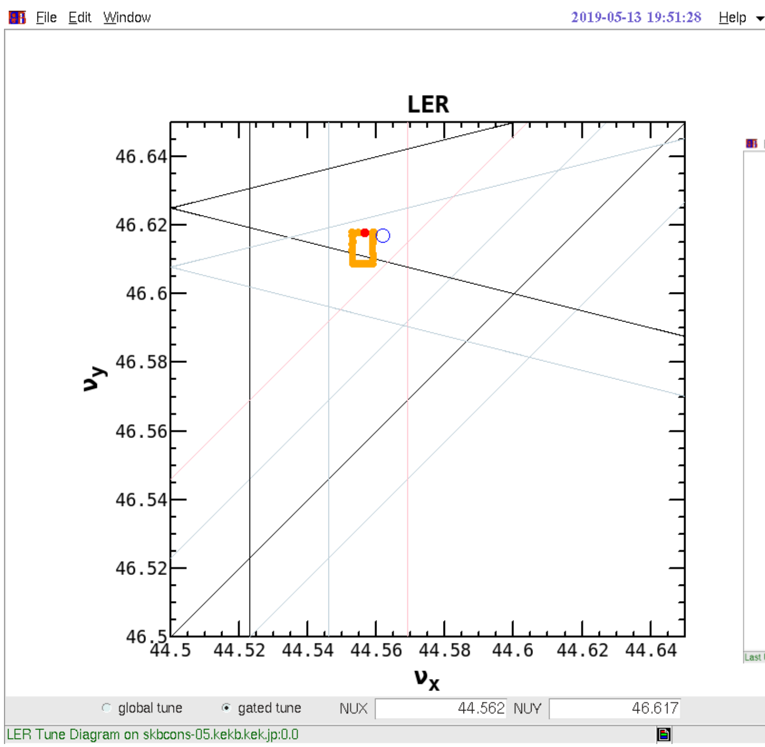


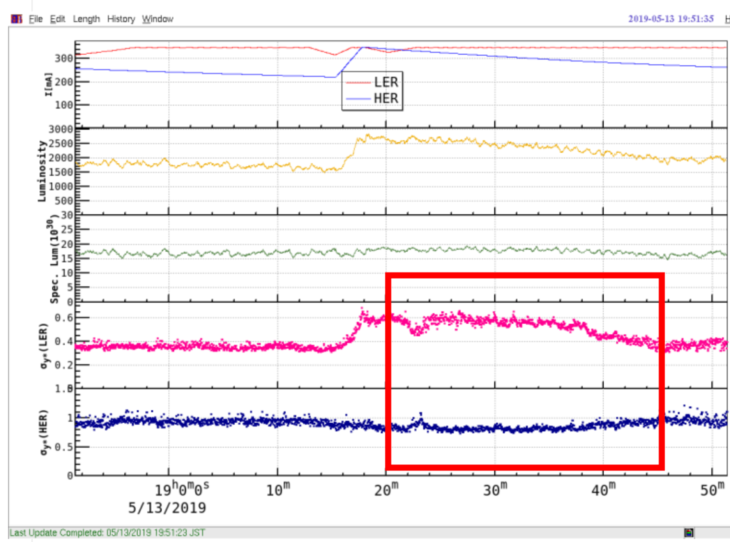
$\nu_x + 4\nu_y = 2.998$ $\nu = (0.57, 0.607)$
3.012 $= (0.56, 0.613)$
3.000 $= (0.552, 0.612)$

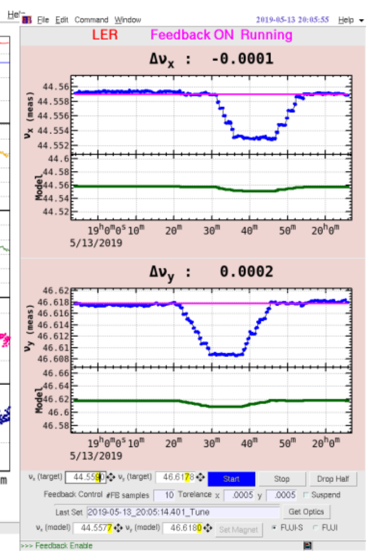
LER tune scan 2019/5/13

- No resonance is seen at $\nu_x+4\nu_y$=int at βx=100(H),200(L)mm.
- The resonance appeared for β_x=200,200mm (2019/3/31) but does not for 100(H),200(L)mm

- This crab waist effect, (1,4) resonance, is weak.





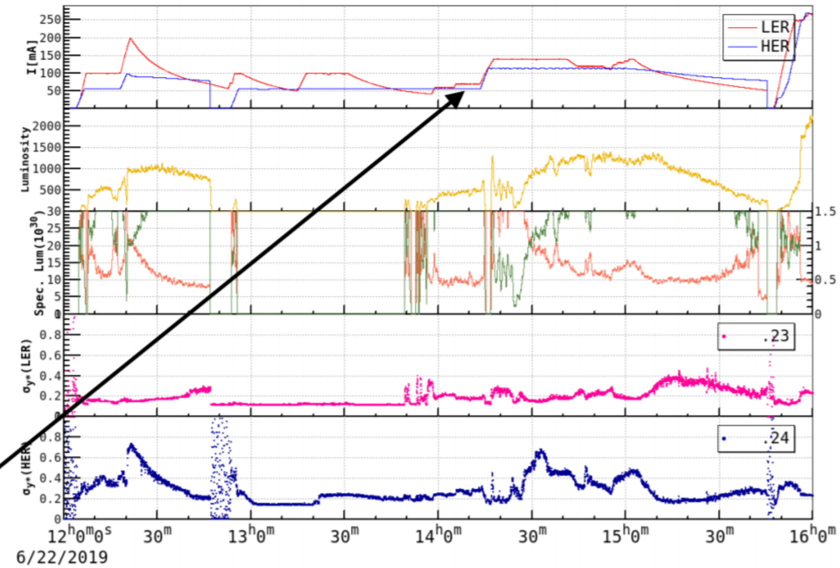


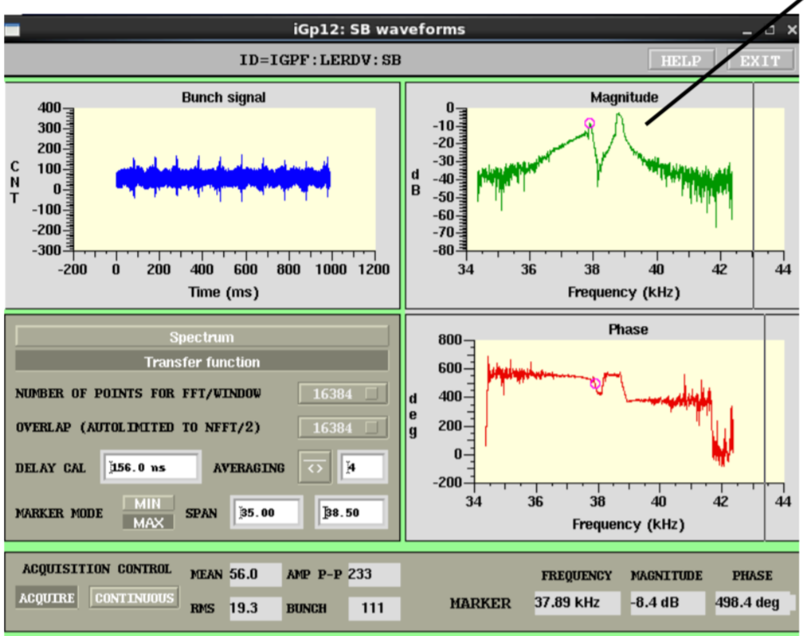
1. 2019.06.22: Beam-beam tune shift study

➤ Experimental observations

- First observation: 14:13 PM
- 70 mA (e+) x 57 mA (e-)
- σy*(e+)=0.18 μm, σy*(e-)=0.29 μm [XRM]
- Lum. ~$5*10^{32}$ cm^{-2}s^{-1}
- Beam-beam parameter estimated from lum.:
  ξ_{y-} ~0.022, ξ_{y+} ~0.011
- From feedback system:
  ξ_{y+} ~(38.79-37.89) kHz /99.39 kHz ~0.009

Fairly good consistency?





$$\mathcal{L} = \mathcal{L}_0 \cdot R_\theta \qquad \mathcal{L}_0 = \frac{N_\mathrm{p} N_\mathrm{e} f N_\mathrm{b}}{2\pi\sqrt{\sigma_\mathrm{xp}^{*2} + \sigma_\mathrm{xe}^{*2}}\sqrt{\sigma_\mathrm{yp}^{*2} + \sigma_\mathrm{ye}^{*2}}}$$

$$R_\theta \approx \frac{1}{\sqrt{1 + \frac{\sigma_\mathrm{zp}^{*2} + \sigma_\mathrm{ze}^{*2}}{\sigma_\mathrm{xp}^{*2} + \sigma_\mathrm{xe}^{*2}} \tan^2\frac{\theta}{2}}}$$

$$\xi_\mathrm{ye0} = \frac{N_\mathrm{p} r_\mathrm{e} \beta_\mathrm{ye}^*}{2\pi\gamma_\mathrm{e}\sigma_\mathrm{xp}^*\sigma_\mathrm{yp}^*} \frac{1}{\sqrt{\left(\frac{\sigma_\mathrm{zp}^*}{\sigma_\mathrm{xp}^*}\tan\frac{\theta}{2}\right)^2 + 1} + \frac{\sigma_\mathrm{yp}^*}{\sigma_\mathrm{xp}^*}}$$

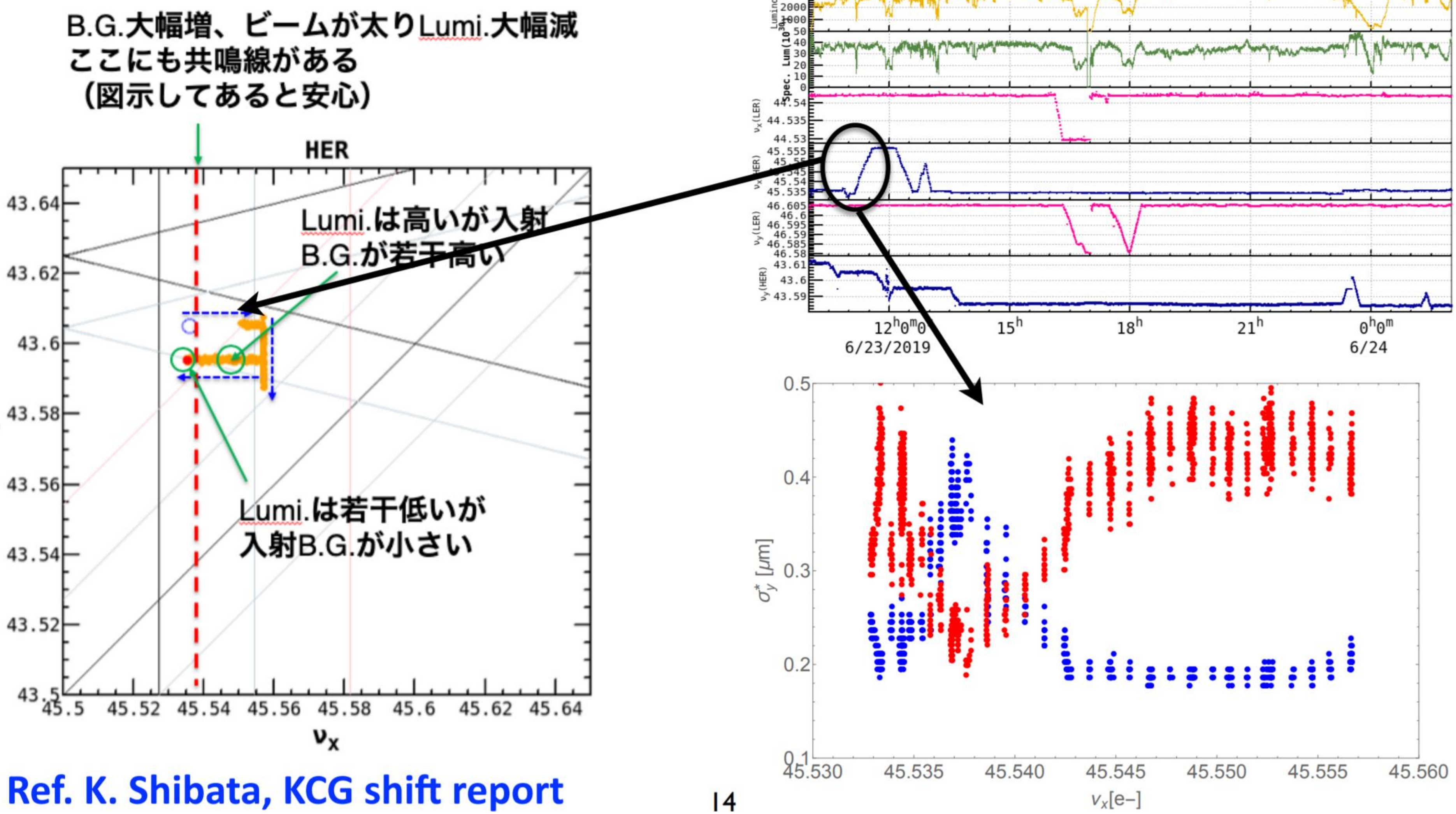
$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_\pm}{\beta_{y\pm}^*}\frac{2\sigma_{x\mp}^*\sigma_{y\mp}^*}{\sqrt{\sigma_{x+}^{*2} + \sigma_{x-}^{*2}}\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

Correct formula?

3. 2019.06.23: Tune scan study

➤ HER ν_x scan with ν_y = 43.605

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

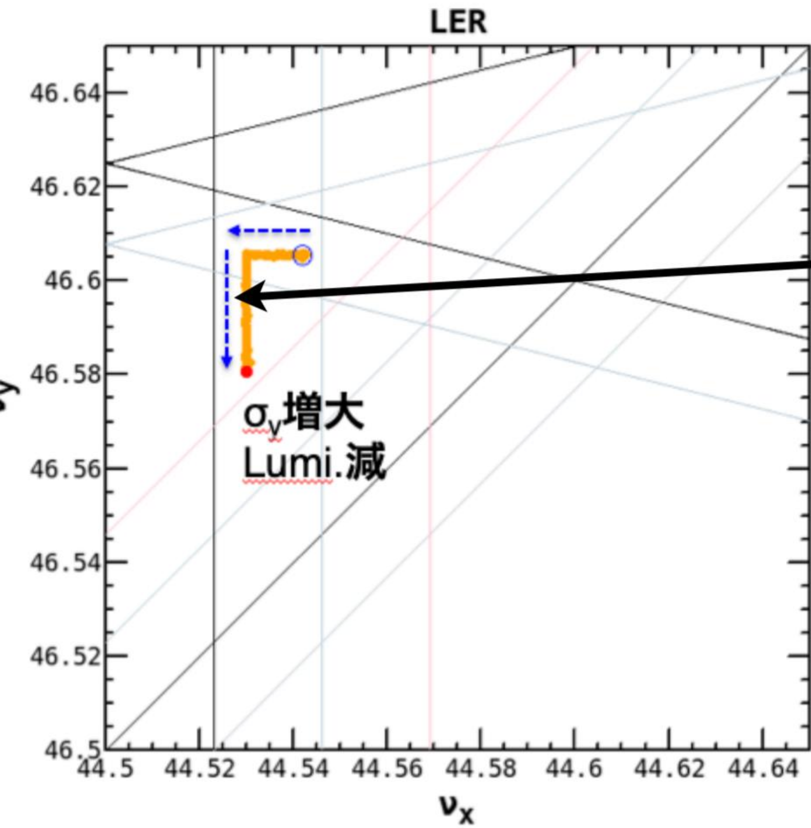


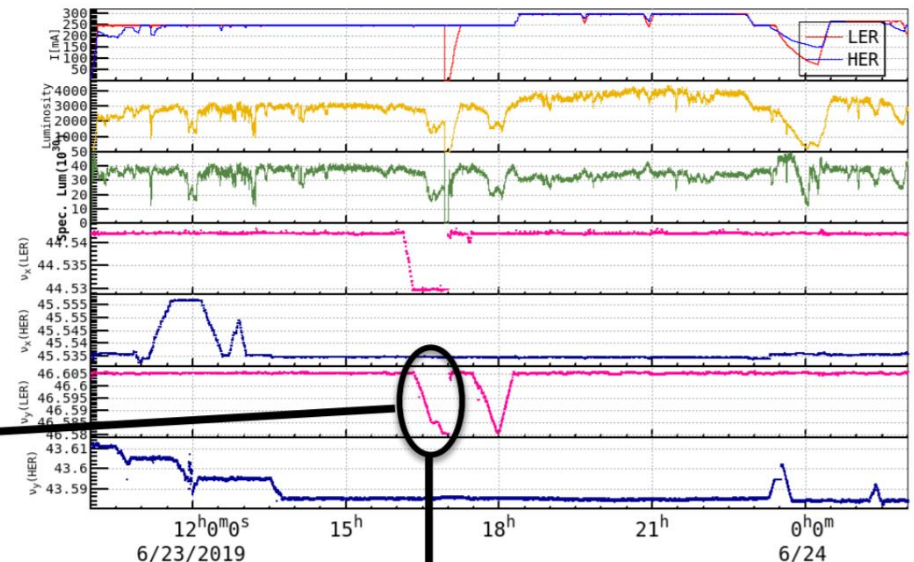
Ref. K. Shibata, KCG shift report

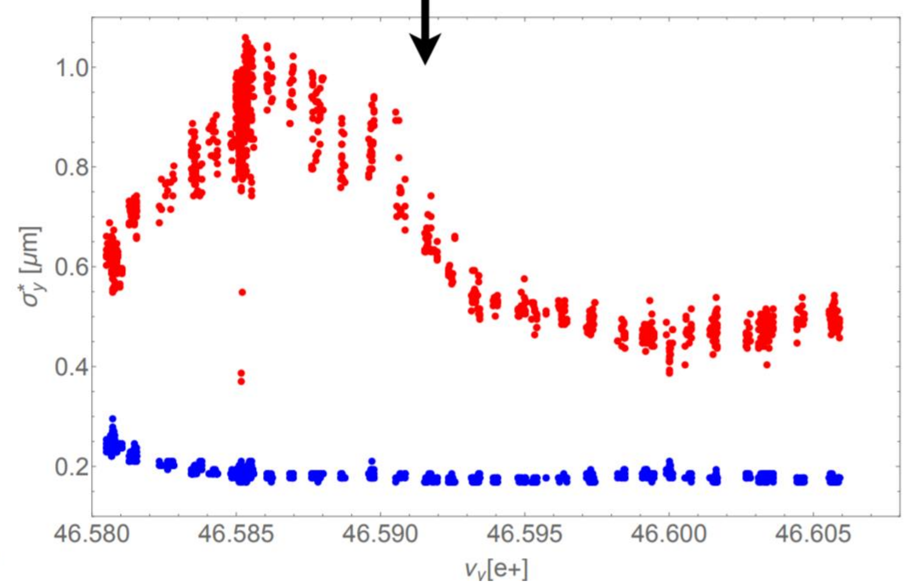
3. 2019.06.23: Tune scan study

➤ LER ν_y scan with ν_x = 44.53

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







Ref. K. Shibata, KCG shift report