SuperKEKB status and experience with collisions at large Piwinski angle

K. Ohmi (KEK/IHEP)

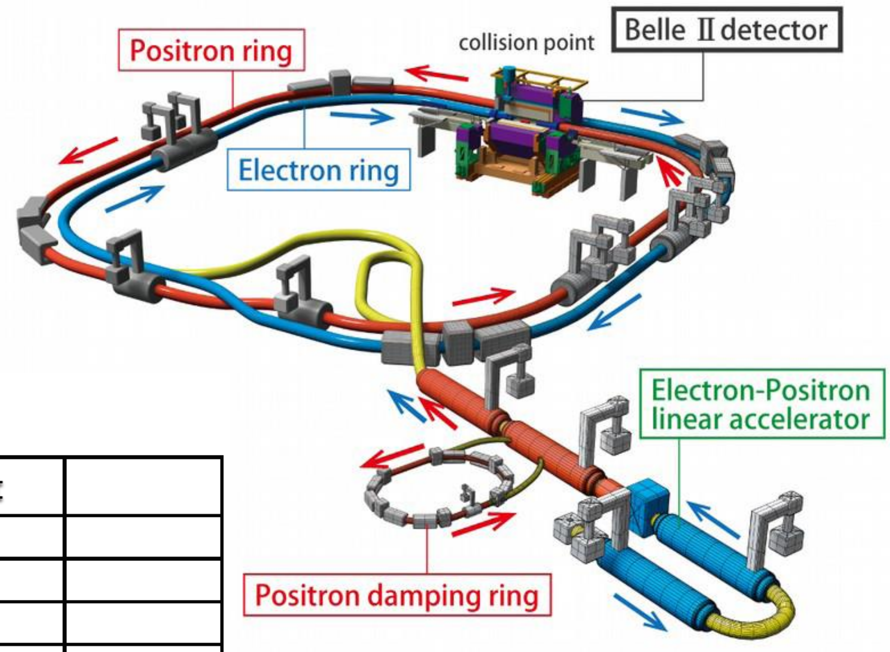
FCCweek 2019, Brussels, Belglum

24-28 June, 2019

On behalf of SuperKEKB commissioning team

SuperKEKB

- Piwinski angle $\sigma_z/\sigma_x\theta_c$=20
- β_y^*=0.3mm



Machine Parameters

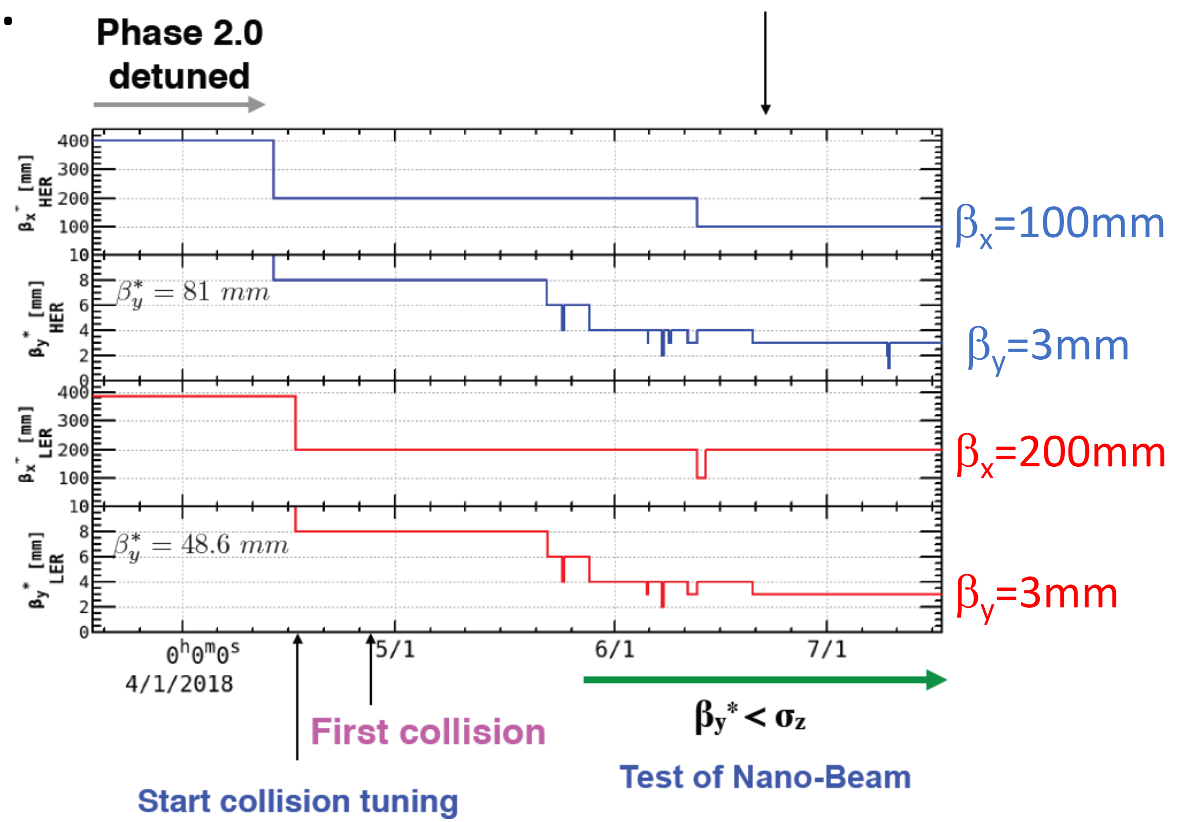
2011/July/20	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/11.5(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle $2\theta_c$	83		mrad	
α_p	3.25×10^{-4}	4.55×10^{-4}		
σ_δ	$8.08(7.73)\times10^{-4}$	$6.37(6.31)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0247	-0.0280		
ν_x/ν_y	44.53/44.57	45.53/43.57		
U_0	1.87	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

θ_c: half crossing angle

http://www-superkekb.kek.jp/

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-2,3

N_{bunch}=788

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

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

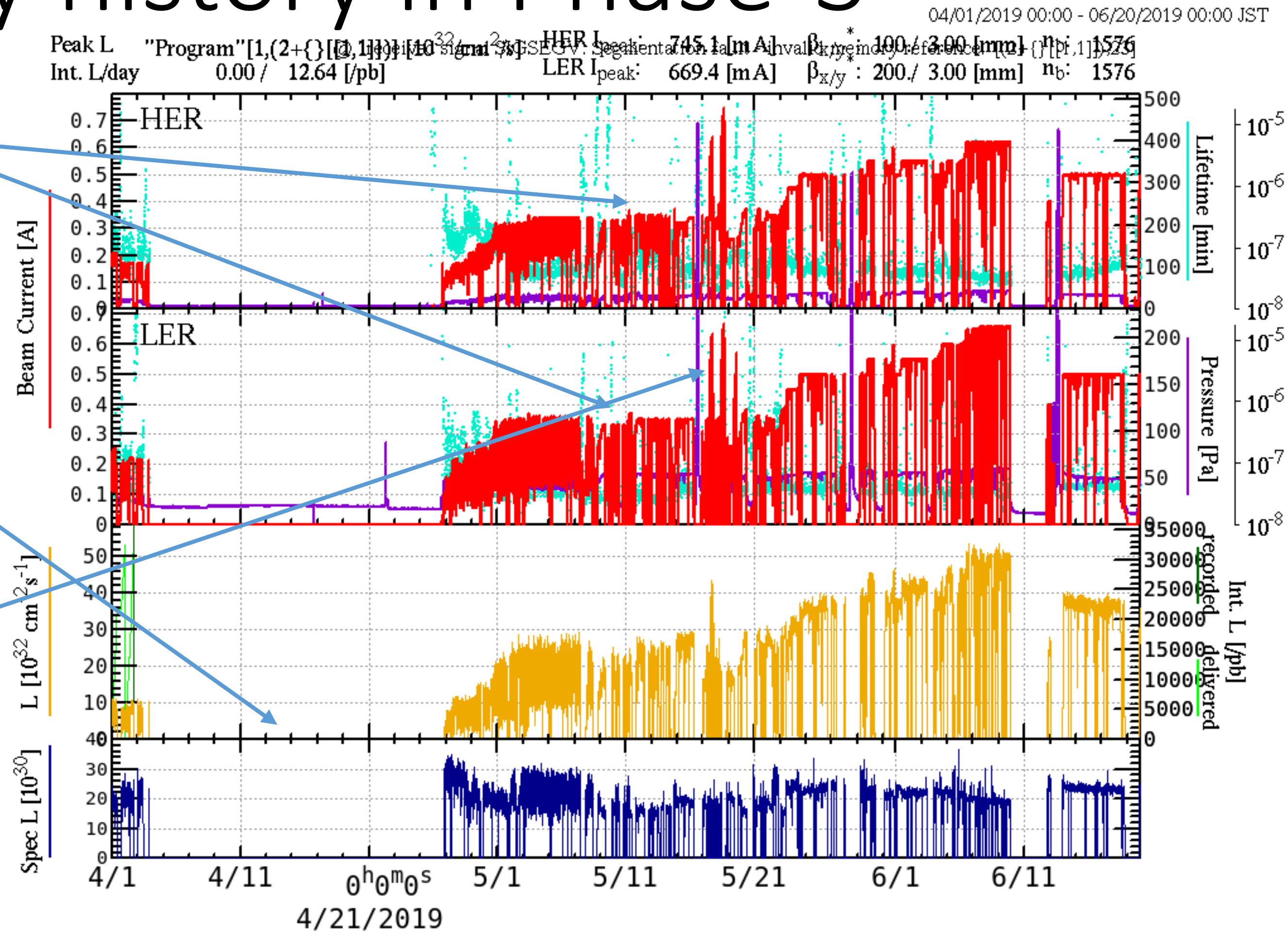
θ_c: half crossing angle

	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	0.406,265	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	0.444,295	0.0264,0.0179
Jun,20	200,100	3	3.30	0.431,0.362	0.0269,0.0182
	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

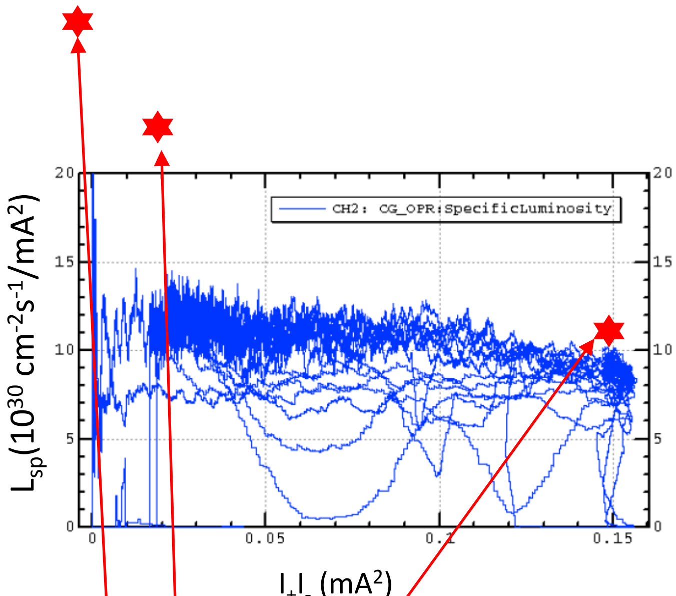


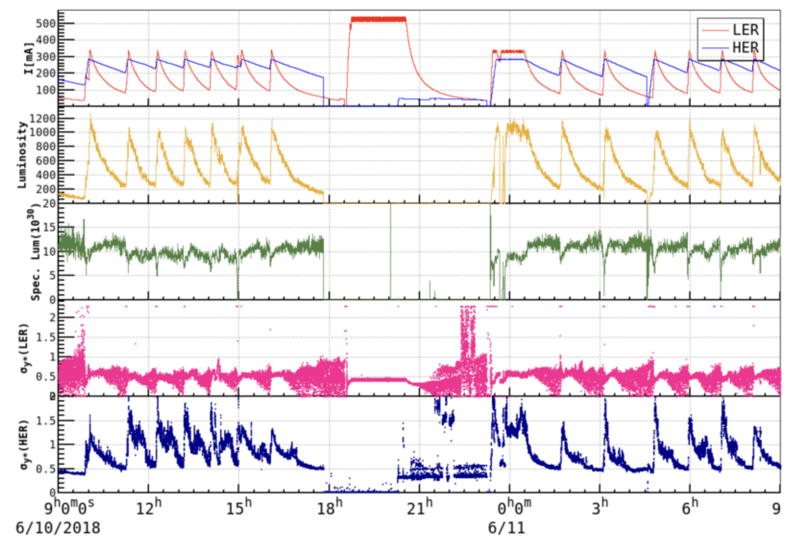
- Belle-2 data taking with β_x=100, 200mm, β_y=3mm.
- Peak Luminosity I=617, 644 mA. L=5.49x10^{33} cm^{-2}s^{-1}, ¼ of KEKB.
- The beam-beam parameter is 0.0176, 0.0295.
- Accumulate 6 fb^{-1}.

L（KEKB) =21.1x10^{33} cm^{-2}s^{-1}

R2 correction

Observations Before June 15, 2018





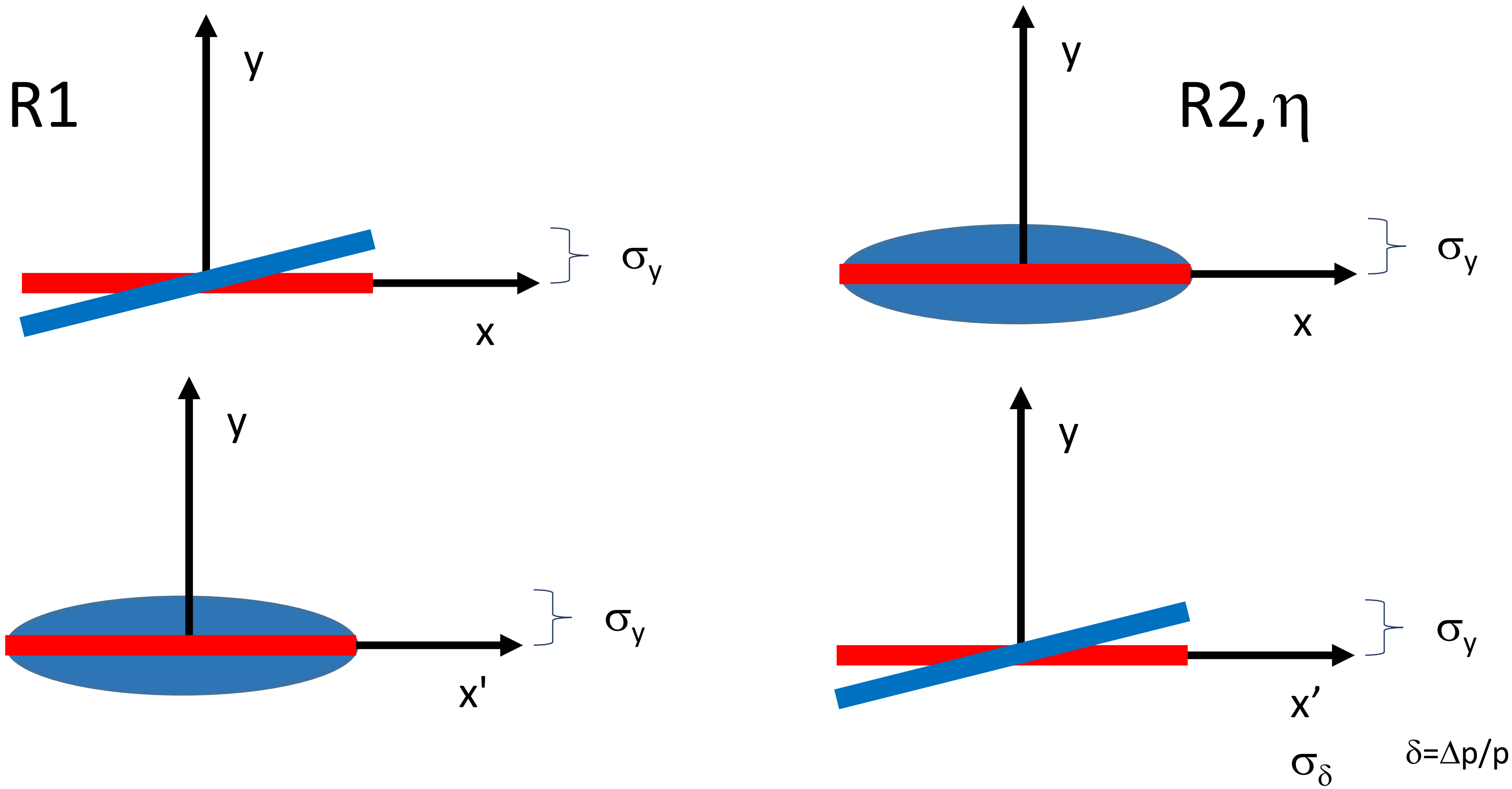
- 0mA, σ_{y0}=0.3µm, 0.4µm, L_{sp}=35
- 200x80mA, σ_{y0}=0.5µm, 0.6µm, L_{sp}=23
- 285x340mA, σ_{y0}=1.5µm, 0.6µm, L_{sp}=11

Lsp agrees with geo value at high current

$$L_{sp} = \frac{1}{2\pi\sigma_{xc}\sigma_{yc}e^2 f_0}$$

$$\sigma_{yc} = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$$

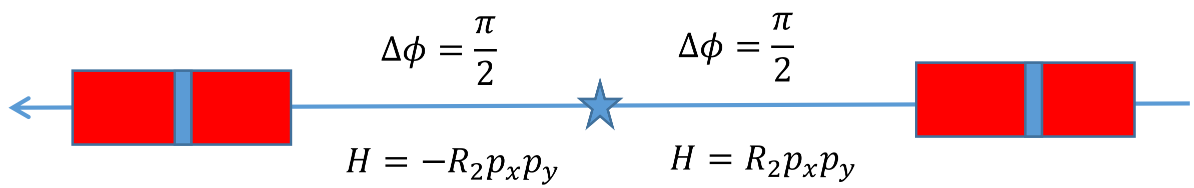
IP coupling and beam distribution at IP



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

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

- Transformation of R2,



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

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

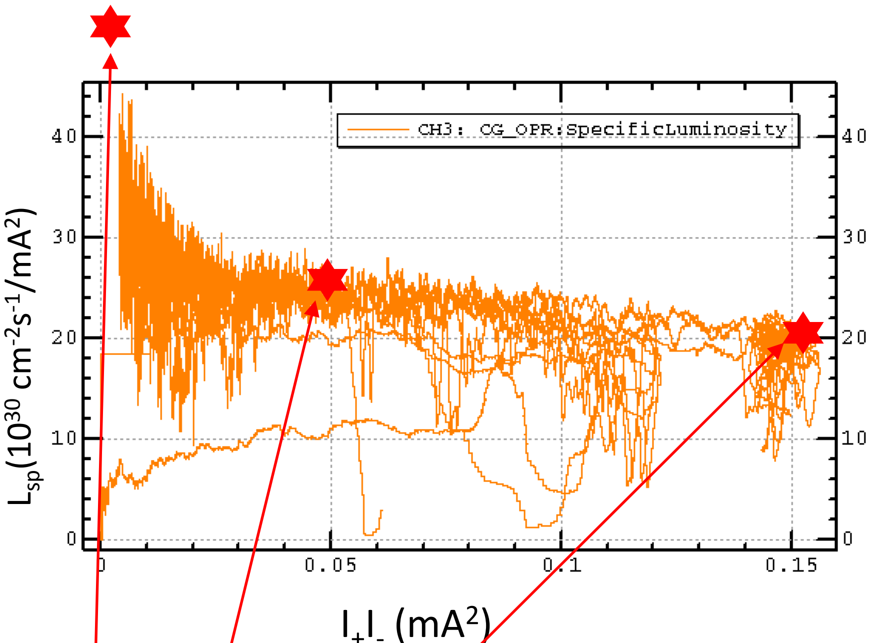
$$H = \pm \frac{R_2}{\sqrt{\beta_x^* \beta_{x,1}}\sqrt{\beta_y^* \beta_{y,1}}} xy \approx \pm R_2 xy$$

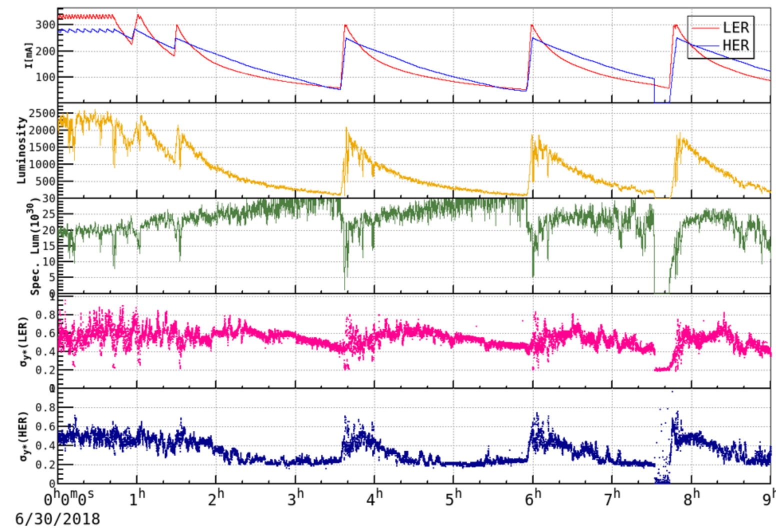
- Skew quad at QC1 is $B'L/B\rho = R_2$, which is independent of β^*.
- Deviation from π/2 induces R3.
- Control of inside of π section is hard from outside. It should be corrected by both side of skew. (like waist correction)

$H = ds p_y^2$
waist shift

June 30, 2018

Observations





- 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

$$L_{sp} = \frac{1}{2\pi\sigma_{xc}\sigma_{yc}e^2 f_0}$$

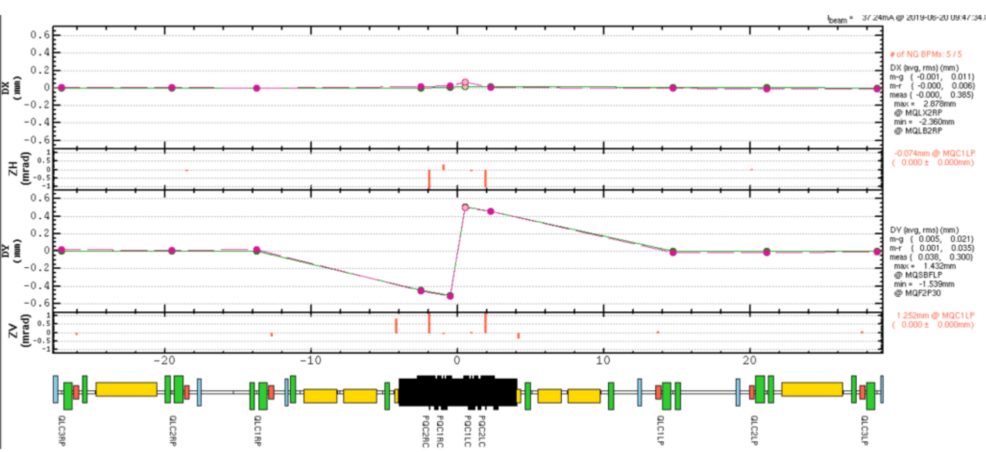
10^{30} cm^{-2}s^{-1}/mA^2

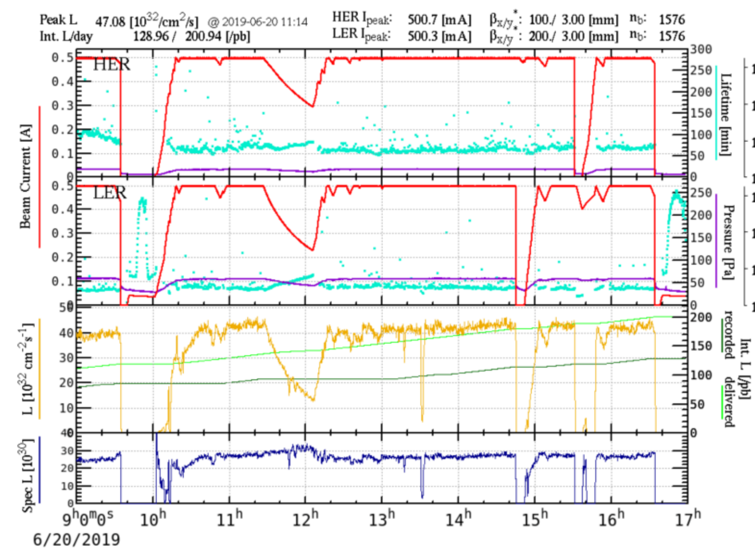
$$\sigma_{yc} = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$$

6/29 21:00- R2 using QCS corrector

Vertical angle at IP, June 20, 2019

- Vertical angle can not be scanned by heating in HER V angle change (done in KEK).
- Change of LER V-angle vertical has induced vertical dispersion at IP.
- V angle scan with dispersion correction was done in 20, Jun 2019.





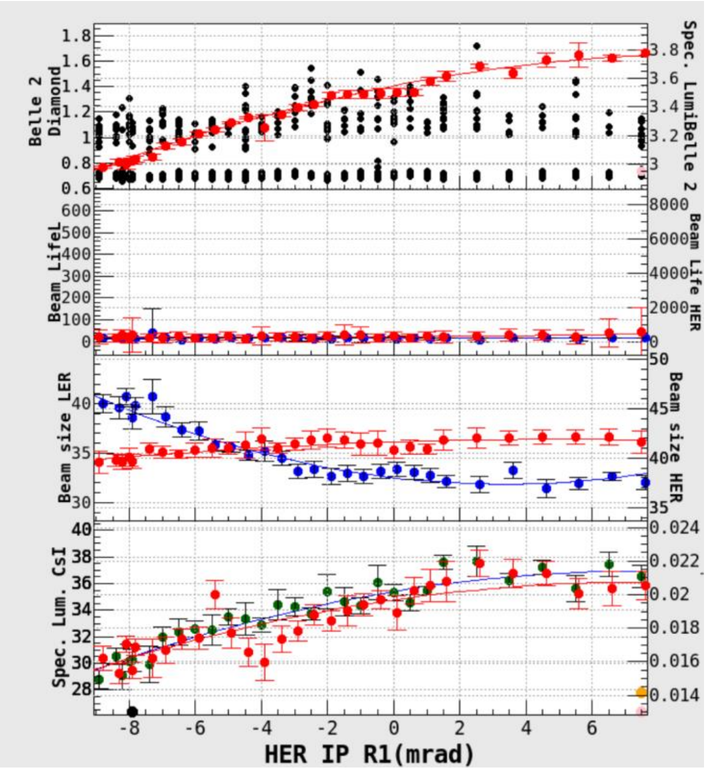
Other tuning done day-by-day

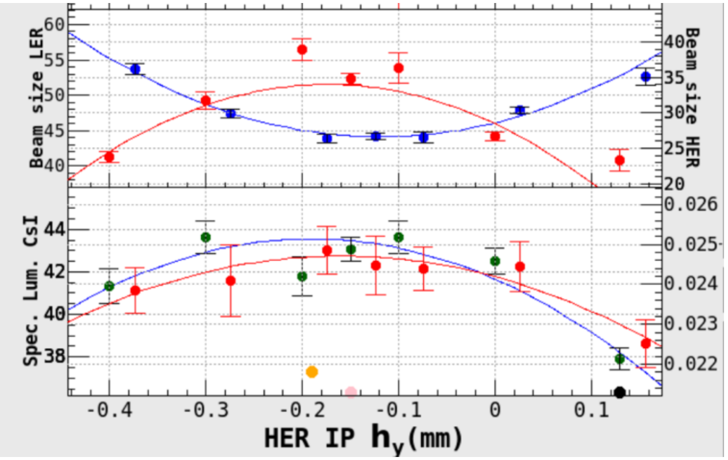
- IP offset, x,y,y', z
- IP linear aberrations, b waist, dispersion, x-y coupling, x-z tilt.

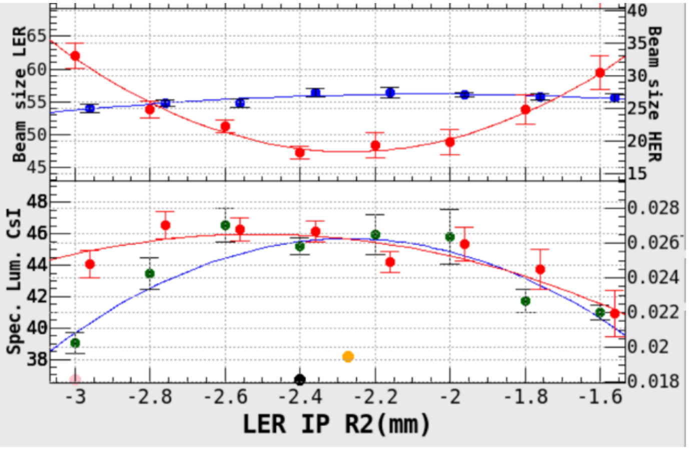
- Beam-beam tune shift is limited 0.02 for electron beam mainly due to σ_y blow-up of positron beam.

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

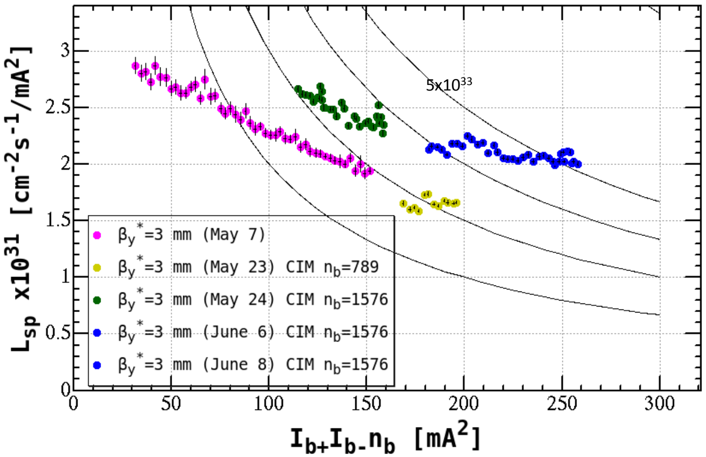
Example of IP knob scan

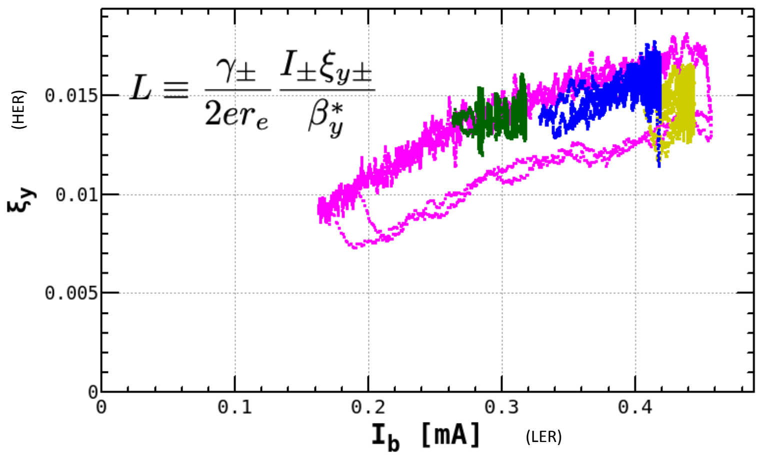




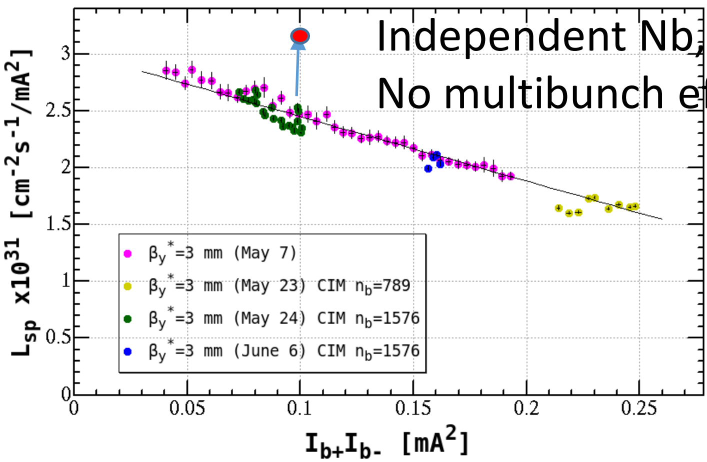


Specific Luminosity and Beam-Beam (Phase 3-1)



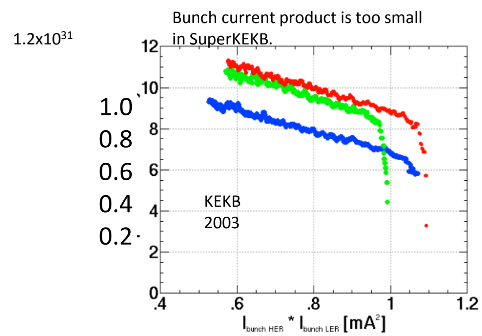


Beam-Beam parameter at the bunch current > 0.5 mA ?



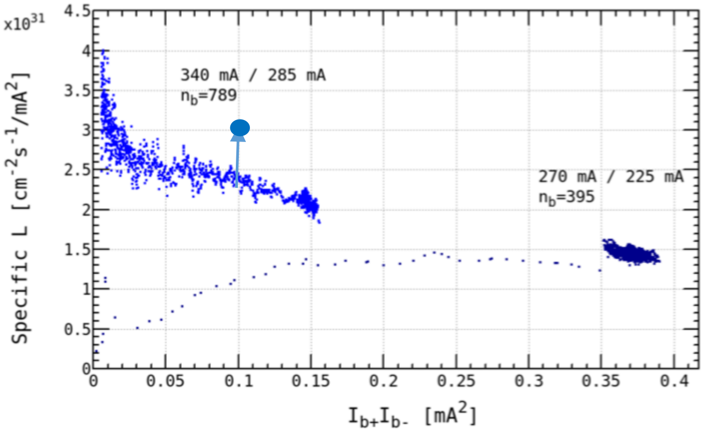
Independent Nb,

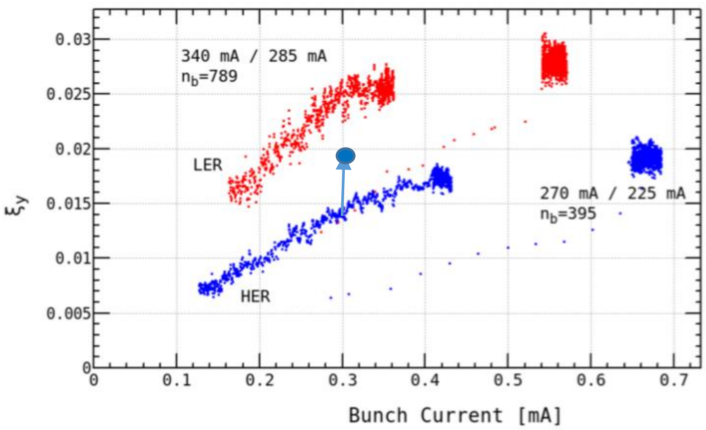
No multibunch effect



Correction of Vertical collision angle made 20% increase of luminosity recently (June 20, 2019)

Specific Luminosity and Beam-Beam (Phase 2)



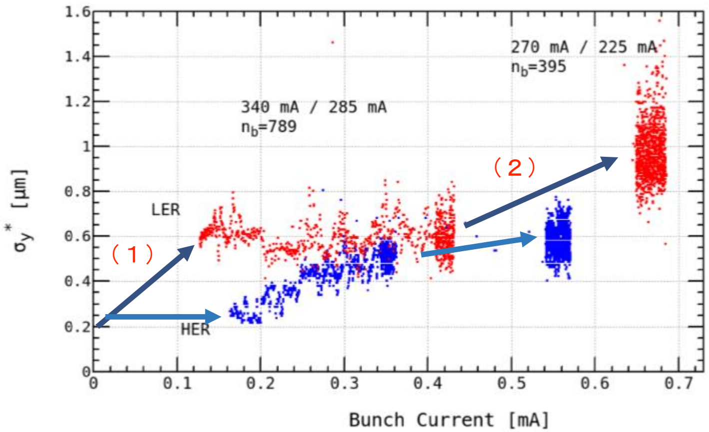


2 stage blow-up of LER beam

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

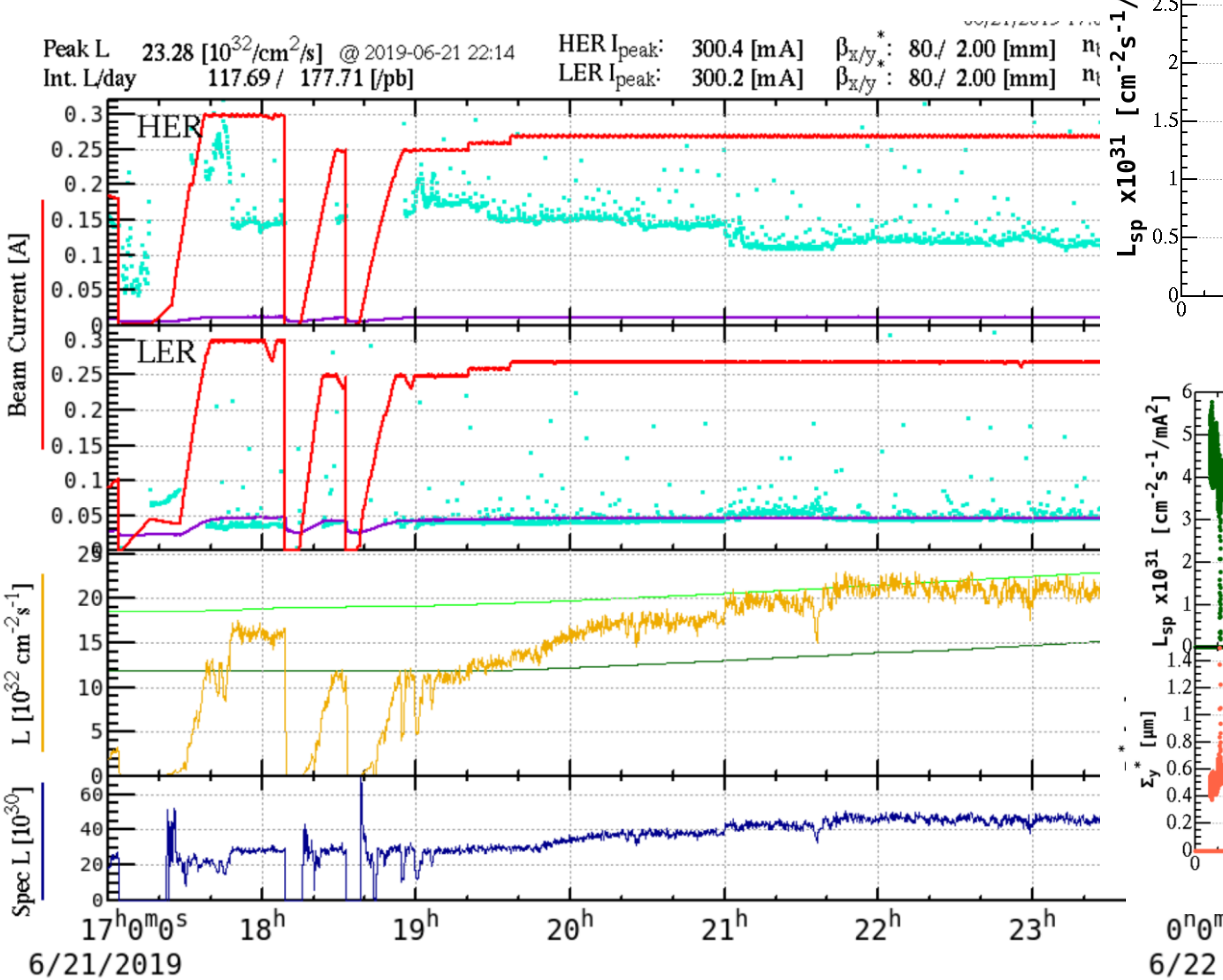
（２） High bunch current I_+>0.5 mA

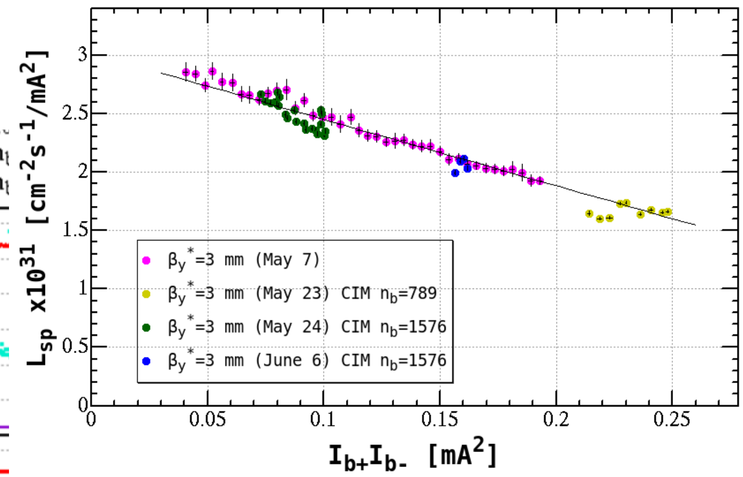
HER beam I_->0.2mA.

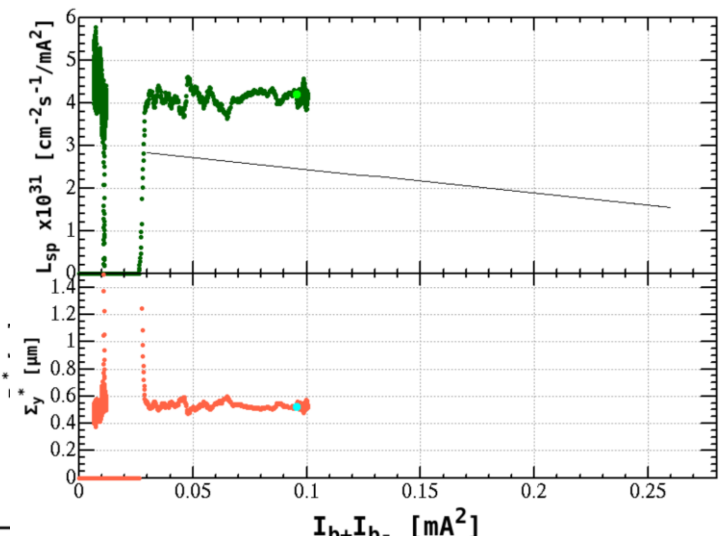


β_y^*=2mm

- Lspec increased twice at loew current.

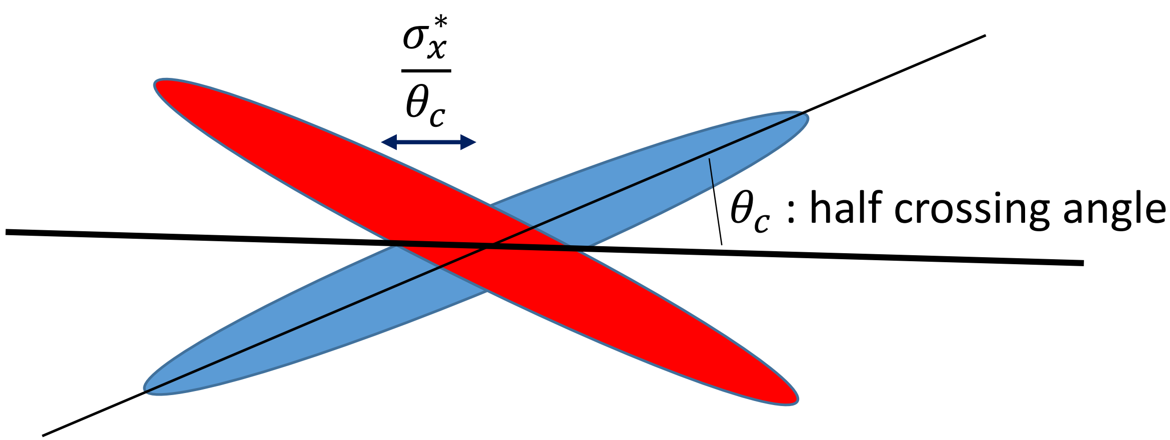






What determines the low beam-beam limit?

- 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

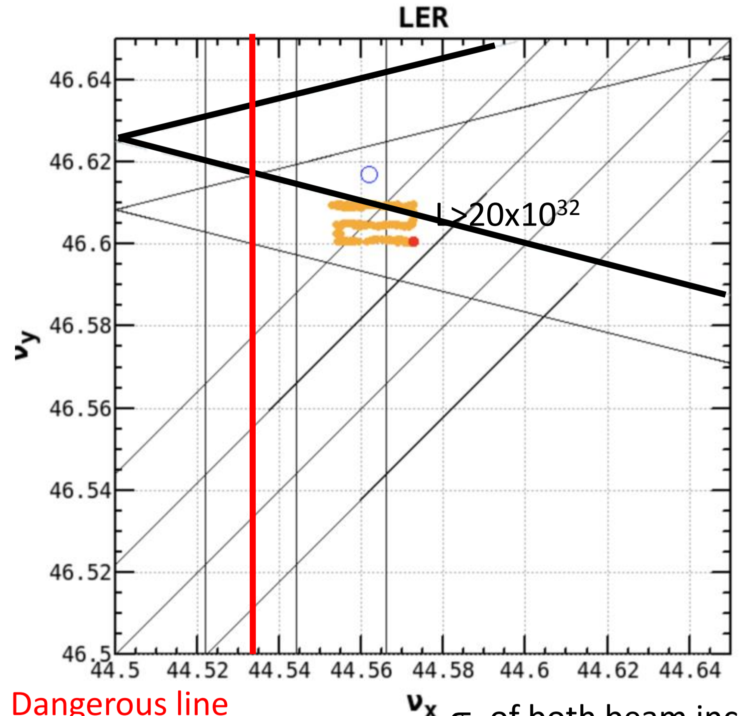
- $\sigma_x/(\theta_c\beta_y)$=0.16 (2018-2019, βy=3mm, βx=100/200mm)
- $\sigma_x/(\theta_c\beta_y)$=0.9 (design βy=0.27/0.3mm, βx=32/25mm)

- Enough margin for the hour glass effect at present.

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

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

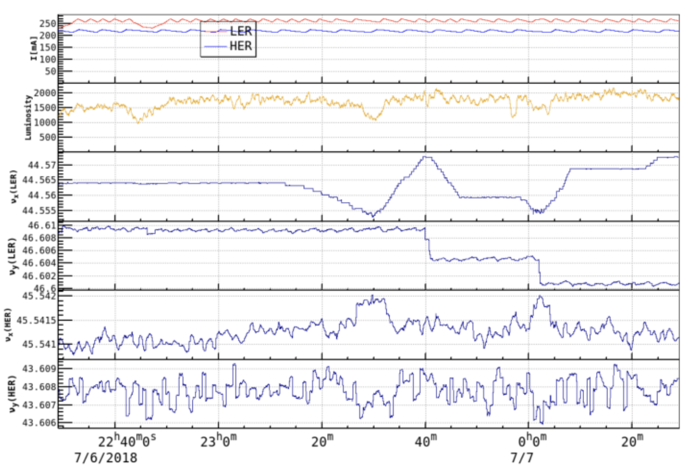


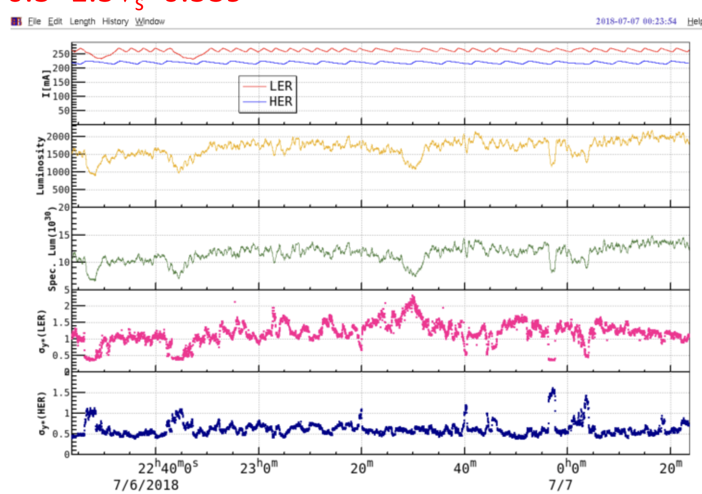
$\nu_x+4\nu_y=0$

Dangerous line

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

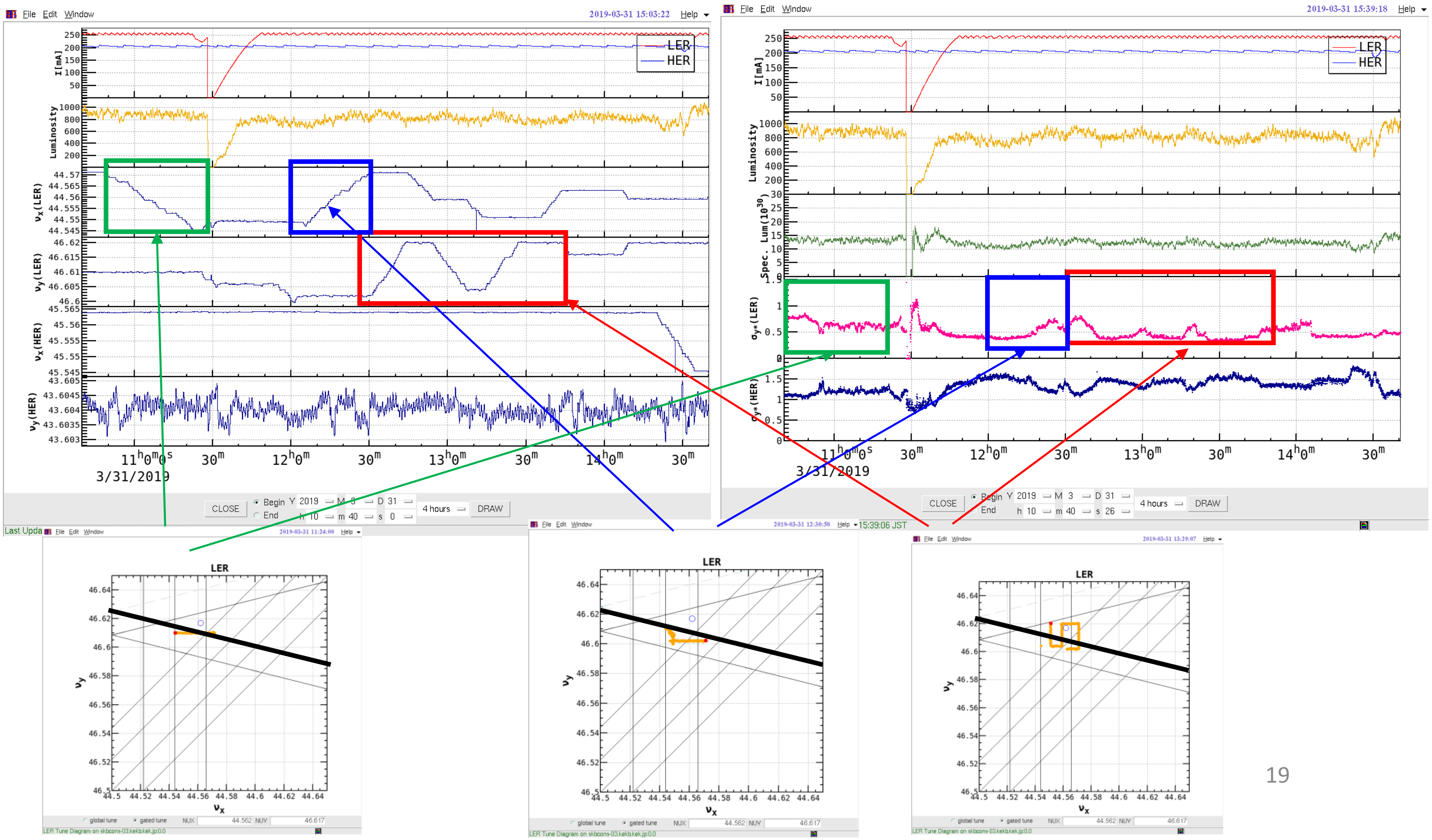
σ_x of both beam increases





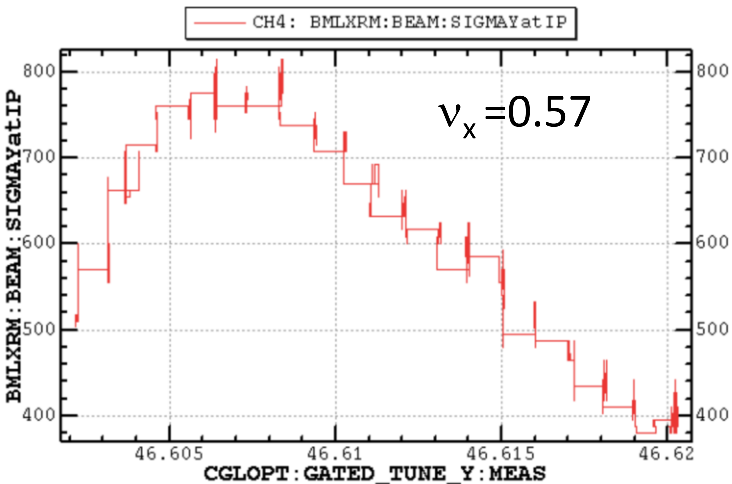
LER tune scan 2019/3/31

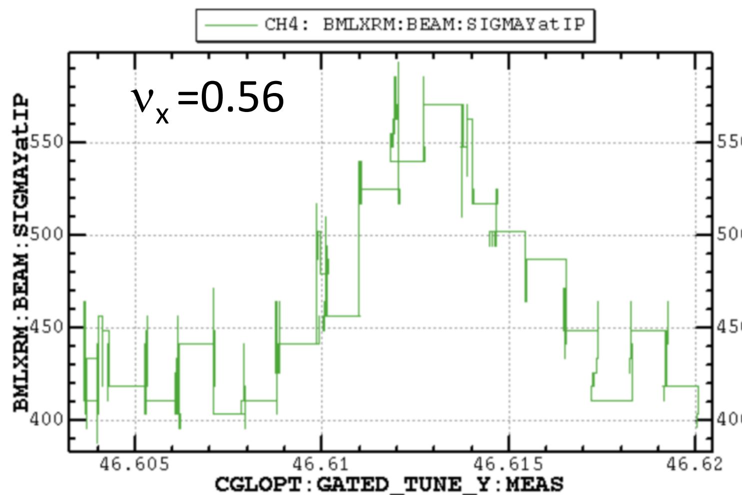
- nx+4ny=int is seen. βx=200/200mm

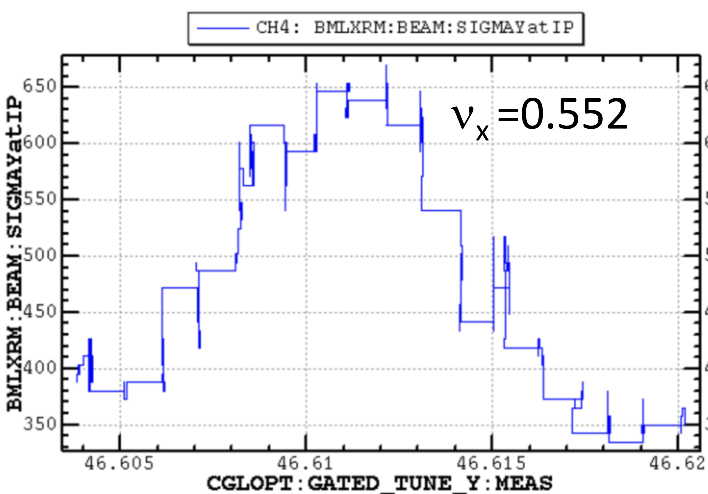


LER tune scan 2019/3/31

- Shift of σ_y peak for ν_x.







$\nu_x + 4\nu_y = 2.998$ $\nu = (0.57, 0.607)$

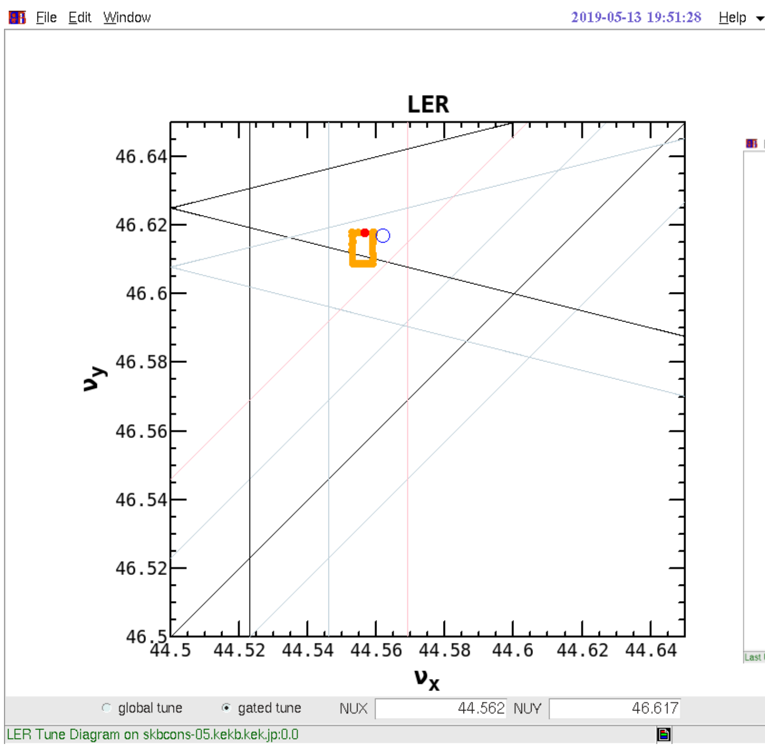
3.012 $= (0.56, 0.613)$

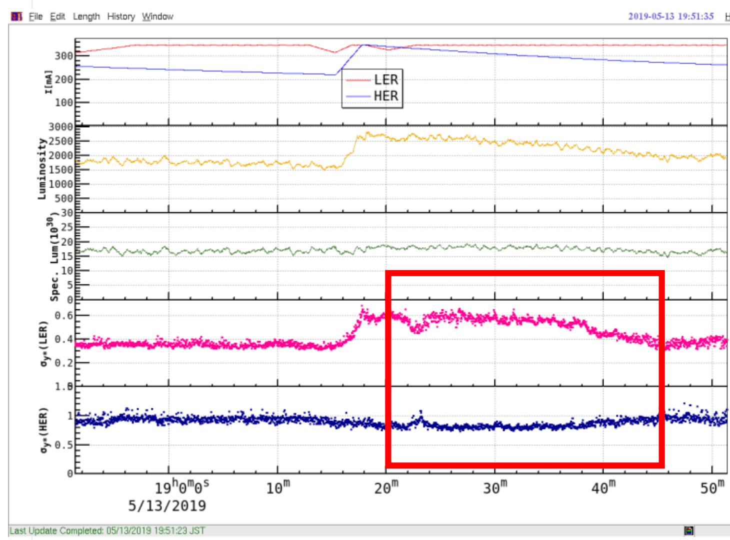
3.000 $= (0.552, 0.612)$

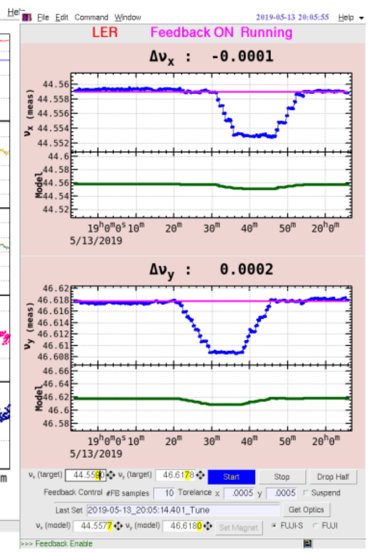
LER tune scan 2019/5/13

- 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.







β_y^*, chromatic, nonlinear aberrations

- Measurement of IP chromatic aberrations

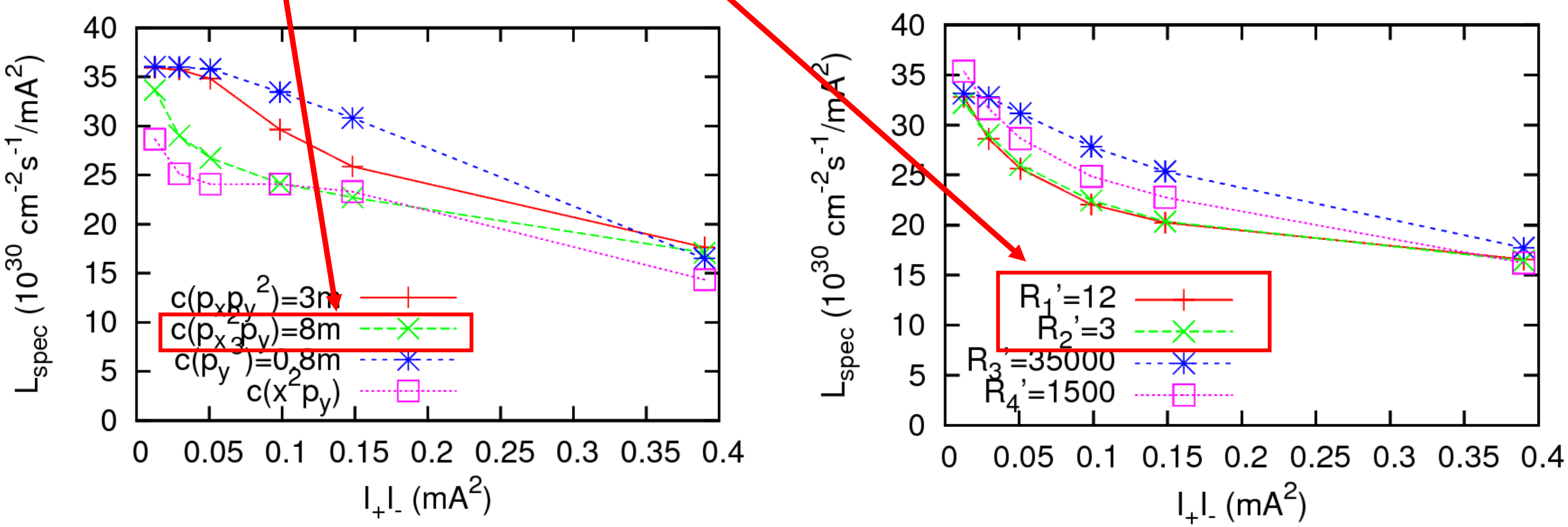
- Scan with nonlinear corrector of QCS

- Chromatic coupling correction
  - HER insufficient skew sextupole now. More Skew SX.
  - LER sextupole hardware rotation system is prepared, but not tried yet.

Chromatic, nonlinear aberrations

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

Weak strong simulation with nonlinear IP aberrations



Measurement of IP chromatic aberrations

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

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

$\beta_x = 0.2\, m$

$\langle \Delta y \rangle = R_1(\delta)\sigma_x = 0.50\ \mu\text{m}$

$$\langle \Delta y \rangle = \frac{R_2(\delta)}{\beta_x}\sigma_x = 0.62\ \mu\text{m}$$

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

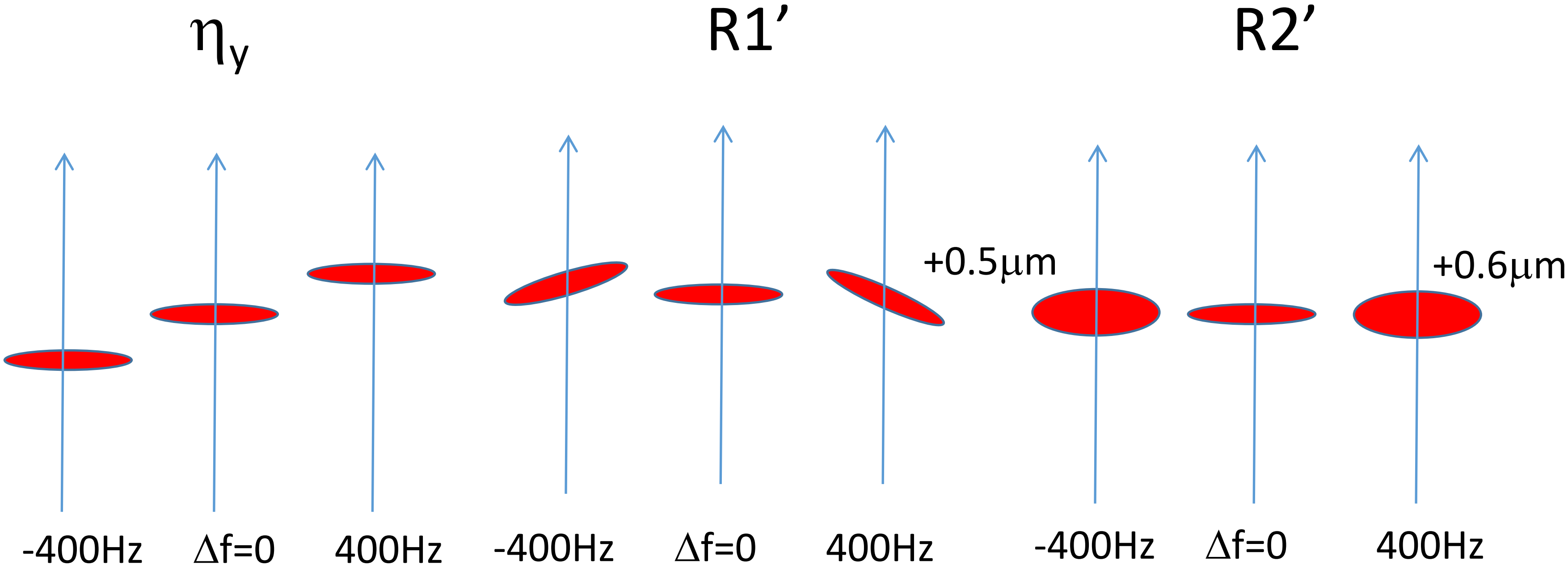
- $H = 8p_x^2 p_y$

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

- 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

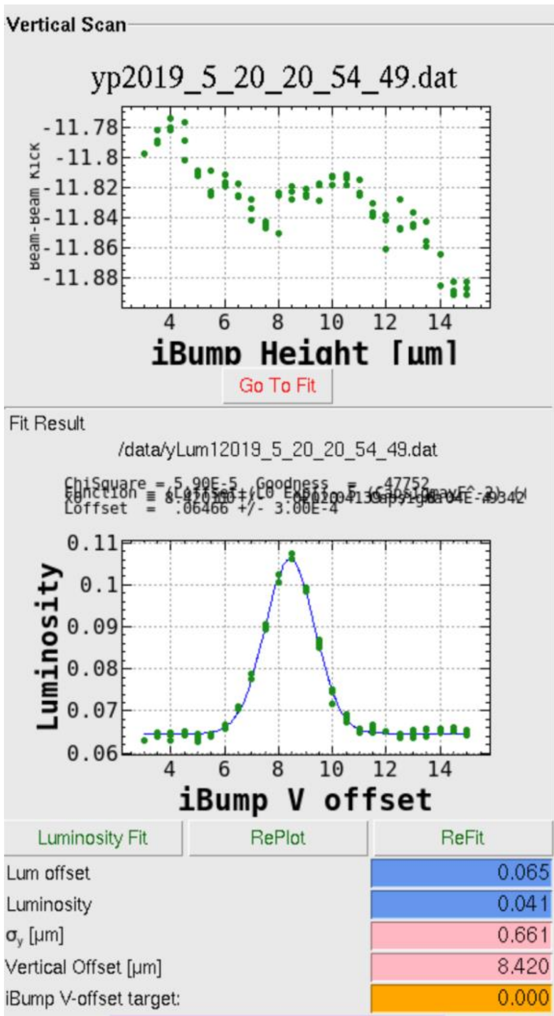
Δf=400Hz → δ=0.17%

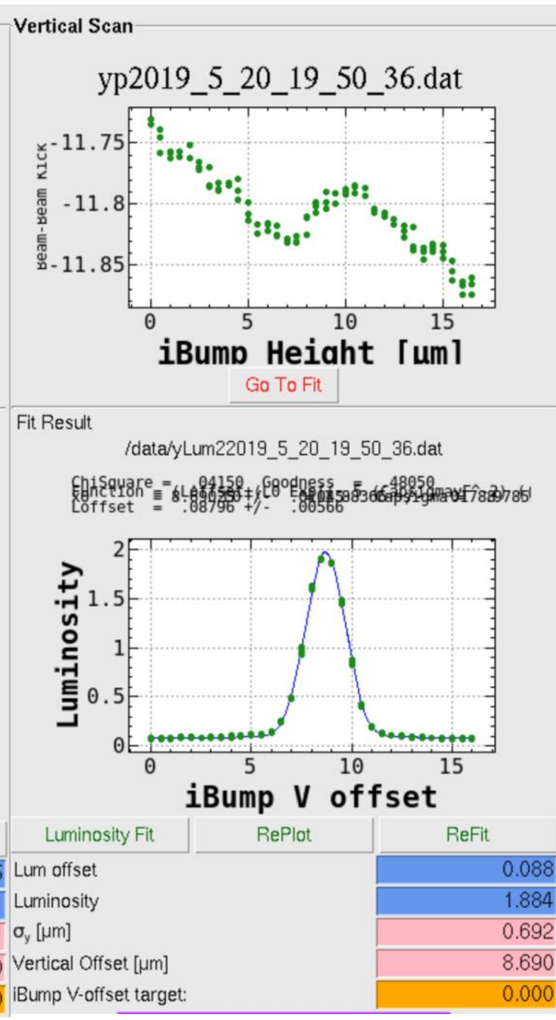


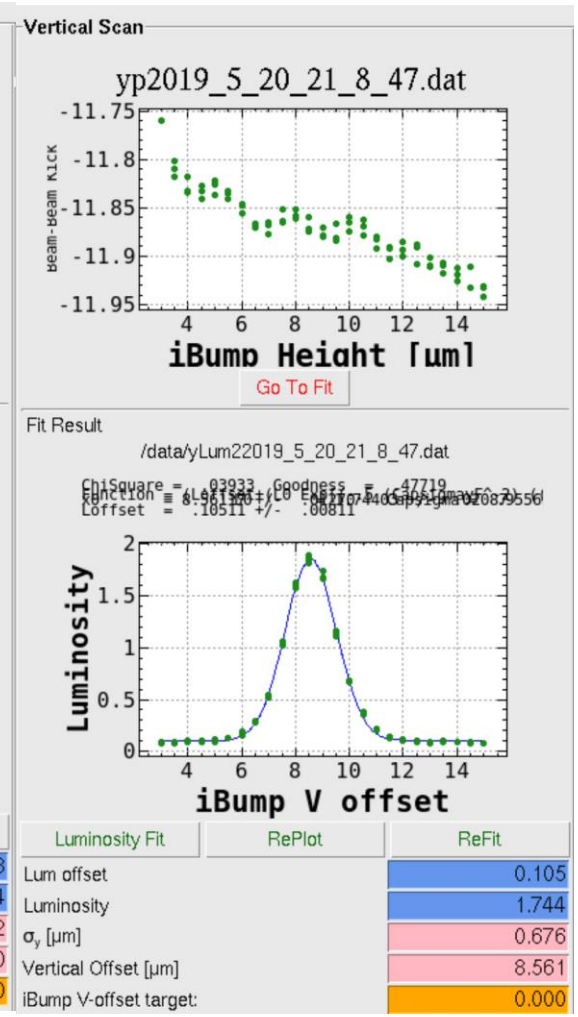
Measure the beam size using beam-beam scan (Luminosity.)

Beam-beam scan with Δf_{RF}

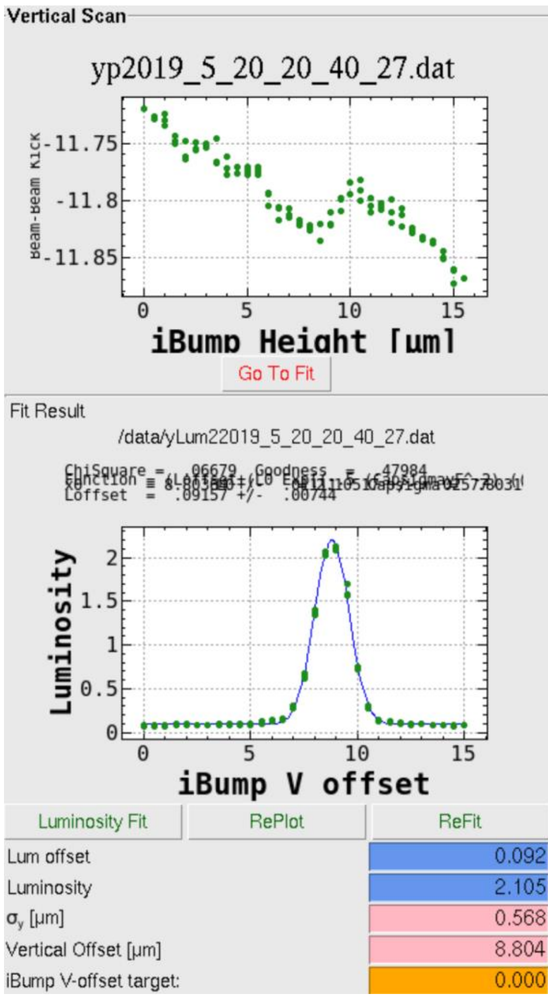
- IP knob off
- Δf=-400Hz 0Hz 400Hz

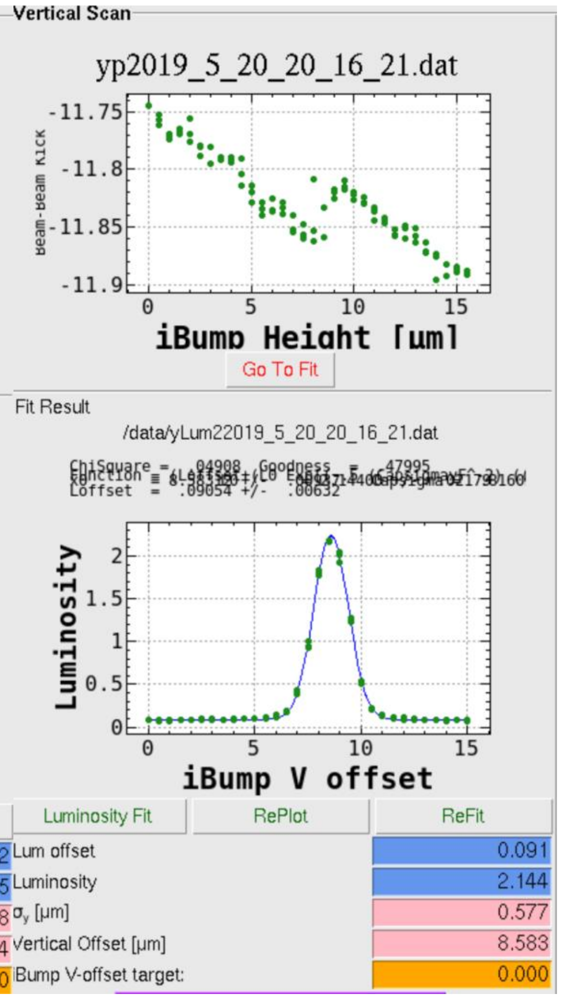


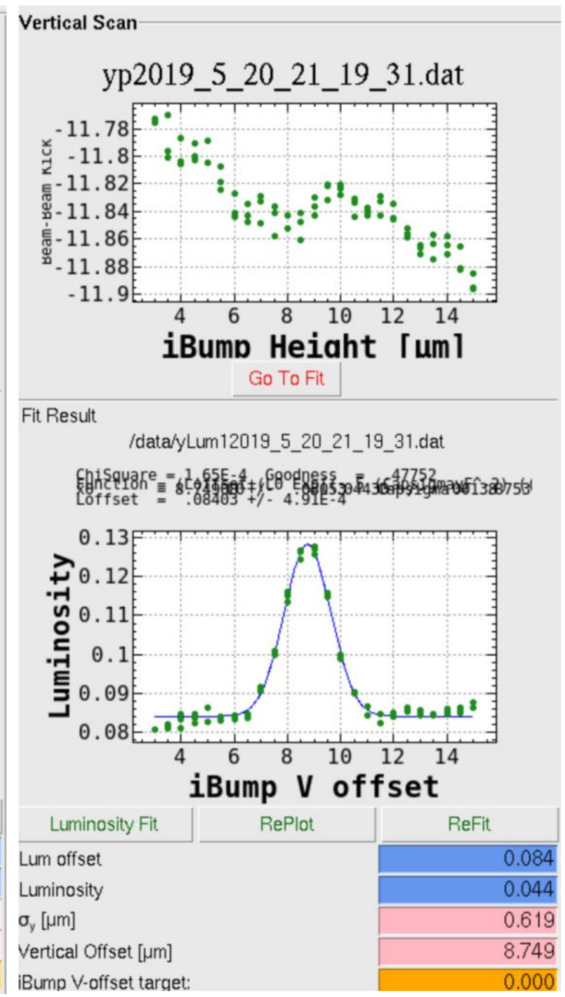




- set IP knob
- Δf=-400Hz 0Hz +400Hz



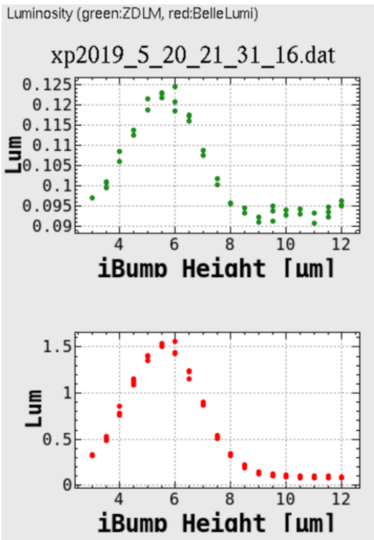


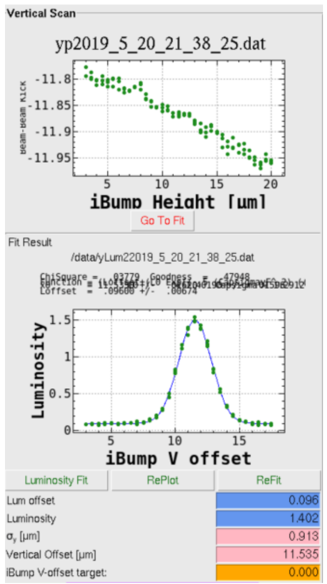


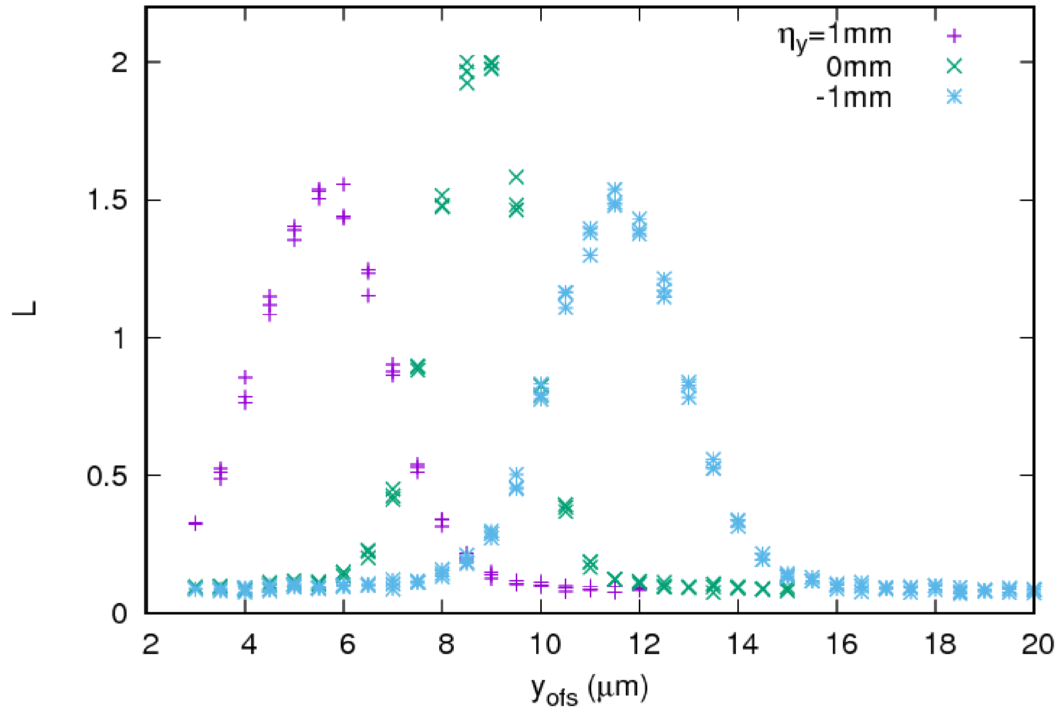
Dispersion at IP

- Δf=400Hz, IP Knob ON

η_y=+1mm η_y=-1mm







Vertical beam size and offset obtained by beam-beam scan

	-400Hz	0 Hz	400Hz
IP knob set, σ_y (μm)	0.619	0.577	0.568
η_y=-0.1mm y_{offset}	8.804	8.583	8.749
IP knob 0, σ_y (μm)	0.661	0.692	0.676
y_{offset}	8.42	8.690	8.561

- No clear change for energy change. Chromatic coupling at IP was not large.
- Chromatic coupling at XSRM was remarkable.

Δf=400Hz δ=0.17% $\eta_y\delta$=1.7μm $\Delta\sigma_y=\eta_y\sigma_\delta$=0.7$\mu$m

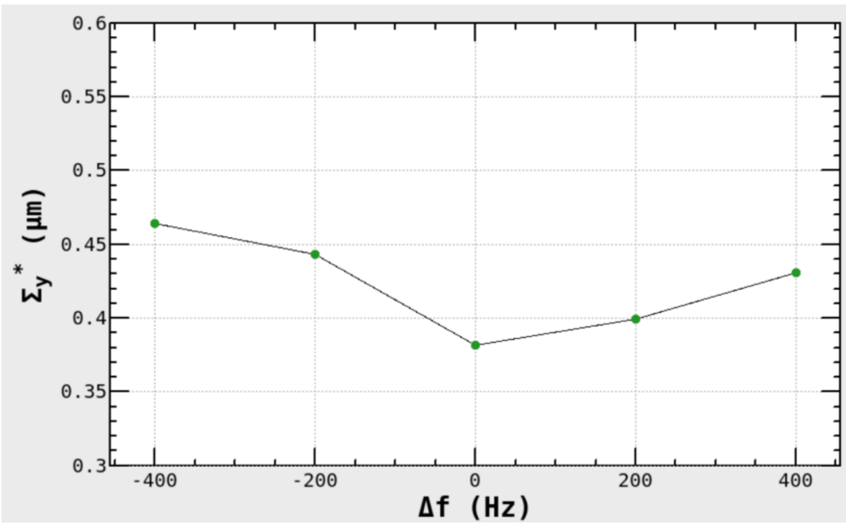
η_y	1mm	0mm	-1mm
σ_y (μm)	0.917	0.577	0.913
Yoffset (μm)	5.560	8.583	11.535

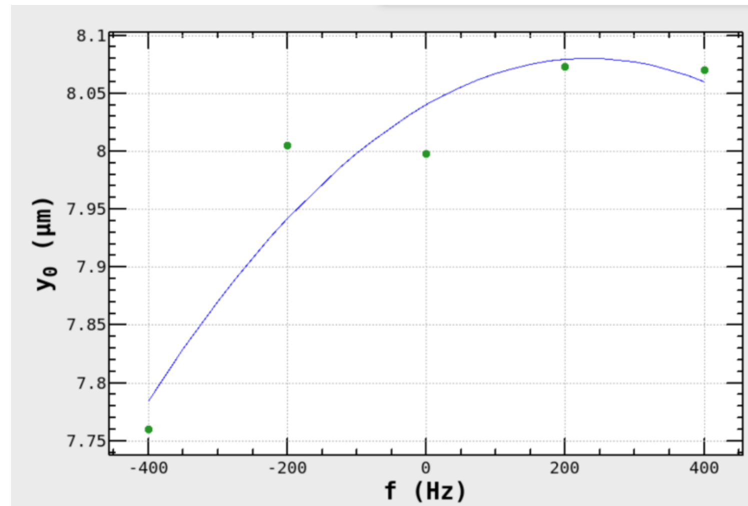
- Offset change was 1.7 times larger than $\eta_y\delta$.
- Beam size change is consistent with $\Delta\sigma_y=\eta_y\sigma_\delta$=0.7$\mu$m.
- Which is reliable, iBump or dispersion knob?

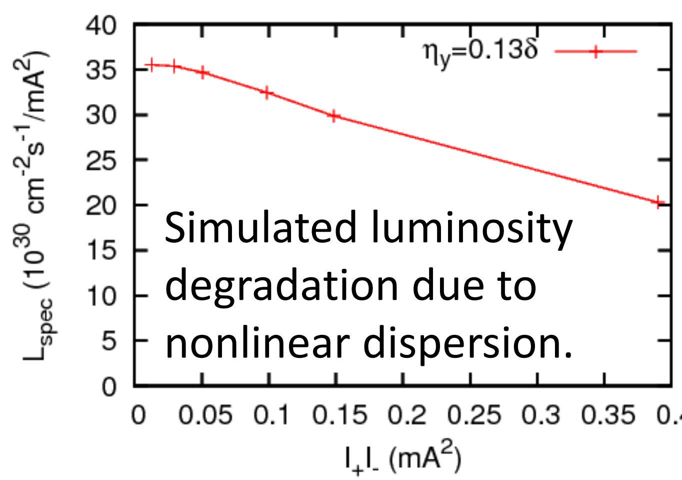
Latest data June 25,2019

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

Nonlinear dispersion also exist at IP.





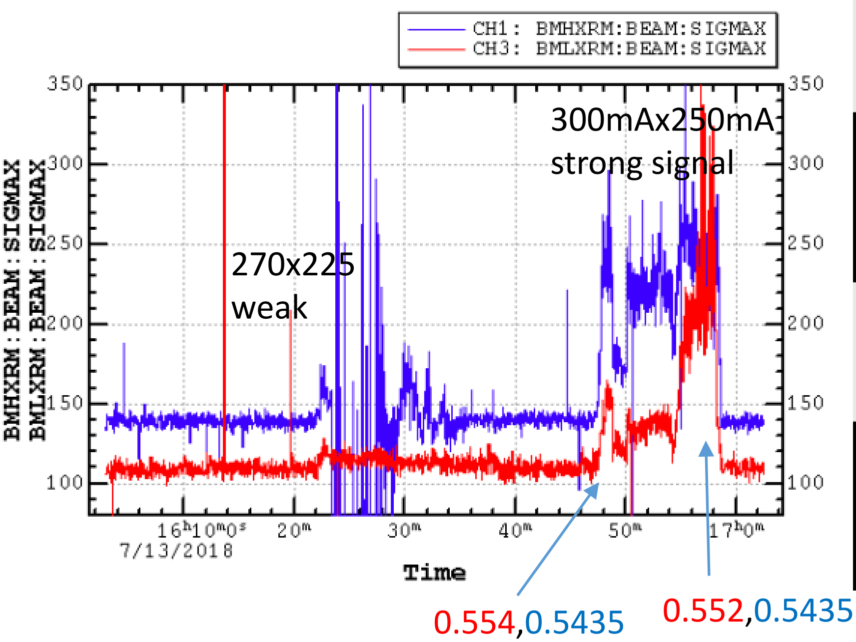


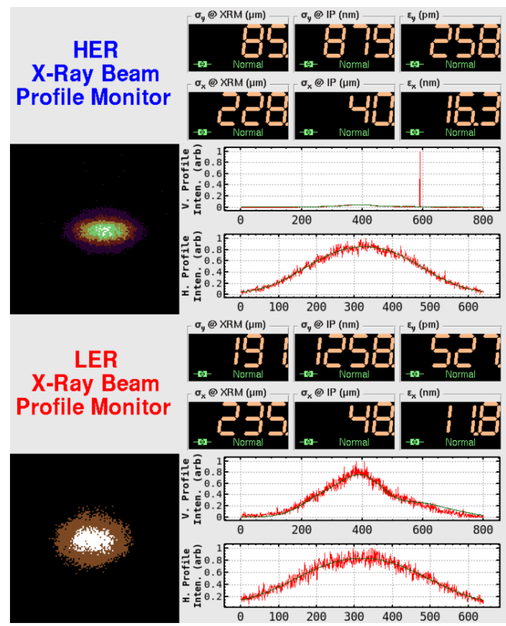
Coherent Beam-Beam-Head-Tail instability study in Phase II

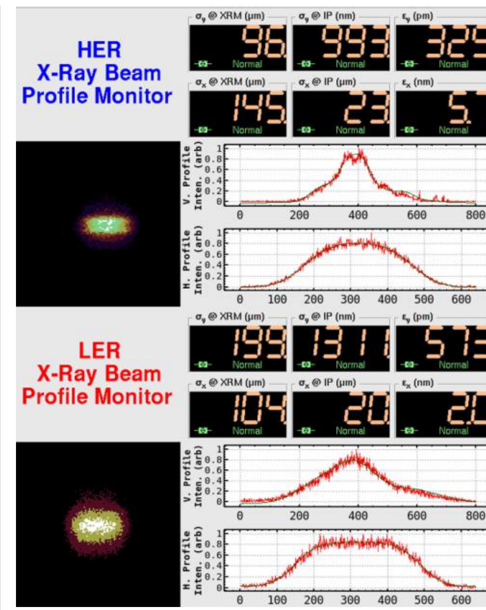
- Typical condition
- β_x=0.2m, 0.1m, β_y=3mm
- I_{tot}=270mA (e+)x 225mA (e-), Nb=395,
- I_b=0.68mAx0.57mA (design 1.44mAx1.04mA)
- Np=4.3×10^{10}, 3.6×10^{10}. (design 9.04×10^{10}x 6.53×10^{10})
- ν_s (e+)=0.022, ν_s (e-)=0.026

Horizontal beam size measurement

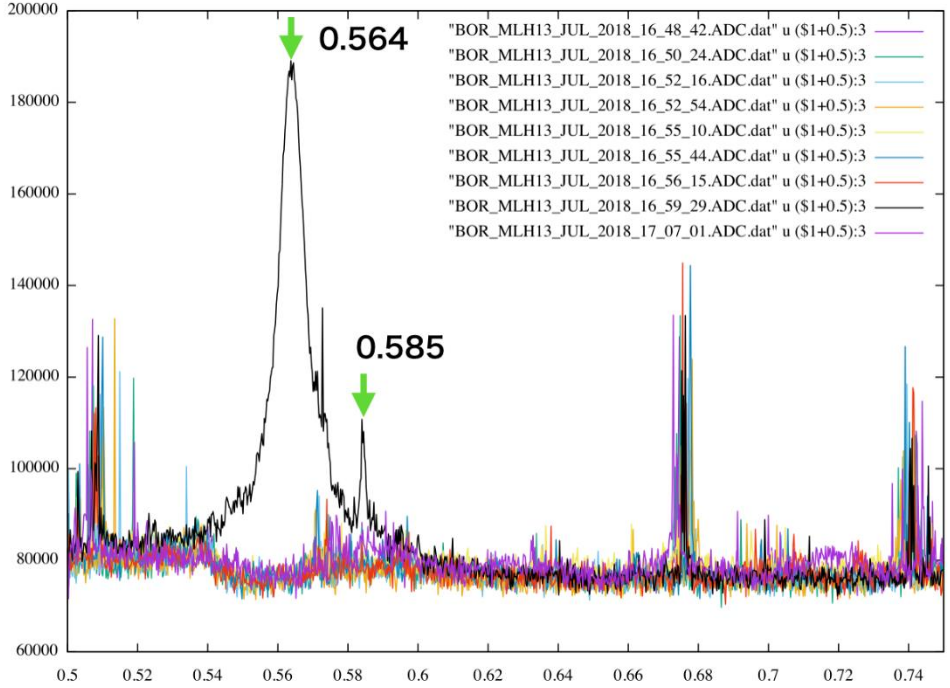
- 16:50 (instability start) & 16:57 (peak), data taking using streak camera x-z and BOR.
- Tune scn, ν_s (e+)=0.022, ν_s (e-)=0.026





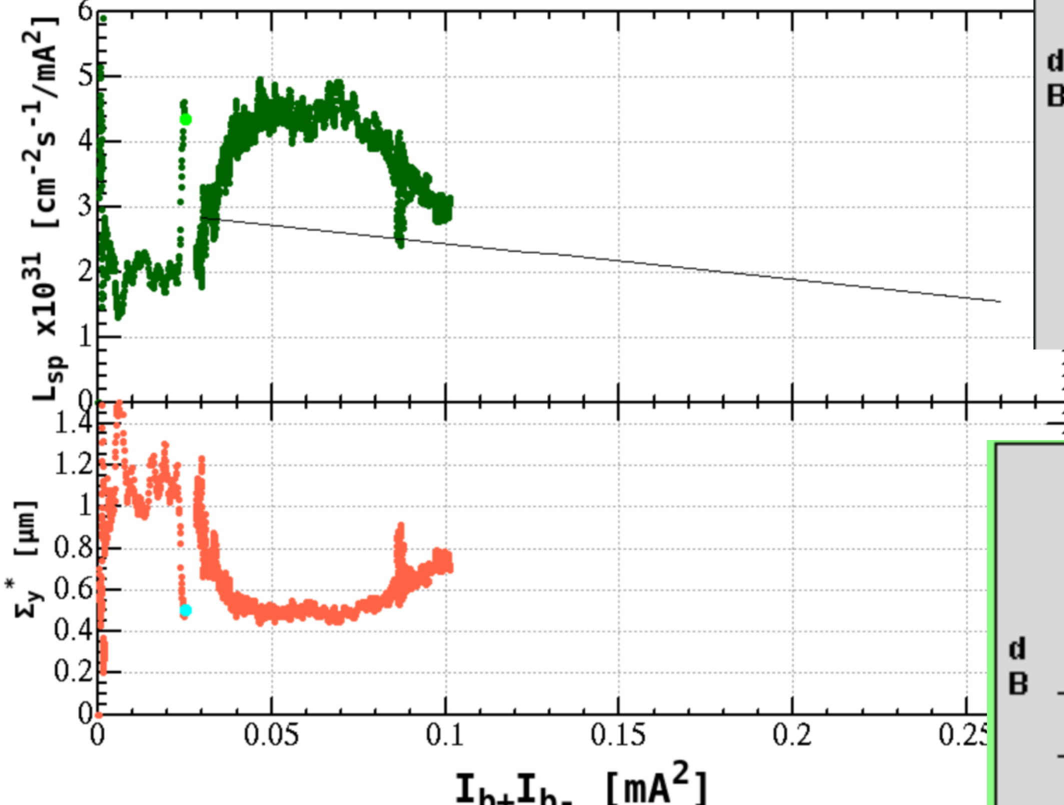


Beam oscillation at the horizontal size blowup

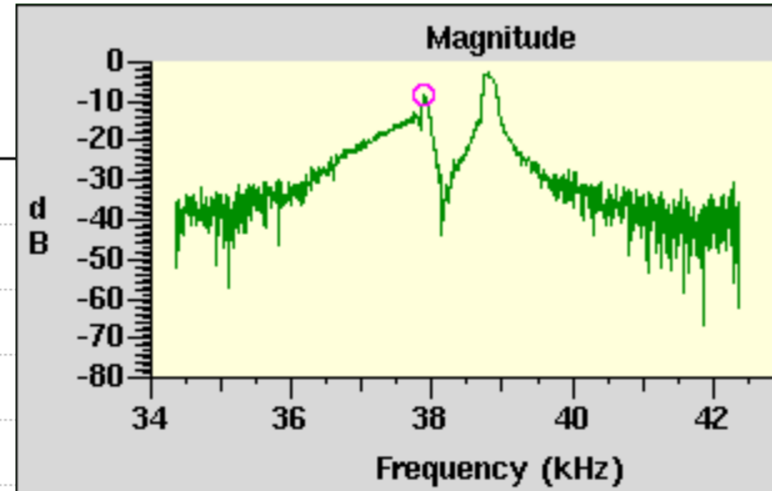


Summary

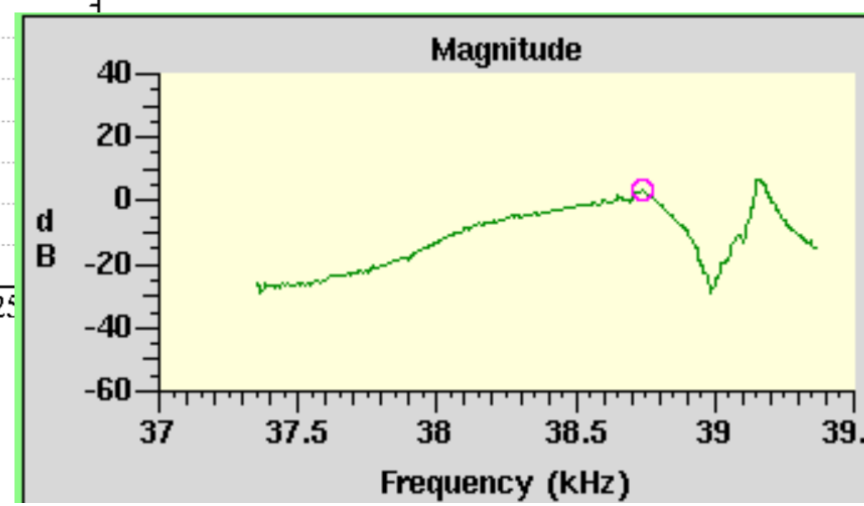
- SuperKEKB collision has been done in 2018 (Ph-2) and 2019 (Ph-3).
- β_y^* is squeezed 8->6->4->3->2mm with keeping high Piwinski angle $\sigma_z\theta_c/\sigma_x^*$~10.
- Achieved beam-beam parameter is 0.02(e-) due to σ_y blow-up of e+ beam.
- We have focused key parameters, which limit the beam-beam parameter, β_y^*, $\sigma_z\theta_c/\sigma_x^*$ or $\sigma_x^*/(\theta_c\beta_y)$.
- Limited beam-beam parameters for several set of (β_x^*, β_y^*) inform what is difficulty.
- Compensation of all linear and nonlinear aberrations at IP should be done.
- Beam-beam head-tail instability has been observed at high bunch current depending on tune, but is not serious at present current.



L_{sp} x10^{31} [cm^{-2}s^{-1}/mA^2]
Σ_y^* [µm]
$I_{b+}I_{b-}$ [mA^2]



Magnitude
dB
Frequency (kHz)



Magnitude
dB
Frequency (kHz)