Low emittance and luminosity tuning in SuperKEKB

K. Ohmi (KEK)

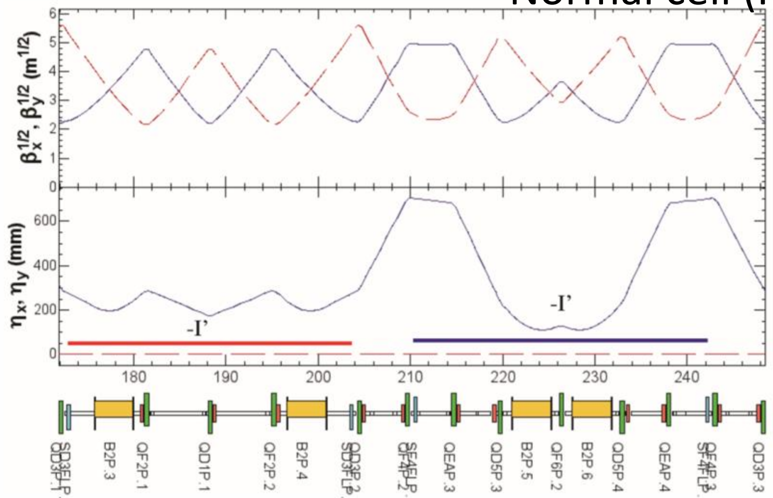
Beam test and commissioning of
Low Emittance storage rings,
18-20 Feb, 2019,
Karlsruhe, Germany

Thanks to Y. Funakoshi, K. Hirosawa, H. Koiso, A. Morita,
Y. Ohnishi, H. Sugimoto, D. Zhou

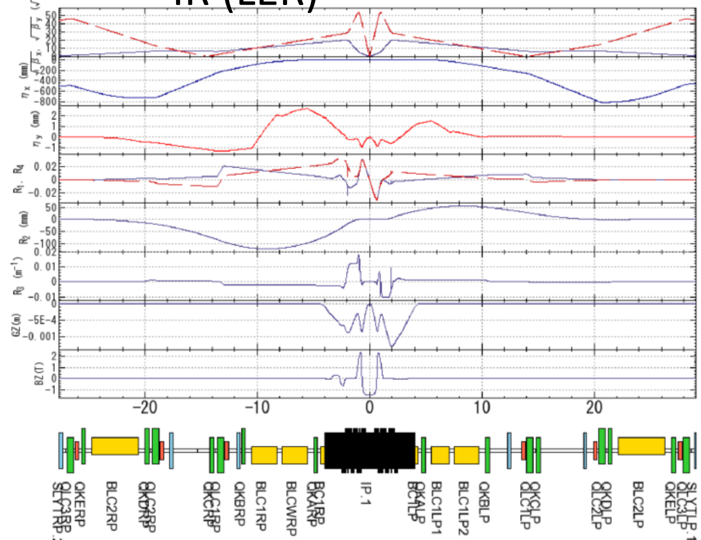
SuperKEKB

- Asymmetric e+e- collider with energy 4 and 7 GeV.
- Collision with large Piwinski angle, $\phi_c\sigma_z/\sigma_x$=26.
- Arc design ~ Very high current 3rd generation light source
- Interaction Point : Extremely low β*, 3cmx0.3mm.
- Very large chromaticity and local correction in the Interaction Region.

Normal cell (HER)



IR (LER)



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	83		mrad	
α_p	$3.25\text{x}10^{-4}$	$4.55\text{x}10^{-4}$		
σ_δ	$8.08(7.73)\text{x}10^{-4}$	$6.37(6.31)\text{x}10^{-4}$		():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	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	

X-y coupling

- Eigenvector to resolve x-y coupling, R.

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

$$\boldsymbol{X}(s+C) = U\boldsymbol{X}(s)$$

$$\boldsymbol{x}(s+C) = M(s)\boldsymbol{x}(s)$$

$$U = \begin{pmatrix} U_X & 0 \\ 0 & U_Y \end{pmatrix} \qquad U_X = \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix}$$

$$M(s) = R(s)B(s)UB^{-1}(s)R^{-1}(s)$$

- R(s) as Twiss parameters

$$R(s) = \begin{pmatrix} r_0 & 0 & r_4 & -r_2 \\ 0 & r_0 & -r_3 & r_1 \\ -r_1 & -r_2 & r_0 & 0 \\ -r_3 & -r_4 & 0 & r_0 \end{pmatrix} \qquad B = \begin{pmatrix} B_X & 0 \\ 0 & B_Y \end{pmatrix} \qquad B_X = \begin{pmatrix} \sqrt{\beta_X} & 0 \\ -\alpha_X/\sqrt{\beta_X} & 1/\sqrt{\beta_X} \end{pmatrix}$$

$$r_0 = \sqrt{1 - r_1 r_4 + r_2 r_3}$$

- Beam envelope matrix

$$\langle \boldsymbol{X}(s)\boldsymbol{X}^t(s) \rangle = \begin{pmatrix} \varepsilon_X & 0 & 0 & 0 \\ 0 & \varepsilon_X & 0 & 0 \\ 0 & 0 & \varepsilon_Y & 0 \\ 0 & 0 & 0 & \varepsilon_Y \end{pmatrix}$$

$$\langle \boldsymbol{x}(s)\boldsymbol{x}^t(s) \rangle = R(s)B(s)\langle \boldsymbol{X}\boldsymbol{X}^t \rangle B^t(s)R^t(s)$$

$$\boldsymbol{x}^t = (x, x', y, y') \qquad \langle yy \rangle = \sigma_y^2$$

Normal mode X,Y and emittance

- Normal mode with eigenvalues, $\exp(\pm i\mu_{X,Y})$.
- Betatron motion, oscillation with frequency, $\mu_{X,Y}$.
- Emittance rms of the normal mode amplitude, $\varepsilon_X = \langle |X|^2 \rangle$, $\varepsilon_Y = \langle |Y|^2 \rangle$.
- Emittance is determined by radiation excitation and damping along the normal mode.

$$\varepsilon_Y \propto \oint \frac{\gamma_Y \eta_Y^2 + 2\alpha_Y \eta_Y \eta_Y' + \beta_Y \eta_Y'^2}{\rho^3} ds$$

$$\boldsymbol{\eta}_{X,Y}(\mathrm{s}) = R^{-1}(s)\boldsymbol{\eta}_{x,y}(\mathrm{s})$$

- To reduce ε_Y, X-y coupling in bend should be suppressed.
- Global coupling determines vertical emittance.

Local x-y coupling and beam size

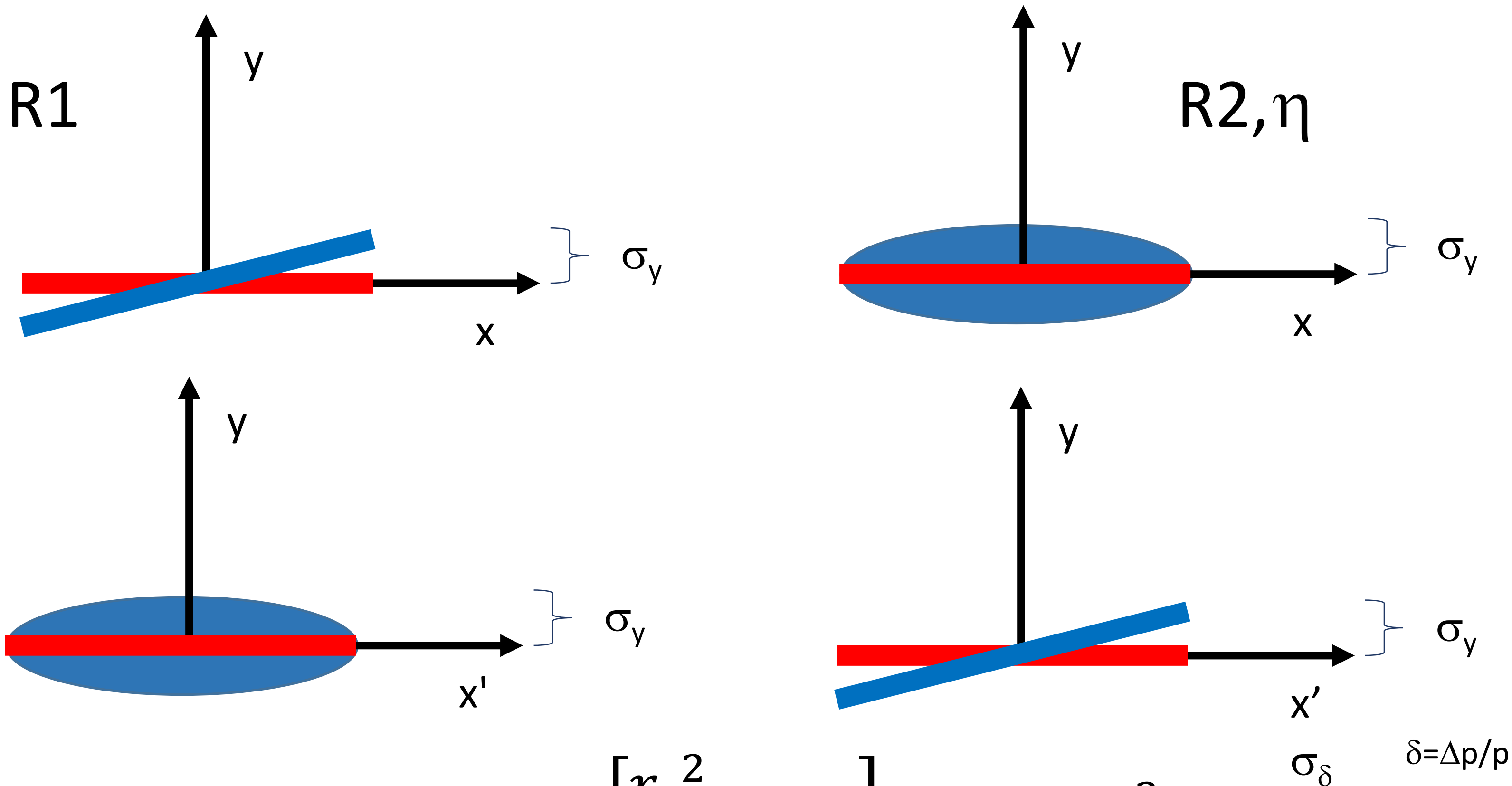
- Beam size at location given Twiss parameters.

$$\sigma_y^2(s) \approx \sigma_Y^2 + \sigma_X^2 \left[\frac{{r_2}^2}{\beta_x^2} + {r_1}^2\right] + \left(\eta_y \sigma_\delta\right)^2$$

$$\sigma_Y^2(\mathrm{s}) = \beta_Y(s)\varepsilon_Y \qquad \sigma_x^2(\mathrm{s}) \approx \sigma_X^2(\mathrm{s}) = \beta_X(s)\varepsilon_X$$

- Local vertical beam size consists of the vertical emittance and local x-y coupling R(s).
- x-y coupling at IP enhances emittance growth due to the beam-beam interaction.
- Beam size at Interaction Point determines luminosity performance.

Local coupling and beam distribution



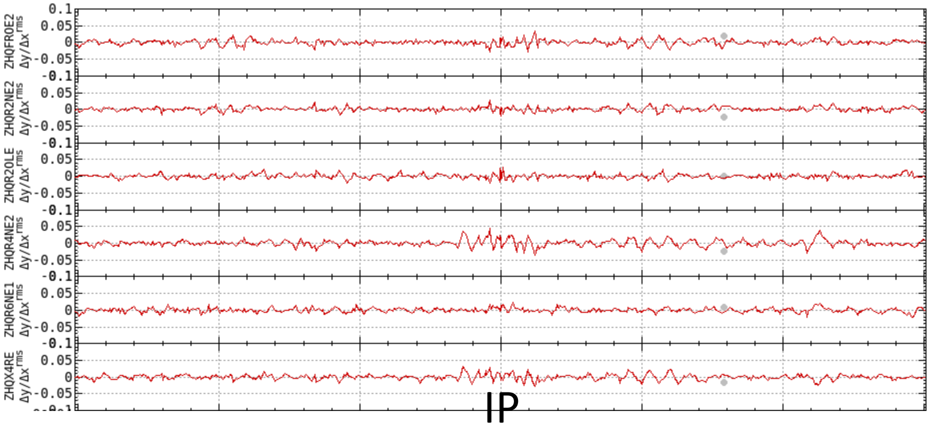
$$\sigma_y^2(s) \approx \sigma_{y,0}^2 + \sigma_x^2\left[\frac{{r_2}^2}{\beta_x^2} + {r_1}^2\right] + \left(\eta_y\sigma_\delta\right)^2$$

R3 and R4 are explained by the same picture for p_y.

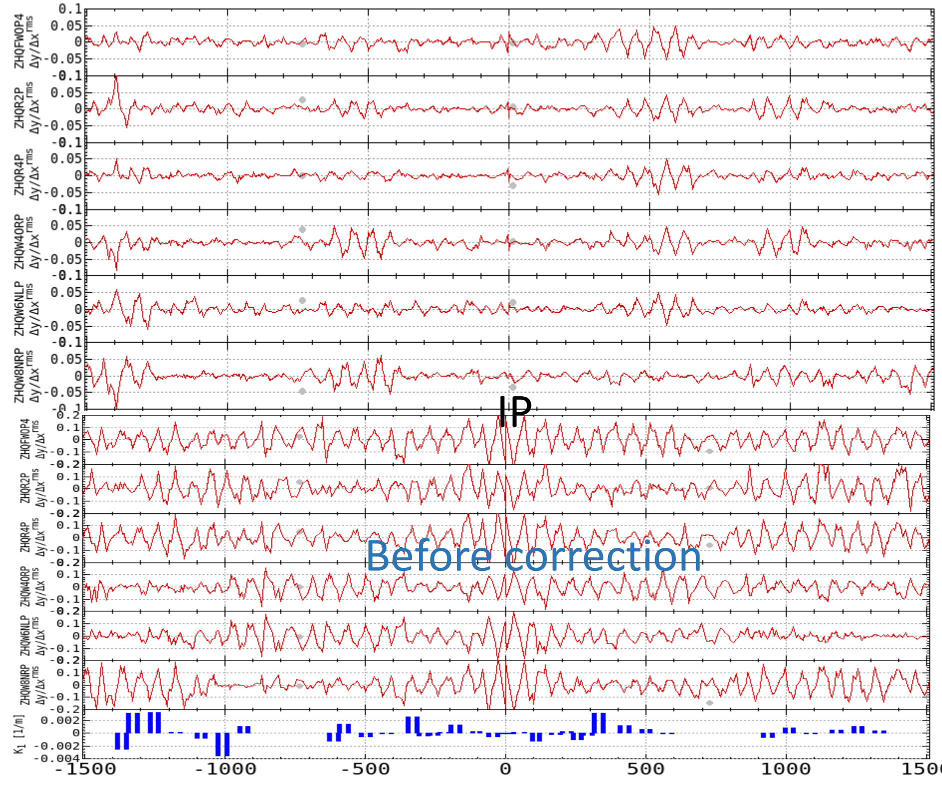
X-y coupling correction in SuperKEKB

- Exciting 6 horizontal steerings one by one, measure closed orbit distortion in each.
- Vertical orbit is corrected by skew quads or vertical bump of sextupoles.

HER



LER



- r1 and r2 at every s is corrected, r3 and r4 are corrected as the result.
- X-y coupling in LER is somewhat worse than HER.

Optics Correction Summary

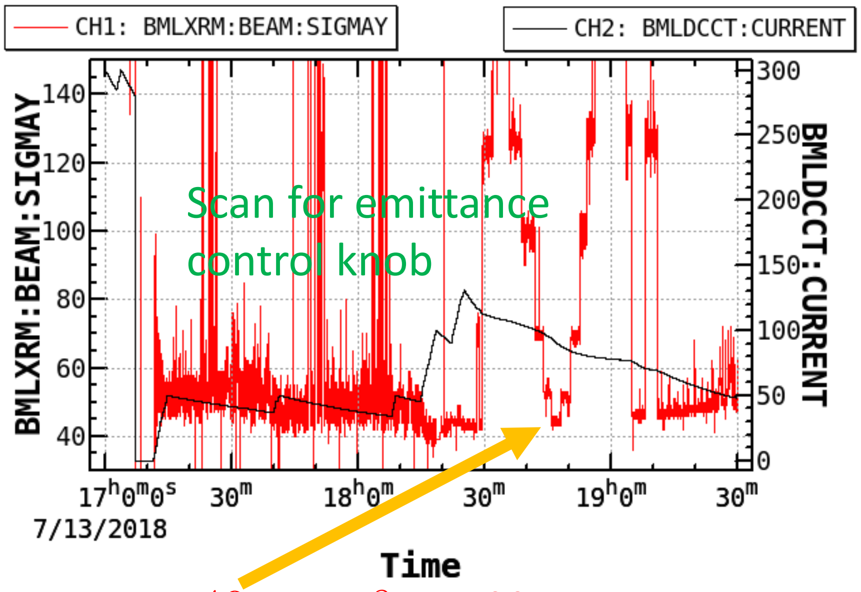
	Phase 1		Phase 2	
	LER	HER	LER	HER
$(\Delta\beta_{x,y}/\beta_{x,y})^{\rm rms}$ [%]	3 / 3	3 / 3	2 / 4	3 / 3
$(\Delta y)^{\rm rms} / (\Delta x)^{\rm rms}$	0.009	0.006	0.014	0.008
$(\Delta\eta_{x,y})^{\rm rms}$ [mm]	8 / 2	11 / 2	10 / 4	9 / 3
$\Delta\xi_{x,y}$	2 / -4	< 1 / < 1	2 / 3	< 1 / 3

HER $(\beta_x^*,\ \beta_y^*) = (100\ \mathrm{mm},\ 3\ \mathrm{mm})$

LER $(\beta_x^*,\ \beta_y^*) = (200\ \mathrm{mm},\ 3\ \mathrm{mm})$

Vertical Emittance in Phase 2

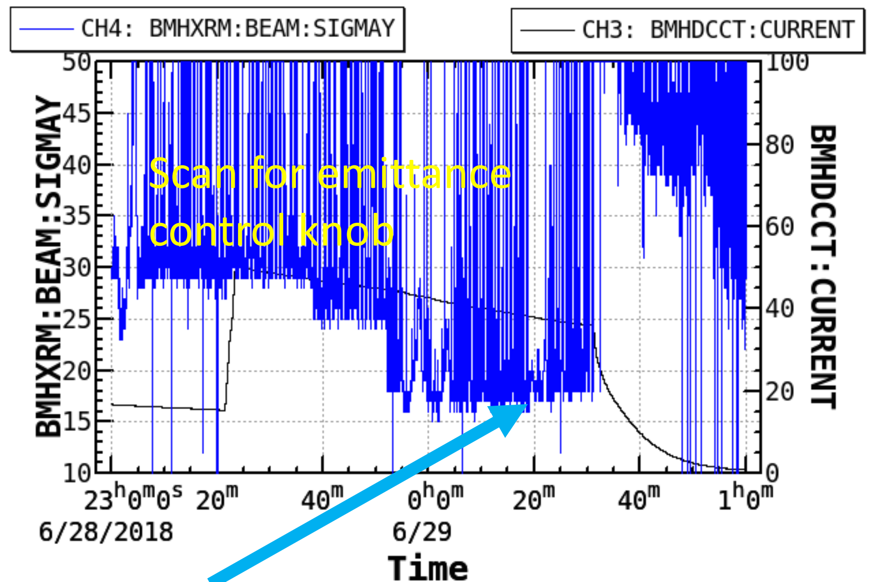
LER



$\sigma_y = 40\ \mu\text{m}\quad \beta_y = 69\ \text{m}$

$\varepsilon_y \sim 23\ \text{pm}$ $\quad \varepsilon_x = 3nm$

HER



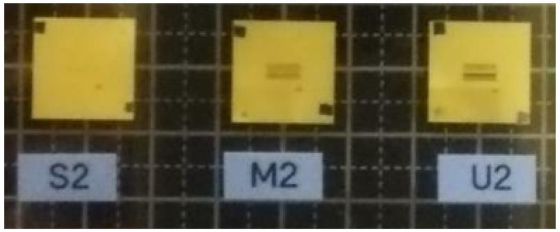
$\sigma_y = 16\ \mu\text{m}\quad \beta_y = 28\ \text{m}$

$\varepsilon_y \sim\ 9\ \text{pm}$

$\varepsilon_x = 5nm$

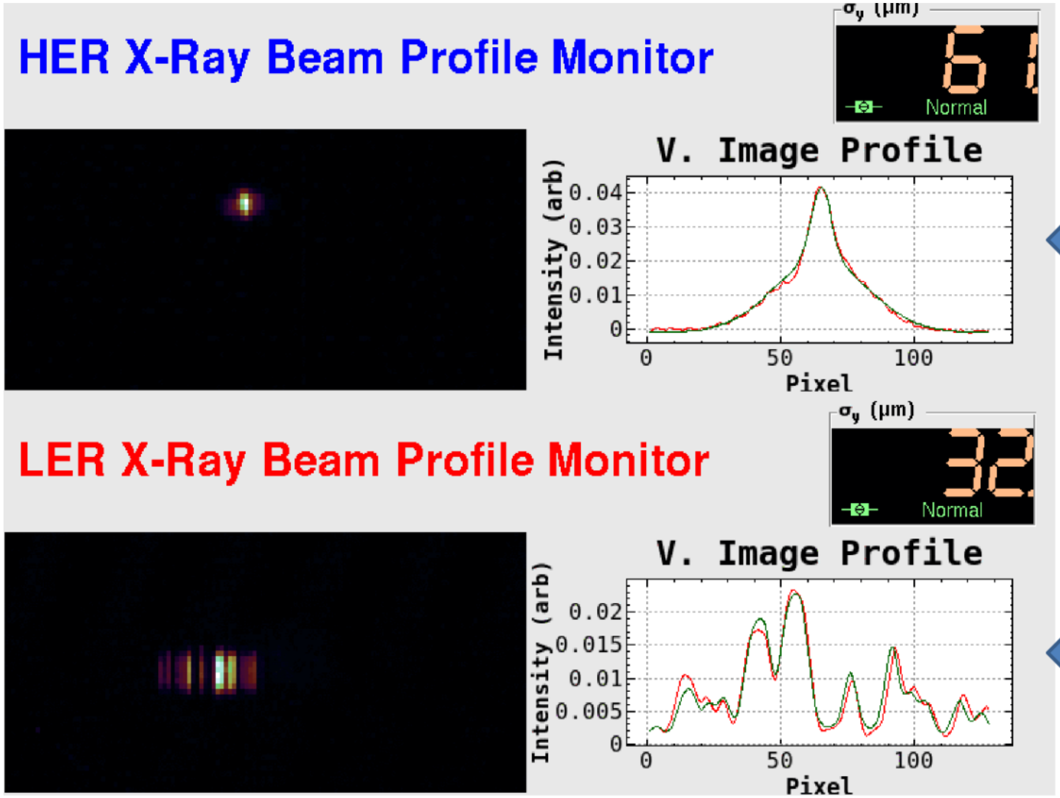
- Emittance of HER is improved compare with Phase 1.
- Emittance of LER is larger than that of Phase 1.
  Note: Residual of XY coupling is larger compare with Phase1.

Beam size measurement using XRM



Masks: ~20 μm Au on 600 μm CVD diamond substrate

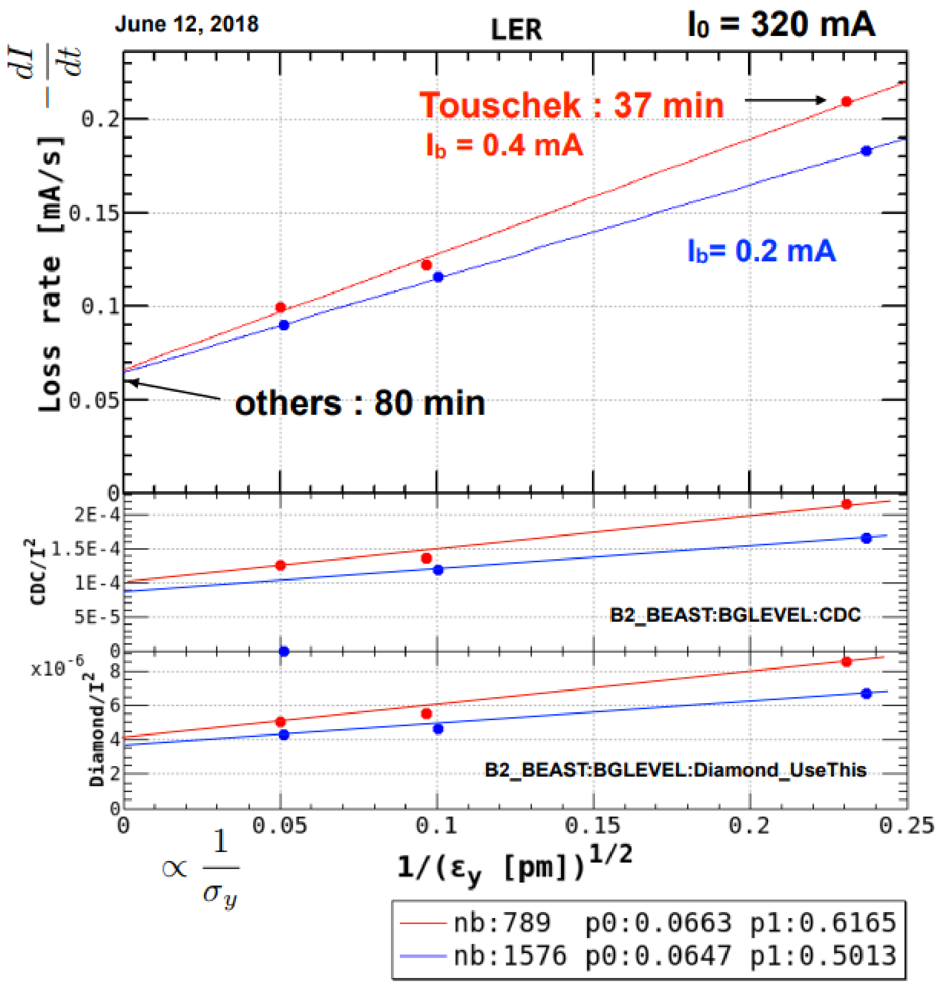
X-ray beam line under construction at LER

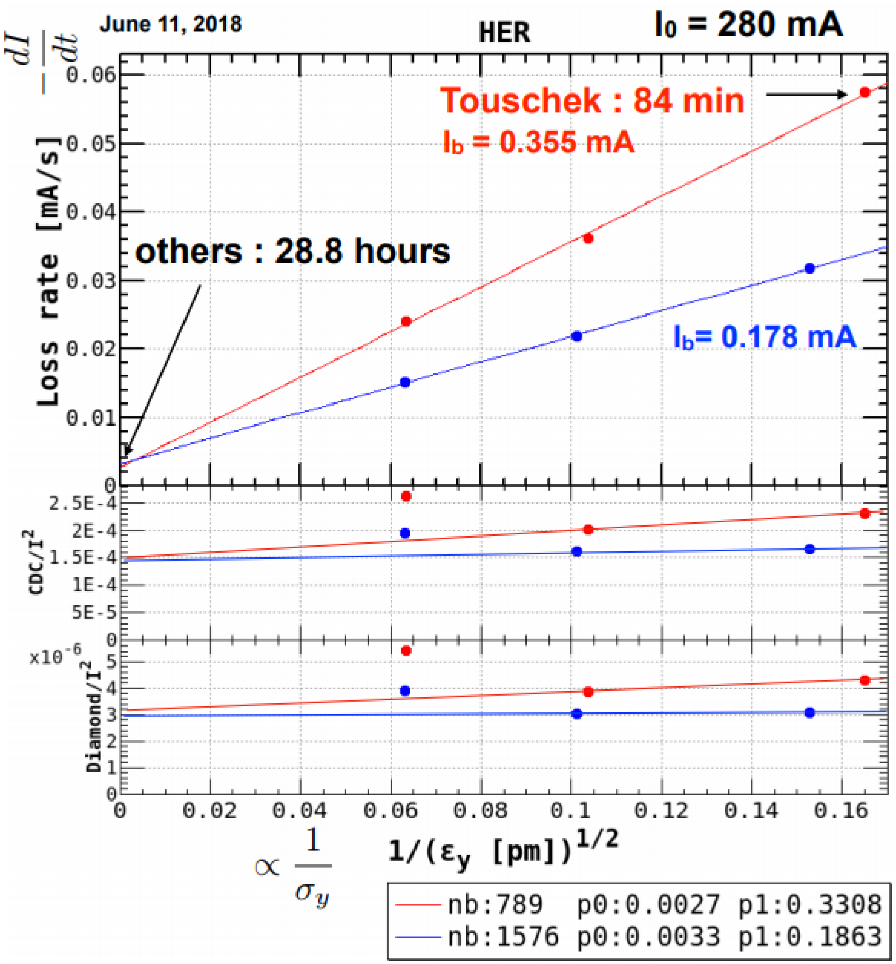


Single-slit mask

URA mask

Beam life time vs vertical emittance





Touschek effect can be observed in LER.

I_b=1mA/bunch-> N_e=6x10^{10}/bunch

SuperKEKB as a low emittance collider

- Compatibility of low emittance, beam-beam tune shift and luminosity
- Collision with Large crossing angle to avoid large horizontal tune shift.
- Extreme small β_y.
- Small x-y coupling for keeping vertical beam-beam tune shift

$$\Delta\nu_x = \frac{N_e r_e}{2\pi\gamma_p}\frac{\beta_x}{\sigma_x(\sigma_x+\sigma_y)}$$

$$\Delta\nu_y = \frac{N_e r_e}{2\pi\gamma_p}\frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}$$

$$L = \frac{N_e N_p}{4\pi}\frac{f_{col}}{\sigma_x\sigma_y} = \frac{N_p\gamma_p\Delta\nu_y}{2r_e\beta_y}f_{col}$$

Effective horizontal beam size

$$\sigma_x = \sqrt{\beta_x\varepsilon_x + (\phi_c\sigma_z)^2}$$

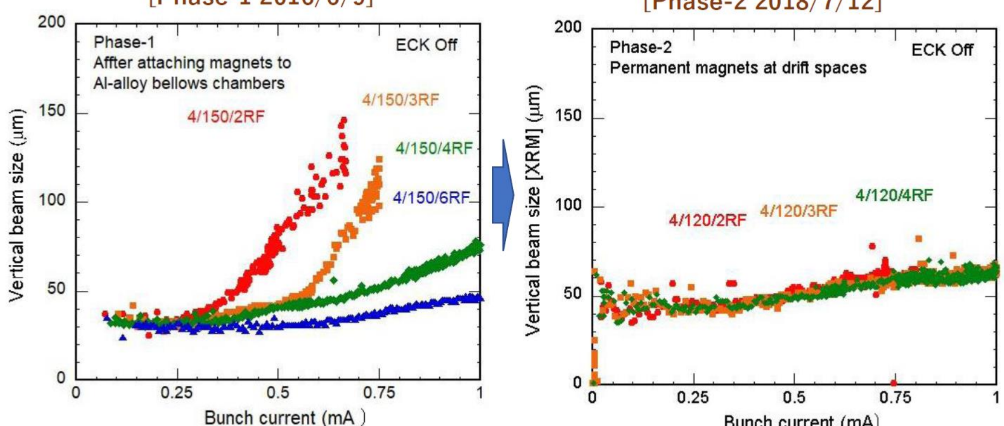
ϕ_c: half crossing angle

Commissioning of SuperKEKB, Phase I

- Low emittance operation
  - X-y coupling, vertical dispersion correction.
  - X-ray beam size monitor using coded aperture.
  - Global X-y coupling <1% is achieved.
  - I_+=1A and I_-=0.7 A achieved without emittance growth.
- Check electron cloud instability, and other instabilities.
  - EC Instability was observed early stage, but suppressed by winding solenoids in bellow section not coated by TiN.
  - Beam size blow-up due to electron cloud is suppressed by 1A at least. N_{bunch}=1500.

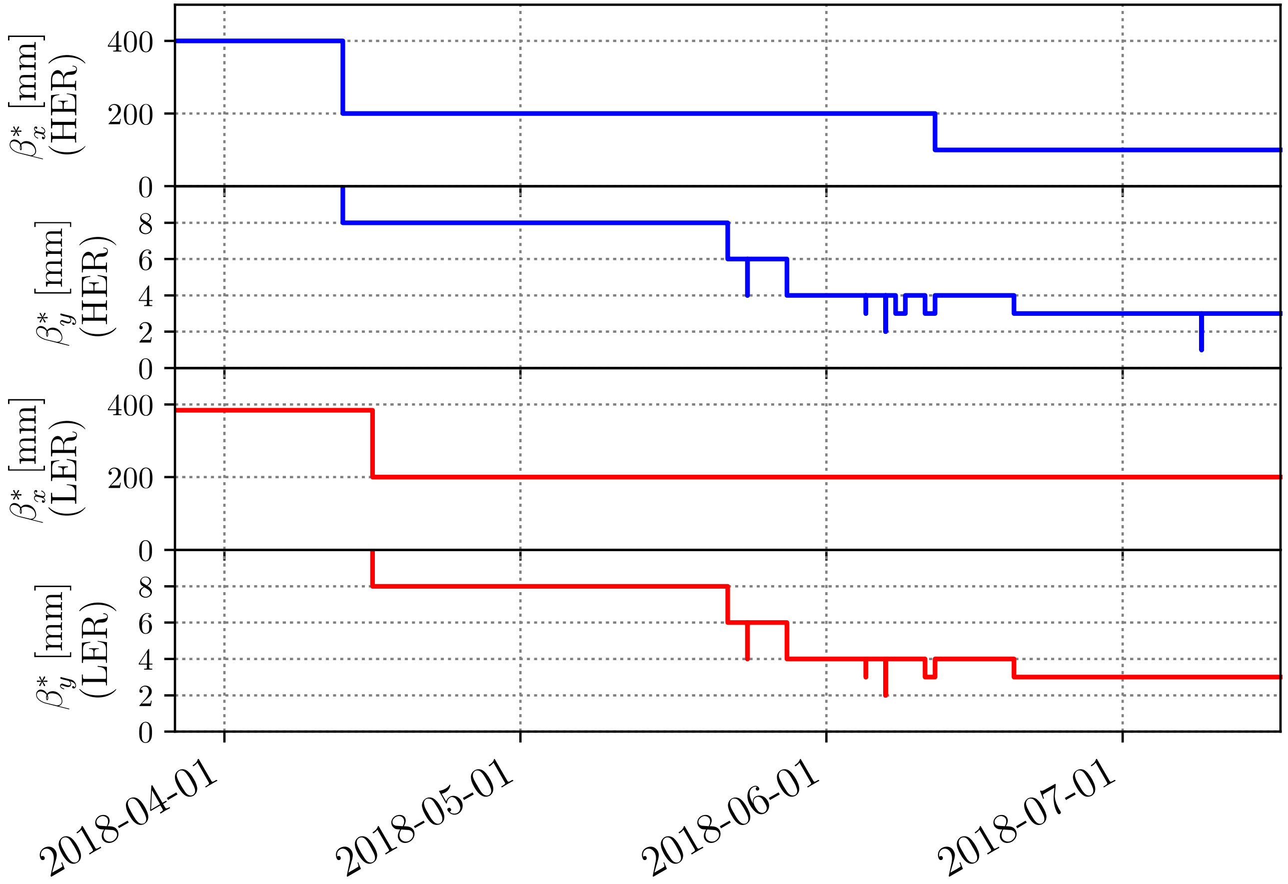
1mA/bunch=6x10^{10}/bunch, C=3016m

[Phase-1 2016/6/9] [Phase-2 2018/7/12]

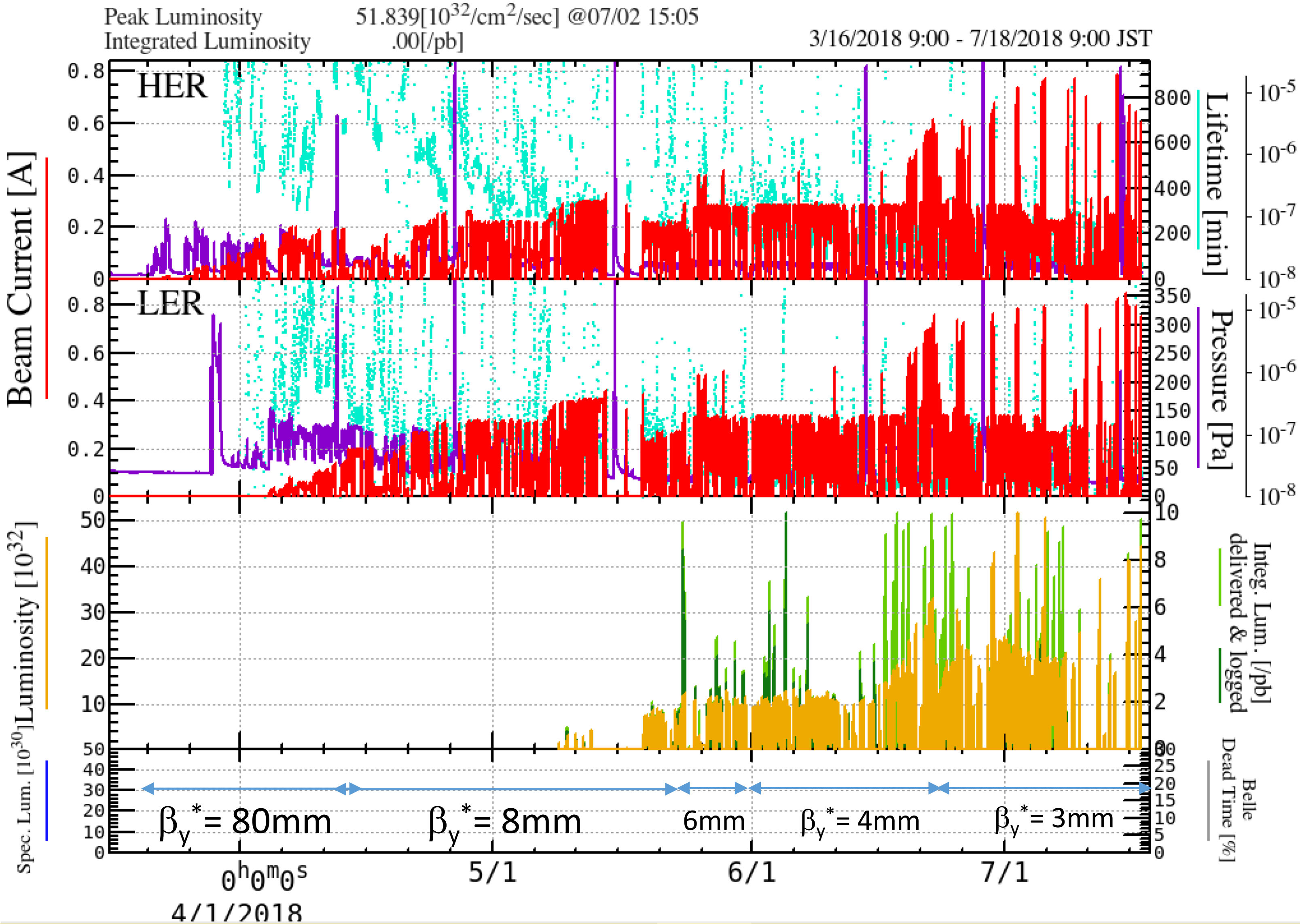


Commissioning of SuperKEKB, Phase II

- β squeezing



History of SuperKEKB Phase 2

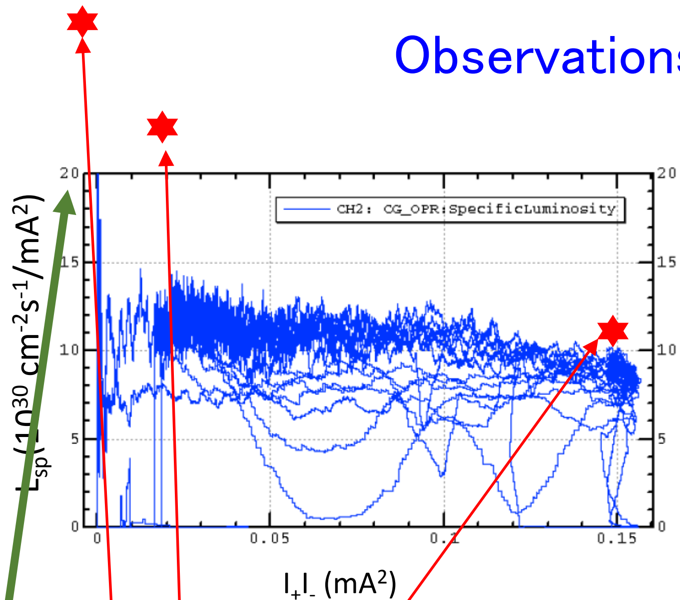


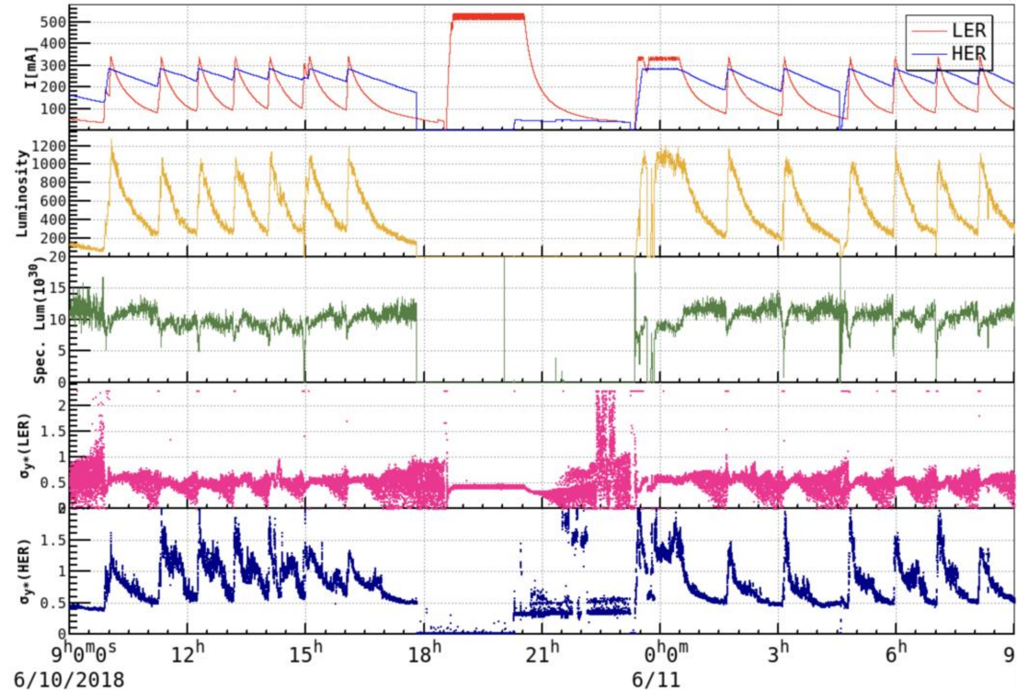
$5.55 \times 10^{33}/cm^2/s$ (βy*3mm, LER: 800mA, HER: 780mA, 1576 bunches/beam July 5th)

$2.29 \times 10^{33}/cm^2/s$ (βy*3mm, LER: 270mA, HER: 225mA, 394 bunches/beam July 3rd)

Lspec at June 10, 2018

Observations





- 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

Lsp=20 was at lowest current, 0.01mAx0.01mA.

L_{peak}=1.2x10^{33} cm^{-2}s^{-1} ,
285x340mA, N_b=788

Blow-up of e- beam was serious.

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

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

1mA/bunch=6x10^{10}/bunch

Optics aberration and tuning at IP

- In early stage of Phase II, luminosity of very low current contradict with the measured emittance.
- Luminosity did not increase for squeezing beta.
- Local coupling R2 at IP could be suspected.

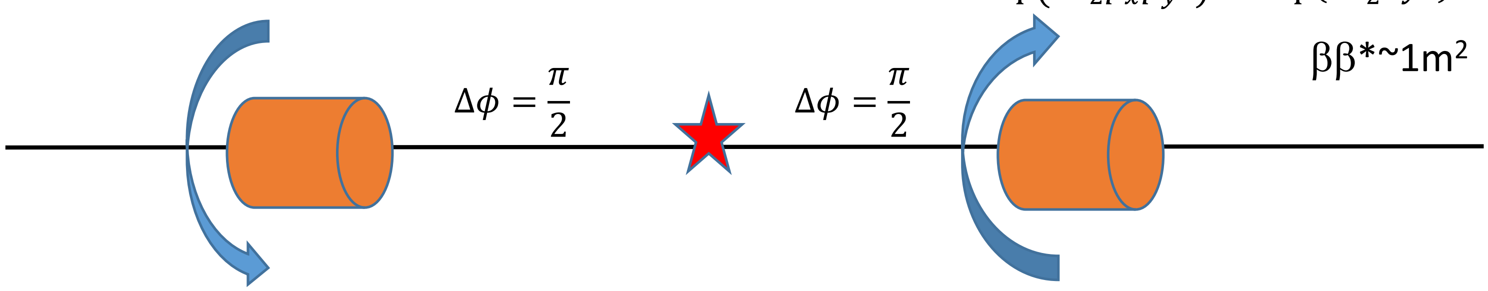
$$\sigma_y^2 \approx \sigma_Y^2 + \sigma_x^2 \left[\frac{{R_2}^2}{\beta_x^2} + {R_1}^2 \right] + \left(\eta_y \sigma_\delta \right)^2$$

$$\sigma_Y^2(\mathrm{s}) = \beta_Y(s)\varepsilon_Y$$
$$\sigma_x^2(\mathrm{s}) \approx \sigma_X^2(\mathrm{s}) = \beta_X(s)\varepsilon_X$$

- R2 can be induced by skew rotation of both side of QCS.
- Induced R2 does not change for squeezing of β*.
- However effect of R2 is enhanced for squeezing β*.

$\mathcal{M} = \exp(-{:}R_2 p_x^* p_y^*{:}) = \exp(-{:}R_2 xy{:})$

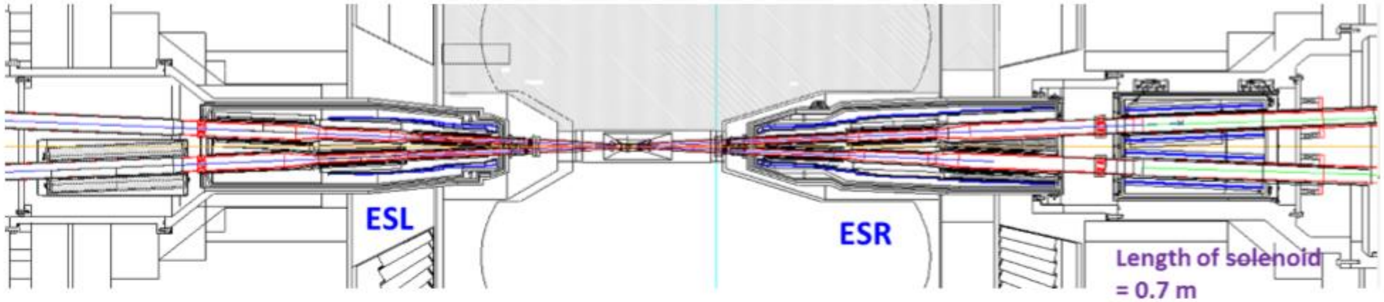
$\mathcal{M} = \exp({:}R_2 p_x^* p_y^*{:}) = \exp({:}R_2 xy{:})$

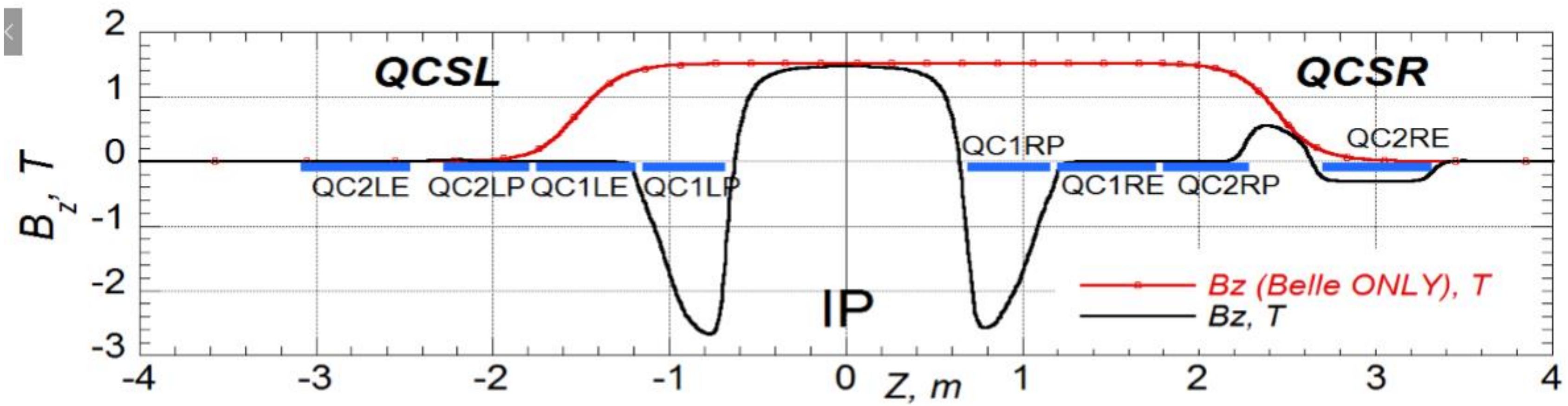


Overview of IR magnets

N. Ohuchi et al.

- Compensation solenoids [ESL, ESR1, ESR2 and ESR3]





- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.

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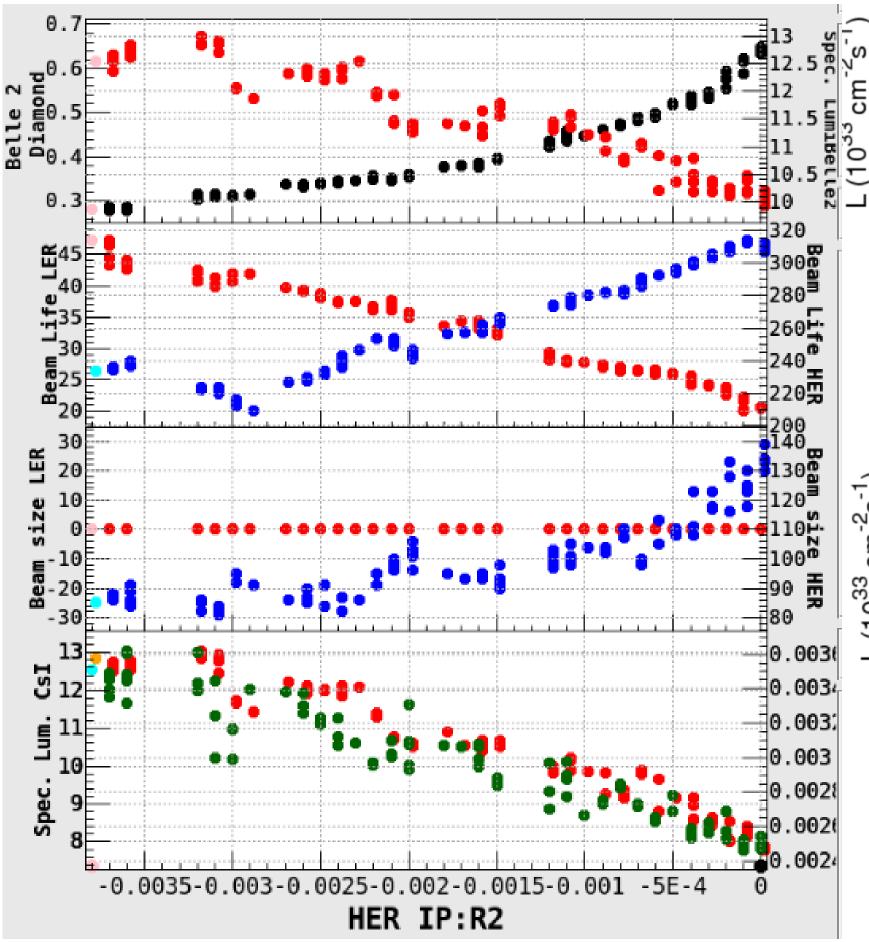
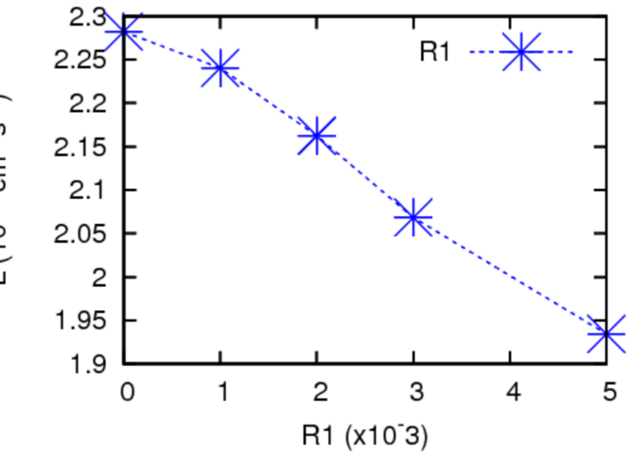
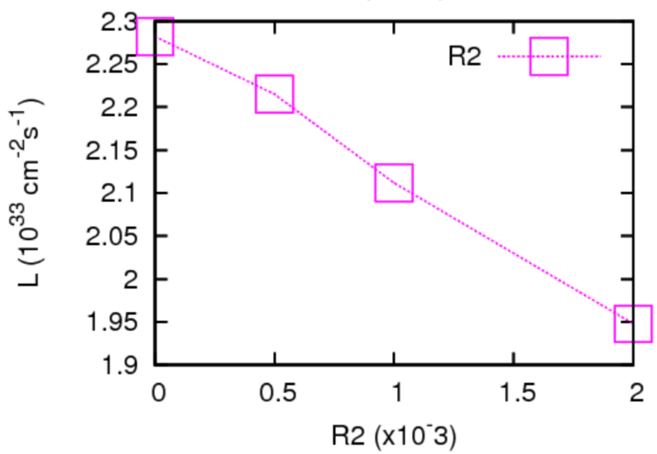
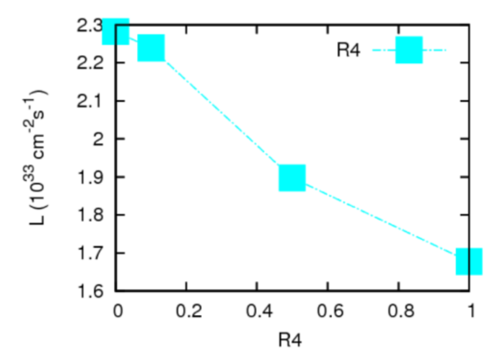
- Linear and nonlinear correction coils including skew are wound in QC1-2.
- R2 was corrected by a1 (skew Q) correction coil of QC1.

R scan in operation and beam-beam simulation





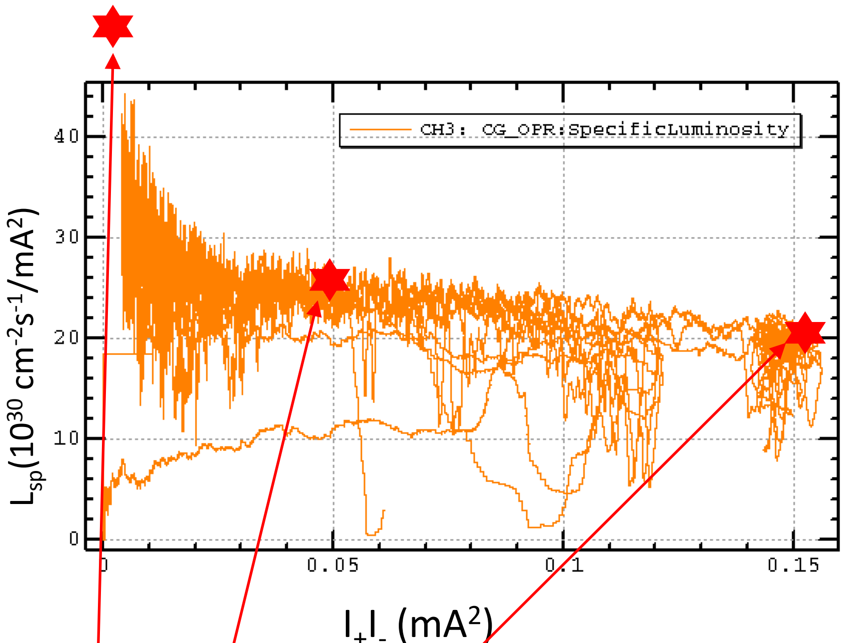


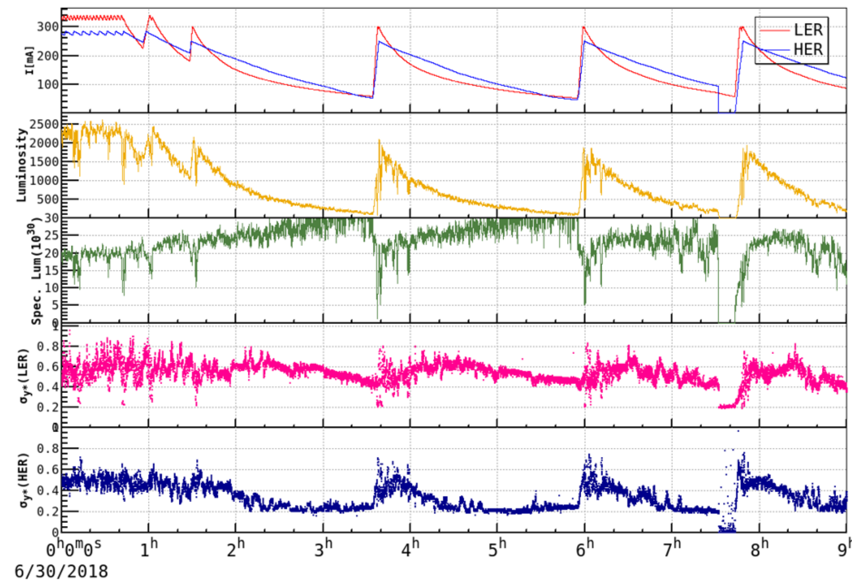


- R2 is changed 7mm in July 15-30, corresponding QCS rotation is ~7mrad.

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

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

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

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

Lsp agrees with geo value at every current

6/29 21:00- R2 using QCS corrector

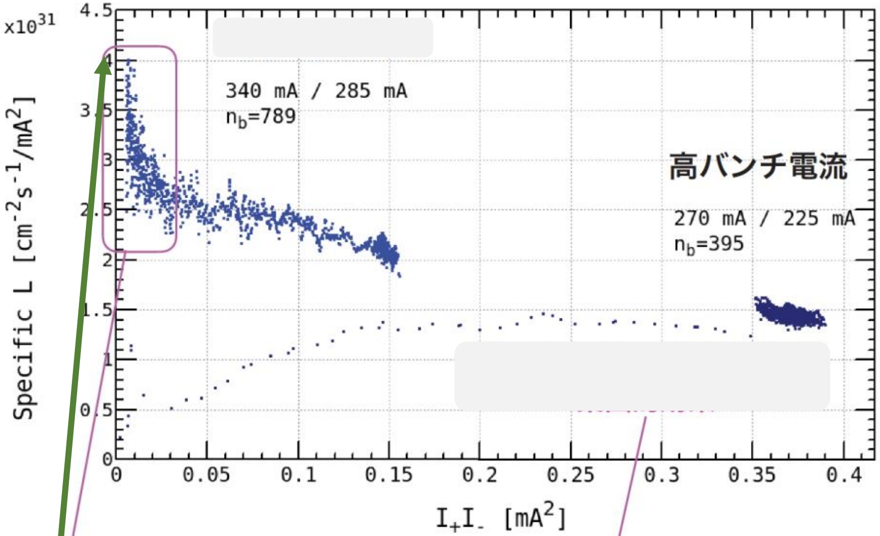
L_{peak}=2.5x10^{33} cm^{-2}s^{-1} , (2 times higher)

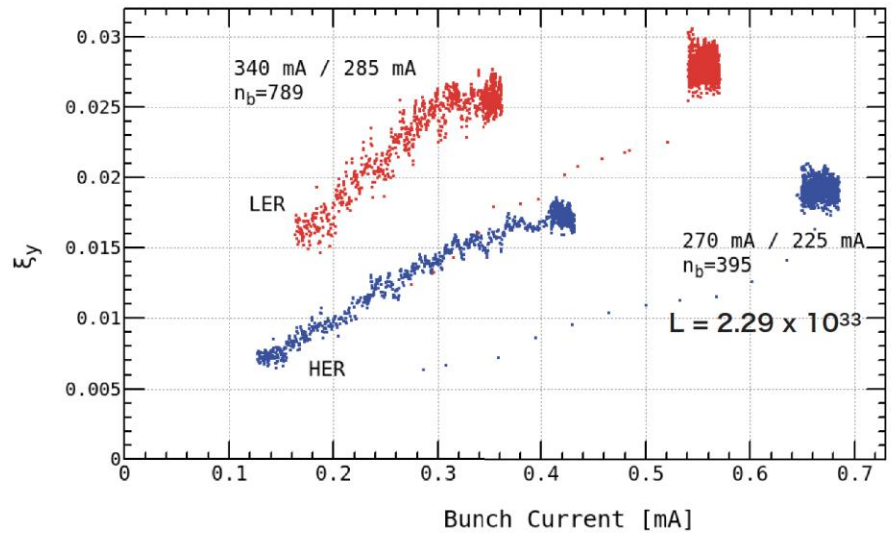
285x340mA, N_b=788

Blow-up of e+ beam was serious.

![SuperKEKB logo]

Specific Luminosity and Beam-Beam Parameter





Specific luminosity dropped at very low current.

$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi(\sigma_z \phi_x)e^2 f_0 \sigma_y^*} = \frac{1.25\times 10^{25}}{\sigma_y^*}\ [cm^{-2}s^{-1}/mA^2]$$

L_{sp} at very low current is consistent with beam size measurement.

$L_{sp} = 4\times10^{31} \rightarrow \sigma_y^* = 300$ nm ($\varepsilon_y = 30$ pm)

$\leftrightarrow \varepsilon_y = 23$ pm Single beam measurement (LER)

Beam-beam tune shift was saturated at $\Delta\nu_y(e^-)$=0.02 due to e^+ beam blow-up.

Achieved: L_{sp}=15×10^{30}cm^{-2}s^{-1}mA^{-2} at 0.4mA^2, $\Delta\nu_y$=0.02 at β_y=3mm

Final goal : L_{sp}=220×10^{30}cm^{-2}s^{-1}mA^{-2} at 1.5mA^2, $\Delta\nu_y$=0.08 at β_y=0.3mm

1mA/bunch=6×10^{10}/bunch

TbT measurement of x-y coupling at IP

$r_i = R_i$

- y motion in X mode.

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

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

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

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

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

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

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

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

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

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

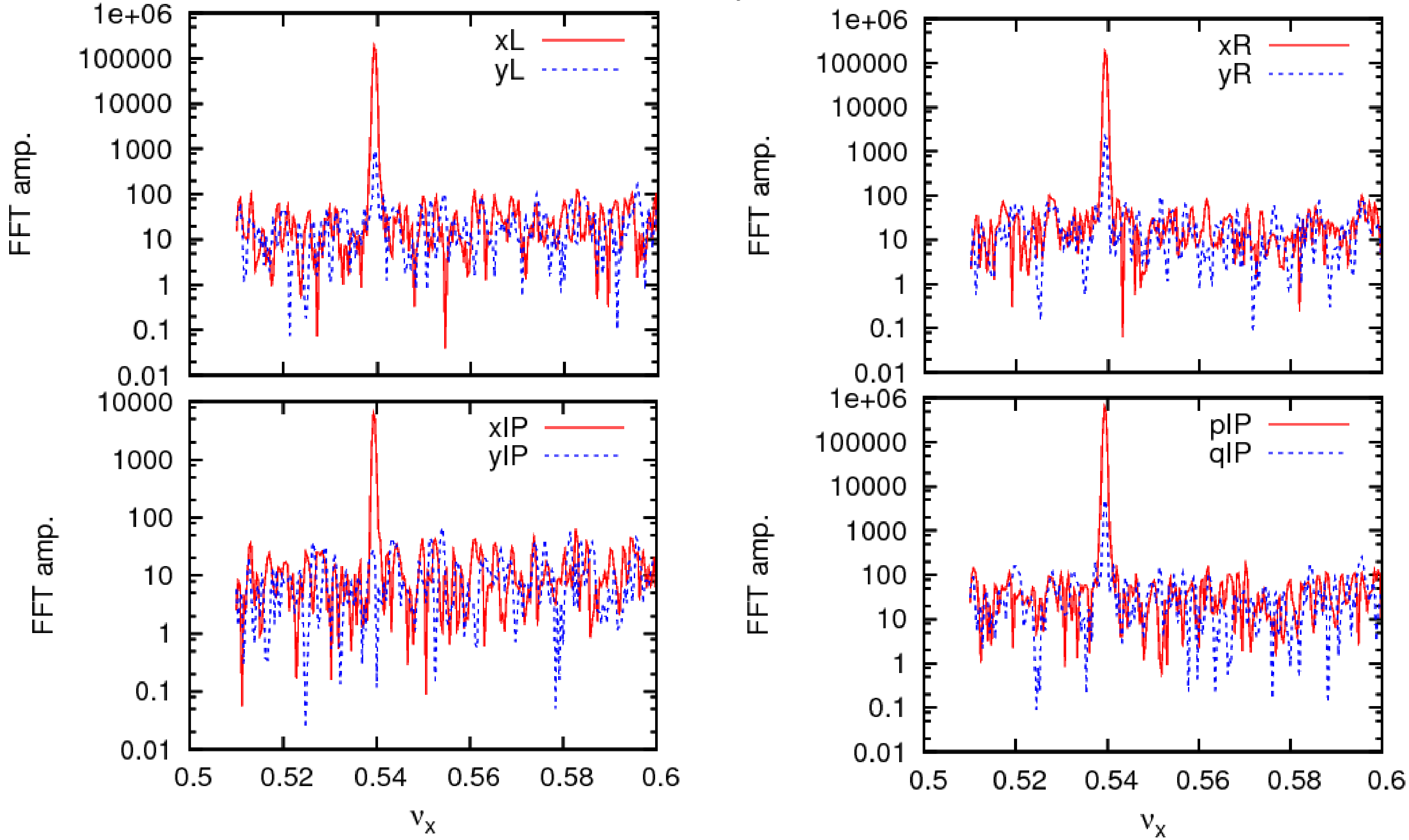
$$p_y = r_3 x - r_4 p_x = r_3 a \cos\phi(s) + r_4 \left[\frac{a}{\beta} \sin\phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos\phi(s)\right]$$

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

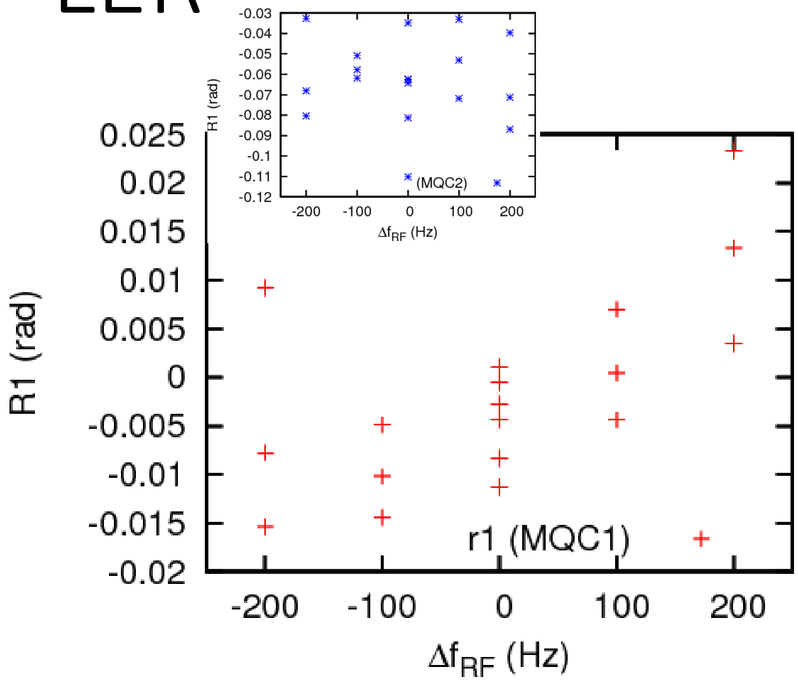
$$\frac{d}{a}\cos(\phi_q - \phi_x) = \left(r_3 + r_4\frac{\alpha}{\sqrt{\beta}}\right) \qquad \frac{d}{a}\sin(\phi_q - \phi_x) = -\frac{r_4}{\beta}$$

FFT of BPM data

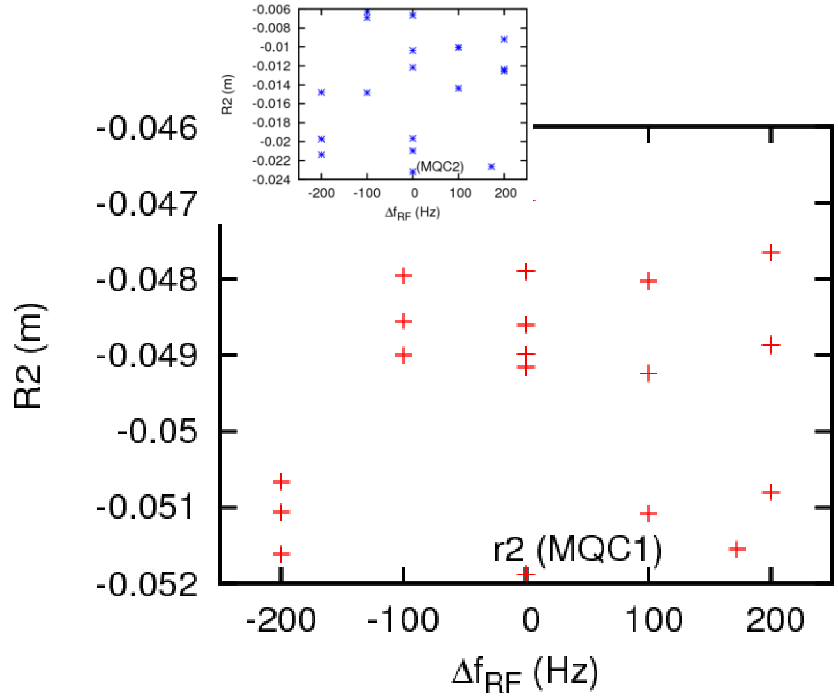
- xL,yL left side and xR, yR right side monitor of IP.
- Small y_{IP}, but enough $p_{yIP}=q_{IP}$. R1 and R2 is hard to measure compare with R3, R4



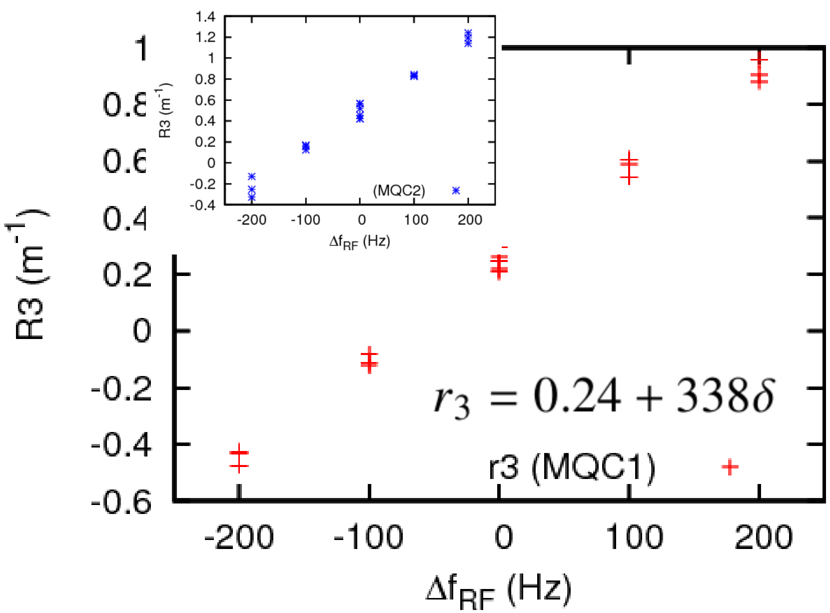
LER



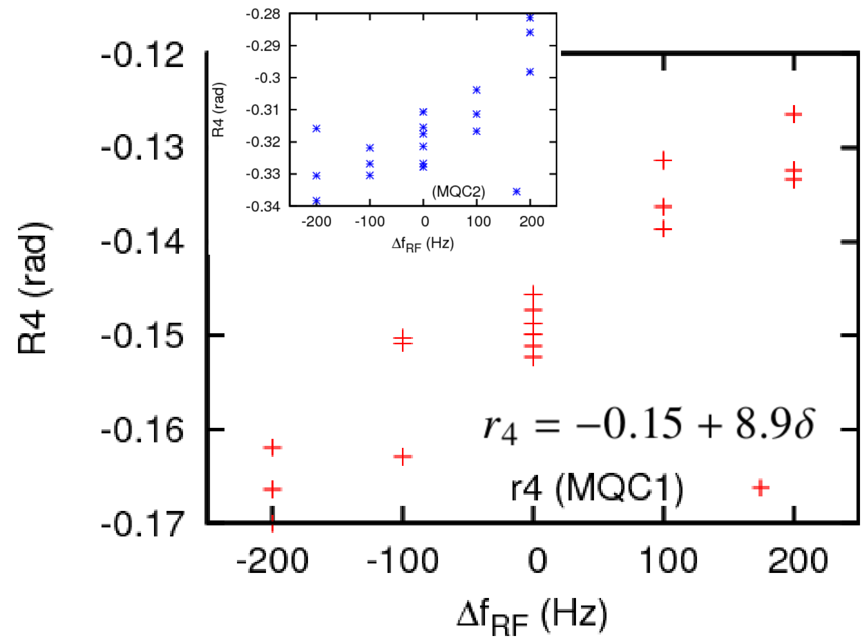
R1 (rad)
Δf_RF (Hz)
r1 (MQC1)
R1 (rad)
Δf_RF (Hz)
(MQC2)



R2 (m)
Δf_RF (Hz)
r2 (MQC1)
R2 (m)
Δf_RF (Hz)
(MQC2)



R3 (m^-1)
Δf_RF (Hz)
$r_3 = 0.24 + 338\delta$
r3 (MQC1)
R3 (m^-1)
Δf_RF (Hz)
(MQC2)

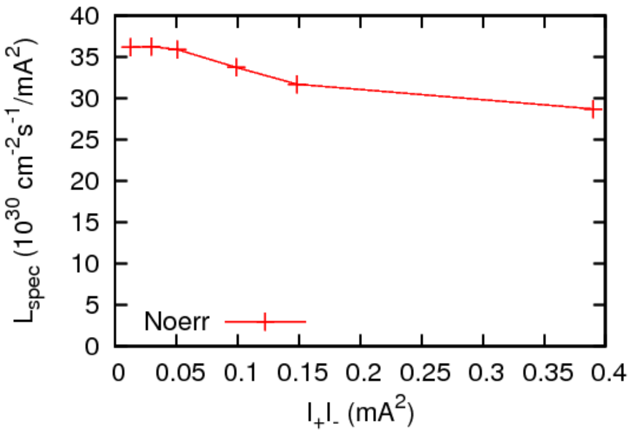


R4 (rad)
Δf_RF (Hz)
$r_4 = -0.15 + 8.9\delta$
r4 (MQC1)
R4 (rad)
Δf_RF (Hz)
(MQC2)

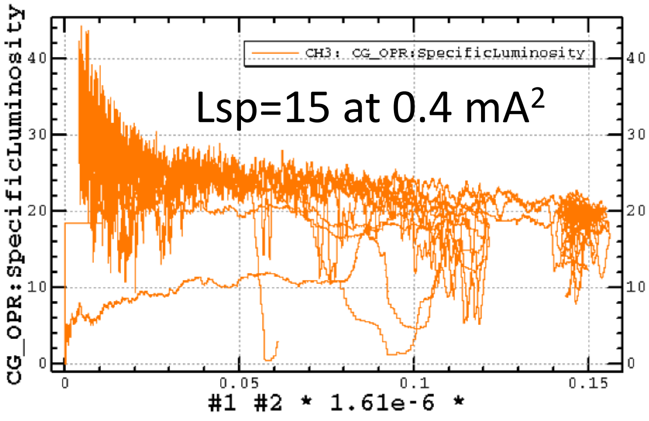
Toward Phase III (start Mar. 2019)

- Squeezing beta*, Luminosity increase is not trivial at all without IP optics tuning.

Lspec without error



Measured Lspec



Luminosity is half at I_+I_-=0.4mA^2.

Design 1.5 mA^2. β_y* 1/10

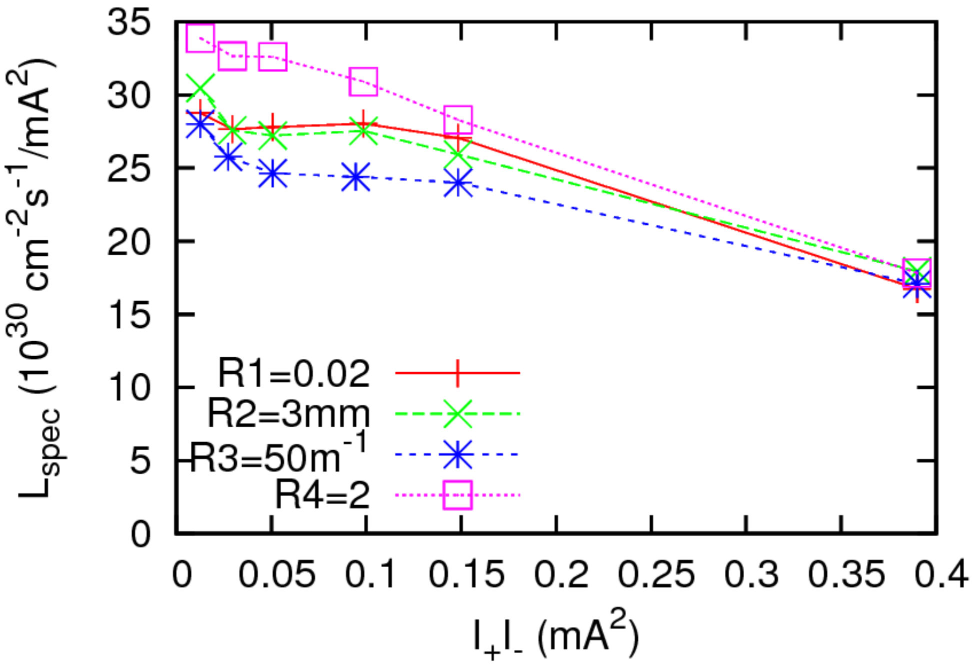
Beam-beam simulation considering optics aberrations at IP

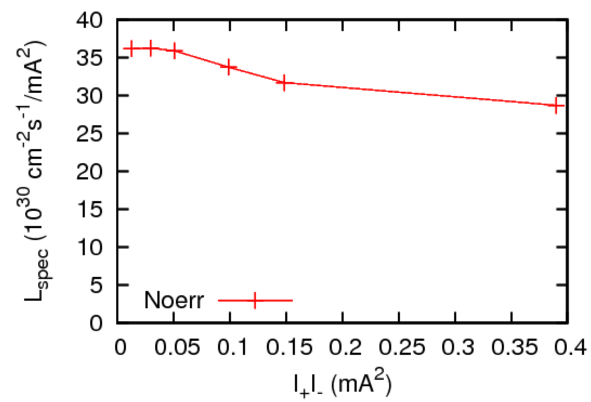
- Linear
- Nonlinear
- Chromatic

- Recent operation showed e+ beam is weaker than e- beam. Weak(e+)-strong(e-) simulation is performed.

Weak(e+)-strong(e-) simulation with errors

- Error strengths of R3 and R4 are much larger than measurement. Discard.
- R1 and R2 were already scanned and given optimum.
- We cleared linear aberrations in Phase-II.



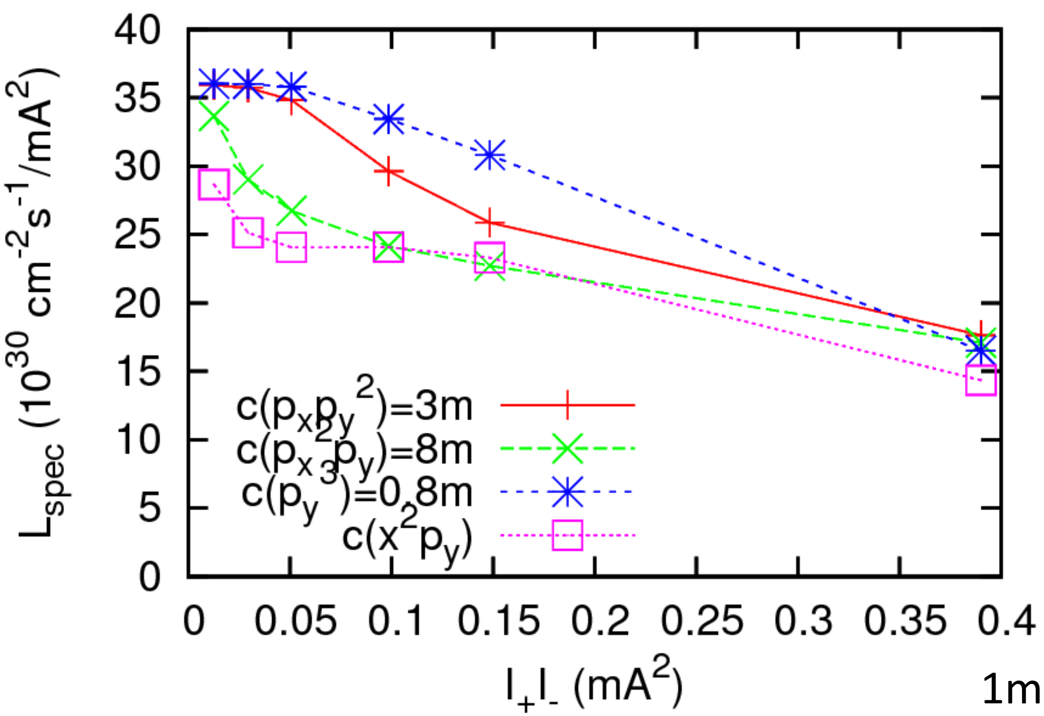


1mA/bunch=6x10^{10}/bunch

Nonlinear aberrations

$$\mathcal{M} = \exp(\pm{:}\, c_{10} p_x^{*2} p_y^{*}{:}\,) = \exp(\pm{:}\, c_{10} x^2 y{:}\,)$$

- $p_x{}^2 p_y$ term was studied before commissiong.
- $p_x{}^2 p_y$ term well reproduces measured L_{sp}.
- The strength is 100 times larger than the value given by design of QCS. $c_{10}=c(p_x{}^2 p_y)=0.07$m.

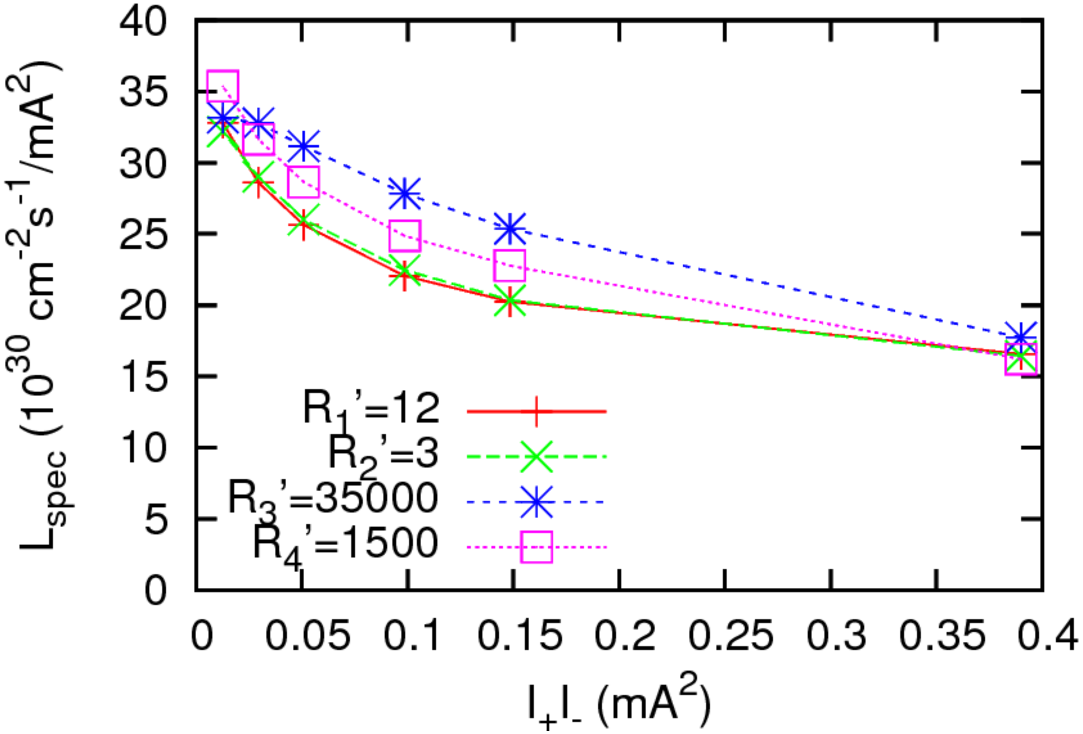


1mA/bunch=6x10^{10}/bunch

Chromatic coupling

$$\mathcal{M} = \exp(\pm\!:R_2' p_x^* p_y^* \delta:\pm\!:R_1' x^* p_y^* \delta:) = \exp(\pm\!:R_2' x y \delta:\pm\!:R_1' p_x y \delta)$$

- R3' and R4' were measured to be R3'=300, R4'=20.
- The behaviors for R1' and R2' are plausible.
- R1' and R2' are hard to be measured in the present monitor. R1' ~-10 was measured. Reliable?



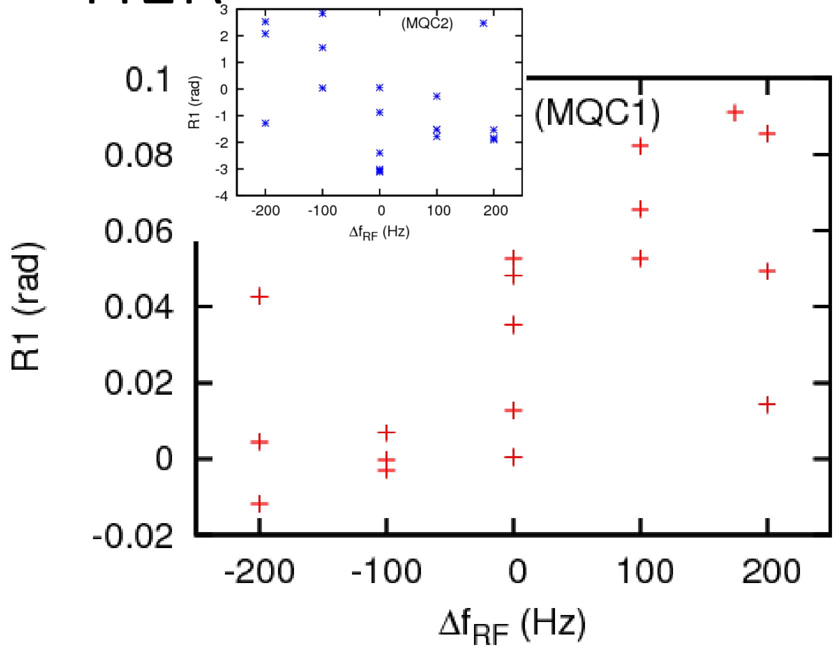
1mA/bunch=6x10[10]/bunch

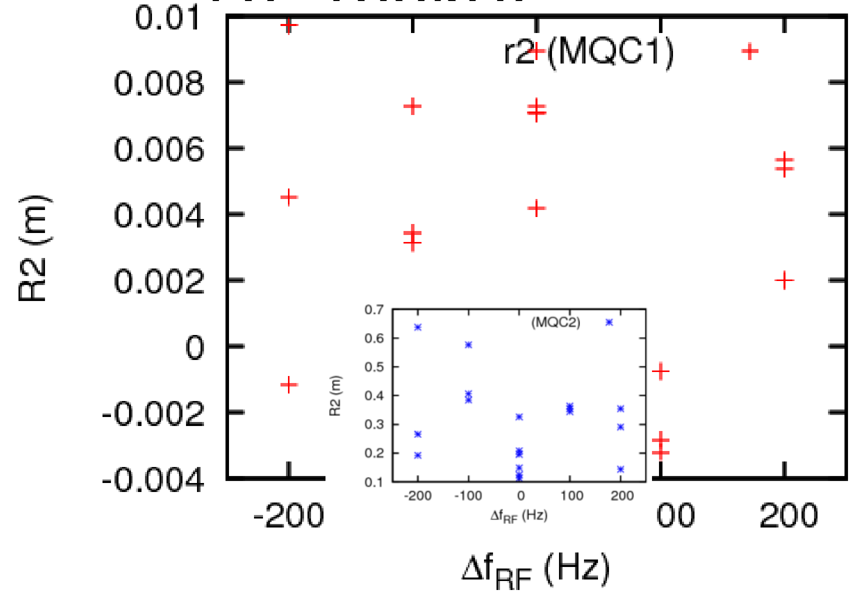
Summary

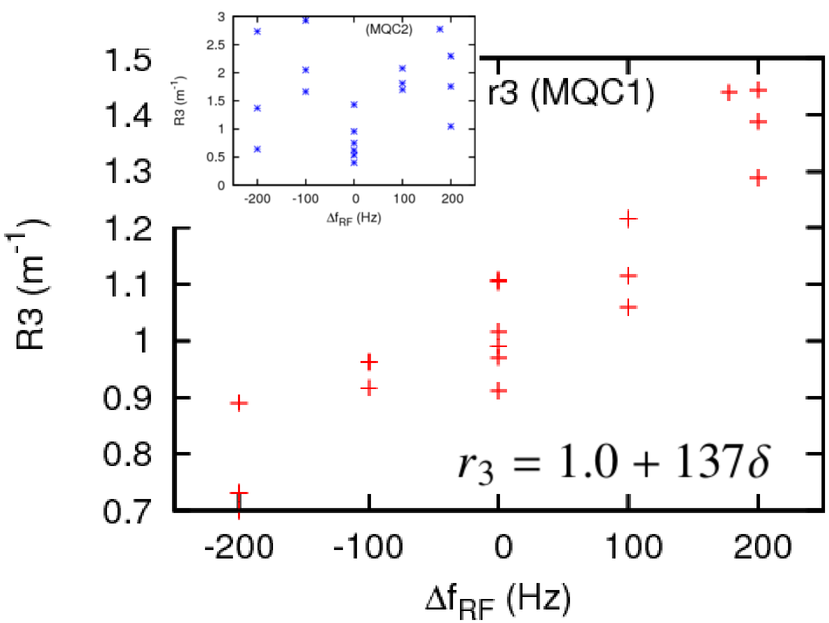
- Phase II commissioning was done by July 2018.
- Collision with β^*_x=0.1m(e^-), 0.2m(e^+), β^*_y=3mm was established.
- Luminosity gain squeezing β^* is not trivial, considering various errors.
- L=5x10^{33} $cm^{-2}s^{-1}$ was achieved. Beam-beam tune shift is limited to be $\Delta\nu_y$(e^-)=0.02 due to e^+ beam blow-up.
- Electron cloud instability seems to be managed well.
- Phase III commissioning starts Mar. 2019.
- $\Delta\nu_y$(e^{+-})=0.04 is minimum target. Final goal 0.06-0.08.
- We expect nonlinear/chromatic aberration at IP as sources of the luminosity degradation.
- The correction can be done skew sextupoles and QCS nonlinear coils.
- Otherwise our luminosity tuning may become deadlock.

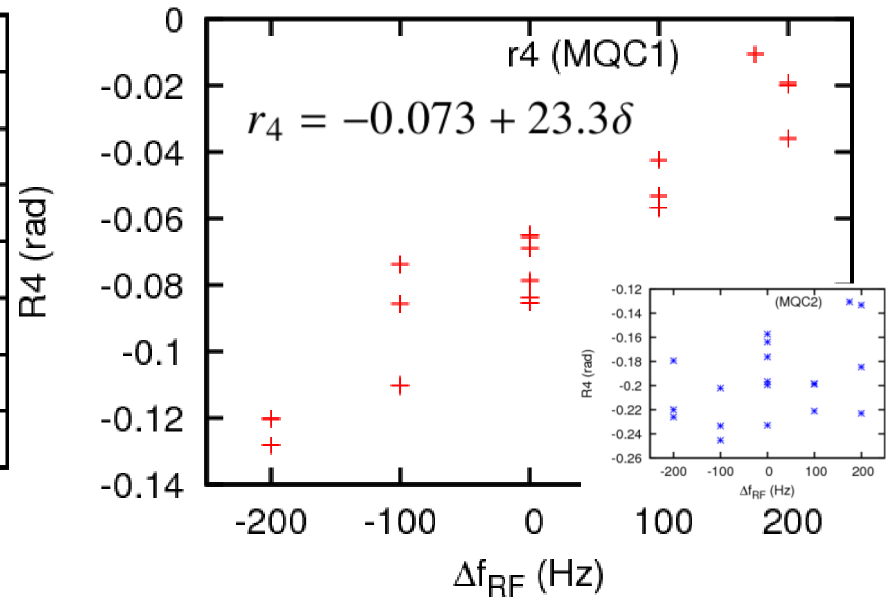
HER

- F0=100kHz

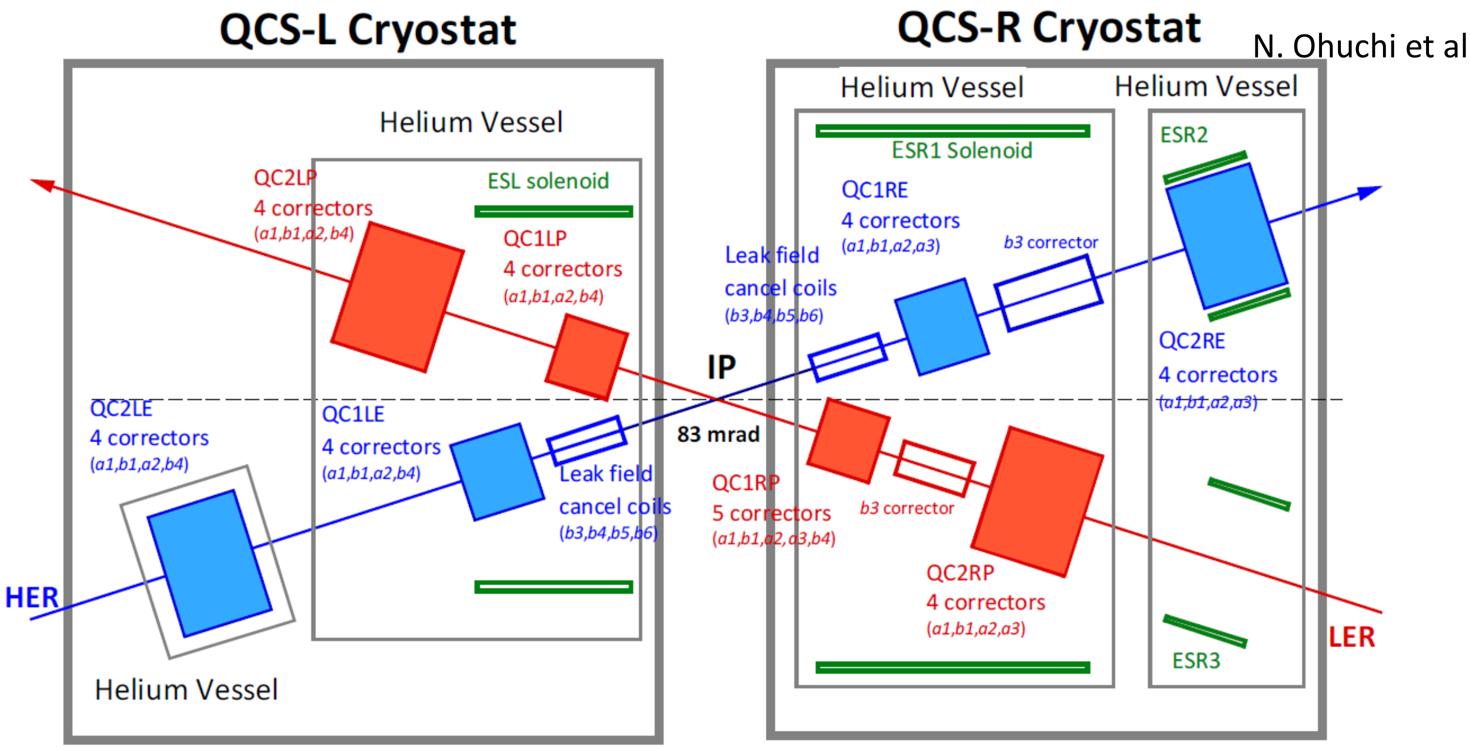








QCS superconducting magnet system



超伝導4極電磁石：4台
超伝導補正磁石（a1, b1, a2, b4）:16台
QC1LP漏れ磁場キャンセル磁石（b3, b4, b5, b6）:4台
超伝導補正ソレノイド：1台

超伝導4極電磁石：4台
超伝導補正磁石（a1, b1, a2, a3, b3, b4）:19台
QC1RP漏れ磁場キャンセル磁石（b3, b4, b5, b6）:4台
超伝導補正ソレノイド：3台

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- R2 was corrected by a1 correction coil of QC1.