SuperKEKB

Optics Tuning and Issues

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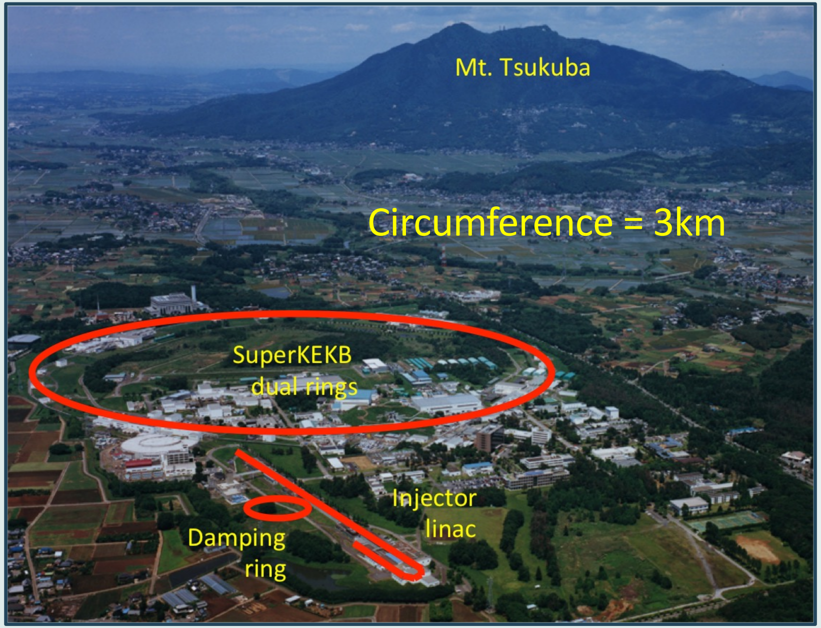
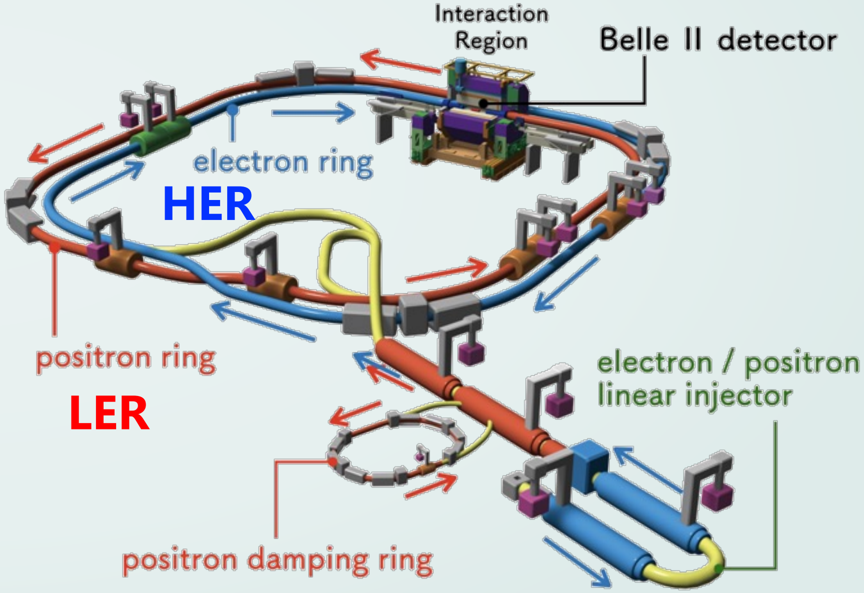
- Overview of Optics Tuning
- **Several Topics and Issues from Recent Operation**

SuperKEKB

- Electron (7GeV) – positron (4GeV) double-ring collider
- Successor project of KEKB B factory
- Beam commissioning W/O final focusing system (QCS) from Feb. 2016 to June 2016.
- Collision operation was started Mar. 2018.

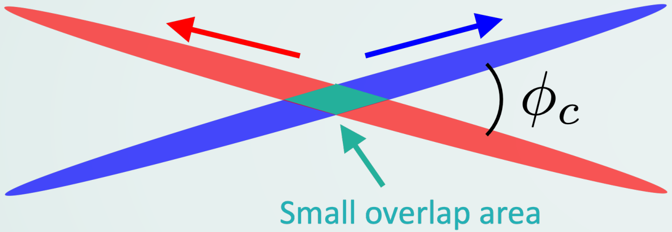




Collision Scheme - Nano Beam Scheme -

- Collision with an extremely small beam size large crossing angle in the horizontal plane.
- Realize small overlap area to realize small β_y^* while avoiding hourglass effect.
- It is equivalent to head-on collision with shorter bunch length

Top view



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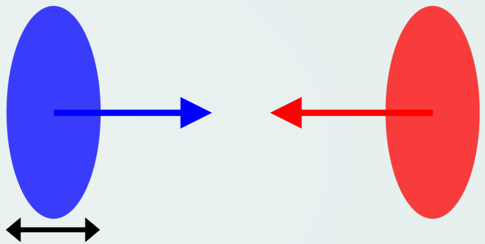
Equivalent head on collision



$$\sigma_z^{\text{effective}} = \sigma_x^* / \sin(\phi_c/2)$$

$$\phi_c = 83 \text{ mrad}$$
$$\sigma_x^* = 10\ \mu\text{m} \longrightarrow \sigma_z^{\text{effective}} = 0.24 \text{ mm}$$
$$\sigma_z = 6 \text{ mm}$$

$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma_z \phi_x)\sqrt{\varepsilon_y \beta_y^*}} \simeq \frac{\gamma_\pm}{2 e r_e} \frac{I_\pm \xi_{y\pm}}{\beta_y^*}$$

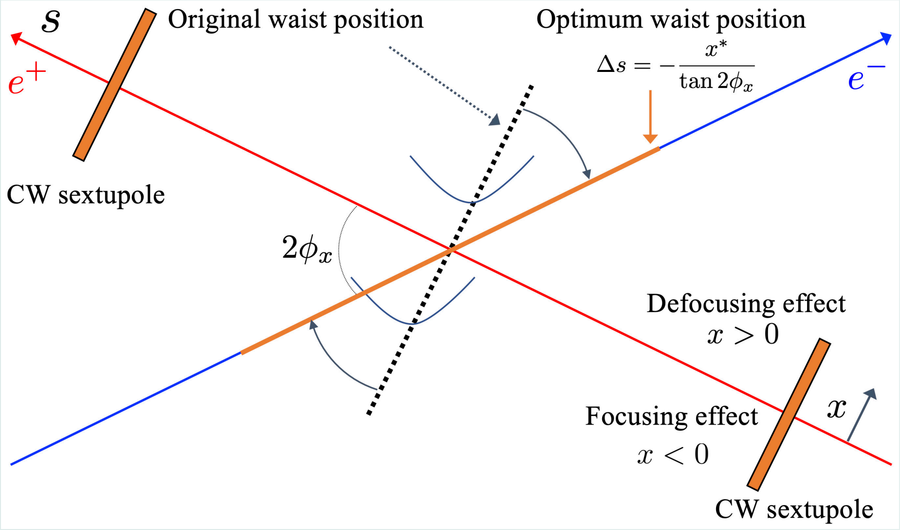
$$\xi_{y\pm} = \frac{r_e N_\mp}{2\pi\gamma_\pm(\sigma_z \phi_x)} \sqrt{\frac{\beta_y^*}{\varepsilon_y}}.$$

Design $\beta_y^* = 0.3$ mm

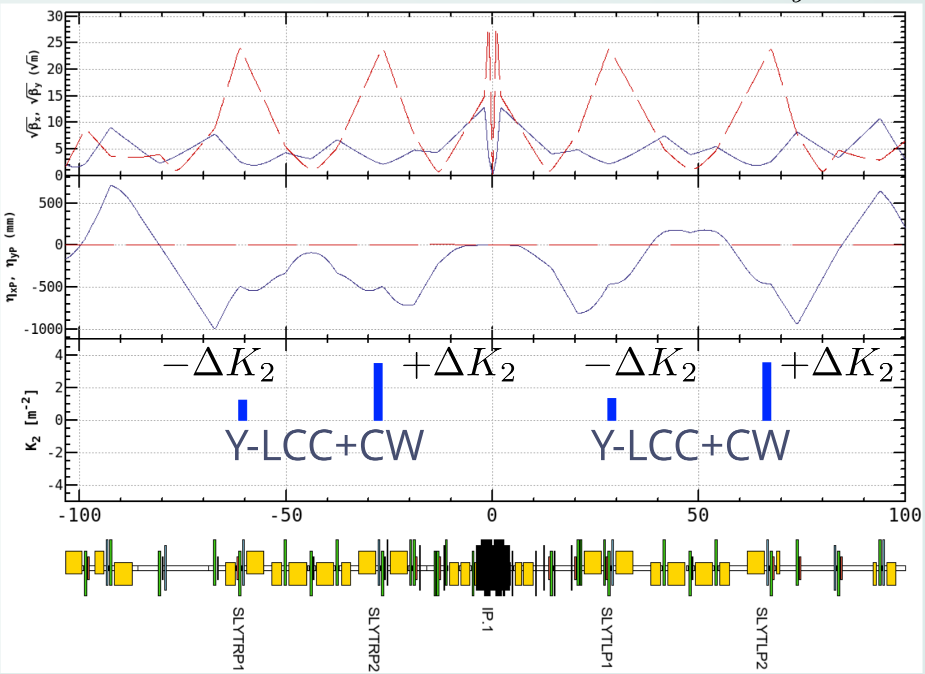
- Low vertical emittance is also essential to keep beam-beam parameter high.

Local Chromaticity Correction(LCC) and Crab Waist(CW)

- Vertical local chromaticity correction (Y-LCC) consists of 2 pairs of sextupole magnets.
- CW is incorporated to both LER and HER in 2020.
- CW is realized by applying different strength of sextupole field to these magnets.



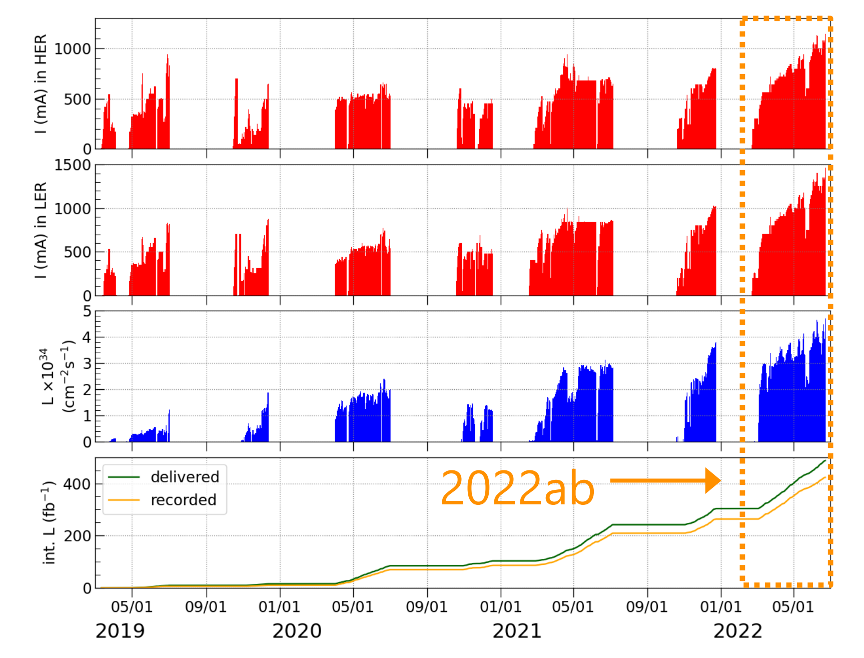
LER $\beta_y^* = 1$ mm



Inspired by
K.Oide, et al., 2016, Phys. Rev. Accel. Beams 19, 111005.

Present Machine Parameters and Status

- The nominal β_y^* in the present operation is $\beta_y^* = 1\ \mathrm{mm}$
- The most recent operation run (2022ab) is devoted to increase beam current to boost up the peak luminosity performance.



	SuperKEKB : June 8, 2022		Unit
Ring	LER	HER	
Emittance	4.0	4.6	nm
Beam Current	1321	1099	mA
Number of bunches	2249		
Bunch current	0.587	0.489	mA
Horizontal size σ_x*	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.303		μm*1
Vertical size σ_y*	0.215		μm*2
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	
β_x* / β_y*	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	
Crab waist ratio	80	40	%
Beam-Beam parameter ξ_y	0.0407	0.0279	
Specific luminosity	7.21 x 10^{31}		cm^{-2}s^{-1}/mA^2
Luminosity	4.65 x 10^{34}		cm^{-2}s^{-1}

*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

Y. Ohnishi

Overview of Optics Tuning

Global Optics Correction and Optics Correction for IP

- **Global correction and low emittance tuning**
  - Based on analysis of closed orbit response
  - Performed at low beam current (~50mA) without beam collision
  - Gain calibration of BPM electrodes are performed every other week
- **Optics parameters at IP**
  - Estimation is, in principle, possible.
  - However, It's so difficult to confirm its reliability.
    - ~ Poor sensitivity due to the extremely small β_y^*
    - ~ Uncertainty in the modeling of the interaction region (IR)
  - Eventually, the correction is based on daily luminosity tuning with knobs.

Global Optics Measurement

- Measurement with closed orbit response.

  - Beta function:

    Orbit response analysis with DC dipole kicks.

$$\Delta x_i = \frac{\sqrt{\beta_i \beta_0}}{2\sin \pi\nu} \Delta\theta \cos\left(|\phi_i - \phi_0| - \pi\nu\right)$$

  - Dispersion:

    Response with RF frequency change.

RF frequency, Orbit change, Phase slip factor, Frequency change

$$\eta_x = f_0 \frac{\Delta x}{\Delta f} \xi$$

  - Horizontal-vertical Betatron coupling (XY-coupling):

    Vertical leakage orbits induced by horizontal kicks.

$$\Delta\tilde{y} \equiv \Delta y / \left(\Delta x\right)^{\mathrm{rms}}$$

Optics Correction

- Corrector strength is obtained by the model response matrix and the measured optics residual.

Corrector strength

$$A \times \Delta \boldsymbol{k} = -(\boldsymbol{x}_{\mathrm{meas}} - \boldsymbol{x}_{\mathrm{model}})$$

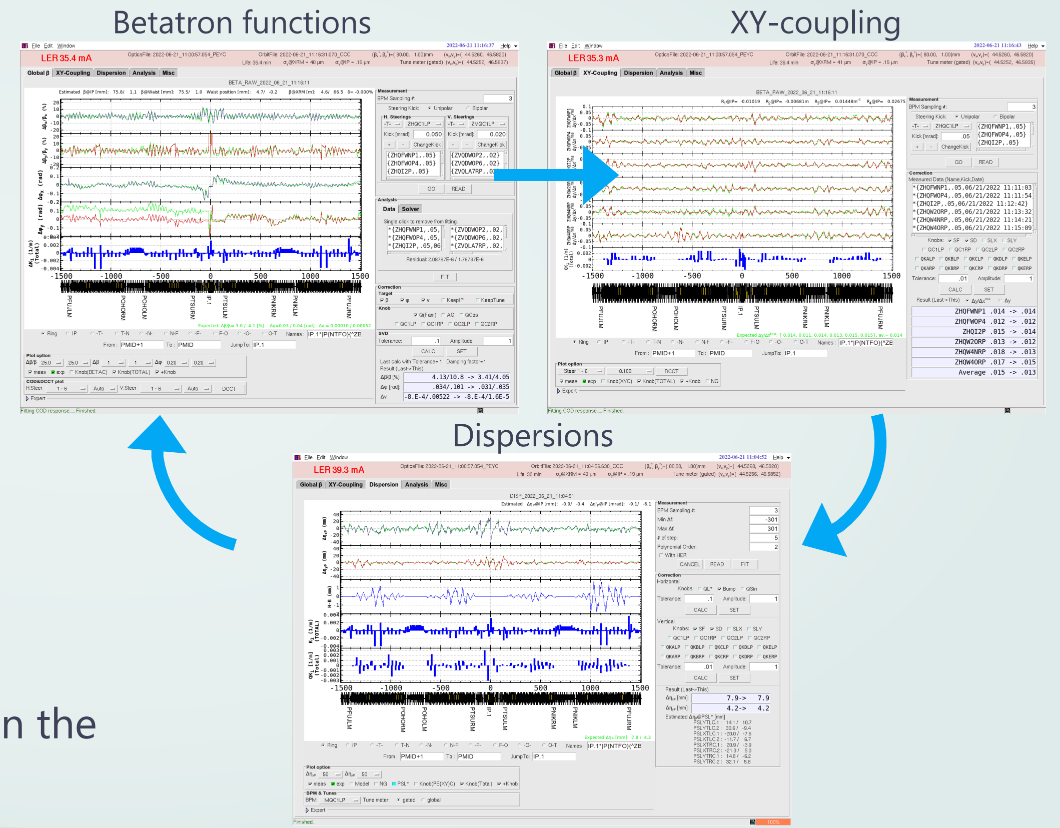
Response matrix (model)

Residual of optics

- Numerical parameters for solving the above eq. is chosen empirically.

- Betatron functions, dispersions and XY-coupling are in general coupled to each others.

- Corrections of them are independently and iteratively performed to break down the size of problem to be solved.



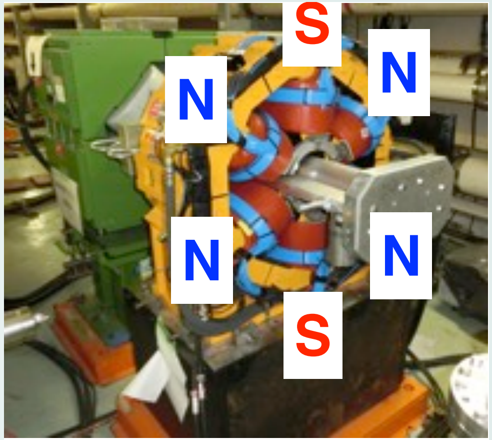
Correctors

* Betatron function & horizontal dispersion
  - Quadrupole magnet families
  - Corrector coils in almost ALL quadrupole magnets
  - Horizontal orbit bump at sextupole magnets

* XY-coupling & vertical dispersion
  - Skew quadrupole coils in ALL sextupole magnets
  - Skew quadrupole magnets installed around IR

* Beam orbit at IP also can be used to correct beam optics

Skew quadrupole winding to sextupole magnet



* QCS has both linear and nonlinear corrector coils.
  However, we do not touch them in usual global optics correction because they may drastically change operation condition.
  We need much time to evaluate its effectiveness. We may lose stable operation at the worst case.

Performance of Global Optics Correction

HER $(\beta_x^*,\ \beta_y^*) = (60\ \text{mm},\ 1\ \text{mm})$
LER $(\beta_x^*,\ \beta_y^*) = (80\ \text{mm},\ 1\ \text{mm})$

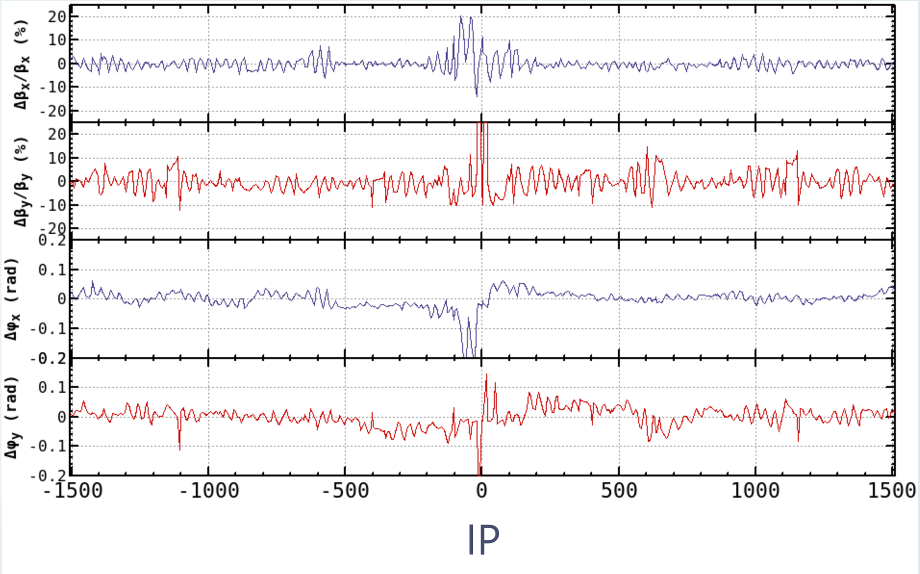
- Typical residual errors just after optics correction (~50mA).

Optics function	LER	HER
$(\Delta\beta_{x,y}/\beta_{x,y})^{\text{rms}}$ [%]	5 / 5 *)	5 / 5
$(\Delta y)^{\text{rms}} / (\Delta x)^{\text{rms}}$	0.016	0.012
$(\Delta\eta_{x,y})^{\text{rms}}$ [mm]	10 / 5	30 / 5
ε_y [pm]	20 ~ 40 **)	20 ~ 40 **)
$\varepsilon_y/\varepsilon_x$ [%]	0.5 ~ 1	0.4 ~ 0.9

*) Two outliers are removed from the evaluation.

**) Depending on daily machine condition.

Example: Beta-beating in LER



- The urgent issues is how to keep the corrected beam optics during the operation.

Several Topics and Issues from Recent Operation

- Field drifting of the final focusing quadrupole (QCS)
- Beam current dependence of betatron tune and orbit at SLY magnets
- Optics degradation due to unknown error sources

Several Topics and Issues from Recent Operation

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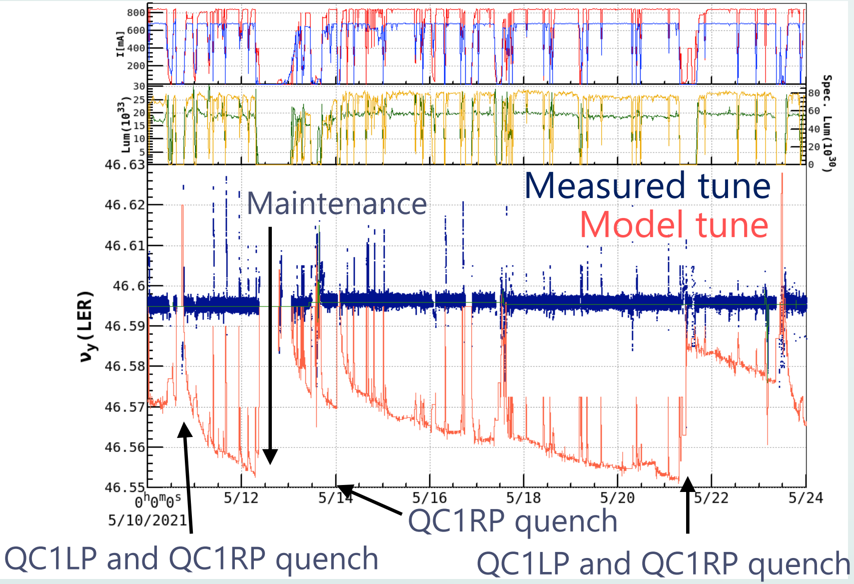
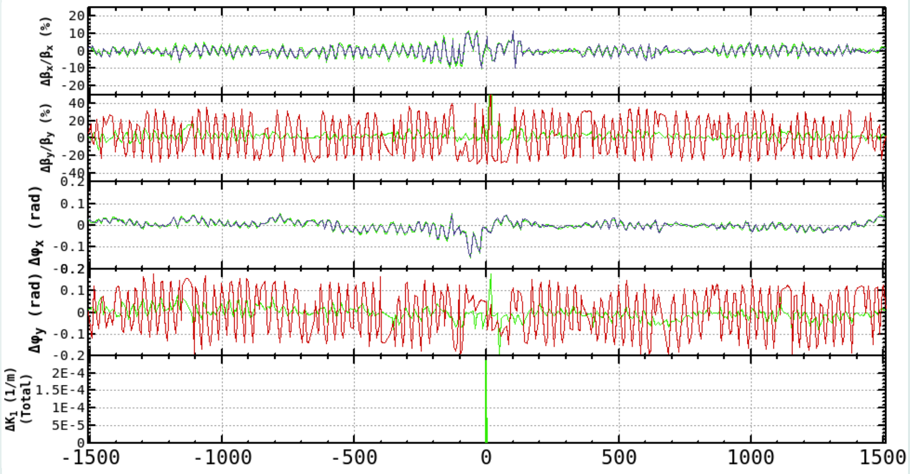
Tune Drifting

- It was pointed out in 2021 that discrepancy between measured tunes and the model tune used in a tune feedback gradually increased.
- Measured tune shift and beta-beating can be explained by QC1s field error of ~10^{-2} %
- It seems that the drifting starts after QCS startup.
- We suspected drifting of QCS magnetic field after its startup.



Expected beat-beating after correction with QC1s

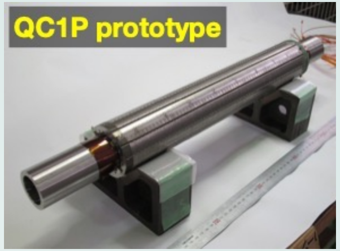


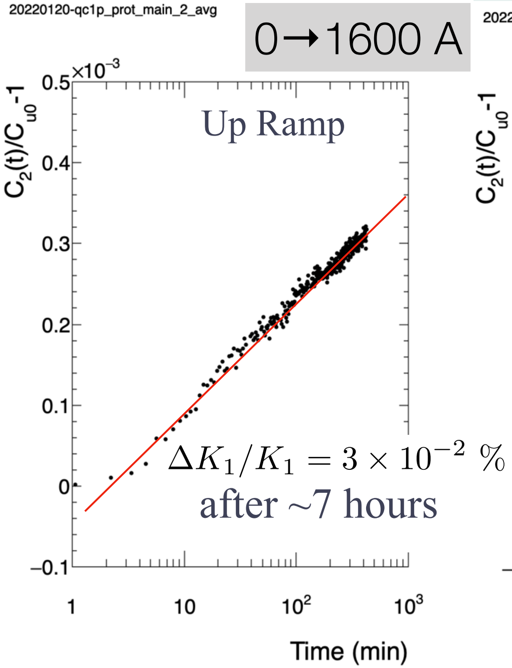
$\Delta K1/K1(QC1RP) = -1.4\times10^{-2}$ % $\Delta K1/K1(QC1LP) = -4.2\times10^{-3}$ %

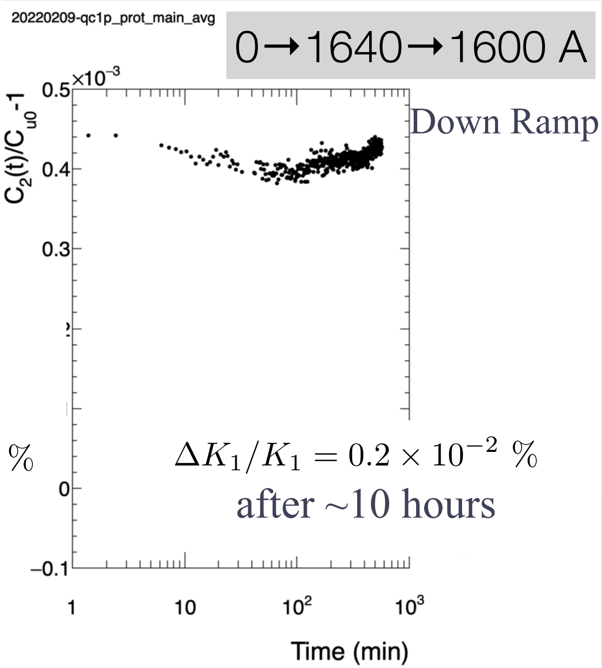
Field Drifting Measurement with QCS Prototype

Y. Arimoto

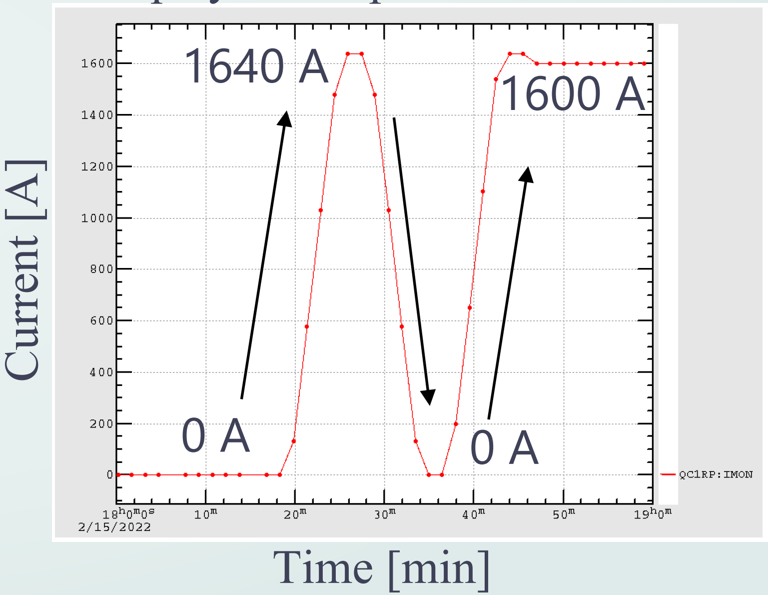
- Measurement with different ramp cycles.
- Field drifting was observed depending on the ramp cycle.
- QCS ramp cycle in the operation was modified considering the results.







Ramp cycle adopted in 2022ab

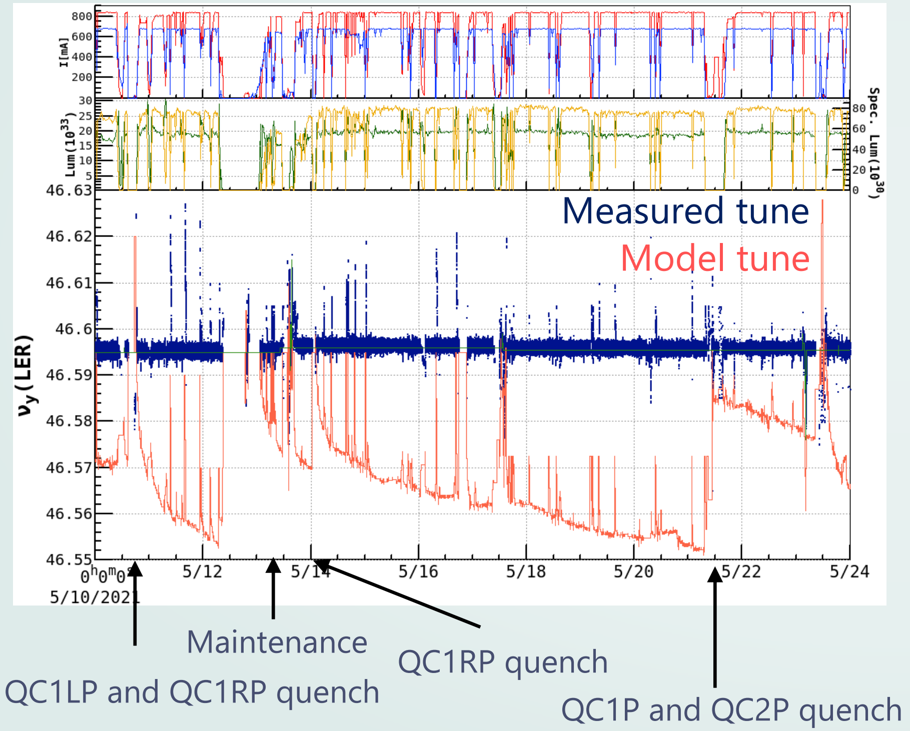


Y. Arimoto will gives details in WG10, Wed.

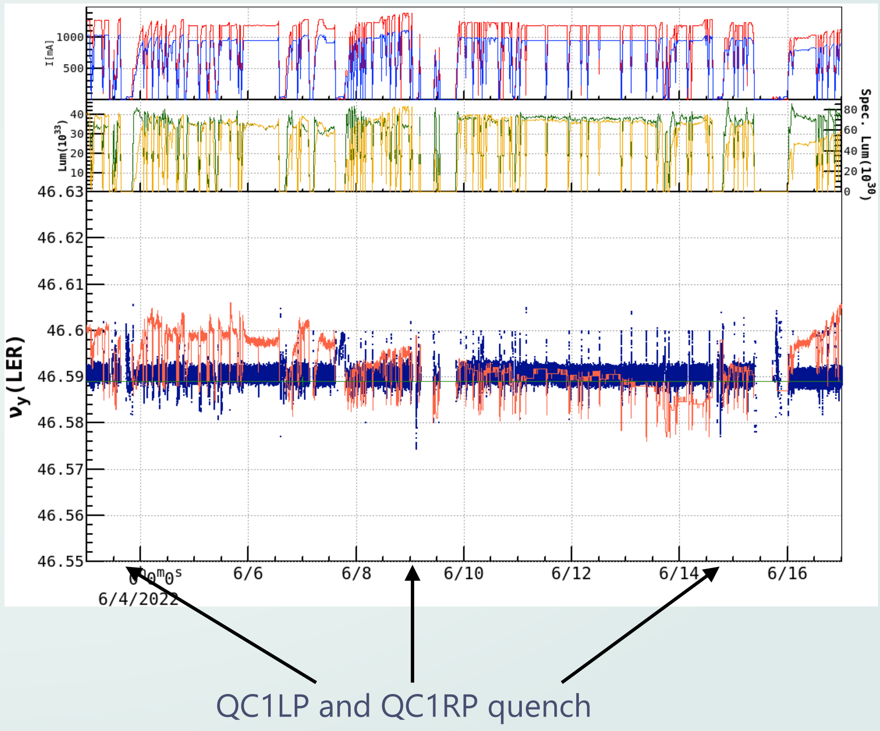
Tune Drifting after the Change of Ramp Cycle

- Tune drifting after QCS startup is much reduced in 2022ab owing to the new ramp cycle.

2021ab



2022ab



Several Topics and Issues from Recent Operation

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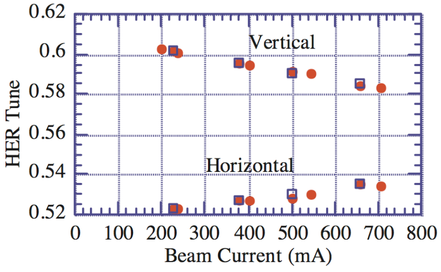
Pilot Bunch Tune Shift and Total Beam Current **HER**

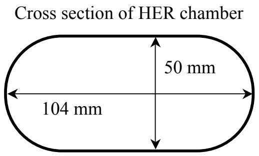
- According to beam study in KEKB era,
  It was considered that resistive wall tune shift is dominant in HER.
- In 2022ab, beam current dependence of tune shift is estimated by the model lattice tune used in a tune feedback system.

KEKB Y. Ohnishi, KEKB Review 2007

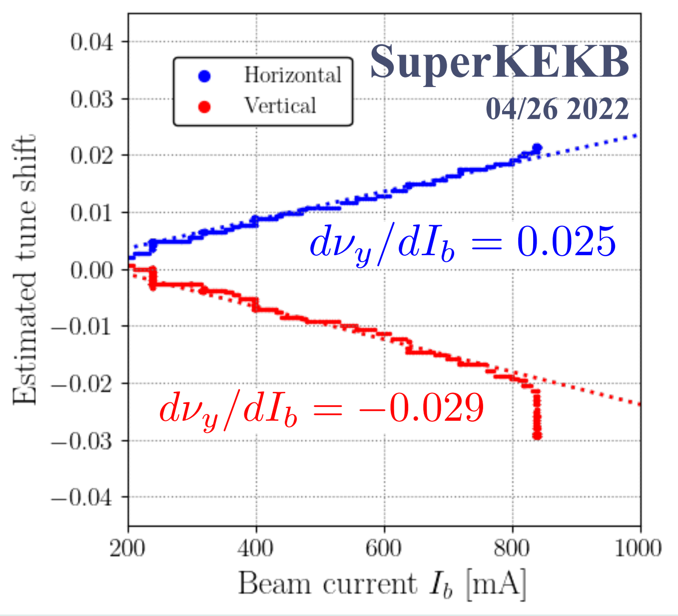
- Tune shift due to a quadupole field induced by resistive-wall of a chamber in HER. The cross section of the chamber is non-axisymmetric.



T. Ieiri et al., Proc. APAC2001



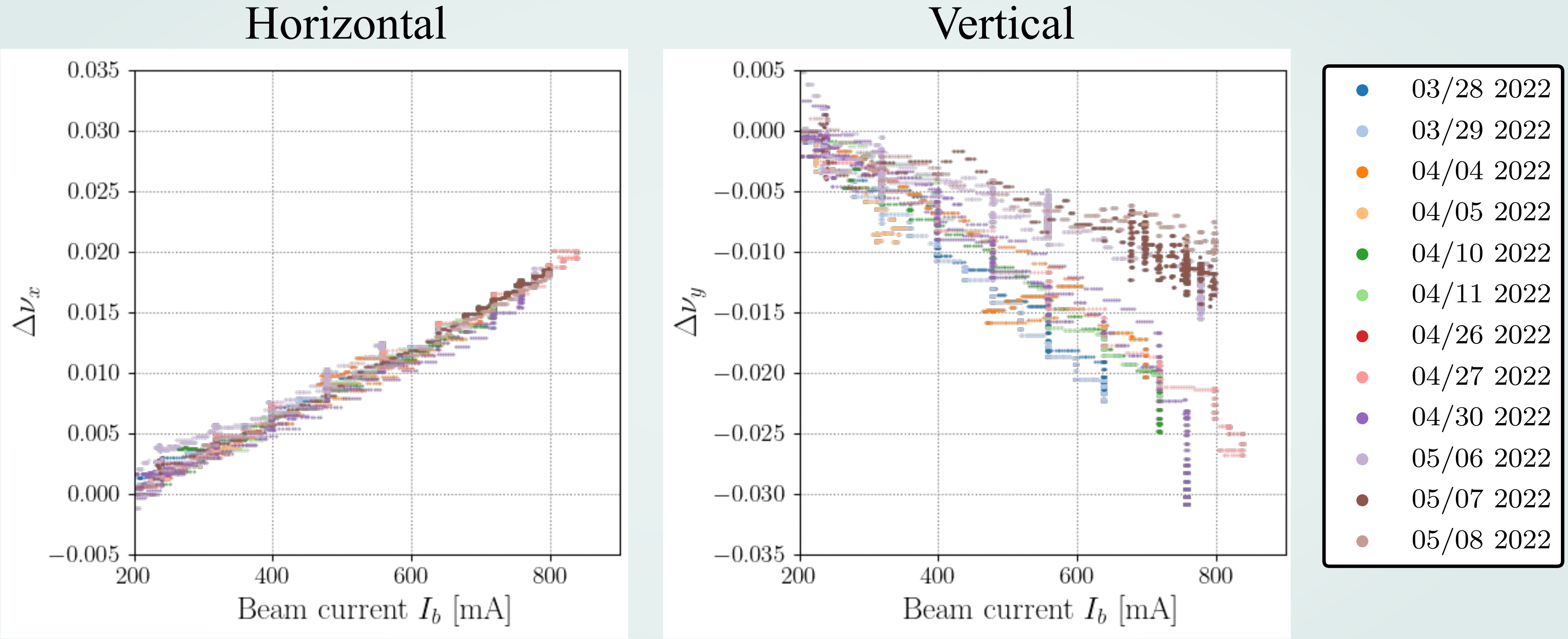
- horizontal tune shift: $\Delta\nu_x$ = +0.026/ A
- vertical tune shift: $\Delta\nu_y$ = -0.037/ A



Day to Day Variation

HER

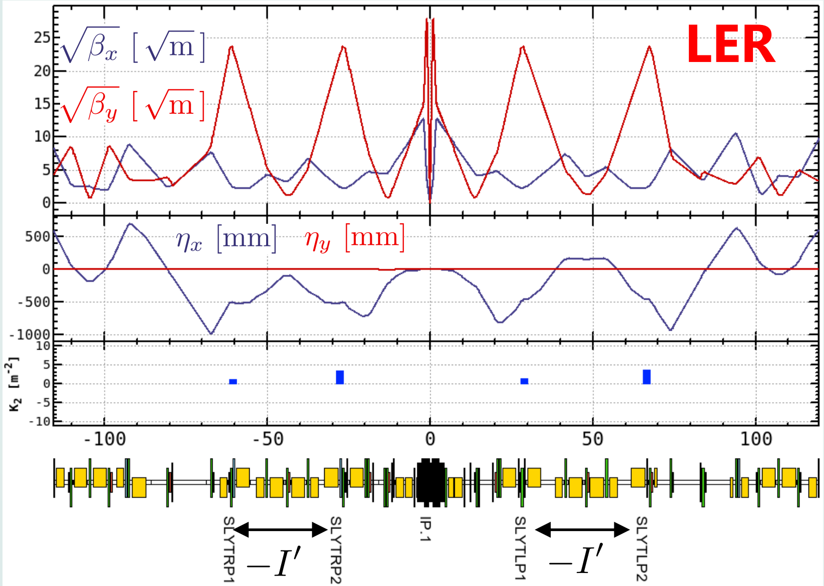
- Horizontal tune shift does not depend on days, while vertical tune shift depends on days.

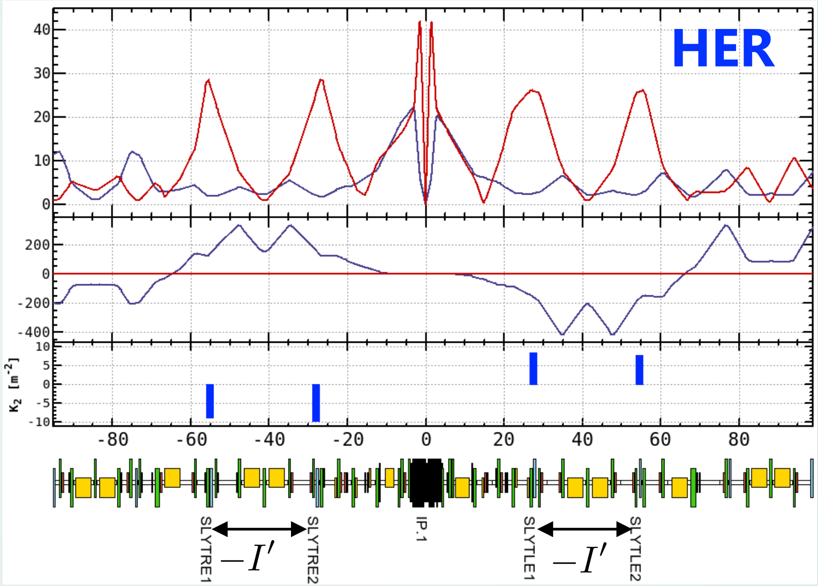


- Other sources of vertical tune shift was suspected.

Sextupole Magnets for LCC (SLY)

- Sextupoles pair connected by a $-I'$ transform are installed in both side of IR.
- Horizontal orbit change at SLYs could cause large tune shift.





SLY pair in Right-side
SLYTRP1 and 2

SLY pair in Left-side
SLYTLP1 and 2

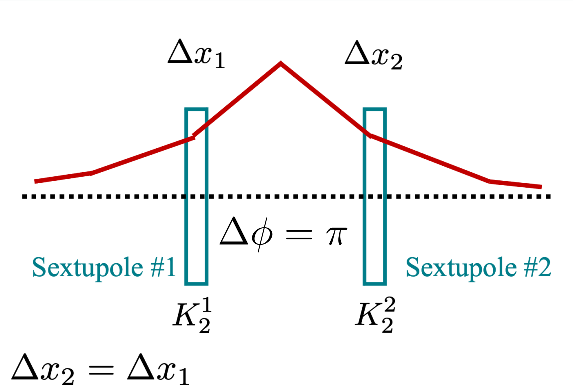
SLY pair in Right-side
SLYTRE1 and 2

SLY pair in Left-side
SLYTLE1 and 2

Tune Shift due to Horizontal Beam Orbit at SLY Pair

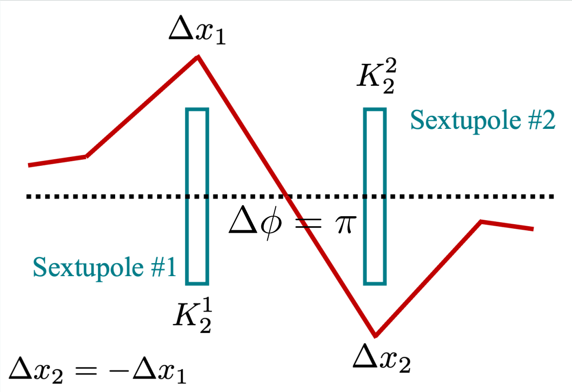
- Horizontal orbit Δx at SLY pair and tune shift

Cosine-like orbit



$$\Delta\nu_{x,y} = \pm\beta_{x,y}(K_2^1 + K_2^2)\Delta x/4\pi$$

Sine-like orbit



$$\Delta\nu_{x,y} = \pm\beta_{x,y}(K_2^1 - K_2^2)\Delta x/4\pi$$

- Only cosine-like orbit causes tune shift in non-CW case because of $K_2^1 = K_2^2$

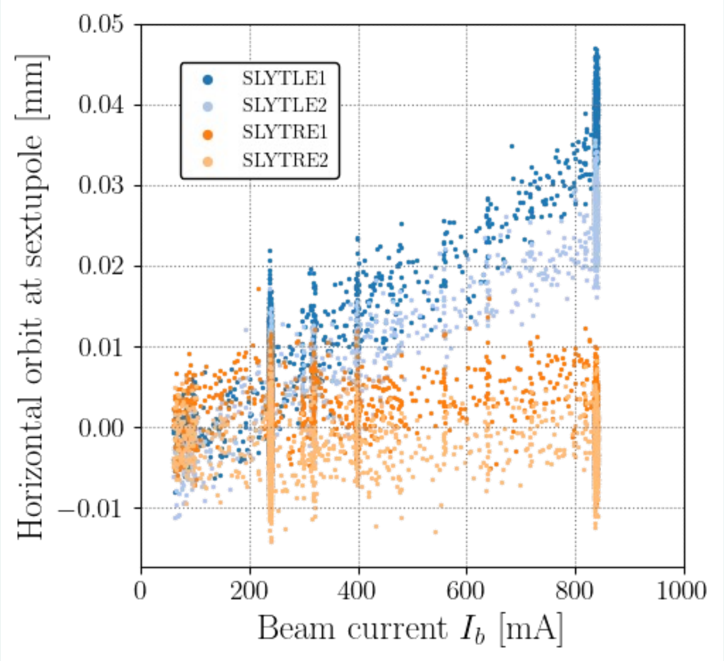
- Assuming cosine-like orbit of 10μm in HER, for example,

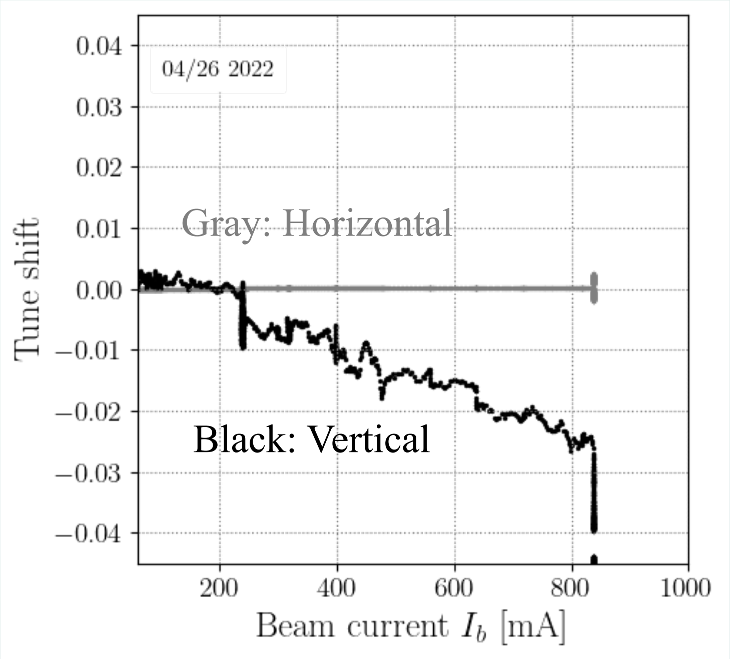
$$\Delta x = 10\ \mu\text{m}$$
$$\beta_y \sim 700\ \text{m} \longrightarrow \Delta\nu_y \sim -0.009$$
$$K_2^1 + K_2^2 \sim 16\ \text{m}^{-2}$$

* Only 10 μm orbit can cause sizable tune shift

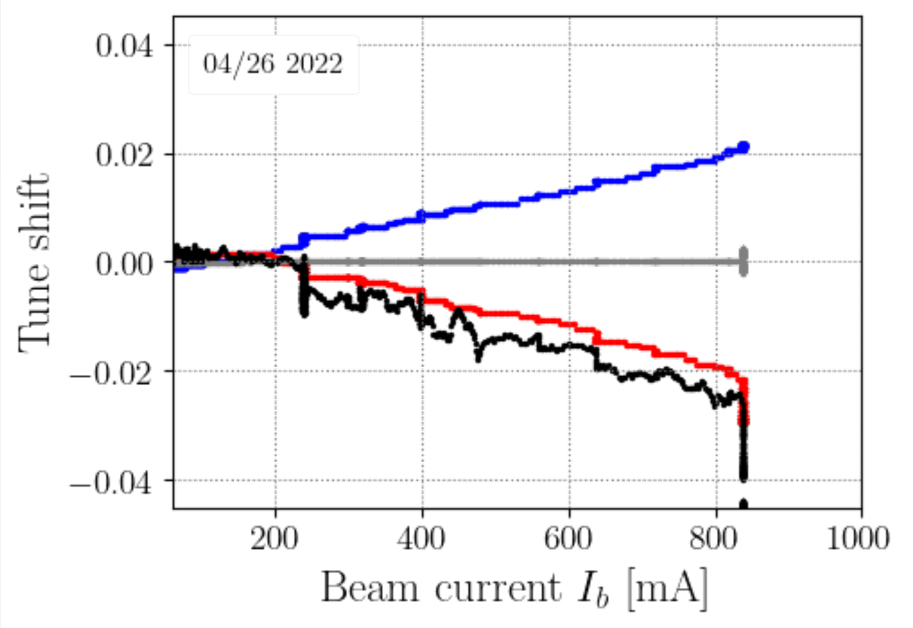
Tune Shift Estimation using Model Lattice

- Beam orbits at SLYs are imported to the model lattice as misalignments of the SLYs
- Tune is evaluated by the model lattice with the misaligned SLYs.





Comparison with Measured Tune Shift



Blue: Measured horizontal tune shift

Red: Measured vertical tune shift

Gray: Estimated horizontal tune shift

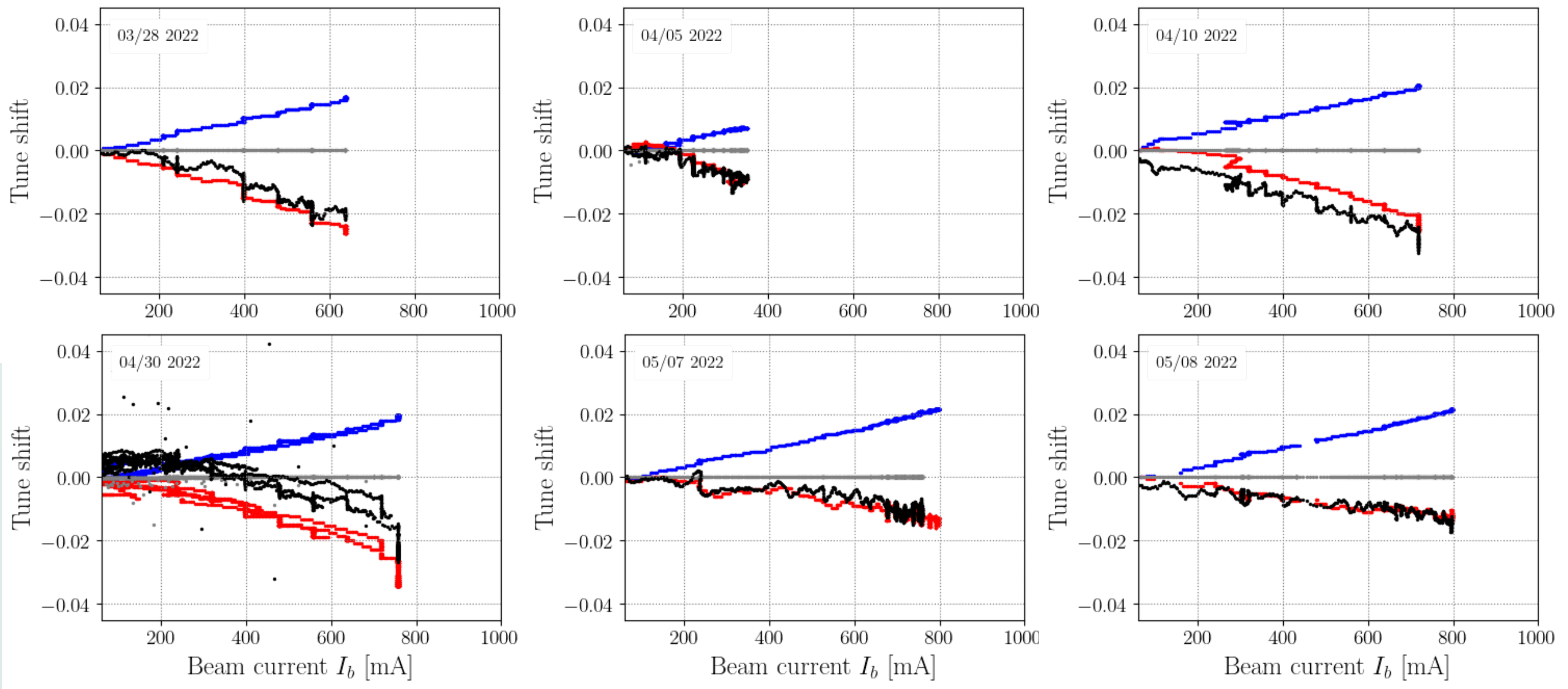
Black: Estimated vertical tune shift

- Beam current dependence of horizontal orbit at SLYs reproduces the measured vertical tune shift.
- Where is resistive wall tune shift in vertical direction? -> No clear explanation so far.

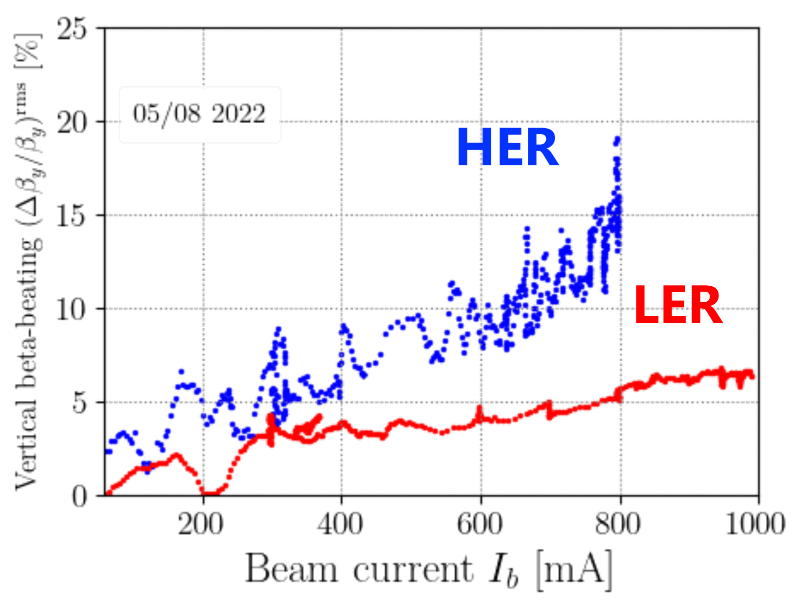
Day to Day Variation

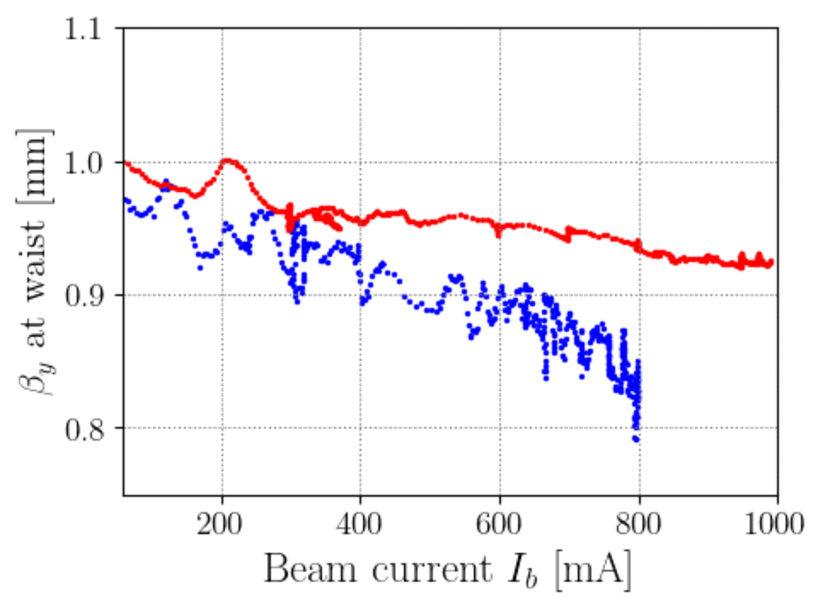
HER

- Day to day variation of vertical measured tune shift is consistent with that of orbit at SLYs.



Estimated Optics Distortion due to Orbit at SLY Magnets

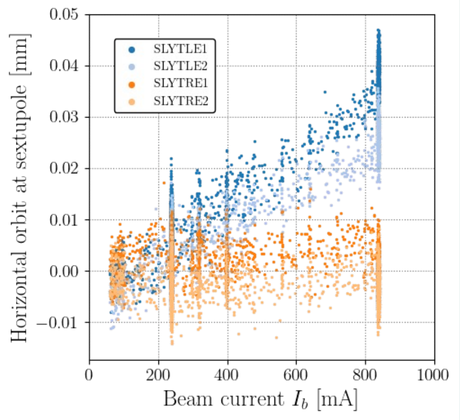


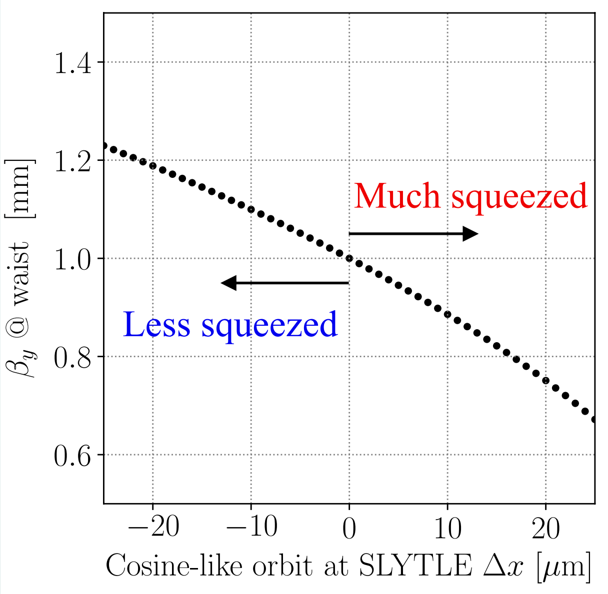


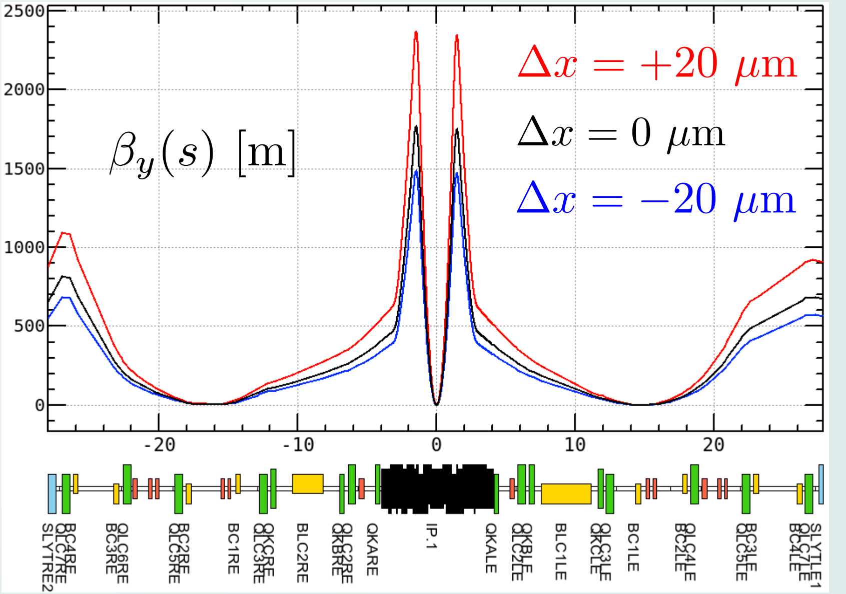
- Orbit at SLYs causes not only tune shift but also beta-beating.
- Vertical beta function at the waist becomes smaller as beam current becomes higher.
  -> It indicates that we operated SuperKEKB with $\beta_y^* < 1$ mm without knowing.

Optics Distortion in IR - Model Calculation -

- The sign of orbit change is somehow always positive.
- Beam is always squeezed too much and vertical beta function in IR becomes larger.
- It makes stable operation more difficult in high beam current.







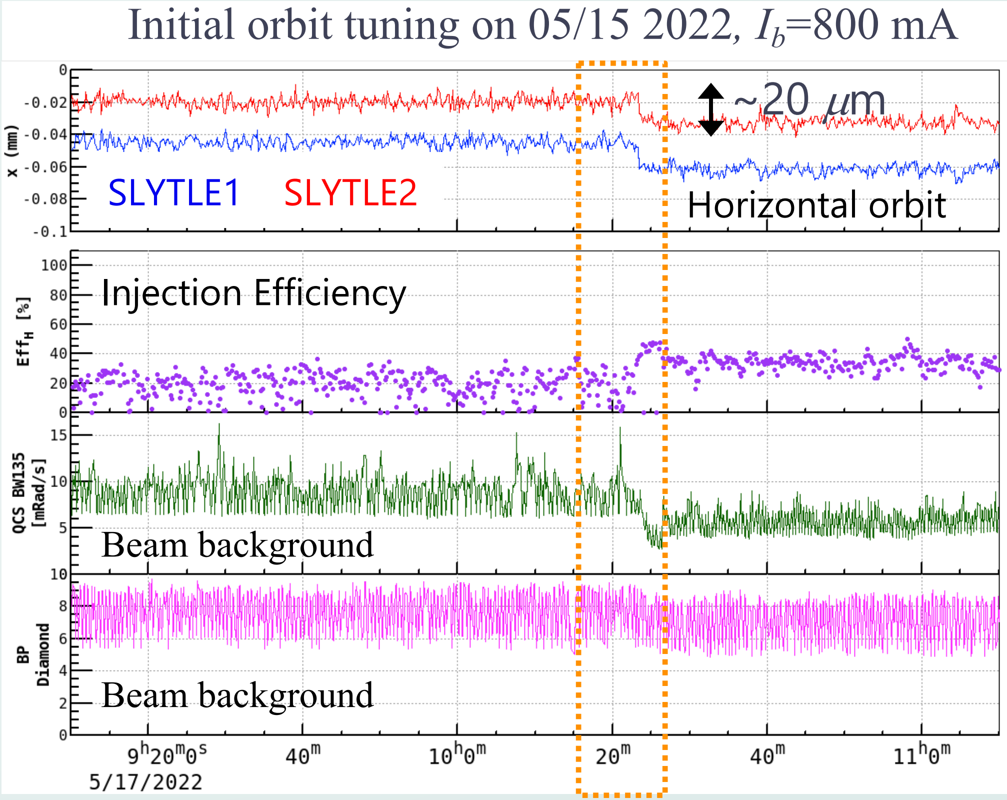
SLY Orbit Tuning with Orbit Bump

- Bump orbit at SLY is applied to compensate current dependence of horizontal beam position.

- The orbit tuning improves injection efficiency and reduces beam background.

- We now watch the beam position at SLY carefully in the operation.

- The orbit adjustment in advance to optics correction reduces # of iterations of the correction.

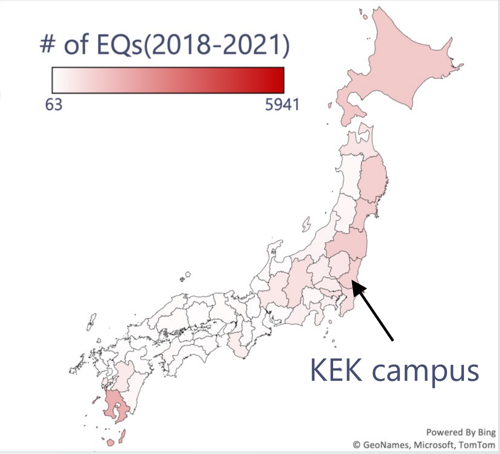


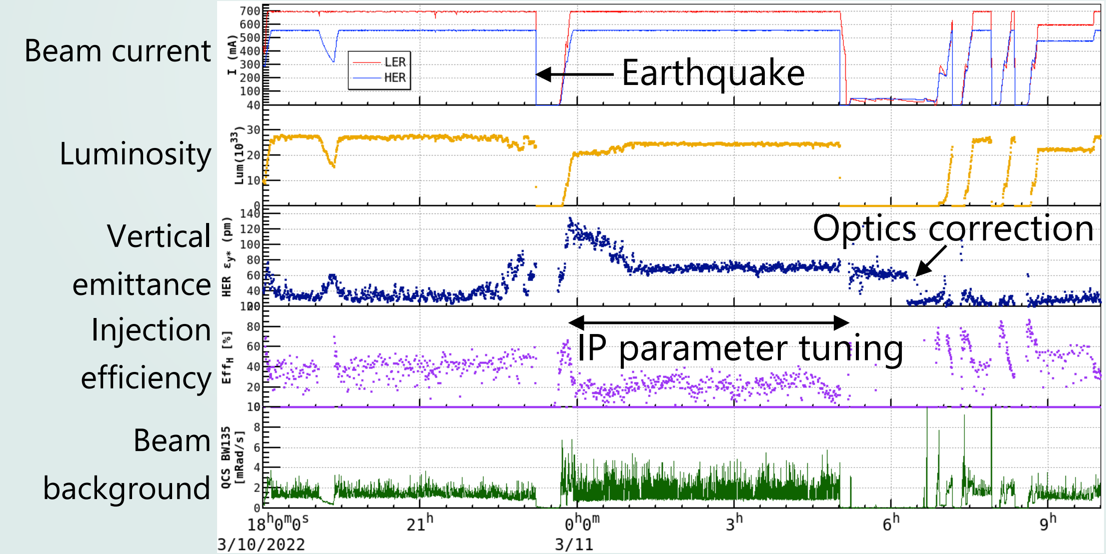
Several Topics and Issues from Recent Operation

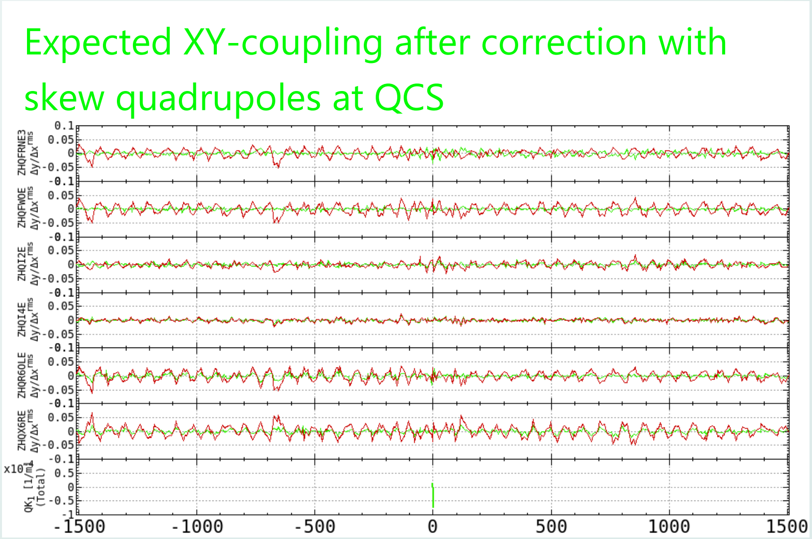
- Field drifting of the final focusing quadrupole (QCS)
- Beam current dependence of betatron tune and orbit at SLY magnets
- Optics degradation due to unknown error sources

Earthquake (EQ)

- Japan is a country of many EQs.
- EQ causes beam abort in most cases.
- HER beam becomes unstable after EQ in some cases.
- Global optics correction is necessary to recover the stable operation.
- Skew quadrupole at sextupole magnets and/or QCS can explain the observed XY-coupling distortion, but there is no direct evidence.







Optics Degradation with Time

- Originally, optics correction is performed every other week (maintenance day)

- Recently, we observe the optics degradation when we try high beam current operation.

- It seems that beam abort and recovery from the abort somehow change machine conditions, and we can not recover the beam optics.

- Reason of the degradation is not understood yet and we need to perform optics correction every 2 or 3 days.

Orbit Fluctuation and Drifting

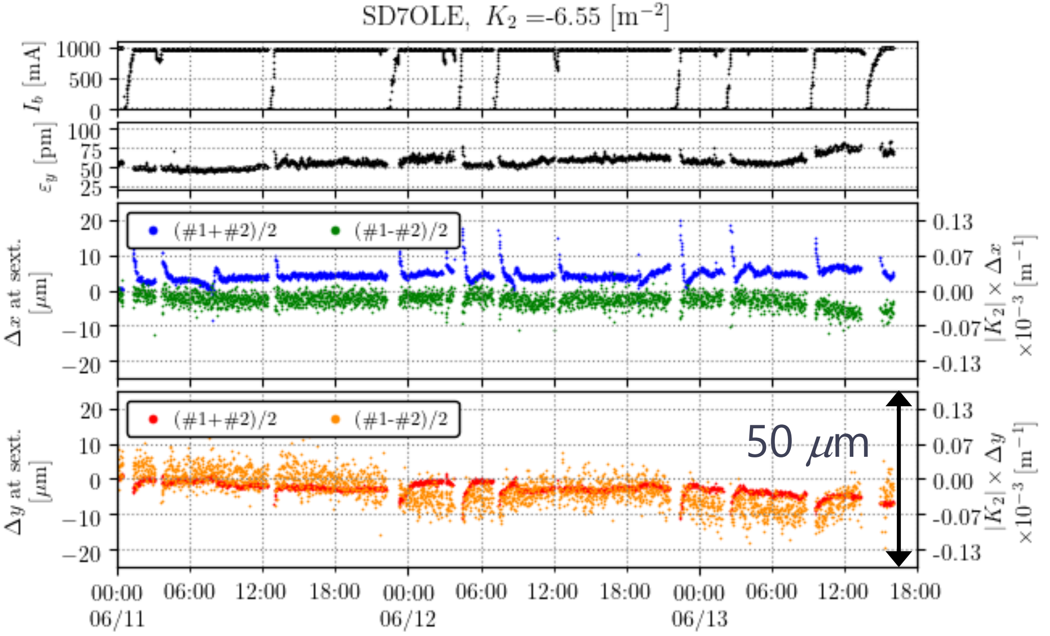
- A possible reason for the optics degradation is orbit fluctuation and/or drifting.
- Numerical estimation indicates that orbit at strong sextupole of a few ten μm is not negligible.

Residual of closed orbit correction is 20~30μm in RMS.

Horizontal orbit at a sextupole magnet
Blue: Cosine-like component
Green : Sine-like component

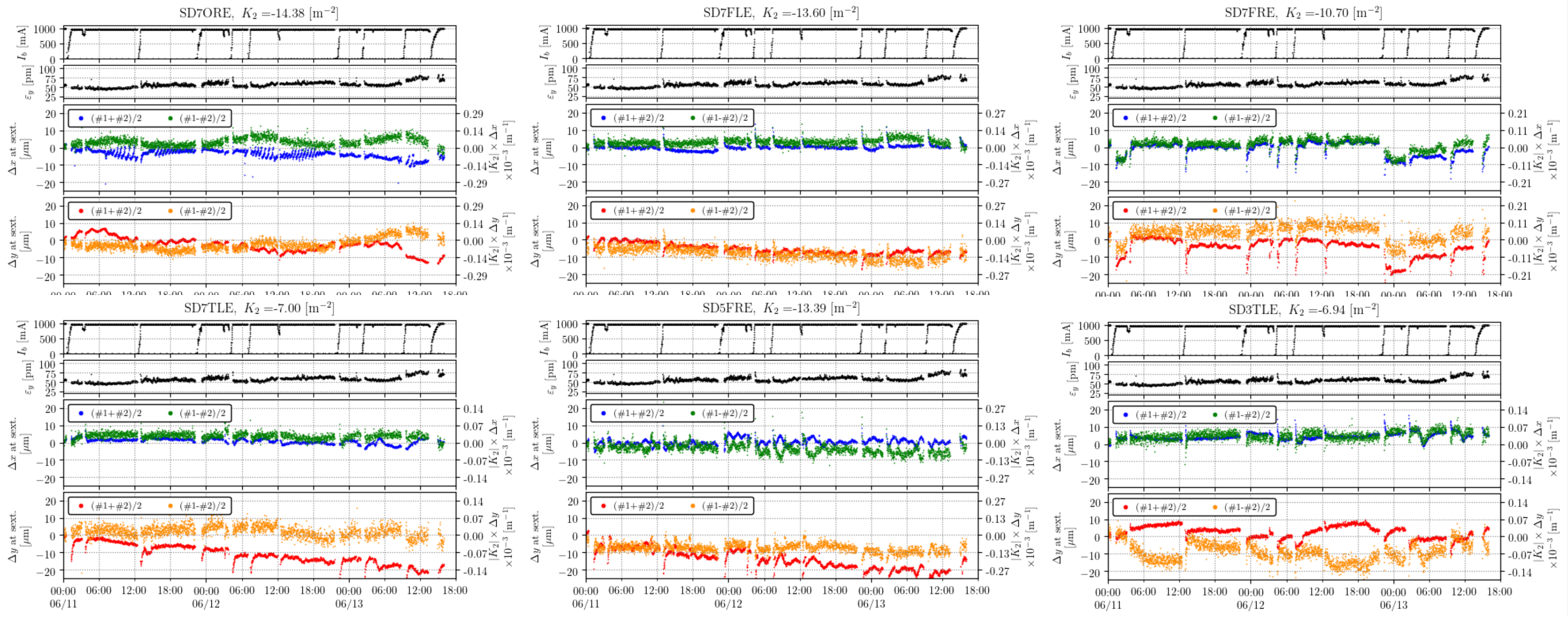
Vertical orbit at a sextupole magnet
Red: Cosine-like component
Orange : Sine-like component

Example of orbit drifting at sextupole in arc section



More Examples

HER



- BPM reading depends on not only real beam orbit but also various effects such as, gain drifting, beamline deformation, air temperature, beam current dependence of the BPM system, etc.
- We need to deal with these effects to obtain real beam position change.

Summary

- Global optics tuning is based on analysis of closed orbit response.

- Optics parameters at IP is based on daily IP knob tuning and observed machine performance.

- Field drifting of QCS depending on ramp cycle was experimentally confirmed.

  -> We modified the ramp cycle in its startup, then the drifting is much reduced.

- Beam current dependency of vertical tune shift is attributed to the beam orbit change at SLYs.

  -> Where is resistive wall tune shift in vertical direction?

  -> The mechanism of the beam current dependence is not understood yet.

  (Beamline deformation due to SR and/or HOM heating?)

- The orbit at SLY is very important parameter to be carefully monitored.

- Optics degradation in a few days is an urgent issue in high beam current operation.

  It seems that a few ten microns orbit change at strong sextipole is not negligible.

  More precise orbit control is probably needed.