

Optics Issues

Hiroshi Sugimoto

On Behalf of SuperKEKB Optics&Commissioning Group

SuperKEKB Optics Group

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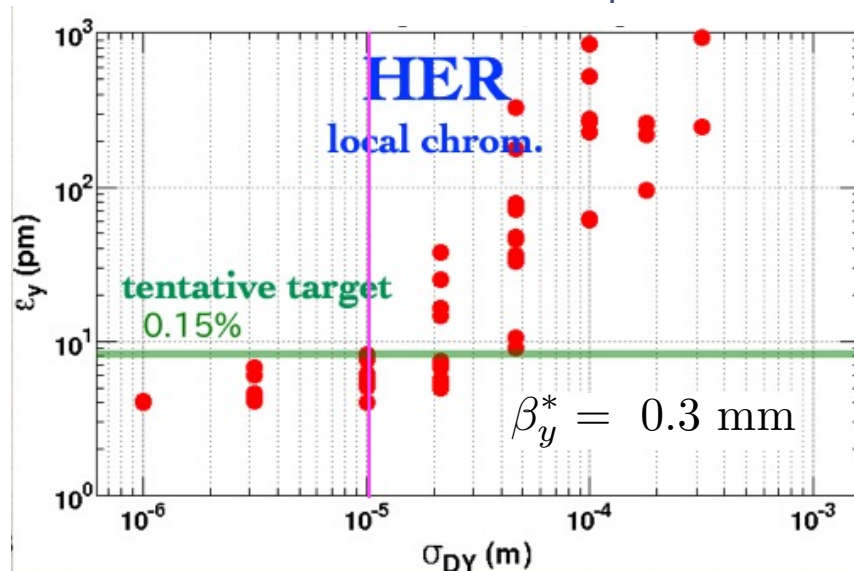
The 26th KEKB Accelerator Review Committee

Introduction

- There was concern in the SuperKEKB lattice design that the machine performance is easily deteriorated by a tiny perturbation.
- In the recent high-beam-current operation, we are struggling with keeping machine performance.
- Optics deterioration due to known and unknown sources is the main part of this talk.

Numerical calculation presented in MAC, 2011

Vertical emittance and sextupole offsets.



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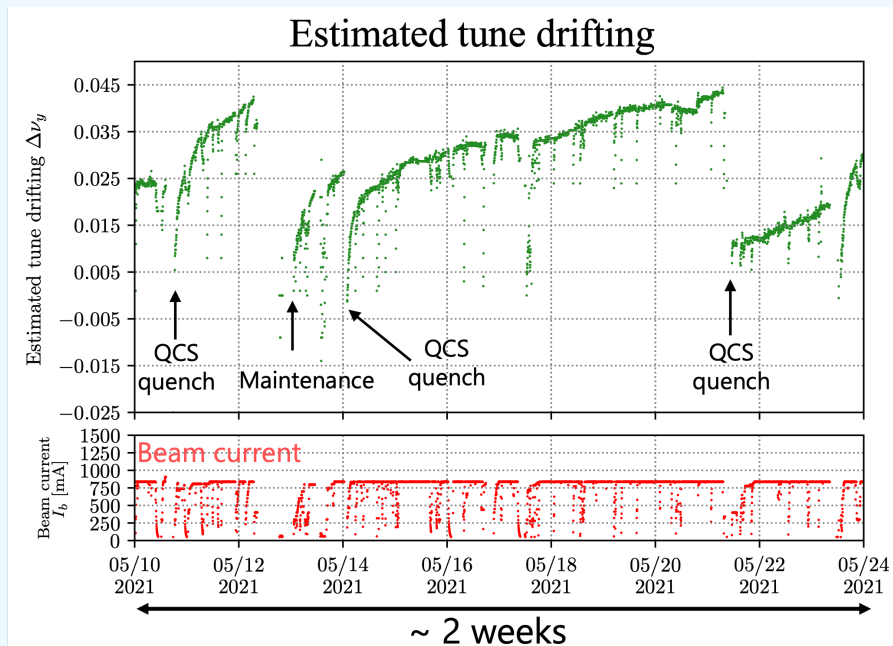
- Field drifting of the final focusing quadrupole magnets (QCS)
- Beam current dependence of Betatron tunes and orbit at SLY magnets
- Optics deterioration due to unknown error sources
- 3 BPM analysis for QCS (by Y. Ohnishi)
- Summary

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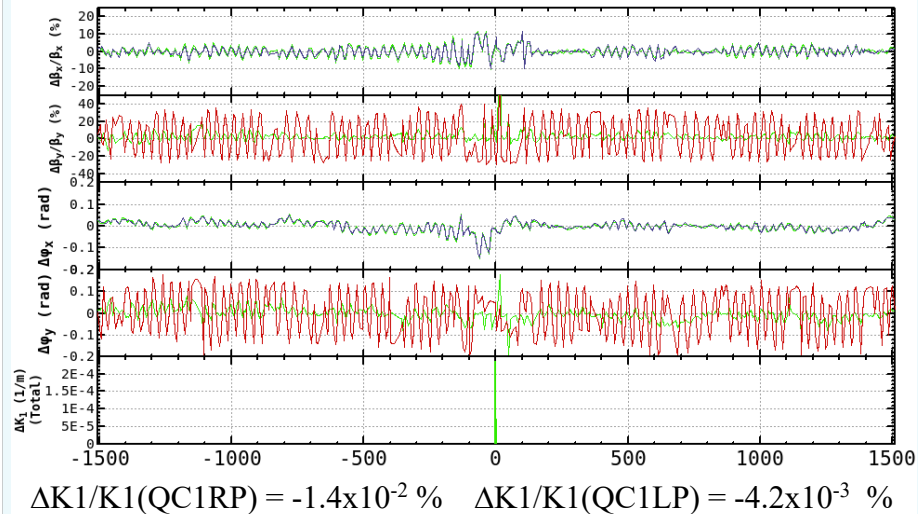
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Vertical Tune Drifting in 2021

- It was pointed out in 2021 that the amount of a tune feedback gradually increased.
- The observed tune shift and beta-beating can be explained by QCS field error of $\sim 10^{-2} \%$.
- It seems that the drifting starts after QCS startup.
- We suspected drifting of QCS magnetic field after its startup.



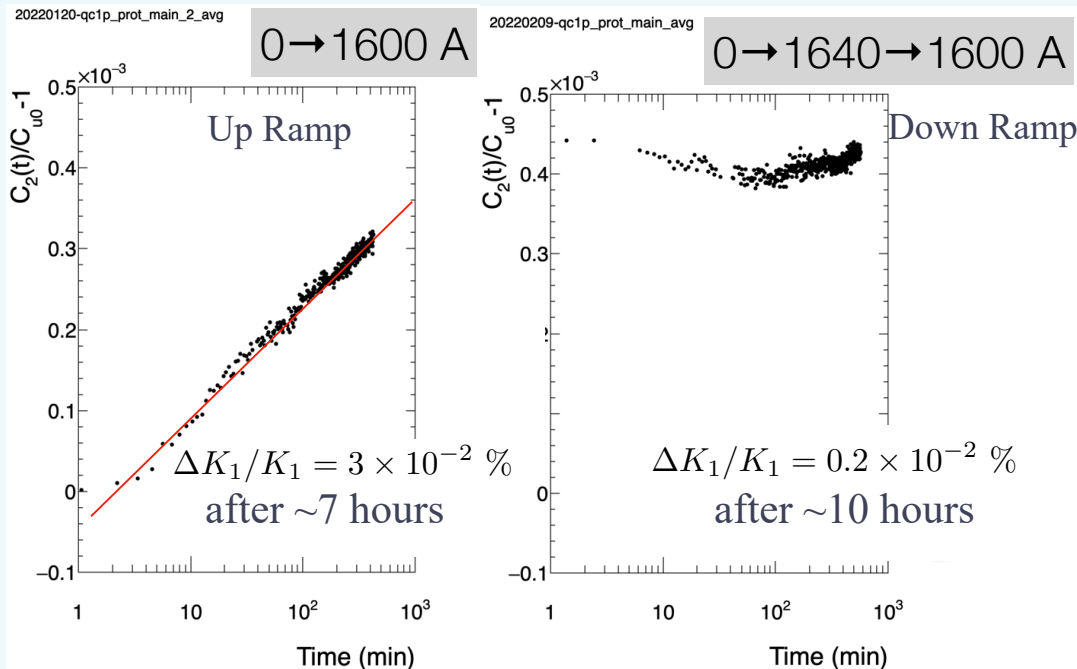
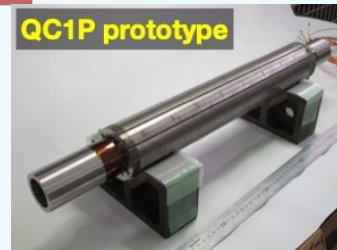
Expected beat-beating after correction with QC1s



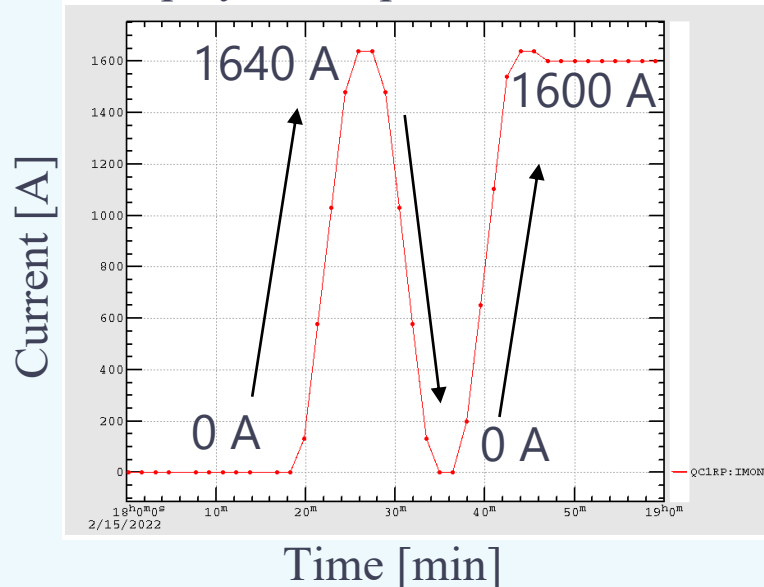
Field Drifting Measurement with QCS Prototype

Y. Arimoto

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



Ramp cycle adopted in 2022ab

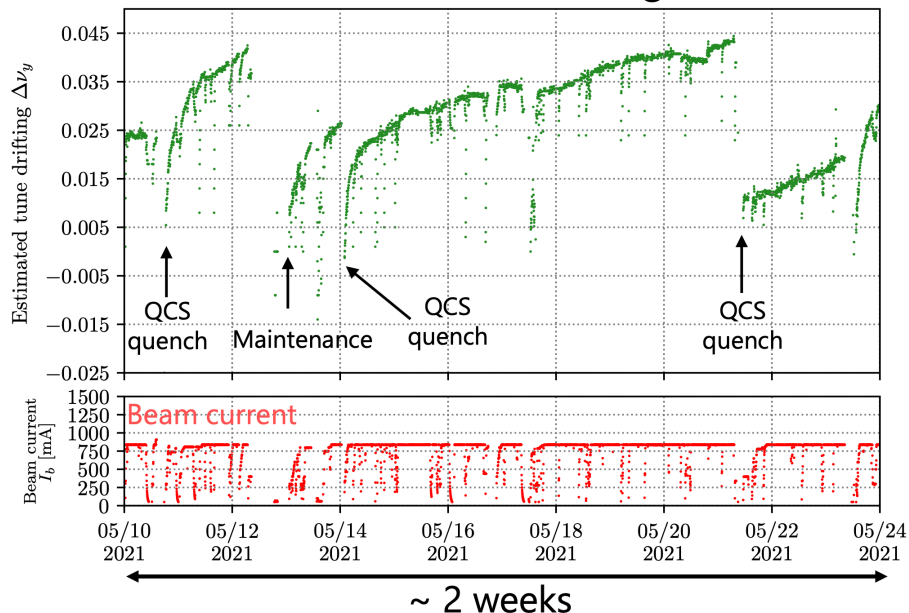


Tune Drifting before&after the Change of Ramp Cycle

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

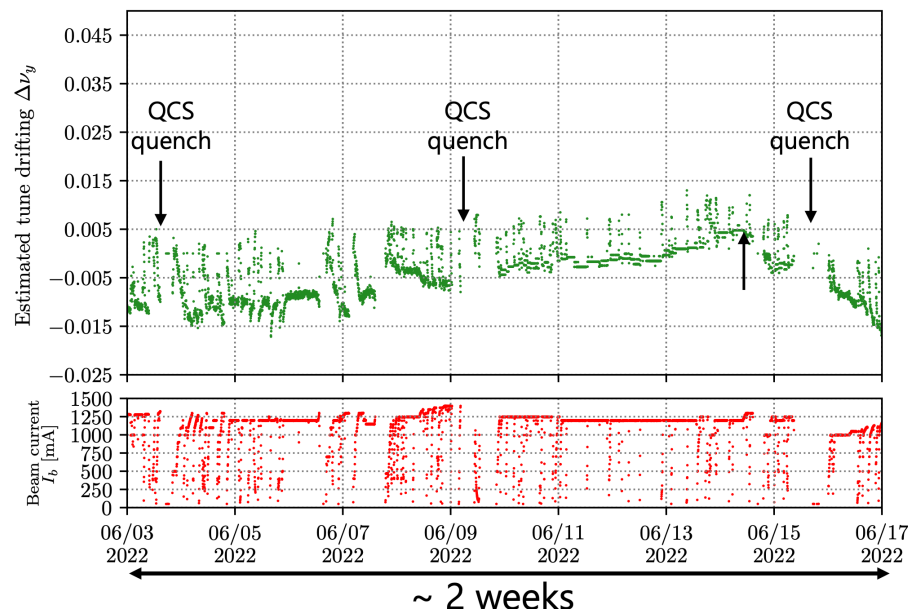
2021

Estimated tune drifting



2022

Estimated tune drifting



Contents

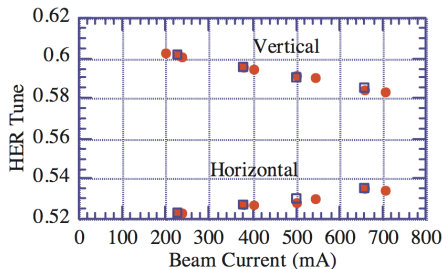
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- According to beam study in KEKB era,
It was considered that resistive wall tune shift is dominant in HER.
- In 2022ab, beam current dependence of tune shift is estimated by the amount of a tune feedback system.

KEKB

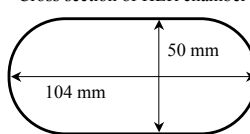
Y. Ohnishi, KEKB Review 2007

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

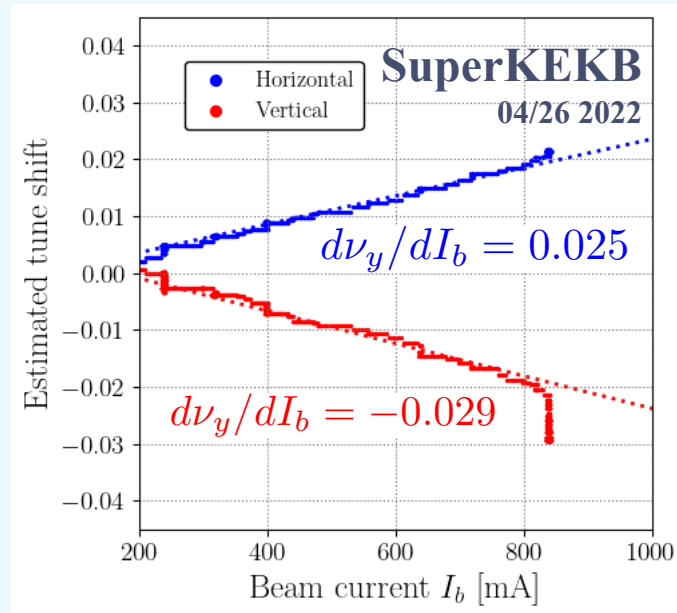


T. Ieiri et al., Proc. APAC2001

Cross section of HER chamber

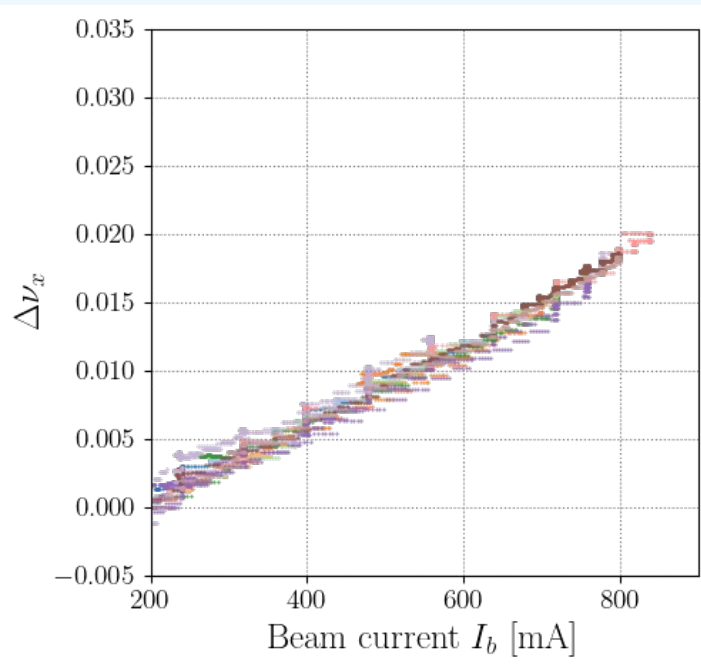


- horizontal tune shift: $\Delta\nu_x = +0.026 / A$
- vertical tune shift: $\Delta\nu_y = -0.037 / A$

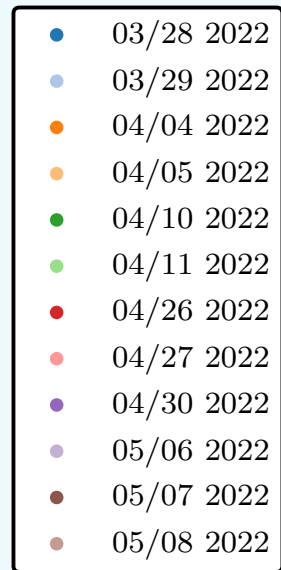
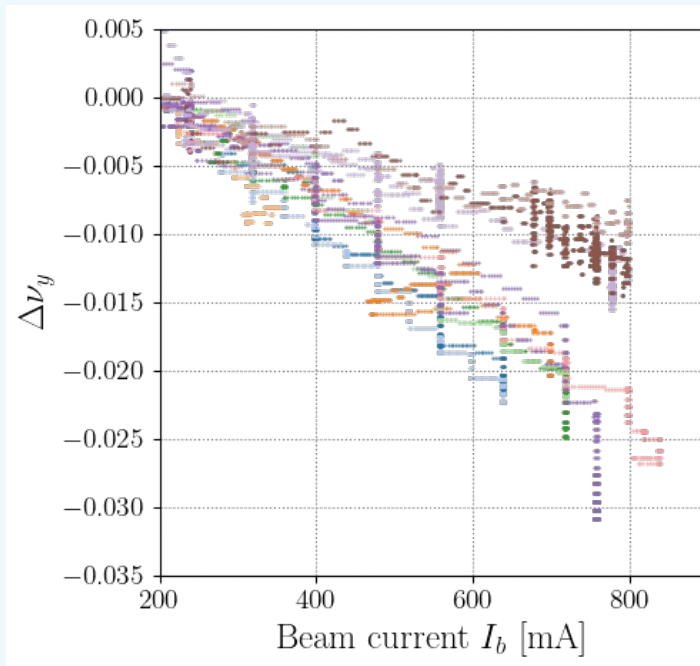


- Horizontal tune shift does not depend on days, while vertical tune shift depends on days.

Horizontal



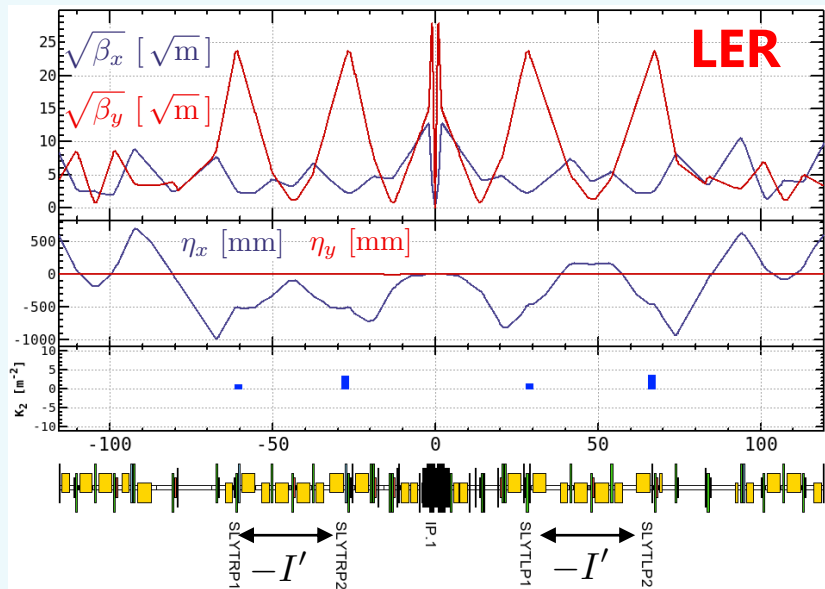
Vertical



- 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 vertical tune shift.

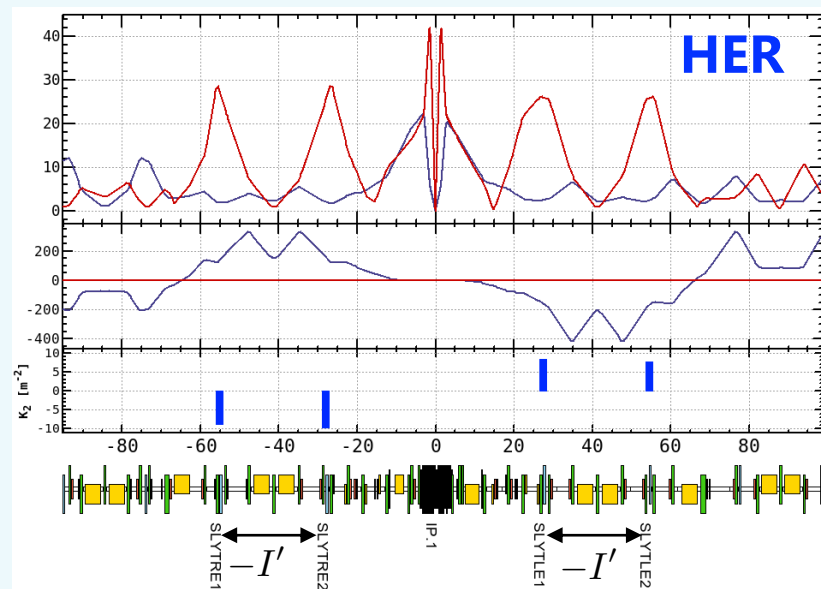


SLY pair in Right-side

SLYTRP1 and 2

SLY pair in Left-side

SLYTLP1 and 2



SLY pair in Right-side

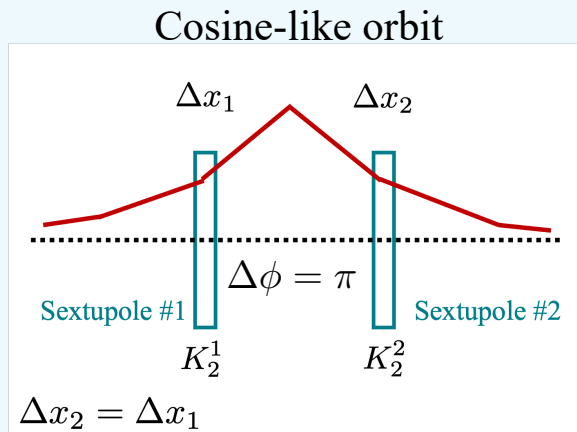
SLYTRE1 and 2

SLY pair in Left-side

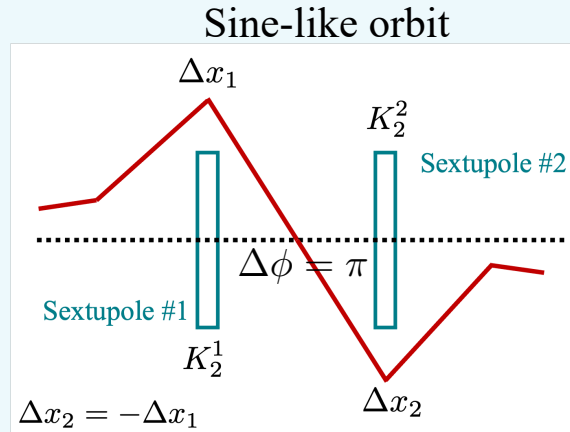
SLYTLE1 and 2

Tune Shift due to Horizontal Beam Orbit at SLY Pair

- Horizontal orbit Δx at SLY pair and tune shift



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



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

- Only cosine-like orbit causes tune shift in non-CW case because of $K_2^1 = K_2^2$
- Assuming cosine-like orbit of $10\mu\text{m}$ in HER, for example,

$$\Delta x = 10 \mu\text{m}$$

$$\beta_y \sim 700 \text{ m}$$

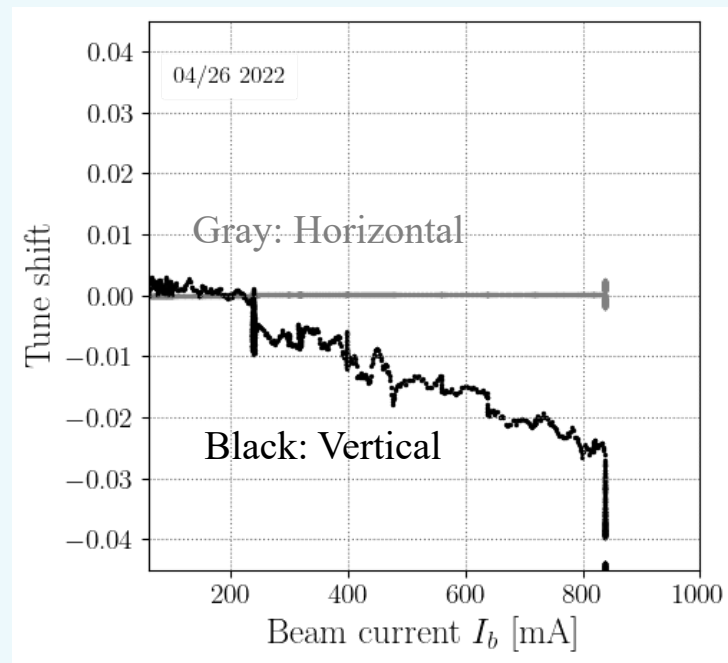
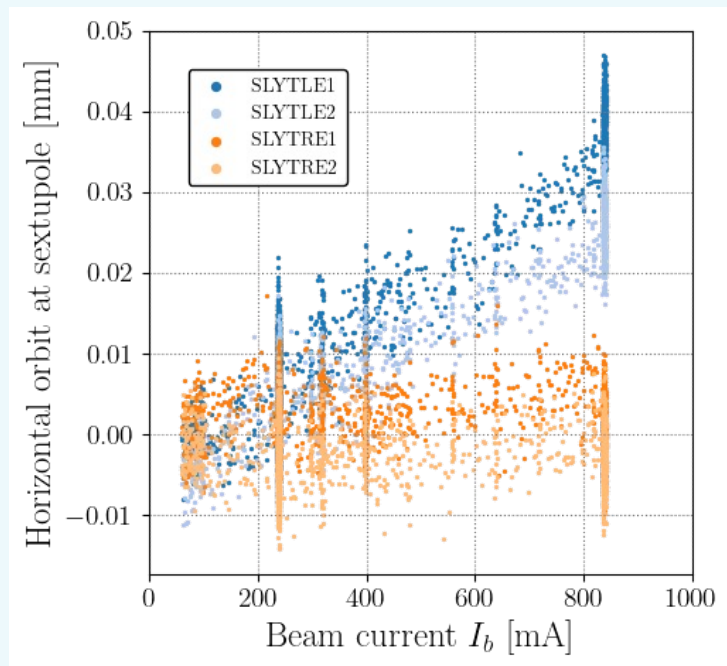
$$K_2^1 + K_2^2 \sim 16 \text{ m}^{-2}$$

$$\longrightarrow \Delta\nu_y \sim -0.009$$

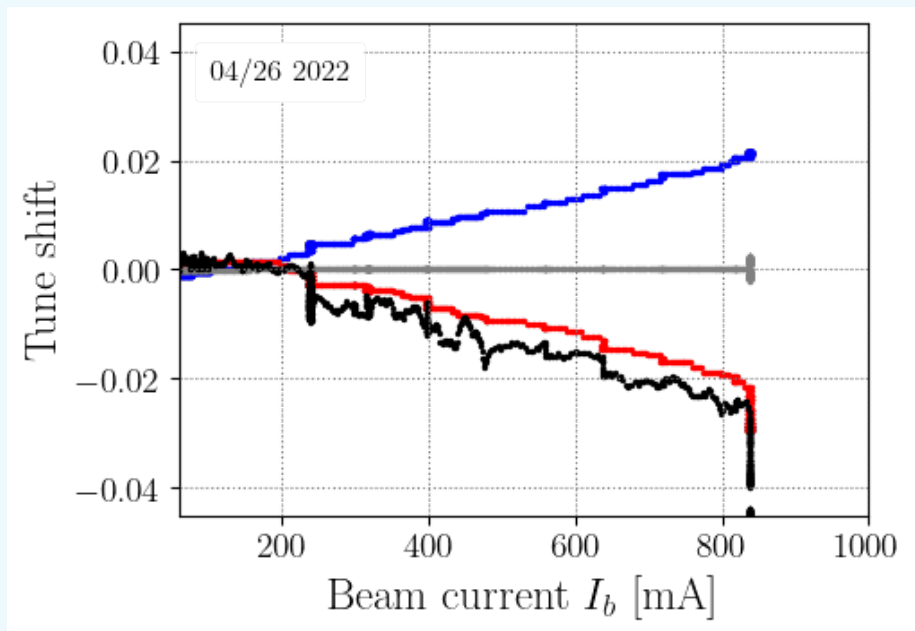
* Only $10 \mu\text{m}$ orbit can cause sizable tune shift.

Tune Shift Estimation using Model Lattice

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



Comparison with Measured Tune Shift



Blue: Measured horizontal tune shift

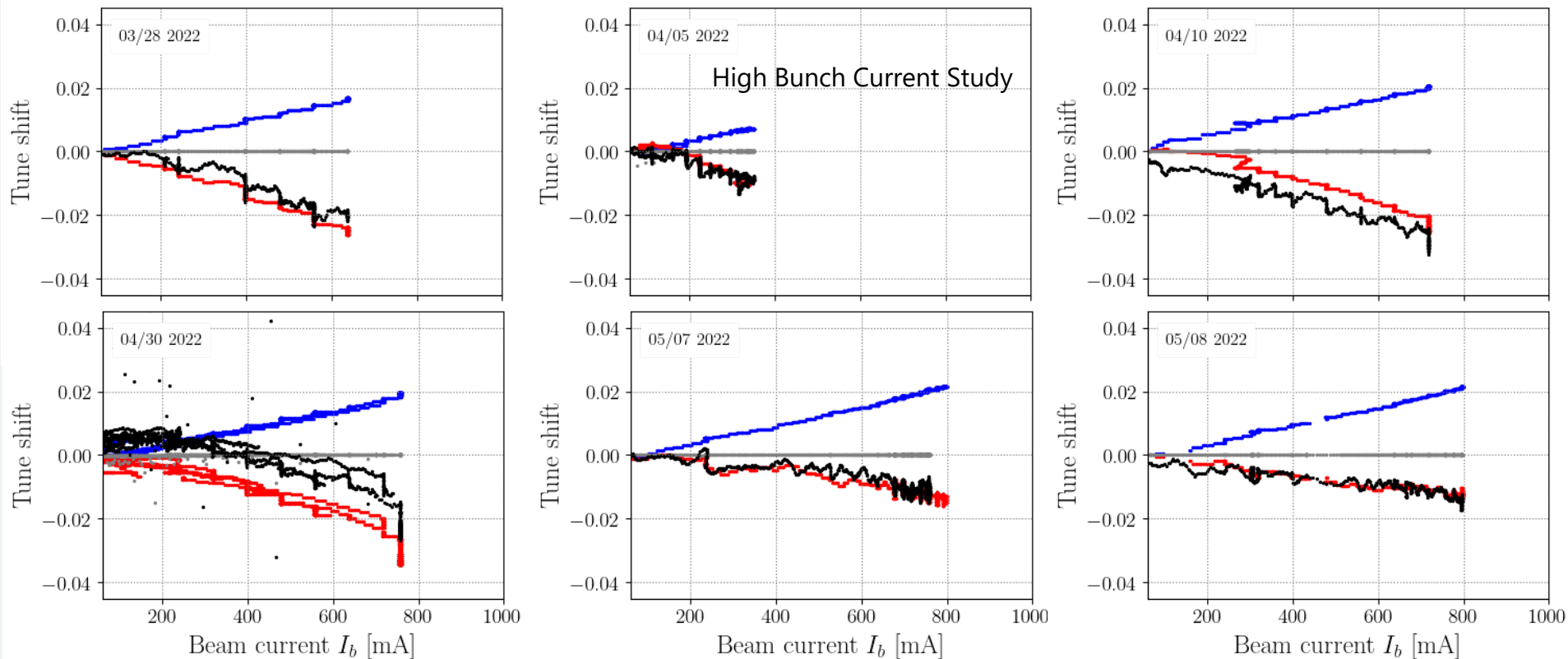
Red: Measured vertical tune shift

Gray: Estimated horizontal tune shift

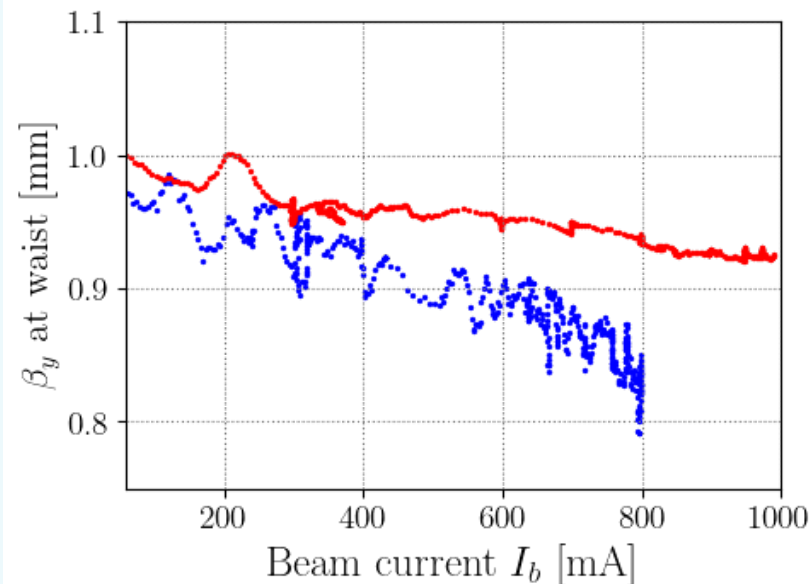
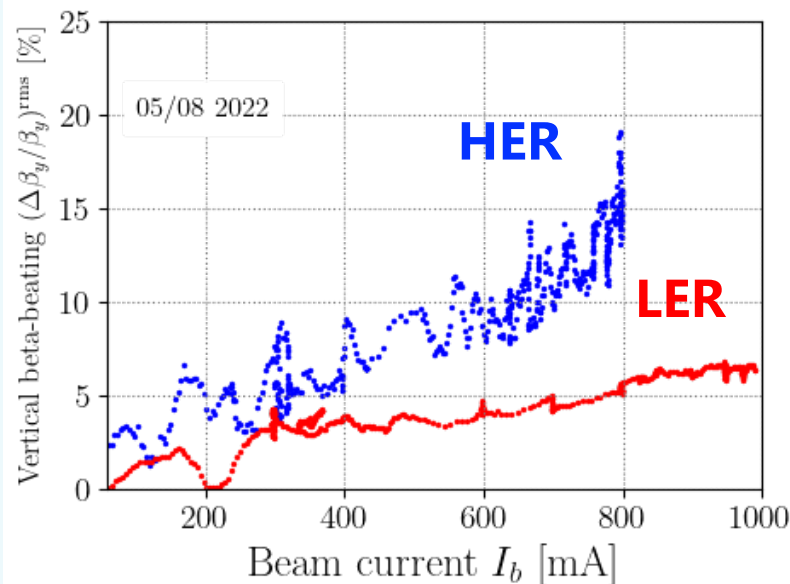
Black: Estimated vertical tune shift

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

- The variation of vertical measured tune shift is consistent with that of orbit at SLYs.



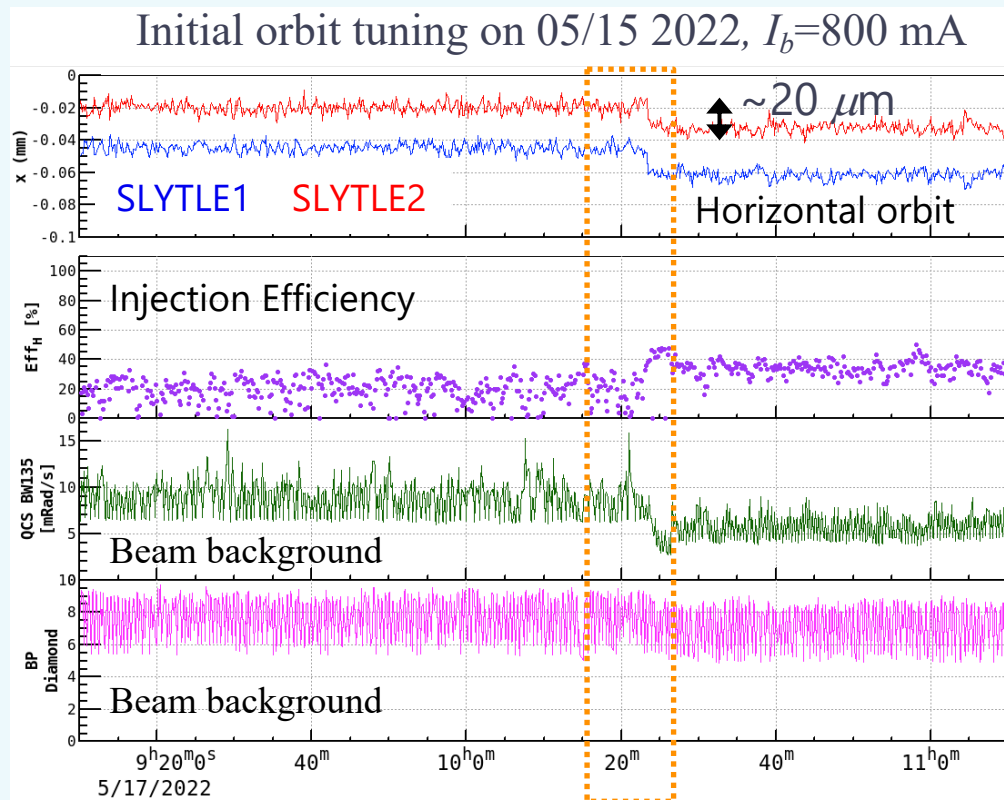
Estimated Optics Distortion due to Orbit at SLY Magnets



- 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.

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



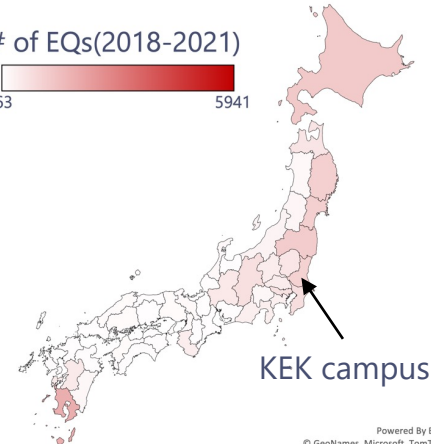
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Earthquake (EQ)

- 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 quadrupoles at sextupole magnets and/or QCS can explain the observed XY-coupling distortion, but there is no direct evidence.

of EQs(2018-2021)



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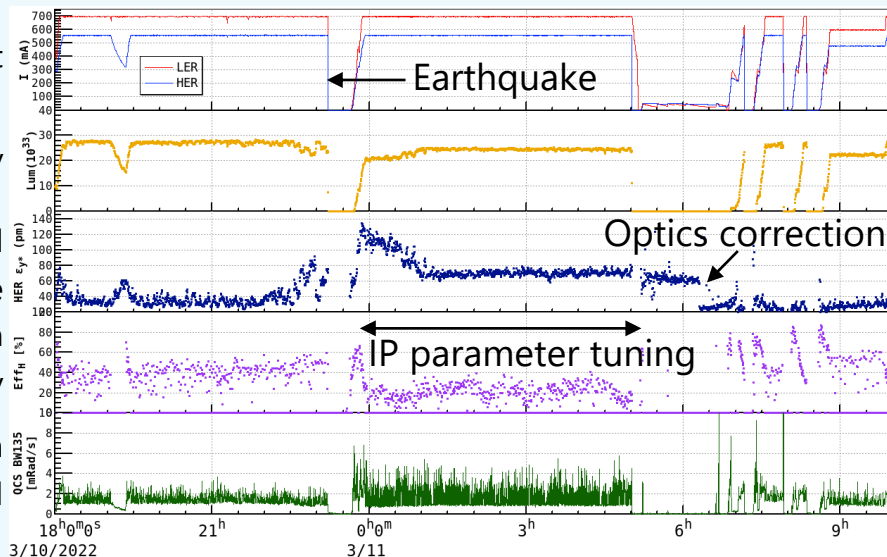
Beam current

Luminosity

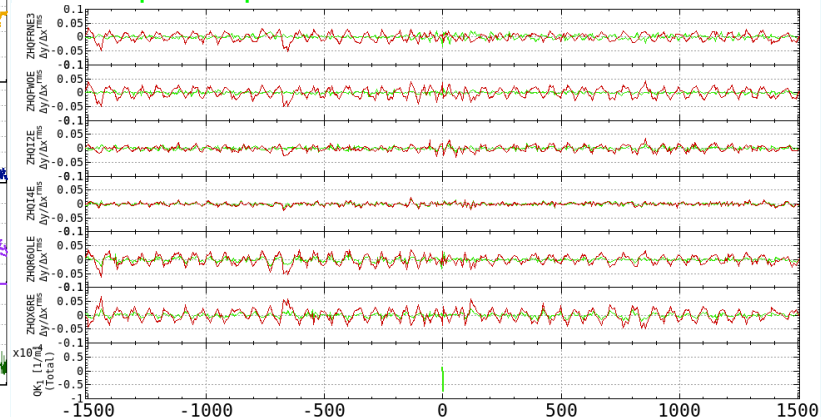
Vertical emittance

Injection efficiency

Beam background



Expected XY-coupling after correction with skew quadrupoles at QCS



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.

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

Horizontal orbit at a sextupole magnet

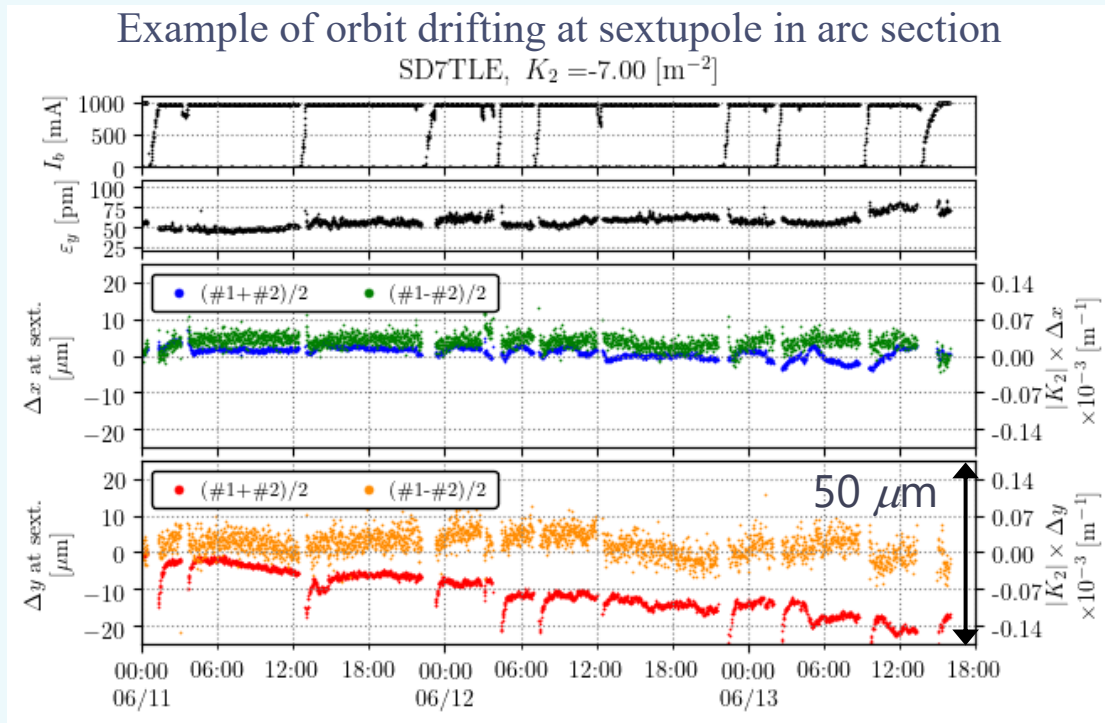
Blue: Cosine-like component

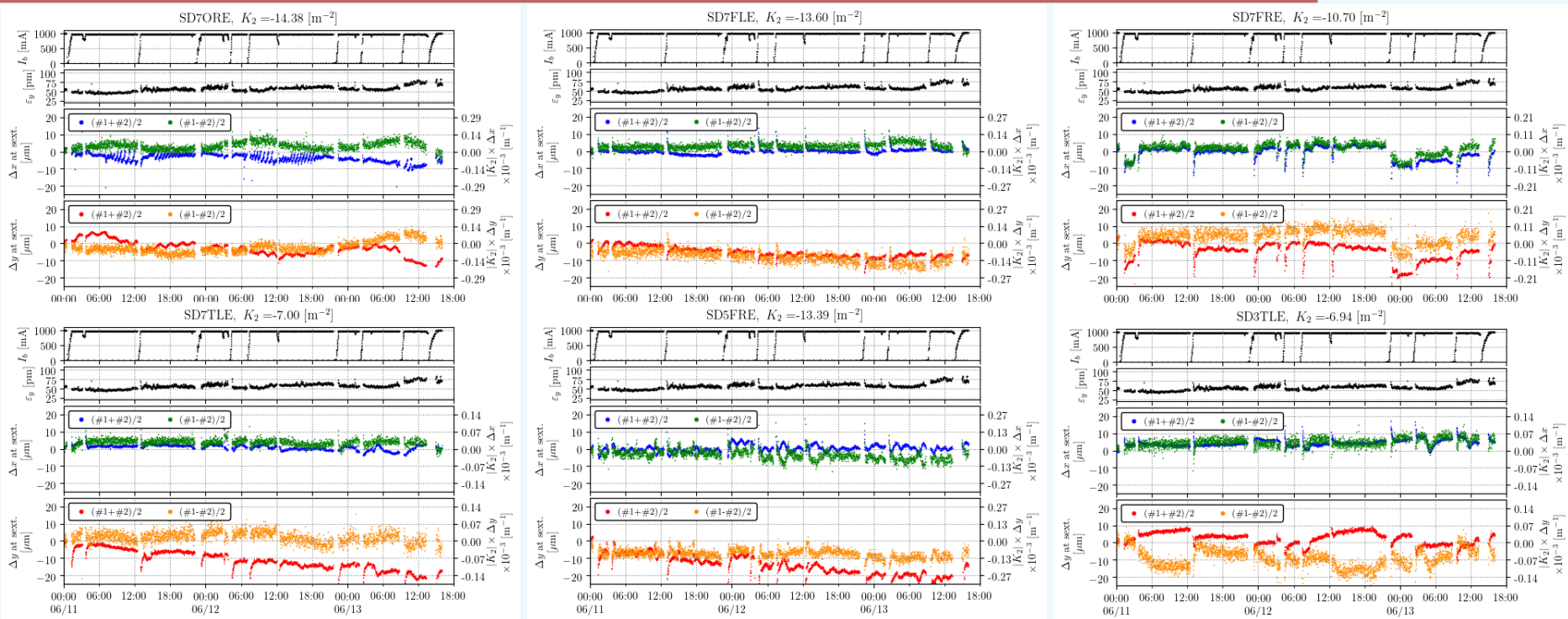
Green : Sine-like component

Vertical orbit at a sextupole magnet

Red: Cosine-like component

Orange : Sine-like component





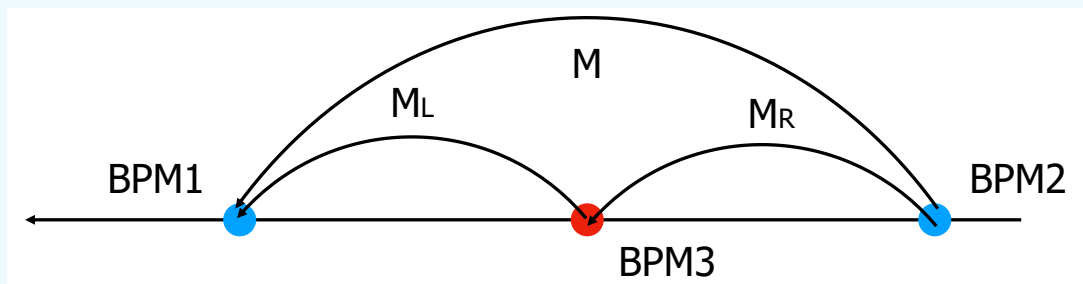
- BPM reading depends on not only real beam orbit but also various effects such as, gain drifting, beamline deformation, air temperature, beam current dependence of the BPM system, etc.
- We need to deal with these effects to discuss real beam position change.

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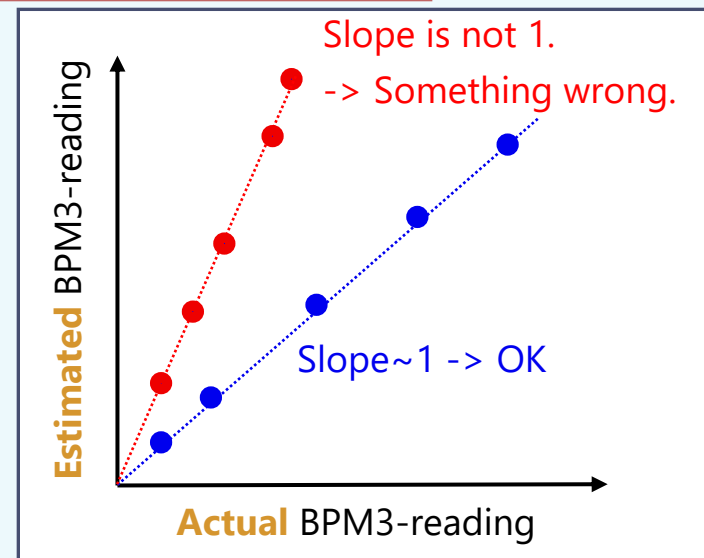
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3 BPM Analysis for QCS

Y. Ohnishi



$$\begin{pmatrix} x_L \\ y_L \end{pmatrix} \quad \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \quad \begin{pmatrix} x_R \\ y_R \end{pmatrix}$$
$$\begin{pmatrix} x_0 \\ p_{x0} \end{pmatrix} = \frac{1}{m_L^{11}m_R^{12} + m_L^{12}m_R^{22}} \begin{pmatrix} m_R^{12} & m_L^{12} \\ m_R^{22} & -m_L^{11} \end{pmatrix} \begin{pmatrix} x_L \\ x_R \end{pmatrix}$$



- Comparison of BPM3's readings and that estimated by BPM1 and BPM2.
- The correlation between them reflects difference between the model and real lattices.
- We tried to inspect QCS only using existing orbit data.
No dedicated measurement was performed.

Analysis Example #1

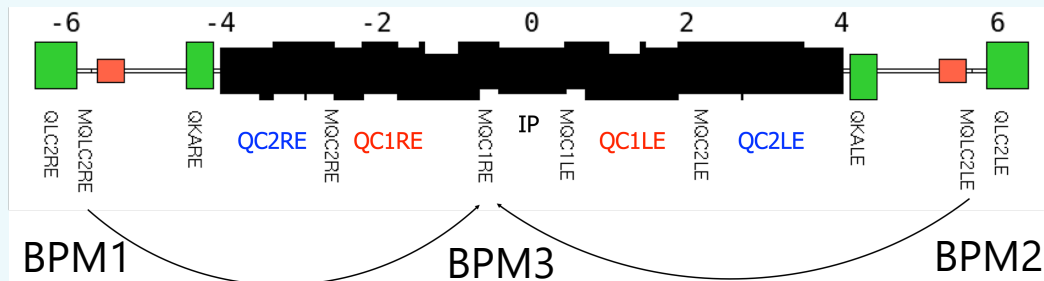
HER

Y. Ohnishi

BPM1: MQLC2RE (out of IR)

BPM2: MQLC2LE (out of IR)

BPM3: MQC1RE (in IR)

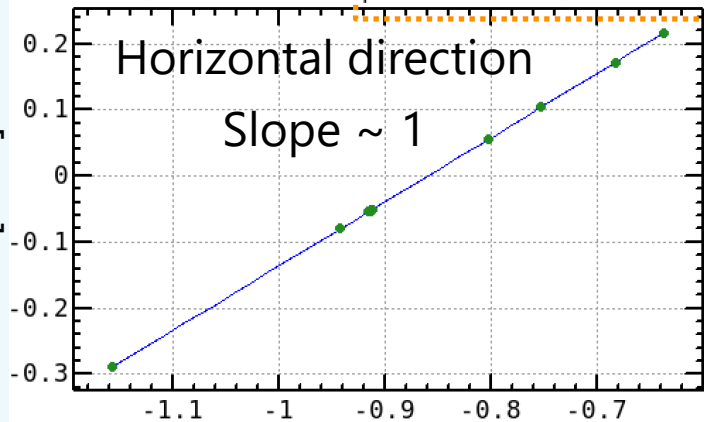


Estimated reading
[mm]

square = 9.83E-6 Goodness = .44568
.83624 +/- .00266 p1 = .97183 +/- .00299

Horizontal direction

Slope ~ 1

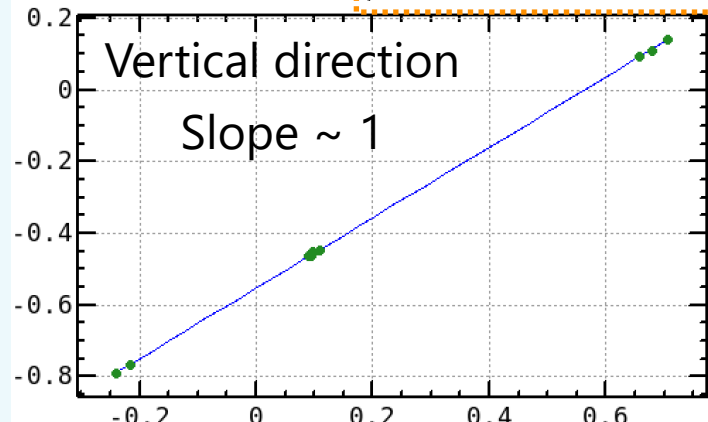


Actual reading [mm]

quare = 6.17E-5 Goodness = .44568
-.55338 +/- .00108 p1 = .98260 +/- .00321

Vertical direction

Slope ~ 1



- The slope is roughly 1, and it looks fine.

Analysis Example #2

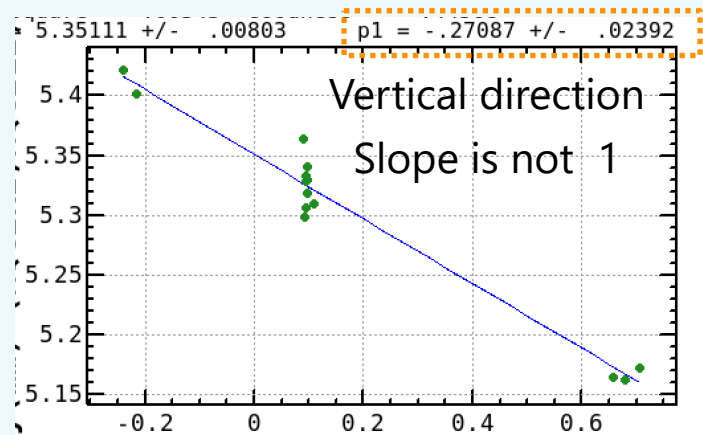
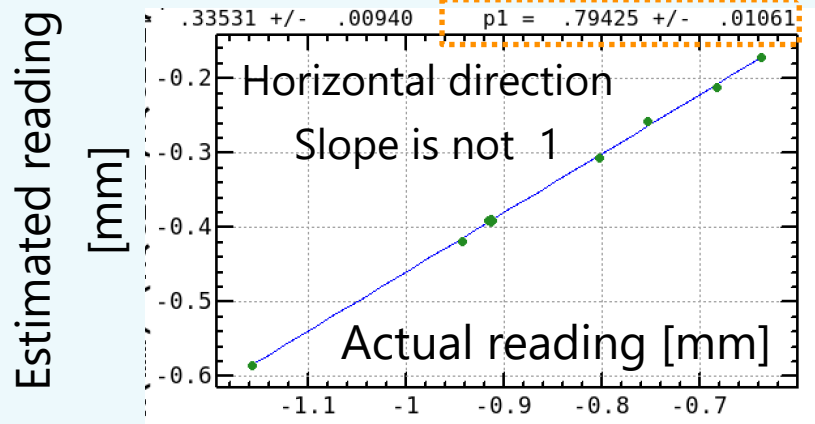
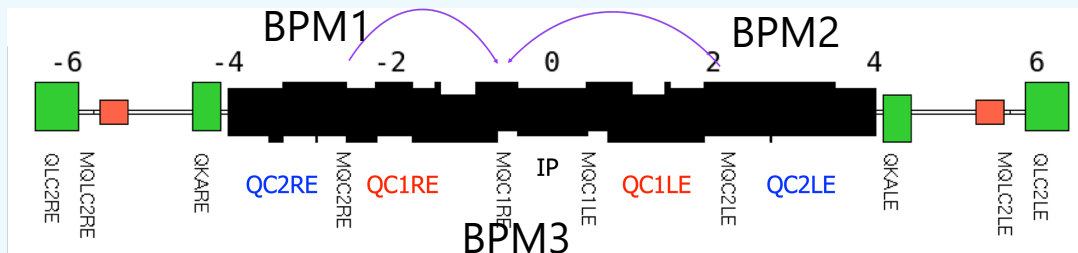
HER

Y. Ohnishi

BPM1: MQC2RE (in IR)

BPM2: MQC2LE (in IR)

BPM3: MQC1RE (in IR)



- Numerical simulation indicates that the field error of $\begin{pmatrix} \text{QC1LE K1: } +3.15 \% \\ \text{QC1RE K1: } -3.15 \% \end{pmatrix}$ can reproduce the measured slope. Error in the IR modeling? It is still under investigation.

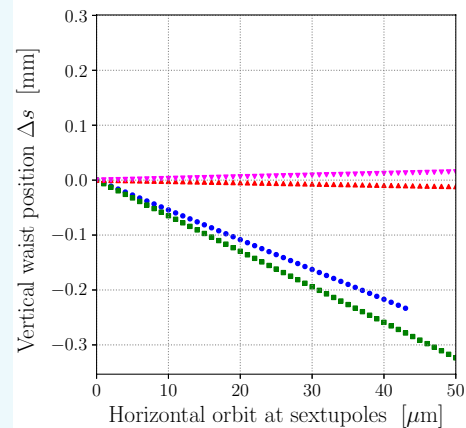
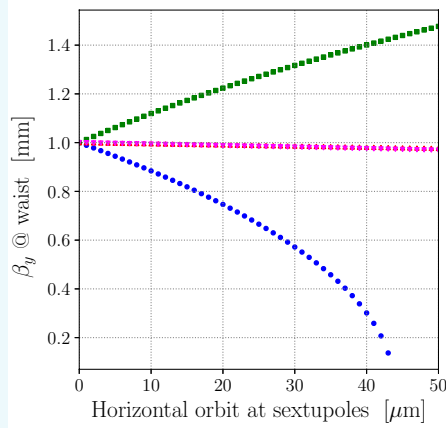
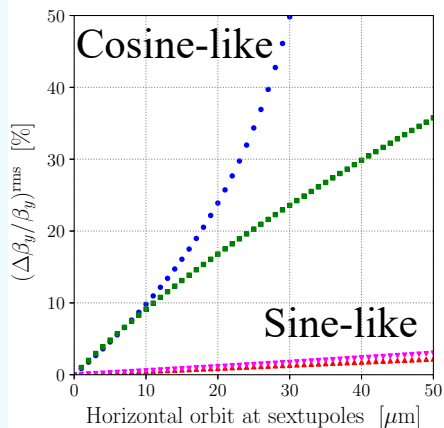
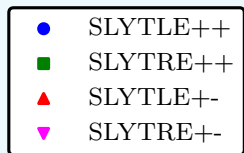
Summary

- **Recent high-beam-current operation highlights difficulties in keeping machine condition.**
 - > Obstacle to both efficient physics experiments and systematic beam study.
- **Tune drifting after QCS startup was pointed out in 2021.**
 - > The drifting is much reduced in 2022 by modifying the ramp cycle.
- **Optics deterioration due to the beam orbit fluctuation at SLYs was recognized.**
 - > The mechanism of the beam current dependence of the orbit is not understood yet.
Beamline deformation due to SR and/or HOM heating?
Some experiments is ongoing to clarify the actual movement of magnets, chamber and BPM.
- **Optics deterioration in a few days is one of the largest concerns in daily operation.**
 - > It seems that a few ten microns orbit change at strong sextupole is not negligible.
Investigation on source of orbit fluctuation including BPM system itself is ongoing.
- **3-BPM analysis implies large error sources in HER IR.**
 - > Correction to the IR modeling and/or real machine is probably necessary.

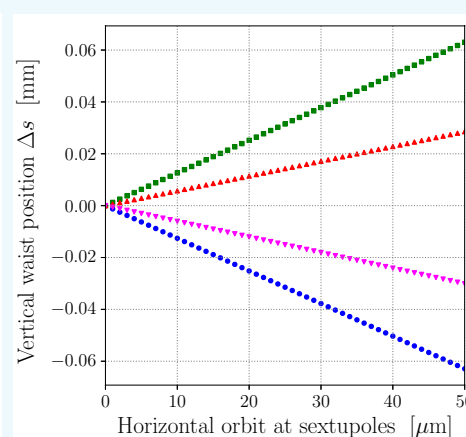
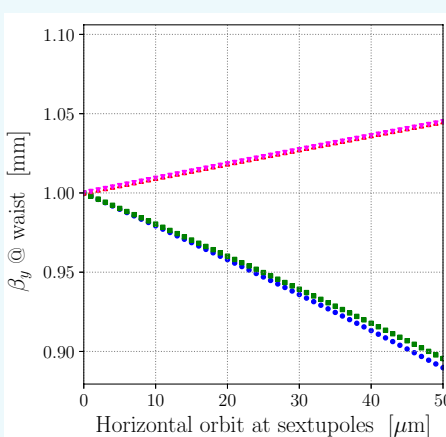
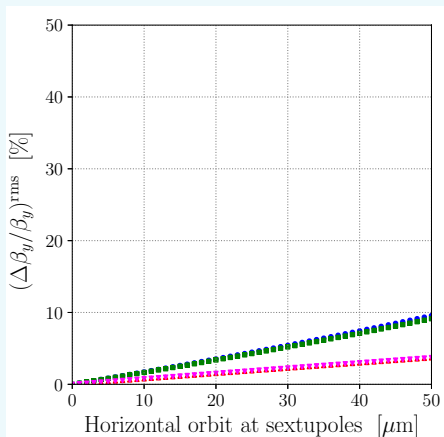
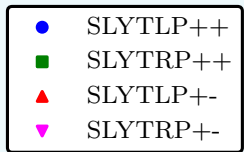
Spare Slides

Beam Orbit at SLYs and Optics Distortion - Model Calculation -

HER

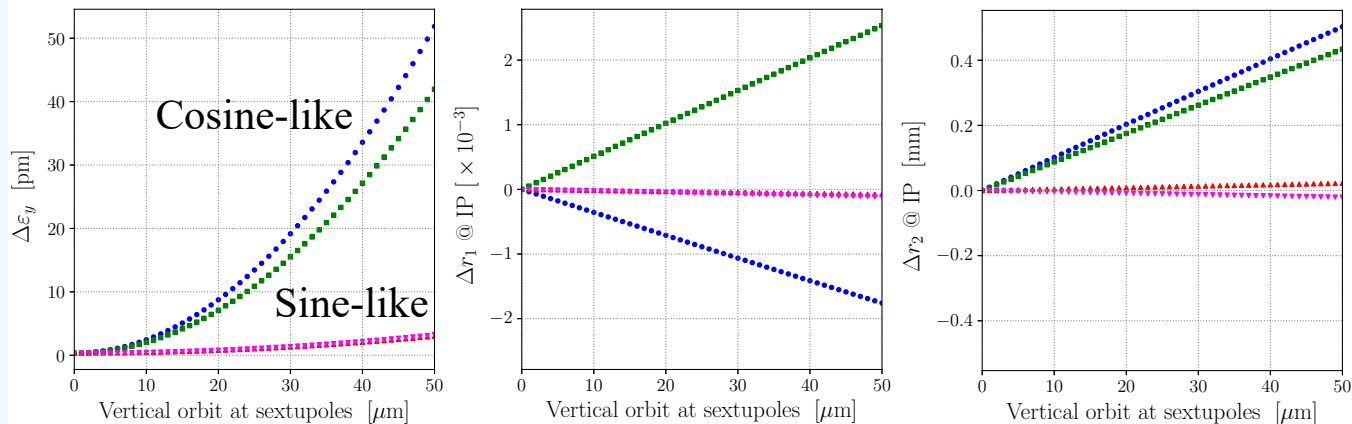


LER

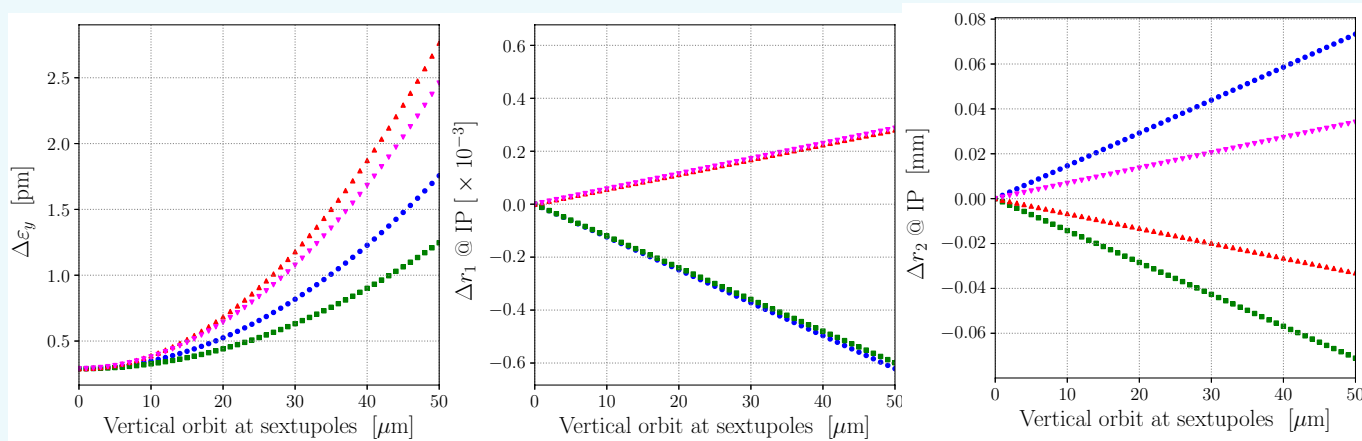
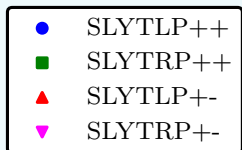


Beam Orbit at SLYs and Optics Distortion - Model Calculation -

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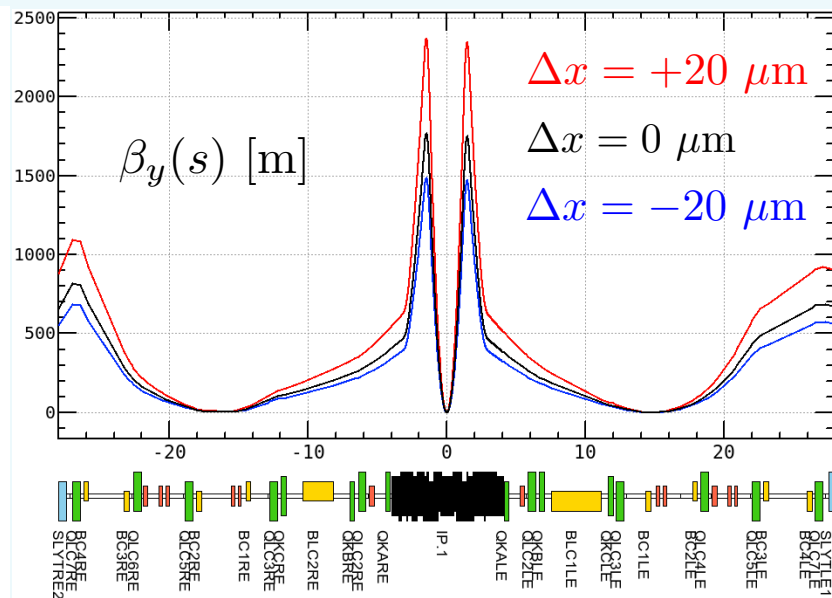
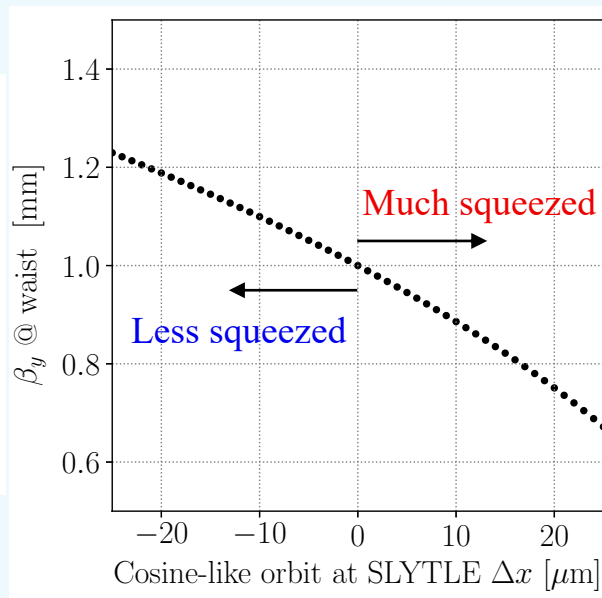
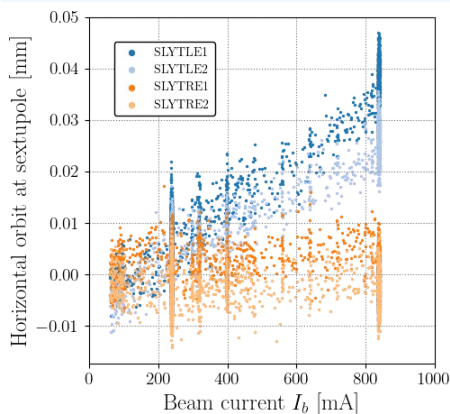


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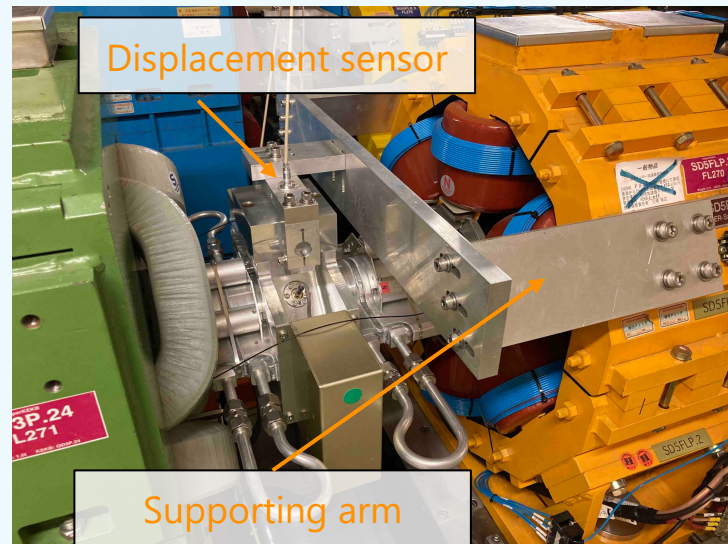
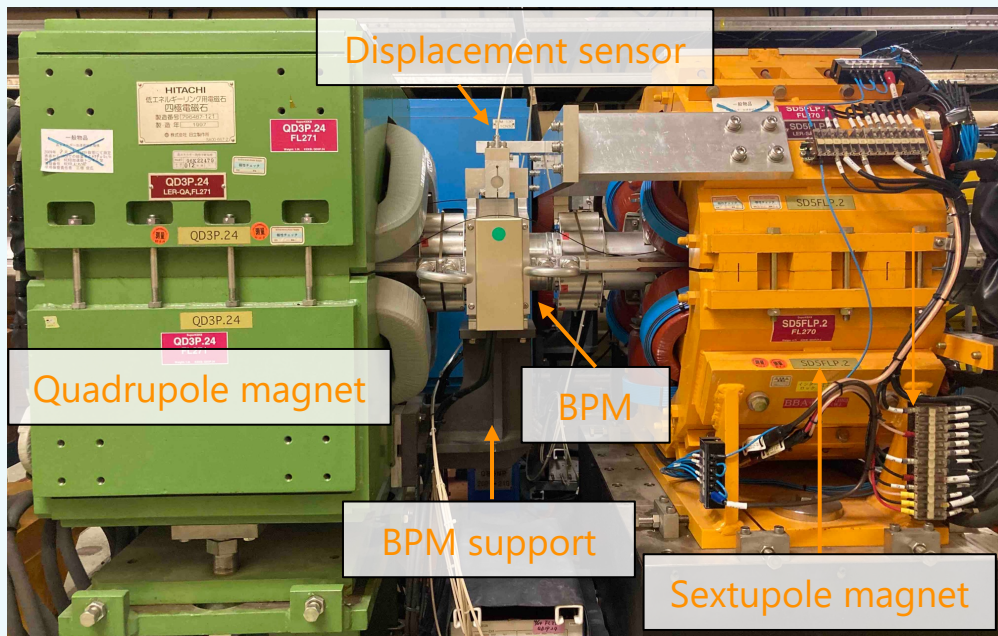
Optics Distortion in IR - Model Calculation -

- 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 at high beam current.

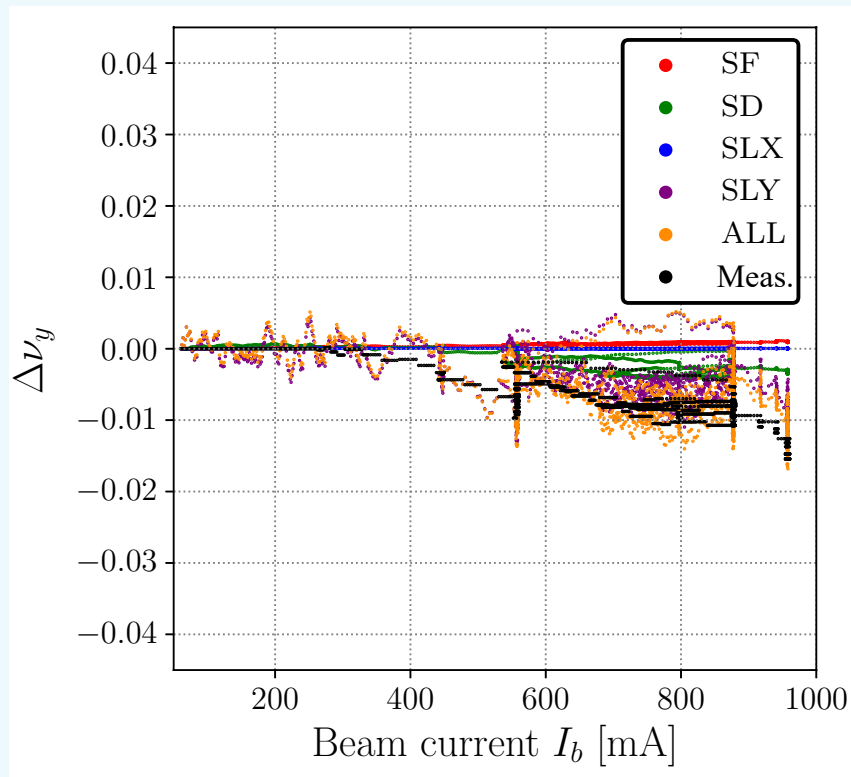


BPM, Sextupole, Quadrupole and Displacement Sensor

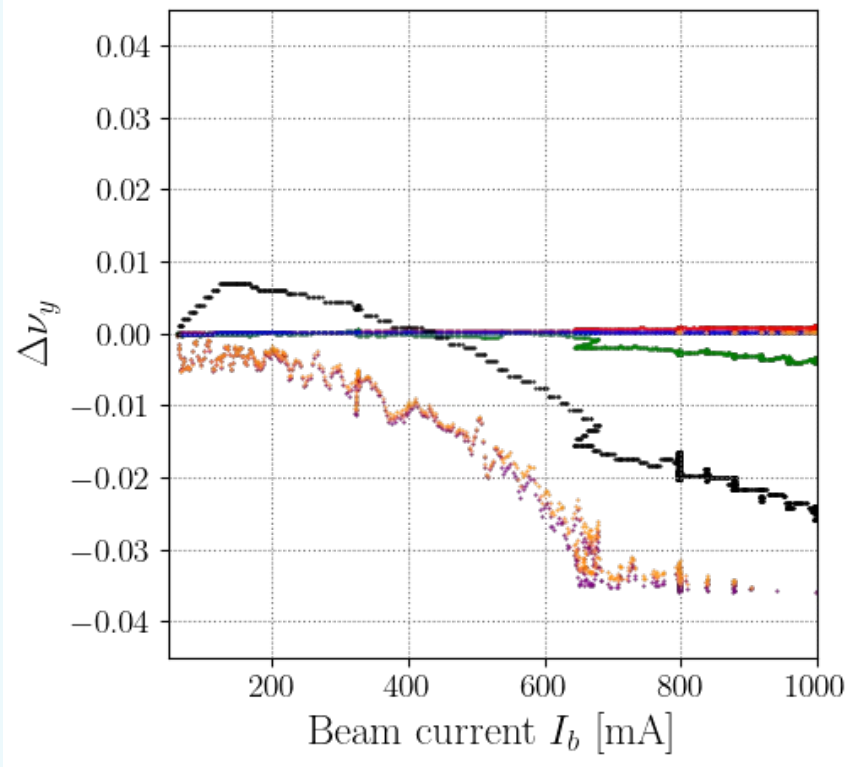
- BPM is attached to quadrupole magnet by supporting stand.
- Displacement sensor is attached to sextupole magnet.
- The movement of a BPM chamber is measured by the displacement sensor.
- Measured displacement is incorporated in the BPM system for COD measurement.



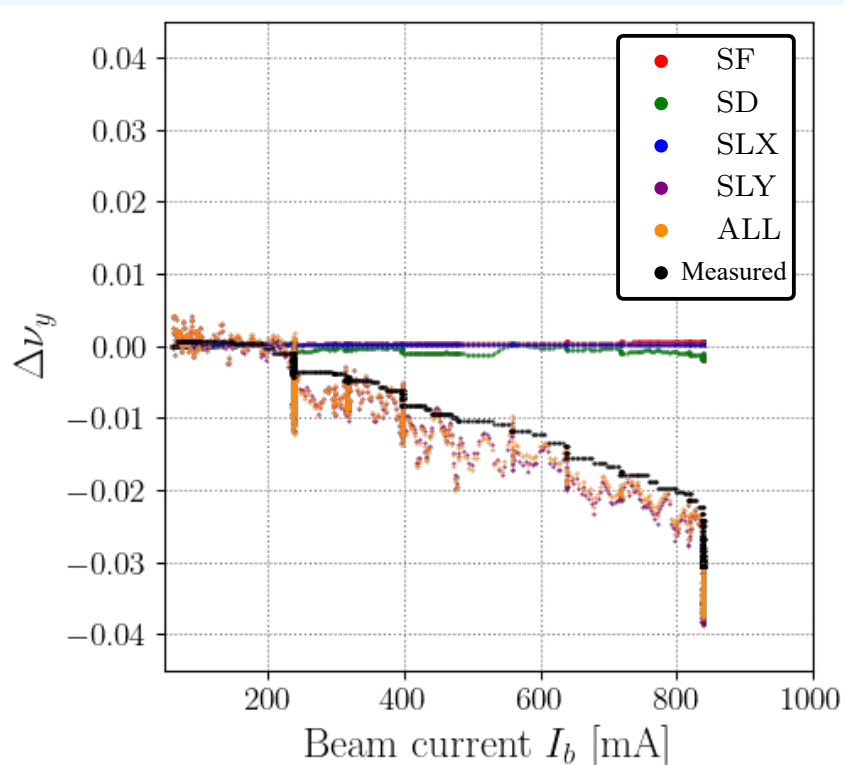
06/09/2022



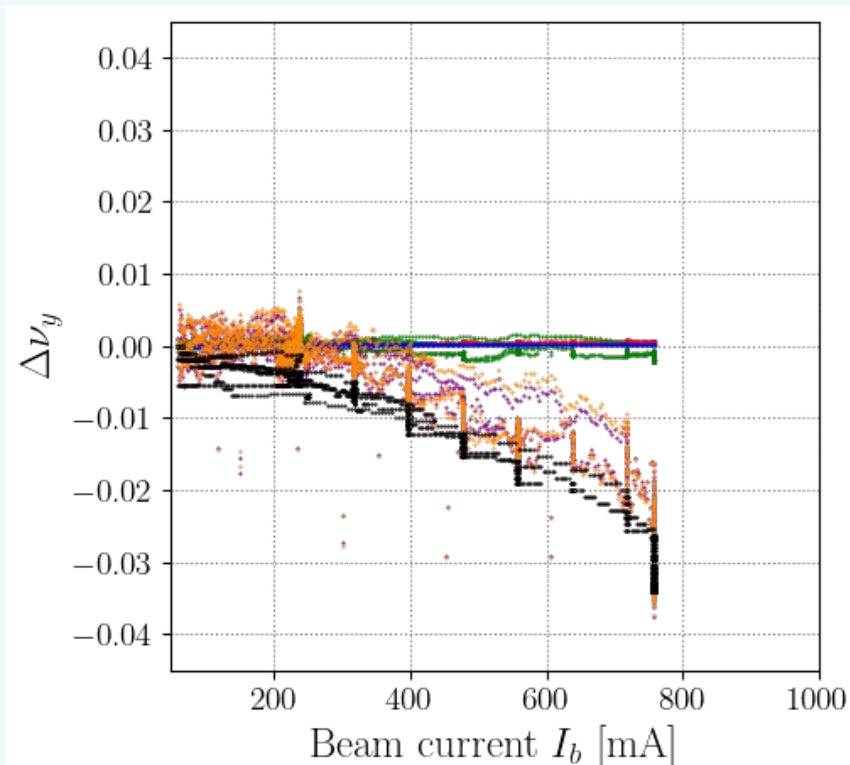
06/19/2022



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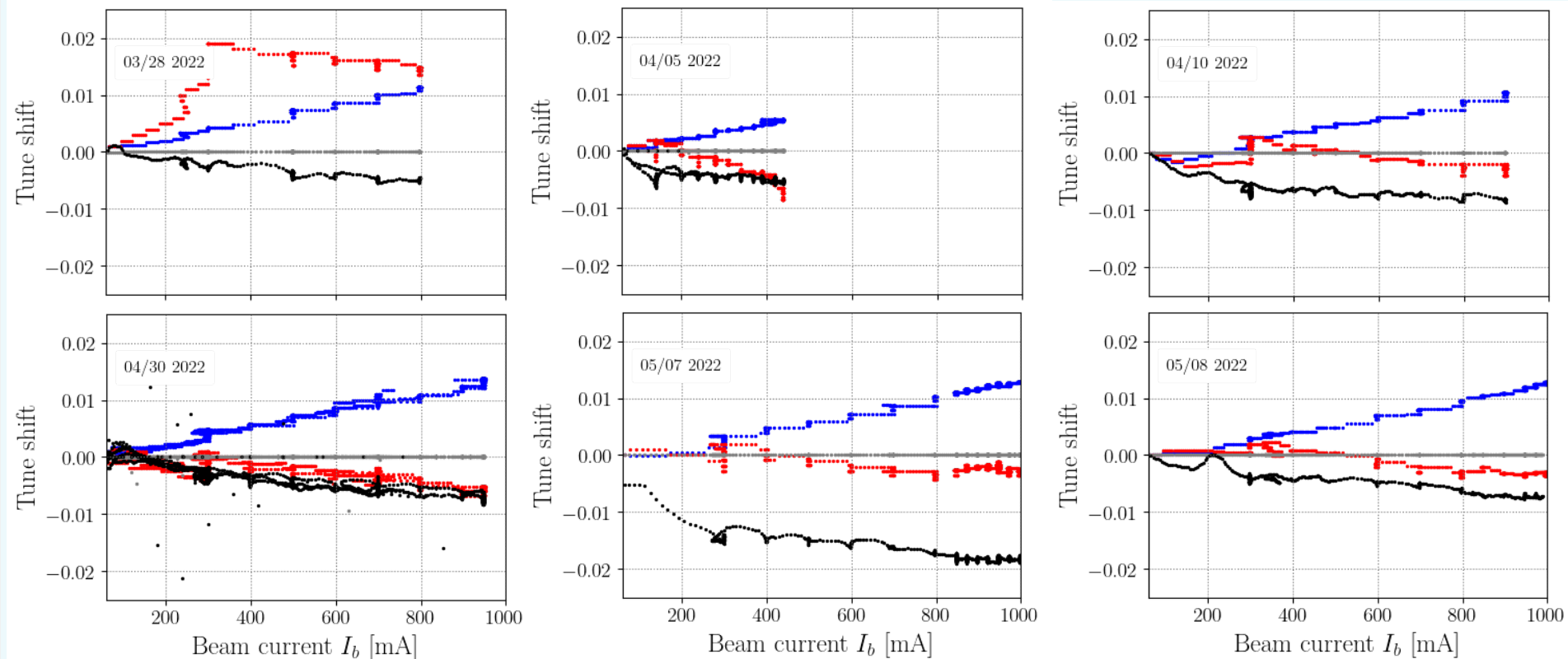
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Day to Day Variation

LER

- Some amount of vertical tune shift seems to be caused by orbit at SLY.

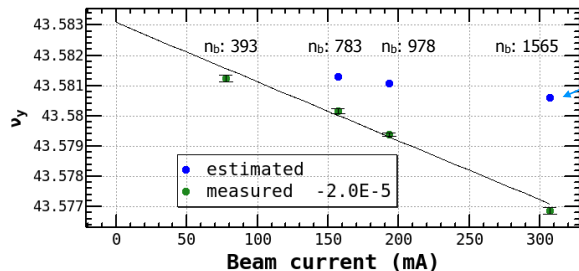
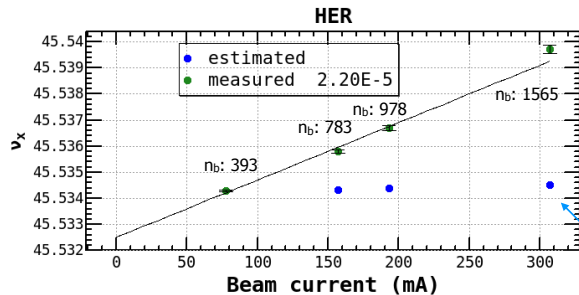


Tune Shift Measurement with a Pilot bunch in HER

Y. Ohnishi

$$\beta_x^*/\beta_y^* = 200 \text{ mm}/8 \text{ mm} \quad (\text{no crab waist})$$

The bunch current is fixed to be 0.2 mA with changing no. bunches.



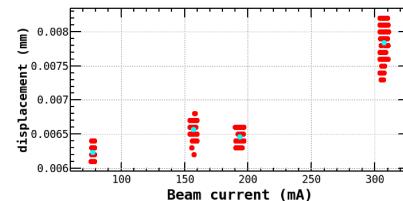
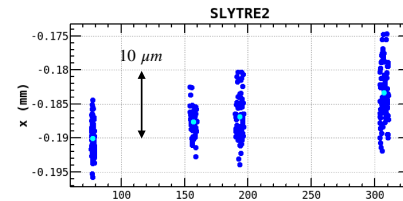
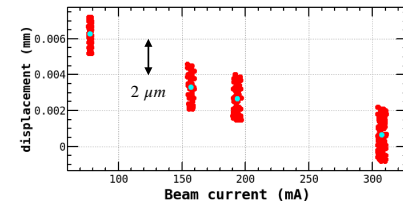
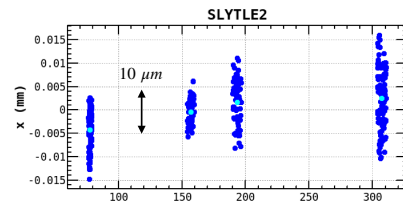
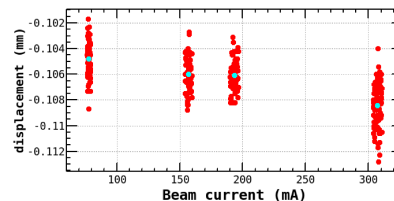
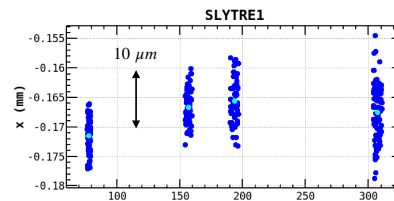
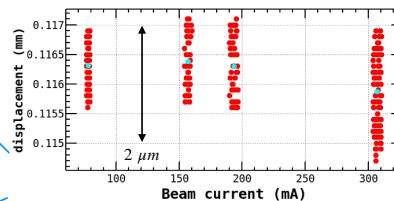
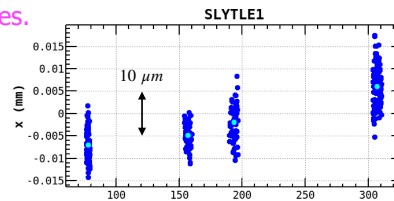
tune shift due to
resistive wall
impedance:

$$\Delta\nu_x/I = +2.2 \times 10^{-5} \text{ (1/mA)}$$

$$\Delta\nu_y/I = -2.0 \times 10^{-5} \text{ (1/mA)}$$

→ $-1.64 \times 10^{-5} \text{ (1/mA)}$
corrected by orbit deviation

HER



18:50 - 23:10, October 26, 2021

Estimation of Resistive Wall Tune Shift

- Design study for chamber shape using field calculation and a parallel plate model.
- To check the validity of their evaluation method, they calculated the resistive wall tune shift and compare it to the measured tune shift in KEKB.

*Proceedings of the 5th Annual Meeting of Particle Accelerator Society of Japan
and the 33rd Linear Accelerator Meeting in Japan (August 6-8, 2008, Higashihiroshima, Japan)*

STUDY ON CROSS-SECTION OF NONCIRCULAR BEAM DUCT TO REDUCE TUNE SHIFT INDUCED BY RESISTIVE-WALL WAKE FIELD

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Abstract

The strength of the resistive-wall wake fields of noncircular beam ducts (parallel plates, racetrack, beam duct with antechambers) were estimated numerically with MAFIA electrostatic solver (2D). To investigate the relationship between the tune shift and the wake field, the tune shifts in the parallel plates with several vertical separations were calculated analytically. On the basis of the results of the parallel plates, the tune shifts in the racetrack duct and the beam ducts with antechambers were estimated from the wake fields. The tune shift in the racetrack duct was consistent with the measured value of KEKB electron ring. In the case of the beam duct with antechambers, it was found that the resistive-wall wake field and tune shift could be reduced by adopting the elliptically-shaped beam channel instead of circular beam channel.

$$\Delta v_x = \frac{-\Gamma}{2\sqrt{2}v_x\omega_0^2} \left\{ g(v_x) - \frac{L}{c} \sqrt{2}h \right\} \quad (3)$$

$$\Delta v_y = \frac{-\Gamma}{2\sqrt{2}v_y\omega_0^2} \left\{ 2g(v_y) + \frac{L}{c} \sqrt{2}h \right\} \quad (4)$$

$$\Gamma = \frac{\pi N r_0 c^2}{6 \gamma b^3} \left(\frac{\delta_0}{2R} \right) \quad (5)$$

$$\frac{1}{n_b} \sum_{m=1}^{n_b} \sum_{k=0}^{\infty} \sqrt{\frac{2}{(k+\frac{m}{c})}} e^{(2\pi i v)(k+\frac{m}{c})} = g(v) + i f(v) \quad h = \frac{1}{n_b} \sum_{m=1}^{n_b} \sum_{k=0}^{\infty} \sqrt{\frac{1}{(k+\frac{m}{c})}} \quad (6)$$

- They conclude that their method can reproduce measured tune shift observed in KEKB.
- The most of beam-pipes in SuperKEKB HER are reused from KEKB.
- Therefore, resistive wall tune shift in SuperKEKB is expected to be similar?

表 1. チューンシフトの計算パラメーター

	LER/HER
Beam Energy	3.5/8.0 GeV
Beam Current	1 A
$V_{x,y}$	x:45.506/44.515, y:43.545/41.580
C	3016 m
L	2200 m
n_b	1584(KEKB), 5018(SuperKEKB)
σ_c	5.4×10^{17} /s (copper)

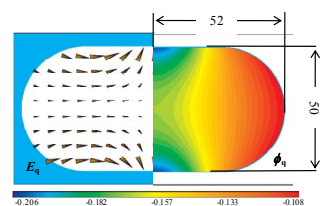


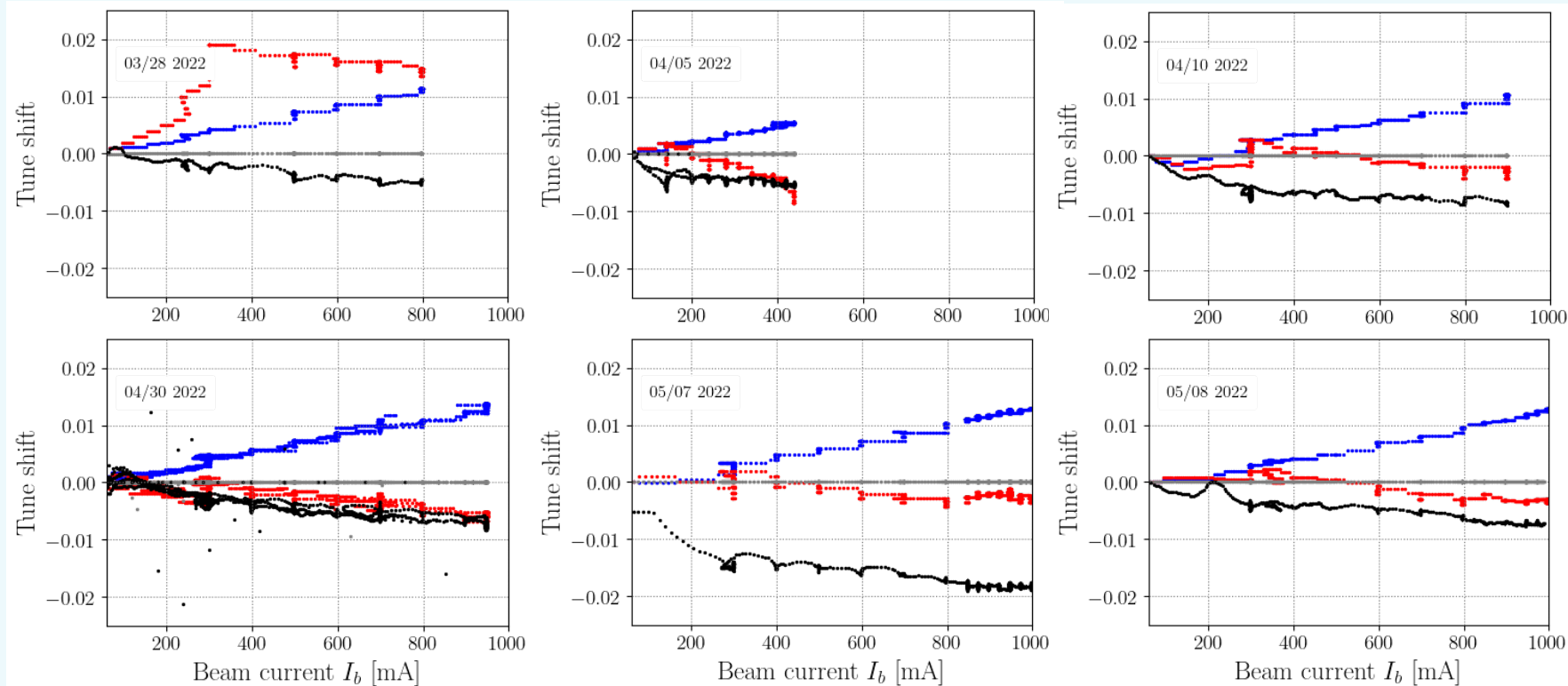
図 2. KEKB HER ダクトの resistive-wall ウェイクフィールドの 4 極成分を表す電場 (左) と電位 (右)

Estimated values

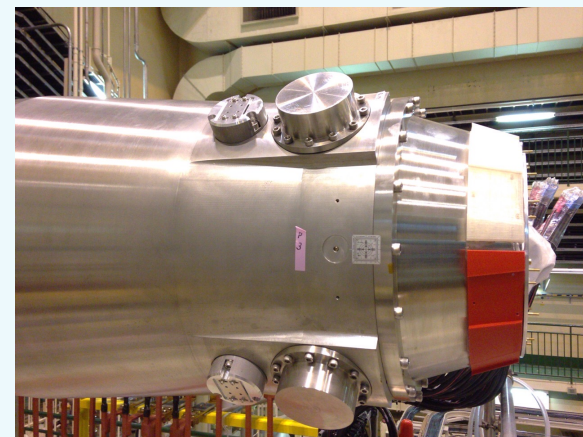
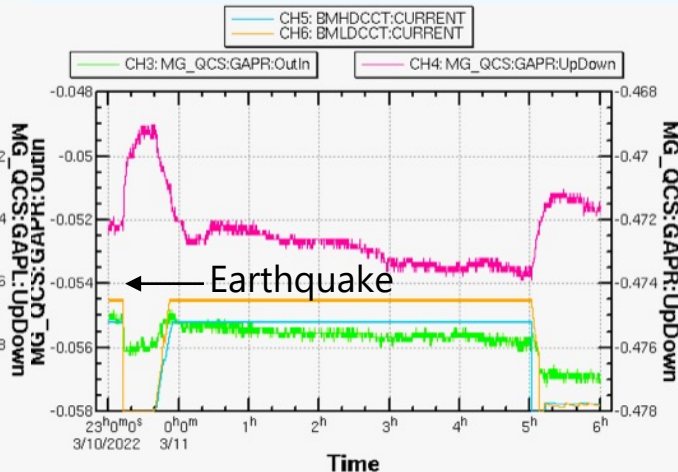
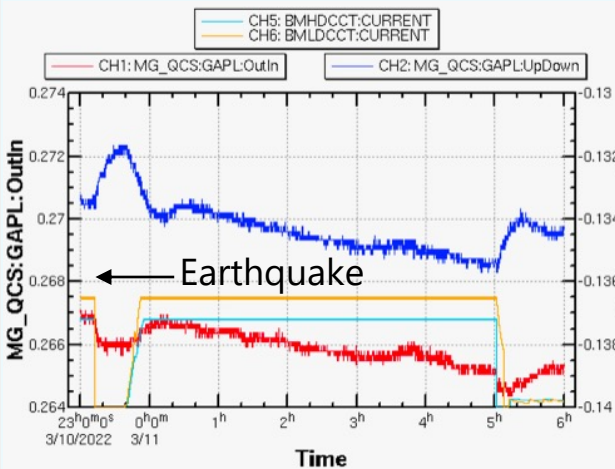
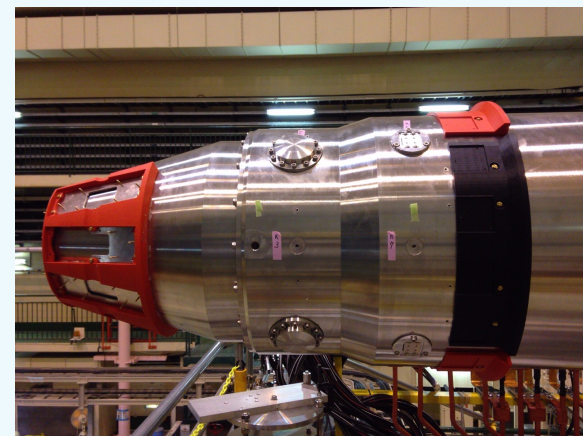
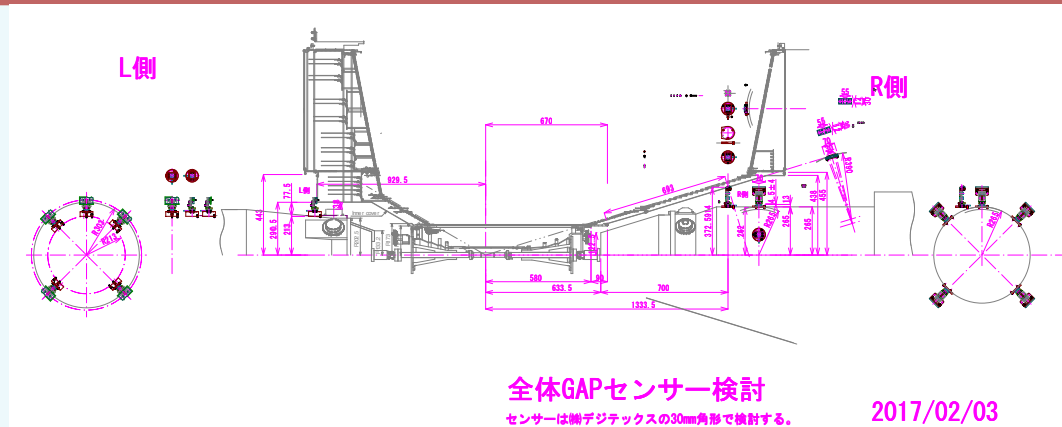
を示す。x、y軸上の4極成分の大きさはそれぞれ、 $A_{Eqx} = -104.5$, $A_{Eqy} = 109.4$ であった。これらの値を、図1のHERのグラフにあてはめて得られたチューンシフトは、 $\Delta v_x/\Delta I = 0.028$, $\Delta v_y/\Delta I = -0.030$ となる。KEKB HERのチューンシフトの実測値は0.03程度なので、この方法で評価したチューンシフトが妥当であることが分かる。

Measured value

- Some amount of vertical tune shift seems to be caused by orbit at SLY.

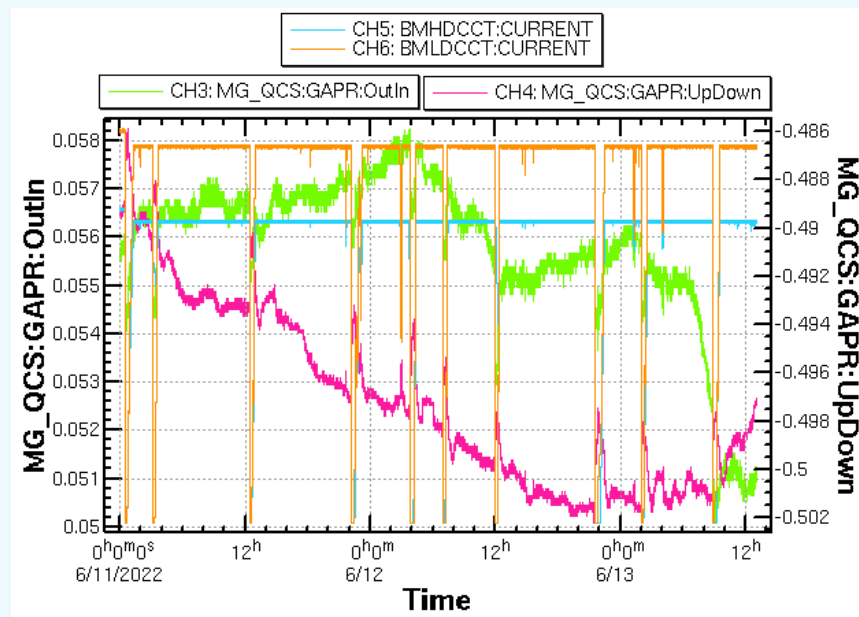
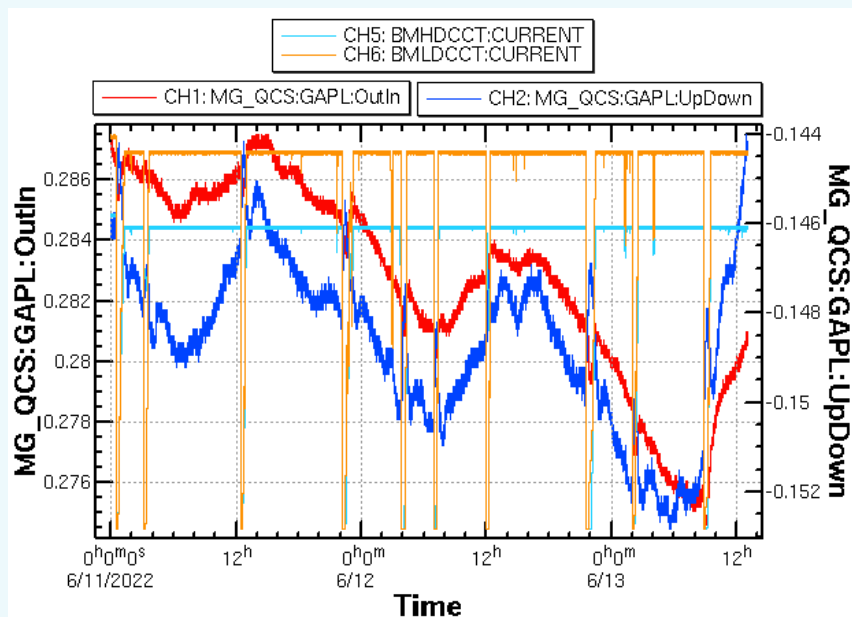
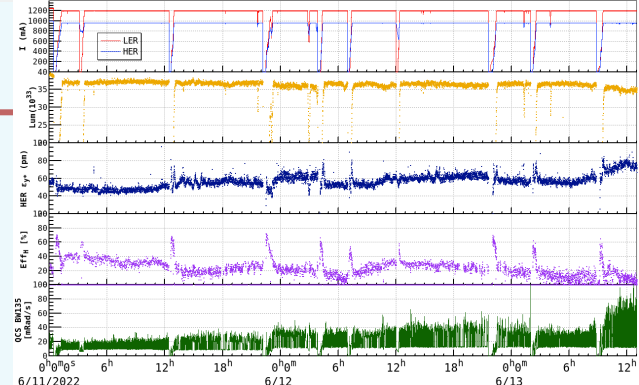


Gap Sensors for the QCS Cryostat



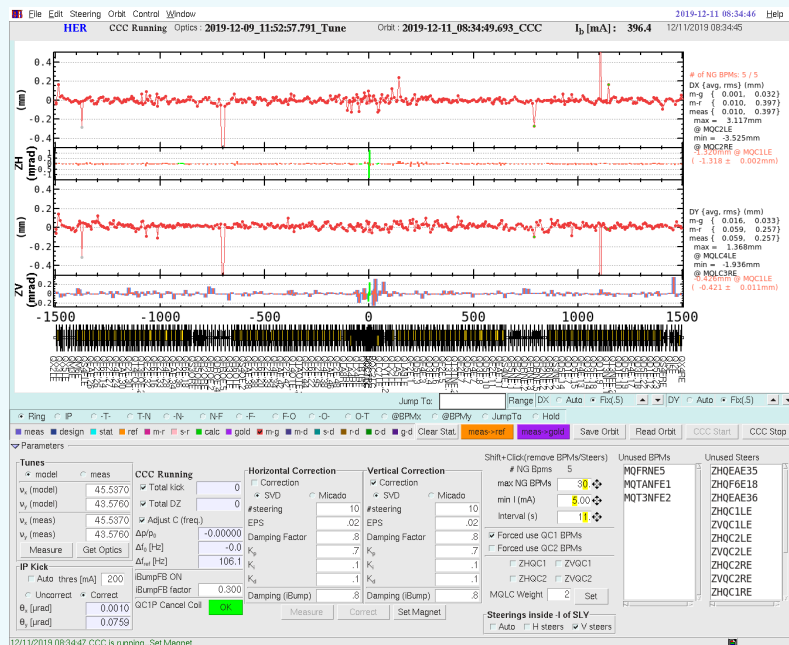
Gap Sensors for the QCS Cryostat

- Is this movement consistent with the HER optics degradation?
- How to utilize the cap sensor in beam orbit and optics tuning?



Continuous Closed Orbit Correction (CCC)

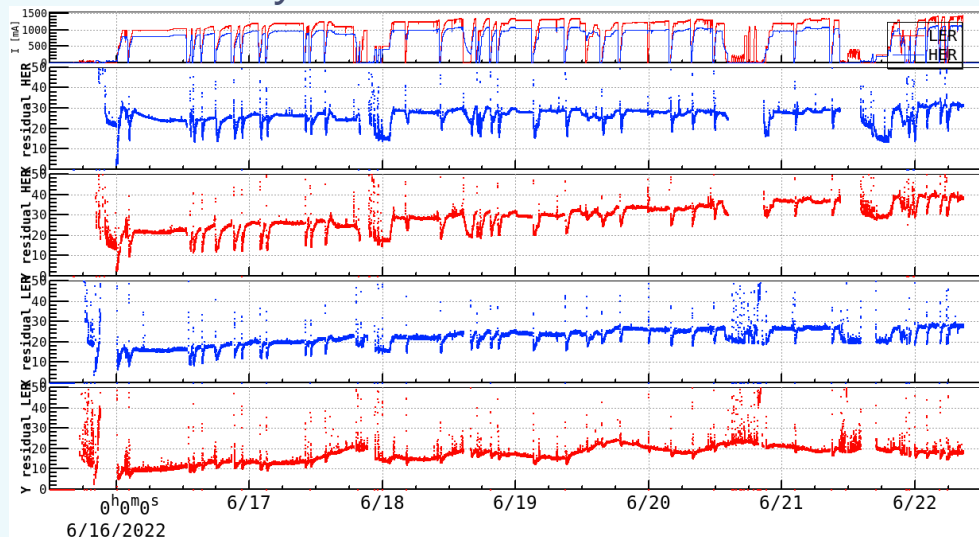
- A closed orbit feedback system named CCC.
- It repeats COD correction with DC steering magnets by ~ 0.1 Hz.
- It applies COD correction so that difference between measured orbit and a reference (golden) orbit is minimized in the root-mean-square (RMS) sense



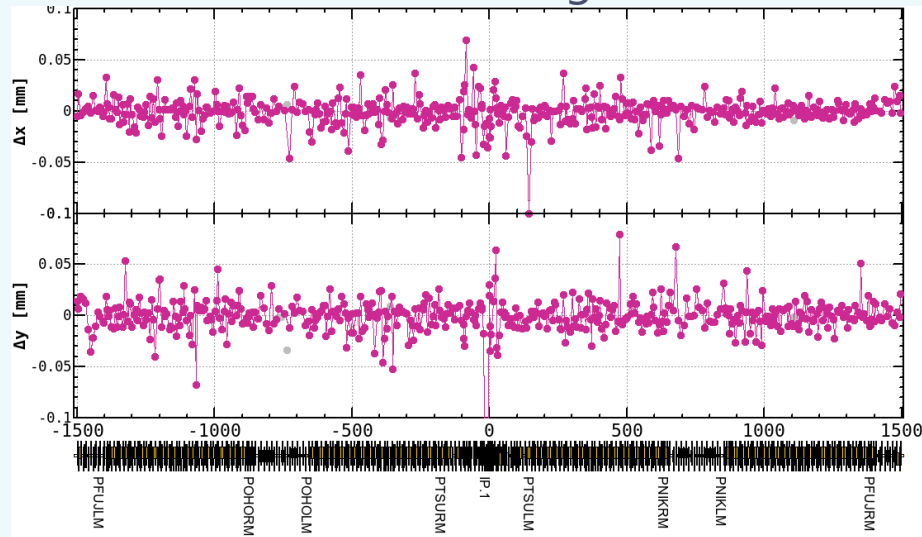
- Residual of the orbit correction is about 20~30 microns in RMS.
- Optics correction is performed on a reference orbit.
- A reference orbit is updated just after The optics correction.

Degradation of Closed Orbit

History of residual of closed orbit



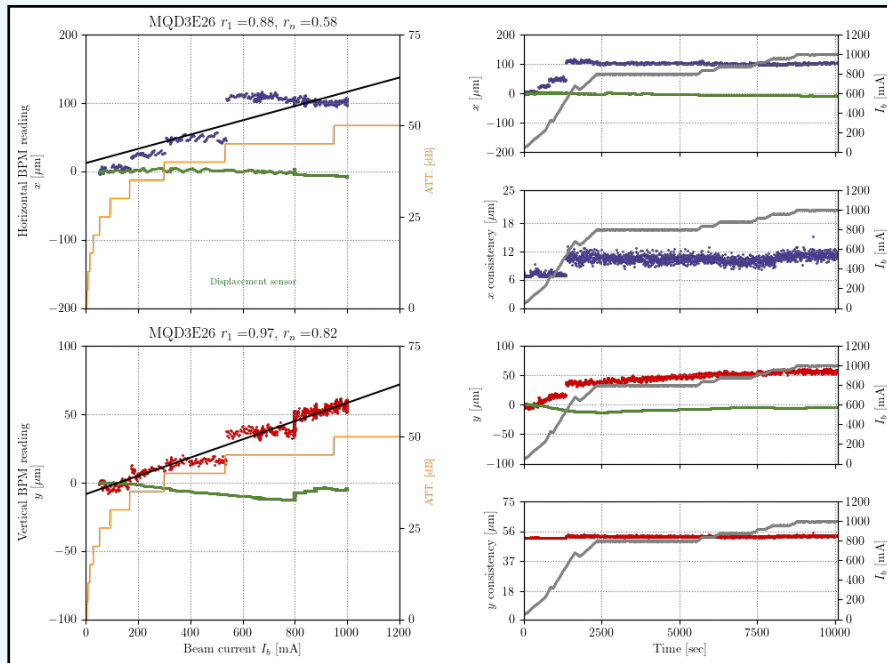
Orbit deviation during ~1 week



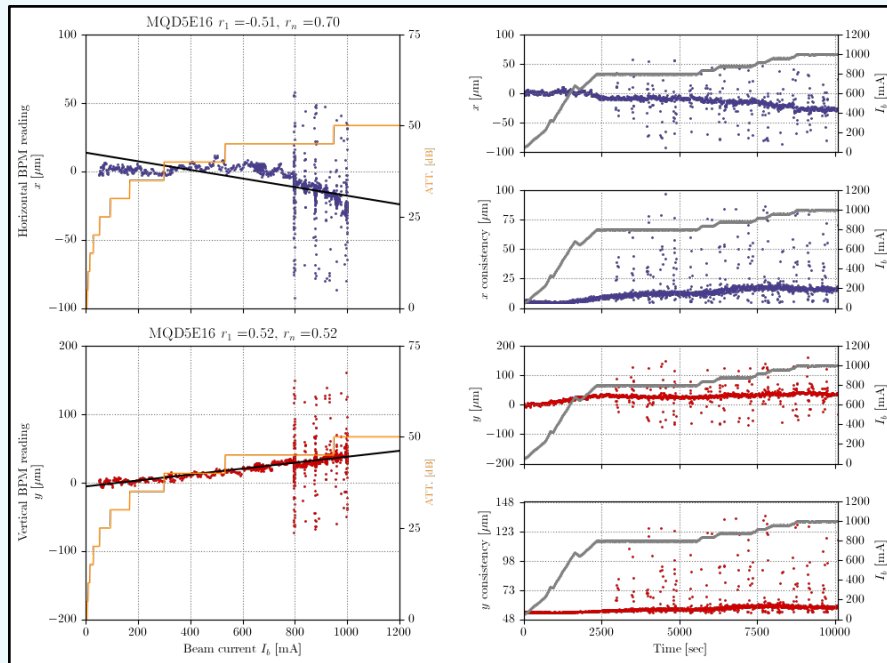
- Residual of the closed orbit is 20-30 micron.
- Unexpected large orbit changes (Spikes shown in the right figure) should be investigated.

Some Examples of BPM

Beam position jump by attenuator switching

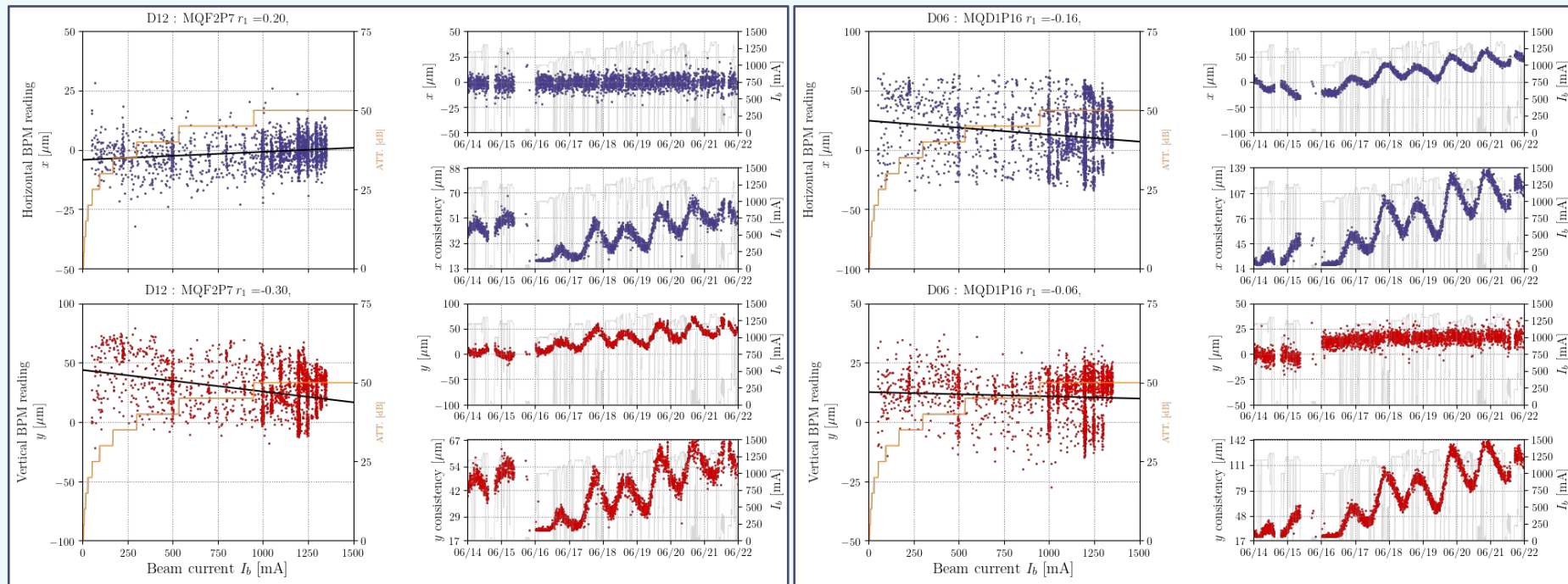


Orbit fluctuation at high beam current

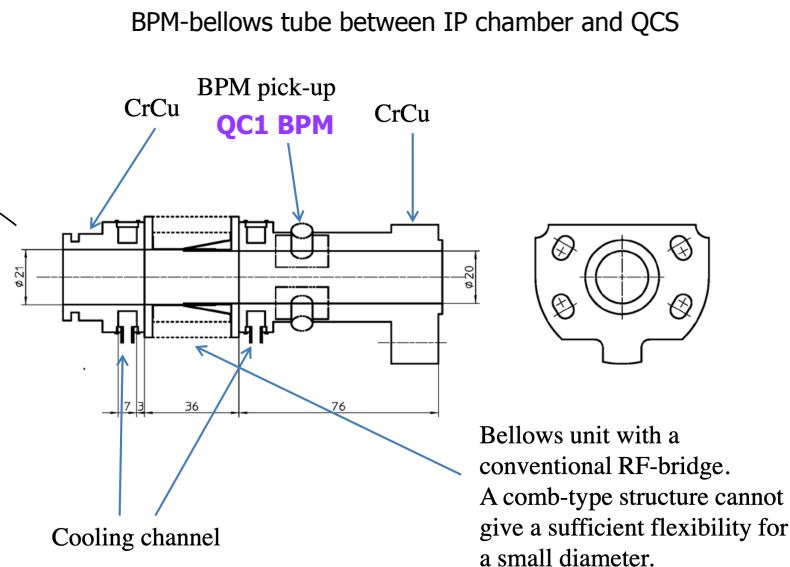
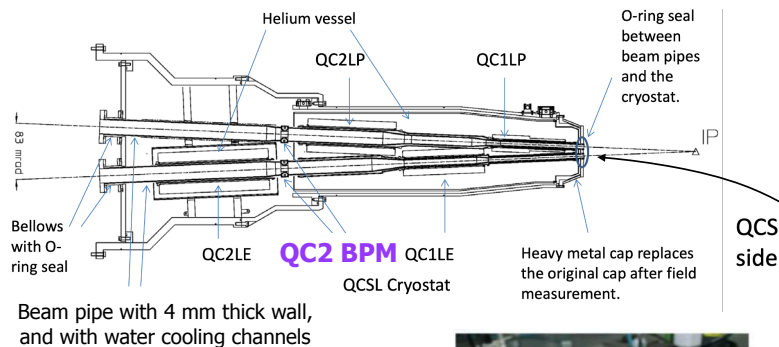


Some Examples of BPM

Day night effects



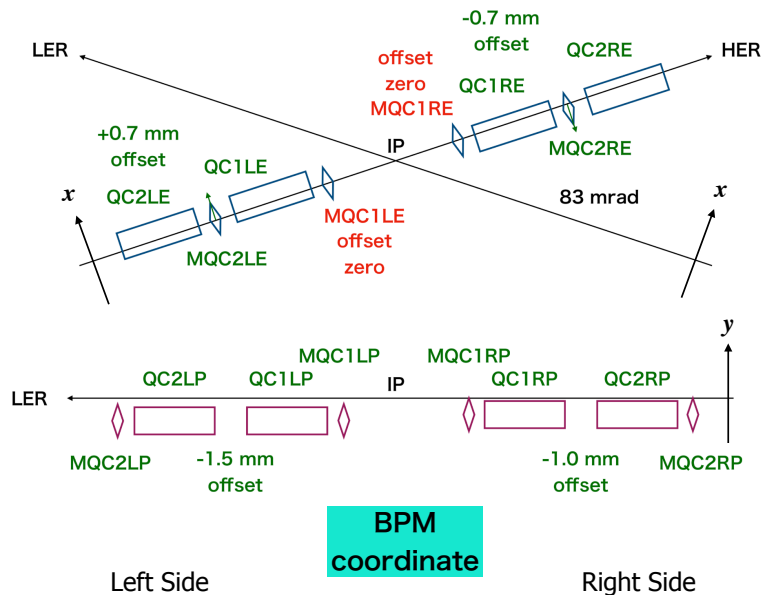
K. Kanazawa, FCC-ee MDI WS, 2018



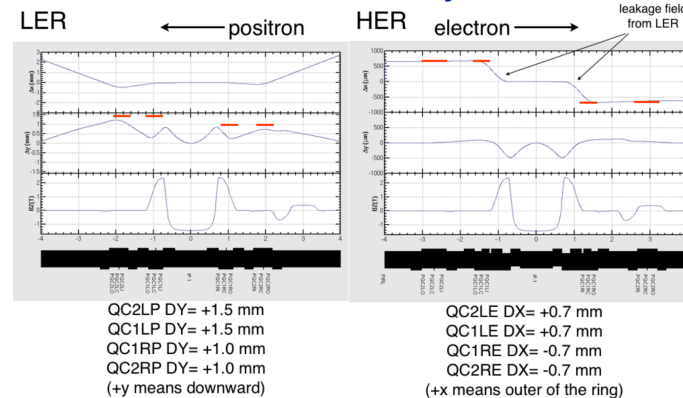
QC1 BPM is not fixed at QC1.
There is a bellows between QCS and QC1 BPMs.

2

Horizontal crossing angle: 83 mrad



Orbit in the vicinity of IP



SAD coordinate

	SuperKEKB : June 8, 2022		SuperKEKB : May 22, 2022		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	1321	1099	744	600	mA
Number of bunches	2249		1565		
Bunch current	0.587	0.489	0.475	0.383	mA
Horizontal size σ_x^*	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y^*	0.303		0.250		μm^{*1}
Vertical size σ_y^*	0.215		0.177		μm^{*2}
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.574	
β_x^* / β_y^*	80 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	mm
Piwinski angle	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	40	%
Beam-Beam parameter ξ_y	0.0407	0.0279	0.0309	0.0219	
Specific luminosity	7.21×10^{31}		8.74×10^{31}		$\text{cm}^{-2}\text{s}^{-1}/\text{mA}^2$
Luminosity	4.65×10^{34}		2.49×10^{34}		$\text{cm}^{-2}\text{s}^{-1}$

*1) estimated by luminosity with assuming design bunch length

*2) divide *1 by $\sqrt{2}$

Design Machine Parameters

2017/September/1	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	
ϵ_x/ϵ_y	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(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		mrاد	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		() : zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	() : zero current
v_s	-0.0245	-0.0280		
v_x/v_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$	