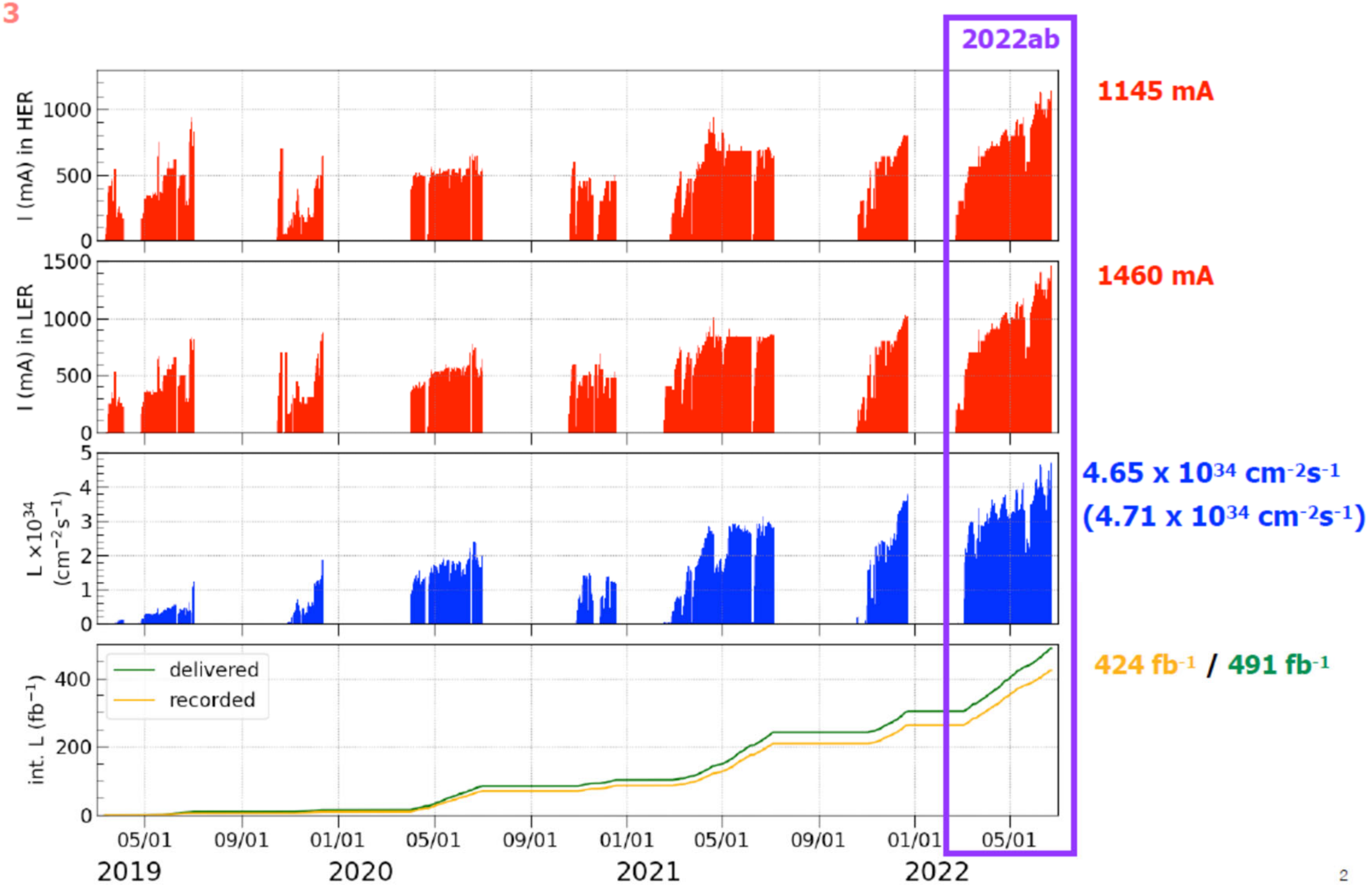
# *Status of SuperKEKB Accelerators*

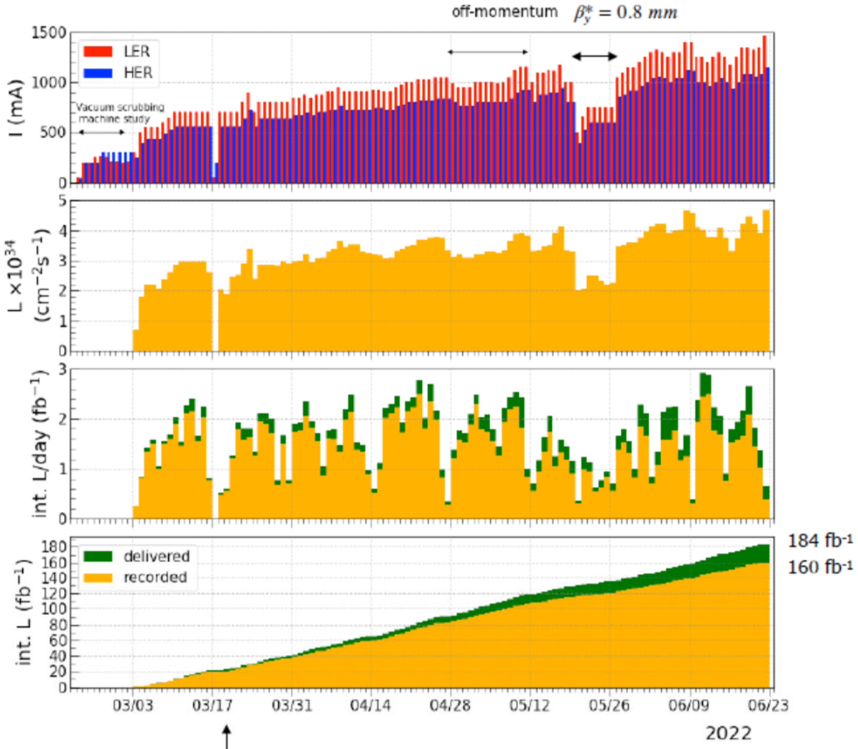
Makoto Tobiyama (KEK Accelerator Laboratory) for SuperKEKB Accelerator Team

# Recent operation

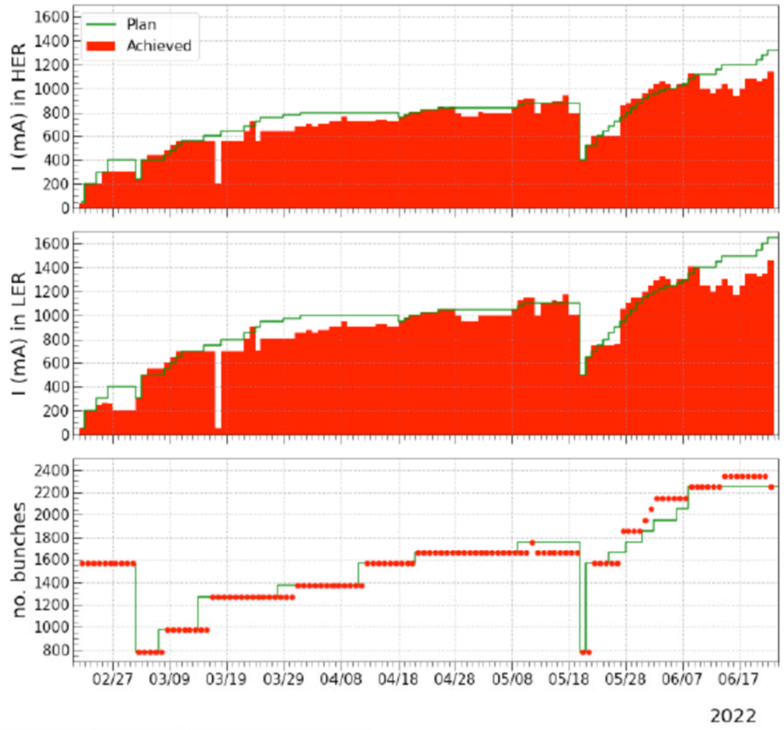
SuperKEKB Phase 3



# 2022ab Run




Accidental fire of LER injection kicker on March 18
The reserver voltage of thyratron was adjusted.




| Integrated luminosity | Recorded | Date | Delivered | Date |
|---|---|---|---|---|
| Shift ($pb^{-1}$) | 958.1 | April 24, swing, 2022 | 1035.9 | April 22, swing, 2022 |
| 1 days ($fb^{-1}$) | 2.503 | April 22, 2022 | 2.912 | June 11, 2022 |
| 7 days ($fb^{-1}$) | 15.001 | April 18 - April 24, 2022 | 16.599 | April 18 - April 24, 2022 |

3

# *Especially on 2022b runs*

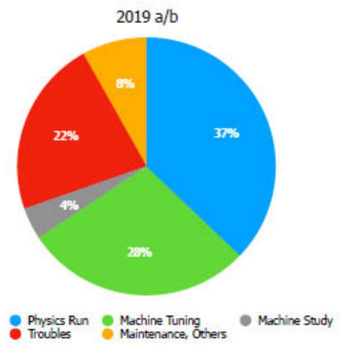
- Strongly required to get higher "peak" luminosity for the 10-years evaluation process of MEXT.
  - Decided to skip various machine studies to understand machine.
  - Could not repair damaged collimator heads.
  - Needed to skip the regular maintenance.
- Due to crazily rising electricity costs, we had no choice but to discontinue operation and enter LS1.
  - The rising of electricity costs is continuing– we are doing our best to reduce the standby power after stopping the operation of 2022b.
    - (Almost) stop the water pumps.
    - Stop the air conditioning of the power supply buildings and the arc section of the tunnel.
    - Tuning off the lights of the tunnel in the night.
    - 25Hz operation of Linac.

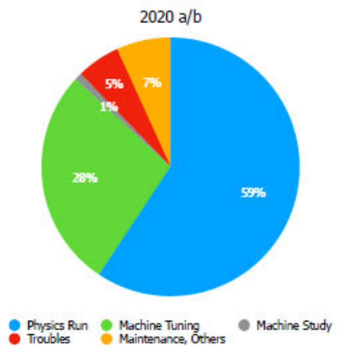
# *Achieved up to now..*

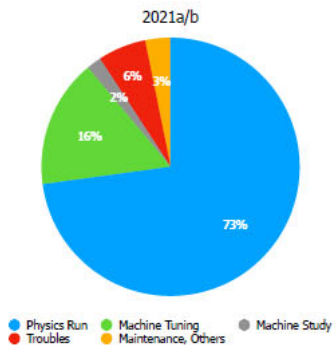
- Peak luminosity : 4.65 x $10^{34}$ $cm^{-2}s^{-1}$ (4.71 x $10^{34}$ $cm^{-2}s^{-1}$ w/o Belle II data taking)
- Integrated luminosity : 424 $fb^{-1}$ (491 $fb^{-1}$)
- Peak currents : 1.46 A (LER) / 1.14 A (HER), 2346 bunches (2-bucket spacing)
- $\beta y^*$: 1 mm (0.8 mm) << bunch length ~6 mm -> proof of the nano-beam scheme
- Crab waist scheme has been applied (80 % in the LER, 40 % in the HER).
  - luminosity improvement
- Beam-Beam parameter : 0.035 at 0.7 mA (0.045 at 1.1 mA for small number of bunches)
- Bunch-by-bunch FB tuning (gain, noise reduction) in the HER ->luminosity improvements
- Bunch-by-bunch FB tuning (number of taps) in the LER ->suppress single bunch blowup, luminosity improvements
- Chromatic X-Y coupling correction with rotatable sextupoles in the LER ->luminosity improvements

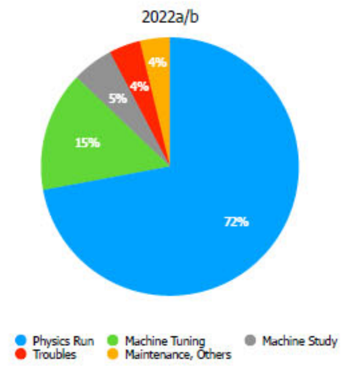
- Long-term drift of QCS magnetic field (beta-beat) <-reduced by new QCS initialization procedure
- Orbit deviation due to IP knob tuning (beta-beat) <- suppressed with QCS corrector (ZHQC2RP)
- Increase of positron charge for the LER injection : 3 nC at the end of e+ beam transport line
- 2-bunch injection for the LER and HER ->improve injection efficiency
- Adjustment of injection orbit in the HER (septum, kicker) ->improve injection efficiency (not enough)
- Reduce leakage orbit from injection kickers <- reduced by additional inductance for the coils

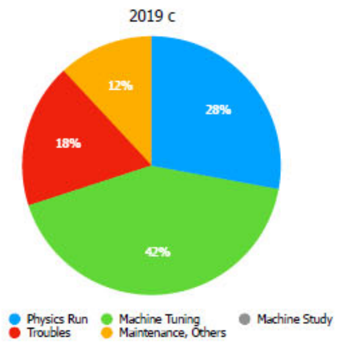
# Operation Statistics

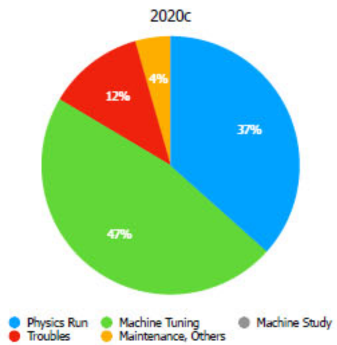


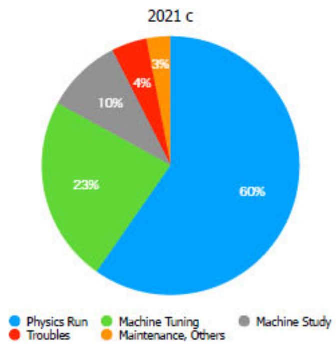



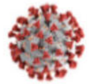

**Operation statistics 2019 -2022**

# Machine parameters

## Machine Parameters

| | 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 $\sigma_x^*$ | 17.9 | 16.6 | 17.9 | 16.6 | μm |
| Vertical cap sigma $\Sigma_y^*$ | 0.303 | | 0.250 | | μm*1 |
| Vertical size $\sigma_y^*$ | 0.215 | | 0.177 | | μm*2 |
| Betatron tunes $\nu_x$ / $\nu_y$ | 44.525 / 46.589 | 45.532 / 43.573 | 44.525 / 46.589 | 45.532 / 43.574 | |
| $\beta_x^*$ / $\beta_y^*$ | 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 $\xi_y$ | 0.0407 | 0.0279 | 0.0309 | 0.0219 | |
| Specific luminosity | $7.21 \times 10^{31}$ | | $8.74 \times 10^{31}$ | | $cm^{-2}s^{-1}/mA^2$ |
| Luminosity | $4.65 \times 10^{34}$ | | $2.49 \times 10^{34}$ | | $cm^{-2}s^{-1}$ |

← twice the size of COVID-19 virus



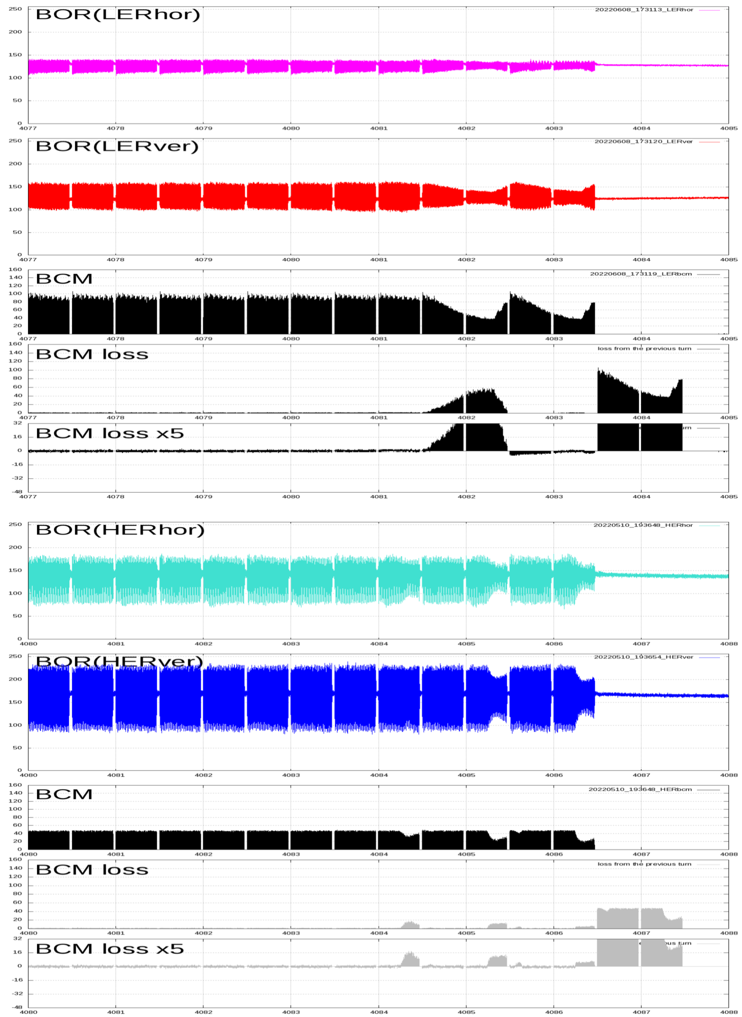
*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

6

# Challenges to improve luminosity

- **Sudden beam loss and damage to the vertical beam collimators**
  - Damaged collimator(s) increases transverse impedance, which makes the threshold of TMCI much lower.
  - Not easy to increase the bunch current.
  - Will be presented in the Ikeda-san's talk.
- **Beam blowup in the LER**
  - Some (or most) of the sources might be coming from the higher transverse beam impedance.
- **IR Optics ($\beta y*$) modulation due to stored current (HER)**
  - Beam-line deformation, especially around the strong sextuplole magnets.
- **Shorter beam lifetime, especially in LER**
- **Injection efficiency and stability of the injector**
  - Emittance growth coming from beam transport line
  - Injection background

# Sudden beam loss

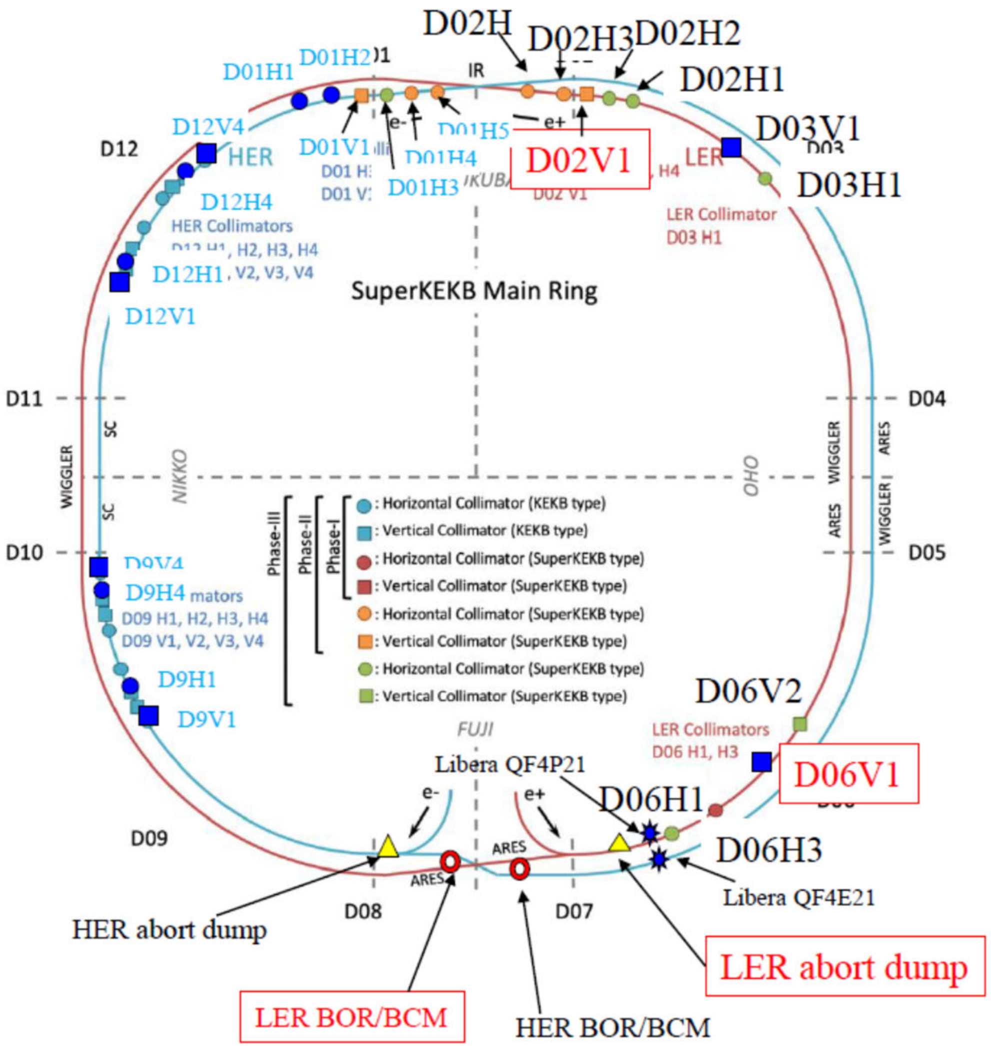



- Without growing the transverse motion, some part of bunches drops within 1–2 turns.
  - Occurs in both LER and HER, but the damage in LER is much greater (QCS quench, vertical collimator damage, etc)
  - After damaging the collimator heads, many unwanted side-effects happen.
    - Much larger background.
    - Larger transverse beam impedance.
- Started ITF-sudden beam loss subgroup.

# Location of BOR/BCM

BOR = Beam Orbit Recorder
BCM = Bunch Current Monitor

https://www.pasj.jp/web_publish/pasj2016/proceedings/PDF/TUOM/TUOM06.pdf

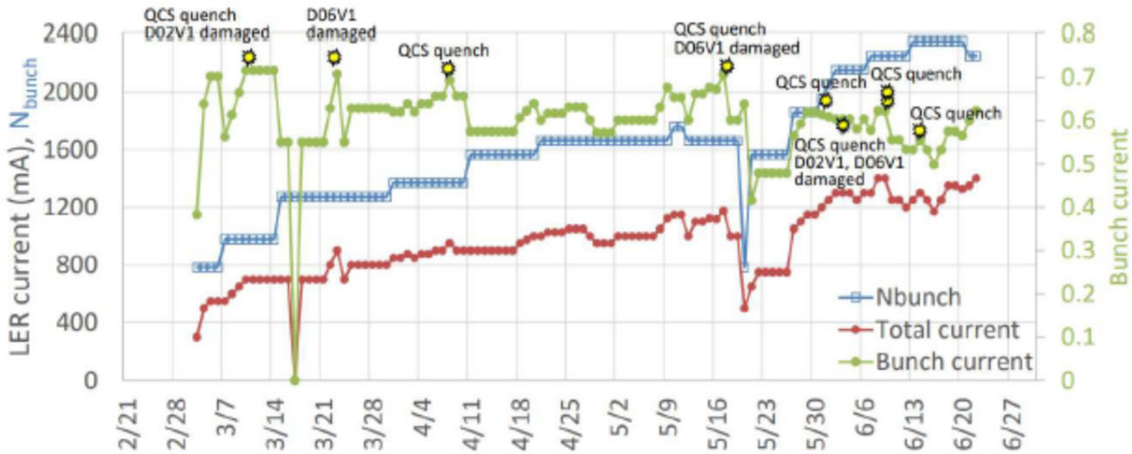



Two fast beam monitors in the ring

- VXD diamond at IP
- BOR/BCM at Fuji

# Beam(bunch) current

- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER.
- It is likely to occur when a certain bunch current is exceeded.
- We don't know if it will happen even with a single beam operation, low current beam because we haven't operated for a long time.

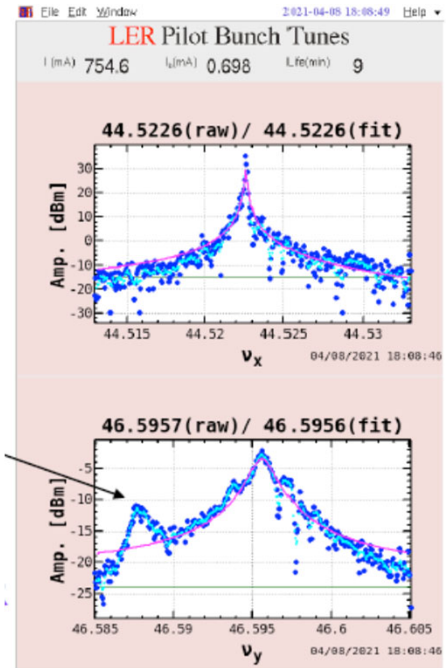


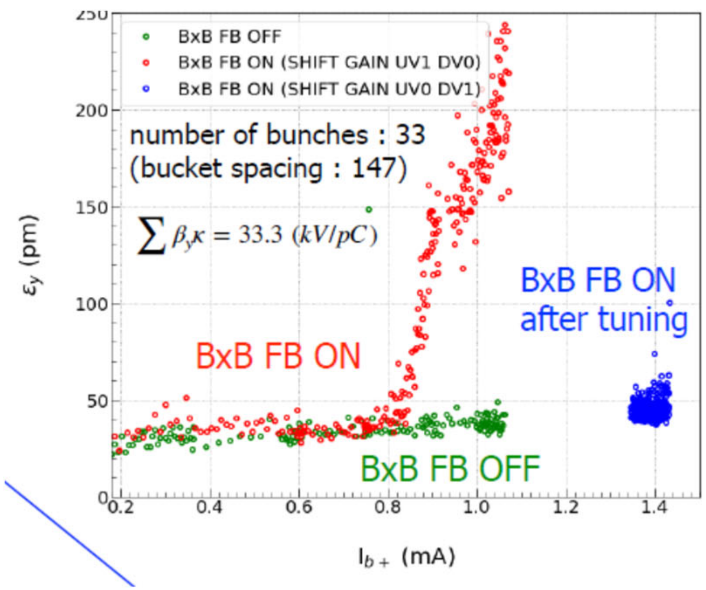

(K.Matsuoka)

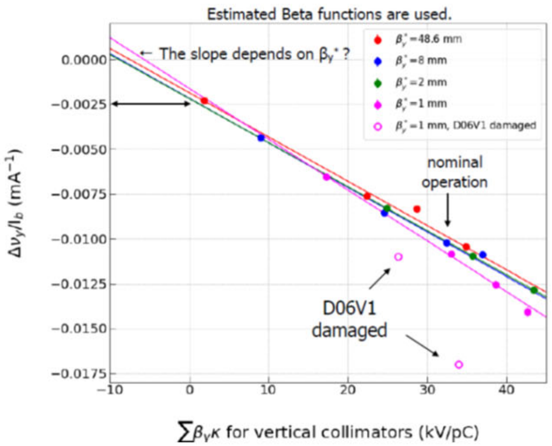
# *Beam blowup in LER*

## ■ Bunch current dependent– TMCI related.

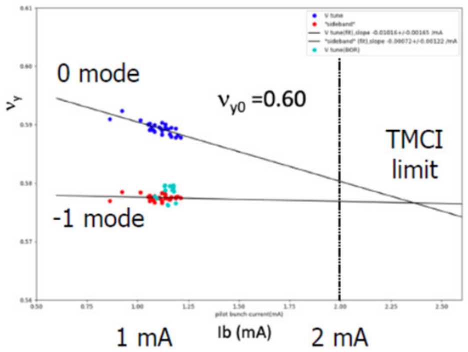
- With the increase of the bunch current, the synchro-betatron sideband (νy+νs) appears (and will finally merge).
- Also coupled with the side-effect of transverse BxB feedback system.
  - Large phase shift coming from the many-tap filter (10 tap FIR) reduced the gain margin of the system, finally excited dipole oscillation at the sideband.
  - By reducing the number of FIR taps (10 ->4), the phase shift in the digital filter was mitigated and the dipole oscillation at the sideband was suppressed.



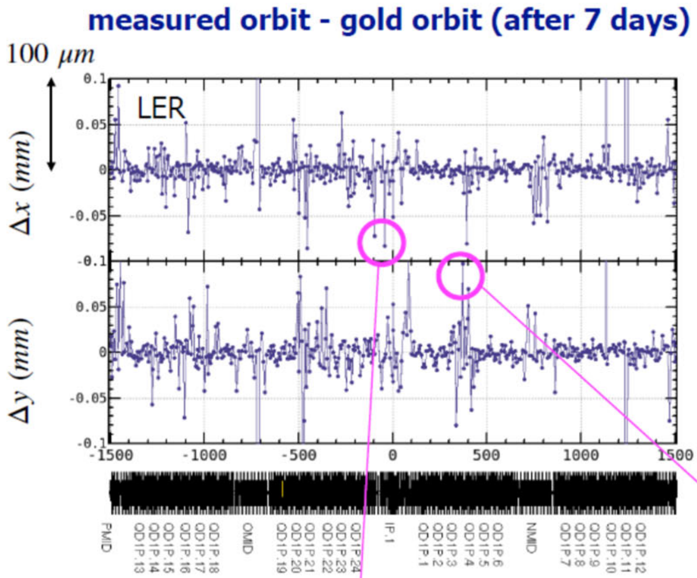



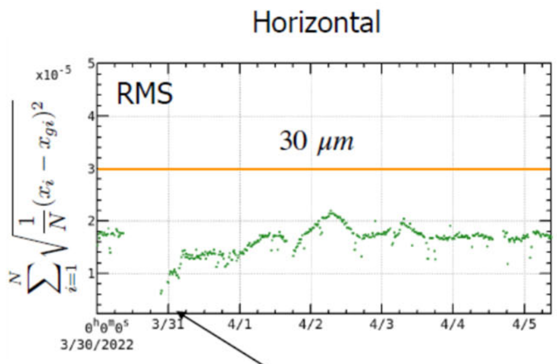



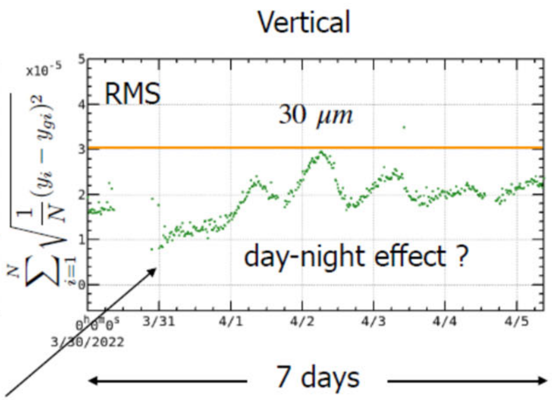
- The threshold seems depend on the aperture of vertical collimators (transverse impedance), selection of vertical tune, vertical chromaticity, BxB FB settings + damage of the head of vertical collimator.
- With the severe damage of the heads of the vertical collimator, the transverse impedance has been increased and the threshold had dropped less than 0.8mA/bunch.
- Non-linear collimator should help to reduce the transverse impedance.



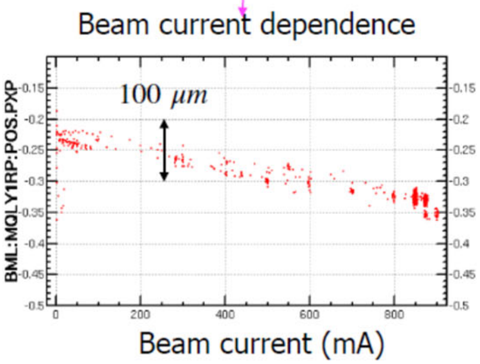
# IR Optics (βy*) modulation due to stored current (HER)

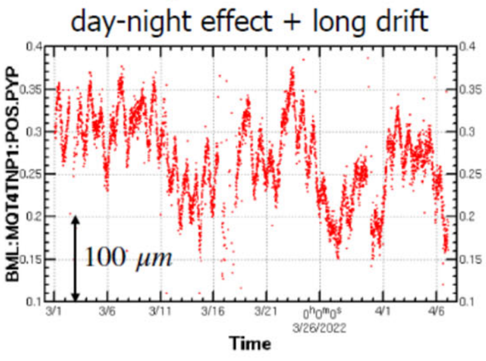



BPM gain mapping
optics correction
set the gold orbit




Number of large BPMs is about 20 - 30.
(RMS is larger than 40 μm)

The deviation comes from:

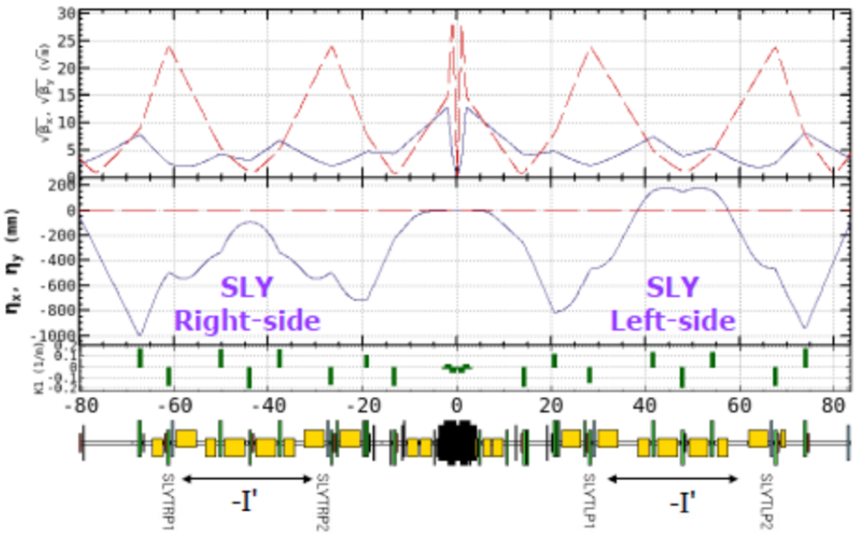
1. beam current dependence
(beam line deformation due to intense SR)

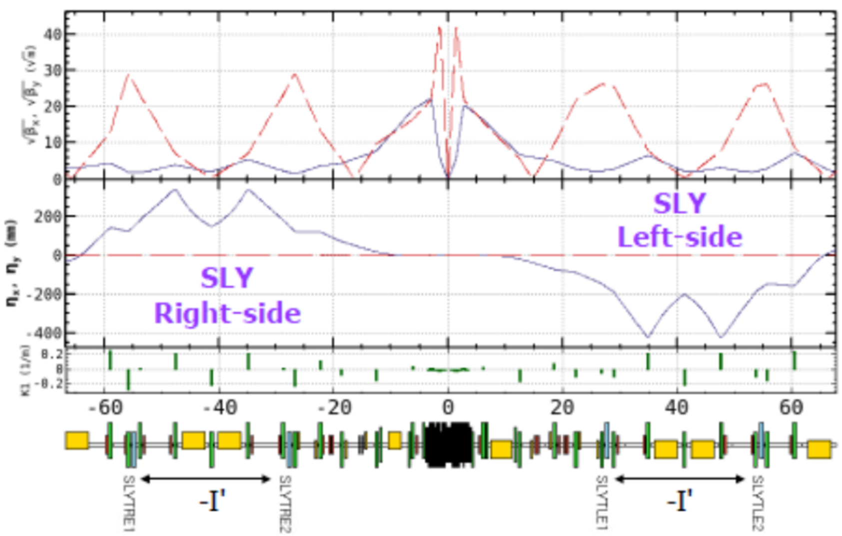
2. day-night effect (atmospheric temperature)

3. Gain of each probe changes.

## Strong Sextupoles (SLY) for Local Chromaticity Correction

**LER** $\beta_y^* = 1\ mm$ **HER**




K2: 1.23 1/m² K2: 3.48 1/m² K2: 1.33 1/m² K2: 3.53 1/m² K2: -8.76 1/m² K2: -9.62 1/m² K2: 8.36 1/m² K2: 7.66 1/m²

$\beta_y = 521\ m$ $\beta_y = 525\ m$ $\beta_y = 702\ m$ $\beta_y = 675\ m$

$\Delta\nu_y = \frac{\beta_y}{4\pi} K_2 \Delta x$ ~0.0028 for $\Delta x = 20\ \mu m$

Horizontal tune shift can be ignored.

**Horizontal orbit in-phase for each pair of SLY induces large beta-beat which changes $\beta_y^*$.**

$\Delta\nu_y$ ~0.01 for $\Delta x = 20\ \mu m$

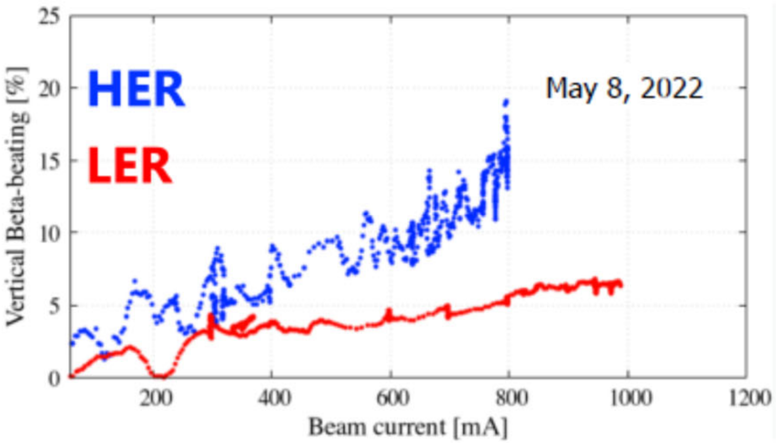
3.6 times larger than LER

30

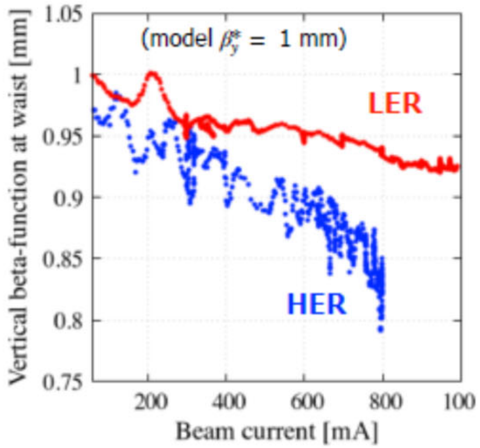
H. Sugimoto
H. Koiso

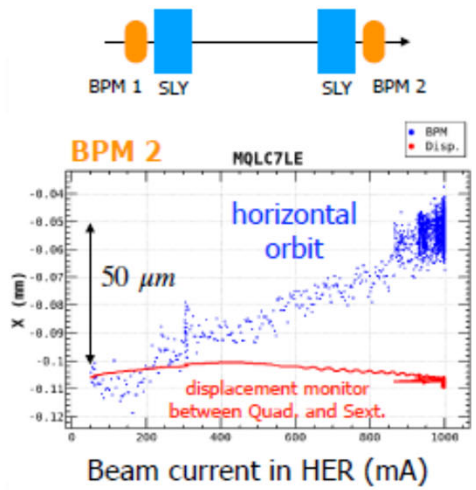
The SR heating deforms the beam line.
The horizontal orbit deviation induces tune shift and beta-beat. As the result, $\beta_y^*$ also changes.
The orbit deviation in the local chromaticity correction (SLY) is always in the outward direction of the ring.
This implies a squeezing of $\beta_y^*$. The HER is larger effects rather than the LER.

$$\frac{\Delta\beta_y}{\beta_y} = \frac{1}{2\sin 2\pi\nu_y}\oint \beta_y(K_2\Delta x)\cos\{2(\pi\nu_y + \psi_s - \psi)\}ds$$



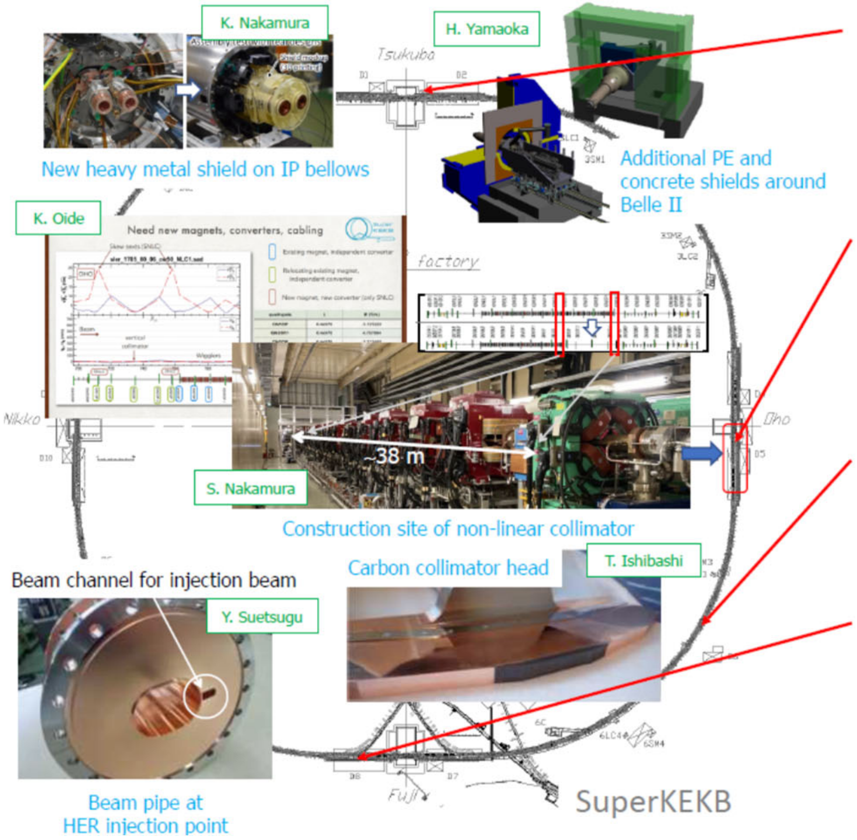

$\beta_y^* = 0.89mm$ for $\Delta x = +20\ \mu m$
at the strong sextupole (SLYTLE1)



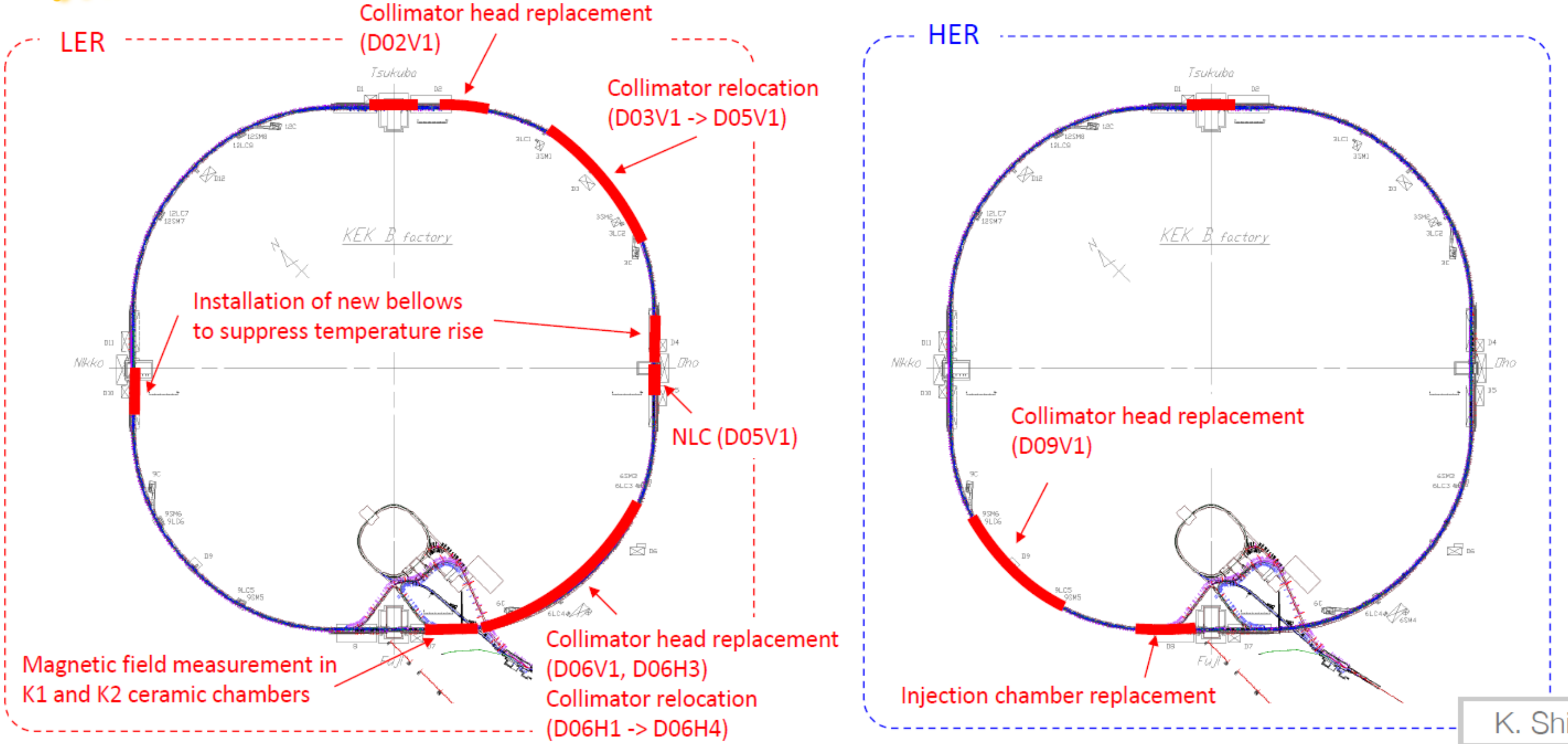

We adopted the local orbit feedback by using local bumps at the strong sextupoles since the end of May, 2022.

# Long Shutdown 1



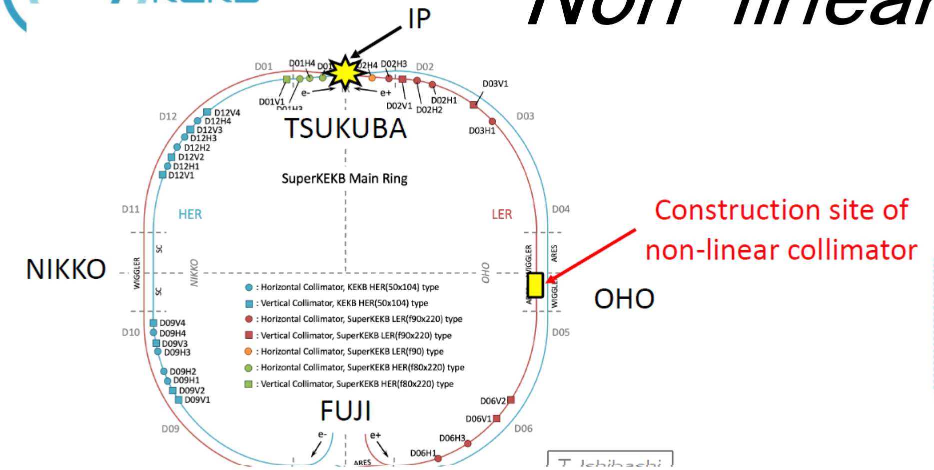

- IR radiation shield modification
  - For BG reduction
    - New heavy metal shields around IP bellows
    - Additional concrete & polyethylene shields around Belle II
    - Material change from W to SUS of QCS cryostat front plate
- Nonlinear collimator (LER)
  - For impedance and BG reduction
    - New collimation scheme less likely to cause TMCI
    - Removal of 50 wiggler magnets
    - Installation of 2 skew sextupole and 5 quadrupole magnets
    - Installation of new vertical collimator with wider aperture
- Robust collimator head (LER)
  - As countermeasure against kicker-pulser misfiring and resulting destruction of collimator
    - Replacement with carbon head of horizontal collimator D06H3
- New beam pipes with wider aperture at HER injection point
  - For improvement of injection efficiency
    - New beam pipes with wider aperture
    - New BPM for precise measurement of injected beam.

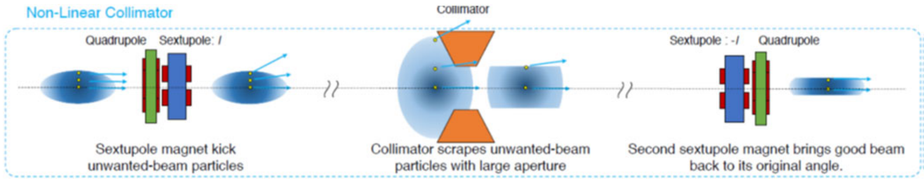
# Vacuum work locations during LS1

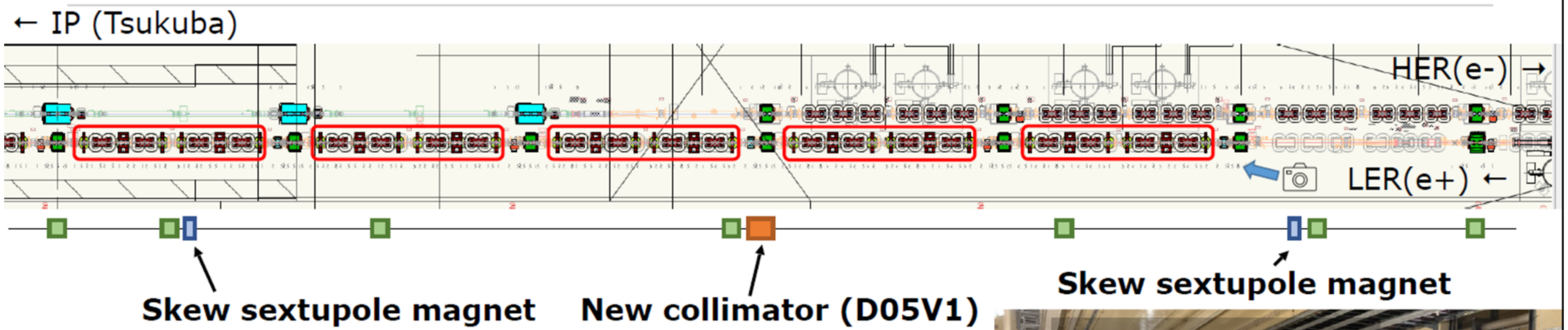



K. Shibata

# Non-linear collimator

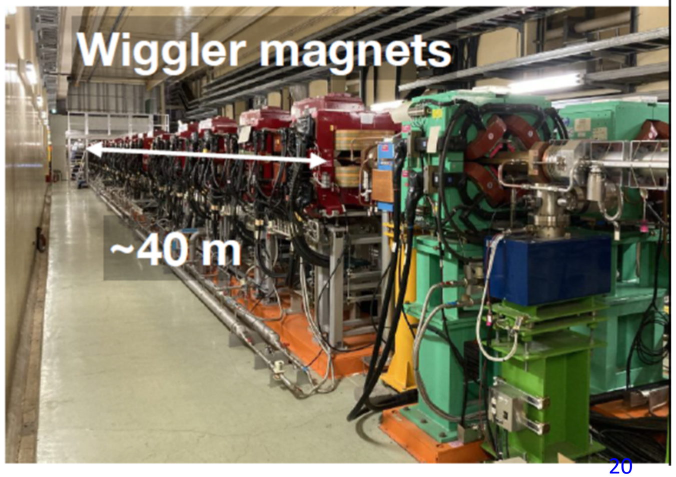



- Take away these wiggler magnets.
  Twenty double pole magnets, ten single pole magnets, ten half pole magnets.
  The weight of the power cable, which is removed together with magnets, is about 3000 kg.
- Relocation quadrupole magnets.
- Install a pair of new skew sextupole magnet.
- Install new vertical collimator (D05V1).

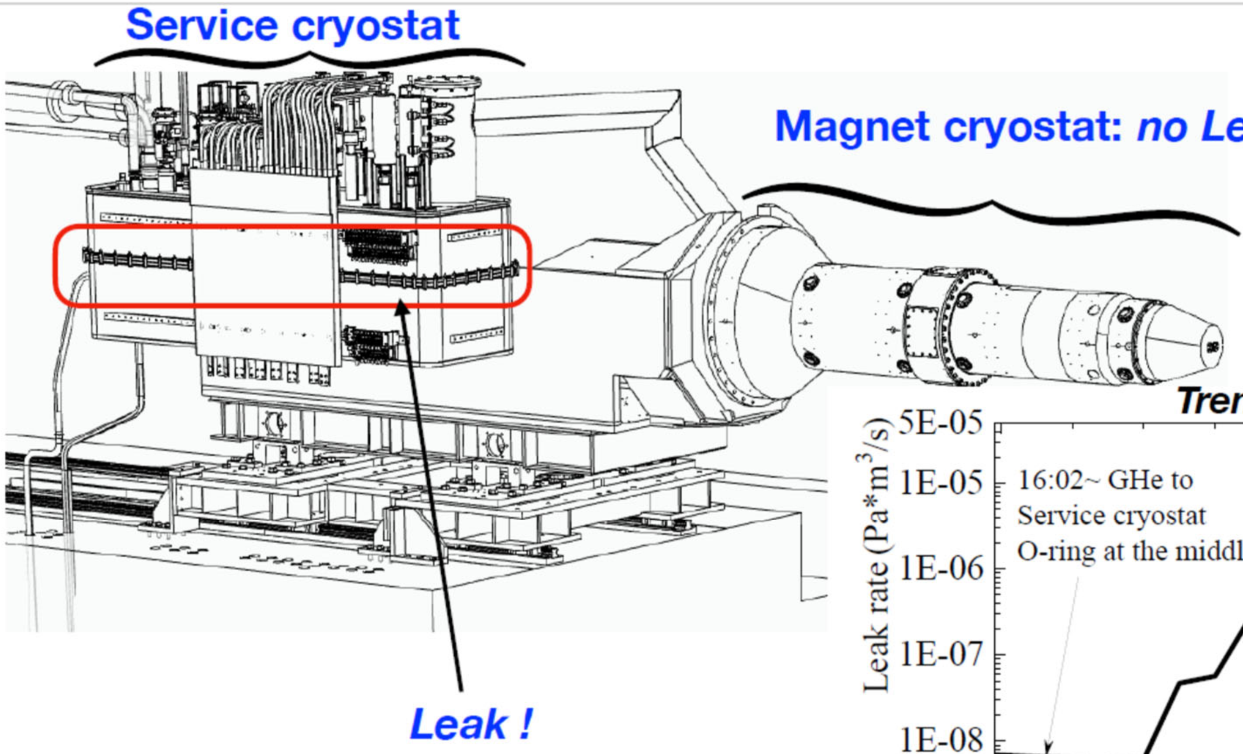
Now we start to remove the wiggler magnets.

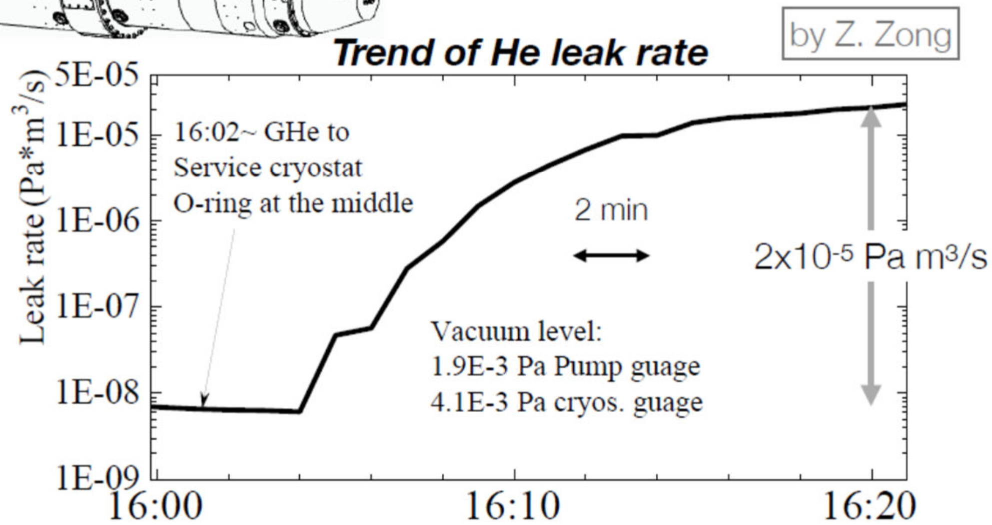


# QCS-R cryostat leak hunting

- **QCS-R and L have been retreated.**
  - Leak check on QCS-R cryostat has been made

## Leak area of QCS-R

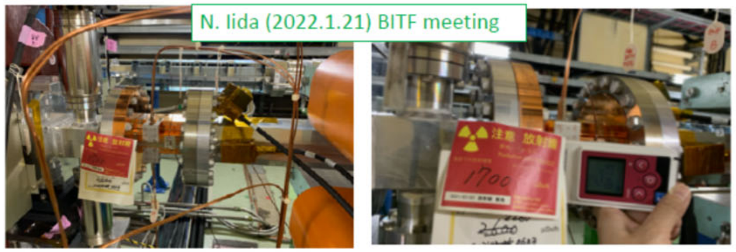


# HER injection line physical aperture

- Problem of HER injection
  - Wall can be an obstacle to injection.
    - A wall should be placed between beam channels for stored beam and injected beam.
    - Injected beam orbit is too close to the wall.
    - High levels of radiation detected at the injection BPM chamber indicates that the injected beam hits the wall.
    - It is hard to modify the injection beam orbit.

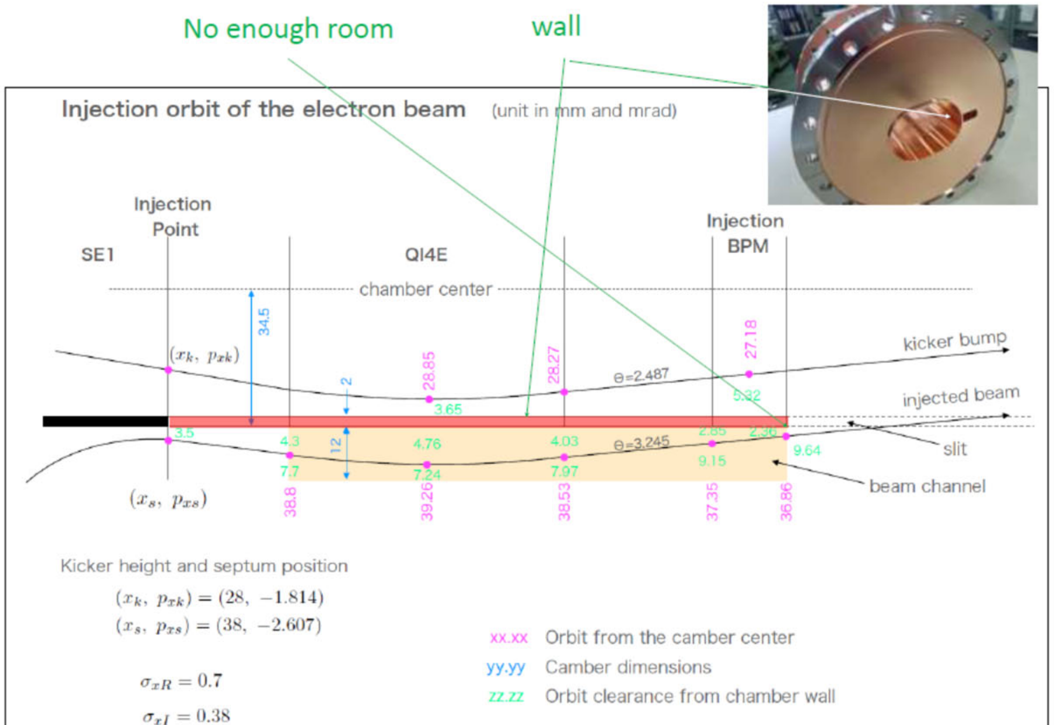
    ⇒ it is necessary to enlarge the horizontal aperture of the injection channel.



N. Iida (2022.1.21) BITF meeting

  - What is planned during LS1
    - Replacement of three beam chambers with new ones.
    - Update of injection BPM

    ⇒ More precise injection tuning

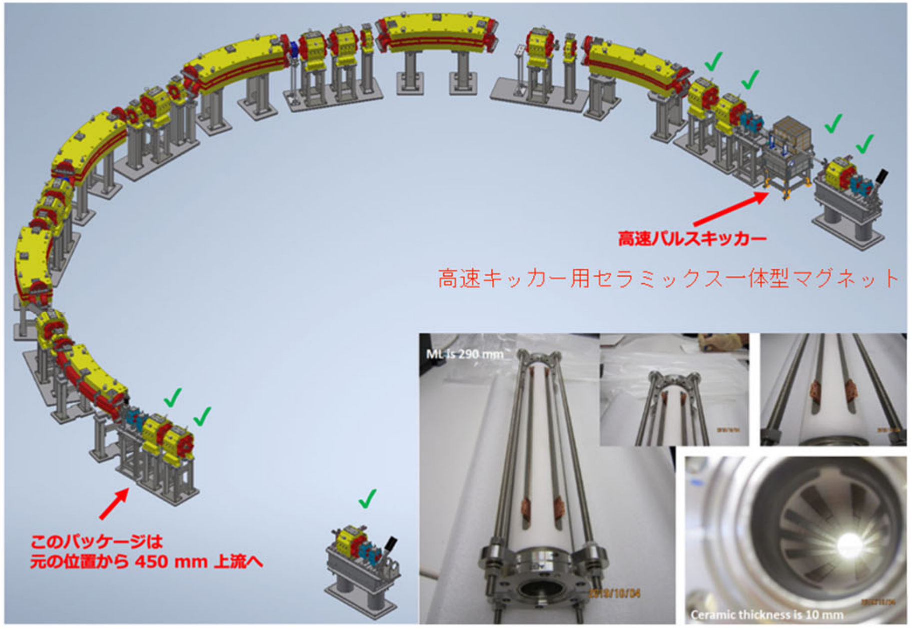


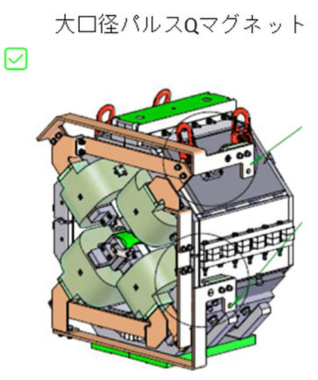

M. Kikuchi (2021.12.03) BITF meeting

K. Shibata

# (LS1) upgrade for Injector

- Fast pulse magnets will be installed at the J-arc and the sector 5 to control the orbit of two bunches independently.
- Large aperture pulse Q will be installed at the end point of J-arc to optically match the e- and e+ (primary high charge e-) beam independently.
- Install 4 sets of large aperture pulse Q magnets around 1-2 sectors to make optical matching for both high energy e- and low-energy e+ beams and to reduce the emittance growth consequently.



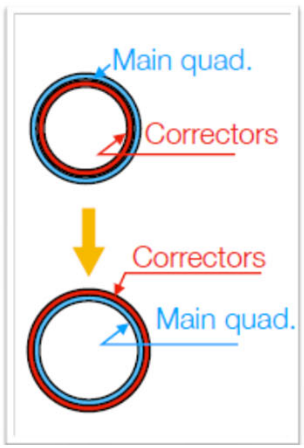



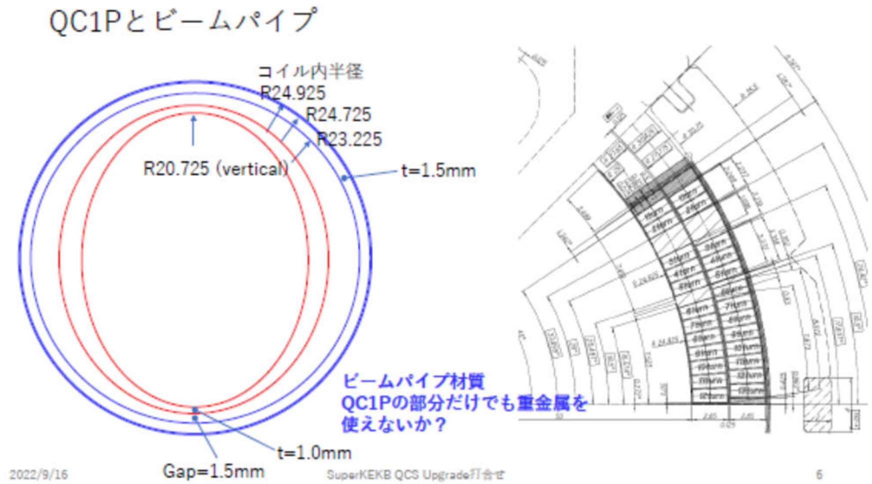
# *Design study for LS2 upgrade*

- We are revisiting the investigation of IR (including QCS) section to achieve much higher luminosity.
- Beam optics study with possible QCS design.
- QCS group are starting considering magnet re-design.
- Vacuum group and QCS group are working for the possible mechanical design.

Option-3

QC1P cross section



# *Summary*

- Peak luminosity of $4.7 \times 10^{34} cm^{-2} s^{-1}$ has been achieved
- Demonstrated stable operation over 1A in the LER (with smaller bunch current less than 0.7mA/bunch)
- Sudden beam loss is serious challenge to increase luminosity and beam current, up to now.
- Many other challenges:
  - Beam blowup in LER
  - Beam line deformation with HER beam current
  - Shorter beam lifetime; both dynamic aperture and physical aperture (beam collimators), need to clarify the effect of crab waist.
  - Injection efficiency, long-term stability of the injector.
- Several upgrade items during long shutdown 1.
- Re-starting design study for LS2 upgrade.