Status report of vacuum system in SuperKEKB

eeFACT2022

2022-09-15

WG9: Vacuum

T. Ishibashi on behalf of KEKB vacuum group

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Introduction - SuperKEKB

- Upgrade project of KEKB B-factory located at KEK Tsukuba campus.
- SuperKEKB accelerator is an electron-positron collider and has about 3 km in the circumferential length.
- The commissioning of the SuperKEKB started on 2016.

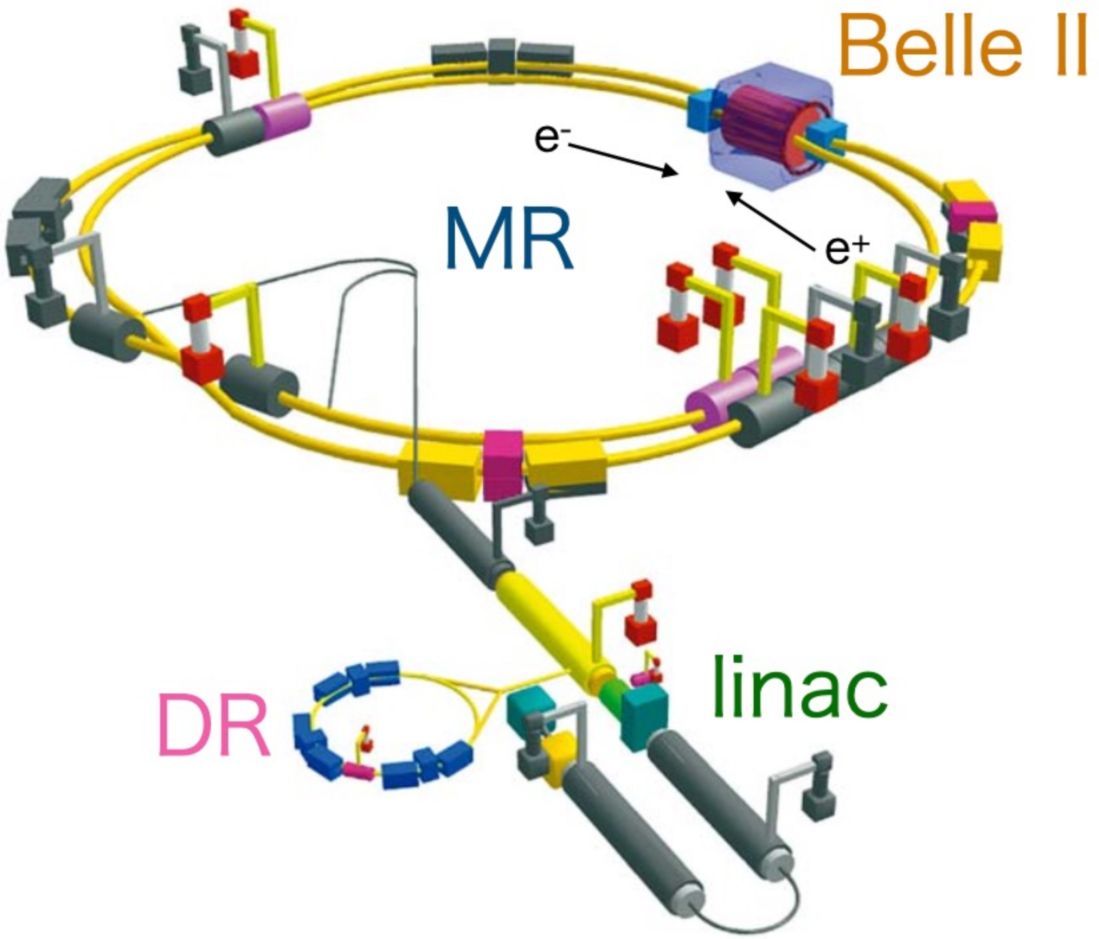
Aerial photo of KEK Tsukuba Campus

Introduction - SuperKEKB

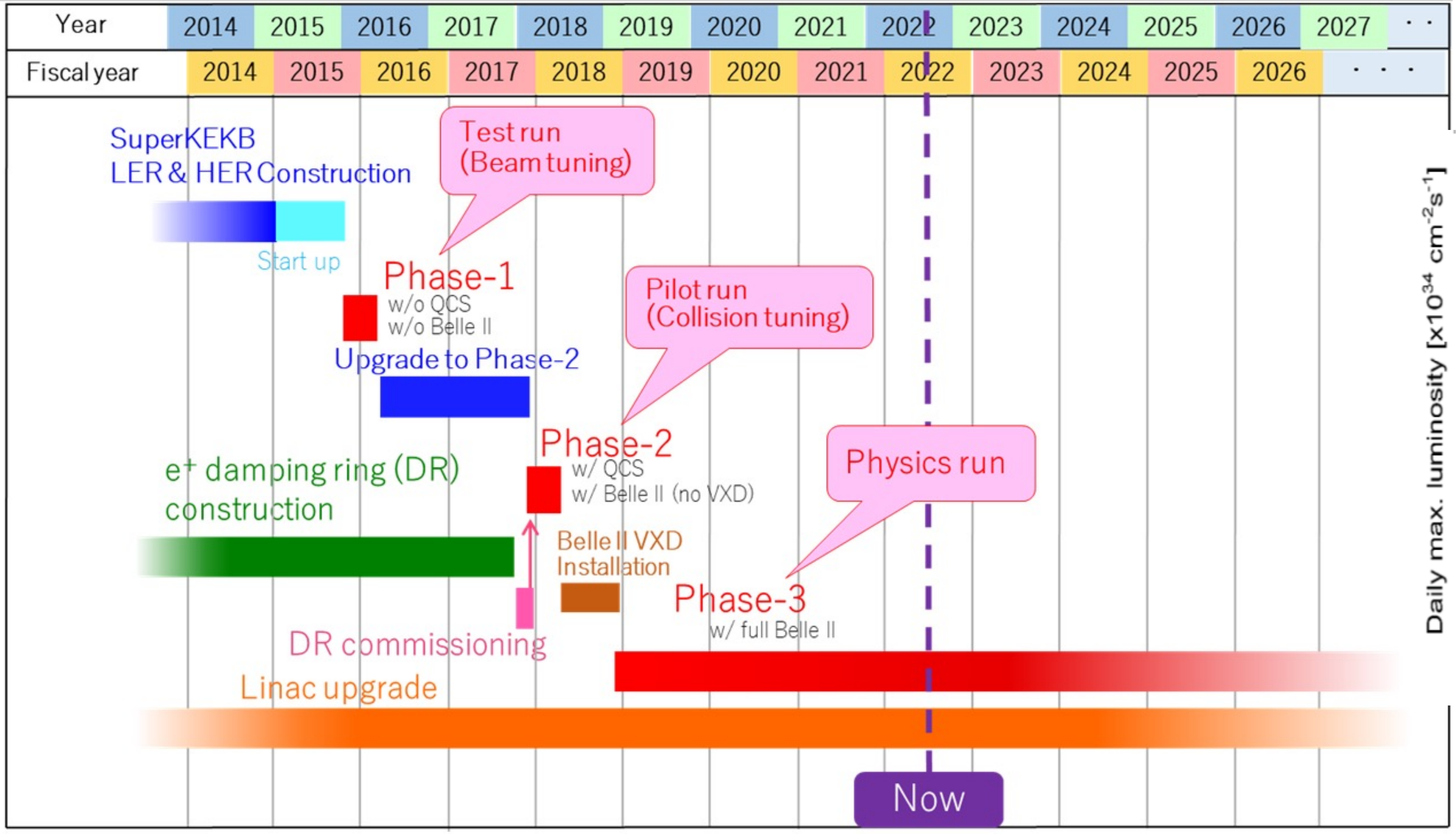
Main components of SuperKEKB

- Linac
  - Length: ~700 m
  - Provide electron or positron beams to 4-ring
    - ➢ SuperKEKB HER, LER
    - ➢ PF (Photon Factory): 2.5 GeV
    - ➢ PF-AR (Photon Factory Advanced Ring): 6.5/5 GeV
- DR (Damping Ring, positron)
  - Circumferential length: ~136 m
  - Energy: 1.1 GeV, 71 mA (design)
- MR (Main Ring)
  - Circumferential length: ~3016 m
  - HER (High Energy Ring, electron): 7 GeV, 2.6 A (design)
  - LER (Low Energy Ring, positron): 4 GeV, 3.6 A (design)
- Belle II (particle detector complex)
- The achieved peak luminosity is ~4.7×10^{34} cm^{-2} s^{-1} with 1.4 A in LER and 1.1 A in HER when the stored bunch number is 2249 during 2022 spring run, and this is the world record.

Schematic drawing of SuperKEKB



Introduction - Timeline



2010-2016: Construction (upgrade work from KEKB)

2016 Feb. to June: Phase-1 Test operation (beam tuning, vacuum scrubbing)

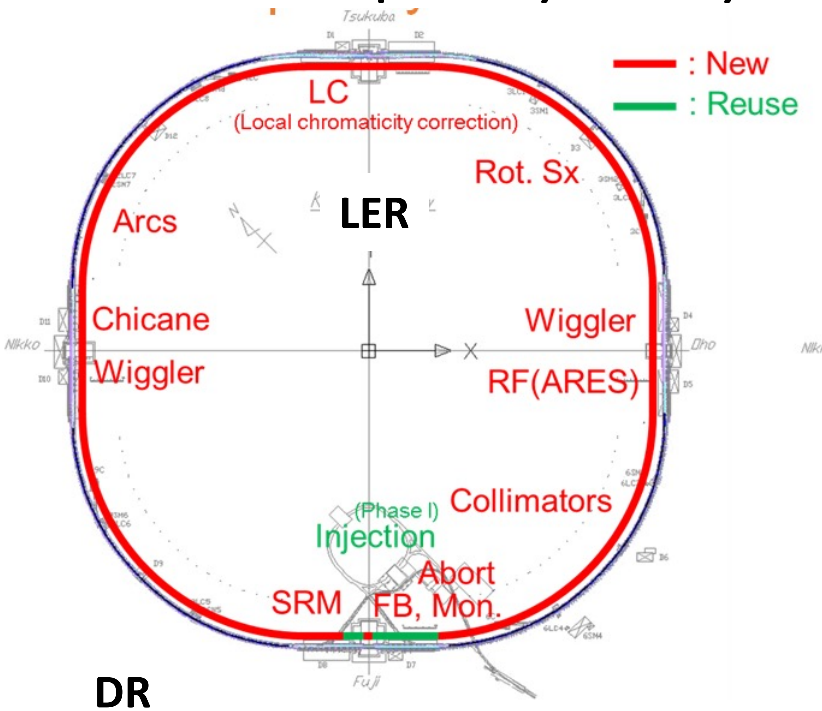
2018 Mar. to July: Phase-2 Commissioning operation (collision tuning)

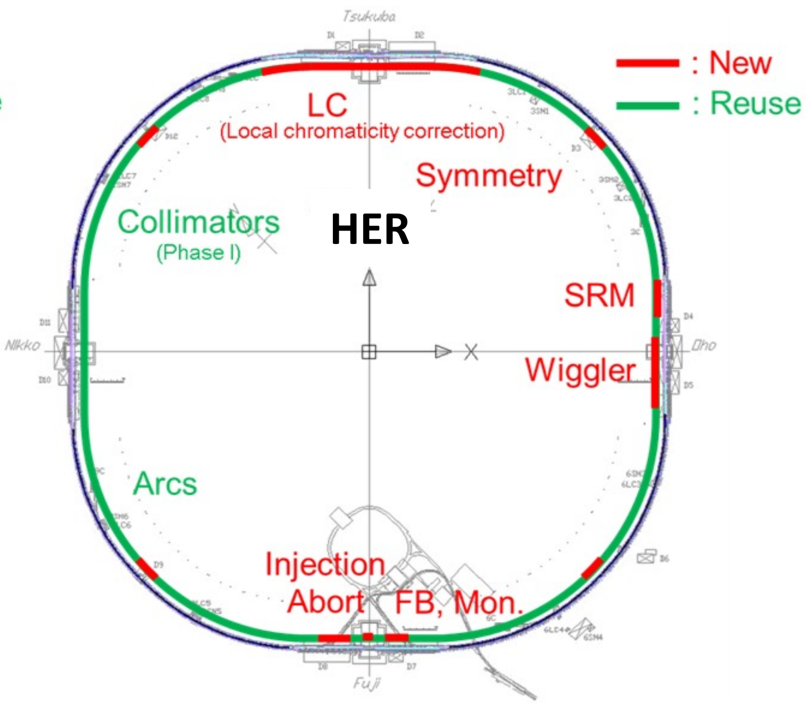
with final focusing SC magnets, Belle II, and DR

2019 Mar. to : Phase-3 Physics operation

Vacuum System

- In LER, ~93% of beam pipes and bellows chambers in length, and pumps were renewed.
- In HER, ~82% of them and pumps were reused.
- DR was completely newly constructed.





DR

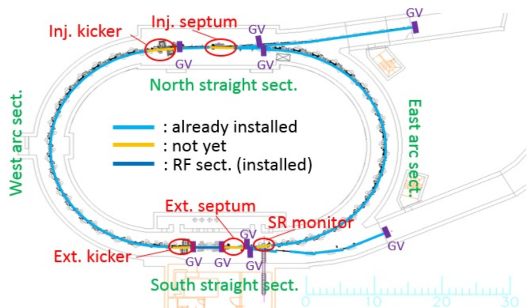
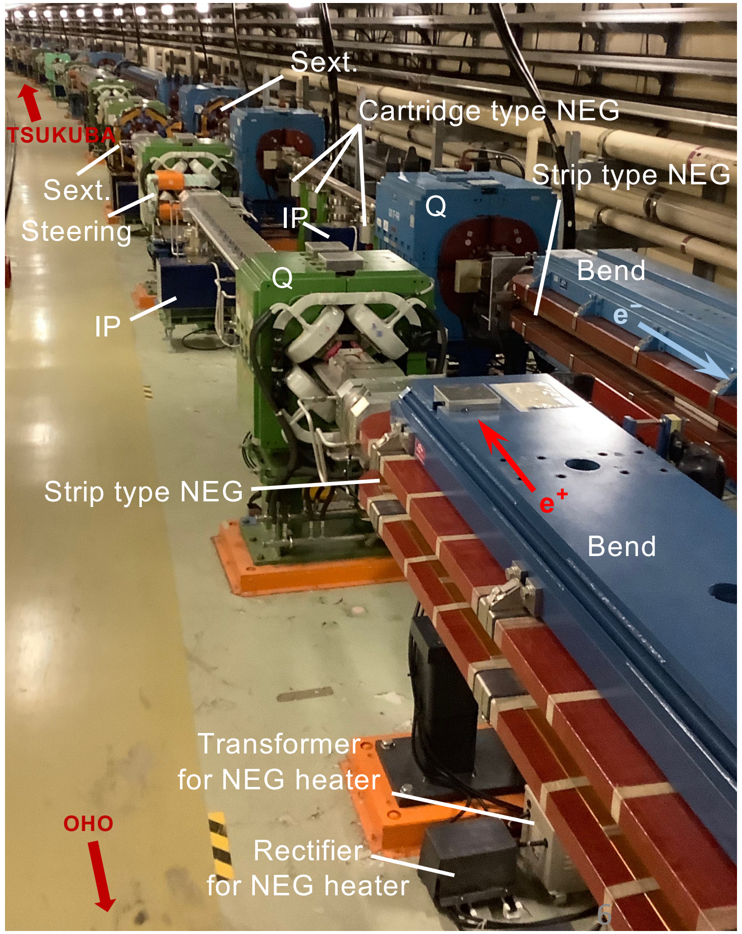


Photo of an arc-section in SuperKEKB main ring

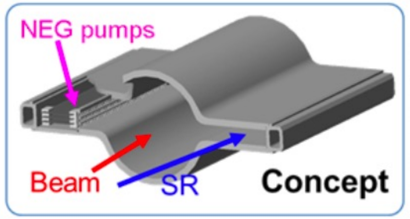


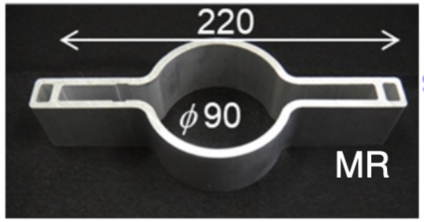
Vacuum System – New Components

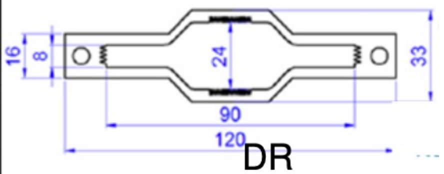
[Y. Suetsugu *et al*, J. Vac. Sci. Technol. A 30, 031602 (2012)]

Beam pipes with antechambers

- Effective to reduce photo electrons

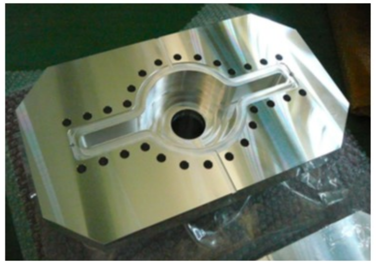


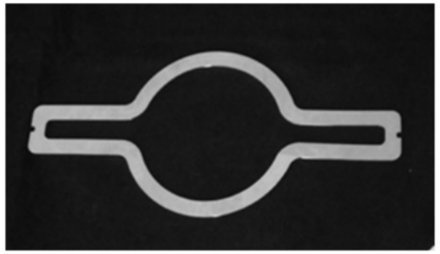




Step-less connection flange (MR)

- No RF-shield finger between flanges
- Adaptable to various cross sections



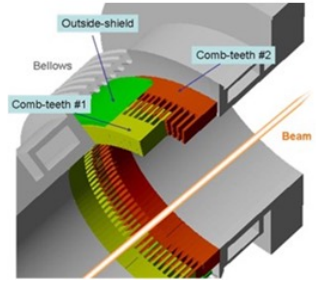


Multi-layer of NEG strips ST707 (MR arc) as a main pump

- Installed into an antechamber
- Activation by micro-heaters embedded between the layers
- Ave. pumping speed of 0.14 $m^3 s^{-1} m^{-1}$ for CO including screens between the pump and beam

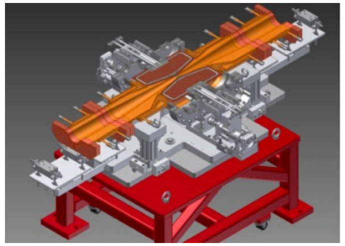
Bellows chambers and gate valves with comb-type RF-shield (MR)

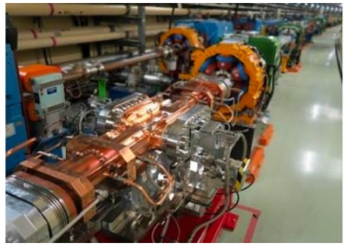
- High thermal strength
- Low beam impedance

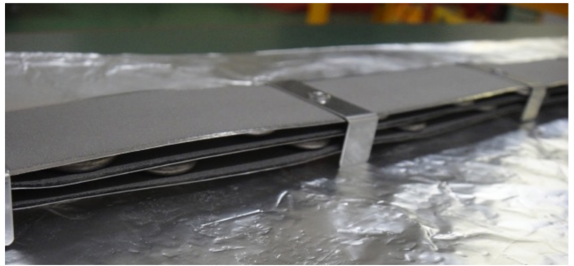


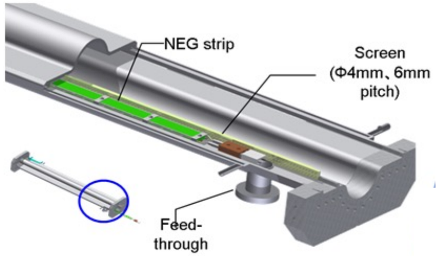
Movable collimator (MR)

- Key component to suppress the detector backgrounds and protect the machine components from beam out of control







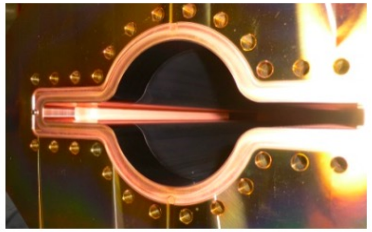


Vacuum System – New Components (measures against ECE)

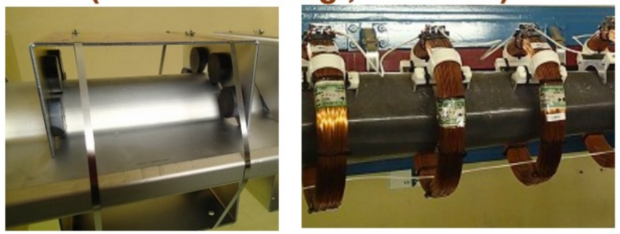
- Countermeasures against electron cloud effect (ECE)
  - ECE is a critical issue for the LER and DR. [Y. Suetsugu, "Mitigation of e-cloud effects in SuperKEKB", eeFACT2022, WG4]
  - Based on various R&D results in KEKB and other institutes, various countermeasures were prepared. [Y. Suetsugu *et al*, Phys. Rev. Accel. Beams 22, 023201 (2019)]

Antechamber

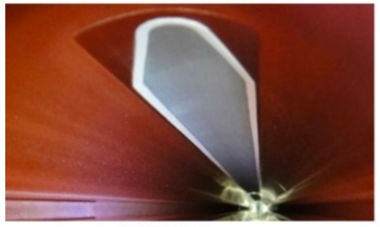
TiN coating



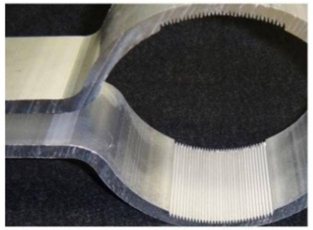
Magnetic field in the beam direction, B_z (Permanent Mag., Solenoid)



Clearing electrode



Grooved surface



Summary of countermeasures for LER (MR)

Sections	L [m]	L [%]	Countermeasure	Material
Drift space (arc)	1629	54	TiN coating + Mag. field	Al (arc)
Steering mag.	316	10	TiN coating + Mag. field	Al
Bending mag.	519	17	TiN coating + Grooved surface	Al
Wiggler mag.	154	5	Clearing Electrode	Cu
Q & SX mag.	254	9	TiN coating	Al (arc)
RF section	124	4	(TiN coating +) Mag. Field	Cu
IR section	20	0.7	(TiN coating +) Mag. field	Cu
Total	3016	100		

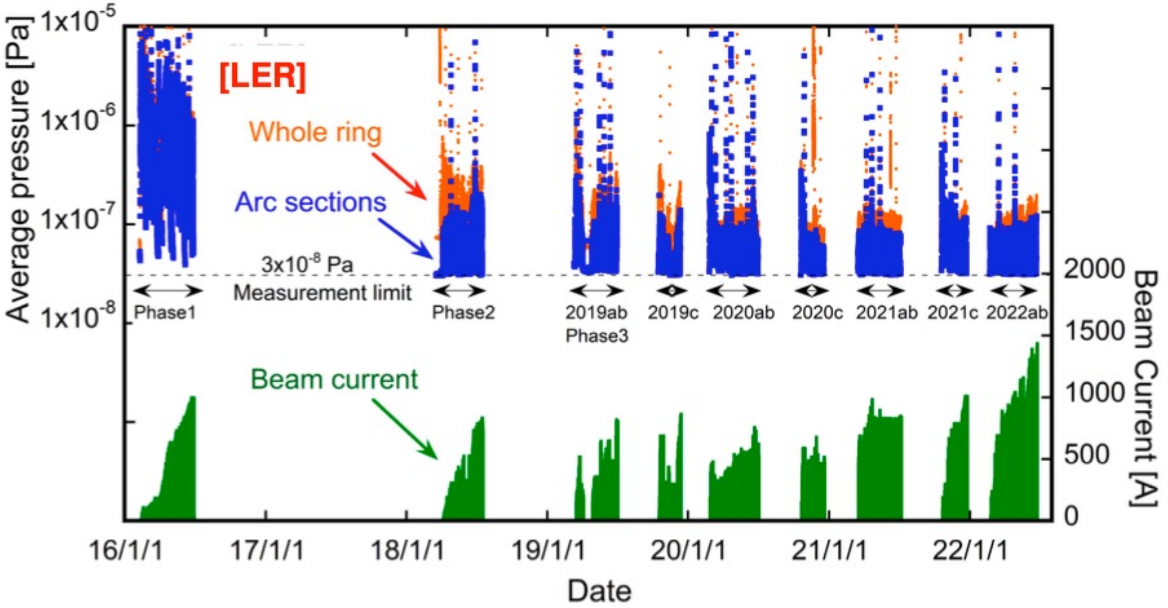
For DR

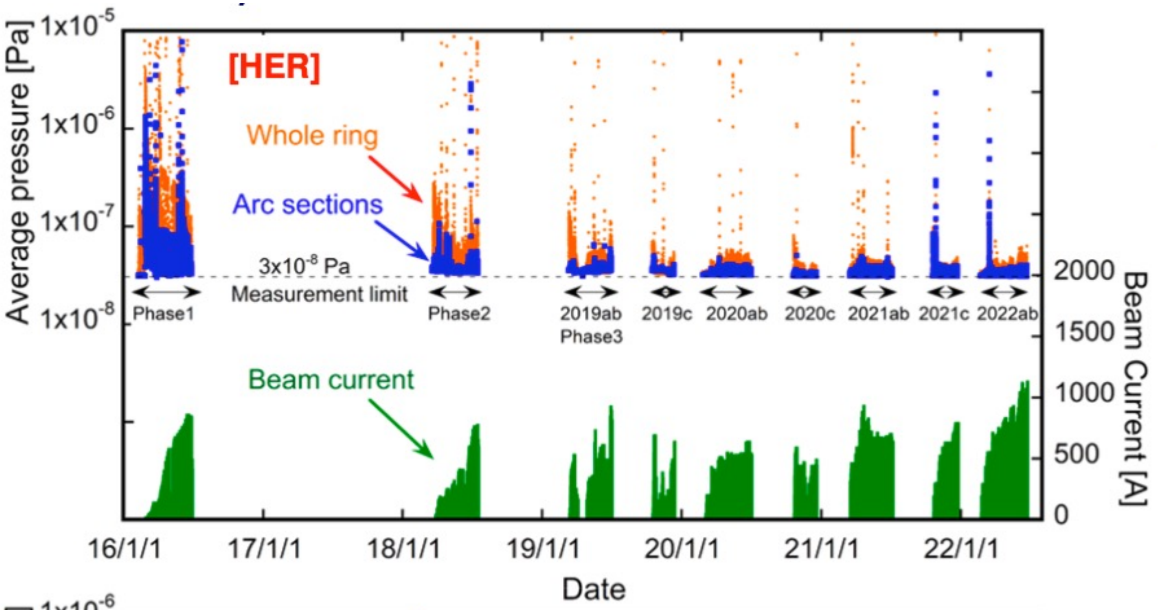
- antechambers with grooved structure at side-wall.
- TiN film coating
- Grooved surfaces on the upper and lower sides of the beam channel (in B-magnets).
- Material: Al

- Expected average e^- density: ~2×10^{10} electrons m^{-3} (MR), ~1.3×10^{13} electrons m^{-3} (DR)
- Less than the threshold estimated by simulations.

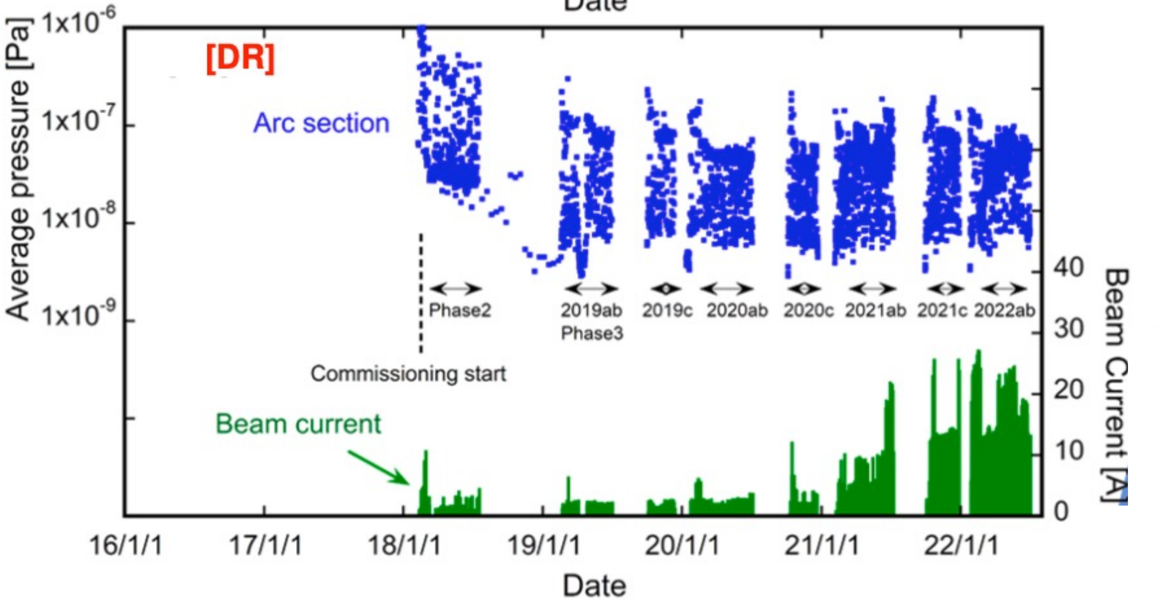
Status – Trend of Pressure

- Trends of pressures and beam currents (2016-2022)



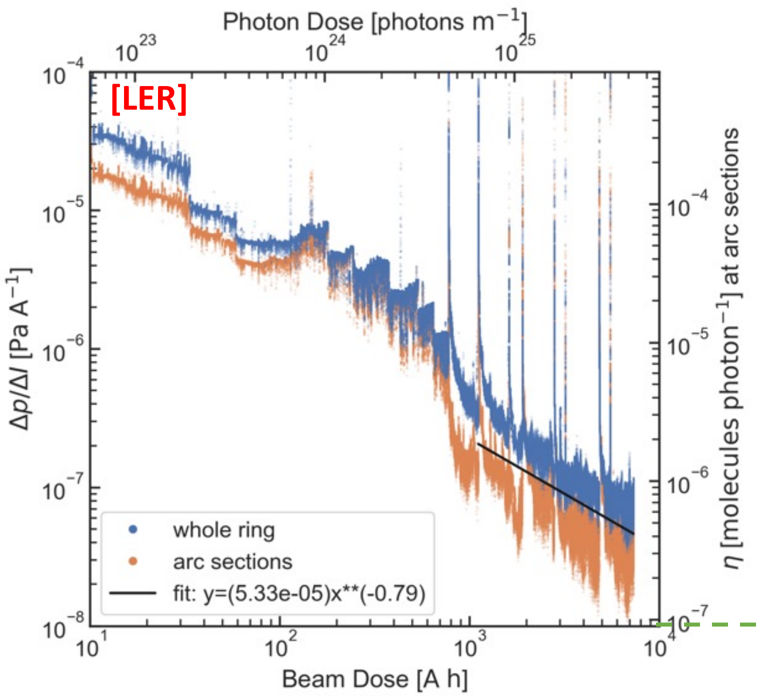


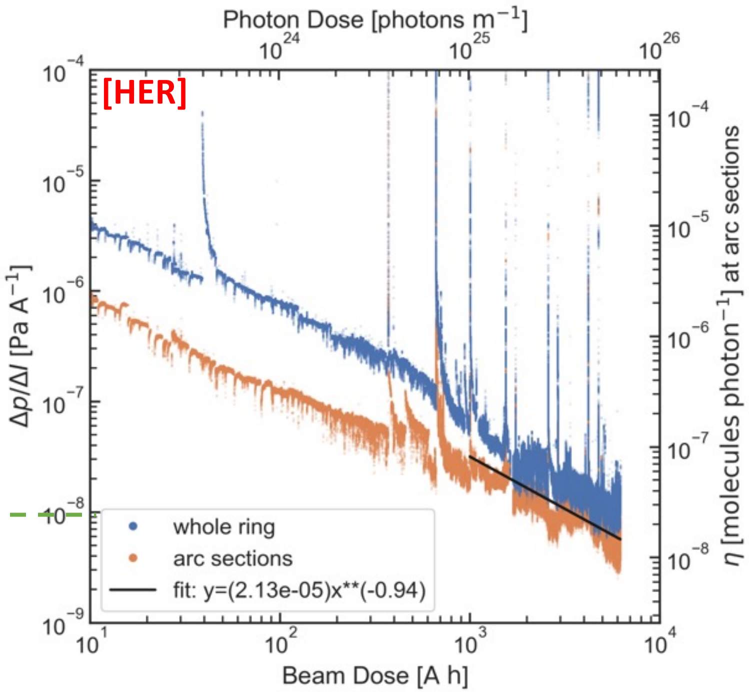
- The pressures decreased steadily although the beam currents are increasing gradually for all rings.
- MR: The pressures with beams in June, 2022, are 2.0×10^{-7} Pa (at 1.46 A, 2249 bunches) and 4.9×10^{-8} Pa (at 1.14 A, 2249 bunches) for LER and HER, respectively. The base pressures without beams are ~3×10^{-8} Pa, and this is near a measurement lower limit in cold cathode gauges (CCG).
- DR: In June, 2022, the pressure at the maximum beam current (30 mA) and the base pressure are 1×10^{-7} Pa and 1×10^{-8} Pa, respectively.

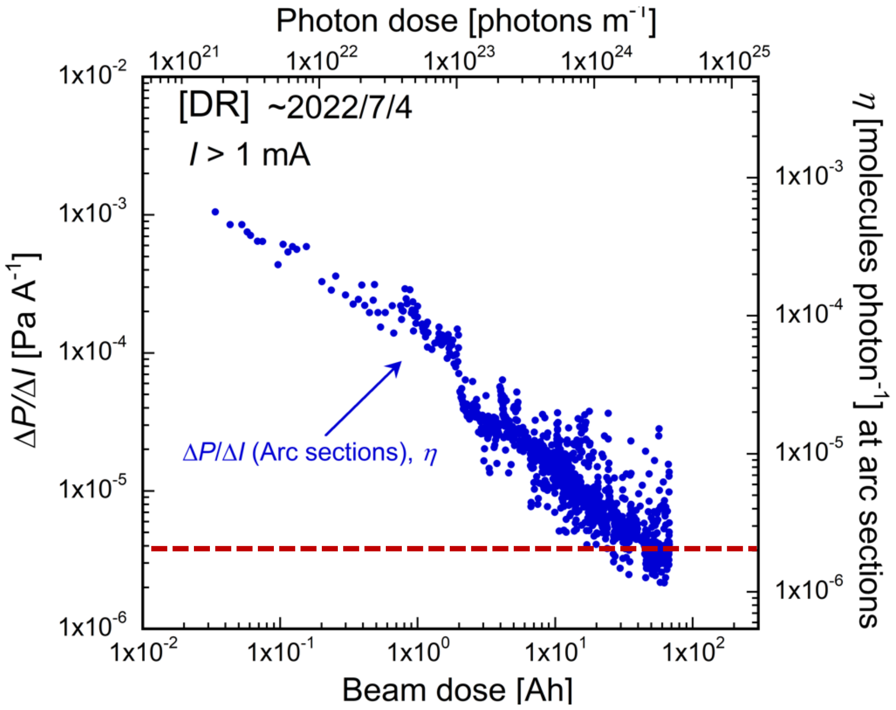


Status – Vacuum Scrubbing

- *ΔP/ΔI* vs beam dose (photon stimulated desorption (PSD) coefficient *η* vs photon dose, 2016-2022).
  - LER: *η* decreased to less than 3×10^{-7} molecules photons^{-1}, at a photon dose of 3.87×10^{25} photons m^{-1}.
  - HER: *η* is lower than LER. For arc section (reused beam pipes), *η* is now 2×10^{-8} molecules photons^{-1}, at a photon dose of 5.74×10^{25} photons m^{-1}. → memory effect
  - DR: *η* is decreasing steadily. For arc section, *η* decreased to 2×10^{-6} molecules photon^{-1}, at a photon dose of 3.47×10^{24} photons m^{-1}.







Status – Beam Current Dependence of Pressure (MR)

- The pressure does not rise in proportion to the total beam current (I) recently. The rise rate becomes larger at higher beam current.
- Furthermore, the pressure depends on the number of bunches (N_b).
- Here, we tried to explain the behaviors of pressure rises including the thermal desorption (TD).
- Assumptions:
  - PSD: $\Delta P_p \propto I$
  - *TD:* $P_t \propto \exp(-E_d/RT) \rightarrow \Delta P_t \propto \exp(-E_d/R(T+\Delta T)) - \exp(-E_d/RT) \rightarrow \Delta P_t \propto (\Delta T)^2 \propto (I^2/N_b)^2$

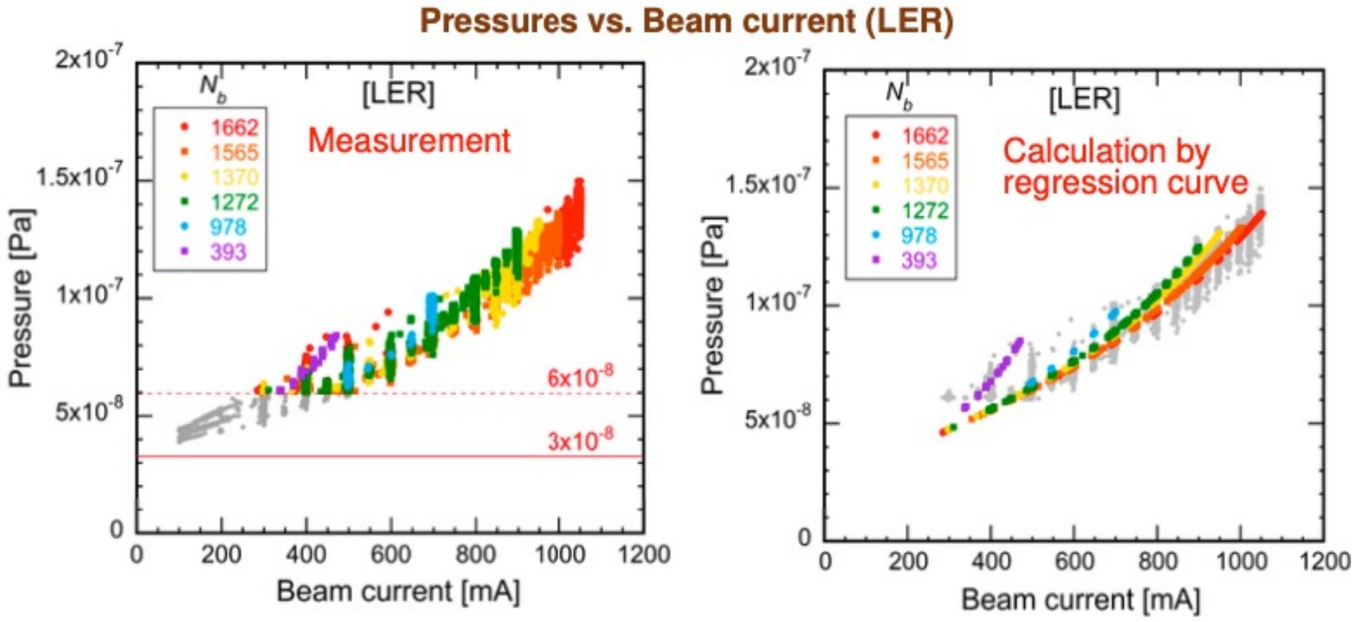
  $\therefore P = P_0 + \Delta P_p + \Delta P_t = P_0 + C_p I + C_t (I^2/N_b)^2$

Notes
- The equilibrium between the molecule in space and those on the surface is almost established.
- E_d: adsorption energy of gas molecules, R: gas constant, T: temperature
- Heating due to the joule loss of wall current and/or the higher order modes (HOM) is considered.

- Constants (P_0, C_p and C_t) were determined by the multi regression analysis using data for LER (Mar. 16th to Apr. 15th). The regression curve:

  $$P = 2.42\times10^{-8} + 7.64\times10^{-11} I + 7.8\times10^{-14} (I^2/N_b)^2$$

- This regression curve well reproduces the measurements.



[Y. Suetsugu *et al*, IVC-22 (2022)]

Status – Beam Lifetime (MR)

- Recent beam lifetime seems to be limited by not only pressure but also the Touschek effect (Touschek lifetime).
  - The pressures have been decreasing steadily, but the apertures are strongly restricted now by beam collimators.
  - Beam emittance is small (ε_y~20 pm), and the bunch length is short (~6 mm).
  - Here, we tried to estimate the contribution of pressure (P) to the beam lifetime (τ).
- Assumptions:

$$\frac{1}{\tau} = \frac{1}{\tau_{\mathrm{p}}} + \frac{1}{\tau_{\mathrm{t}}} = C_{\mathrm{p}}P + C_{\mathrm{t}}\frac{I}{N_{\mathrm{b}}\sigma_{\mathrm{z}}}$$

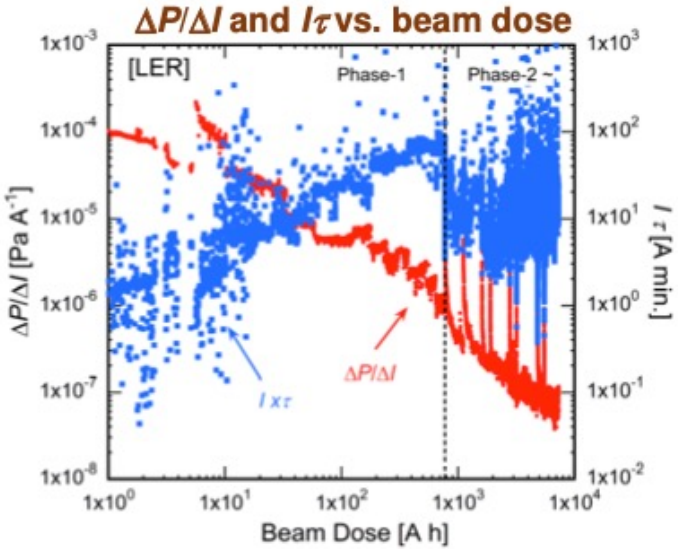
Notes
- τ_{b}: beam lifetime due to pressure, τ_{t}: Touschek lifetime, σ_z: beam size
- Dependence on the emittances was not included in the Touschek effect here, since the measured emittances were scattered.
- Only single beam (no collision) was considered.

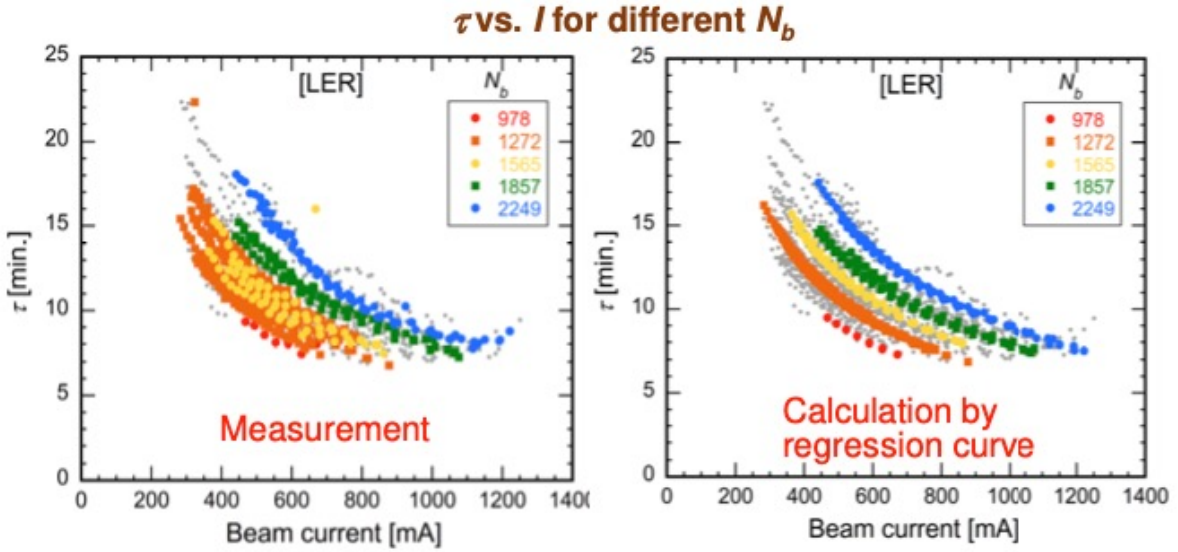
- Constants (C_{p} and C_{t}) were determined by the multi regression analysis using data for LER.

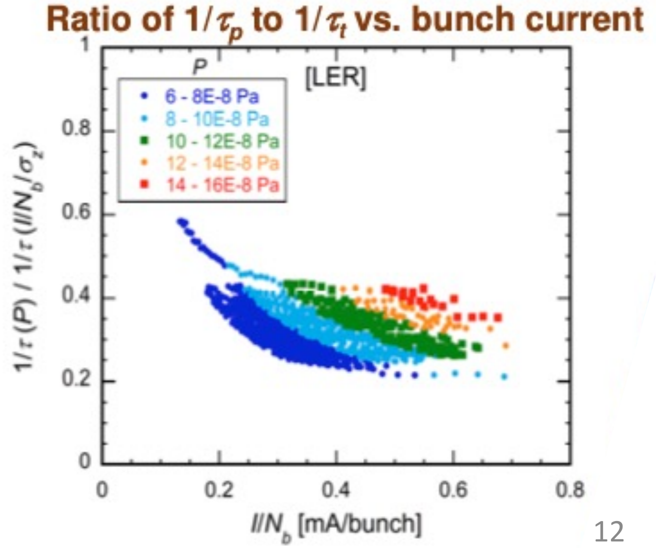
$$\frac{1}{\tau} = 2.61\times10^{5}P + 0.979\frac{I}{N_{\mathrm{b}}\sigma_{\mathrm{z}}}$$

- The regression curve well reproduces the measurements.
- Approximately 60-80% of the total lifetime was determined by the Touschek lifetime at present.

[Y. Suetsugu *et al*, IVC-22 (2022)]





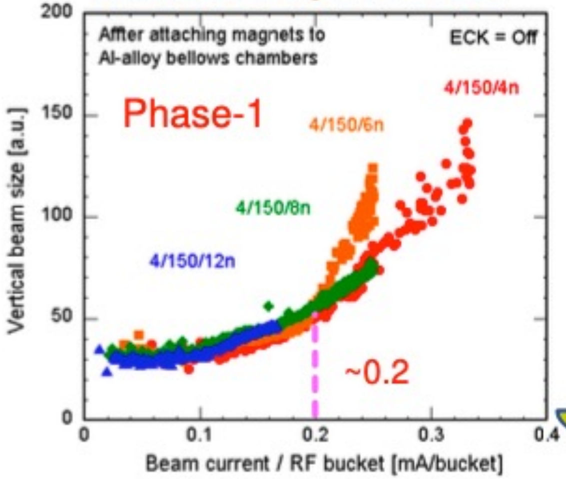


Status – Electron Cloud Effect (MR)

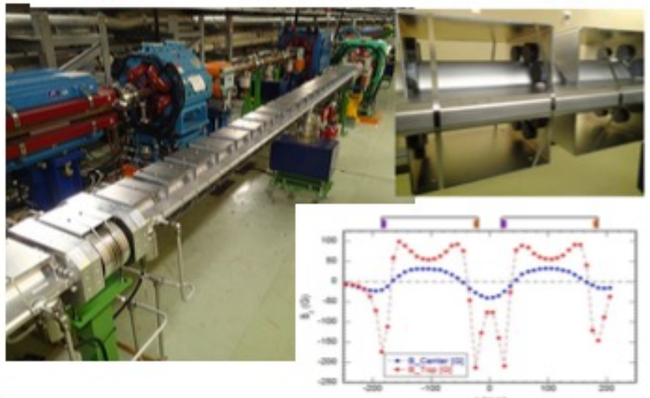
[Y. Suetsugu *et al*, Phys. Rev. Accel. Beams 22, 023201 (2019)]
[Y. Suetsugu, “Mitigation of e-cloud effects in SuperKEKB”, eeFACT2022, WG4]

- The ECE was firstly observed during Phase-1 commissioning (w/o magnetic fields, B_z).
  - Non-linear behavior of pressure, beam size blow-up, instability at typical mode.
  - The sources of EC were Al-alloy bellows chambers and also TiN-film coated beam pipes with antechambers at drift spaces.
- This ECE was cured by adding permanent magnets around beam pipes after Phase-1.
  - Magnetic field of ~50 G in the beam direction (B_z).
- The reason of the ECE w/o B_z at lower beam currents than expected was found to be that the intensity of photons in the beam channel is actually stronger than expected due to the vertical spread or scattering of synchrotron radiation (SR).
  - This emphasizes the importance of suppressing photoelectron in the ring.
- At present, any obvious signs of the ECE have not been observed in usual collision experiments.
  - The threshold of the current linear density is now over 0.53 mA/bunch/RF-bucket.

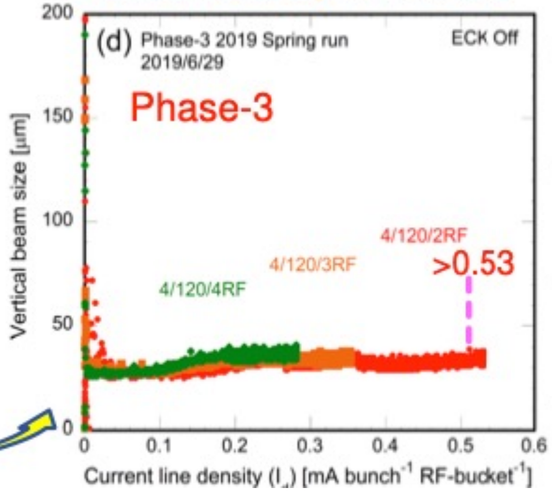
Vertical beam size vs. current density in Phase-1



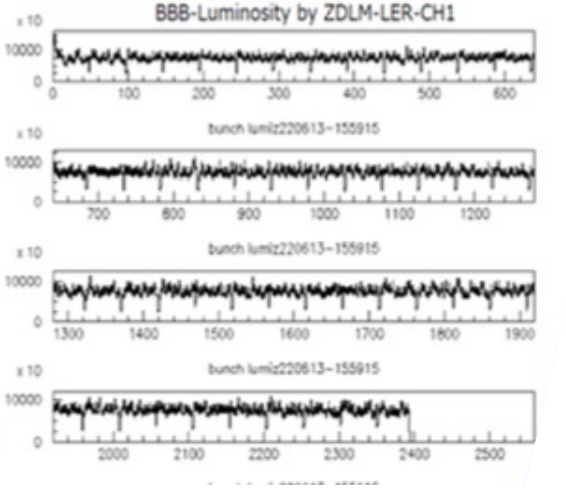
Magnet units attached to beam pipes



Vertical beam size vs. current density in Phase-3

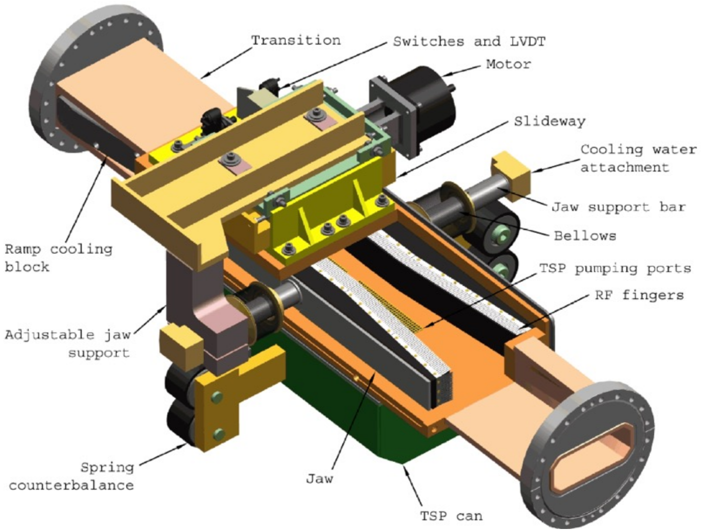


Bunch by bunch luminosity along a train by ZDLM (S. Uehara)



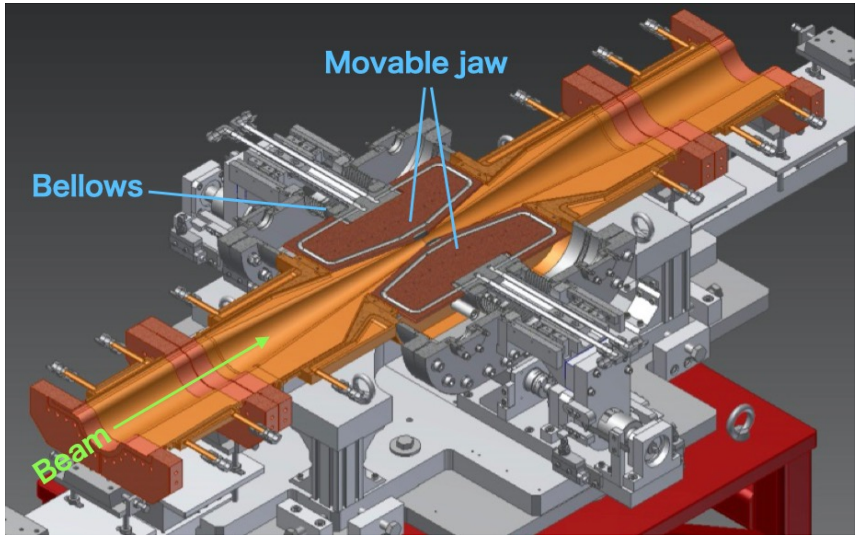
Experiences – Collimator

- We referenced movable collimators for PEP-II in SLAC for the basic design of the SuperKEKB type.
- A collimator chamber has two movable jaws, which are placed the horizontal/vertical direction.
- Part of the movable jaws is hidden inside the antechambers to avoid a trapped mode in gaps between the movable jaw and the chamber.
- The chamber is tapered to the center of the collimator in order to avoid excitation of trapped-modes.
- Materials at the tip of the jaws are tungsten (1st ver.), tantalum (2nd ver.), carbon (low-Z, special ver.), and hybrid (C+Ta, special ver.).

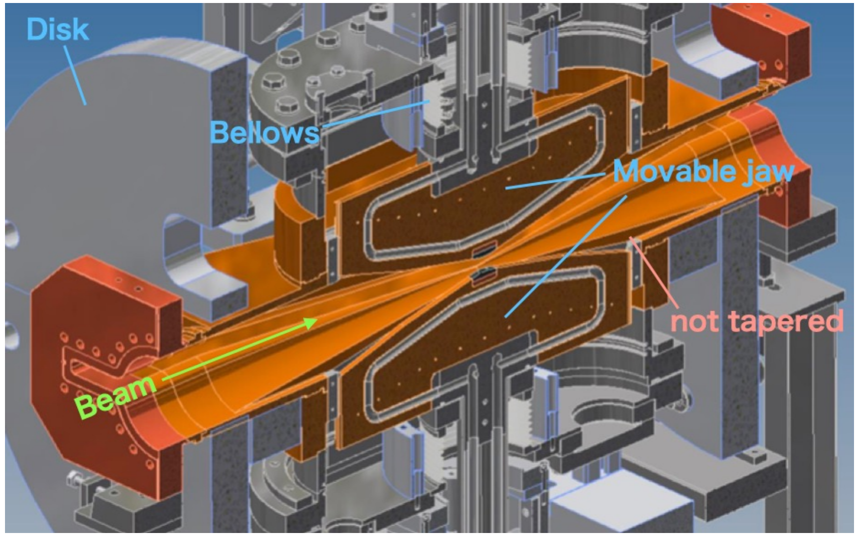


Collimator in PEP-II

[S. DeBarger et al., SLAC-PUB-11752]



Horizontal direction



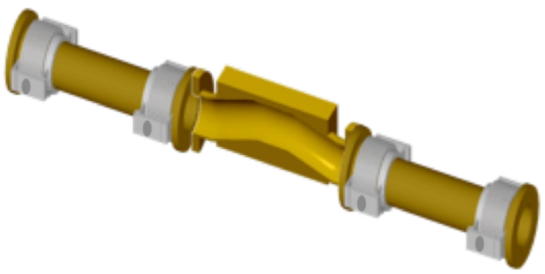
Vertical direction

SuperKEKB type collimator

Experiences – Collimator

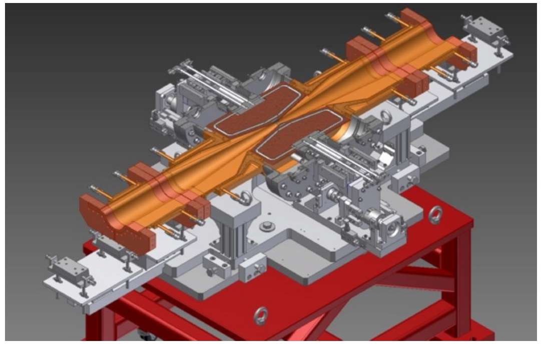
- There are two types of collimators in SuperKEKB MR.
  - ➢ KEKB type: Tapered chamber itself approach the beam. The tip is made of Cu coated titanium.
  - ➢ SuperKEKB type: A chamber has two movable jaws, and they approaches the beam.

- In HER, 8 horizontal and 8 vertical KEKB type collimators have been reused at the same location as KEKB era. 3-horizontal and 1 vertical SuperKEKB type collimators have been installed in Tsukuba straight section.
- In LER, 7 horizontal and 4 vertical SuperKEKB type collimators have been installed.



KEKB type

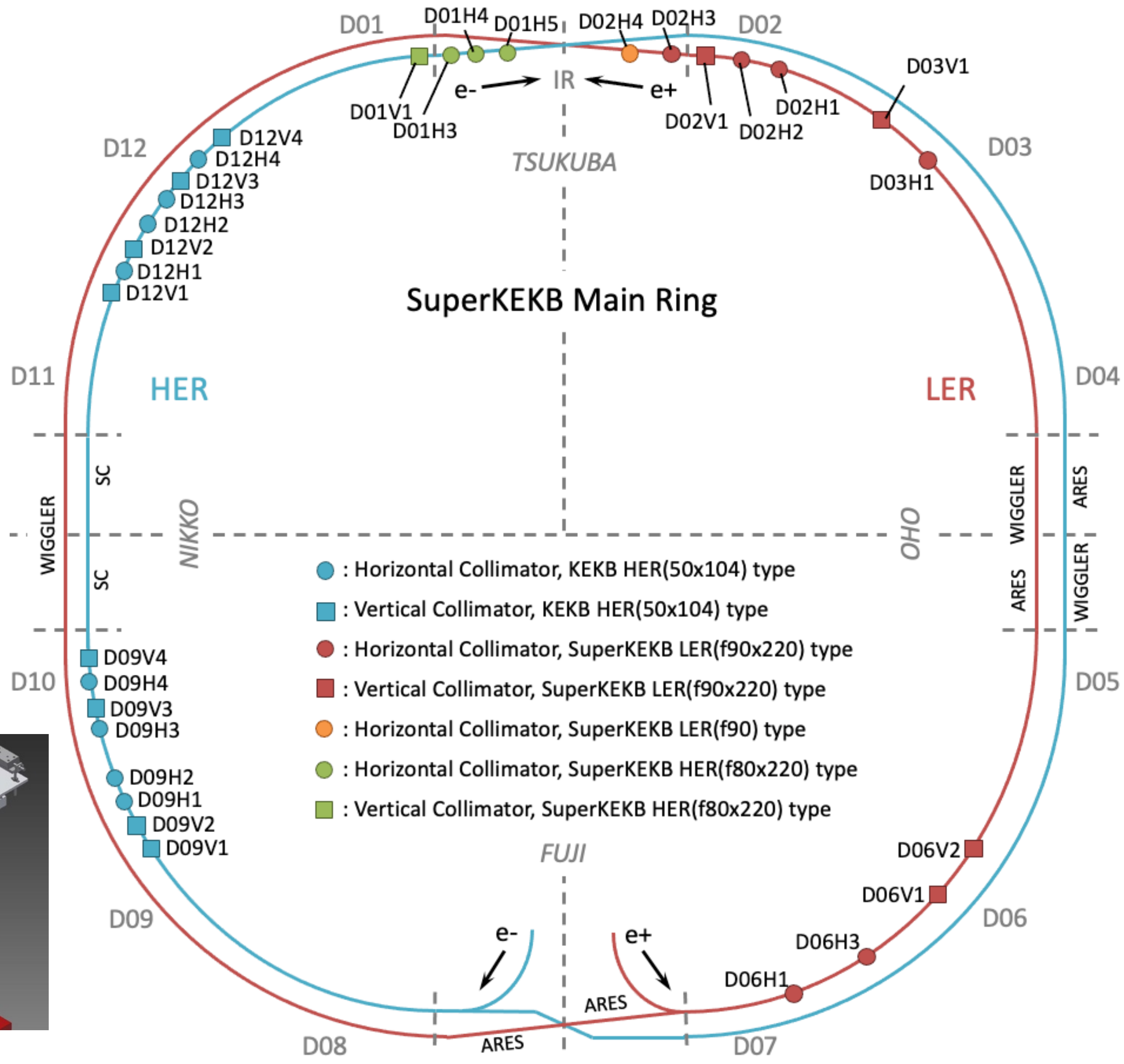
[Y. Suetsugu et al., NIM A **513**, 465 (2003)]



SuperKEKB type

[T. Ishibashi et al., PRAB **23**, 053501 (2020)]

Location of Collimators

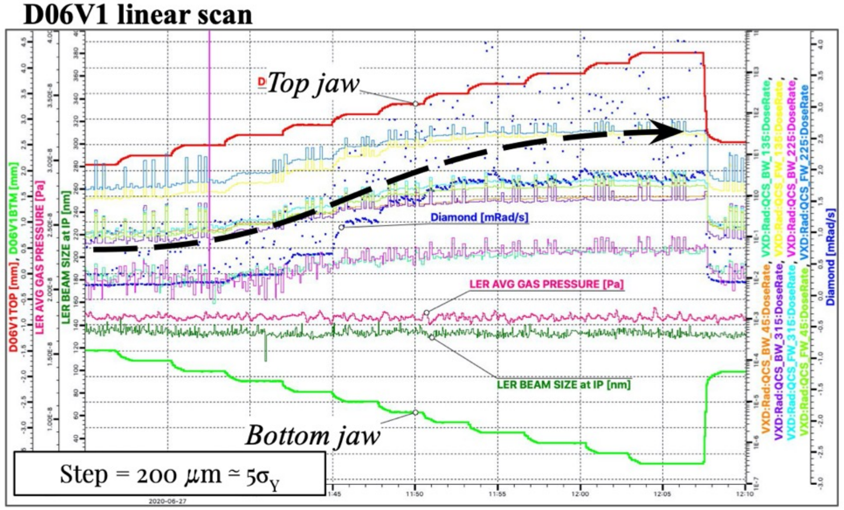


Experience – Collimator BG suppression

- The SuperKEKB type collimators have been working well as expected up to the beam current of ~1.4 A in LER without abnormal temperature rises and discharges.
- These collimators have been indispensable in terms of the background suppression in Belle II, avoid quenches in final focusing superconducting quadrupole magnets (QCS).

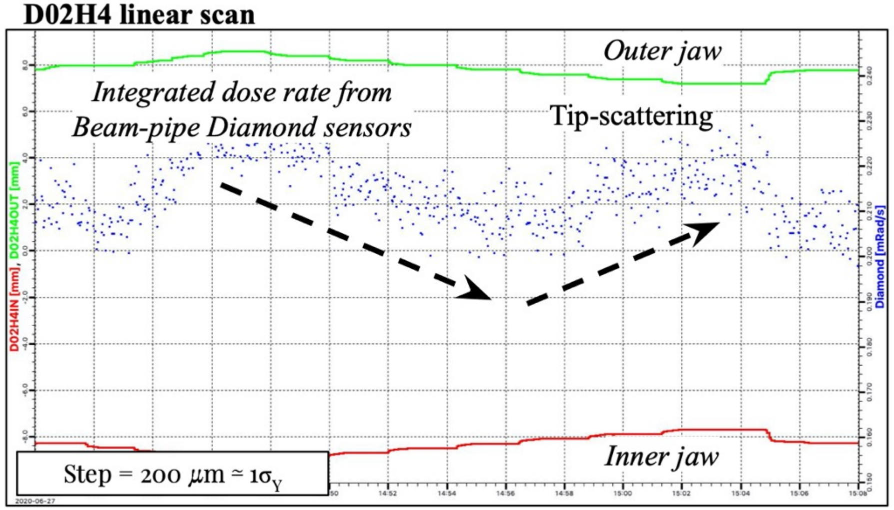
Machine settings:	LER ring, $\beta^*_{X/Y}$ = 60/0.8mm , CW = 80%, **I = 200 mA, Continuous injection**, Rep = 12.5Hz, Nb = 978
Detector settings:	Belle II HV → OFF, **Diamond sensors** only

D06V1 linear scan



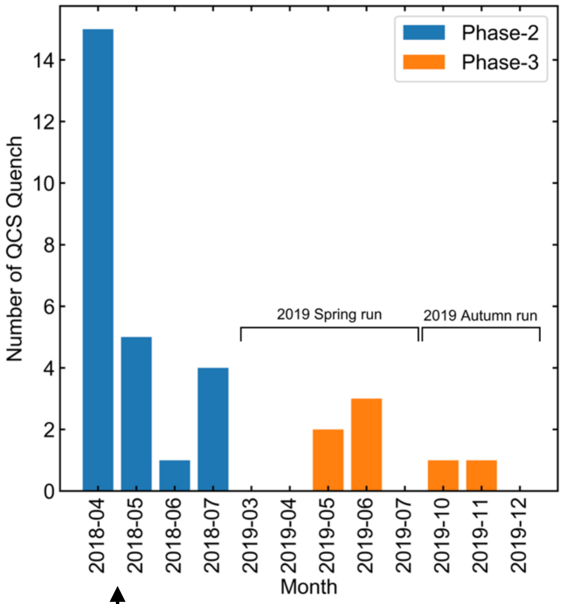
Opening the primary LER V-collimator we see an increase of the IR background rate.

D02H4 linear scan



Closing the LER H-collimator we observe an increase of the IR background rate → tip-scattering.

Number of QCS quenches derived from beam loss in QCS (monthly).



Collimator adjustment was done in earnest

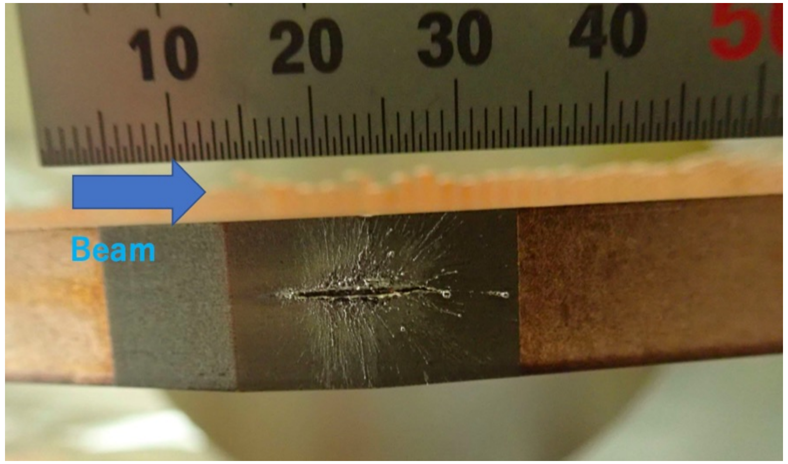
[Andrii Natochii *et al.*, Phys. Rev. Accel. Beams 24, 081001 (2021)]

Experiences – Collimator Damage

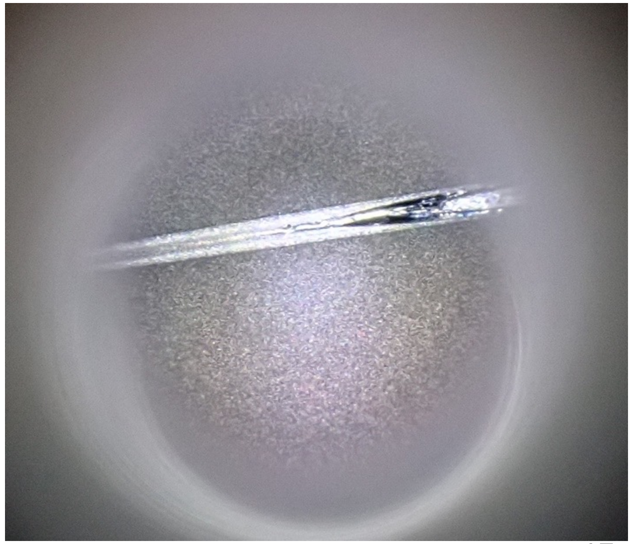
- The collimators have been frequently damaged due to beam hits.
- The source of beam instability that causes damage to the vertical collimators is still unknown (named sudden beam loss). If the collimators are severely damaged, we cannot continue the physics run because of the high background level.
- On the other hand, there are damaged events for known reasons, and that is the damage to a horizontal collimator (D06H3) caused by accidental-firings of injection kickers in LER. As countermeasures against this,
  - Carbon jaws will be installed in D06H3 and used as a spoiler of the crazy beams.
  - D06H1 will move to D06H4 and used as an absorber of the crazy beams.

Damaged jaw of D06H3 in LER due to the accidental-firings

Damaged jaw of D02V1 in LER due to the sudden beam loss

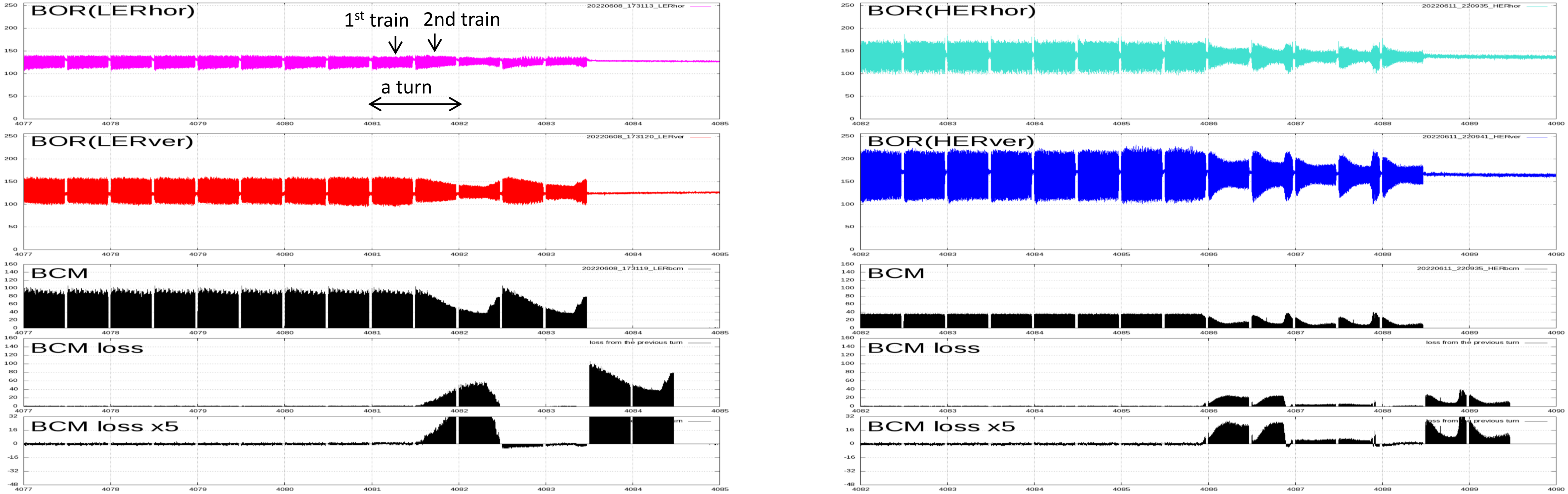


Damaged tip of D09V1 (KEKB type) in HER due to the sudden beam loss



Experiences – Collimator Damage (sudden beam loss)

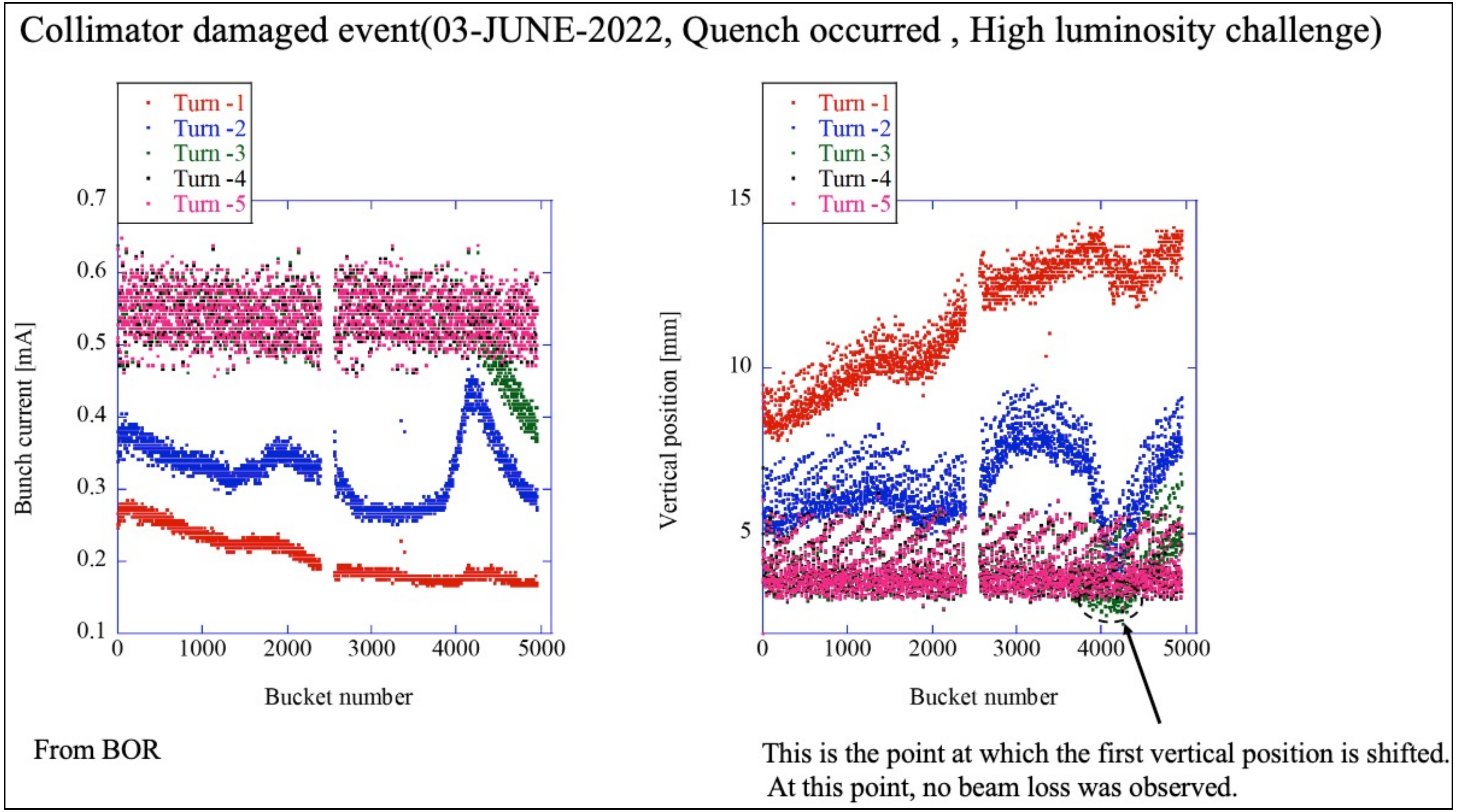
- Sudden beam loss has occurred within approximately 2-turn (~20 μs) before the beam abort.
- Beam orbit displacements in horizontal and vertical direction has been observe (H. Fukuma and S. Terui).
- No increase in the beam size has been observed by a fast beam size monitor (G. Mitsuka).
- This beam loss has never happened in single beam operation (because the short operation time with single beam?).
- It is more common in LER, but has also occurred in HER.
- Candidates of the cause [kick-off meeting of ITF sudden beam loss working group, https://kds.kek.jp/event/43499/]:
  - X-abort, dust, fire-ball in collimators, electron cloud in vertical collimators, accidental-firings in abort kicker…



Bunch oscillation recorder (BOR) and bunch current monitor (BCM), BOR signal is proportional to (bunch displacement)×(bunch intensity).

Experiences – Collimator Damage (sudden beam loss)

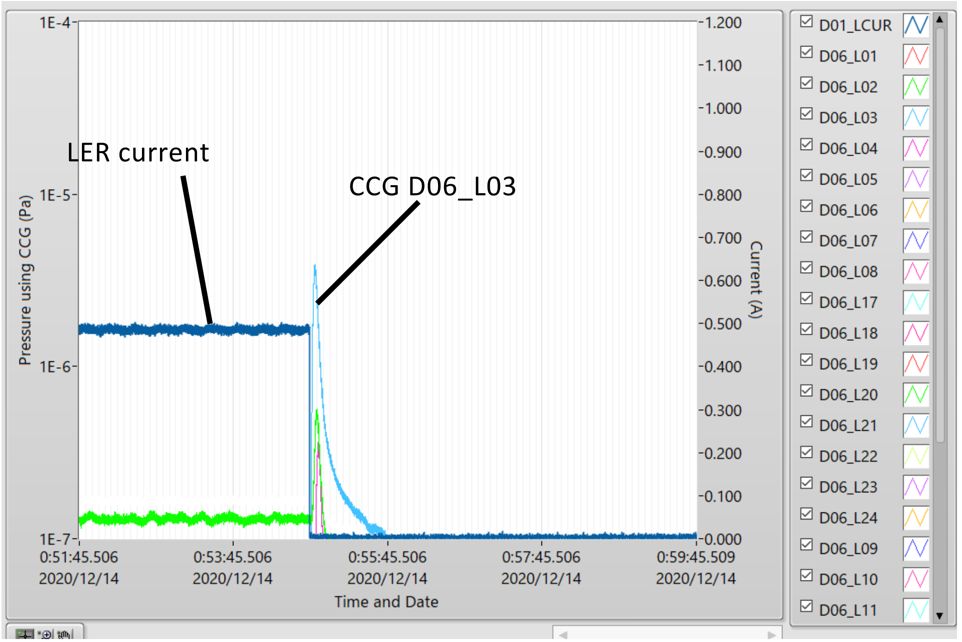
- Beam orbit displacements in horizontal and vertical direction has been observed.



[S. Terui]

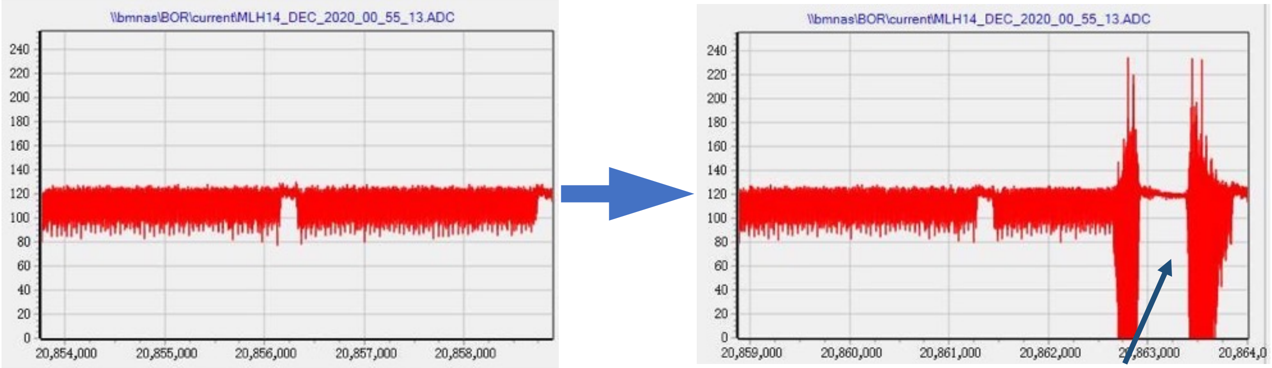
Experience – Accidental firings of injection kickers

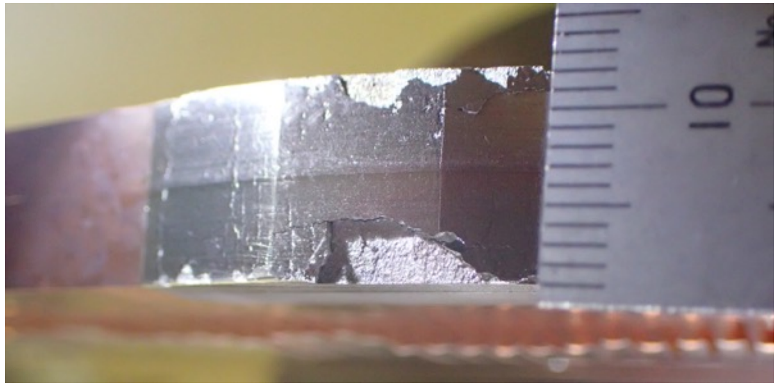
- Accidental firings of injection kickers have happened in LER.
- (example) 2020-12-14 0:55, beam abort (VXD diamond) with pressure burst at D06H3.
  - LER: 480 mA, HER: 449.9 mA
  - A part of the bunches was suddenly kicked by an accidental firing of the injection kickers.
  - Tips of D06H3 were seriously damaged by the beam hit.
- In the current system, we cannot make the probability of the accidental firing zero, so some horizontal collimators in each ring has been used to protect the components against the accidentally kicked beams. Carbon jaw in horizontal collimators can be a better option.



BOR(H)

[S. Terui]





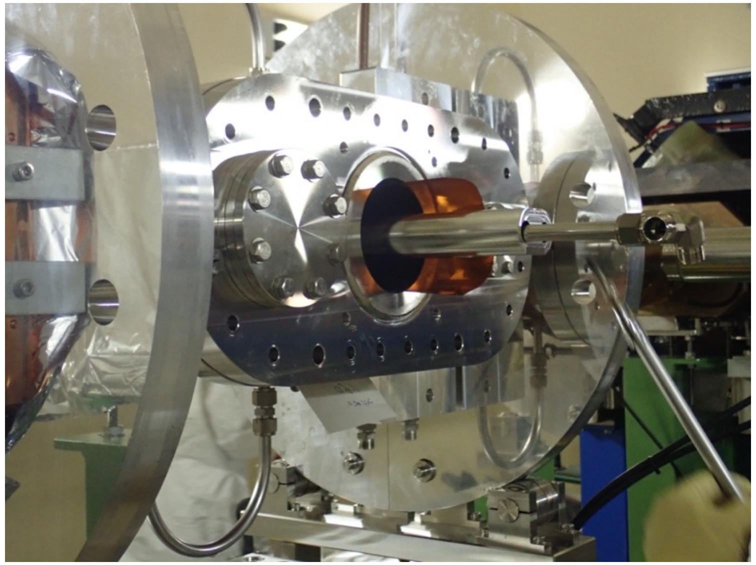
Replacement Work

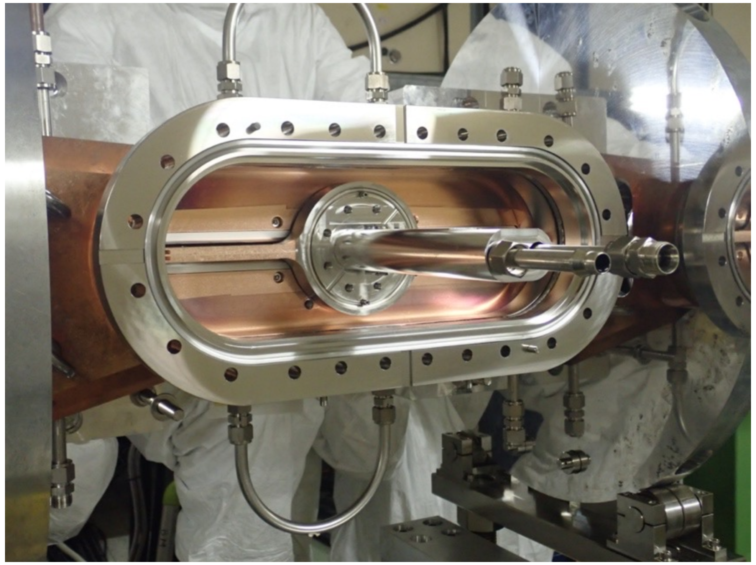
- Before the replacement, we purge the beam pipes in the section where the collimator is located with nitrogen and remove the drive mechanisms and cooling water pipes. It is also necessary to investigate the cooling water whether it’s radioactive.

Clearing out the people

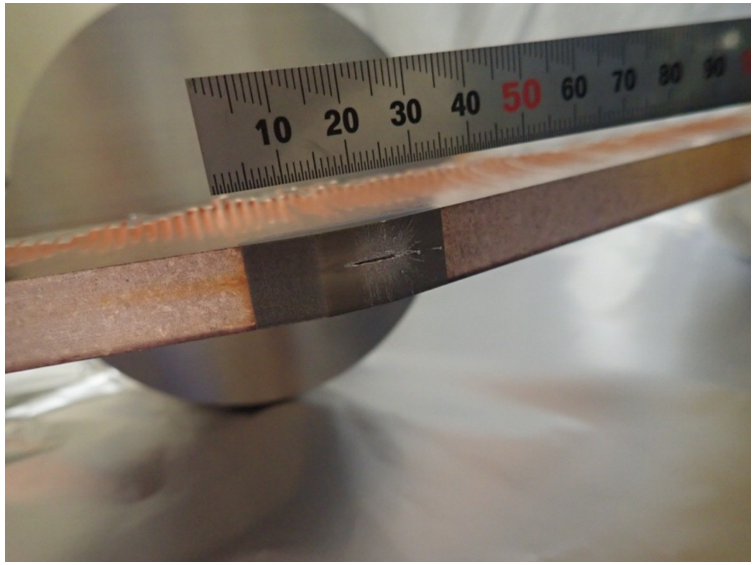
Remove the beam-pipes nearby, and rotate the chamber 90 degrees

Replacement Work

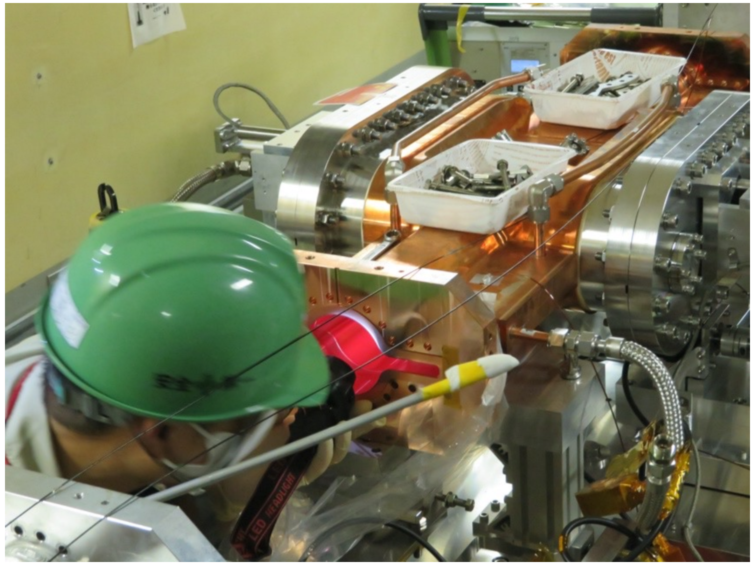




Remove the racetrack type flanges in which the jaws are inserted.



Remove the damaged jaws.

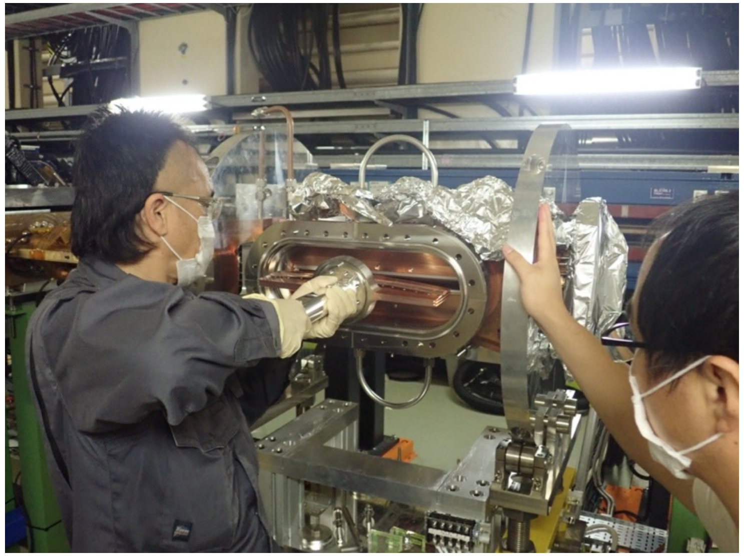


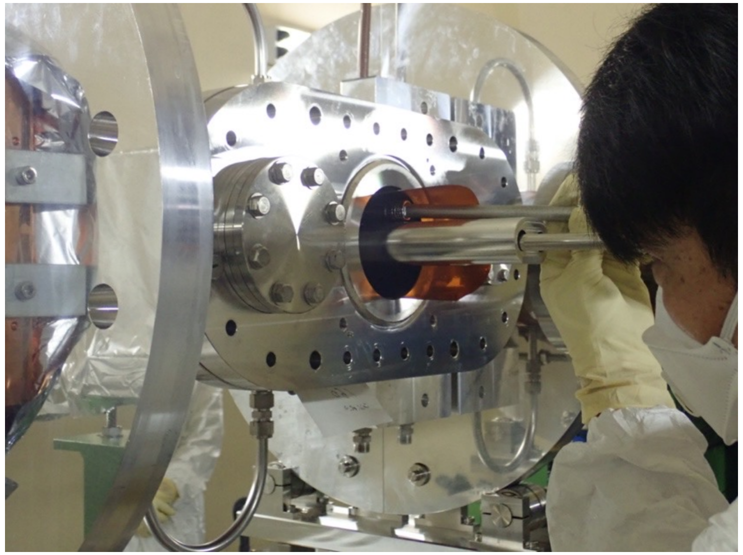
(← this photo shows a cleaning work for D06H3. I was not able to find the photo for D02V1.)

Clean the inside of the flange and chamber to remove deposits such as activated dust.

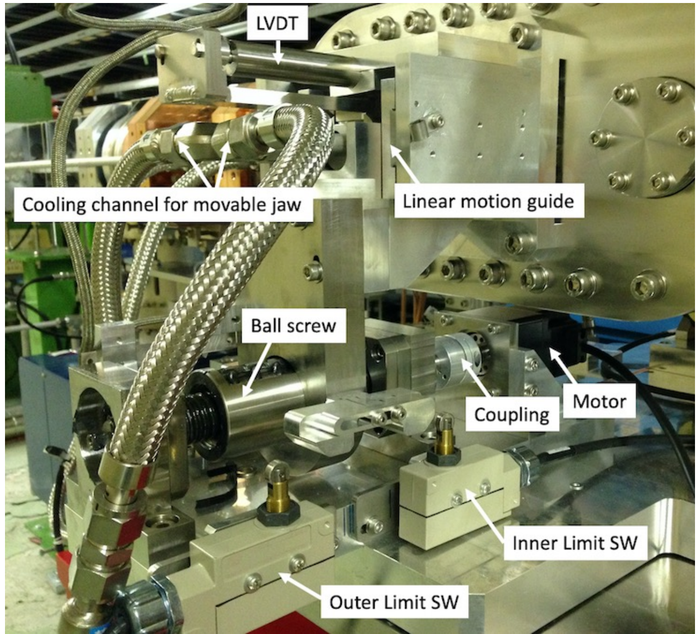
Replacement Work


Attach RF-fingers to the spare jaws.


Insert them carefully so as not to break the fingers and so on.


Tighten the flanges.

- After that, we rotate the chamber -90 degrees and connect the beam-pipes nearby and cooling water pipes. Then, after the leak check pass, we re-install the drive mechanisms and fine tune them.
- Align the collimator (chamber) for adjacent electromagnets using a laser tracker with the help of Magnet Group if necessary.

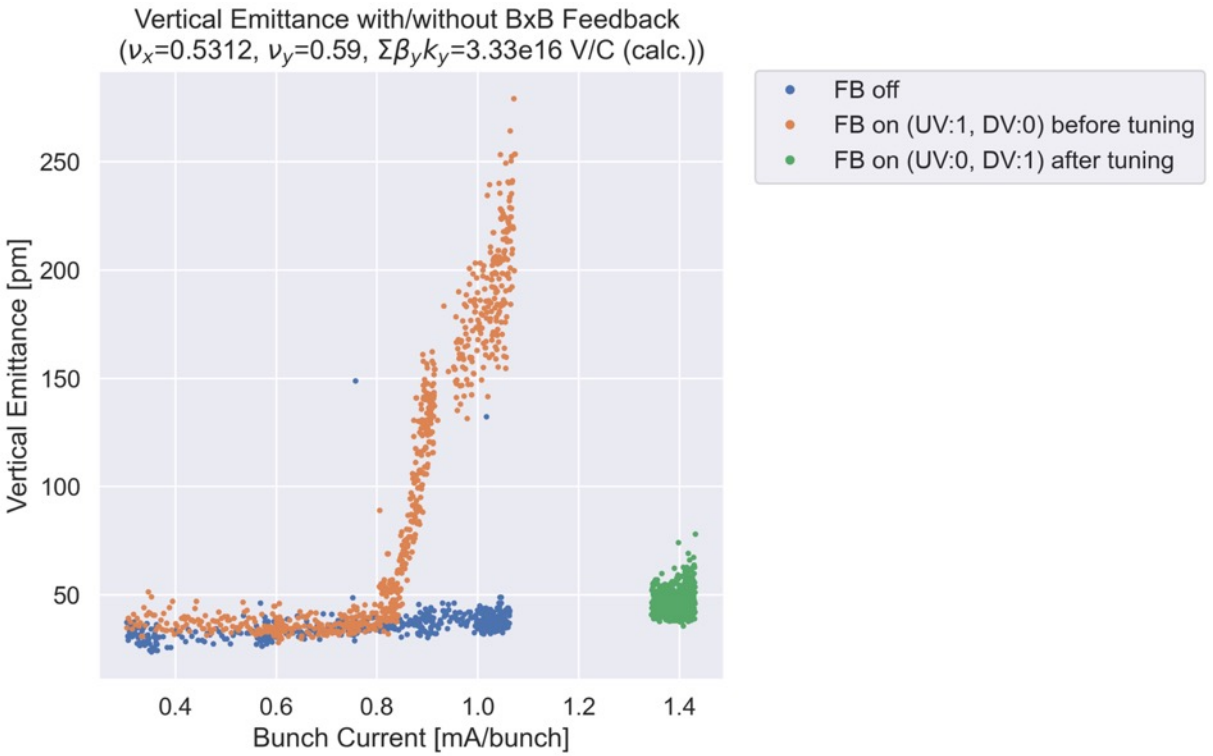


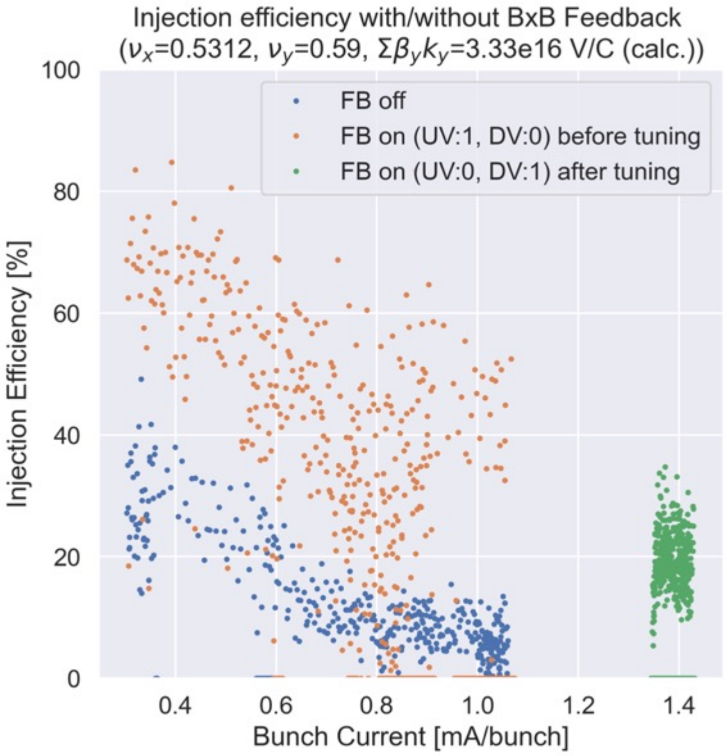
Drive mechanism

Experience - Beam instability caused by impedance in LER

[K. Ohmi, "Impedance and instability at SuperKEKB", eeFACT2022, WG4]

33-bunch operation

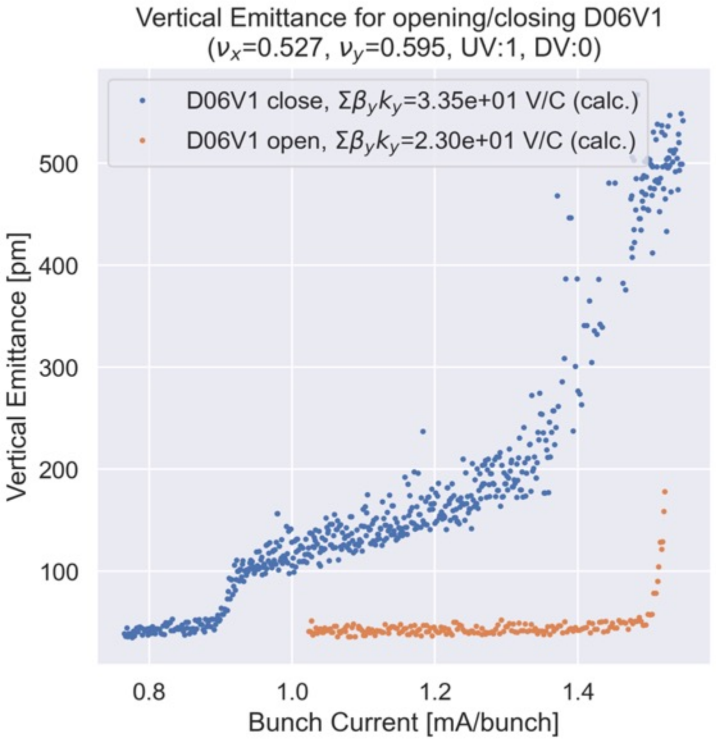


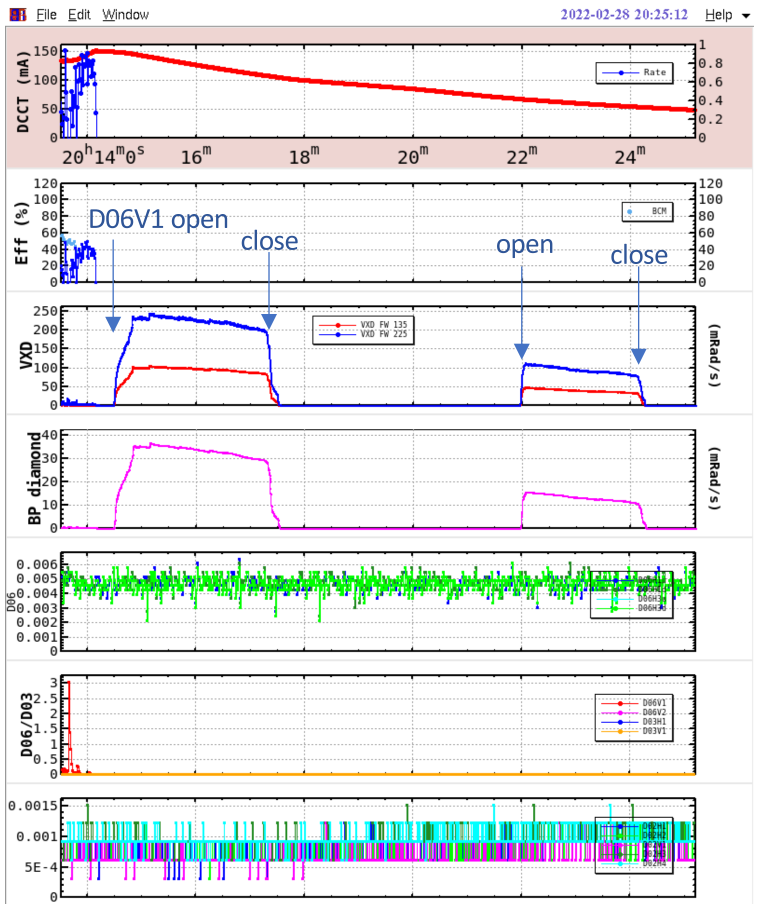


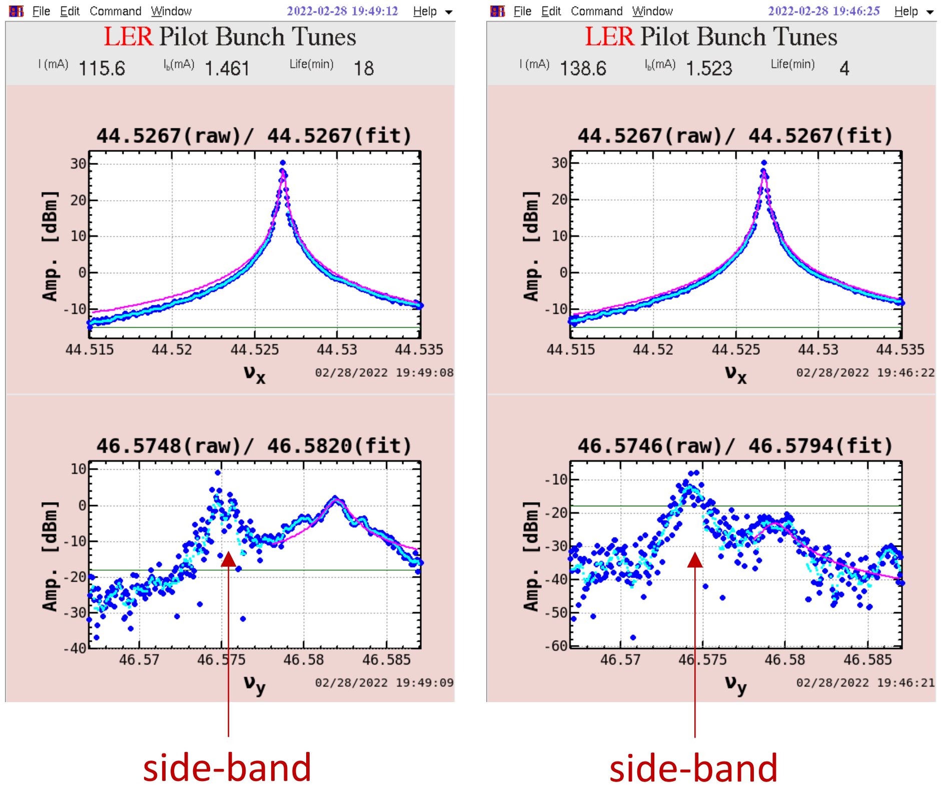
- We've observed vertical beam-size blow-ups around 0.8-1.0 mA/bunch in LER, and this is much lower than an expected threshold of TMCI (Transverse Mode Coupling Instability), which is 1.5-2.0 mA/bunch. When these blow-ups occur, a coherent oscillation at the frequency corresponding to -1 mode (ν_y-ν_s) has observed (so we call this "-1 mode instability").
- We observed the vertical emittance by turning on/off the feedback (FB) with small number of the bunches to avoid multi-bunch instabilities.
- When we turned on the FB, the blow-up occurred around 0.85 mA/bunch.
- When we turned off the bunch-by-bunch FB, the vertical emittance blow-up didn't occur up to around 1.06 mA/bunch (poor injection rate above than this current).
- After the tuning of the FB to suppress the -1 mode instability, the blow-up didn't occur up to ~1.44 mA/bunch (design bunch current in LER).

Experience - Beam instability caused by impedance in LER

[K. Ohmi, “Impedance and instability at SuperKEKB”, eeFACT2022, WG4]

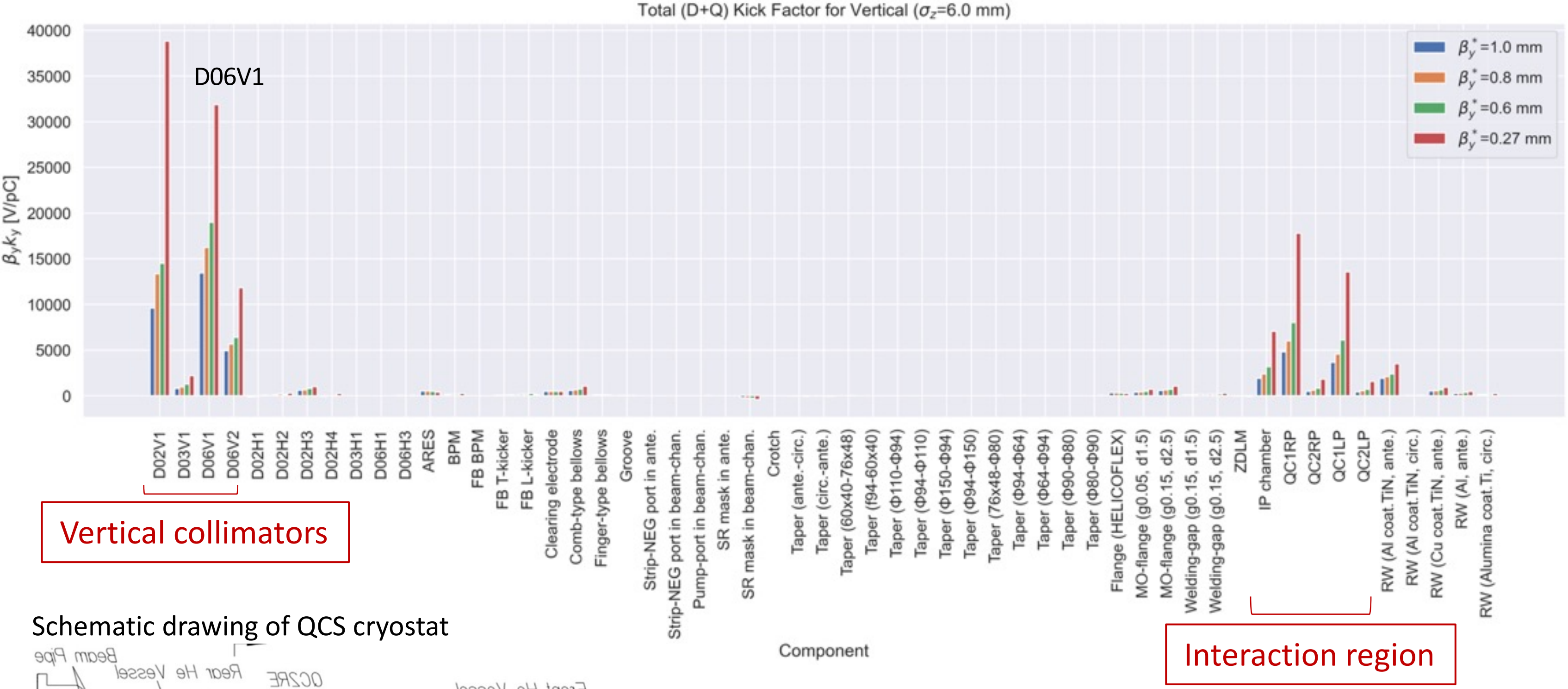




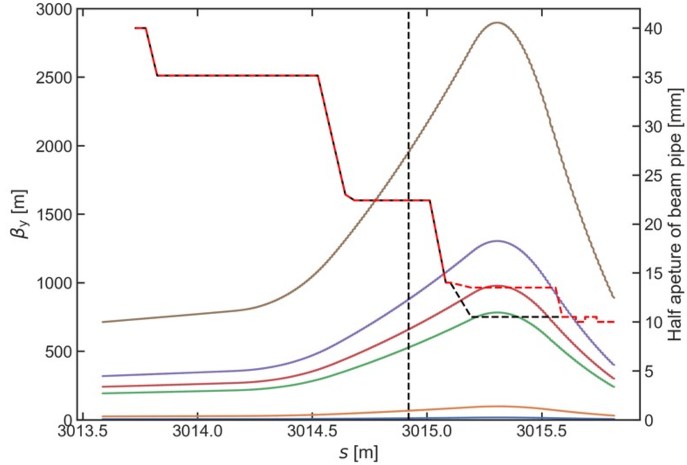


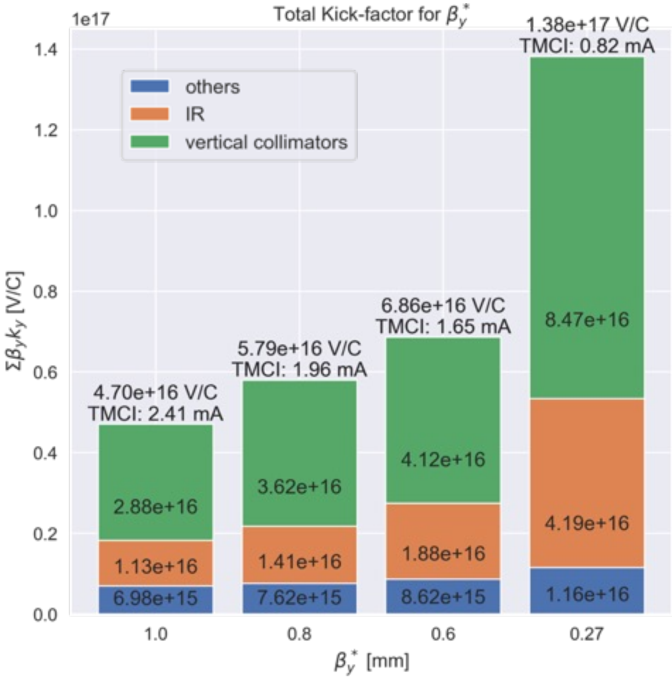
- When we fully opened the aperture of D06V1, the vertical emittance blow-up didn’t occur up to ~1.5 mA/bunch.
  - ➢ (D06V1 aperture) close: ±2.9 mm, open: ±8 mm
- The background level derived from the storage beam increased when we opened it. We‘ve used D06V1 as a primary collimator to cut off the injection backgrounds, but these observations indicate this collimator contribute to suppress the storage backgrounds too.
- This instability can be reproduced by simulation using transverse wake and high gain multi-tap feedback [K. Ohmi].

Experience – Impedance budgeting in LER

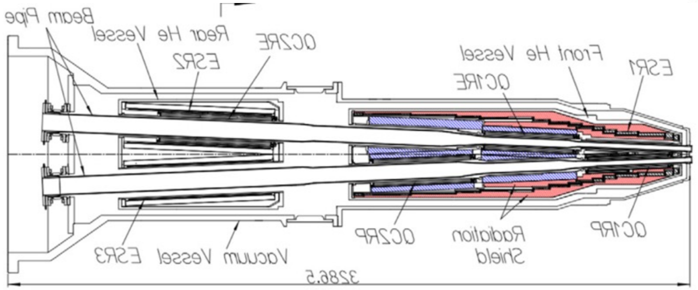


Half aperture of a QCS beam-pipe and vertical beta-function with each vertical beta-function at the interaction point as a function of the longitudinal location





Schematic drawing of QCS cryostat



[N. Ohuchi *et al.*, Nucl. Instrum. Methods Phys. Res.A, 1021, 165930 (2022)]

$$I_{th} = \frac{4\pi\nu_s(E/e)}{T_0 \sum_i \beta_{y,i} k_{y,i}}$$

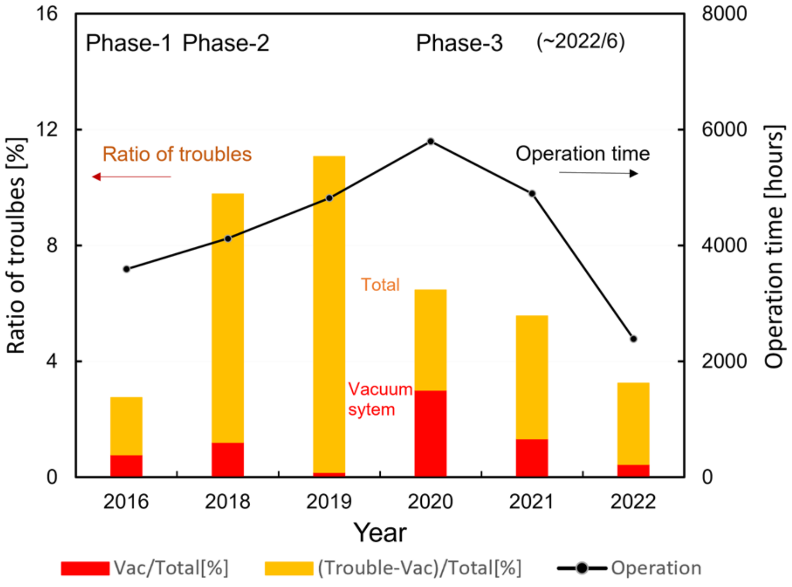
$\nu_s = 0.022, E/e = 4$ GV, T_0 = 1e-5 s

- The collimator setting is based on that in physics run during 2021c with β_y^* = 1.0 mm.
  - β_y^*: vertical beta function at the interaction point, QCS: final focusing superconducting magnets
- The main vertical impedance sources are the vertical collimators and beam-pipes in the interaction region.
- The reason why the kick factor in IR increases with squeezing β_y^* is the β_y becomes bigger and bigger with the squeezing.
- The calculated threshold of transverse mode coupling instability is 0.82 mA/bunch for β_y^* = 0.27 mm, and this can limit the current in the future.

Summary

- The SuperKEKB vacuum system has been working mostly well.
- New components developed have been functioned well.
- Vacuum scrubbing progressed steadily.
- Recent behaviors of pressure against beam current are explained including thermal desorption (heating by wall current and HOM) as well as PSD.
- Recent beam lifetime is mostly limited by the Touschek effect rather than pressure.
- The countermeasures against ECE are working almost as expected, although the effect of photo-electrons seems larger than expected.
  - ➢ No clear indication of ECE has been observed with permanent magnets.

Operation time, the ratios of total machine troubles and troubles related to vacuum system per year.



Summary (Issues)

- Temperature rise of beam pipes in wiggler magnet section (not mentioned in this talk).
  - Installation of bellows chambers with SR masks is ongoing.
- Abnormal pressure rises due to HOM (not mentioned in this talk).
- Collimators have been frequently damaged due to
  - accidental firings of injection kickers in LER,
  - sudden beam loss in the both rings.
  - For a measure against the accidental firings of injection kickers, we will develop and install carbon jaws in D06H3 as a spoiler and move D06H1 to D06H4 that used for an absorber for the crazy beams.
  - For a measure against the sudden beam loss,
    1. there is a possibility that the Cu coating on the tip of the jaw can avoid the sudden beam loss if they are triggered by fire-balls (T. Abe) [Y. Funakoshi, "Overview and prosperous of the SuperKEKB commissioning", eeFACT2012, WG12]. We will coat the tip in all of the vertical collimators with Cu. This would also be effective to reduce the resistive-wall impedance.
    2. we will install short titanium jaws in D06V1 and use it as a spoiler, and use D05V1 (non-linear collimator) as an absorber for the crazy beams [A. Natochii, MDI taskforce meeting, https://kds.kek.jp/event/42881/].
- Vertical beam size blow-ups have been observed in the vertical direction.
  - This instability can be reproduced by simulation using transverse wake and high gain multi-tap feedback [K. Ohmi].
  - The impedance will be dramatically reduced by using a non-linear collimator instead of D06V1 collimator (not mentioned in this talk), and this will increase the threshold of the bunch current.
  - Optimizations of the collimators' structure could reduce the impedance, but previous studies have shown that it does not decrease dramatically.
    - ✓ longer collimator, non-linearly tapered collimator and so on
  - One side jaw such as KEKB type collimators may reduce the transverse dipole wake.

Thank you for your attention.