Collimator Issues

2022-12-14

The 26th KEKB Accelerator Review Committee

T. Ishibashi

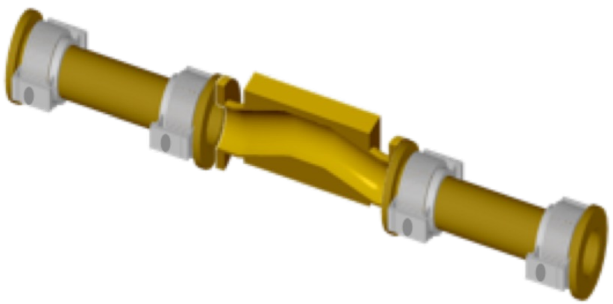
Design

KEKB type

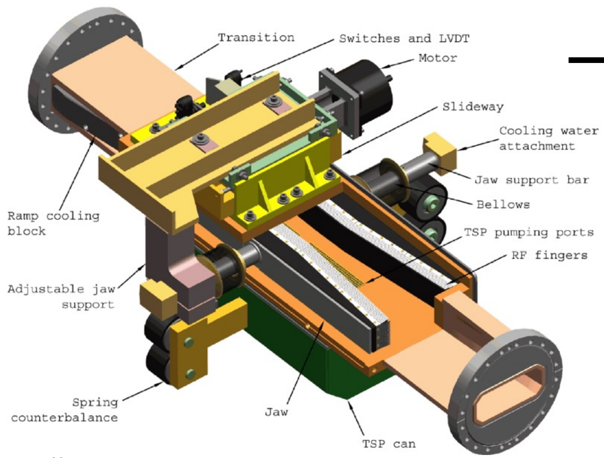
- KEKB type collimator has been used since KEKB era.
- It has a tapered beam-pipe and approaches the beam through 4 bellows chambers on both sides.
- These have been reused in 2 arc sections in HER.
- The tip is made of copper coated titanium with a length of 40 mm.

SuperKEKB type

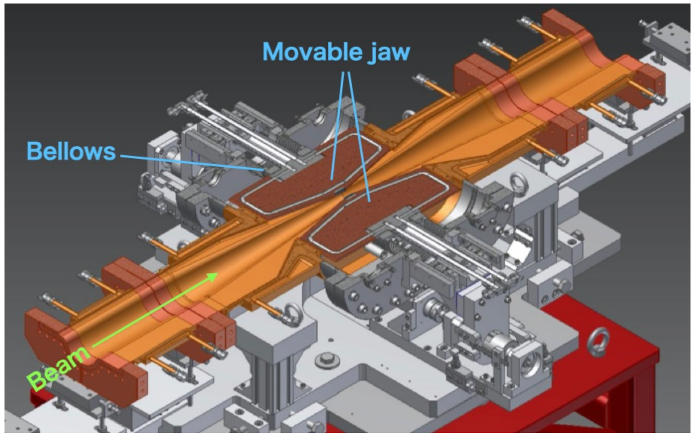
- We referenced movable collimators for PEP-II in SLAC for the basic design of the SuperKEKB type.
- A collimator chamber has two movable jaws with RF-shields.
- Part of the movable jaws is hidden inside the antechambers to avoid trapped modes in gaps between the movable jaw and the chamber. The chamber is also tapered to the center of the collimator in order to avoid excitation of trapped-modes around the jaws.
- 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.).



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

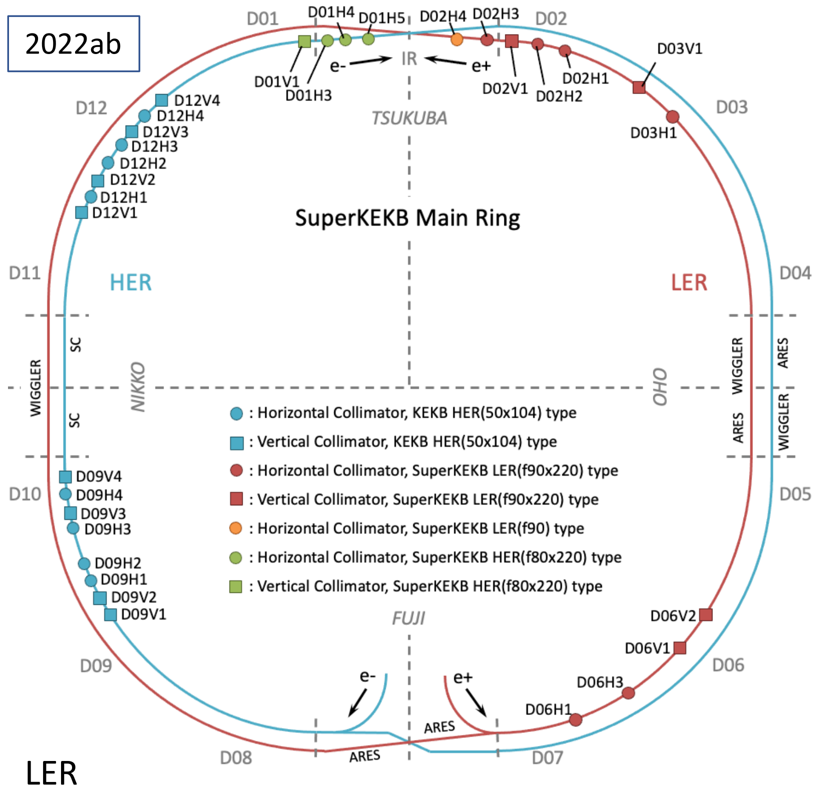


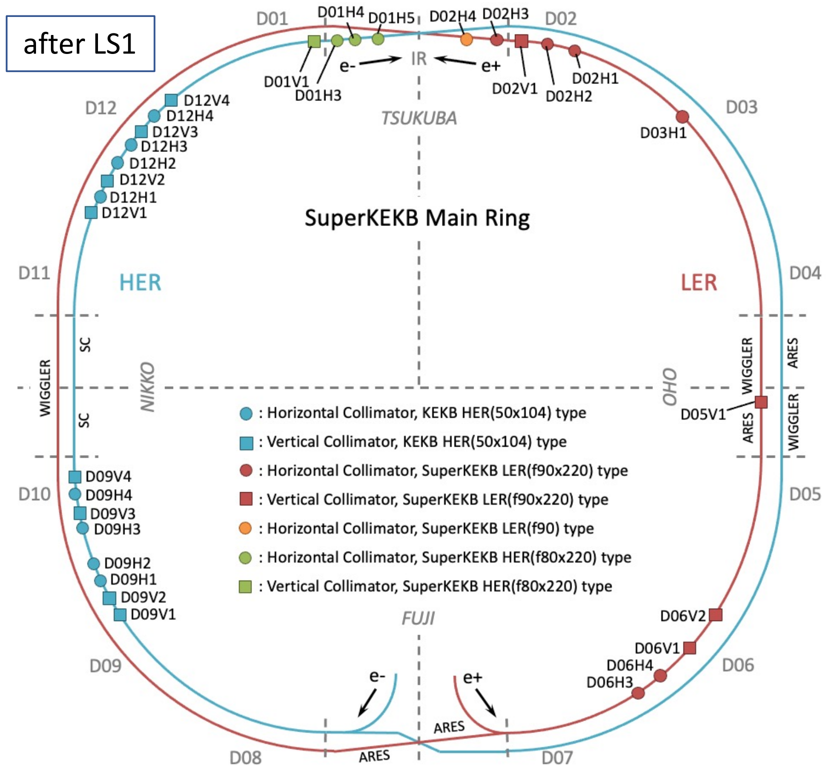
Collimator in PEP-II
[S. DeBarger et al., SLAC-PUB-11752]



SuperKEKB type collimator (horizontal)
[T. Ishibashi et al., PRAB **23**, 053501 (2020)]

Location



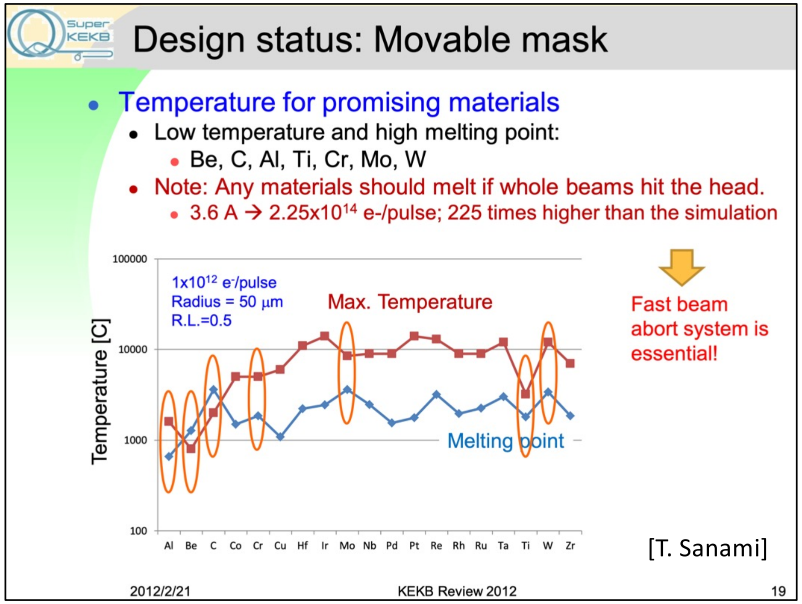


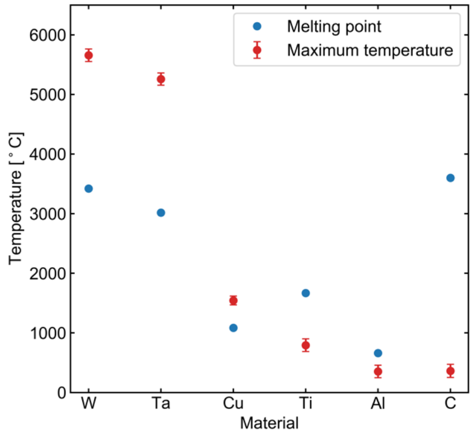
LER
- D06V1: primary collimator to suppress the injection BG
- D02V1: collimator closest to interaction point (IP) and very important to suppress the detector BG.
- D06V1, D03V1: backups
- D06H3: absorber against accidental firings of the injection kickers

During LS1
- D03V1 will move to D05V1, that is a non-linear collimator.
- D06H1 will move to D06H4 that used for an absorber (countermeasure for accidental firings of injection kickers. D06H3 will be used as the spoiler by installing carbon jaws in it).

Material

- Any materials should melt if high current beam hit the jaw.
- Tungsten (W) was used for the material of the tip at first, but it was found that if it was damaged by the beam hit, it become embrittled and generate a lot of radioactive dusts.
- After that, tantalum (Ta) have been used as a default material of the tip.
- A special type of jaws named low-Z/carbon made from carbon fiber reinforced carbon (CFC) was developed for a more robust collimator, but the impedance problem arose in 2020c and was removed (the radiation length of the carbon is long (~19.32 cm) compared with W/Ta (~0.35 cm/0.41 cm, and its conductivity is low (~3.0e5 S/m @ 5.044 GHz)), so we need longer jaw to suppress the background).
- A special type of jaws named hybrid made from CFC and Ta was developed for the robust collimator. This jaw has been used without being damaged and so on, if a high beam current induced in, it will break, and we don't know what state it will be in if it breaks (In the worst case, cracks may be formed at the junction and discharges may occur.).

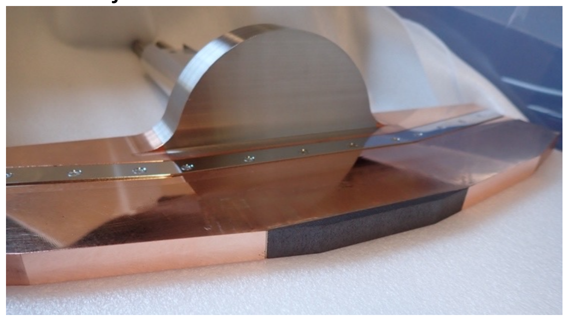




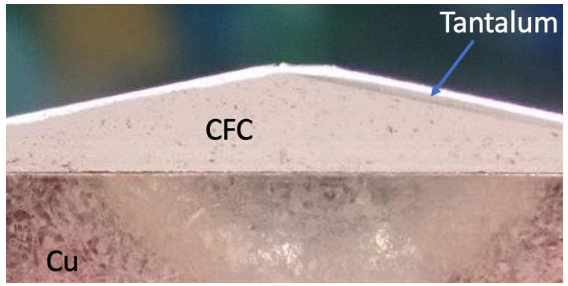
[T. Ishibashi]

Maximum temperatures within 1 RL and melting points for each material, induced by the positron beam. The beam profile and energy are respectively Gaussian and 4 GeV. Dx=y and the injected current are 0.5 mm and 50 mA (3.12 × 1012 positrons), respectively.

Carbon jaw



Hybrid jaw (CFC+Ta)



Investigation of Materials for more robust collimators

- High-Z (Ta, W)
  - The radiation length is short (Ta: 0.41 cm, W: 0.35 cm), and we can decrease the length at the tip of the jaw to a few mm.
  - The electric conductivity is acceptable (Ta: 7.61e6 S/m, W: 18.9e6 S/m). [Ref. Cu: 59.6e6 S/m]
  - Easy to damage. Jaws with a short tip length of ~4 mm has been installed in the vertical collimators in the arc section for the robustness because the scratch mark caused by the beam hit starts after one radiation length in the beam traveling direction. A tip length of 10 mm has been installed in only D02V1 and D01V1.
  - Large effect to raise the IR background when it’s damaged (This is derived from the mass density of the protrusions on the tip surface?)
  - Generate radioactive dusts when it’s damaged. Radiation Science Center has commented that the half-life time of the Ta may be longer compared to that of W. However, it’s very easy to generate the dusts for W when it’s damaged…
  - In the future, the radioactivity can limit the replacement work. We may have to wait the decay of the radioactivity and be not able to replace during runs.
- Low-Z (Carbon)
  - The radiation length is long (C: 19.32 cm) . We need longer tip (>60 mm) to shield the halo, and this raise the geometrical impedance.
  - The electric conductivity is very low (C: ~3.0e5 S/m @ 5.044 GHz), and the resistive wall also raises the impedance. However, we can avoid this by adopting Cu plate on the carbon.
  - The melting point is high.
  - Very difficult to damage.
- Mid-Z (Ti)
  - The radiation length is intermediate (Ti: 3.56 cm), and we can adopt a dozen mm for the tip length.
  - The electric conductivity is acceptable (Ti: 2.38e6 S/m). If we need Cu plating, we can do it as with the jaws of KEKB type collimators.
  - Easy to damage from the experiences of KEKB type collimators in HER.
  - Nevertheless, we’ve used damaged Ti jaws in HER without major impact on the IR backgrounds. (This is derived from the mass density?)

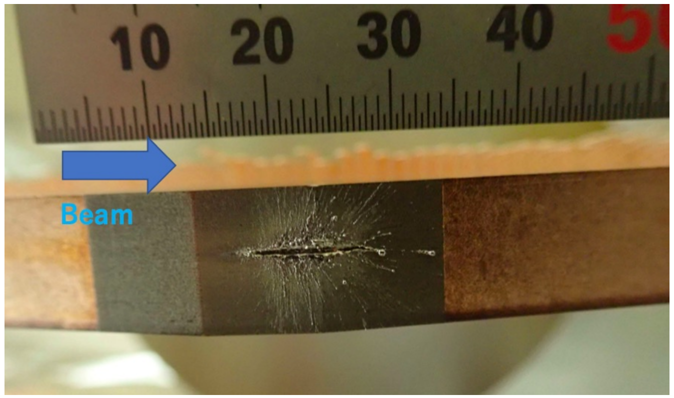
  (→ Titanium jaws may have good balance in terms of the durability and the impedance.)
  - Difficult to generate the radioactive dusts when it’s damaged from the experiences of KEKB type collimators in HER.
- We are developing carbon, hybrid (C+Ta), titanium, and MoGr jaws as collimators that are hard to damage or have little effect on the background even if they are damaged.

Major Issues – damage

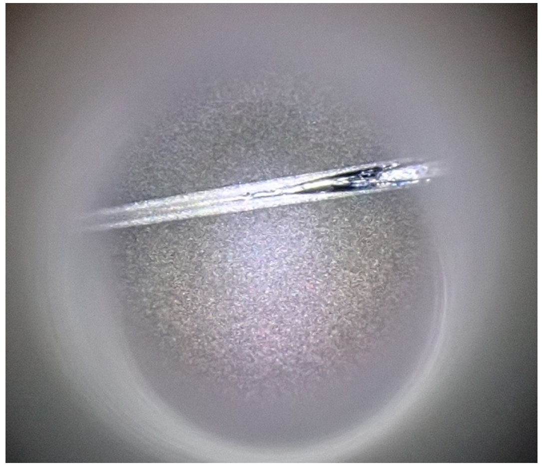
- The collimators have been frequently damaged due to beam hits.
- The source of beam instability that causes damage to the vertical collimators is still unknown (sudden beam loss, H. Ikeda will report the details later).
- On the other hand, there are damaged events for known reasons, and that is the 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 for the uncontrollable beams.
  - D06H1 will move to D06H4 and used as an absorber.

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

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

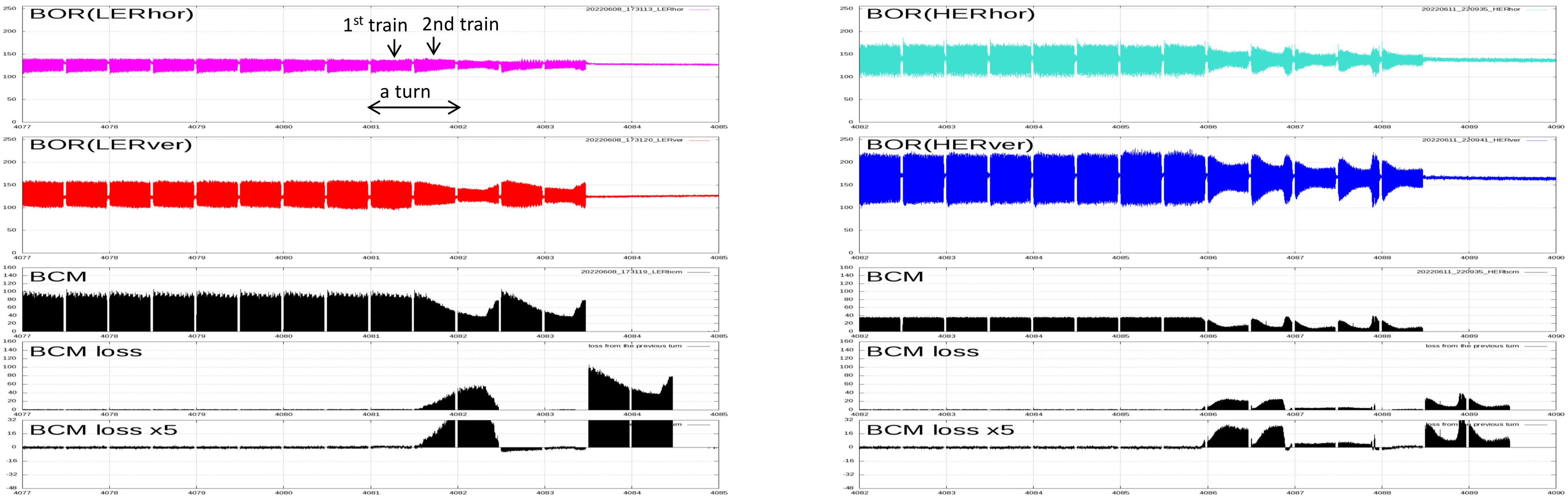


Damaged tip of D09V1 (KEKB type) in HER due to the sudden beam loss during 2022b.



Major Issues - damage (sudden beam loss)

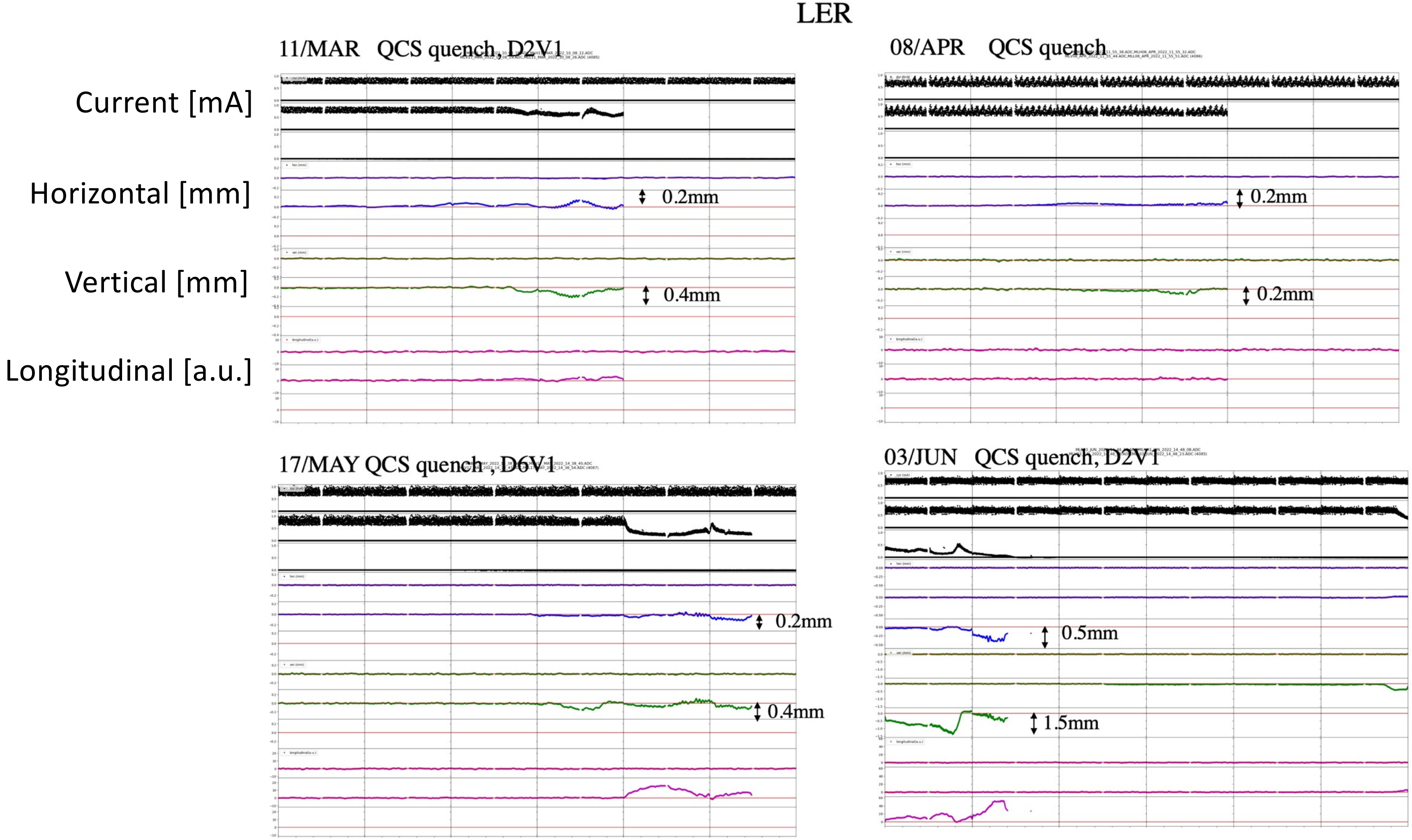
- Sudden beam loss has occurred within approximately 2-turn (~20 μs) before the beam abort.
- Beam orbit displacements in horizontal and vertical direction has been observe [H. Fukuma and S. Terui].
- No increase in the beam size has been observed by a fast beam size monitor [G. Mitsuka].
- This beam 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 …



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

Major Issues - damage (sudden beam loss)

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

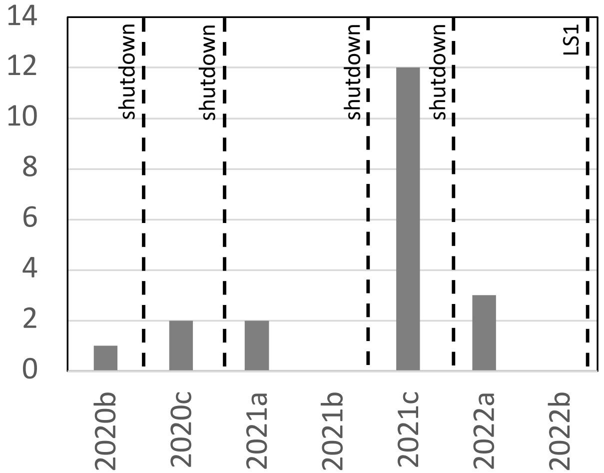


[H. Fukuma]

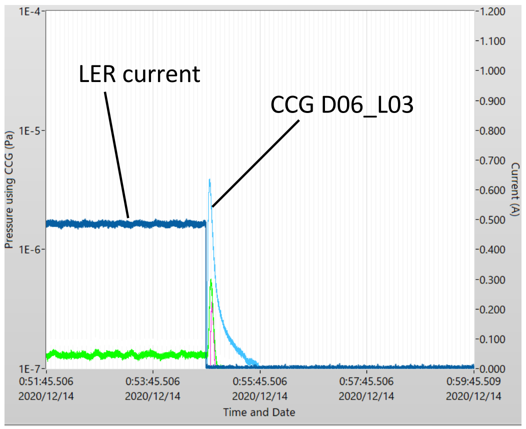
Major Issues - accidental firings of injection kickers

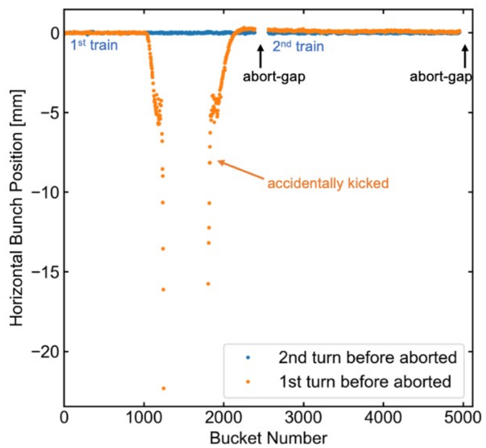
- Accidental firings of injection kickers have happened in LER.
  (It seems that the accidental firings tend to occur more frequently after the shutdown period somehow.)
- When this event occurs, pressure burst near a horizontal collimator named D06H3 is observed due to the beam hit.
- In the current system, we cannot make the probability of the accidental firing zero, so some horizontal collimators in each ring has been used to protect components against the accidentally kicked beams.
- As countermeasures against this,
  - Carbon jaws will be installed in D06H3 and used as a spoiler for the uncontrollable beams.
  - D06H1 will move to D06H4 and used as an absorber.

The number of the accidental firings on each run period.



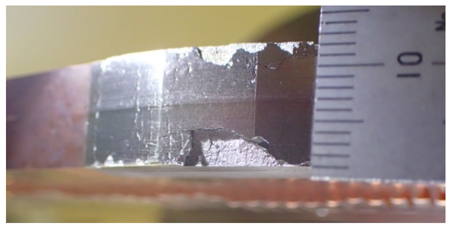
Pressure burst near D06H3 collimator.





Horizontal position of the center of gravity for each bunch measured with BOR and the bucket number when an accidental firing of an injection kicker occurred.

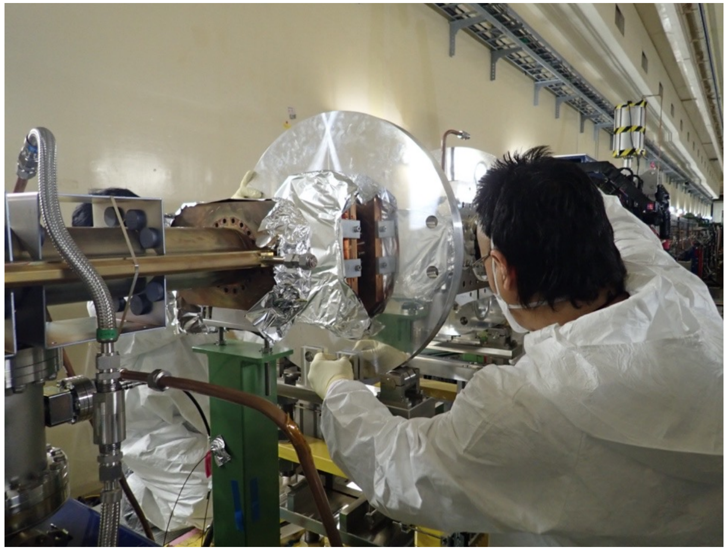
Damaged jaw in D06H3 by accidental firings.



Replacement Work (vertical collimator)

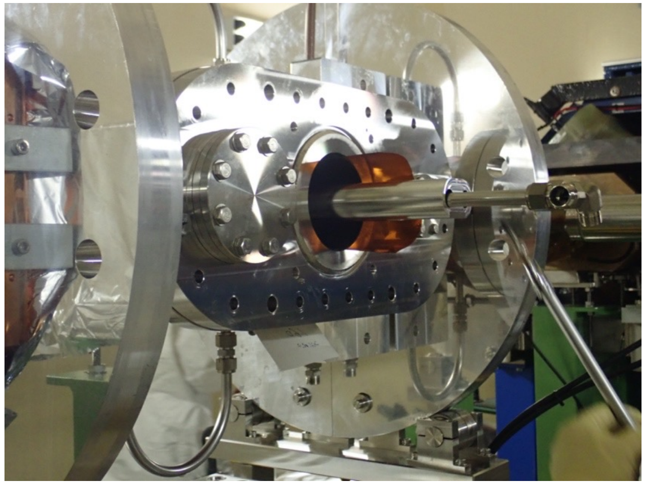
- Before the replacement, we purge the beam pipes in the section where the collimator is located with nitrogen and remove the drive mechanisms and cooling water pipes.
- It is also necessary to investigate the cooling water whether it's radio activated.

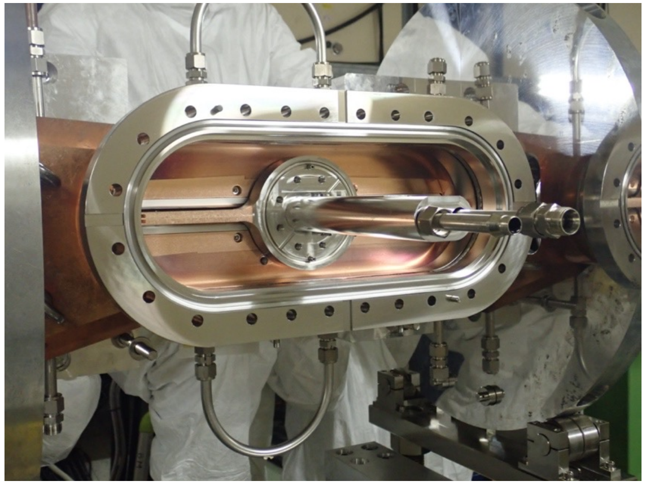
Clearing out people



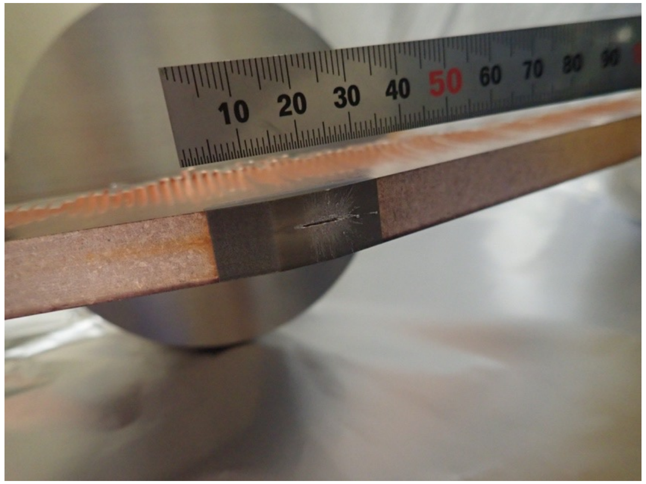
Remove the beam-pipes nearby, and rotate the chamber 90 degrees

Replacement Work

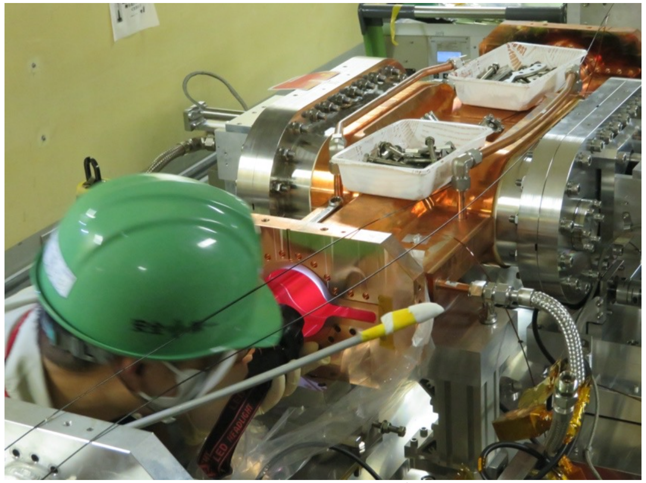




Remove the racetrack type flanges in where the jaws are inserted.



Remove the damaged jaws.

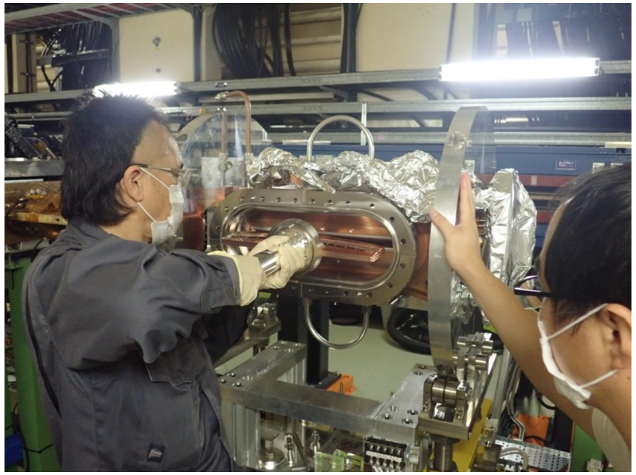


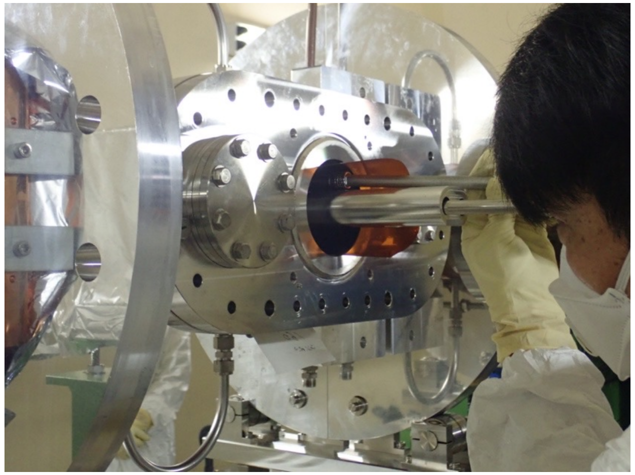
(← this photo shows a cleaning work for D06H3. I was not able to find the photo for D02V1.)

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

Replacement Work

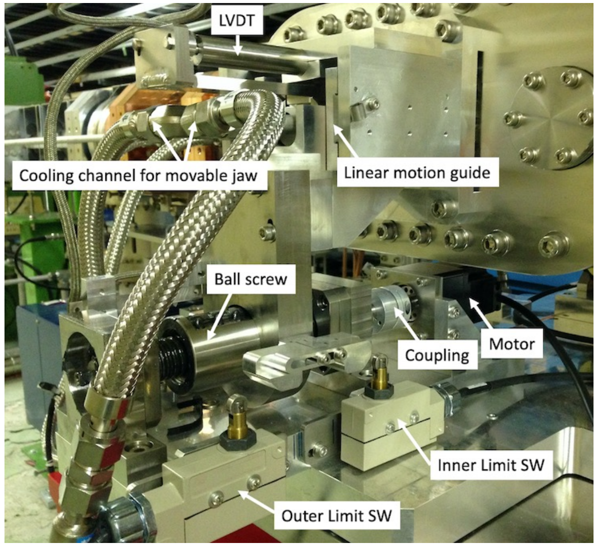

Attach RF-fingers to the spare jaws.


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 using a laser tracker with the help of Magnet Group if necessary.

Drive mechanism



Current condition – HER

	Name	Type	Tip Material (): longitudinal length in mm	Tip Condition	Drive Mechanism	Work Plans during LS1
arc	D09H1	KEKB	Cu coated Ti (40)	damaged		
	D09H2	KEKB	Cu coated Ti (40)	damaged		
	D09H3	KEKB	Cu coated Ti (40)	damaged		
	D09H4	KEKB	Cu coated Ti (40)	damaged		
	D12H1	KEKB	Ti (40)	healthy		
	D12H2	KEKB	Cu coated Ti (40)	damaged		
	D12H3	KEKB	Ti (40)	healthy		
	D12H4	KEKB	Cu coated Ti (40)	healthy		
Tsukuba straight	D01H3	SuperKEKB	W (10)	healthy	-	
	D01H4	SuperKEKB	W (10)	healthy	-	
	D01H5	SuperKEKB	W (10)	healthy	-	
arc	D09V1	KEKB	Cu coated Ti (40)	damaged		jaw replacement (Cu coated Ti (40)), drive mechanism upgrade?
	D09V2	KEKB	Cu coated Ti (40)	healthy		
	D09V3	KEKB	Cu coated Ti (40)	healthy		
	D09V4	KEKB	Cu coated Ti (40)	healthy		
	D12V1	KEKB	Cu coated Ti (40)	damaged	upgraded	
	D12V2	KEKB	Cu coated Ti (40)	damaged		
	D12V3	KEKB	Cu coated Ti (40)	healthy		drive mechanism upgrade
	D12V4	KEKB	Cu coated Ti (40)	healthy	upgraded	
Tsukuba straight →	D01V1	SuperKEKB	W (10)	damaged (only BTM)	-	jaw replacement (Cu coated Ta (10))

- D09V1 was damaged during 2022b and will be replaced with new one during LS1.
- There was a problem with the displacement sensor in D12V3 during 2022ab, and the drive mechanism will be upgraded during LS1.
- There is a request to upgrade the drive mechanism of D09V1 for the precise positioning.
- We plan to coat spare jaws for D01V1 with Cu and install them as a countermeasure for fire-balls during LS1.

Current condition- LER

	Name	Type	Tip Material (): longitudinal length in mm	Tip Condition	Work Plans during LS1
arc	D06H1	SuperKEKB	W (10), fully opened	healthy	move to D06H4, jaw replacement (Ta (10?))
	D06H3	SuperKEKB	OUT: Ta (10), IN: W (10)	damaged	jaw replacement (Cu coated C (160))
	D03H1	SuperKEKB	W (10)	healthy	
	D02H1	SuperKEKB	W (10)	healthy	
	D02H2	SuperKEKB	W (10)	healthy	
Tsukuba straight	D02H3	SuperKEKB	W (10)	healthy	
	D02H4	SuperKEKB	W (10)	healthy	
arc	D06V1	SuperKEKB	Ta (4)	damaged	jaw replacement (Cu coated Ti (10?))
	D06V2	SuperKEKB	Cu coated C-Ta hybrid (3)	healthy	
	D03V1	SuperKEKB	Ta (10)	healthy	move to D05V1 (currently installed jaws will be spares)
Tsukuba straight →	D02V1	SuperKEKB	Ta (10)	damaged	jaw replacement (Cu coated Ta (10))

- D06H1 will move to D06H4 and used as an absorber of uncontrollable beams due to accidental firings of injection kickers. The jaws will also be replaced with new ones.
- Carbon jaws will be installed in D06H3 and used as a spoiler of the uncontrollable beams.
- Cu coated Ti jaws, which are one of candidates of durable jaws, will be installed in D06V1 and can be also used as a spoiler for sudden beam loss (D05V1 can be used for the absorber) [A. Natochii, https://kds.kek.jp/event/42881/].
- D03V1 will move to D05V1 (non-linear collimator), and the jaws will also be replaced with new ones (Cu coated Ta, the length depends on the radiation safety in OHO-section).
- We plan to coat spare jaws of the vertical collimators with Cu as a countermeasure for fire-balls and install them in D02V1 and D05V1.

Major Issues – impedance (summary of -1 mode instability in vertical direction)

In single-beam operation (no collision) in LER:

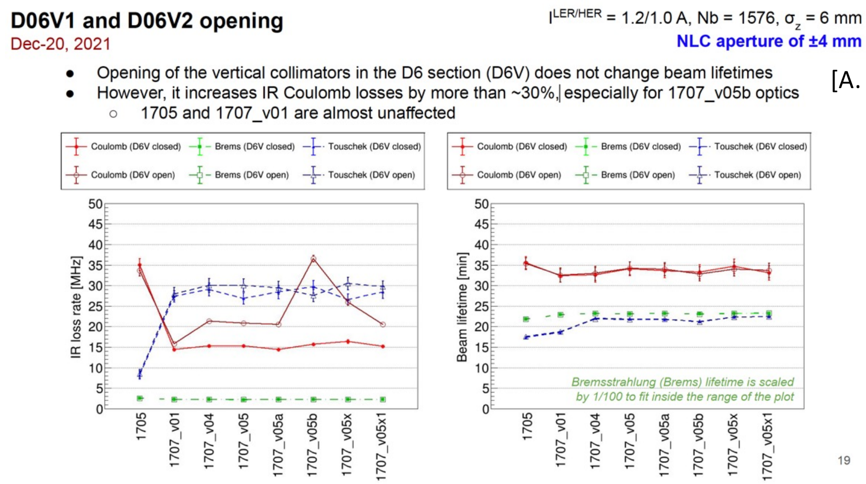
- Vertical beam size blow-ups have been observed at ~1.0 mA/bunch, and the threshold of the -1 mode instability depends on the aperture setting of the vertical collimators, tuning of the vertical bunch-by-bunch feedback and so on.
- ITF TMCI working group (contact person: Mauro Migliorati, sub-contact person: me) had tackled to find countermeasures against this and investigation of the mechanism through simulations and machine studies.
  - ITF TMCI working group: https://kds.kek.jp/category/2247/
  - ITF meetings: https://kds.kek.jp/category/2322/
- A peak around ν_y-ν_s appears when the blow-ups occur (so we've called this "-1 mode instability in the group).
- Tune surveys indicate that this instability is not derived from a stop band of ν_y-ν_x-2ν_s=N.
- The dipole oscillation due to the -1 mode instability is spontaneously damped.
  - ✓ The growth time is 3.5 ms to 8 ms.
- The 0- and -1-mode seem to be coupled at around ~2.0 mA (ordinary TMCI) from a linear regression in a measurement.
- We've found some effective countermeasures to the -1 mode instability.
  1. Tuning of the vertical bunch-by-bunch feedback (BxB FB),
  2. Increase the vertical tune,
  3. Increase the vertical chromaticity,
  4. Reducing the impedance in the vertical direction by opening vertical collimators.
  - ✓ The forth item is one of motivations to construct a non-linear collimator, and we've decided to construct it (A. Morita will report about the non-linear collimator later).
- K. Ohmi has reproduced this instability in simulations taking transverse wake and high gain feedback system with a multi-tap FIR filter in to account (K. Ohmi will report later).

Non-linear collimator

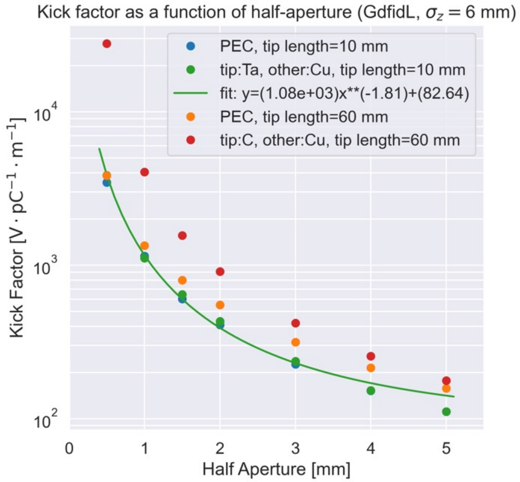
[example] collimator setting and $\beta_y k_y$ for βy^*=1 mm optics.

Collimator	β_y [m]	Half-aperture [mm] a)	$\beta_y k_y$ [$\times 10^{15}$, V/C] b)
D06V1	67.35	2.9	16.15
D06V2	20.57	2.6	5.64
D03V1	16.96	8.0	1.83
D02V1	11.89	1.1	11.76
D05V1	4.05 c)	4	0.69

a) averaged value of top and bottom half-aperture at 2021-12-22
b) ky is a kick-factor obtaind by GdfidL simulations and a fit for σ_z=6 mm and Ta-jaw of 10 mm in the longitudinal length.
c) sler_1707_80_1_cw80_NLC_04



[A. Natochii]



Bunch current threshold of TMCI

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

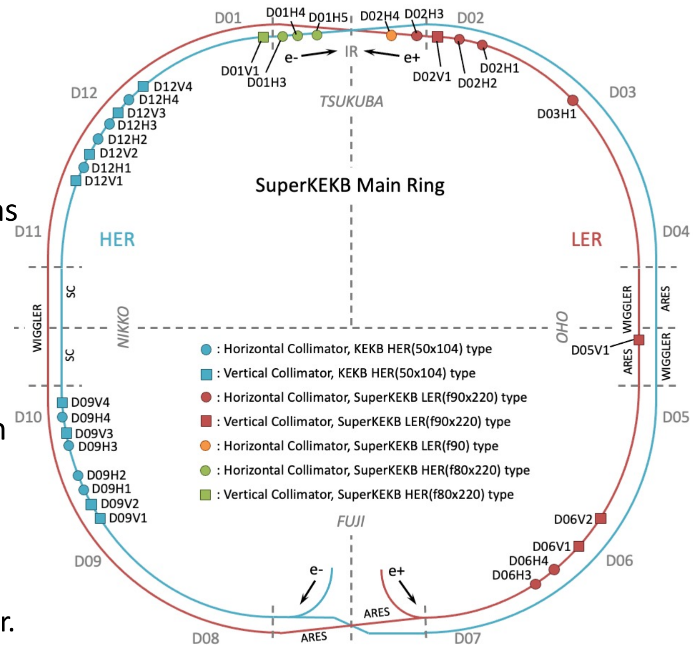
- D05V1 is a vertical collimator in the non-linear collimation system.
- D06V1 has been used to suppress the injection backgrounds (primary collimator) and has a large $\beta_y k_y$ because the β_y is large, and the aperture is narrow.
- D05V1 can have a small β_y and almost the same performance of the background reduction as D06V1 with the wider aperture.

→ It can decrease the $\beta_y k_y$ to approximately 1/20 if we can use D05V1 instead of D06V1.

Summary - Major Issues

- Collimators have been frequently damaged due to
    - ➢ accidental firings of injection kickers in LER,
    - For a measure against this, we will develop and install carbon jaws in D06H3, and it will be used as a spoiler. Then, we will move D06H1 to D06H4 that used for an absorber for the uncontrollable beams.

    - ➢ sudden beam loss in the both rings.
    - 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). We will coat the tip in all of the vertical collimators with Cu.
        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 uncontrollable beams [A. Natochii, MDI taskforce meeting, https://kds.kek.jp/event/42881/].
            - ➢ Large β_y of ~67 m at D06V1 is unwanted for the vertical impedance, but good for the spoiler.
            - ➢ We have to set narrow aperture in D06V1, so the impedance situation remains unchanged.
        3. If there is a possibility that electron cloud in the collimators can cause the sudden beam loss (under investigating), we may put solenoid coils around them.



- Vertical beam size blow-ups in LER have been observed caused by the impedance and feedback in the vertical direction.
    - This instability can be reproduced by simulations taking transverse wake and high gain feedback with a multi-tap and FIR filter system into account [K. Ohmi].
    - The impedance can be dramatically reduced by adopting a non-linear collimation system instead of D06V1, and this will increase the threshold of the bunch current.

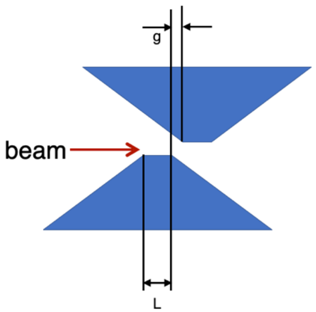
Summary - Status and Future Plans

- We've developed new jaws (C, hybrid, Ti, and MoGr) for a more robust system in terms of the beam hits.
  - However, even if these are realized, they are only tentative measures, because any materials should melt if high current beam hit the jaw.
  - It is essential to eliminate sources that causes the uncontrollable beam (sudden beam losses and accidental-firings in injection kickers).

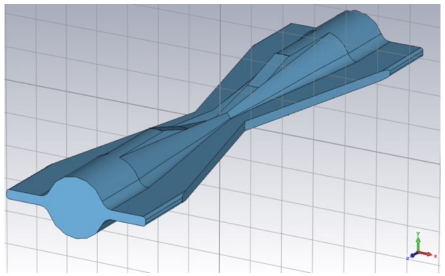
- In addition, several ideas have been proposed to make the collimator system more robust.
  - alternate jaws to prevent deposition of metal on the opposing surface at tip (impedance increase and trapped mode)
  - wider jaws to make room for the horizontal shift (impedance increase)
  - operation of double D02V1 in tandem (trapped mode)
  - vertical collimator at downstream of IP, that is D01 for example, to install jaws that have ultra-thin tips (BG reduction)

  (): concerns

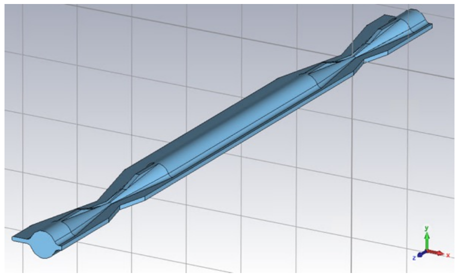
alternate jaws



wider jaws



vertical collimator in tandem



back-up

Spares that we have as of now

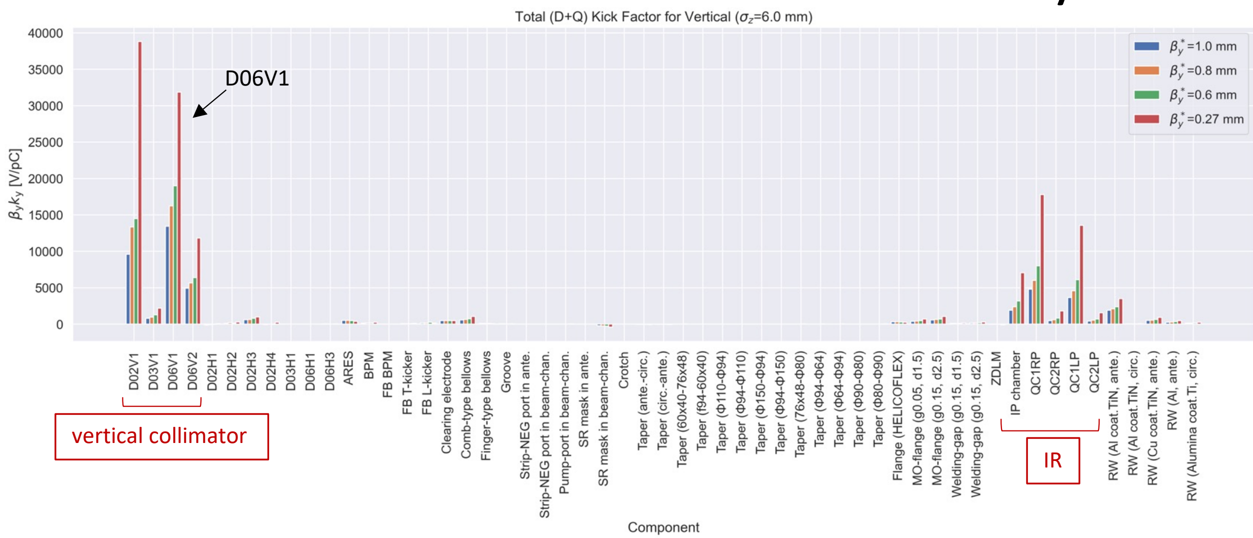
Tip Material (): longitudinal length in mm	Collimator to be installed (assumed)	Work Plans during LS1
HER vertical: W (10)	D01V1	
HER vertical: Ta (10)	D01V1	plan to coat with Cu
HER vertical: Ta (10)	D01V1	plan to coat with Cu
HER vertical: Cu coated Ti (40)	D09V1-V4, D12V1-V4	
LER vertical: Ta (10)	D02V1	plan to coat with Cu and install on D02V1
LER vertical: Ta (10)	D02V1	plan to coat with Cu and install on D02V1
LER vertical: Ta (10)	D02V1	plan to coat with Cu and install on D05V1(?)
LER vertical: Ta (10)	D02V1	plan to coat with Cu and install on D05V1(?)
LER horizontal: Ta (10)	D01H3-H5, D02H1-H4, D06H4	

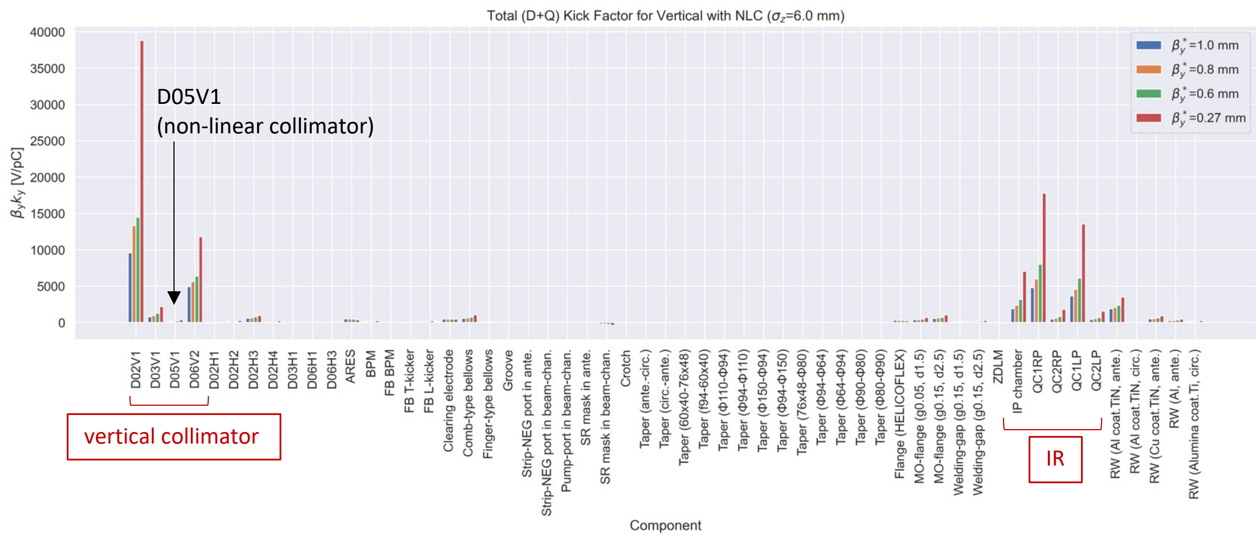
Scheduled to be manufactured (FY2022)

Tip Material (): longitudinal length in mm	Collimator to be installed (assumed)	Remaks
LER vertical: Cu coated Ta (3.5-10)	D05V1	longitudinal length depends on the radiation safety in OHO-section
LER vertical: Cu coated Ta (3.5-10)	D05V1	longitudinal length depends on the radiation safety in OHO-section
LER vertical: Cu coated Ti (10?)	D06V1	can be used for spoiler against sudden beam loss (D05V1 can be the absorber)
LER vertical: Cu coated Ti (10?)	D06V1	can be used for spoiler against sudden beam loss (D05V1 can be the absorber)
LER horizontal: Ta (10?)	D06H4	absorber for crazy beam due to accidental firings in inj. kickers
LER horizontal: Ta (10?)	D06H4	absorber for crazy beam due to accidental firings in inj. kickers
LER horizontal: Cu coated C (160?)	D06H3	spoiler for crazy beam due to accidental firings in inj. kickers
LER horizontal: Cu coated C (160?)	D06H3	spoiler for crazy beam due to accidental firings in inj. kickers
HER vertical: Cu coated Ti (40)	D09V1-V4, D12V1-V4	KEKB type jaw
HER vertical: Cu coated Ti (40)	D09V1-V4, D12V1-V4	KEKB type jaw

- In addition to these, we plan to investigate MoGr [M. Pasquali *et al.*, https://doi.org/10.1007/s40870-019-00210-1] as one of candidates of the durable jaws,

Major Issues (impedance - β_y^* dependence)

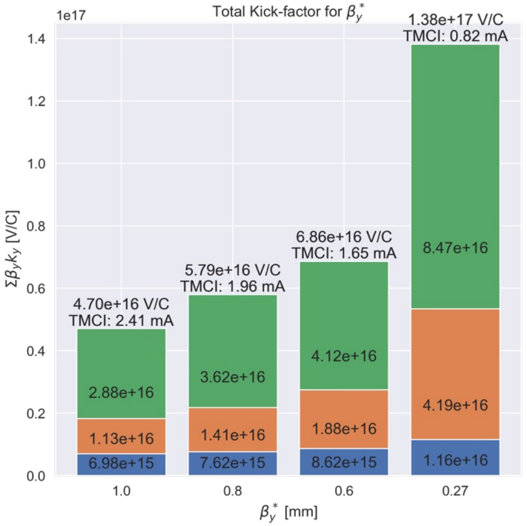


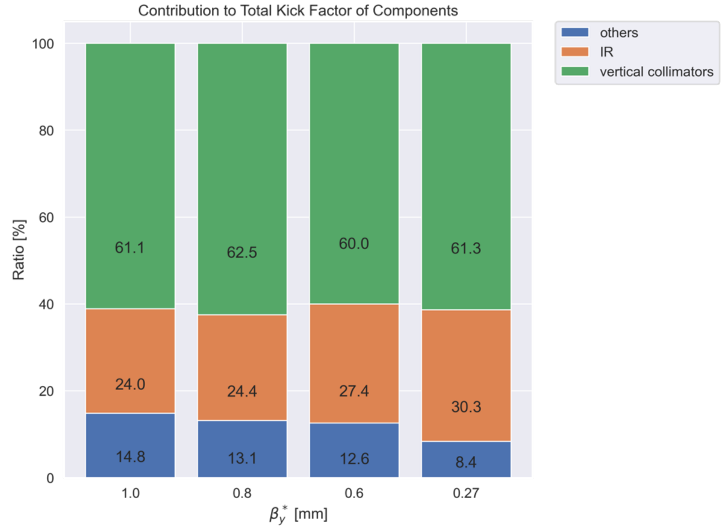


- The collimator setting is based on that in physics run during 2021c.
- The aperture of the vertical collimators are scaled by $\sqrt{\beta_y}$ at each collimator and $\sqrt{\beta_y^*}$.
- Each region of the beam-pipes in IR is below.
  - IP chamber: X-shaped beam-pipe around the collision point between “QC1RP505” and “QC1LP505”.
  - QC1LP: tapered beam-pipe including a BPM, bellows, and welding-gap between “QC1LP515” and “QC1LP1375”.
  - QC2LP: tapered beam-pipe including a BPM and welding-gap between “QC2LP1385” and “QC2LP2475”.
  - QC1RP: tapered beam-pipe including a BPM, bellows, and welding-gap between “QC1RP1375” and “QC1RP485”.
  - QC2RP: tapered beam-pipe including a BPM and welding-gap between “QC2RP2715” and “QC2RP1385”.
  - ✓ The resistive-wall impedance is included in this model.

Major Issues (impedance - β_y^* dependence)

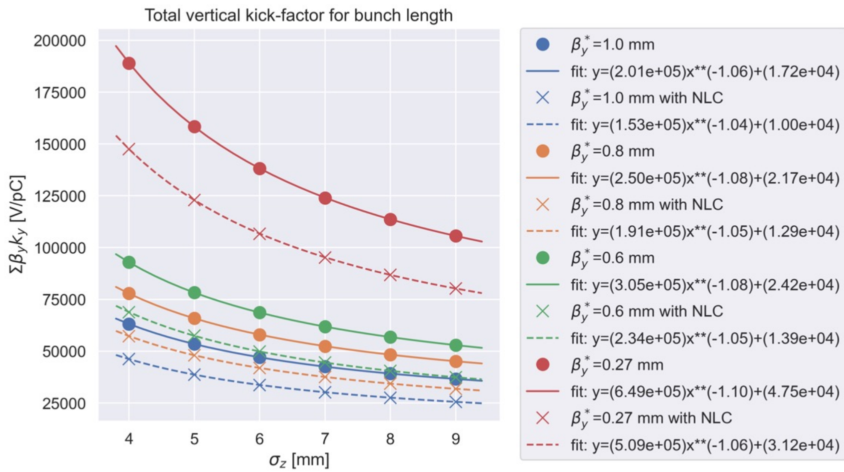
Without NLC





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

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



With NLC