Development and operation experience of collimators at SuperKEKB

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Acknowledgment

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Outline

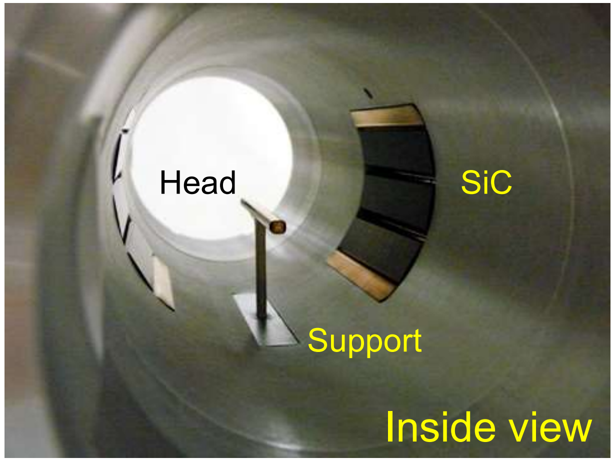
- Introduction
- Design of SuperKEKB-type collimator
- Operational experience
  - Collimator damage events
  - Vertical beam-size blow-up due to -1 mode instability
- Summary

Introduction: Experience of collimators during the KEKB era

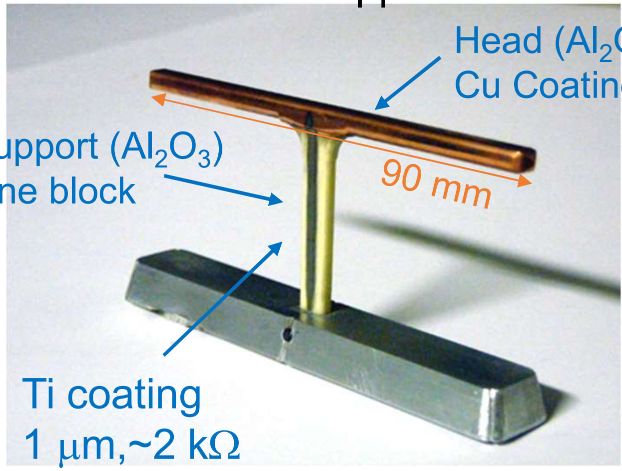
Introduce Suetsugu-san's experience with collimator trouble during KEKB era.

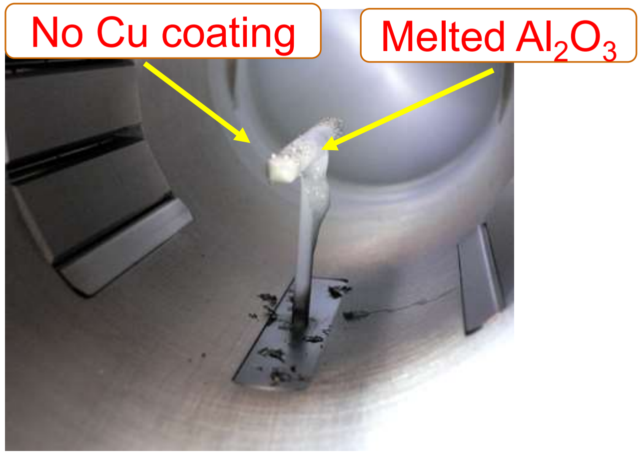
Experience 1.

Inside view of mask chamber



Mask head and support of Ver.6.0





[Y. Suetsugu et al., KEKB Review 2007]

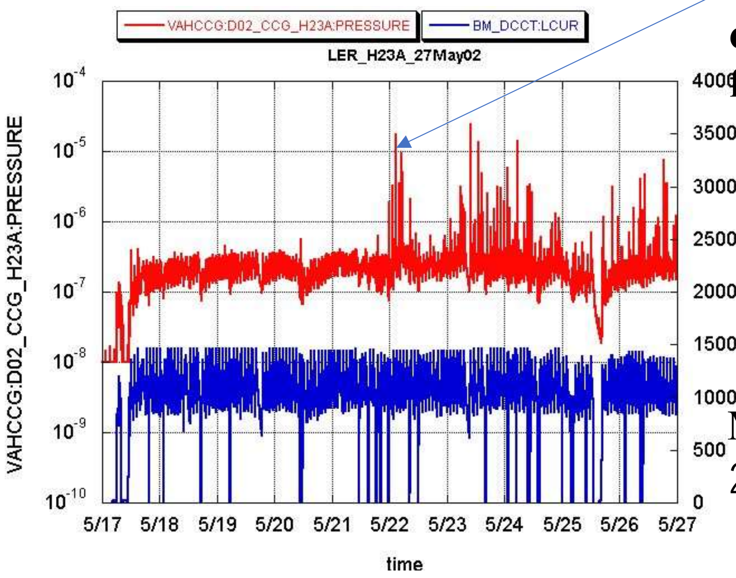
Excess heating was observed from the beginning.

At 700 mA (1389 bunches), copper coating had evaporated, and Al_2O_3 had melted! .

Cause :

Underestimate of tan δ ; temperature dependence of tan δ was not considered.

Experience 2.

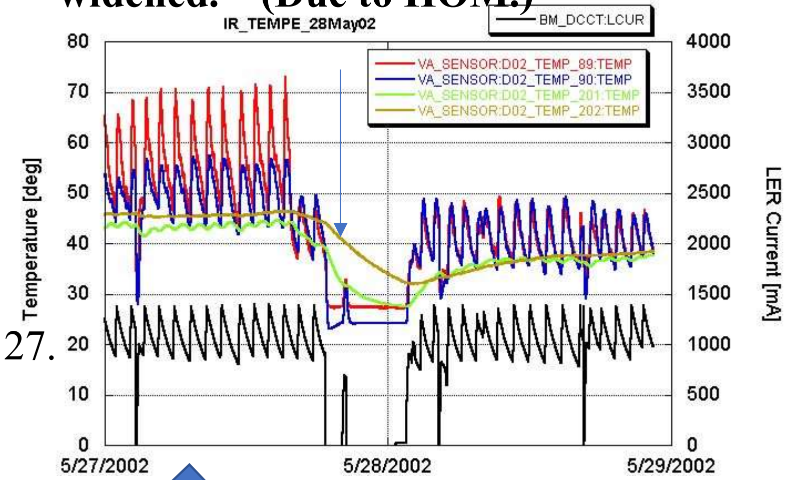


Pressure bursts (CCG near collimator) began to occur frequently on May 22.

May 22.
2002

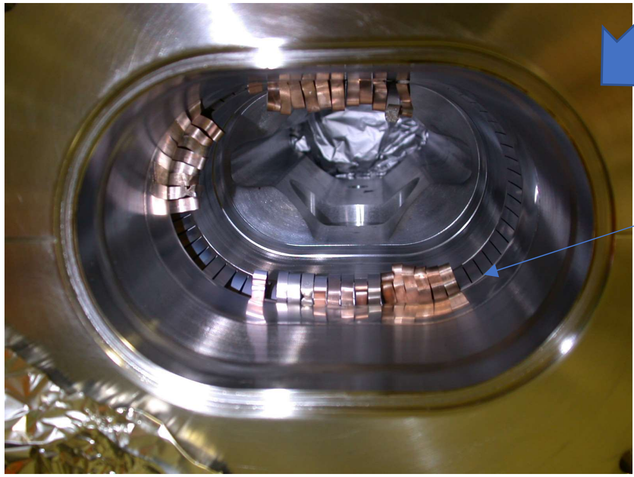
May 27.

The temperature of the bellows and collimator(LER V mask near IR) dropped as the collimator gap was widened. (Due to HOM.)



Heating of neighboring bellows

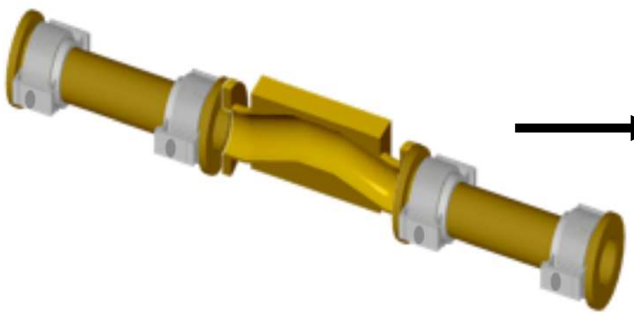
May 30.



collimator(LER V mask near IR) removed.
Neighboring to an LER V mask near IR,
a bellows's fingers were severely damaged.

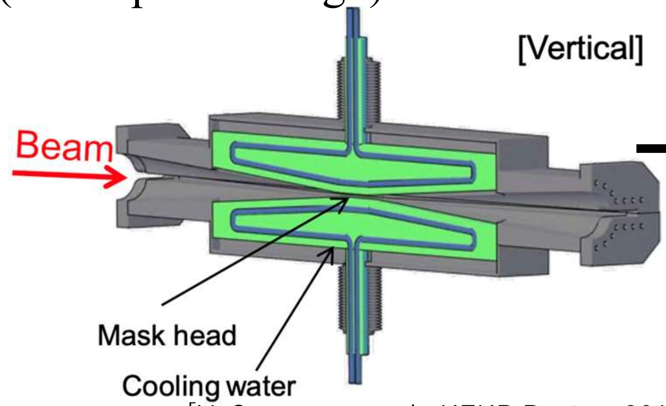
Introduction: Development of SuperKEKB-type collimator

KEKB type



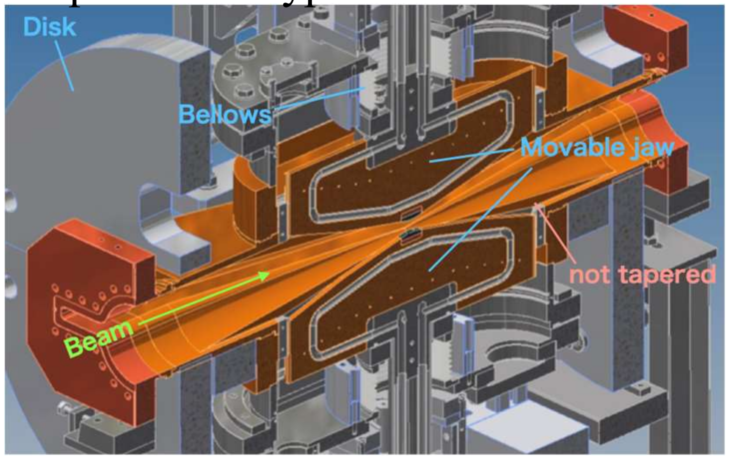
[Y. Suetsugu et al., NIM A 513, 465 (2003)]

SuperKEKB type (Conceptual Design)



[Y. Suetsugu et al., KEKB Review 2012]

SuperKEKB type

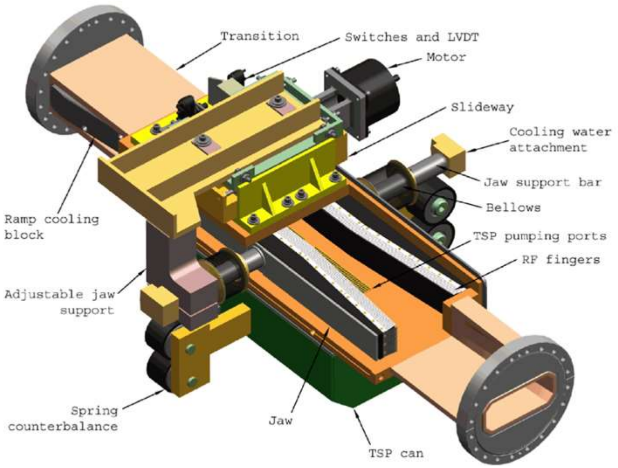


[T. Ishibashi et al., PRAB 23, 053501 (2020)]

- For the construction of SuperKEKB, a study of new collimators has started.
- Main constraints for the design of new collimators in LER.
  - Fit the antechamber scheme.
  - From KEKB to SuperKEKB, the lengths of the bending magnets were increased. The drift sections were shortened, and the spaces for the collimator was shortened.
  - Minimize the impedance in the vertical direction (For SuperKEKB, one small-gap vertical collimator can limit the bunch current due to the transverse mode coupling instability (TMCI)).
- An idea of putting the jaws inside the antechamber (or antechamber-like structure) was proposed, leading to the present structure. Advantages of this structure are
  - The beam doesn't see gaps or protrusions between the movable jaw and chamber.
  - The excitation of the trapped modes around them can be avoided.
  - Similar level of the impedance with shorter collimator length.
  - Compact and simple structure.

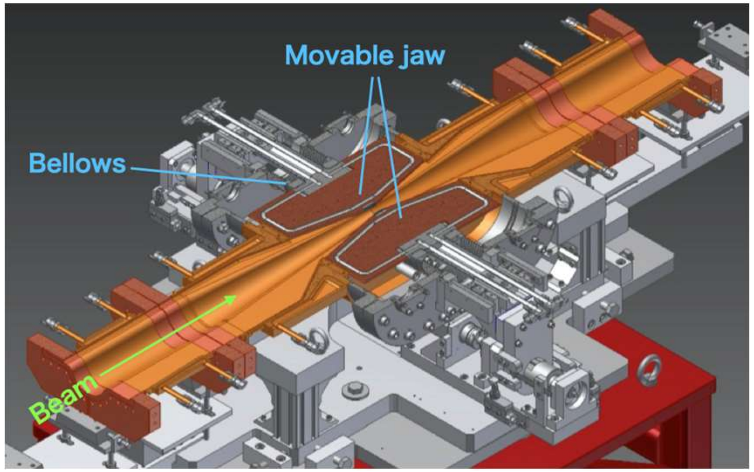
Introduction: Development of SuperKEKB-type collimator

- We referenced movable collimators for PEP-II in SLAC for the basic design of the SuperKEKB type.
- The final design of the new collimators was fixed with the support from the KEK-SLAC collaboration.
- 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.).



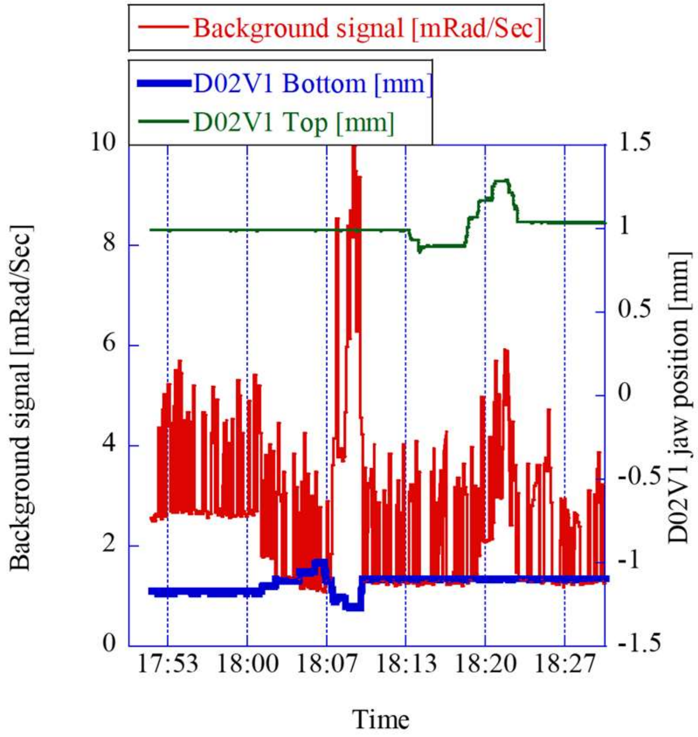
Collimator in PEP-II

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



Horizontal direction

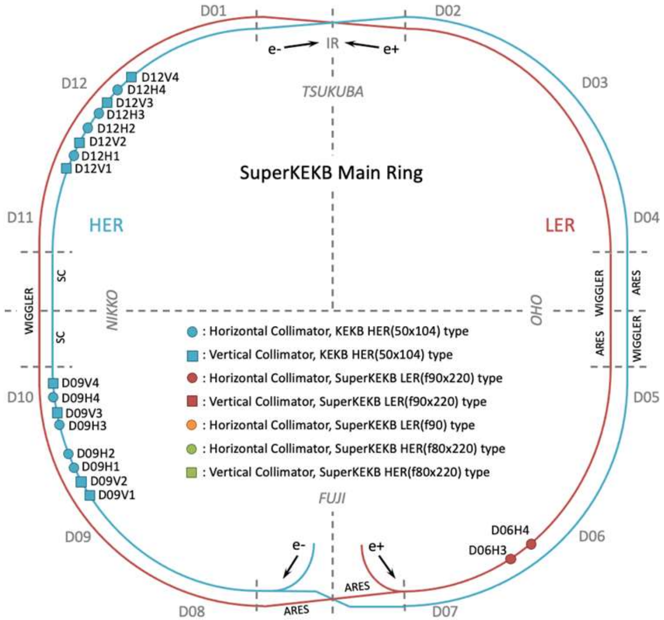
SuperKEKB type collimator



Beam operation showed the effectiveness of collimators:
The BG decreases/increases when the collimator gap is narrowed/ widened.

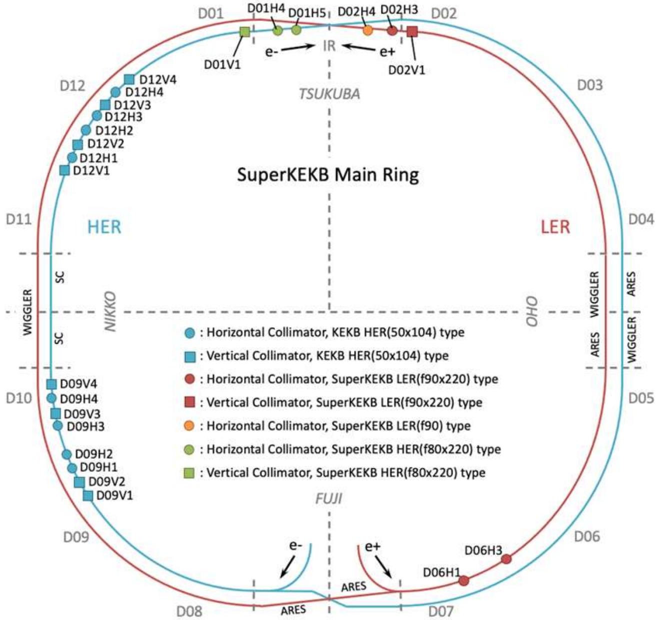
Introduction: Yearly status of SuperKEKB collimators

Phase-I



- Two SuperKEKB type horizontal collimator (D06H3, D06H4) were installed in LER (D06 test section).
- Test section is short length between GVs and can be worked without significant impact if problems occur

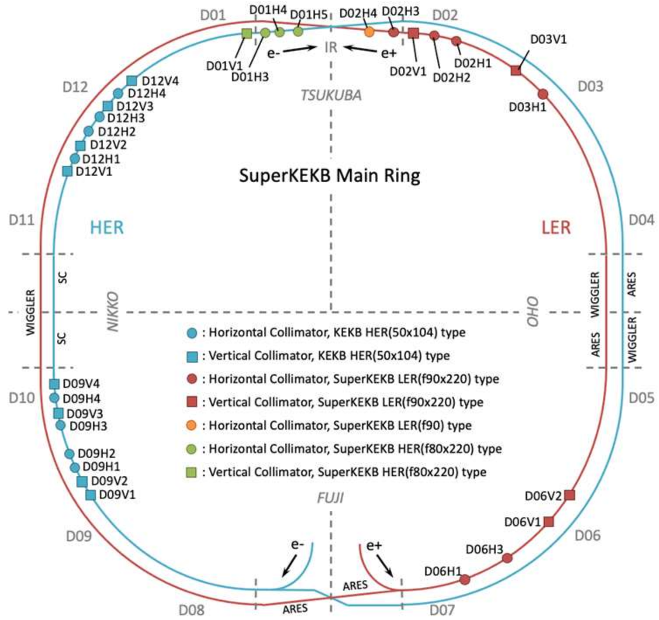
Phase-II



- One SuperKEKB type vertical collimator (D02V1) and two horizontal collimators (D02H3, D02H4) were installed in LER.
- D06H4 was moved to D06H1 in LER.

- One SuperKEKB type vertical collimator (D01V1) and two horizontal collimators (D01H4, D01H5) were installed in HER.

Phase-III (2021ab)

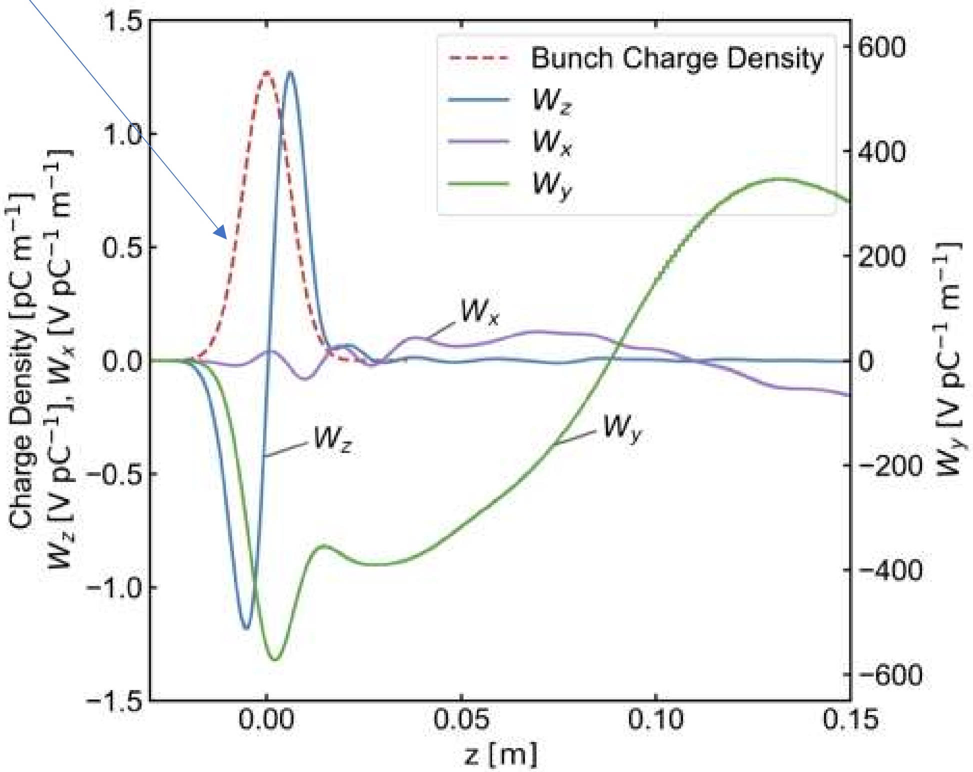


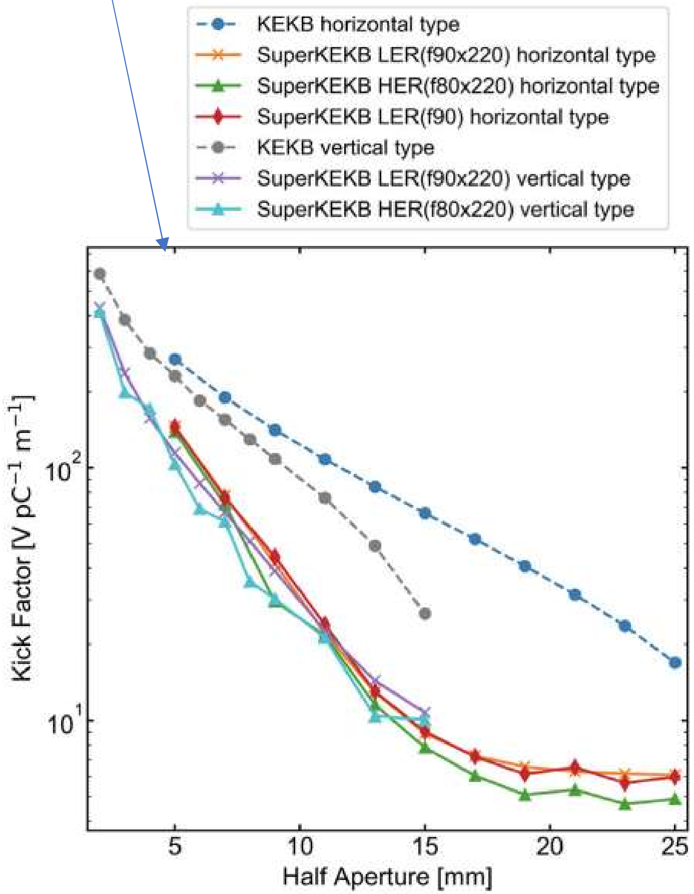
- Three SuperKEKB type vertical collimator (D06V2, D06V1, D03V1) and three horizontal collimators (D02H2, D02H1, D03H1) were installed in LER.
- D02V1 was shifted to the upstream side in 2021.

- One SuperKEKB type horizontal collimators (D01H3) was installed in HER.

Design :Impedance

- Impedance calculations showed that the kick factor of the SuperKEKB-type collimator is smaller than that of the KEKB-type collimator.
- Large trapped modes were not seen.
- Wake calculations: Bunch length 6 mm using GDFIDL

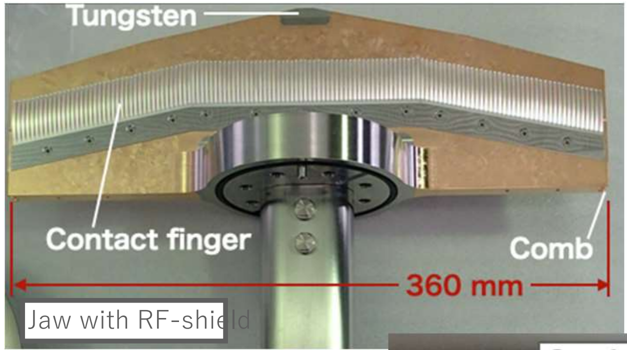


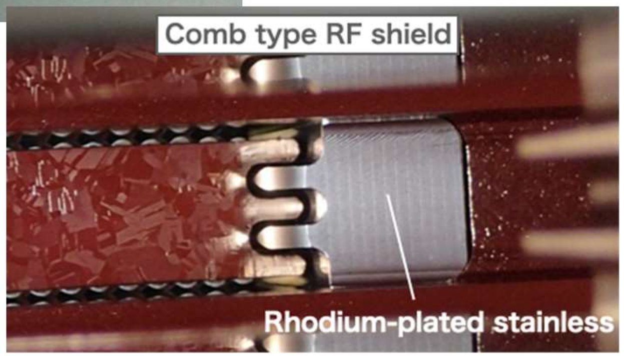


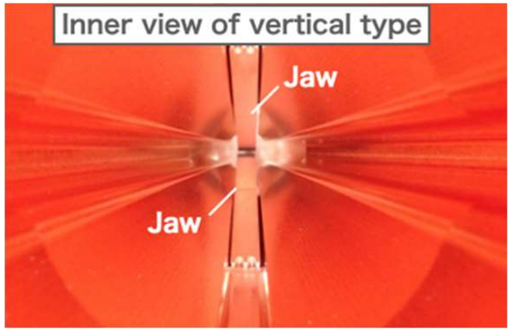
[T. Ishibashi et al., PRAB **23**, 053501 (2020)]

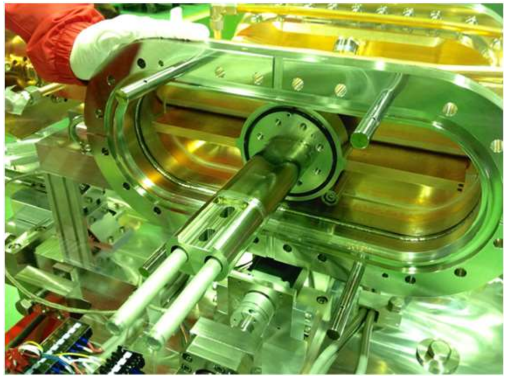
Design :RF-shield

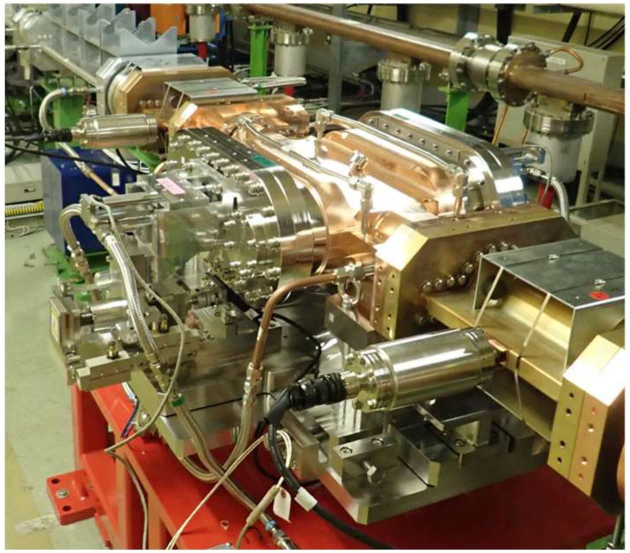
- To avoid cavity structures between the jaws and the chamber, finger-type RF shields are attached to the side walls of each jaw.
  - The fingers are made of silver-plated INCONEL.
  - The contact surface on the chamber is made of rhodium-plated stainless steel.
- A Contactless comb-type RF shield is adopted between the longitudinal end of the jaw and the facing surface of the chamber.





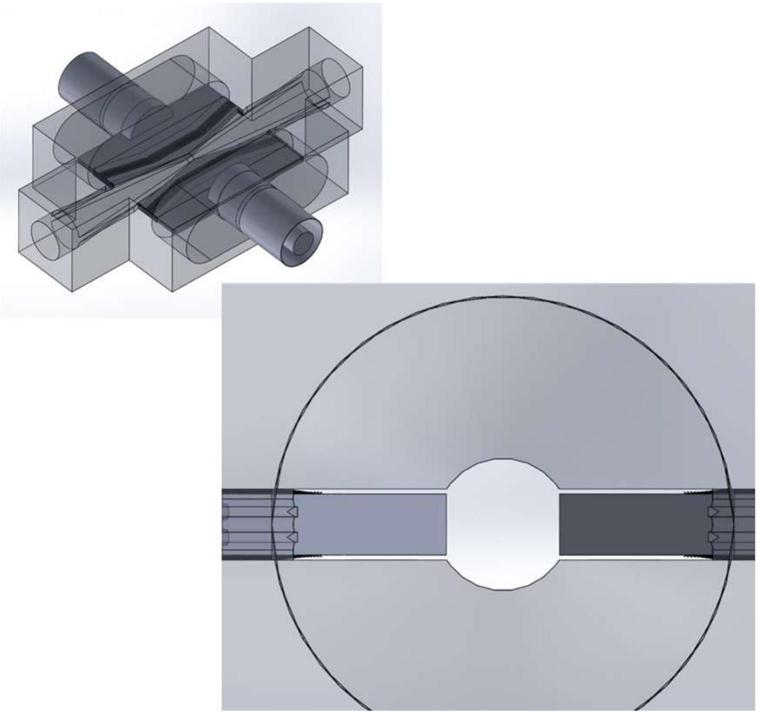




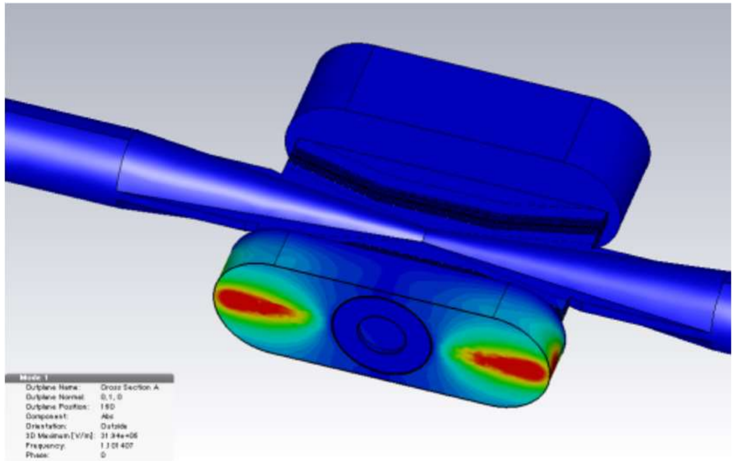


- Eigen-mode solver of CST Studio was used to estimate the effectivity of the RF shields.
- Beam's RF fields leak into the chamber holding the jaws. However, the coupling between the beam channel and the outer chamber is small.

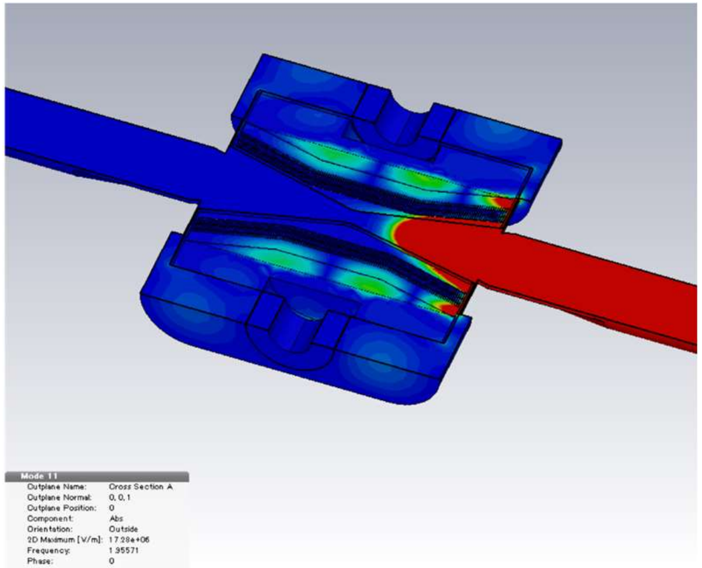
Simulation model in CST Studio



E-field strength in jaw's chamber
(1.1014 GHz)



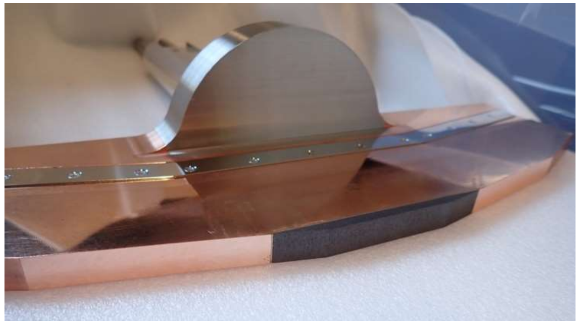
E-field strength in beam channel
(TE_{111}: 1.9557 GHz)



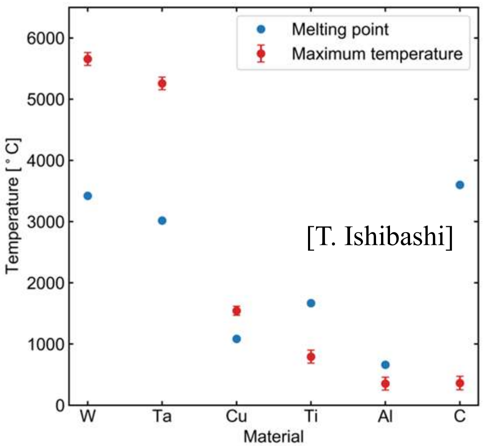
Design :material

- In principle, any material should melt if the whole beam (LER design beam current 3.6 A) hits the jaw.
- Tungsten (W) was used for the tip material at first, but it was found that if it is damaged by the beam hit, it will become embrittled and generate a lot of radioactive dust.
- Tantalum (Ta) has been used as the default material of the tips.
- 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 and was given up (the radiation length of the carbon is long (~19.32 cm) compared with W/Ta (~0.35 cm/0.41 cm), so we need longer jaw to suppress the background).
- Hybrid jaws made from CFC and Ta were developed to improve the robustness of collimators. These jaws have been used without being damaged so far.

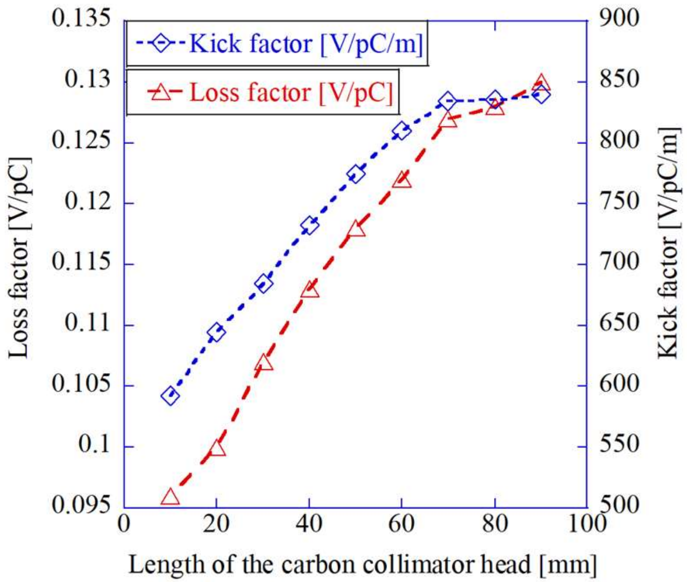
Carbon jaw (head length 60 mm)



Hybrid jaw (CFC+Ta) (head length 3 mm)



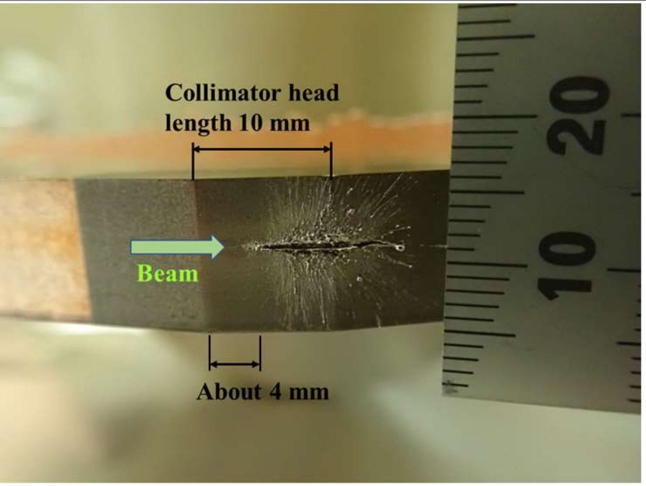
Maximum temperatures within 1 RL and melting points for each material, induced by the positron beam. The beam profile and energy are respectively Gaussian and 4 GeV. Dx=y and the injected current are 0.5 mm and 50 mA (3.12×10^{12} positrons), respectively.



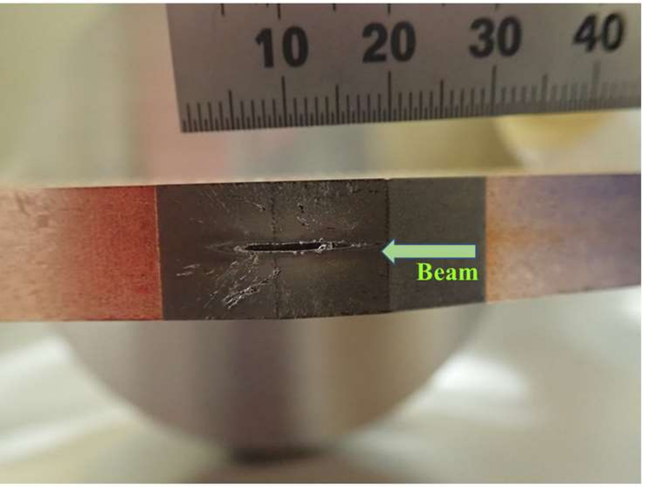
Impedance increases with longer head length.
Half gap 2mm, bunch length 6 mm

Impedance increases with longer head length.
Half gap 2mm, bunch length 6 mm
Since the electrical resistance of CFC was found to be high, the Hybrid collimator was coated with copper.

Operation experience: Collimator damages

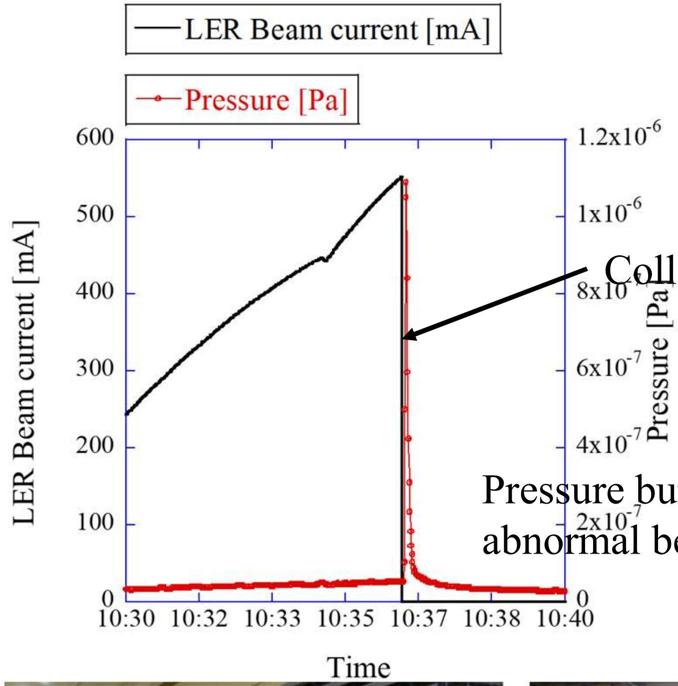


(a)



(b)

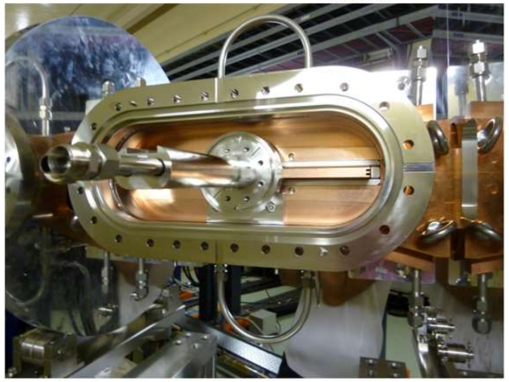
Photograph of the damaged (a) D02V1 top, and
(b) D02V1 bottom collimator heads.



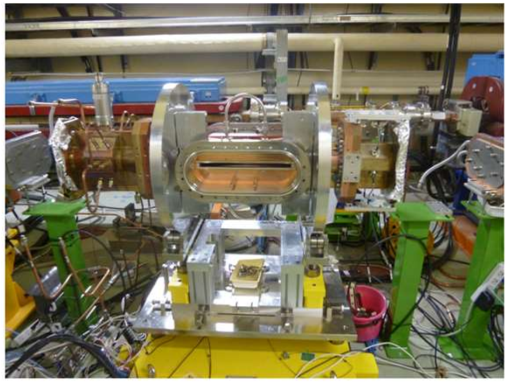
Collimator damage event

Pressure burst observed when an abnormal beam hit collimator

(a)



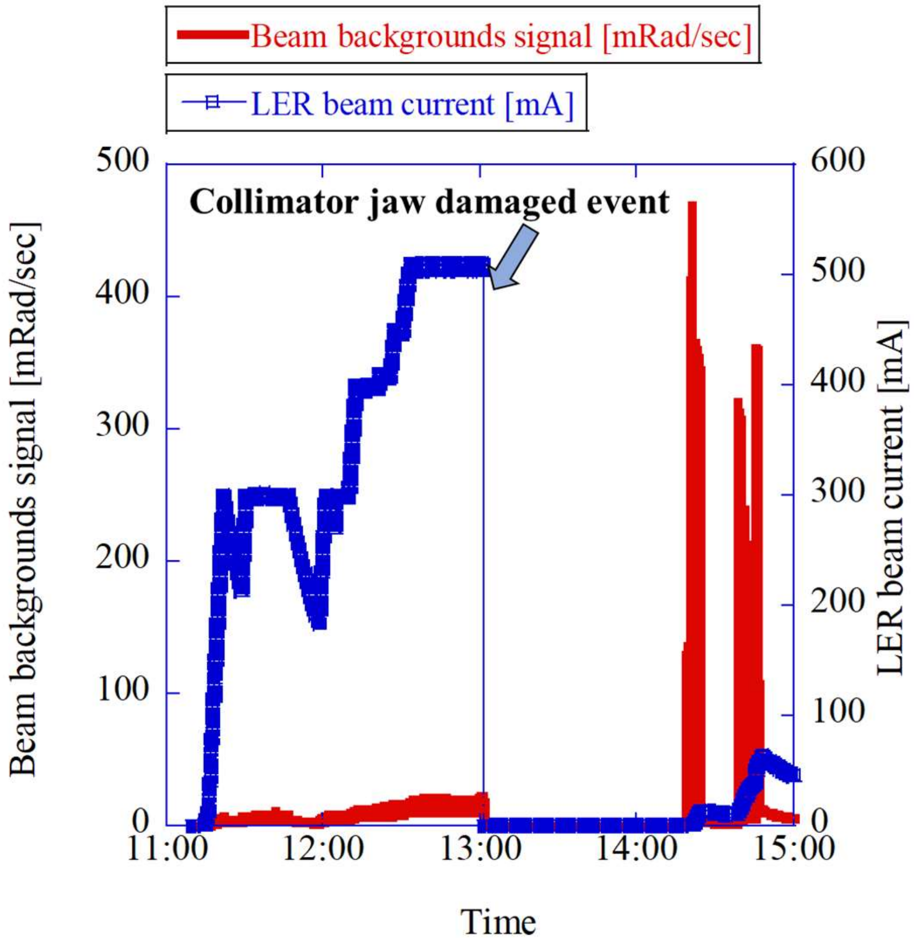
(b)



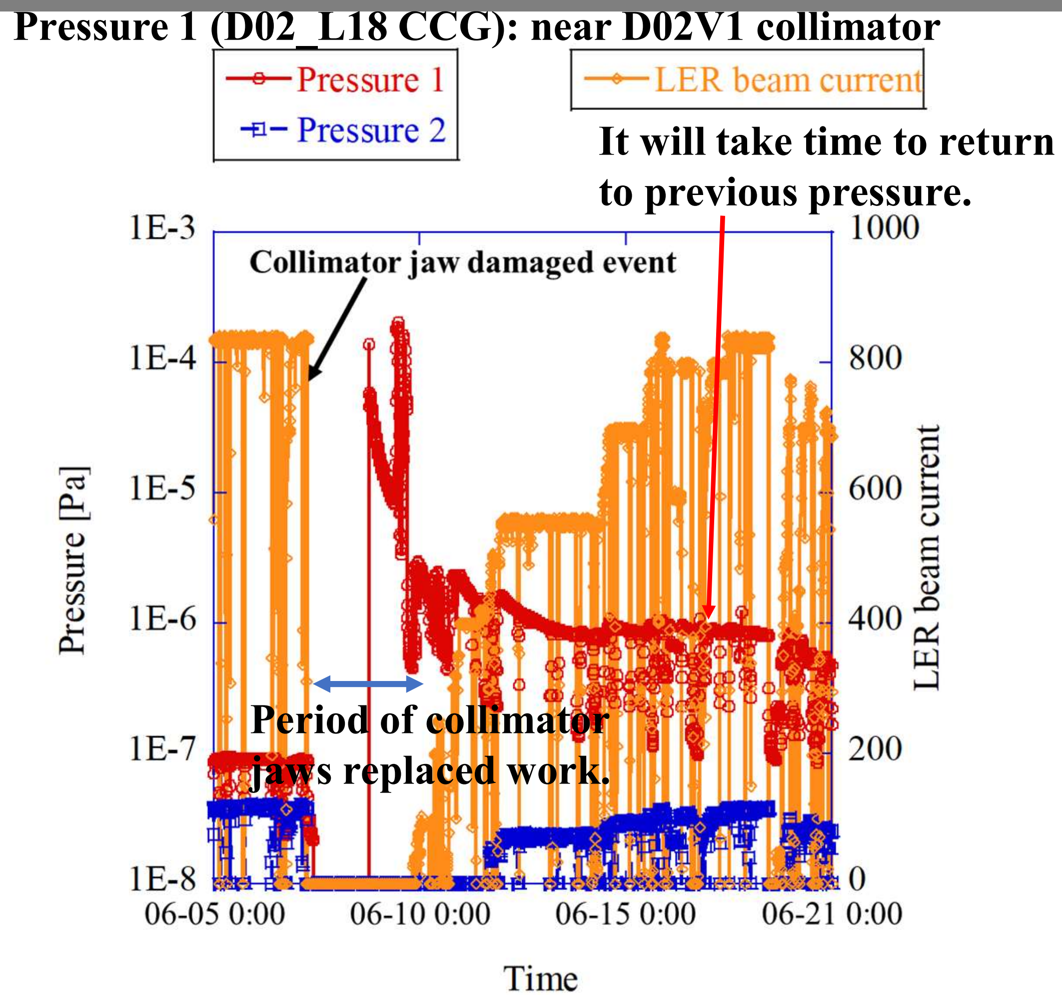
(c)

(a) Before replacing the collimator jaws, measure the dose.
(b) Rotate the collimator chamber to replace the vertical collimator jaws.
(c) Remove the collimator jaws from the chamber.

Operation experience: Collimator damages



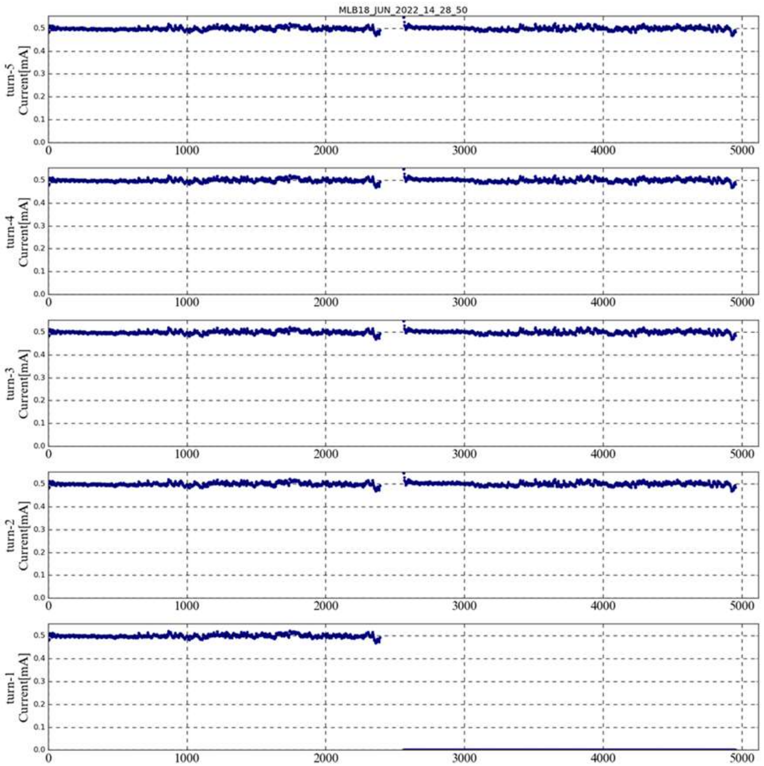
Measured beam background in the IR before and after the event of the damaged collimator jaw.
BG increased after damage.



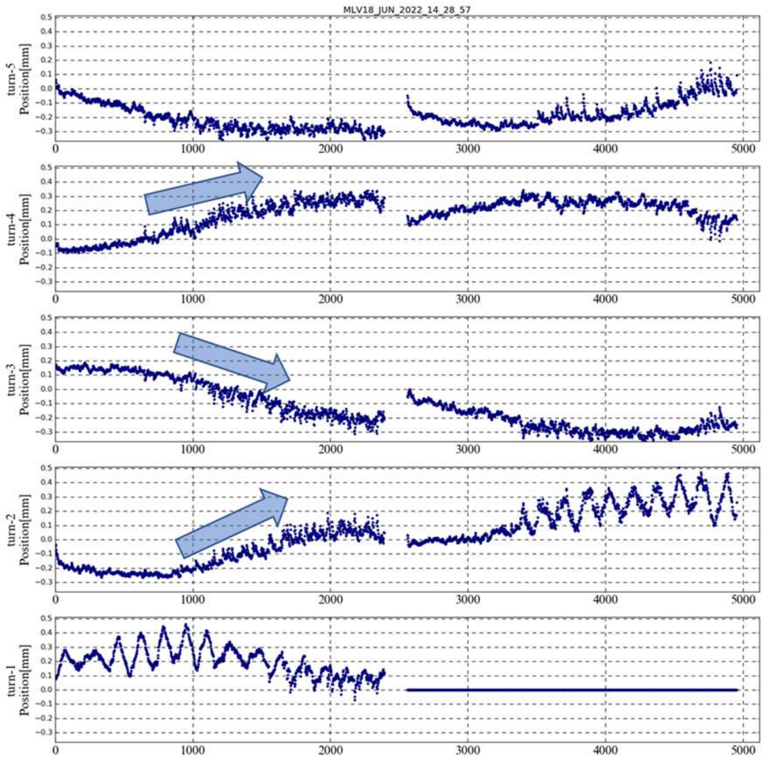
Replacement work of damaged jaws requires extra beam scrubbing to recover the vacuum pressure.

Operation experience: Collimator damages

When the beam abort was triggered, the feedback system's bunch oscillation recorder (BOR) automatically saved data for each bunch in the beam. Analysis of BOR data can provide information on beam dynamics.
As extracted from the BOR data, the bunch current and vertical position is shown as a function of the bucket number during the last nine machine turns prior to aborting the beam. The subfigure at the bottom presents the data of turn 0, i.e., at the instant of the beam abort. Abort one turn prior was marked as turn-1.



Data of bunch current from LER BOR when instability was observed

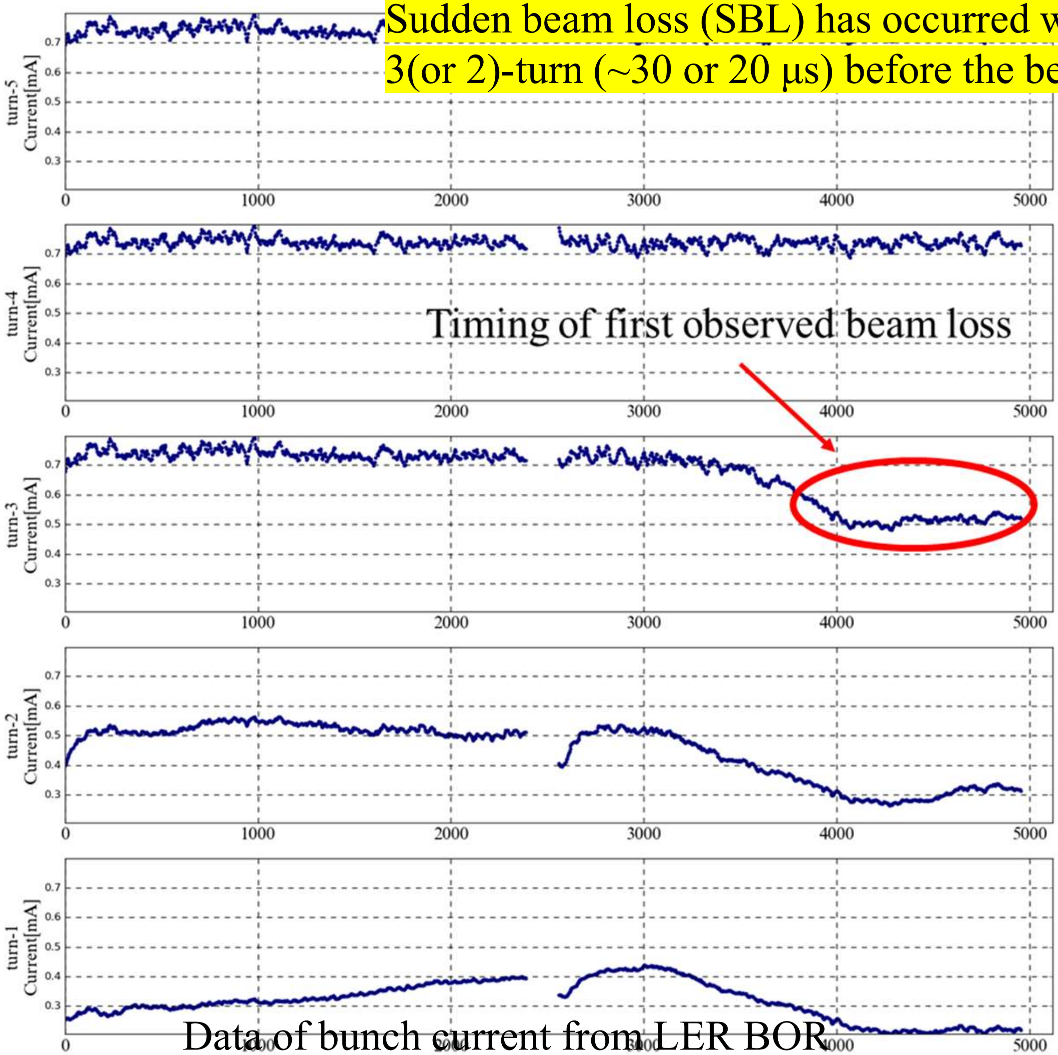


Data of vertical position from LER BOR when instability was observed

Data from LER BOR when oscillation due to beam instability was observed.
The collimator is not damaged at this time. Shown for comparison with next page.

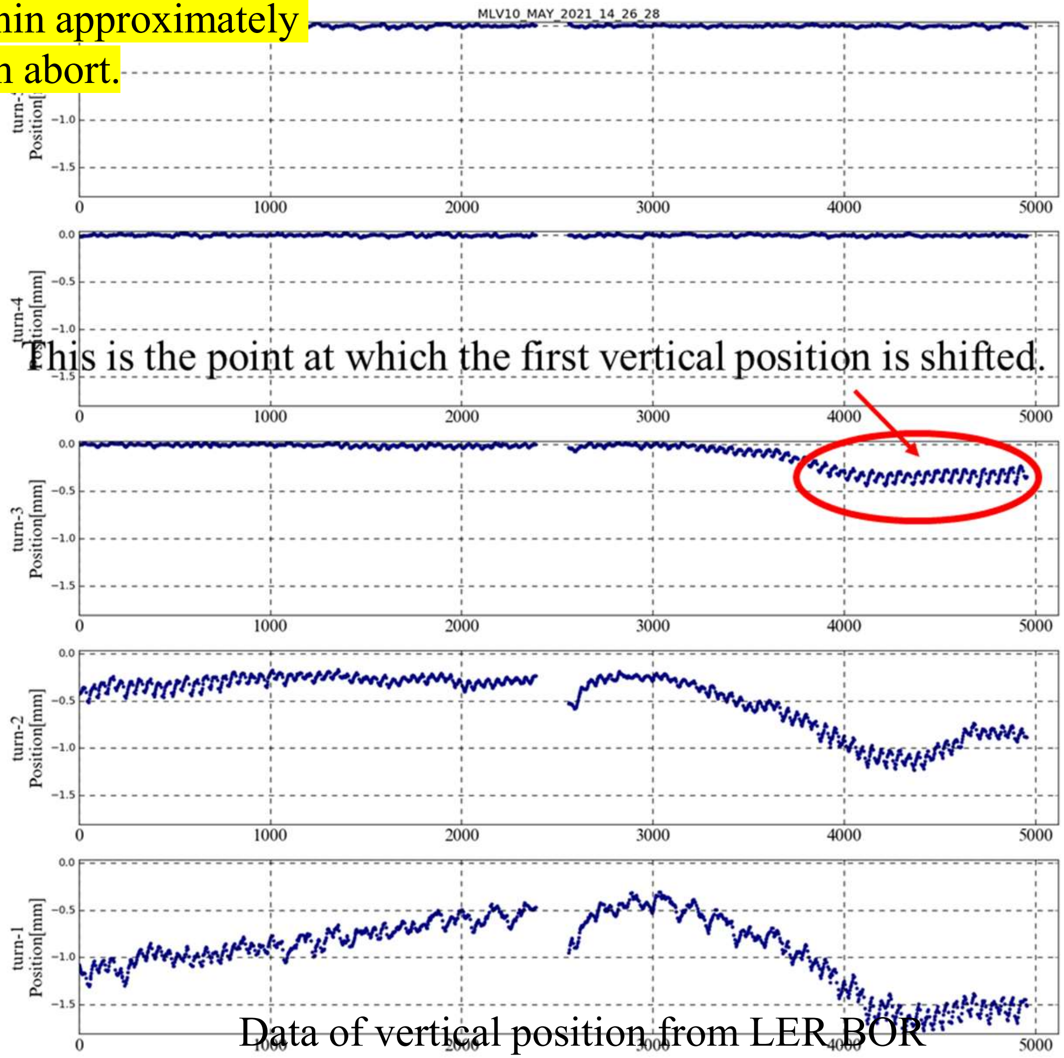
Operation experience: Collimator damages

Sudden beam loss (SBL) has occurred within approximately 3(or 2)-turn (~30 or 20 μs) before the beam abort.



Timing of first observed beam loss

Data of bunch current from LER BOR when collimator is damaged

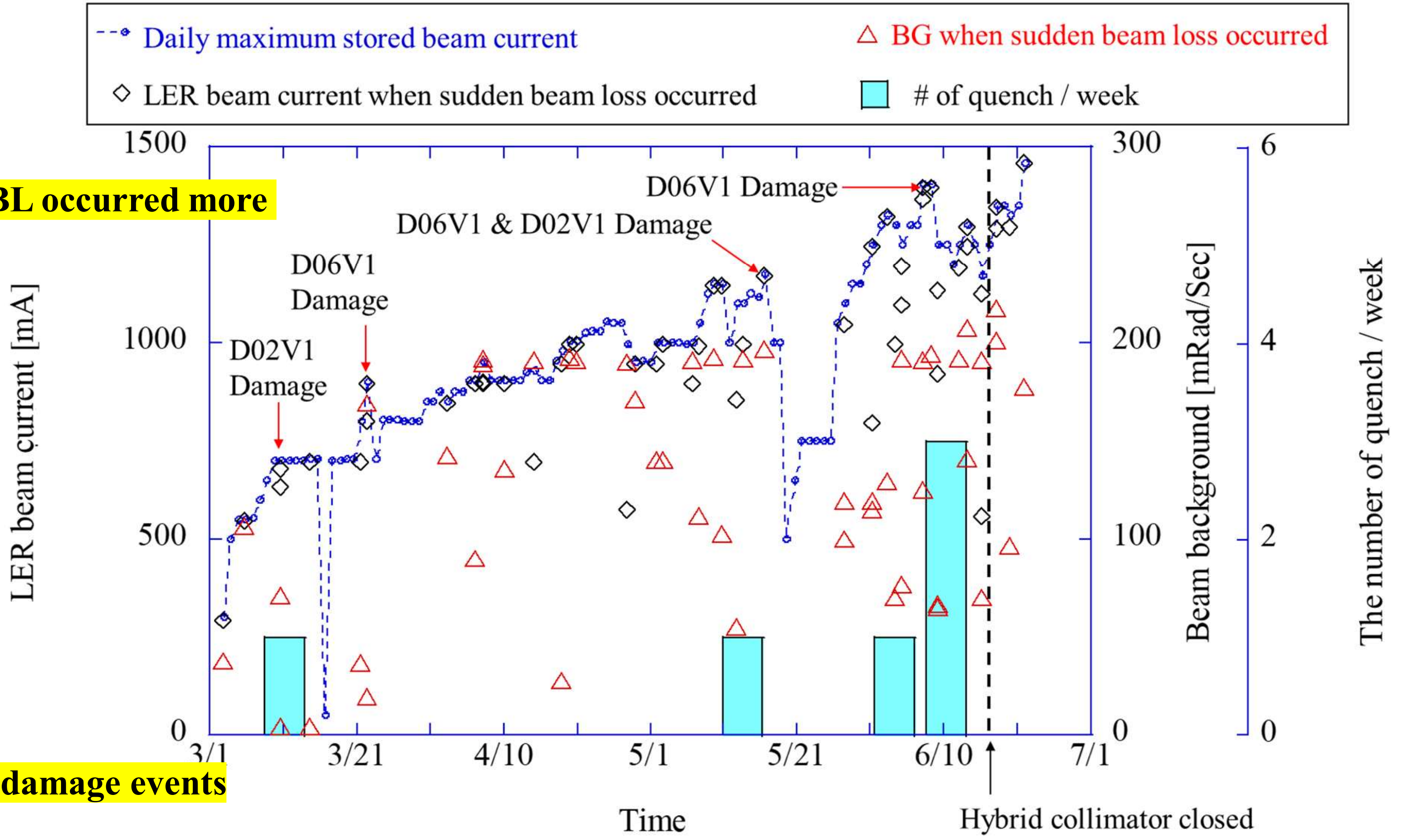


This is the point at which the first vertical position is shifted.

Data of vertical position from LER BOR when collimator is damaged

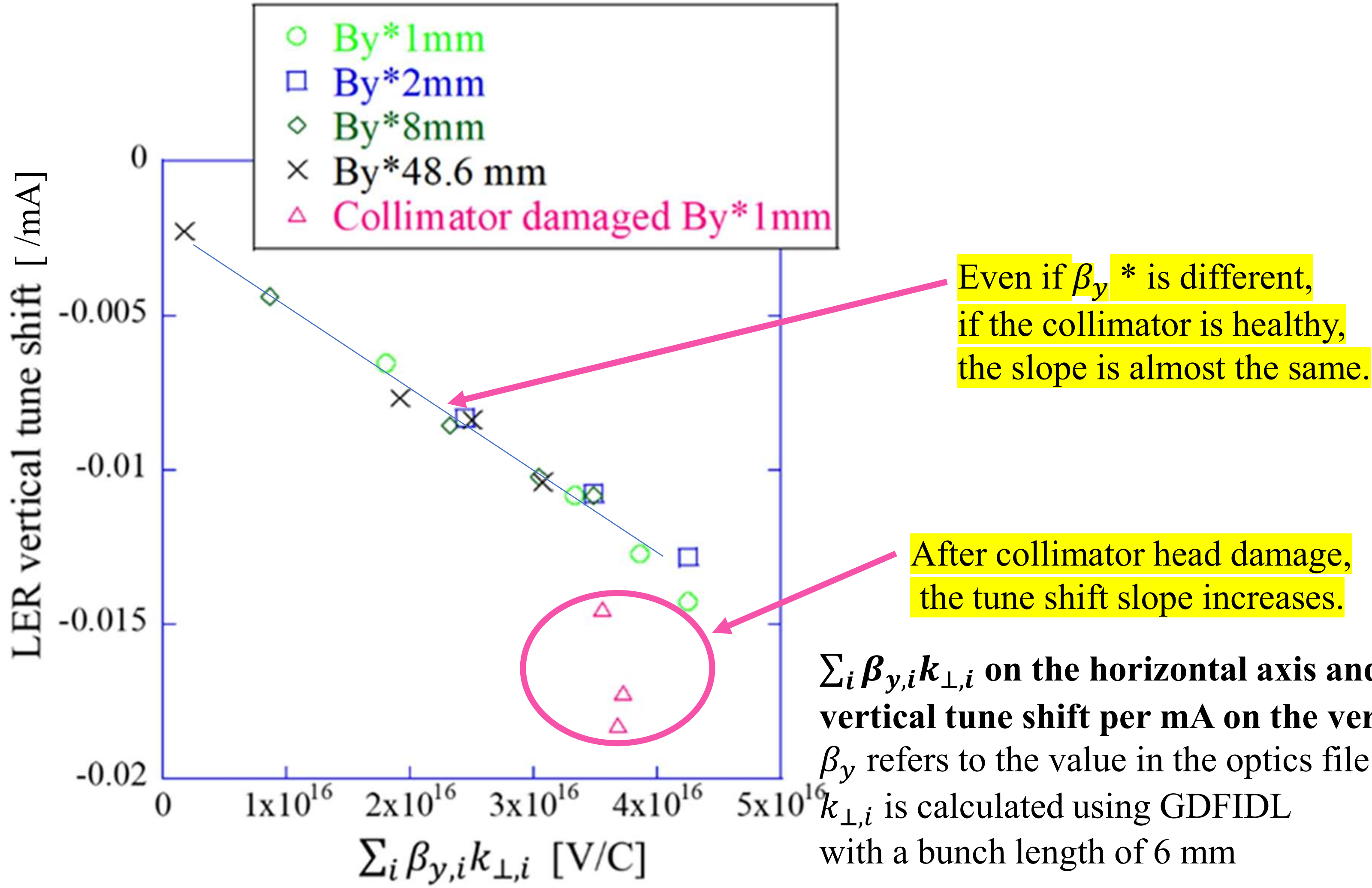
Sudden beam losses (SBLs) occasionally caused severe damages to collimator jaws.

During the 2022ab run, SBL occurred more than 40 times.



There were four collimator damage events during the 2022ab run.

Operation experience: Vertical beam size blow-up due to -1 mode instability



$\sum_i \beta_{y,i} k_{\perp,i}$ on the horizontal axis and vertical tune shift per mA on the vertical axis.

β_y refers to the value in the optics file.

$k_{\perp,i}$ is calculated using GDFIDL with a bunch length of 6 mm

Operation experience: Vertical beam size blow-up due to -1 mode instability

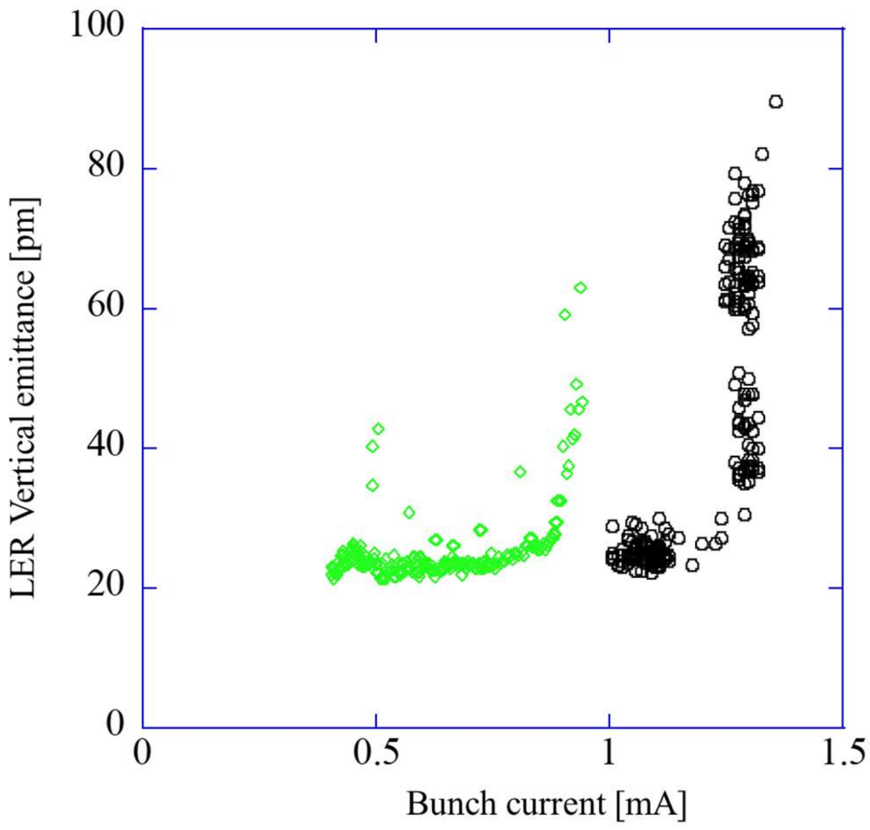
21/June
After collimator damage

× $\sum_i \beta_{y,i} k_{\perp,i}$ = 35.6E15 V/C

Operation was difficult without narrowing the collimator by this value.

1/March
Before collimator damage

○ $\sum_i \beta_{y,i} k_{\perp,i}$ = 33.5E15 V/C



This figure shows the bunch current on the horizontal axis and the LER vertical emittance on the vertical axis.
When the collimator head was damaged, the threshold for beam size blowup was found to be lowered.
See Ohmi's talk for details on -1 mode.

Summary

- SuperKEKB type collimators have been designed and installed, taking into account impedance and RF property.
- SuperKEKB collimators have been used to reduce beam background and contribute to protect components in the ring from uncontrollable beams.
- Collimators damages due to beam hit (sudden beam loss and accidental firings in injection kickers) have been one of major issues in SuperKEKB

See KEKB review Ishibashi-san’s slide