SuperKEKB collimation design and experience

EIC Workshop
2020-10-09, Session 5.1

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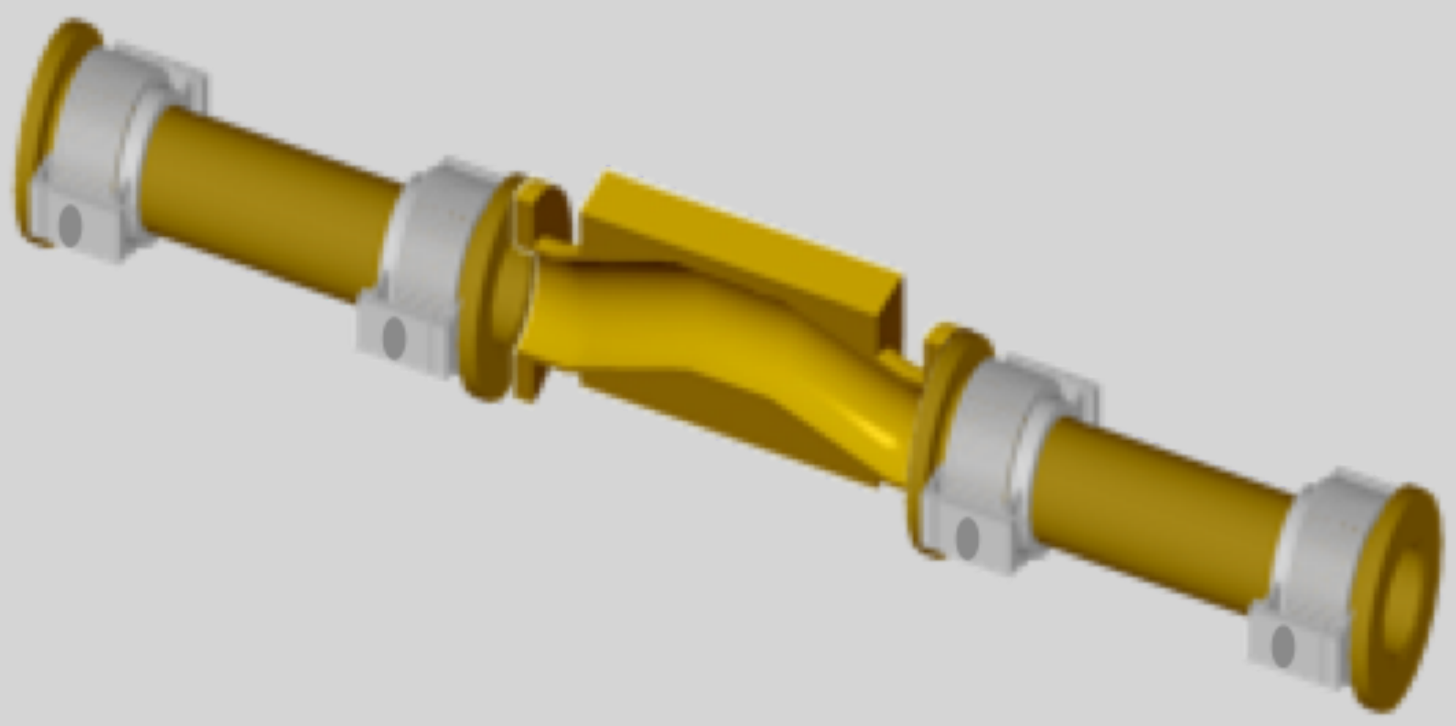
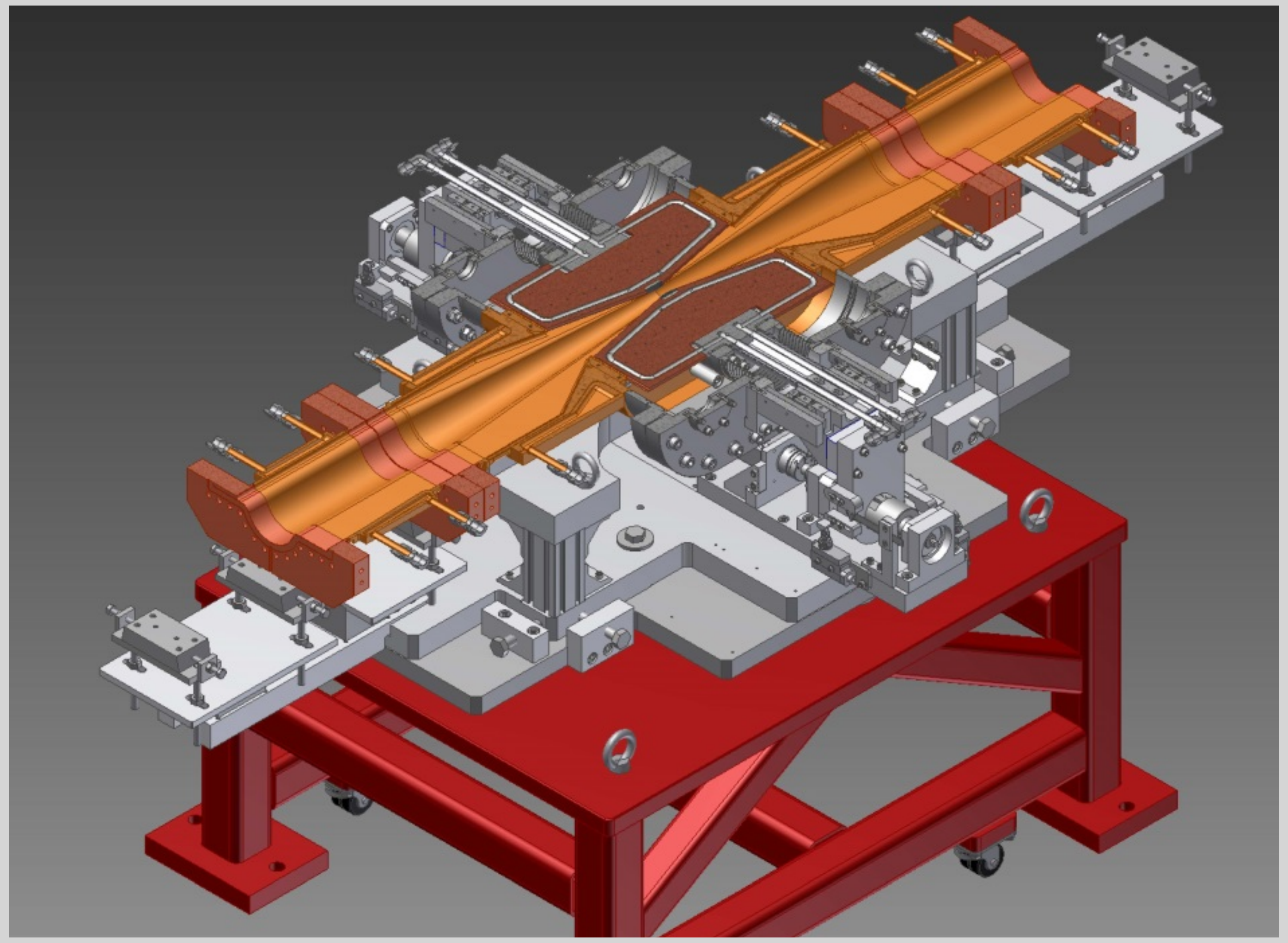
Beam collimators in SuperKEKB

- We developed new type collimators for SuperKEKB main ring.
- 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.



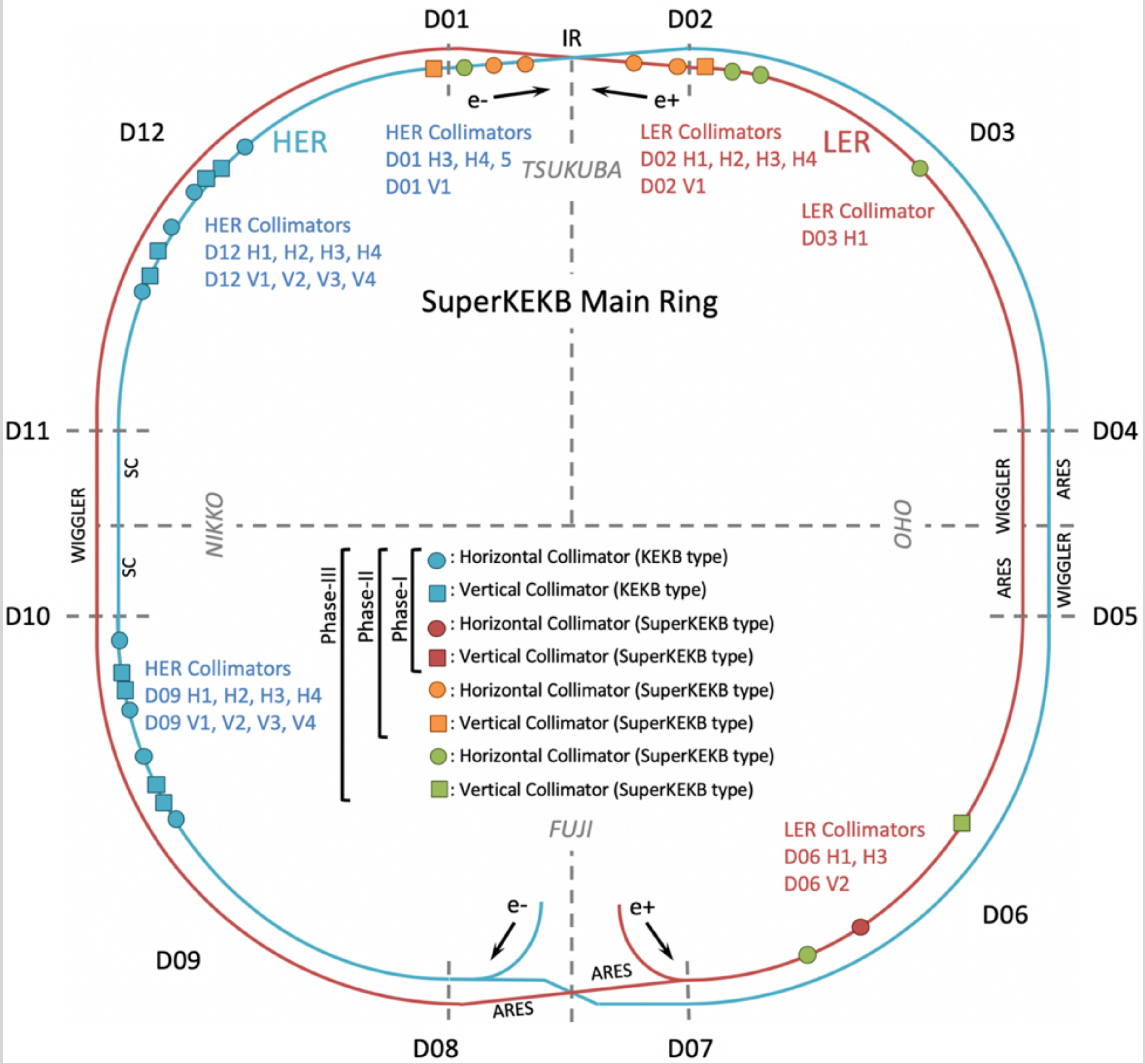
KEKB type

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



SuperKEKB type

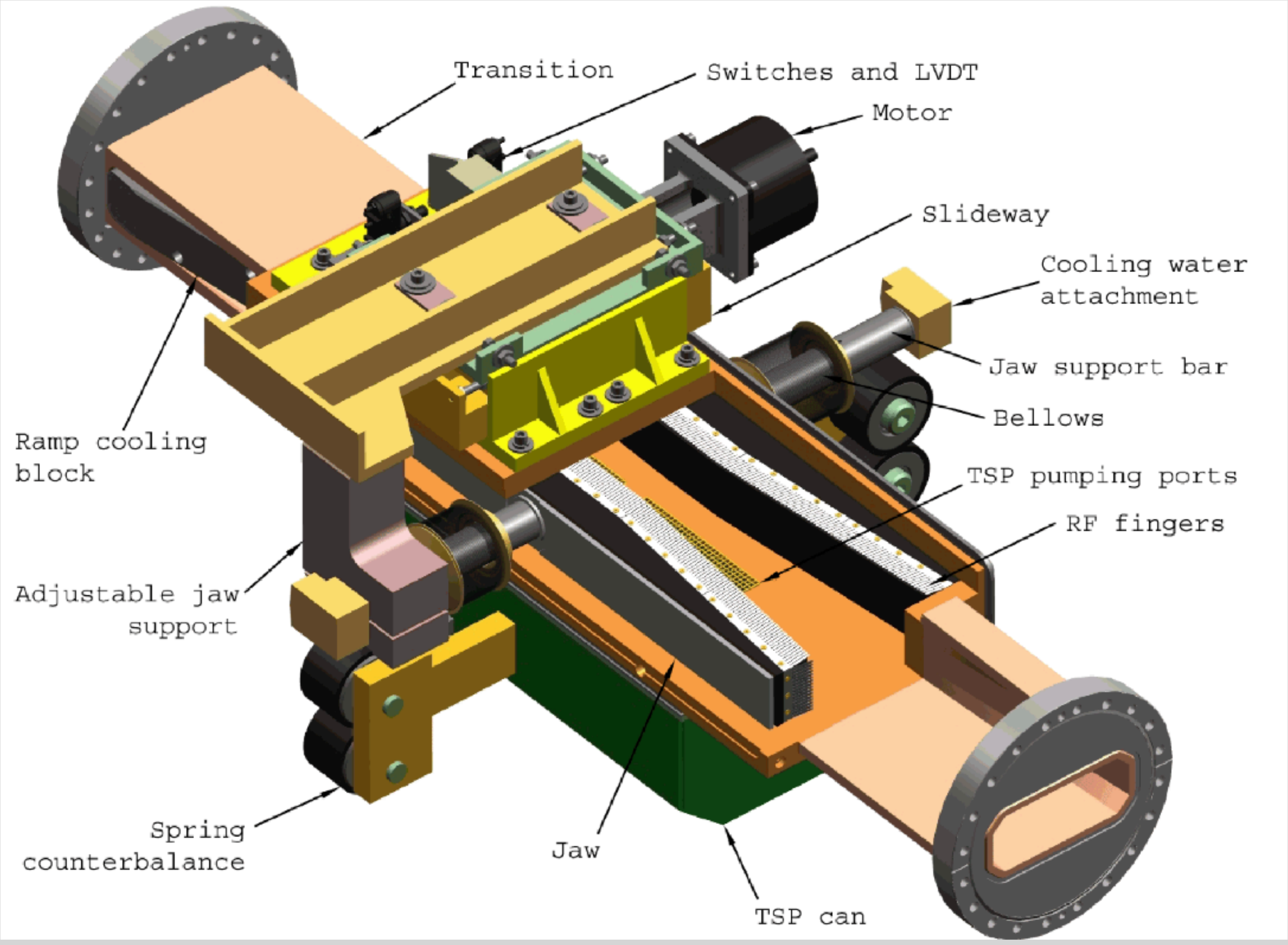
[T. Ishibashi et al., PRAB **23**, 053501 (2020)]



Location of collimators in MR

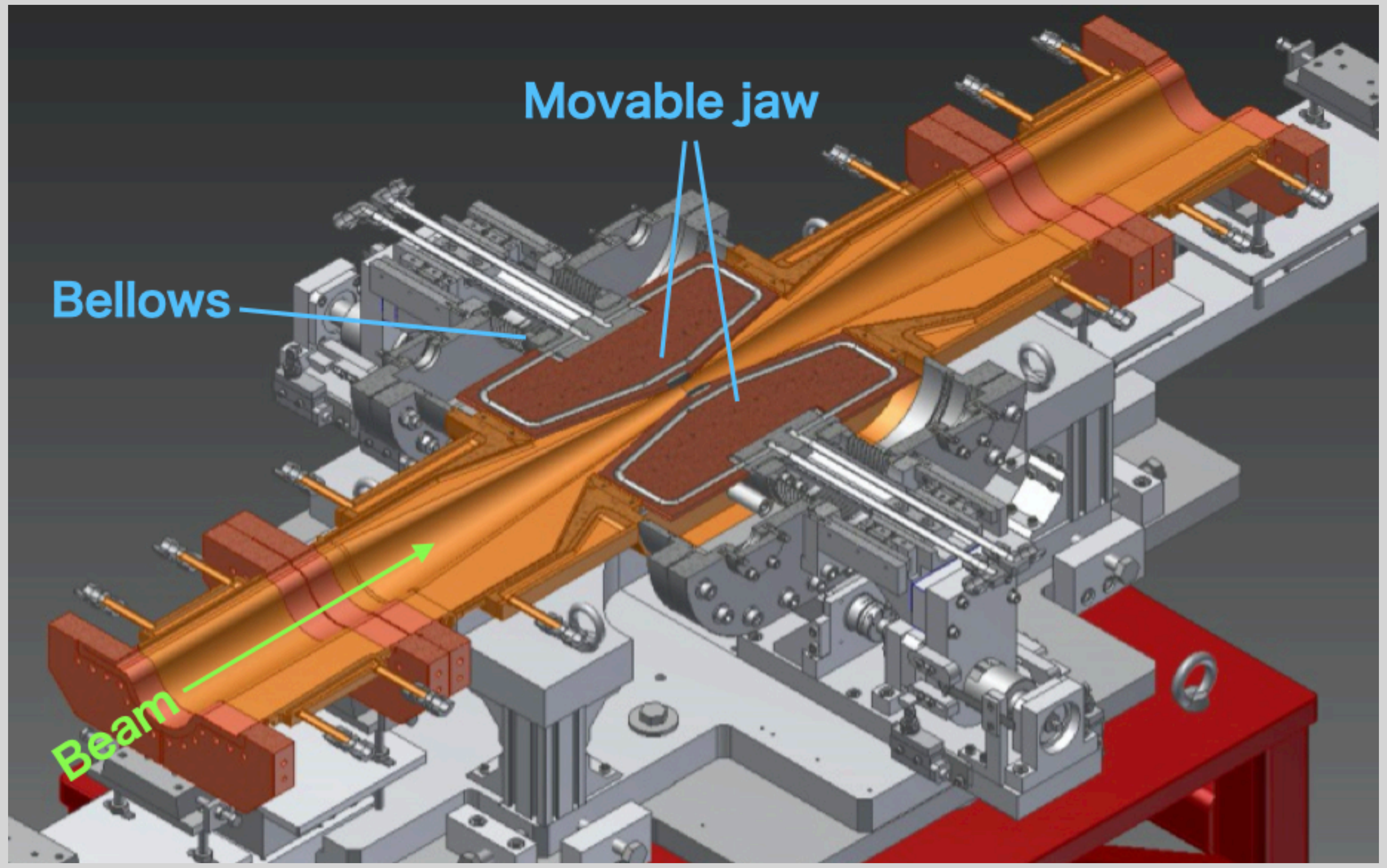
Design

- We referenced movable collimators for PEP-II in SLAC for the basic design.
- 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 reduce the impedance.
- 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.), or carbon (special ver.).

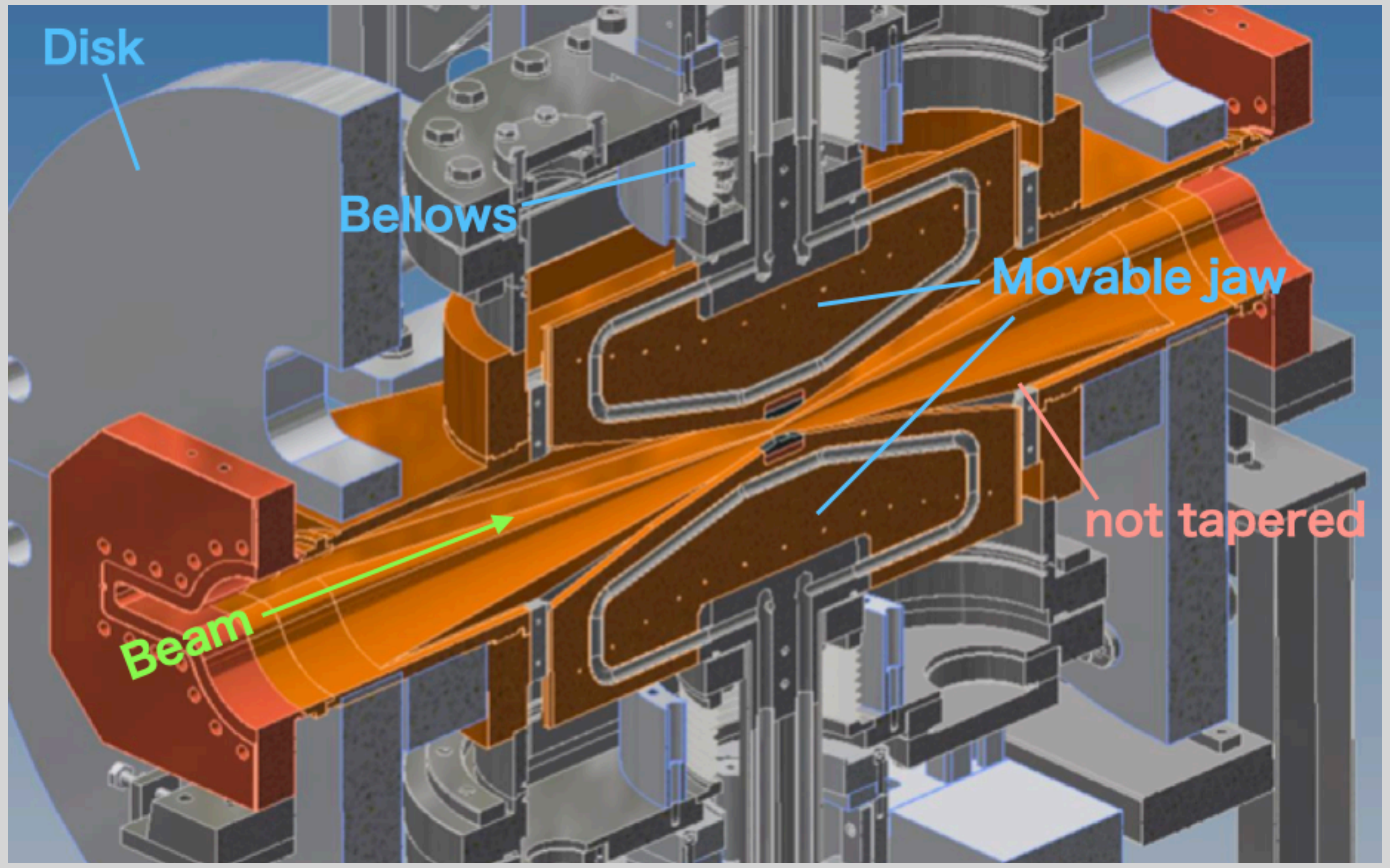


Collimator in PEP-II

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



Horizontal direction

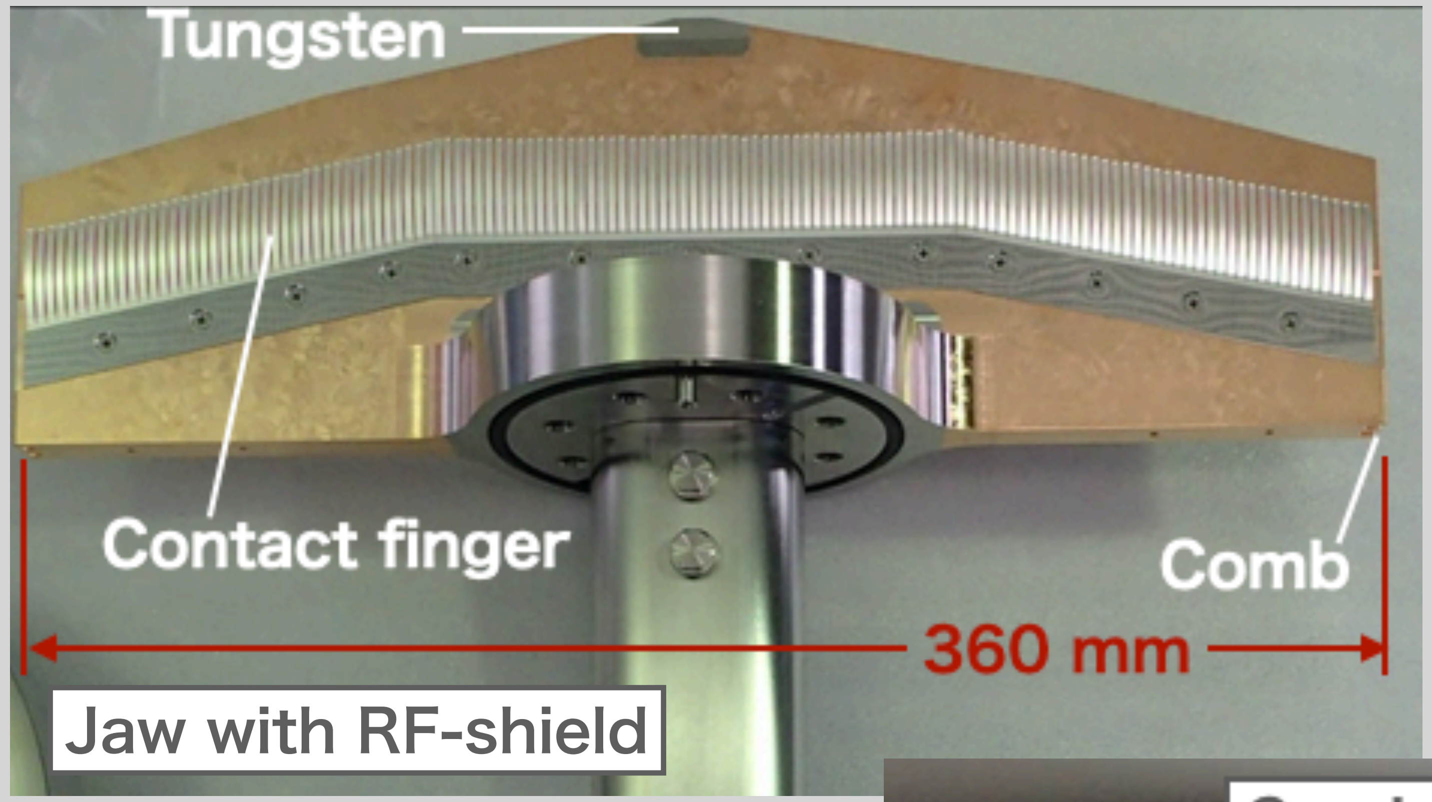


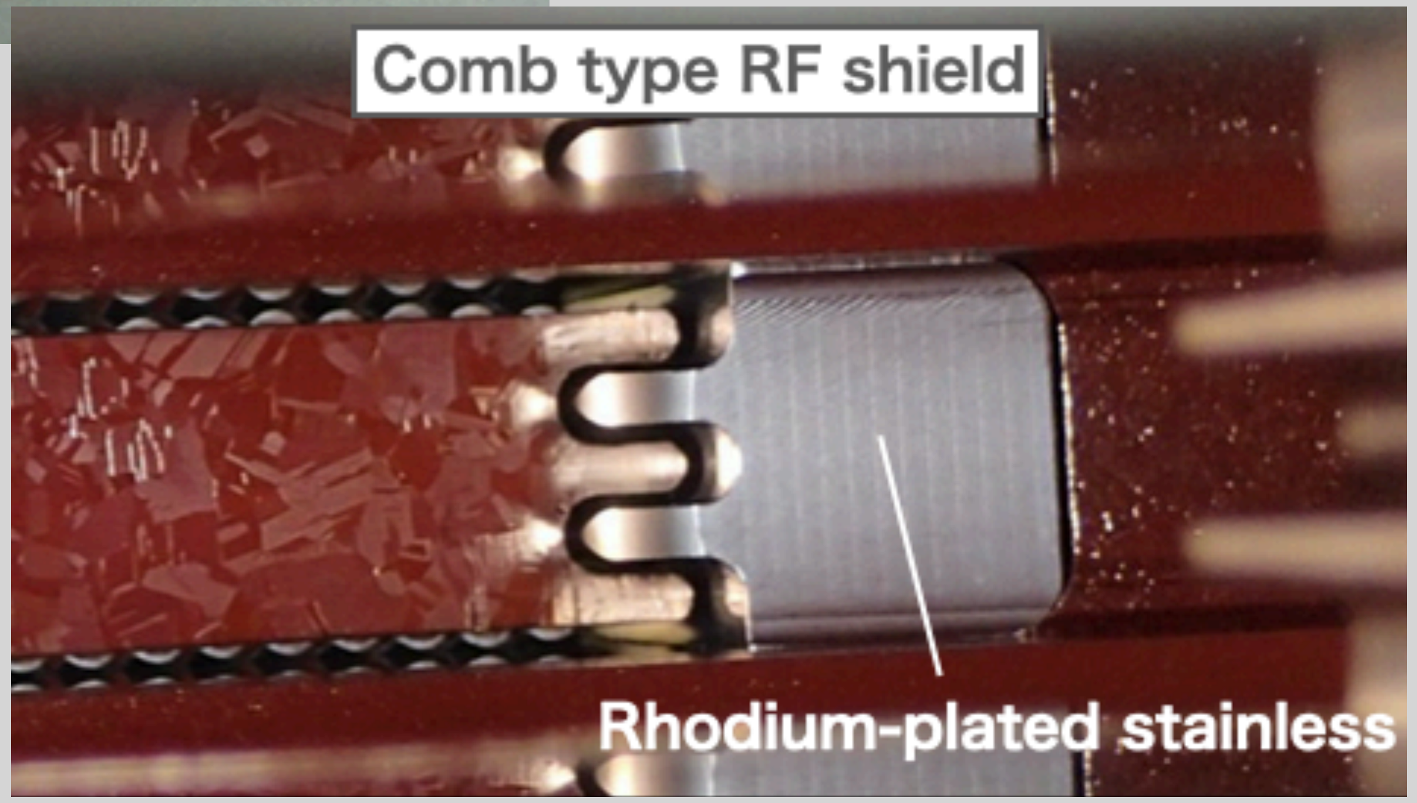
Vertical direction

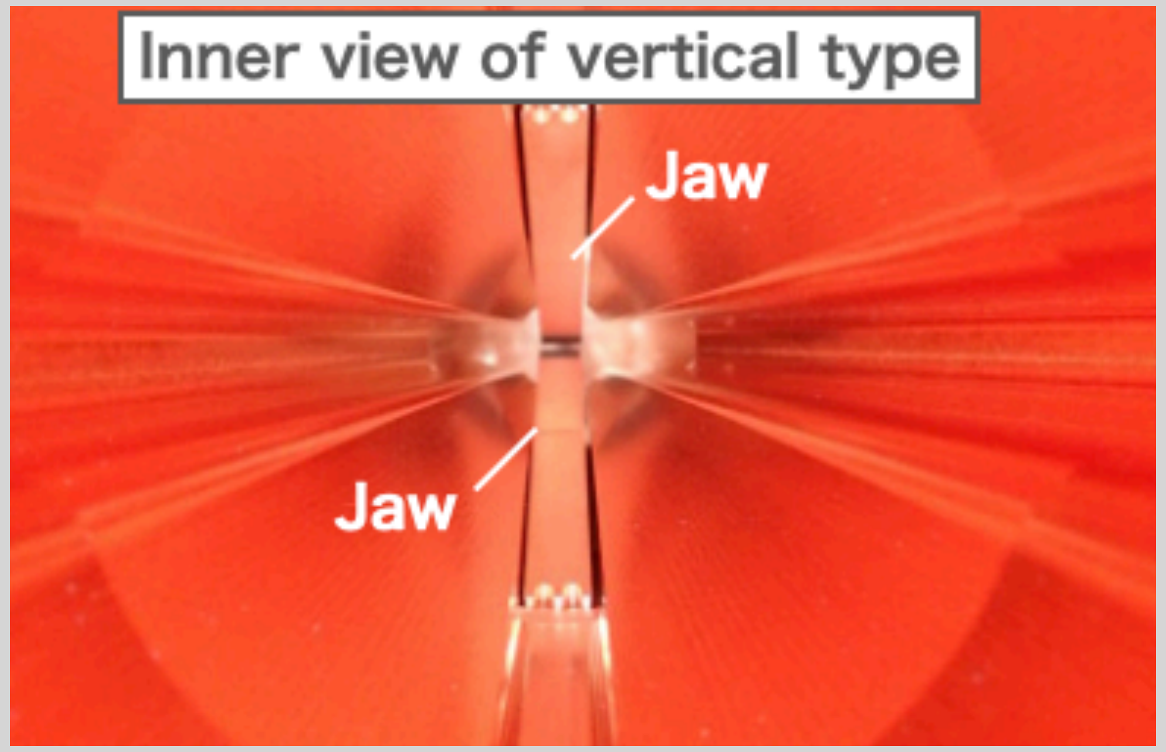
SuperKEKB type collimator

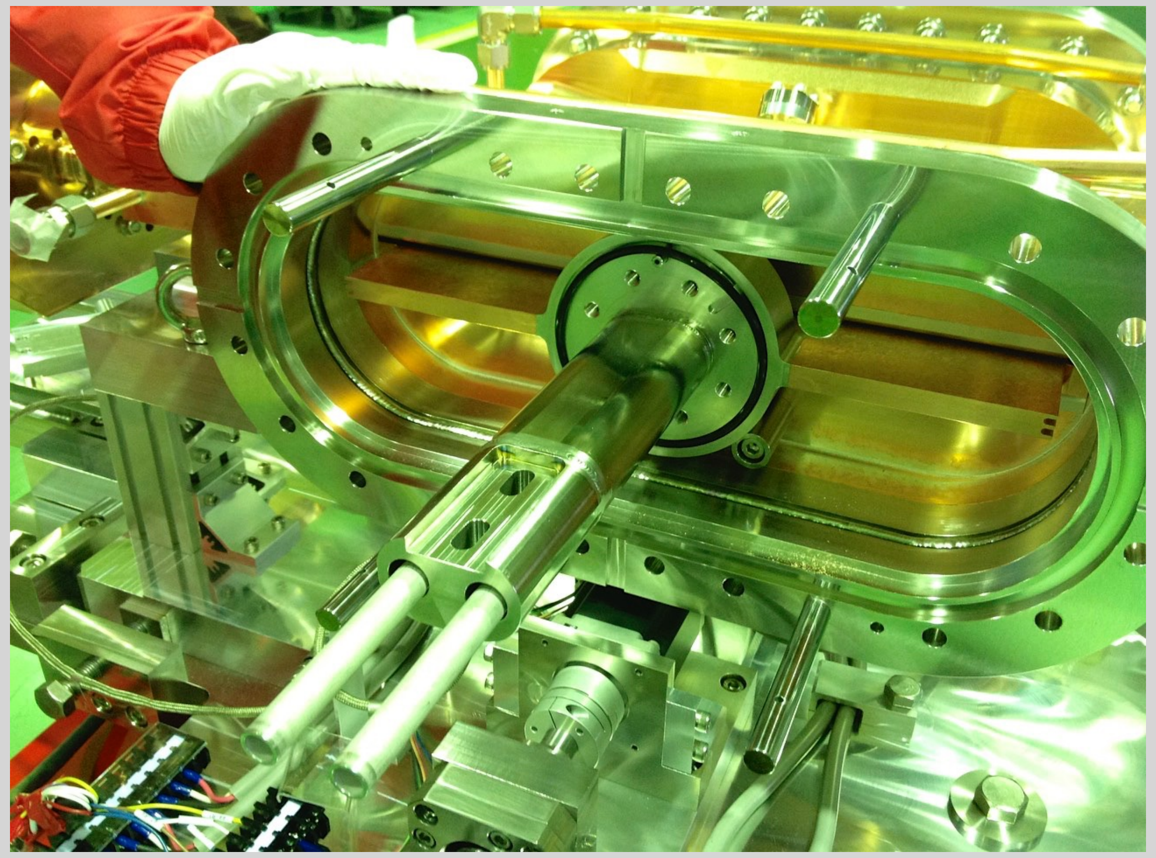
Design - RF property

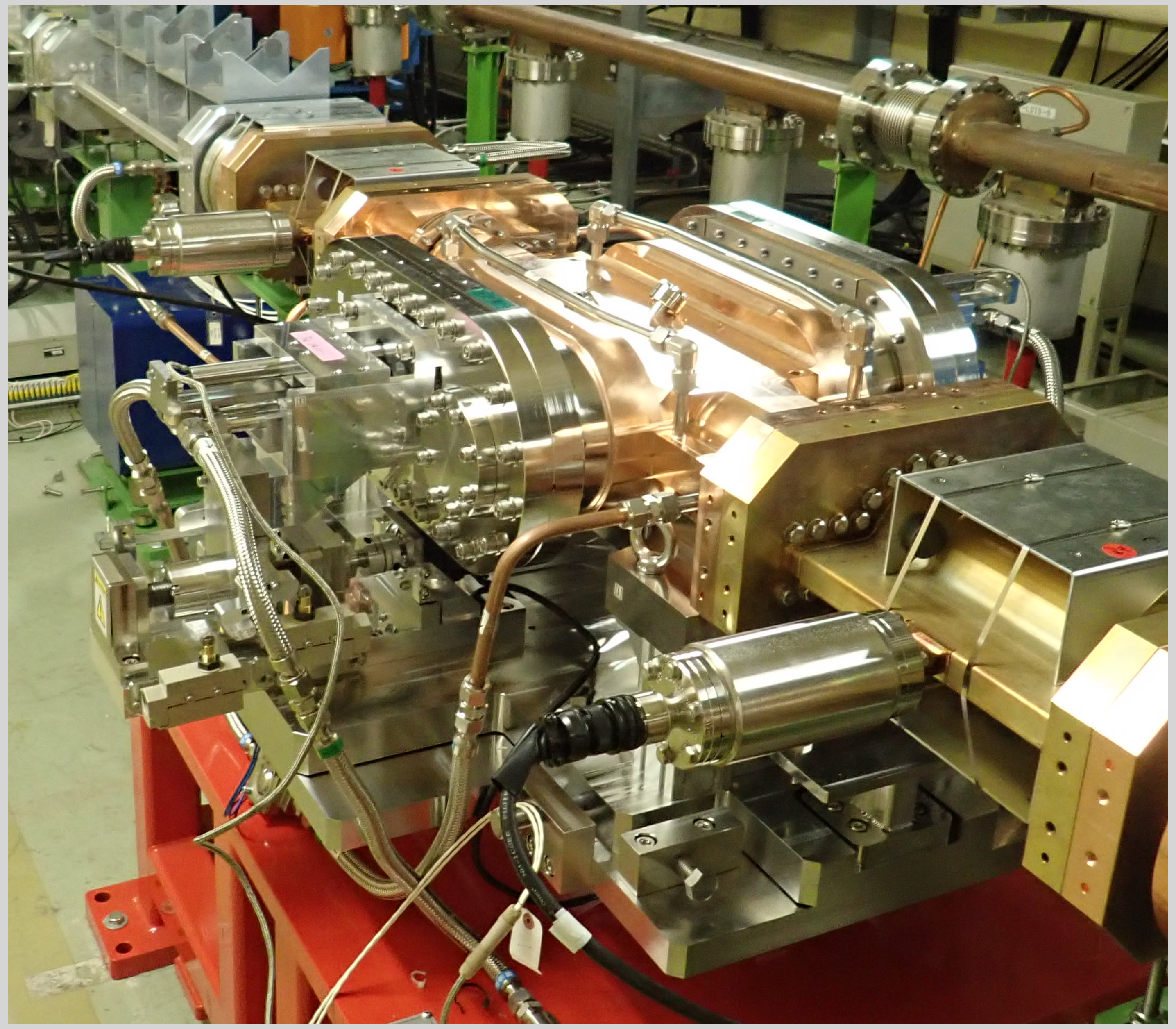
- Contact finger-type RF shield is attached on the top and bottom of each jaw.
  - The fingers are made of silver-plated INCONEL.
  - The contact surface on the chamber is made of rhodium-plated stainless steel.
- Contact-less comb-type RF shield is adopted between the longitudinal end of the jaw and the facing surface on the chamber.







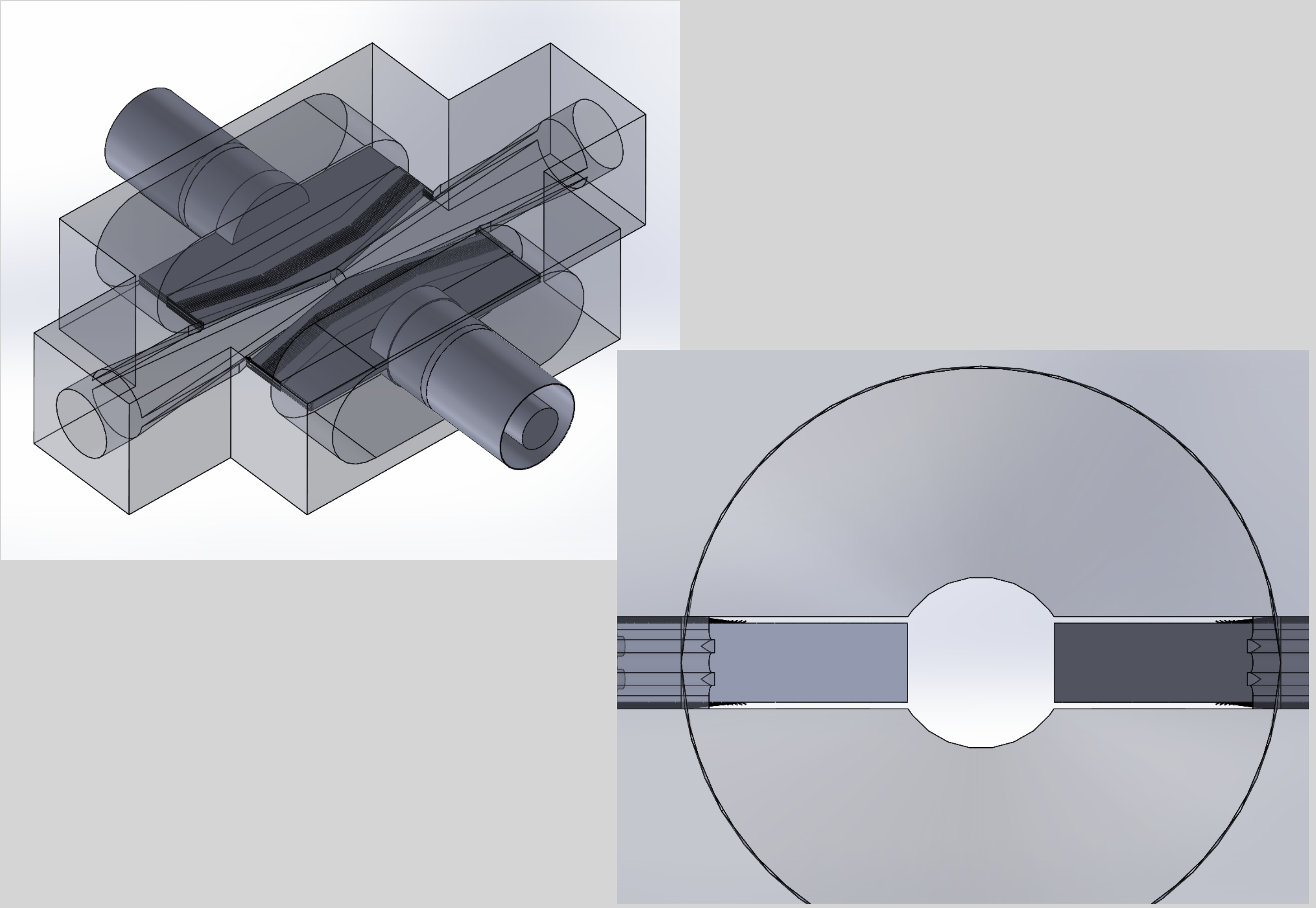




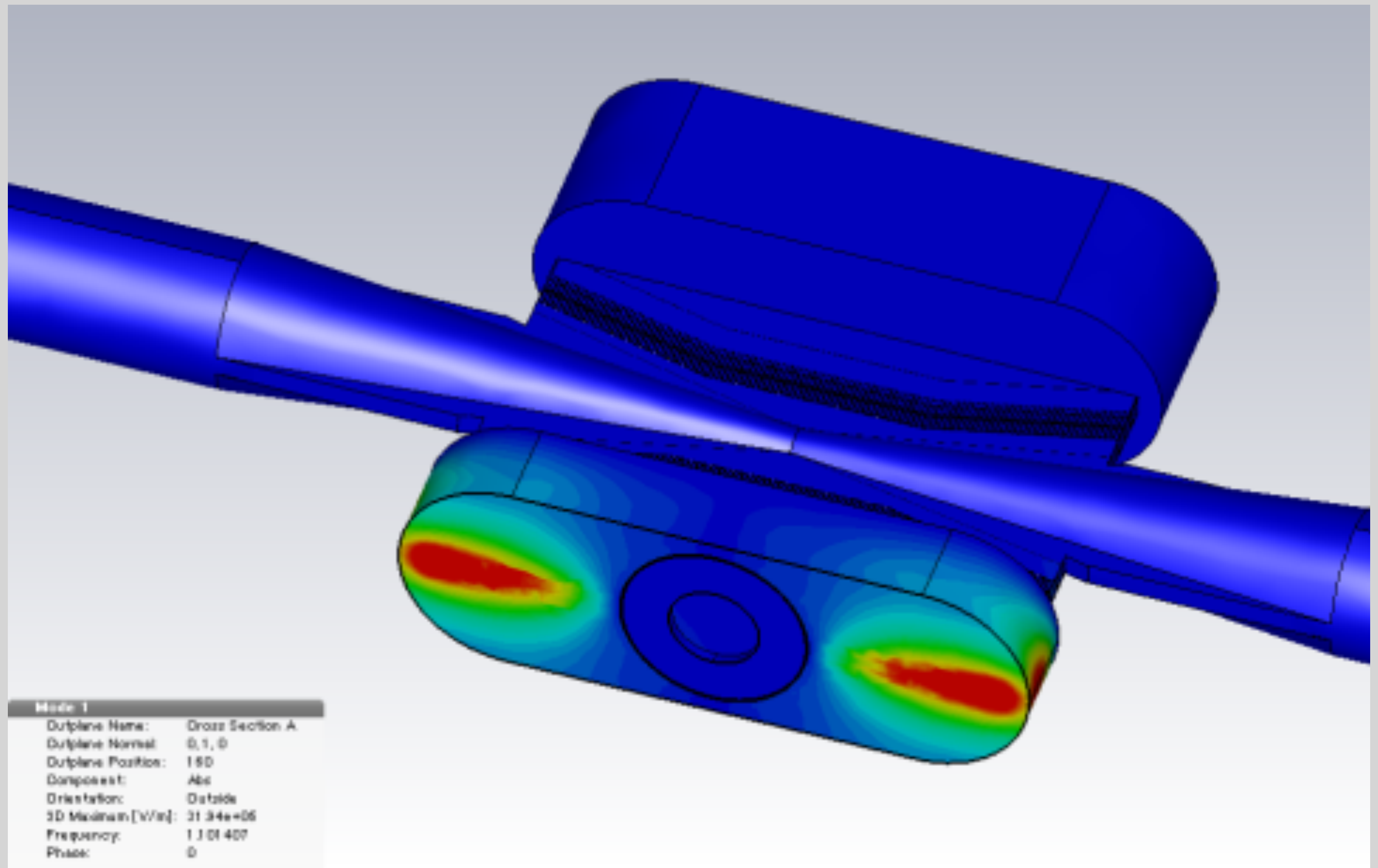
Design - RF property

- We estimated effectivity of the RF shields using Eigen-mode solver in CST Studio.
- The maximum electric field strength in the beam channel is 1.7×10^{7} V m^{-1}, and 10 V m^{-1} in a gap between the jaw and the chamber wall.
- RF in the beam channel is intruded into the chamber placed the jaw. However, the coupling between the beam channel and the chamber is small.

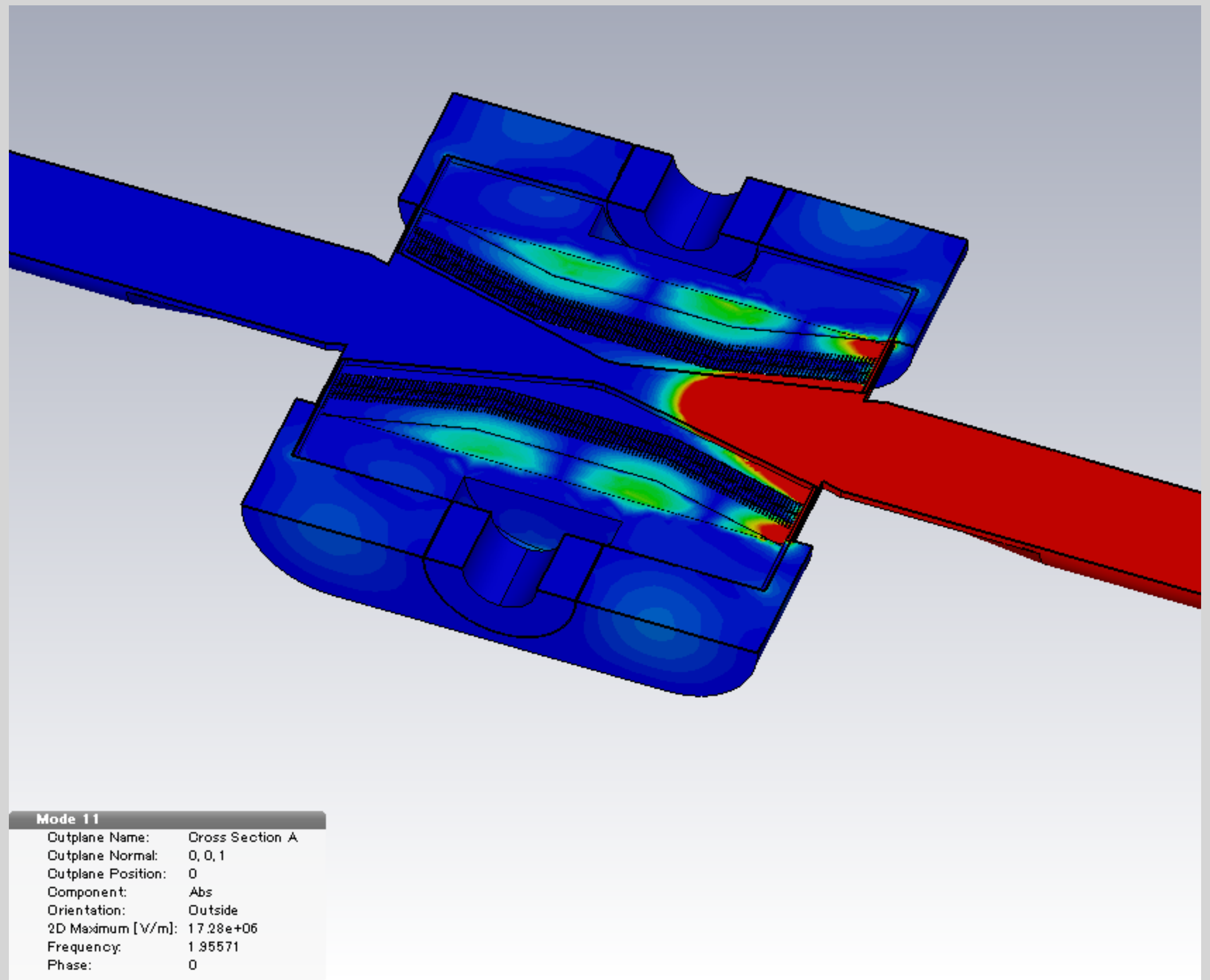
[T. Ishibashi et al., PRAB **23**, 053501 (2020)]



Simulation model in CST Studio



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

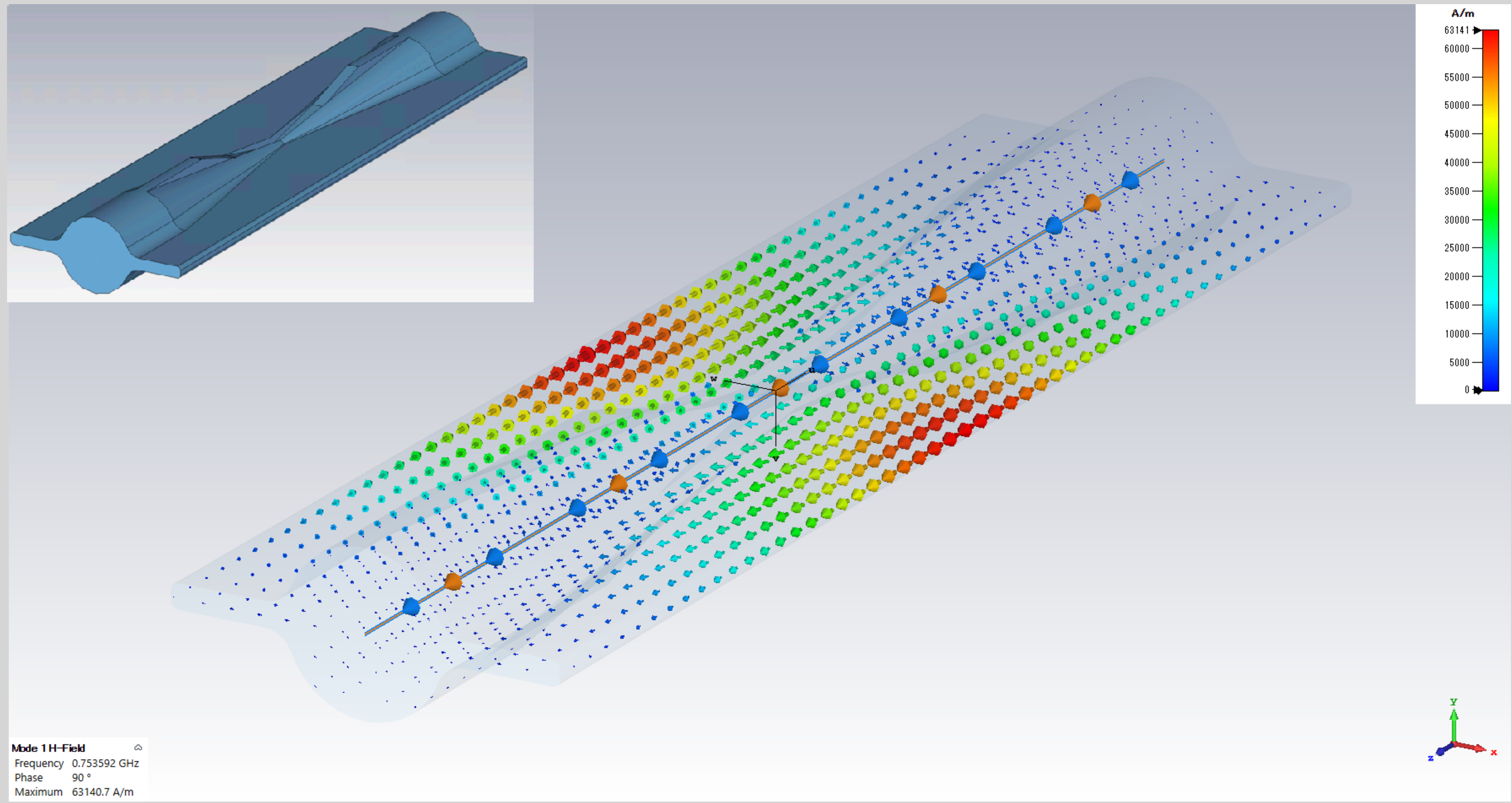


E-field strength in beam channel (TE_{111}: 1.9557 GHz)

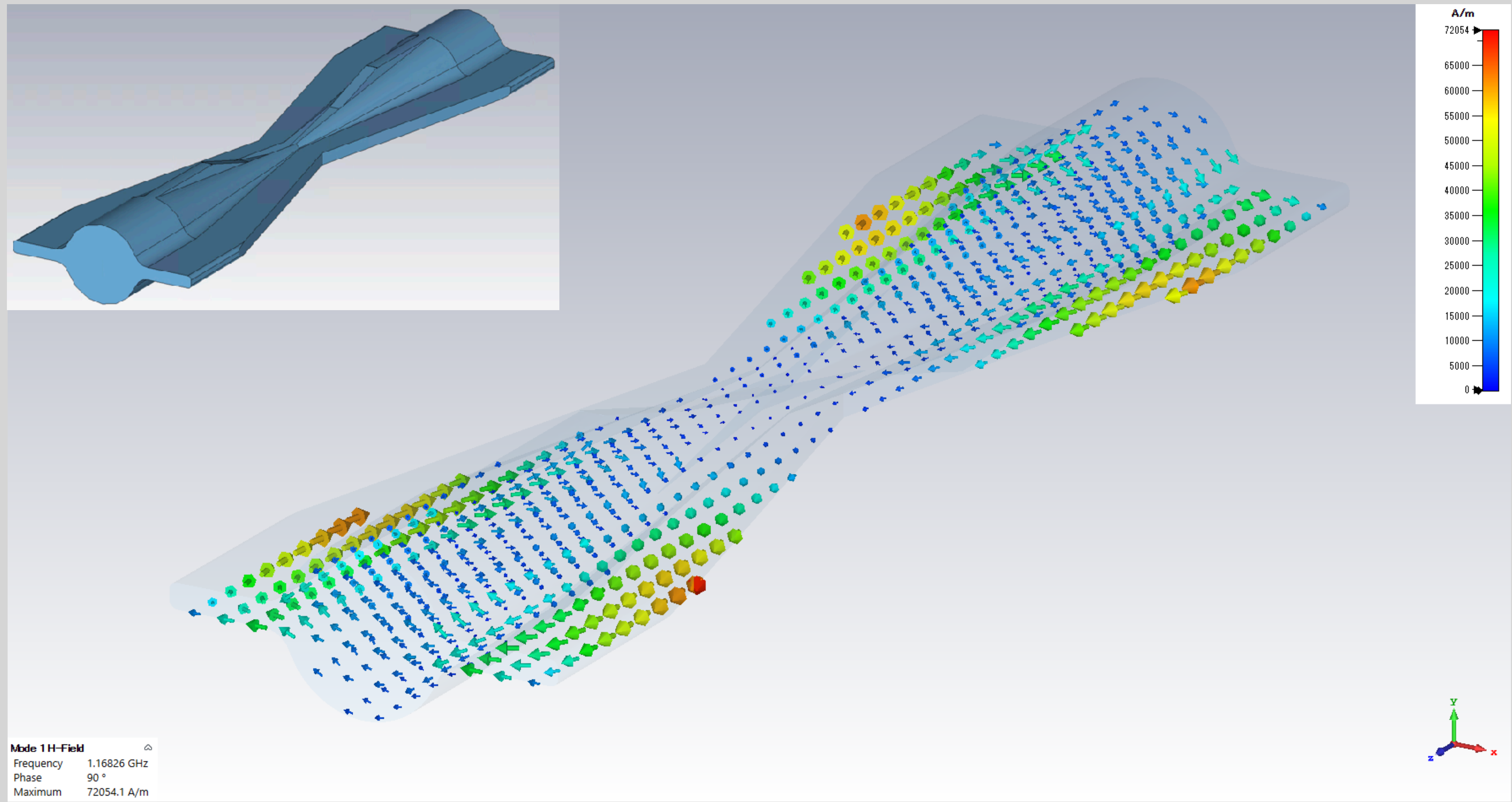
Design - RF property

- A trapped mode is excited around the jaws in the vertical collimator with straight shaped antechambers.
- The excitation of the trapped mode is avoided by means of tapering the inside of the antechambers to the center of the vertical collimator.

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



Height in antechambers at center: 0 mm
(0.7536 GHz)



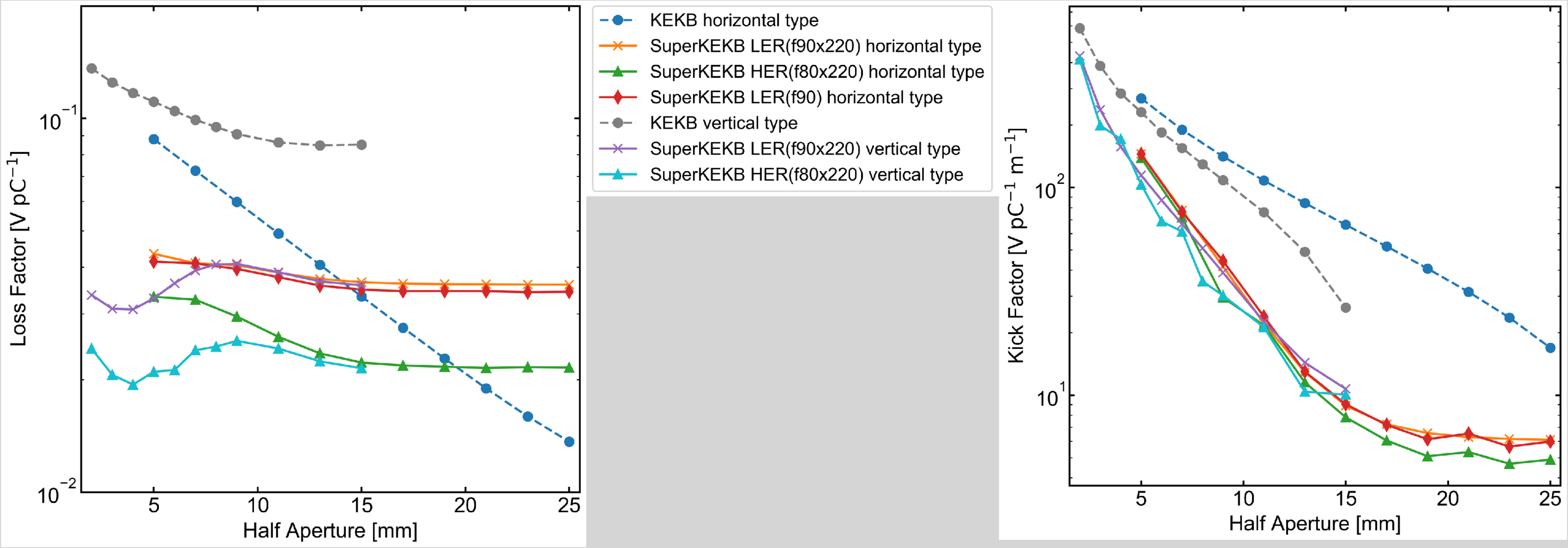
Height in antechambers at center: 70 mm
(1.1683 GHz)

E-field

Design - Impedance

- Impedance in the collimators is calculated with GdfidL.
- The loss and kick factors of the SuperKEKB collimators are less than those of the KEKB ones except for loss factors in the aperture of 15 mm or wider for a horizontal collimator of KEKB.

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



Loss factor (bunch length: 6 mm)

Kick factor (bunch length: 6 mm)

Design - Impedance

- The total loss factor in LER is approximately 14.24 V pC^{-1}.
- The contribution of the collimators is 3.16 %, and the loss factor of the collimators is no problem.

Component	k_z [V C^{-1}]	Quantity	$k_{z,\text{total}}$ [V pC^{-1}]
Resistive wall (Al)	1.03×10^9	2200 m	2.26
Pumping port (rf screen)	3.65×10^2	2200 m	8.04×10^{-7}
Connection part of MO flange	1.28×10^7	2000	0.03
Comb-type bellows chamber	3.00×10^9	1000	3
Gate valve	3.00×10^9	30	0.09
SR mask	1.82×10^{-3}	1000	1.82×10^{-12}
Vertical collimator	3.37×10^{10}	4	0.15
Horizontal collimator	4.34×10^{10}	7	0.3
Tapered beam pipe	3.83×10^8	16	6.13×10^{-3}
beam position monitor (BPM)	1.63×10^8	440	0.07
BPM for feedback	5.90×10^8	10	5.90×10^{-3}
Transverse feedback kicker	5.01×10^{11}	1	0.5
IP chamber	8.00×10^8	1	8.00×10^{-4}
rf cavity (ARES)	4.35×10^{11}	18	7.83
Total			14.24

Estimation of loss factor in LER (bunch length: 6 mm) with GdfidL.

[K. Shibata, 15th KEKB Review (2010)]

Design - Impedance

- The kick factors of the collimators could be problem for the Transverse Mode Coupling Instability (TMCI). Design bunch current in LER: 1.44 mA/bunch (3.6 A, 2500 bunches).

β_y^* = 0.8 mm, ε_y = 21 pm (assume that 1% coupling)
Kick factors were calculated with GdfidL (σ_z = 6 mm).
a) D06V1 has 5 mm tip on the both of jaws.
b) D06V1 has 60 mm tip on the both of jaws (low-Z).

Setting referred to 2020-06-27(2020b).

Achieved max. bunch current was 0.71 mA/bunch for bunch length measurements on 2020-06-30 (day shift, 280 mA, 393 bunches).

Collimator	β_y [m]	$\Delta\nu_y$	aperture [mm]	# of σ_y	k_T [V/pC/m]
D06V1 a)	67.3	0.02	±2.2	59	359
D06V2	20.6	0.16	±1.9	93	445
D02V1	18.4	0.03	±1.5	76	649
QC1	977.8	0	13.5	94.2	

$I_{\mathrm{b,th}} \approx 1.51$ mA/bunch

393 bunches: 593 mA
978 bunches: 1477 mA
1565 bunches: 2363 mA

2020c (D03V1 close)

Collimator	β_y [m]	$\Delta\nu_y$	aperture [mm]	# of σ_y	k_T [V/pC/m]
D06V1 b)	67.3	0.02	±2.2	59	552
D06V2	20.6	0.16	±1.9	93	445
D03V1	16.96	0.09	±1.1	58	1070
D02V1	18.4	0.03	±1.5	76	649
QC1	977.8	0	13.5	94.2	

$I_{\mathrm{b,th}} \approx 0.89$ mA/bunch

393 bunches: 450 mA
978 bunches: 870 mA
1565 bunches: 1393 mA

$$I_{\mathrm{b,th}} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\mathrm{T},i}(\sigma_z)}$$

[Handbook of Accelerator Physics and Engineering 3rd Printing (2009)]

$C_1 \approx 8,\ f_s = 2.13\,[\mathrm{kHz}],\ E/e = 4\,[\mathrm{GV}]$

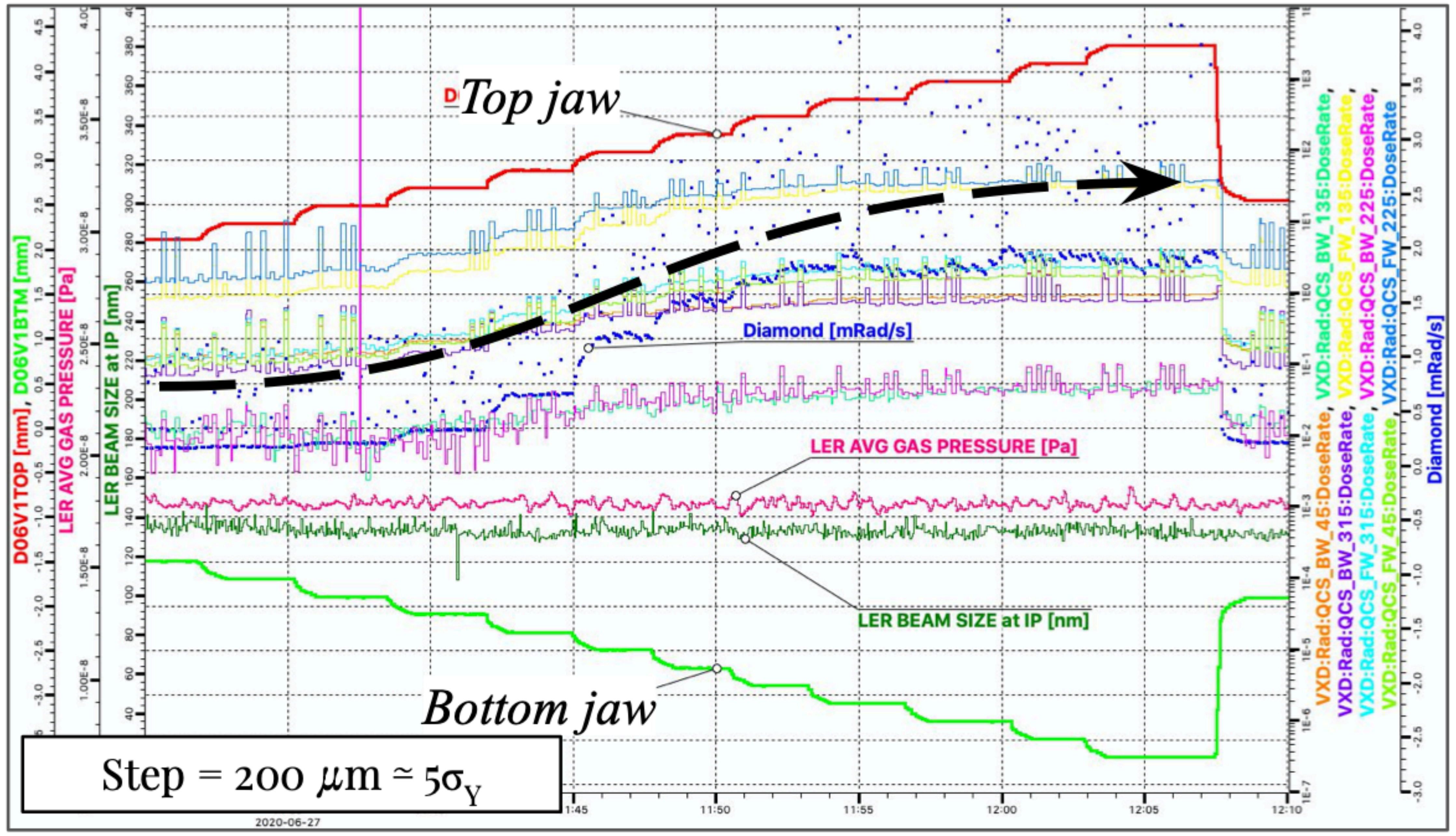
Experience - BG suppression

- The SuperKEKB type collimators have been working well up to the beam current of approximately 1 A. These collimators have been indispensable for Belle II and SuperKEKB.
- The detail of the beam background will be presented in next session (Session 5.2, H. Nakayama, SuperKEKB beam background).

[Andrii Natochii (Univ. of Hawaii) et al.]

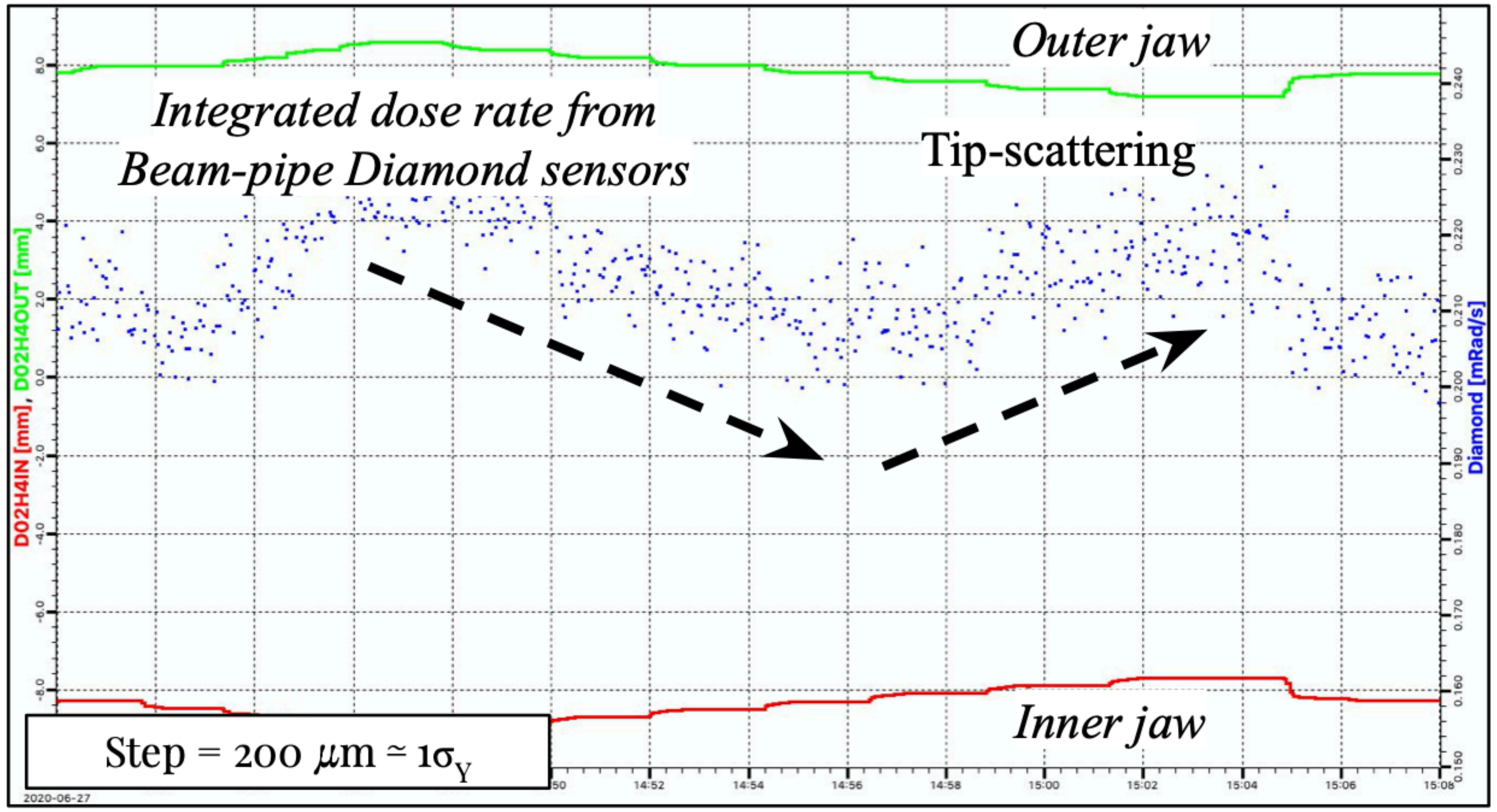
Machine settings:	LER ring, $\beta^*_{X/Y}$ = 60/0.8mm , CW = 80%, **I = 200 mA, Continuous injection**, Rep = 12.5Hz, Nb = 978
Detector settings:	Belle II HV → OFF, **Diamond sensors** only

D06V1 linear scan



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

D02H4 linear scan

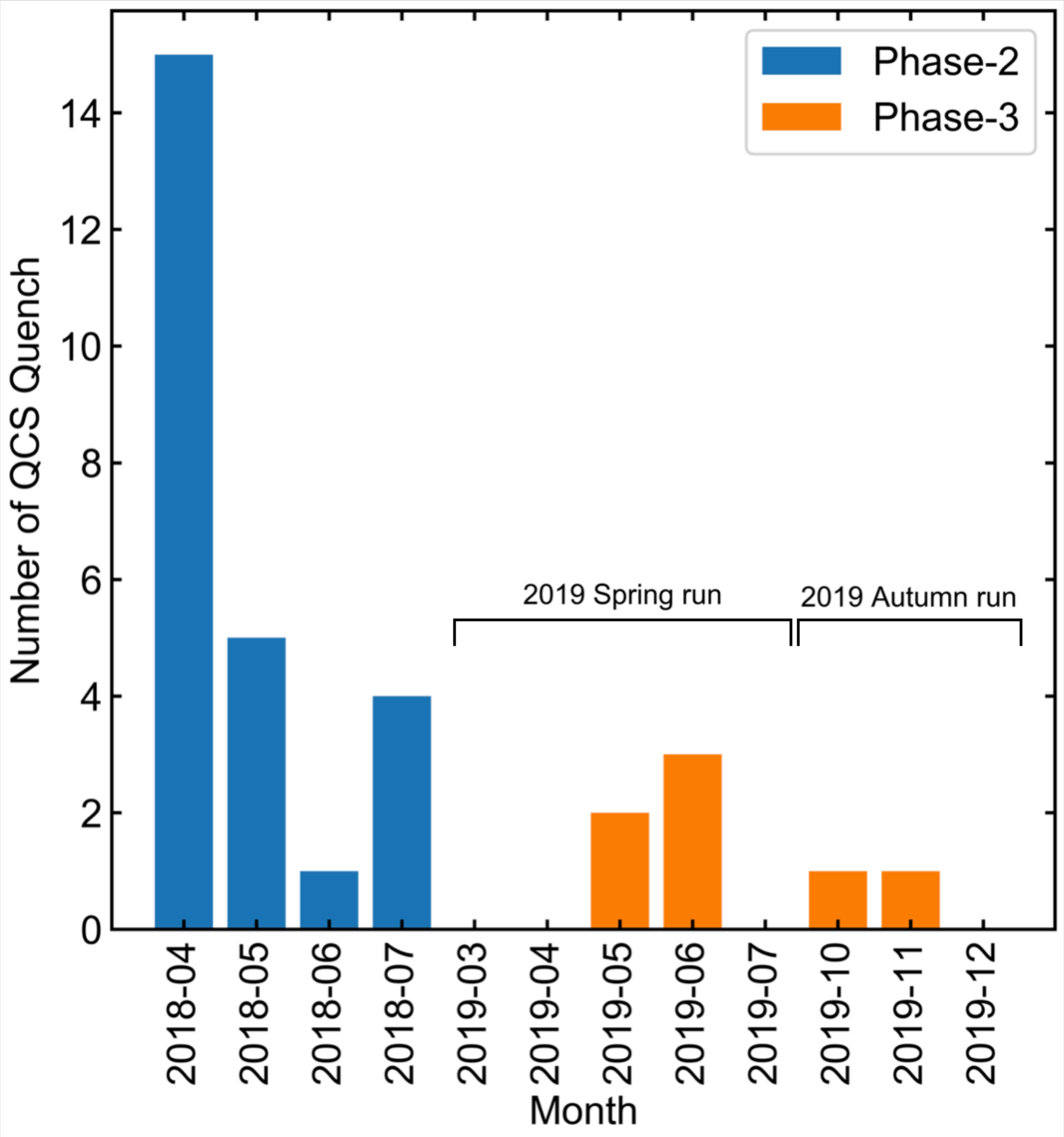


Closing the LER H-collimator we observe an increase of the IR background rate → tip-scattering.

Experience - QCS protection

- The SuperKEKB type collimators have been working well up to the beam current of approximately 1 A.
- Thse collimators have been indispensable for Belle II and SuperKEKB.

- The collimators were tuned on April 23rd in 2018, and there were no QCS quenches in that month after this tuning.
- Then, the number of the occurrences was dramatically decreased.



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

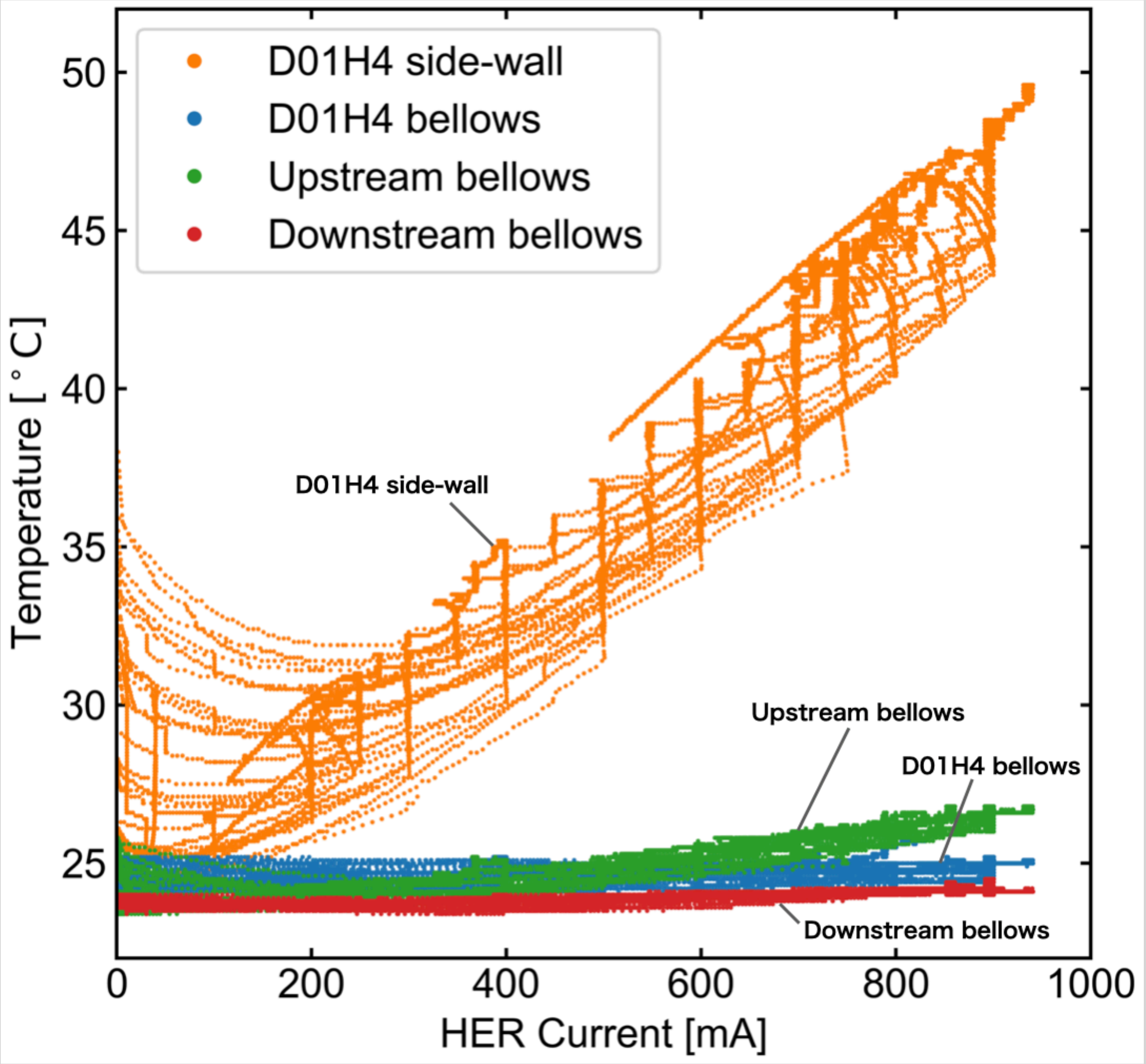
[T. Ishibashi et al., PRAB **23**, 053501 (2020)]

Experience - Heating

- An abnormal heating in the collimators themselves and components near them has not been observed.
- We cannot see any temperature rise with an RTD on a bellows, which is a connection part between the movable jaw and the chamber in the collimator.

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

- The temperature on the collimator and the bellows chambers beside it increases linearly. This heating is derived from the SR mainly.
- The SR power density on the tapered wall with 12 degrees is approximately 18.2 kW m^{-1} in D01H4 collimator. This is the highest power density in all of the collimators in SuperKEKB MR.



Temperature on D01H4 collimator using RTD.

Experience - Pressure

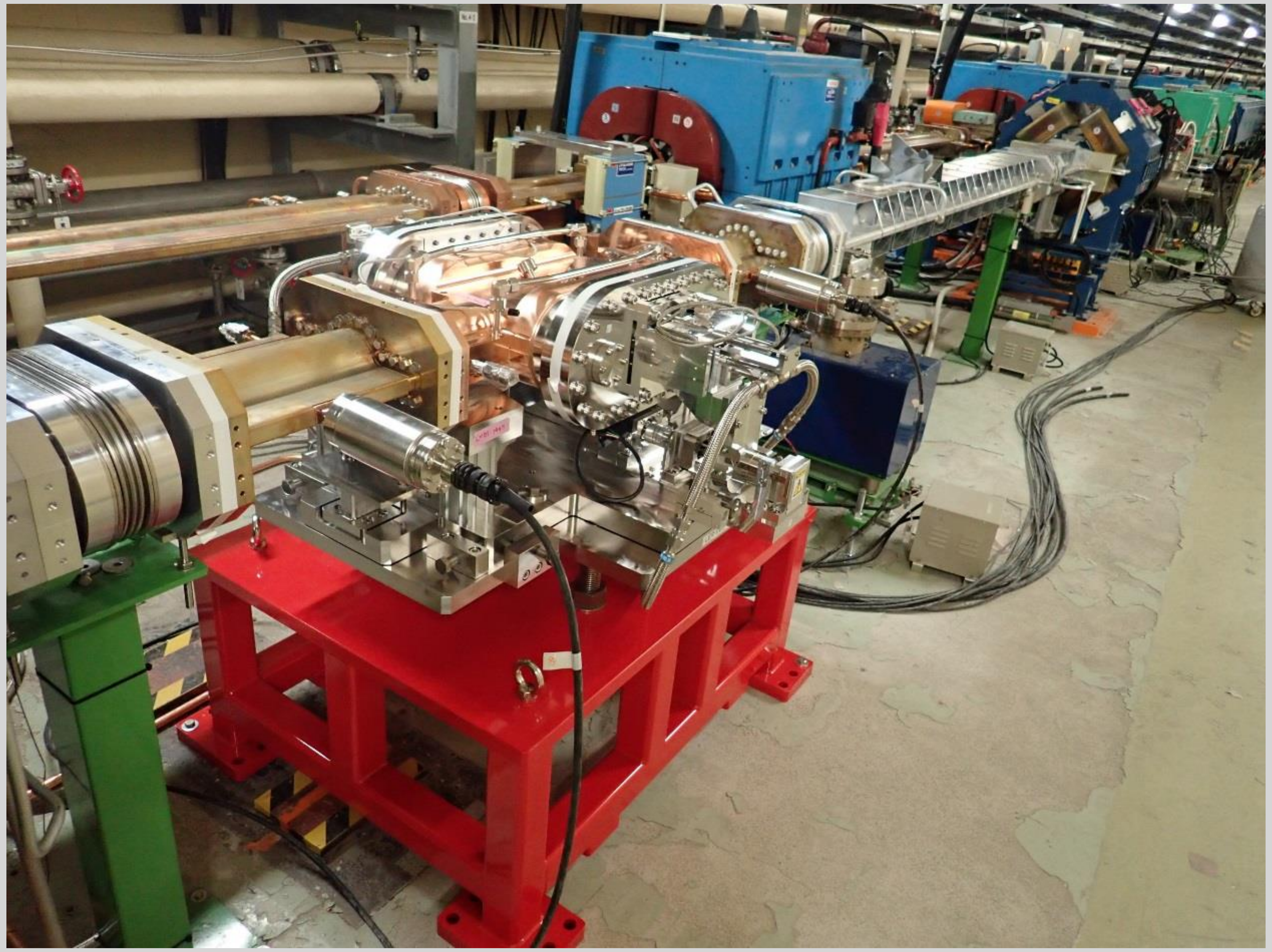
- Pressure upstream of IP in LER.
  - Vacuum component is dominant for BG in LER.
  - Especially, pressures near D02V1 and D02H1 had been high during 2019 spring run.
    - D02H1 collimator had had a water leakage trouble before the run, so it could raise the pressure.

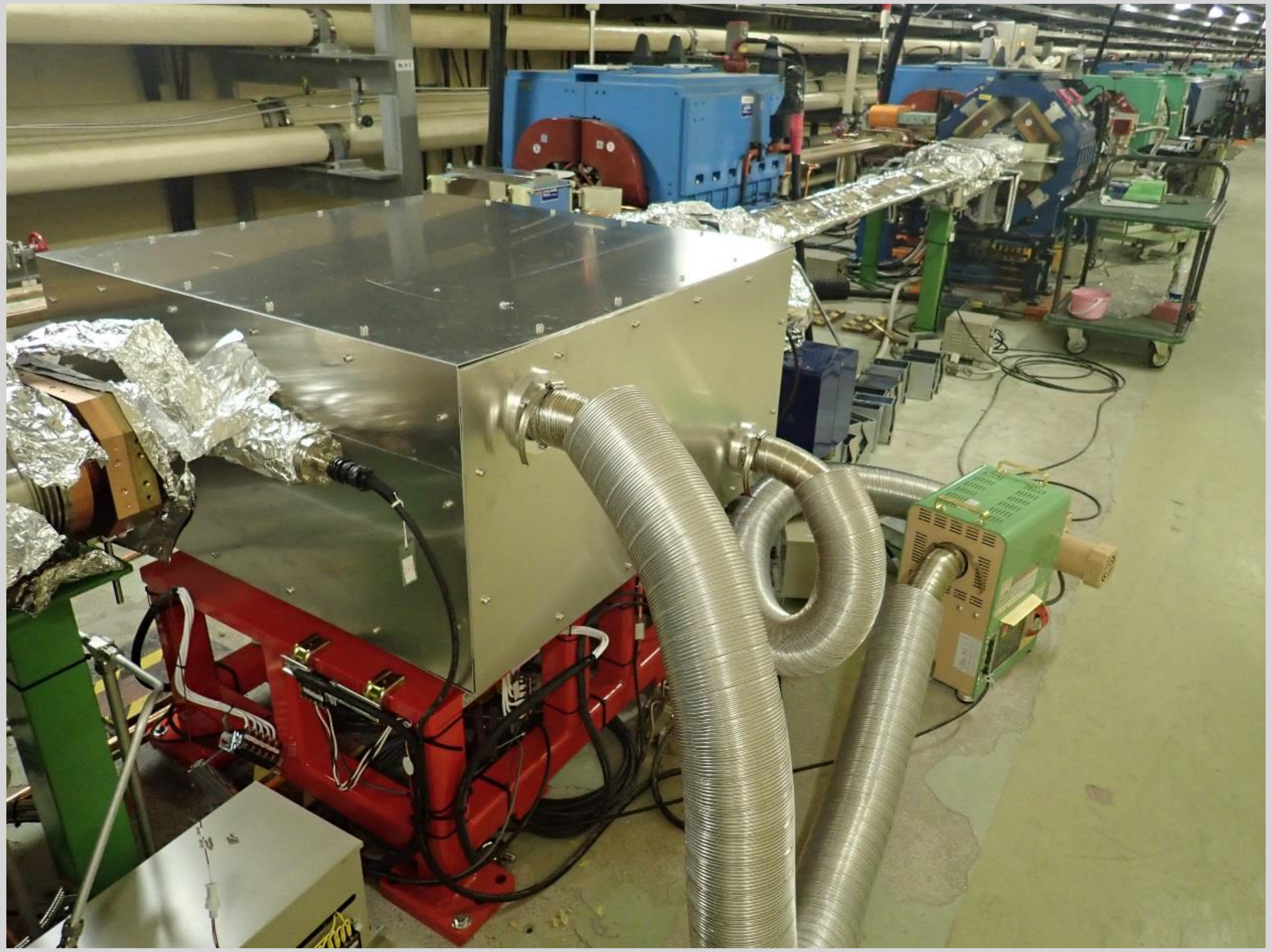
→ baked out these collimators and beam pipes in tunnel before 2019 autumn run.

LER pressure distribution in 2019 spring run

Experience - Pressure

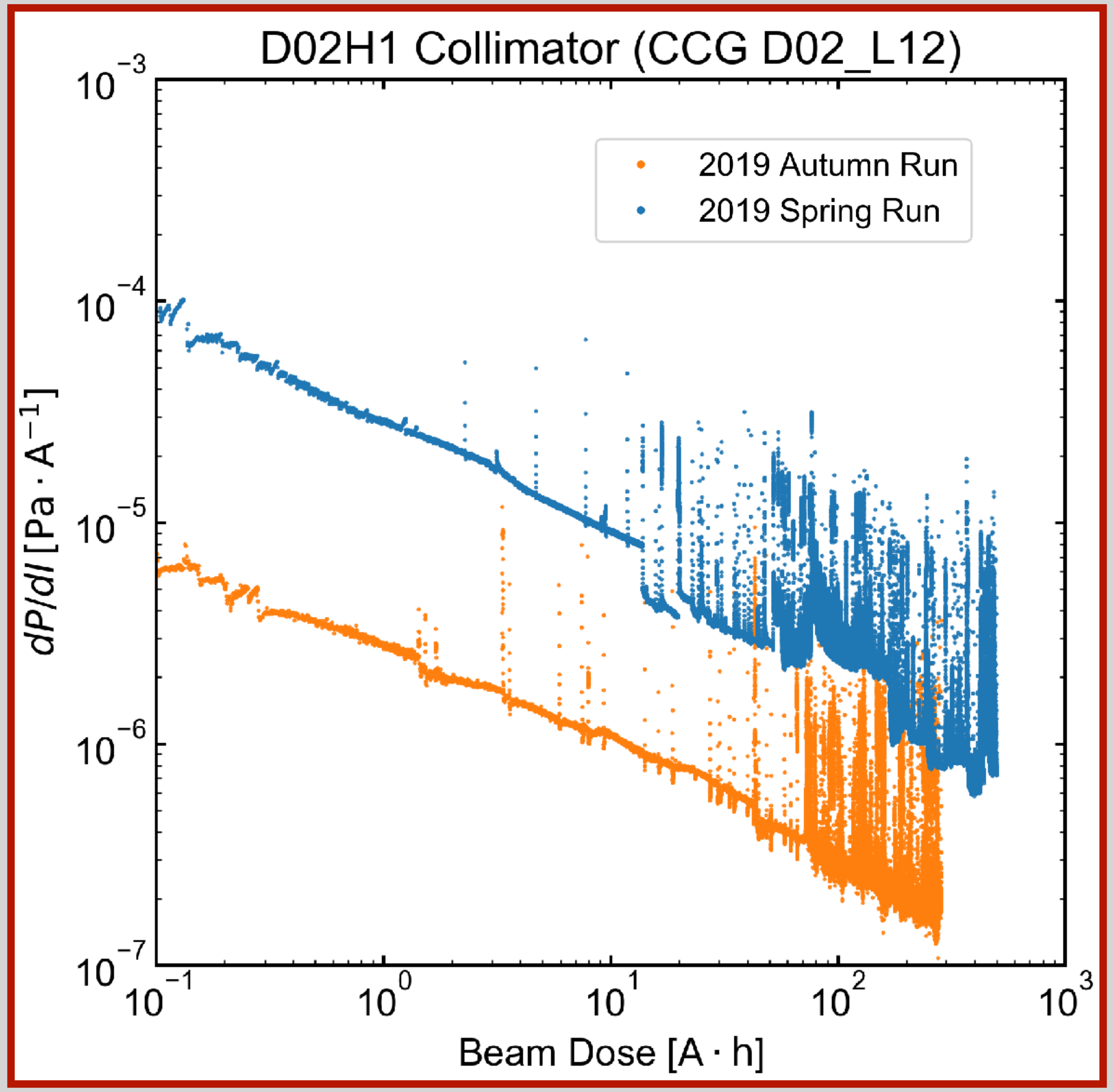
- D02H1, H2 collimator:
  - ion pumps bake-out: ~32 hours (2019-09-03 10:00 ~ 09-04 16:00)
  - NEG activation: ~33 hours (2019-09-04 10:00 ~ 09-05 17:00)
- D02V1 collimator:
  - ion pumps bake-out: ~24 hours (2019-09-11 10:00 ~ 09-12 10:00)
  - NEG activation: ~43 hours (2019-09-11 15:00 ~ 09-13 10:00)

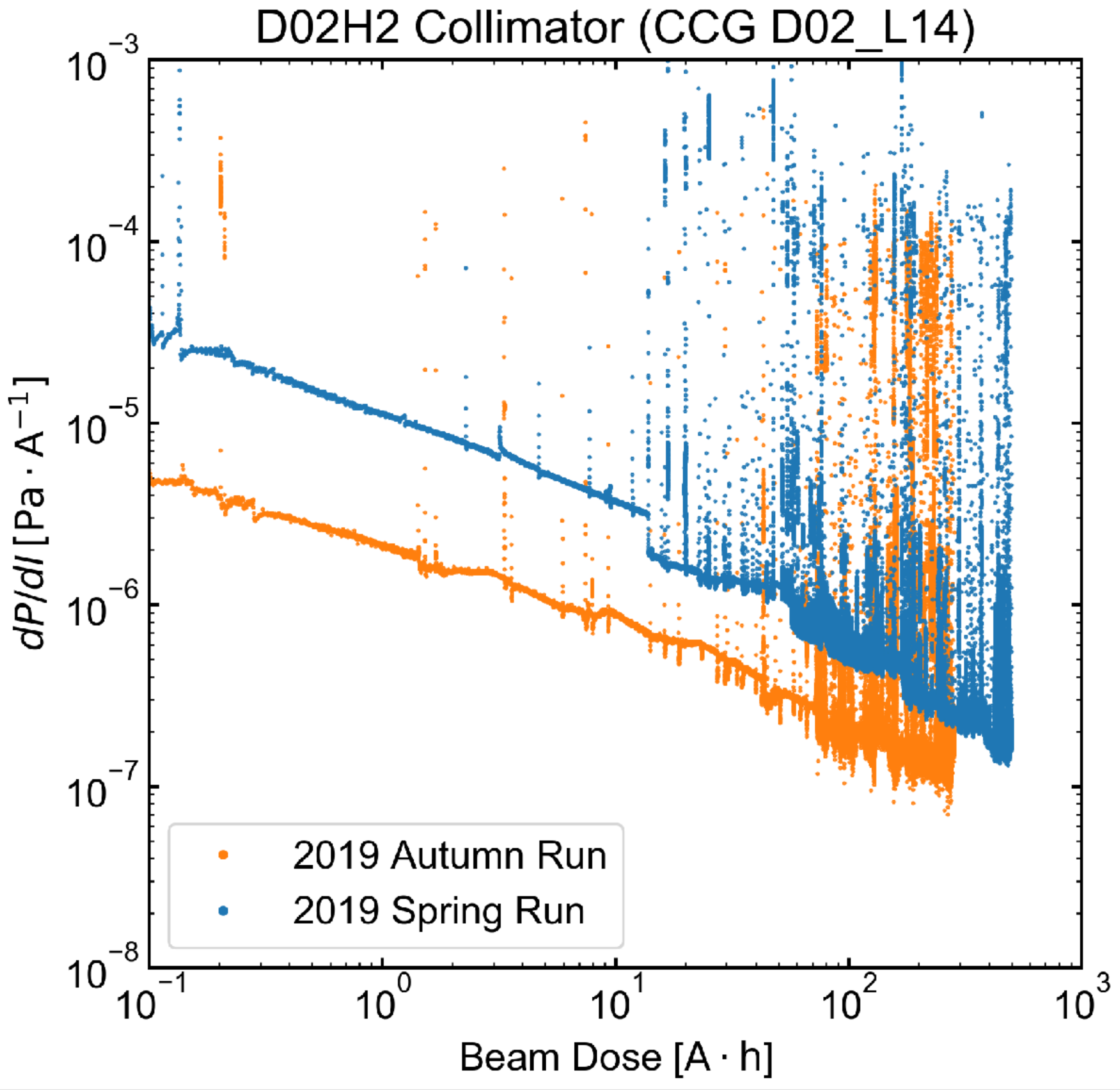


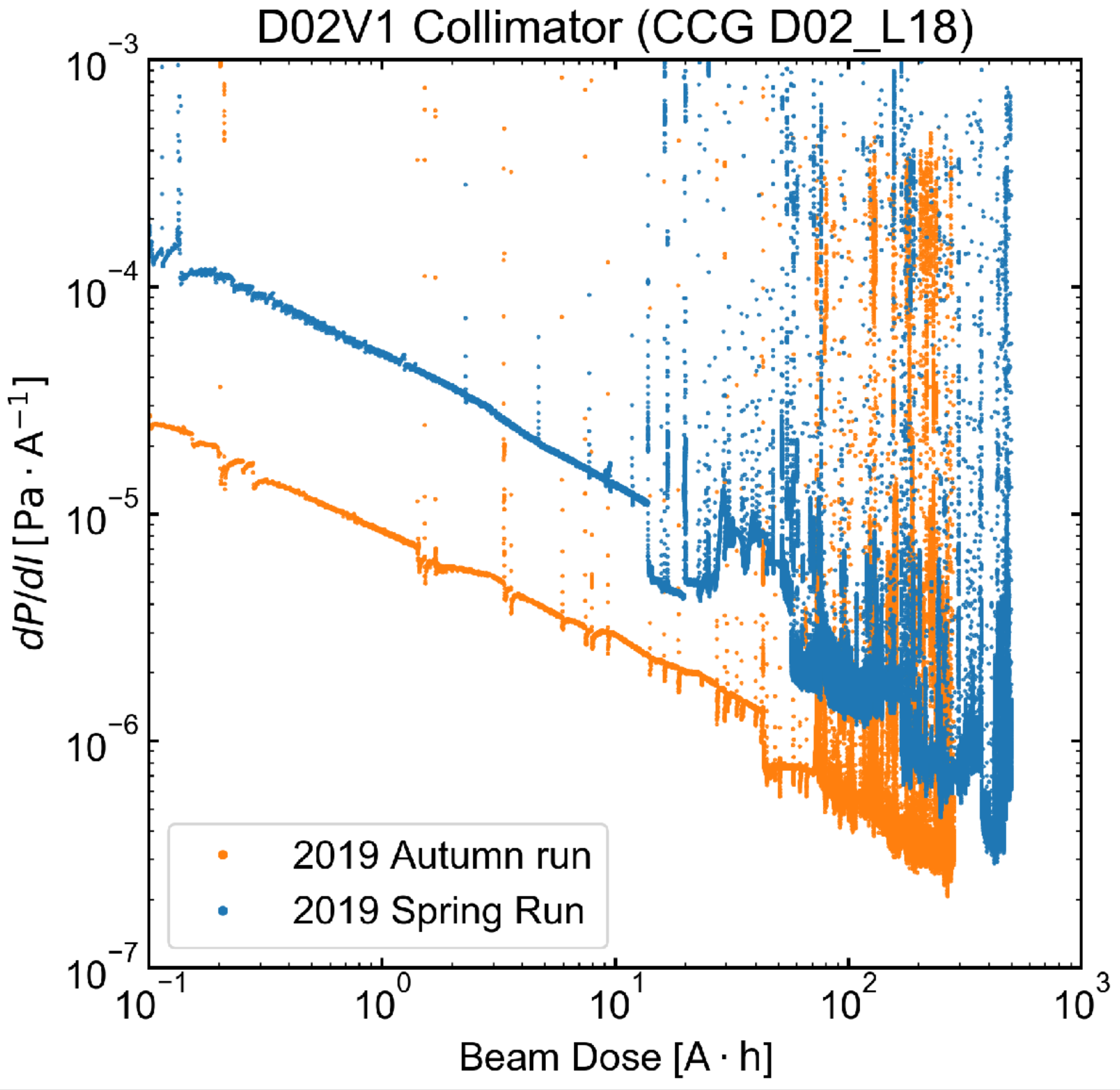


Experience - Pressure

- The bake-out was very effective for D02H1 collimator especially, because there was a water leakage trouble.
- Reduction effect for the dynamic pressure in D02V1 seems to be small because of the history effect.



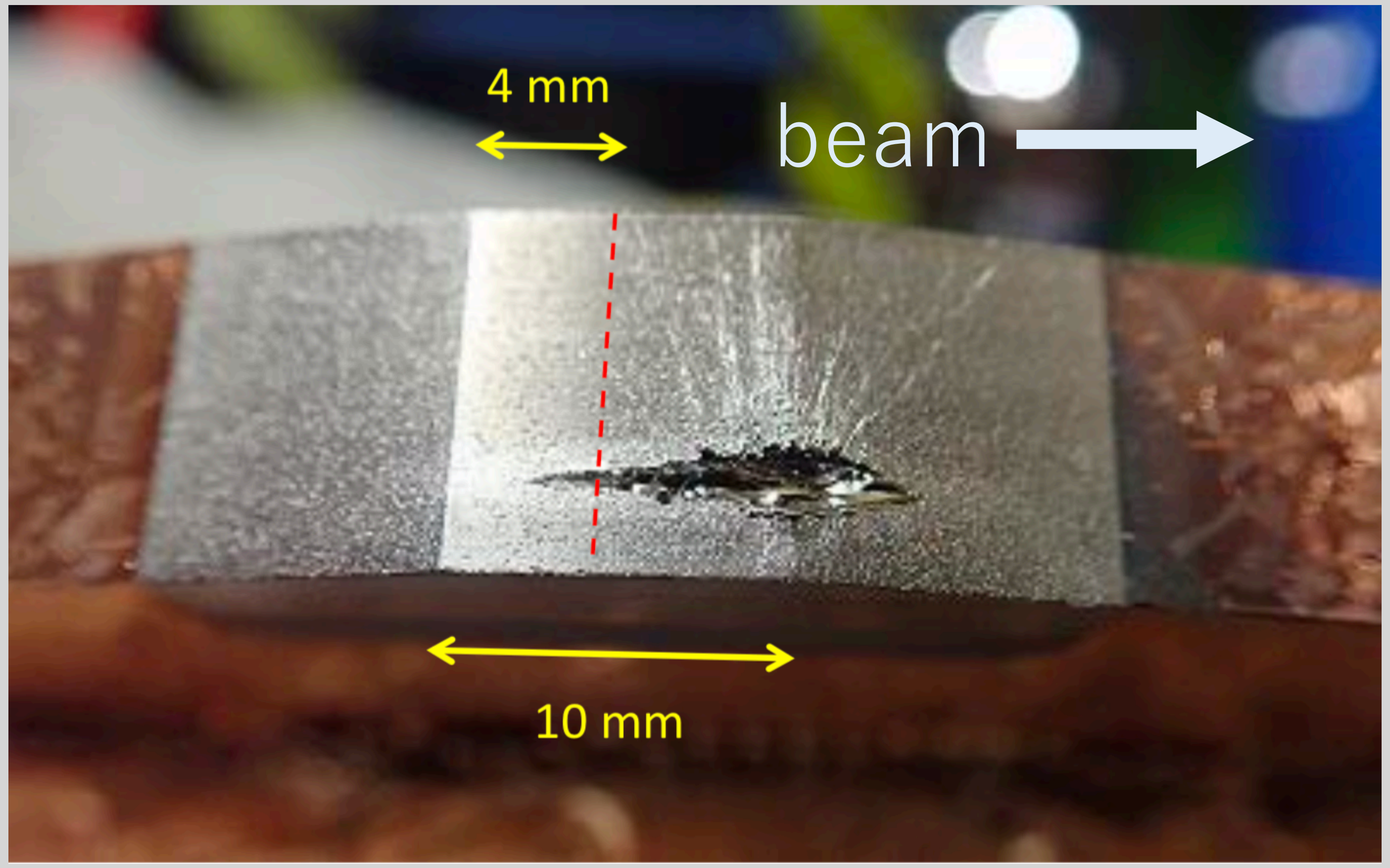




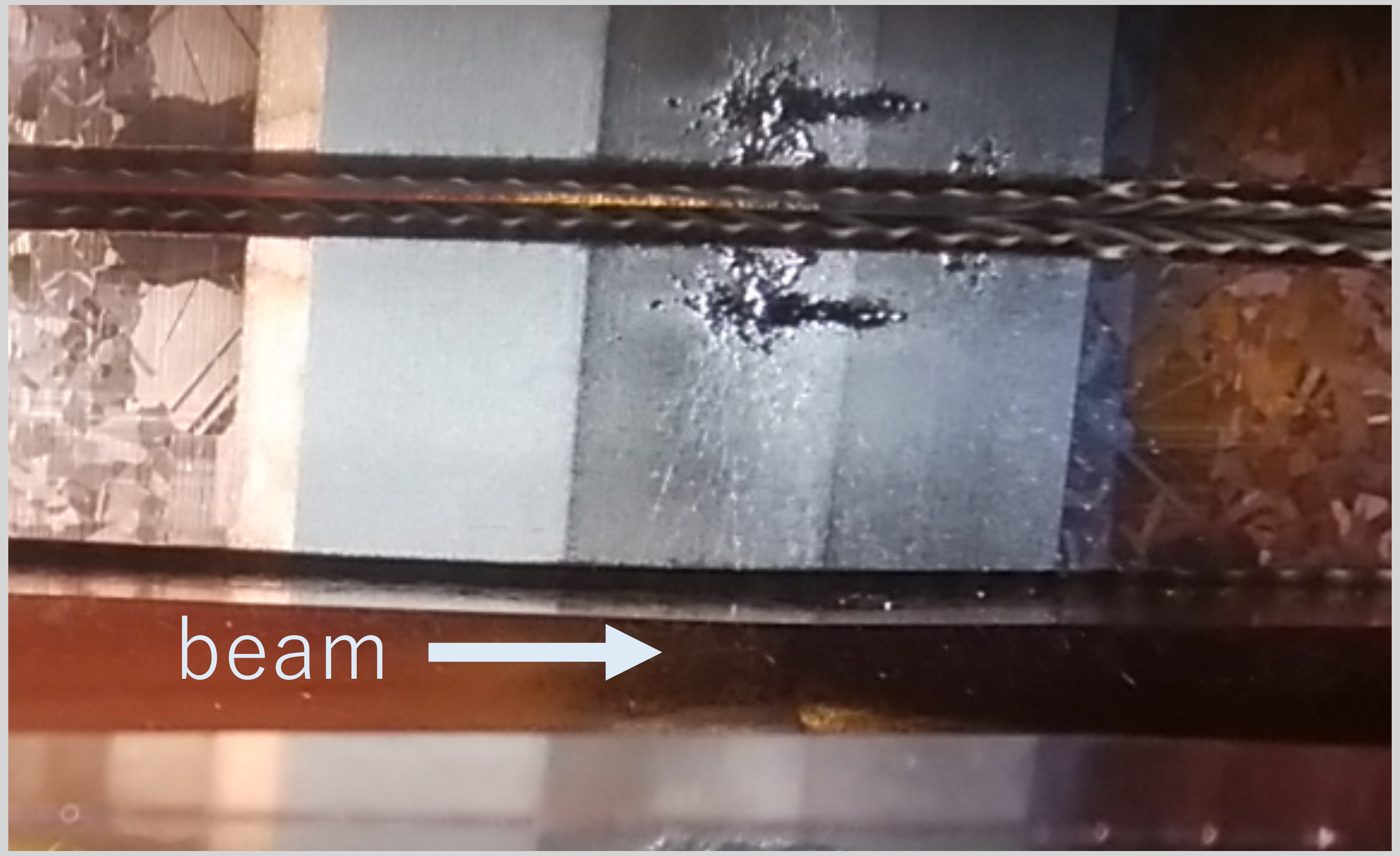
Experience - Damage

- Jaws of the collimators were damaged by beam hit.
  - LER: D06V1 (2020 spring run)*, D06V2 (2019 autumn run), D02V1 (2019 spring run), D02V1 (Phase-2)
  - HER: D01V1 (Phase-2)
- A huge beam loss and pressure burst happened near them with a QCS quench.
- The damaged tungsten tip embrittled.
- The cause, which induces the abnormal beam, is unknown.
  - A candidate is dusts in the beam pipes.

* short tantalum tip (see slide 20).



D02V1 bottom side

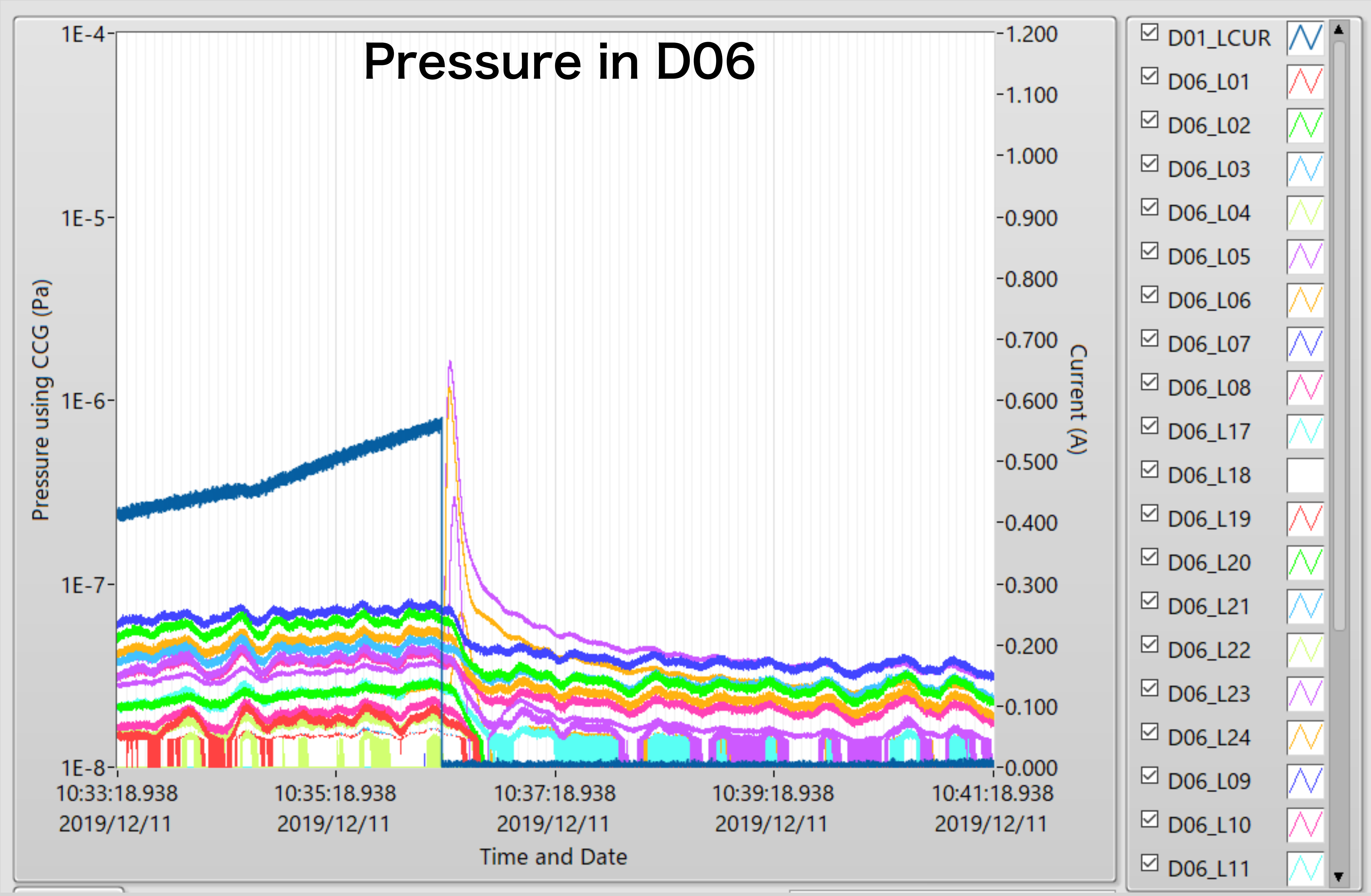


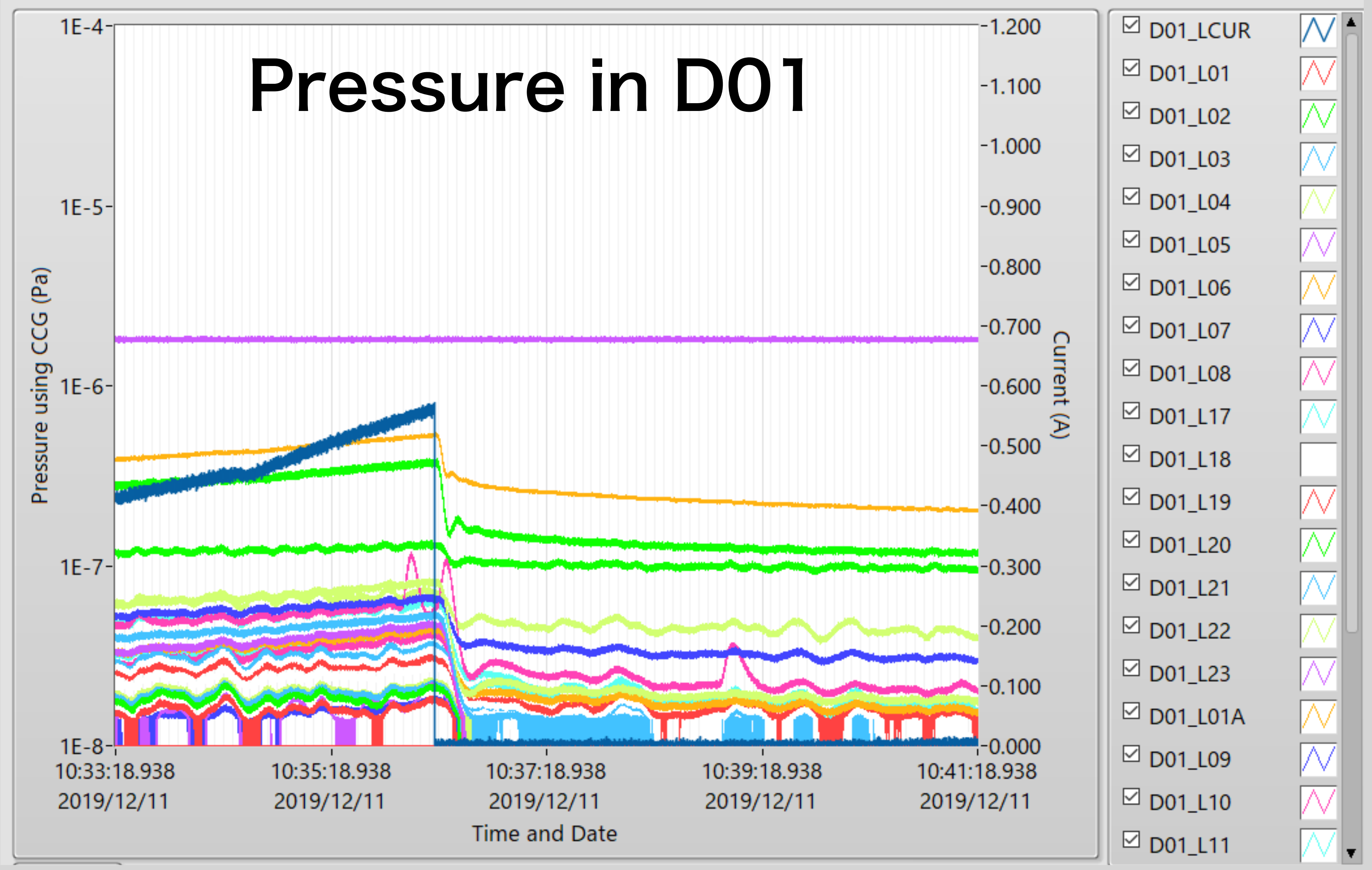
D02V1 top side

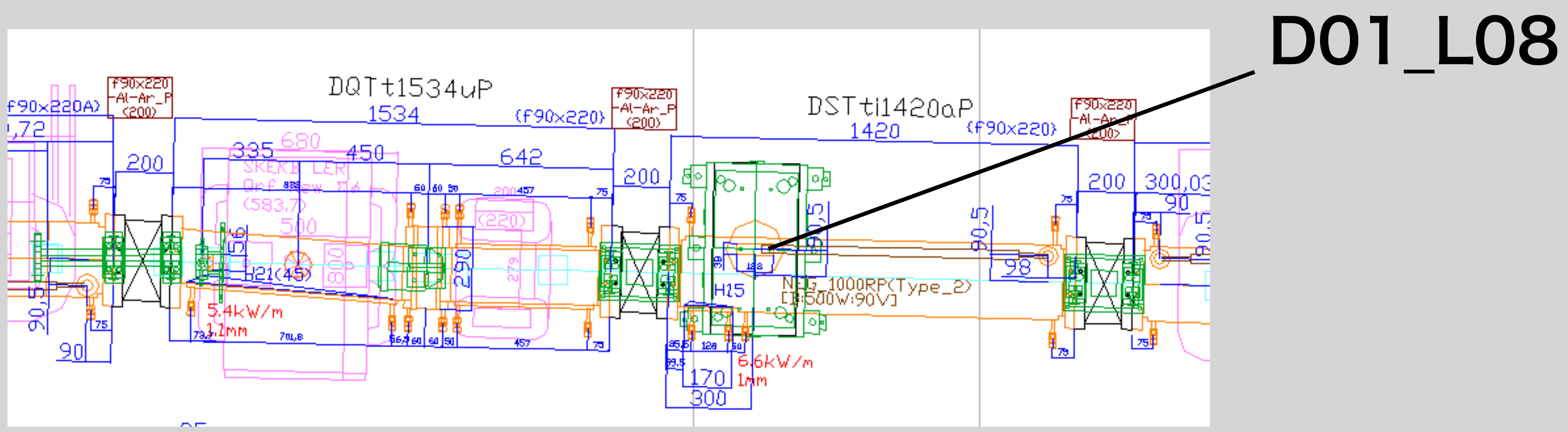

Replacement work in the presence of Radiation Science Center.

Experience - Damage

- In case of a damaged event in 2019-12-11 10:36 (2019 autumn run).
- Pressure near CCG D06_L24 and L25, which are placed near D06V2 collimator, was increased instantaneously.
- Before the beam abort, pressure at CCG D01_L08 was also increased.



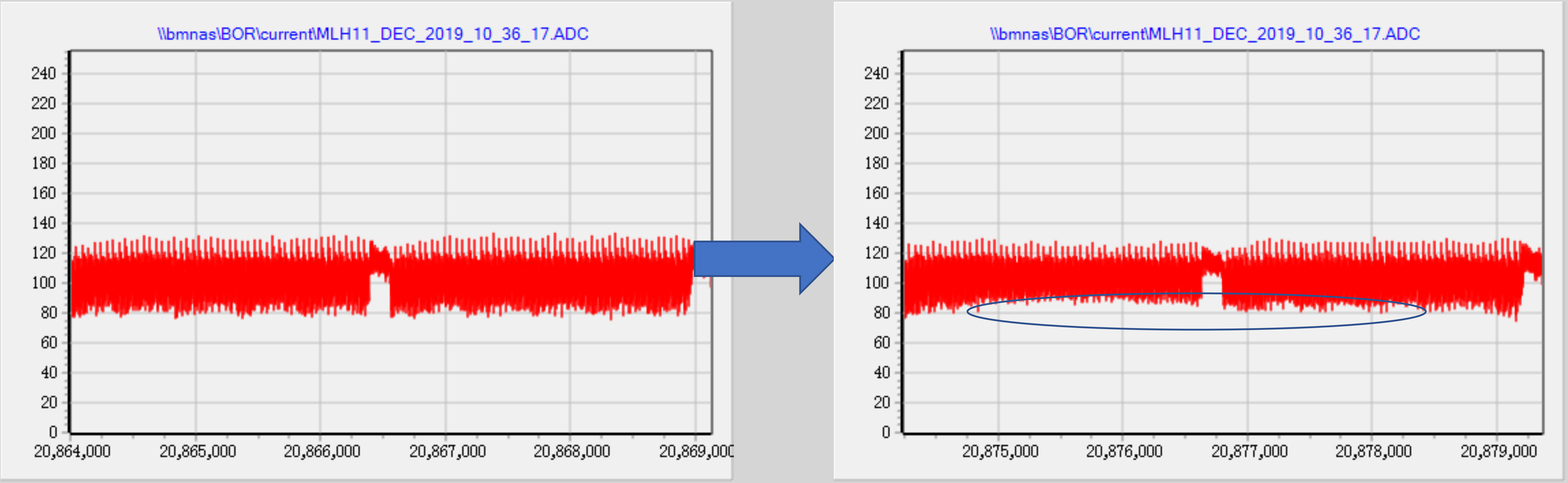




Experience - Damage

- An amplitude in a bunch oscillation monitor, which refers to "(displacement) × (charge)" in each bunch, was decreased around the middle of the trains (Did a part of these bunches hit the collimator?).
- An abnormal oscillation and orbit change were not observed before the beam abort.

[S. Terui (KEK)]

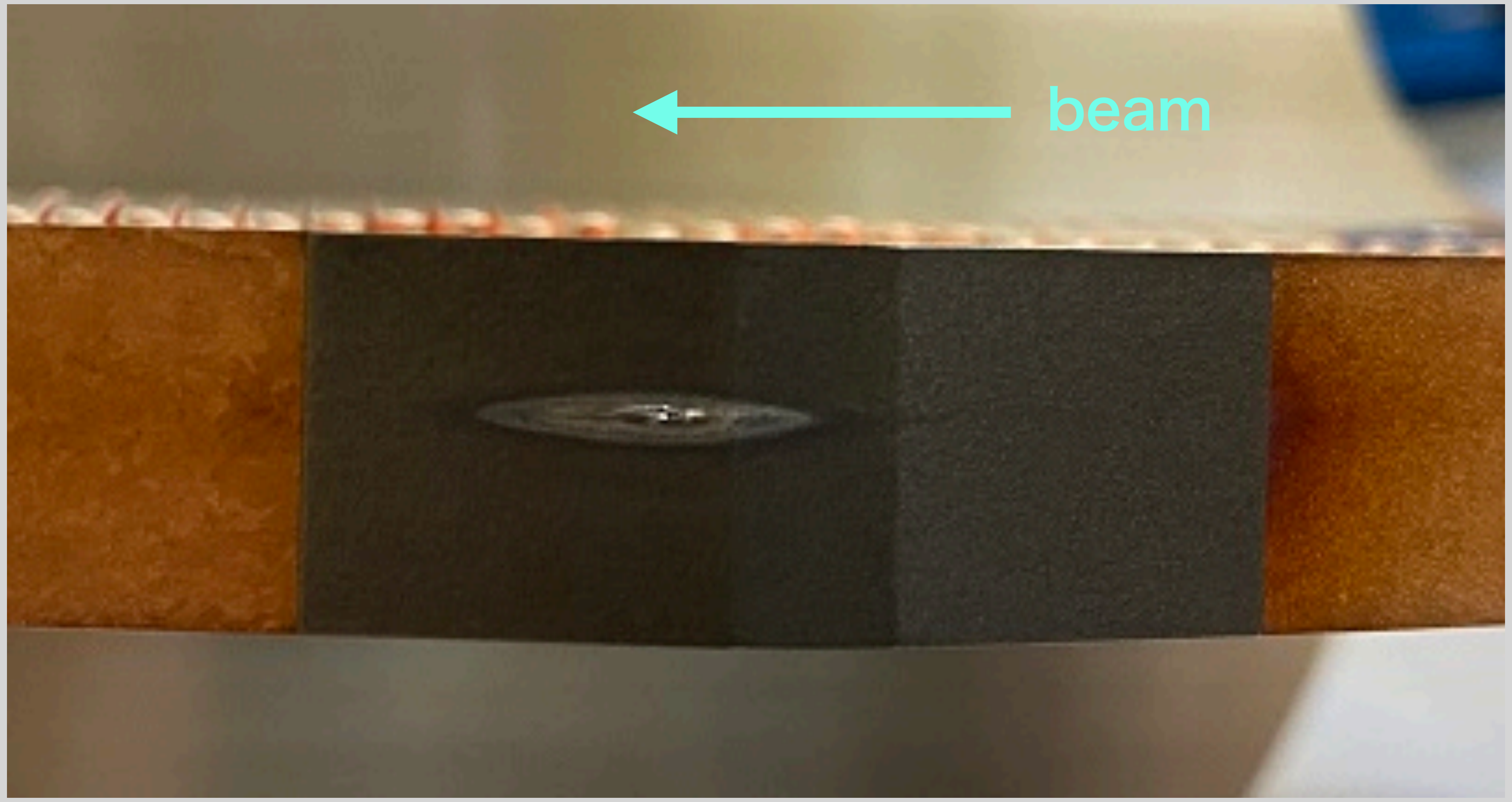


3rd turn before no beam **2nd turn before no beam**

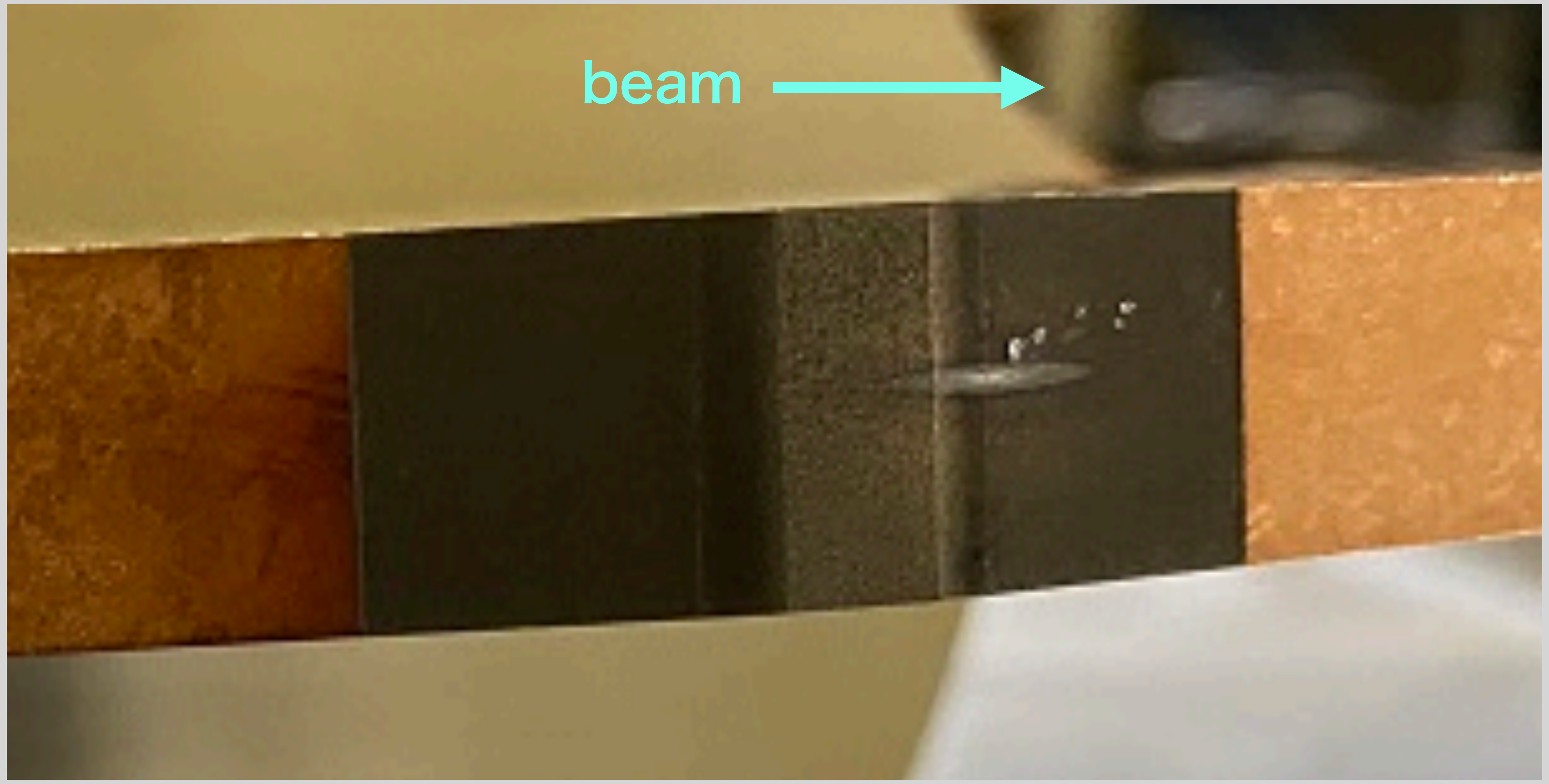
Bunch oscillation monitor (horizontal)

Experience -Short Tip

- After the damaged accident, the background level became higher.
    - horizontal orbit bump
    - horizontally shift the collimator
    - replace them to new ones during shutdown
- We developed a tantalum tip with a short length (5 mm).
- This jaw was also damaged during 2020 Spring run, however we didn’t observe the background growth (we didn’t notice that until we opened the collimator chamber for a carbon jaws’ installation work).
- We didn’t observe any embrittlement on the damaged tip (In a way, good news).



top side jaw



bottom side jaw

Tantalum jaw with 5 mm length

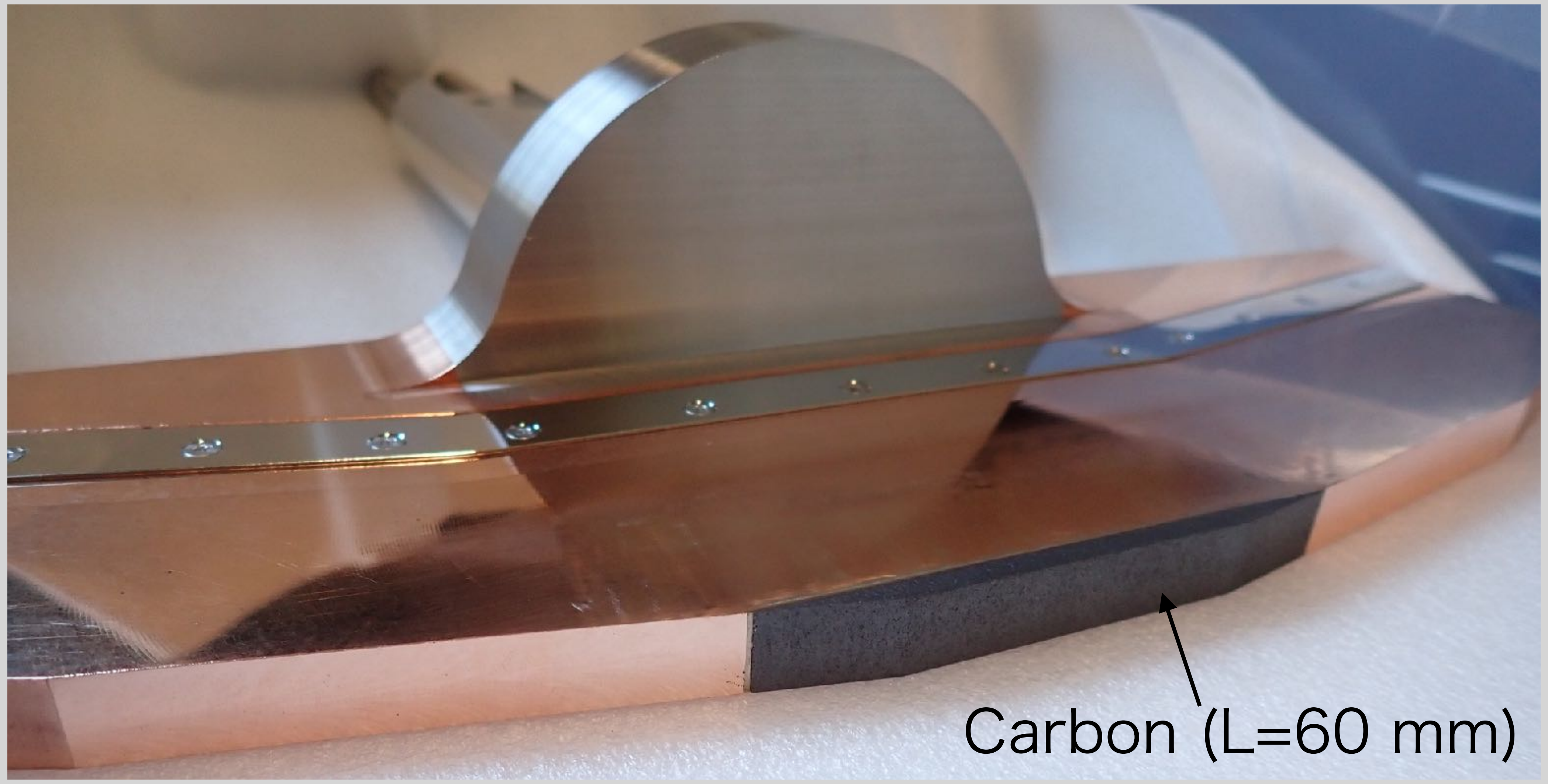
Low-Z collimator

- Materials with a short radiation length is very effective as a beam tail shield, however the beam loss is localized and the temperature of that exceeds the melting point.
- In order to protect the collimators for BG suppression from abnormal beams, we developed a collimator with carbon*.

* Glass like carbon coated and impregnated C/C composite (GCX2002-U_GP2B, Toyo Tanso Co.,Ltd.).

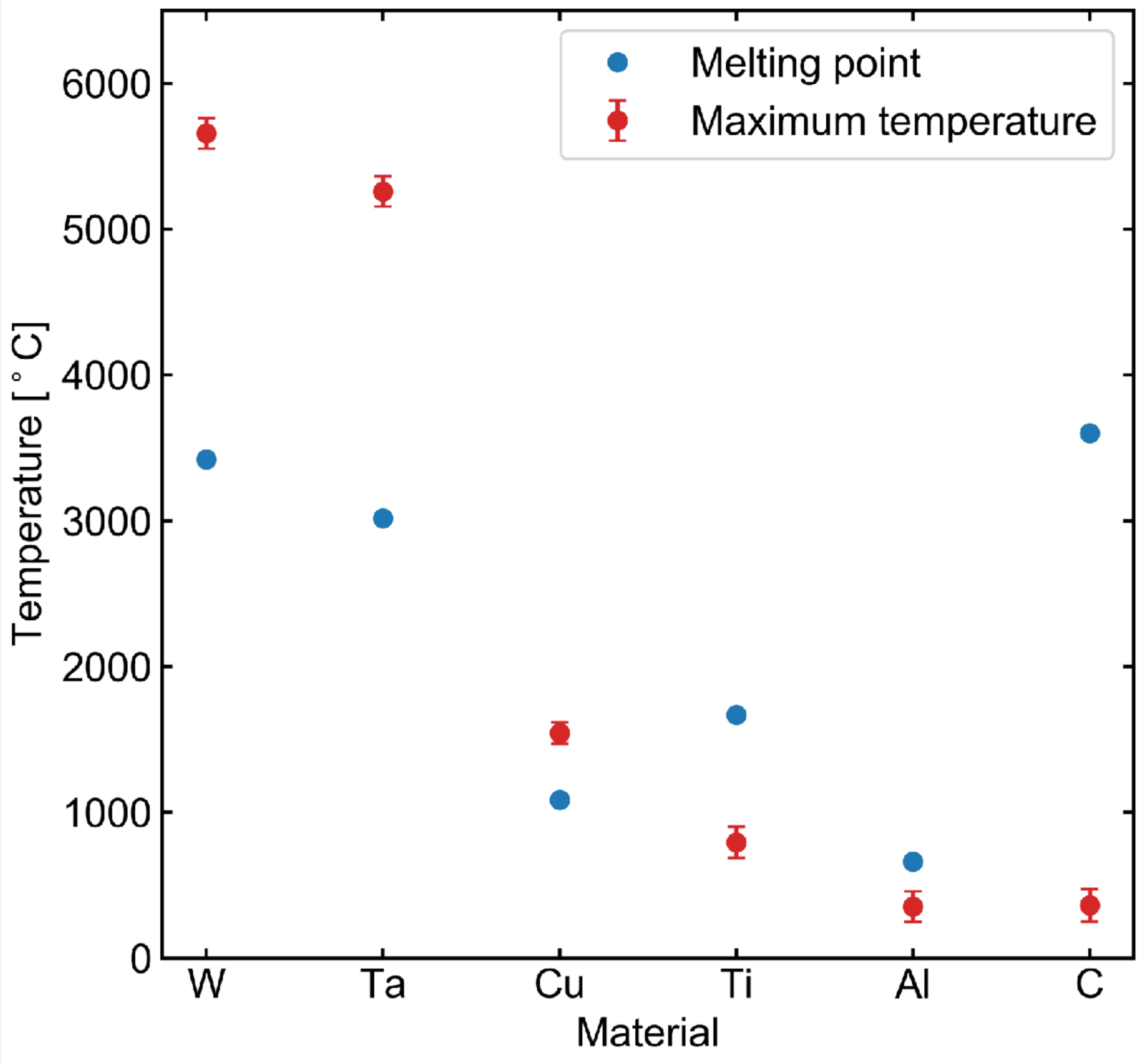
  - Tested: bonding test, tensile test, impregnation/coating test for dust and outgassing reduction, RF absorbing test(2.45 GHz, 5.04 GHz), radiation degradation

- Installed in a existing collimator (D06V1) during this summer shutdown.



Carbon Jaw installed in D06V1.

Maximum temperatures within 1 RL and melting points (e+, 4 GeV. D: 0.5 mm, 50 mA, FLUKA).



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

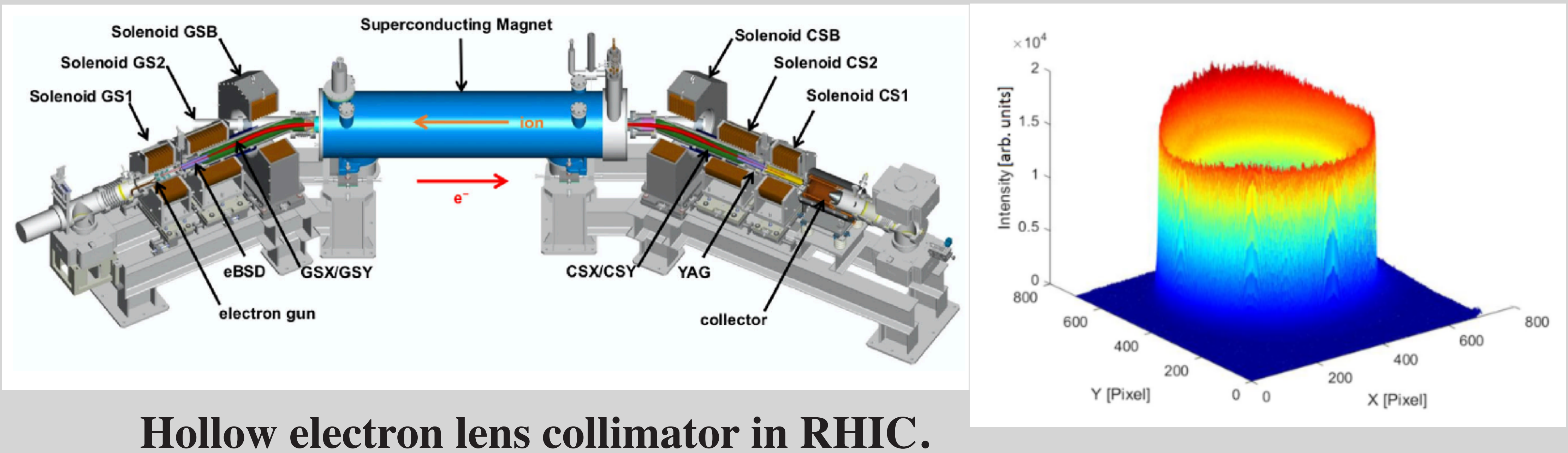
Summary

- The SuperKEKB type collimators have been working well up to the beam current of approximately 1 A.
- These collimators have been indispensable for Belle II and SuperKEKB.
- We developed and installed carbon jaws to protect collimators for the BG suppression.

Future plans

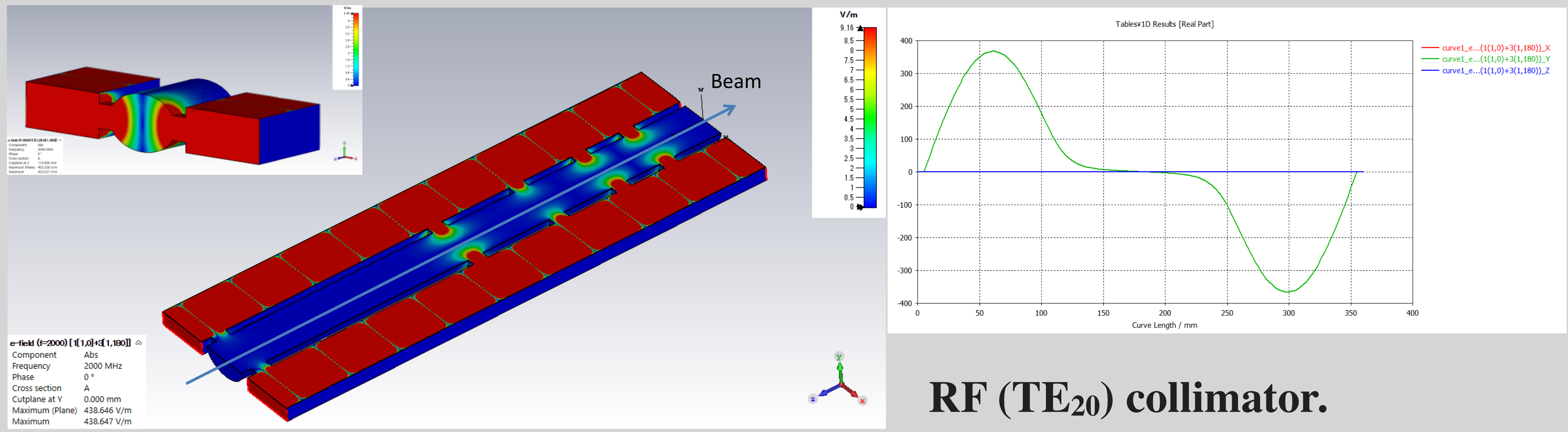
- We'll test the newly installed collimator (D03V1) and the carbon collimator (D06V1) during 2020c.
- We keep investigating a soundness for the installed collimators in high beam current.
- We've just stated studying alternative collimators to open the aperture of the existing collimators.
  - Electron seat beam collimator (referenced electron hollow lens collimator in RHIC)
  - RF collimator

[X. Gu et al., PRAB **23**, 031001 (2020)]



Hollow electron lens collimator in RHIC.

[K. Watanabe(KEK)]



RF (TE_{20}) collimator.

backup

Low-Z collimator

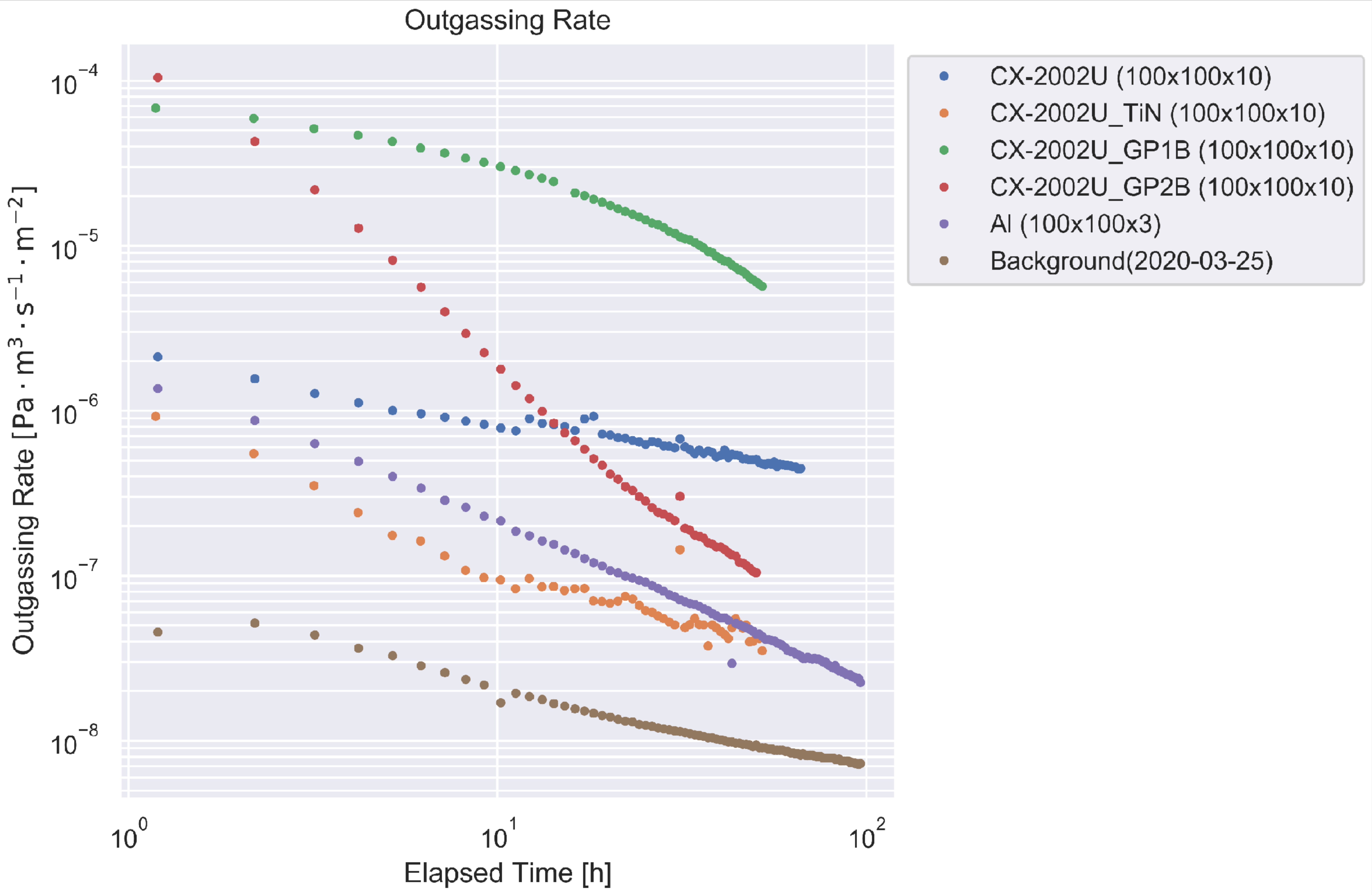
- Feasibility of titanium for the collimator had been already checked in KEKB.
- We've started checking the feasibility for a C/C composite material.

	Electrical conductivity [μΩ m]	Thermal conductivity [W m^{-1} K^{-1}]	Density [g cm^{-3}]	Melting point [℃]	Radiation length [mm]	Tensile strength [MPa]	Bondability	Outgassing	Dust generation
C/C composite*	2.7, 3.4, 5.1 (x, y, z)	390, 320, 190 (x, y, z)	1.65	3800	approx. 200	35, 30, 11 (x, y, z)	OK	Low	High
Titanium	0.42	21.9	4.5	1663	35.6	350	OK	Low	Low
Tantalum	0.131	57.5	16.65	2985	4.0	200	OK	Low	Low
Tungsten	0.528	173	19.25	3422	3.5	>800	OK	Low	Low
Diamond	$>10^{16}$	2000-2300	3.5	(2000)	120	1000	TBC	Low	Low

*** CX2002-U (carbon fiber felt), Toyo Tanso Co.,Ltd.**

Low-Z collimator

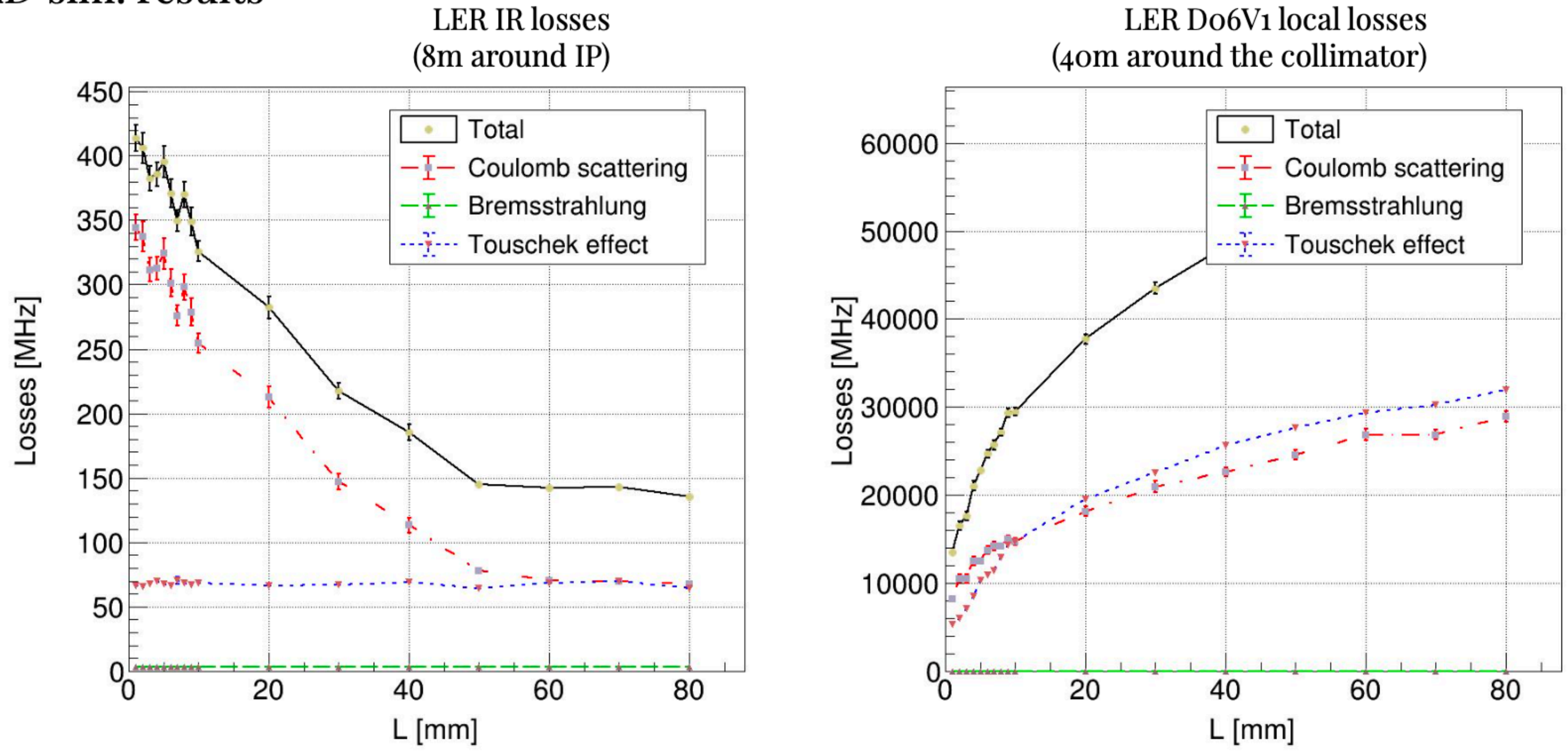
- Samples were baked with 250 ℃ for approximately 24 hours.



Low-Z collimator

[Andrii Natochii (Univ. of Hawaii) et al.]

LER D06V1 *SAD* sim. results



- We expect the same IR BG level with L_Z = 60mm for Graphite head compared to Tantalum with L_Z = 5mm.
- Changing the length of the tip-part of the collimator head:
  - Reduction of the IR losses:
    - 50mm < L_Z < 80mm is a flat total IR losses behaviour.
    - 1mm < L_Z < 50mm is almost linear dependence of the Coulomb IR losses.
  - Increase of the local beam losses due to the absorption/collimation of stray particles and tip-scattering.
- Absorbed particle rate by the mask ~ length of the tip-part within a given range.
- Graphite radiation length (*RL*) = 19.32 cm