SuperKEKB collimation system

IAS Program on HEP 2022

2021-07-01

Mini-workshop: Accelerator Physics

Key Beam Physics and Technologies Issues for Colliders

Day 1 - Session 3 (MW-AP-D1-S3)

KEK Accelerator Laboratory

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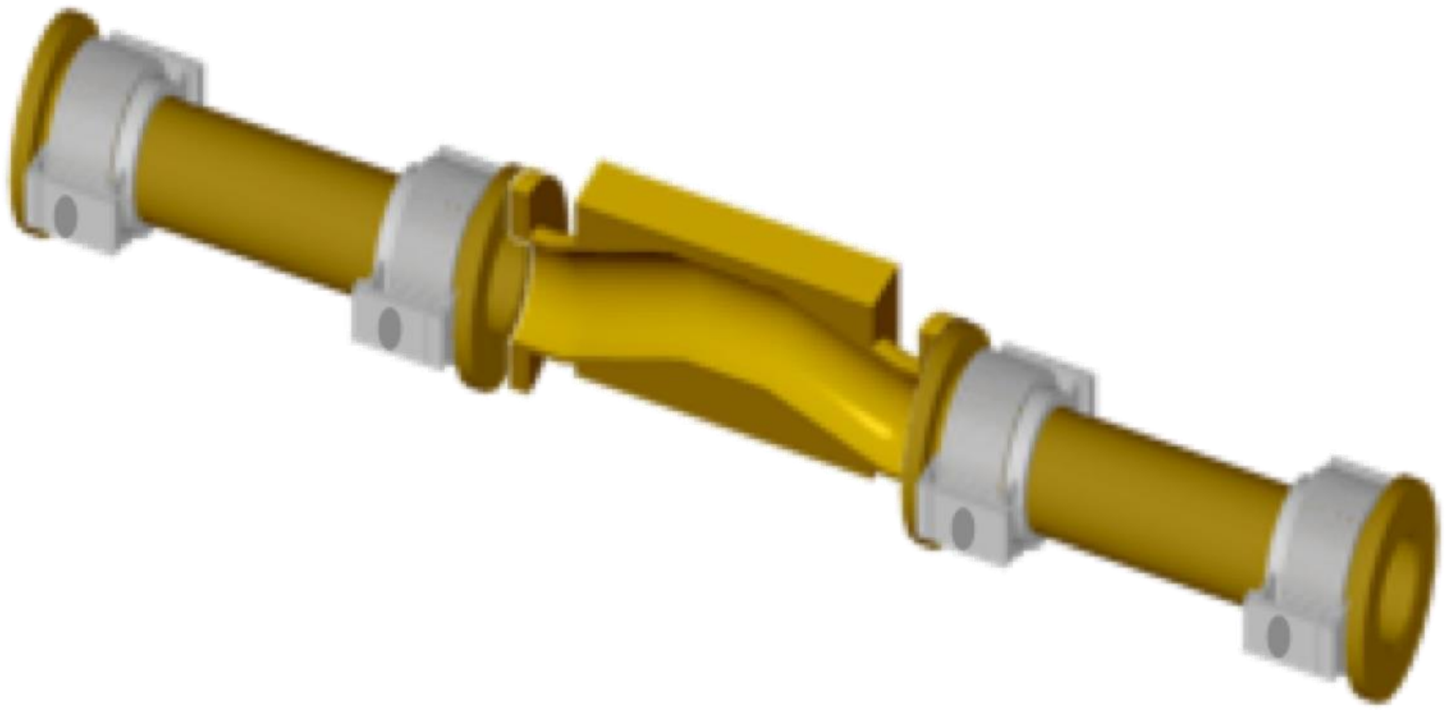
on behalf of KEKB Vacuum Group

Contents

Beam collimators in SuperKEKB

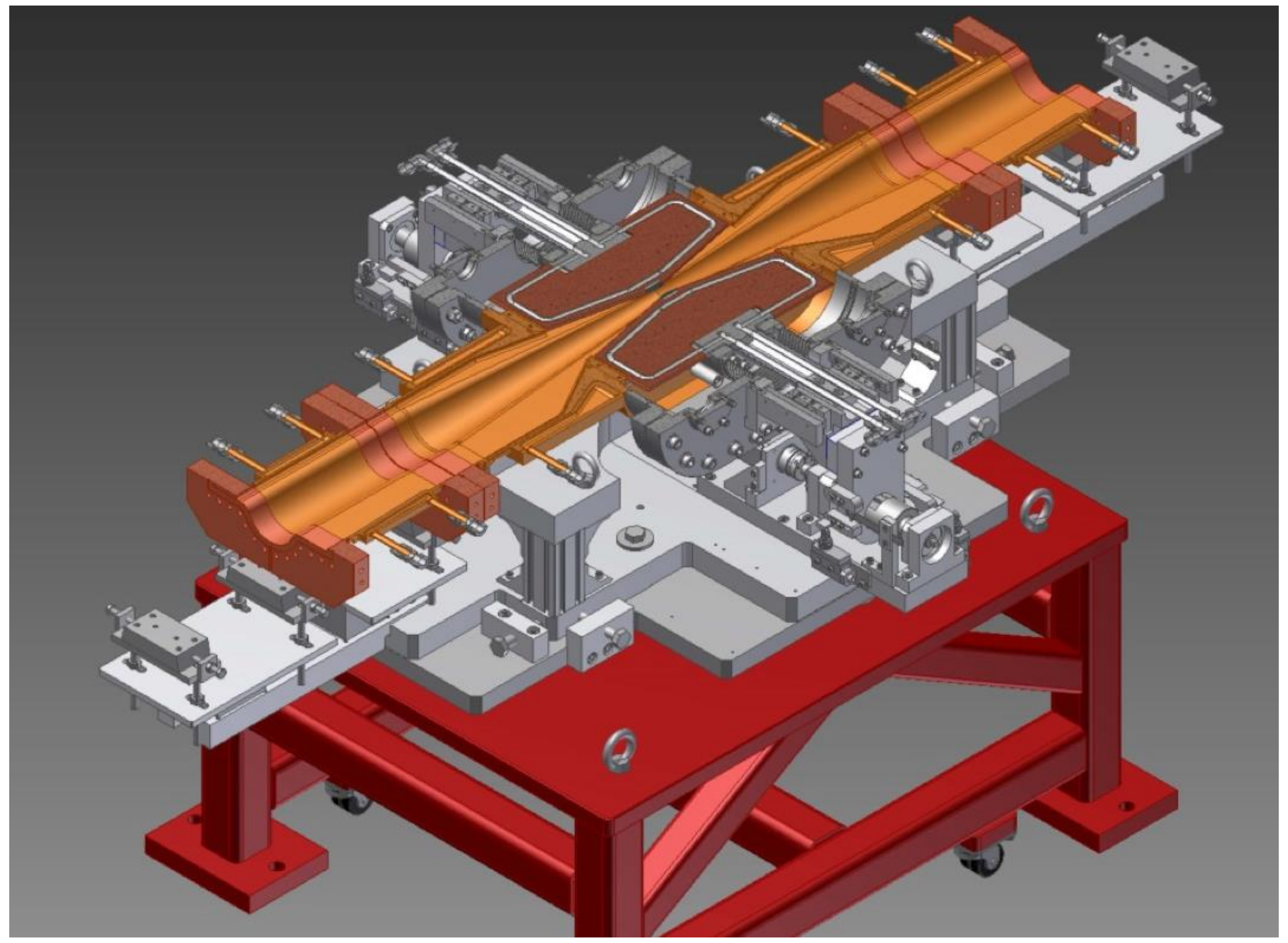
- There are two types of collimators in SuperKEKB MR.
  - ➢KEKB type: Tapered chamber itself approaches the beam. The tip is made of Cu coated titanium.
  - ➢SuperKEKB type: A chamber has two movable jaws, and they approaches the beam.

- 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.



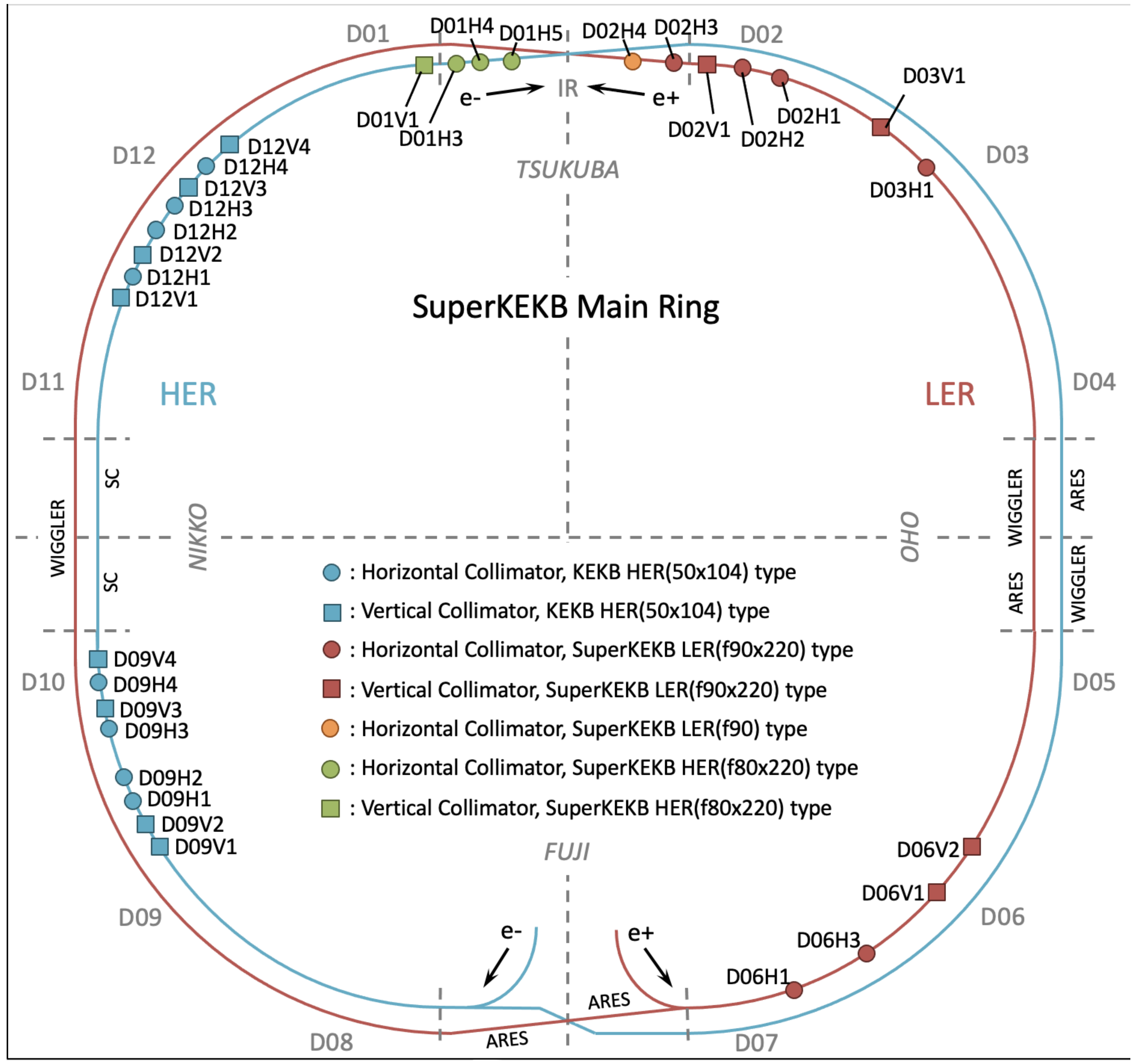
KEKB type

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



SuperKEKB type

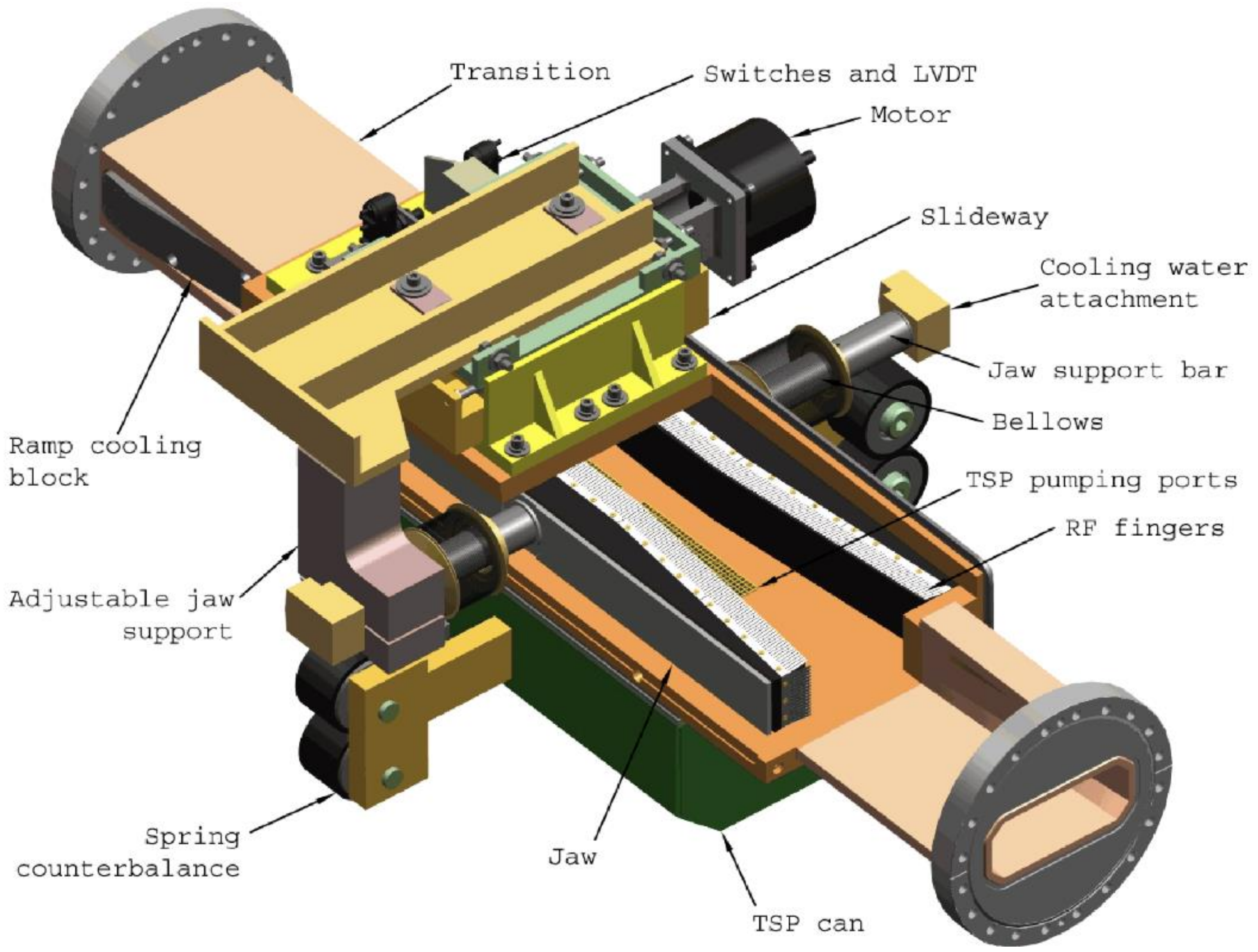
[T. Ishibashi et al., PRAB 23, 053501 (2020)]



Location of collimators in MR

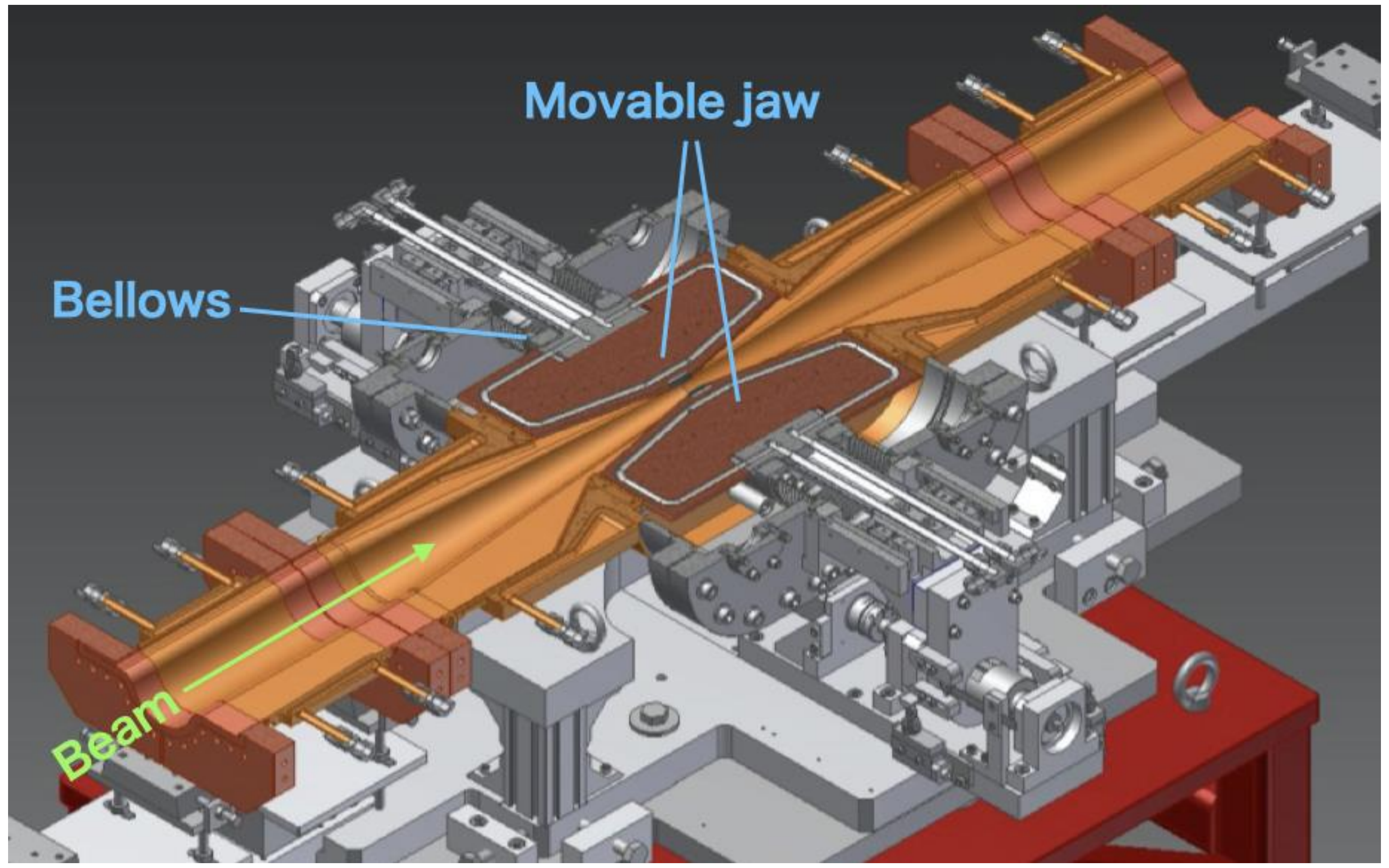
Design

- 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.), and carbon (low-Z, special ver.).

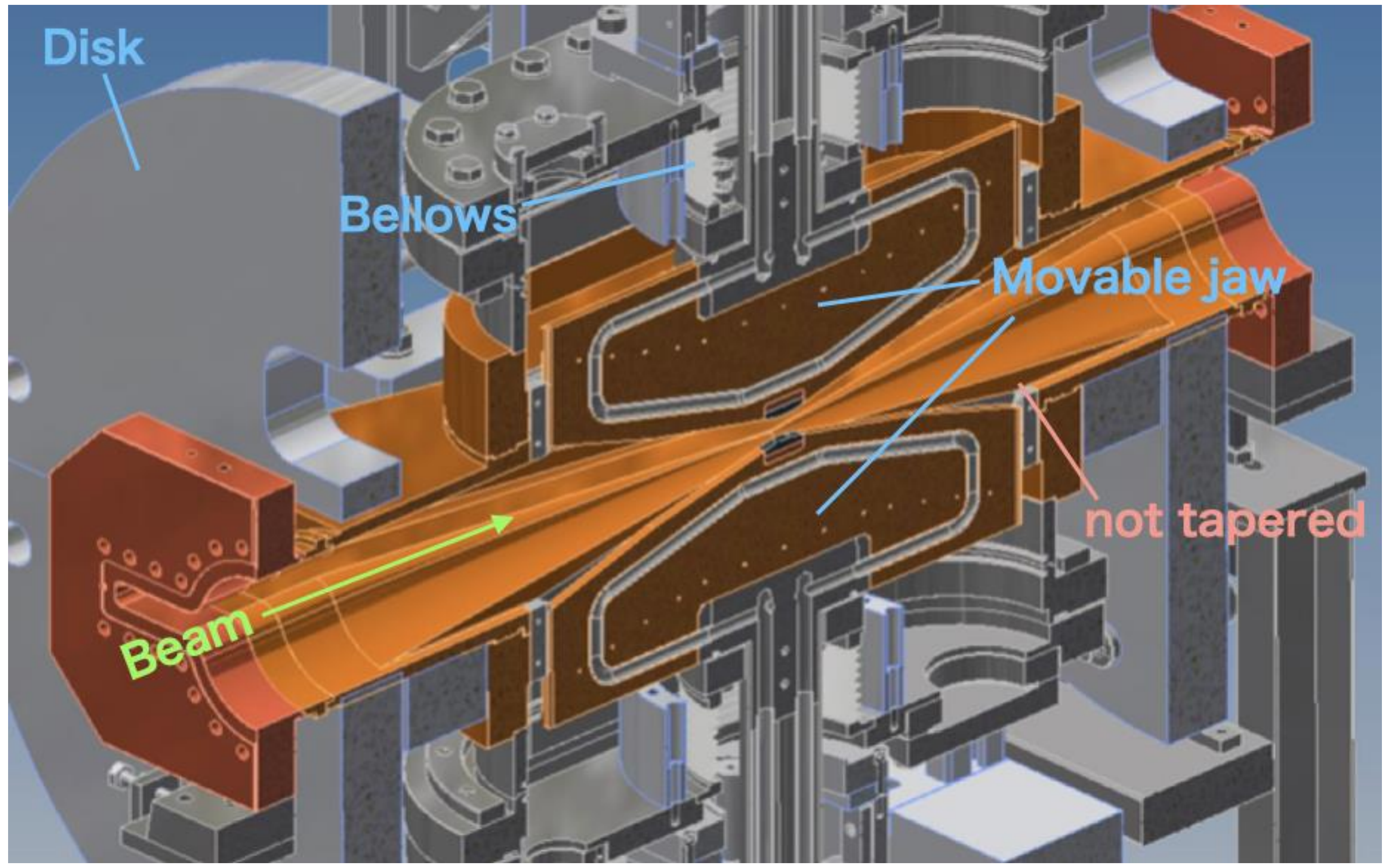


Collimator in PEP-II

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



Horizontal direction

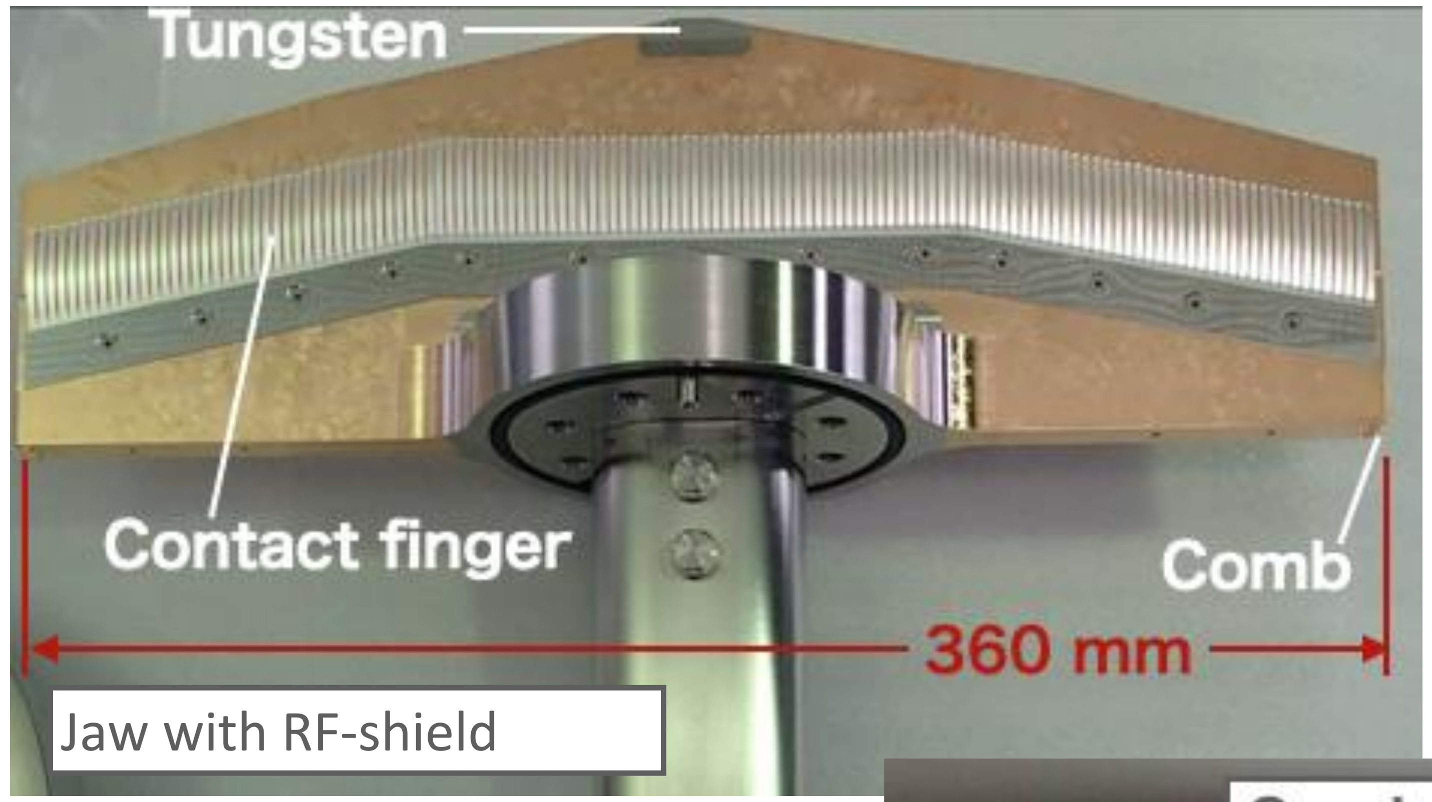


Vertical direction

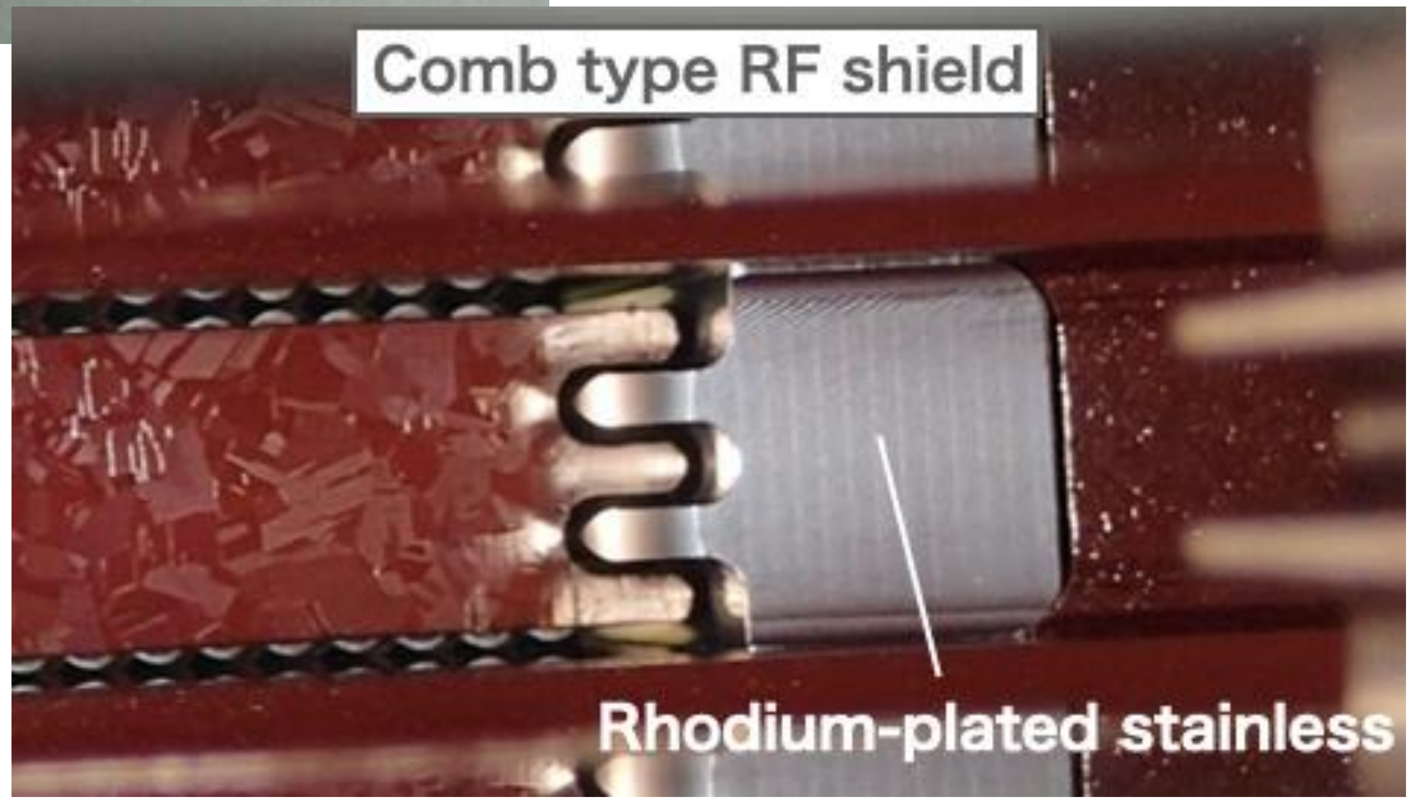
SuperKEKB type collimator

Design - RF shield

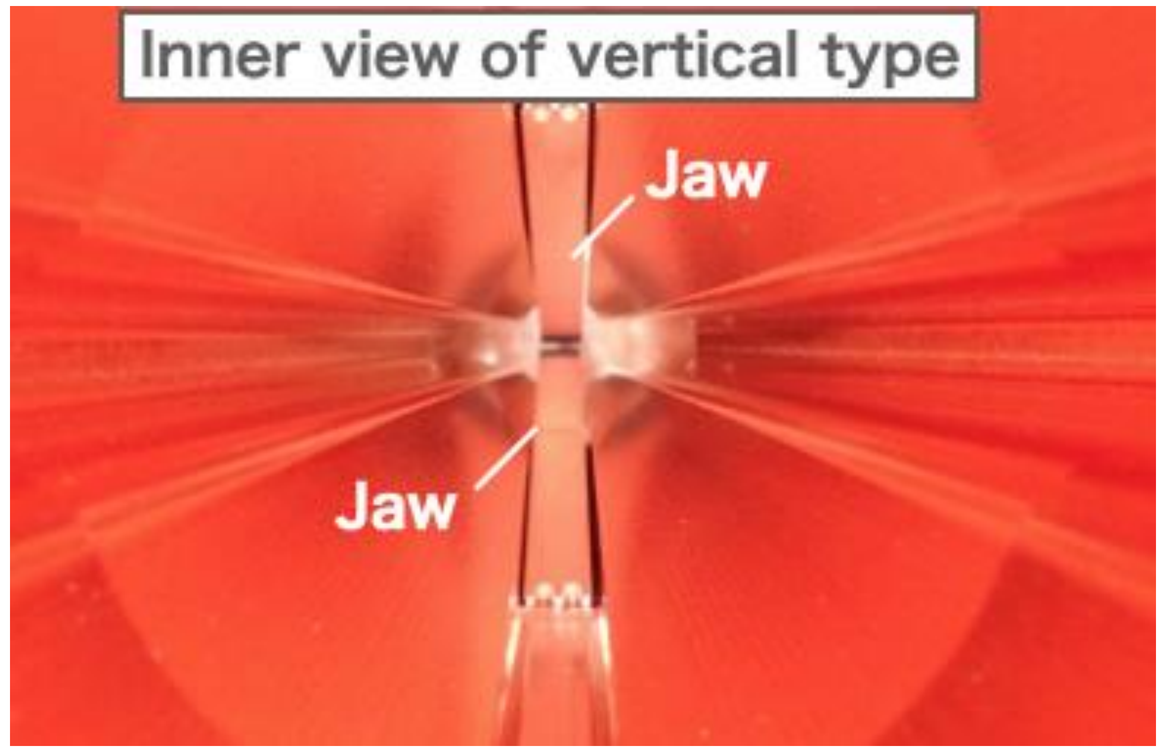
- Contact finger-type RF shield is attached on the side wall of each jaw.
  - The fingers are made of silver-plated INCONEL.
  - The contact surface on the chamber is made of rhodium-plated stainless steel.
- Contact-less comb-type RF shield is adopted between the longitudinal end of the jaw and the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



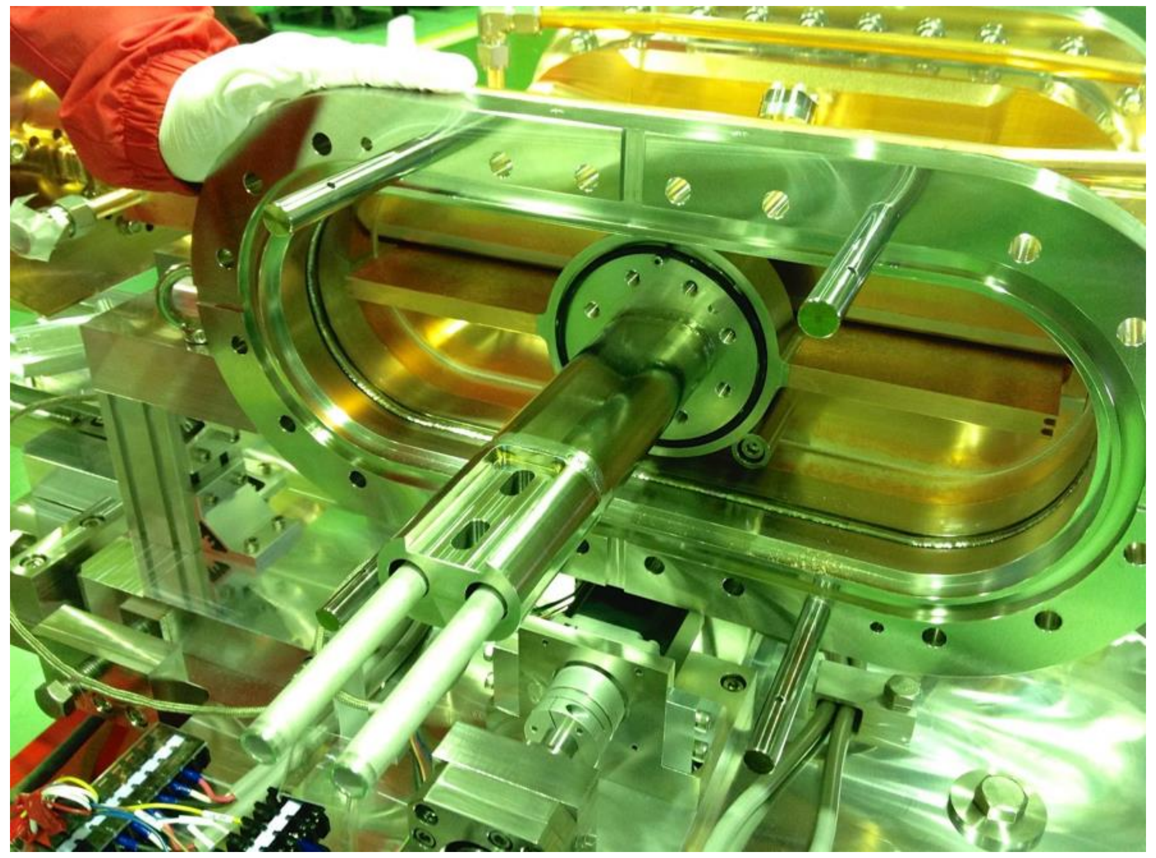
Jaw with RF-shield

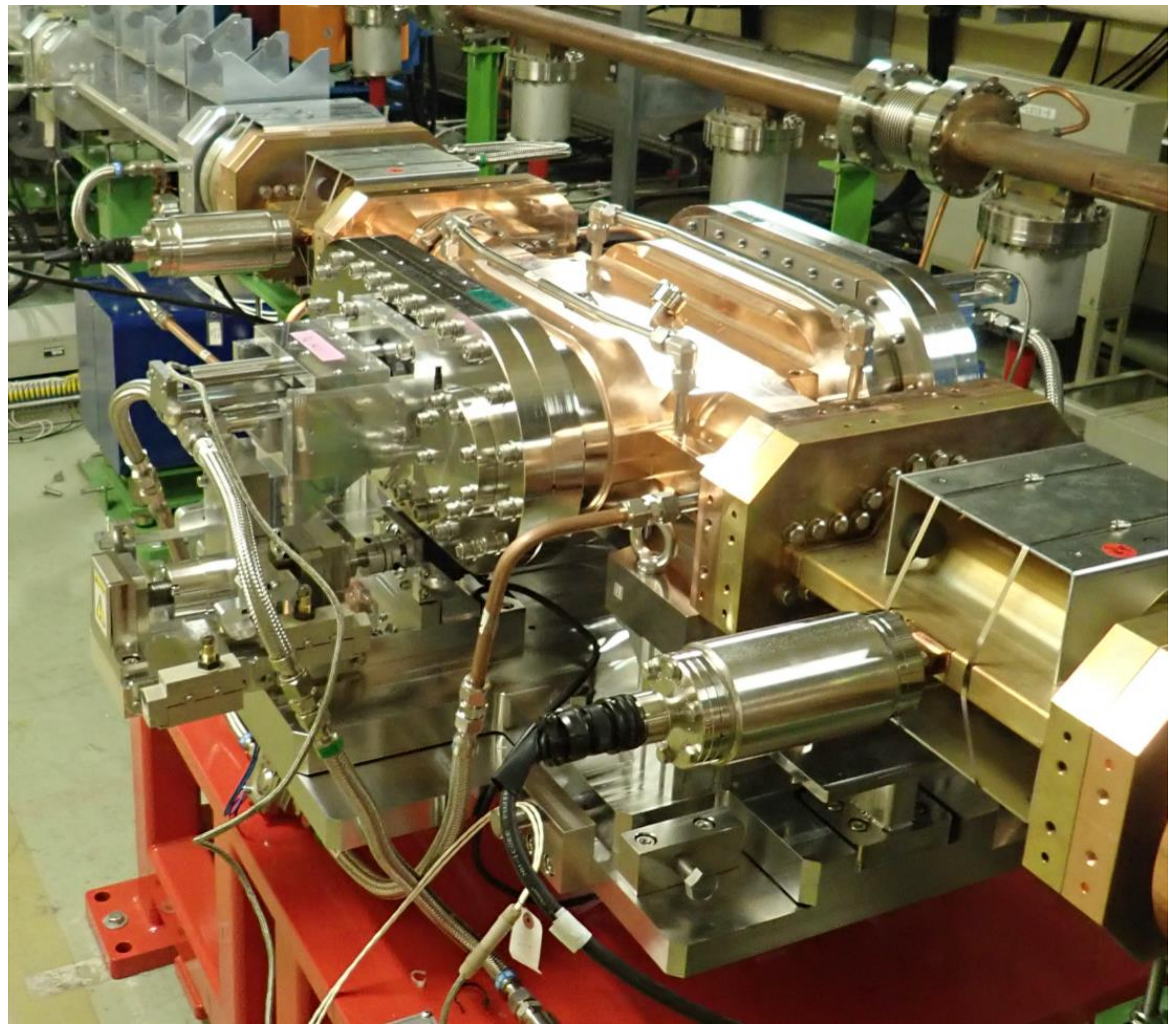


Comb type RF shield



Inner view of vertical type





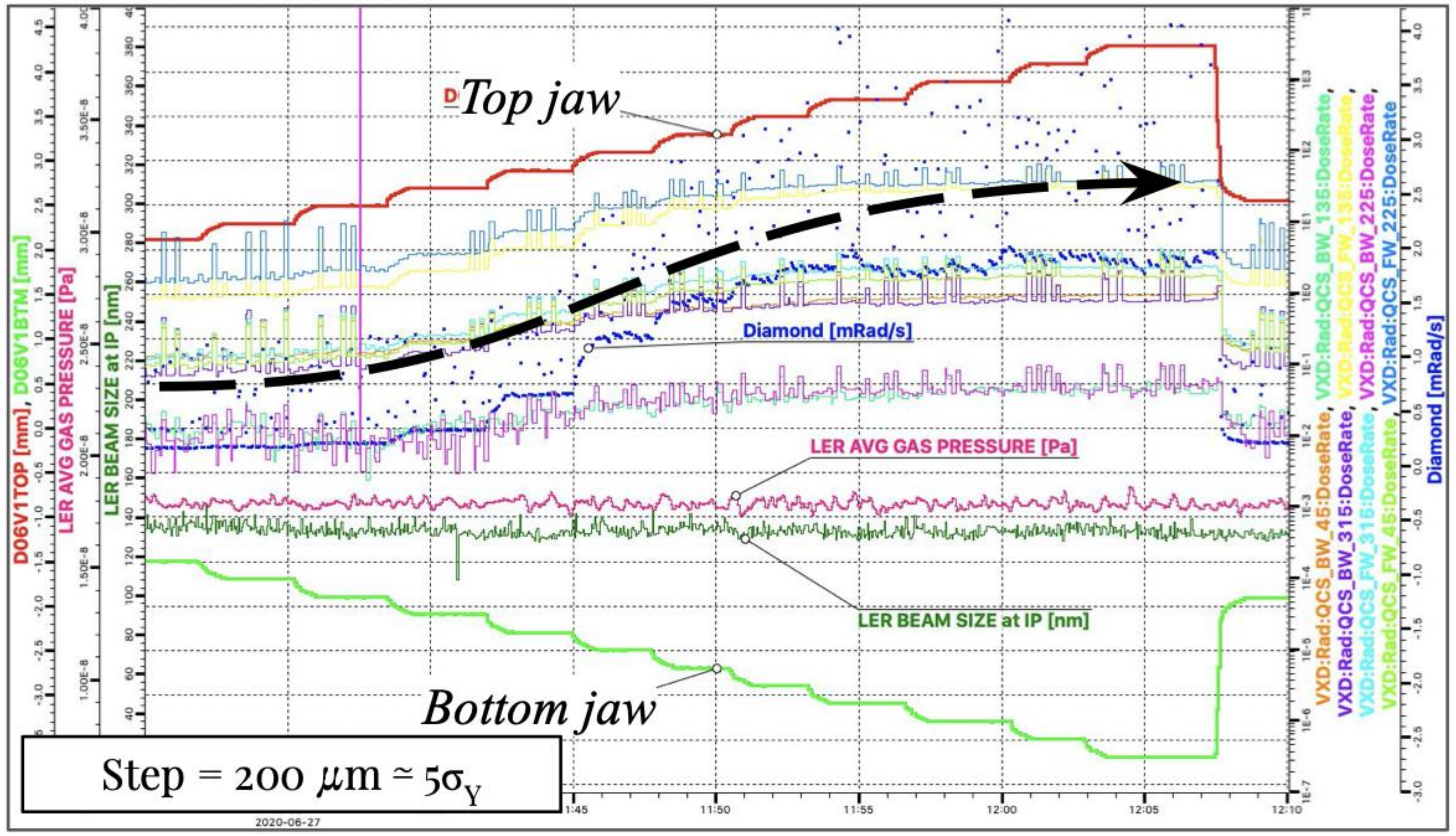
Experience - BG suppression

- The SuperKEKB type collimators have been working well up to the beam current of 1.02 A in LER.
- These collimators have been indispensable for Belle II and SuperKEKB.

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

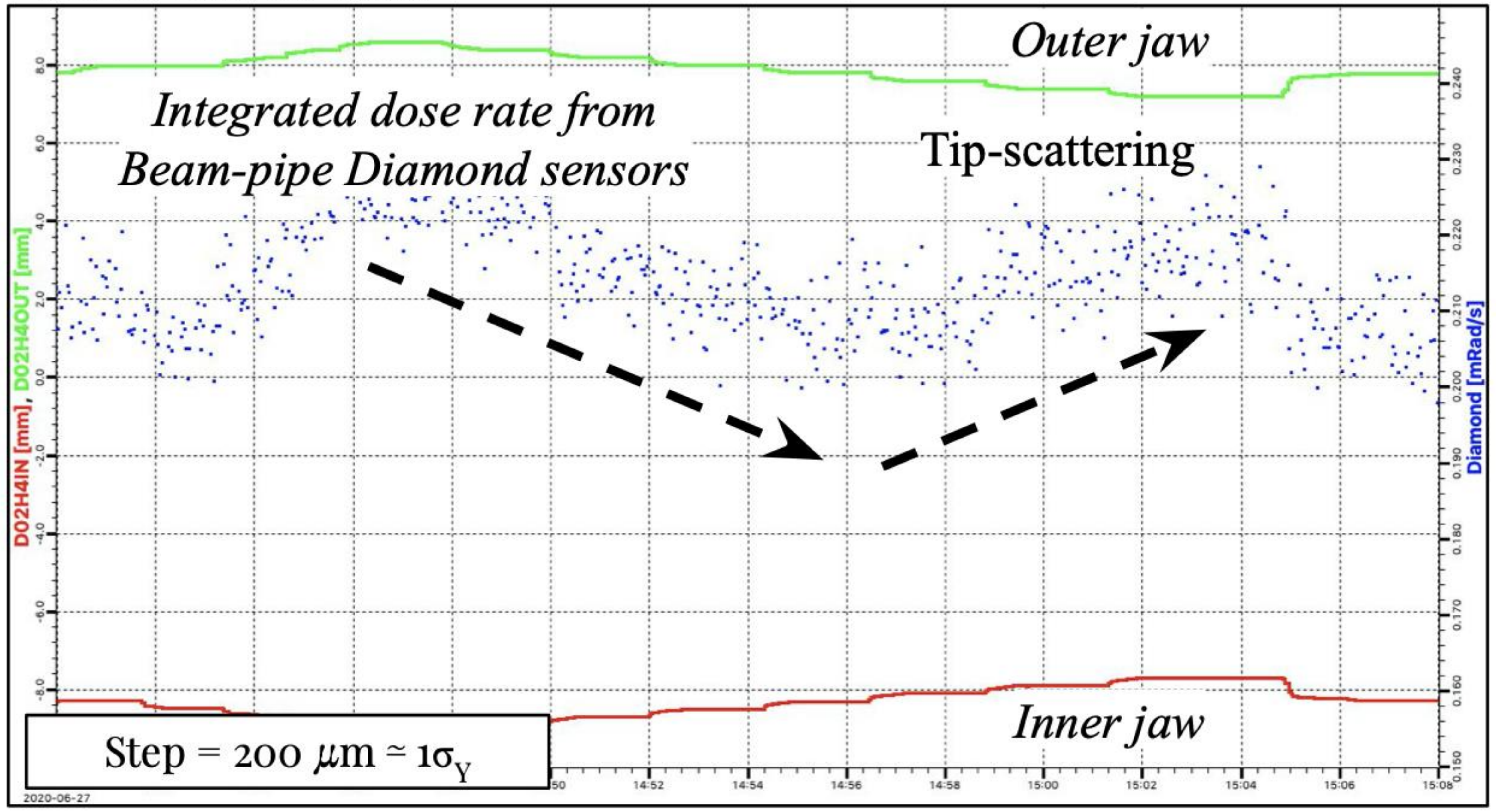
Machine settings: LER ring, $\beta^*_{X/Y}$ = 60/0.8mm , CW = 80%, **I = 200 mA, Continuous injection**, Rep = 12.5Hz, Nb = 978
Detector settings: Belle II HV → OFF, **Diamond sensors** only

D06V1 linear scan



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

D02H4 linear scan

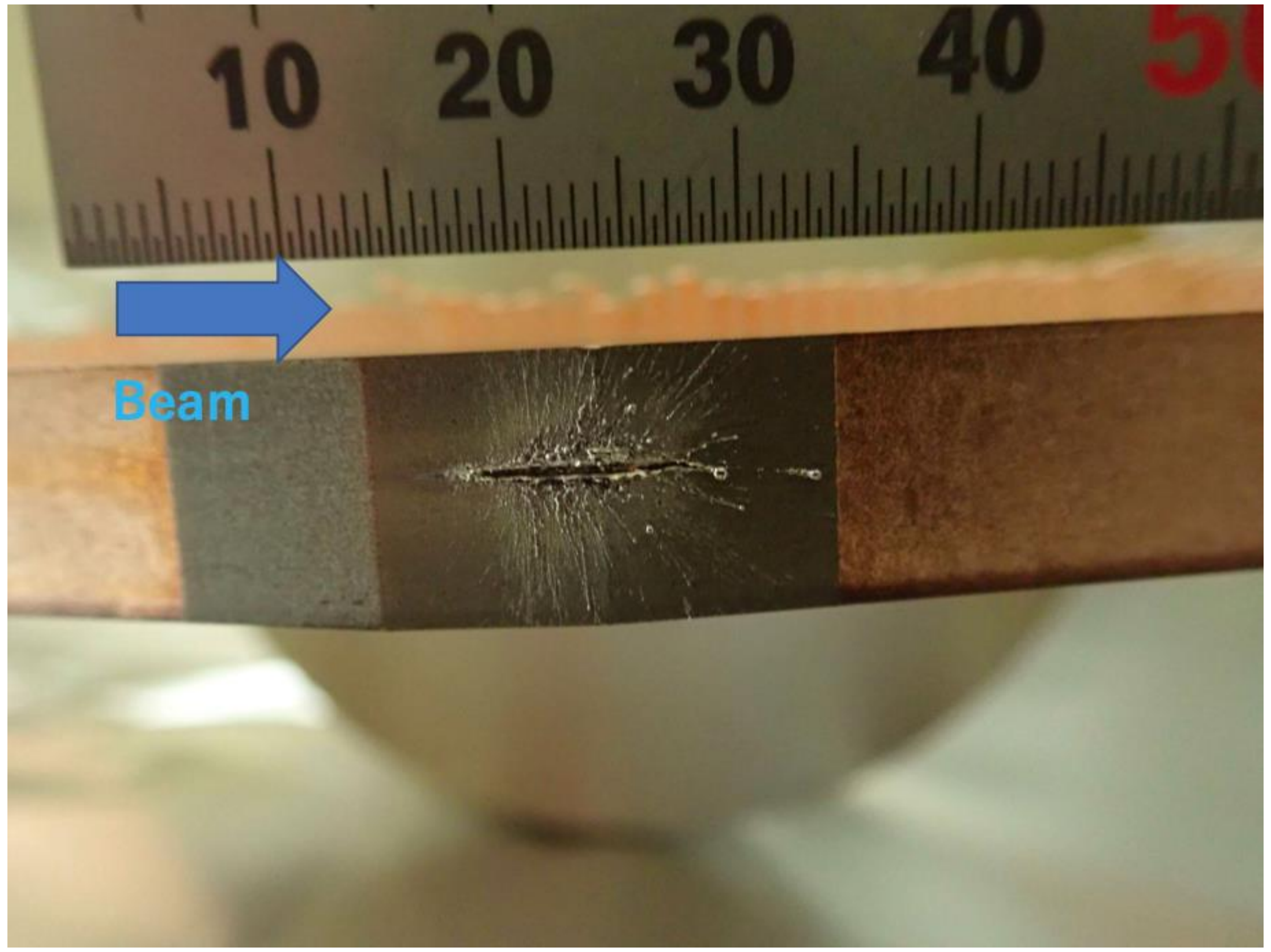


Closing the LER H-collimator we observe an increase of the IR background rate → tip-scattering.

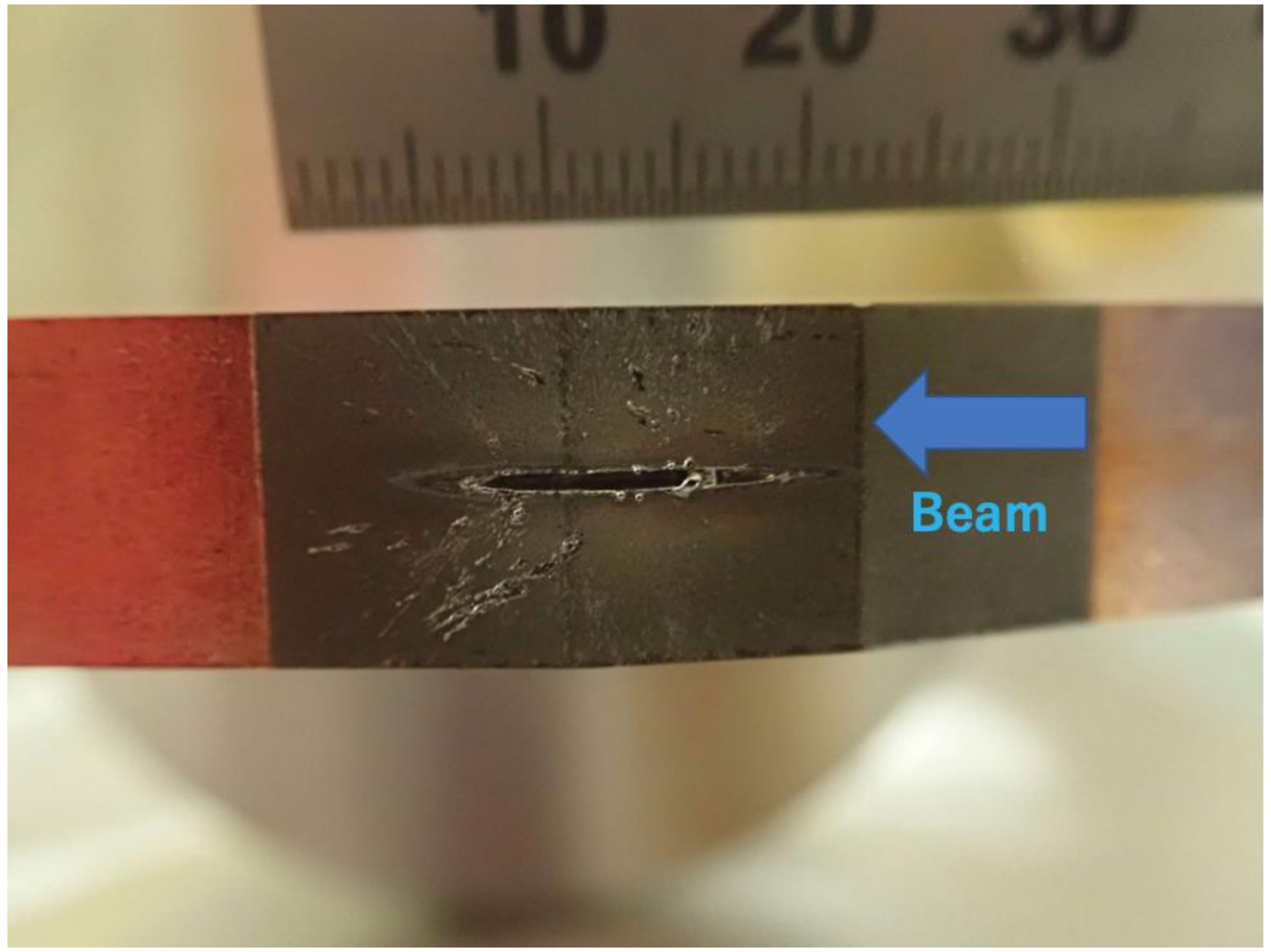
Experience - Damage

* short tantalum tip which has 5 mm.

- Jaws of vertical collimators were damaged by beam hit.
  - LER: D02V1 (2021ab), D06V1(2021ab)*, D06V1 (2020ab)*, D06V2 (2019c), D02V1 (2019ab), D02V1 (Phase-2)
  - HER: D01V1 (Phase-2)
- A huge beam loss and pressure burst has happened near them with a QCS quench .
- The damaged tungsten tip has embrittled. For the tantalum tip, it did not embrittle.
- The cause is unknown. A candidate is an interaction between the beam and a dust in the beam pipes.
- The damaged jaws of D02V1 were replaced once during 2020c and 2021b because of the high BG level.



D02V1 bottom side (38 μSv/h)



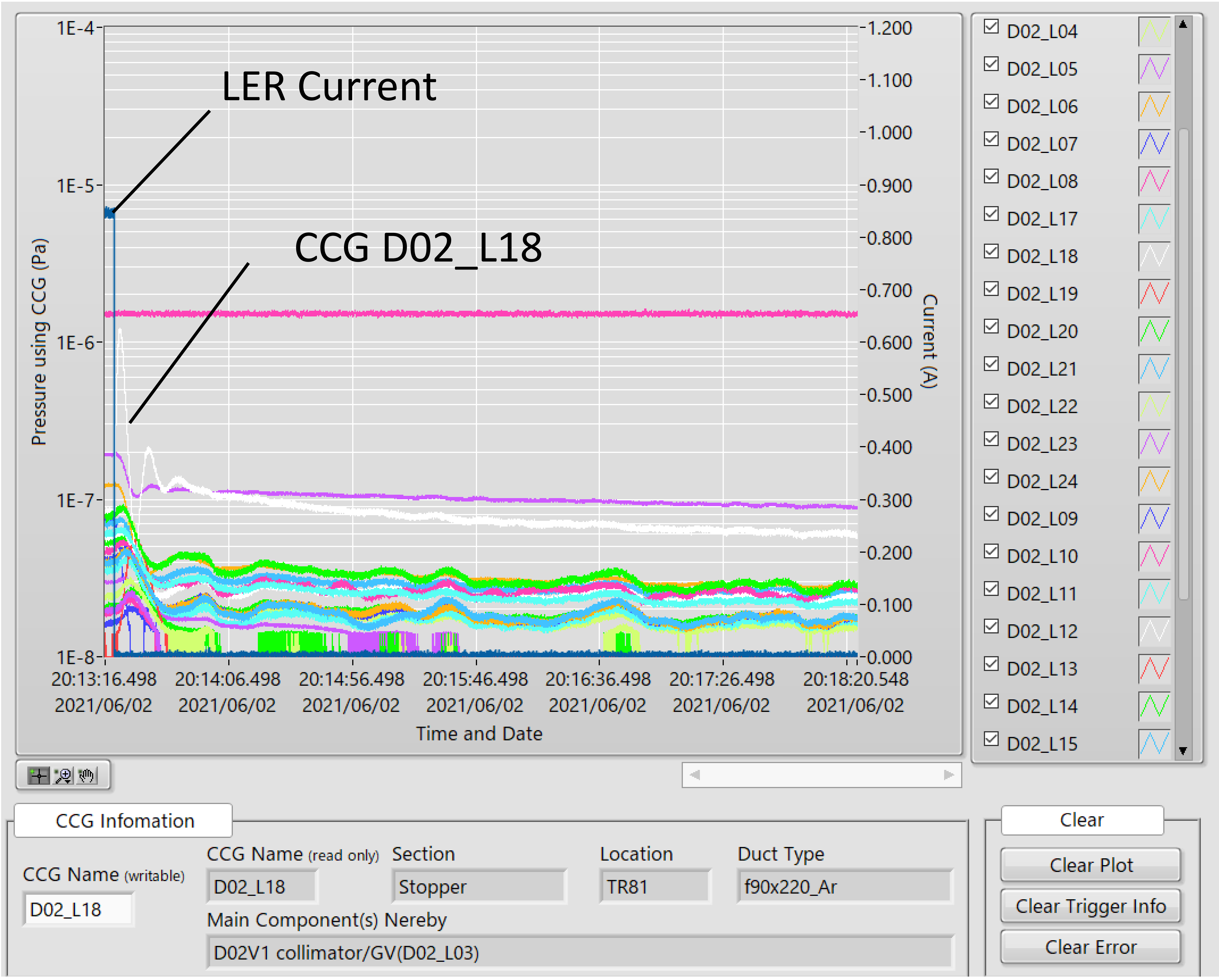
D02V1 top side (95 μSv/h)

Replacement work in the presence of Radiation Science Center.

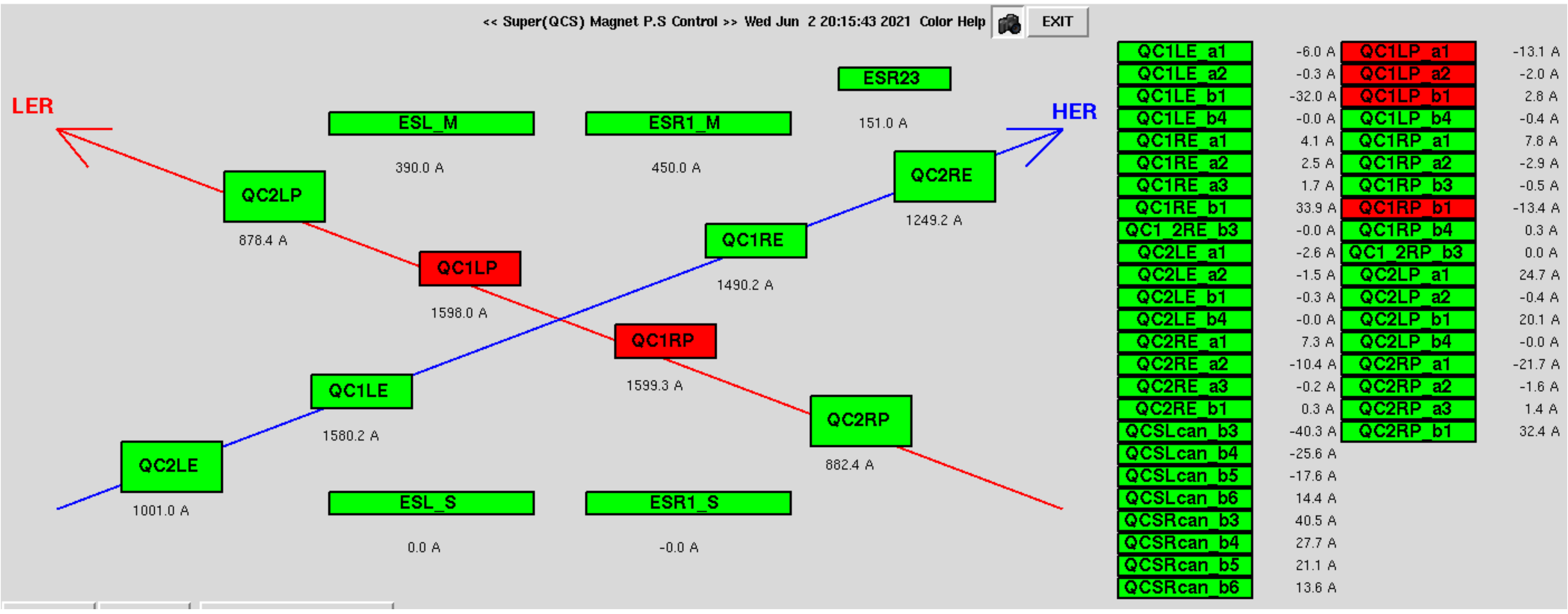
Experience - Damage

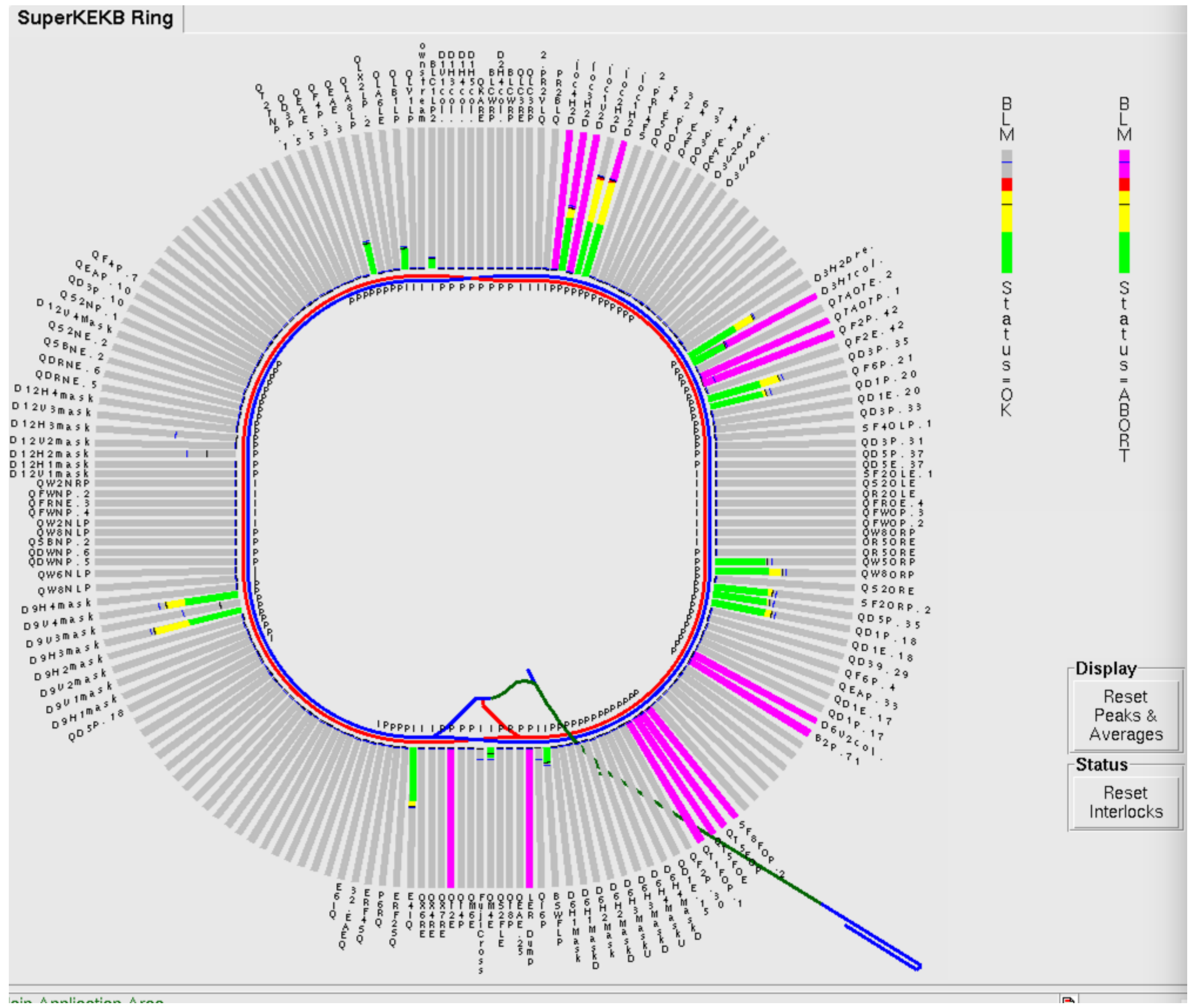
- In case of a damaged event in 2021-06-02 20:13 (2021b run).
- Pressure near CCG D02_L18 and D06_L12, which are placed near D02V1 and D06V1 collimator respectively, was increased instantaneously (beam hit the jaws probably).
- QCS quench happened (QC1LP, QC1RP in LER).

Pressure and beam current



Status of QCS

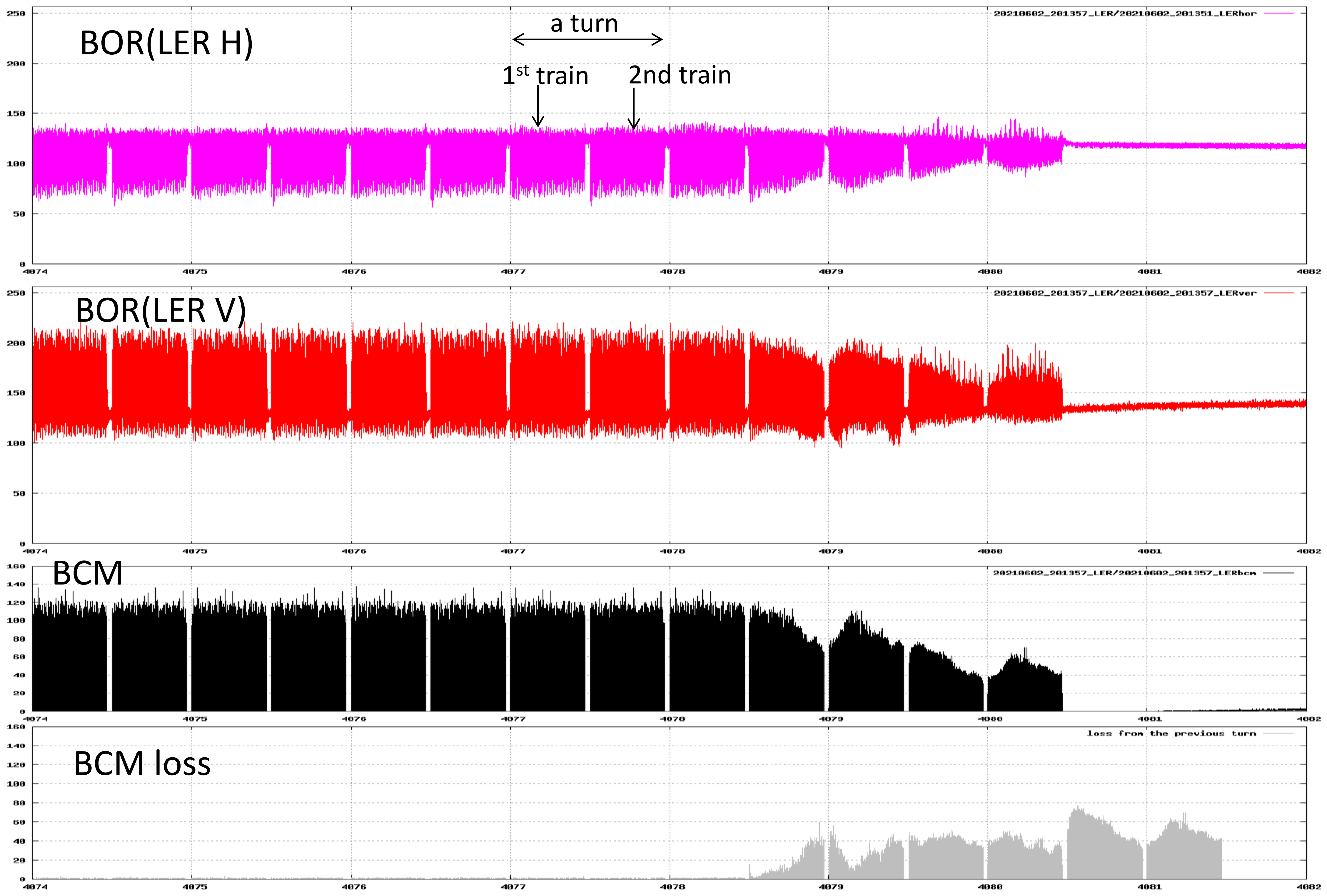




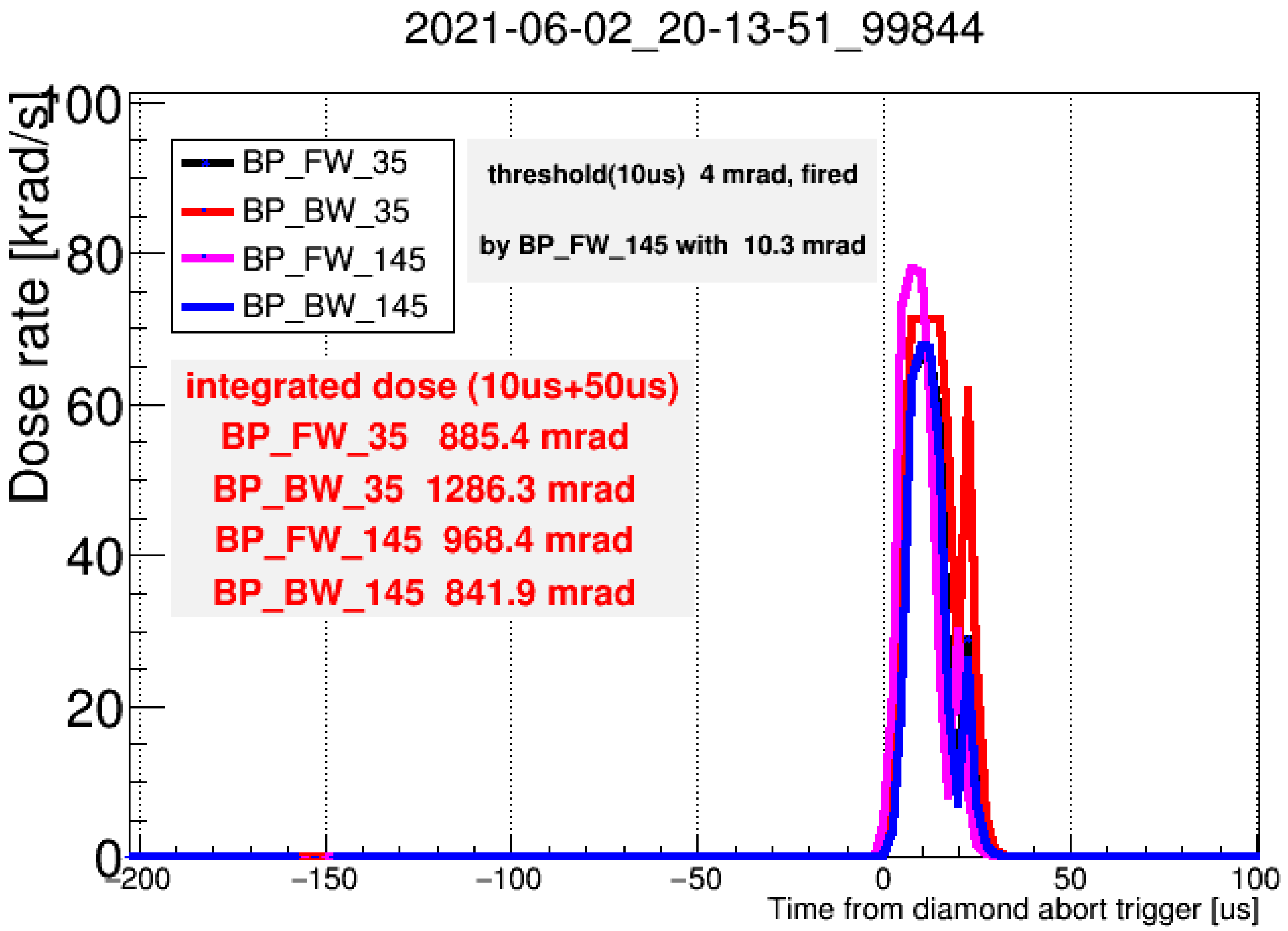
Loss monitors in the rings

Experience - Damage

- Sudden beam loss happened within 2-turn before the beam abort.
- Dose on VXD diamond sensors of Belle II were extremely high and the signal saturated (usual beam loss abort: ~50 mRad or less).
- The cause of the huge beam loss is unknown so far. One of the candidates is the interaction between the beam and a dust in the beam pipe.
  - Results of simulations indicate that the beam loses at not the vertical collimators but the horizontal collimators mainly [Y. Funakoshi].



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

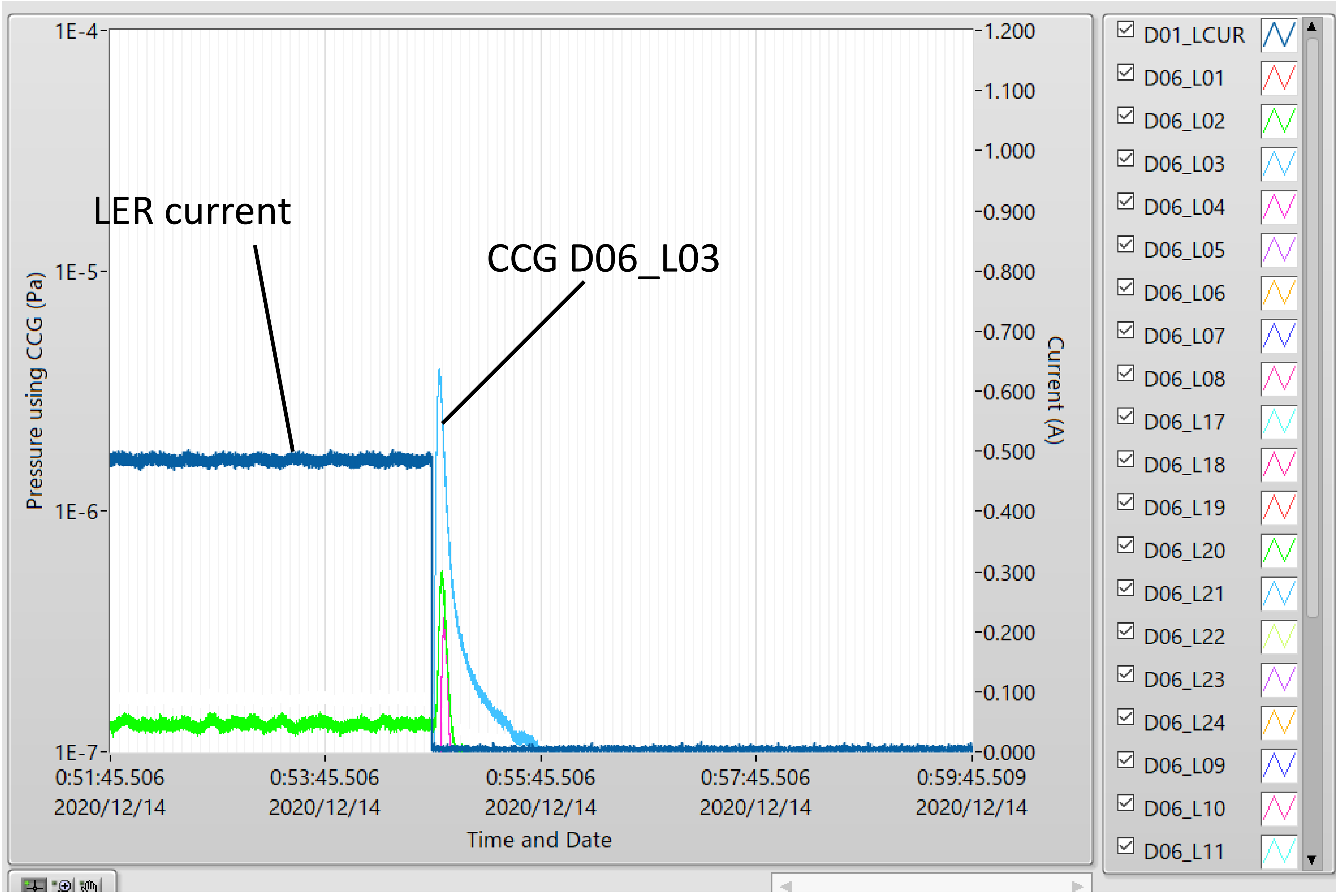


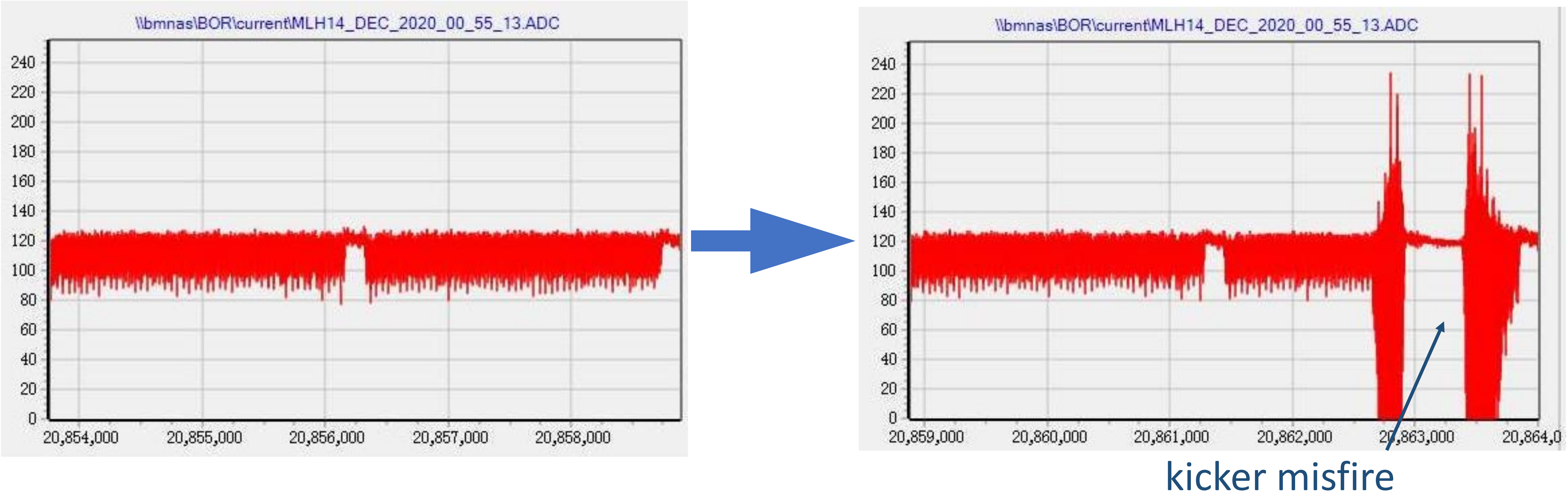
Dose in VXD diamond sensors of Belle II

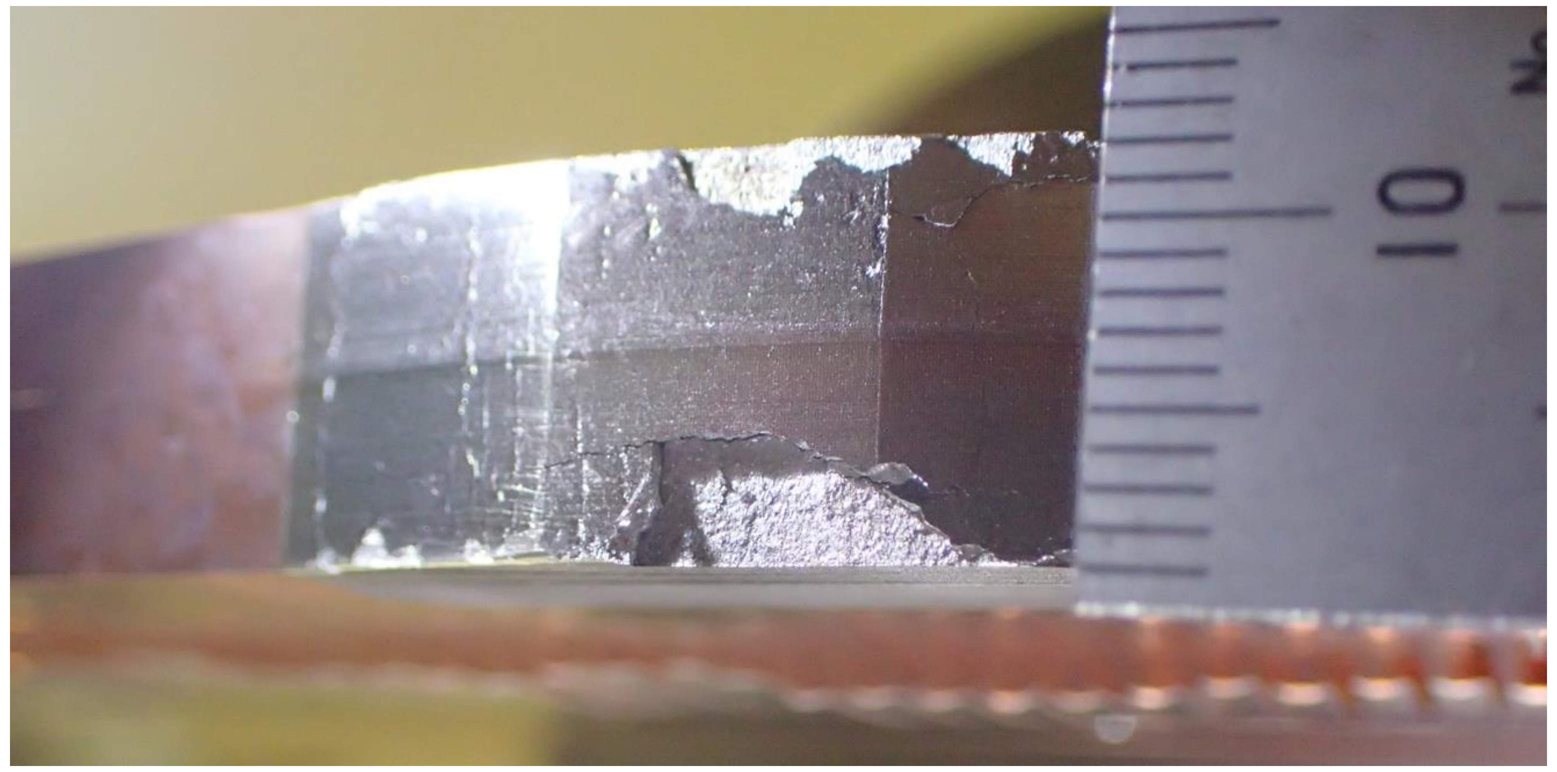
Experience – Accidental firings of injection kickers

- 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 caused 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 this. Carbon jaw in horizontal can be a better option.

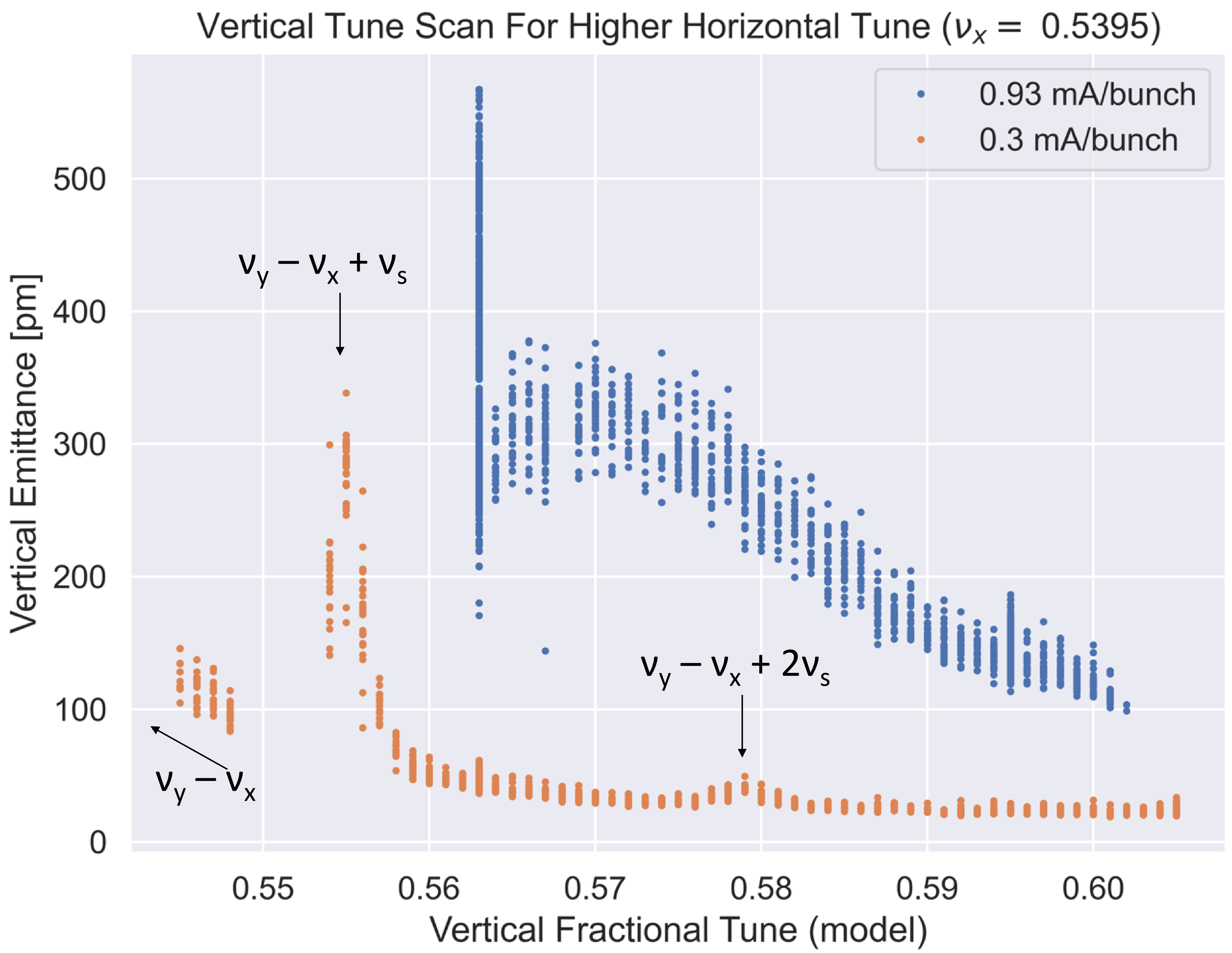
[S. Terui]

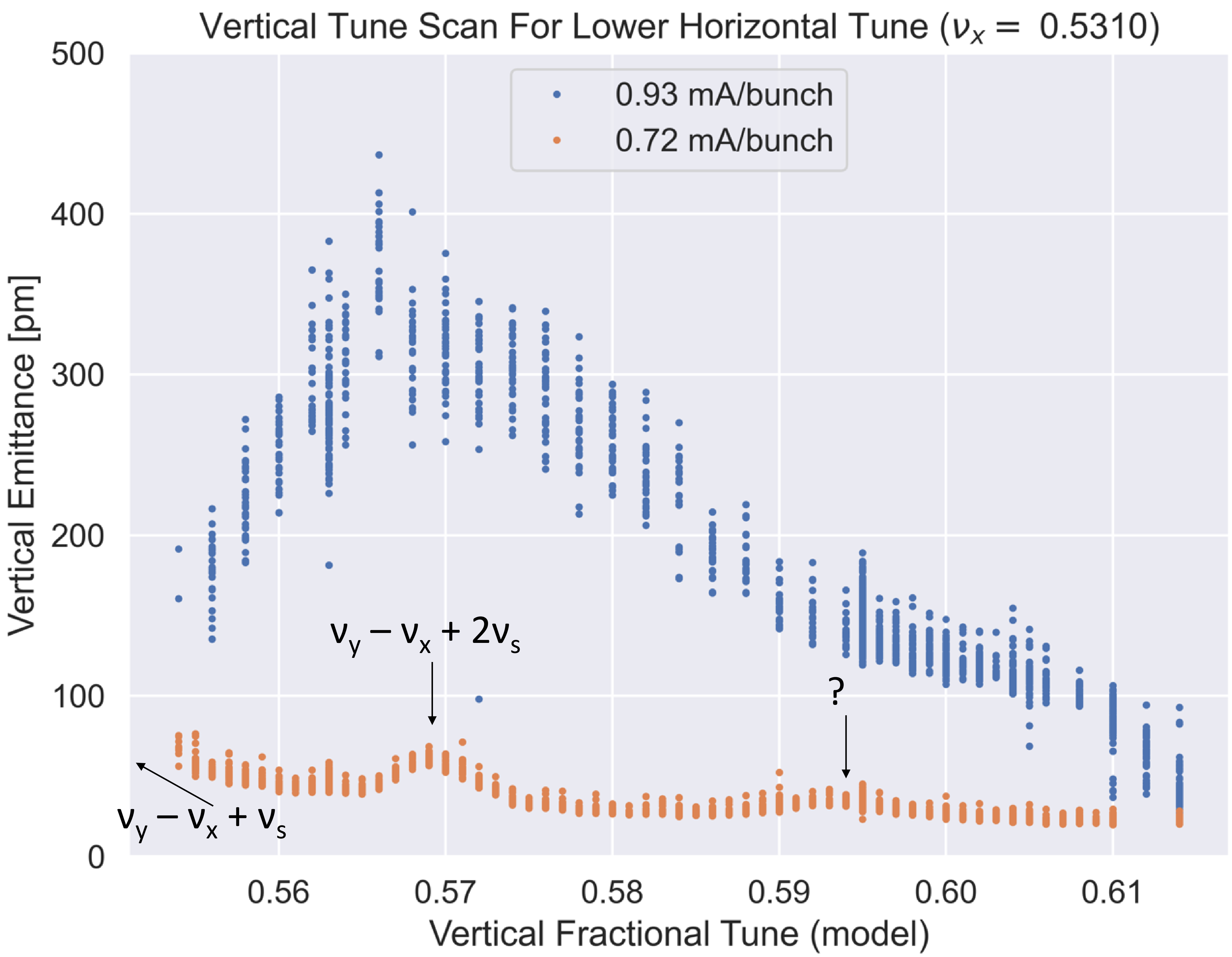






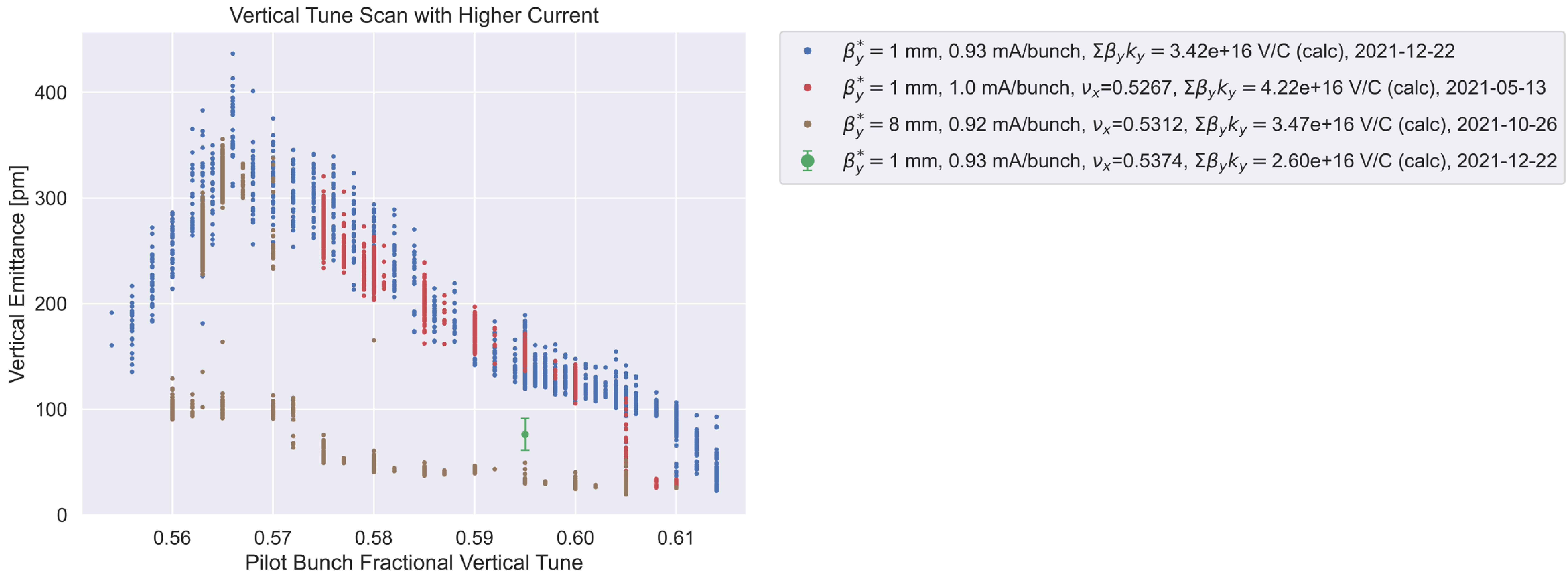
Experience – Vertical Beam-size blow-up





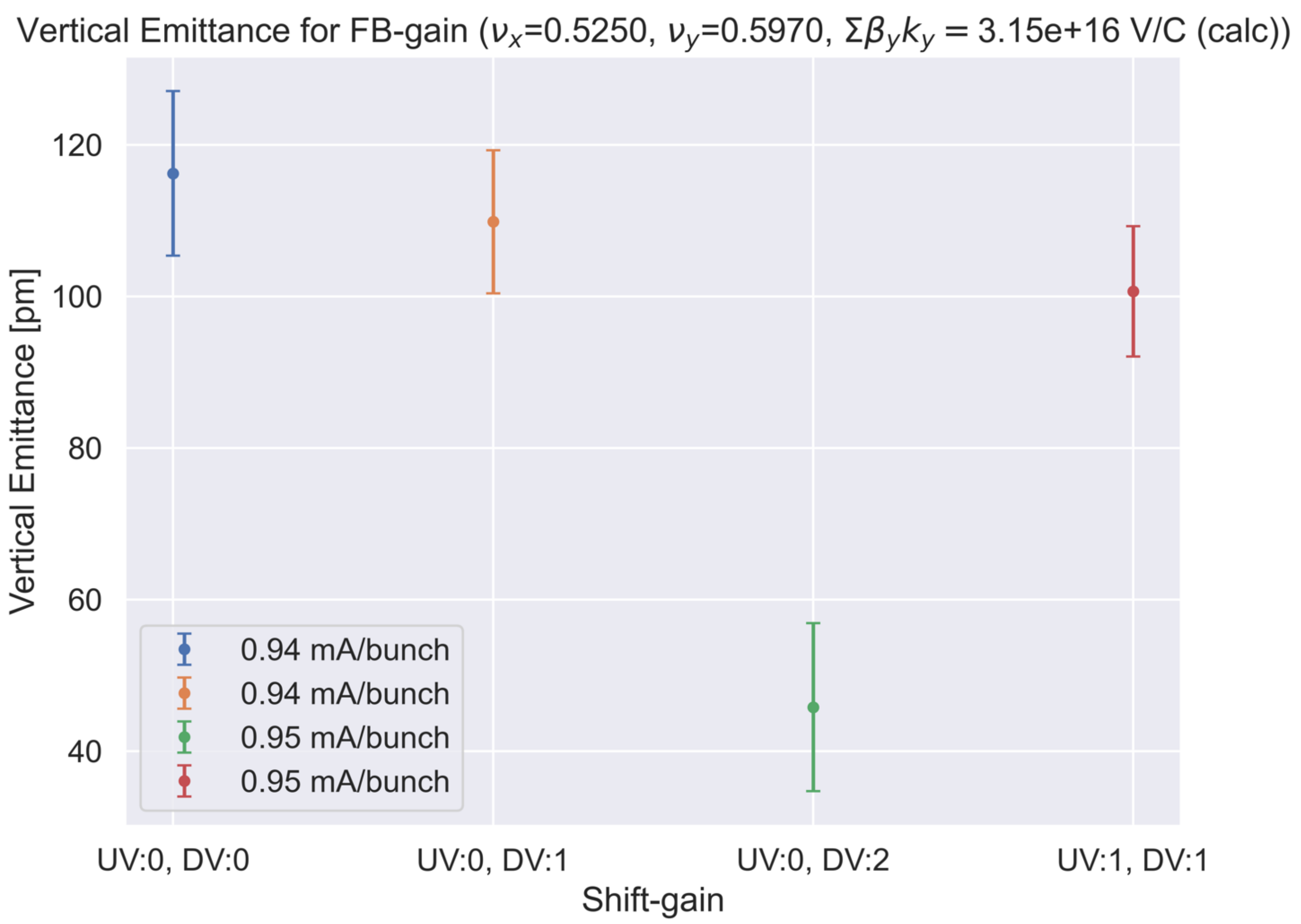
- Vertical beam-size blow-up related to impedance in LER has observed in the single-beam operation.
- The calculated bunch current threshold of Transverse Mode Coupling Instability (TMCI) is about 1.6 mA/bunch or more, but this blow-up has occurred around ~1.0 mA/bunch.
- The bunch current threshold depends on the vertical tune, so this is caused by not the ordinary TMCI but the localized wake in the vertical collimators.
- The tune scan had performed for βy^*=1 mm, no collision, 97 bunches.

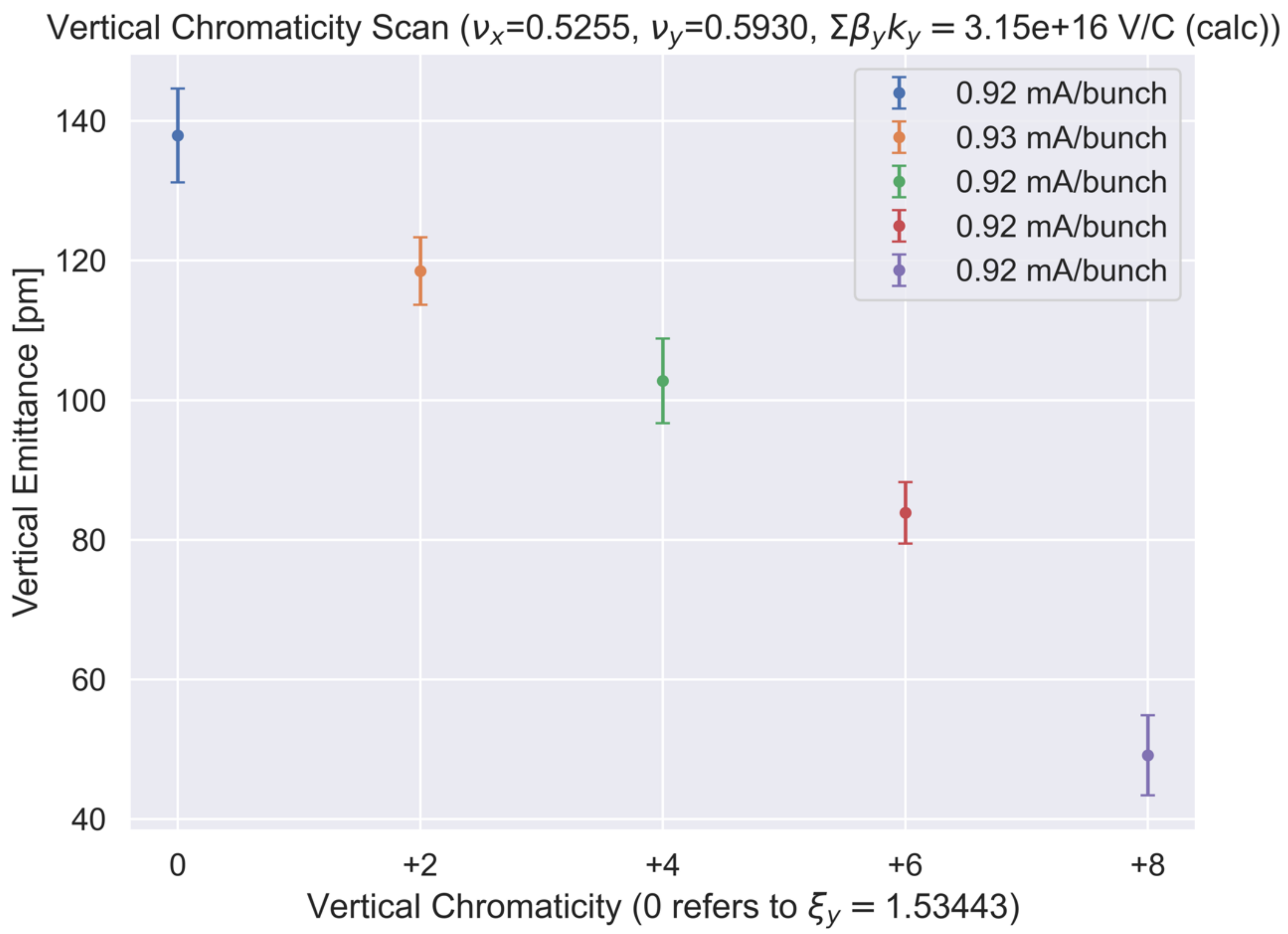
Experience – Vertical Beam-size blow-up

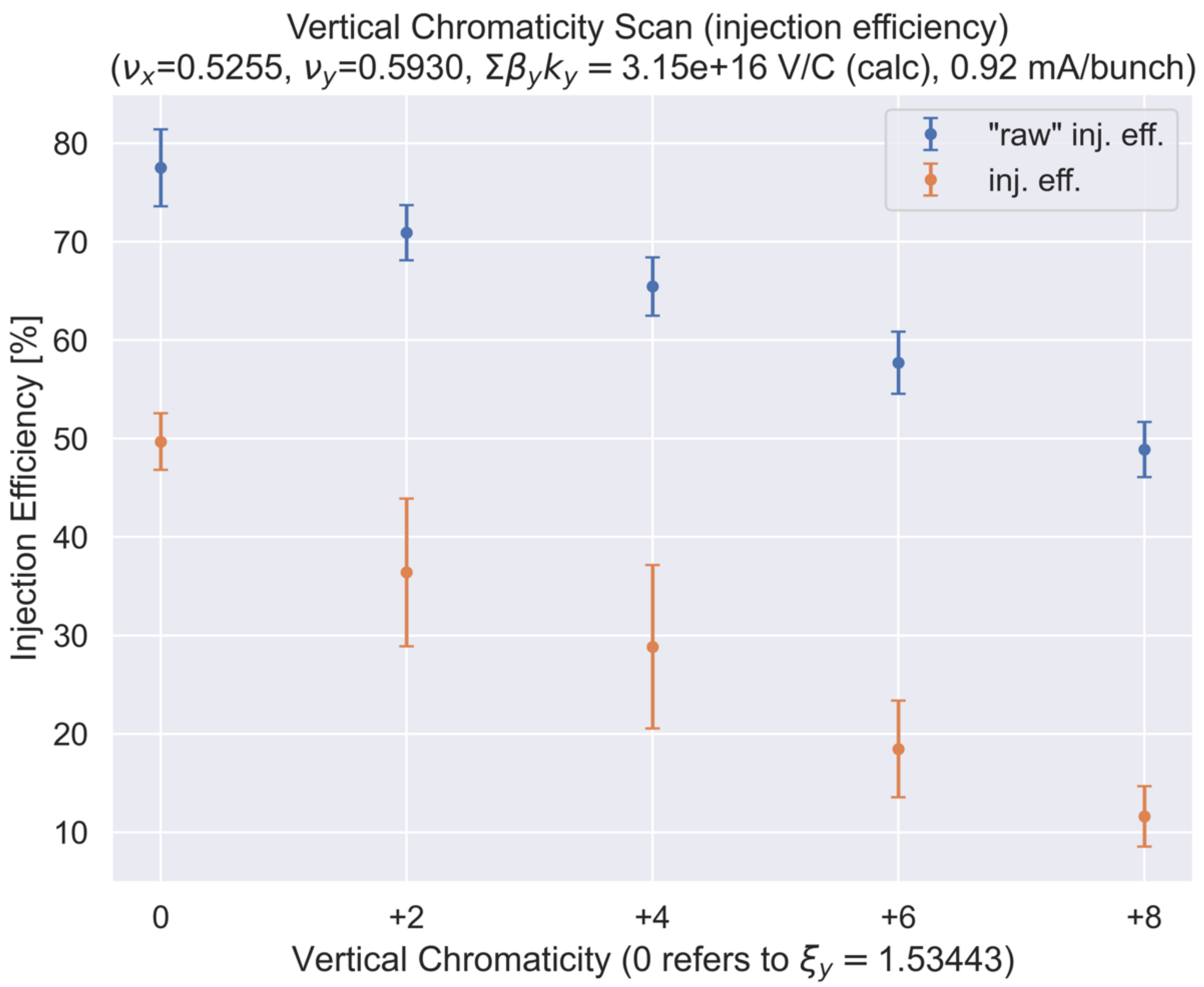


- The bunch current threshold for the vertical beam size blow-up decreases in the situation of βy* = 1 mm compared with βy* = 8 mm.
- In the study on Dec. 22nd, there were no damaged vertical collimators, but the situation looks same as that on May. 13th.
  - ✓ There had been damaged vertical collimators on May. 13th.
- When we opened apertures of some vertical collimators, the beam-size decreased (green colored dot with error bar).
- The stop-band is remarkably spread when the instability occurs.

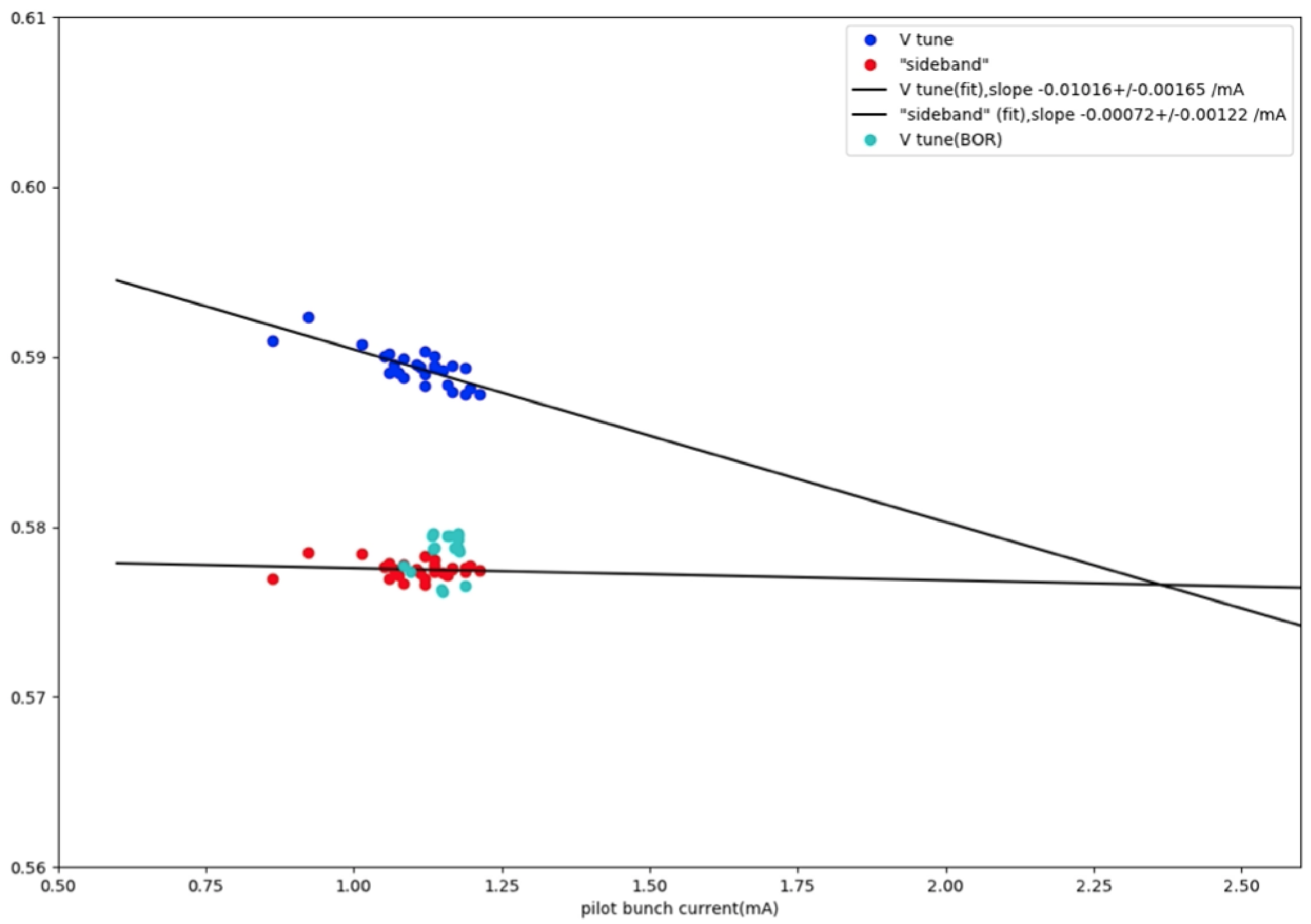
Experience – Vertical Beam-size blow-up







- BxB FB can suppress the beam size blow-up.
- We can also suppress the beam size blow-up by increasing the vertical chromaticity, however the injection efficiency becomes lower and lower.



- The bunch current threshold of this beam size blow-up is ~1.0 mA/bunch.
- However, the mode 0 and -1 seems to be coupled ~2.3 mA/bunch.

[H. Fukuma]

Summary

- The SuperKEKB type collimators have been working well up to the beam current of approximately 1 A in LER.
- These collimators have been indispensable for Belle II and SuperKEKB.
- However, there are serious issues:
  - ➢ Beam induced damage
  - ➢ Vertical beam-size blow-up in LER caused by localized wake in vertical collimators.

- Non-linear collimator at LER OHO section could relax the instability. We have plans to construct this during Long Shutdown-1 (LS1), 2022.

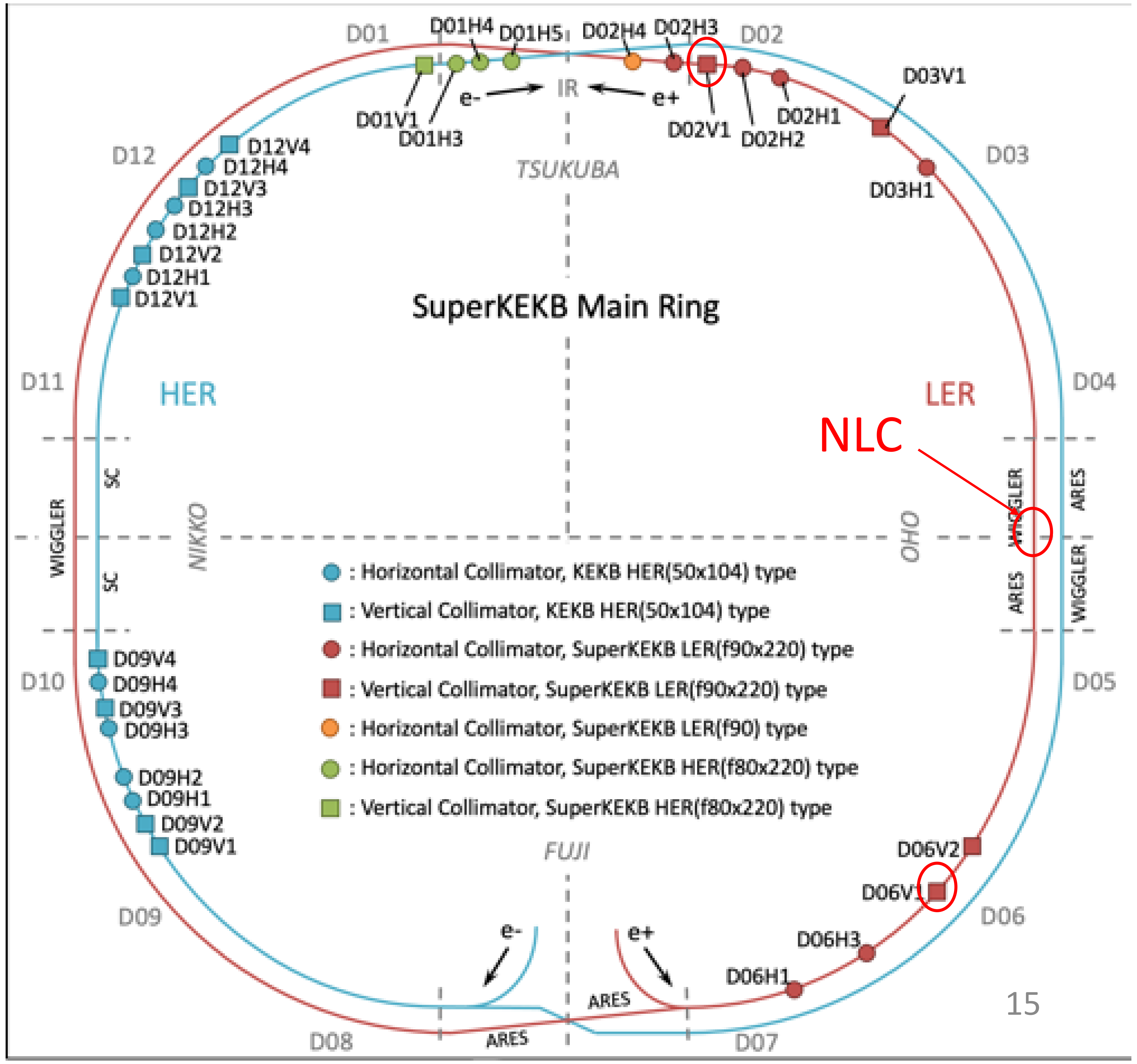
- We're also working to understand the observed transverse blow-up through machine studies, building a machine impedance model able to reproduce the instability in a TMCI working group of SuperKEKB International Task Force. If there is a person who are interested in or wants to join this TMCI sub-group, let me know (takuya.ishibashi@kek.jp).

Contact person: Mauro Migliorati (SAPIENZA - Università di Roma)
Sub-contact person: Takuya Ishibashi (KEK)

Plan – Non-linear collimator at LER OHO section

- Present collimator setting (2021ab)
  - D06V1: primary collimator: most tightly closed and suppresses the injection BG.
  - D02V1: second collimator: closest vertical collimator to IP and very important to suppress BG
  - D06V2, D03V1: backup: not so tightly closed. D03V1 can be used for a backup of D02V1.

- If we can replace D06V1 collimator with non-linear collimator (NLC) for example, the $\Sigma\beta_y k_y$ dramatically decreases.
  (βy: vertical beta function, ky: vertical kick factor)



Plan – Non-linear collimator at LER OHO section

- Collimator setting (half-aperture) during physics run in 2021b (βy^*=1 mm)

	β_y [m]	2021-06-30 [mm]	2021-07-02 [mm]
D06V1 top	67.3	3.06	3.84
D06V1 bottom		-2.65	-2.65
D06V2 top	20.6	2.27	2.25
D06V2 bottom		-2.26	-2.24
D03V1 top	17.0	8.00	7.99
D03V1 bottom		-8.00	-7.99
D02V1 top	13.9	1.30	1.71
D02V1 bottom		-1.14	-1.35
NLC@OHO	2.9	5.7	5.7

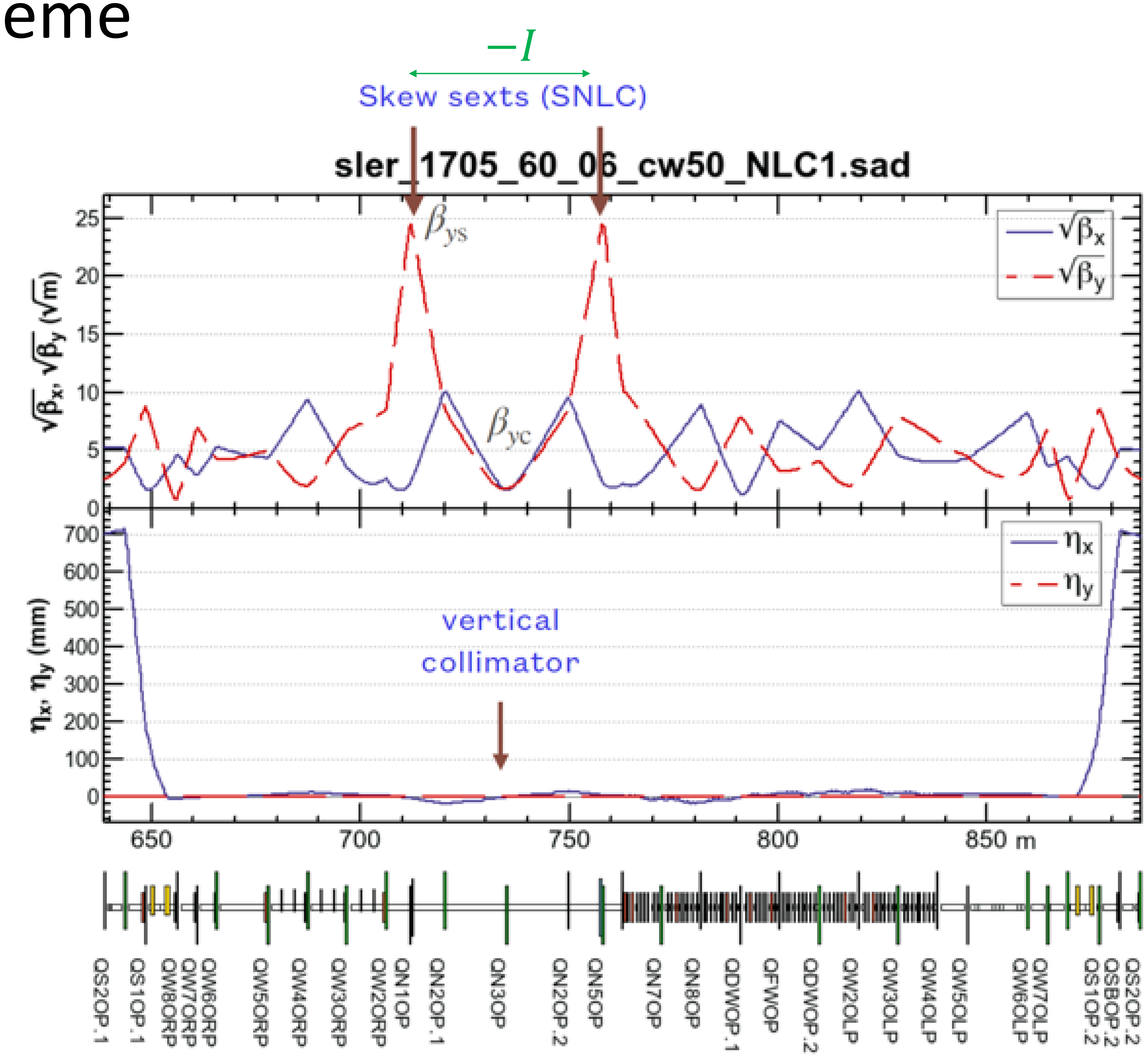
- The β_y at the D06V1 is large, and the aperture is narrow.
- The β_y at the NLC is small, and the aperture is wide.

→ We could dramatically decrease the $\Sigma\beta_y k_y$ if we can replace D06V1 with NLC.

Plan – Non-linear collimator at LER OHO section

- Scheme

[K. Oide]



Requirements for the NLC optics:

- Large $\beta_y = \beta_{ys}$ at the (skew) sextupole.
  - $\beta_y = \beta_{yc}$ at the collimator: $\sqrt{\beta_{yc}\beta_{ys}} \approx 1.7 \times L_{sc}$
- A (skew) sextupole pair connected by a $-I$ transformation.
- No dispersion at the sextupoles and the collimator.
- ≈ 0.25 vertical phase advance between the sexts and the IP.

Five sections of wigglers are removed!

L_{sc}

$\Delta\mu_y = \frac{\pi}{2}$

Here the collimator is placed right before the center quad (QN3OP).
If the quad is split into two pieces, the collimator can be placed in the middle of them.

Plan – Non-linear collimator at LER OHO section

[K. Oide]

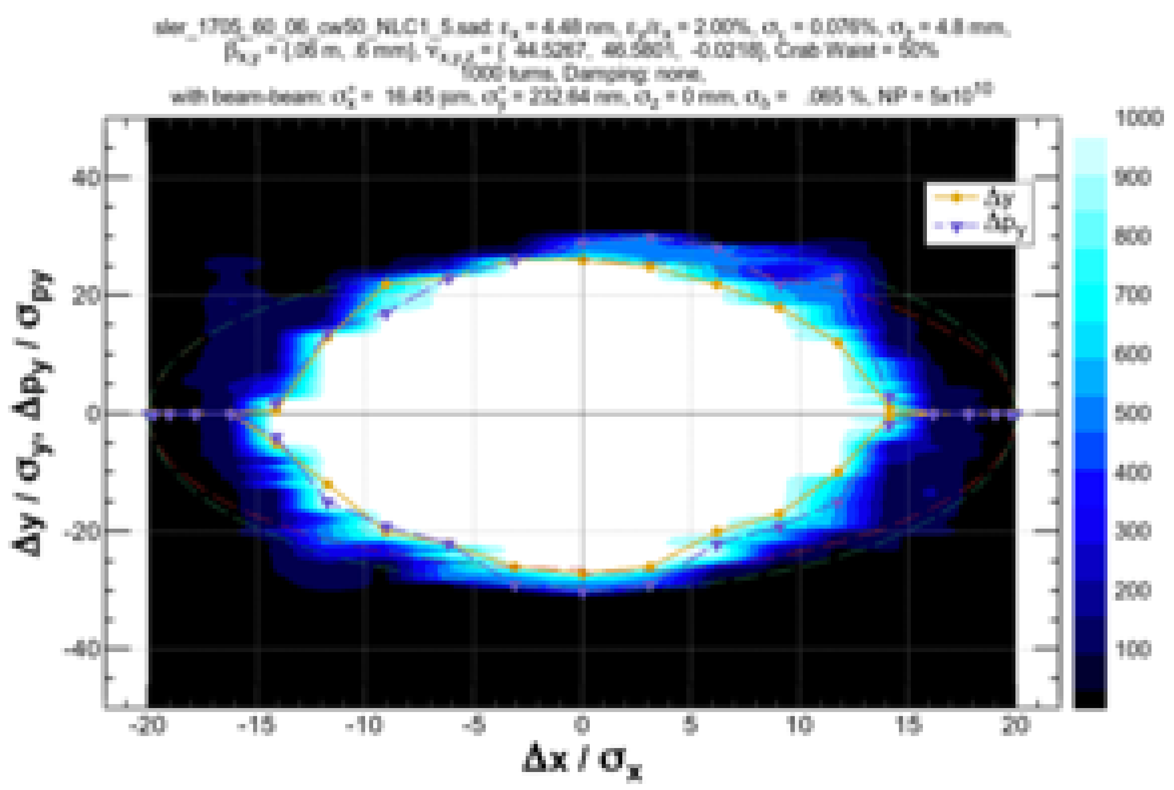
LER optics for (60,0.6) mm

CW = 50%

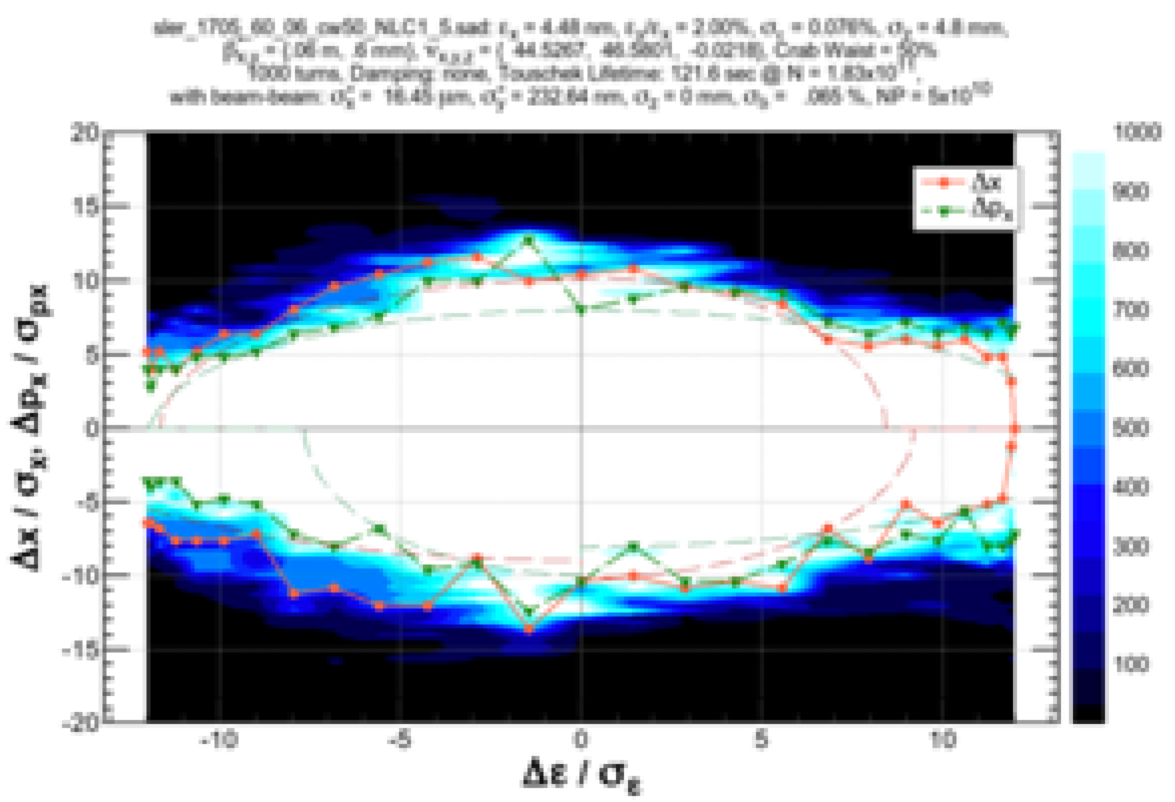
Requirements on the collimation

SuperKEKB

Dynamic aperture (X-Y) with NLC



Dynamic aperture (Z-X) with NLC



- Consider a collimation at a vertical amplitude y_{q}, which is equal to the *dynamic aperture*.
  - For the (60,0.6) mm optics, $y_{\mathrm{q}} = 10.0\,\mathrm{mm}$ at QC1 ($30\sigma_y$ with $\varepsilon_y/\varepsilon_x = 2\%$).
- It is equivalent to $y_{\mathrm{s}} = y_{\mathrm{q}}\sqrt{\beta_{y\mathrm{s}}/\beta_{y\mathrm{q}}} = 6.8\,\mathrm{mm}$ at the NLC skew sextupole SNLC.
- The sextupole kicks the beam vertically by

$$\Delta p_{y\mathrm{s}} = \frac{s'}{2}(y_{\mathrm{s}}^2 - x_{\mathrm{s}}^2)\,, \qquad (1)$$

$$s' \equiv \frac{L_{\mathrm{s}}}{B\rho}\frac{\partial^2 B_x}{\partial y^2}\,. \qquad (2)$$

  - For instance, $s' = 6.0/\mathrm{m}^2$, $\Delta p_{y\mathrm{s}} = 0.14\,\mathrm{mrad}$, with $|y_{\mathrm{s}}| \gg |x_{\mathrm{s}}|$.
- Then the kick makes a vertical displacement at the collimator:

$$\Delta y_{\mathrm{c}} = R_{34}\Delta p_{y\mathrm{s}} = 5.7\,\mathrm{mm} \qquad (3)$$

$$R_{34} \approx \sqrt{\beta_{y\mathrm{c}}\beta_{y\mathrm{s}}} = 40.8\,\mathrm{m} \qquad (4)$$

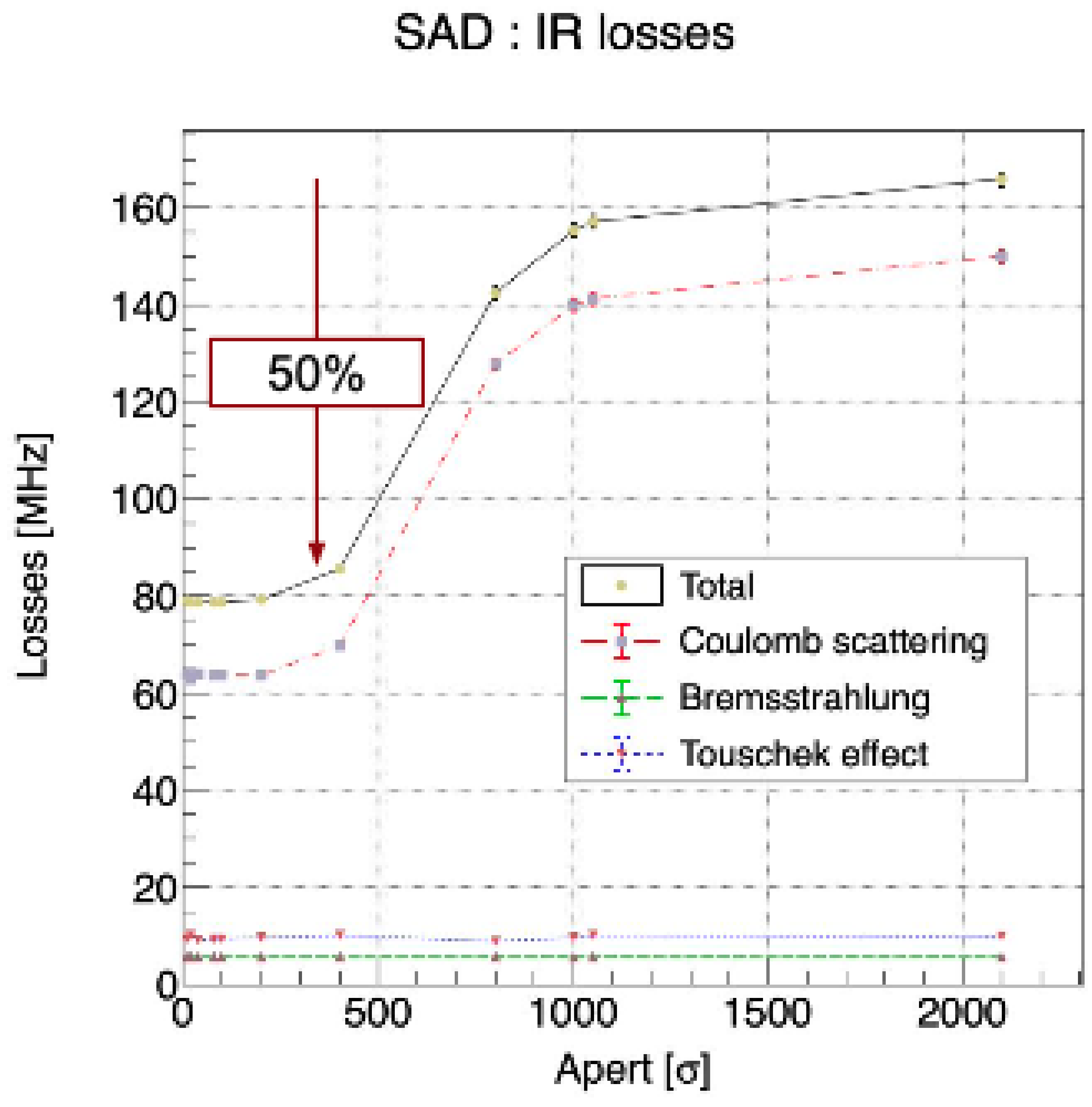
- This example optics: $\beta_{y\mathrm{s}} = 570\,\mathrm{m}$, $\beta_{y\mathrm{c}} = 2.9\,$ m.

Plan – Non-linear collimator at LER OHO section

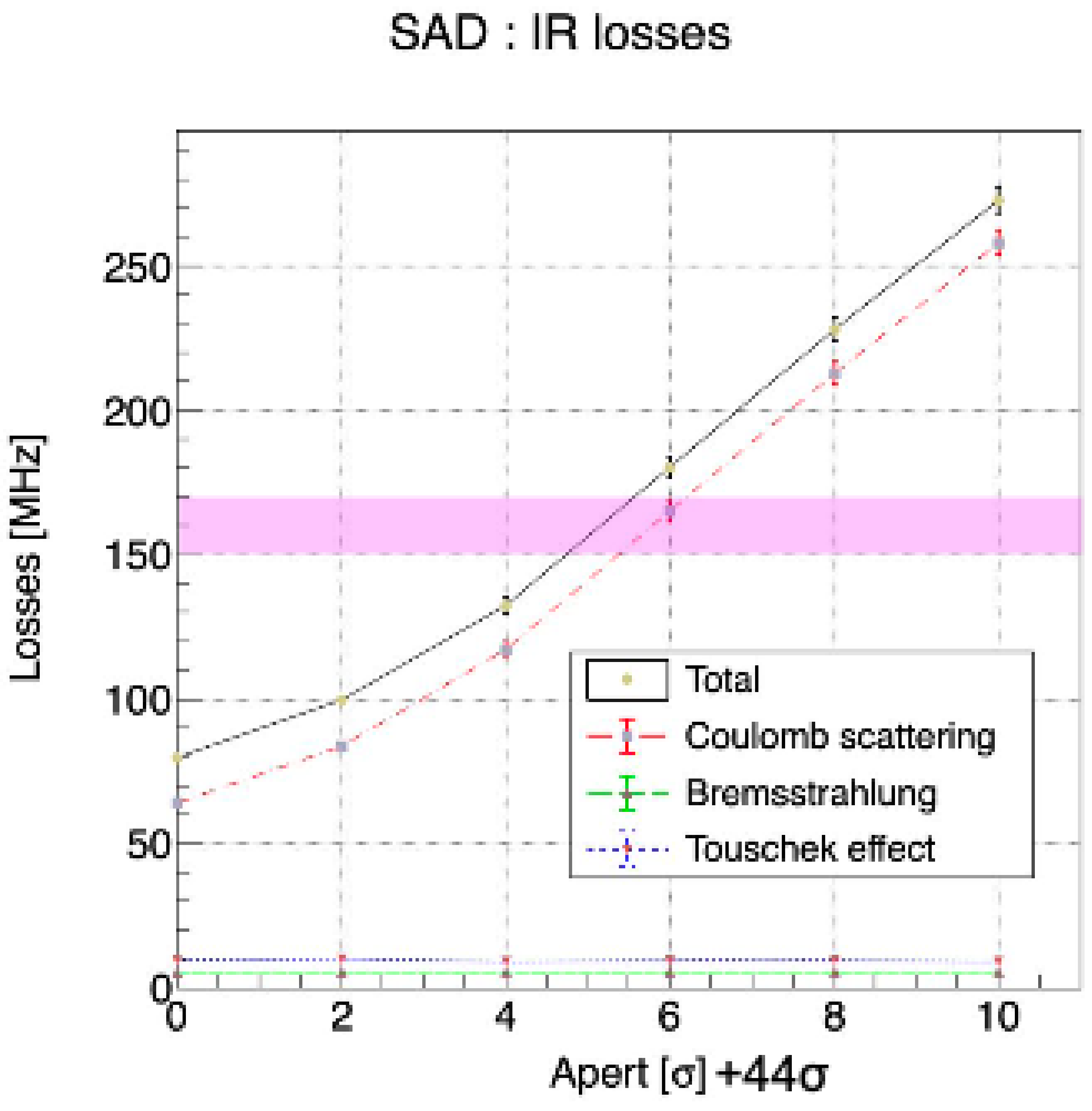
[A. Natochii]

Storage background impact

- For β^{*}_{Y} = 1mm and ε_{y} = 80pm in LER, **NLC can significantly reduce IR storage backgrounds** at ~300σ (±5.7mm), which corresponds to ~40σ at skew sextupoles, while QC1 is at ~50σ
- **D06V1 can be fully opened** with no harm to the IR
- **D02V1 can be opened** up to the acceptable level of beam-induced backgrounds in the IR



NLC aperture scan



Acceptable level of IR backgrounds

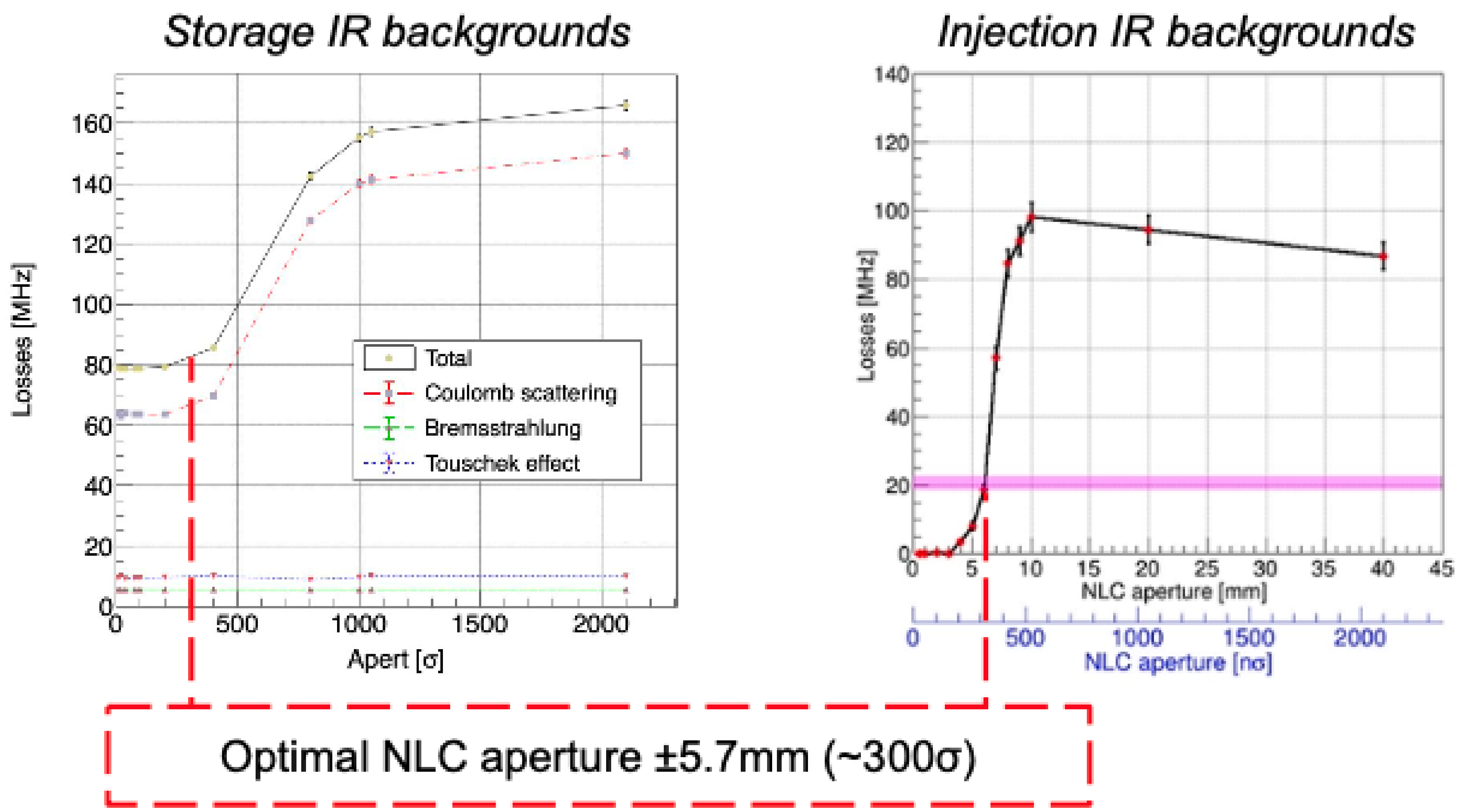
D02V1 aperture scan while NLC is closed

Plan – Non-linear collimator at LER OHO section

[A. Natochii]

Conclusion

- The optimal NLC aperture for storage and injection backgrounds mitigation is ±5.7mm which is about 300σ at the NLC and 40σ at skew sextupoles
- D06V1 can be fully opened with no harm to the IR while using NLC
- Closing NLC, opening D06V1, and keeping D02V1 & D06V2 collimators at the QC1 aperture increases the TMCI bunch current threshold from 1.6mA up to 4.2mA
- For more simulation and analysis details use this *link*

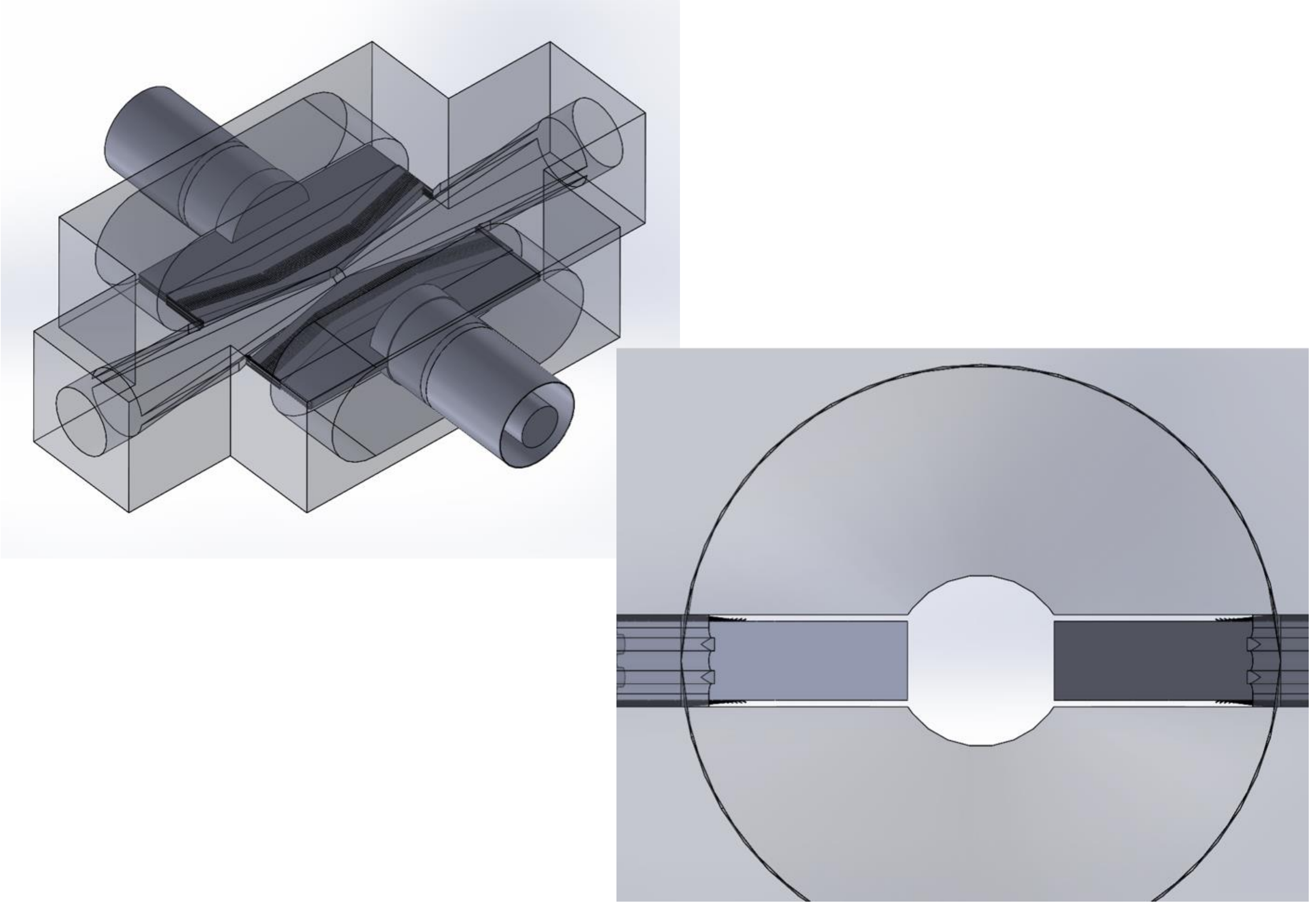


backup

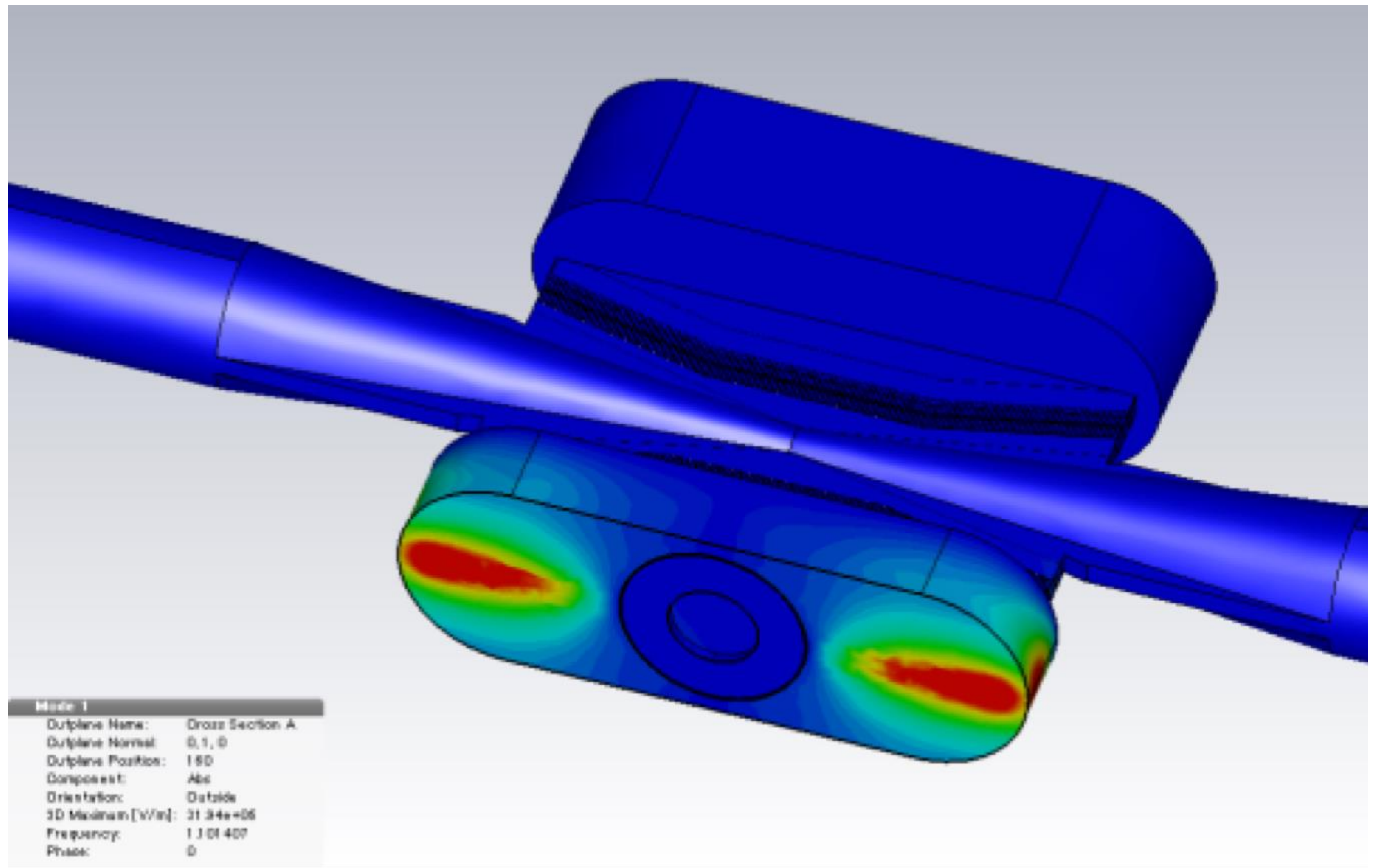
Design - RF property

- 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.

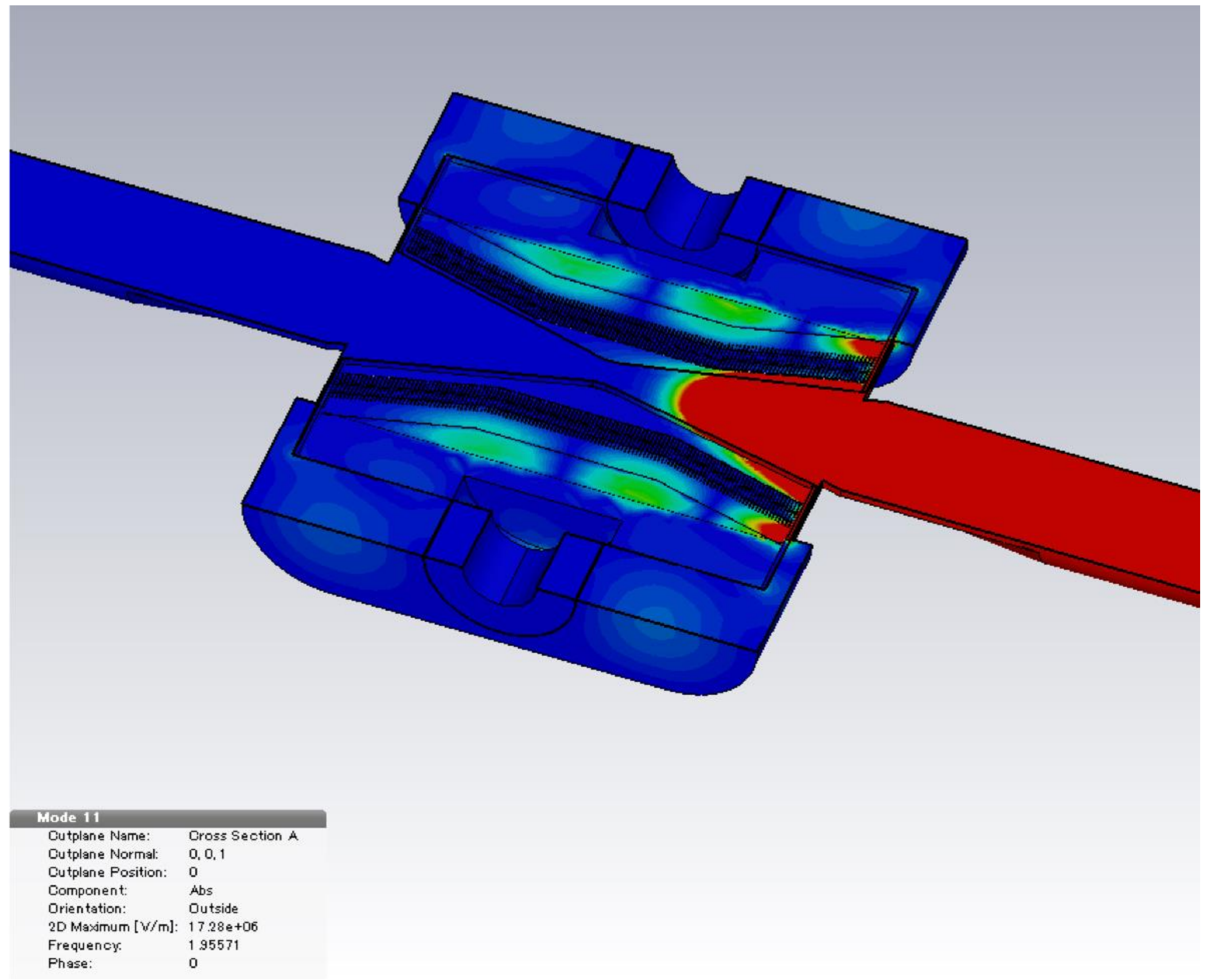
[T. Ishibashi et al., PRAB 23, 053501 (2020)]



Simulation model in CST Studio



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

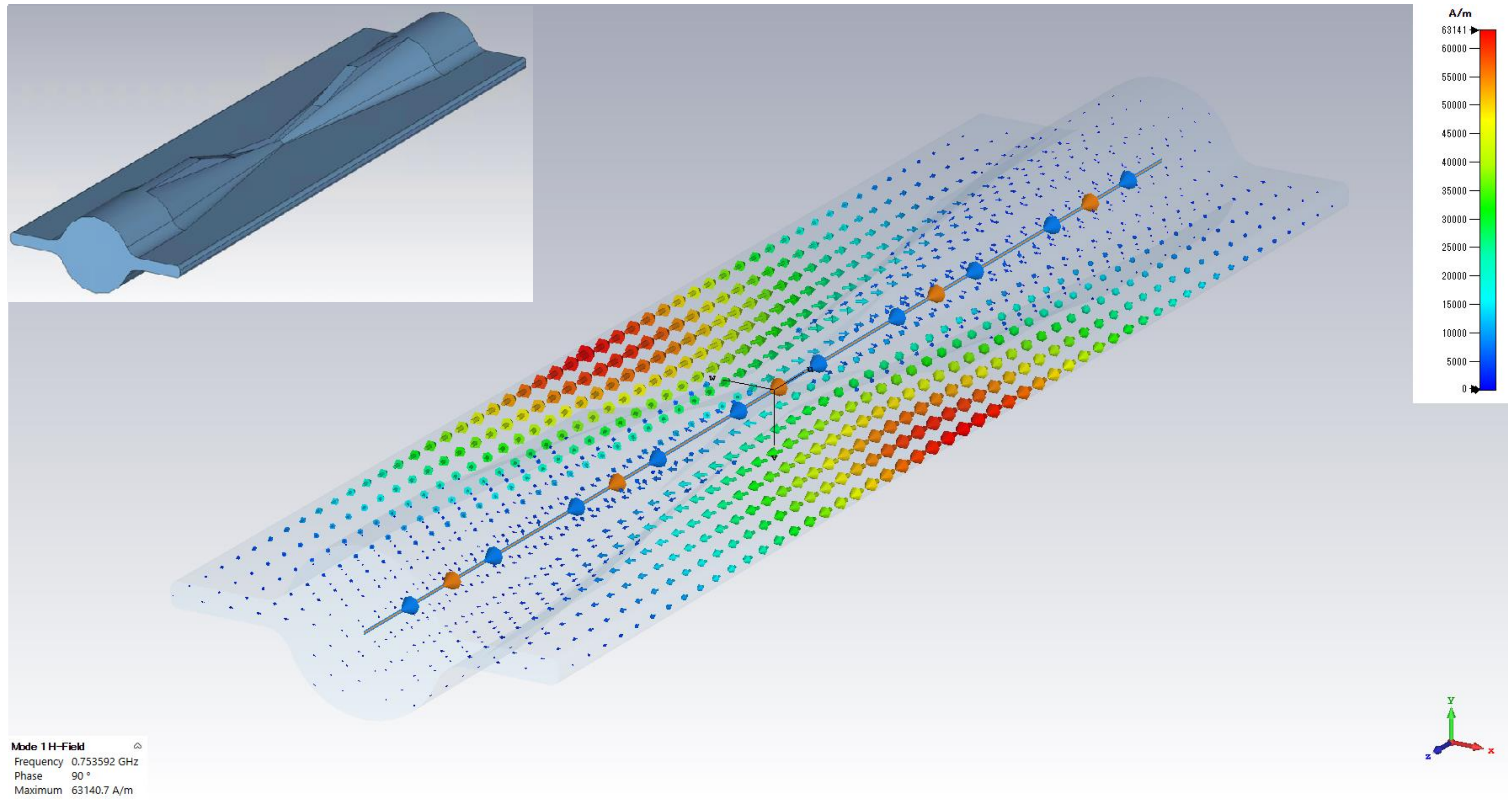


E-field strength in beam channel (TE_{111}: 1.9557 GHz)

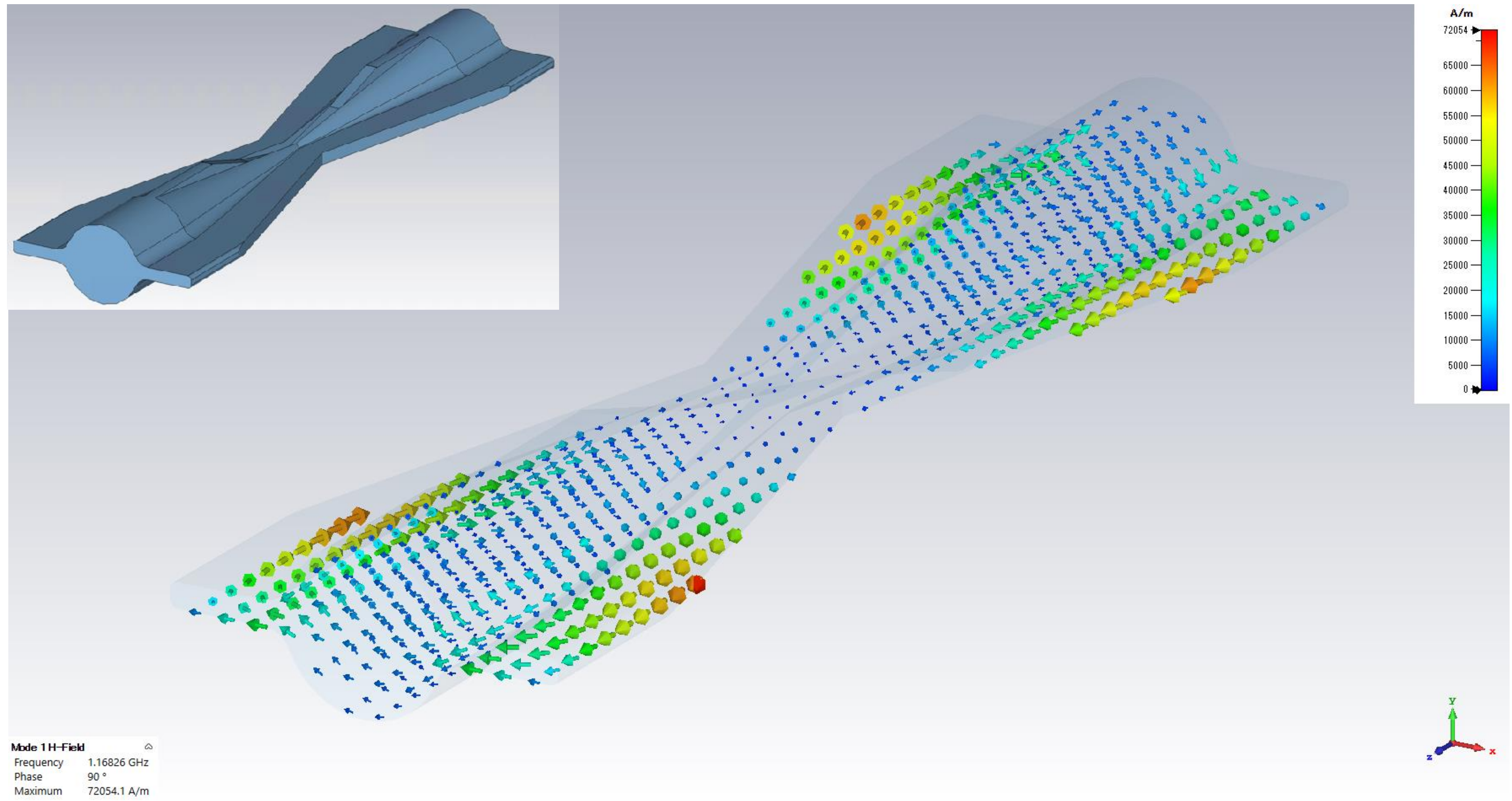
Design - RF property

- 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)

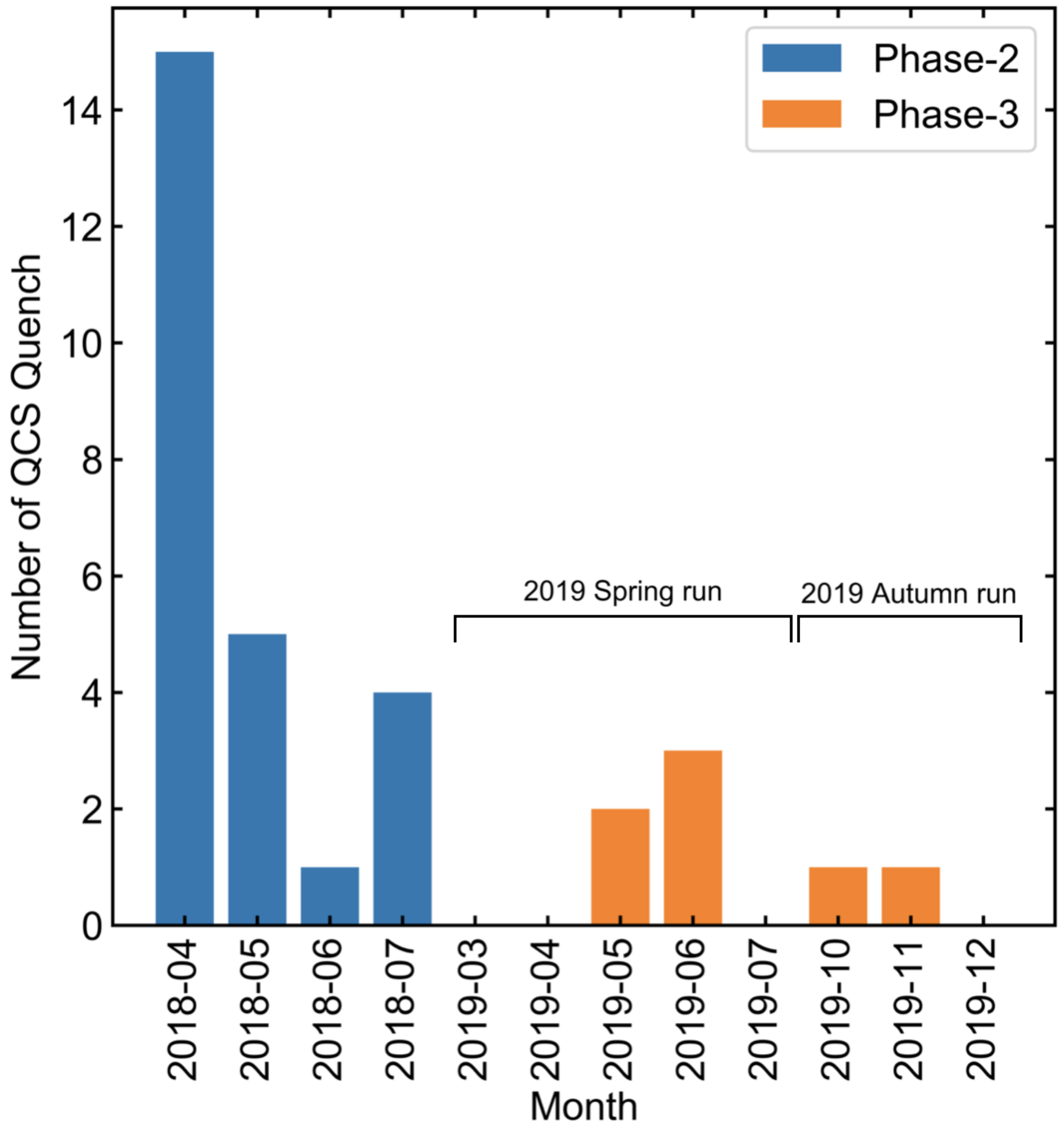


Height in antechambers at center: 70 mm
(1.1683 GHz)

E-field

Experience - QCS protection

- 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).

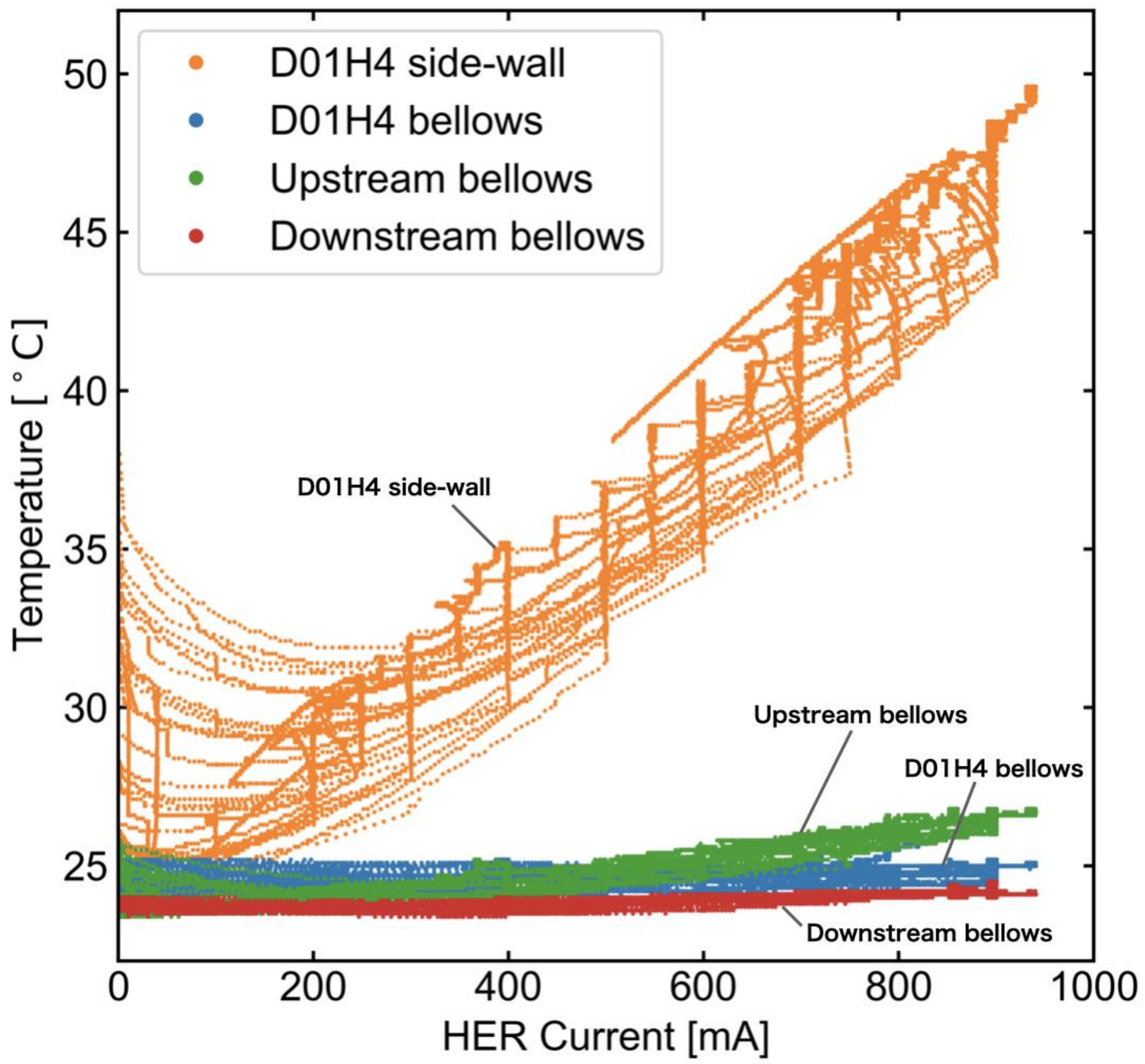
[T. Ishibashi et al., PRAB 23, 053501 (2020)]

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

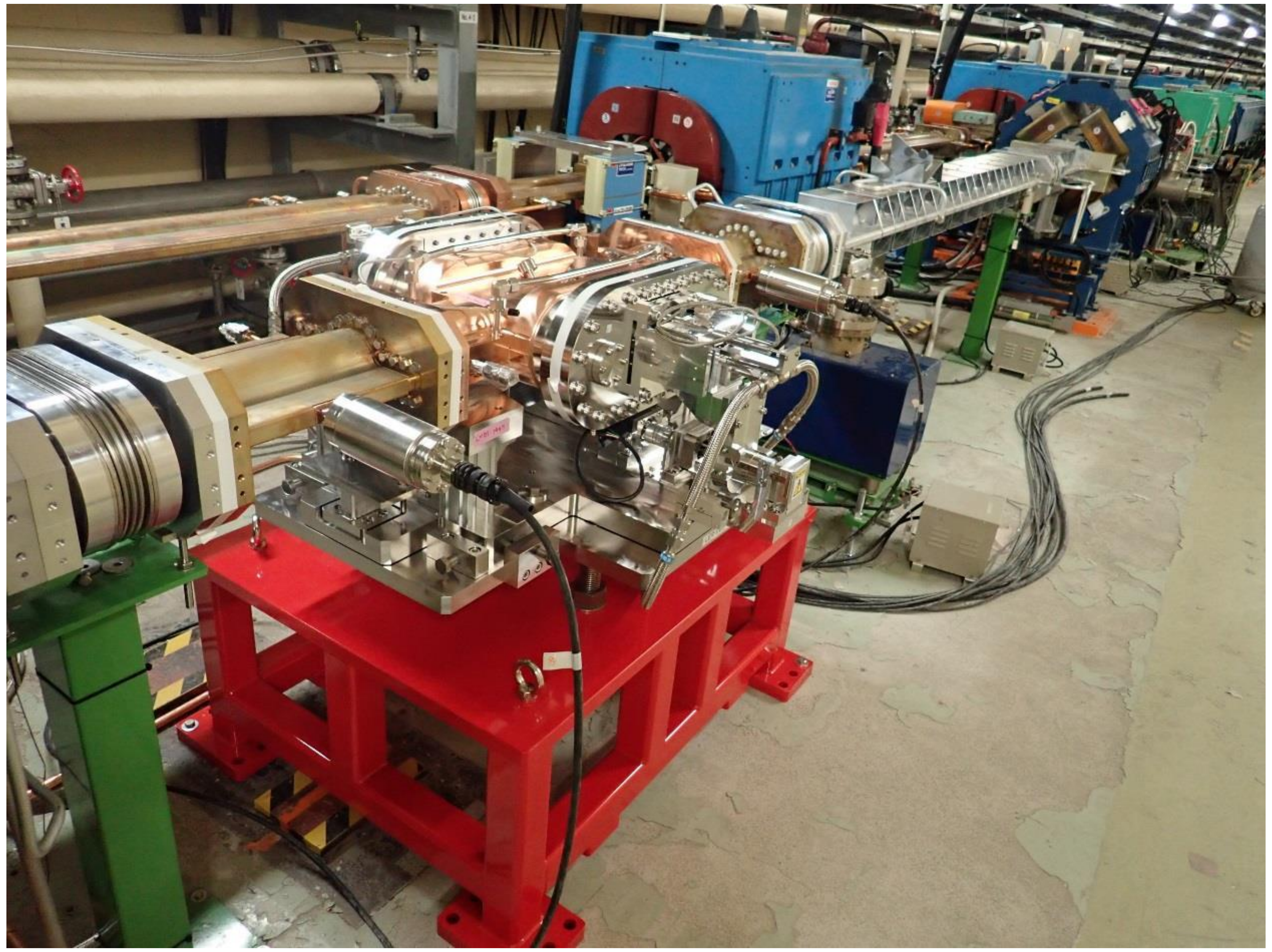
- Pressure upstream of IP in LER.
  - Vacuum component is dominant for BG in LER.
  - Especially, pressures near D02V1 and D02H1 had been high during 2019 spring run.
    - D02H1 collimator had had a water leakage trouble before the run, so it could raise the pressure.

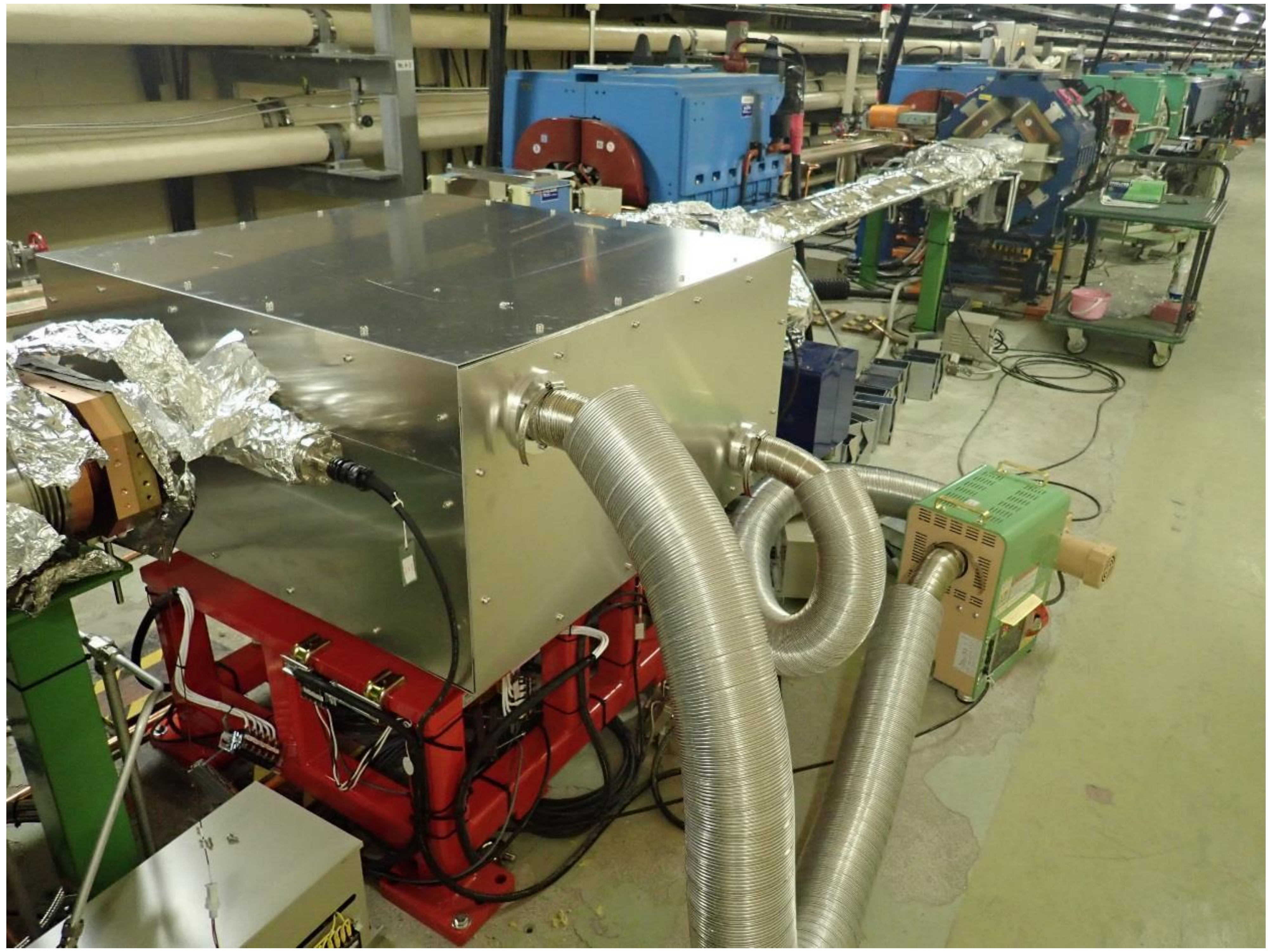
→ baked out these collimators and beam pipes in tunnel before 2019 autumn run.

LER pressure distribution in 2019 Spring run.

Experience - Pressure

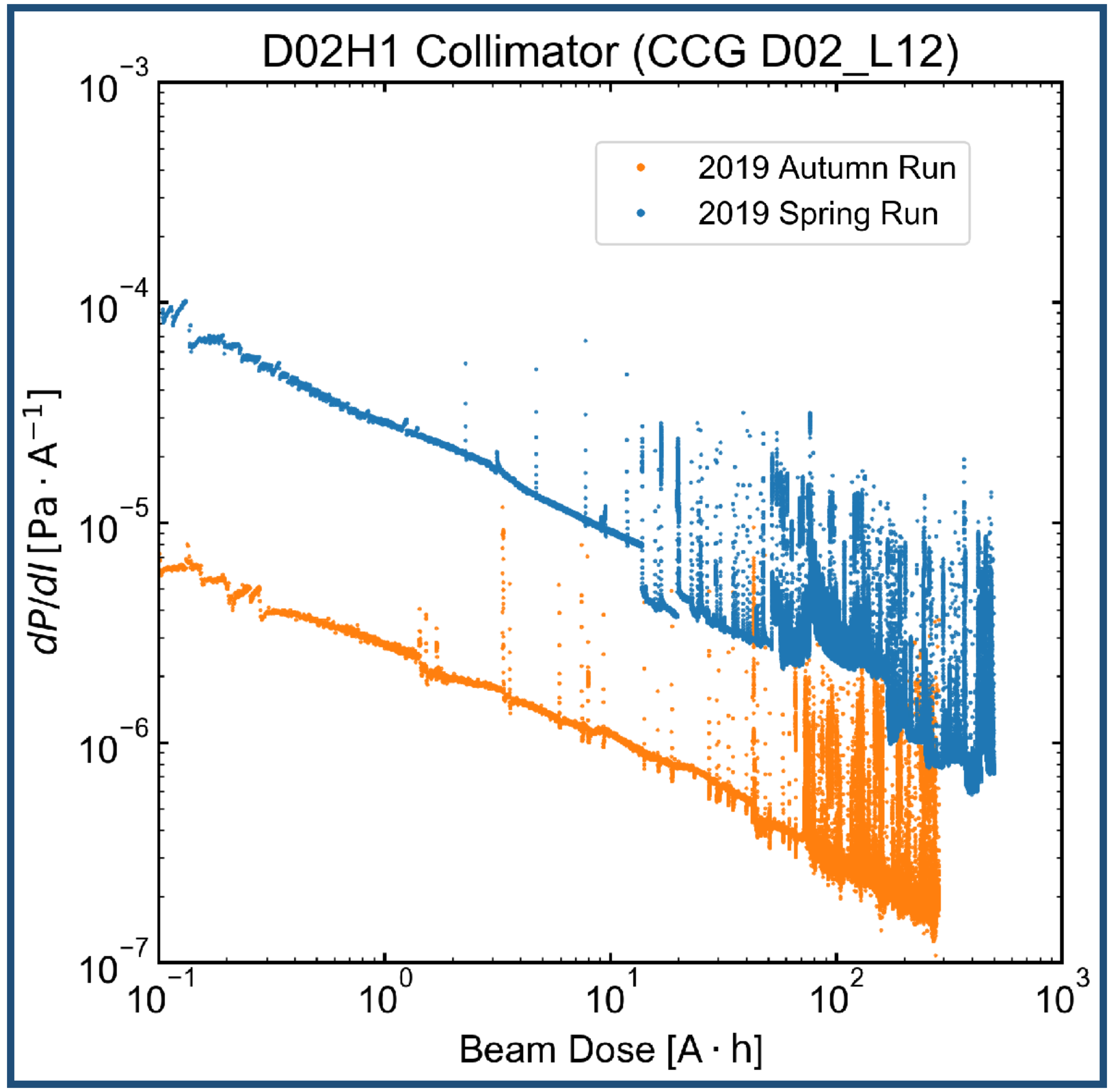
- D02H1, H2 collimator:
  - ion pumps bake-out: ~32 hours (2019-09-03 10:00 ~ 09-04 16:00)
  - NEG activation: ~33 hours (2019-09-04 10:00 ~ 09-05 17:00)
- D02V1 collimator:
  - ion pumps bake-out: ~24 hours (2019-09-11 10:00 ~ 09-12 10:00)
  - NEG activation: ~43 hours (2019-09-11 15:00 ~ 09-13 10:00)

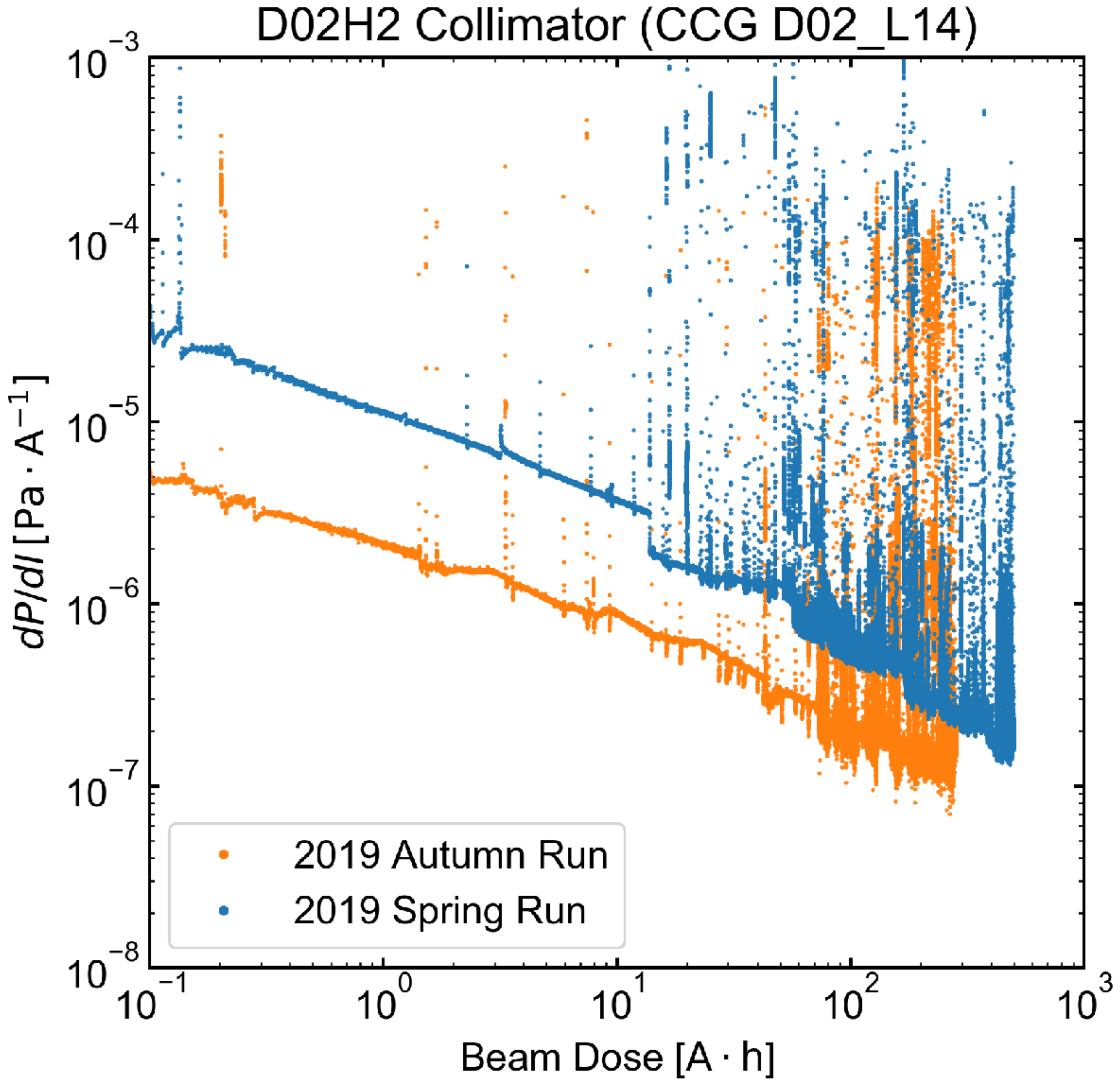


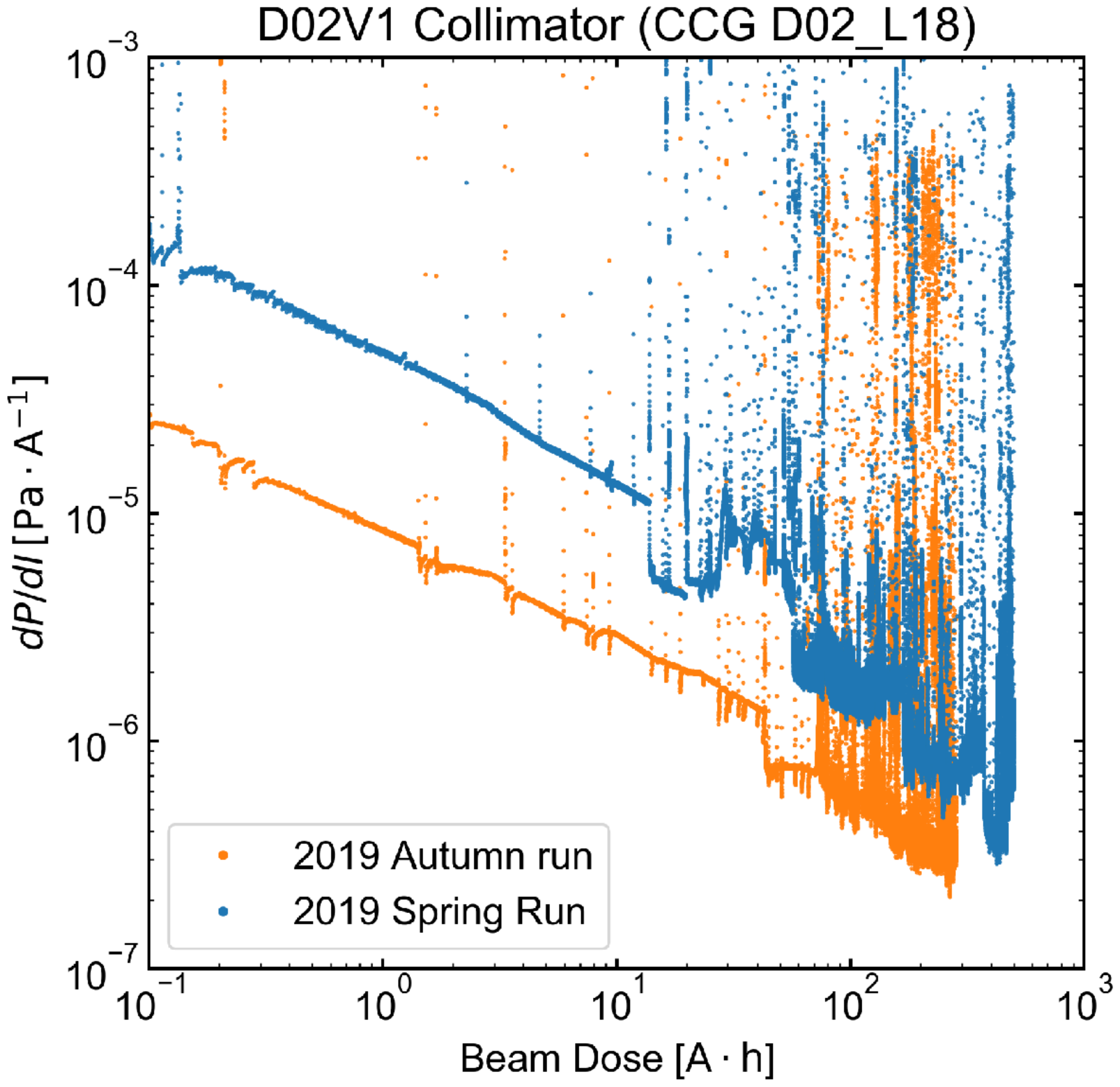


Experience - Pressure

- 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.

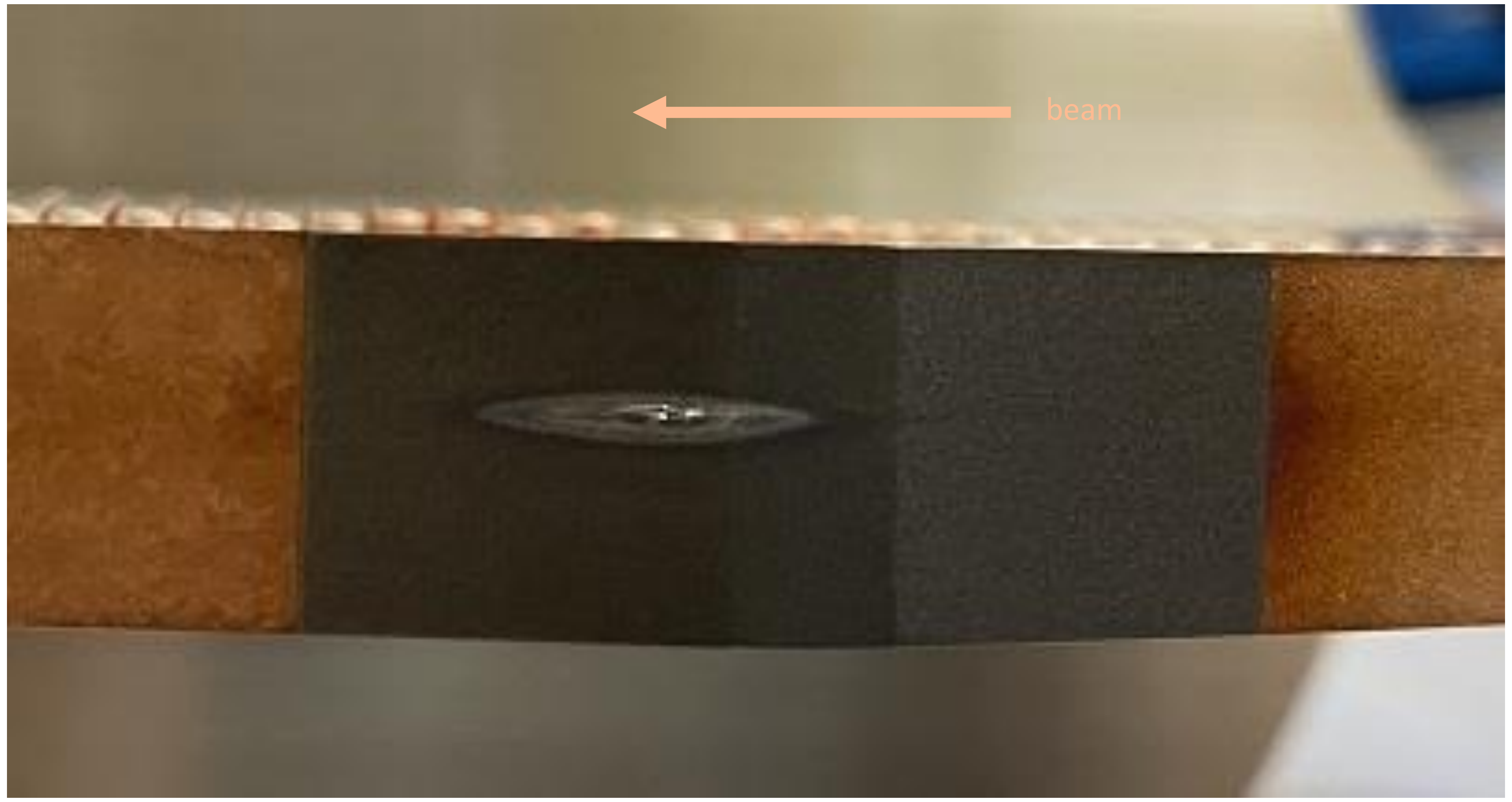




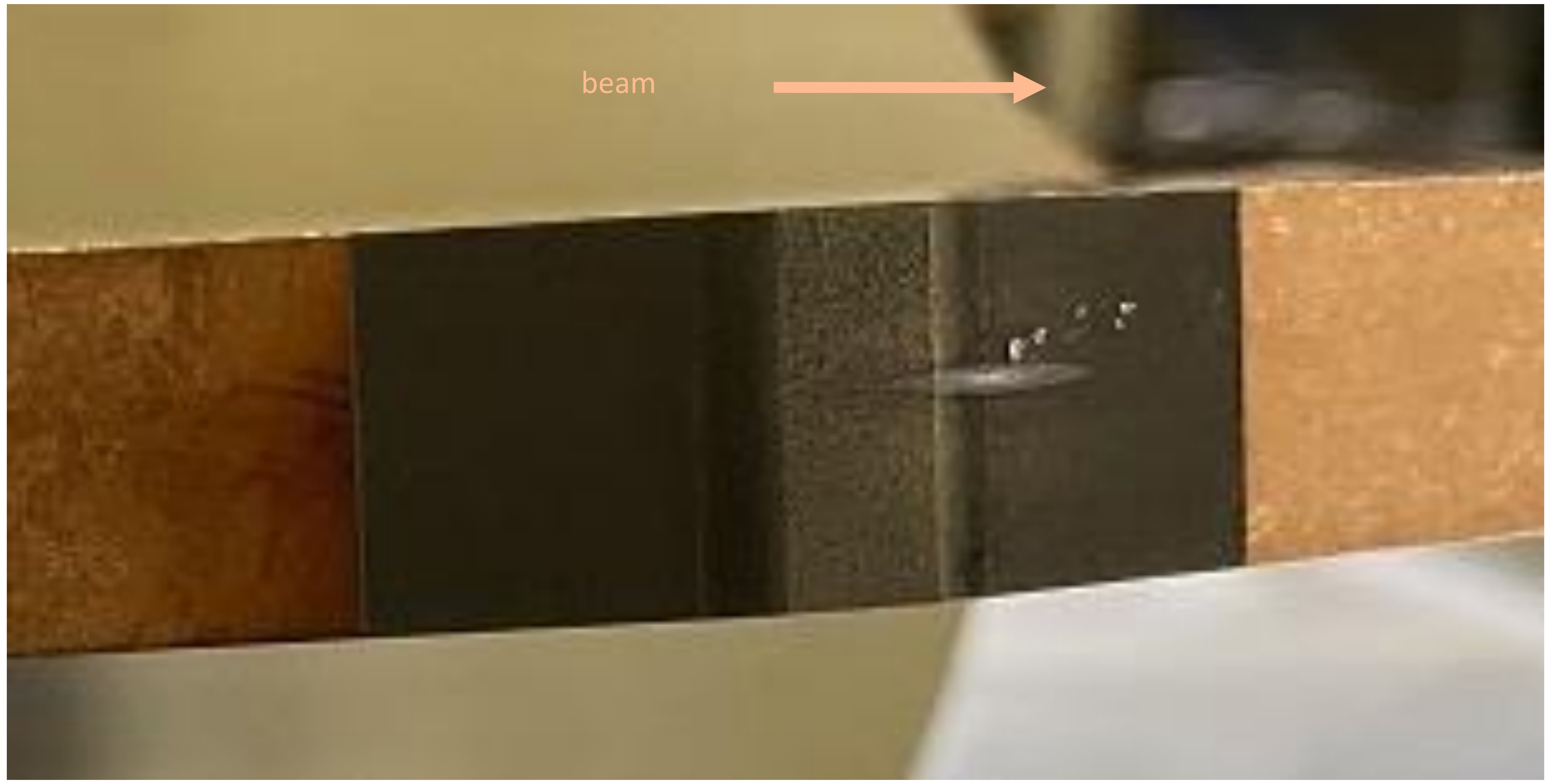


Experience -Short Tip

- 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

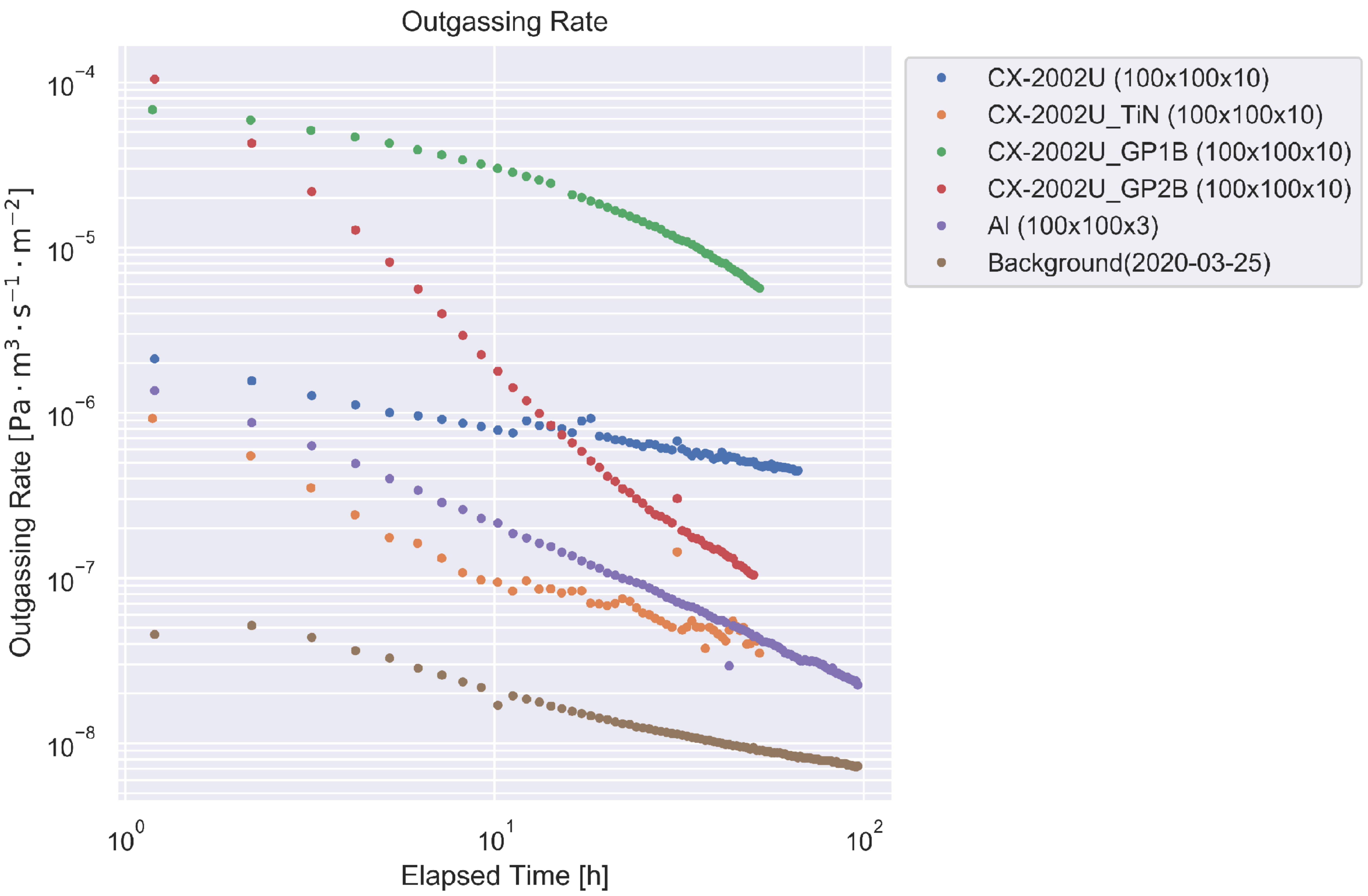
- Feasibility of titanium for the collimator had been already checked in KEKB.
- We've started checking the feasibility for a C/C composite material.

	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.

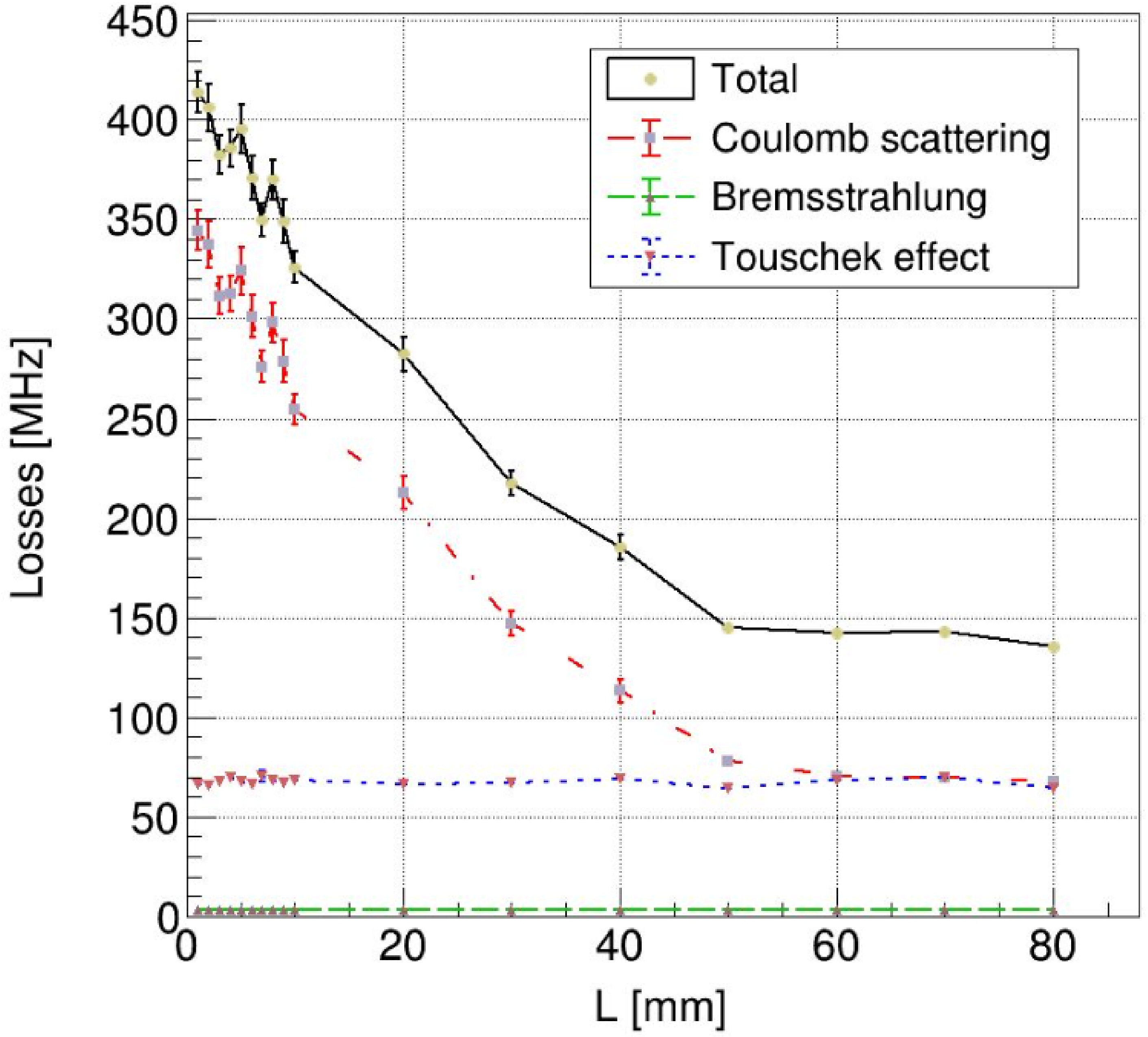


Low-Z collimator

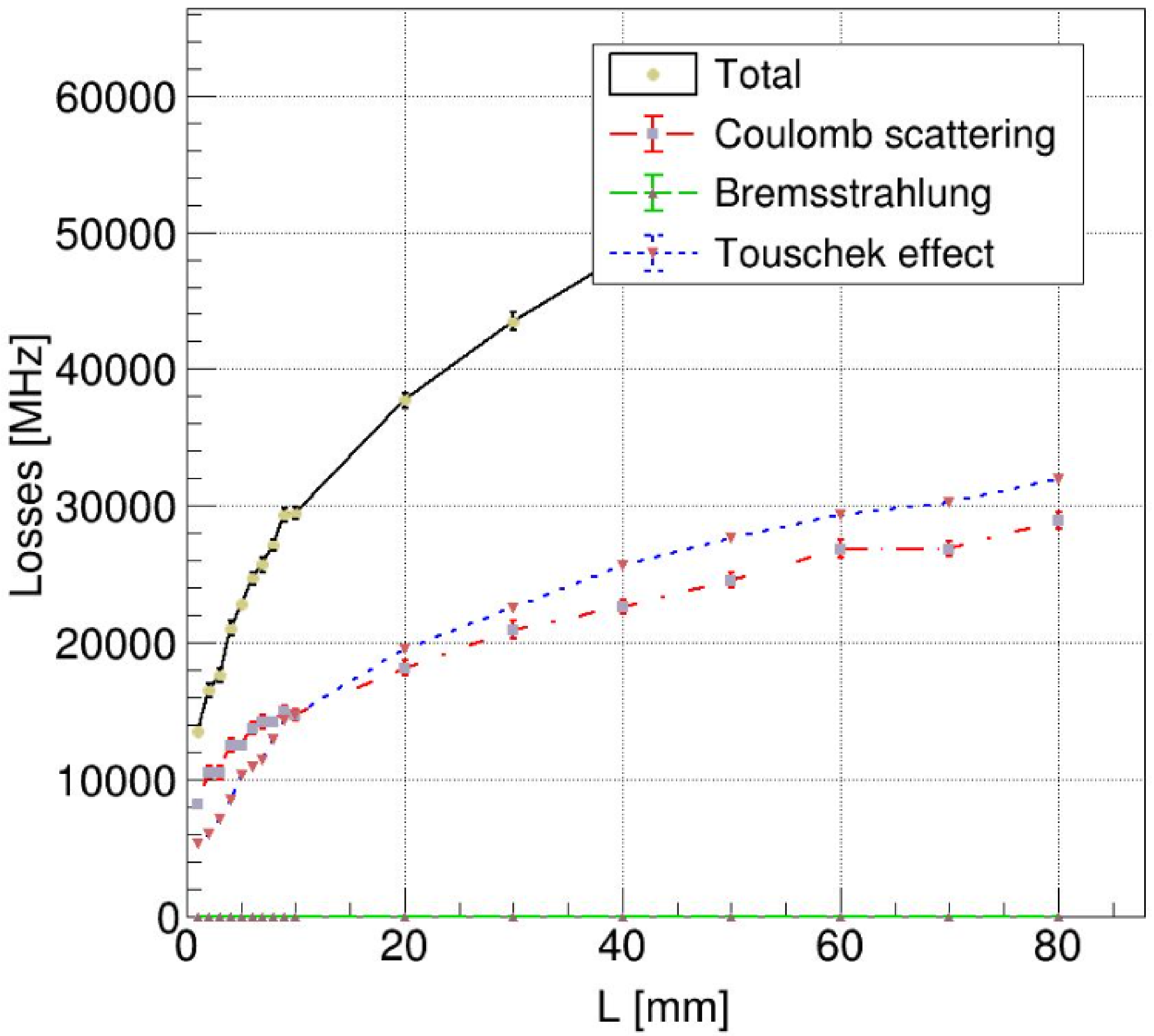
[Andrii Natochii (Univ. of Hawaii) et al.]

LER D06V1 *SAD* sim. results

LER IR losses
(8m around IP)



LER D06V1 local losses
(40m around the collimator)

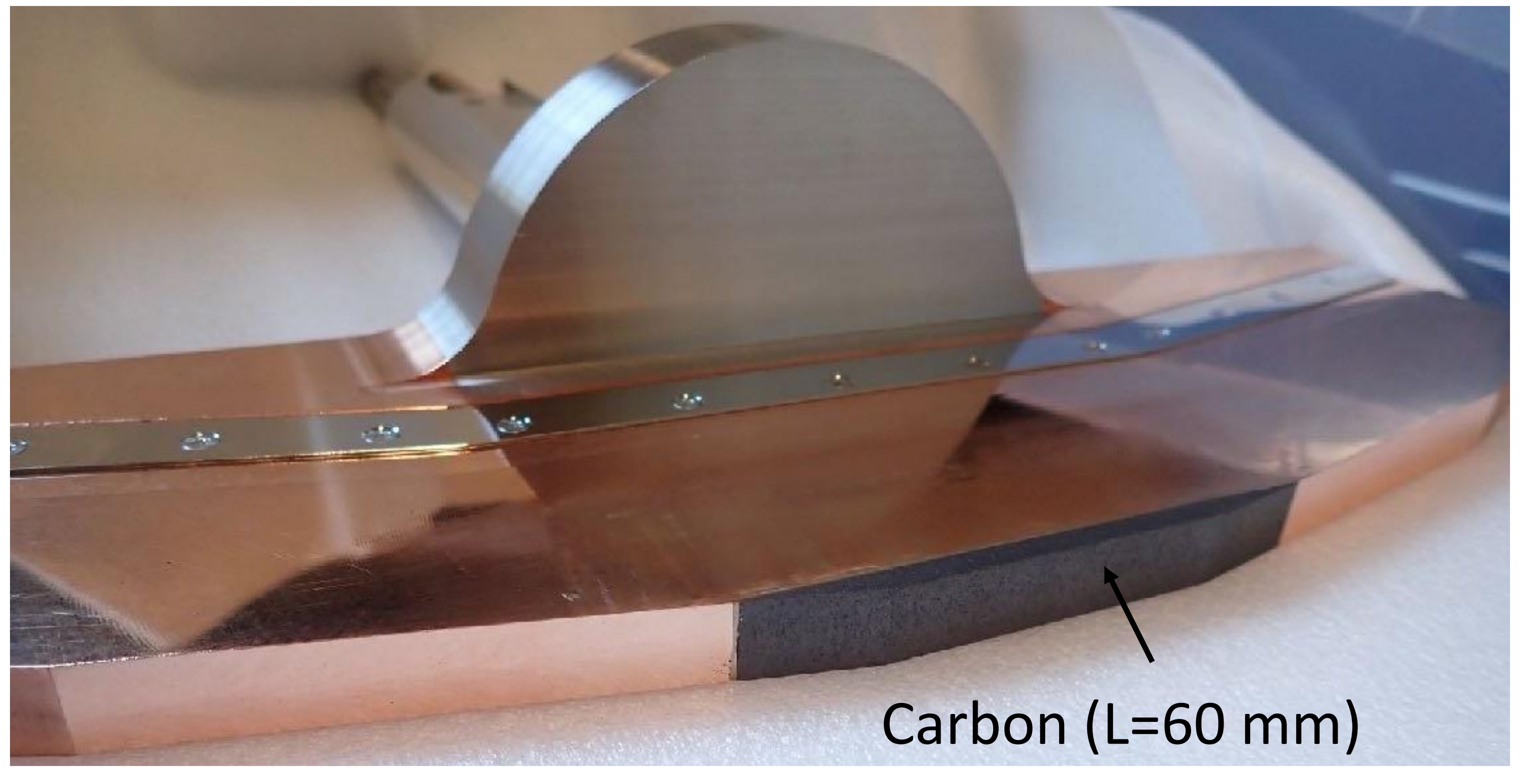


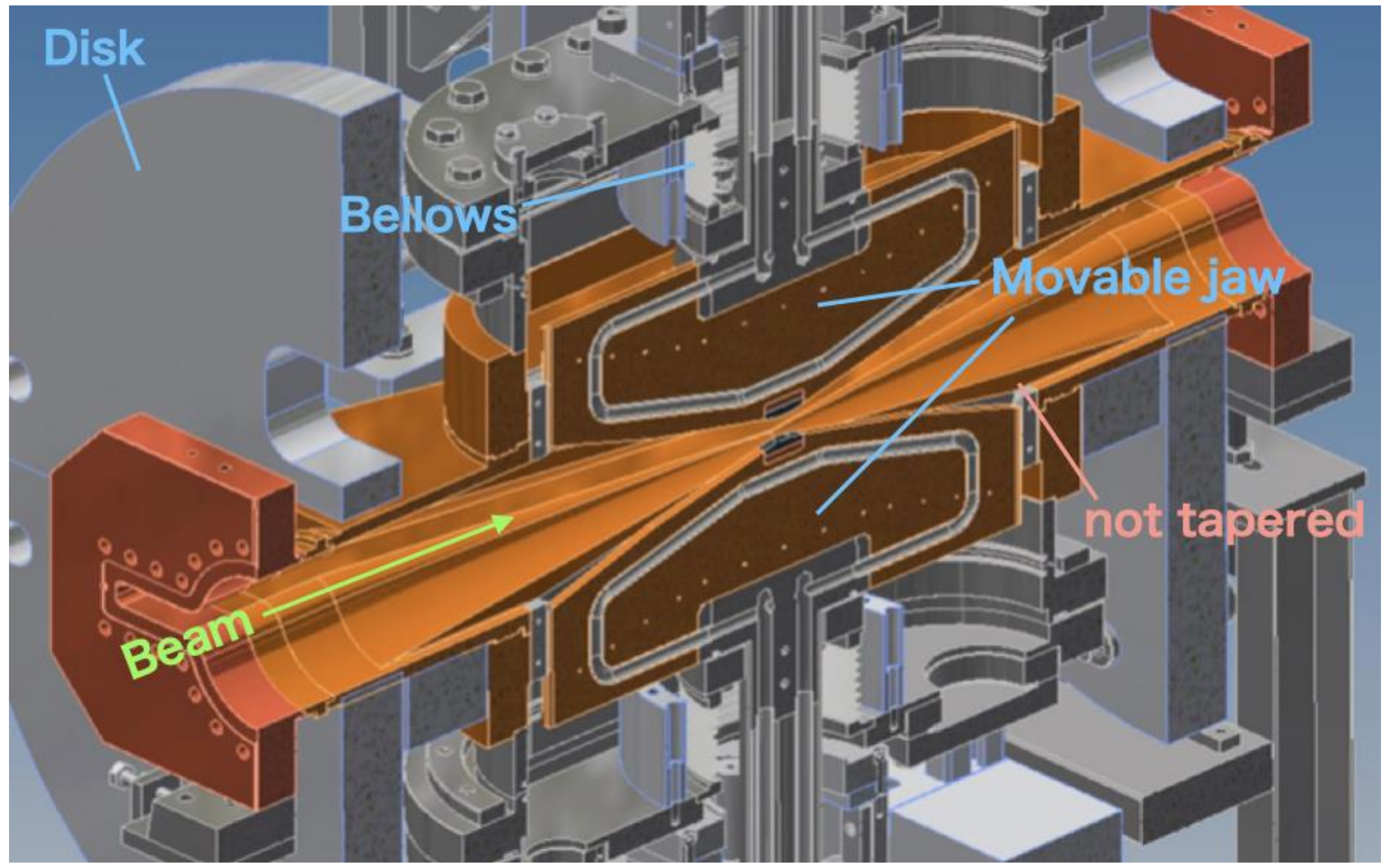
- We expect the same IR BG level with L_Z = 60mm for Graphite head compared to Tantalum with L_Z = 5mm.
- Changing the length of the tip-part of the collimator head:
  - Reduction of the IR losses:
    - 50mm < L_Z < 80mm is a flat total IR losses behaviour.
    - 1mm < L_Z < 50mm is almost linear dependence 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

Topics: Low-Z (Carbon) collimator in D06V1 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* and installed it in D06V1 during 2020 summer shutdown.
- No abnormal pressure rise and heating are observed, however its impedance lower the bunch current threshold.

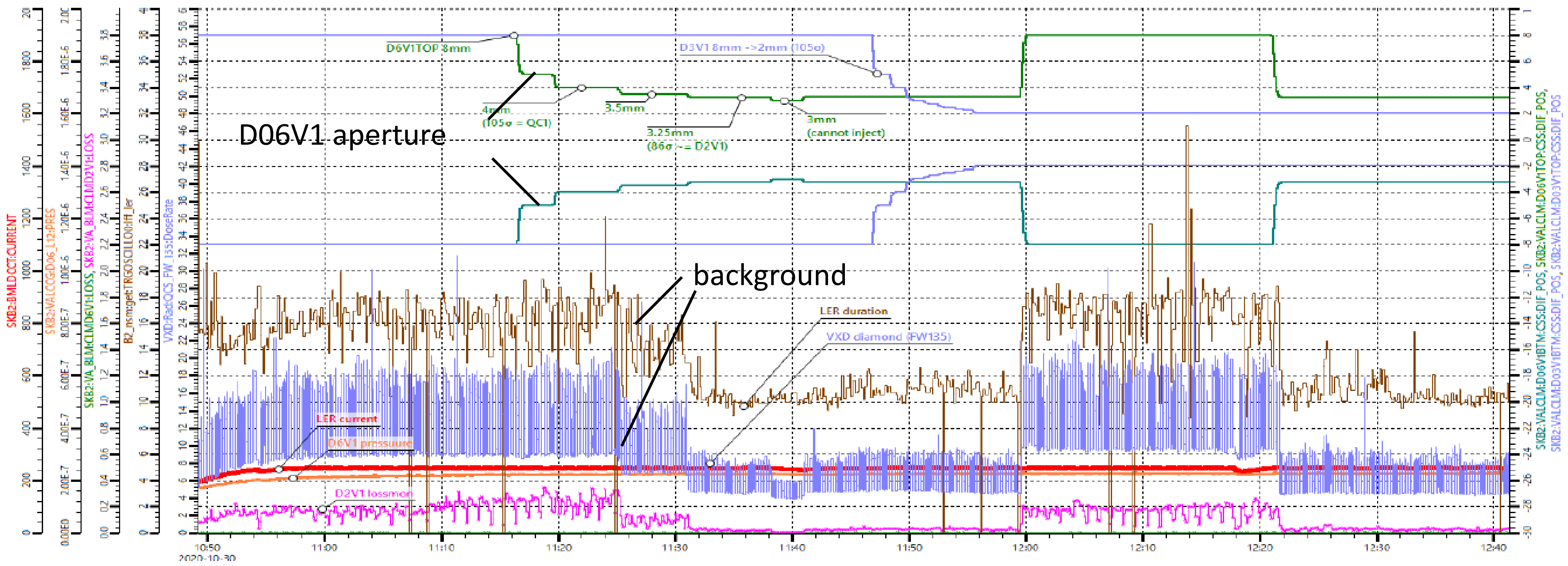
* Glass like carbon coated and impregnated C/C composite (GCX2002-U_GP2B, Toyo Tanso Co.,Ltd.).





D6V1 vs. diamond, duration

H. Nakayama



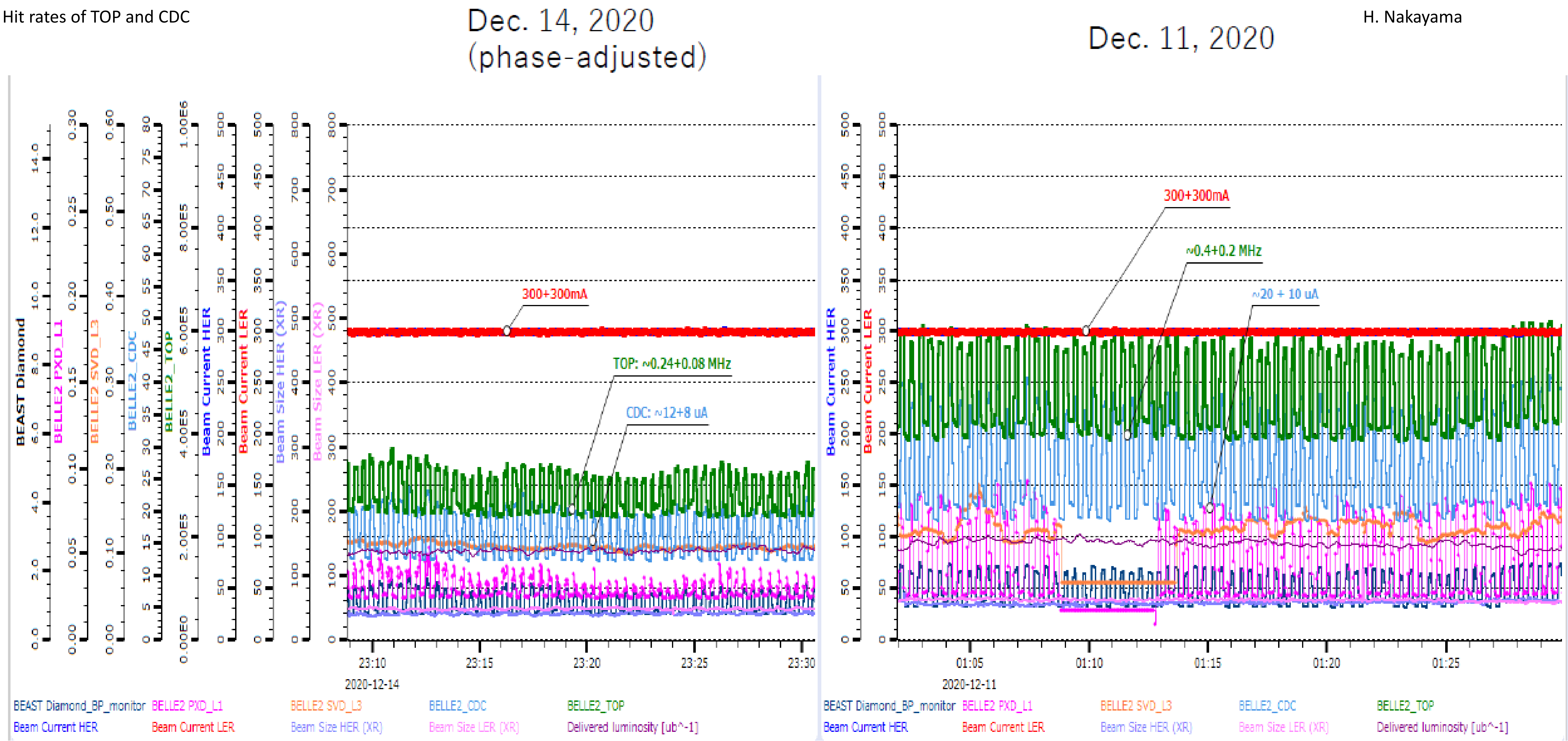
1) We closed D6V1 down to 3mm at I=250mA and didn't observe pressure increase around D6V1. The collimator is well baked now ☺
2) The background changes as expected against D6V1 width:
 - When D6V1 became narrower than QC1, **diamond injection/storage loss** and **injection duration** significantly improved. D2V1 loss also became smaller.
 - When D6V1 became narrower than D2V1, injection efficiency dropped significantly, so we stopped there.
3) We also closed D3V1 down to 2mm and didn't observe any significant improvement in BG, as expected for b*y=1mm optics.

Topics: Trial of phase matched optics between collimators in LER

- In its final stage (Dec. 14th), LER optics was changed to one where the phase advance between D02V1-D03V1 and D02V1-D06V1 are 3.5 and 16, respectively.
  - Protecting D02V1 by the two collimators.
- By closing the D03V1 aperture to ±1 mm、the storage BG in TOP was decreased by 30-40%. However, injection BG in VXD was increased and the effect of collimators' impedance became prominent (talk later).

Hit rates of TOP and CDC

H. Nakayama



Topics: Bunch length measurements for collimator apertures

- We measured the bunch length in LER in the collimators' impedance study simultaneously.
- No correlation for the collimators' apertures.
- However, it's longer than expected.

H. Ikeda