Beam collimators
(focusing on 2020c, 2021ab mainly)

25th KEKB Review

2021-09-01

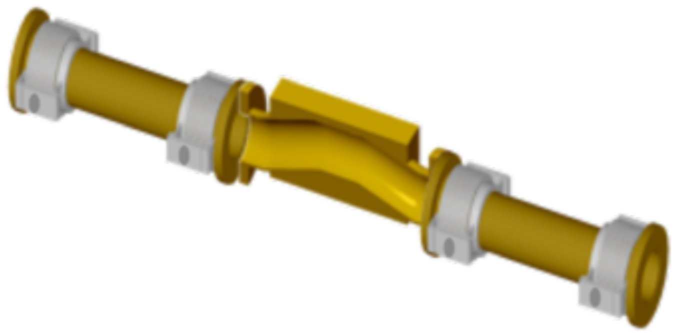
T. Ishibashi

Contents

- Beam collimators in SuperKEKB main ring
- Design
  - Basic design
  - RF shield
  - Impedance
- Issue
  - Damage
  - Low-Z collimator
  - Beam size blowup in LER (TMCI)
  - Accidental firing of injection kickers
- Plan
  - Replacement of the damaged jaws, installation of hybrid type jaws
  - Relocation of D02V1 collimator to match the betatron phase between this and QC1RP
  - Non-linear collimator at LER OHO section (during Long Shutdown-1 in 2022)
- Summary

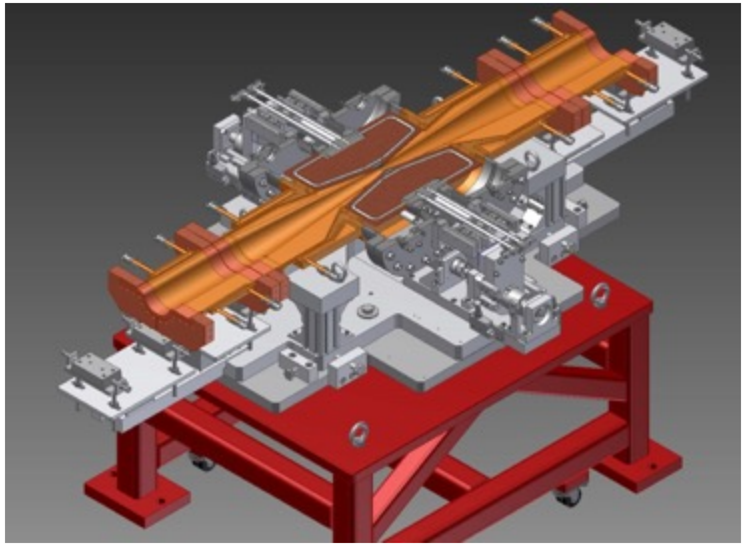
Beam collimators in SuperKEKB

- 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.



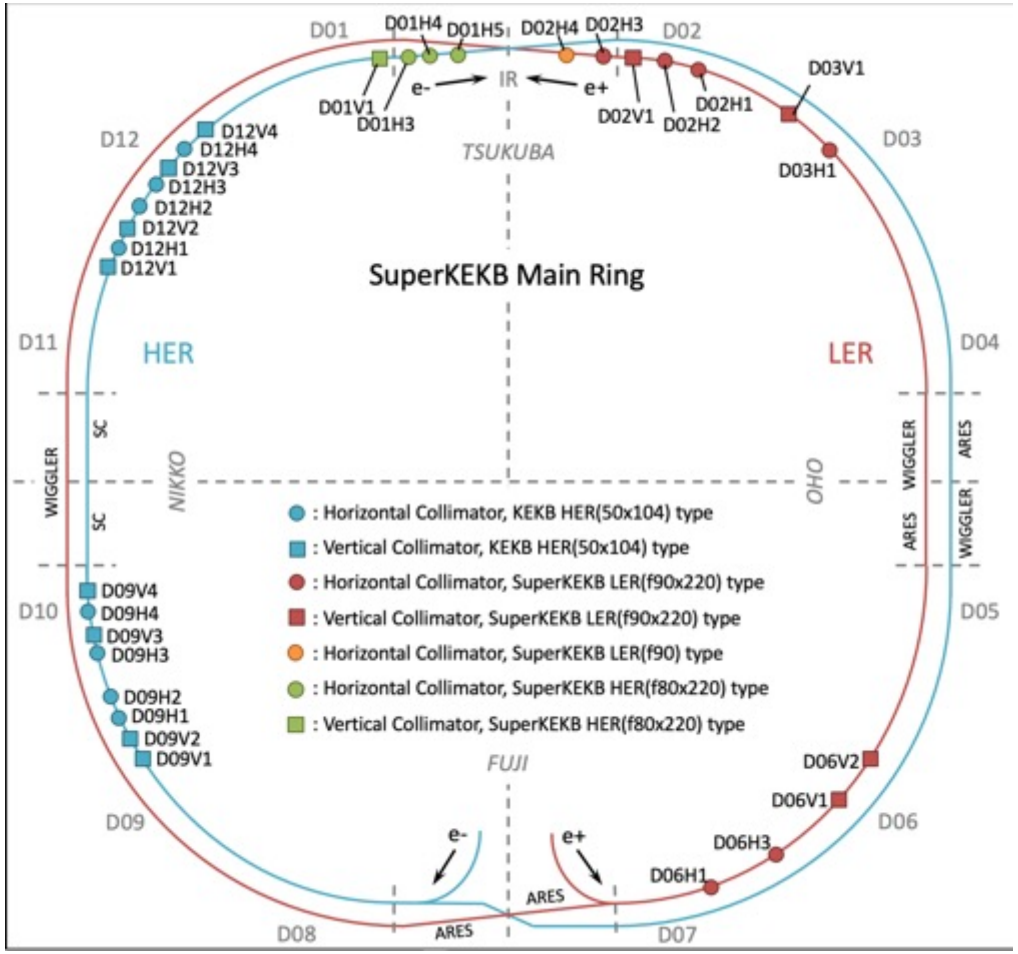
KEKB type

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



SuperKEKB type

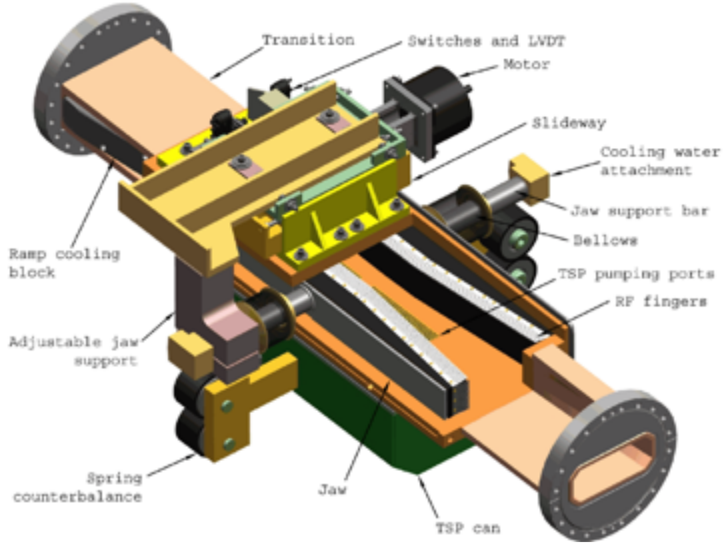
[T. Ishibashi et al., PRAB 23, 053501 (2020)]



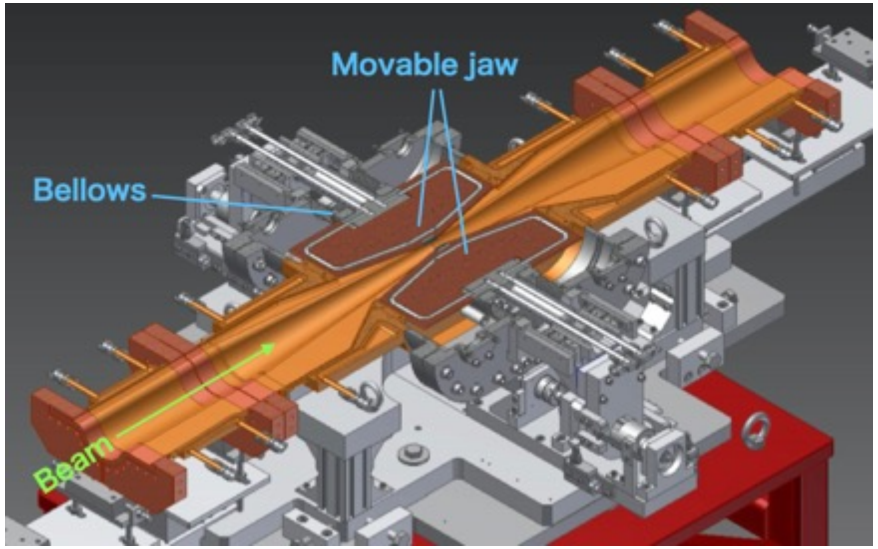
Location of collimators in MR

Design

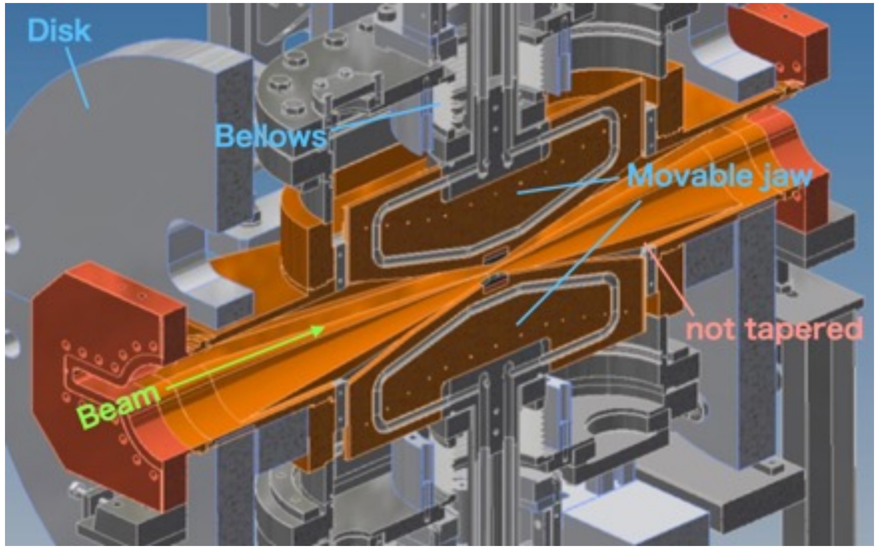
- We referenced movable collimators for PEP-II in SLAC for the basic design.
- A collimator chamber has two movable jaws, which are placed the horizontal/vertical direction.
- Part of the movable jaws is hidden inside the antechambers to avoid a trapped mode in gaps between the movable jaw and the chamber.
- 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

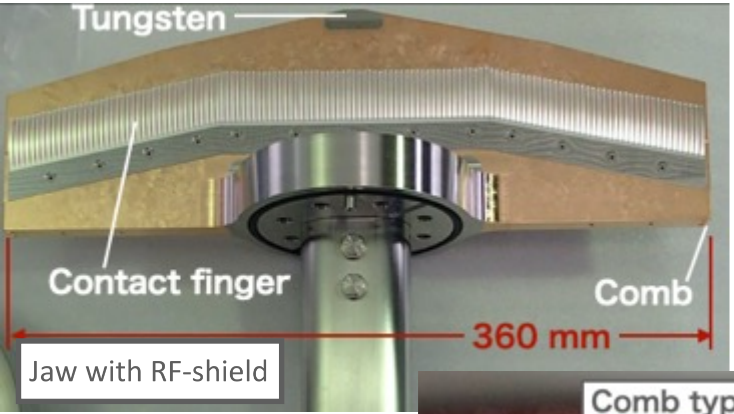


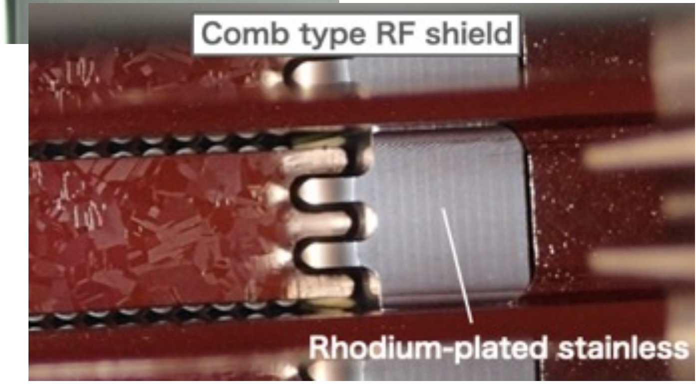
Vertical direction

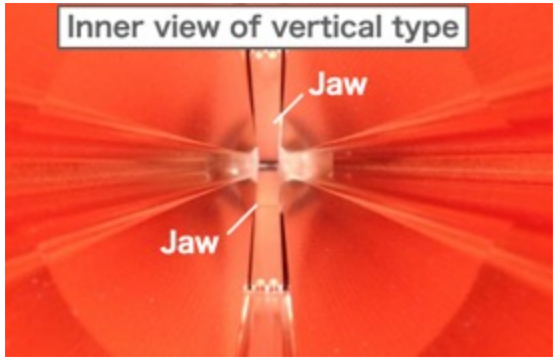
SuperKEKB type collimator

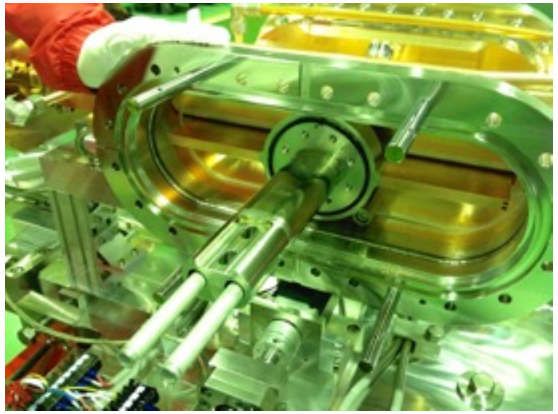
Design – RF shield

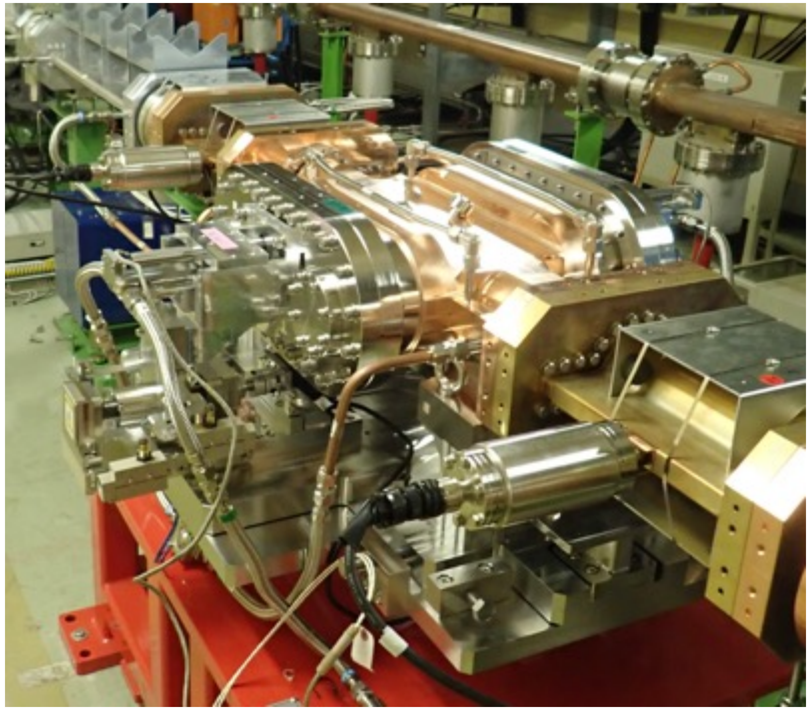
- Contact finger-type RF shield is attached on the side wall of each jaw.
  - The fingers are made of silver-plated INCONEL.
  - The contact surface on the chamber is made of rhodium-plated stainless steel.
- Contact-less comb-type RF shield is adopted between the longitudinal end of the jaw and the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







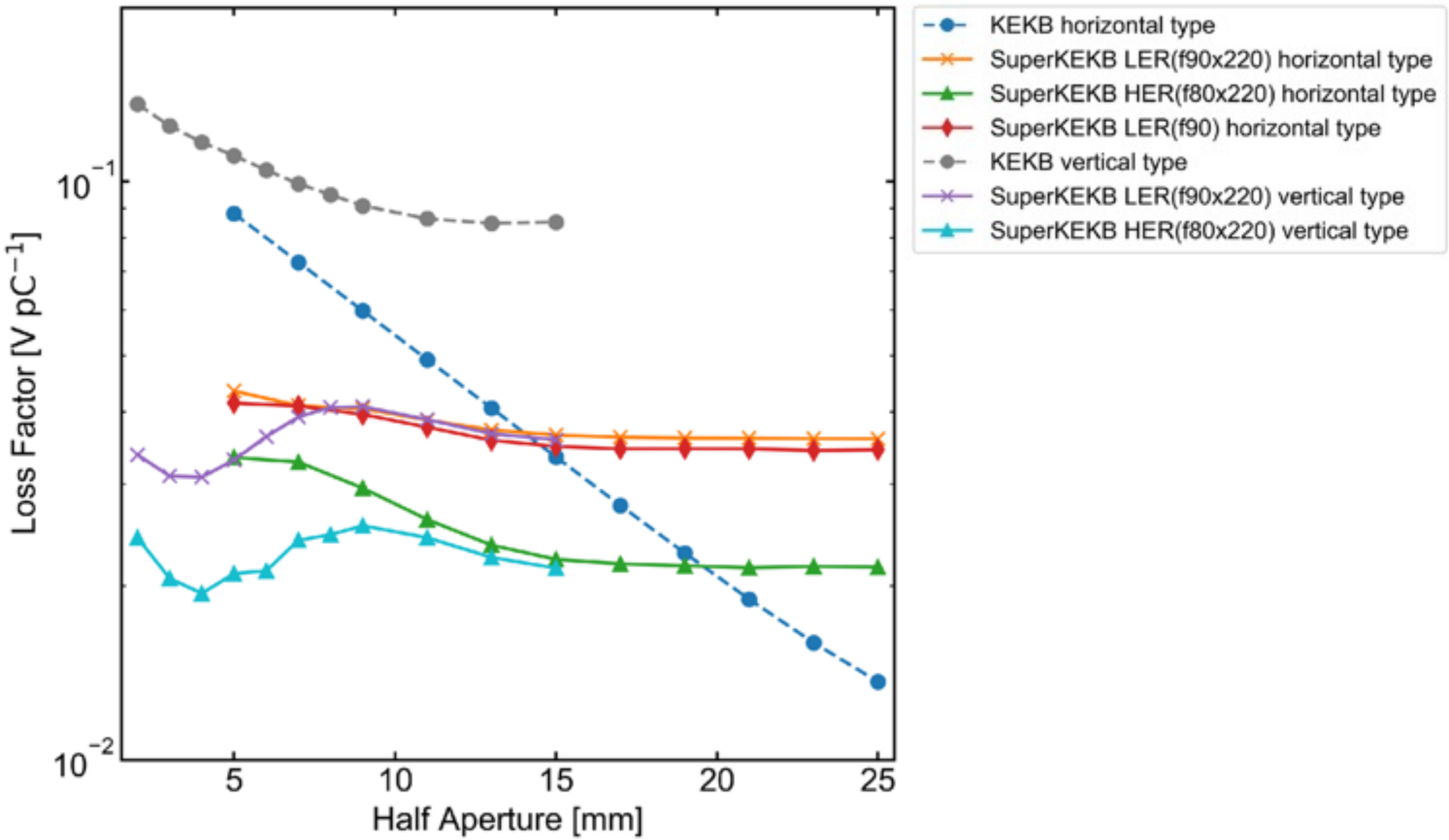




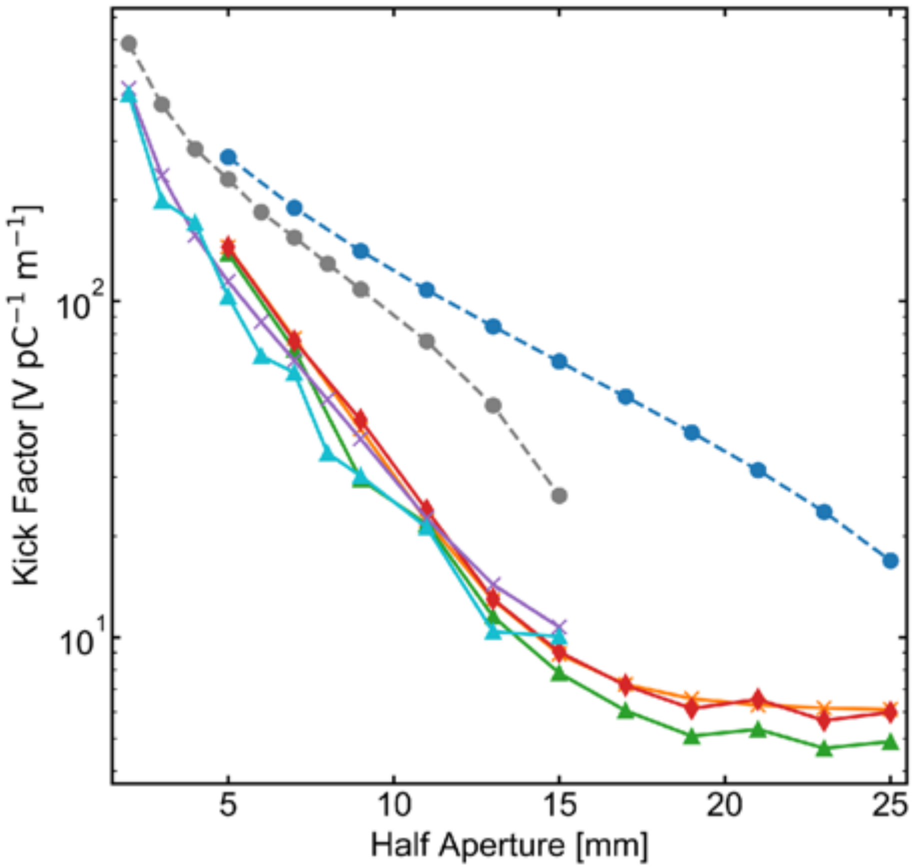
Design – Impedance

- 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)



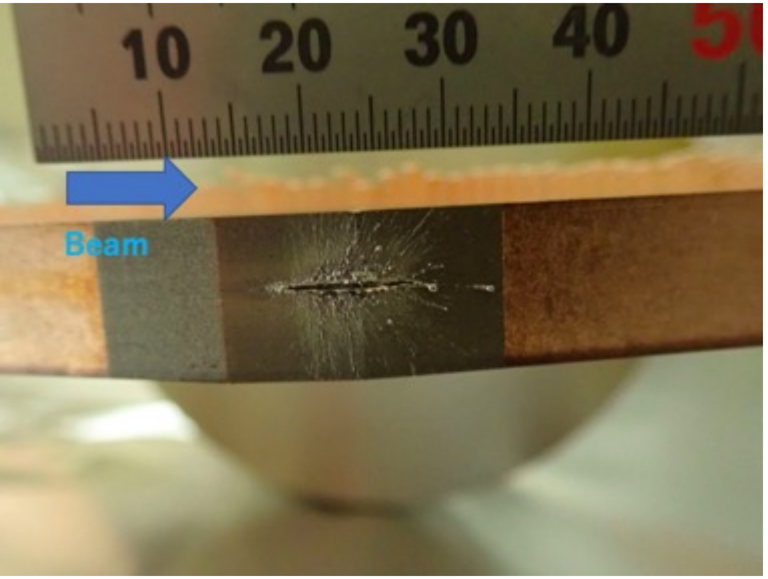
Kick factor (bunch length: 6 mm)

Issue – Damage

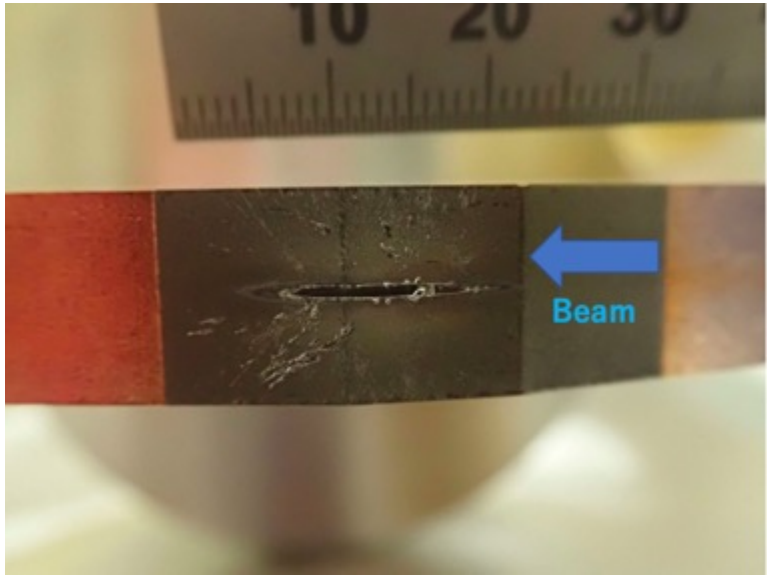
* short tantalum tip which has 5 mm.

- Jaws of the 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 happened near them with a QCS quench .
- The damaged tungsten tip 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.

[S. Terui]



D02V1 bottom side (38 μSv/h)

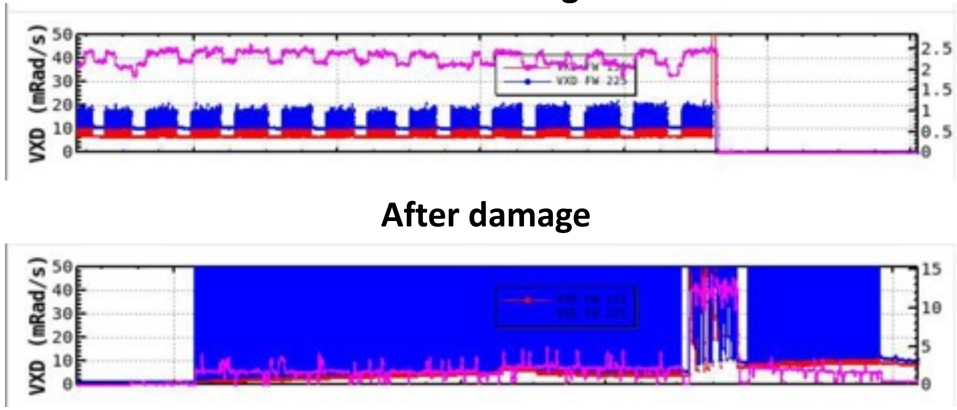


D02V1 top side (95 μSv/h)

taken on 2021-06-08

Before damage

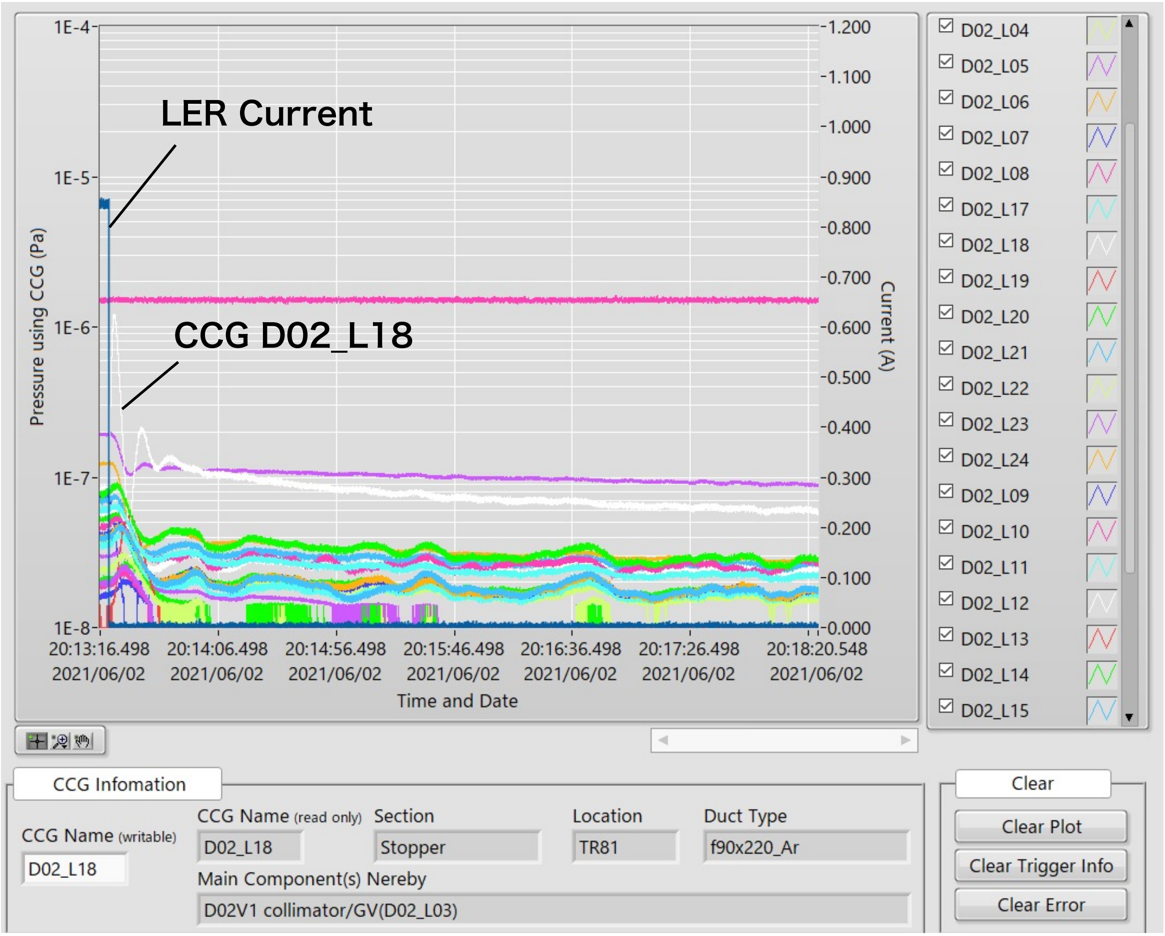
After damage



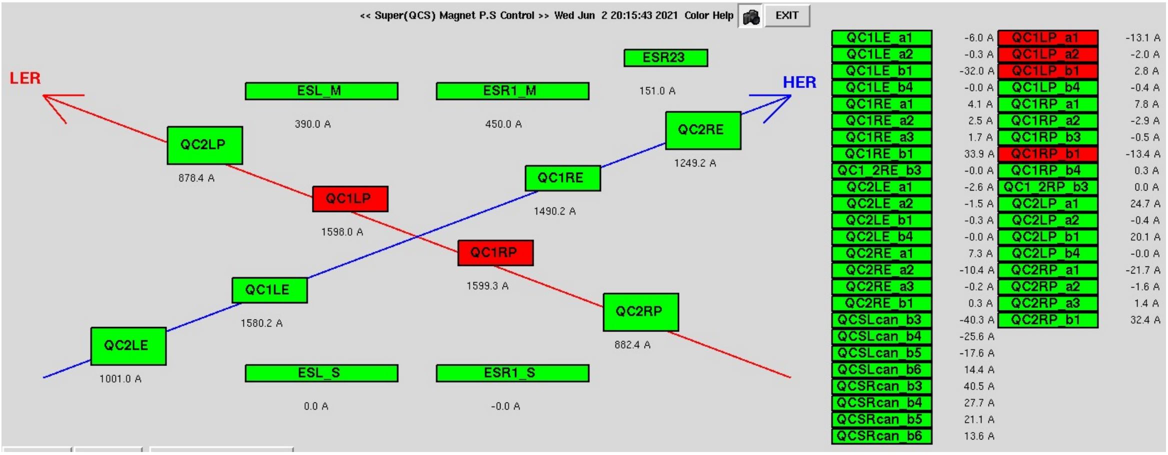
Issue – Damage

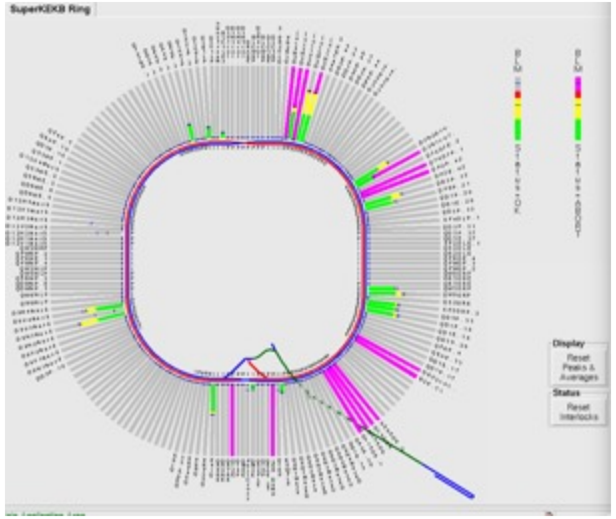
- In case of a damaged event in 2021-06-02 20:13 (2021b run).
- Pressure near CCG D02_L18 and D06_L12, which are placed near D02V1 and D06V1 collimator respectively, was increased instantaneously (beam hit the jaws probably).
- QCS quench happened (QC1LP, QC1RP in LER).

Pressure and beam current



Status of QCS

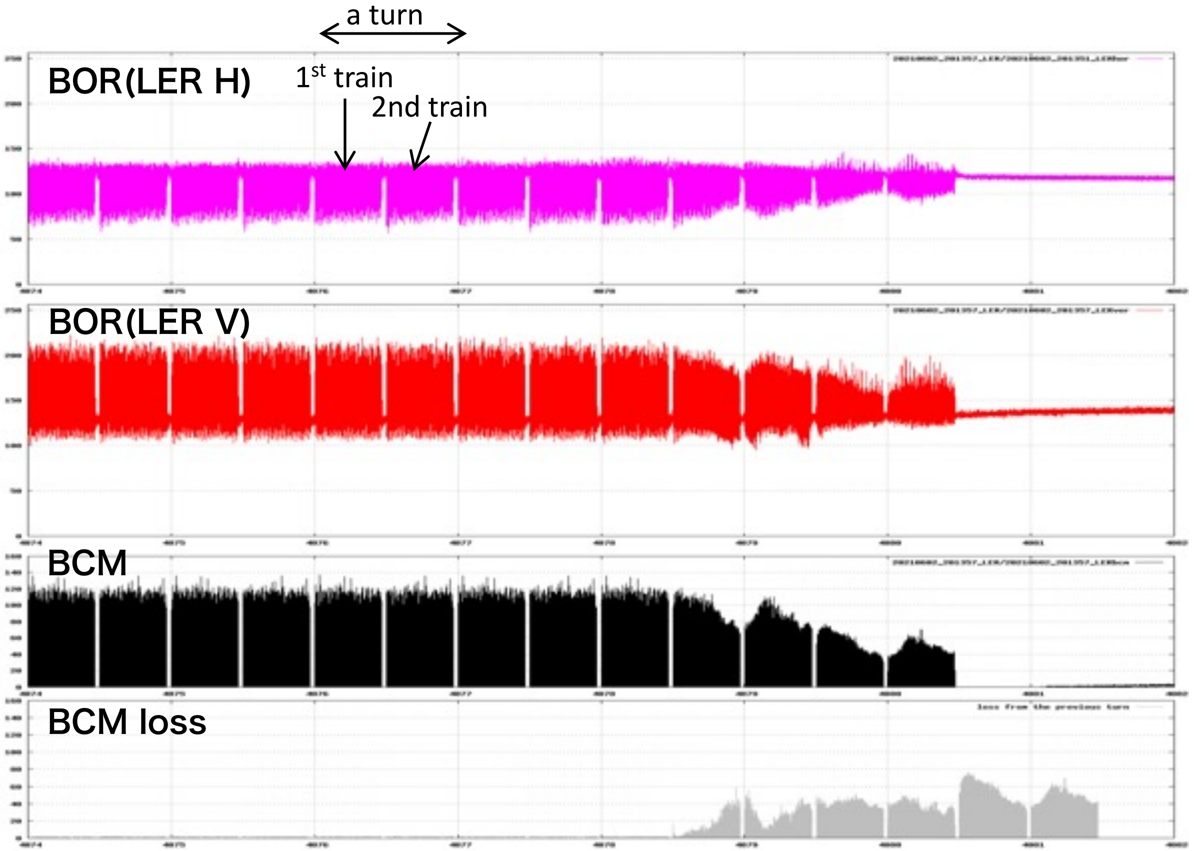




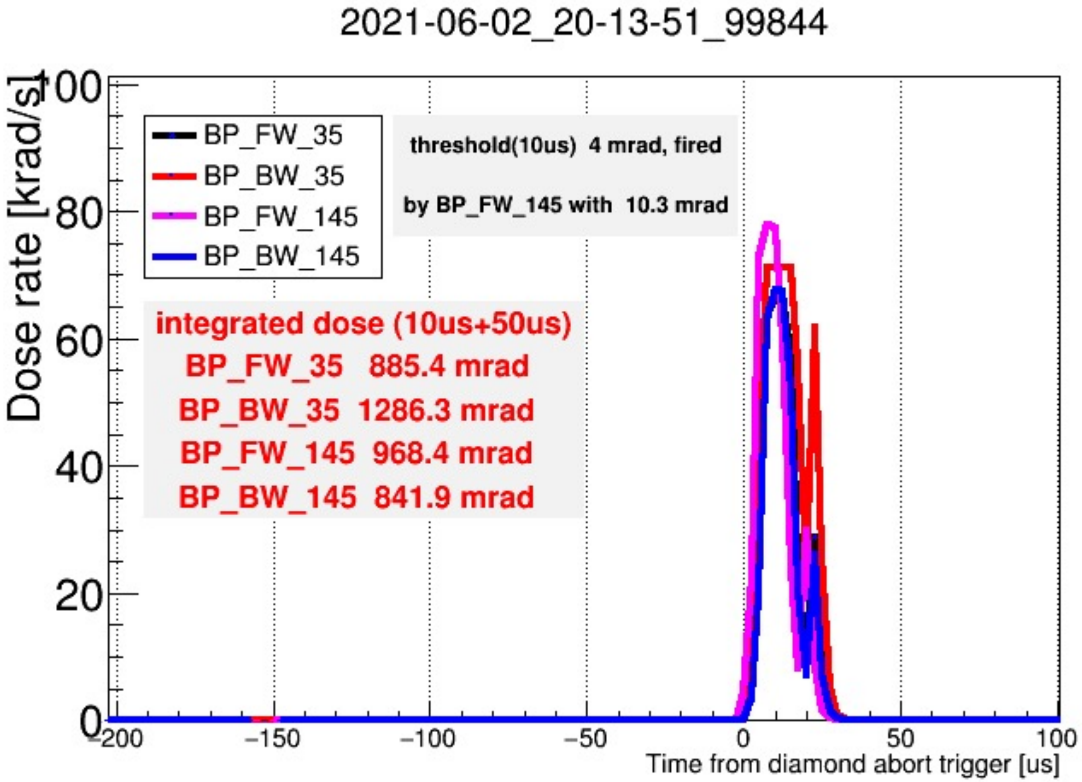
Loss monitors in the rings

Issue – 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

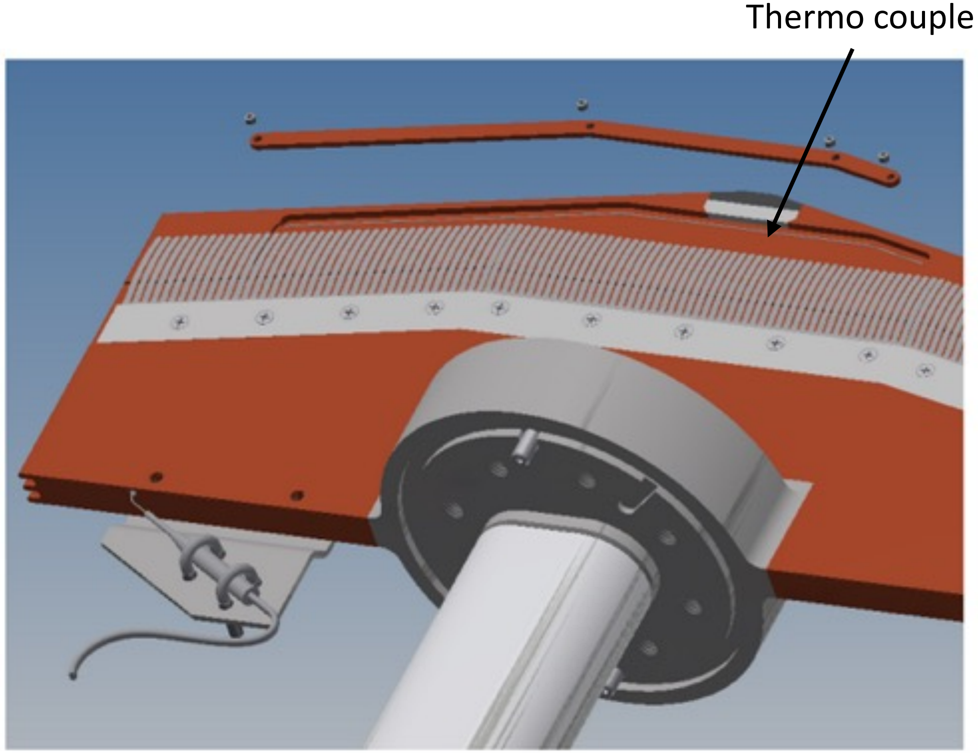
Issue – Damage

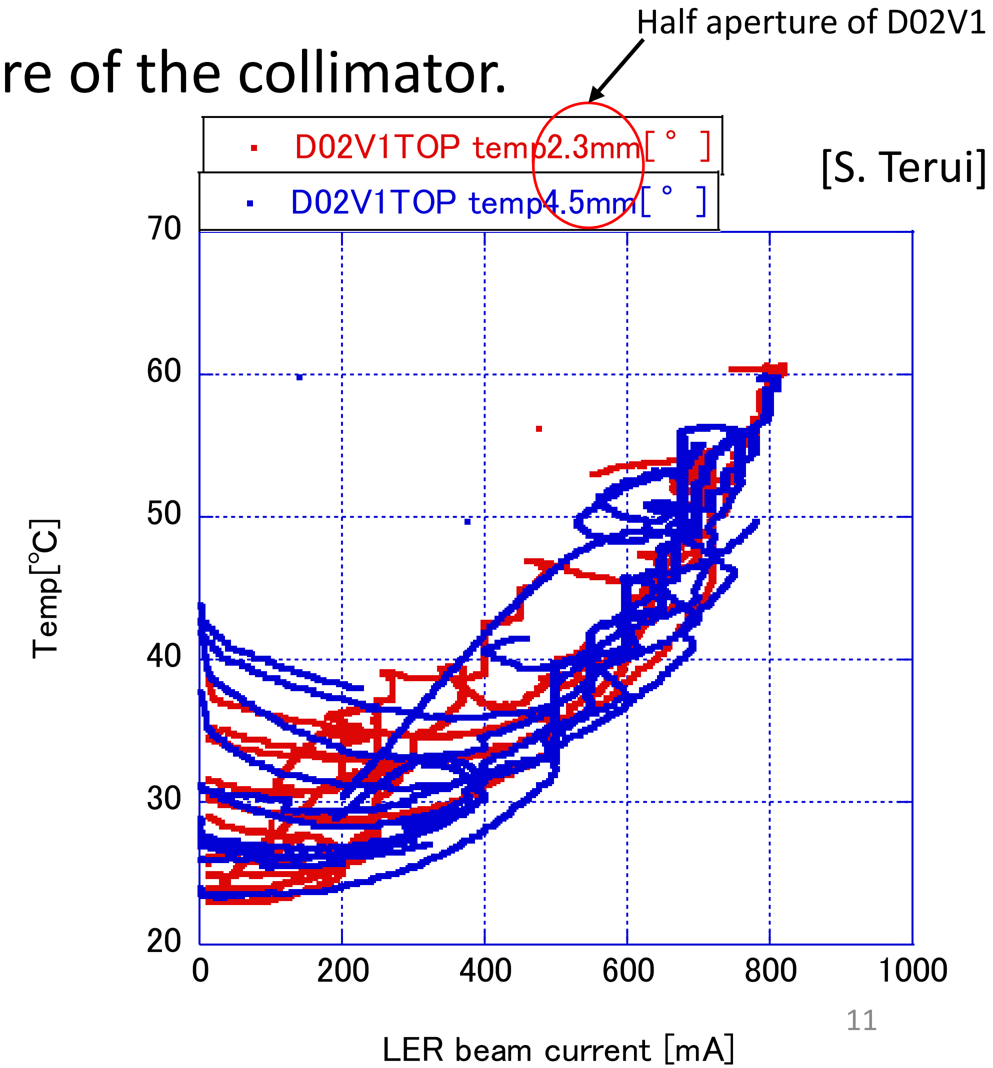
- Question from Frank Zimmermann
  - Can we perhaps get a thermomechanical analysis of the effect of beam loss at a collimator and also a calculation of deformation mode frequencies of a collimator?

- Answer
  - We’ve started to investigate the displacement and the deformation mode frequencies.
  - The deformation during the operation is dozens of microns by our calculations and measurements, probably.
  - We’ve observed a deformation mode frequency around 10 Hz and the amplitude in the vertical direction is ~5e-8 m.

Issue – Damage

- Temperature at the tip
  - We have used a special jaw, which has a thermocouple at the tip, in D02V1 during 2019b (βy*=2 mm)
  - The temperature does not depend on the aperture of the collimator.
  - The temperature depends on the beam current.

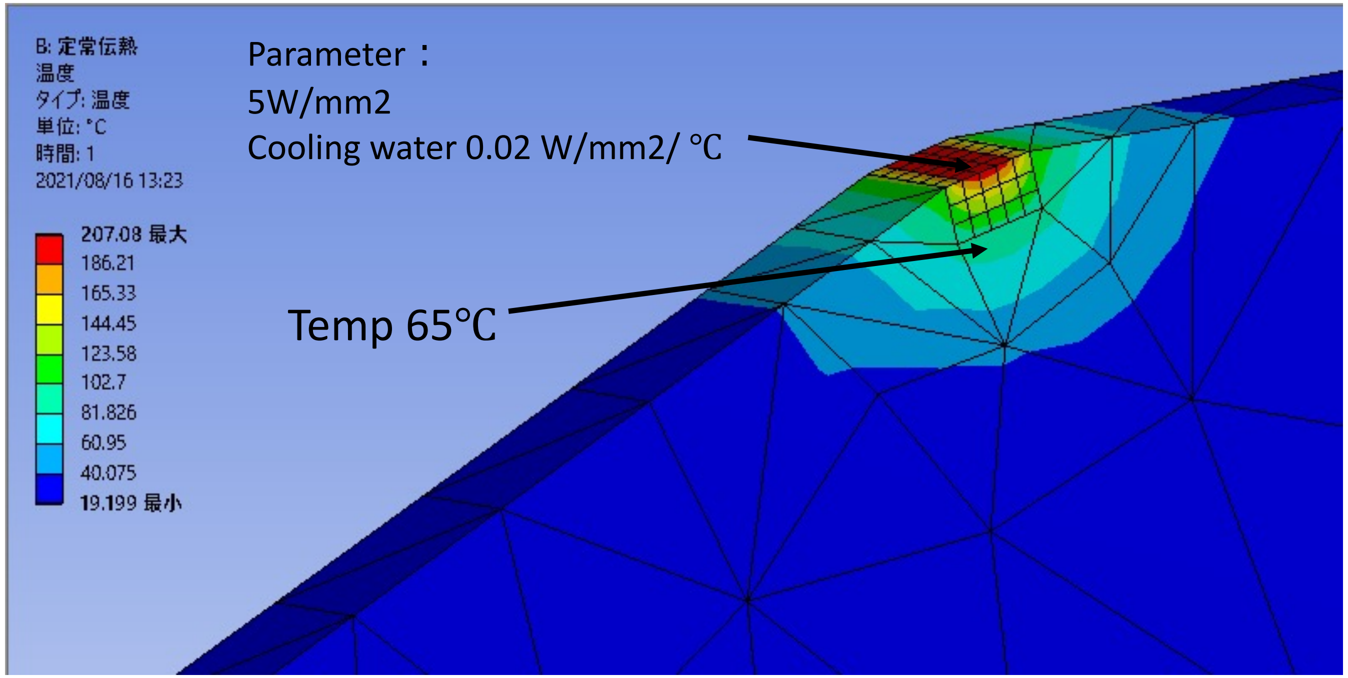




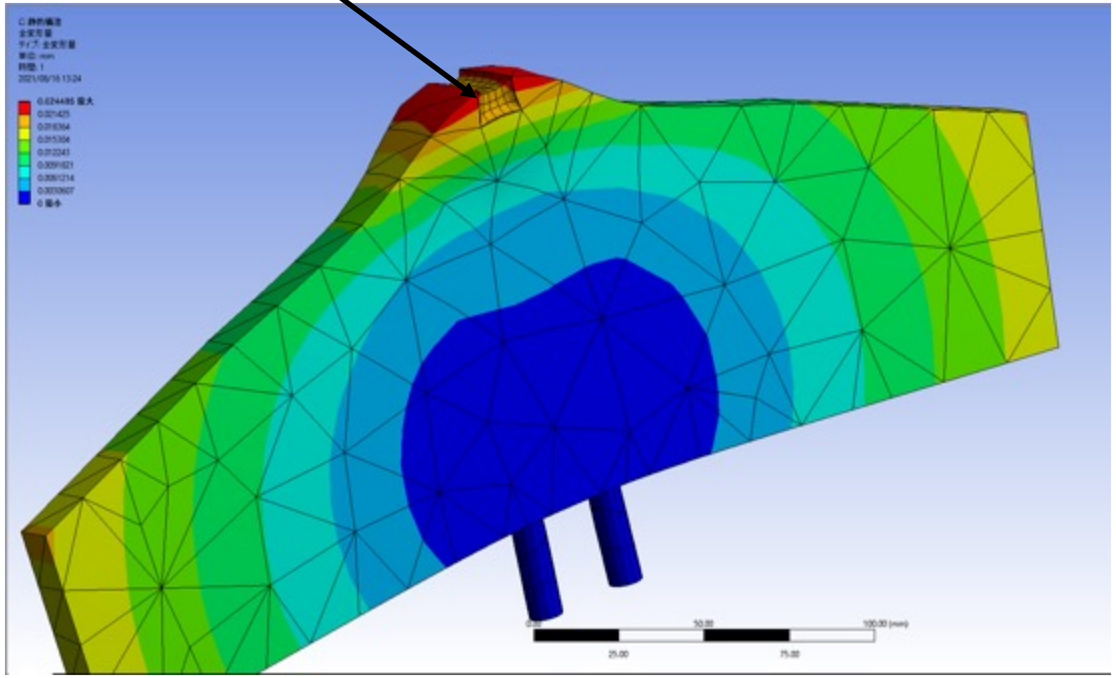
Issue – Damage

- The heat input at the tip was roughly estimated using CST particle studio for a condition of I_{LER}=800 mA.
- The temperature at the embedded temperature sensor is ~65℃ in ANSYS, and this is consistent with it during the operation.
- In this thermomechanical analysis using ANSYS, the displacement is ~20 μm.

[S. Terui]



Maximum displacement at tungsten: ~20 μm

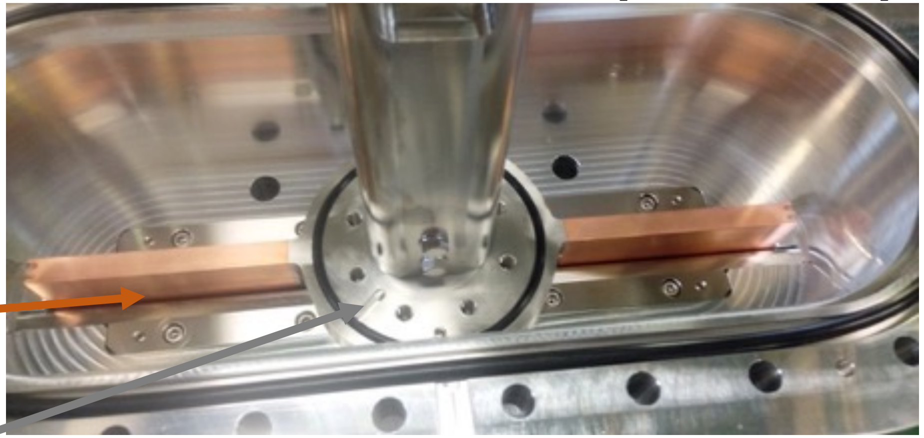


Issue – Damage

[S. Terui et al.]

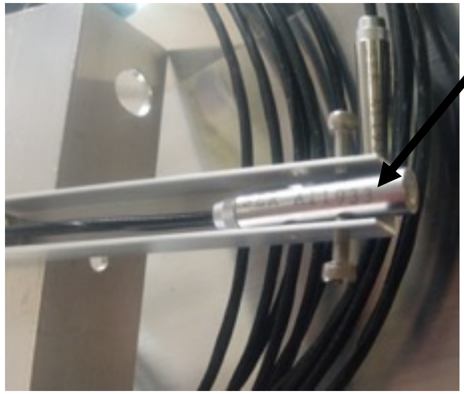
- We measured the displacement at the tip by the heating.
- The displacement is less than 20 μm in this setup.

preliminary

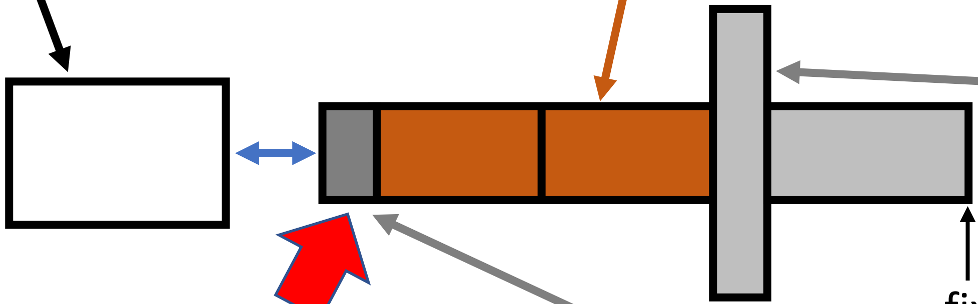


(without cooling water)

Displacement meter
(capacitor type)



Collimator jaw (Cu)

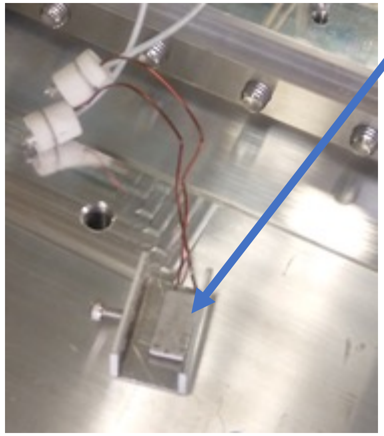


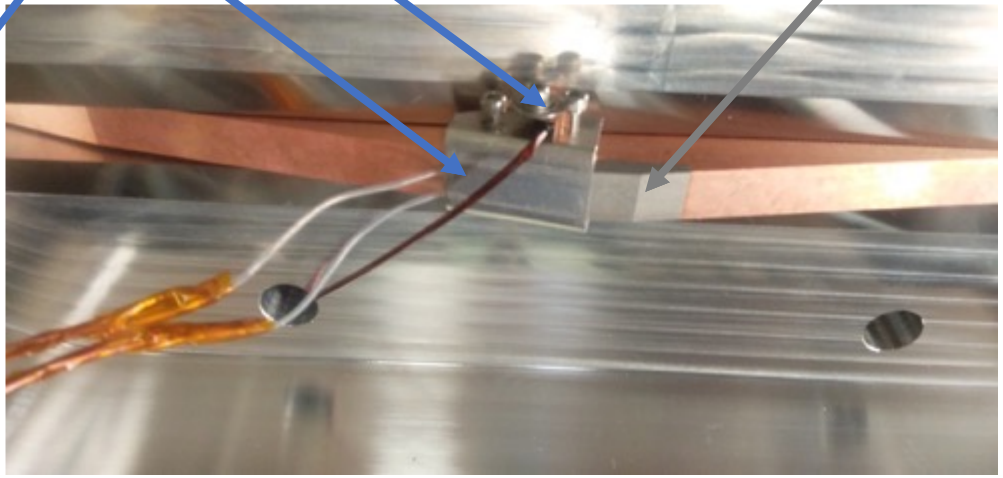
Collimator head flange (SUS)

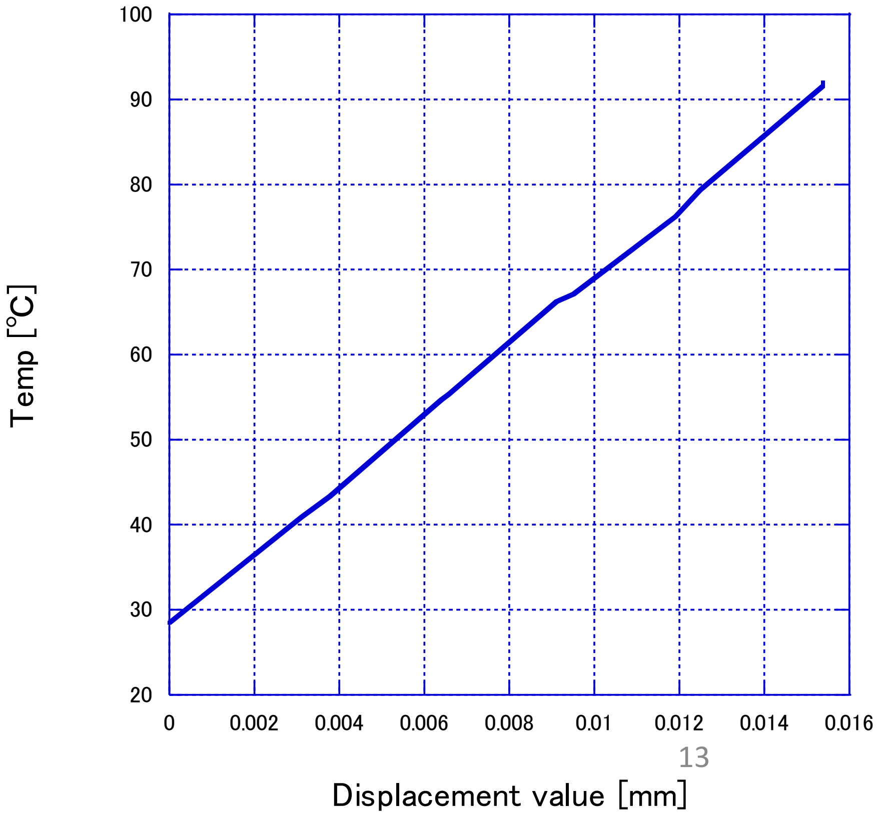
fix

Attached a ceramic heater and thermometer
on the tip.

Collimator jaw (W)

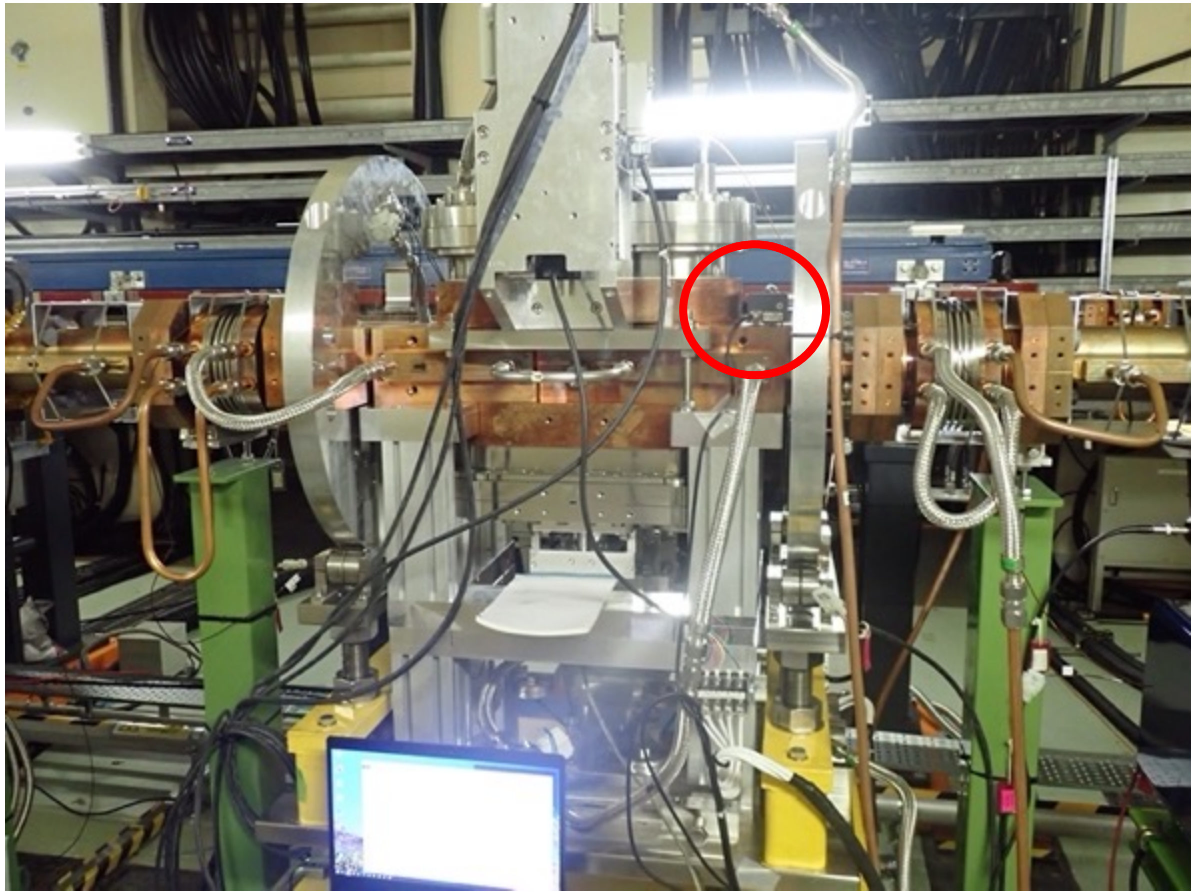






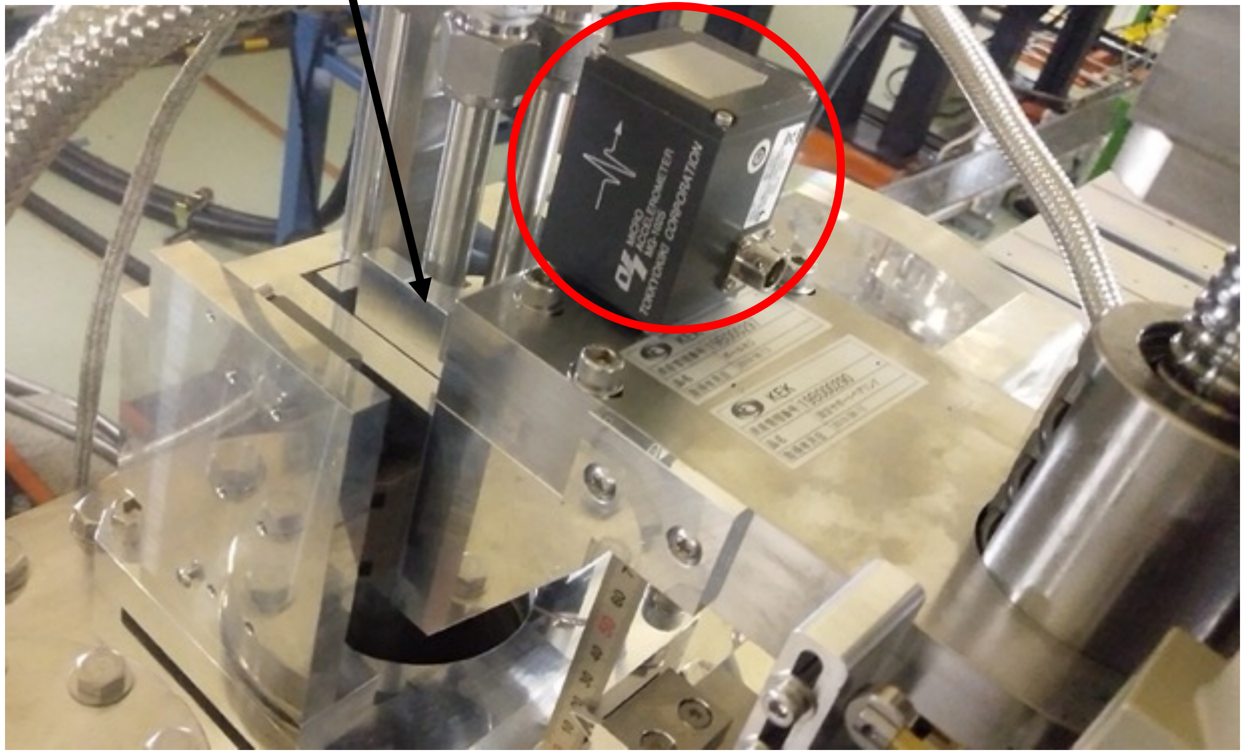
Issue – Damage

- Mode frequencies measurement
  - We measured the deformation mode frequencies in the actual machine (D02V1 collimator) with the water flow on/off.



Measurement for the chamber

Jaw's axis



Measurement for the jaw (+ chamber)

Issue – Damage

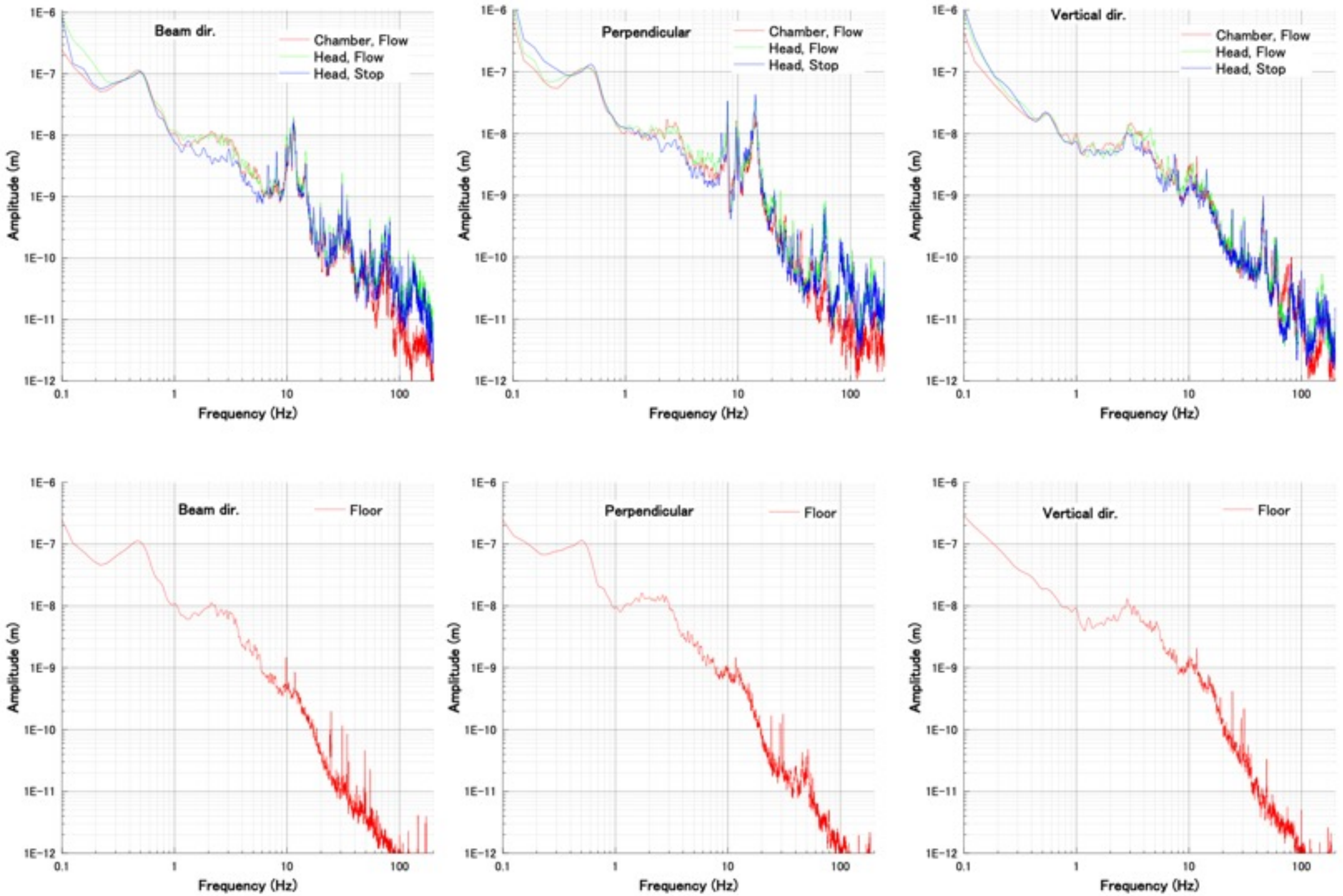
- Mode frequencies measurement
  - There is an eigenmode around 10 Hz, and the maximum amplitude to the beam (vertical direction) is ~5e-8 m for the jaw with the cooling water flow.

[H. Yamaoka et al.]

Amplitude

D02V1

Floor



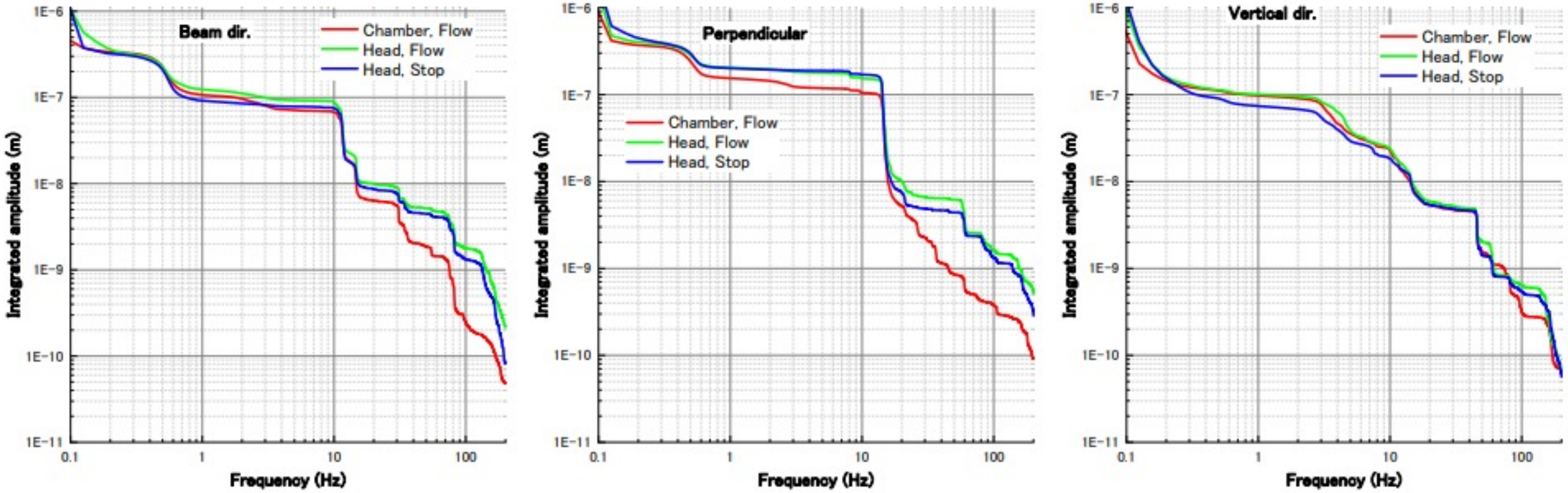
Issue – Damage

- Mode frequencies measurement

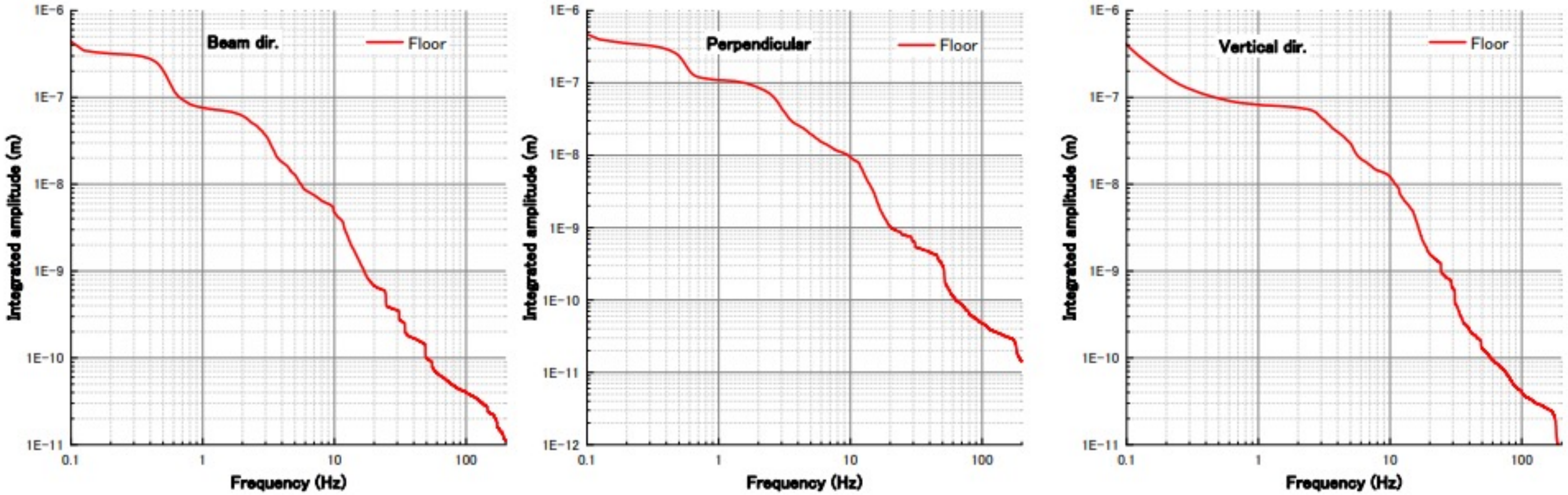
[H. Yamaoka et al.]

Integrated power spectrum density regarding to the frequency

D02V1



Floor



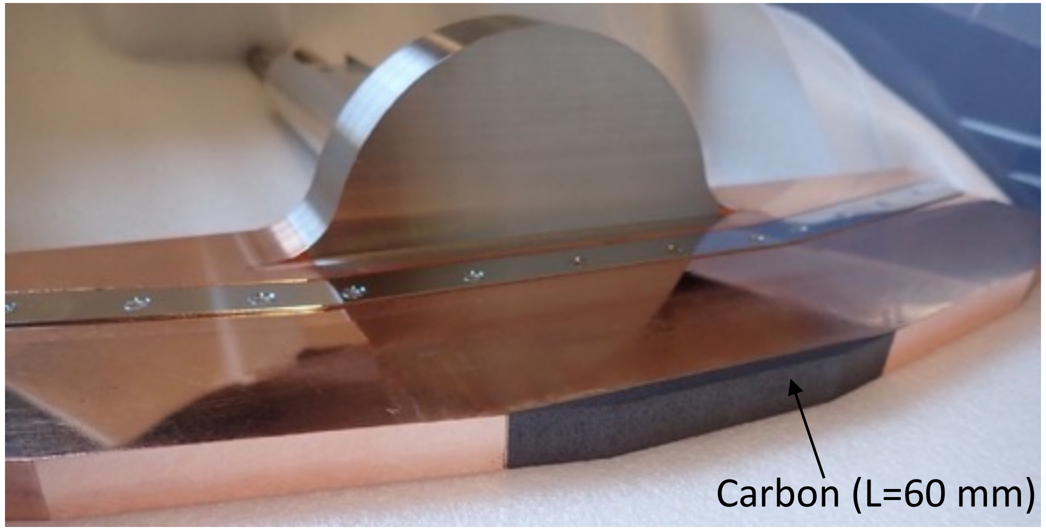
Issue – Low-Z collimator

- 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*.

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

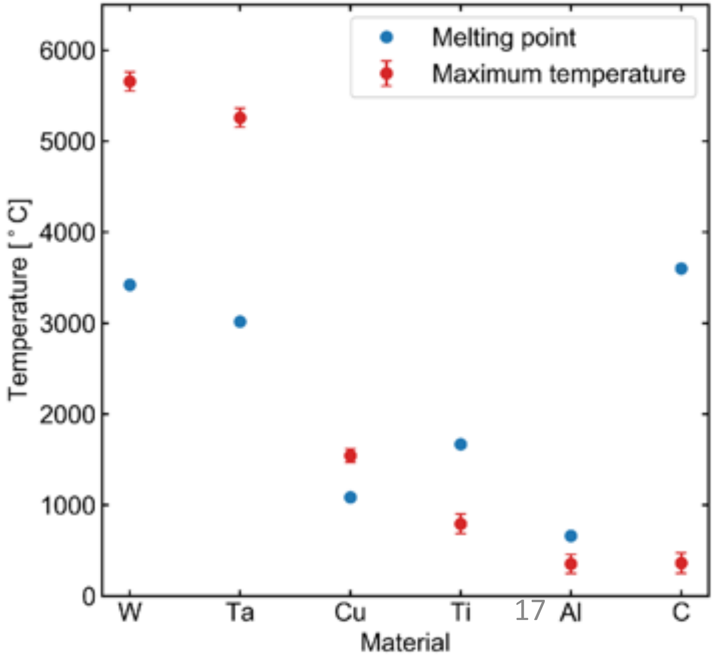
* Glass like carbon coated and impregnated C/C composite (GCX2002-U_GP2B, Toyo Tanso Co.,Ltd.).

- Installed in a existing collimator (D06V1) during 2020 summer shutdown and worked for BG suppression during 2020c, however removed during 2021 winter shutdown because of the impedance problem.



Carbon jaw installed in D06V1.

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



Issue – Beam size blowup in LER (TMCI)

- First high bunch current study with the single-bunch operation to observe the threshold.

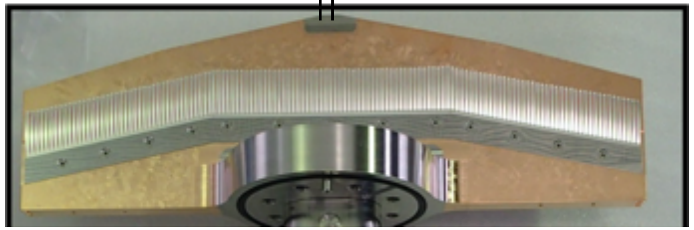
D06V1 (Carbon, L=60 mm) survey on 2020-12-02

In the study, the maximum bunch current was ~1.04 mA/bunch (We were not able to inject above this).

Collimator	β_y [m]	aperture [mm]	k_T [V/pC/m] [a]	
D06V1	67.3	±2.0	841 [b] ←	552 [c]
D06V2	20.6	±3	237	
D03V1	17	±3	237	
D02V1	13.9	±3	237	

Calculated value: $I_{\mathrm{b,th}} \approx 0.99$ mA/bunch ← (1.49 mA/bunch)

L: length of the flat region at the tip



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

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

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

a) Kick factors are calculated by GdfidL (σ_z: 6 mm) .
b) including lossy metal (GdfidL 2020-07-23, T. Ishibashi).
c) loss-free (GdfidL 2013-10-15, T. Ishibashi)

This study is conducted taking the beam orbit and the D06V1, D03V1 vertical offset into consideration.

B-PosY [mm]	V-offset [mm]
D06V1: 0.44	D06V1: -0.3
D06V2: 0.22	D06V2: 0
D03V1: 0.04	D03V1: 0.4
D02V1: 0.16	D02V1: 0

D06V2 (Ta, L=10 mm) survey on 2020-12-02

We were able to accumulate ~1.5 mA/bunch at least (We were able to inject above this).

Collimator	β_y [m]	aperture [mm]	k_T [V/pC/m] [a]	
D06V1	67.3	±4.0	249 [b] ←	205 [c]
D06V2	20.6	±1.8	490	
D03V1	17	±2.0	430	
D02V1	13.9	±1.0	1287	

Calculated value: $I_{\mathrm{b,th}} \approx 1.31$ mA/bunch

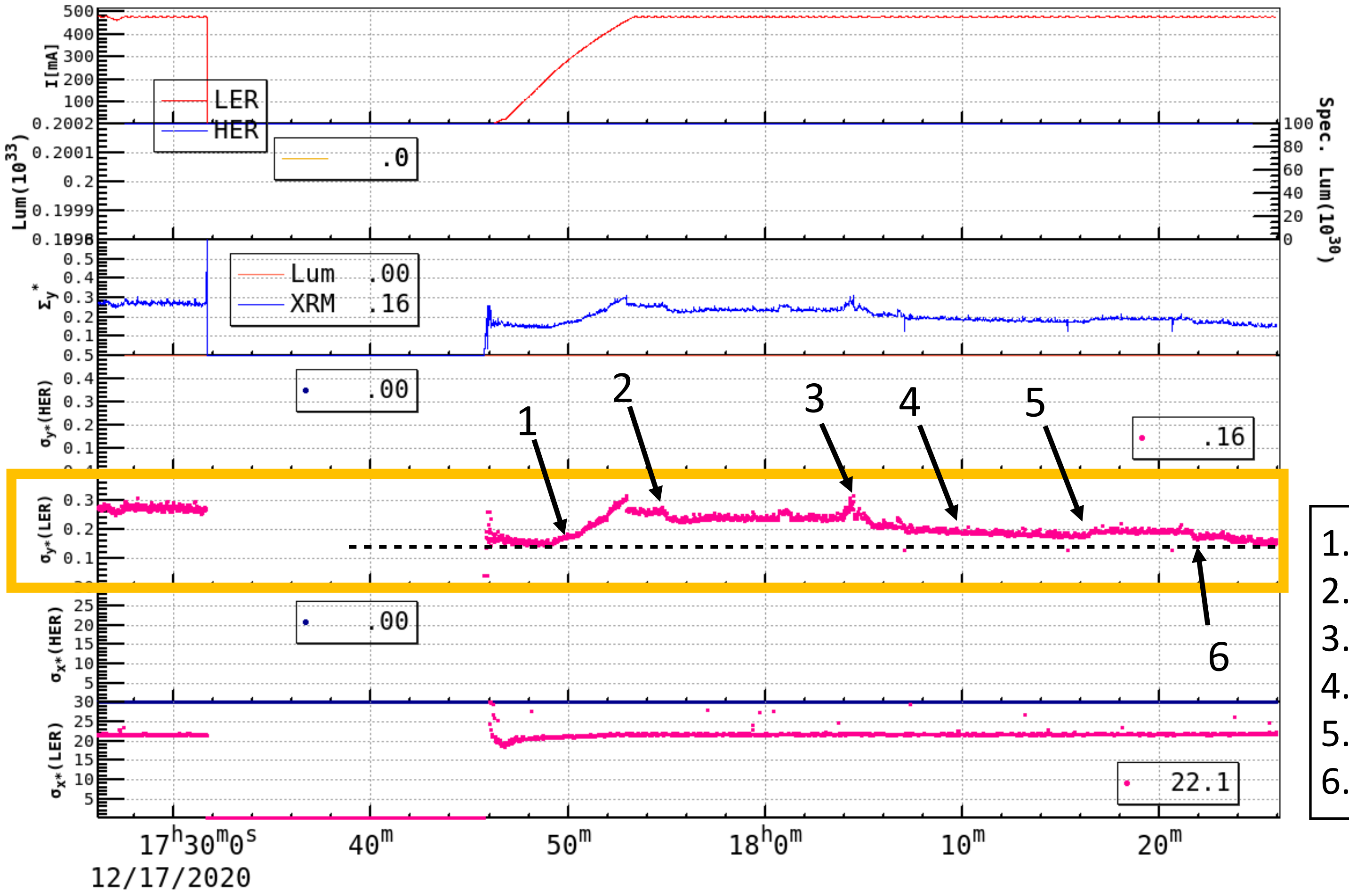
- In this study, the maximum bunch current looks consistent with the calculated value, but we didn't measure the beam size because of the single-bunch operation.
- After this study, a vertical beam size blowup derived from collimators' impedance has observed for the multi-bunch operation, and the threshold is 0.7-0.8 mA/bunch (much lower than the calculated value).

Issue – Beam size blowup in LER (TMCI)

- The impedance of D06V1 is larger than that of D03V1.
  - The kick factor of D06V1 (carbon, L=60 mm) is about twice larger than that of D03V1（tantalum, L=10 mm） by GdfidL.

→ Replaced the low-Z jaws with tantalum jaws before 2021a.

[Y. Ohnishi]

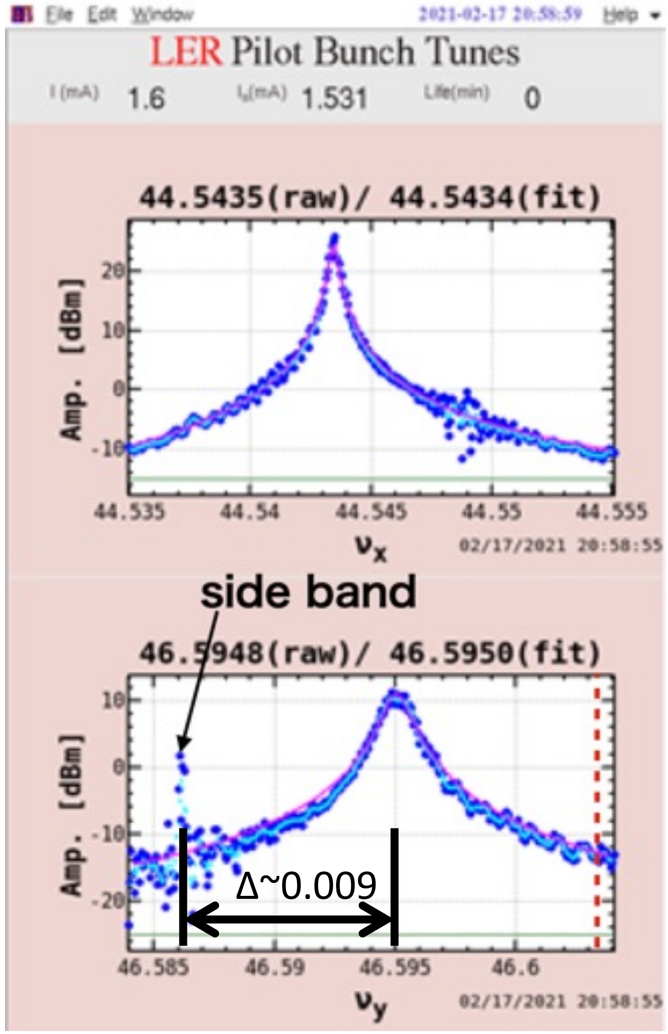


Carbon jaw installed in D06V1.

1. vertical beam size blowup with increasing bunch current
2. changed vertical tune
3. adjusted BxB FB gain
4. D03V1 open（18:09-18:14, ±1mm → ± 2 mm)
5. D03V1 close（18:16, ±2 mm → ±1mm)
6. D06V1 open（18:22, ±1.95 mm → ±2.25mm)

Issue – Beam size blowup in LER (TMCI)

- We can accumulate ~1.5 mA/bunch at least in this study.
- We've not observed the coupling of the modes 0 and -1 yet.
- We've observed the vertical beam size blowup before the coupling.



2021-02-17
βy* = 8 mm, single-bunch operation

Tune shift: ~0.008 mA^{-1}
ν_y ~ 0.595 @ 1.6 mA/bunch

We were not able to inject up to ~1.7 mA/bunch (rep. rate 1 Hz).
TMCI threshold (calc.): ~1.77 mA/bunch

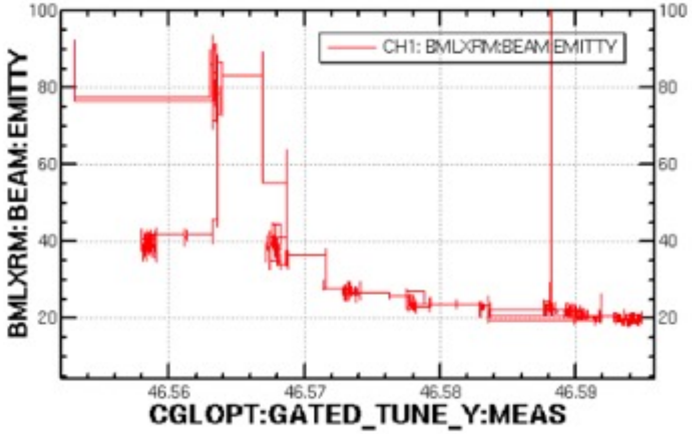
D02V1: 2.17 mm, -1.8 mm, D03V1: ±9 mm,
D06V1: ±2 mm, D06V2: ±9 mm

Issue – Beam size blowup in LER (TMCI)

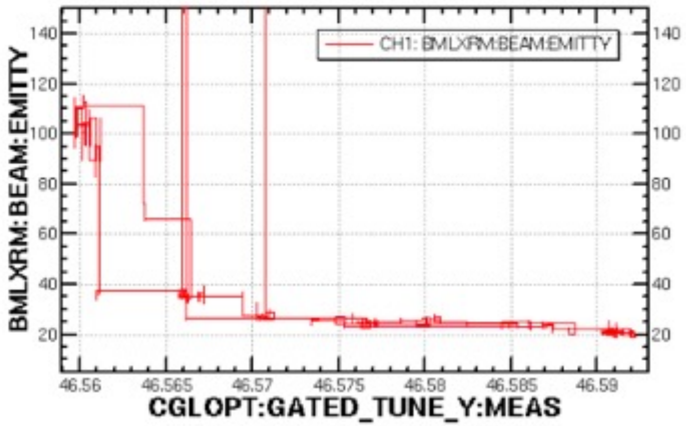
[K. Ohmi et al.]

ε_y vs ν_y at $K\beta=36\times10^{15}$ V/C (June 29)

- 50mA (16:10-16:30)

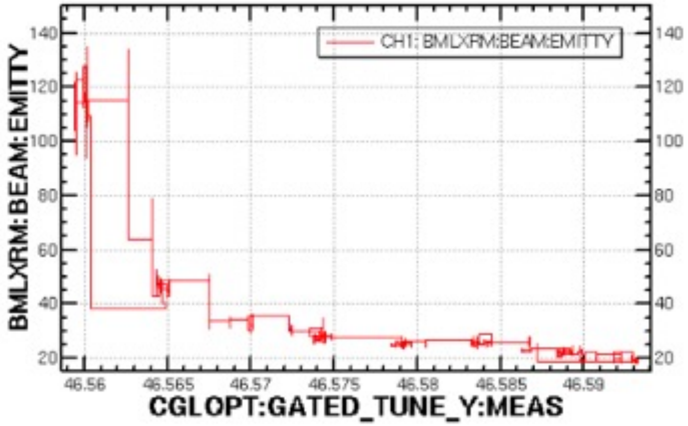


70mA(16:55-17:05)

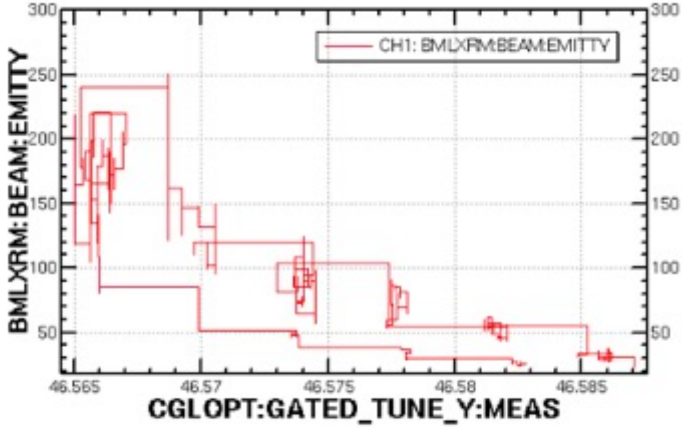


- Emittance growth due to current independent resonance (nx-ny-2ns or 2ny-6ns=n) for I=<80mA.
- Emittance growth due to tune dependent TMCI (localized wake) was seen I>=90mA
- ε_y=150pm at I=100mA ν_y=0.588
- I_{th}=95mA at Kb= 36×10^{15} V/C.

- 80mA (17:05-17:15)



90mA (17:20-17:28)



Issue – Beam size blowup in LER (TMCI)

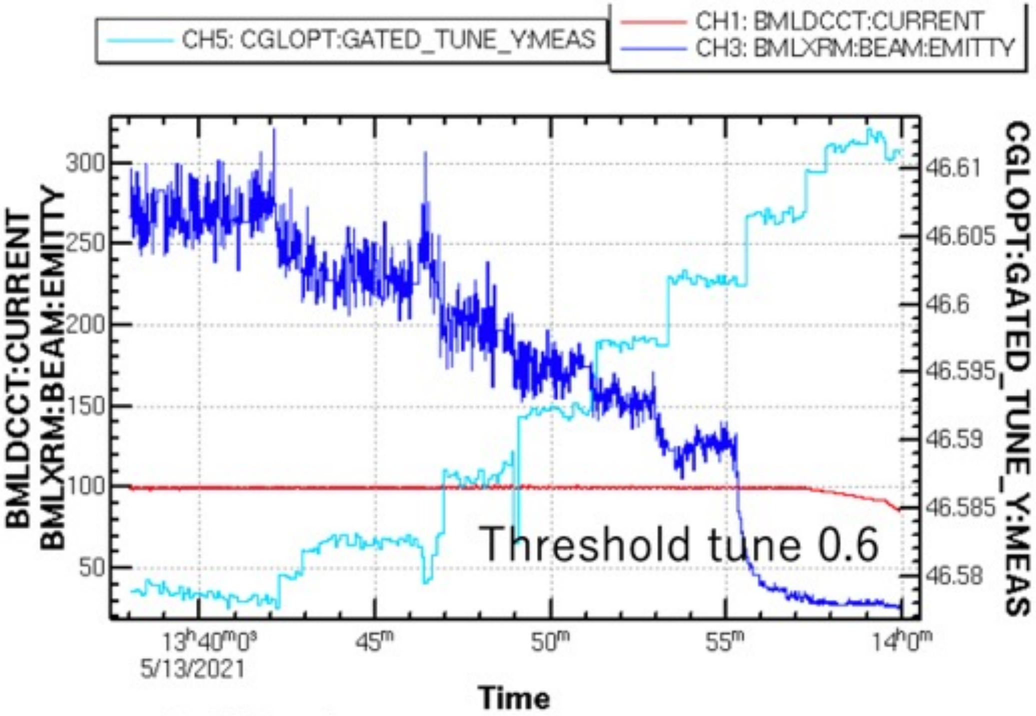
[K. Ohmi et al.]

LER measurement at May 13

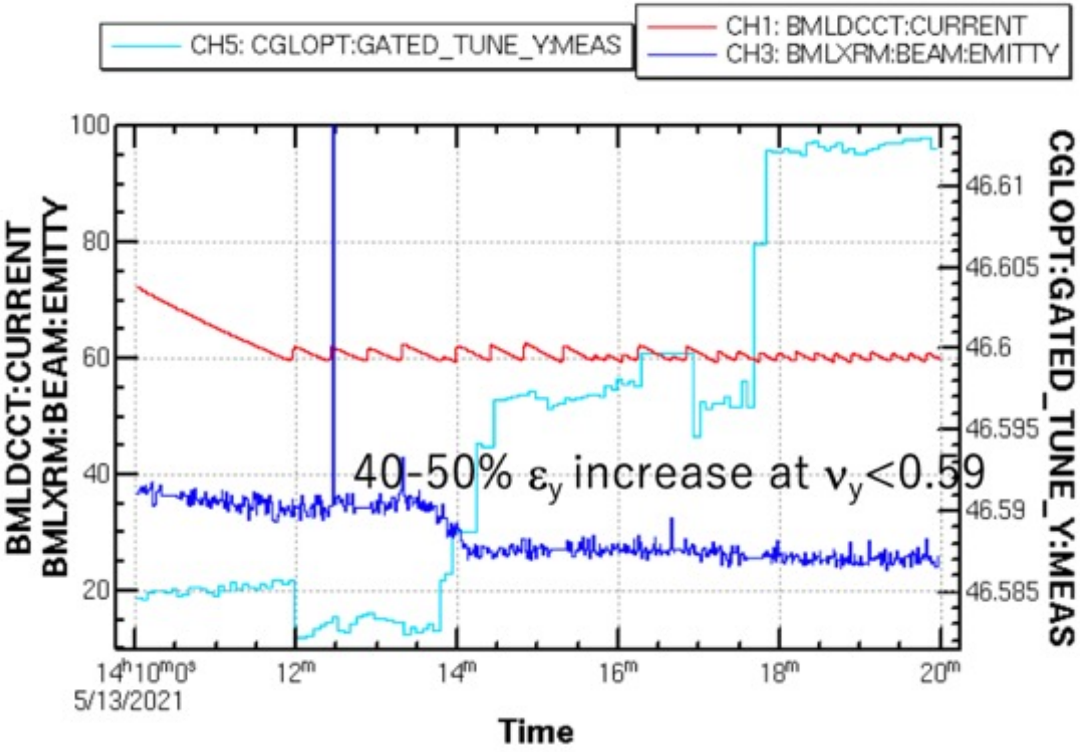
$d\nu_y/dI = 0.008/mA$

- Keep current scan V-tune 0.570-0.610

100mA



60mA



BOR data taking

Emittance blow up was seen at 1mA/bunch.

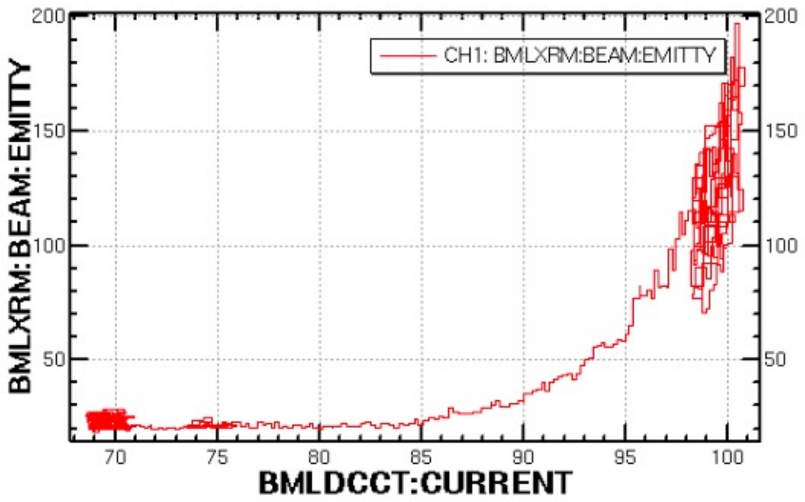
Issue – Beam size blowup in LER (TMCI)

[K. Ohmi et al.]

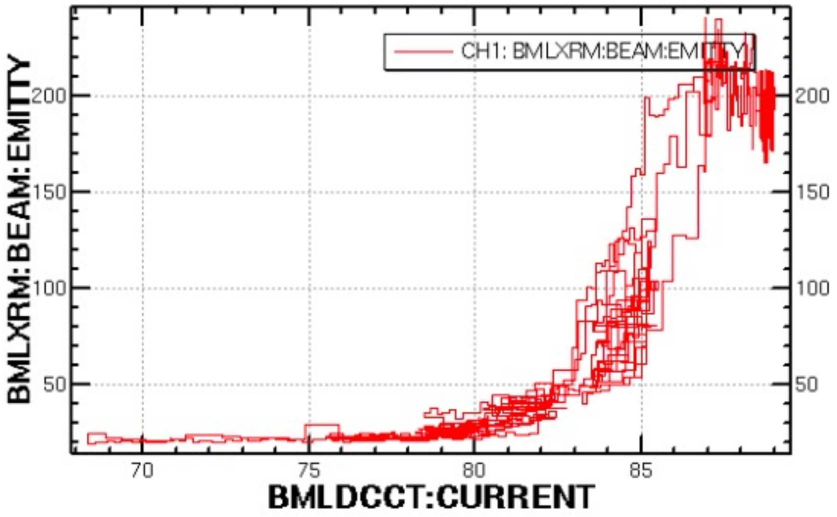
Threshold change for Collimator gap

ν_y=0.59

$K\beta$=36x10^{15} V/c



$K\beta$=41.6x10^{15} V/c

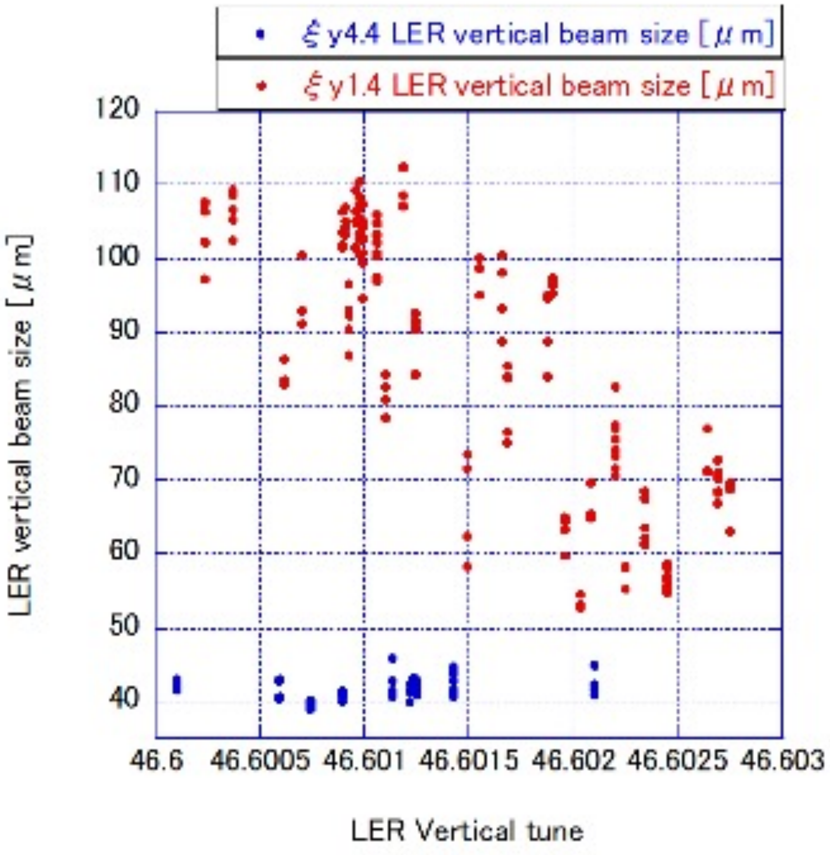


- The threshold almost scales to $K\beta I$.
- The emittance growth seems to be due to TMCI, though not ordinary TMCI.

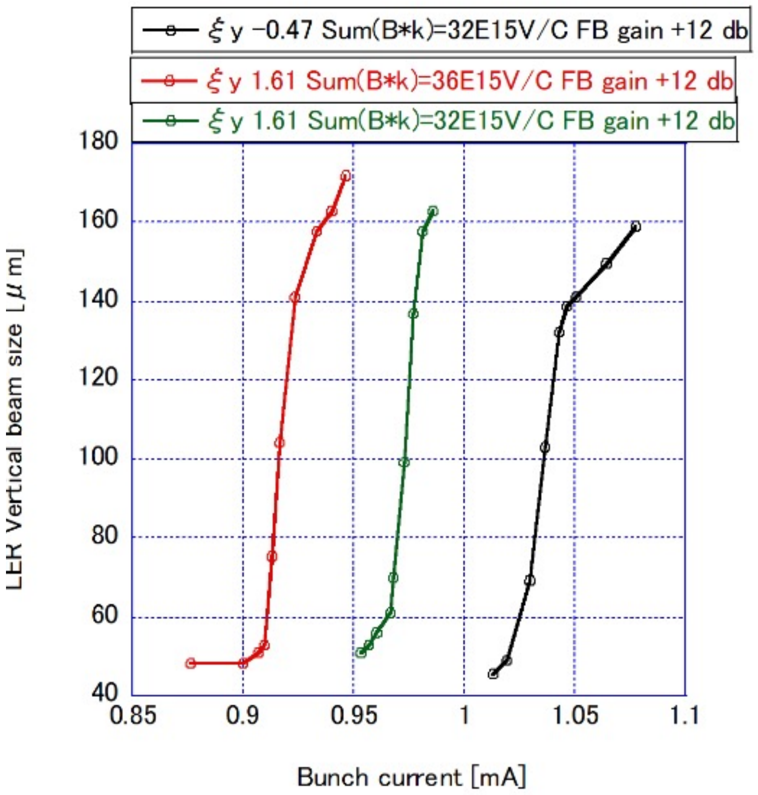
Issue – Beam size blowup in LER (TMCI)

[S. Terui et al.]

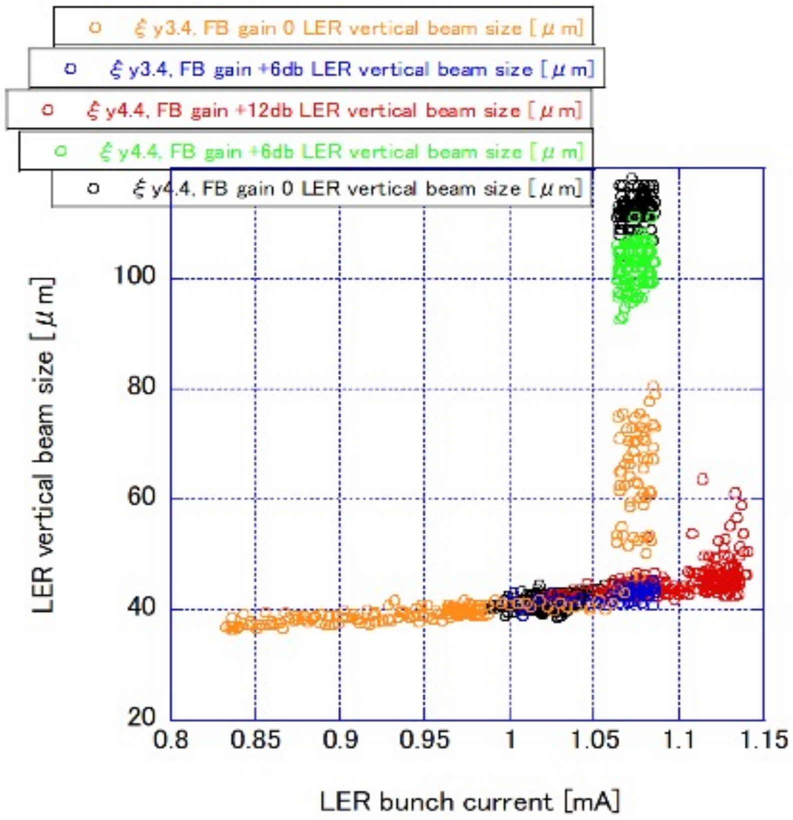
Change chromaticity



Change chromaticity and collimator's aperture



Change chromaticity and FB gain



- The beam size blowup can be suppressed by increasing the vertical chromaticity.
- The threshold of the blowup increases with the negative chromaticity.
- The blowup can be suppressed by increasing the feedback gain.

Issue – Beam size blowup in LER (TMCI)

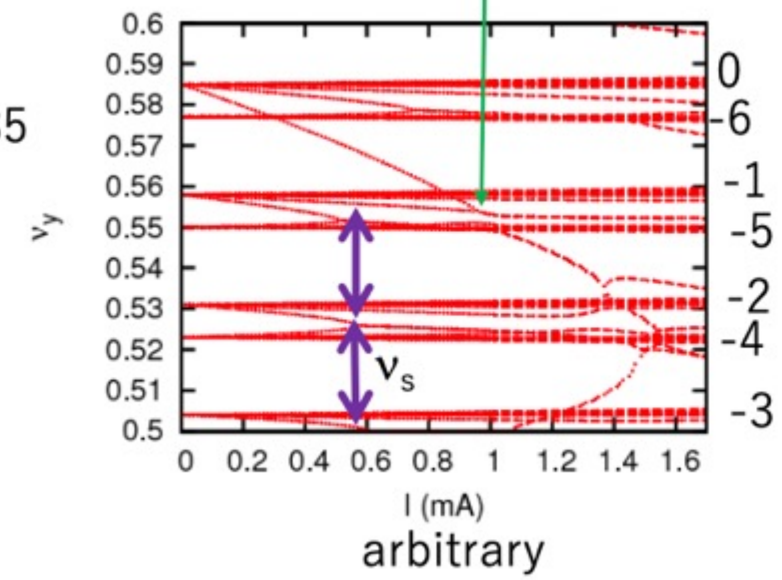
[K. Ohmi]

Mode coupling for localized wake

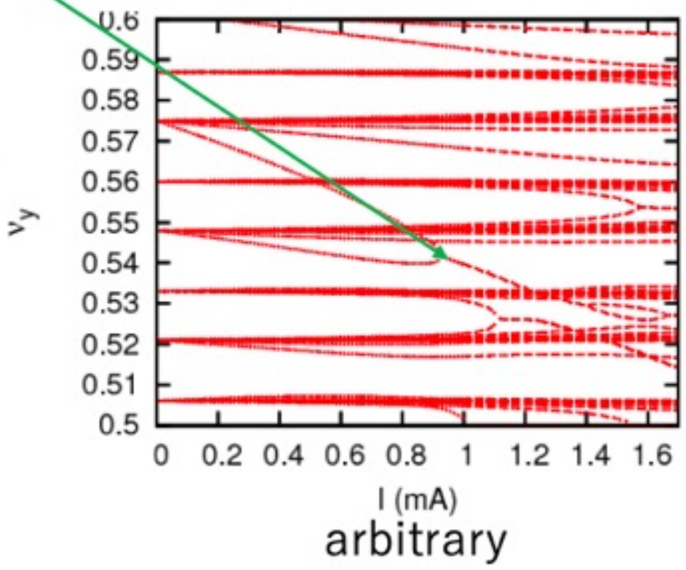
- In ordinary mode coupling, the betatron tune does not have meaning, but only tune different between sidebands, ns has meaning.
- In mode coupling due to a localized wake, the betatron tune has meaning. Sideband modes wrapped at 0.5

Broad band resonator wake 50GHz, Q=1

ν_y=0.585



ν_y=0.575



Issue – Beam size blowup in LER (TMCI)

- Summary of TMCI in LER
  - We can accumulate the bunch current up to a calculated values using a broad impedance model, however we've observed the vertical beam size blowup around ~60% of the calculated values.
    - We've not observed the coupling of the modes 0 and -1, so K. Ohmi has suggested that we should observe this, which is an "ordinary" TMCI, in a higher vertical tune ($\nu_y > 0.6$).
  - The beam size blowup has been observe for the single-beam operation (no collision). We've observed a beam size blowup in LER with the collision. It has been caused by the beam-beam, because the beam size depends on not the collimators' aperture but the current balance between LER and HER. We've not been able to accumulate the bunch current till the TMCI threshold with the collision so far.
  - The bunch current threshold about the beam size blowup depends on the tune and the chromaticity.
    - Proper vertical tune and/or higher chromaticity can increase the threshold.
  - The threshold of the blowup may increase at least up to ~0.9-1.0 mA with present collimator setting by choosing the vertical tune and/or the vertical chromaticity.
  - For higher beam current operation that is assumed for $L=1\times10^{35}$ cm^{-2} s^{-1}, a bunch current more than 1.0 mA will be needed for LER, so this beam size blowup may be more serious.
  - There is a possibility that the tune to avoid the blowup is not good for the luminosity performance.
    - D. Zhou's strong-strong beam-beam simulation has predicted that the luminosity will increase by 10% by moving from the present tune to the designed tune $(\nu_x, \nu_y)=(.53, .57)$.

Issue – Beam size blowup in LER (TMCI)

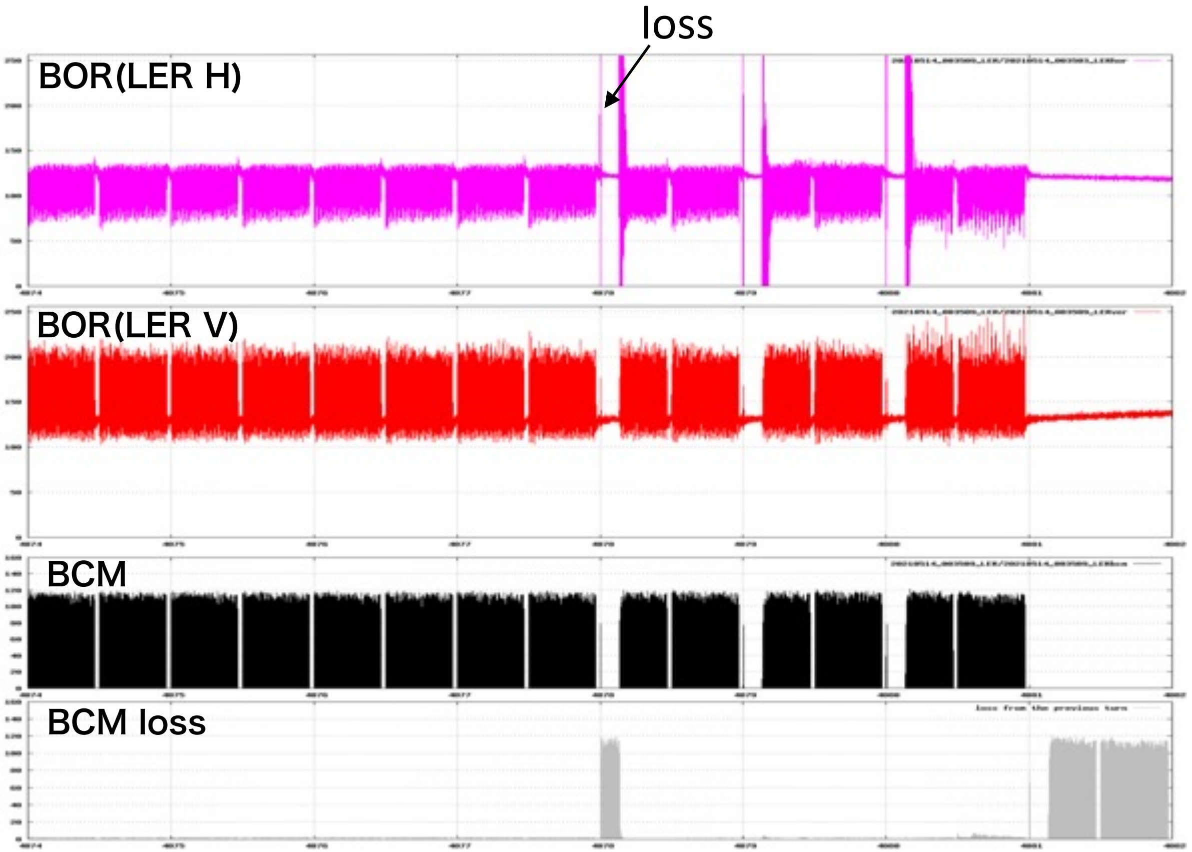
- (Example) parameter sets for L=1×10^{35} cm^{-2} s^{-1}.

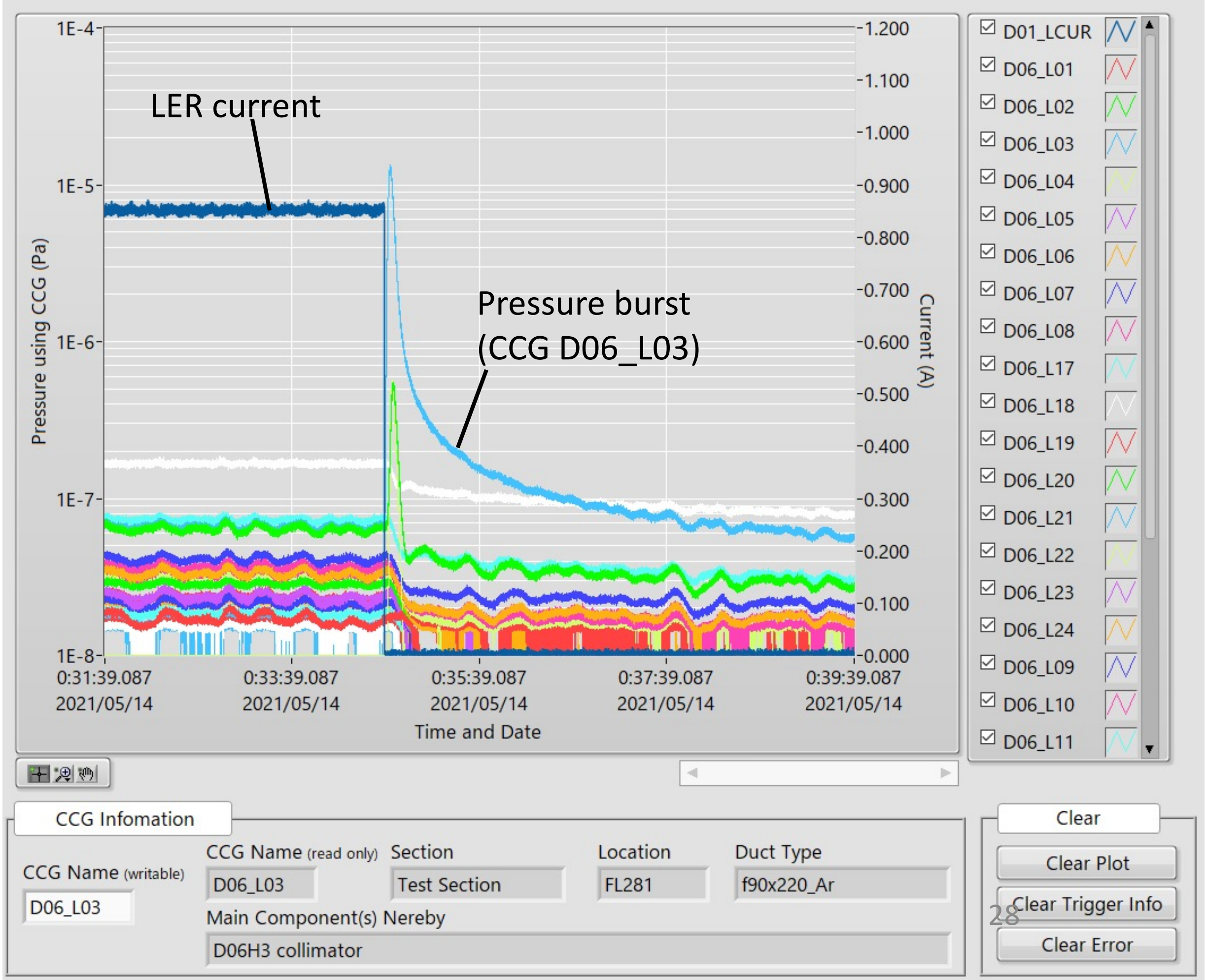
[Y. Funakoshi]

	LER	HER	LER	HER
# of bunches	1564+1		2345+1	
Luminosity	4.79 x 10^{34} $cm^{-2}s^{-1}$		1.0 x 10^{35} $cm^{-2}s^{-1}$	
I_{total}	1.41 A	0.986 A	2.35 A	1.64 A
I_{bunch}	0.898 mA	0.630 mA	1.0 mA	0.7 mA
βy^*	1 mm	1 mm	0.8 mm	0.8 mm

Issue – Accidental firing of injection kickers

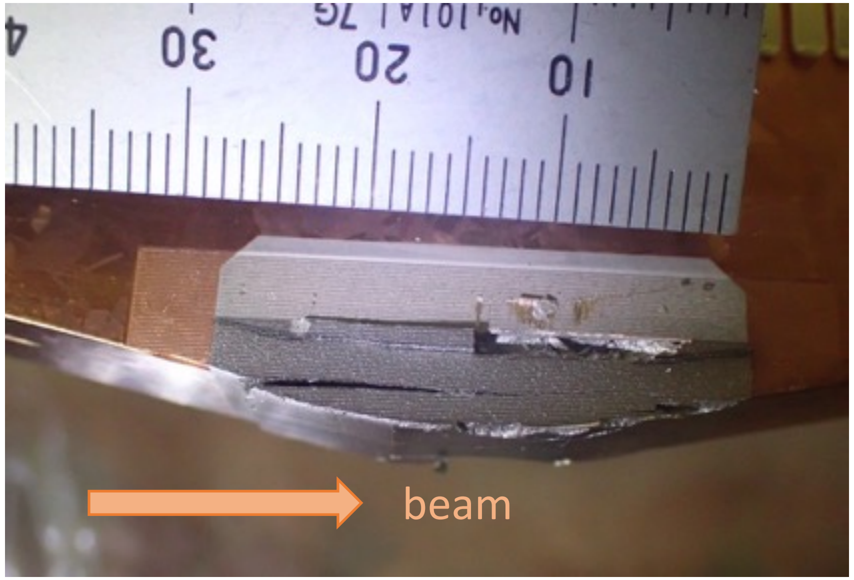
- Accidental firing of injection kickers in LER has happened.
- Example:
  - On 2021-05-14 00:35, a both ring abort happened.
  - QCS quench (QC1RP a1, a2, b1).
  - A pressure burst at D06H3 collimator was observed.



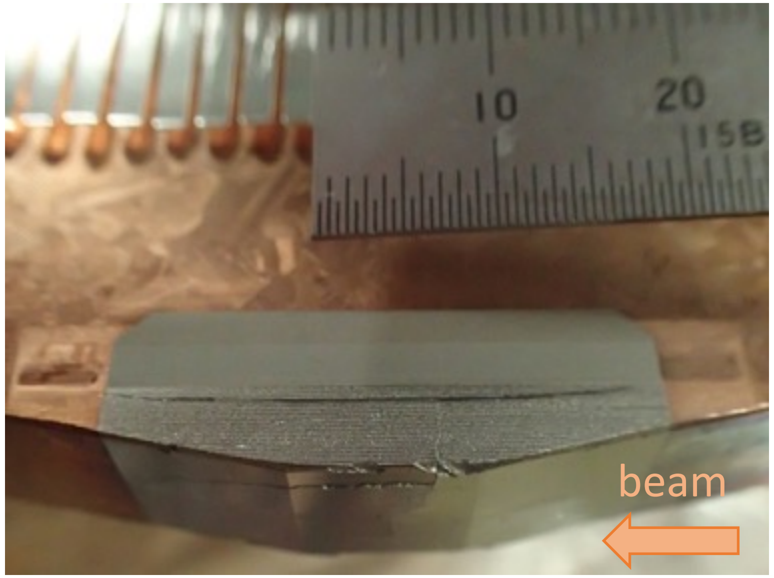


Issue – Accidental firing of injection kickers

- D06H3 collimator has used for the protection from the accidental firing, and it was severely damaged.
- We replaced them with healthy ones during this summer shutdown.
  - We don't have the spare jaws for D06H3 collimator. Thus, we removed jaws of D06H1 and installed them into D06H3.
  - We installed new jaws into D06H1 instead, however the length of the jaws is short for this collimator. The minimum aperture of D06H1 is ±14 mm.
  - We're staring to manufacture the spare jaws made of tantalum, and it'll be delivered till the beginning of next Jan.
- Plan to replace all of the thyratrons with another ones, which have higher breakdown voltage, during this summer shutdown [T. Mimashi].



D06H3 IN (~700 μSv/h)



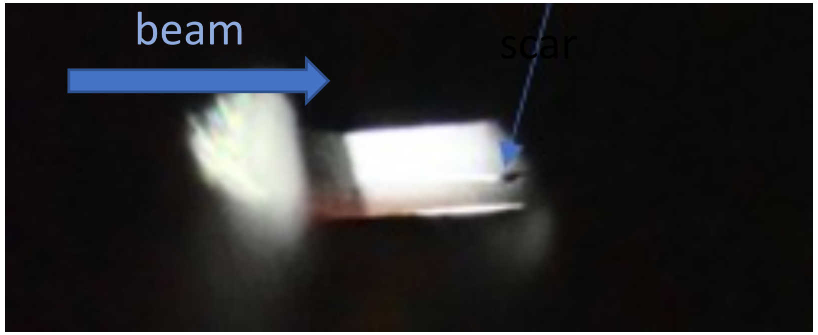
D06H3 OUT (~320 μSv/h)

Plan – Replacement of the damaged jaws, installation of hybrid type jaws

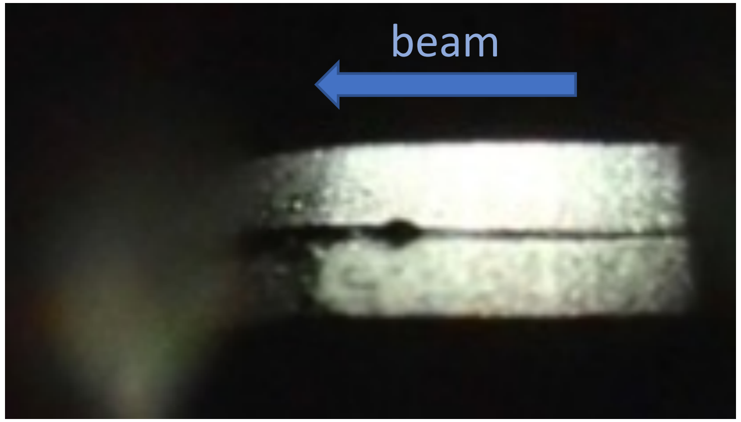
- We plan to replace the damaged jaws during this summer shutdown.
  - LER: D06V1 (Ta, L=4 mm), D06V2 (Ta-C hybrid, L=4 mm)
  - HER: D09V1 (Cu-plated Ti, L=40 mm), D09V2 (Cu-plated Ti, L=40 mm)

  (): type of new jaws

D06V1 Top (2021-06-08)



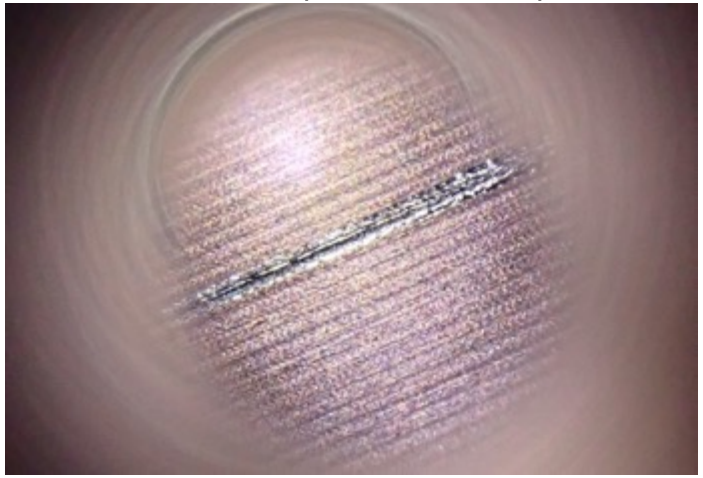
D06V1 Bottom (2021-06-08)



D06V2 Top (2020-12-18)

D06V2 Bottom (2020-12-18)

D09V2 (2021-07-09)

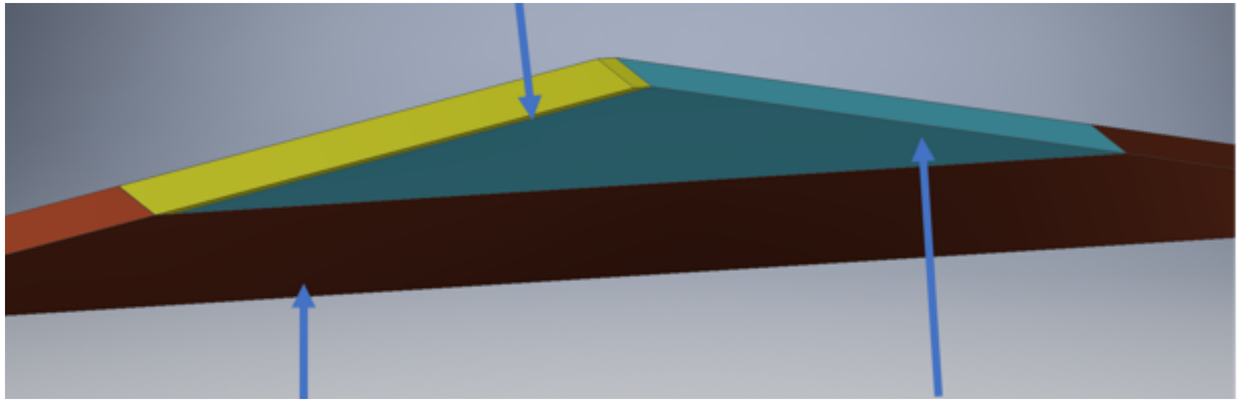


D09V2 (2020-07-10)

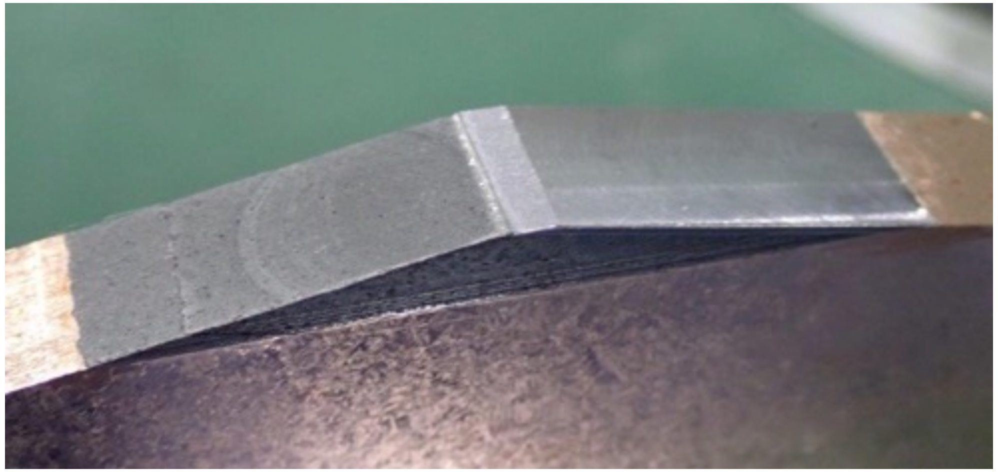
Plan – Replacement of the damaged jaws, installation of hybrid type jaws

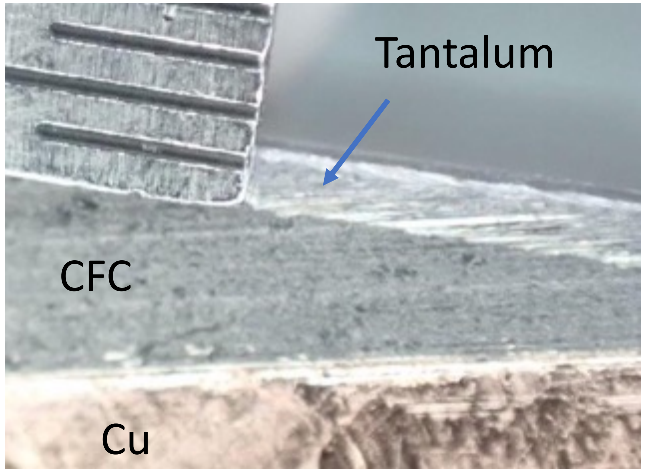
- We plan to replace the damaged jaws of D06V2 with hybrid type jaws, which has carbon and tantalum at the tip in order to improve the robustness regarding to the beam hit, for the test purpose.

Model

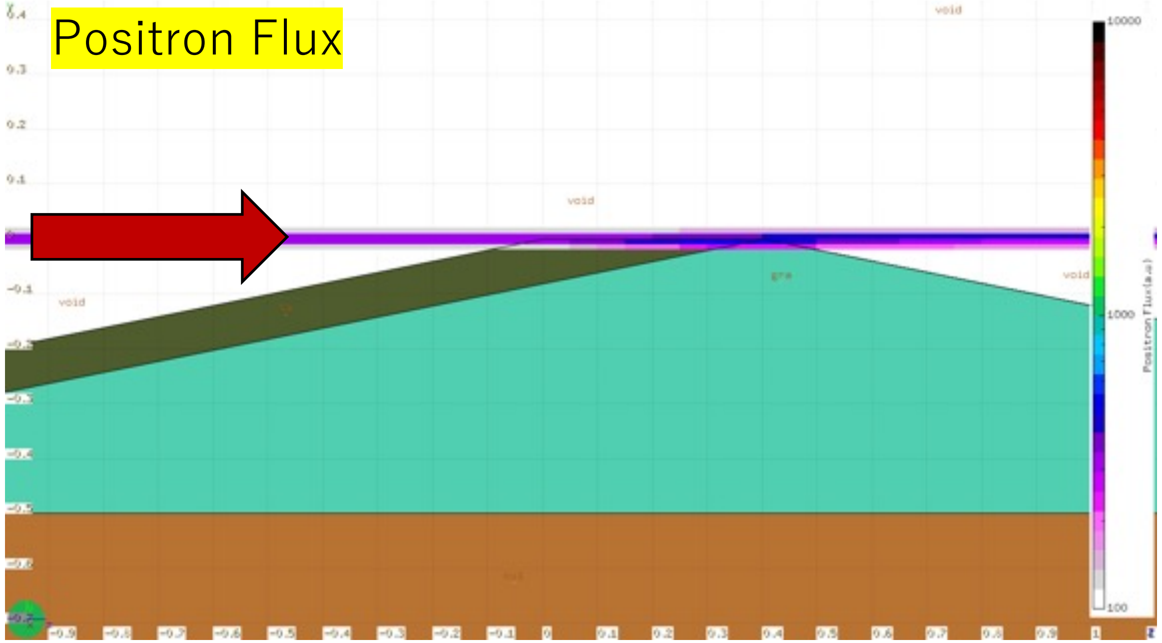


Actual





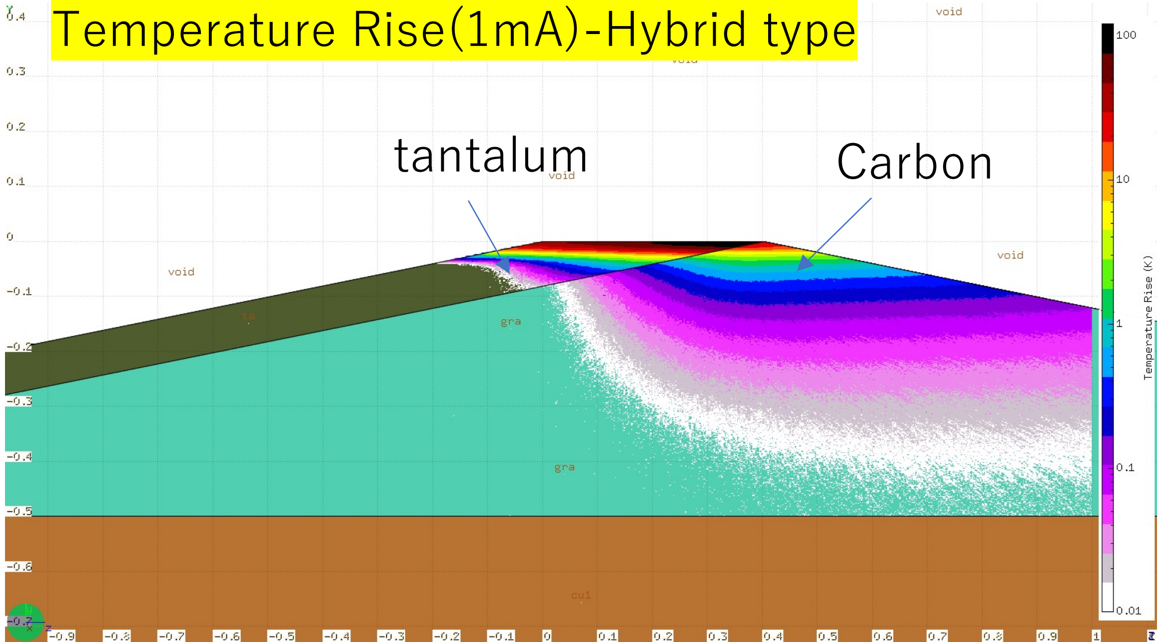
Plan – Replacement of the damaged jaws, installation of hybrid type jaws

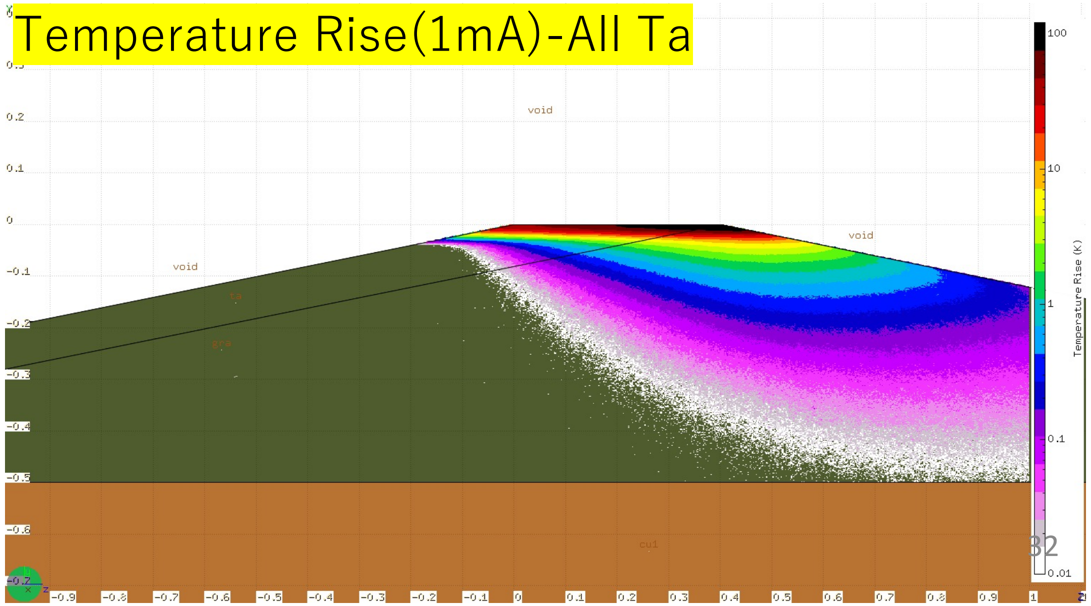


[Positron Beam]

- Beam Size： σy = 100um, σx = 300u property
- Beam Energy： 4 GeV
- No energy spread
- Lower half of the beam hit the jaw
- Beam current (assuming 99.4kHz)：
  1 mA, 5 mA, 10 mA, 30 mA, 50 mA

[Y. Morikawa, S. Terui]

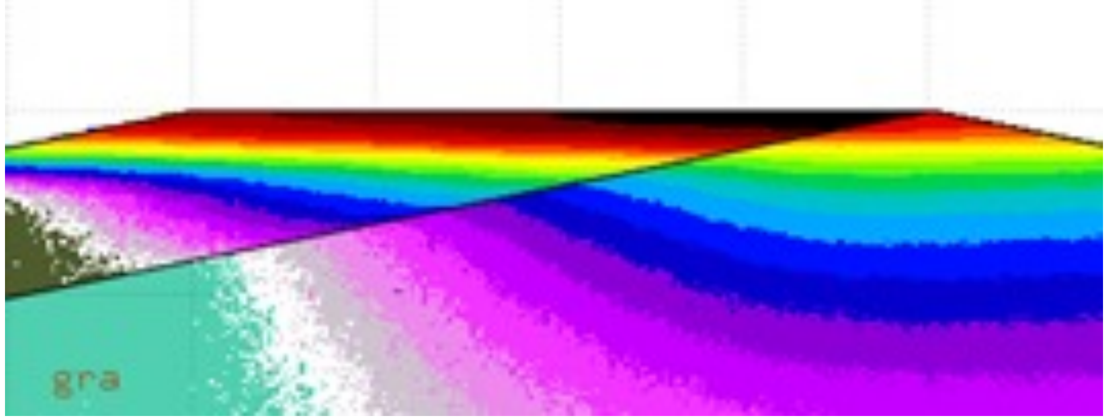




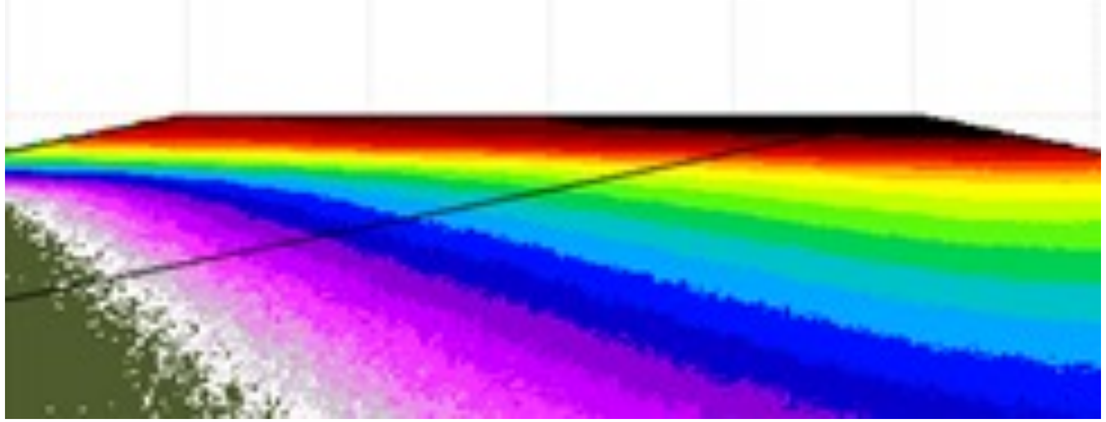
Plan – Replacement of the damaged jaws, installation of hybrid type jaws

Temperature Rise(1mA)-Hybrid type

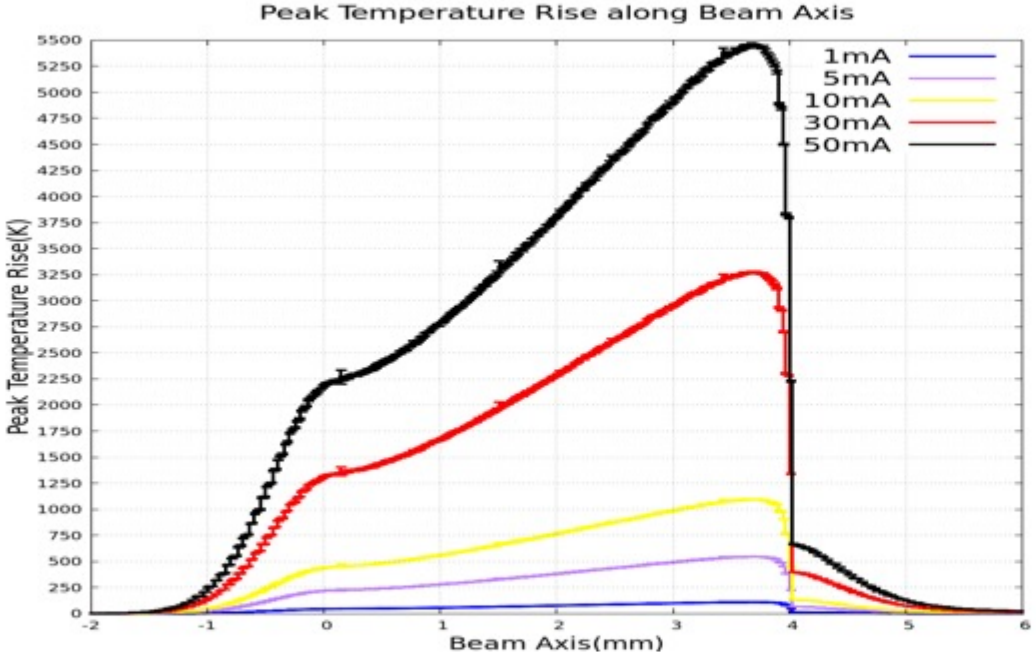
[Y. Morikawa, S. Terui]

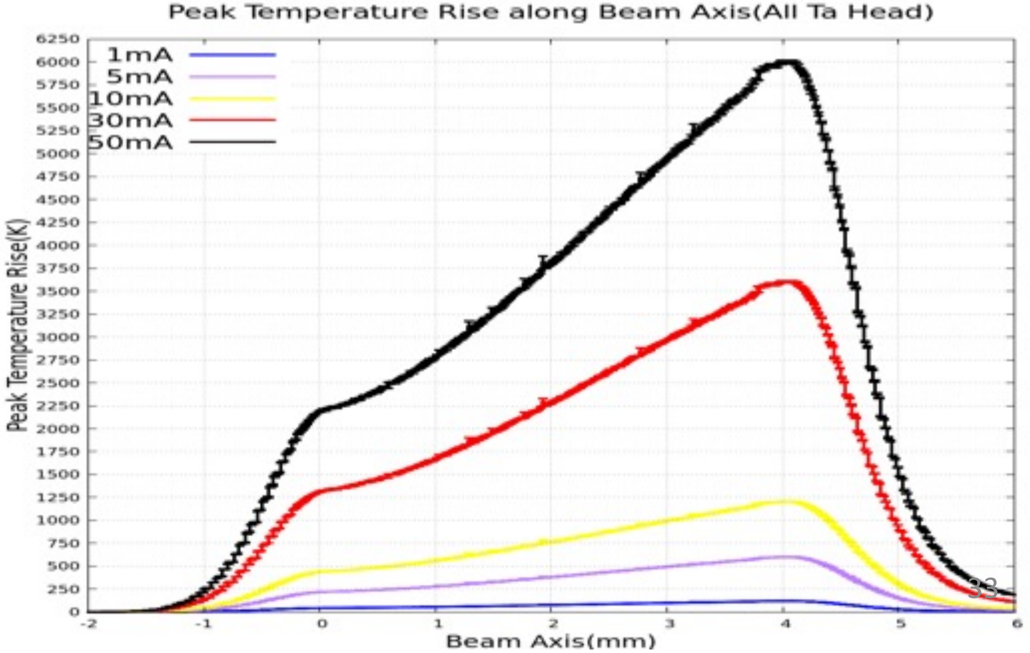


Temperature Rise(1mA)-All Ta



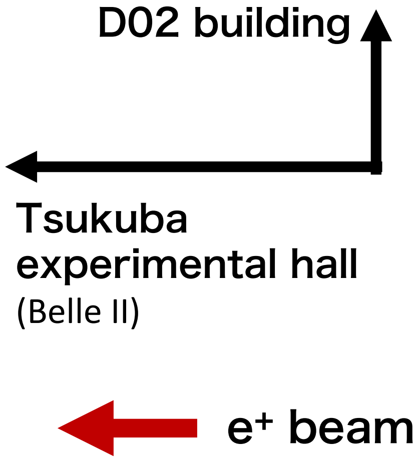
When 30 mA beam hits the jaw, the volume of the melting tantalum is 68 % less compared to the standard jaw. This might relax the bad effect on the background (durable jaw?).

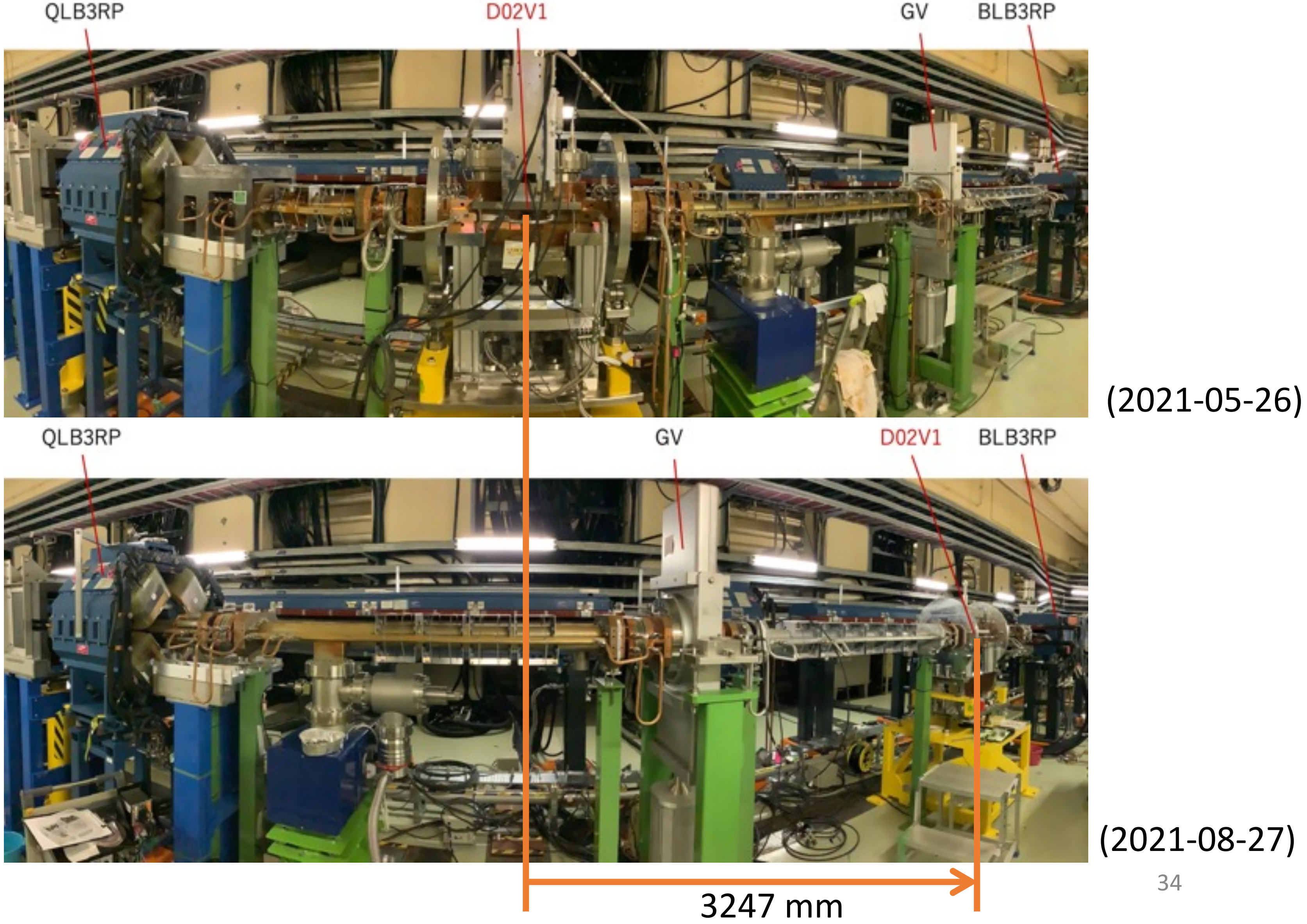




Plan – Relocation of D02V1 collimator

- Phase matching between D02V1 collimator and QC1RP in LER as much as possible by moving the collimator.
- We moved D02V1 3247 mm by the reconstruction of the existing components.





Plan – Relocation of D02V1 collimator

- For the β_y^*=1 mm optics, the target of the moving length is 3000 mm, however the actual length is 3247 mm to relocate during this shutdown.
- Simulations by A. Natochii indicate that even this configuration (3247 mm shift) can reduce the detector background.

[H. Koiso]

β_y^* [mm]	Length of move [m]	Phase difference before relocation	$\beta_x/\beta_y/\eta_x$ before relocation [m]	Phase difference after relocation	$\beta_x/\beta_y/\eta_x$ after relocation [m]
1	2.964	1.463	10.89/13.95/0.1380	1.500	24.53/12.00/0.3569
0.8	3.871	1.469	13.01/18.40/0.1362	1.500	34.17/21.10/0.4209
0.5	2.074	1.478	16.31/14.32/0.1382	1.500	32.01/16.27/0.2908
0.27	3.235	1.495	25.22/98.09/0.1289	1.500	61.43/48.25/0.3640

- We plan to bake around the D02V1 after the relocation work.

Plan – Relocation of D02V1 collimator

SAD simulation results. IR beam losses and beam lifetime

[A. Natochii]

- The actual drift space (LLB3RA/LLB3R) is enough to shift D02V1 collimator by 3.247m upstream.
- This shift will change collimator optics parameters
    - Vertical β-function : 13.95 → 11.88 [m]
    - Phase advance w.r.t. QC1 : 0.037 → 0.004 [1/2π]
- Keeping the initial collimator aperture at 72/78σ_Y the TMCI bunch current limit is slightly relaxed by 0.02mA.
- Due to better phase matching with QC1, the D02V1 collimator shift reduces IR backgrounds by ~20% and ~50% for Touschek and Coulomb components, respectively.
- Beam lifetime is unchanged.

LER May 9, 2020 [**original**]
β*X/Y = 80/1 mm | CW = 60%

Coulomb IR losses:	56.84 ± 0.36 [MHz]
Brems IR losses:	4.78 ± 0.02 [MHz]
Touschek IR losses:	32.29 ± 0.80 [MHz]
Coulomb lifetime:	25.72 ± 0.51 [min]
Brems lifetime:	1524.57 ± 2.98 [min]
Touschek lifetime:	6.76 ± 0.01 [min]

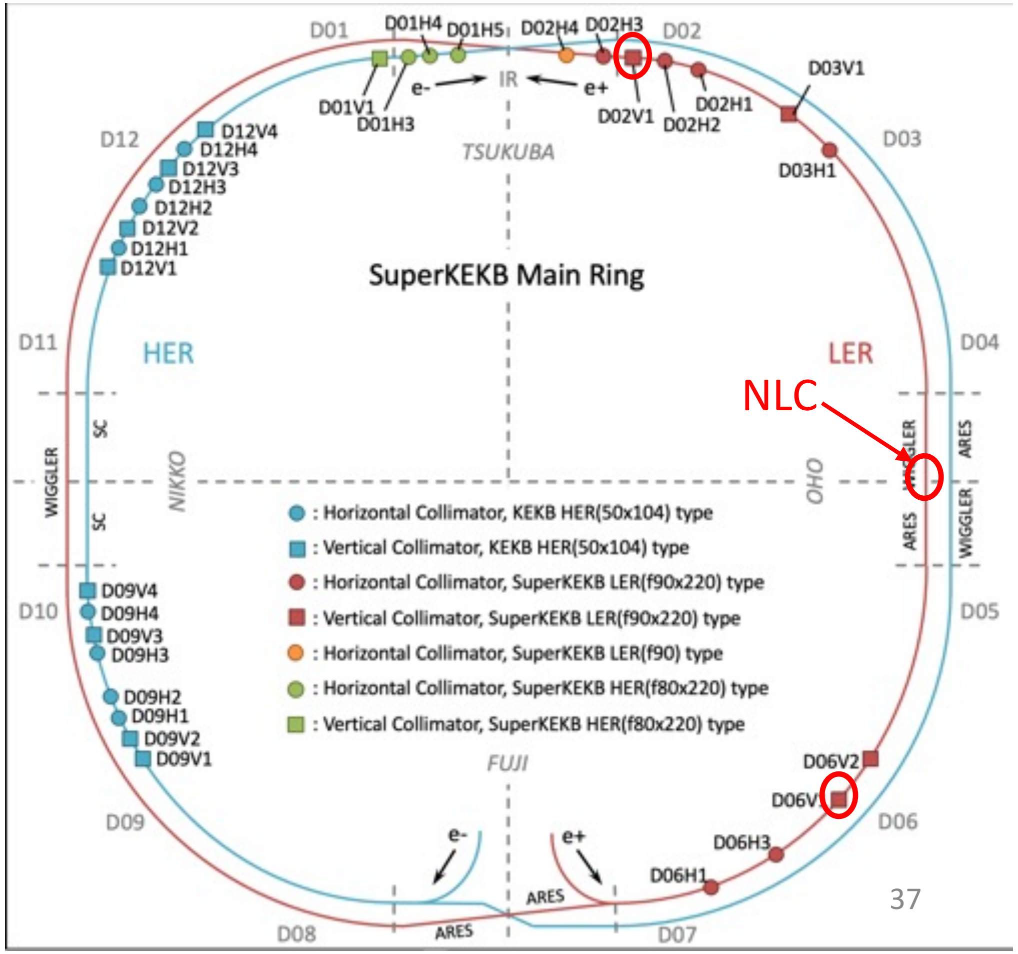
LER May 9, 2020 [**modified**]
β*X/Y = 80/1 mm | CW = 60%

Coulomb IR losses:	29.86 ± 0.09 [MHz]
Brems IR losses:	4.80 ± 0.02 [MHz]
Touschek IR losses:	26.58 ± 0.82 [MHz]
Coulomb lifetime:	25.56 ± 0.53 [min]
Brems lifetime:	1526.41 ± 3.05 [min]
Touschek lifetime:	6.75 ± 0.01 [min]

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.



Plan – Non-linear collimator at LER OHO section

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

	β_{yc} [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

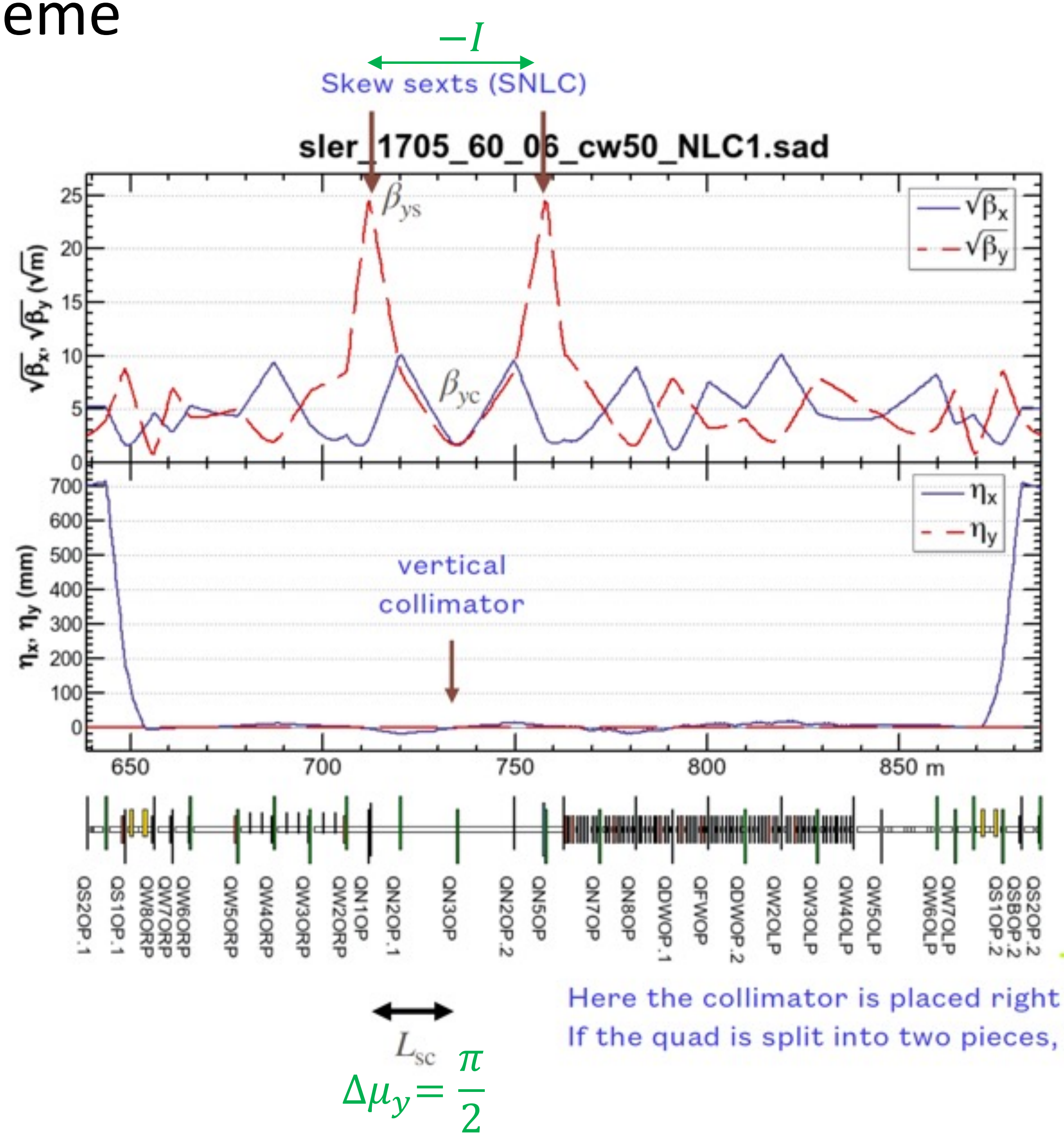
- The β_y at the D06V1 is large, and the aperture is narrow.
- The β_y at the NLC is small, and the aperture is wide.

→ can 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!

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.

June 17, 2021 K. Oide

Plan – Non-linear collimator at LER OHO section

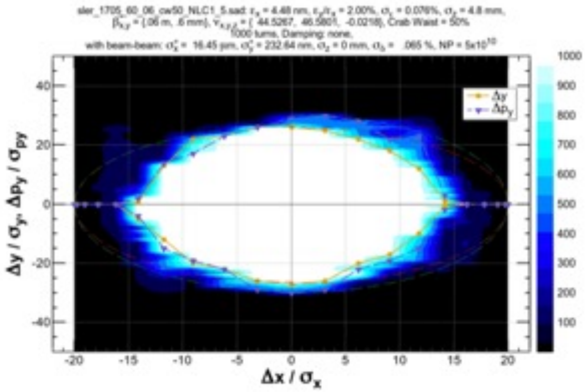
[K. Oide]

LER optics for (60,0.6) mm

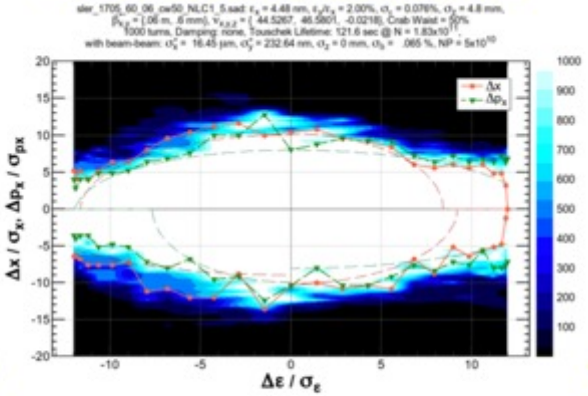
CW = 50%

Requirements on the collimation

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

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

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

  - 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:

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

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

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

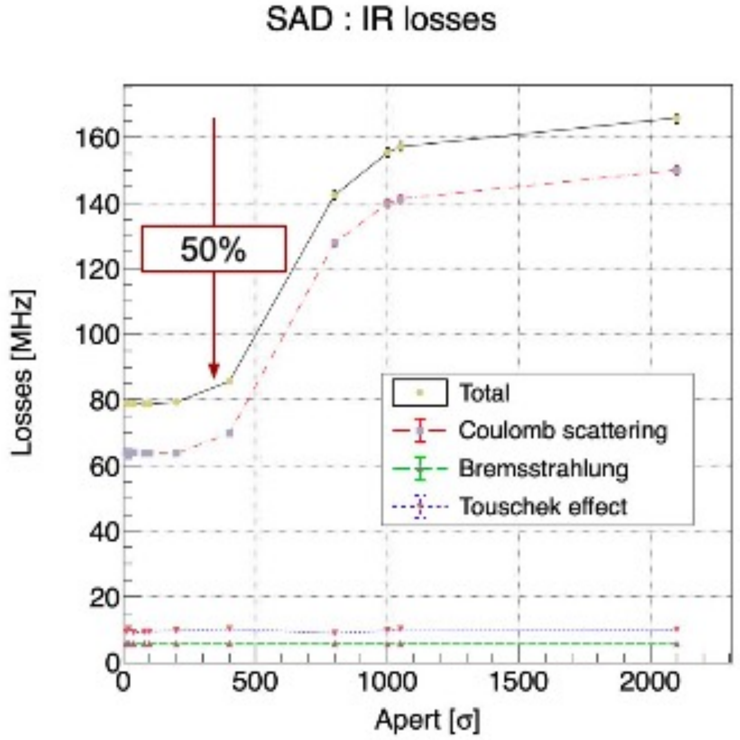
June 17, 2021 K. Oide

Plan – Non-linear collimator at LER OHO section

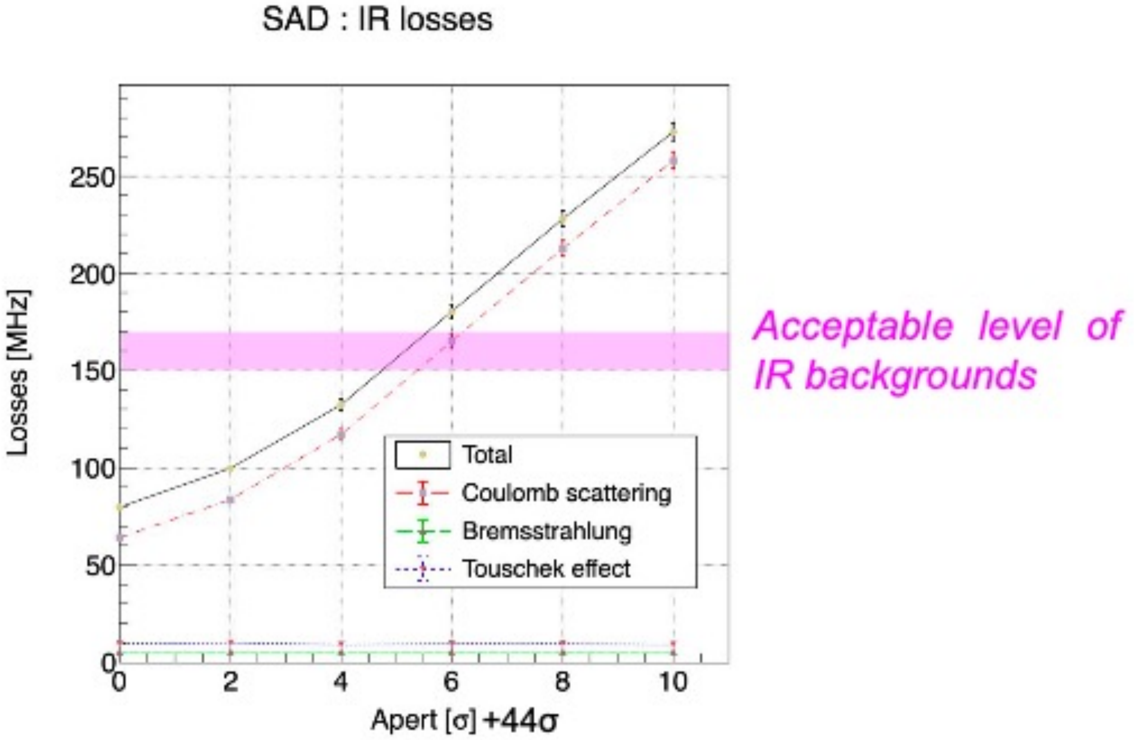
[A. Natochii]

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



D02V1 aperture scan while NLC is closed

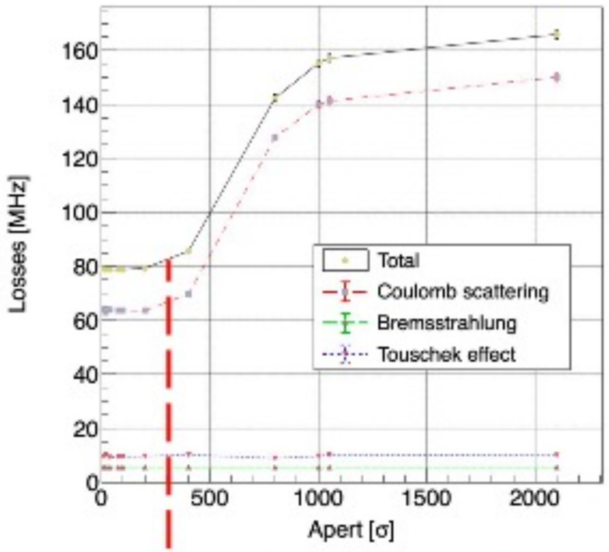
Plan – Non-linear collimator at LER OHO section

[A. Natochii]

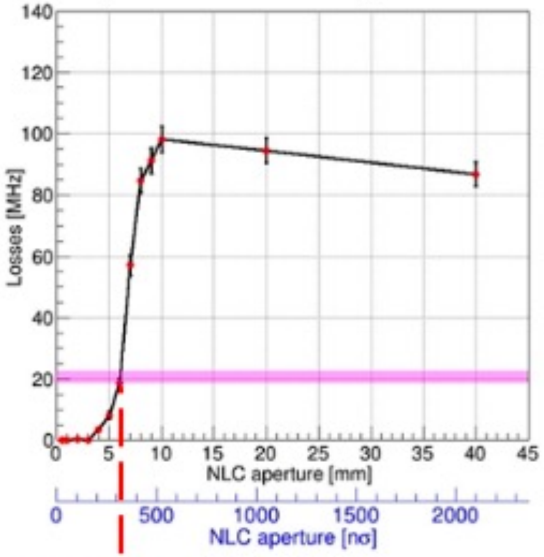
Conclusion

- 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*

Storage IR backgrounds



Injection IR backgrounds



Optimal NLC aperture ±5.7mm (~300σ)

Summary

- Collimators are indispensable to reduce the detector BG and avoid the QCS quench. However, there are issues:
  - Damage
  - TMCI
- Relocation of D02V1 during this summer could relax the TMCI bunch current limitation because we can open the aperture when we keep the same BG level during 2021ab.
- Non-linear collimator at LER OHO section could relax the TMCI. We have plans to construct this during Long Shutdown-1 (LS1), 2022.

backup

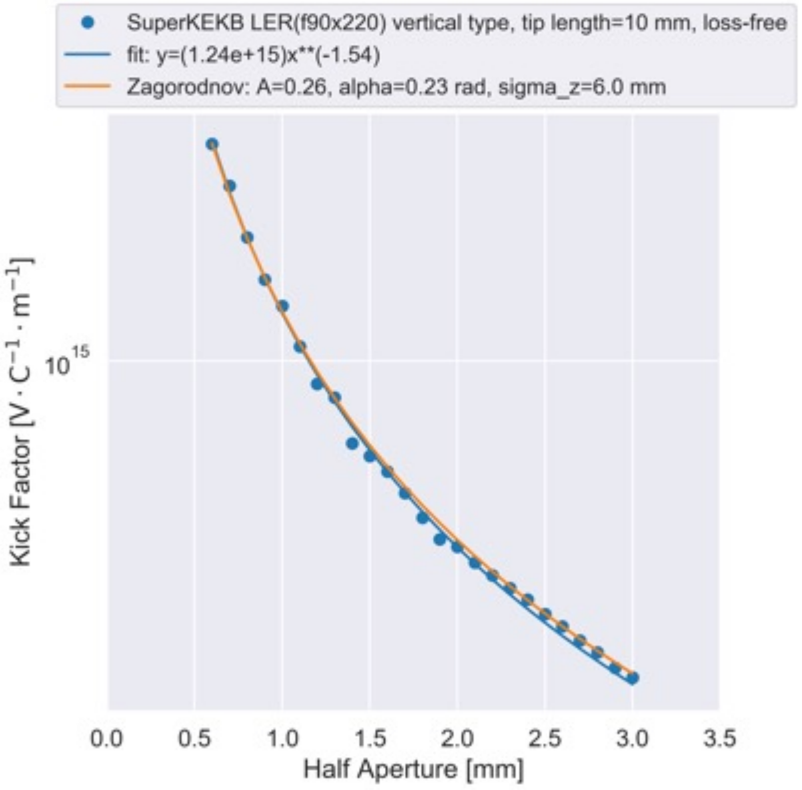
Design – Impedance

Zagorodnov's equation

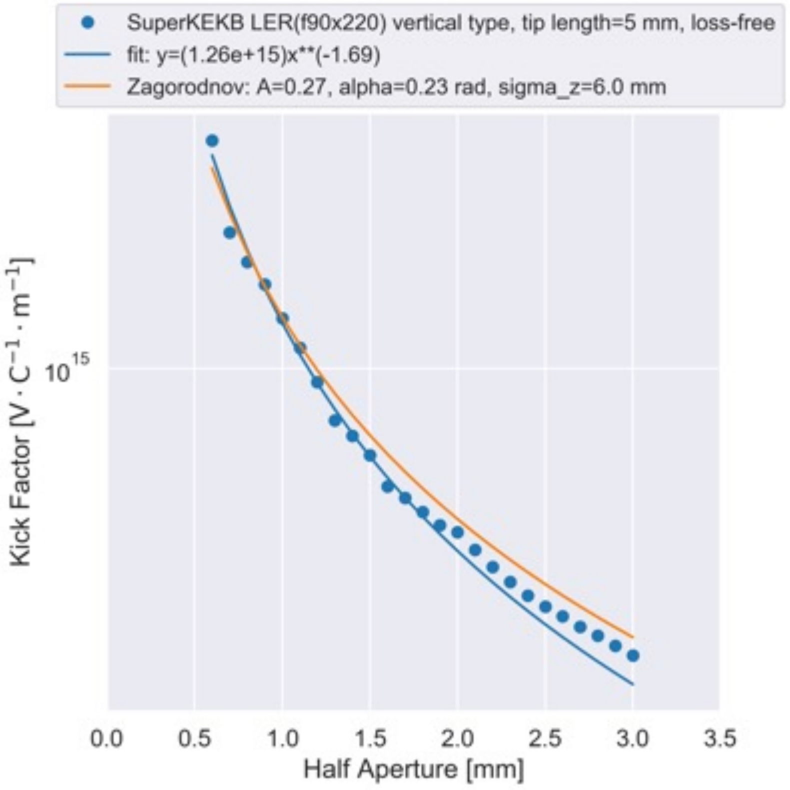
$$k_\perp = 0.215 A Z_0 c \sqrt{\frac{\alpha}{\sigma_z d^3}}$$

[I. Zagorodnov, Wakefield Calculations for 3D Collimators, EUROTeV-Report-2006-074.]

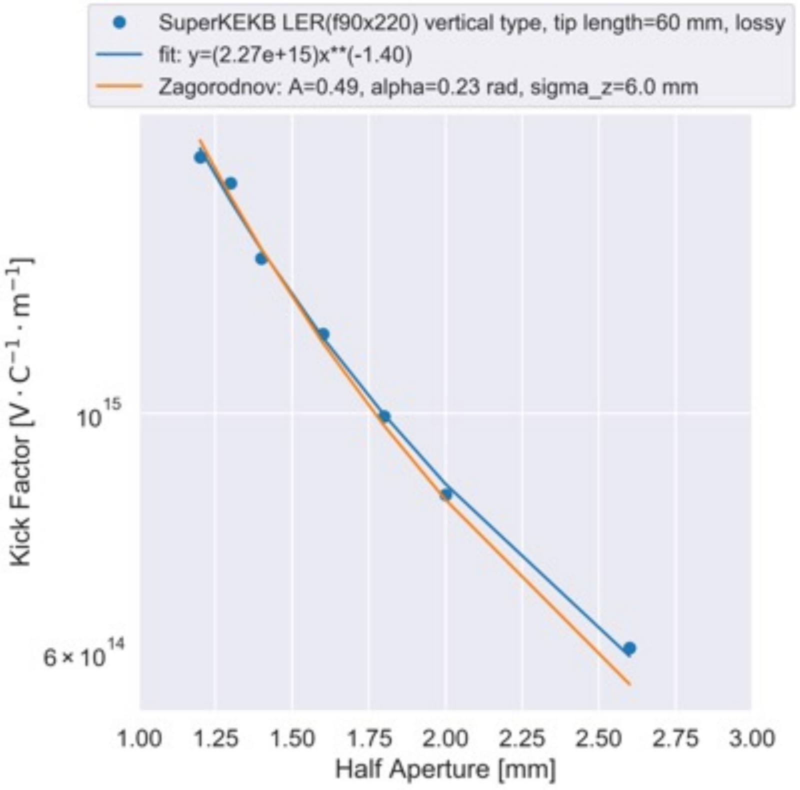
L=10 mm



L=5 mm



Carbon, L=60 mm



Non-linear slope (geometry to reduce the impedance)

- K. Yokoya, Impedance of Slowly Tapered Structures, CERN SL/90-88(AP).

For given length of the taper $l = (b-a)/\theta$, we can reduce the wake by shaping the wall properly (the dashed line in Fig.2). The best shape (for the dipole wake) is the exponential function

$$a(z) = a\left[\frac{b}{a}\right]^{(z/l)}$$

for which $I = [\log(b/a)]^2/l$. The reduction factor is

$$\frac{I_{\rm exponential}}{I_{\rm linear}} = \frac{R(\log R)^2}{(R-1)^2} \qquad (R = b/a).$$

The exponential shaping is effective when R is large. (A reduction by half for $R = 20$.) It is interesting that the linear taper is the best for the monopole wake.

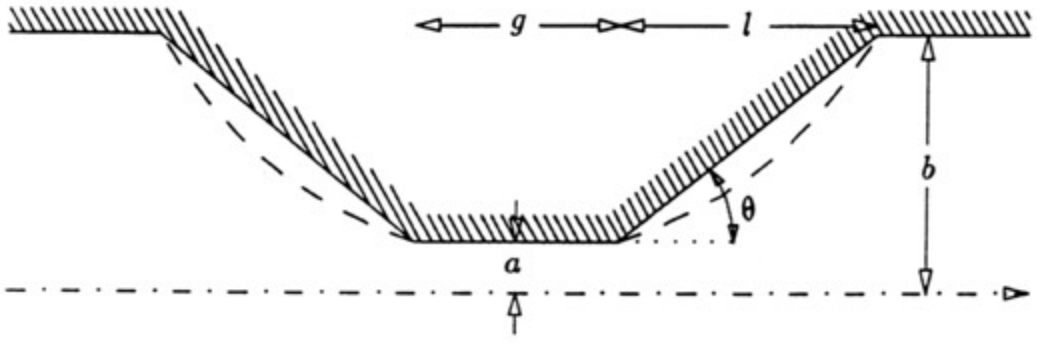
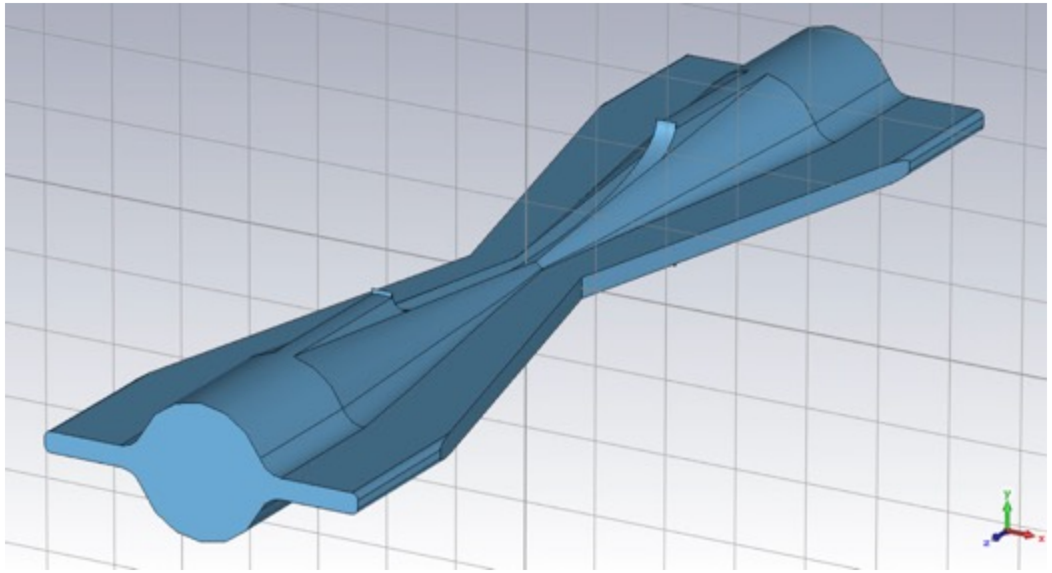


Fig.2. Linearly and exponentially tapered scrapers.

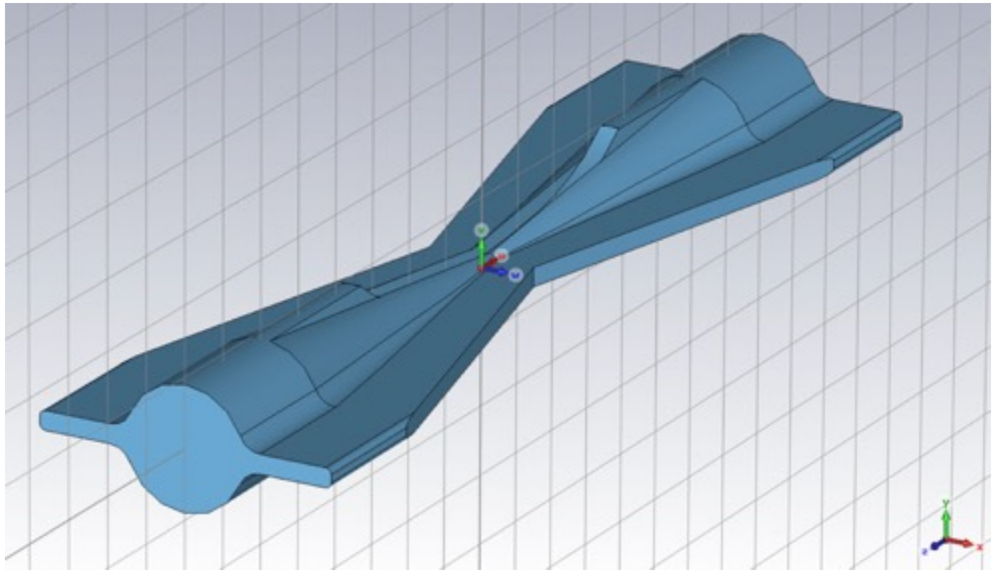
In our case, a~2 mm, b=45 mm, R=22.5.
The reduction factor is ~0.47.

Non-linear slope (geometry to reduce the impedance)

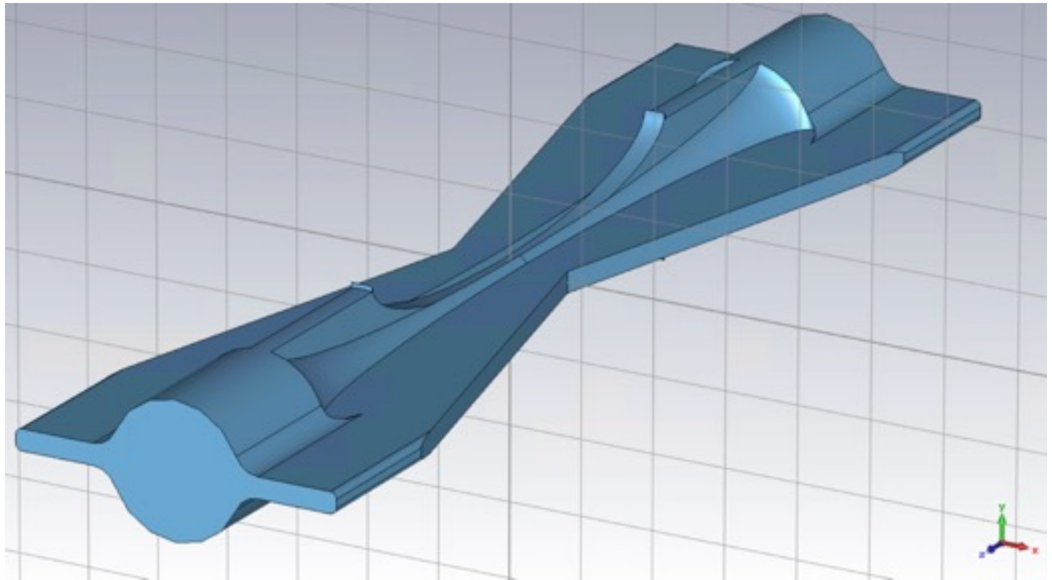
Elliptical jaw



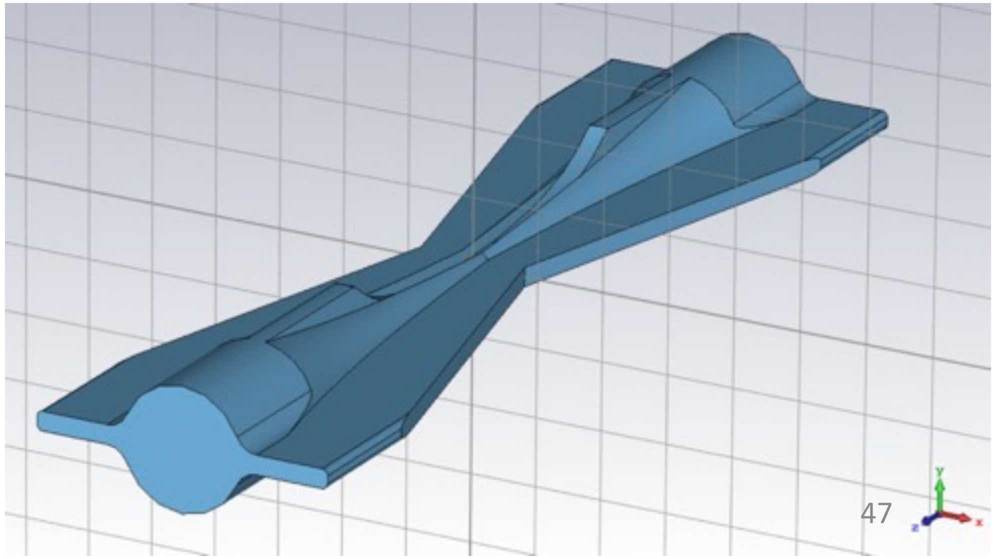
Exponential jaw



Elliptical jaw + Elliptical pipe

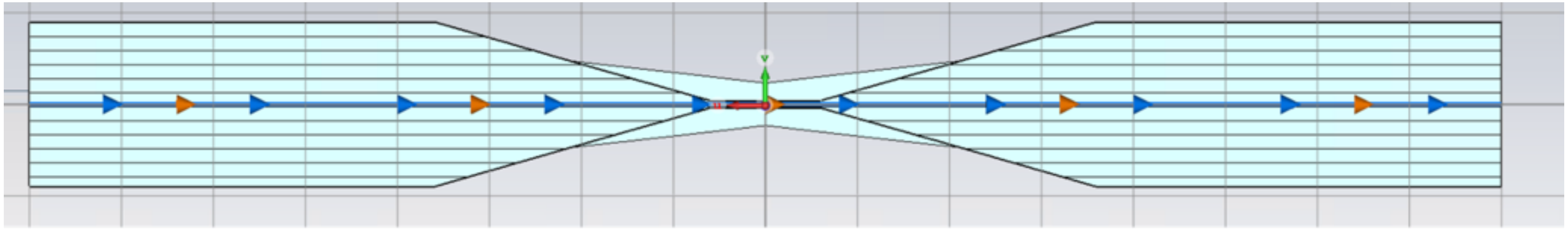


Exponential jaw + Exponential pipe

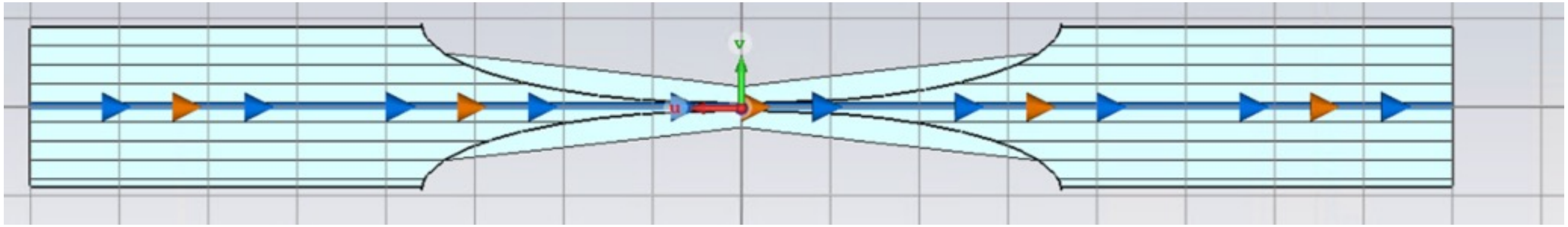


Non-linear slope (geometry to reduce the impedance)

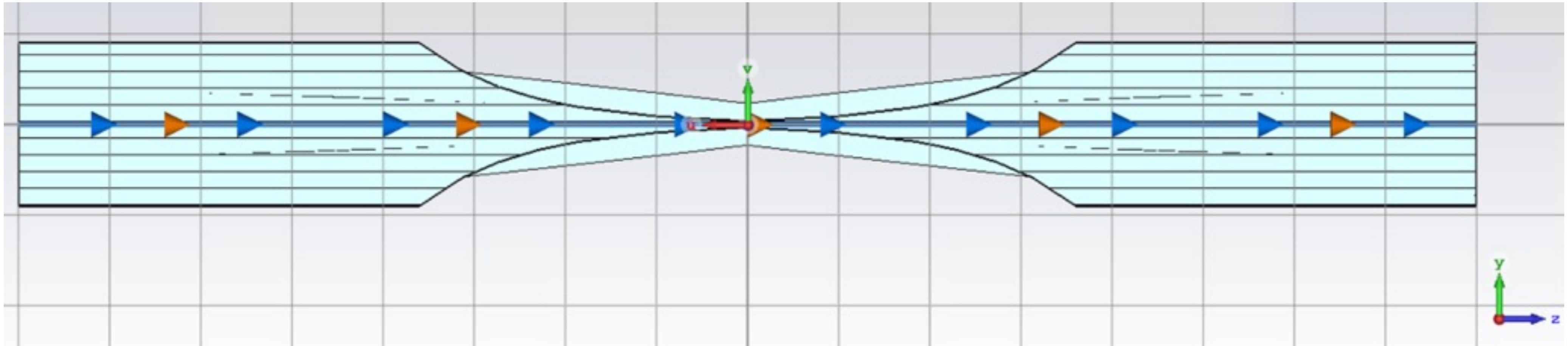
Linear jaw



Elliptical jaw

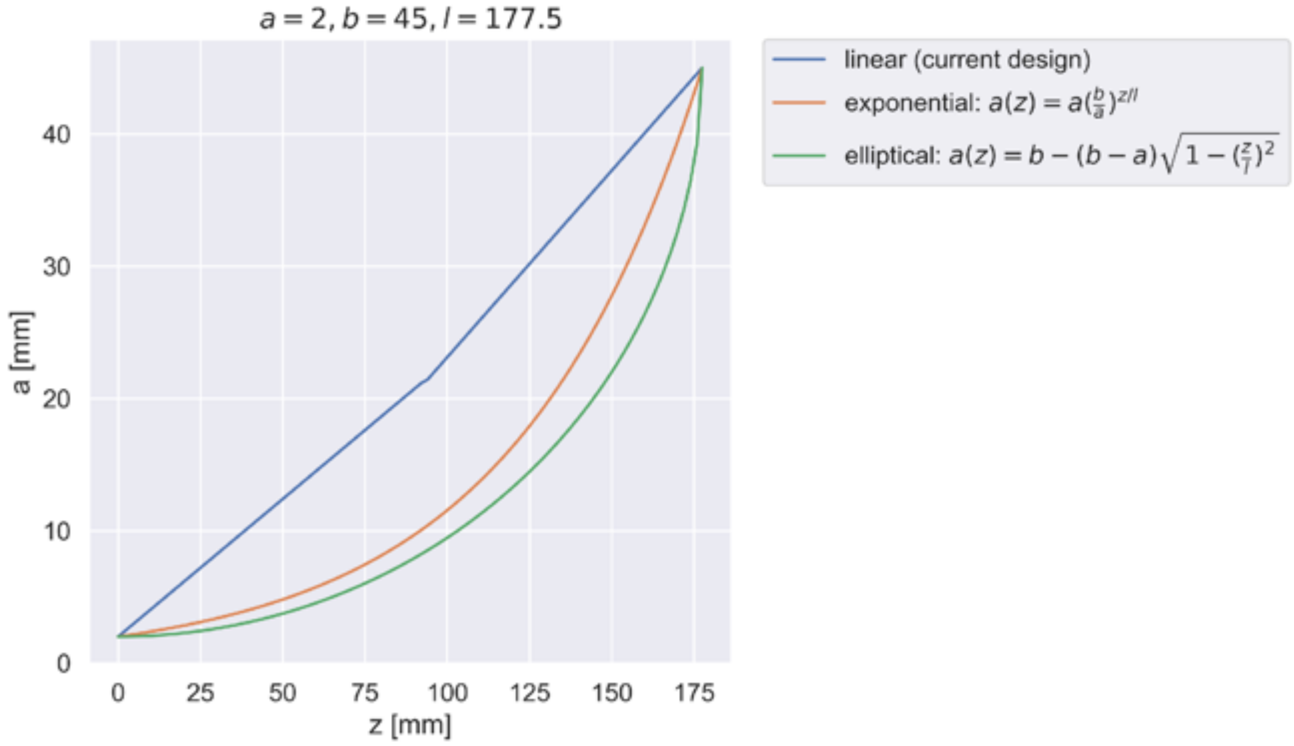


Exponential jaw



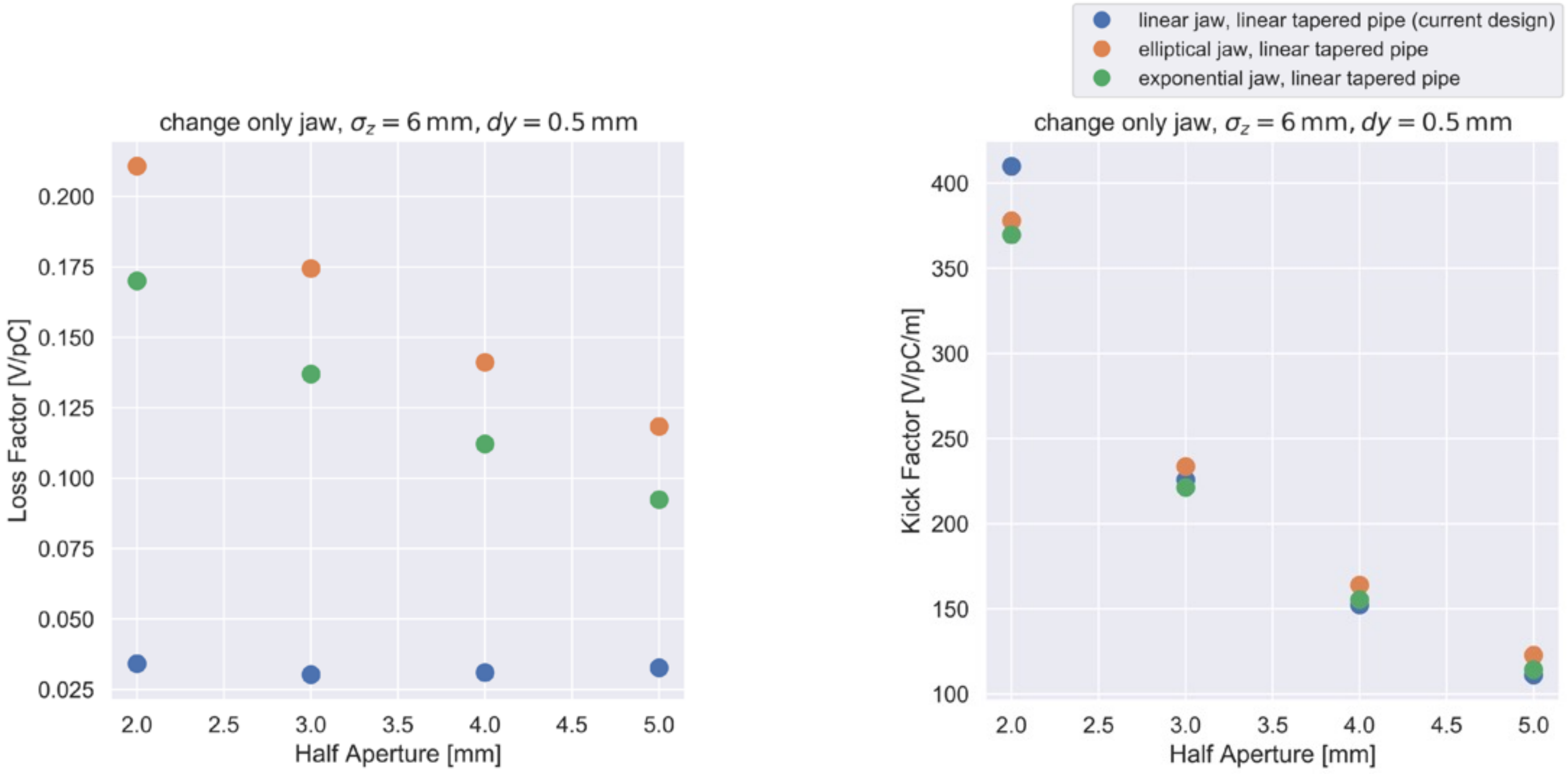
Non-linear slope (geometry to reduce the impedance)

Current design vs exponential vs elliptical



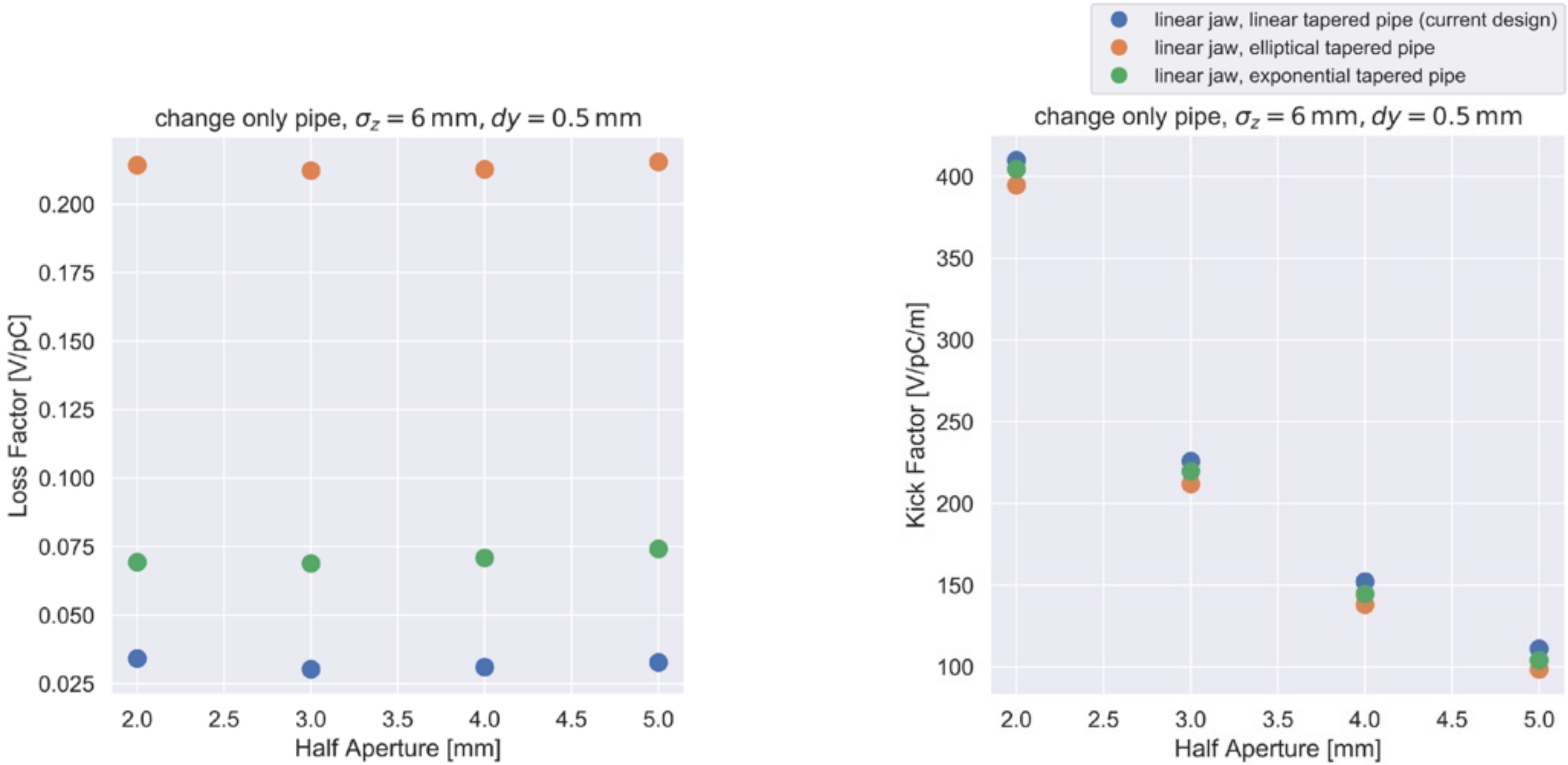
Cut test for aluminum plate using wire-cutting machine

Non-linear slope (geometry to reduce the impedance)



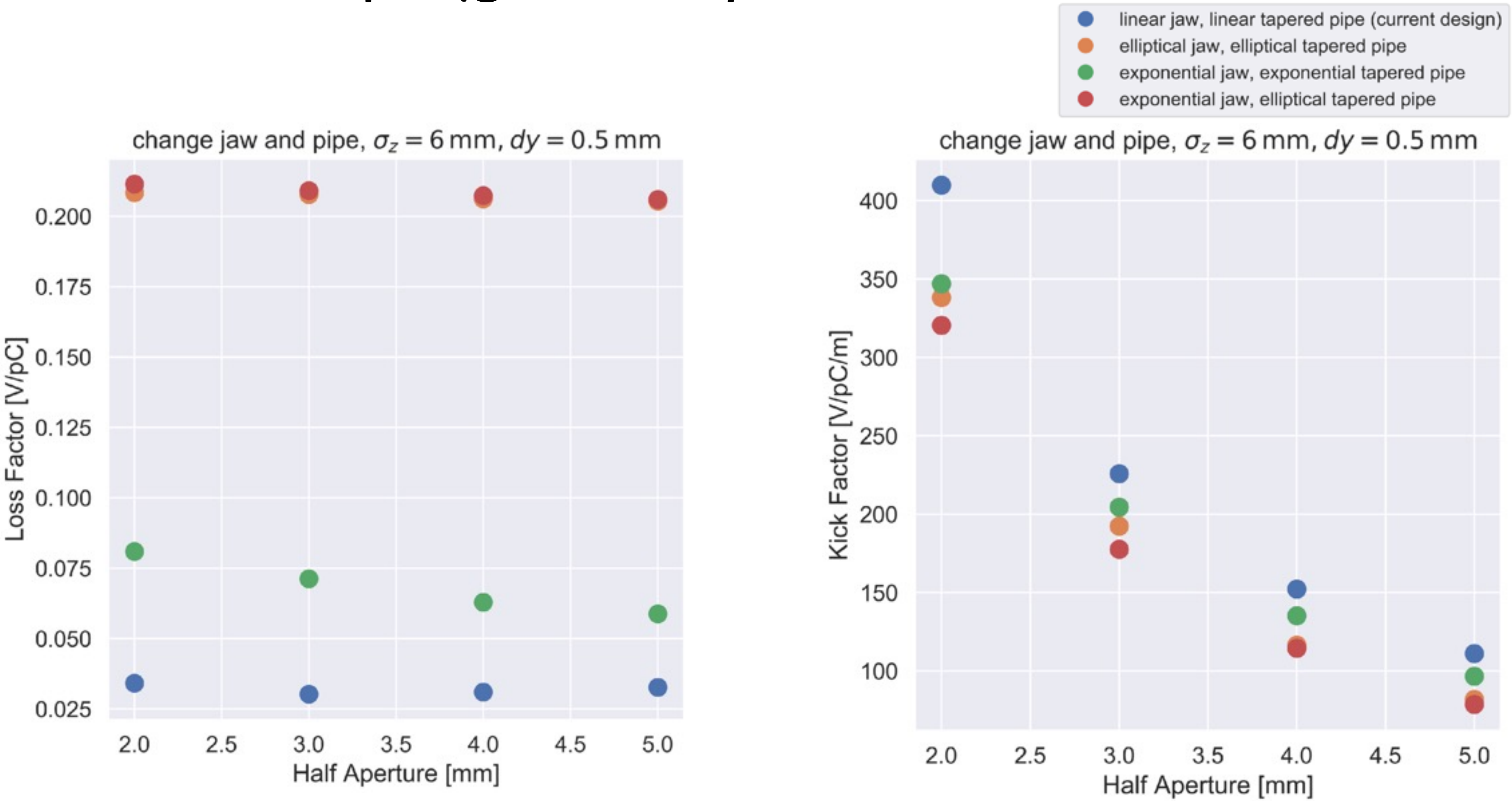
The exponential jaw is the best to reduce the kick factor for the narrow aperture.
The kick factor of the exponential one is smaller than that of the linear one by ~10% for H.A.=2 mm.

Non-linear slope (geometry to reduce the impedance)



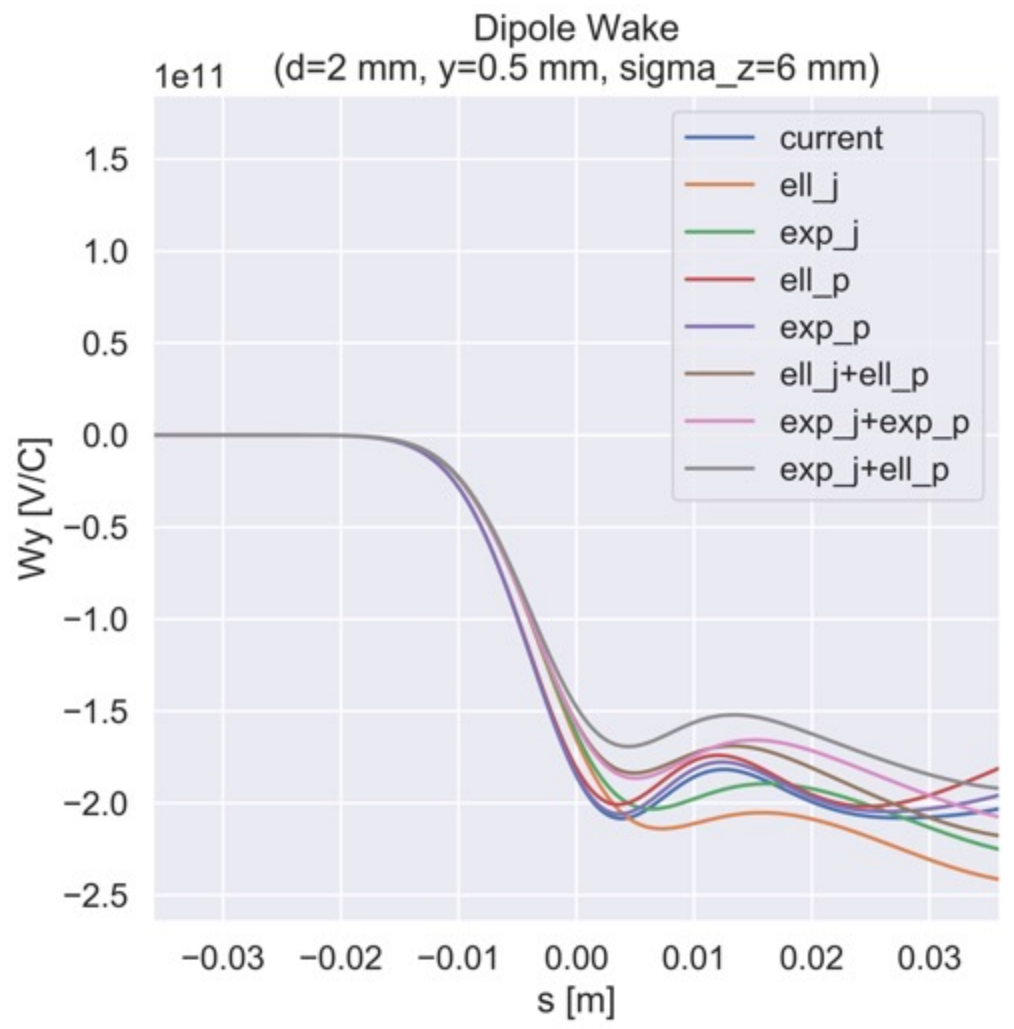
The elliptical tapered pipe is the best to reduce the kick factor.
The kick factor of the elliptical one is smaller than that of the linear one by ~4% for H.A.=2 mm.

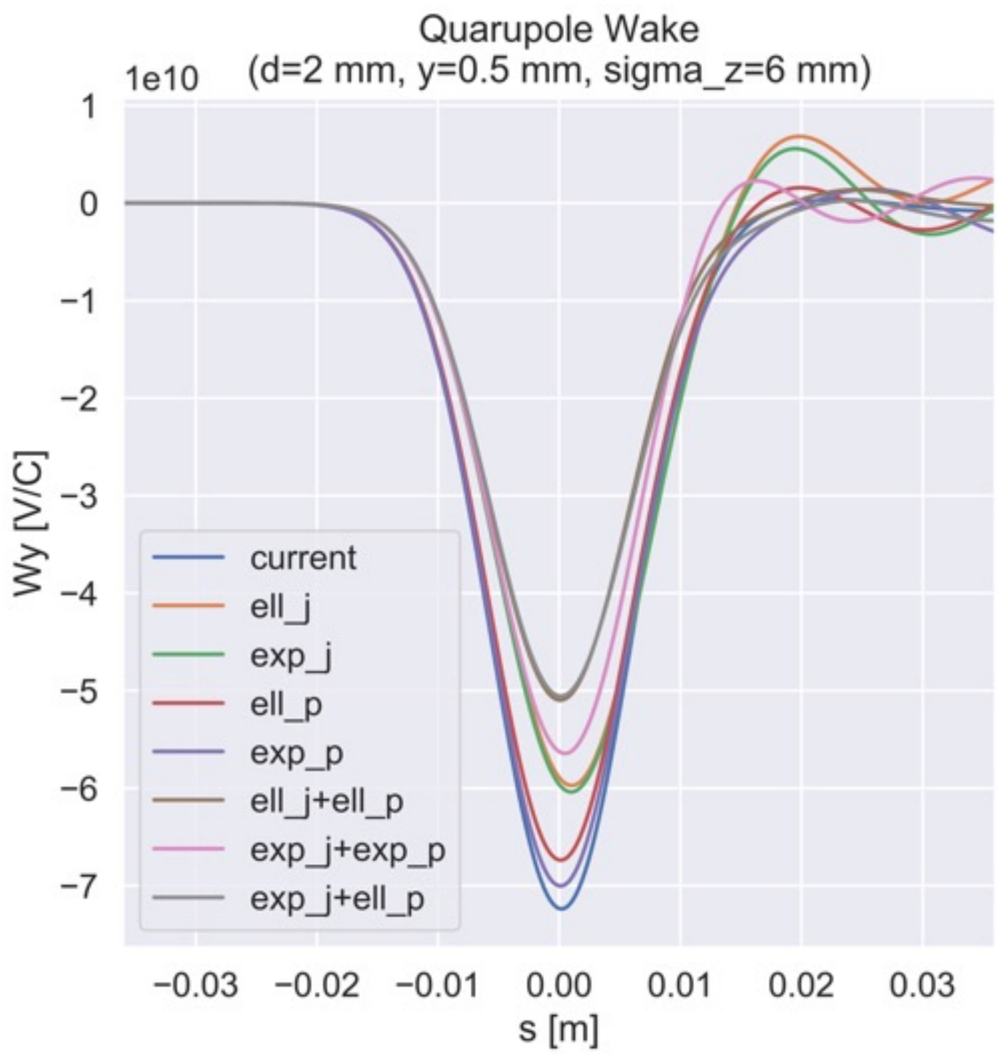
Non-linear slope (geometry to reduce the impedance)



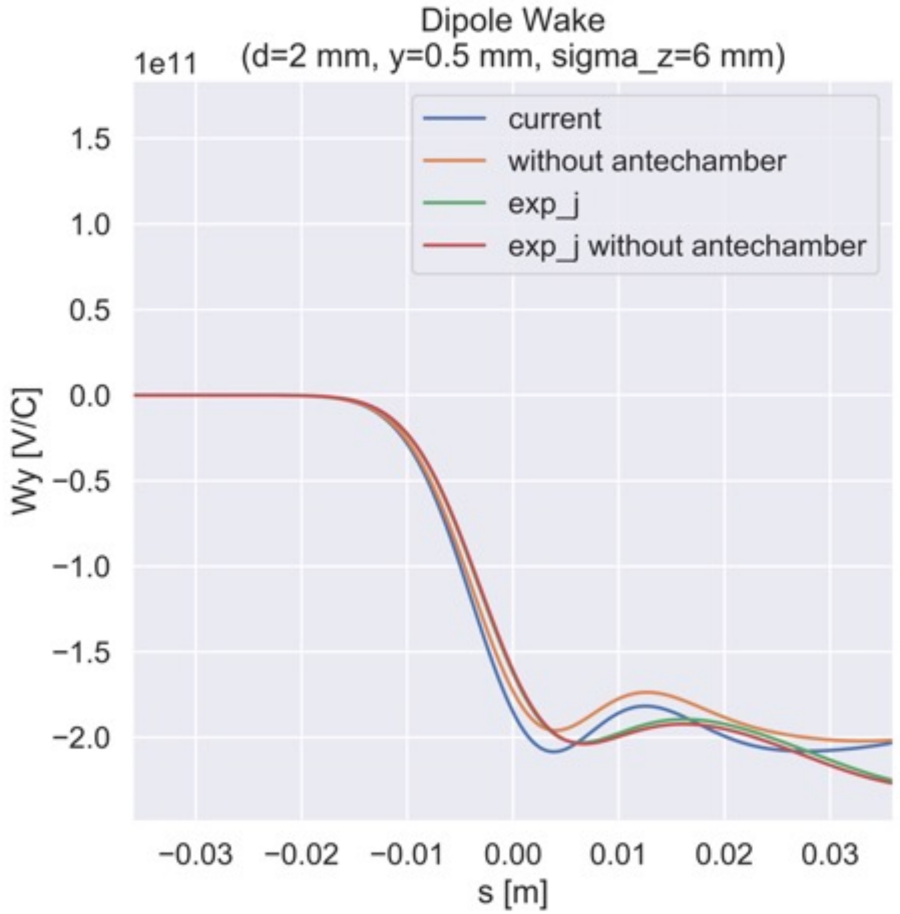
The combination of the exponential jaw and the elliptical tapered pipe is the best to reduce the kick factor.
The kick factor of this combination is smaller than that of the current design by ~22% for H.A.=2 mm.

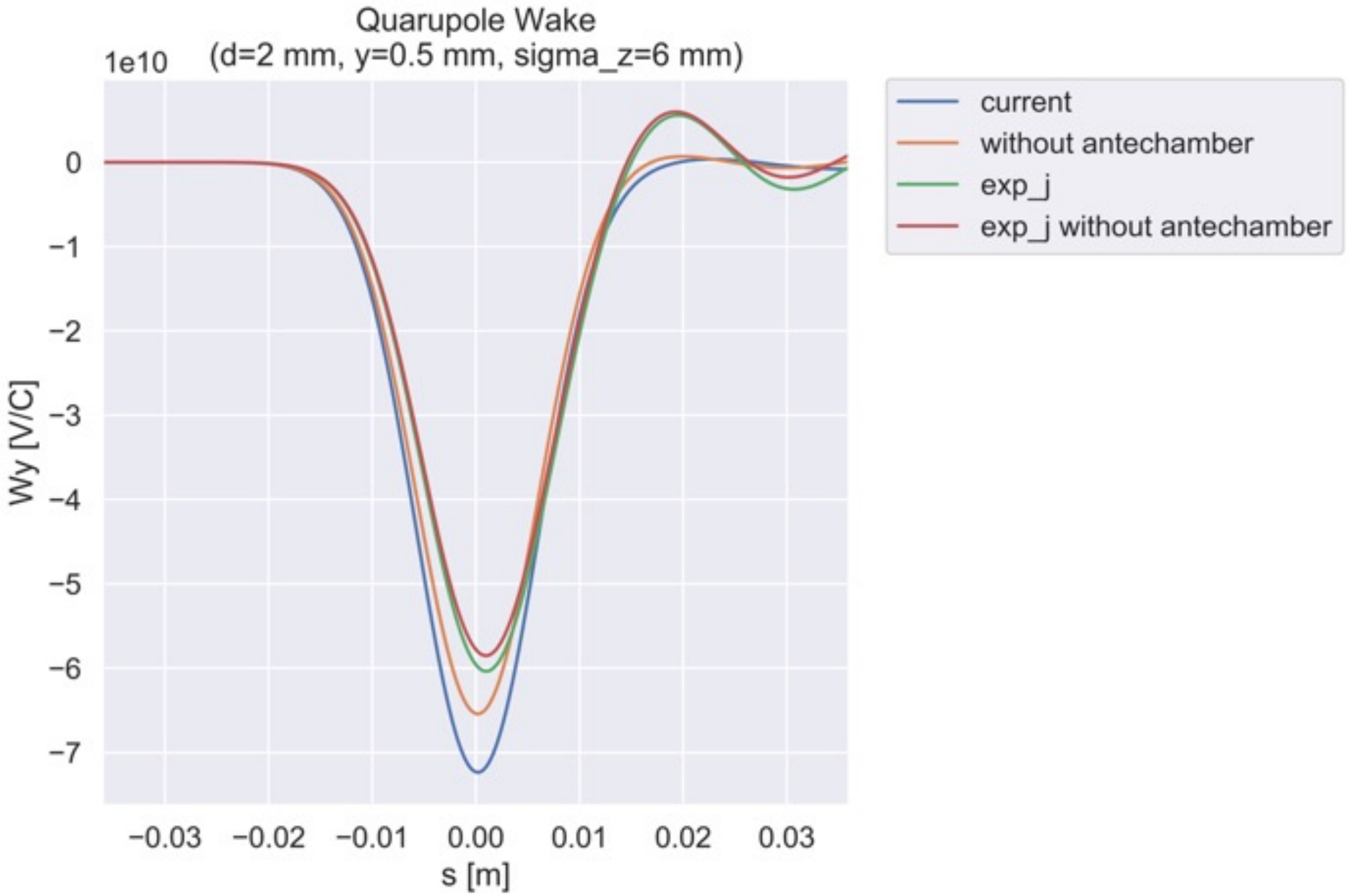
Non-linear slope (geometry to reduce the impedance)





Non-linear slope (geometry to reduce the impedance)



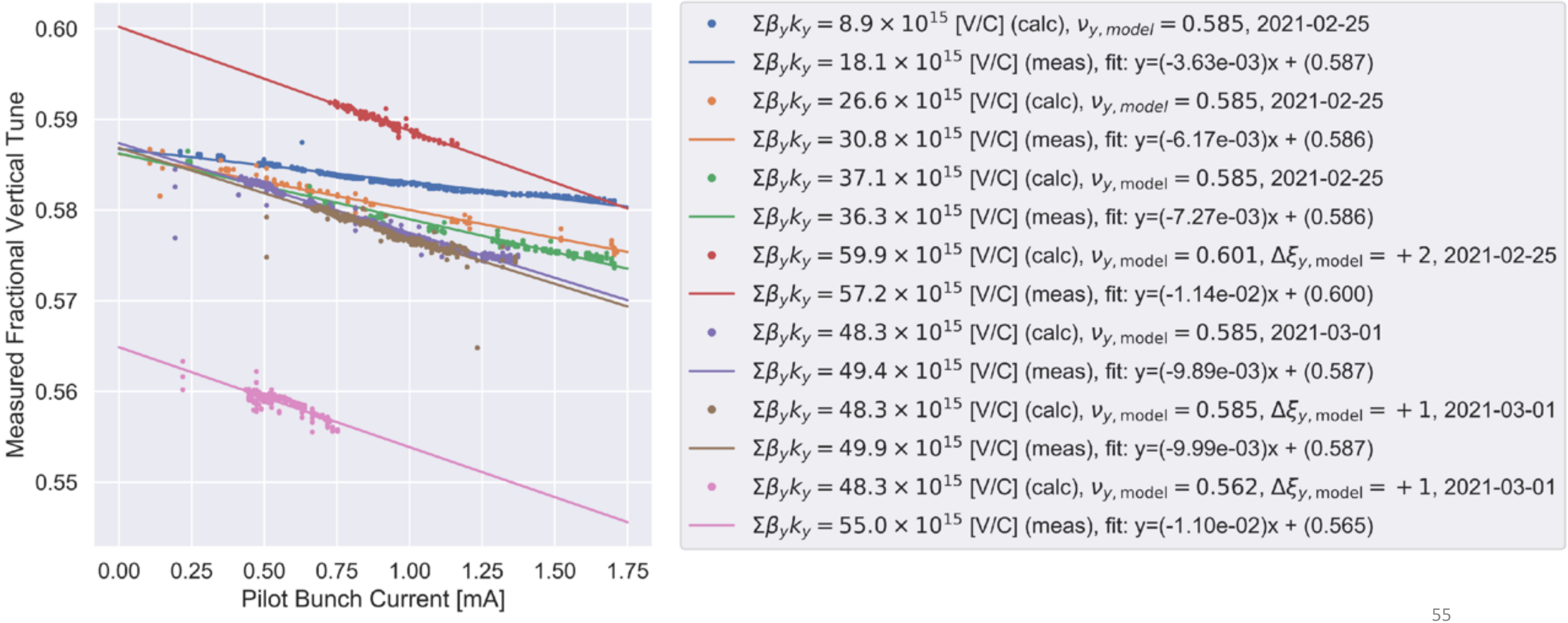


Vertical tune shift

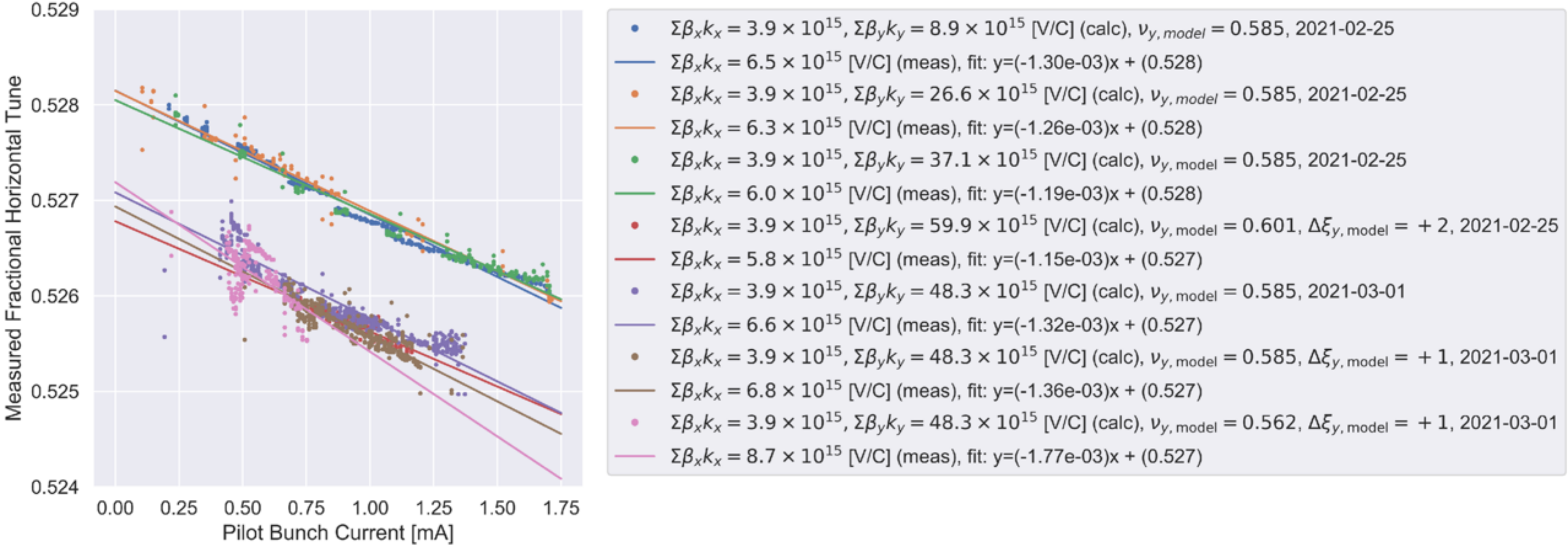
$$\boxed{\Delta\nu_{x/y} = \frac{I_b T_0}{4\pi(E/e)}\Sigma\beta_{x/y}k_{x/y}}$$

T_0 = circ./c ~1e-5 s

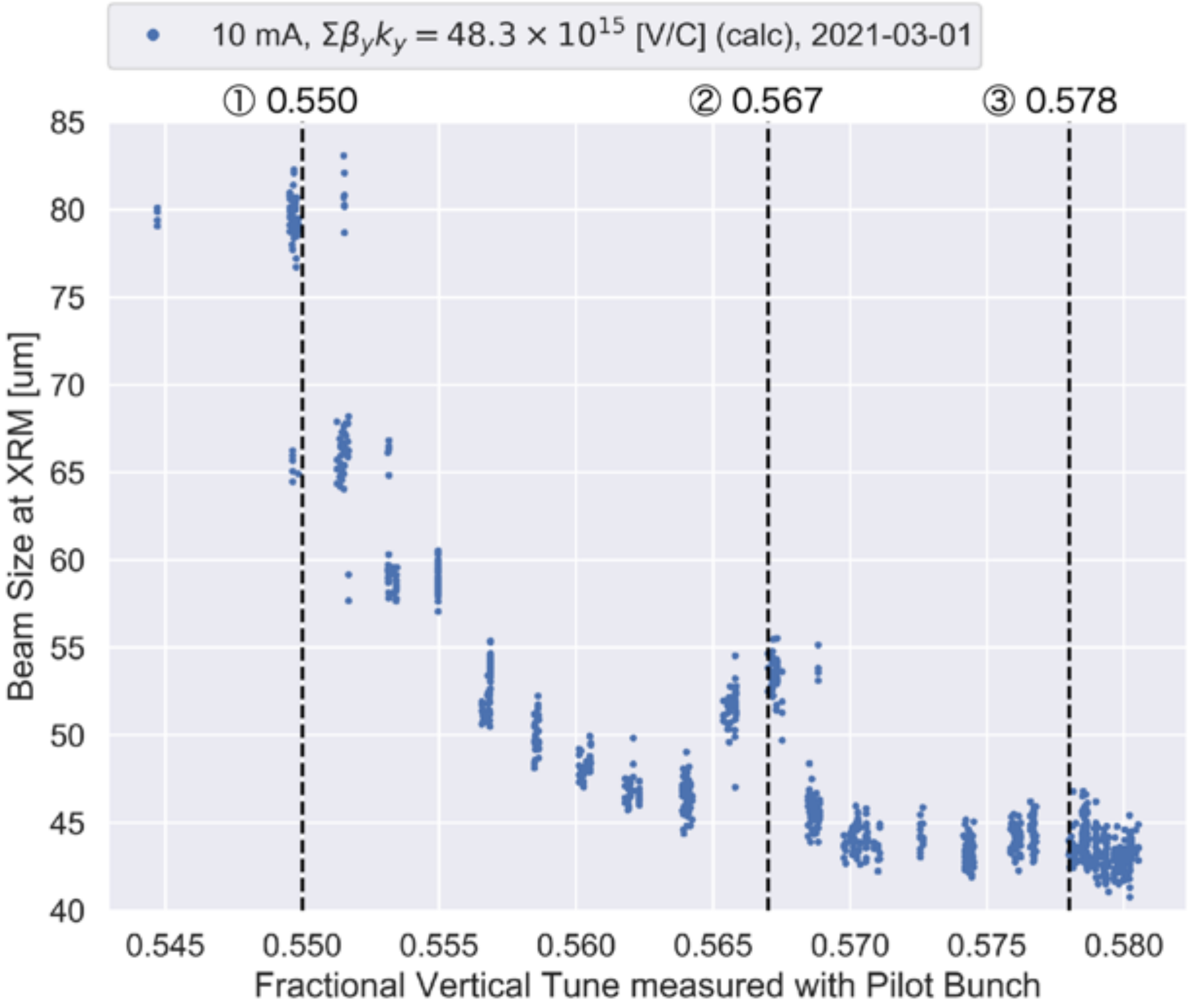
E/e = 4 GV

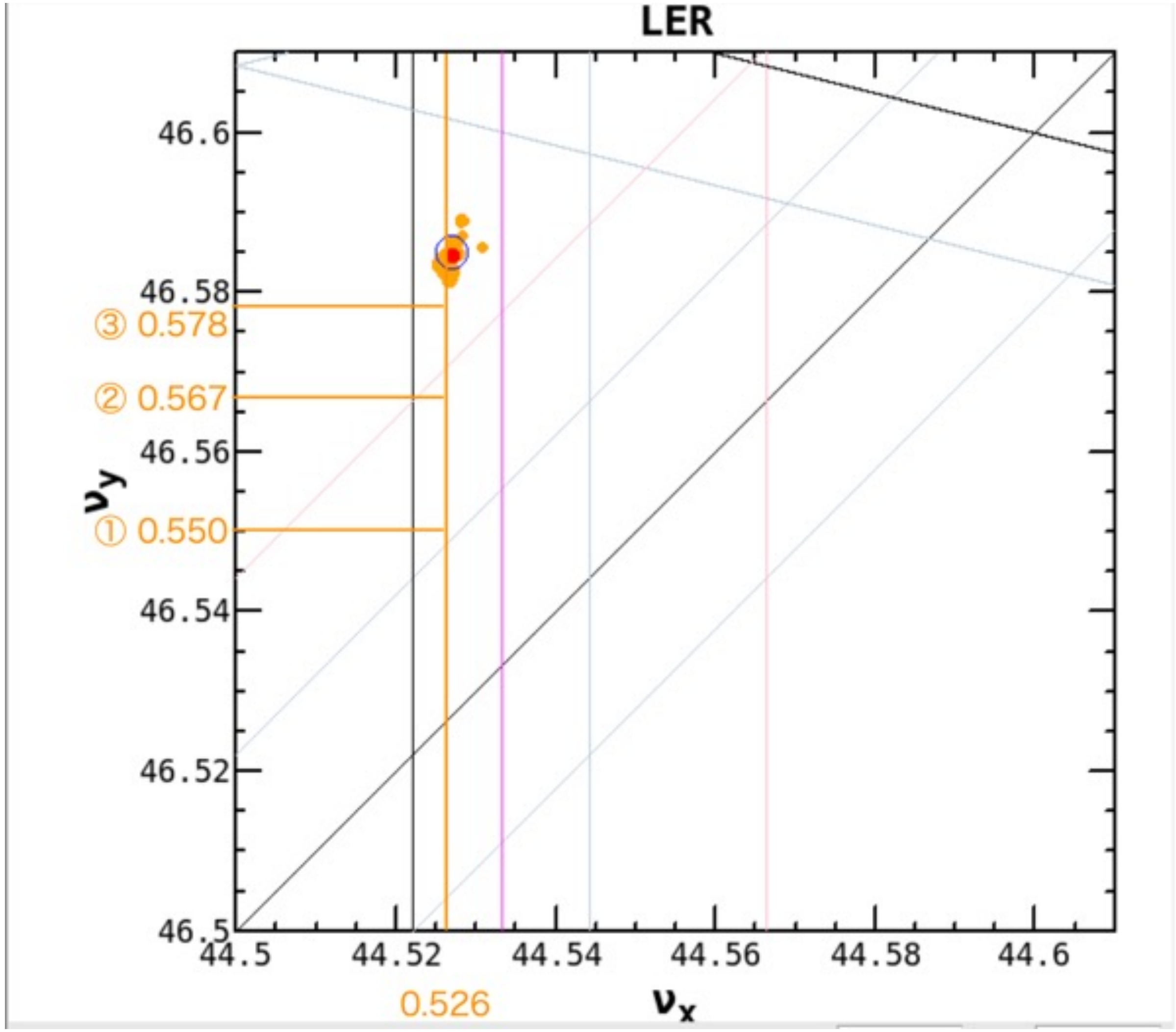


Horizontal tune shift

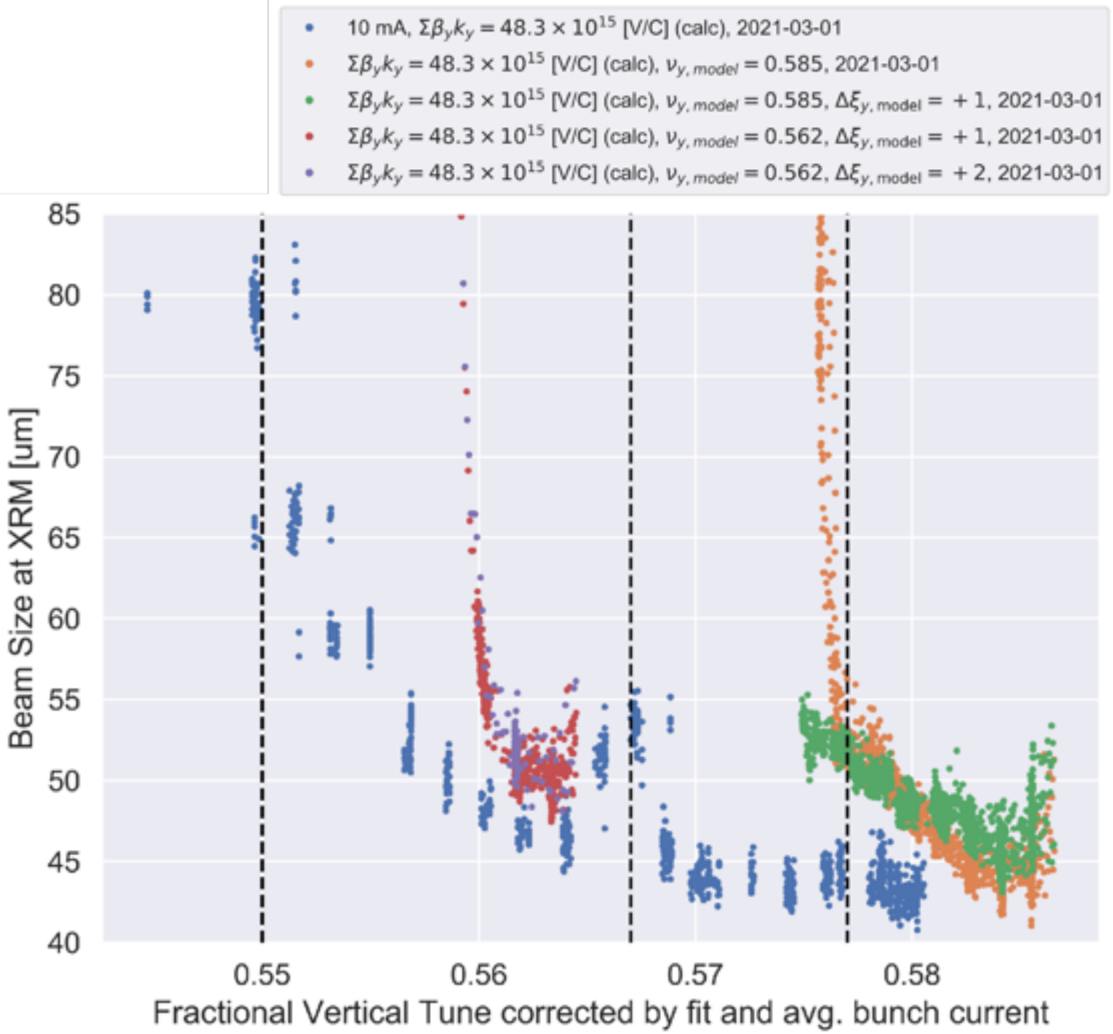


Vertical tune scan

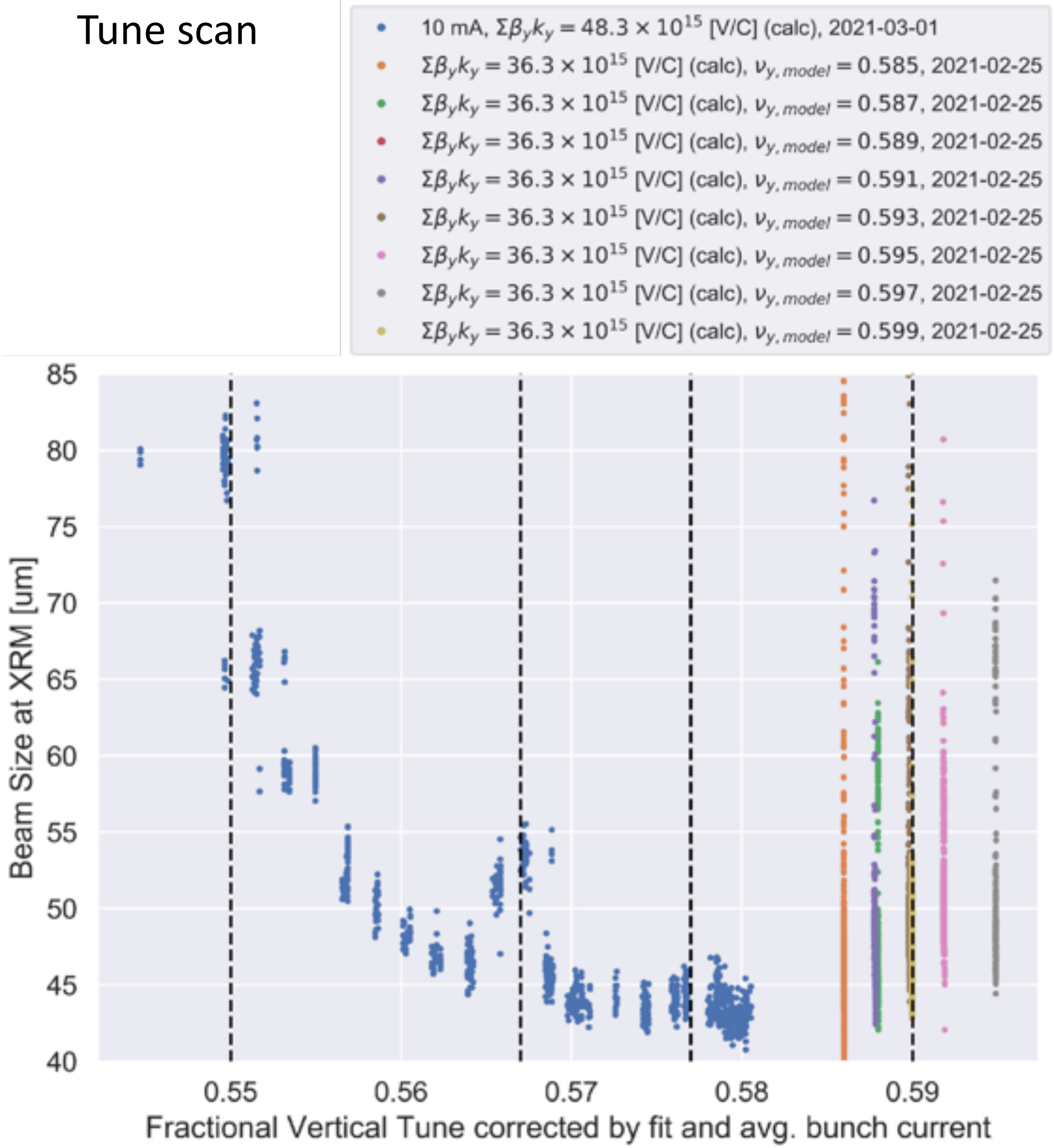




Beam size blowup

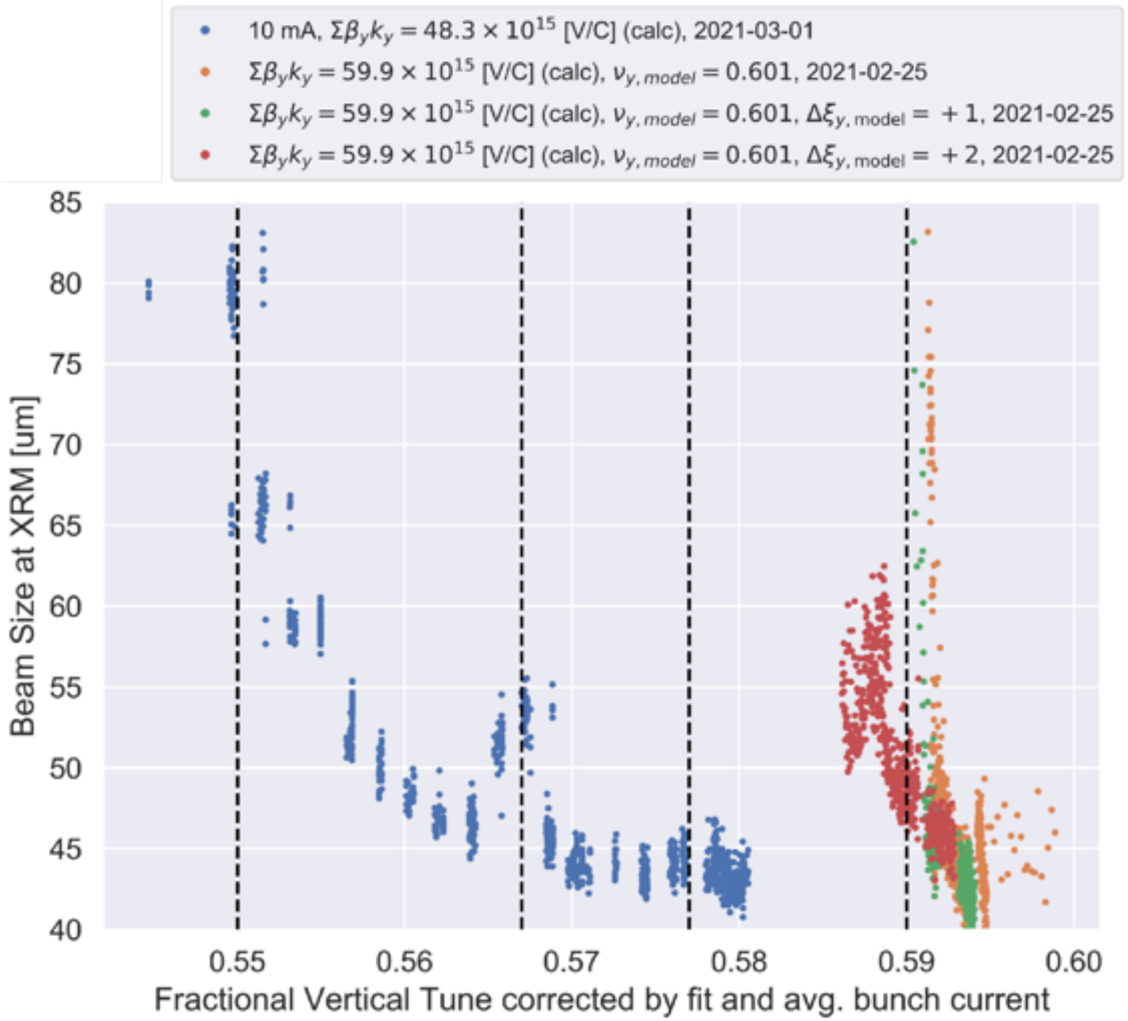


Tune scan

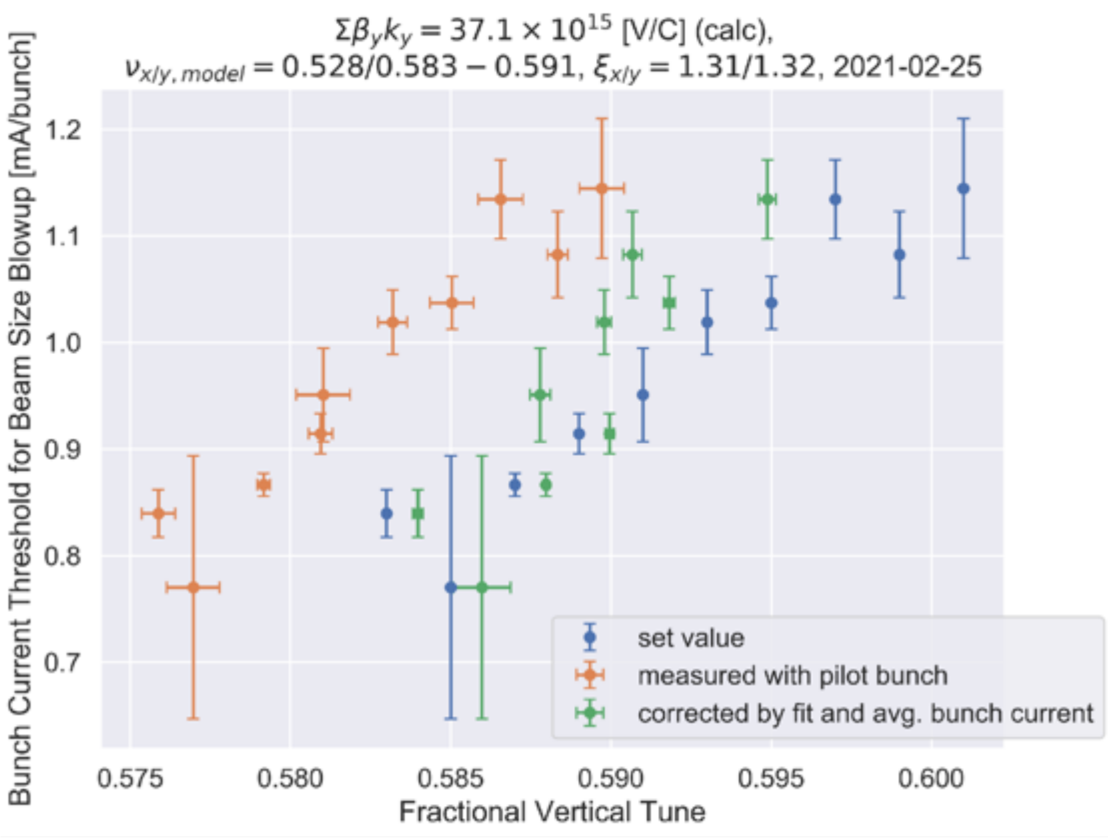


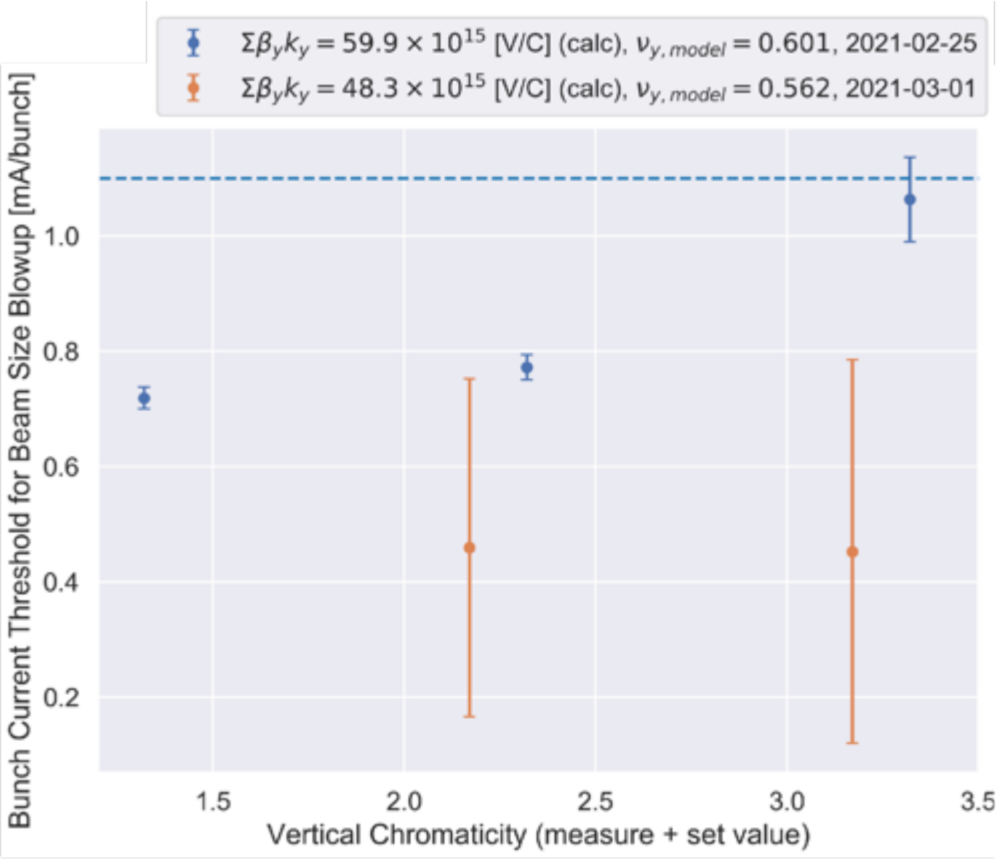
Beam size blowup

Chromaticity scan



Beam size blowup





TMCI threshold (calc): ~1.6 mA/bunch
Reference sigma_y at XRM: 45.5 μm
Judgement value of beam size blowup: 54.6 ± 2.9 μm

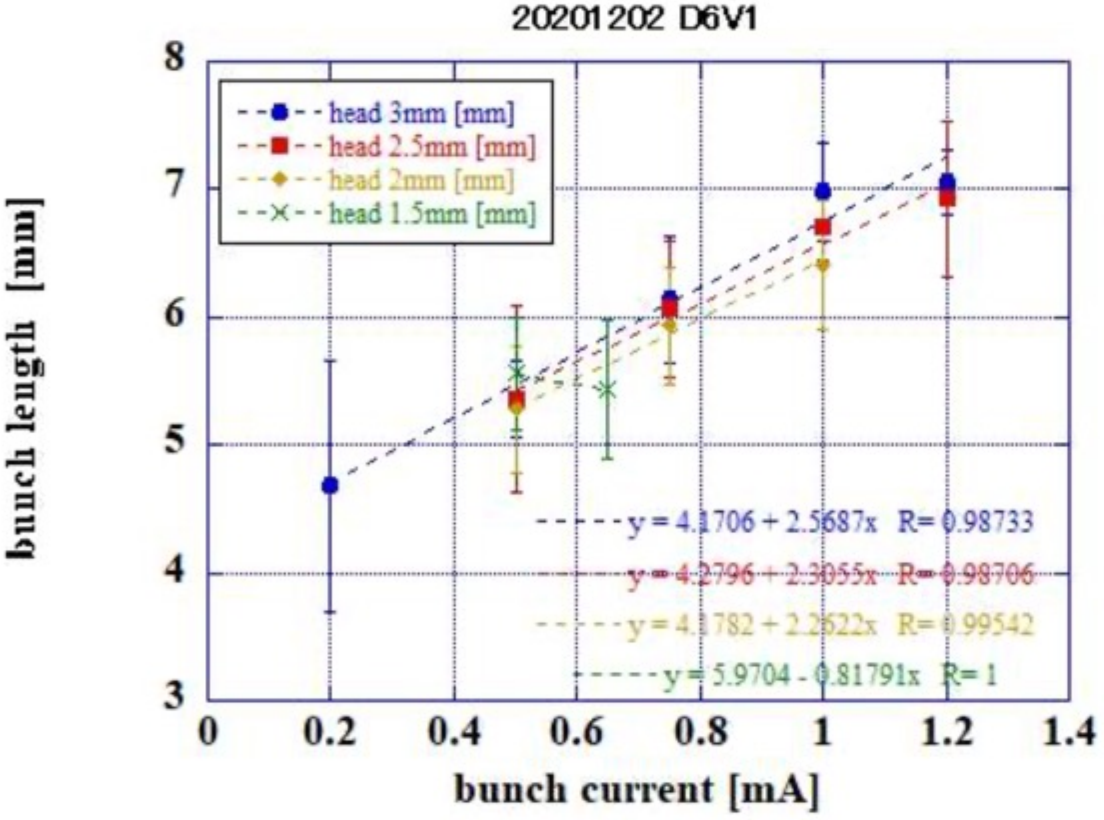
Defining the beam size blowup as (reference sigma_y)*1.2 ± (std).
(reference sigma_y) is averaged sigma_y at XRM in low current.
(std) is the standard deviation of the sigma_y at XRM in low current.
Low current is defined from 9 mA to 11 mA in total current here.

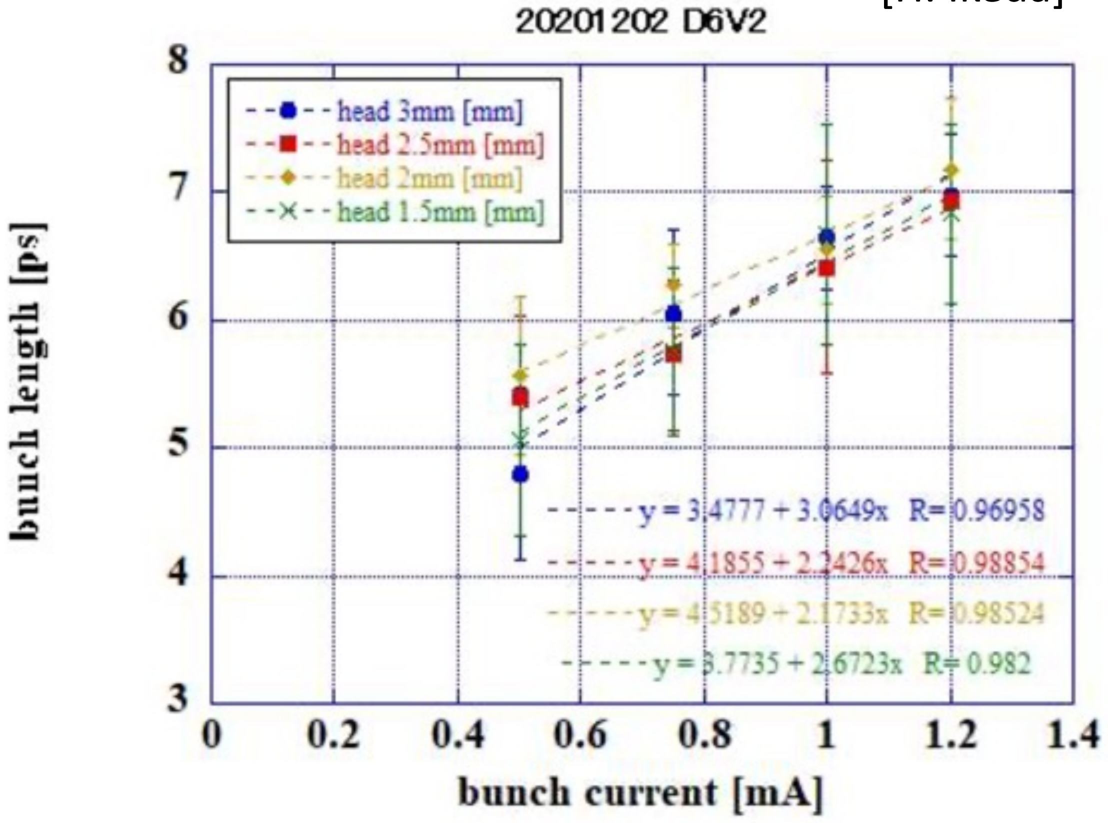
TMCI threshold (calc): ~1.1 mA/bunch ($\Sigma\beta_y k_y$ = 59.9×10^{15} V/C, Feb. 25th)
Reference sigma_y at XRM: ~44.2 μm (Feb. 25th), ~51.6 μm (Mar. 1st),
Judgement value of beam size blowup: ~53.0 ± 2.1 μm (Feb. 25th), ~62 ± 2.8 μm (Mar. 1st),

Defining the beam size blowup as (reference sigma_y)*1.2 ± (std).
(reference sigma_y) is averaged sigma_y at XRM in low current.
(std) is the standard deviation of the sigma_y at XRM in low current.
Low current is defined from 9 mA to 11 mA in total current here.

Beam length measurements for collimator apertures

[H. Ikeda]





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.