Sudden Beam Loss

The 27th KEKB Accelerator Review Committee

2024/3/25 H. Ikeda

Contents

“Sudden Beam Loss”

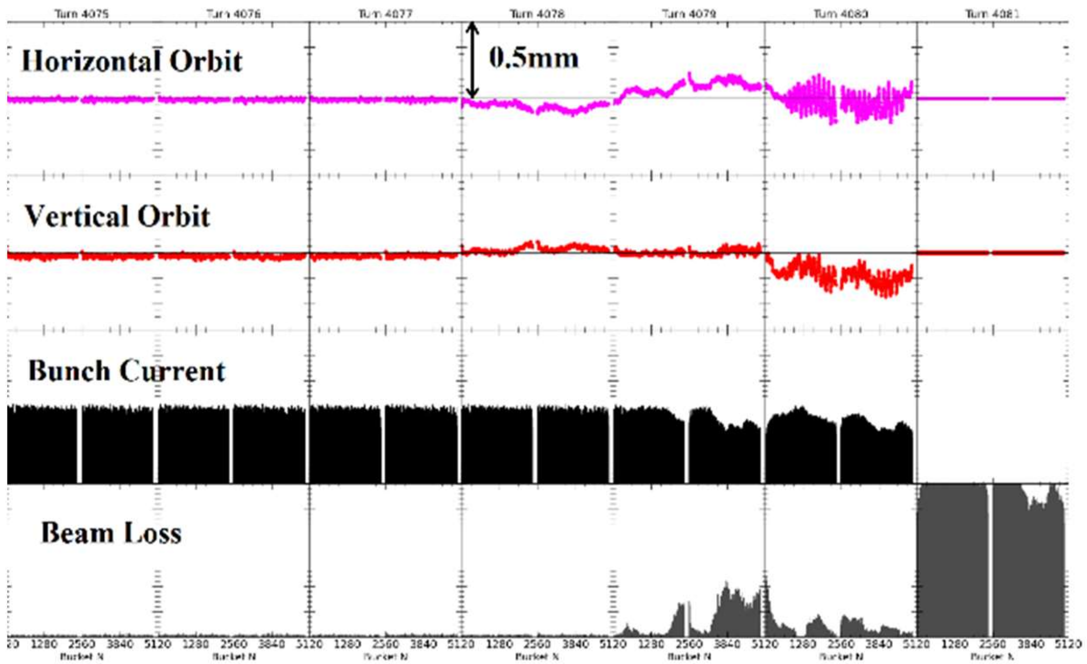
Beam loss that occurs suddenly within 1 turn (10μs) without precursory phenomena.
＝　Sudden Beam Loss　（SBL）

- The cause of SBL is unknown.
- A significant percentage of the beam is lost before the abort trigger is applied.

→　Harmful effects of SBL;

  - Damage to collimators and other accelerator components,
  - Quench of the final focusing superconducting magnets (QCS),
  - Large backgrounds to the Belle-II detector,
  - Inability to store high current due to beam abort.

Beam signal measured by
Beam Oscillation Recorder(BOR) & Bunch Current Monitor(BCM)



Observation

- The beam suddenly disappears just before the abort.
- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER.
- We don't know if it will happen even with a single beam or low current beam because we haven't operated for a long time.
- The starting point of beam loss depends on the tuning of the collimator and is not limited to a specific location.
- Just before the beam loss begins, the orbit appears to move, but its value is small～O(0.1 mm).
- The orbit is changing < O(1mm) after the beam loss.
- No oscillations that could be precursors to beam loss are observed.
- Pressure bursts have been observed all over the place and rarely occur in the same place except at the collimator section.
- Regarding the pressure of D06H3 and H1 collimators there are rapid or nonlinear increase of pressure depending on the beam current.

Possible Reasons for SBL

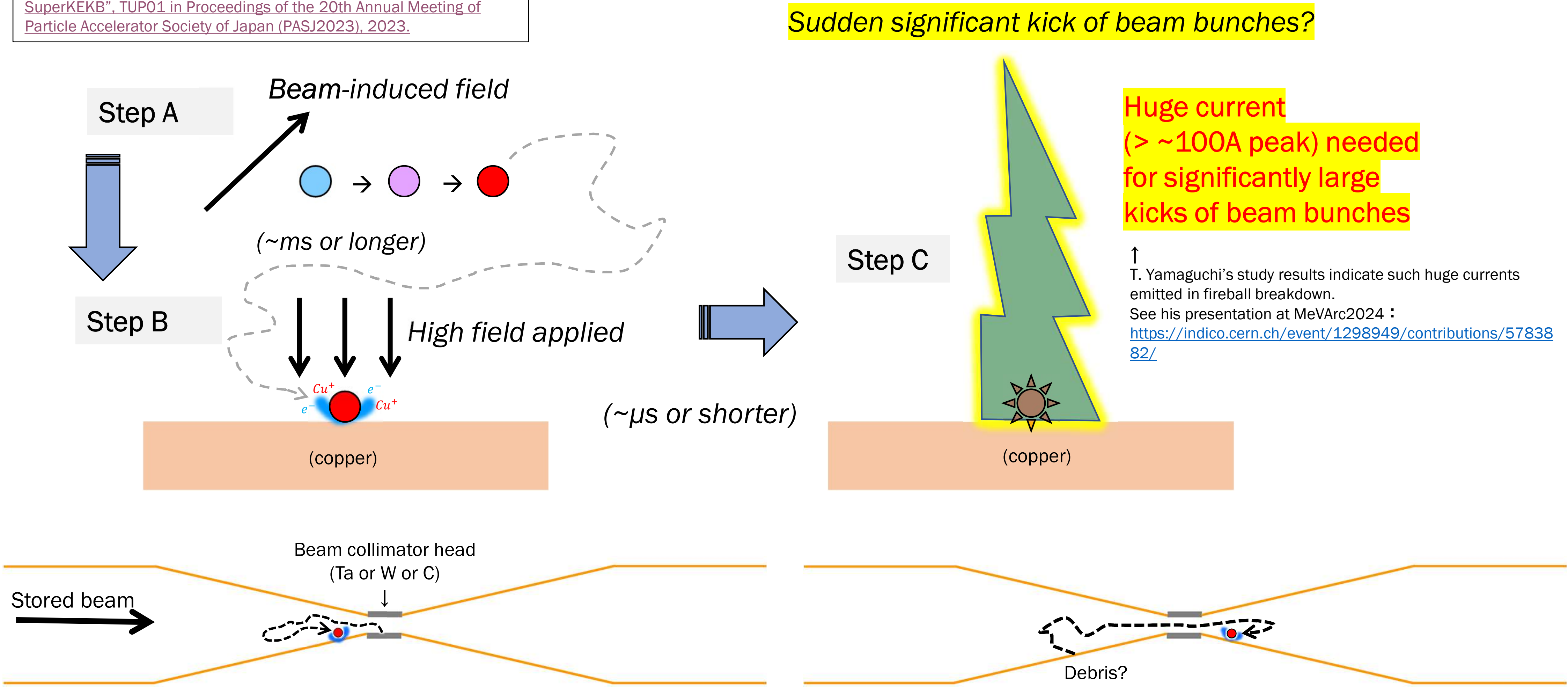
- Damage of vacuum component (RF Finger) @KEKB & PEP-II
  - Beam phase changes (beam energy losses) observed ms to several hundred μs before aborts. → The time scale differs from that of SBL.
  - Abnormal temperature rise at bellows chambers had been observed and the catastrophic damages in the RF-finger had been confirmed. → We could not find that damage.
- Dust : Early stage @ SuperKEKB
  - Vacuum chambers were cleaned or tapped to remove as much dust as possible.
- Electron Cloud
  - SBL should be measured only in LER.→ SBL is also measured in the HER beam.
  - Curious behavior of the pressure in D06H3 collimator may suggest the formation of a discharge or electron cloud.
  - Simulations show that the electron density distribution changes with time and a maximum electron density is on the order of 1E13/m3 to 1E14/m3 → How this relates to SBL?
- Fireball : Measured @ RF cavity
  - The vacuum chamber is made of copper with low sublimation point and collimator head is made of tungsten or tantalum with high sublimation point.

  → The situation has the potential for a fireball to be formed.
  - This fireball hypothesis could explain SBL (~μs) due to the fast plasma evolution (~100 ns at the fastest).

The fireball hypothesis for SBL

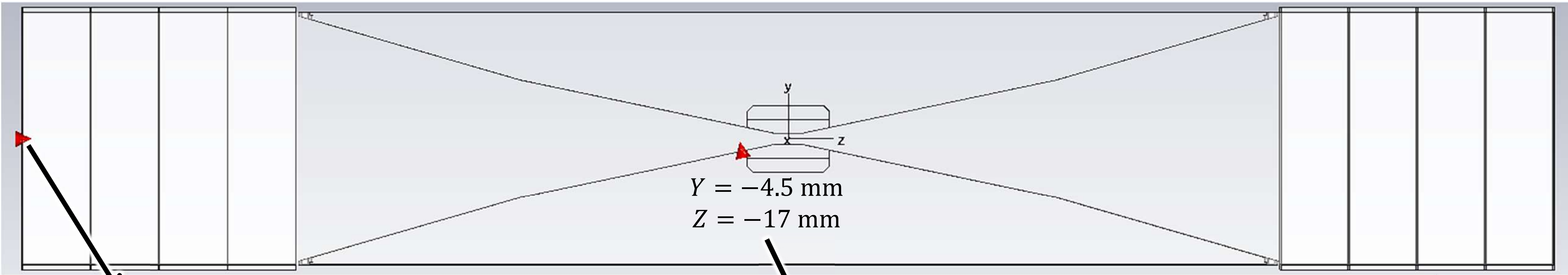
For the details, see the following paper:

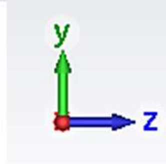
T. Abe, “Fireball Hypothesis for the Trigger of Sudden Beam Losses at SuperKEKB”, TUP01 in Proceedings of the 20th Annual Meeting of Particle Accelerator Society of Japan (PASJ2023), 2023.



Aperture: ±1mm at min. at SuperKEKB

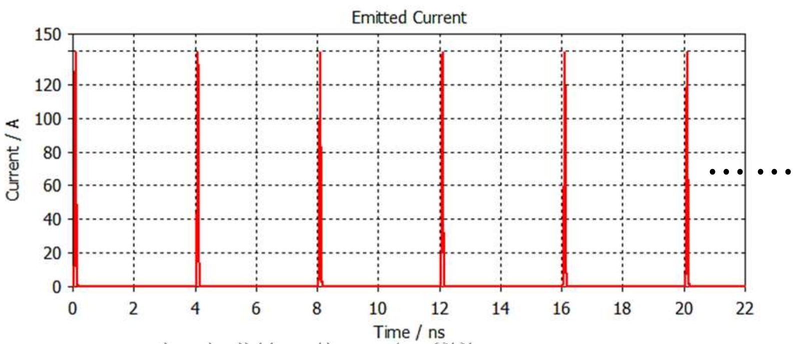
CST PIC Simulation / Particle Sources





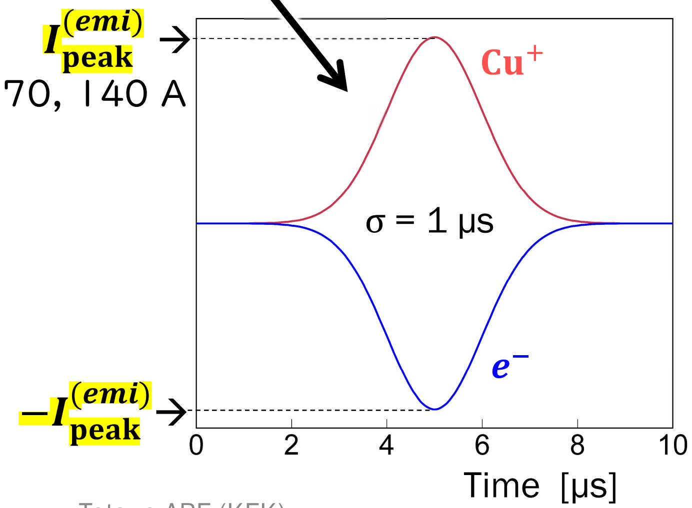
e^+ bunches

- 4 GeV
- 7 nC/bunch
- 6 mm length in z with no transverse size
- 4ns spacing



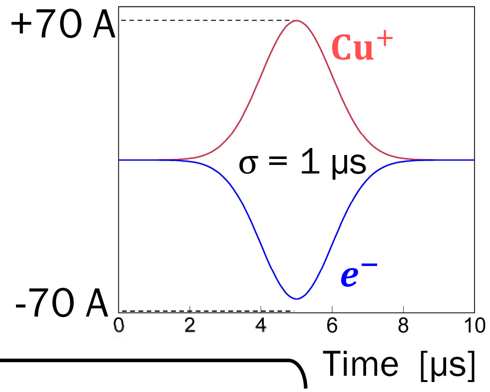
Simulating plasma generation

$= 35, 70, 140$ A など

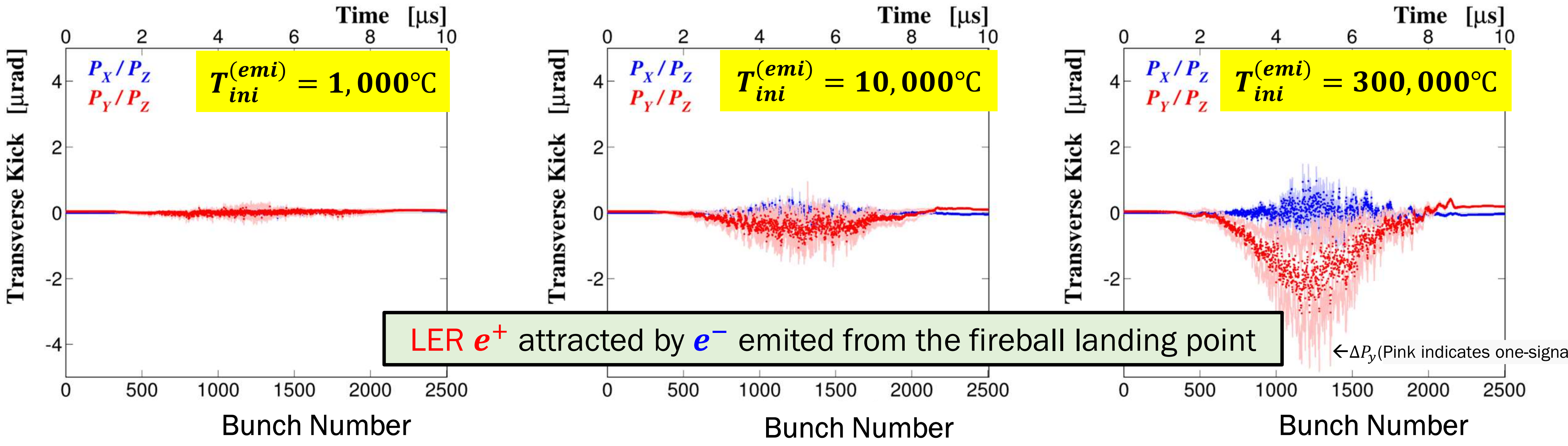


Initial velocities of emitted particles are determined from the initial temperature ($T^{(emi)}_{ini}$) of the plasma according to Maxwellian distribution

[Examples of the simulation results]
Transverse kick angles for $I_{peak}^{(emi)} = 70\ A$



$I_{peak}^{(emi)} = 70\ A$



- ✓ According to the Funakoshi-san's study, several tens of μrad kick angles are needed for SBL.
- ✓ Further study is on-going for making larger kick angles based on the fireball hypothesis.

Work during LS1

For preventing SBL

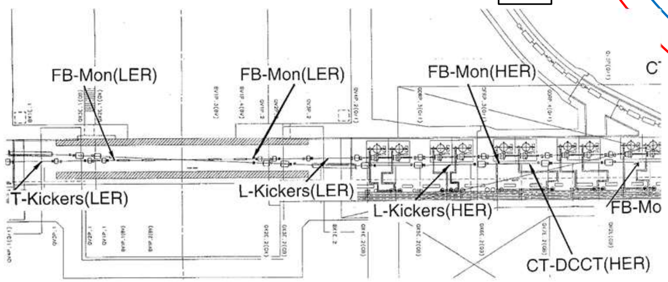
- Replacing damaged collimator head.
- Copper coating of collimator heads (D6H3, D6V1, D5V1, D2V1). （Cover material with a high sublimation point, which could be the seed of a fireball, with material with a low sublimation point.)
- Installation of permanent magnets in all SuperKEKB-type horizontal collimators. （In order to reduce the electron cloud effect…）
  - LER D02H4, D02H3, D02H2, D02H1, D03H1, D06H3, D06H4
  - HER D01H3, D01H4, D01H5

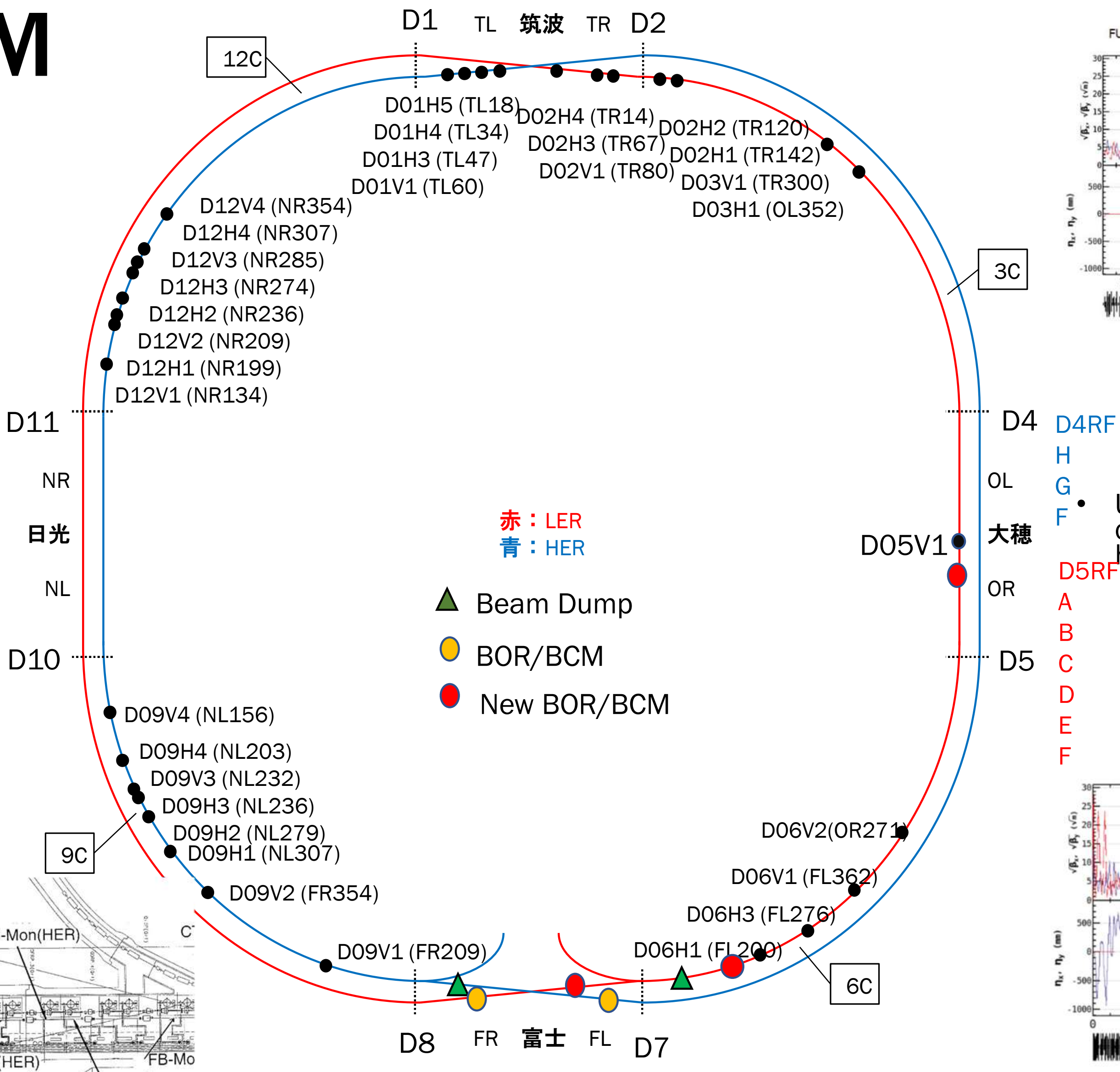
For investigation the cause of SBL

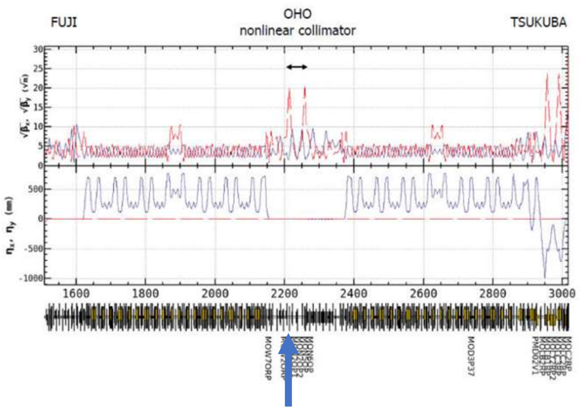
- Add BOR to investigate beam orbit change in locations that may be the cause of SBL.
  - Measure the orbit at two different locations with phase differences. ：Existing BOR
  - Add a simplified version to measure in phase with the collimator, although with less accuracy. ：New BOR
- Add loss monitor for timing measurement
- Install acoustic sensors to observe the sound when the Fireball occurs.(D2V1:minimum physical aperture, D5V1:new collimator, QCS, D6V2)

BOR/BCM

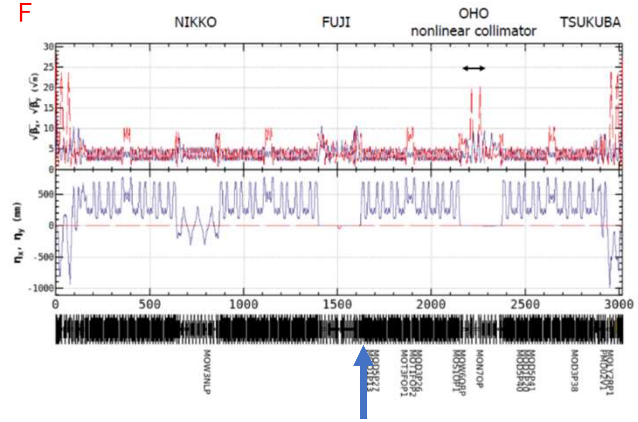
- Use original FB monitor (upstream and downstream).



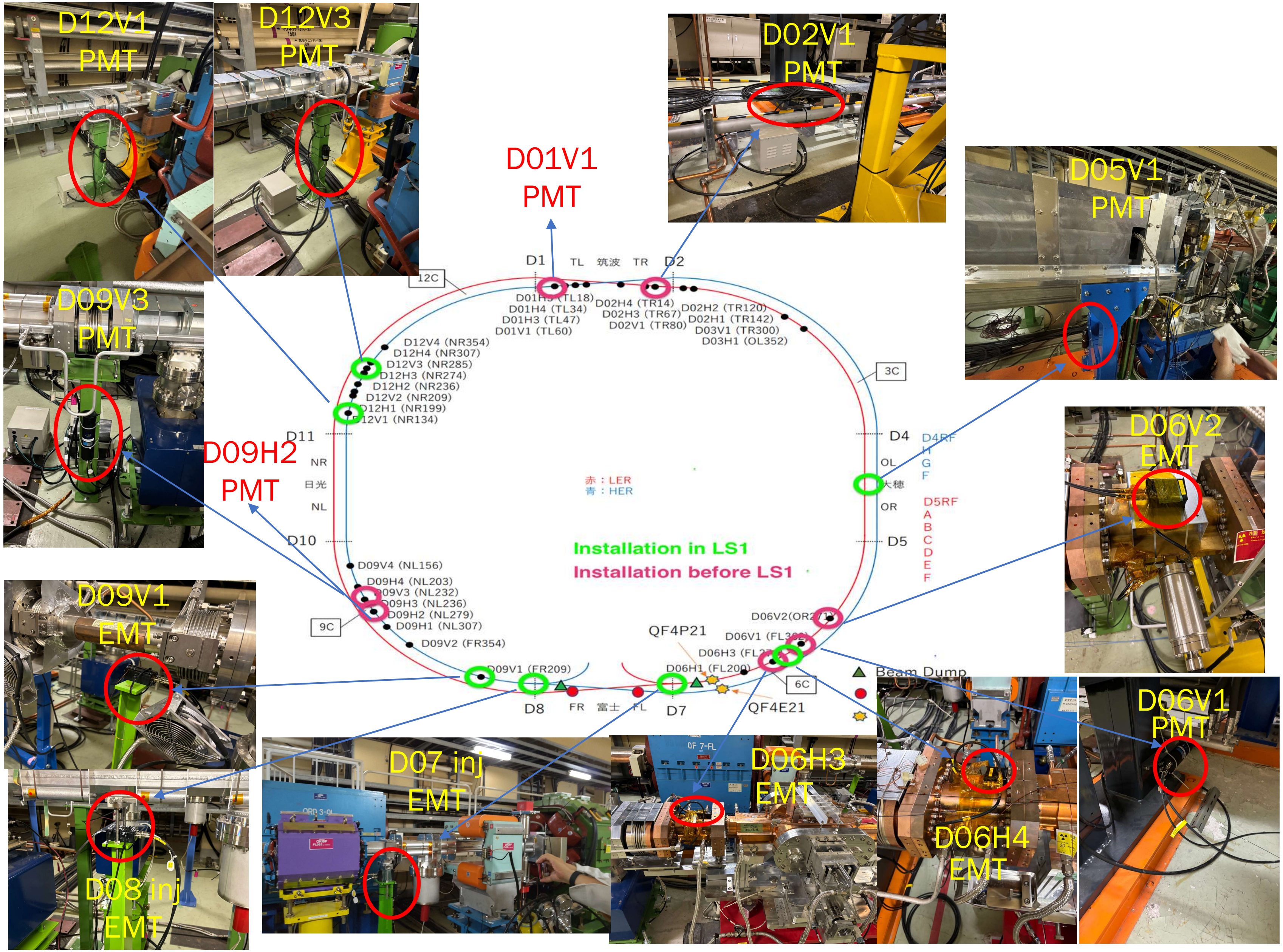




- Use BPM that is upstream of the collimator in phase with the collimator head.
  - Same vertical betatron phase as D2V1 : MQN10P D5 BM2 66.7m
  - Same vertical betatron phase as D6V1 : MQD5P26 D7 BM3 144.4



LM

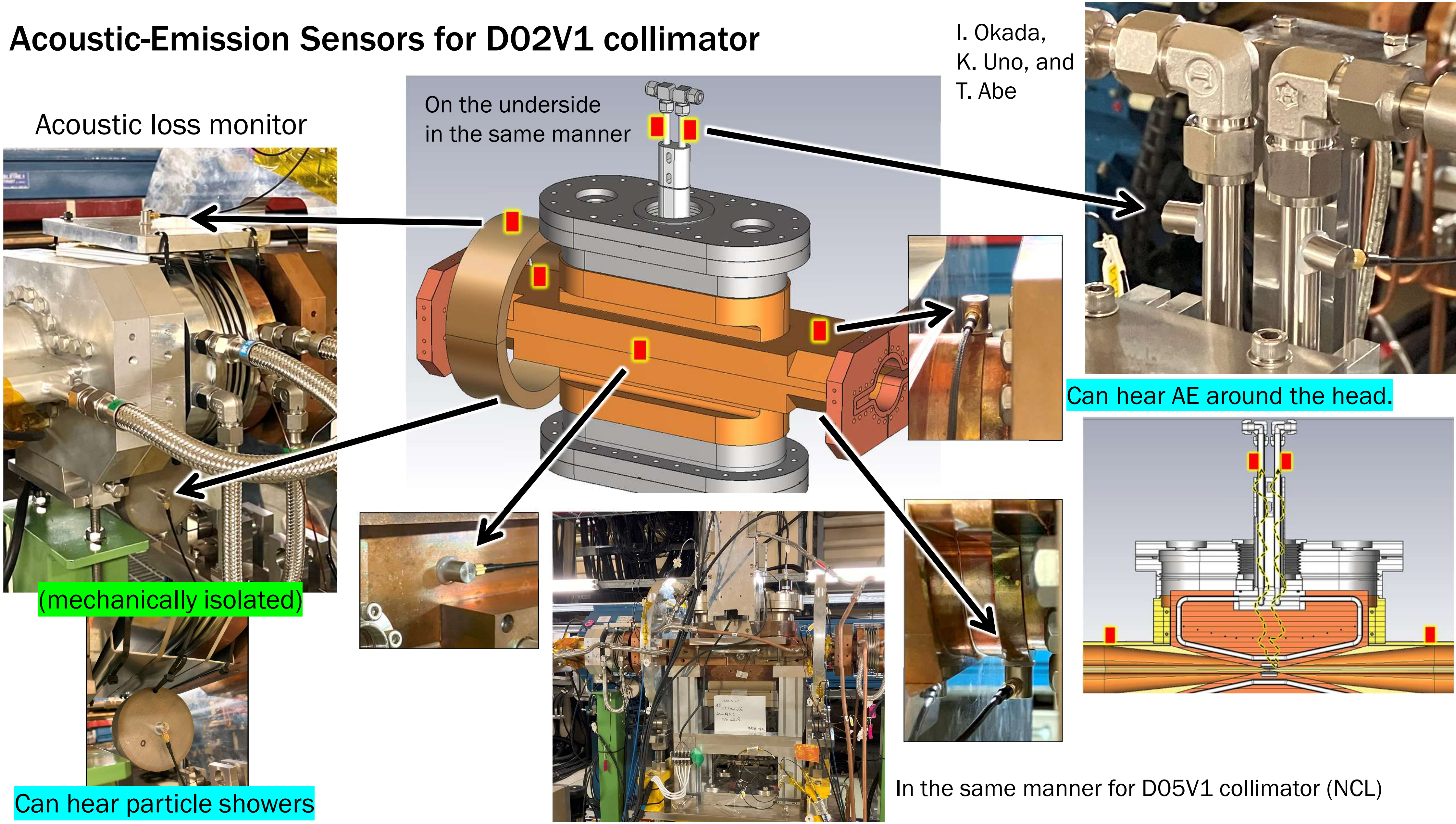


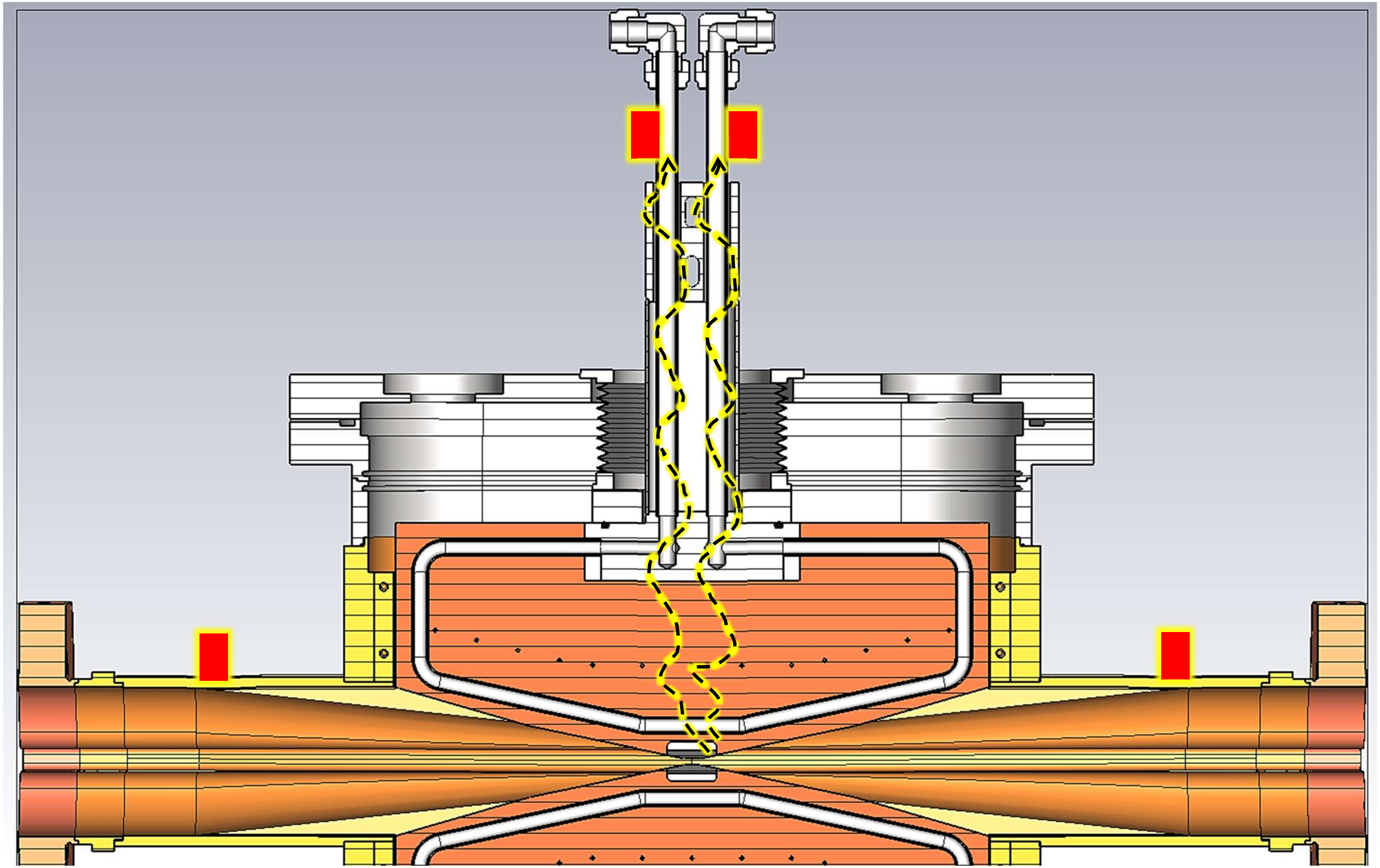
D12V1
PMT
D12V3
PMT
D02V1
PMT
D01V1
PMT
D05V1
PMT
D09V3
PMT
D09H2
PMT
D06V2
EMT
D09V1
EMT
D08 inj
EMT
D07 inj
EMT
D06H3
EMT
D06H4
EMT
D06V1
PMT
D1
TL
筑波
TR
D2
12C
3C
9C
6C
D01H4 (TL34)
D01H3 (TL47)
D01V1 (TL60)
D02H4 (TR14)
D02H3 (TR67)
D02V1 (TR80)
D02H2 (TR120)
D02H1 (TR142)
D03V1 (TR300)
D03H1 (OL352)
D12V4 (NR354)
D12H4 (NR307)
D12V3 (NR285)
D12H3 (NR274)
D12H2 (NR236)
D12V2 (NR209)
D11
NR
日光
NL
D10
D4
D4RF
OL
大穂
OR
D5RF
D5
赤：LER
青：HER
Installation in LS1
Installation before LS1
D09V4 (NL156)
D09H4 (NL203)
D09H3 (NL236)
D09H2 (NL279)
D09H1 (NL307)
D09V2 (FR354)
QF4P21
D09V1 (FR209)
D8
FR
富士
FL
D7
QF4E21
Beam Dump

(K. Uno et al.)

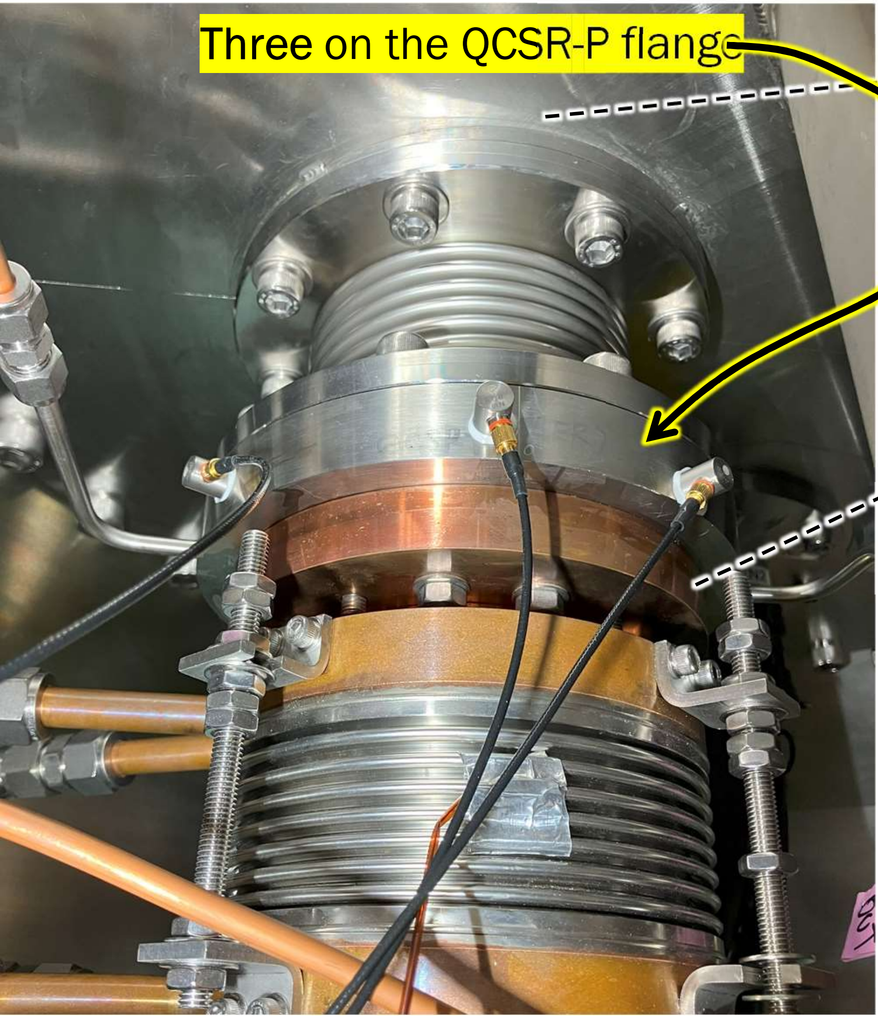
Acoustic-Emission Sensors for D02V1 collimator

I. Okada,
K. Uno, and
T. Abe



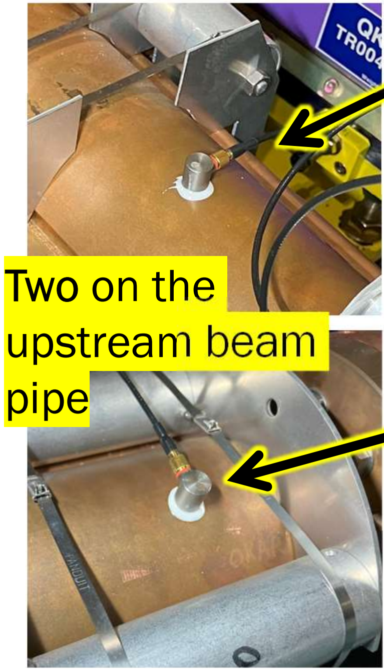


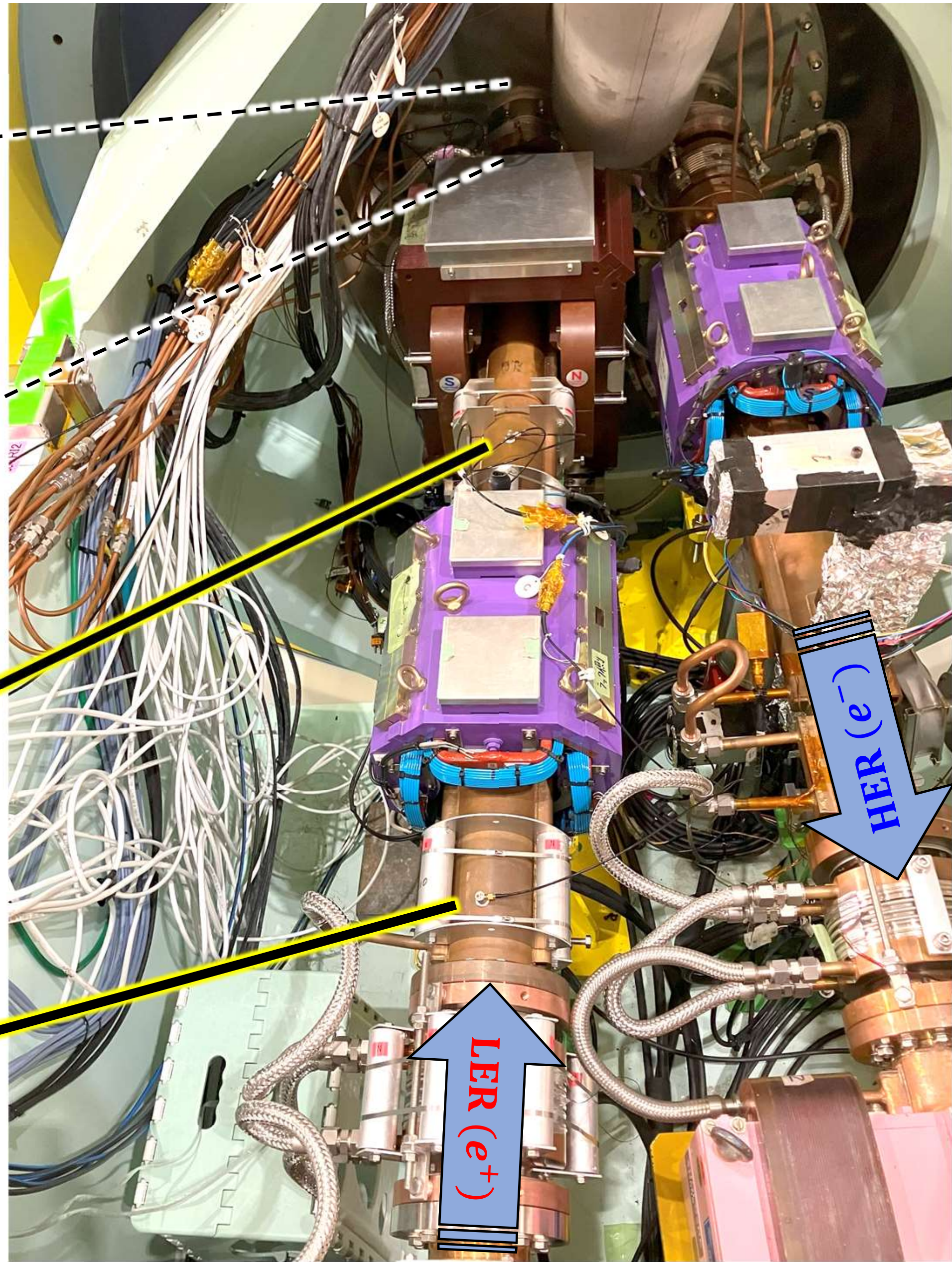
Five Acoustic-Emission (AE) Sensors around QCSR-P



Can hear AE from the beam pipe in QCSR-P

Y. Arimoto,
K. Uno, and
T. Abe



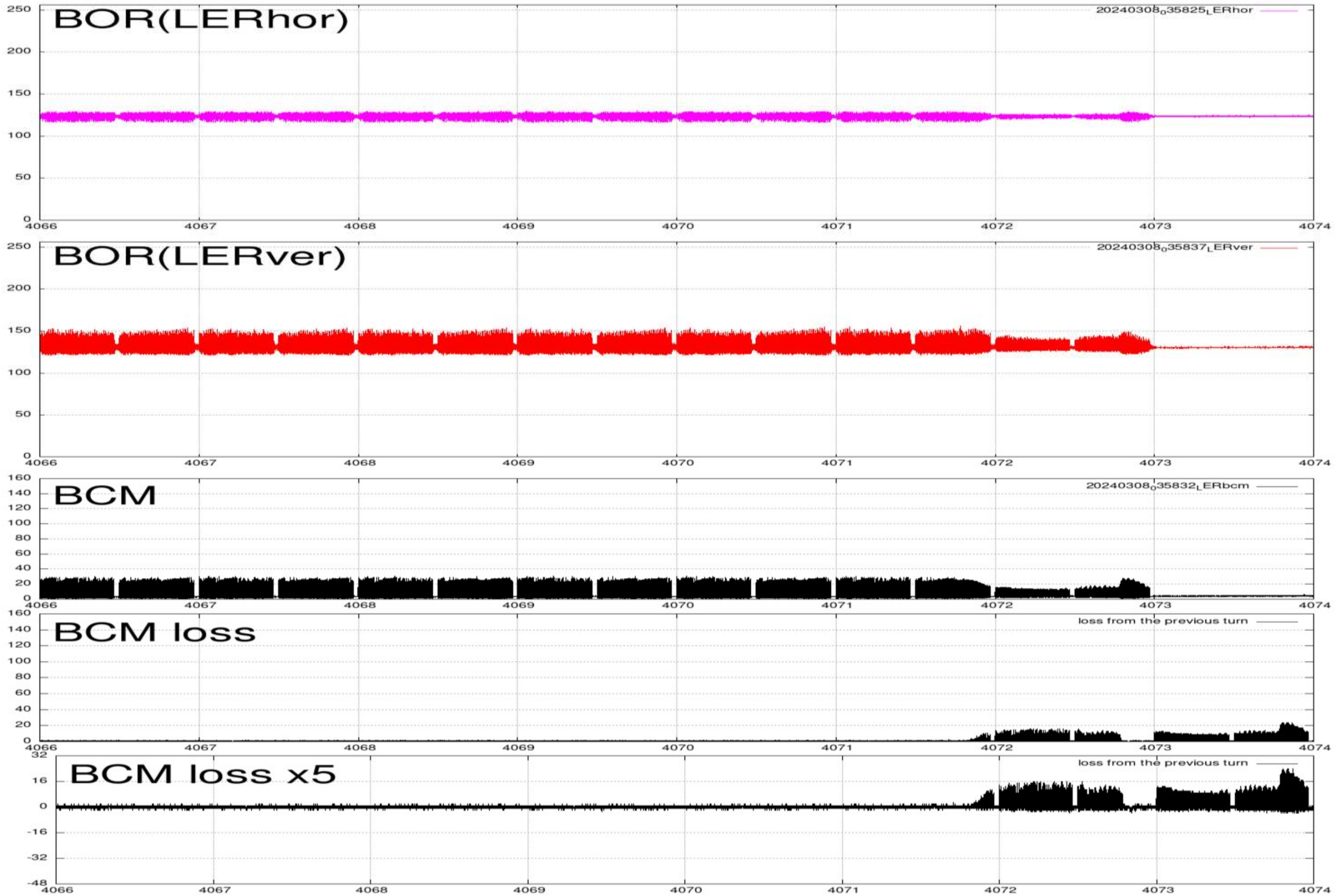


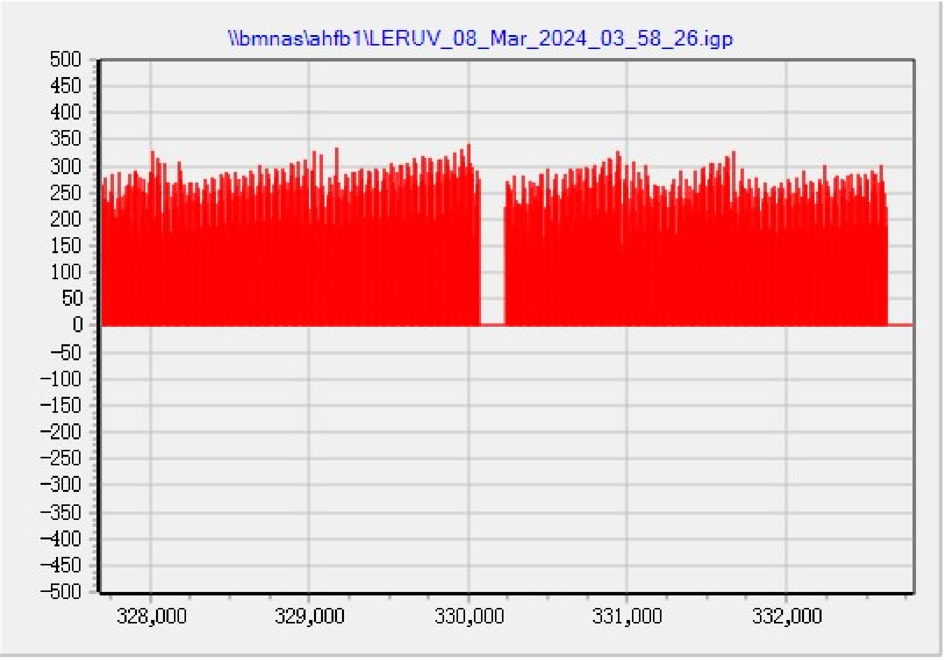
Calibration

- Acoustic sensor operation check and timing calibration.(T. Abe)
  - Close the target collimator (D02V1 or D05V1) as much as possible, and open the collimator upstream as much as possible.
  - Set the orbit to hit near the collimator head by the vertical steering upstream of the collimator.
  - Single bunch injection into LER.
    - Total beam loss at target collimator without making one revolution→Loss monitor abort→Acoustic data acquisition
  - The sound waves generated around the collimator head can be observed and confirmed using a beam 。
  - Confirm how to determine the timing of sound wave generation near the collimator head from the observation data of the acoustic sensor attached to the atmospheric cooling water pipe.
- BOR timing tuning and calibration.（M. Tobiyama）

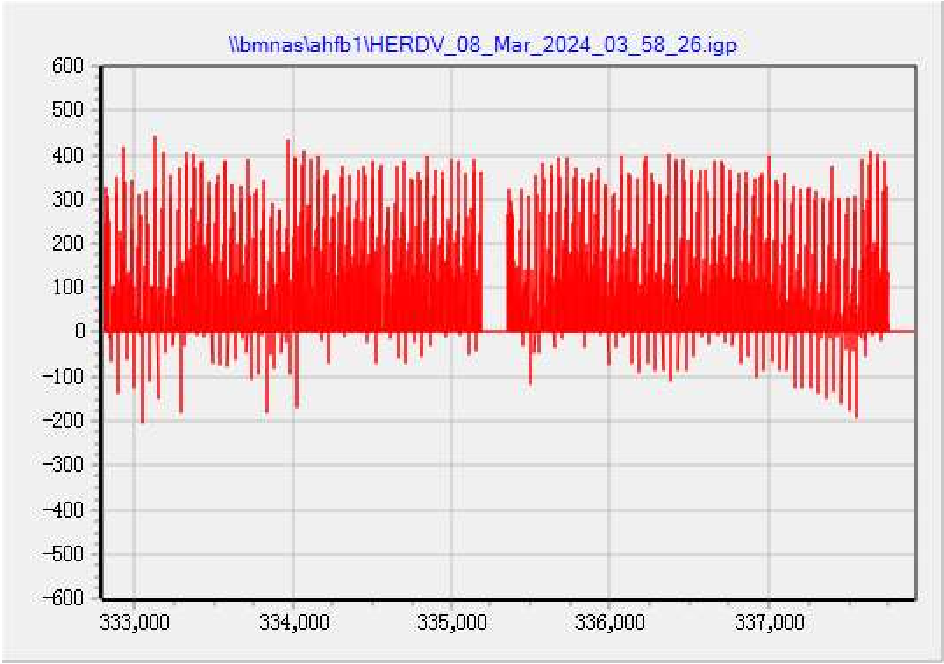
SBL event after LS1

- On March 8th, we observed the first SBL-like abort event after LS1.
- 2024/3/8 03:58:25
  - Mode : Physics Run
  - I_LER : 259[mA]
  - I_bunch : 259/783=0.33[mA/bunch]
  - Beta at IP : 80 mm / 1 mm

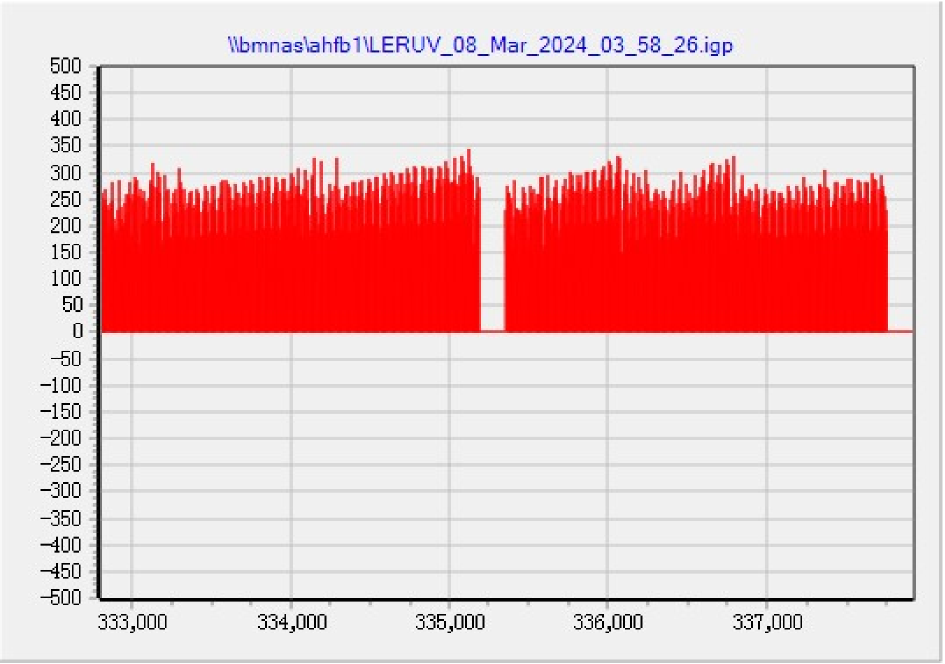




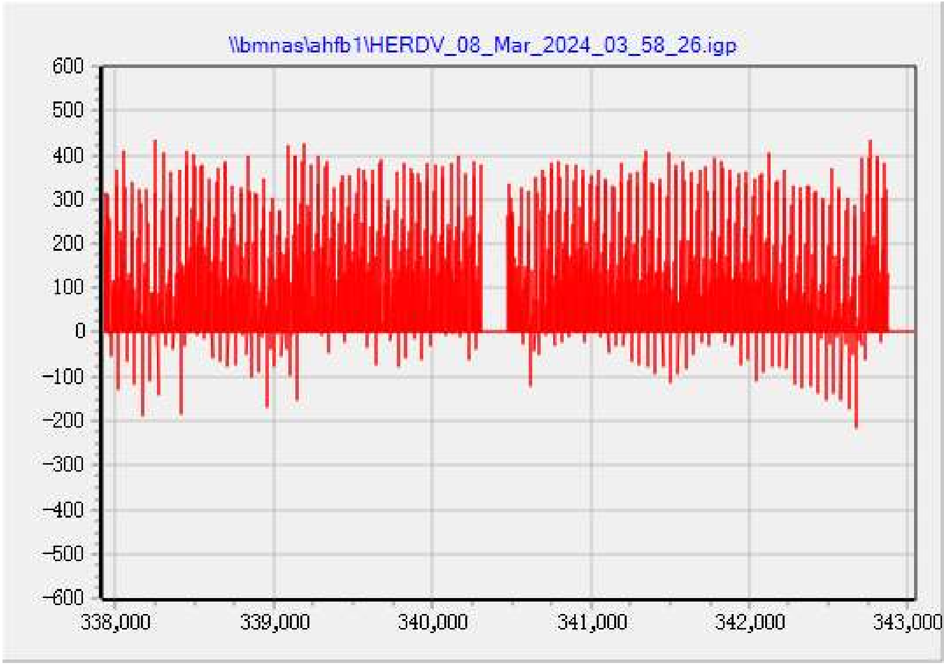
Upstream BOR : V



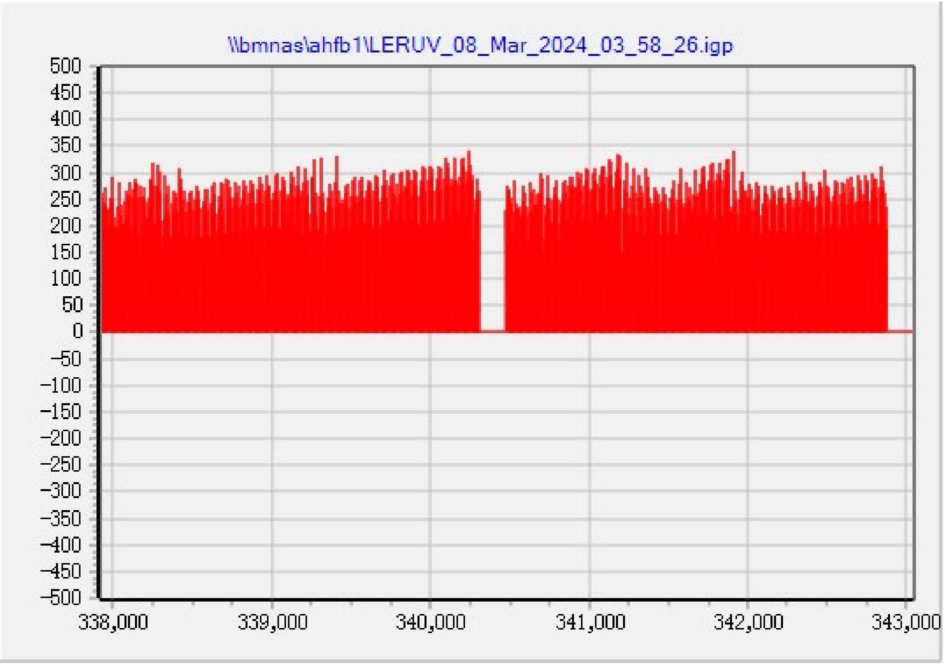
Downstream BOR : V



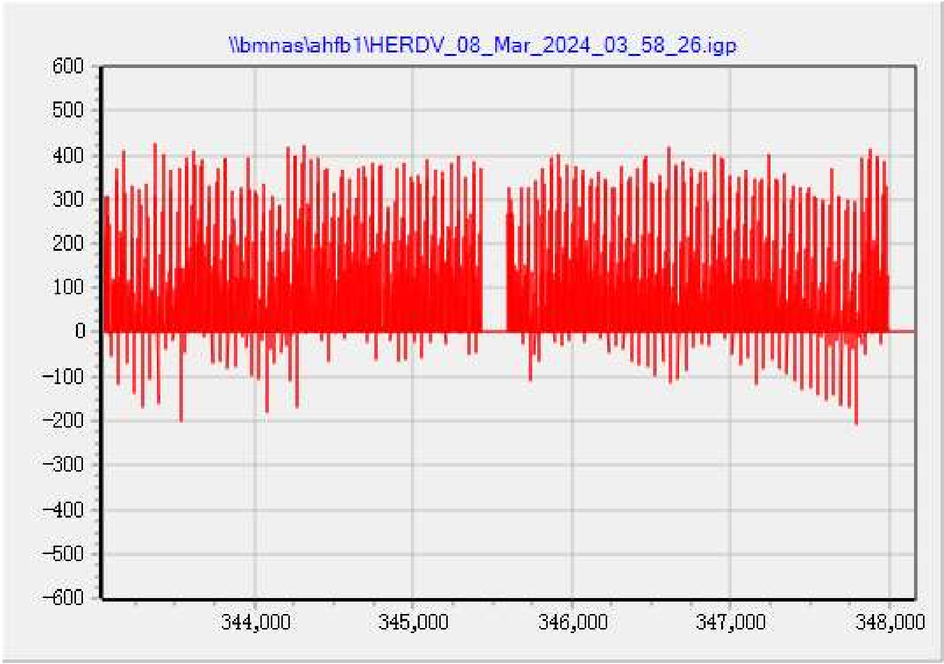
Upstream BOR : V



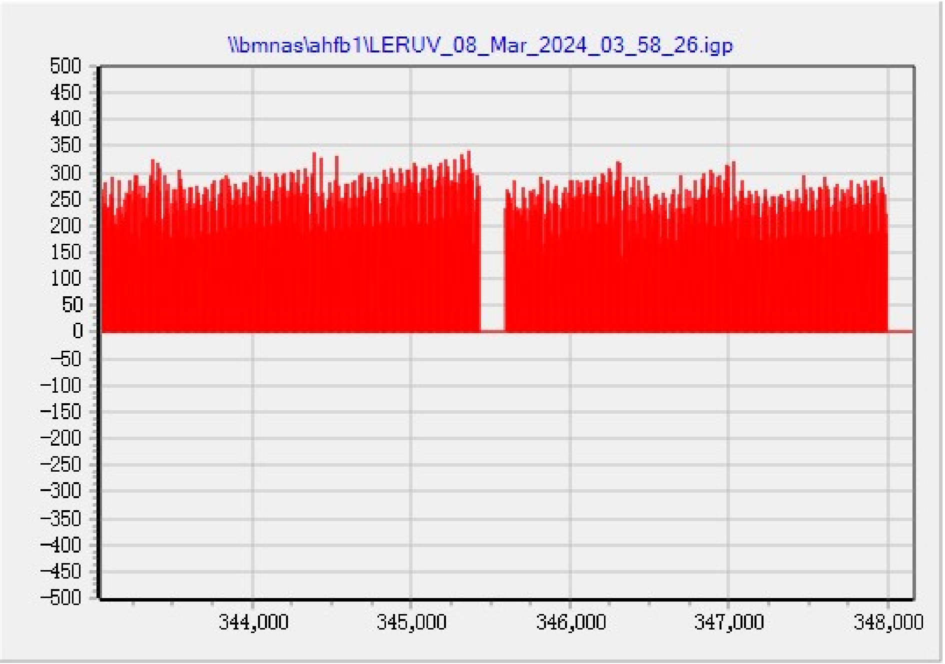
Downstream BOR : V



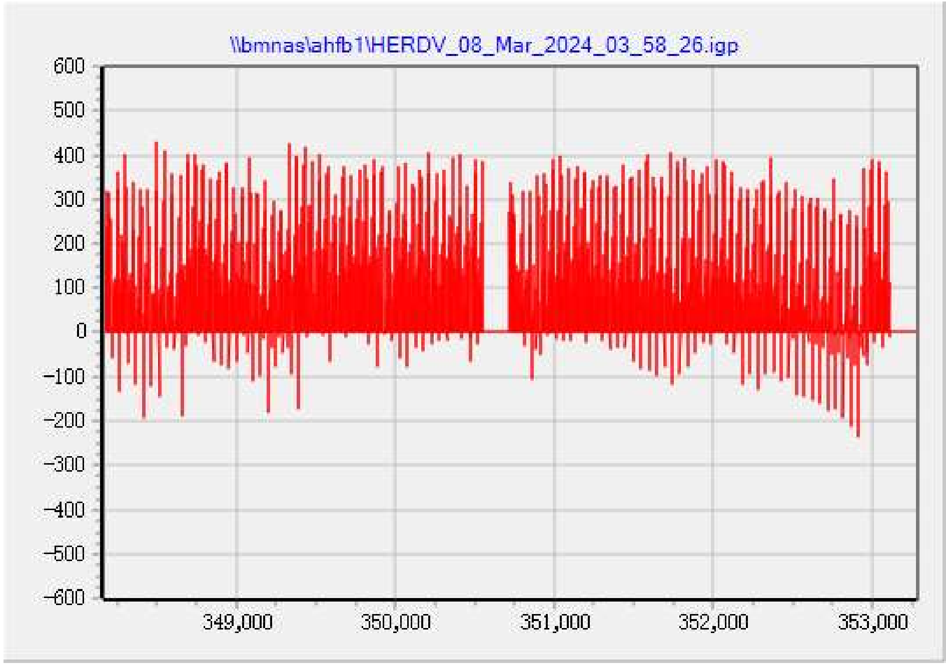
Upstream BOR : V



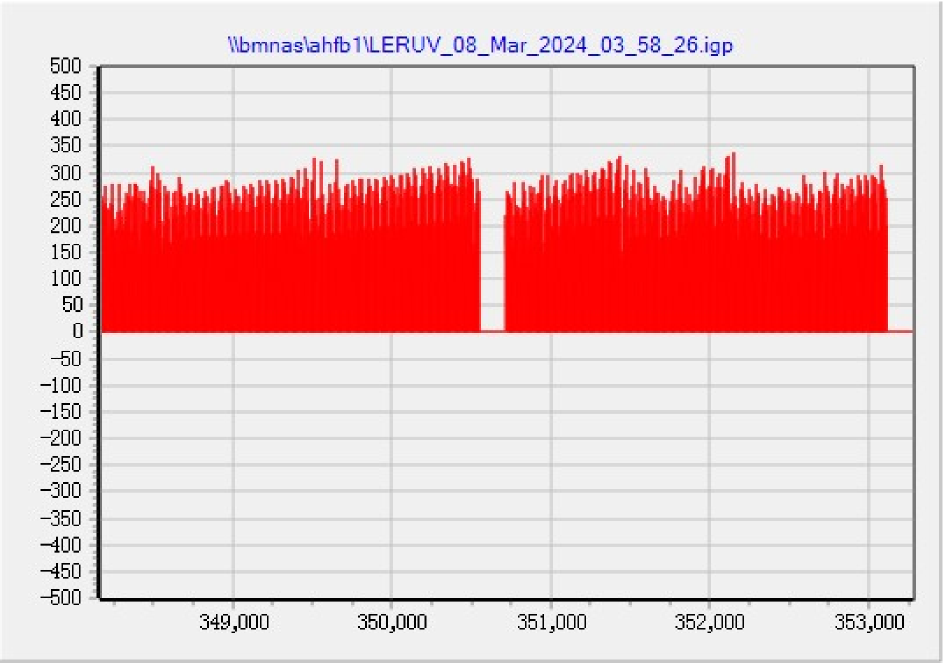
Downstream BOR : V



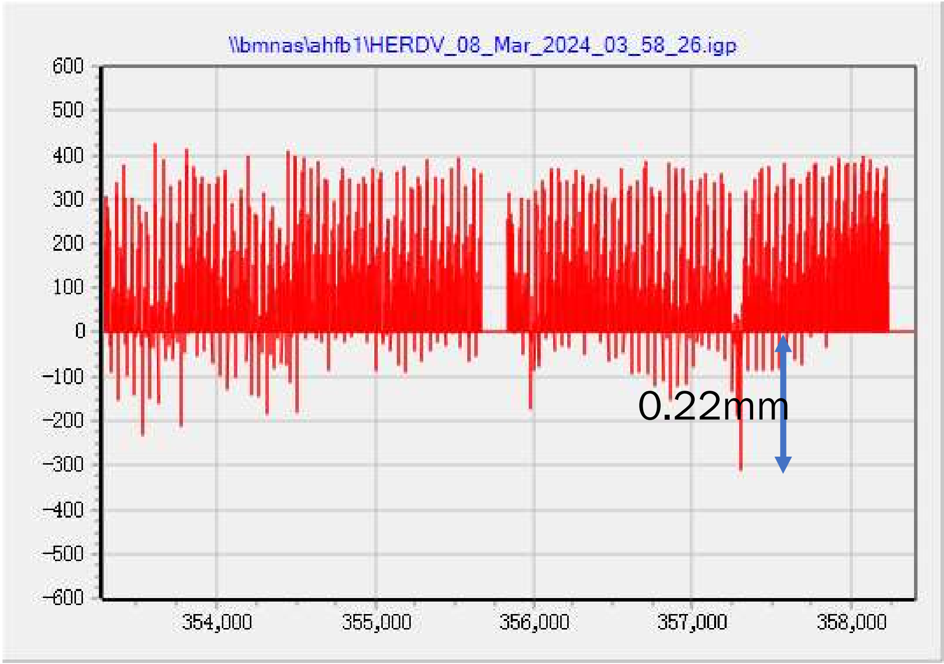
Upstream BOR : V



Downstream BOR : V

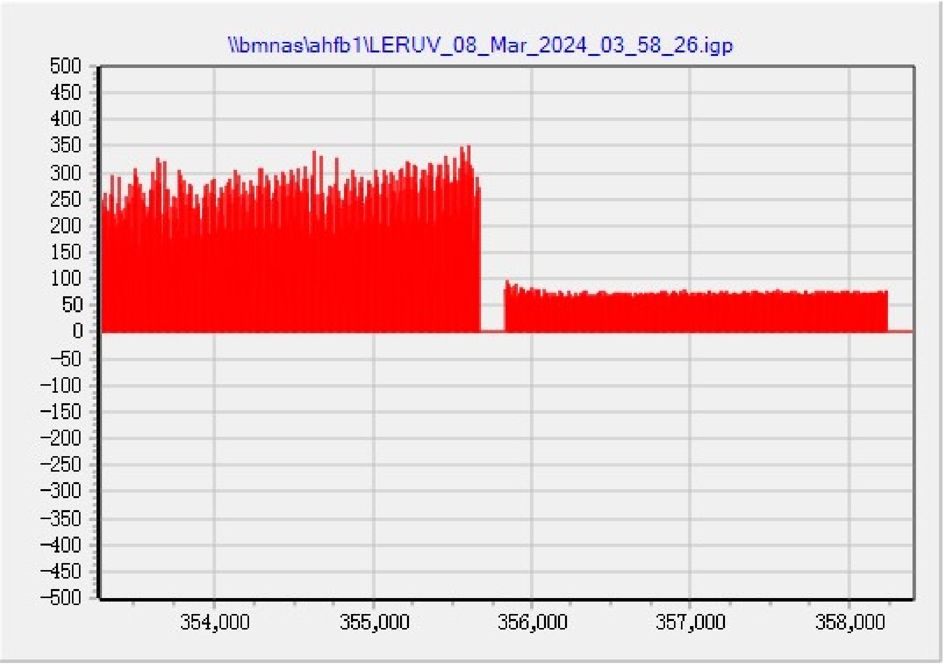


Upstream BOR : V

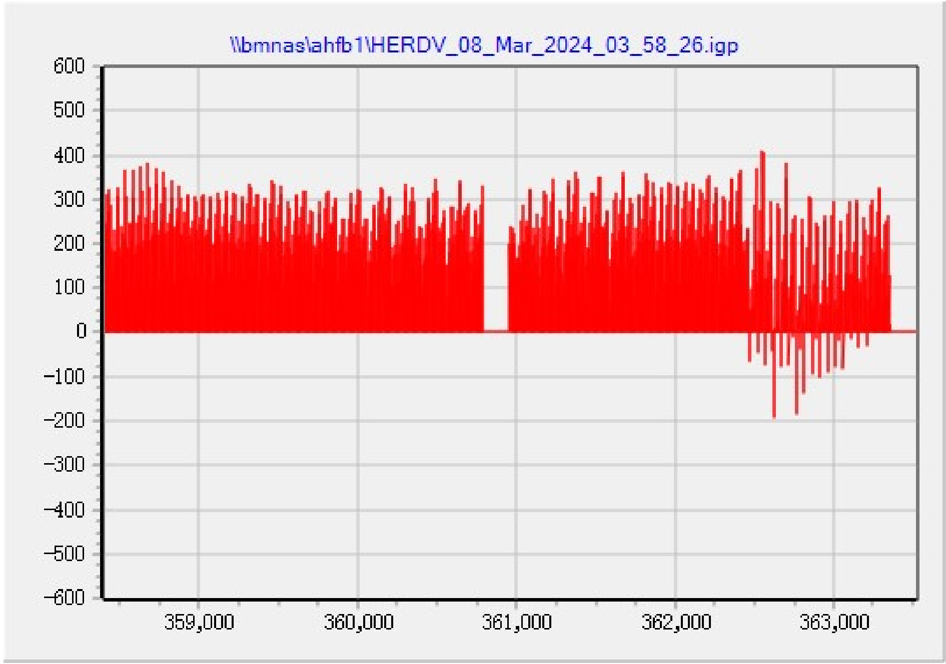


Downstream BOR : V

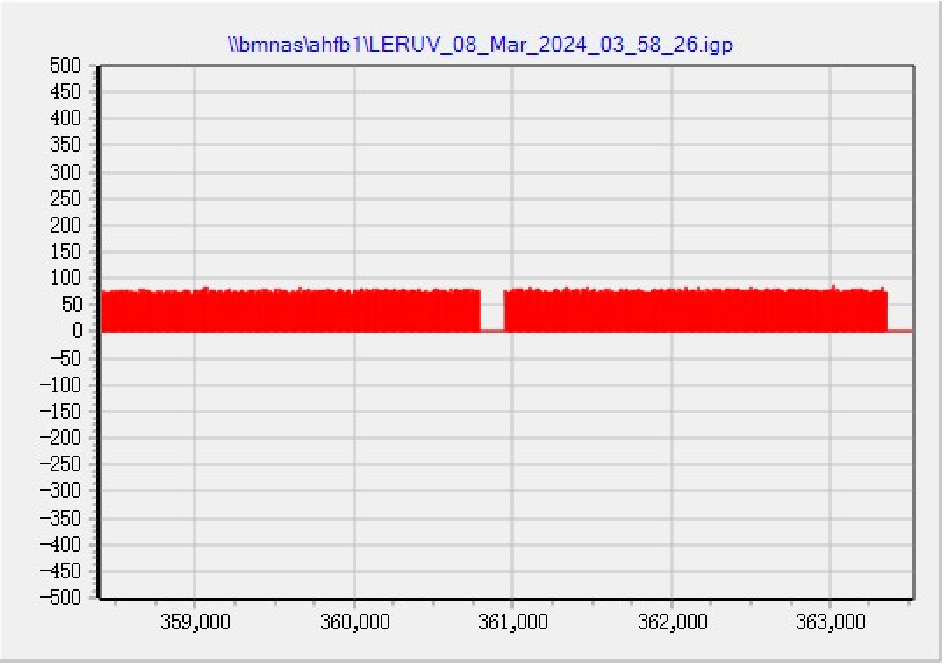
Two turns before the abort, the orbit change was measured at the downstream BOR.
The orbit change bunches were not the beam lost bunches.



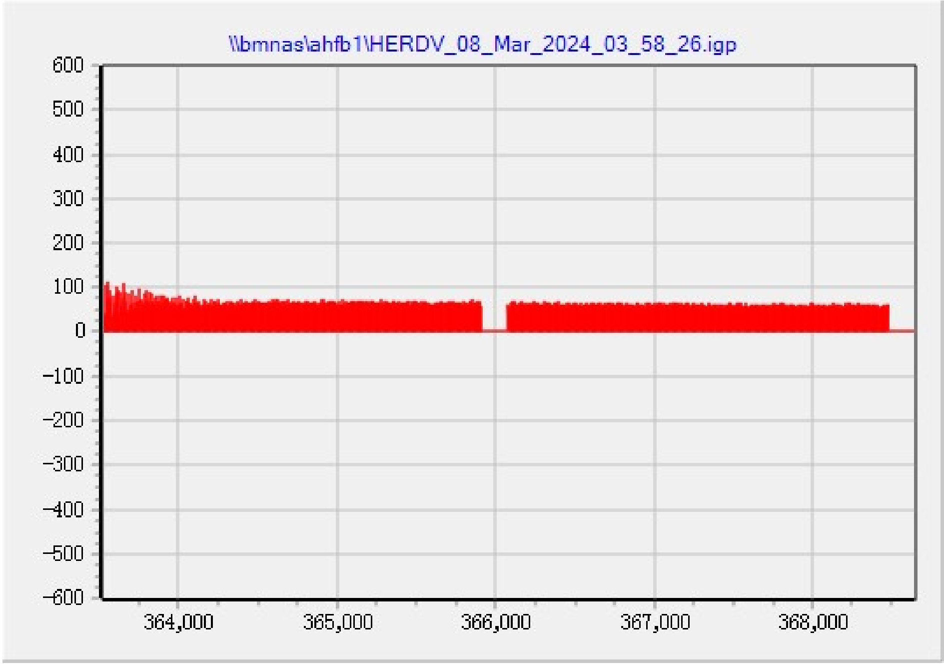
Upstream BOR : V



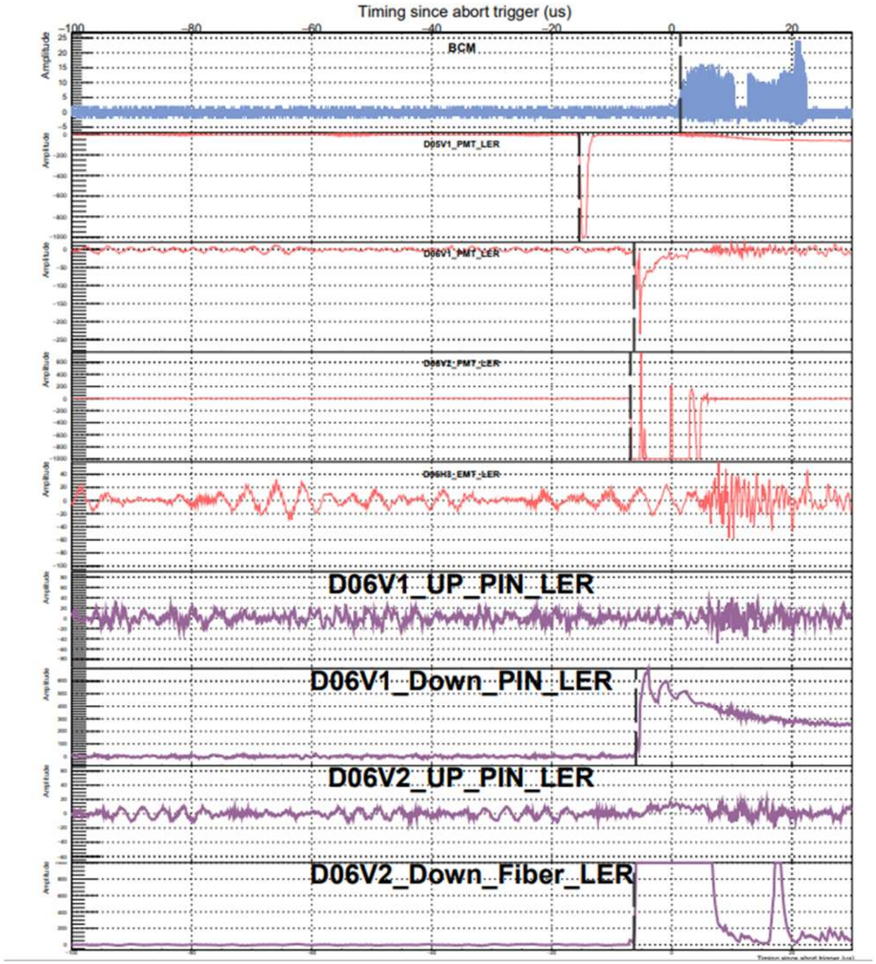
Downstream BOR : V

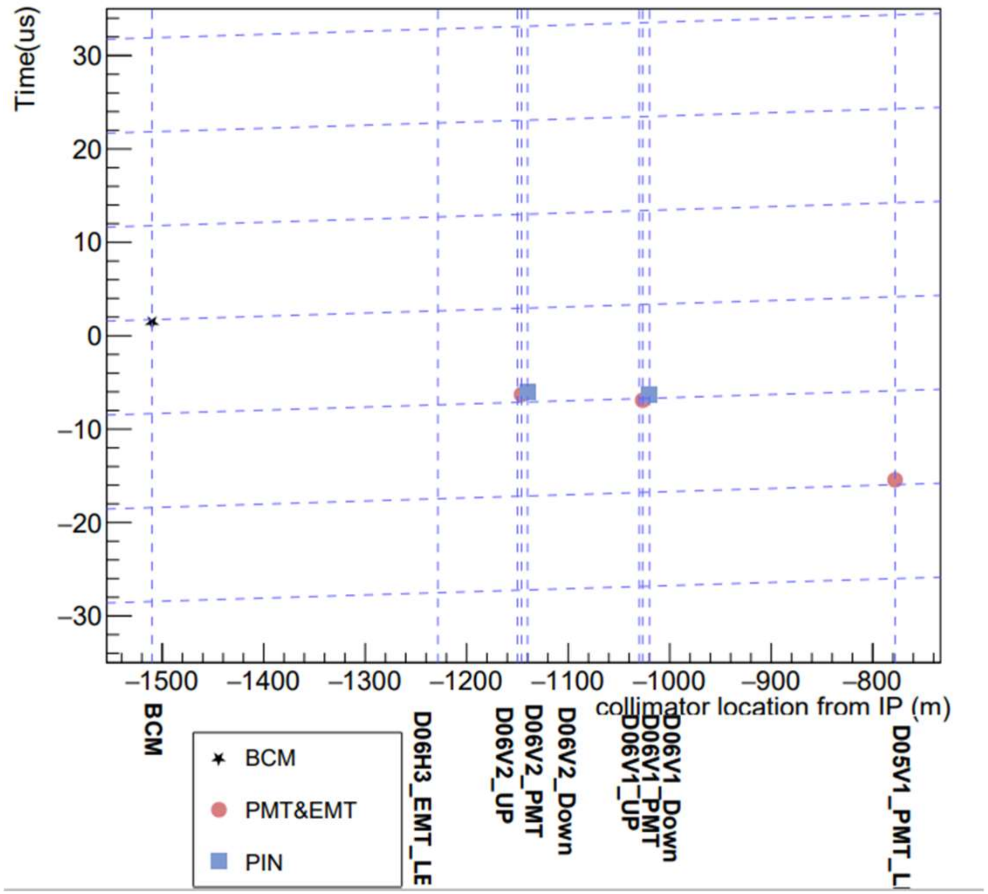


Upstream BOR : V

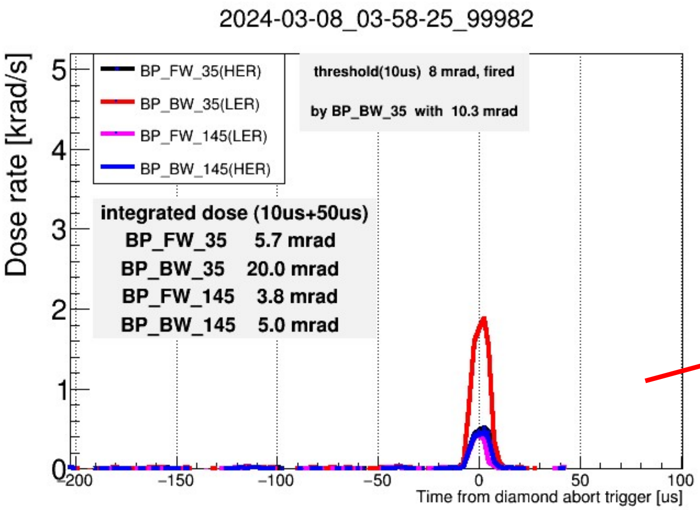


Downstream BOR : V

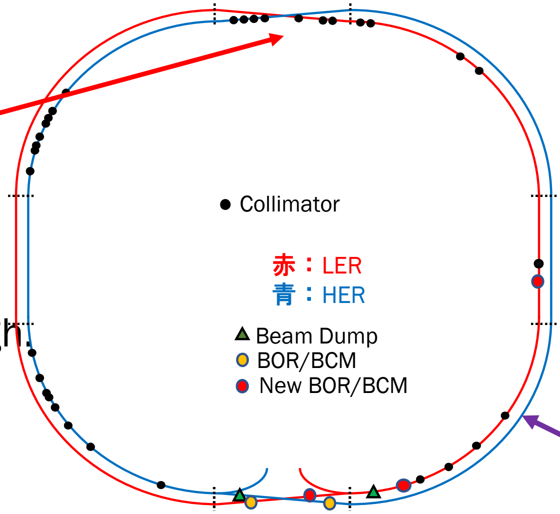


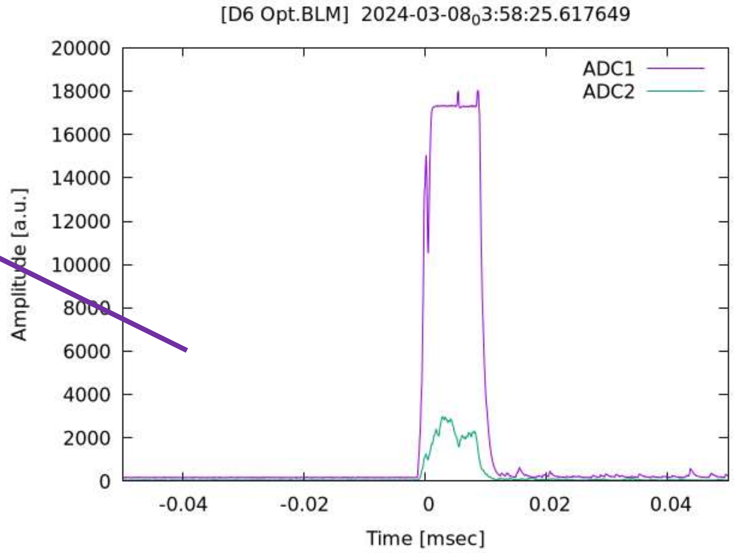


Beam loss was first measured at D5V1, but because the amount of beam loss was small, it was not aborted at that time, and in the next turn, the loss monitor downstream of D6V2, which had a large amount of loss, fired an abort. At the same time, a vacuum burst was also observed at D5.



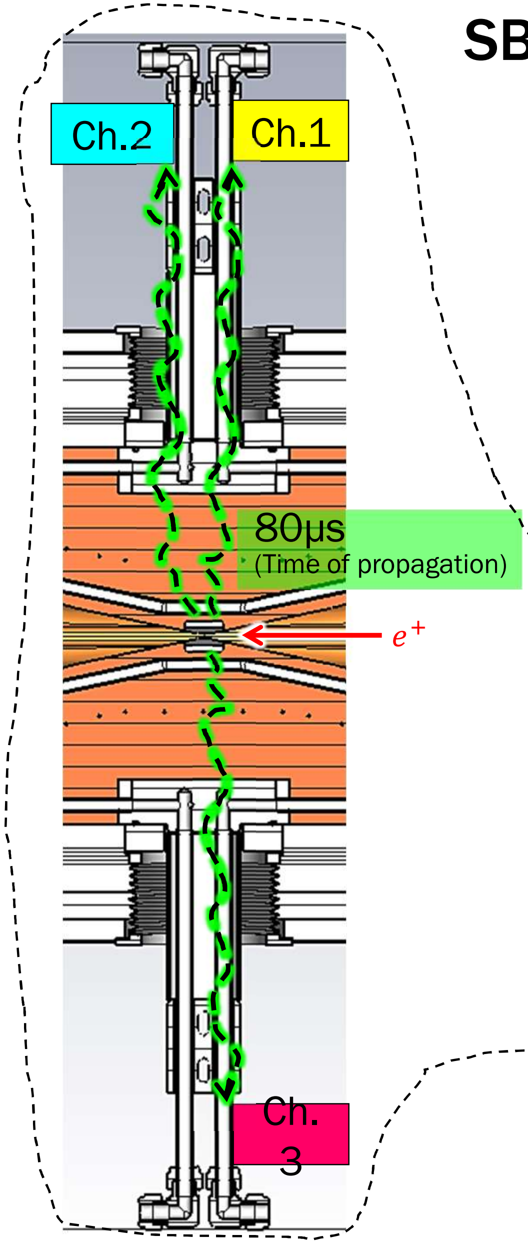
Belle dose (diamond sensor) was not so high.

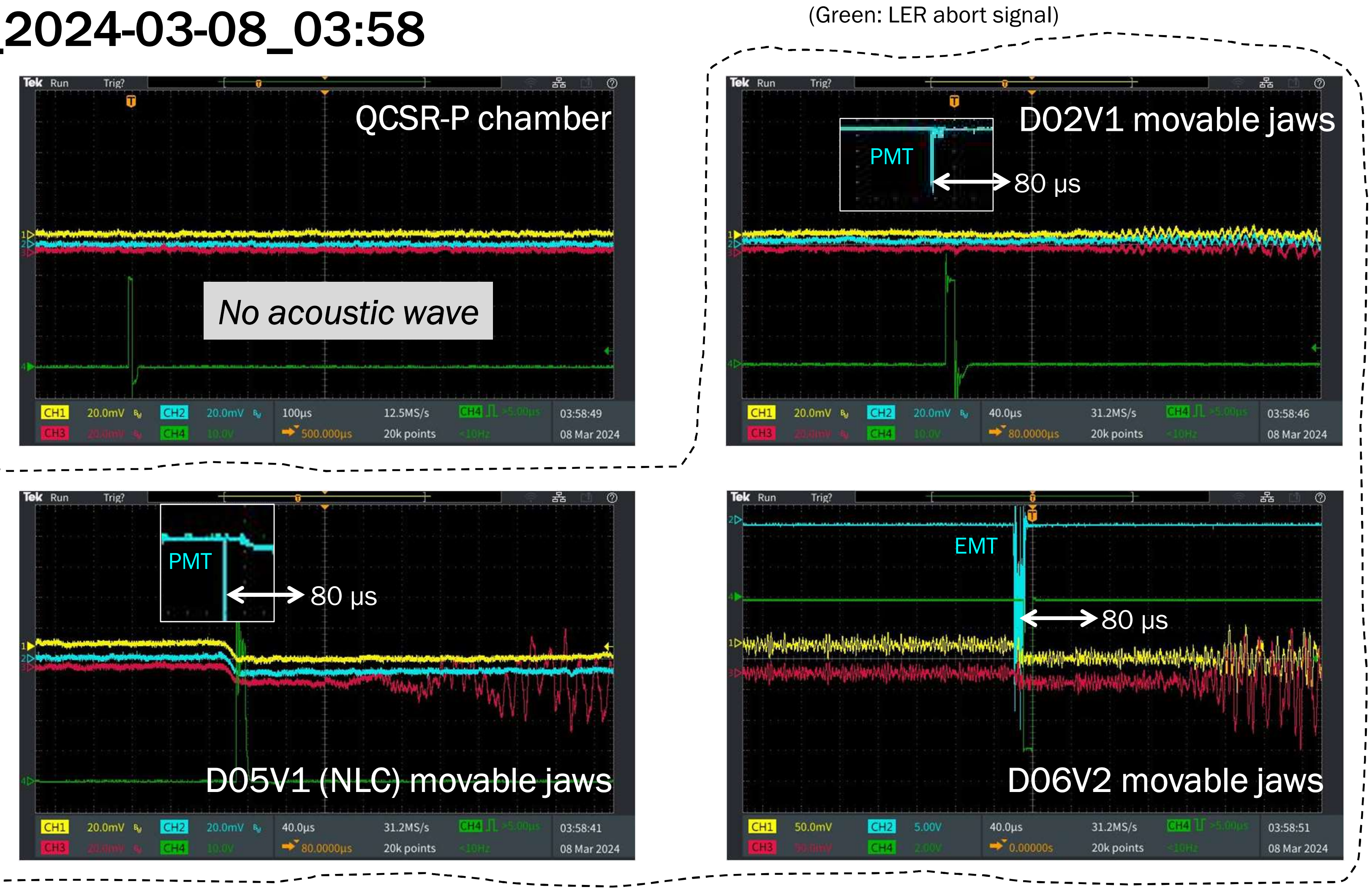




Beam Loss Monitor (Optical fiber) @downstream of D6V2 issued the abort trigger first.

SBL_2024-03-08_03:58





No acoustic wave observed within 80 μs from each loss detection by PMT/EMT means:

A) No acoustic generation before the loss started at each place.

B) All the acoustic waves are understood to be made by beam particles.

Collimator Setting :

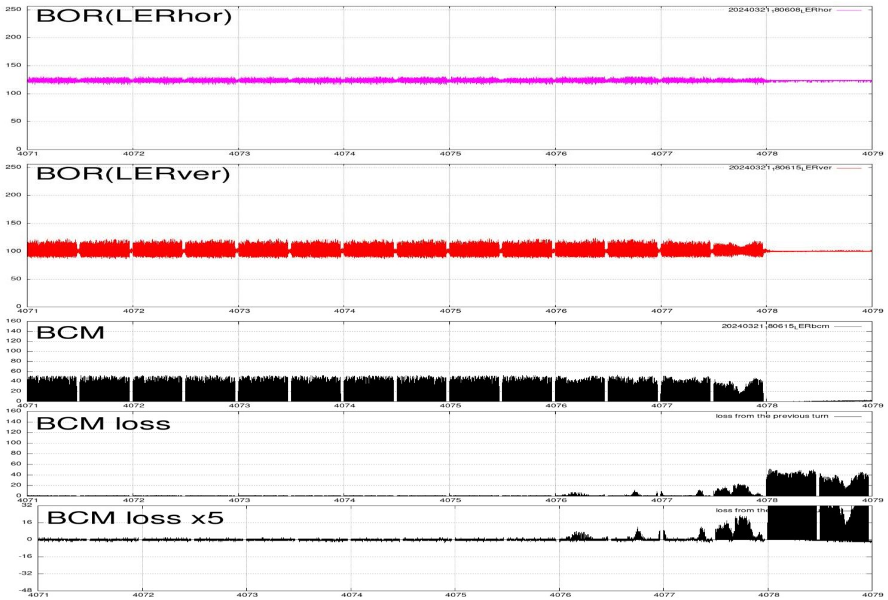
- D6V1(TOP/BTM) : 4.2 mm/-4.2 mm
- D6V2(TOP/BTM) : 1.7 mm/-1.8 mm
- D5V1(TOP/BTM) : 14 mm/-14 mm
- D2V1(TOP/BTM) : 0.95 mm/-1.4 mm

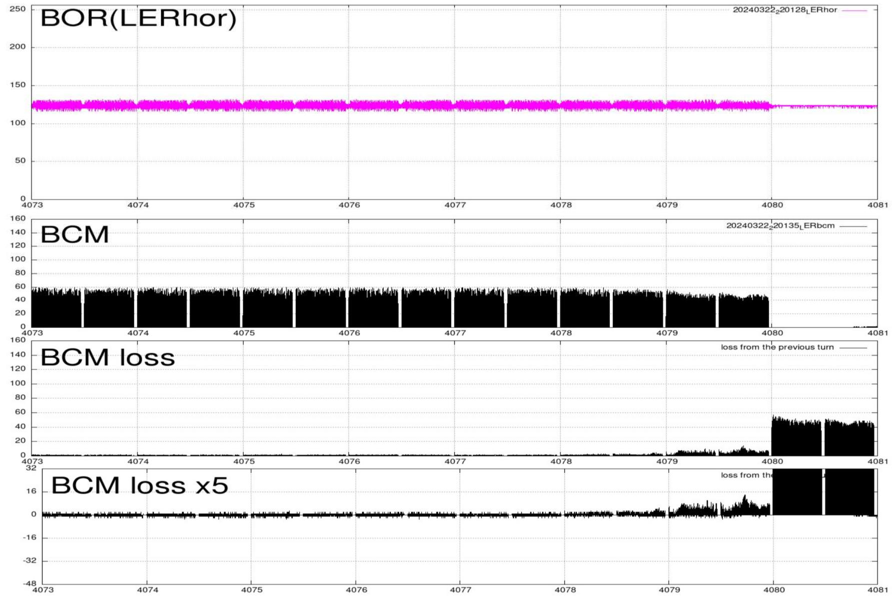
Nsigma (beta)

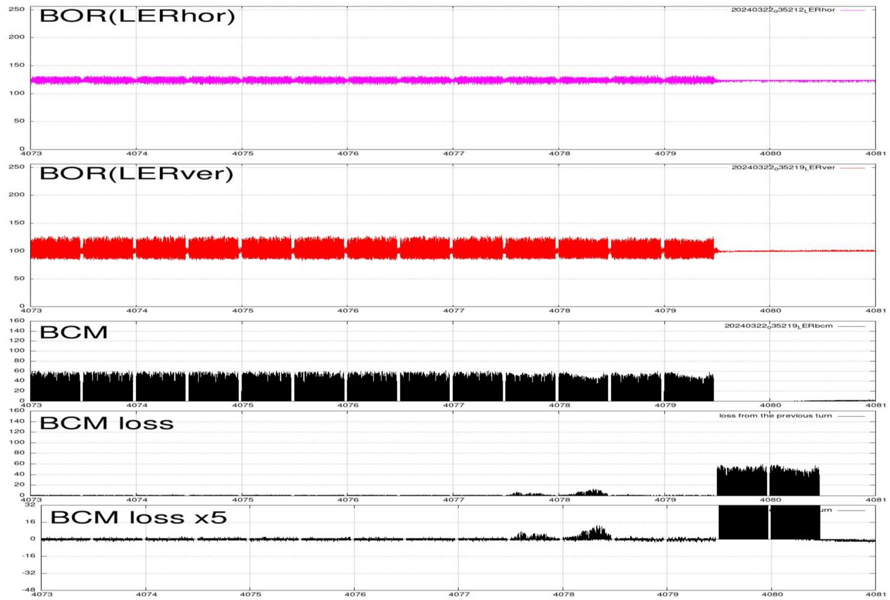
- QC1:149.0
- D6V1 (TOP/BTM) : 103.4/117.9
- D6V2 (TOP/BTM) : 101.5/65.5
- D5V1 (TOP/BTM) : 125.4/125.9
- D2V1 (TOP/BTM) : 115.5/90.8

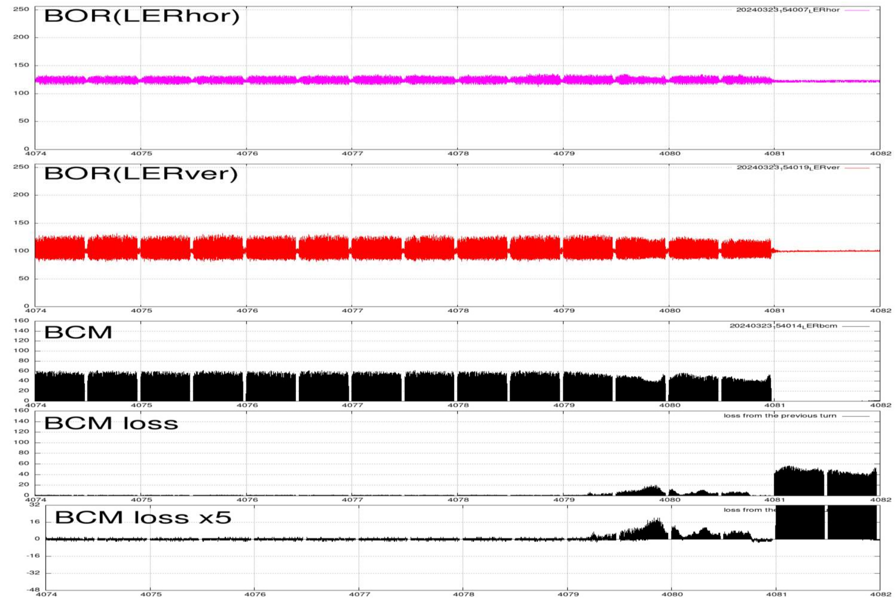
- The large beam loss occurred with D6V2 because it had the narrowest aperture.
  - The background was cut well, so the doses of D2V1, QCS and Belle-II were small.
- In order to protect the head of D2V1, we made D6V1 the narrowest, then D6V2, and finally D2V1 after this event.

→The beam loss at D6V1 became largest, and the number of abort trigger increased at D6V1 LM (PIN) .









SBL has happened several times after that.

We are currently in the process of adjusting trigger settings and brushing up on analysis methods.

Some events have seen beam oscillation, orbit change or no changes, so we would like to organized the condition at each abort data and try to determine the cause.

Summary

- There had been a sudden beam loss for an unknown reason from previous run.
- There is an urgent issue to investigate the cause of this SBL, as it may cause damage to hardware or disrupt operations due to beam abort.
- For now, the fire-ball hypothesis remains a candidate for the cause and simulations are on-going..
- During LS1, the damaged collimator head was replaced and coated to take measures against SBL, and BOR, LM, and AS were added for preparation to investigate the cause of SBL.
- We looked at the data on the first SBL-like event afterLS1.
- We are currently in the process of establishing an analysis method for the monitoring system, so we would like to determine the cause (position) of SBL from the relationship between orbit fluctuations, discharge sounds, and beam loss positions.

backup

Beam Abort Categorization

After the categorization:

Aborts N.	2022/02	2022/03	2022/04	2022/05	2022/06	2022
HER	1	62	87	101	76	323
LER	10	29	66	88	65	258
Machine	0	2	1	1	0	4
Unknown	0	0	2	1	0	3
Total	11	93	156	191	141	592

SBL HER	0	6	9	10	9	34
SBL LER	2	8	10	12	21	56
Injection Related	4	16	48	81	24	173
RF/magnet/vacuum /earthquake	7	42	39	43	31	162

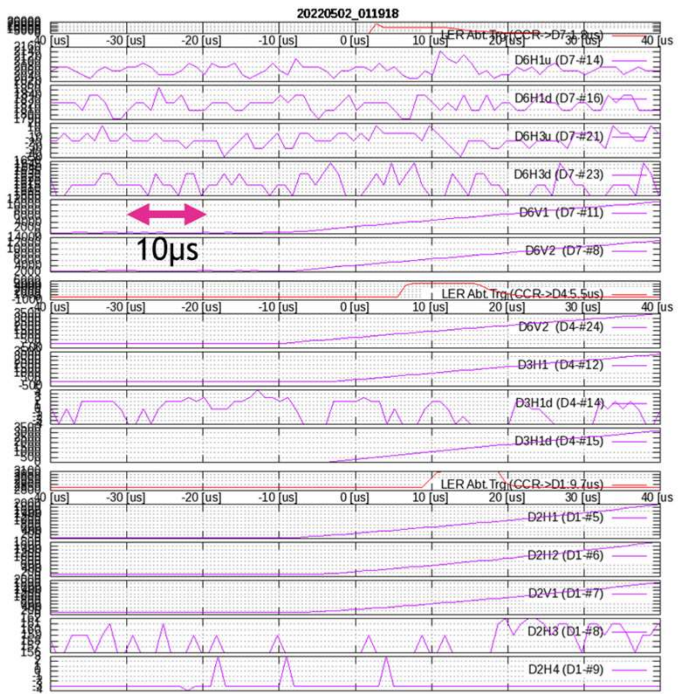
No particular correlation was found

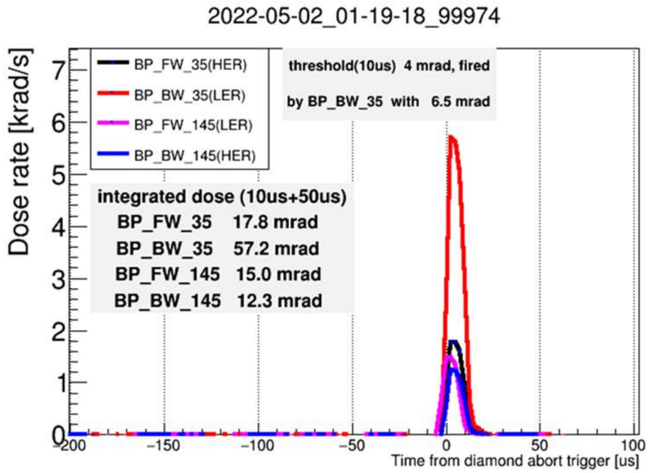
Observation : Beam Loss Monitor

- Checked the loss monitor at the time of abort occurrence which was probably due to beam loss.

↓

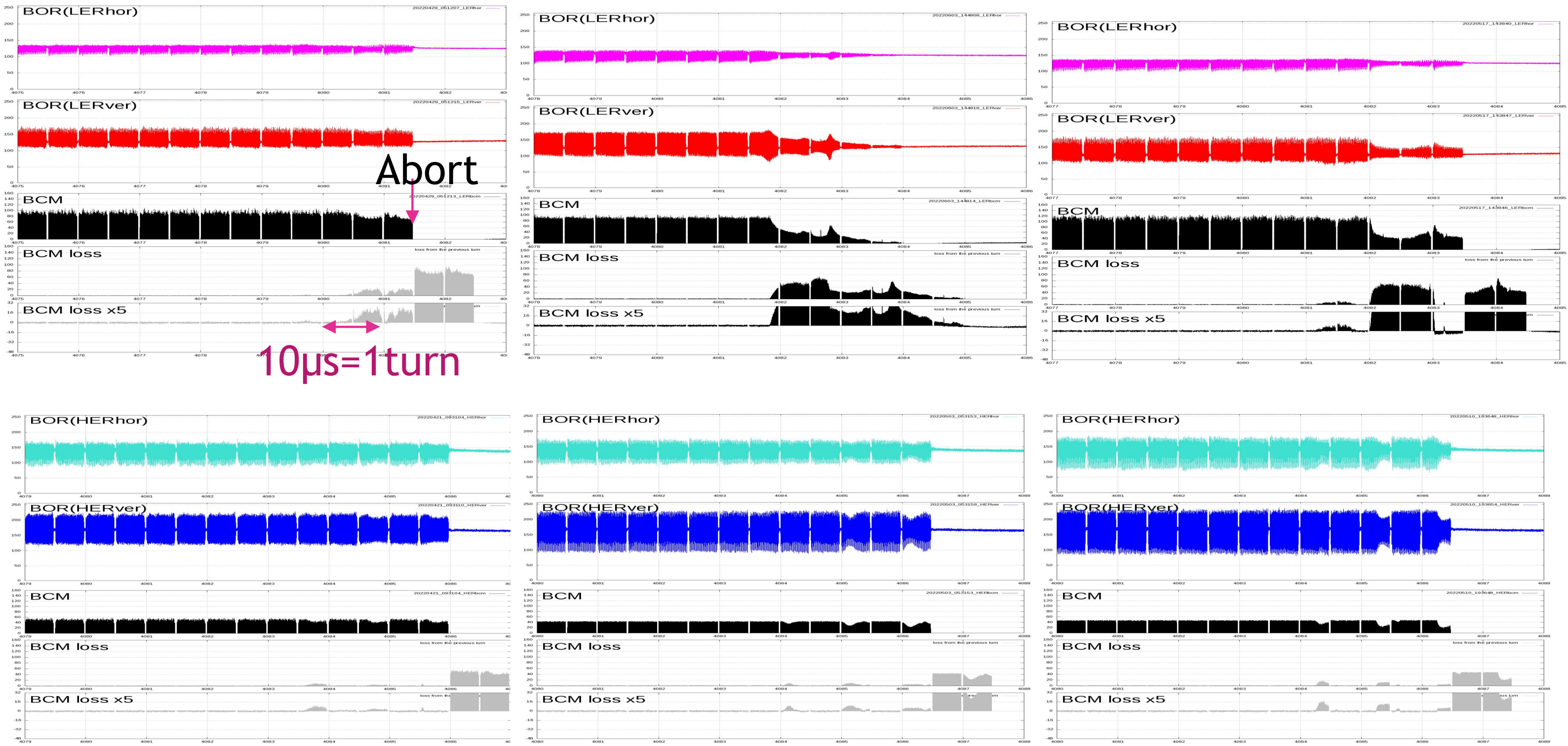
- There were many instances of sudden beam loss occurring simultaneously in the entire ring collimator section and in the Belle-II detector.



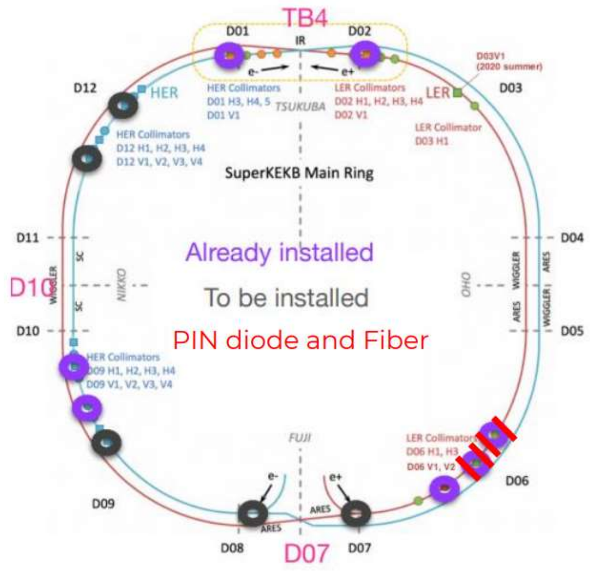


Observation :
Bunch Current monitor & Bunch Oscillation Recorder

- The beam suddenly disappears just before the abort.
- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER.

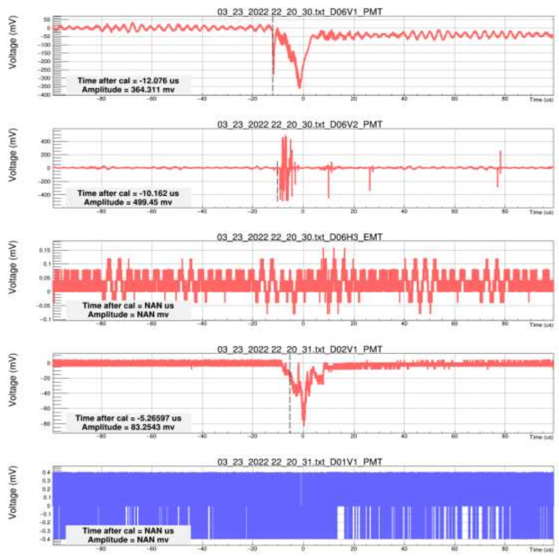


Observation :
Loss Monitor Specialized for Timing Measurements

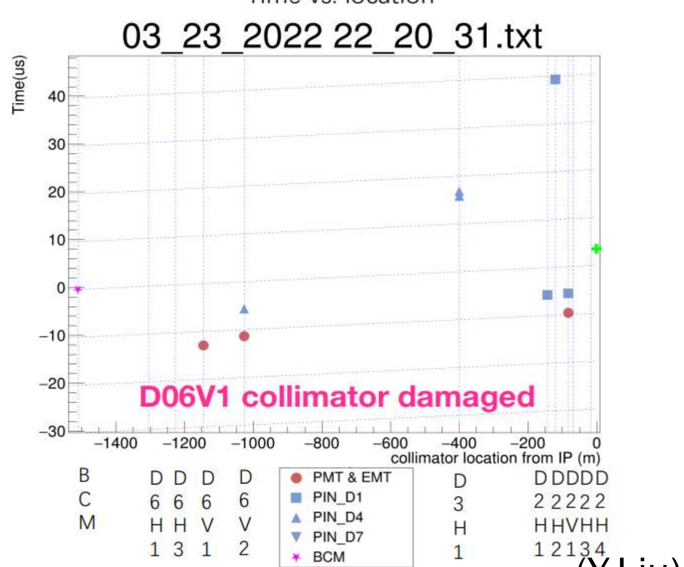


- We checked the starting point of SBL in the ring by using loss monitors specialized for position identification
- The beam loss mainly started at the D06V1 collimator (a narrow aperture to suppress background to Belle-II detector).
- When the D6 collimator was damaged and the aperture was widened, beam loss began in the D2 collimator section near the IR.

→The starting point of beam loss depends on the tuning of the collimator and is not limited to a specific location.



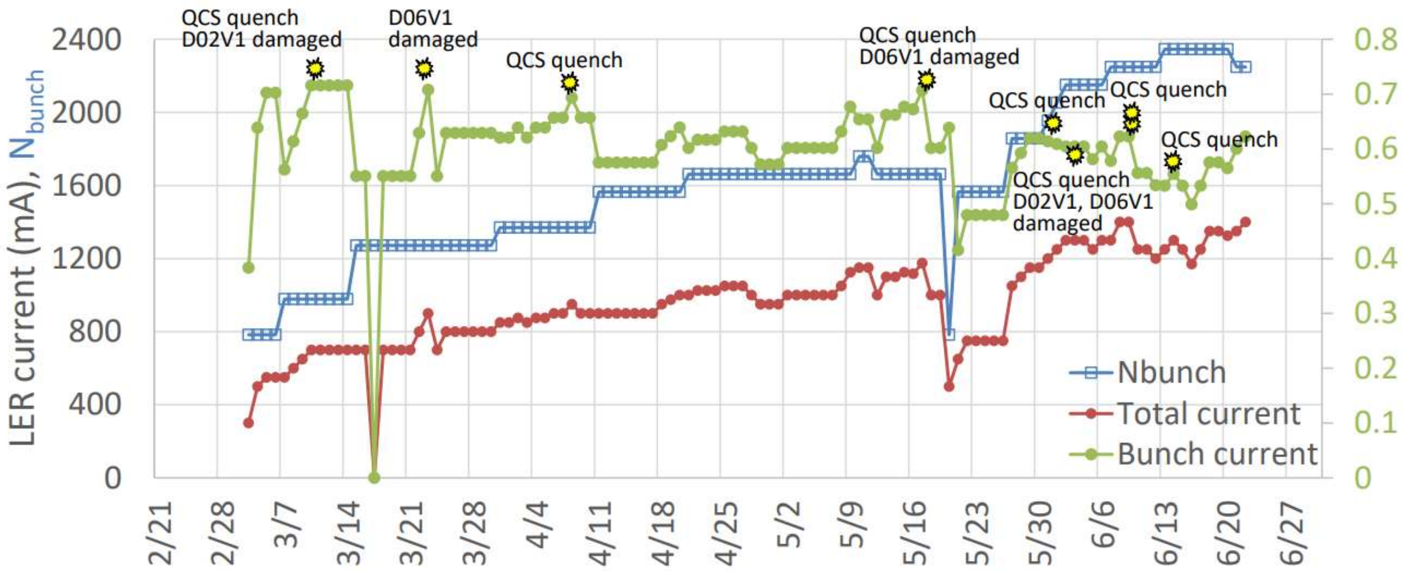
PMT & EMT



(Y.Liu)

Observation : Beam/Bunch Current Dependence

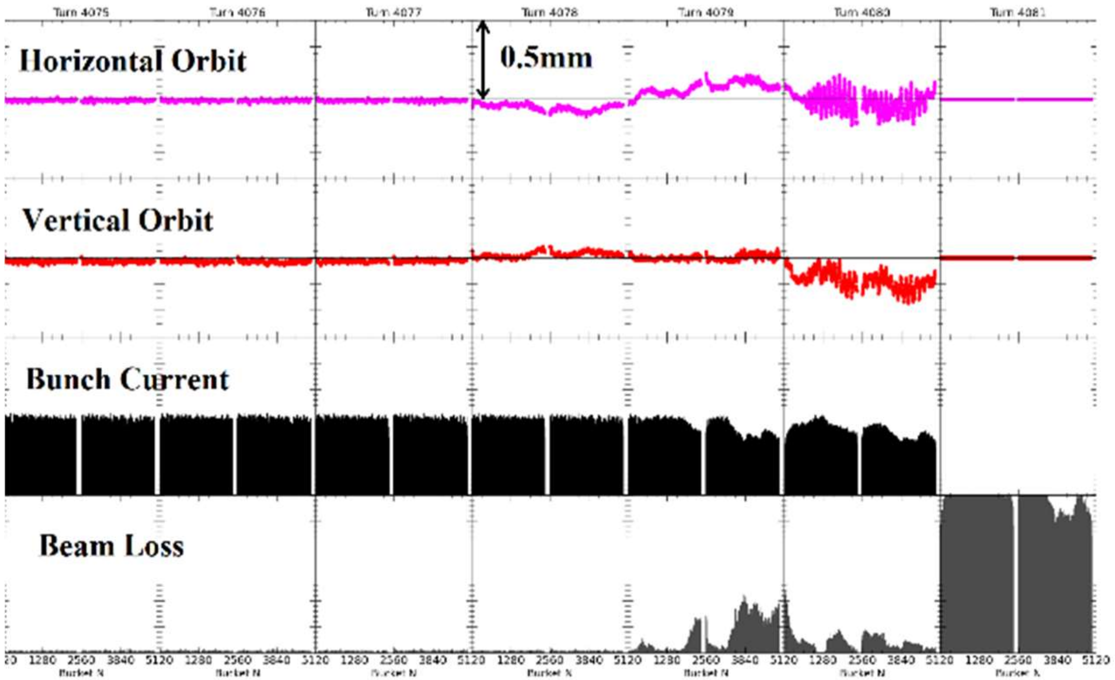
- It is likely to occur when a certain bunch current is exceeded.
- We don't know if it will happen even with a single beam or low current beam because we haven't operated for a long time.



(K.Matsuoka)

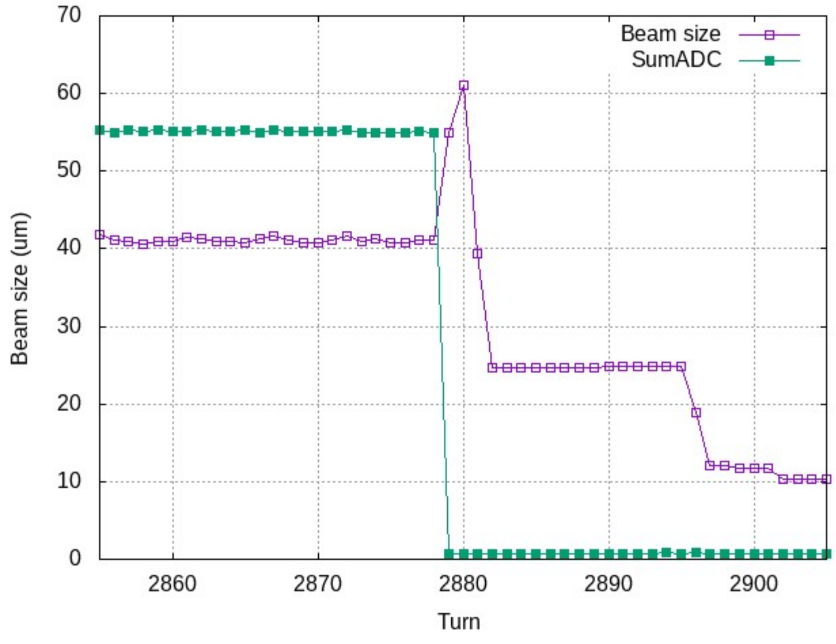
Observation : Beam Orbit

- Just before the beam loss begins, the orbit appears to move, but its value is small～O(0.1 mm).
- The orbit is changing < O(1mm) after the beam loss.
- No oscillations that could be precursors to beam loss are observed.



Observation : Beam Size

- We checked for beam size fluctuations by installing an ultra-high speed CMOS camera in the X-ray monitor to take 1μs data at 100kHz when the abort is triggered.
- There was no sign of a significant change in beam size before the SBL.



Status of LER collimator

Name	Type	Tip Material (): longitudinal length in mm	Tip Condition	Remarks
D06H3	SuperKEKB	Cu coated C (160)	healthy	spoiler against inj. kickers' accidental firings
D06H4	SuperKEKB	Ta (10)	healthy	absorber against inj. kickers' accidental firings
D03H1	SuperKEKB	W (10)	healthy	
D02H1	SuperKEKB	W (10)	healthy	
D02H2	SuperKEKB	W (10)	healthy	
D02H3	SuperKEKB	W (10)	healthy	
D02H4	SuperKEKB	W (10)	healthy	
D06V1	SuperKEKB	Cu coated Ti (10)	healthy	
D06V2	SuperKEKB	hybrid (3)	healthy	
D05V1	SuperKEKB	Cu coated Ta (4)	healthy	
D02V1	SuperKEKB	Cu coated Ta (10)	healthy	

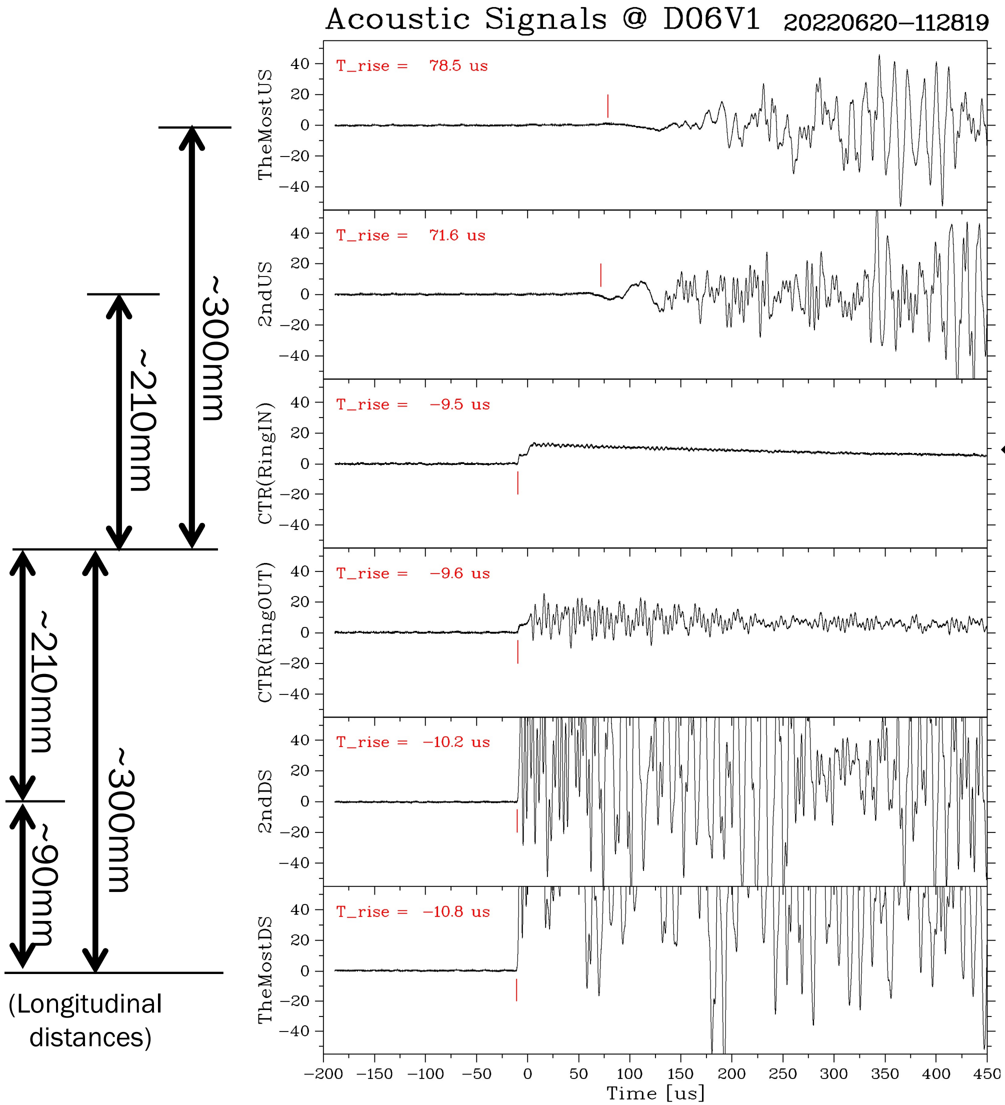
(T. Ishibashi)

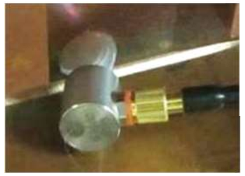
Status of HER collimator

Name	Type	Tip Material (): longitudinal length in mm	Tip Condition	Drive Mechanism	Remarks
D09H1	KEKB	Cu coated Ti (40)	damaged		
D09H2	KEKB	Cu coated Ti (40)	damaged		
D09H3	KEKB	Cu coated Ti (40)	damaged		
D09H4	KEKB	Cu coated Ti (40)	damaged		
D12H1	KEKB	Ti (40)	healthy		
D12H2	KEKB	Cu coated Ti (40)	damaged		
D12H3	KEKB	Ti (40)	healthy		
D12H4	KEKB	Cu coated Ti (40)	healthy		
D01H3	SuperKEKB	W (10)	healthy	-	
D01H4	SuperKEKB	W (10)	healthy	-	
D01H5	SuperKEKB	W (10)	healthy	-	
D09V1	KEKB	Cu coated Ti (40)	damaged	upgraded	Plan to replace with new jaw (Cu coated Ti (40))
D09V2	KEKB	Cu coated Ti (40)	healthy		
D09V3	KEKB	Cu coated Ti (40)	healthy		
D09V4	KEKB	Cu coated Ti (40)	healthy		
D12V1	KEKB	Cu coated Ti (40)	damaged	upgraded	
D12V2	KEKB	Cu coated Ti (40)	damaged		
D12V3	KEKB	Cu coated Ti (40)	healthy	upgraded	
D12V4	KEKB	Cu coated Ti (40)	healthy	upgraded	
D01V1	SuperKEKB	Cu coated Ta (10)	healthy	-	

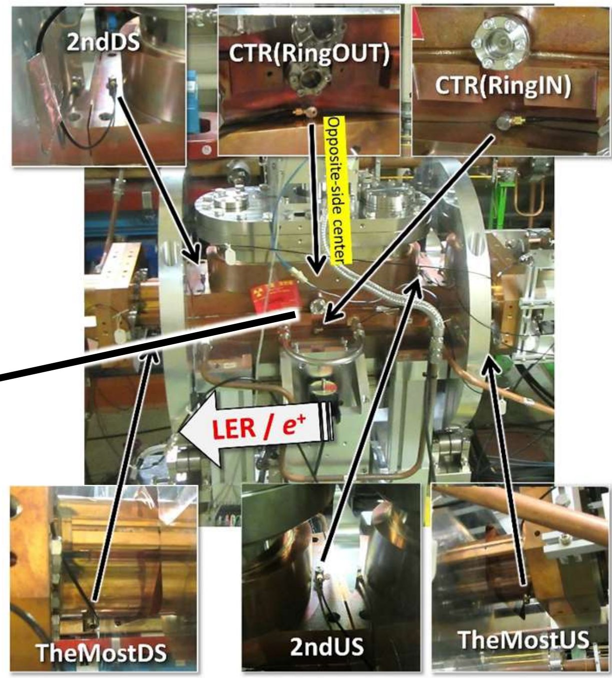
(T. Ishibashi)

2022ab / LER_{1299mA} sudden beam-loss abort : Example (CLAWS and Diamond)



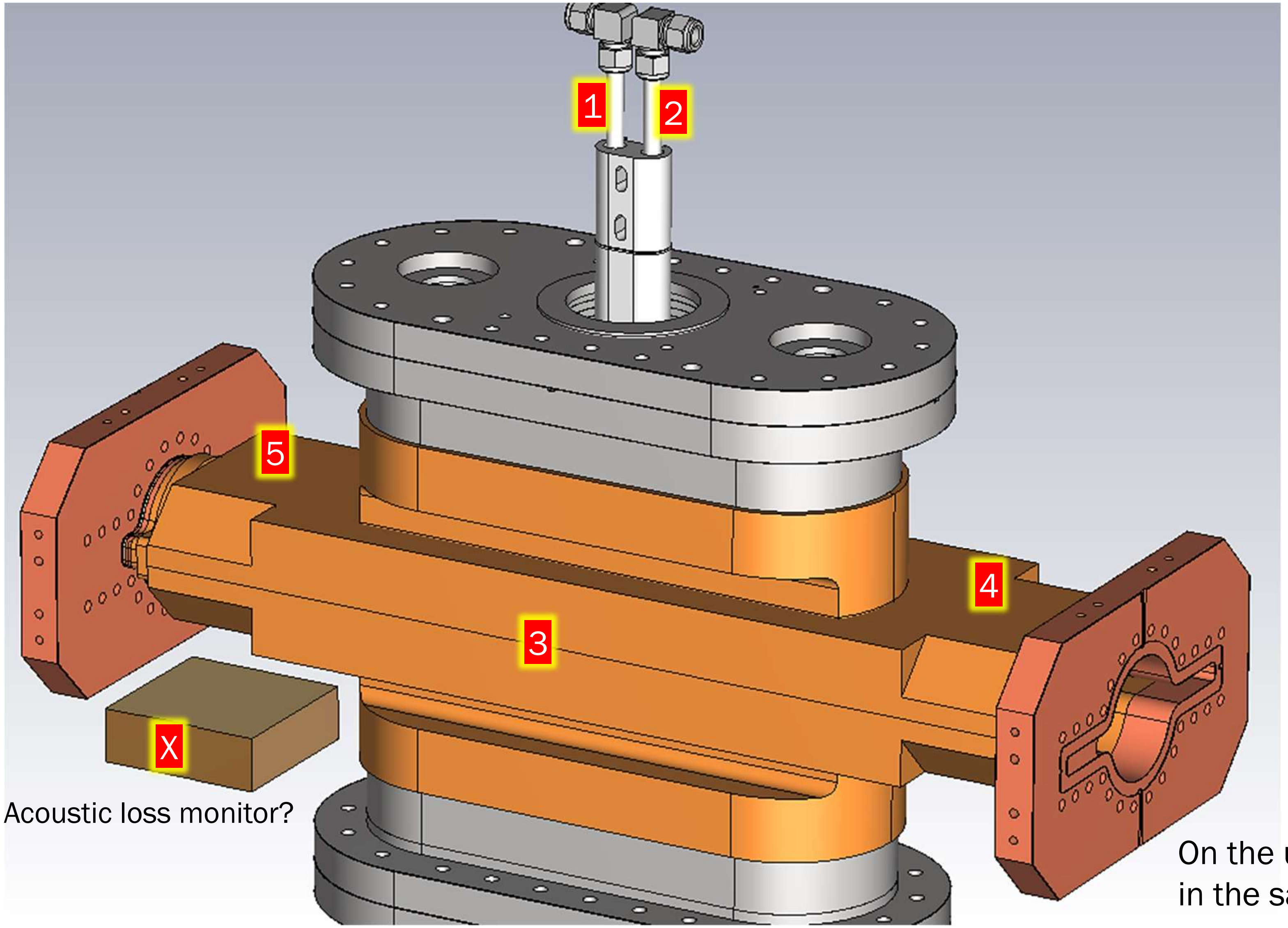


コリメータ側面に貼った
この音響センサー（CTR(RingIN)）
は外れていた！

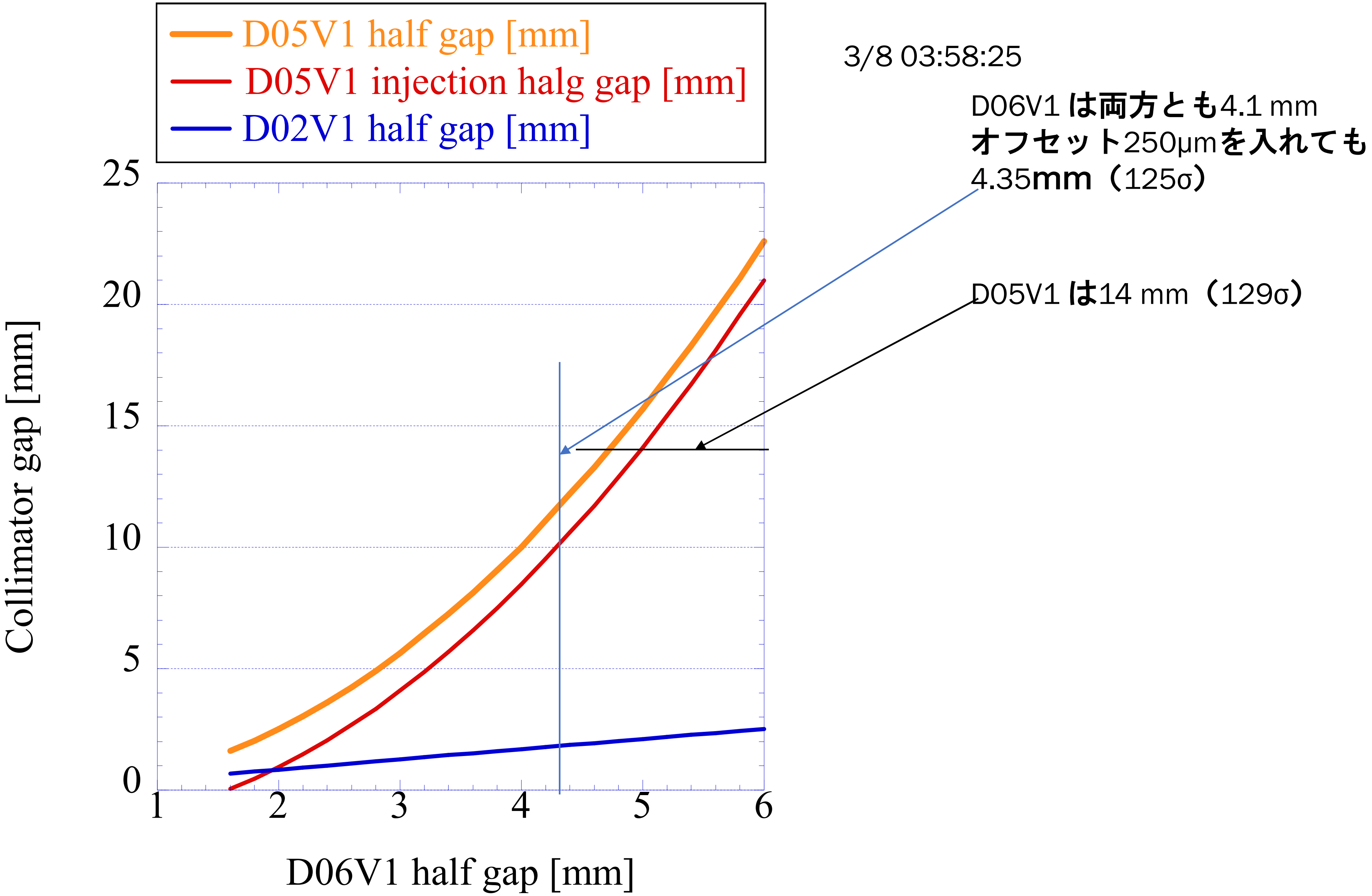


外れていたCTR(RingIN)の音響センサーは粒子シャワー発生源（コリメタ・ヘッド）に近く、短い時間で大量の放射線を浴びたと考えられて、そのような場合、20μsくらいの時間で信号にオフセットが生じる（極性は正負両方あり）。

: Acoustic sensor

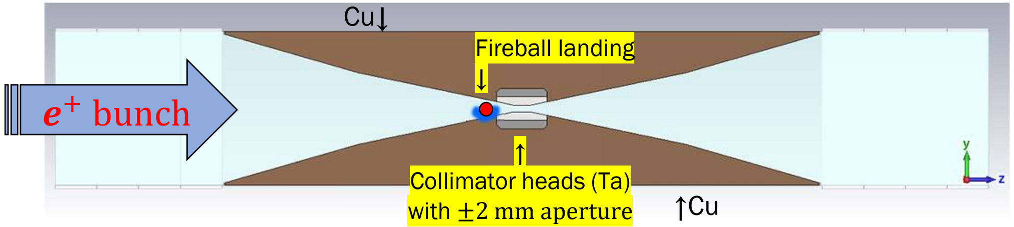


On the underside
in the same manner



D05V1 half gap [mm]
D05V1 injection halg gap [mm]
D02V1 half gap [mm]
Collimator gap [mm]
D06V1 half gap [mm]
0
5
10
15
20
25
1
2
3
4
5
6
3/8 03:58:25
D06V1 は両方とも4.1 mm
オフセット250μmを入れても
4.35mm（125σ）
D05V1 は14 mm（129σ）

Results of the CST PIC Simulation



Full simulation of the dynamics of the LER e^+ and emitted e^- , Cu^+ and interactions among them

+ positive charge

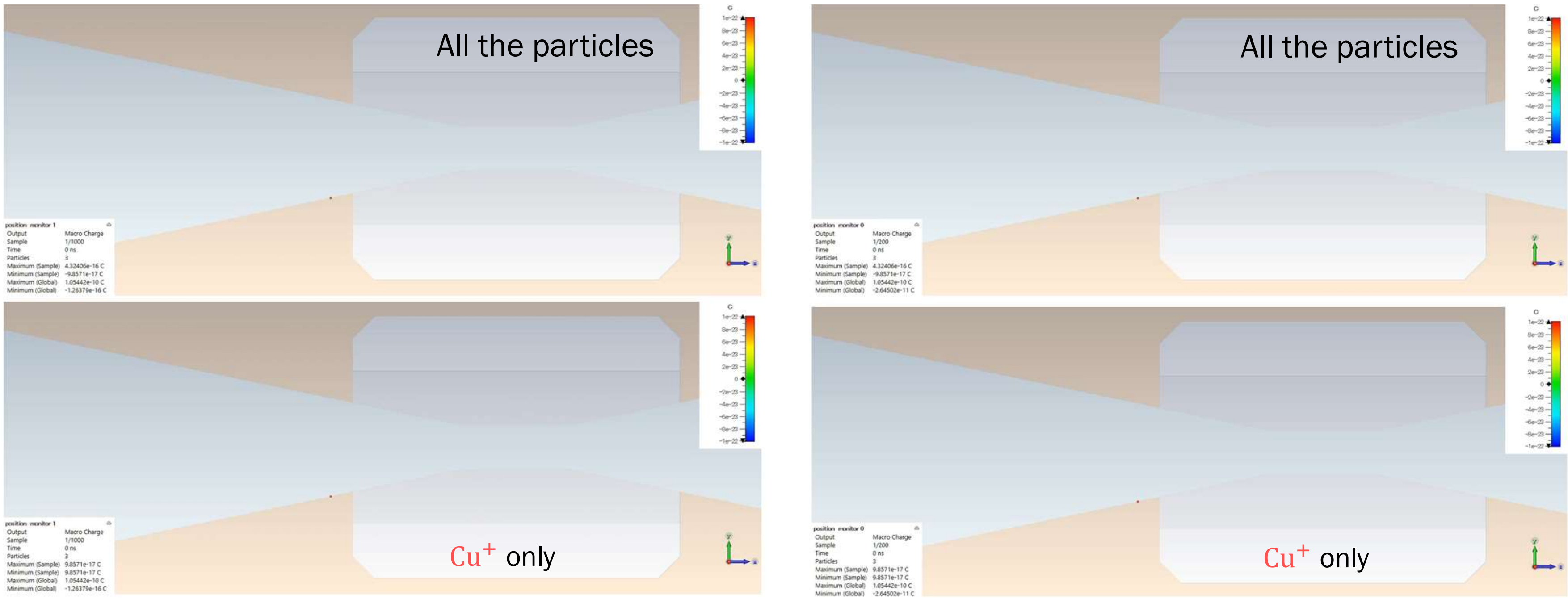
− negative charge

(Short time range)

t = 0–50 ns

(long time range)

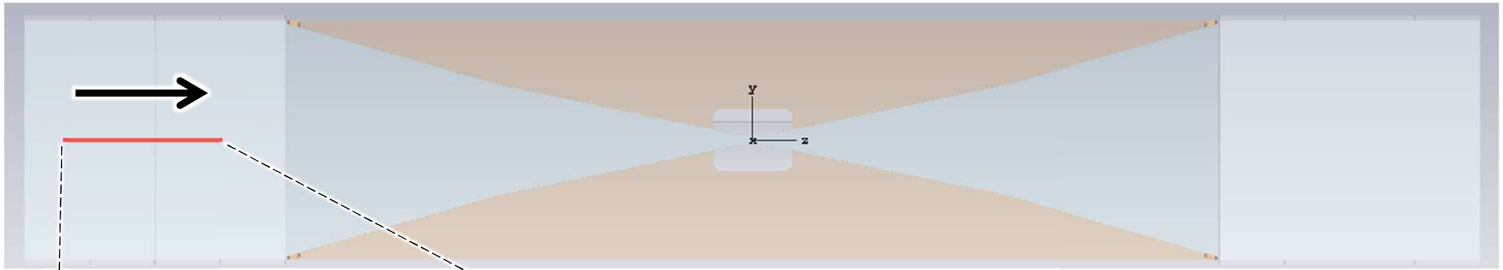
t = 0–10 μs



https://youtu.be/Ow0IX8bEB9g

https://youtu.be/5pHMwFmjSyo

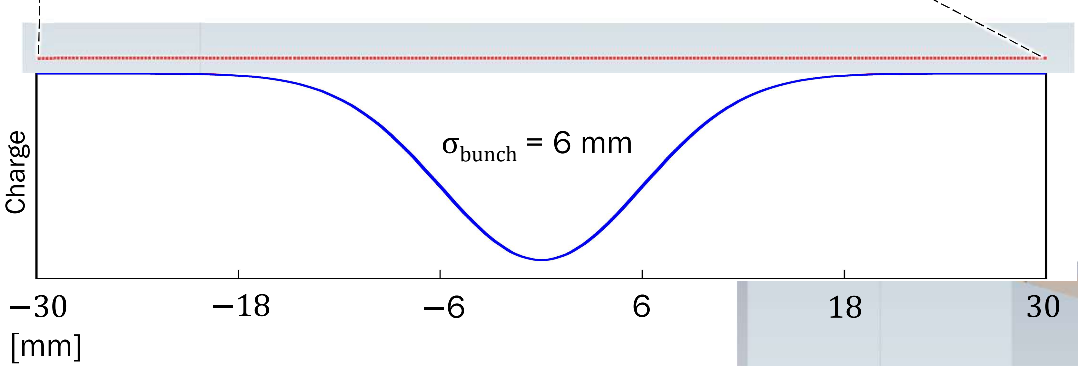
Calculation formula of the transverse kick



Initial state

$p_y^{(i)} = 0$

(i: macro-particle, $1, 2, \cdots, \mathbf{265}$)



Final state

$$k_y = P_y / P_z$$

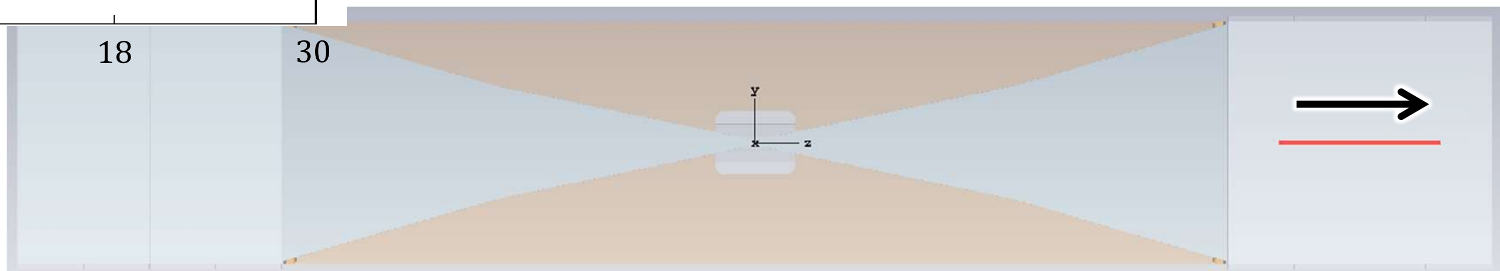
$$P_y = \frac{1}{Q_b} \sum_{i=1}^{N_{\text{mp}}} p_y^{(i)} q^{(i)}$$

$$\Delta P_y = \sqrt{\frac{1}{Q_b} \sum_{i=1}^{N_{\text{mp}}} \left(p_y^{(i)} - P_y\right)^2 q^{(i)}}$$

$p_y^{(i)}$: Y-momentum of particles in the i-th macro-particle

$q^{(i)}$: Charge of the i-th macro-particle

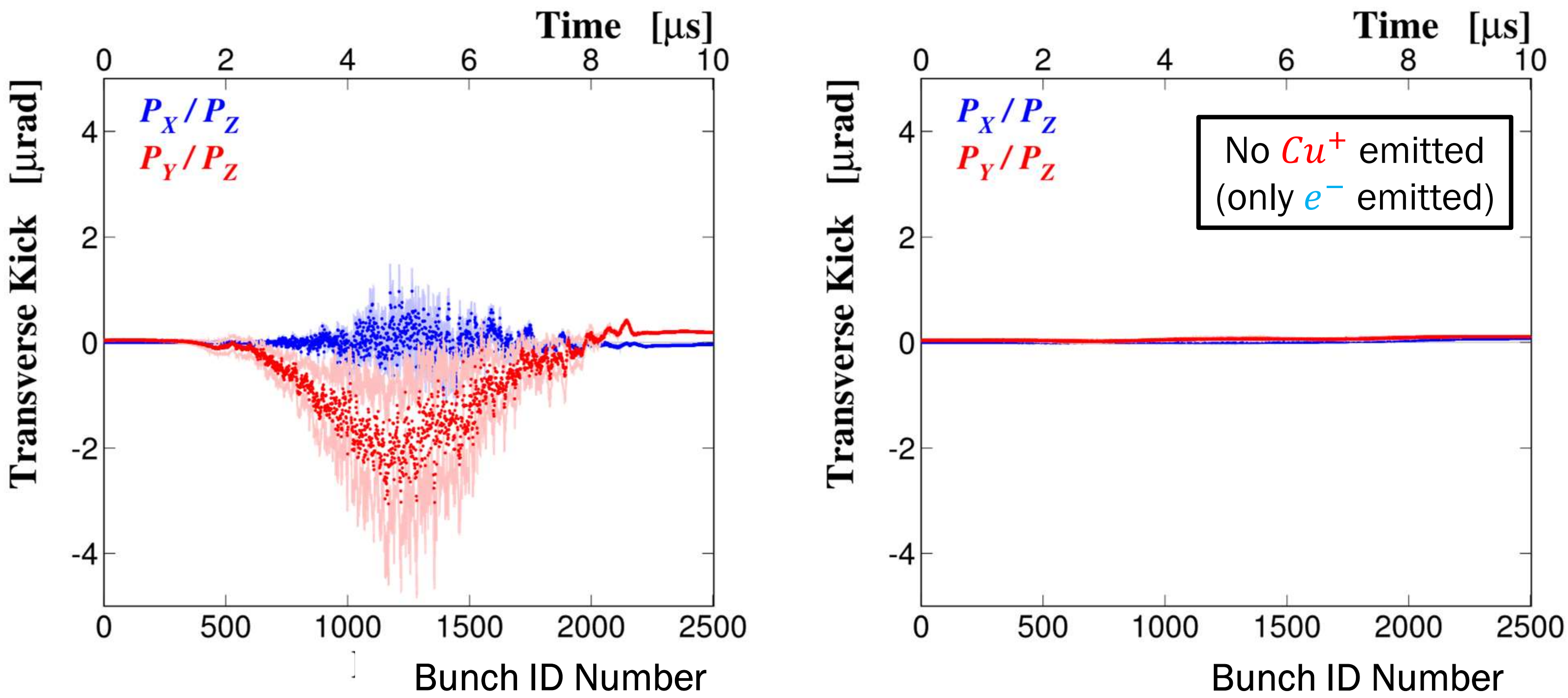
Q_b: Bunch charge



Comparison between w/ a

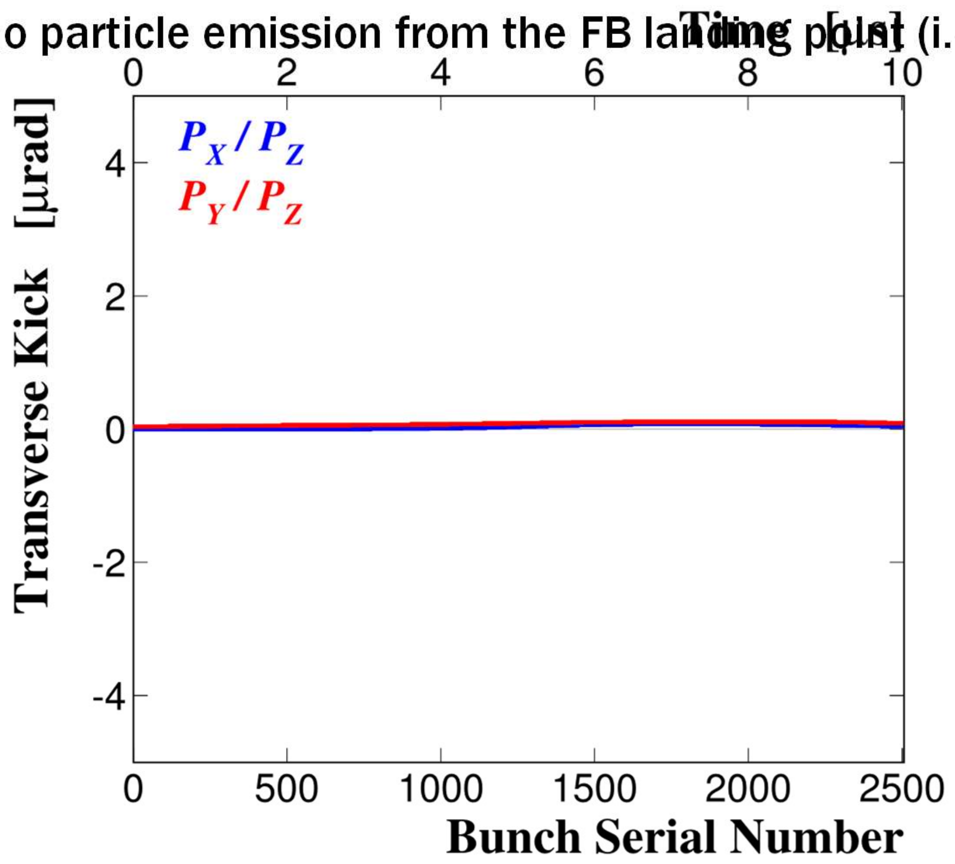
$$I_{peak}^{(emi)} = 70\ A$$

$$T_{ini}^{(emi)} = 300,000℃$$



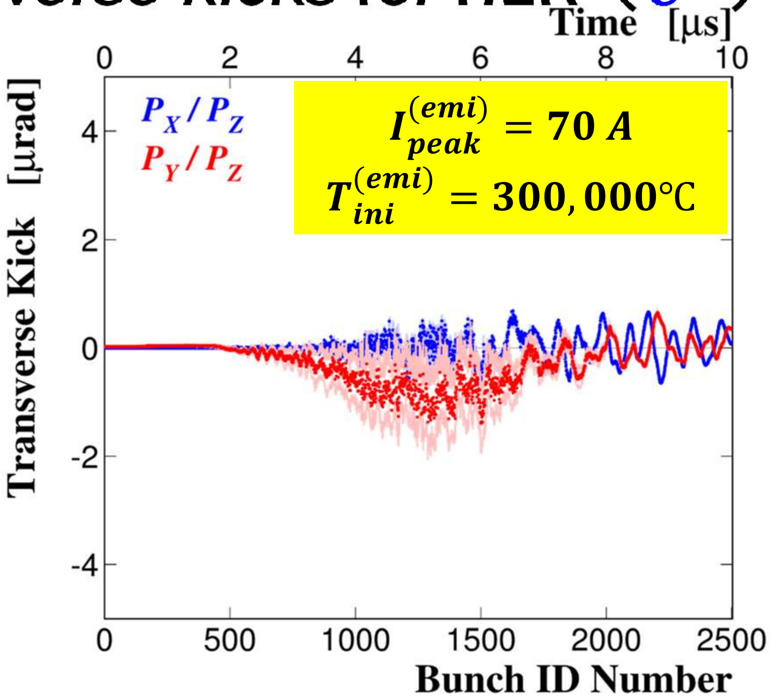
Cu^+ pushes up the space charge limit of emitted e^-

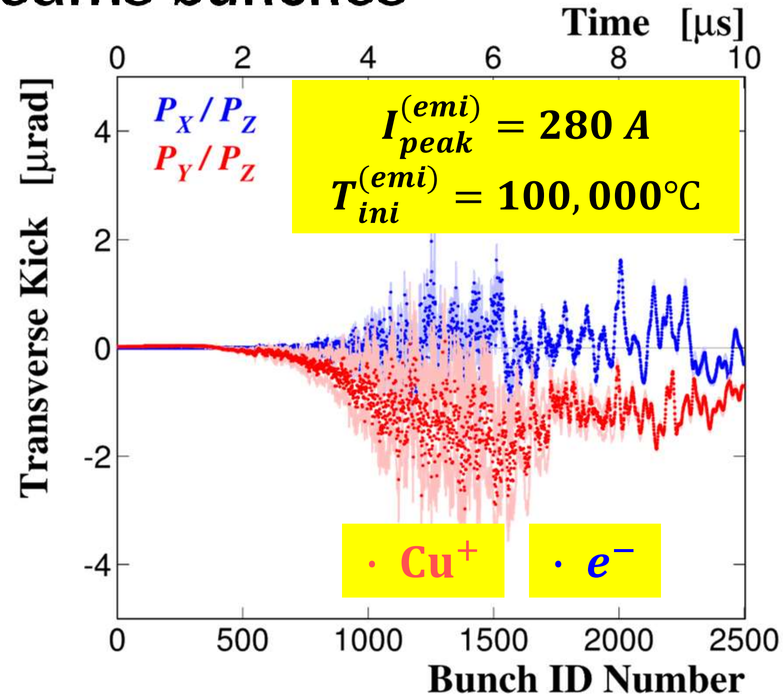
In the special case of no particle emission from the FB landing point (i.e., $I_{\mathrm{peak}}^{(emi)} = 0$)



Numerical noise level in the PIC simulation: ≲ 0.1μrad

Transverse kicks for HER（e^-） beams bunches

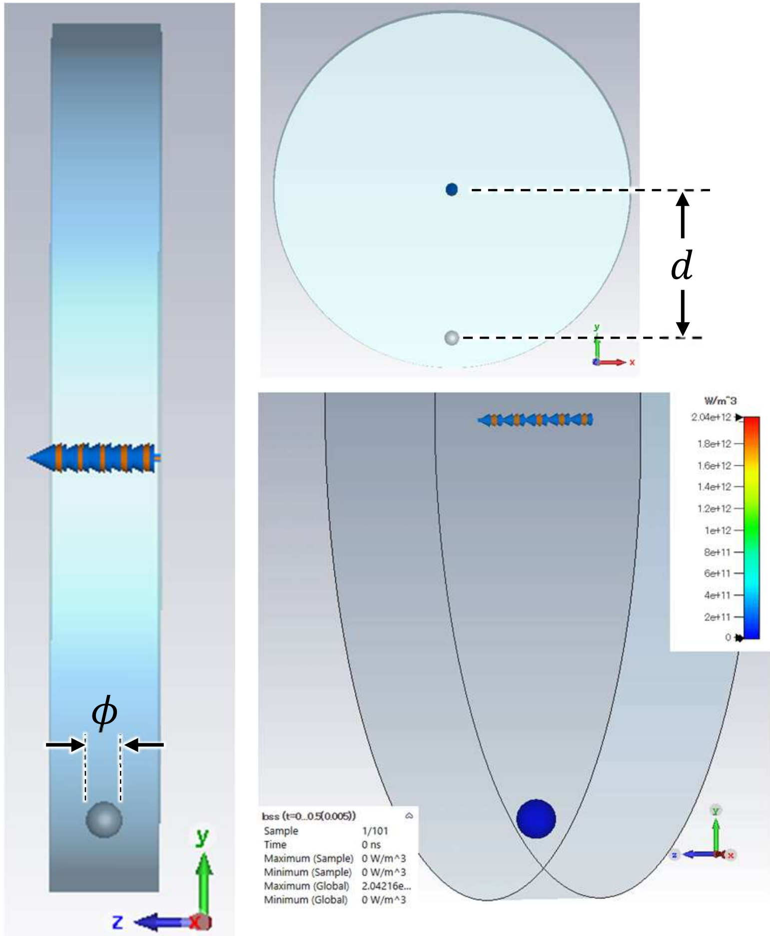




- ✓ Looks different from the results for LER(e^+)
- ✓ Under detailed study

[Step A] Beam-induced field can generate fireballs?

Simulation using a first-principle simulator (CST Wakefield Solver)



For a bunch length of 6 mm, total current of 900 mA, and 1272 bunches per ring, which is a typical set of operational parameters for sudden beam losses at SuperKEKB/LER.

<Results>

Table 1: Simulated equilibrium temperatures in Celsius of spherical microparticles made from tungsten. The time in second to reach 1000 °C from 30 °C is also shown in parentheses. ϵ_e and ϕ indicate emissivity and diameter of the microparticle, respectively. d indicates the transverse distance between the beam bunch and the center of the microparticle.

	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	1019 (0.4)	595	842	467	748	400
0.05	1600 (0.7)	802	1253 (0.7)	597	1079 (0.9)	495
0.10	1542 (1.6)	767	1194 (1.9)	567	1022 (2.6)	469
0.50	1670 (6.6)	819	1293 (7.3)	607	1107 (8.5)	503
1.00	1704 (12)	763	1322 (13)	558	1133 (15)	458

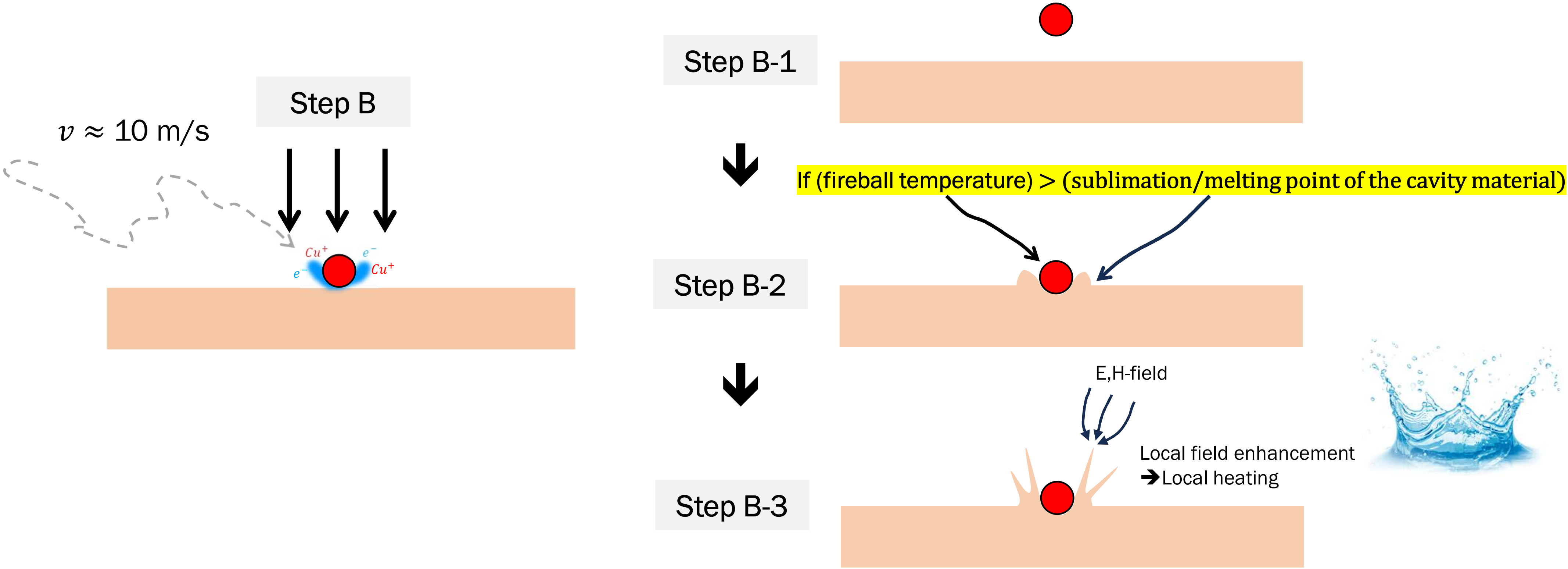
Table 2: The same as in Table 1 for tantalum.

	$\epsilon_e = 0.1$		$\epsilon_e = 0.2$		$\epsilon_e = 0.3$	
ϕ [mm]	d = 2 mm	5 mm	2 mm	5 mm	2 mm	5 mm
0.01	923	534	759	421	673	362
0.05	1687 (0.4)	904	1347 (0.4)	695	1175 (0.5)	589
0.10	1625 (1.0)	877	1284 (1.1)	668	1113 (1.3)	564
0.50	1799 (3.7)	940	1423 (4.0)	718	1235 (4.3)	607
1.00	1830 (7.0)	896	1449 (7.4)	679	1258 (7.9)	570

The results show that fireballs can be generated realistically if a submillimeter or smaller micro-particle gets to a few millimeters from beam bunches for a second with a low emissivity of the fireball material.

Essential Condition for FB BD

Coexistence of different materials
with largely different sublimation/melting points in the same place

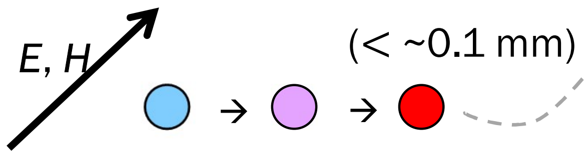


(Just my speculation; detailed investigations needed)

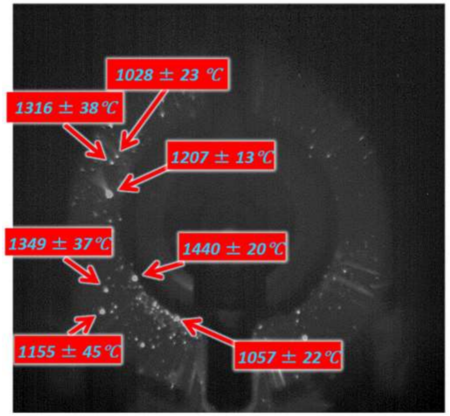
Physical process of the fireball breakdown revealed by the observations

Step A

A microparticle is heated by the RF field into a fireball.

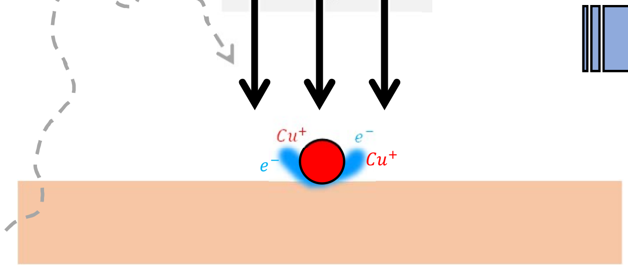


Proven by



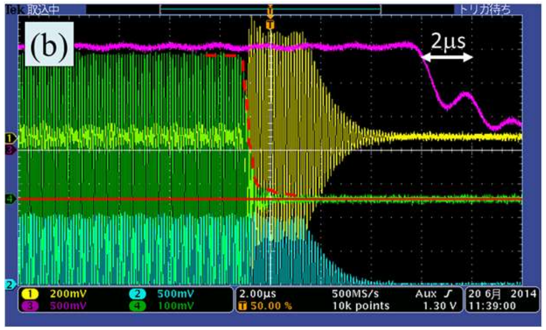
Temperature measurements

Step B



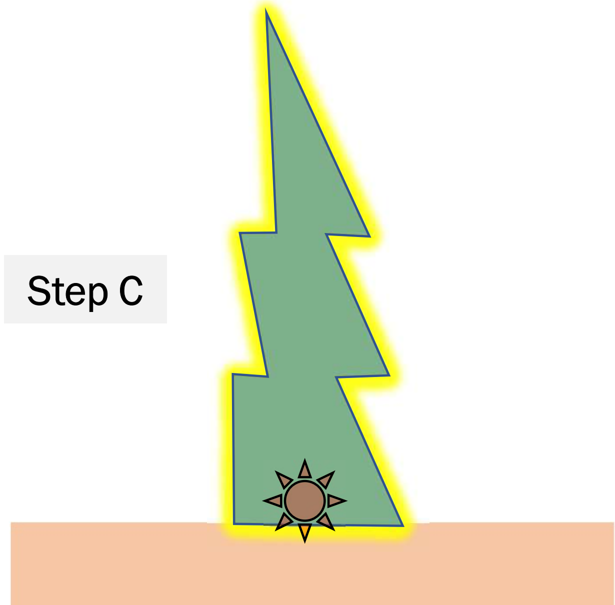
Plasma is generated with eating the RF field in the cavity.

Proven by



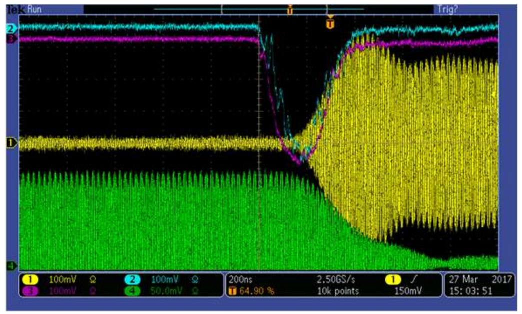
Fast drop of the accelerating field, and
Very high power density of ~GW/cm²

Step C



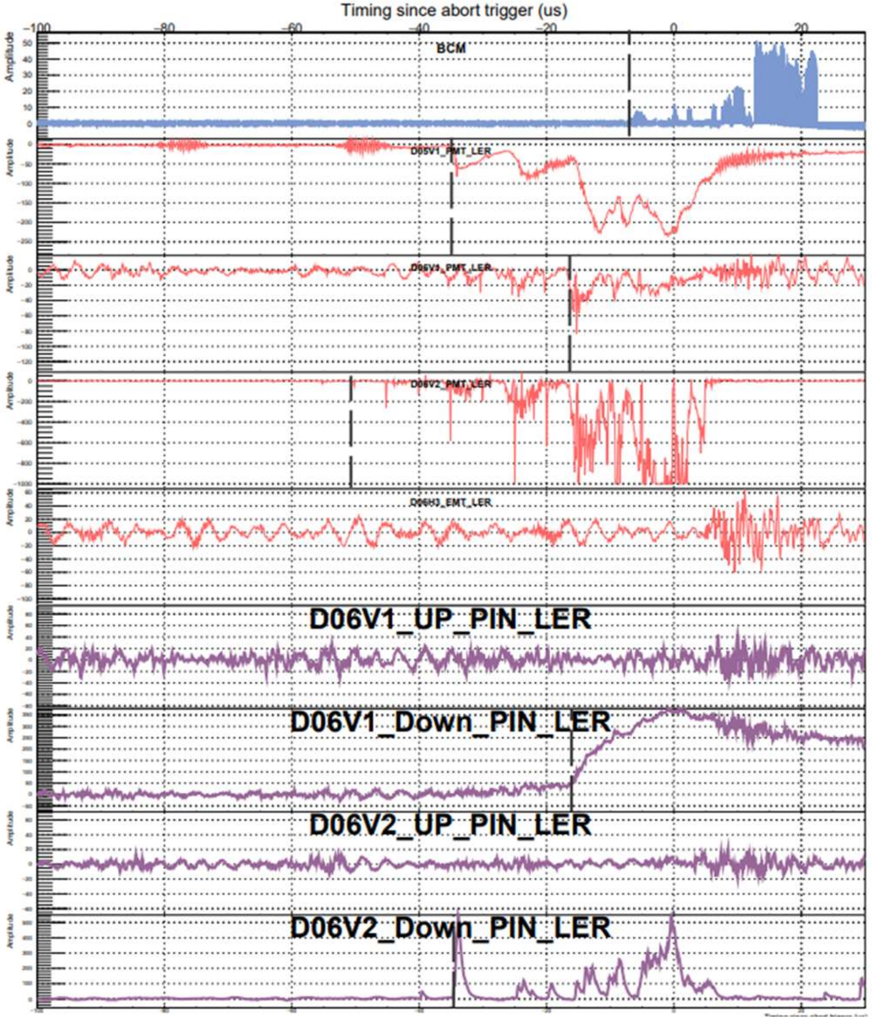
<u>Huge current</u> flow leads to vacuum breakdown.

Proven by

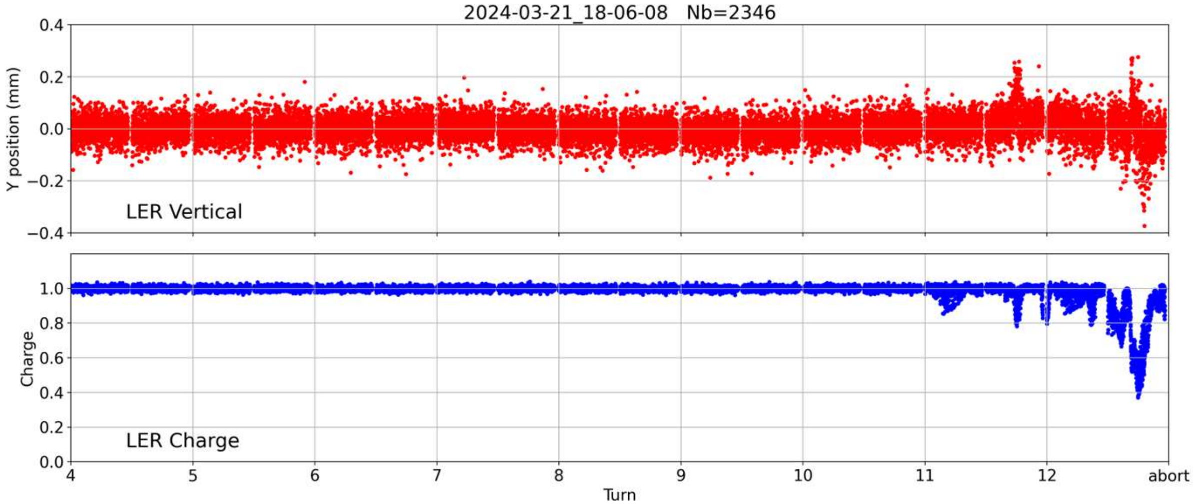


Huge X-ray detection

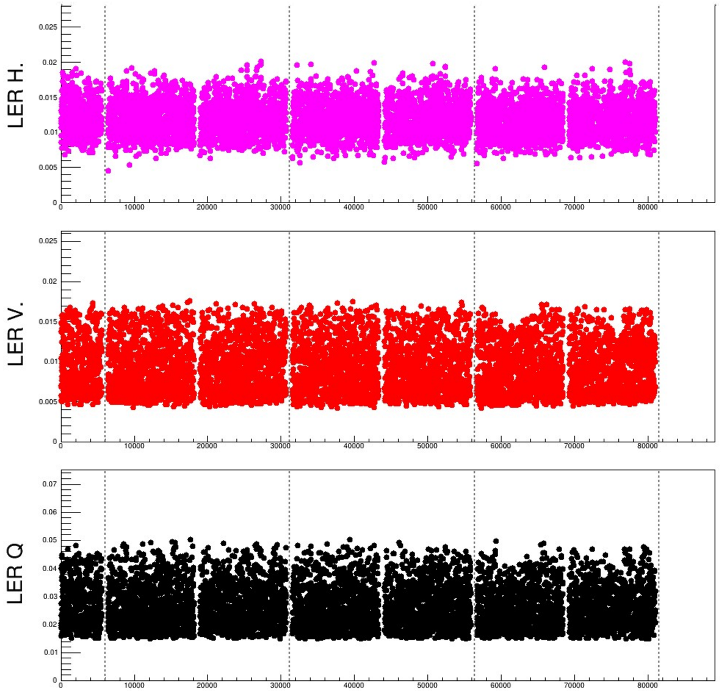
(Plasma generation and its exponential growth are needed for vacuum breakdown.)



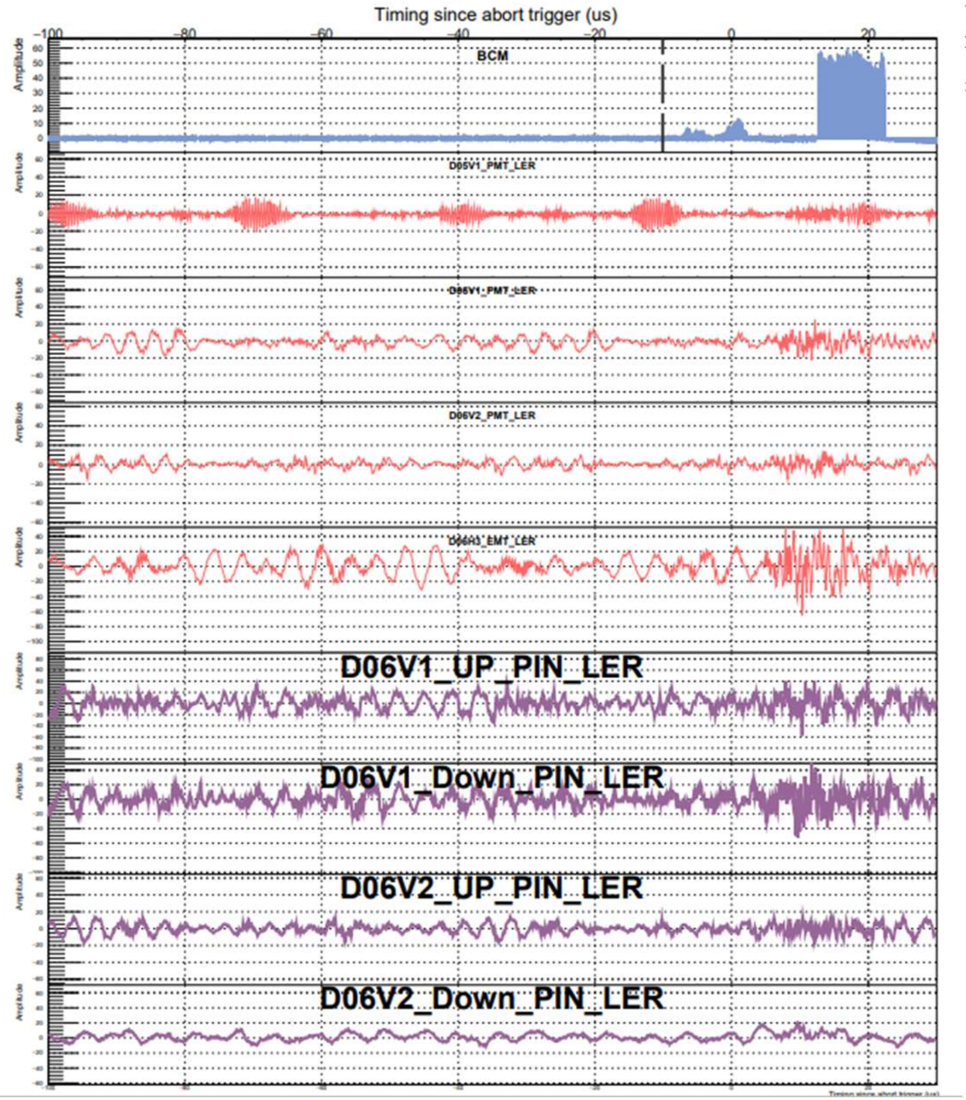
Timing since abort trigger (us)
BCM
D06V1_PMT_LER
D06V2_PMT_LER
D06V1_UP_PIN_LER
D06V1_Down_PIN_LER
D06V2_UP_PIN_LER
D06V2_Down_PIN_LER

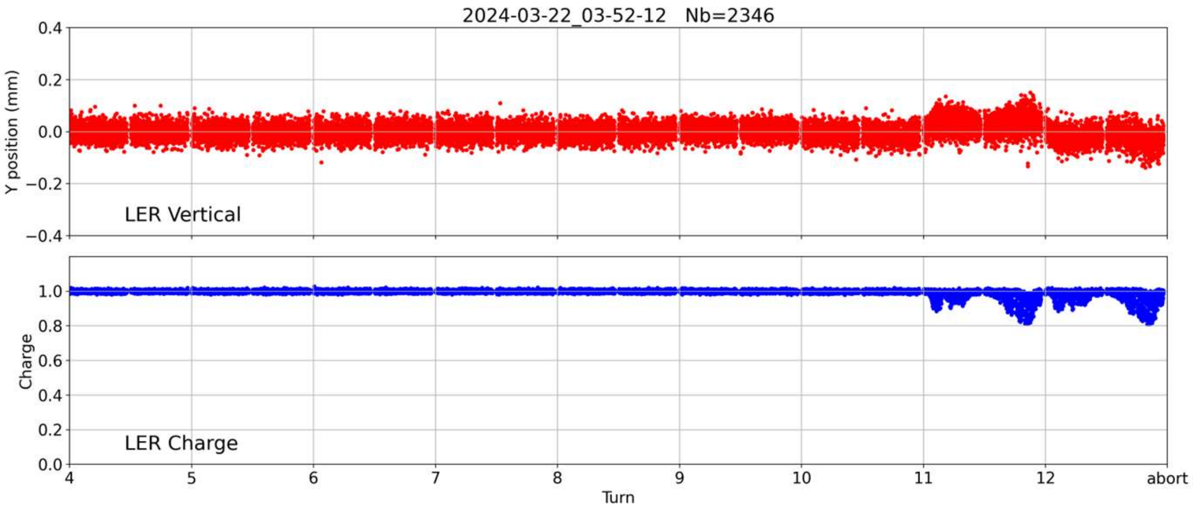


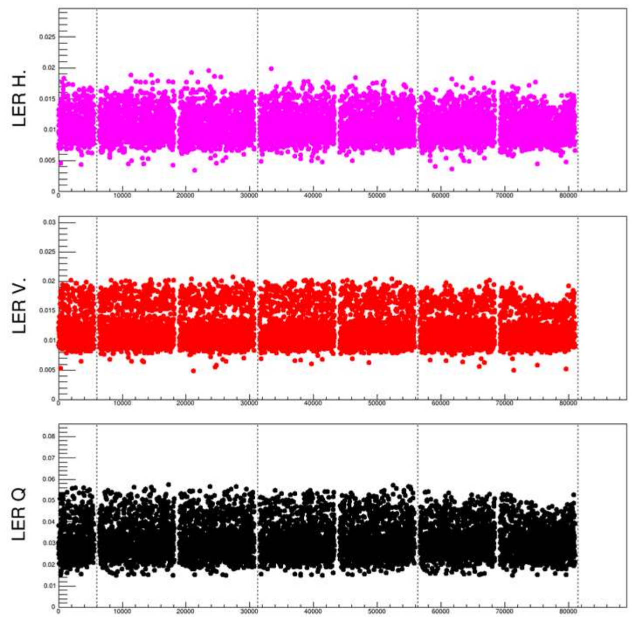
2024-03-21_18-06-08 Nb=2346
Y position (mm)
LER Vertical
Charge
LER Charge
Turn
abort



LER H.
LER V.
LER Q


Timing since abort trigger (us)
BCM
D05V1_PMT_LER
D06V1_PMT_LER
D06V2_PMT_LER
D06V1_UP_PIN_LER
D06V1_Down_PIN_LER
D06V2_UP_PIN_LER
D06V2_Down_PIN_LER
Amplitude


2024-03-22_03-52-12 Nb=2346
Y position (mm)
LER Vertical
Charge
LER Charge
Turn
abort


LER H.
LER V.
LER Q

RFSoC
(Fuji下流)

D6BOR
(QD5P.26)

D6コリメータ

D5BOR
(QN1OP)