“SuperKEKB beam diagnostics & fast losses“

2024/6/17 FCC week

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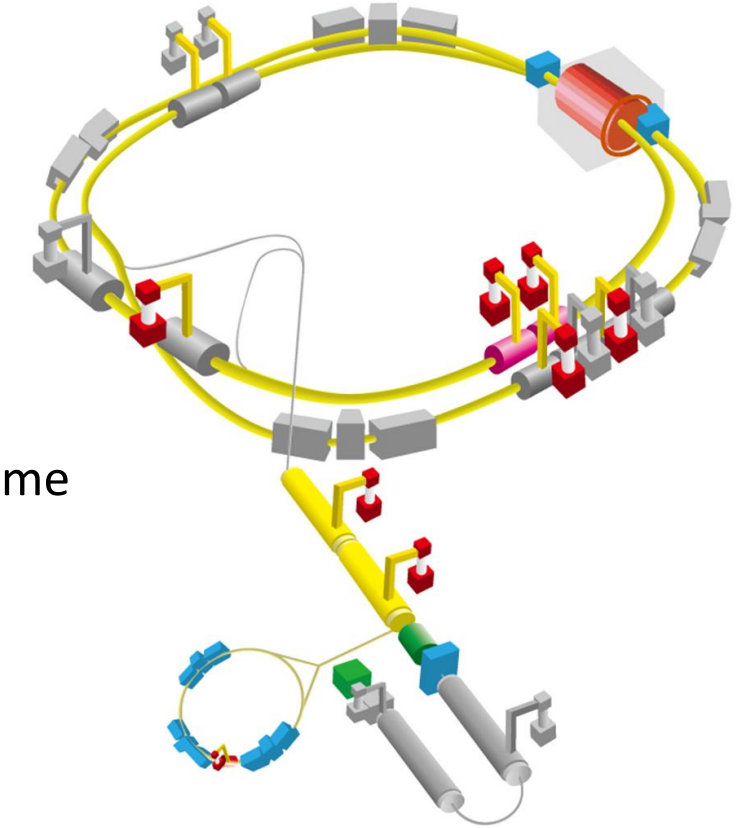
on behalf of the SuerKEKB group

Contents

1. SuperKEKB



- SuperKEKB
  - collider with 7 GeV electron and 4 GeV positron.
  - Circumference 3km
- Aiming for the highest luminosity in world, we have adopted a nanobeam scheme
  - Squeezing βy* with nano-beam collision scheme (x20)
  - Twice beam current of KEKB (x2)
- Recorded a peak luminosity

  twice that of KEKB.

	KEKB achieved		SuperKEKB 2022/6/8	
	LER	HER	LER	HER
Ibeam [A]	1.673	1.188	1.321	1.099
# of bunch	1585		2249	
Ibunch [mA]	1.033	0.7495	0.5873	0.4887
βy*	5.9	5.9	1.0	1.0
Luminosity[10^{34}cm^{-2}s^{-1}]	2.11		4.65	

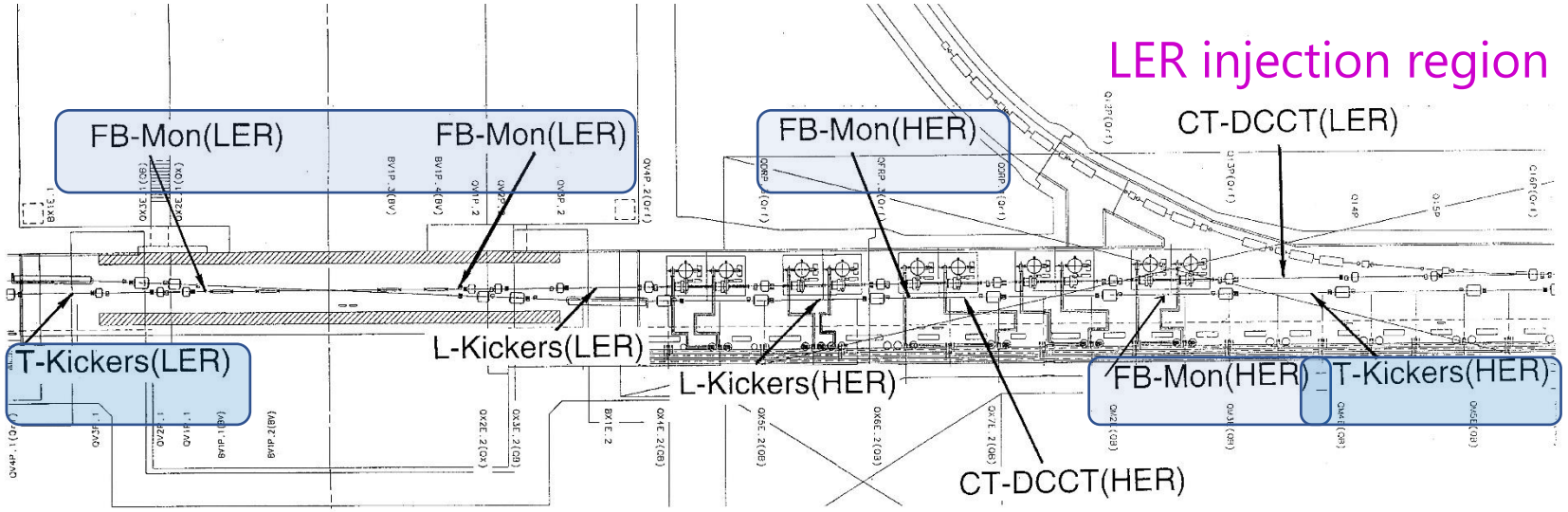
2. SuperKEKB Beam Instrumentation System

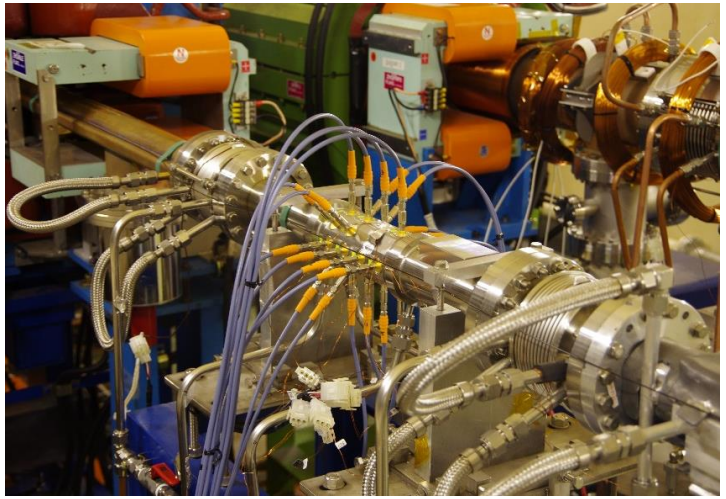
System	Quantity		
	HER	LER	DR
Beam position monitor (BPM)	466	444	83
Displacement sensor	110	108	0
Transverse bunch feedback system	2	2	1
Longitudinal bunch feedback system	0(1)	1	0
Visible SR size monitor	1	1	1
X-ray size monitor	1	1	0
Beamstrahlung monitor	1	1	0
Betatron tune monitor	2	2	1
Beam loss monitor	207		34
DCCT	1	1	1
CT	1	1	0
Bunch current monitor	1	1	1

Bunch-by-bunch feedback system

FUJI straight section

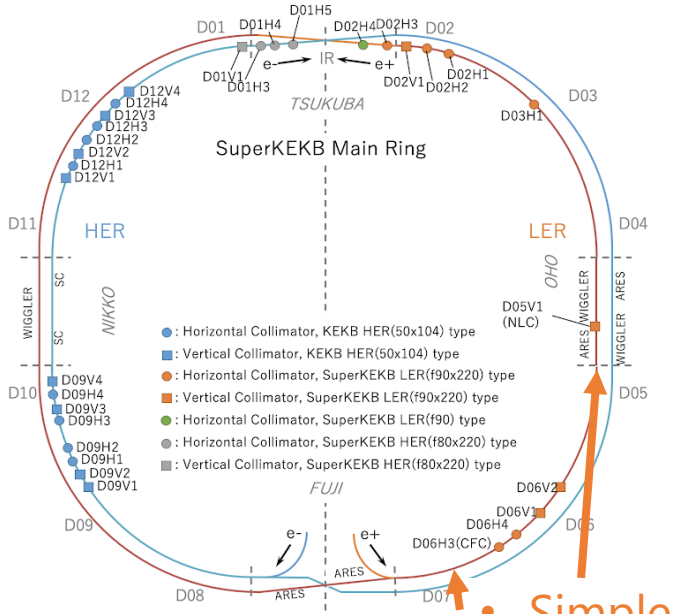
LER injection region





Bunch Oscillation Recorder (BOR)

- Since 2022, we have developed several types of BORs. BORs measure the bunch position just before the beam aborts over a few or more turns.
- We added BORs more densely in LER, where Sudden Beam Loss (SBL) events were severe in before LS1, especially across the D06 collimators.
- Although the locations of the RFSoC and oscilloscope were later changed, measurements with multiple BORs continued.
- BORs other than iGp12 also measure bunch current at the same time.



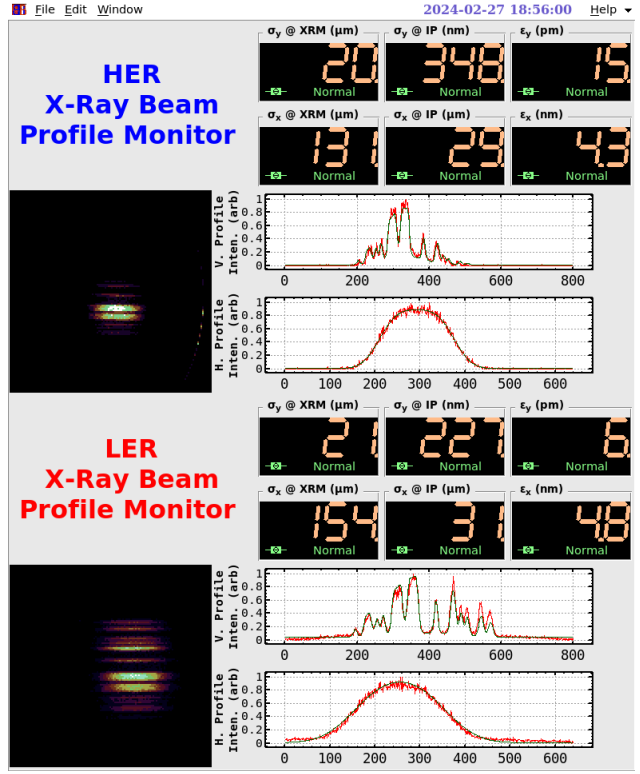
- Simple
- BOR
- iGp
- RFSoC

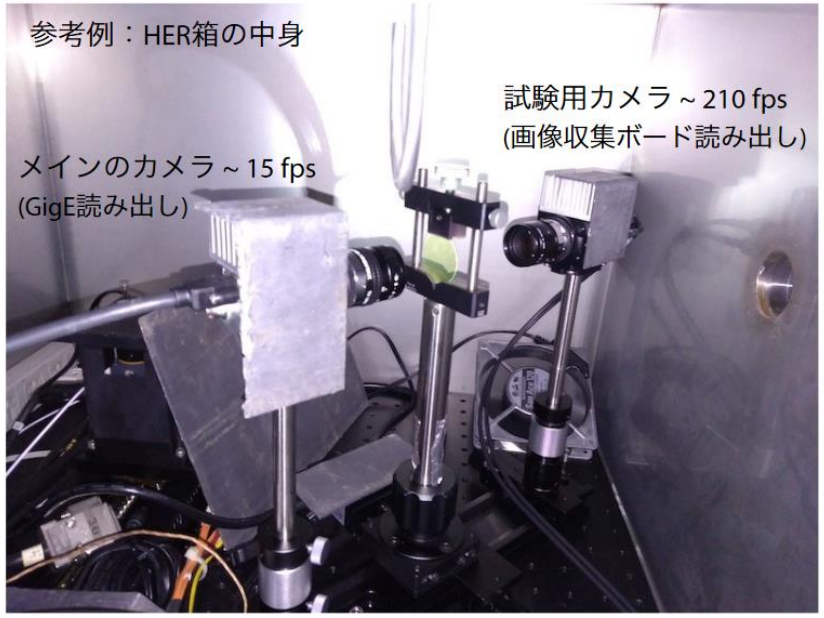
HER	Location	ADC bit	RF sync.
BOR	Fuji Upward	8	Yes
iGp BOR	Fuji Up & Down	12	Yes

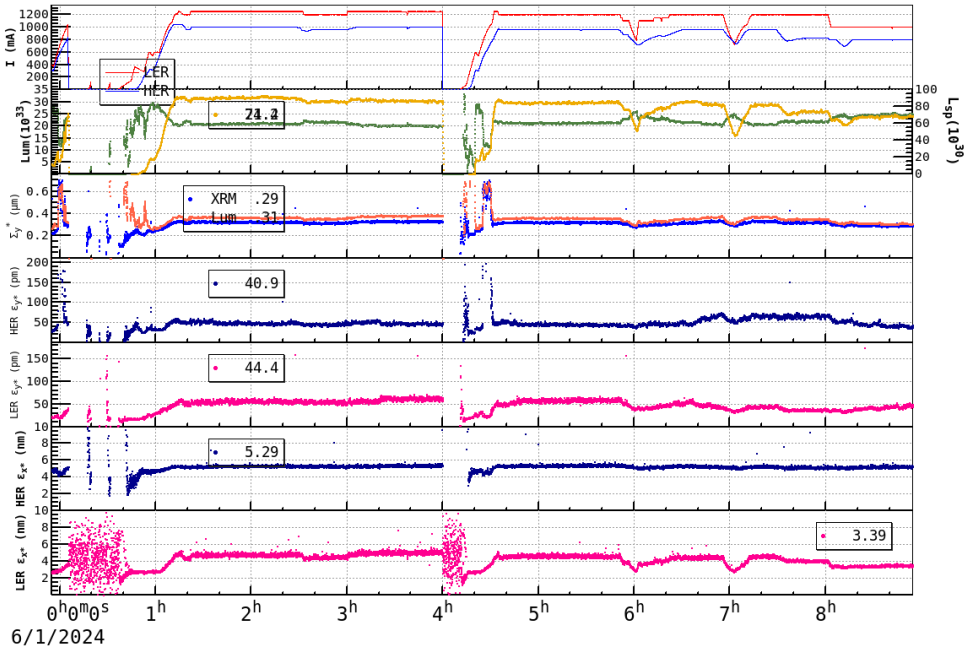
LER	Location	ADC bit	RF sync.
BOR	Fuji Upward	8	Yes
iGp BOR	Fuji Up & Down	12	Yes
RFSoC BOR	Fuji Downward	12	Yes
Simple BOR (Oscilloscope)	D05	8	No (5Gsps)
	D06	8	No (2.5Gsps)

X-ray size monitor (XRM)

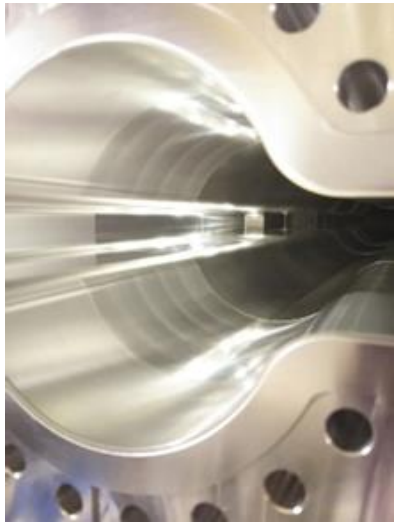
- Measure the beam size.
- Introduced a monitor using the short emission light of the wavelength from SuperKEKB to measure smaller beam size.
- Pinhole, URA mask, etc.
- σy (σx)

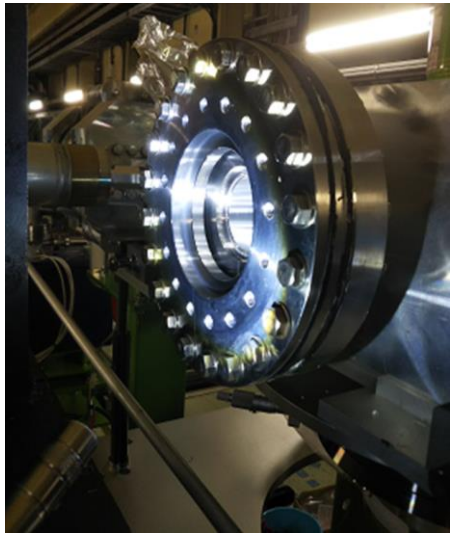


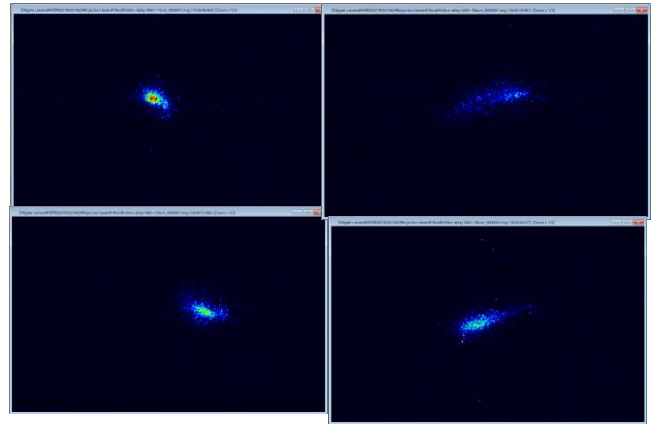




Visible SR size monitor

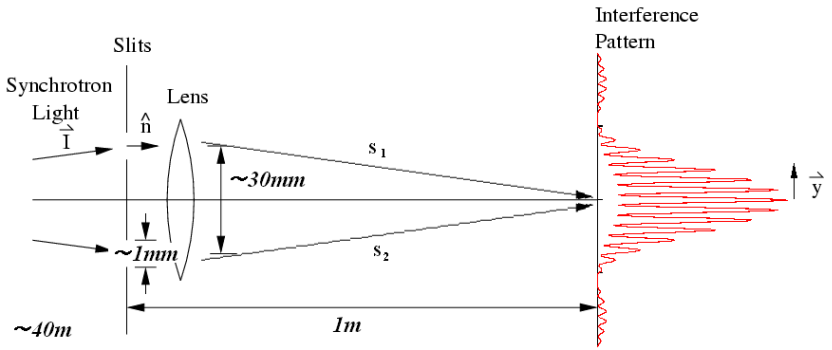



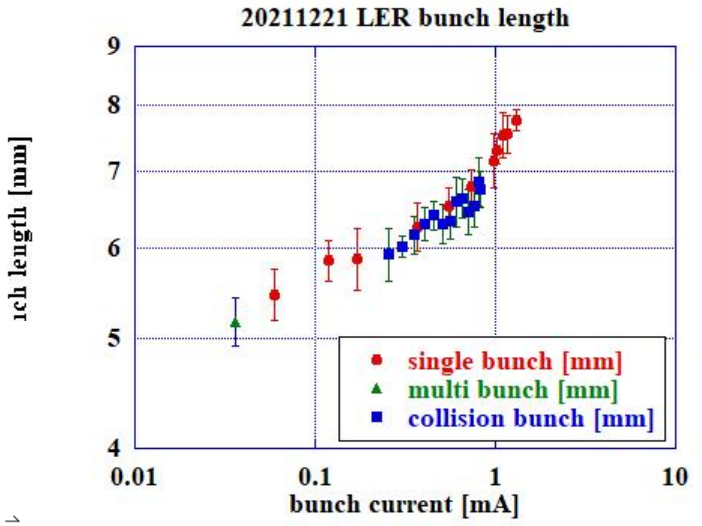




Gated camera : bunch profile

- We take emission light out of the bending magnet that set in last part of the arc section.
- Extraction chamber
  - Set up to downstream 23 m of source bend magnet.
  - Diamond mirror is inserted
  - Optical window





Streak camera : bunch length

3.Fast Loss (Sudden Beam Loss)
3-1 What is “SBL(Sudden Beam Loss)” ?

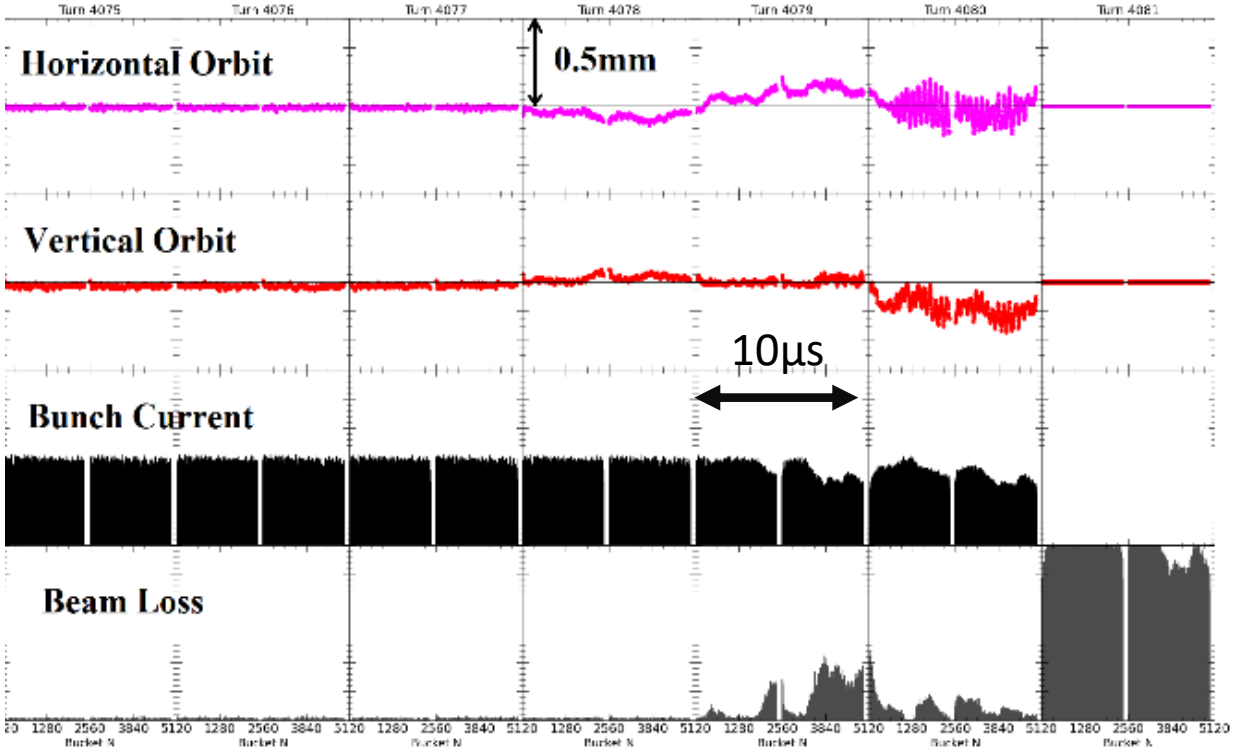
Beam loss that occurs suddenly within 1 turn (10μs) without precursory phenomena. ＝ Sudden Beam Loss（SBL）

- The cause of SBL had been unknown.
- A significant percentage of the beam is before the abort trigger is issued and stored beam is dumped

→ 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
Bunch Oscillation Recorder(BOR) & Bunch Current Monitor(BCM)



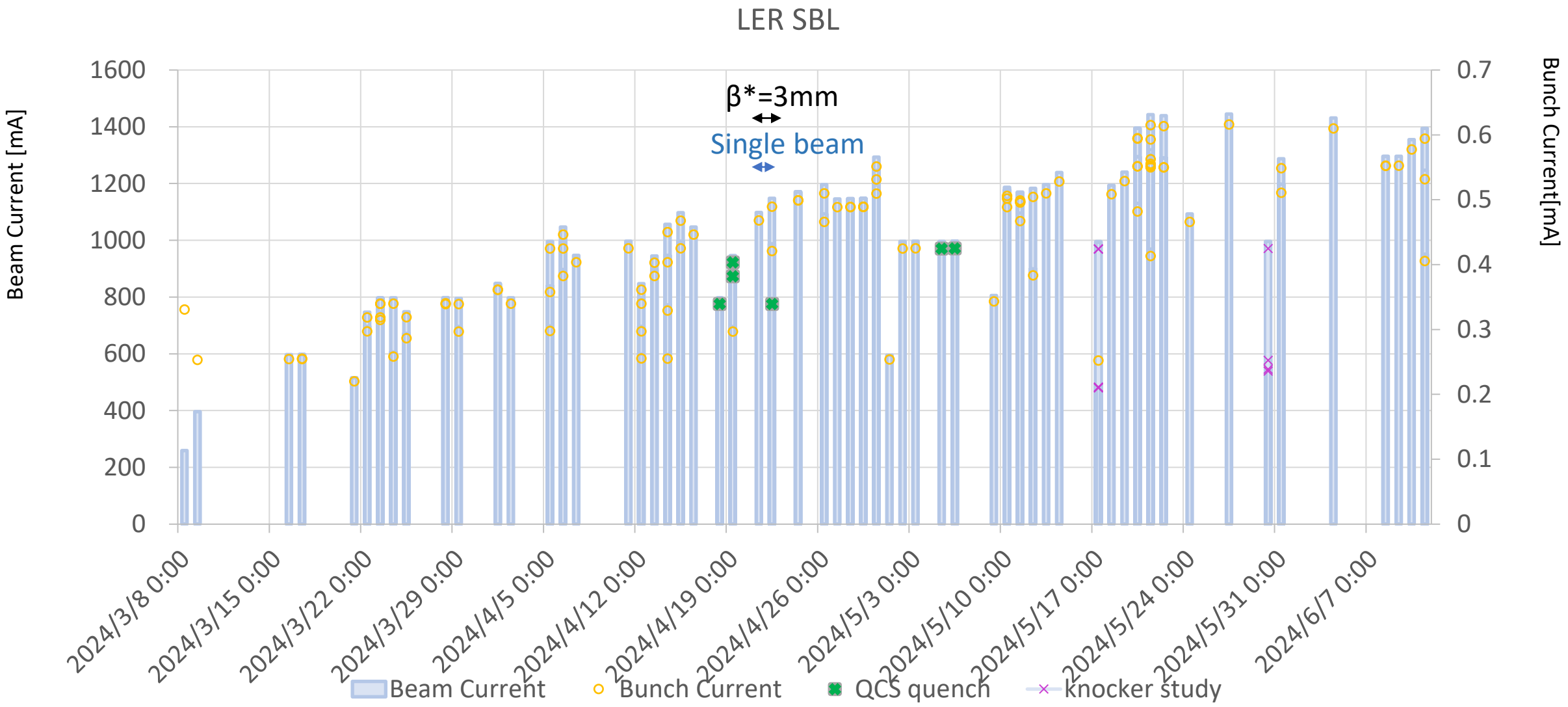
3-2. Observations

- A large fraction of the stored beam is suddenly lost before the abort.
- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when the loss occurs in LER.
- The starting point of beam loss depends on the collimator setting and is not limited to a specific location.
- Just before the beam loss begins, the orbit appears to move, but the displacement is small～O(0.1 mm).
- After the start of the beam loss, orbit displacement is <O(1mm).
- So far, no acoustic observation clearly considered a vacuum arc at any collimator when SBL occurred.
- SBL can occur with both single beam and collision beam.
- SBL occurs both at β*=1mm and 3mm.

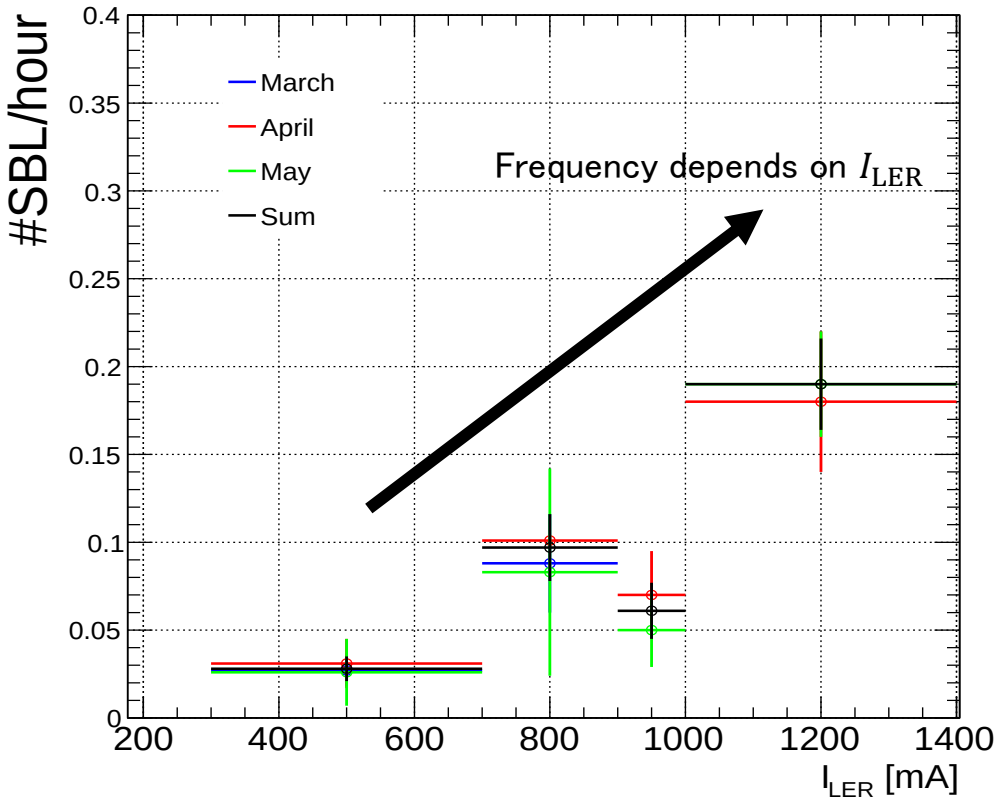
- Aging effect of vacuum pressure might be seen.
- The vacuum pressure spiked at D04 or D10 in the most cases when LER SBL occured.
- Vertical Beam Size increases when SBL occurs compared to other abort.

LER SBL statistics

The beam current which SBL occurs looks increasing.
Aging effect?



Beam current dependency



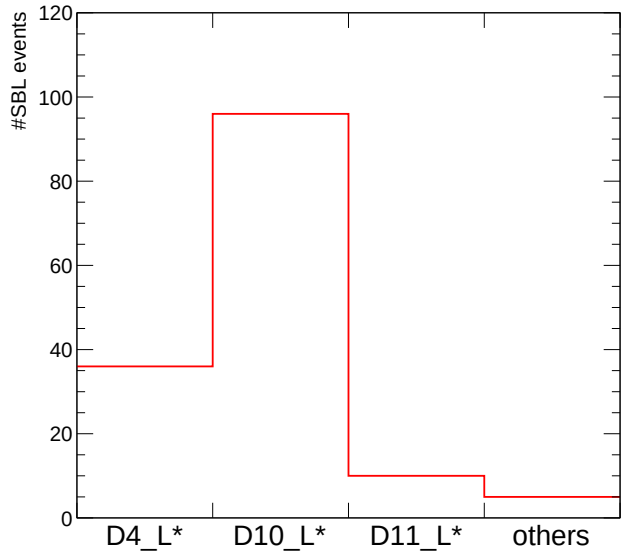
Mar.1st - May. 22 at 19:00

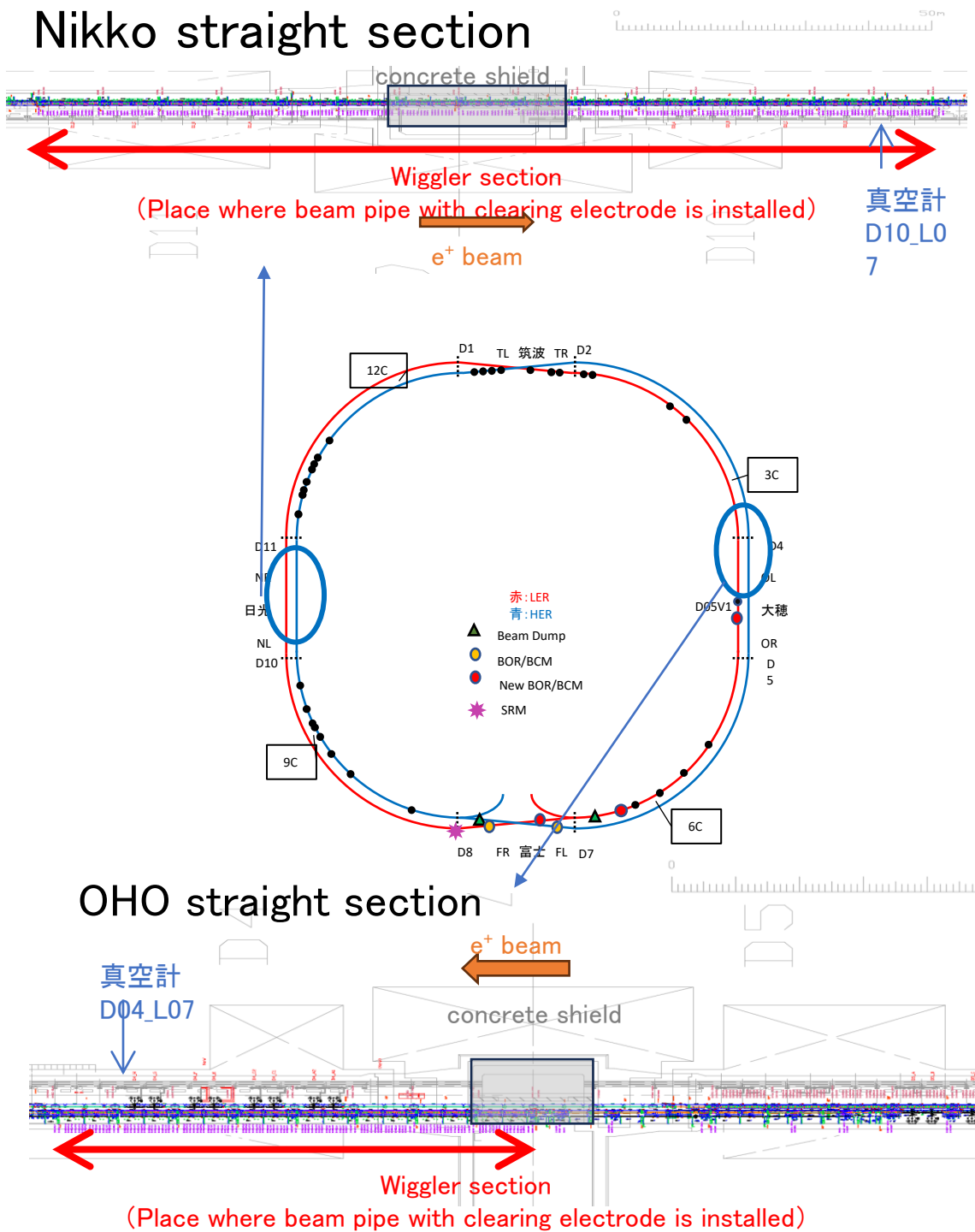
I_{LER} [mA]		[300, 700]	[700, 900]	[900, 1000]	[1000,]
March	#LER SBL	9	10	0	0
	Operation time [hour]	331	114	0	0
	#SBL/hour	0.027 ± 0.009	0.088 ± 0.028	–	–
April	#LER SBL	5	13	8	20
	Operation time [hour]	159	120	114	110
	#SBL/hour	0.031 ± 0.014	0.101 ± 0.003	0.07 ± 0.025	0.18 ± 0.04
May	#LER SBL	2	2	6	30
	Operation time [hour]	76	24	115	159
	#SBL/hour	0.026 ± 0.019	0.083 ± 0.059	0.05 ± 0.021	0.19 ± 0.03

- Frequency (#SBL/hour) depends on the LER beam current

Pressure Burst

- There are many vacuum bursts in the Wiggler(D10/D4) section, but they also occur when SBL is not occurring.
  - The spike never coincided in D04 and D10.
  - The spike never coincided at different locations within D04 or D10.
- LM(PIN) were installed downstream of the Wiggler section, but no beam loss was observed.



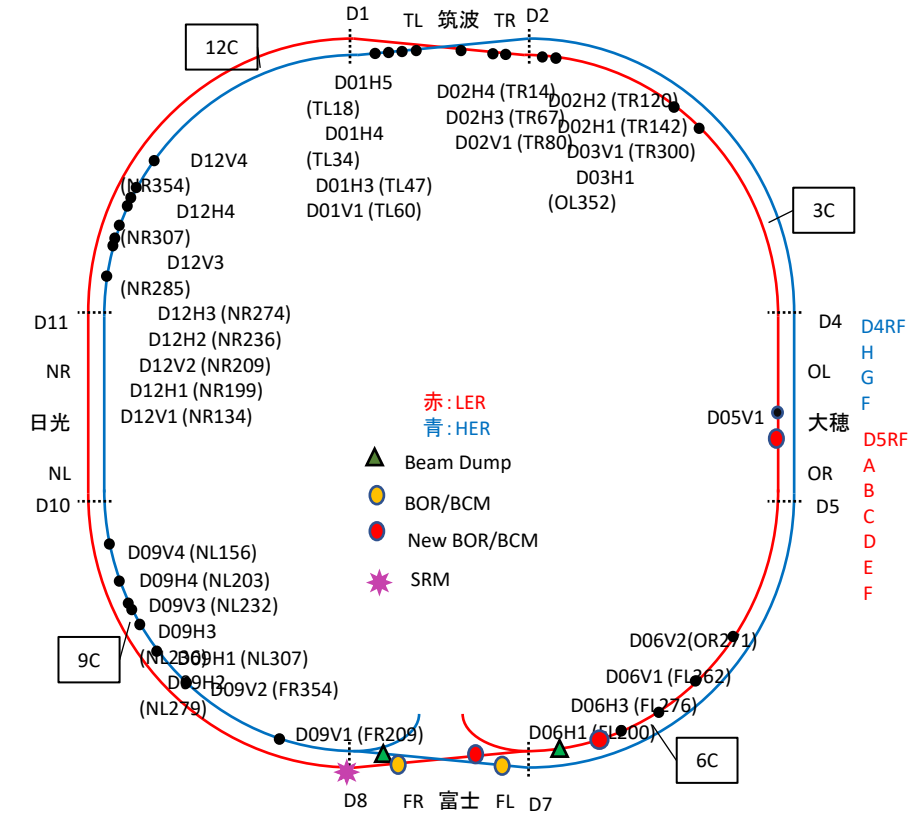


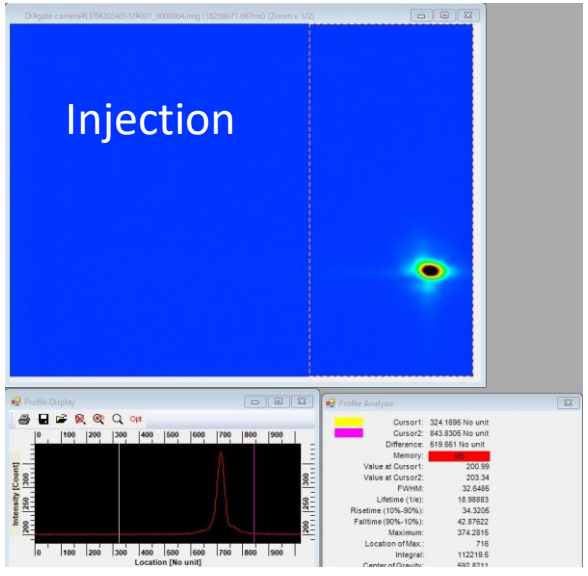
Beam size measurement @SBL

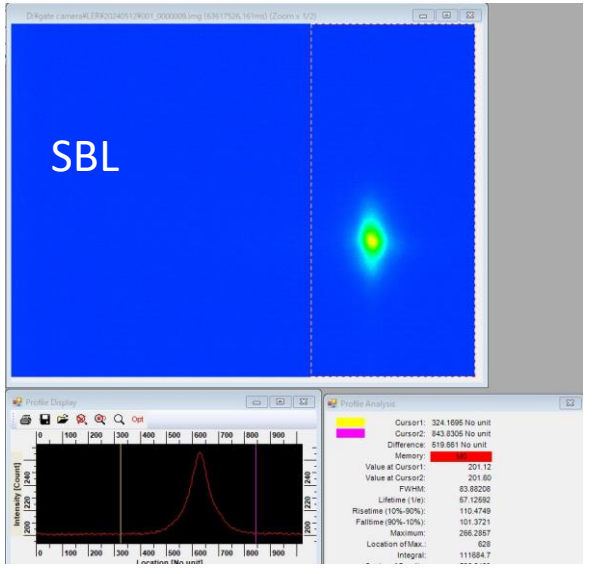
- A beam image at the abort timing was measured using a D8 SRM gated camera.
- trigger : Abort trigger
- Gate width : 10us
- When the Abort trigger is sent to the kicker, a signal is also sent to D8.
- The beam goes in the order of D8 → BOR → Abort kicker, so we should be able to see the image of the last turn.

↓

- Vertical Beam Size increases when SBL occurs compared to other abort.







3-3. Causes of SBL from observations

- No. of SBL depend on beam current.
- The vacuum pressure spiked at D04 or D10 (Wiggler section) were happened for most of SBL events.
- Aging effect might be seen.
- Vertical Beam Size increases when SBL occurs compared to other abort.

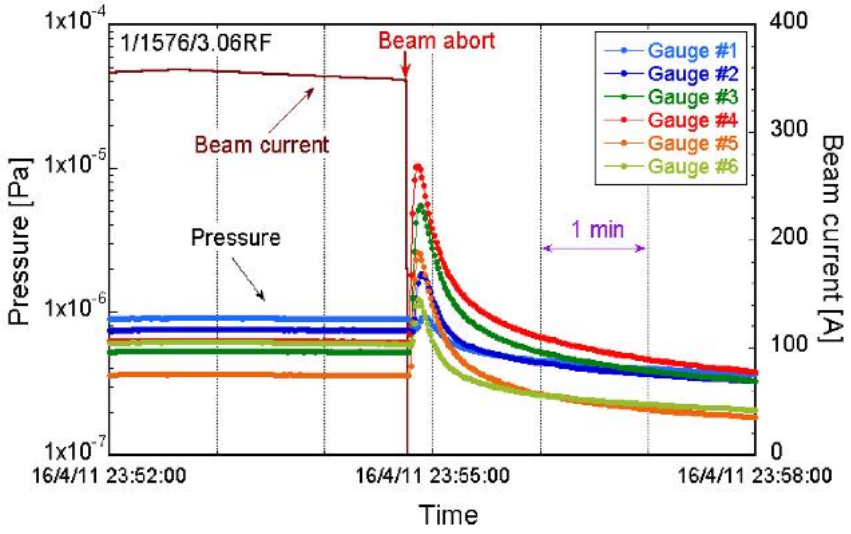
↓

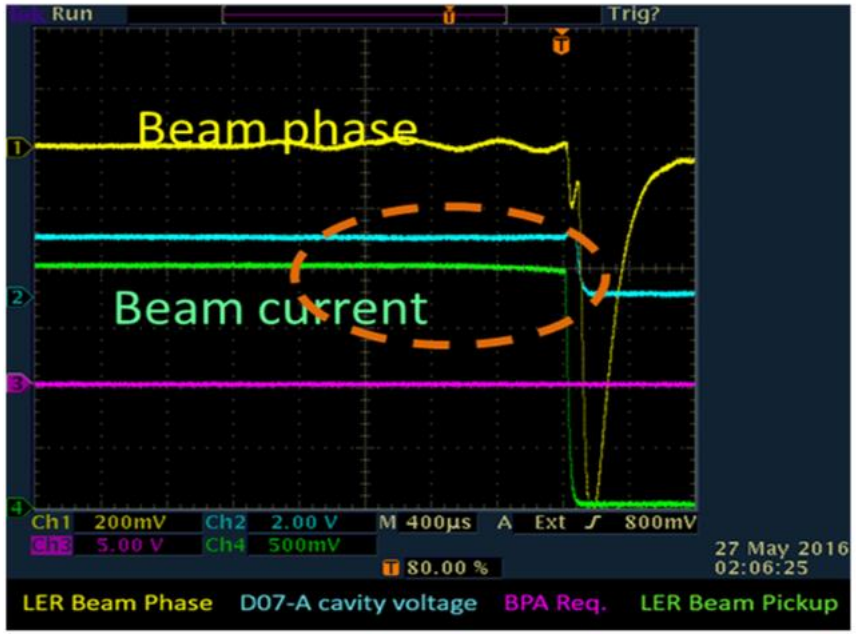
What does this mean?

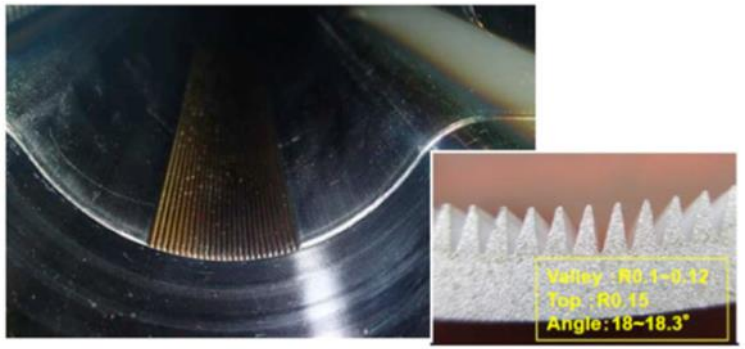
- We're back to the possibilities of dust.

Dust event (our experience)

- At the Phase-1, pressure bursts with beam loss were frequently observed in the LER, which was an obstacle to beam current increase.
  - ➢ When a loss monitor was triggered and issued abort, the pressure momentarily jumps to the 10^{-7}-10^{-6} Pa range in some parts of the ring at the same time.
  - ➢ The beam was lost over several 100 μs, and oscillations in the beam phase were observed.
- Estimating the location of pressure bursts from the CCG indications, most of the pressure bursts occurred in the vicinity of the grooved aluminum beam pipes in the bending magnets.
- The beam current at which pressure bursts occurred increased with the maximum beam current at that time. The frequency of pressure bursts tended to decrease after a while of operation at the same maximum beam current (aging effect).

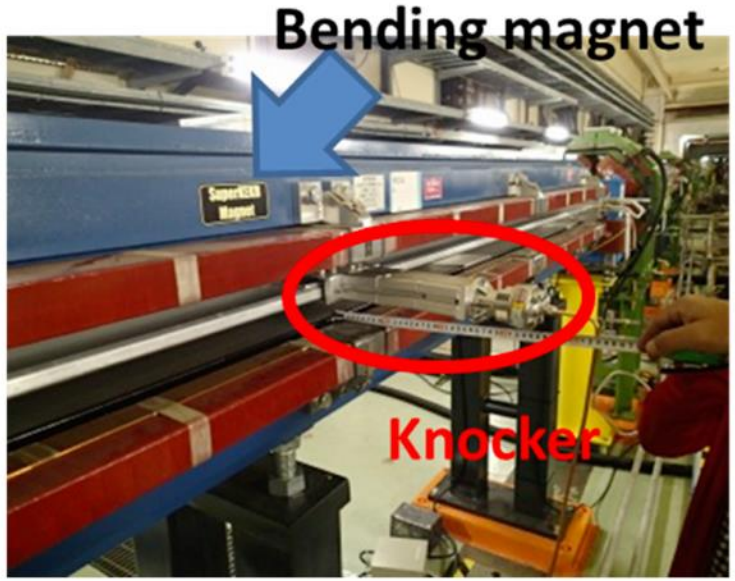


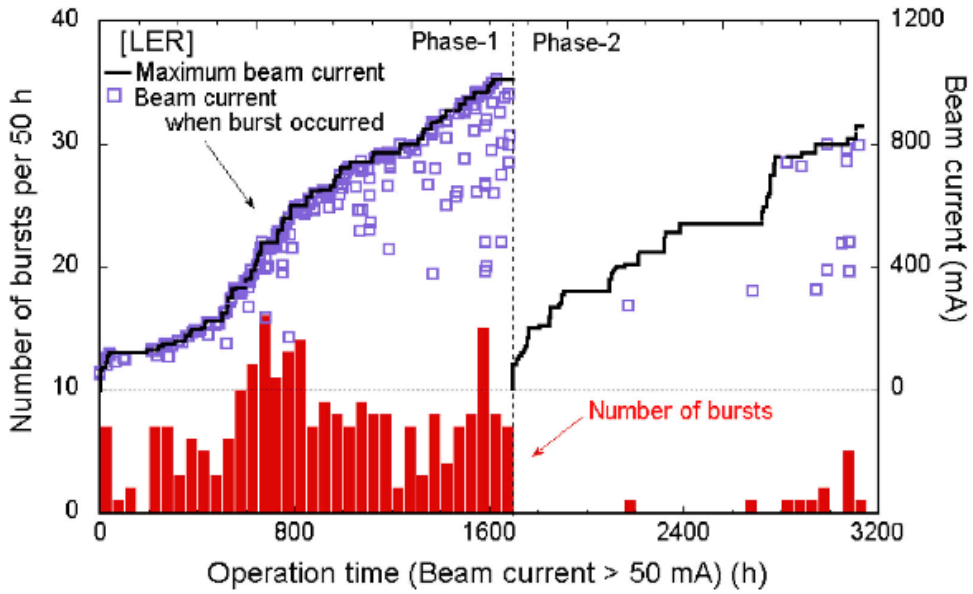




Dust event (our experience)

- We speculated that this phenomenon was caused by dusts trapped in groove structures falling into the beam. To verify this, a knocker was installed in the LER beam pipe.
- When this knocker was operated during beam operation and the beam pipe was struck, the above phenomenon was reproduced.
- As a countermeasure for Phase-2 operation, the grooved aluminum beam pipe was knocked around with a knocker during the shutdown period. As a result, the frequency of pressure bursts with beam loss was dramatically reduced.
- However, the frequency of occurrence has not been reduced to zero. Then, sometimes dust events occur even at low beam currents.





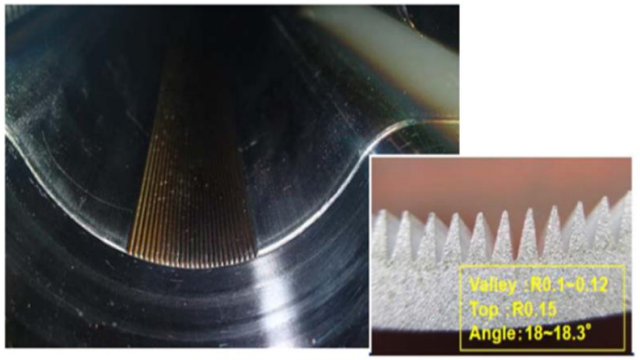
Similarities between SBL and dust event

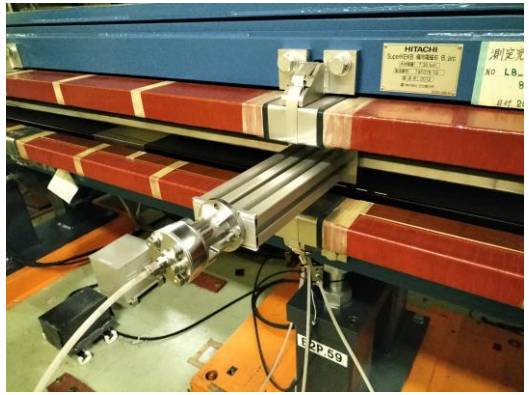
- The frequency of SBL (Sudden Beam Loss) in LER increased after LS1.
  - During LS1, there was vacuum work in about 2/3 of the LER, and dusts may have moved significantly through the beam pipe in that section due to nitrogen purging and pumping, etc.
- Pressure bursts are sometimes observed along with SBLs.
- The beam current that SBL occurs is gradually increasing→Aging effect.

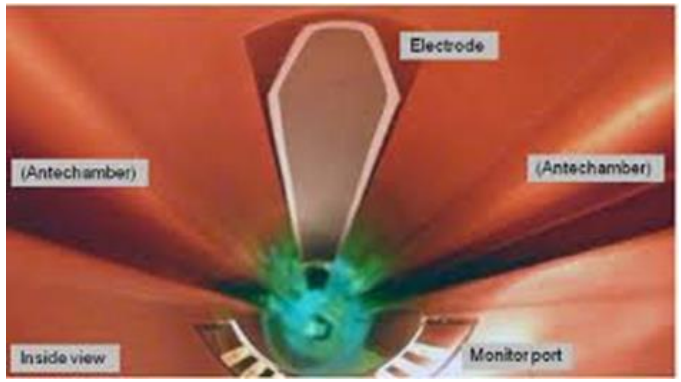
- **However, in the case of dust events, slow beam loss and aborts with oscillations in the beam phase were observed, but no such phenomena were observed in the SBL.**
- However, the abort itself with slow beam loss and oscillations in the beam phase did not occur at all in this phase.
- We thought since there is still a myriad of dusts in the beam pipe, it is also unnatural that no dust events have occurred at all.
  - Is it possible that the SBLs is caused by dusts, and that squeezing the β_y^* has changed the way we see dust events?

3-4. Knocker study

- We reinstalled the knocker to the beam pipe and see how the abort due to the current dust event is observed.
- Knocker installation locations
  - Where there is vacuum work during LS1 and dusts are likely to be re-trapped in the grooves. And where the collimator passes from the Belle II and QCS safety point of dust generation to the IP.
    - ✓ **Aluminum beam pipe with grooves in bending magnet in D06 arc section**
  - A location where pressure often jumps and is suspicious when SBL occurs. And where the collimator passes from the Belle II and QCS dust generation point to the IP for safety reasons.
    - ✓ **Beam pipe with clearing electrode in D10 Nikko Wiggler section** : Electrodes are formed by spraying alumina and tungsten onto copper beam pipes (electrodes are on top of the beam) .

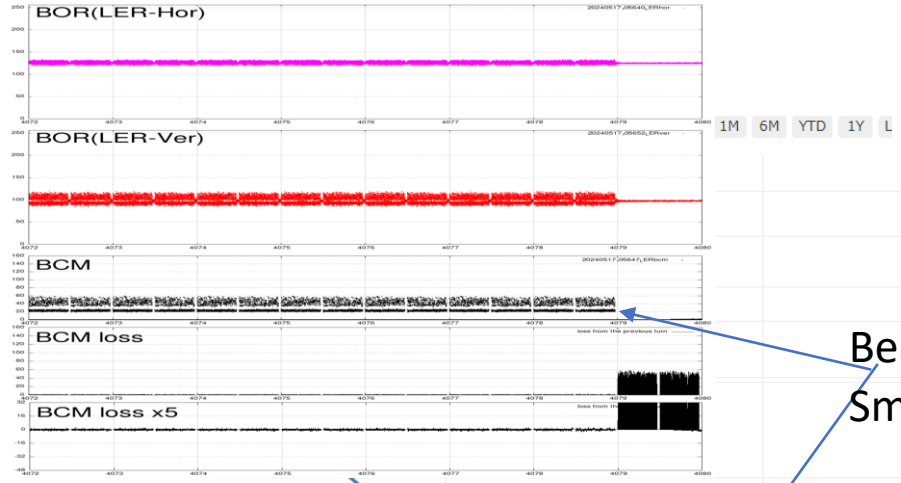






Aluminum beam pipe with grooves

Beam was aborted on the knock count =3.
However, it was not an SBL.
Pressure burst observed.



Later knocks had pressure bursts larger than the pressure burst at abort, but were not aborted.

Beam abort
Small amount of Beam Loss only @ D5V1

Knock count
1,2,3

1->0 is Knock timing

Beam pipe with clearing electrode in D10 Nikko Wiggler section

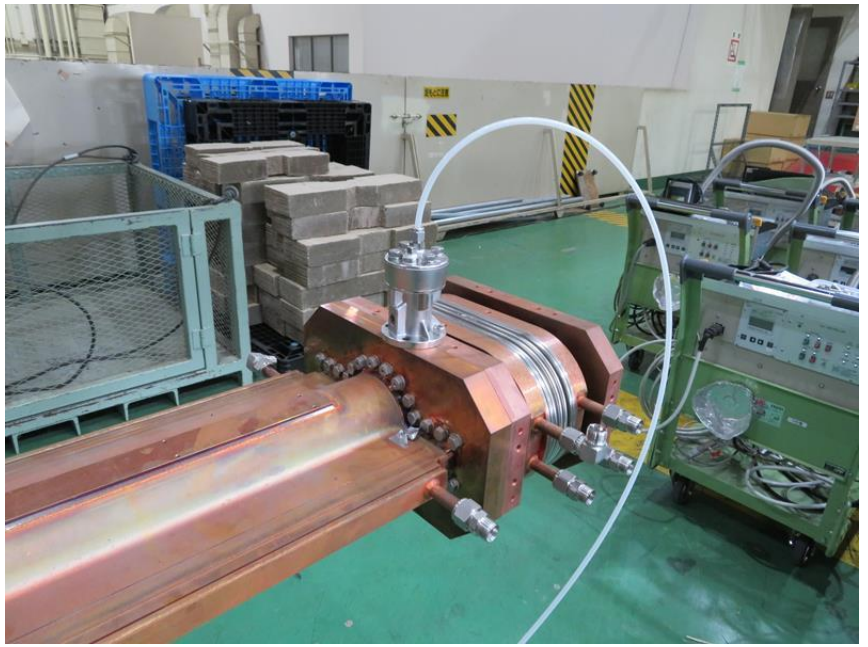
We kept knocking and the abort stopped happening.
Aging effect?

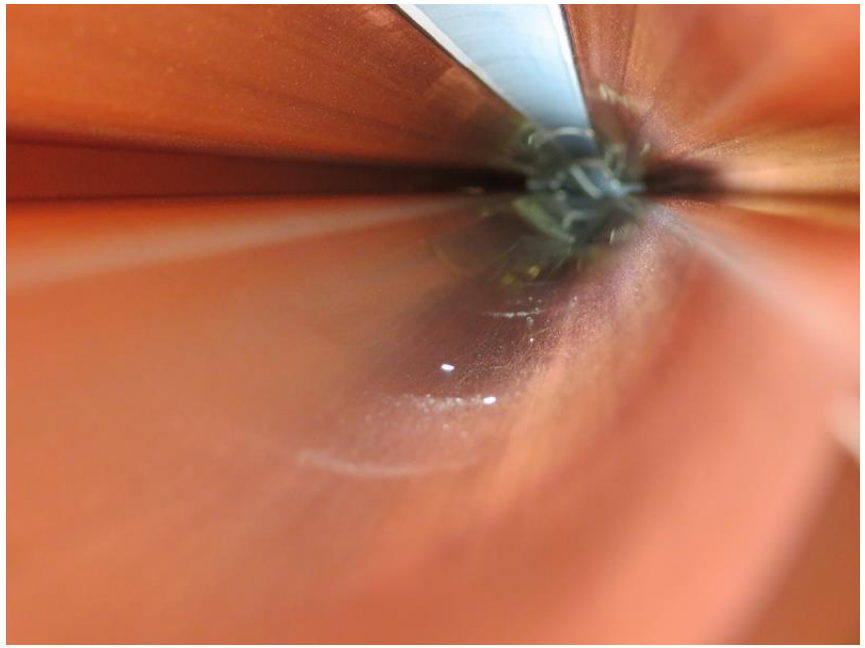
Losses are not proportional to
the amplitude of the pressure burst.

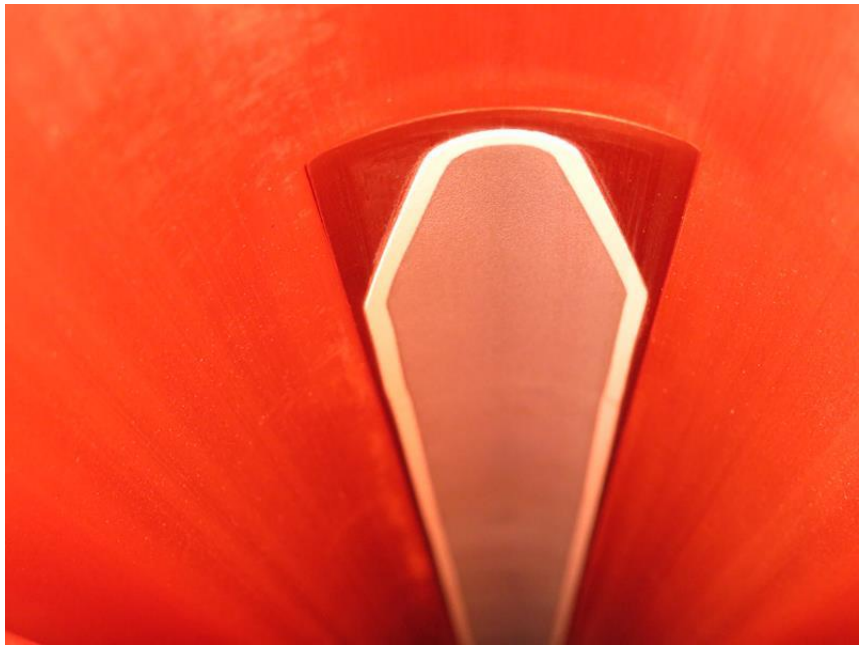
- **Aluminum beam pipe with grooves in bending magnet;**
  - **Abort occurred once but beam loss was small and only in D5V1 collimator.**
  - After continuous knocking only vacuum bursts occurred, but stopped as the knocking continued.
  - No beam abort and pressure burst at knock timing @another beam pipe.
- **Beam pipe with clearing electrode;**
  - Up to 800mA, abort occurred with small amount of beam loss.
  - **SBL Abort occurred with beam loss at all around in the ring by increasing to 1000mA.**
  - After that, the amount of beam loss decreased and eventually vacuum bursts no longer occurred. →**aging effect?**
  - **When the Chamber was changed, SBL Abort occurred even at 500 mA, and then knocked several tens of times, but no aging effect was observed.**
- In both cases, the magnitude of the vacuum burst is not particularly proportional to the magnitude of Beam Loss.
- We checked the current dependence by knocking. →At low currents, even if an Abort occurs, it did not reach SBL.

There seems to be a problem with the beam pipe with clearing electrode, so the vacuum group investigated in the experimental room with test-chamber（Chamber with electrodes taken out from tunnel at LS1).

Dust from chamber gotten by knocking was sent for chemical analysis, but no tungsten was detected in the dust.

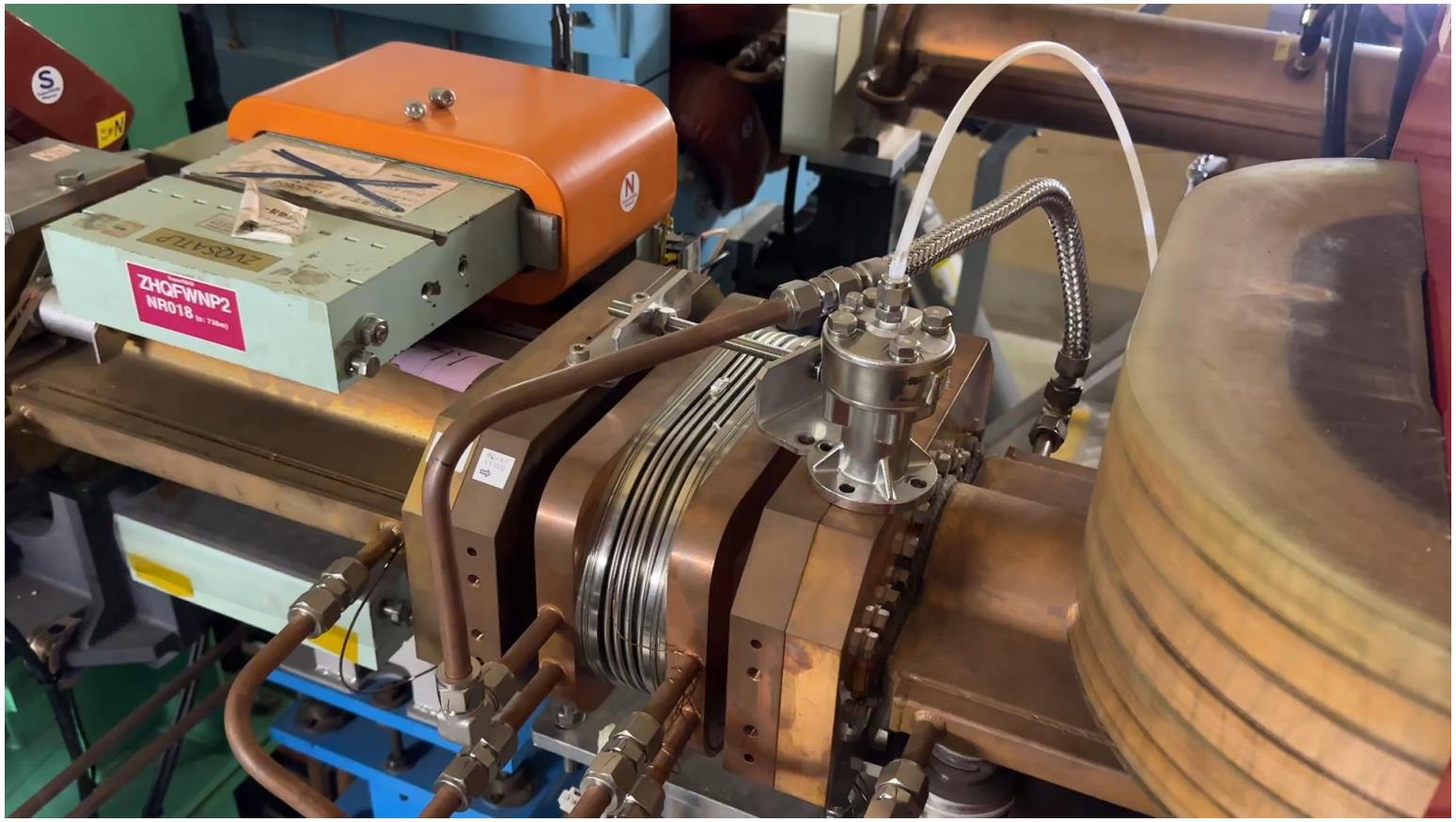






- We knocked the D10（almost）/D11(3)　wiggler chamber with a knocker (about 100 times each) at maintenance day (5/29) to remove as much dust as possible.

→If it works and we get less serious SBL, we may knock on other places too.

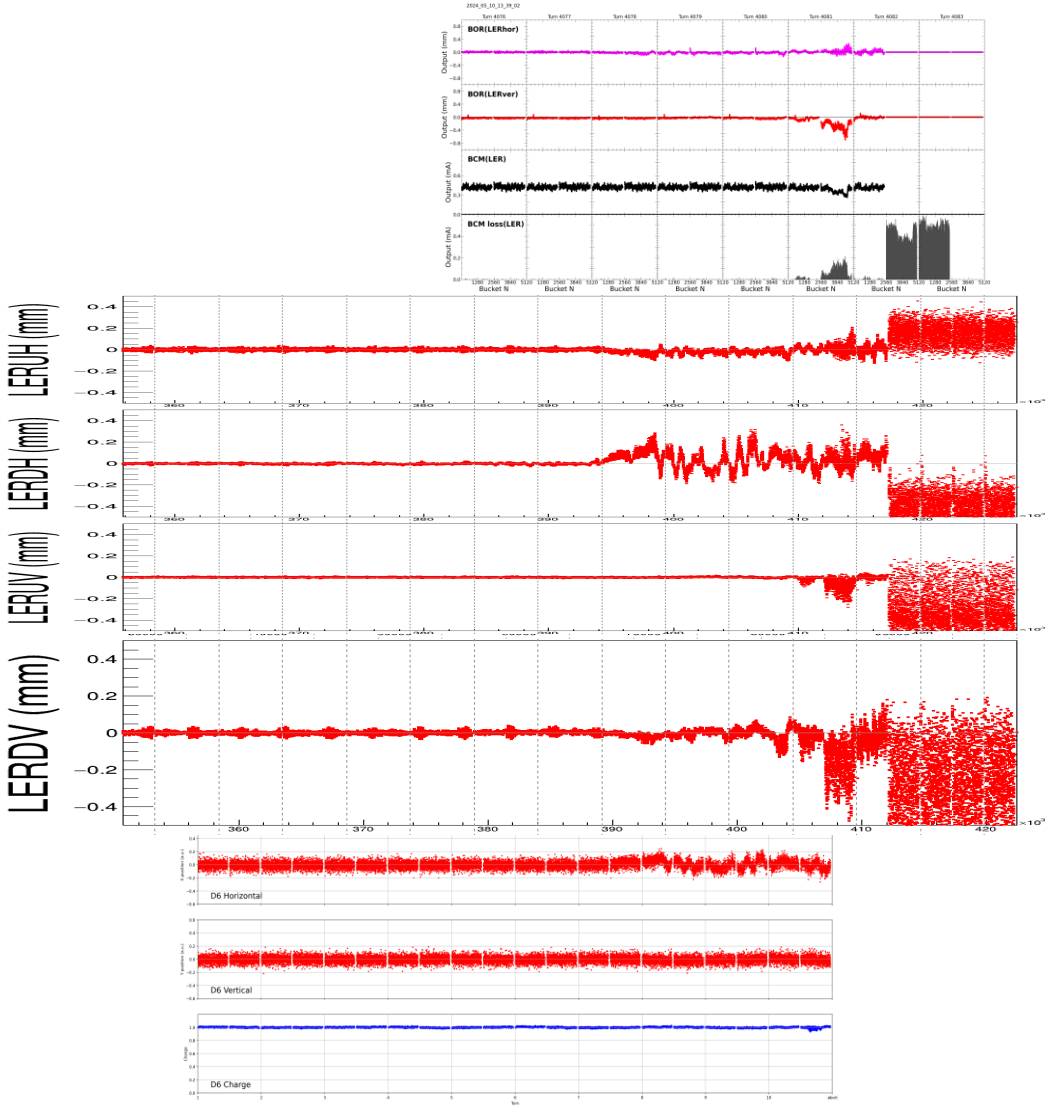


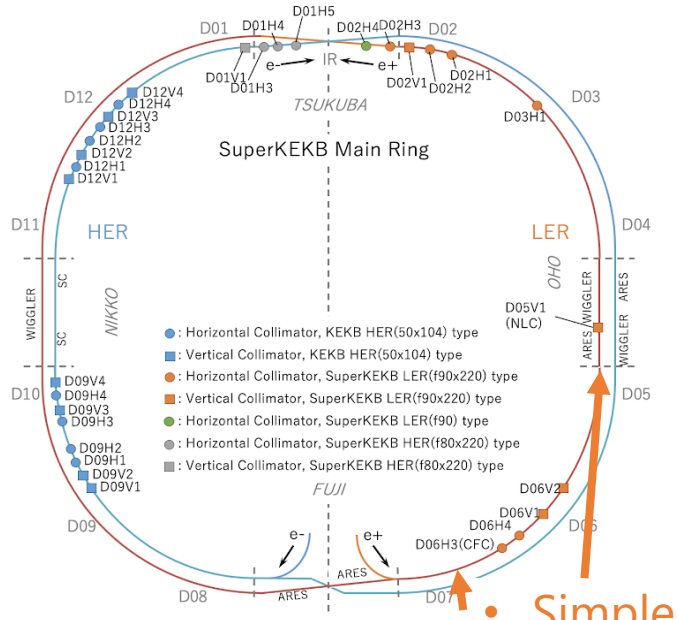
4. Summary

- SuperKEKB has beam instrumentation system for beam diagnostics.
- We had been suffering from “SBL” before LS1, and were working hard to find out the cause using a beam diagnostic system.
- Although the mechanism is still unclear, there are signs of a causal relationship between dust and SBL.
- The observed event depends on the type of dust, the location where it falls, and the beam current.
- There seems to be a problem with the beam pipe with clearing electrode, so the our investigation underway.

backup

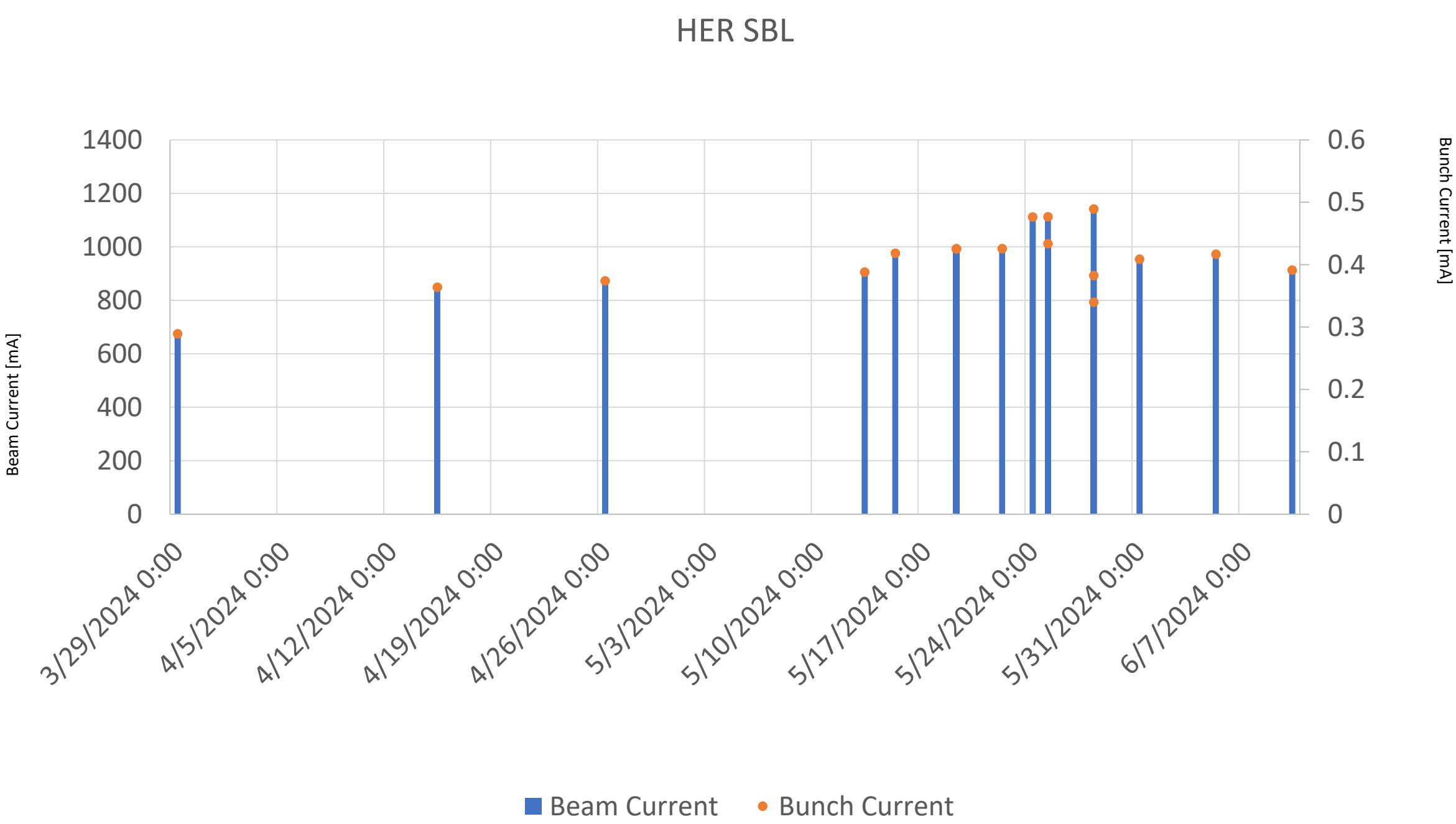
BOR&BCM signal





- Simple
- BOR
- iGp
- RFSoC

2024-05-10 13:39:02 LER SBL event


HER SBL
Beam Current [mA]
Bunch Current [mA]
1400
1200
1000
800
600
400
200
0
0.6
0.5
0.4
0.3
0.2
0.1
0
3/29/2024 0:00
4/5/2024 0:00
4/12/2024 0:00
4/19/2024 0:00
4/26/2024 0:00
5/3/2024 0:00
5/10/2024 0:00
5/17/2024 0:00
5/24/2024 0:00
5/31/2024 0:00
6/7/2024 0:00
Beam Current
Bunch Current

Works during LS1

To Mitigate SBL

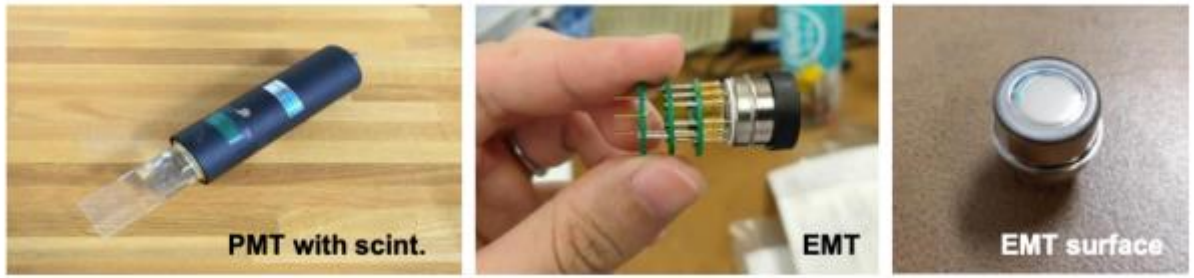
- Replaced damaged collimator heads.
- Copper coating of collimator heads .（Cover material with a high sublimation point, which could be the seed of a fireball, with material with a low sublimation point.)
- Installed permanent magnets in all SuperKEKB-type horizontal collimators.（In order to reduce the electron cloud effect…）

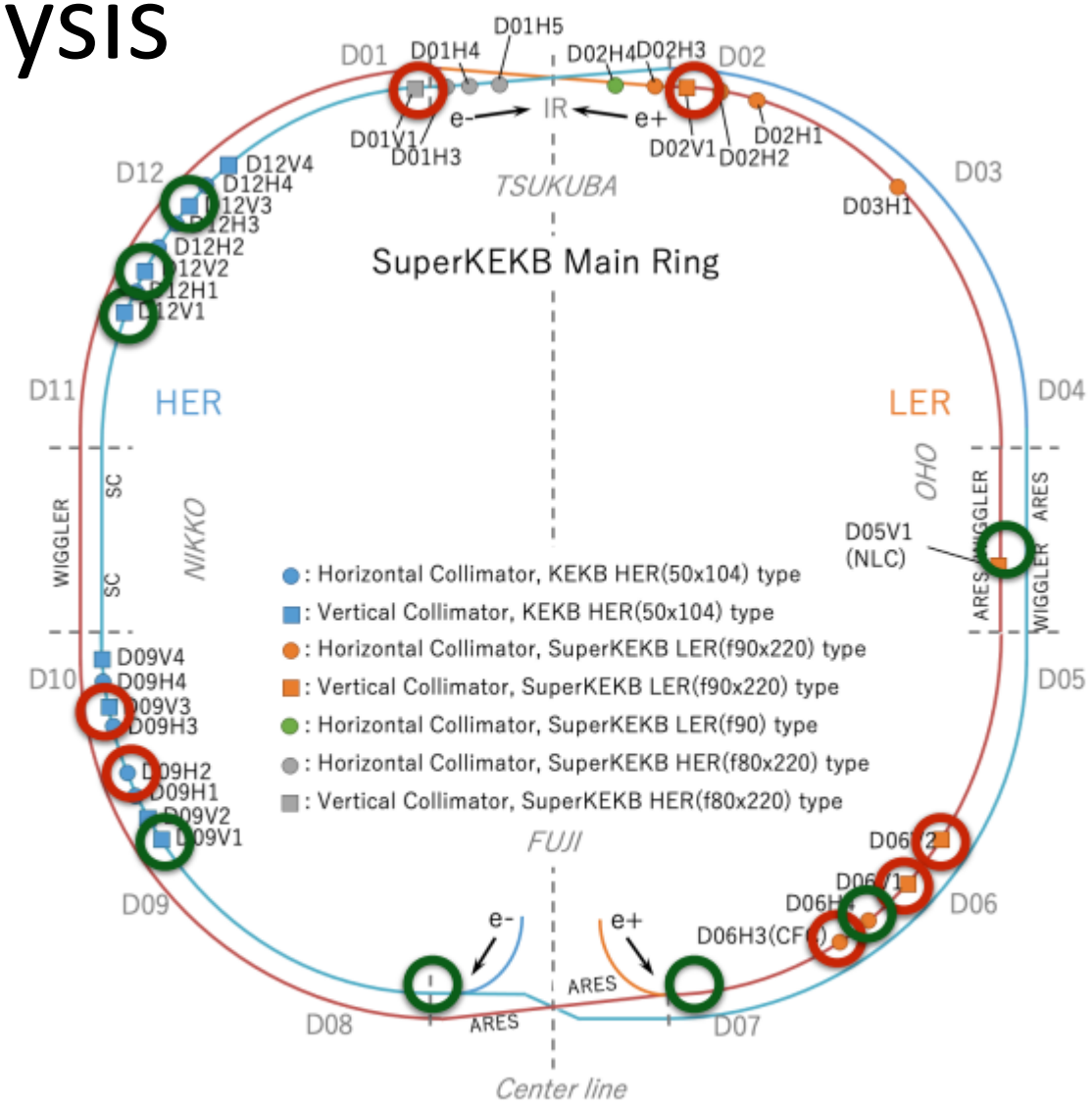
To Investigate the cause of SBL

- Installed more loss monitors for timing analysis.
- Added BORs (Bunch Oscillation Recorders) 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
- Installed acoustic sensors to detect acoustic waves due to thermal shock generated by vacuum arc for investigation the cause of LER SBL.

Loss Monitor for Timing analysis

- To gain more information about beam aborts, especially SBL, some PMT/EMT are installed during LS1.
- We shall analysis the waveform of each sensors to determine the signal time and synchronize all the sensors.



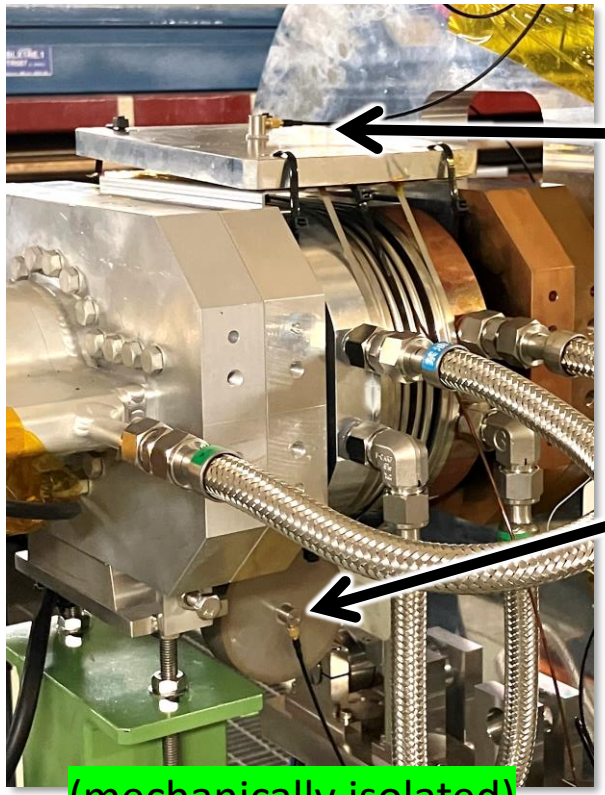


Installation in LS1
Installation before LS1

Acoustic-Emission Sensors for D02V1 collimator

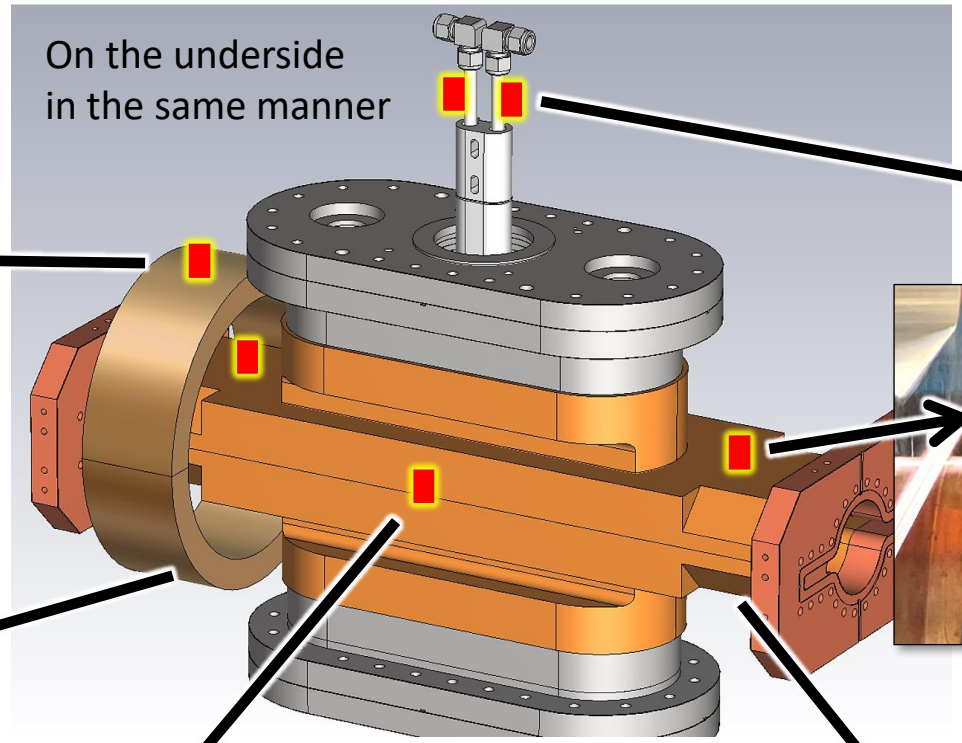
I. Okada,
K. Uno, and
T. Abe

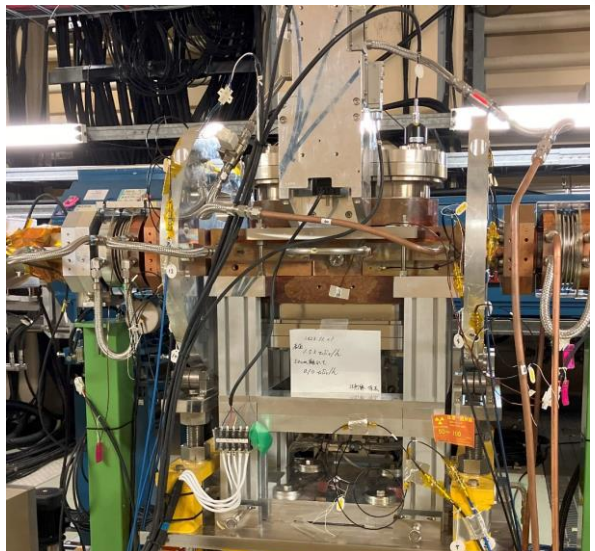
Acoustic loss monitor

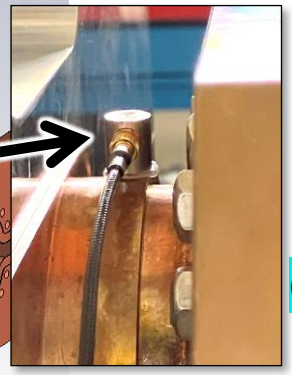


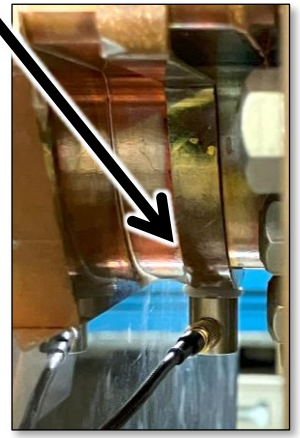
(mechanically isolated)

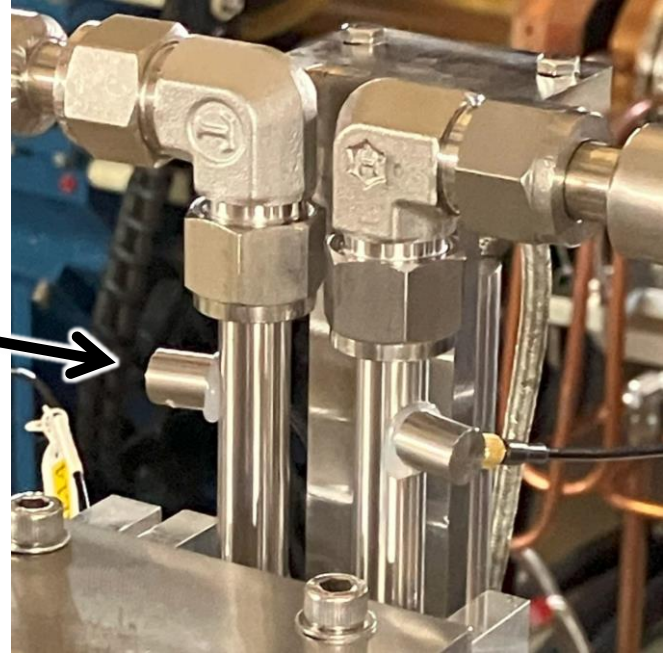
Can hear particle showers



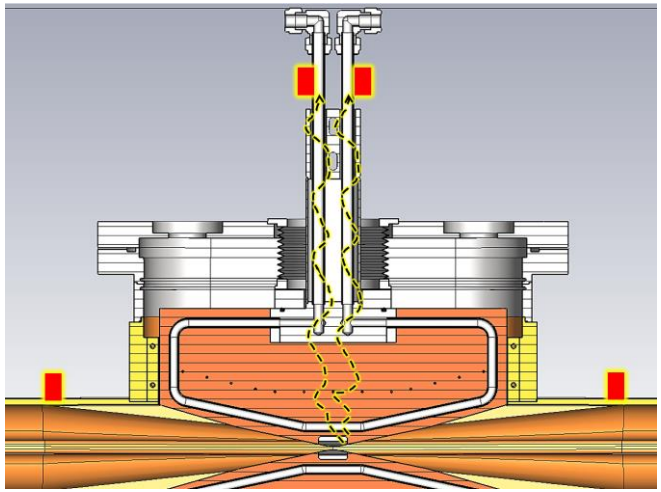








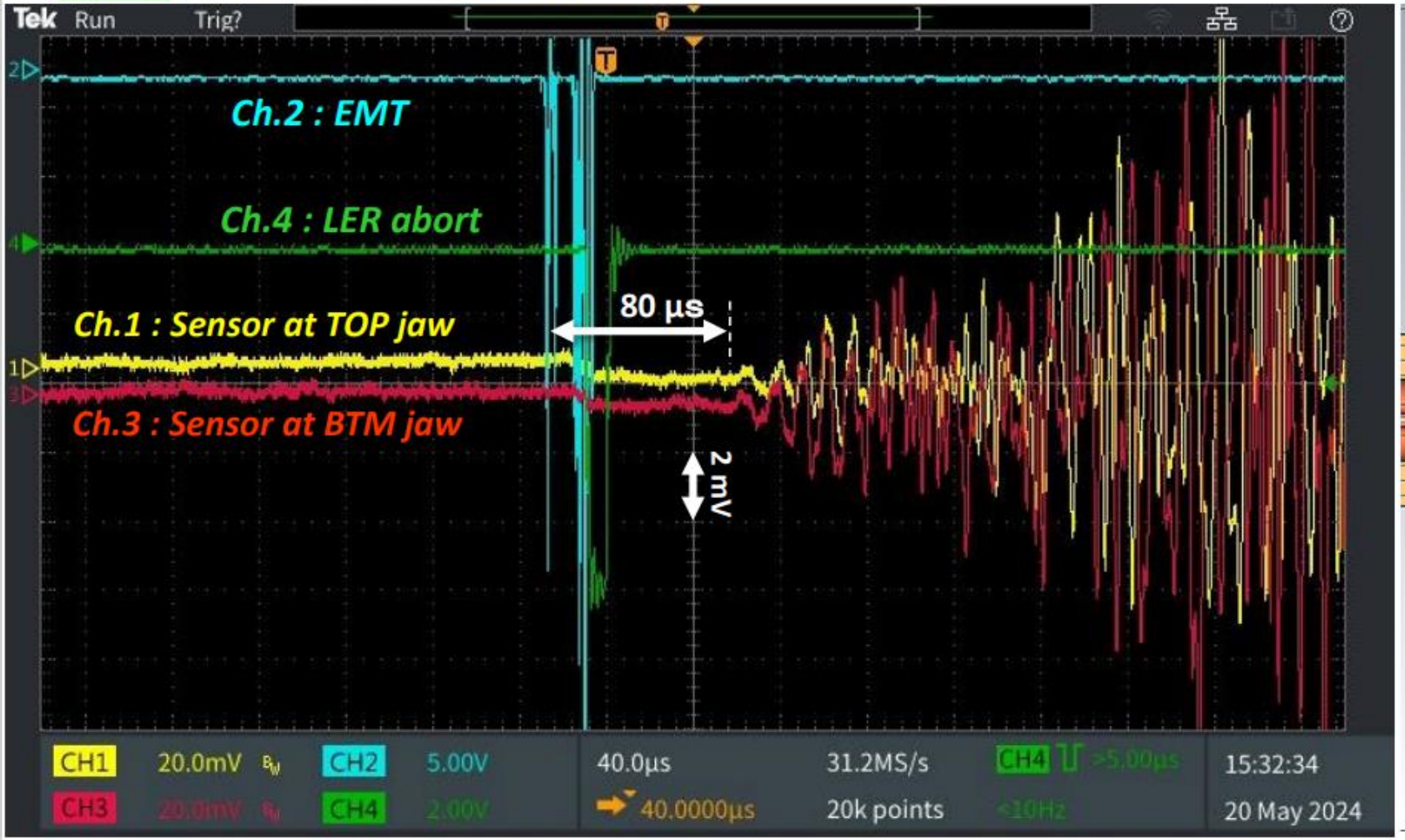
Can hear AE around the head.

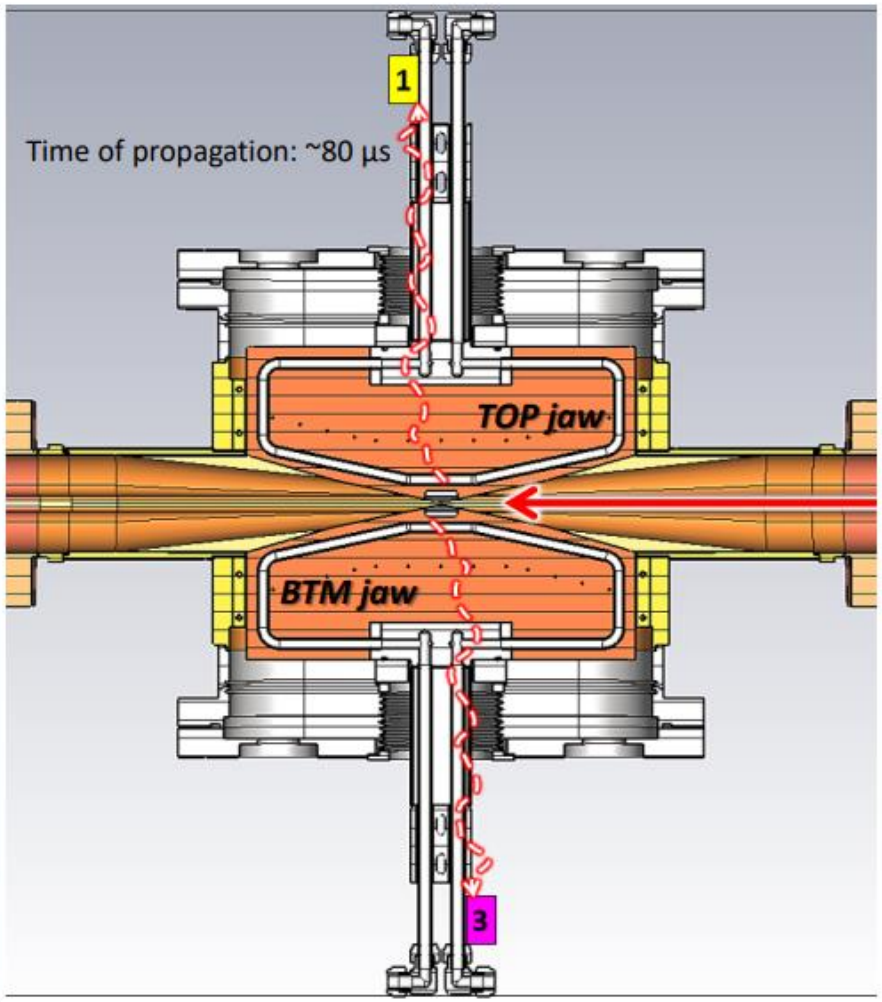


In the same manner for D05V1 collimator (NCL)

Example of typical acoustic waves (1/2)

At **D06V2**, LER SBL at 2024-05-20 15:32





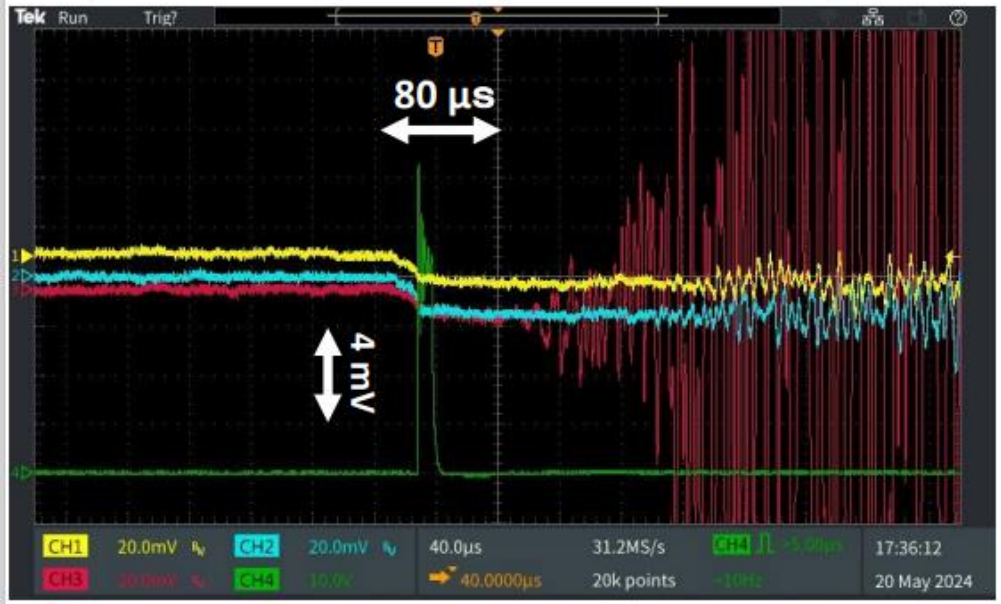
- ✓ The start of the acoustic-wave detection is consistent with the time of propagation (~80µs), where the acoustic-wave generation is understood to be caused by **LER beam particles impacting the head**
- ✓ The simultaneous start of waves at both the TOP and BTM means that the beam was **vertically spreaded**.

(D06V2 TOP: +1.94 mm, BTM: -2.72 mm at 2024-05-20 15:32)

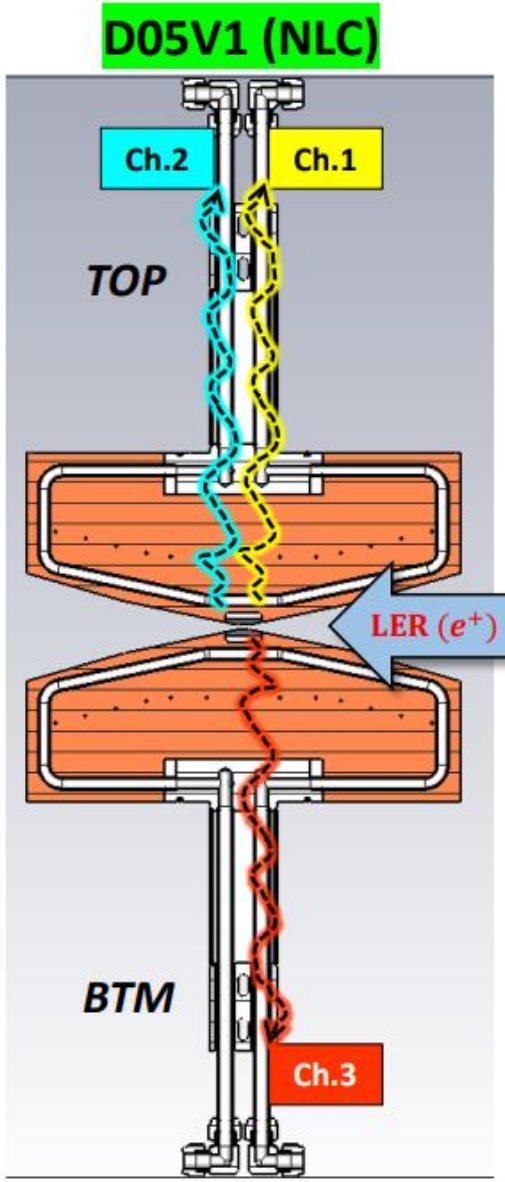
(T. Abe)

Example of typical acoustic waves (2/2)

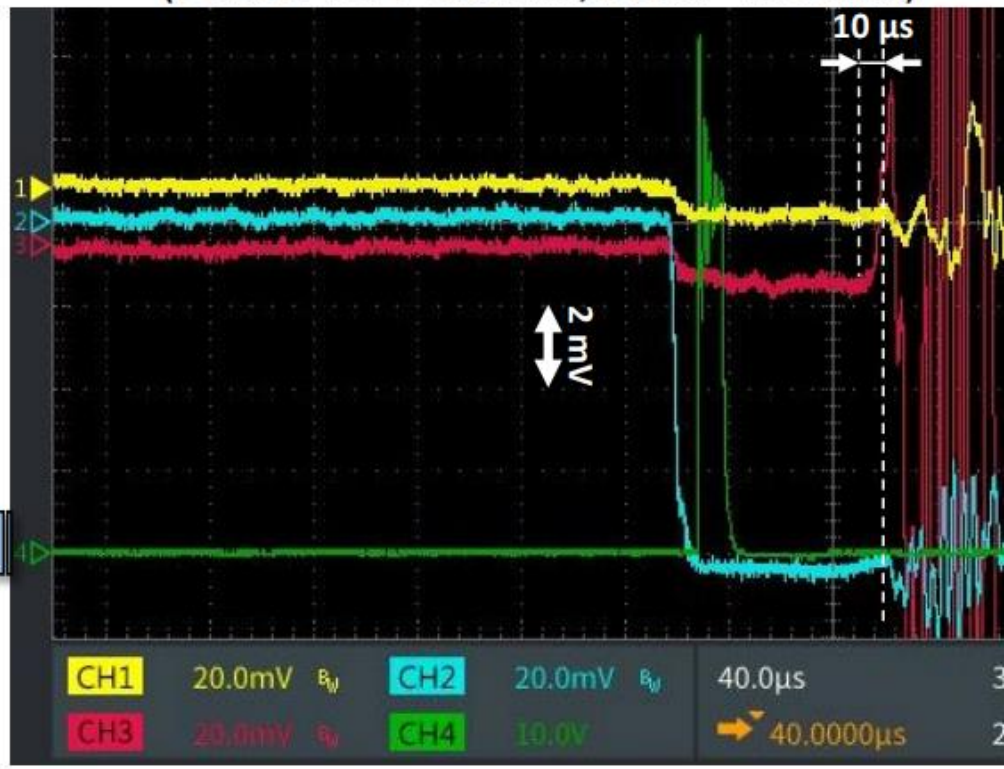
LER SBL at 2024-05-20 17:35
(D05V1 TOP: +10 mm, BTM: -4.54 mm)



Significant wave only from BTM,
which means the beam was **vertically spreaded**,
then dumped by the LER beam abort system



LER SBL at 2024-05-21 18:38
(D05V1 TOP: +10 mm, BTM: -4.78 mm)



Significant wave from BTM,
followed by one from TOP after 10 µs,
which means the beam was **vertically spreaded**,
then **horizontally spreaded** in the next turn
before dumped by the LER beam abort system

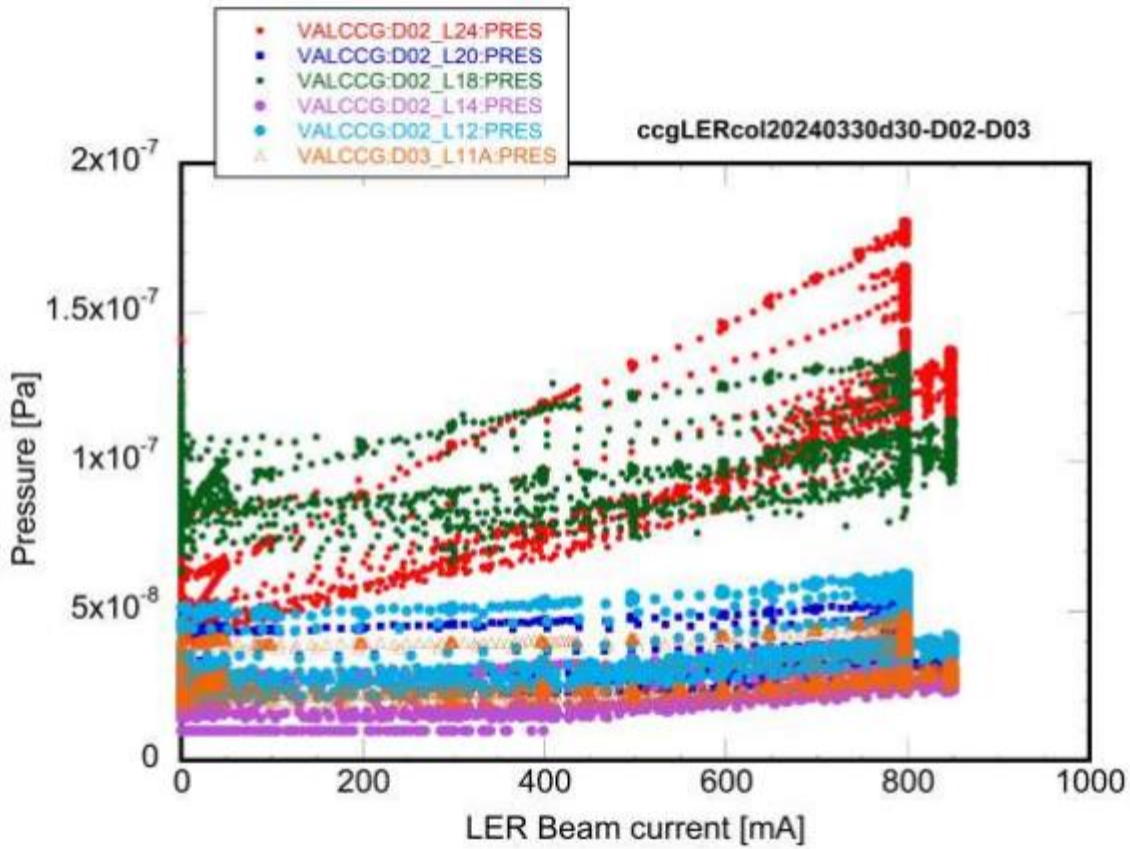
We can know the beam status from the acoustic observation.

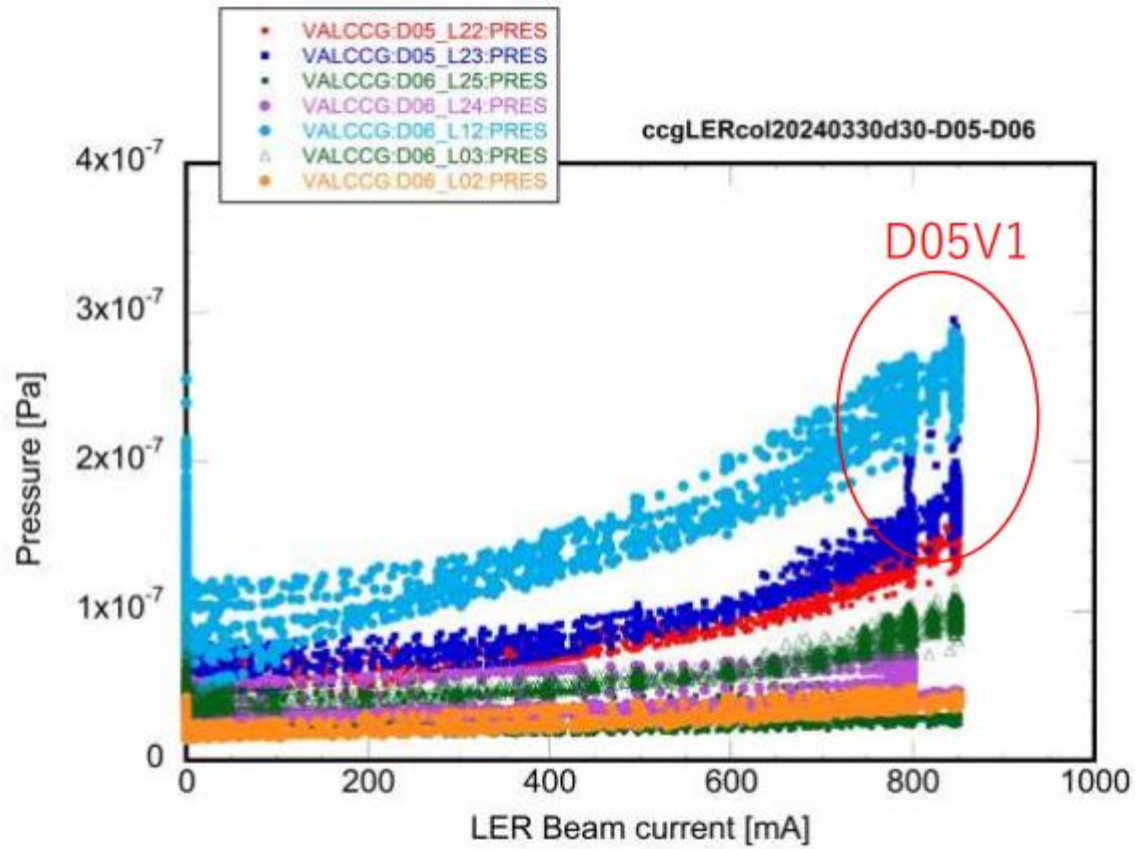
(T. Abe)

LER

2024/3/28-3/30

CCG	Collimator	CCG	Collimator
D02_L24	D02H4	D05_L22, L23	D05V1
D02_L20	D02H3	D06_L25, L24	D06V2
D02_L18	D02V1	D06_L12	D06V1
D02_L14	D02H2	D06_L03	D06H4
D02_L12	D02H1	D06_L02	D06H3
D03_L11A	D03H1		



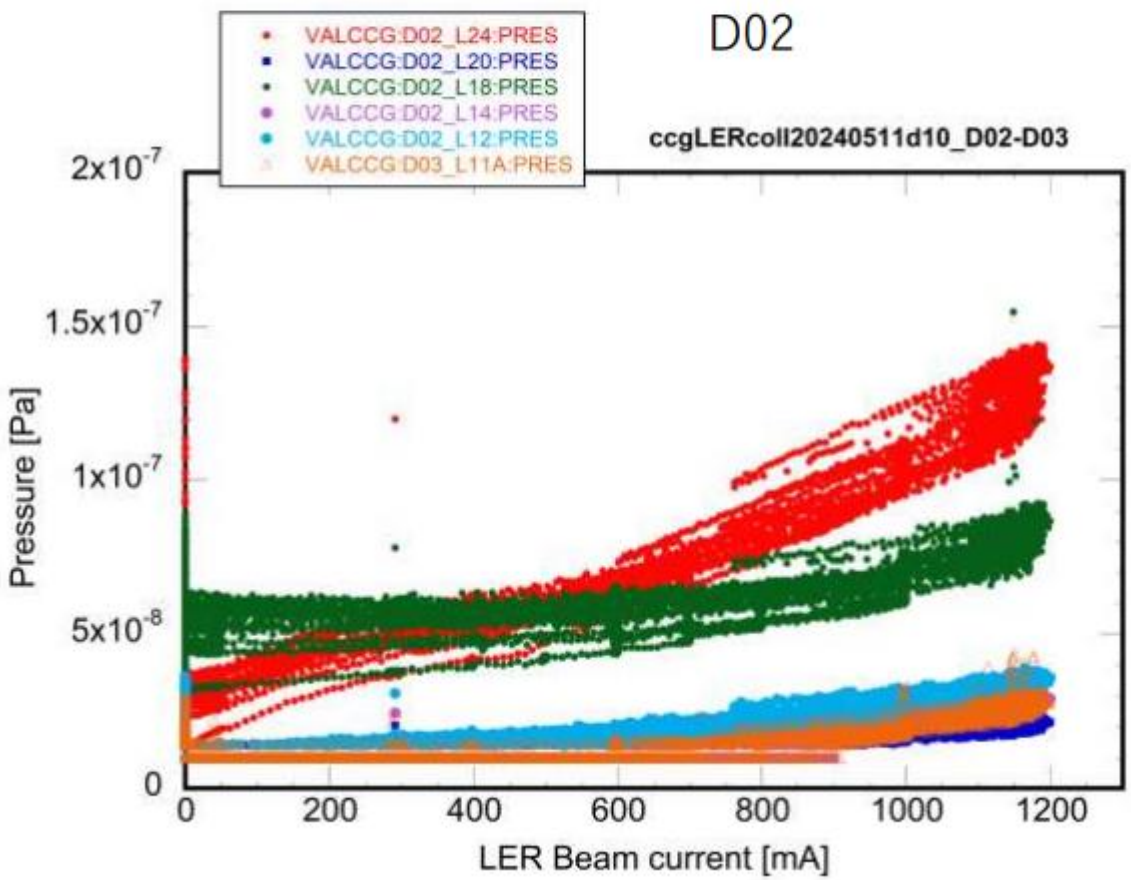


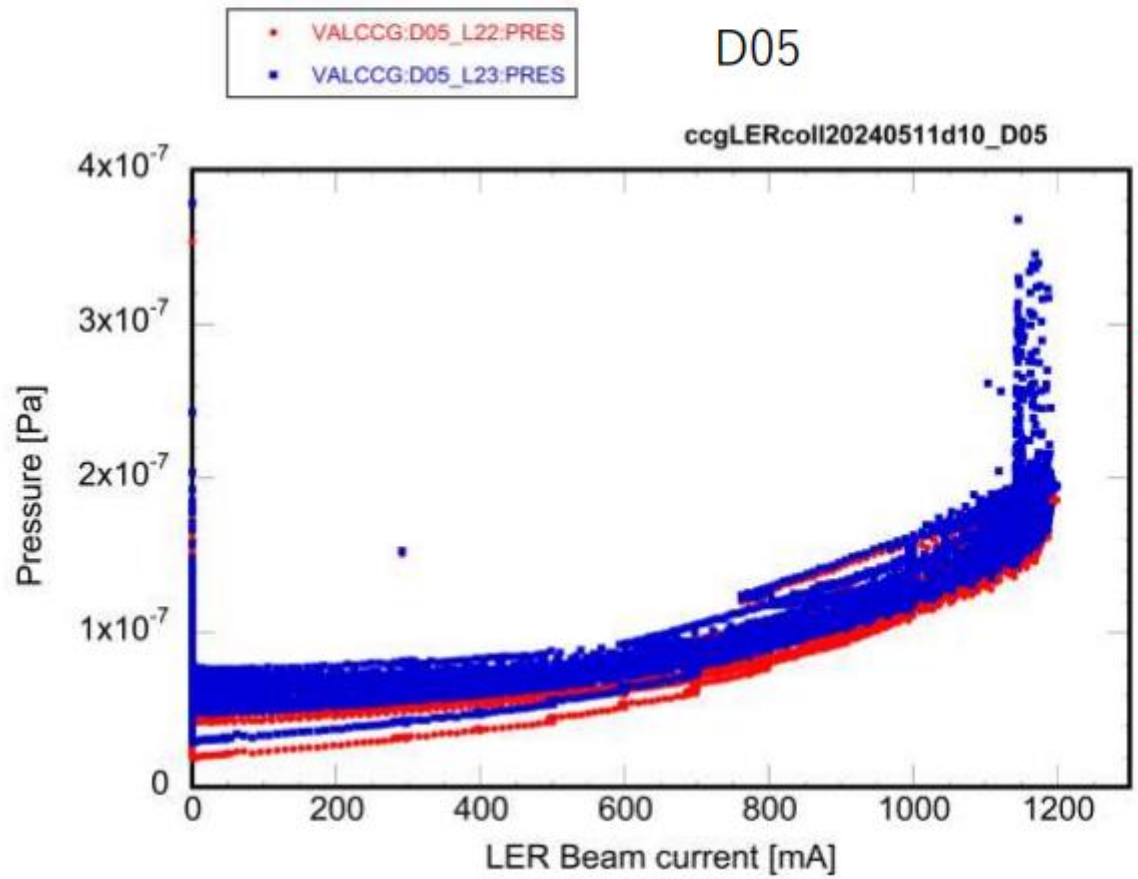
(Y. Suetsugu)

LER

2024/5/8-5/11
Nb = 2346

CCG	Collimator	CCG	Collimator
D02_L24	D02H4	D05_L22, L23	D05V1
D02_L20	D02H3	D06_L25, L24	D06V2
D02_L18	D02V1	D06_L12	D06V1
D02_L14	D02H2	D06_L06	D06H4
D02_L12	D02H1	D06_L03	D06H3
D03_L11A	D03H1		





(Y. Suetsugu)

LER

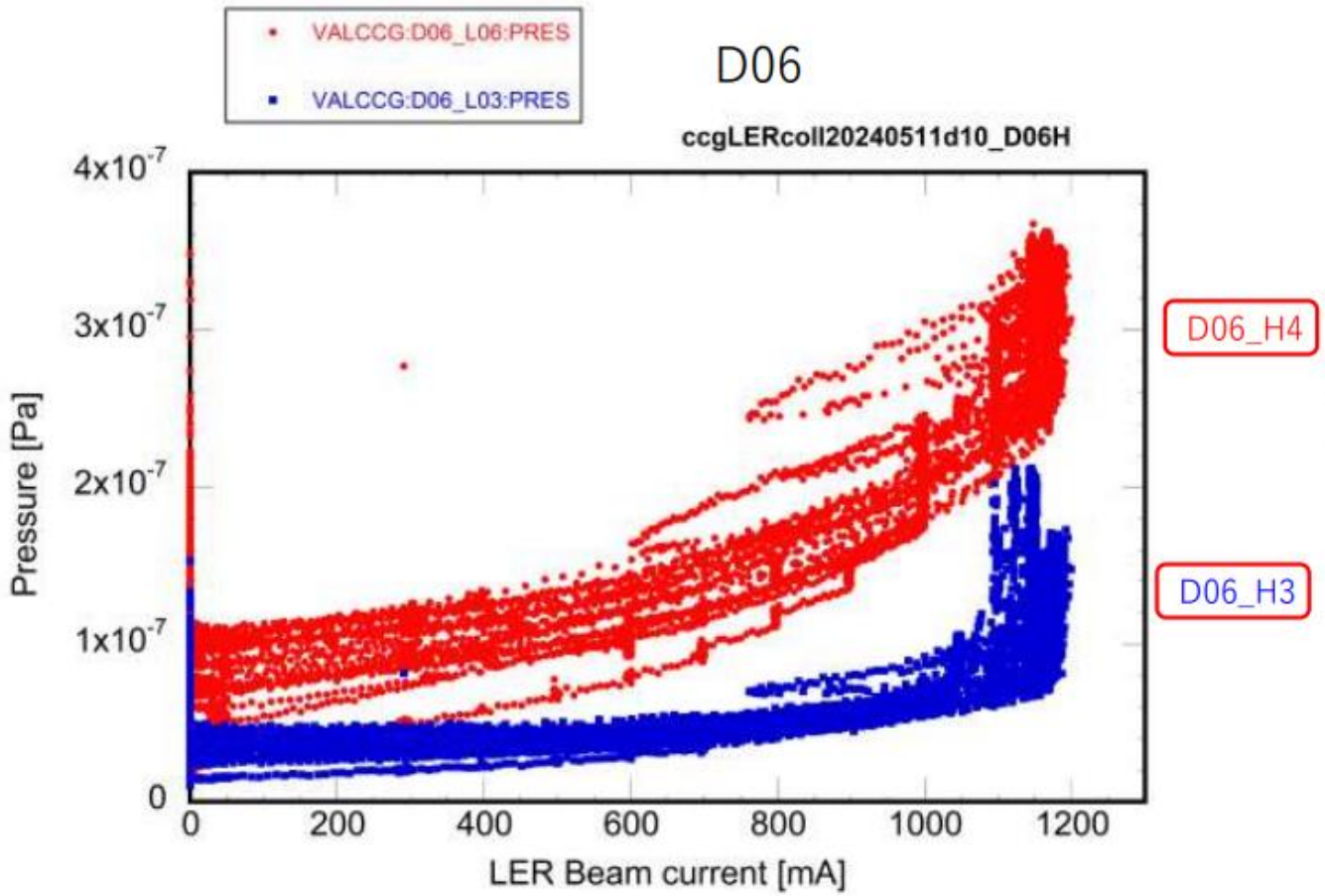
2024/5/13-5/15
Nb = 2346

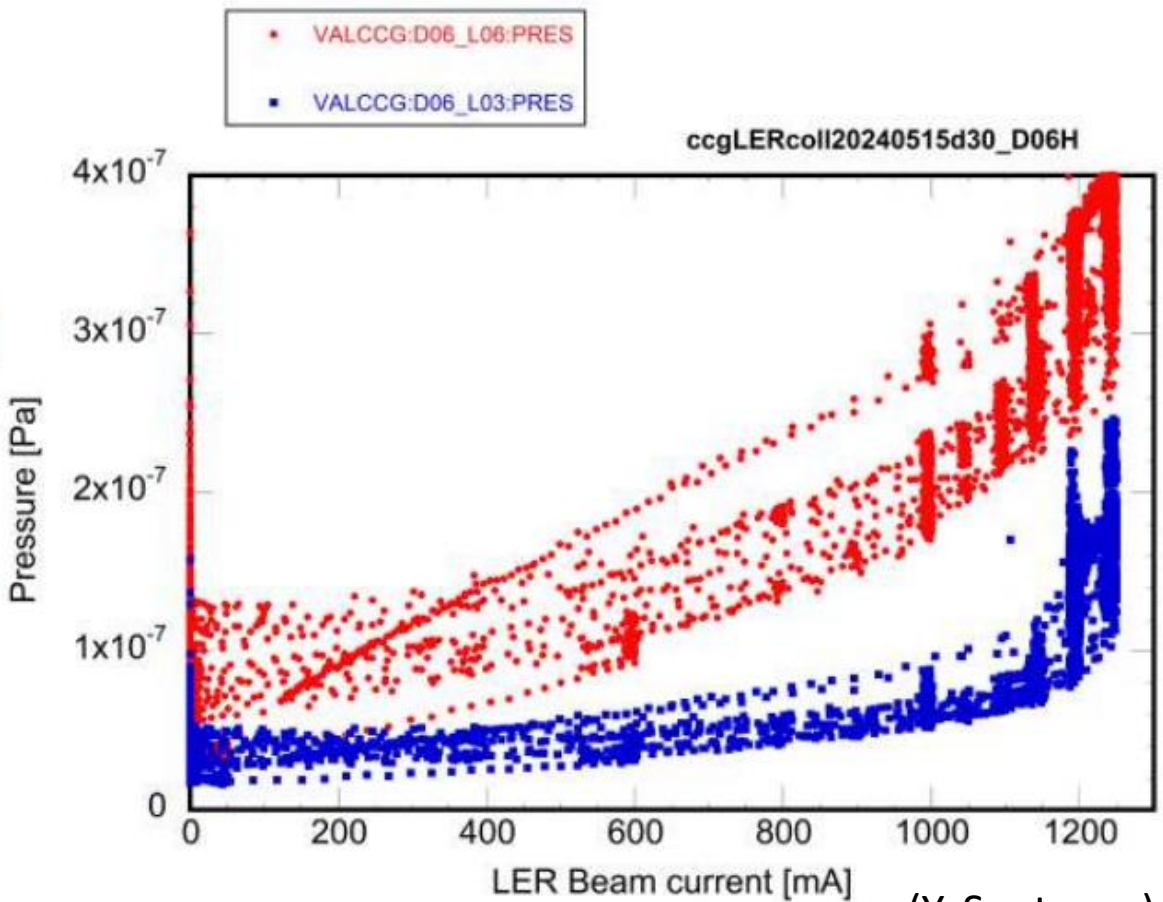
D06_H3はまだエージングが進んでいるよう

CCG	Collimator	CCG	Collimator
D02_L24	D02H4	D05_L22, L23	D05V1
D02_L20	D02H3	D06_L25, L24	D06V2
D02_L18	D02V1	D06_L12	D06V1
D02_L14	D02H2	D06_L06	D06H4
D02_L12	D02H1	D06_L03	D06H3
D03_L11A	D03H1		

前回のプロット

D06

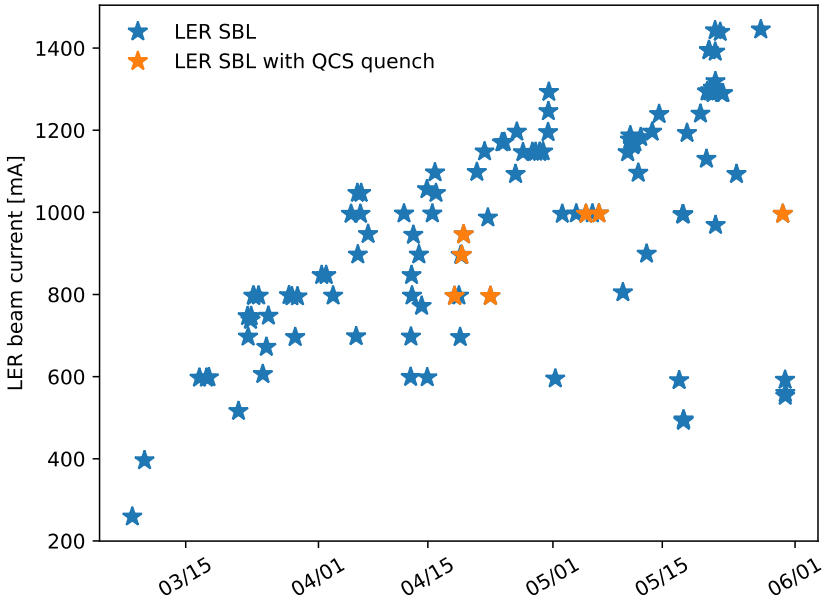




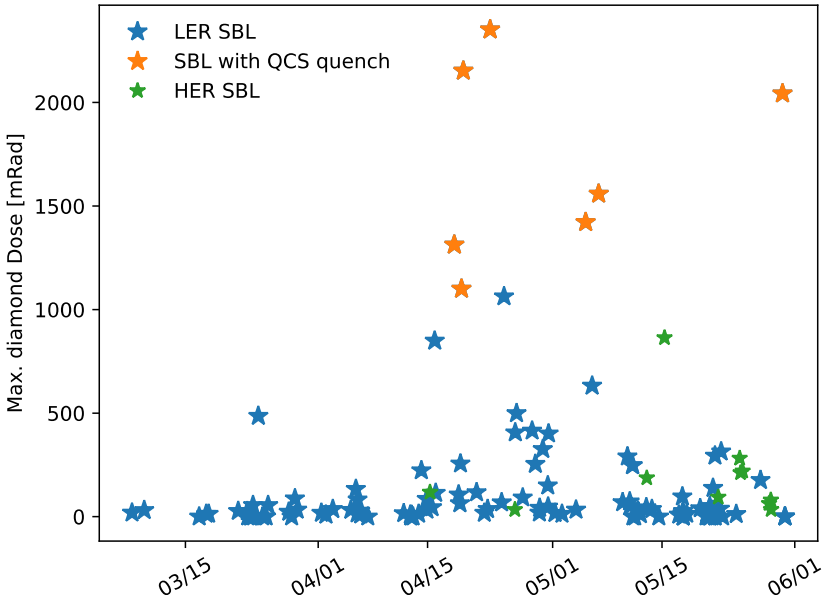
(Y. Suetsugu)

SBL: Mar.1st – June. 2nd

118 LER SBLs (incl. SBL with QCS quench) + 11 HER SBLs



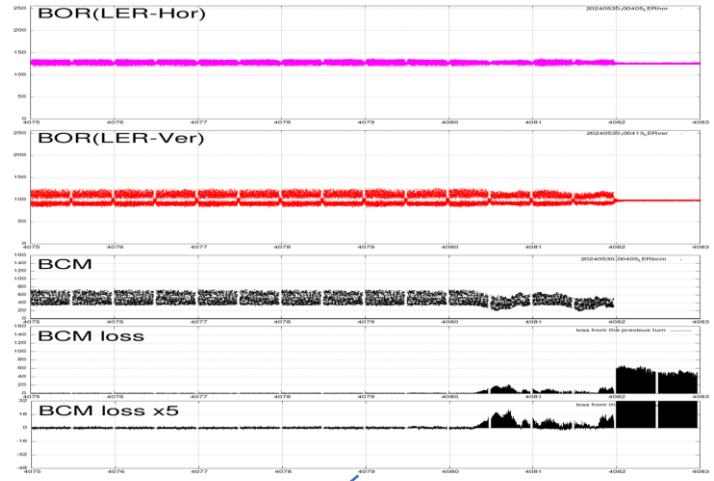
I_{LER} [mA]	#LER SBL
[0.0, 300]	1
[300,500]	4
[500,800]	34 (incl. 2 quench)
[800,1000]	27 (incl. 5 quench)
[1000, 1200]	31
[1200,]	21



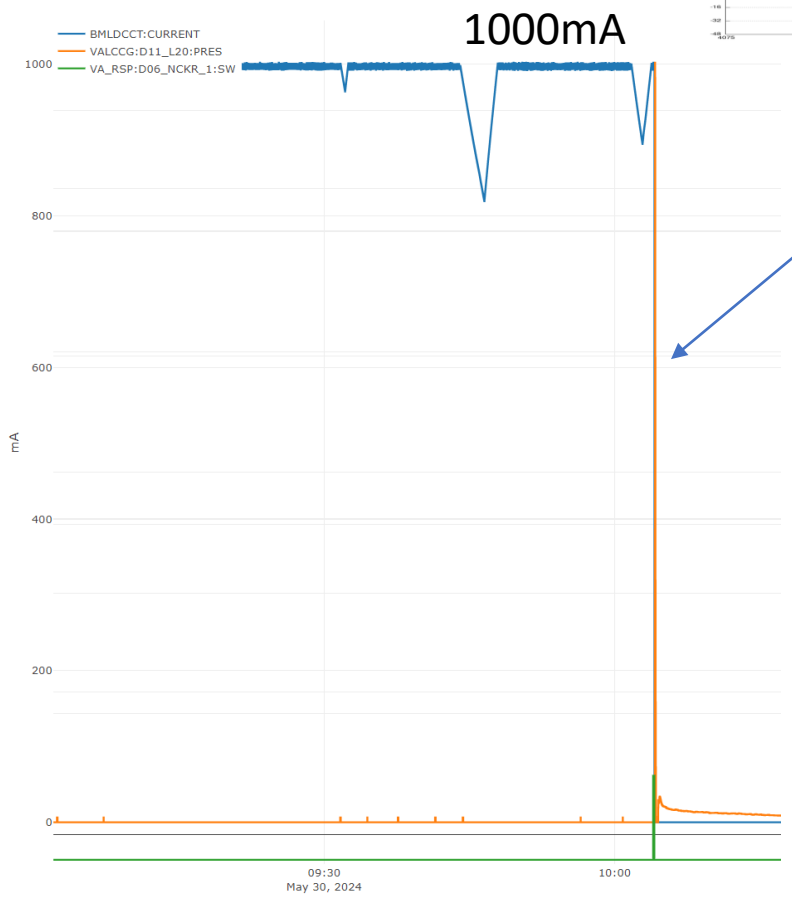
Max. Dose [mRad]	#LER SBL	May.9th※ -
[0.0, 100]	87	38
[100,300]	14	6
[300,500]	7	1
[500,800]	1	0
[800, 1000]	1	0
[1000,]	8	1 ← Knocker study

※ Closed LER horizontal collimators on May 9th

Current dependence

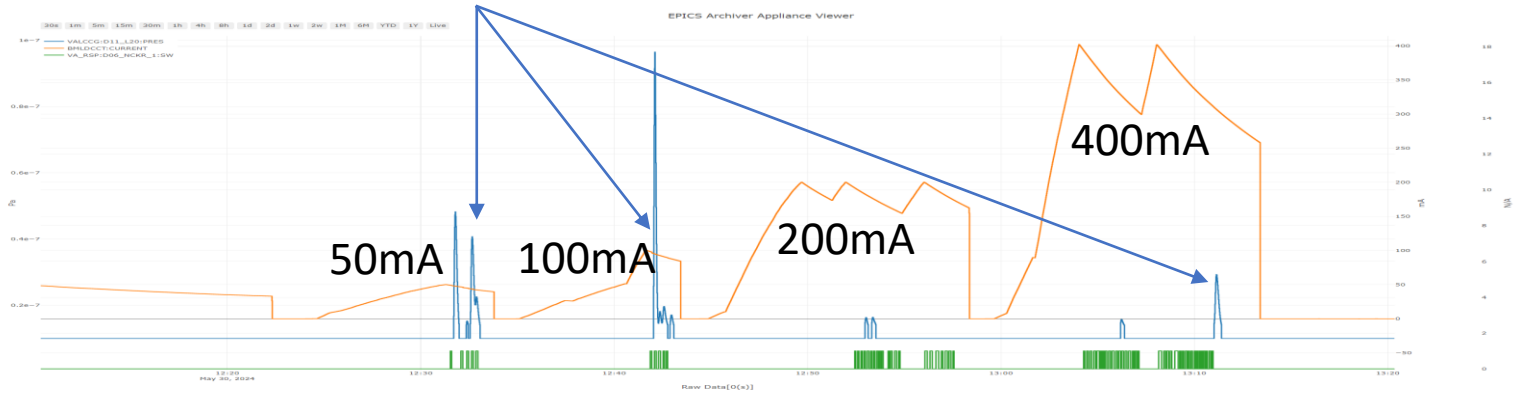


SBL and QCS quench occurred @1000mA .
Pressure bursts were observed at any current without beam abort request.



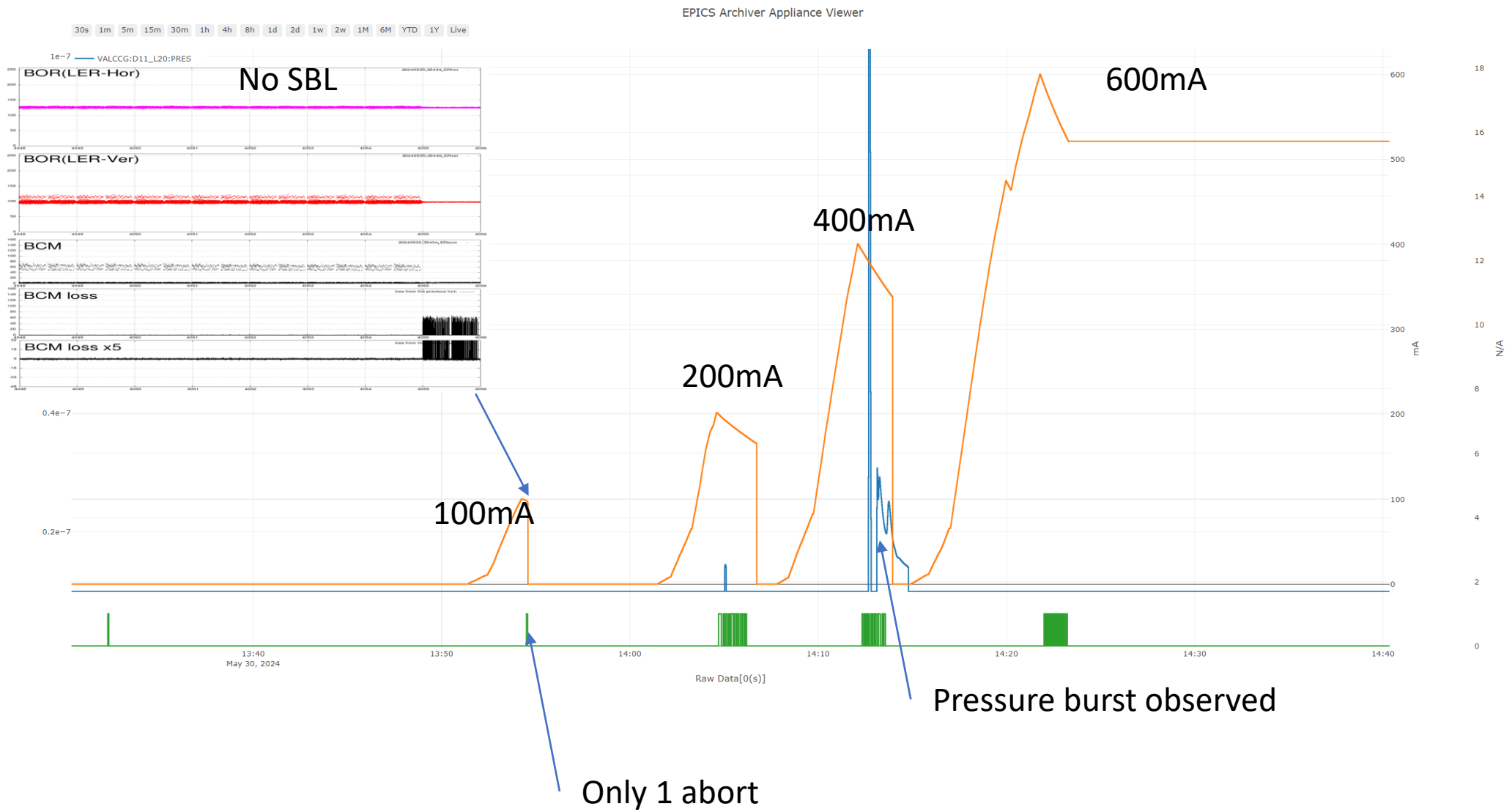
Maybe aging observed

Pressure burst observed



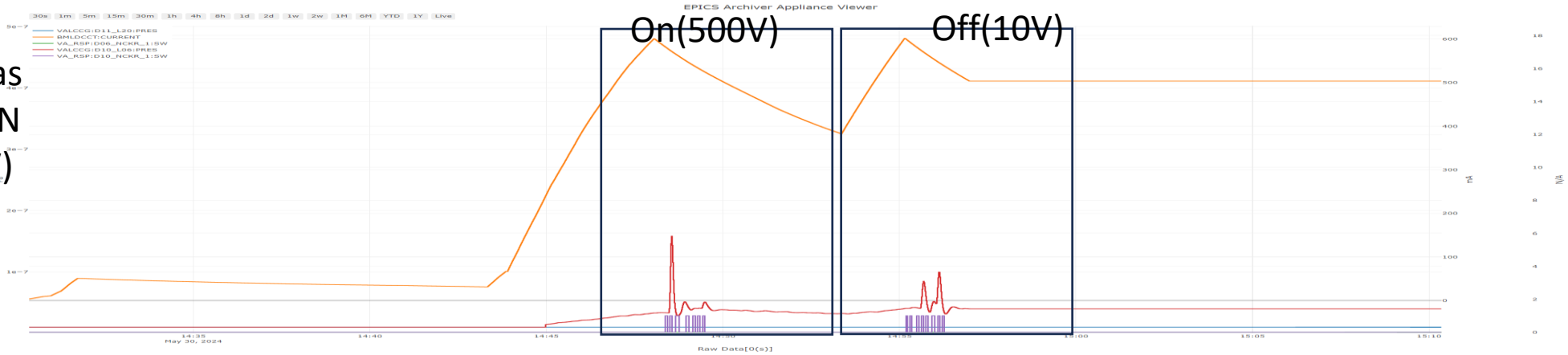
Current dependence next chamber

Abort（not SBL）@100mA.
Pressure burst @ 400mA,
After that, the pressure burst disappeared.

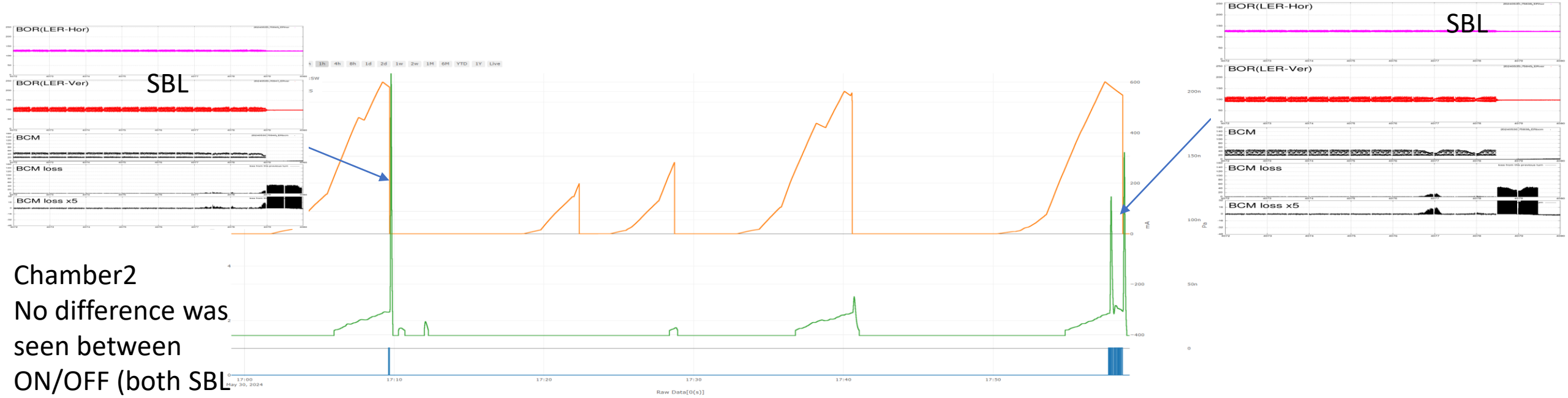


Clearing electrode On/Off dependence

Chamber1
No difference was seen between ON (500V)/OFF (10V) (both without Abort)



Chamber2
No difference was seen between ON/OFF (both SBL Abort)



2nd knocker study

- We knocked the upstream chambers.
  - In that chamber, there was less vacuum burst (&SBL) at lower current, but bursts could be seen when the beam current became higher.

- We applied voltage to the clearing electrode and compared with voltage OFF.

→No difference was observed by applying voltage to the clearing electrodes.

*Fill pattern was changed for each current to keep the bunch current constant.

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.
- Interaction with Dust : Early stage @ SuperKEKB
  - Beam aborts accompanied by local pressure bursts. → not observed the burst that causes it in SBL
  - Beam loss lasted a few ms before the beam abort. → time scale is different
  - Vacuum chambers were cleaned or tapped to remove as much dust as possible and fixed the problem.
- Vertical abort kicker misfire
  - We are using the same thyratron for horizontal kicker.
- FB kicker trouble or lack of power : measured @ BEPC II
  - Sinch the growth time of coupled bunch instability might be O(～several 10 turns), our sbl was not caused by FB system problem.

Possible Reasons for SBL

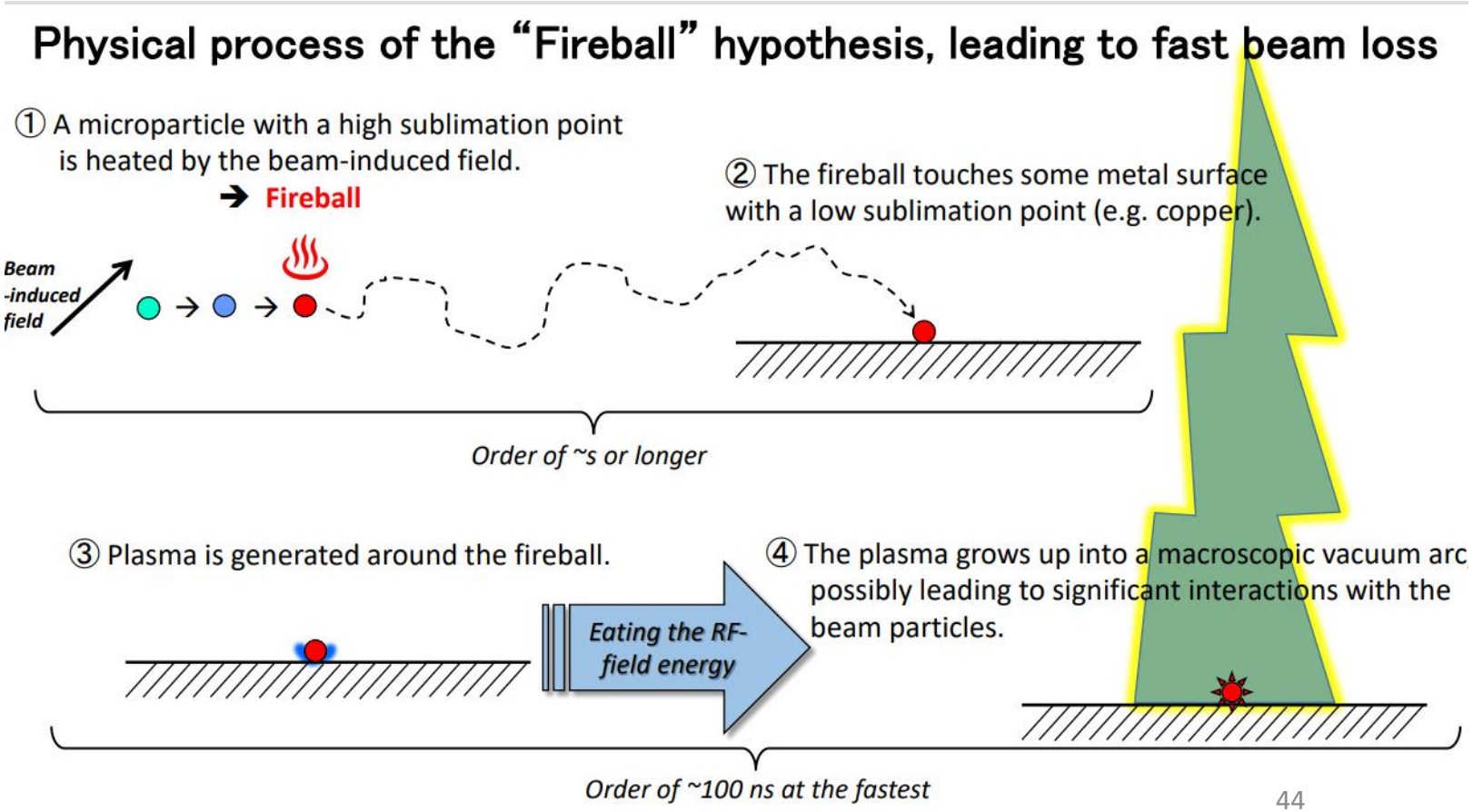
- Equilibrium of tuners, piezo's parameter, LLRF, noise from transmitter, 50Hz filter of RF system could cause sudden beam loss. : measured @ BEPC II, DAFNE
  - RF system are monitored at each abort, and were not seen abnormal signal.
- Electron Cloud
  - SBL should be measured only in LER.→ SBL is also 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/m^3 to 1E14/m^3 → 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).

Candidate Reasons for SBL : Fireball

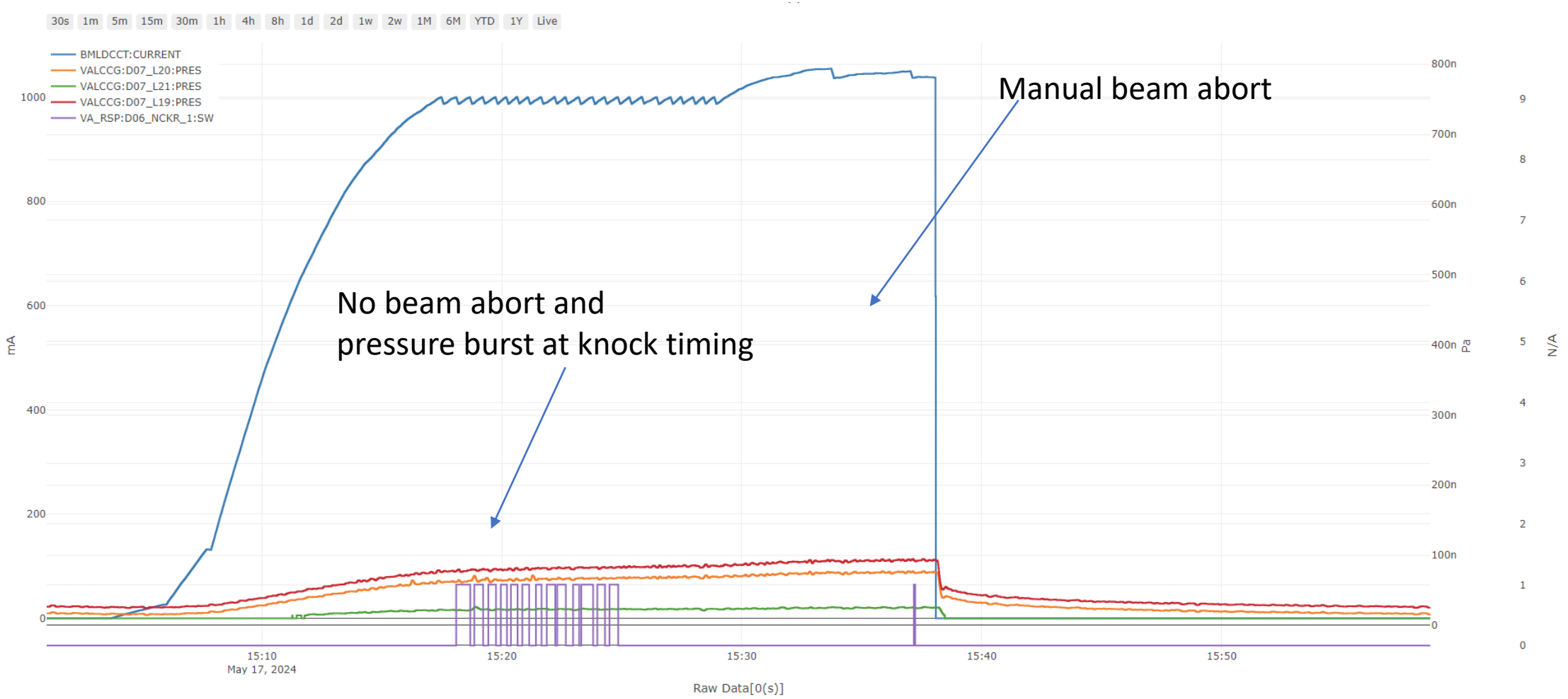
- Fireball : Measured @ RF cavity
- The vacuum chamber is made of copper with low sublimation point and collimator head is made of tungsten or tantalum with high sublimation point.

→ The situation has the potential for a fireball to be formed.

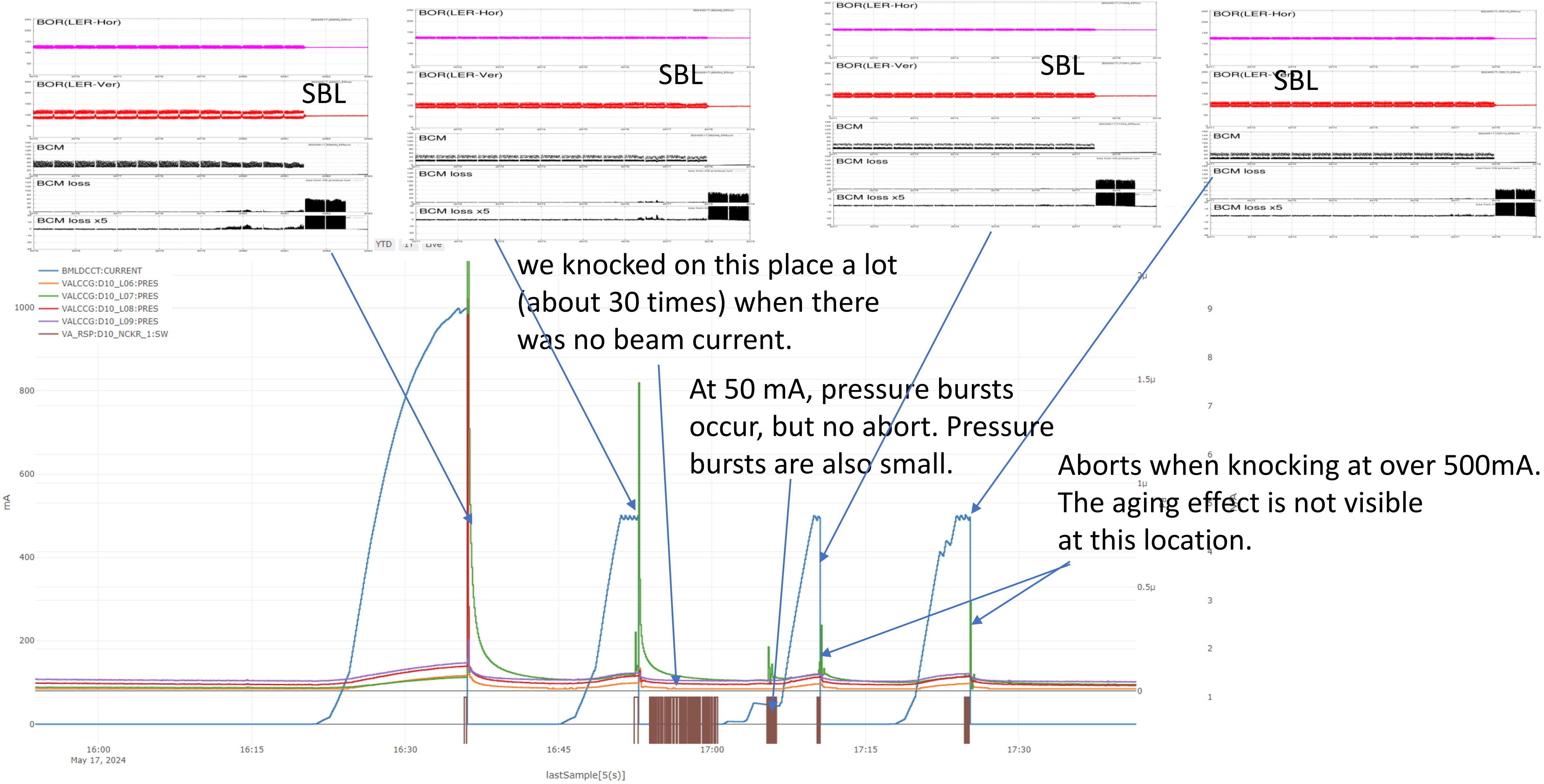
- This fireball hypothesis could explain SBL (~μs) due to the fast plasma evolution (~100 ns at the fastest).



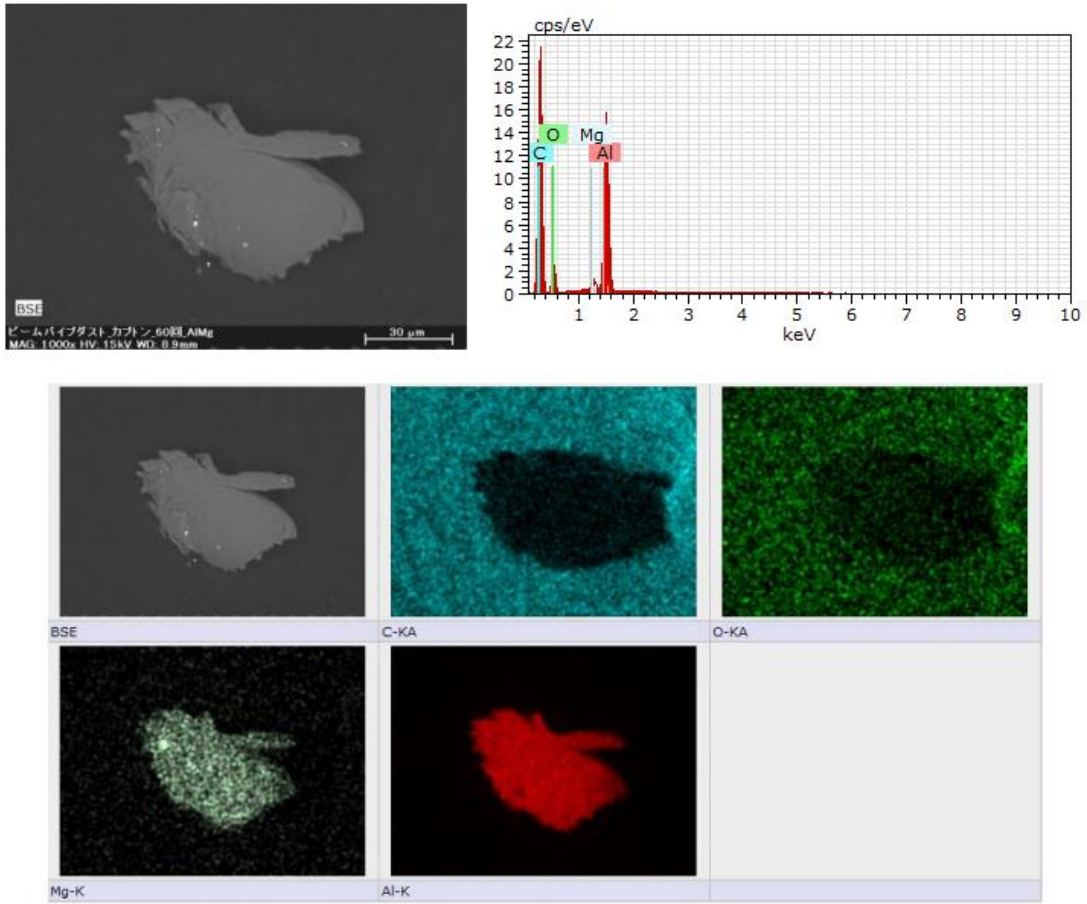
D06:B2P.60 groove point



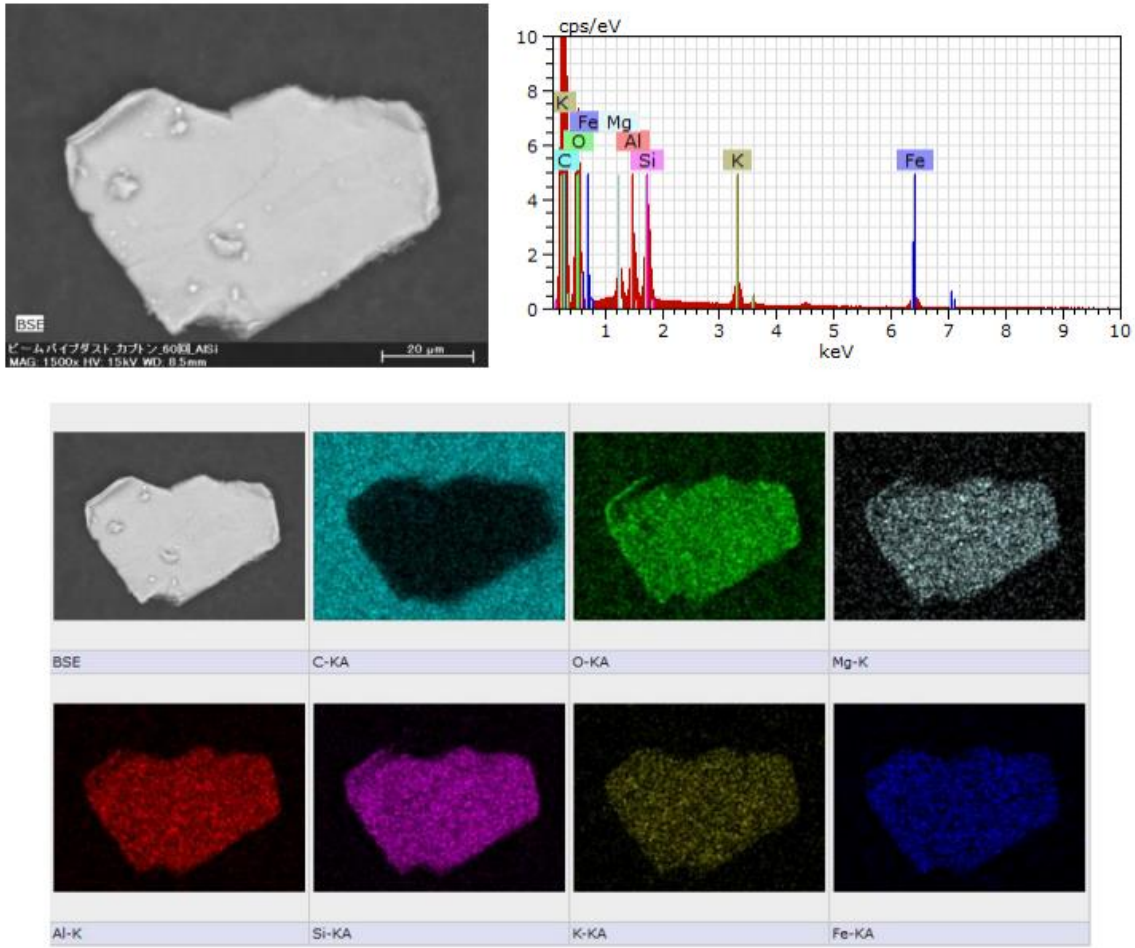
D10: BW0NLMP.14 clearing electrode point



Component analysis of collected dust



図第 1 号：固体①（Al を含む固体を複数個確認）



図第 2 号：固体②（Si を含む固体を複数個確認）