Sudden Beam Loss

The 28th KEKB Accelerator Review Committee
2025/1/14 H. Ikeda
on behalf of the SuperKEKB ACC. Group

Contents

1. Sudden Beam Loss (SBL)

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

- A significant percentage of the beam is lost before the abort trigger is applied.
- Just before the beam loss begins, the orbit appears to move, but its value is small～ O(0.1 mm).

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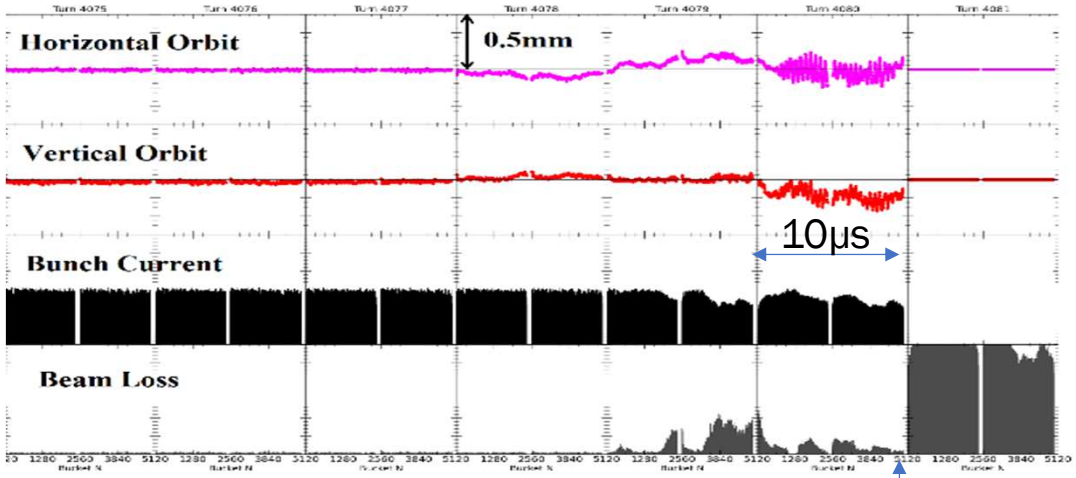
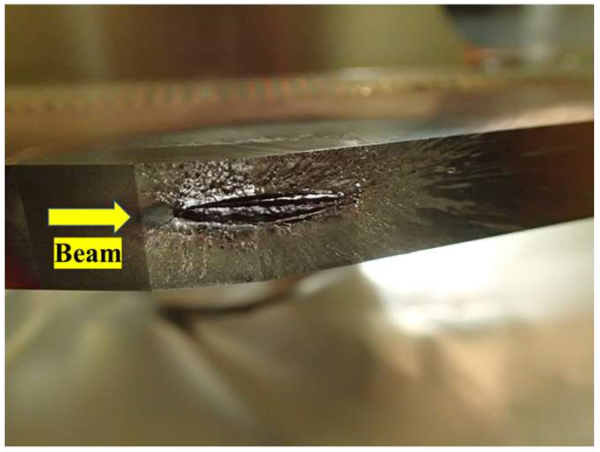
- Damage to collimators and other accelerator components,
- Quench of the final focusing superconducting magnets (QCS),
- Large backgrounds to the Belle-II detector,
- Inability to store high current due to beam abort.

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



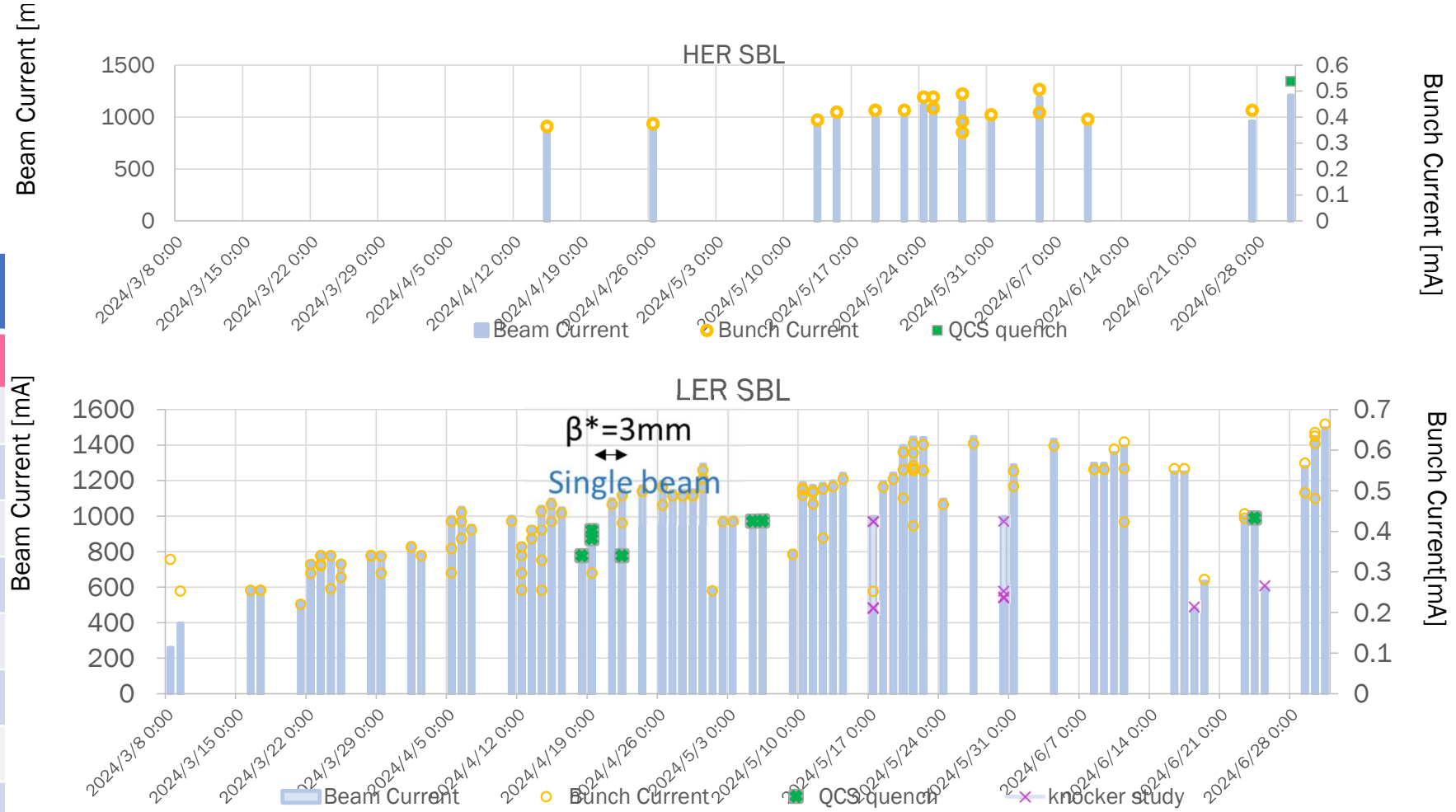


Abort

2. Before Summer Shutdown : SBL statistics(2024/1/30-7/1)

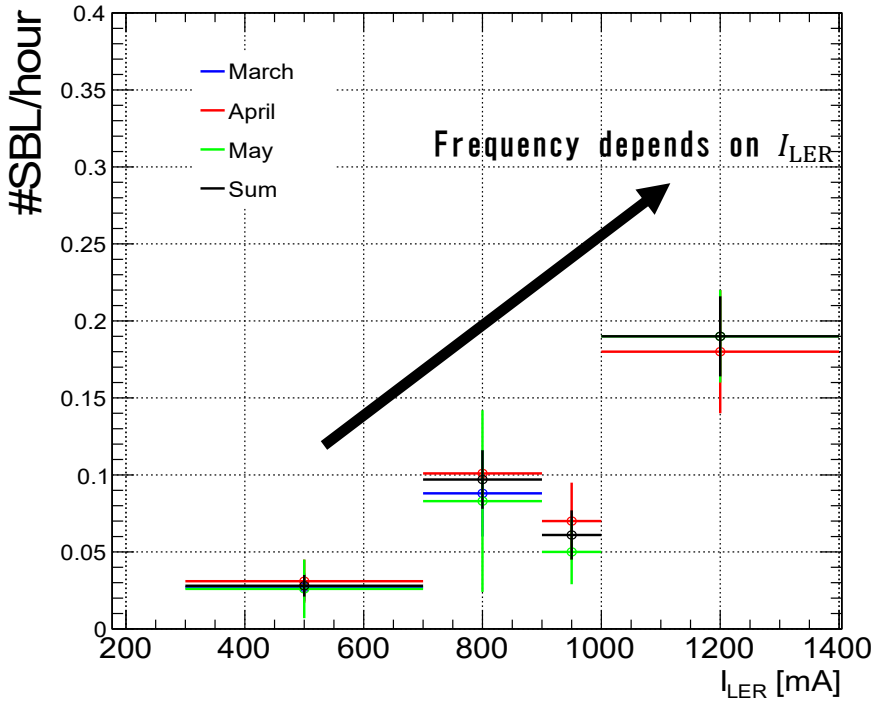
- HER 19
- LER 144
- QCS Quench 7

ring	LER	HER
SBL	144	19
Beam Loss	320	268
Injection	355	1445
RF	78	57
Mag.	16	9
Vac.	4	15
EQ	12	32
Tuning		
Others	16	25
Sum	1473	2531



SBL occurs in both HER and LER, but the number is higher in LER and the damage to the hardware is particularly large when loss occurs in LER.

Beam Current Dependency



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

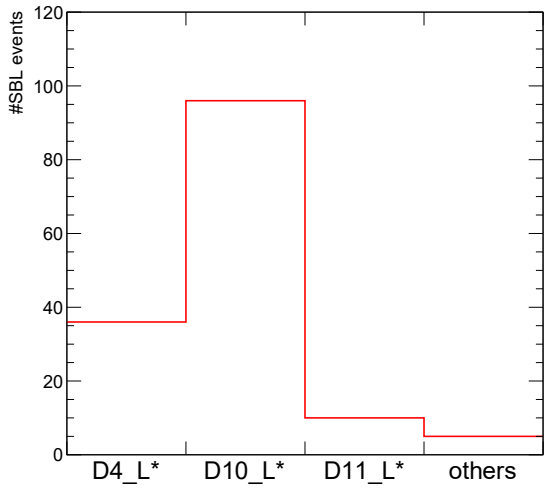
I_{LER} [mA]		[300, 700]	[700, 900]	[900, 1000]	[1000,]
March	#LER SBL	9	10	0	0
	Operation time [hour]	331	114	0	0
	#SBL/hour	0.027 ± 0.009	0.088 ± 0.028	–	–
April	#LER SBL	5	13	8	20
	Operation time [hour]	159	120	114	110
	#SBL/hour	0.031 ± 0.014	0.101 ± 0.003	0.07 ± 0.025	0.18 ± 0.04
May	#LER SBL	2	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

(K. Uno)

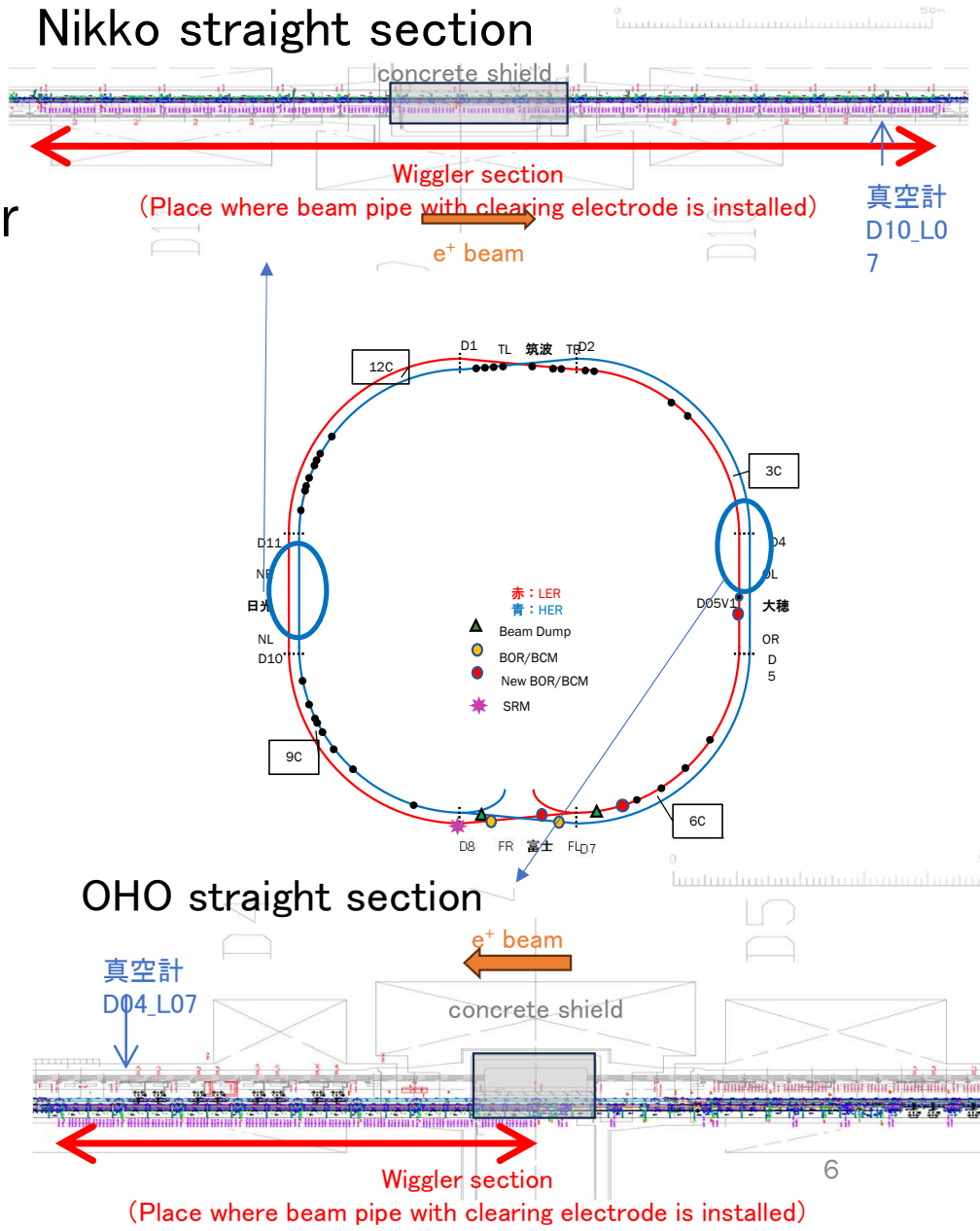
- Frequency (#SBL/hour) depends on the LER beam current

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.



(K. Uno)



Beam Size

- 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.

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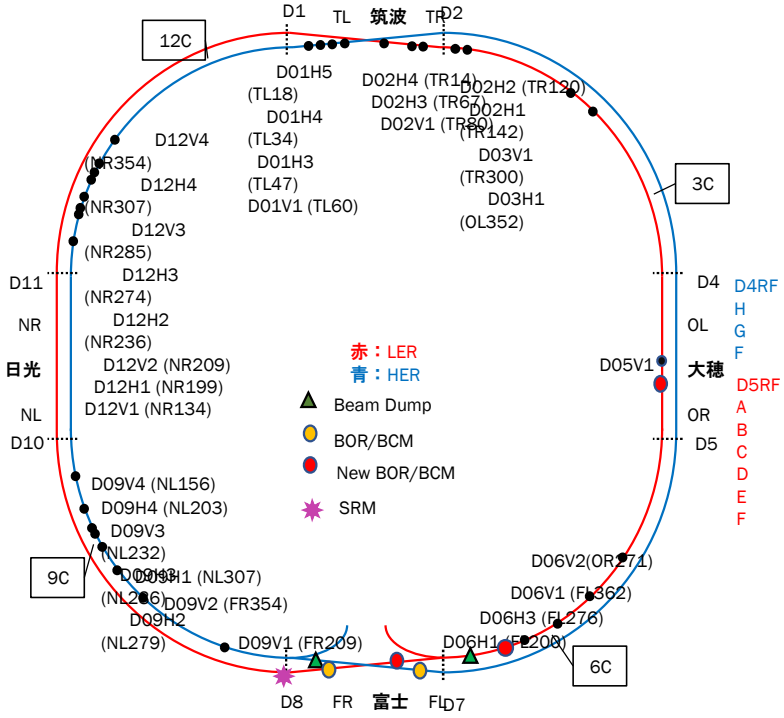
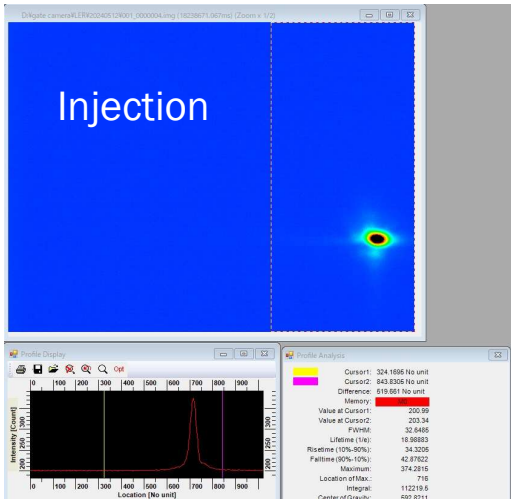
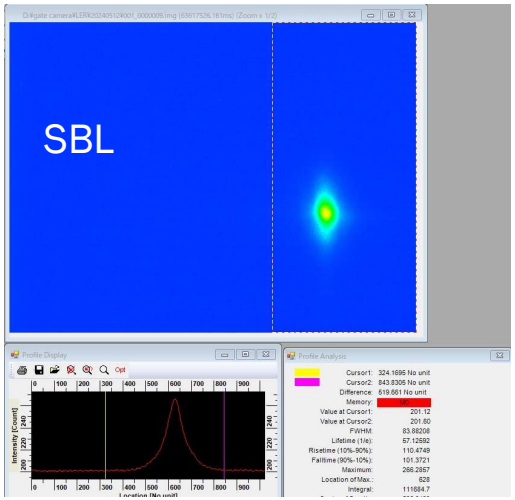
- Vertical Beam Size increases when SBL occurs compared to other aborts.







Knocker Study

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

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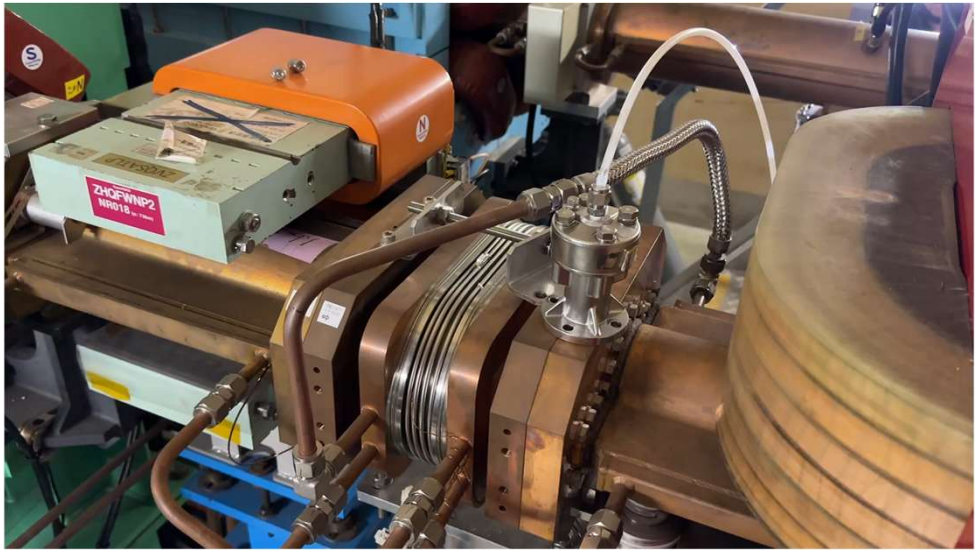
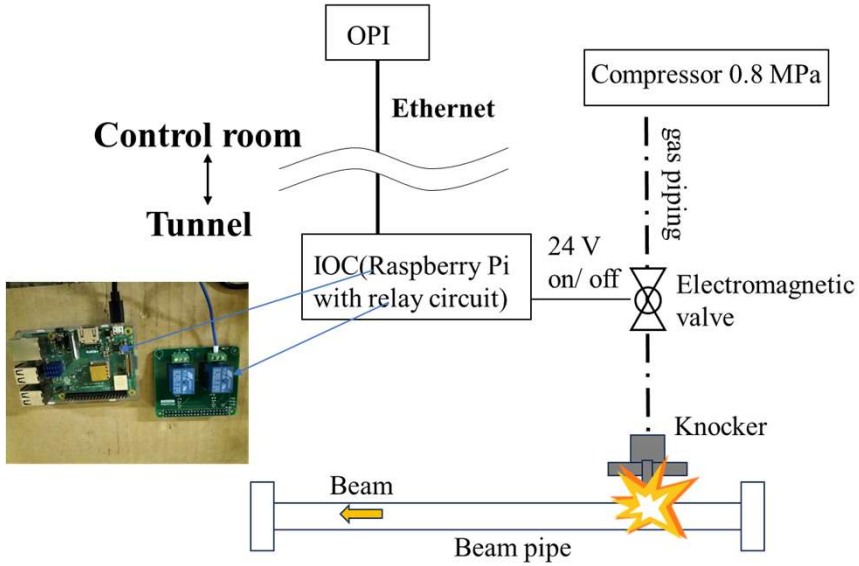
- We suspected that the SBLs were caused by dust-beam interactions, so we performed a knocker study.

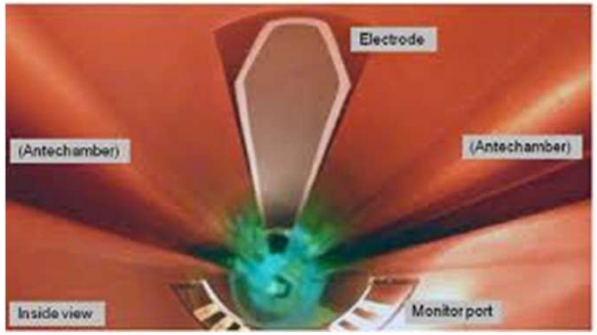


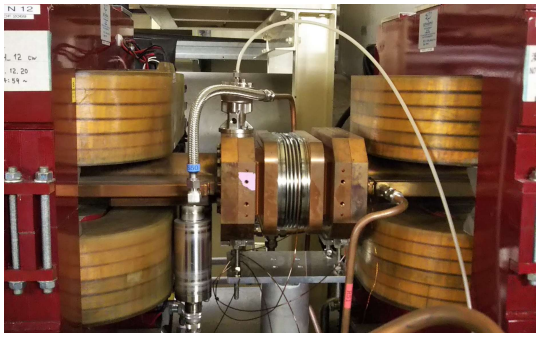


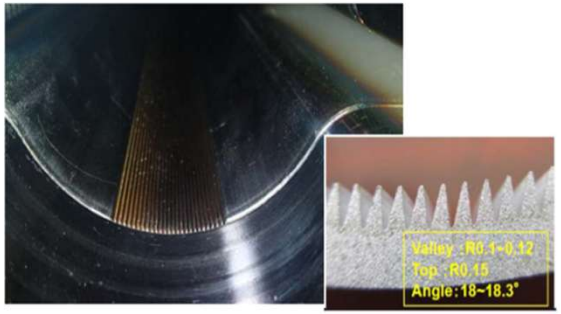
Knocker Study

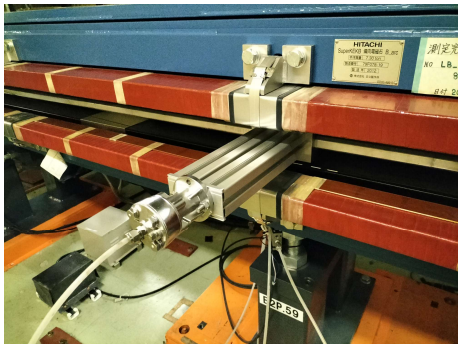
◆Knocker installation locations

- ◆**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) in order to reject the photo-electron.
- ◆**Aluminum beam pipe with grooves** in bending magnet in D06 arc section.
- ◆**Normal Drift chamber** for comparison.



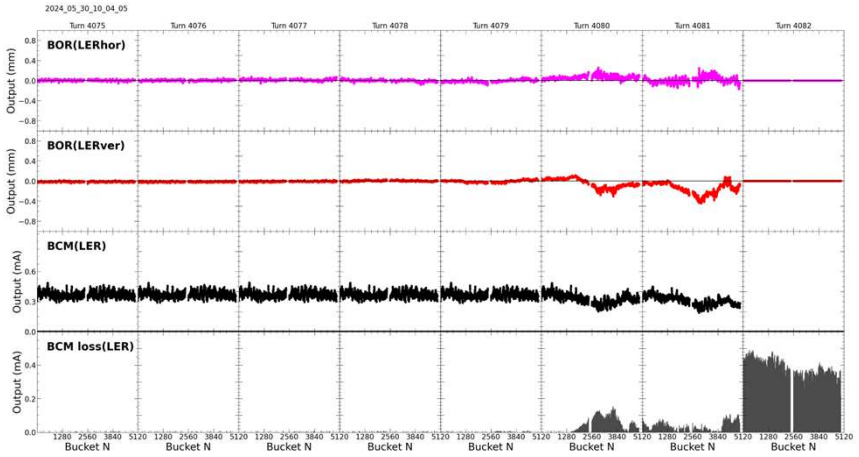


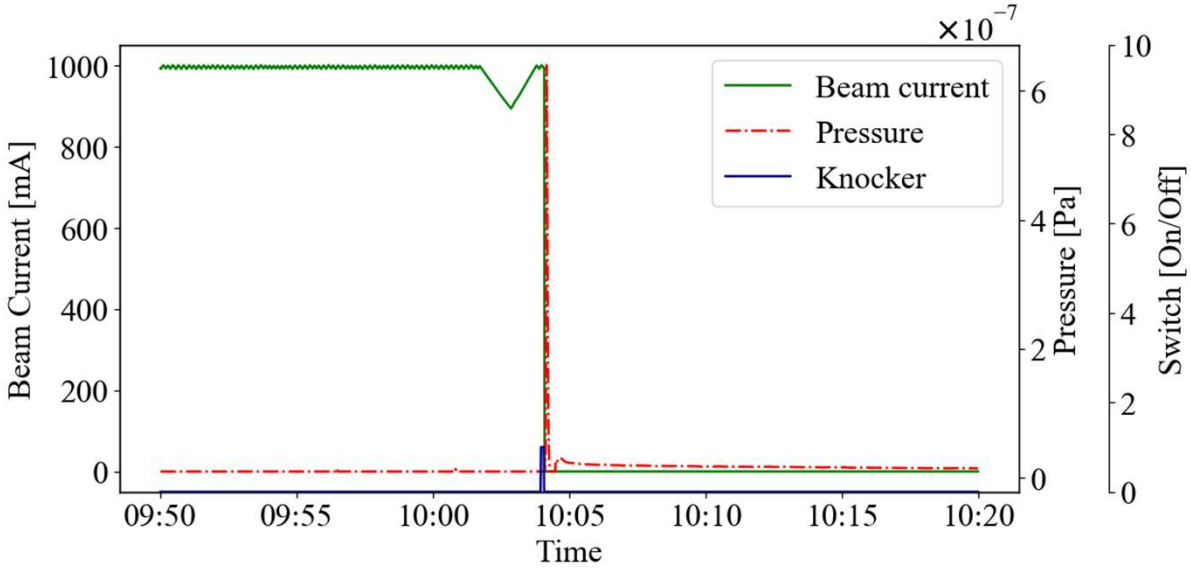


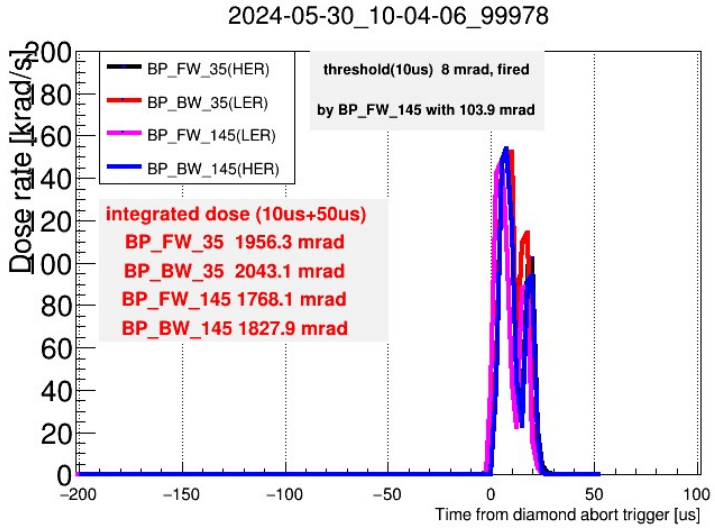


Knocker Study

- SBL with pressure burst was observed during the knocker study at the wiggler section and LM abort with pressure burst at the grooved beam pipe.
- In particular, the beam pipe with clearing electrode was highly suspected because a large number of SBLs were observed with pressure burst in the wiggler section where the beam pipe with clearing electrode was installed.

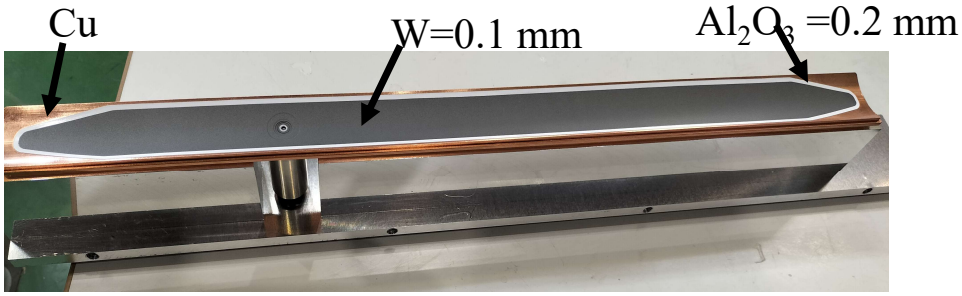


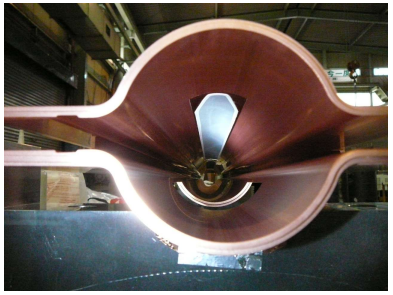


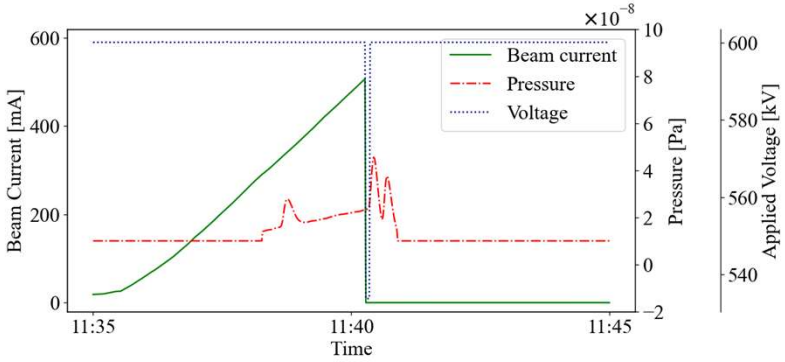


Knocker Study

- 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.
- We tried applying voltage the cleaning electrode to prevent SBL , but the results were the same with no-voltage case.

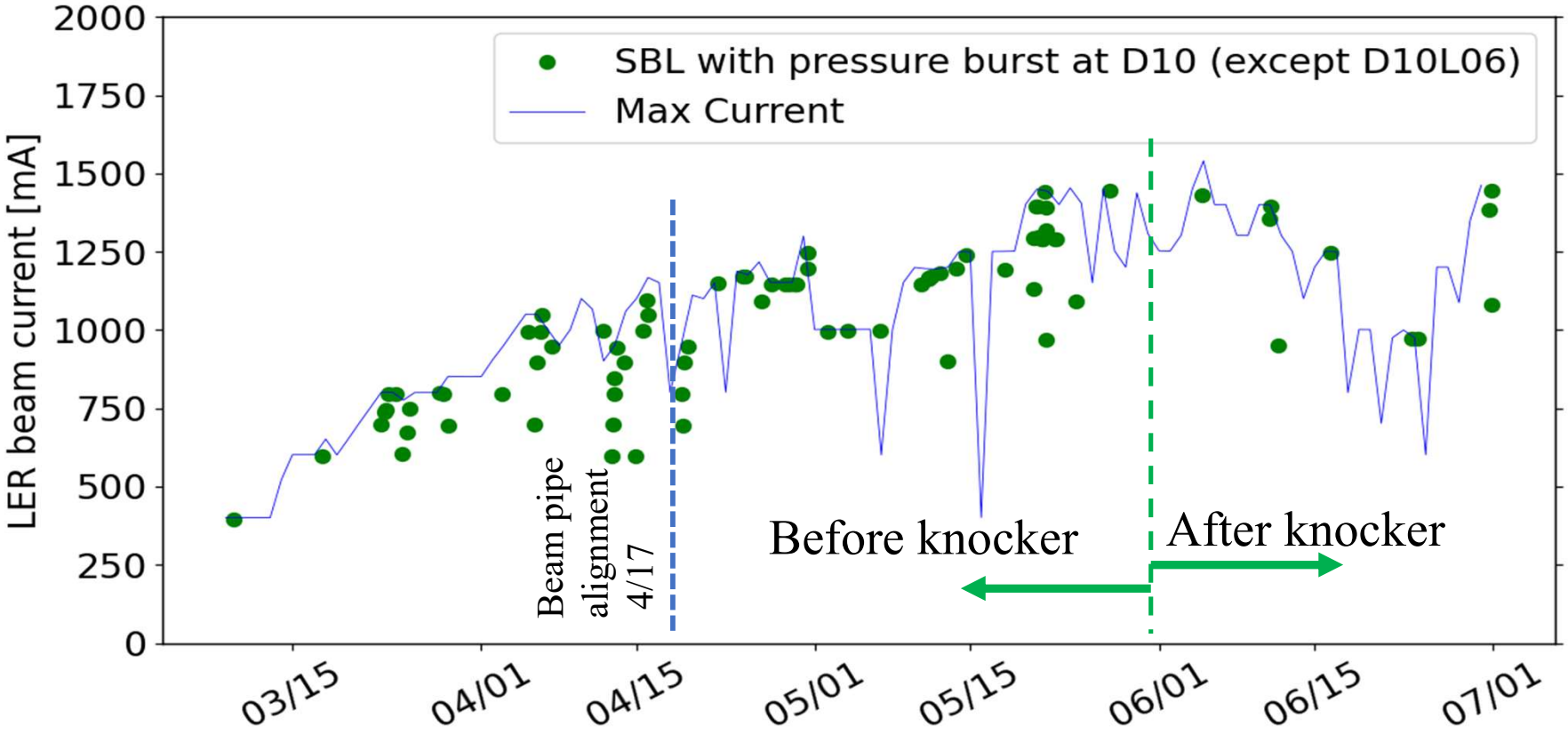






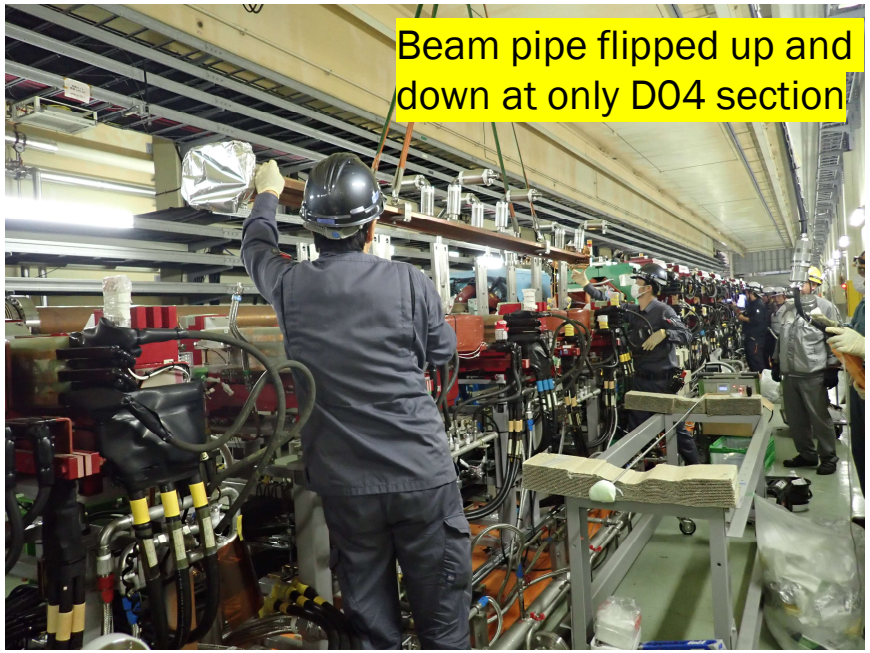
Knocker Study

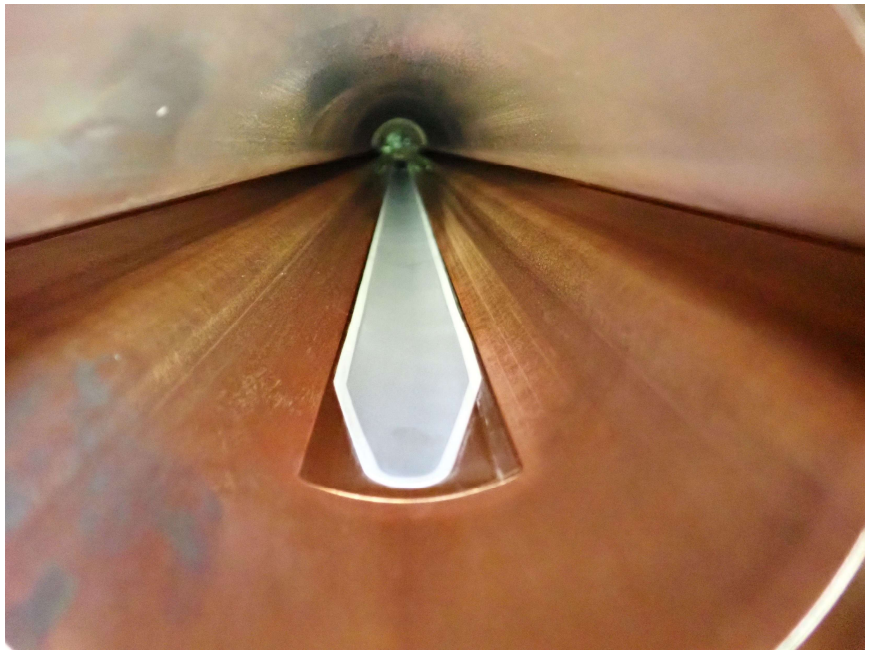
If the SBL is caused by dust falling into the beam pipe, it is best to knock it off when there is no beam.The D10 Wiggler section was knocked on a maintenance day. The number of SBLs decreased after that, but did not completely disappear.

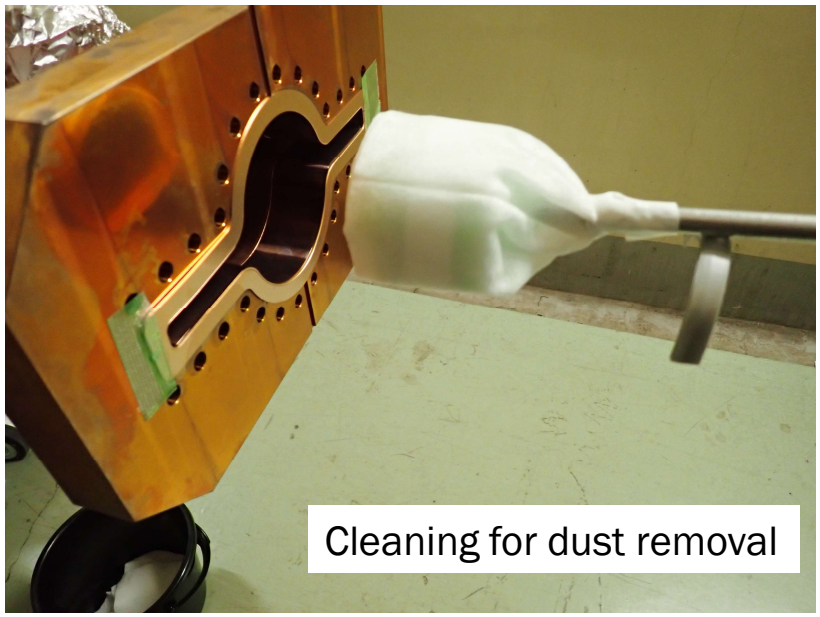


3. Summer Shutdown

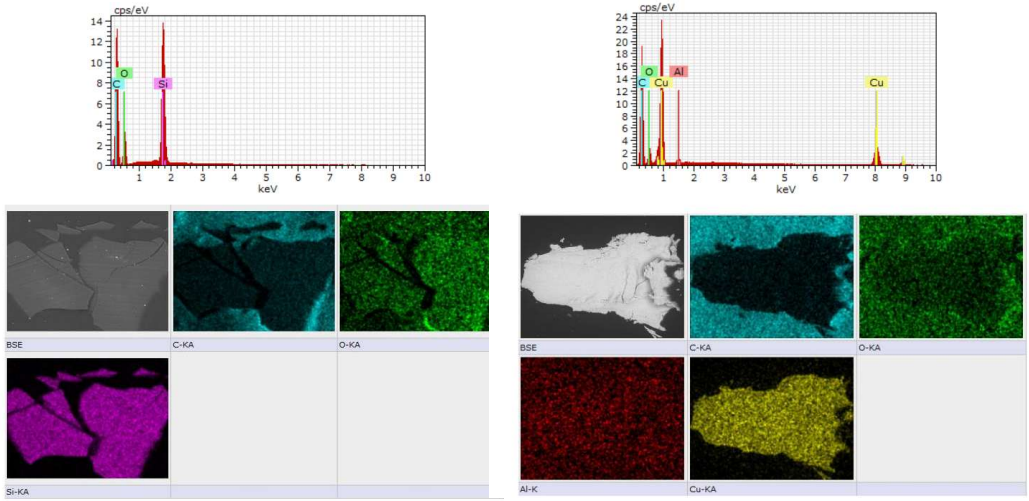
- Flipped upside down the beam pipe with clearing electrode in section D04 (13 outside the OHO concrete shield) in order to check whether dust falling from the electrode is the cause of SBL .
- Cleaned the wiggler section to remove debris.
- Knocked the grooved beam pipe and the beam pipe with clearing electrodes, at all around the ring.







There was a black stain near the flange of the beam pipe. To be safe, the black stain was removed in D04 (the TiN coated area was not removed).

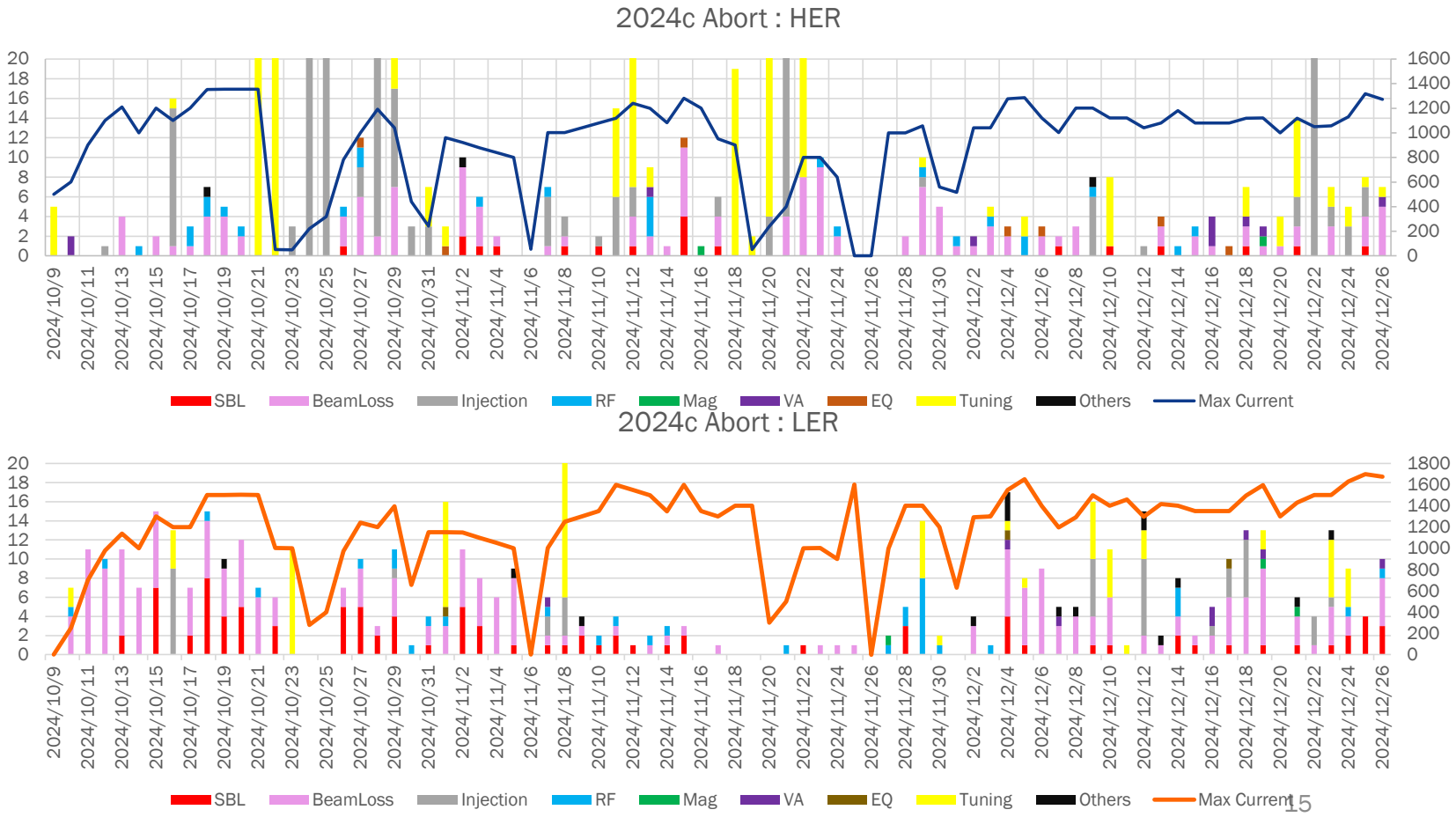


Silicon, Copper, Iron, and Aluminum were collected from inside the beam pipe.

(S.Terui)

4. After Summer Shutdown : Abort Statistics (2024/10/9-12/27)

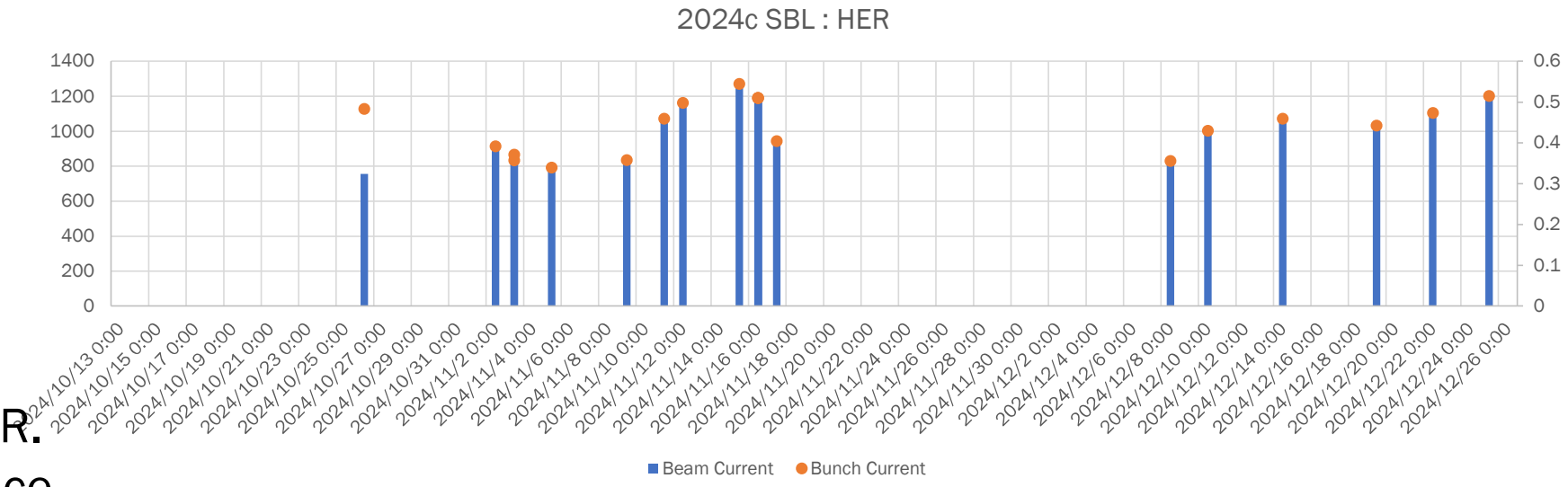
ring	LER	HER
SBL	95	19
Beam Loss	214	138
Injection	44	379
RF	34	29
Mag.	3	2
Vac.	8	10
EQ	3	8
Tuning	103	337
Others	15	2
Sum	877	1269

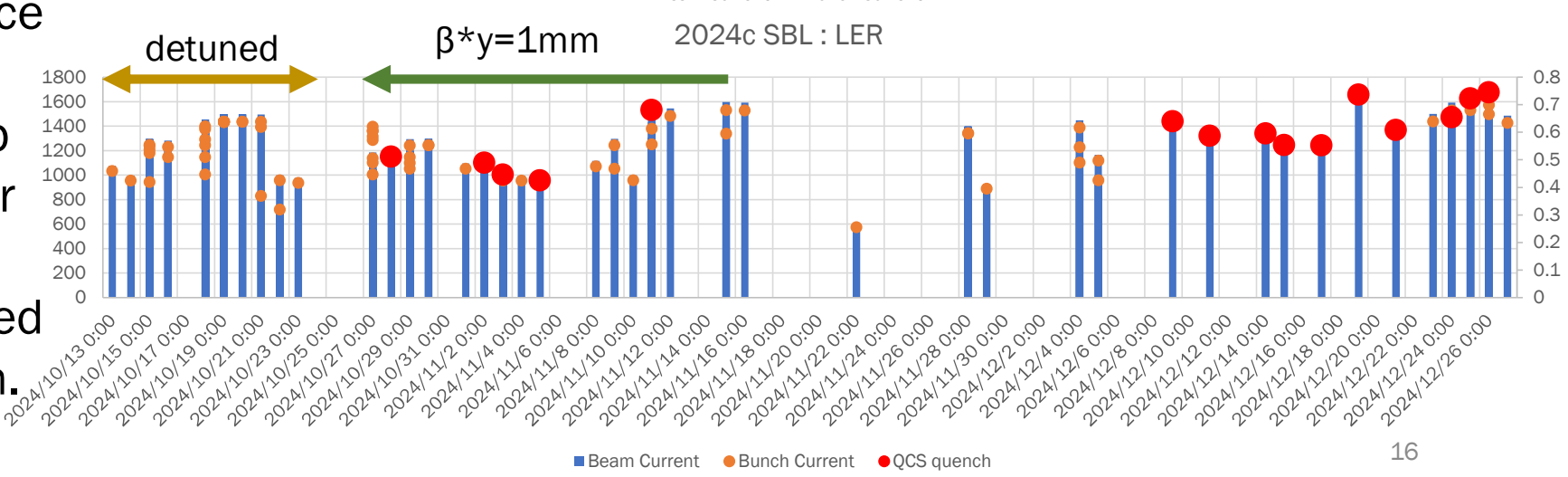


SBL Statistics(2024/10/9-12/27)

- HER 19
- LER 95
- QCS Quench 15

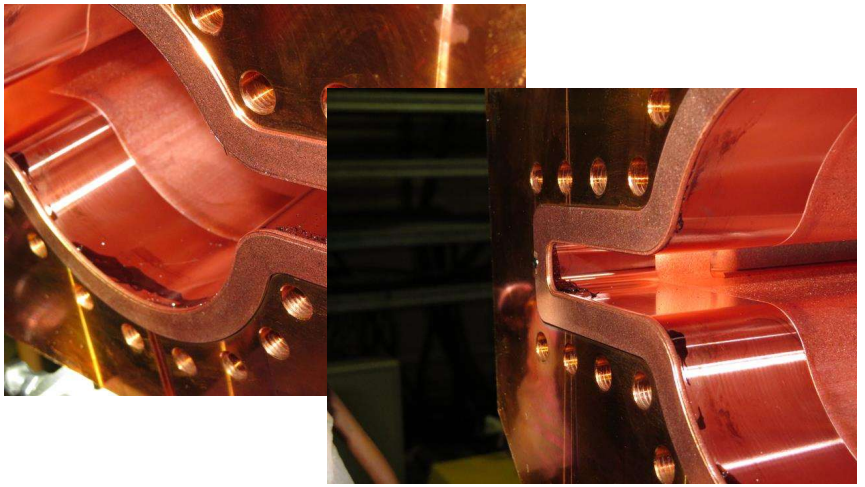
- SBL still occurs primarily in the LER.
- Current dependence is seen.
- During the start-up period, the number of SBLs was increased compared to the previous run.

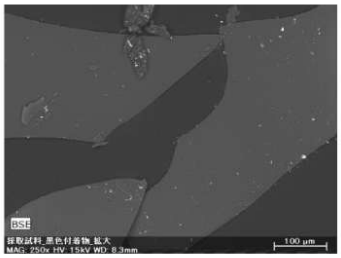


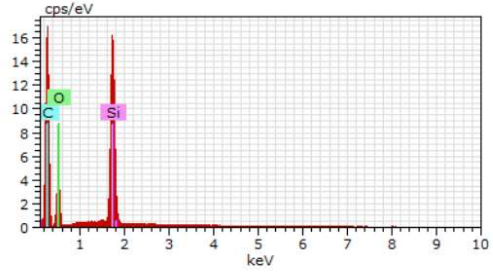


SBL with Pressure Burst

- There are many SBLs with pressure bursts at D10L02/L03. This place was opened to check the inside during the summer shutdown.
- 11/16: Opened the bellows between L02 and L03 and found the black stain.
- After replacing the bellows and clean up the beam pipe, SBL with D10L02 or L03 pressure burst has not been observed.
- The main component of the black stain in the beam pipe was silicon, and since the main component of the vac seal is also silicon, this black stain is considered to have originated from the vac seal.

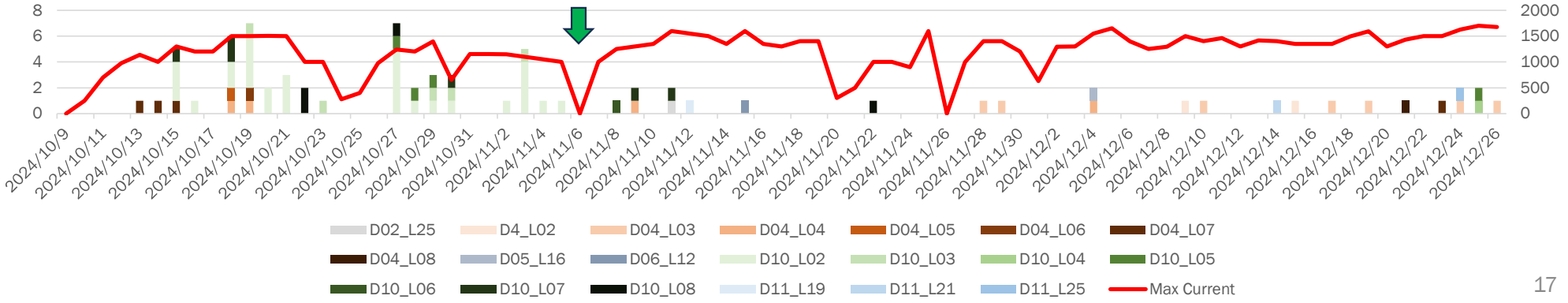






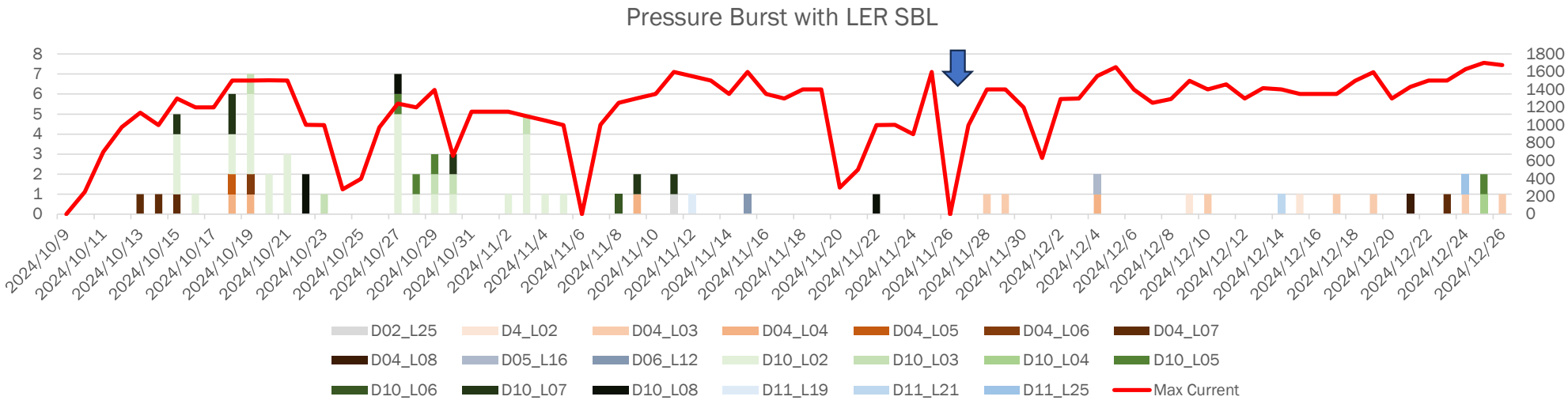
Pressure Burst with LER SBL

(S. Terui)



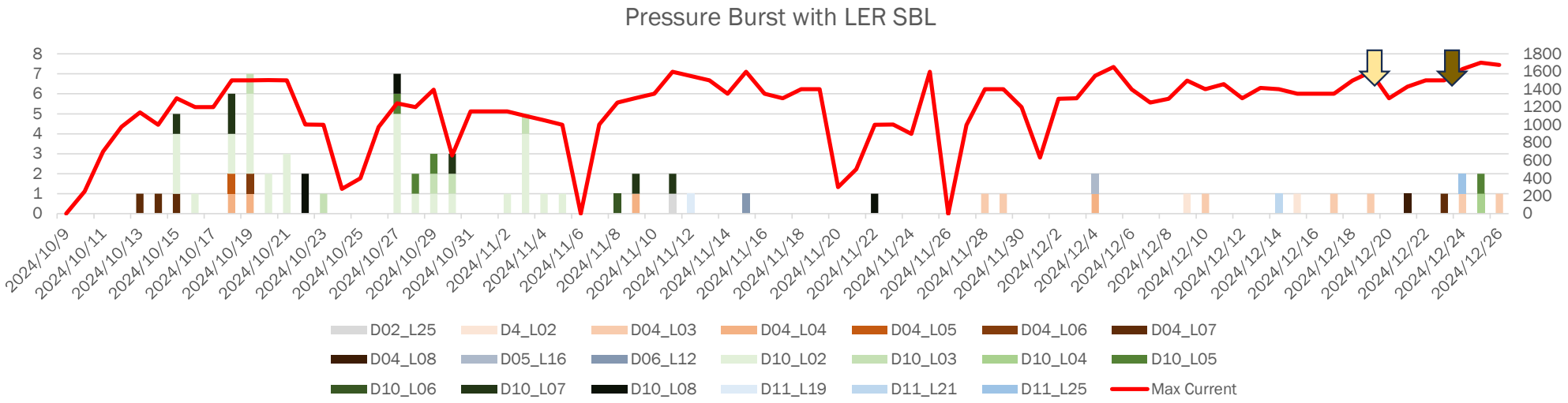
SBL with pressure burst

- SBL with pressure bursts in other D10 place started.
- 11/26:Clean up D10(L03,L07,L08) bellows.
- After that, SBL with D10 pressure burst has not been observed.



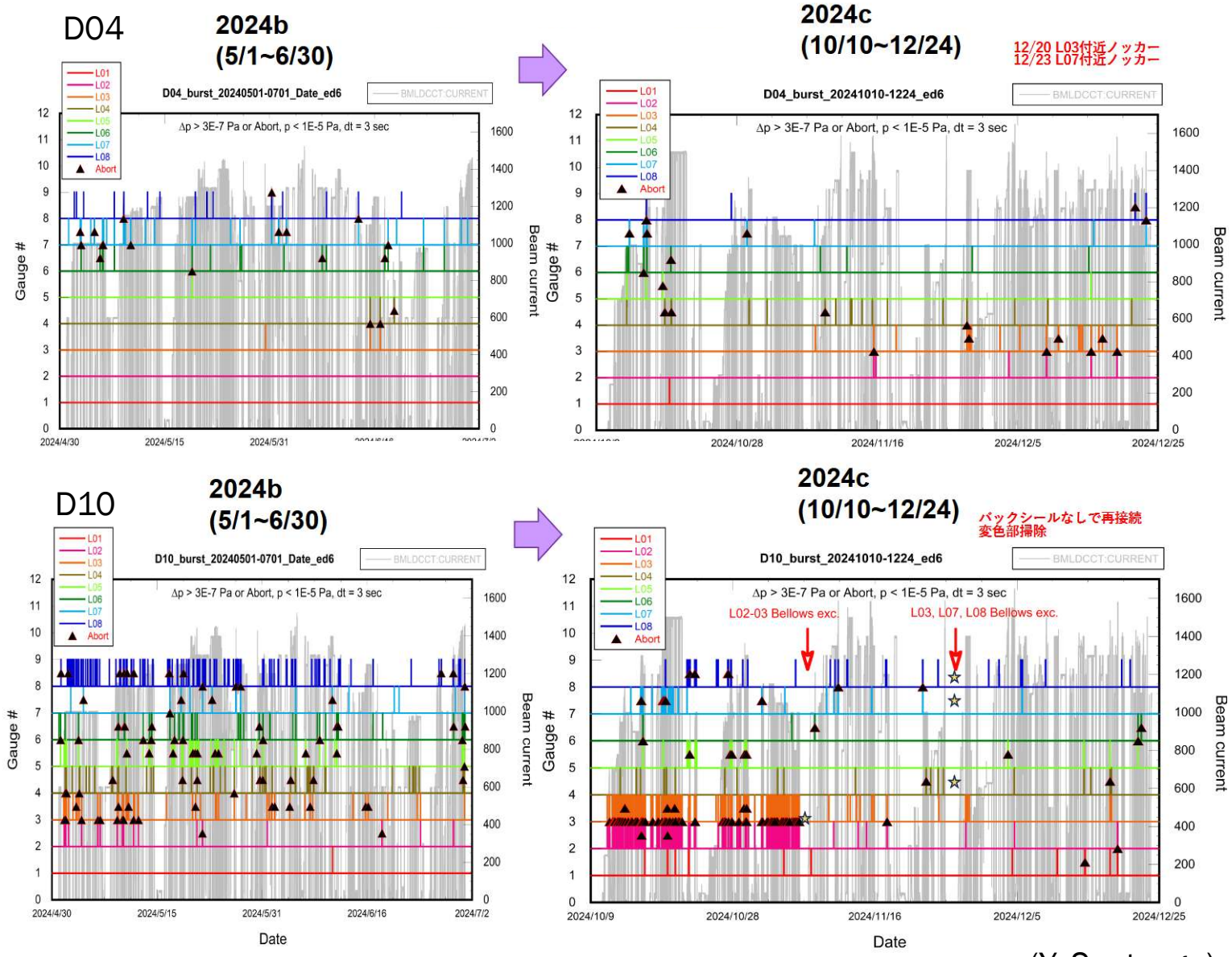
SBL with Pressure Burst

- SBL with D04 pressure burst started again.
- Pressure bursts were mainly observed in D04L02 to L04, which were turned over during the summer shutdown. This is a place where we did not apply a vac sheal.
- 12/19: Knocked 5 places around D04L02～L04 100 times.
- 12/23: Knocked 3 places around D04L07～L08.
- The pressure burst at that location seemed to disappear, but it has reoccurred in some locations.



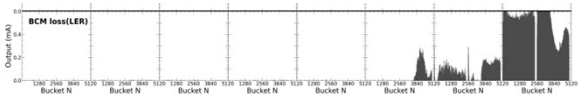
Pressure Burst

- Pressure bursts and beam aborts that have not reached SBL are checked.
- It shows that the effect of overturning the beam pipe is not clear.
- The effect of bellows replacement is obvious.

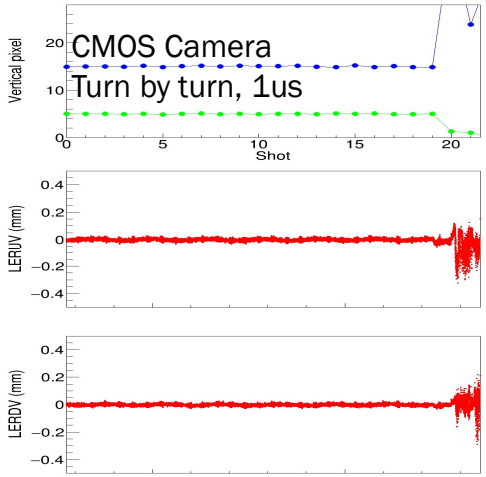


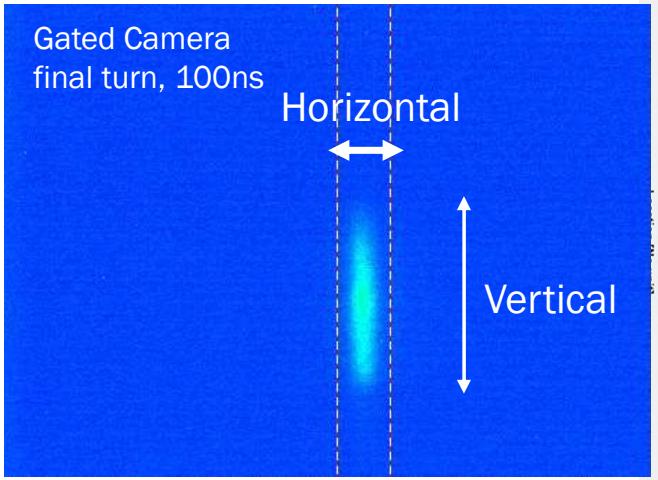
(Y. Suetsugu)

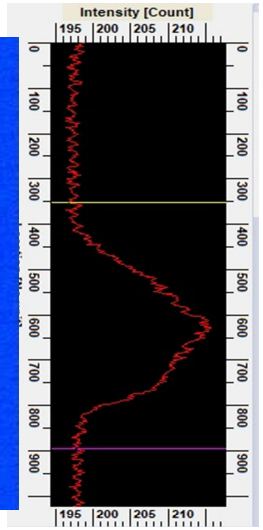
Beam Size @ SBL



2024-12-14 10:06:03 LER SBL

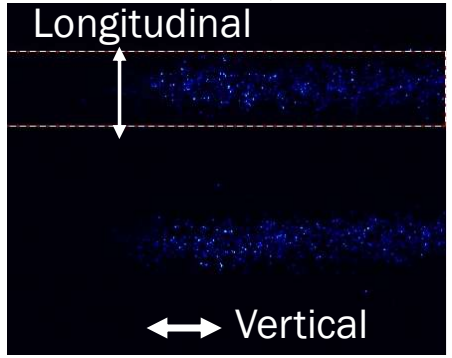


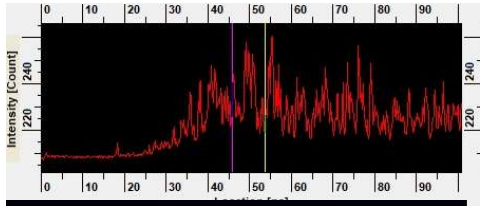




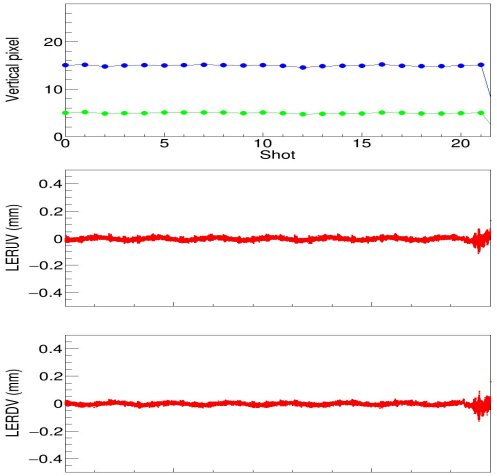
Streak Camera

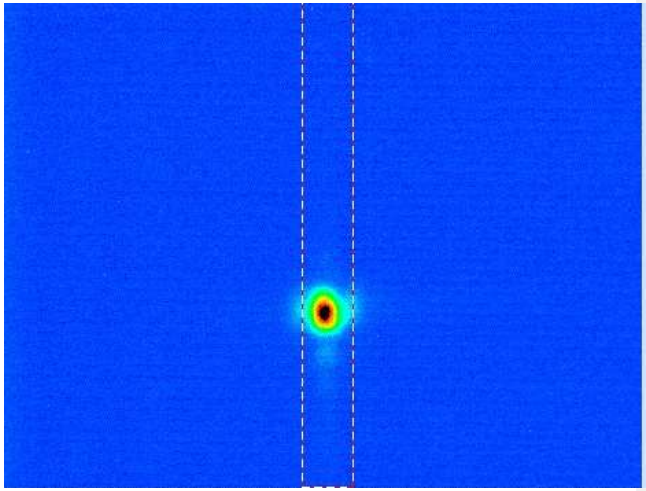
final turn, bunch by bunch 100ns

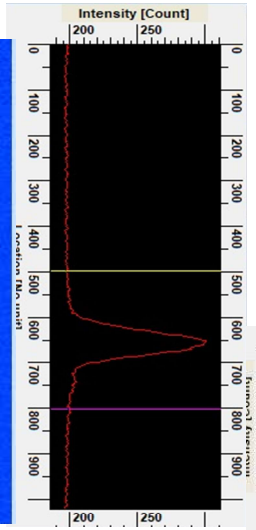


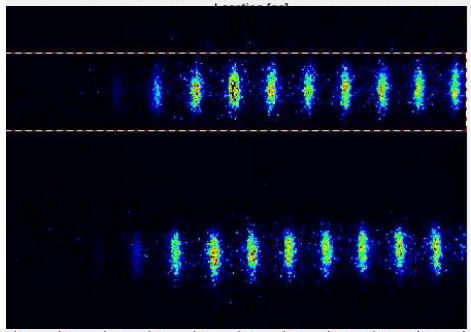


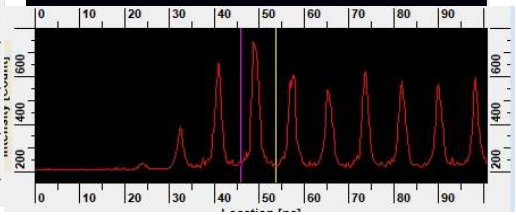
2024-12-14 18:49:33 LER RF



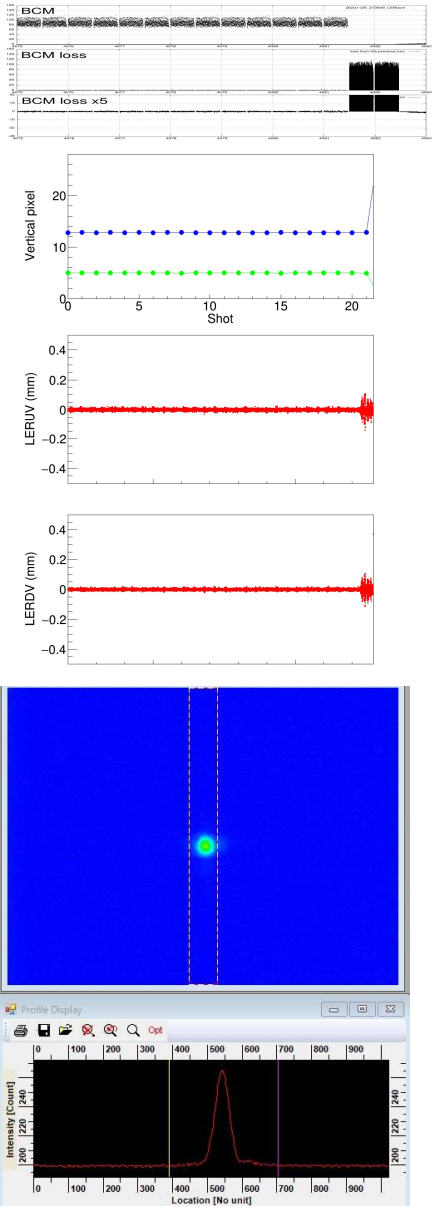




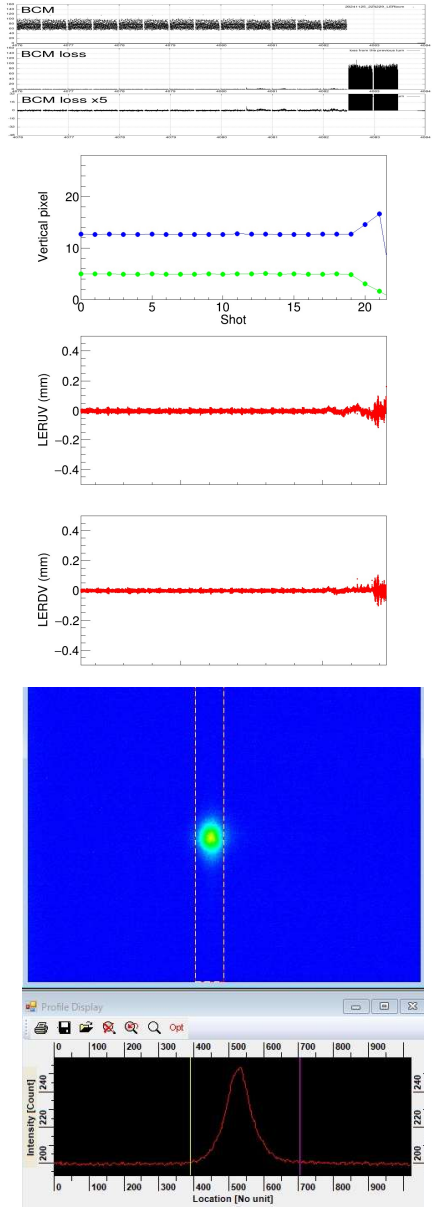




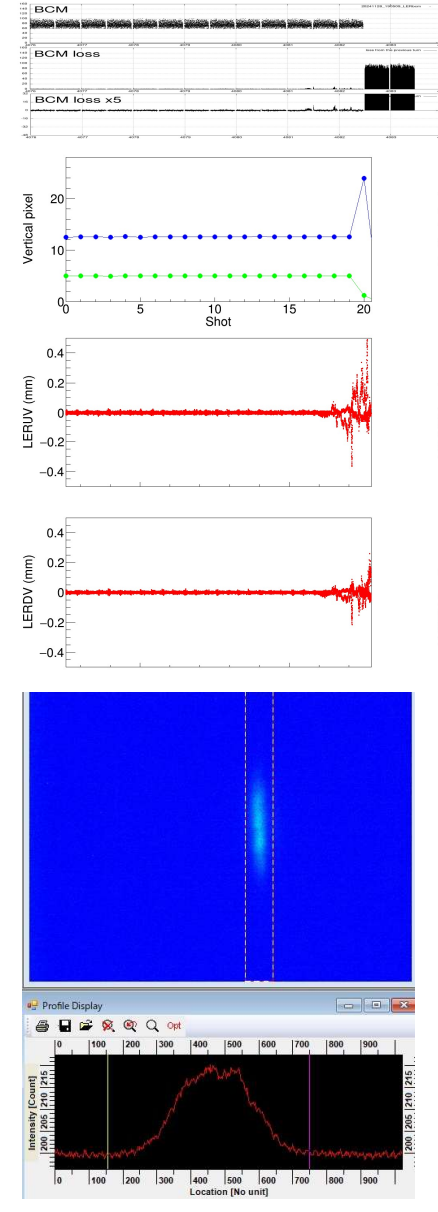
2024/11/25 21:39 manual



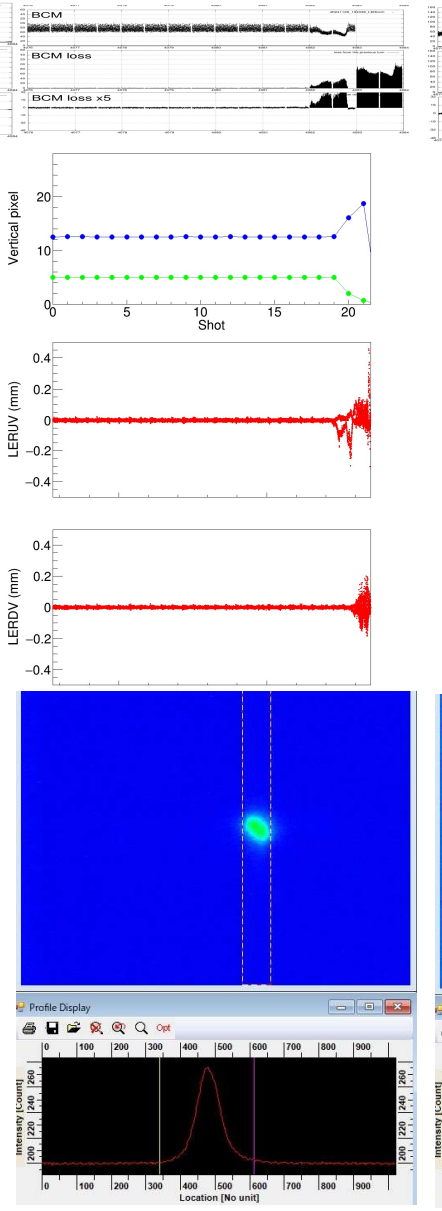
2024/11/25 22:42 MBL



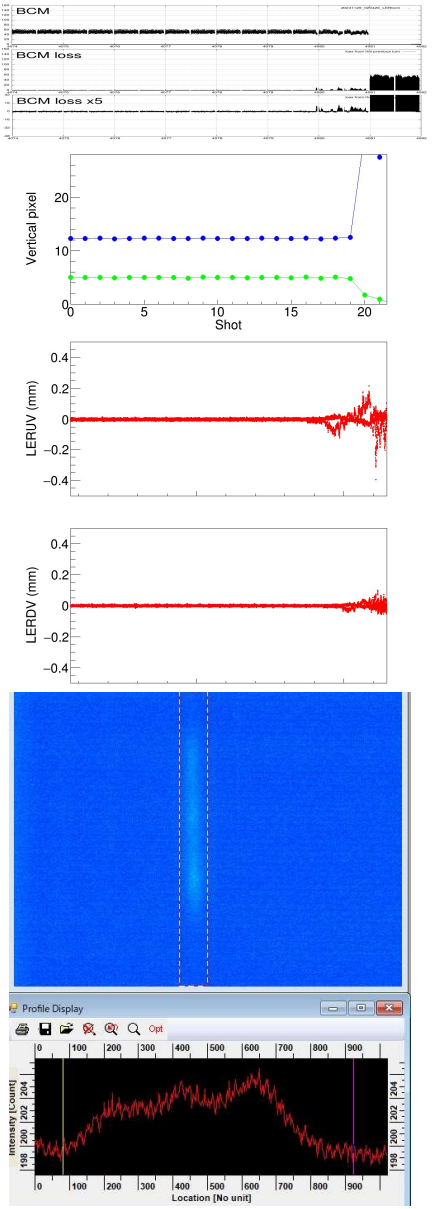
2024/11/28 19:05SBL



2024/11/28 19:40 SBL

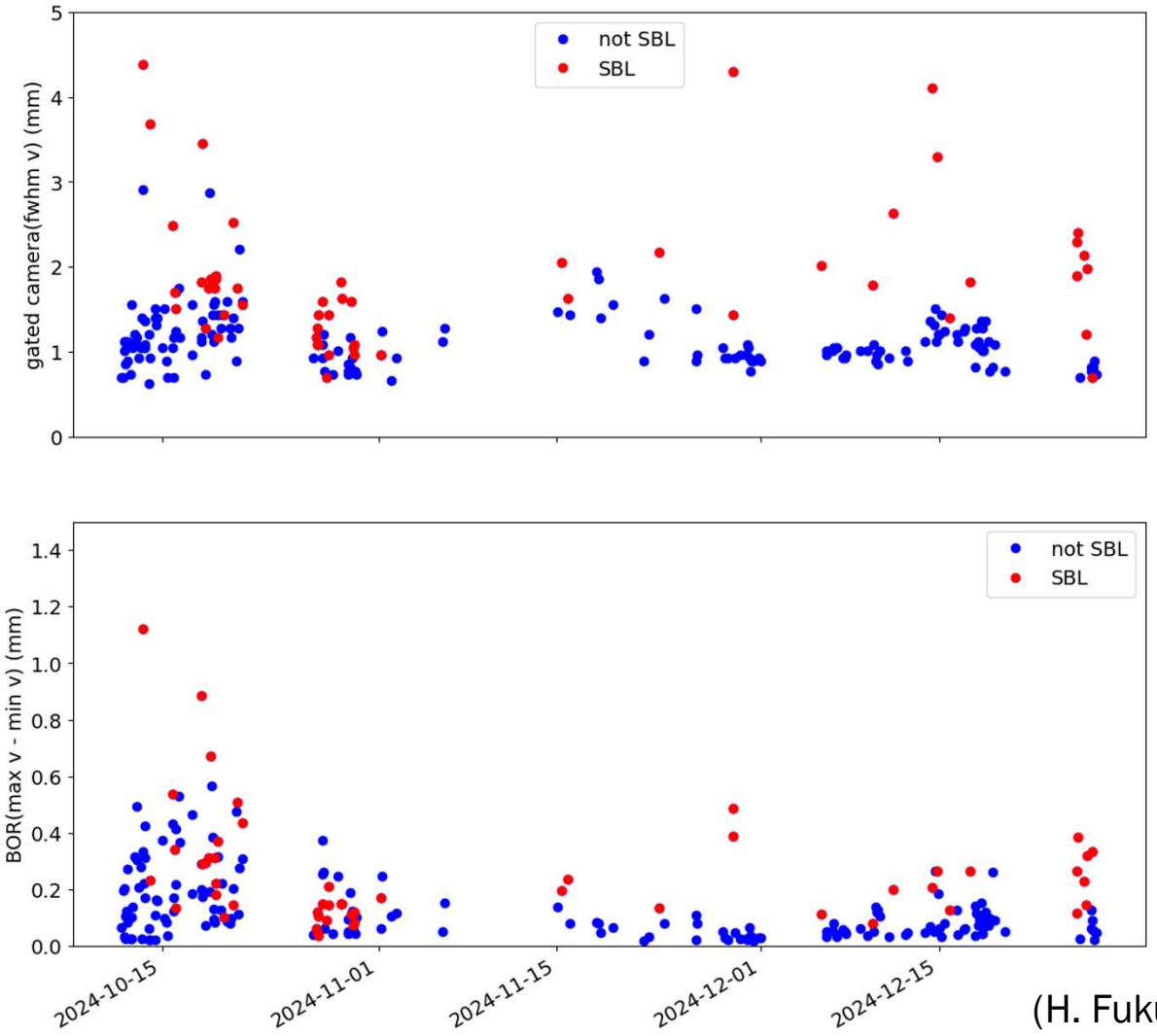


2024/11/29 02:04 SBL



Beam Size @ SBL

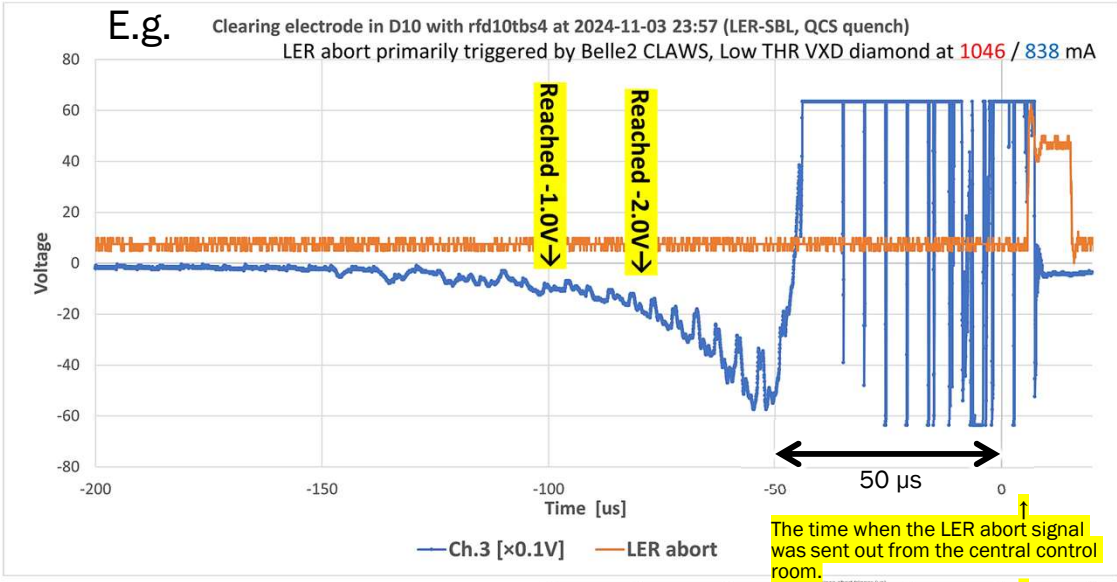
- We measured the beam profile at that time of SBL using three types of cameras, and the results were consistent, with the size increasing compared to other aborts.
- The beam size increase is larger than the beam orbit change, and it looks increasing for each bunch from the streak image.

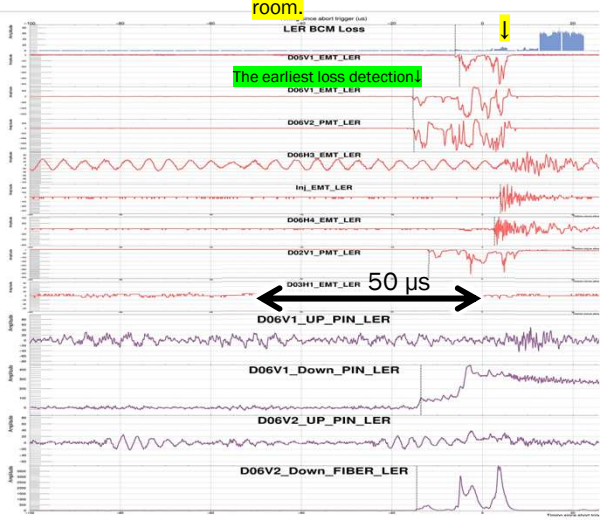


(H. Fukuma)

Discharge Signals from the Clearing Electrodes in D10 (@ SBL)

- We connected twelve of the clearing electrodes in D10 to the ground via 50Ω, then the voltages across the resistors were measured with oscilloscopes.
- At 38 LER aborts during 2024c, we detected significant voltages which should be a result of discharge at one of the clearing electrodes. 15 of the abovementioned 38 LER aborts were SBLs.
- Such voltages were never observed at more than one electrode simultaneously.
- The polarity of the detected voltages is negative and/or positive.
- Any LER abort with such abnormal voltage detection was accompanied by vacuum-pressure burst detected at the nearest gauge.
- In some events, the bunch-train structure was seen.
- In some events, the discharge signal appeared earlier than any beam-loss detection.
- We will try to simulate such events using CST.





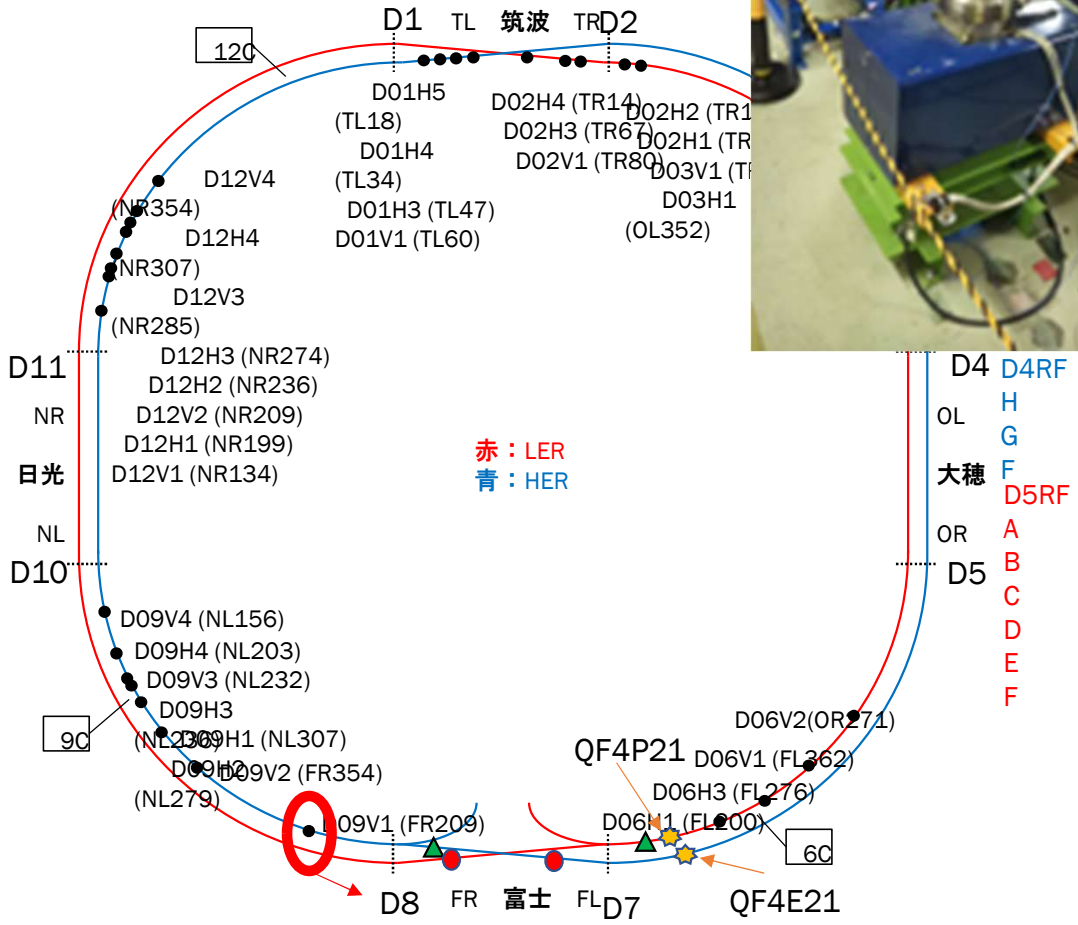
(T. Abe)

5. Speed up of Abort trigger

- We tried to issue an abort trigger as soon as possible to reduce hardware damage by SBL.
- HER : LM (Optical Fiber)
- LER : D7 Master → Control (A. Morita) and MDI (H. Nakayama) tark

HER : LM (Optical Fiber)

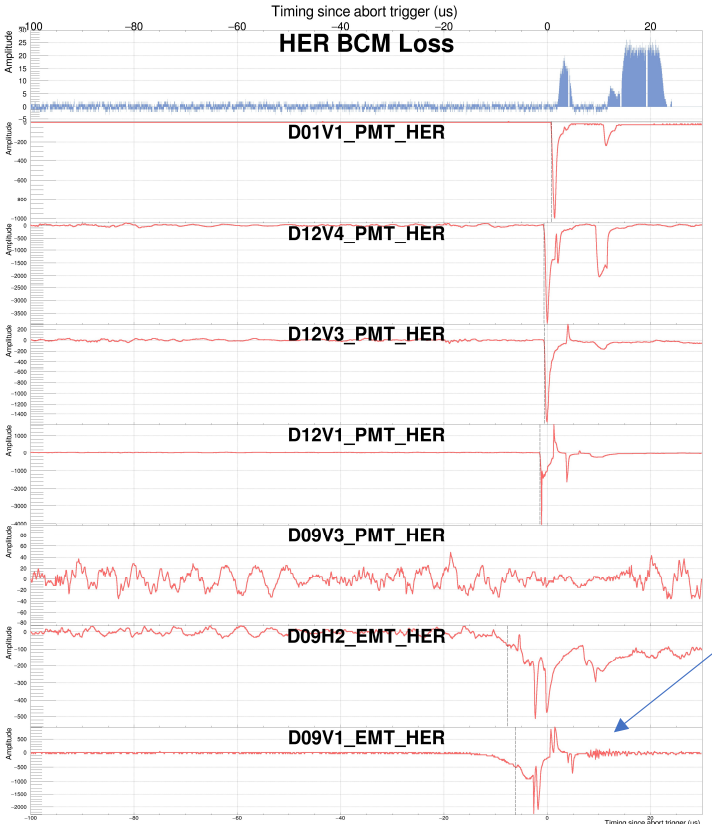
- Starting in 2022, we introduced an LM using optical fiber near the LER D6V2 collimator and built a system that sends the abort trigger to the CCB as quickly as possible, and it is useful.
- Therefore, we decided to introduce a similar system to HER, and installed an optical fiber LM on D9V1, the most upstream of the HER collimators.
- The original loss monitor signals are collected in D10, so it can be sped up by going through D8.

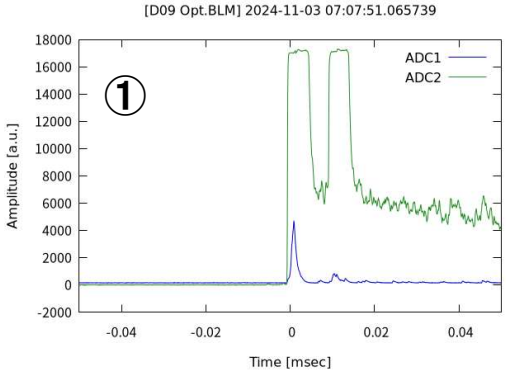


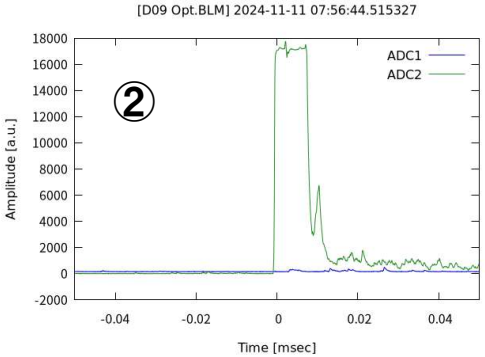
Beam Dump
BOR/BCM
Libera

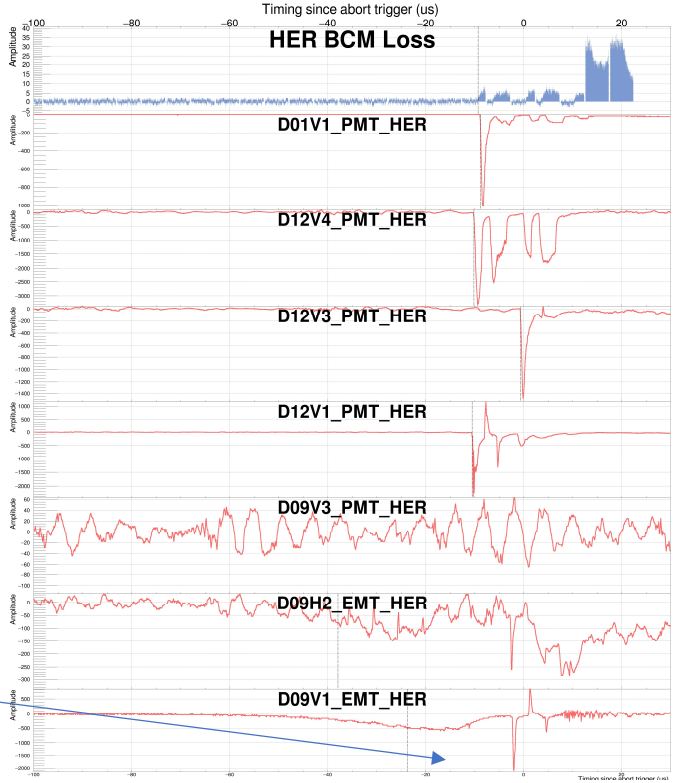
① HER SBL is triggered 13/18 times by optical fiber, especially useful because it is triggered earliest (6/13) for events with large beam loss.

② However, if the beam loss begins downstream from here, nothing can be done.



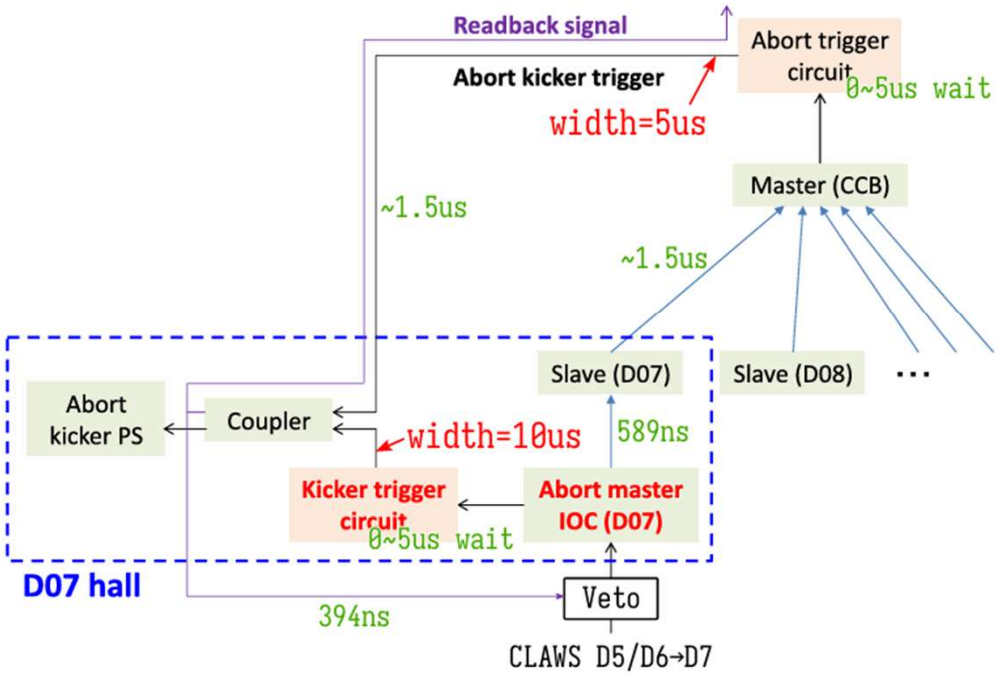


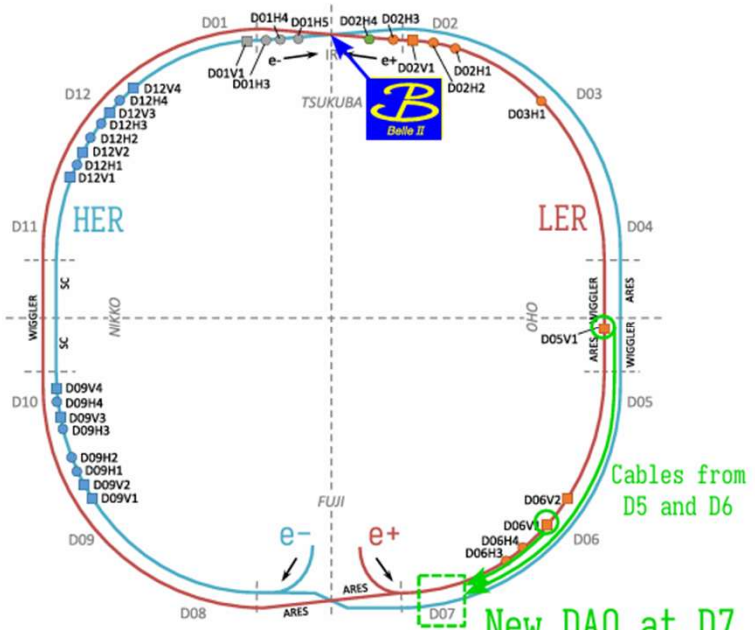




LER : D7 Master

- All abort triggers are collected in the central control building (CCB) and sent to the Abort kicker on D7 after taking OR.
- If we send the signal directly to the abort kicker without going through the CCB, we can fire the kicker faster.
- We introduced D7 Master system which send the LM signal from D6/D5 collimator directly to D7 abort site.
- The D7 Master had the earliest trigger with 16/28 SBLs since we turned it on.





(B. Urbschat)

Summary

- SBL still occurs especially in LER.
- SBL occurs when a pressure burst occurs at a specific location, and since an increasing of beam size is observed at that time, we suspected an interaction between the dust and the beam and conducted a knocker study before summer shutdown.
- Since SBLs occurred when knocking on beam pipes with clearing electrodes, and the number of SBLs decreased after many knocks, some beam pipes were flipped in the summer shutdown.
- The effect of flipping the beam pipe upside down is not clear. We decided not to flip the remaining beam pipes.
- An internal inspection was conducted and vac seal was applied to bellows during the summer shutdown, and many SBLs occurred with pressure burst at that place. After cleaning the dirt that was thought to be caused by the vac sheal, the number of SBLs decreased.

  →Regarding the work to be done during this shutdown, refer to Vacuum (Mu-Lee Yao) talk.
- When SBL (or pressure burst event) occurs, the beam size increases, discharge at the electrodes, etc. are measured.
- Based on these data, we will investigate the mechanism leading to beam loss.

- In addition to investigating the cause of SBL, efforts are being made to speed up aborts in order to reduce damage when SBL occurs.

Back up

- **In SuperKEKB, which uses a nano-beam scheme, the beam size becomes very large in the QCS. This causes a very large beam loss in IR. To reduce this IR loss, the collimator is set to a very narrow setting during operation.**

0.89 mm
@By=11.9m !

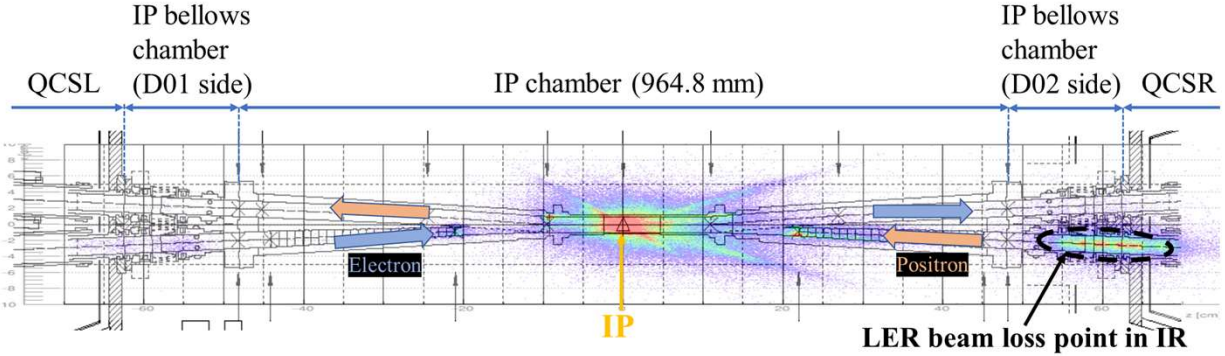
	DIF_POS [mm]	beta_y [m]	nu_y	Nsigma (beta)	LM	beta_y*[mm]	beta_x* [mm]
D06V1TOP	3.01	67.3	28.85	80.1	0.00	1.0	80.0
D06V1BTM	-3.12	67.3	28.85	82.9			
D06V2TOP	2.60	20.6	30.49	125.2	0.00 0.00		
D06V2BTM	-2.77	20.6	30.49	133.0			
D03V1TOP	7.97	17.0	41.42	422.2	0.00		
D03V1BTM	-8.01	17.0	41.42	424.2			
D02V1TOP	0.89	11.9	44.83	56.2	0.06		
D02V1BTM	-1.25	11.9	44.83	79.4			
QC1 (1.12m)	13.5	782.2	46.33	105.3			

80 %

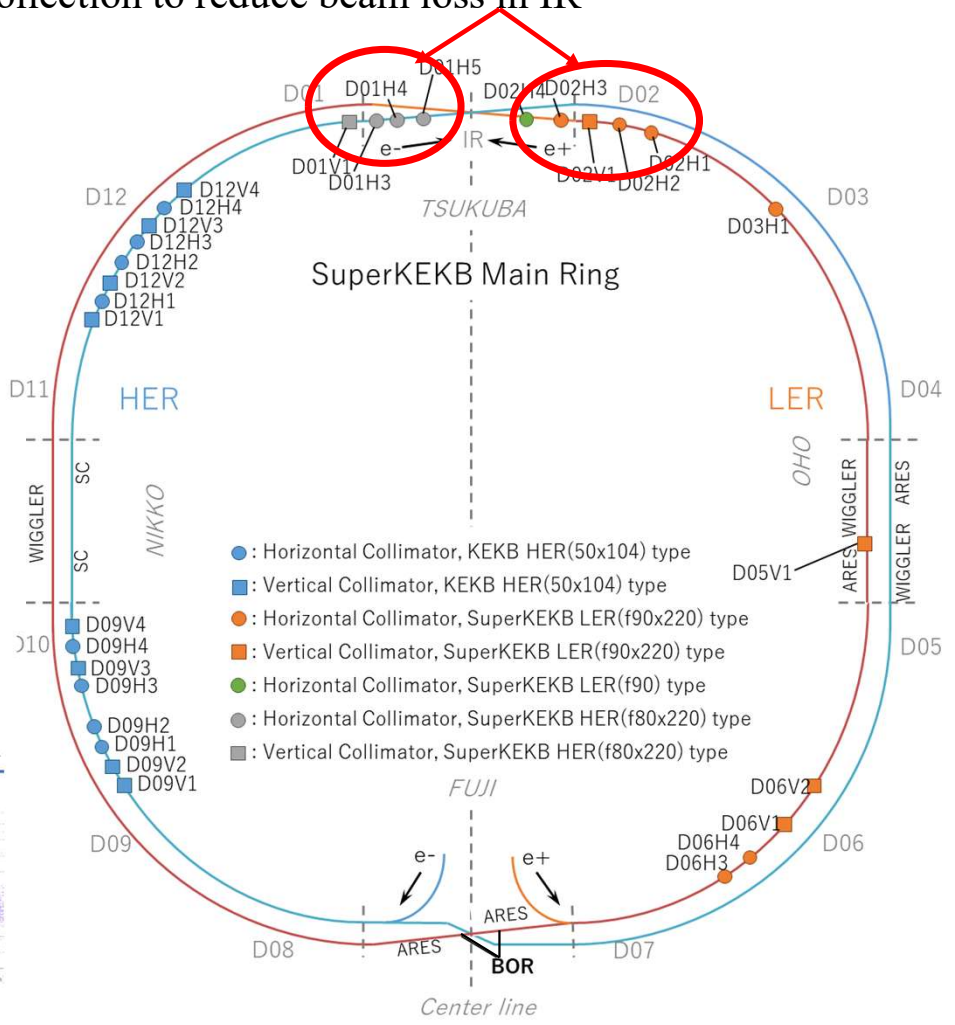
20211001_1mm_D2V1moved_sler_2021-07-01_

emit_x [nm] 2.10
emit_y [nm] 0.021
emit_y [nm] by XRM 0.046
Sigmay by XRM [um] 56.1
current [mA] 955

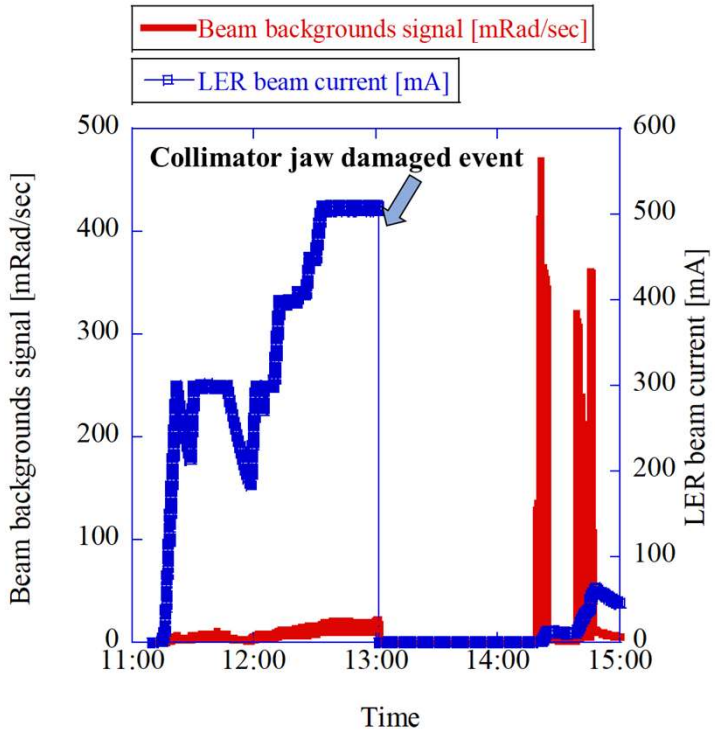
Dia QCSFW

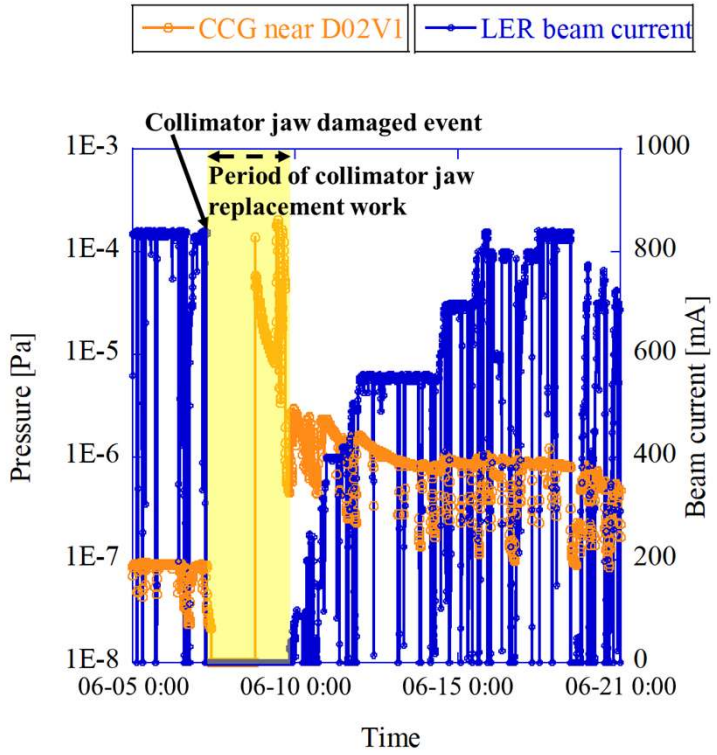


Collimators are also installed in the local chromaticity collection to reduce beam loss in IR



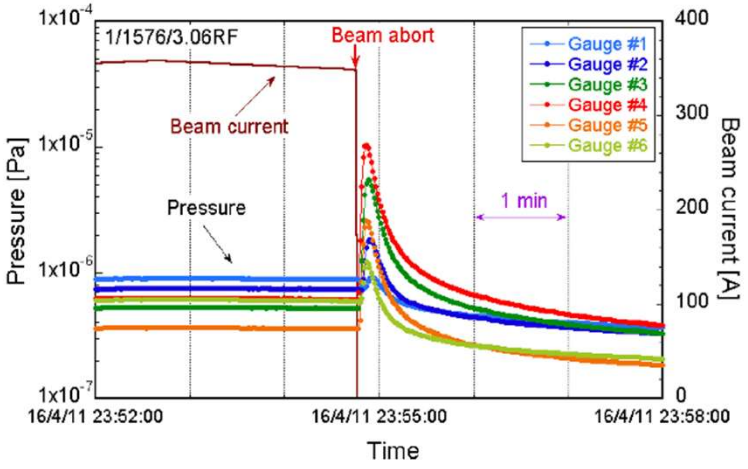
- **If the beam background becomes too large, it is not possible to apply HV to Belle. In such cases, the collimator jaws are replaced, but the pressure does not easily return to the pressure before collimator damage even after operation because of the atmospheric release process.**

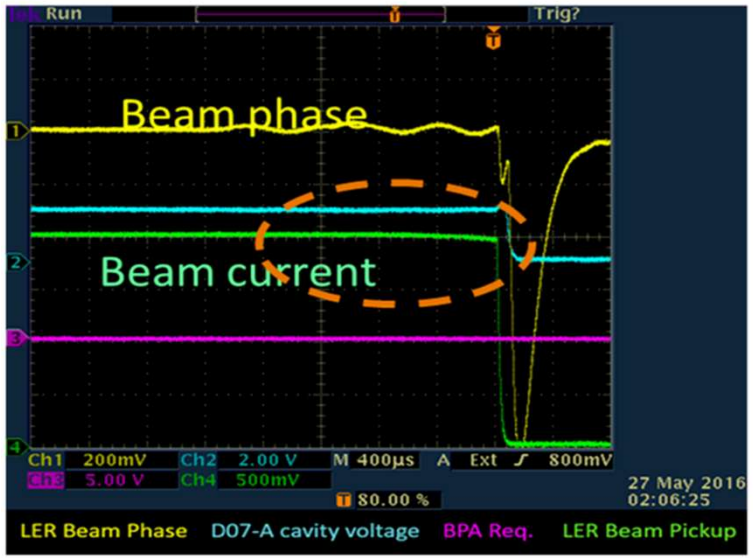


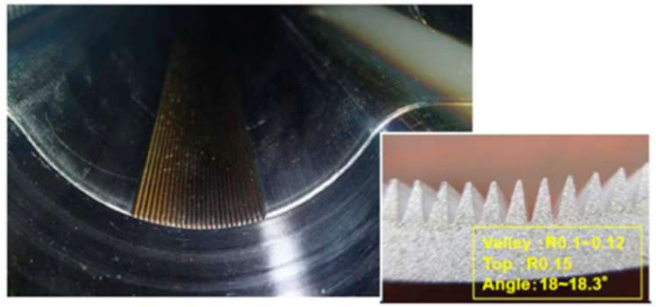


Dust event (our experience)

- 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).

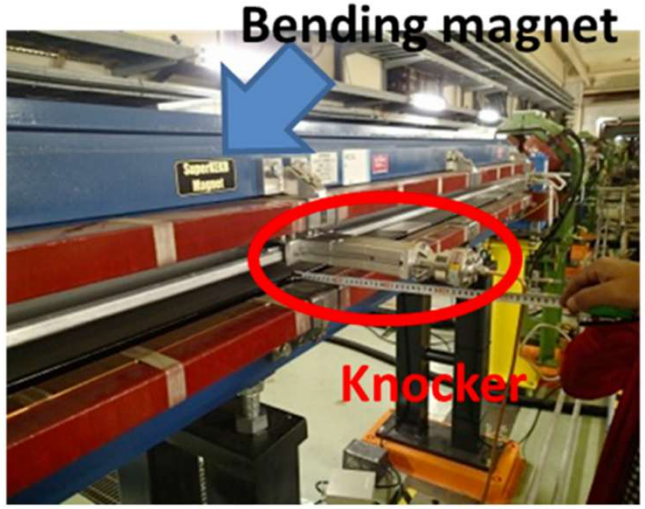


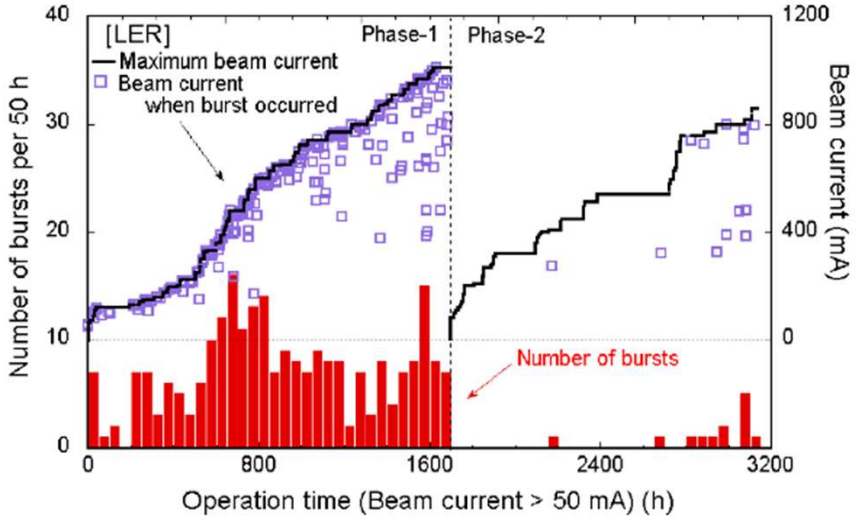




Dust event (our experience)

- 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.



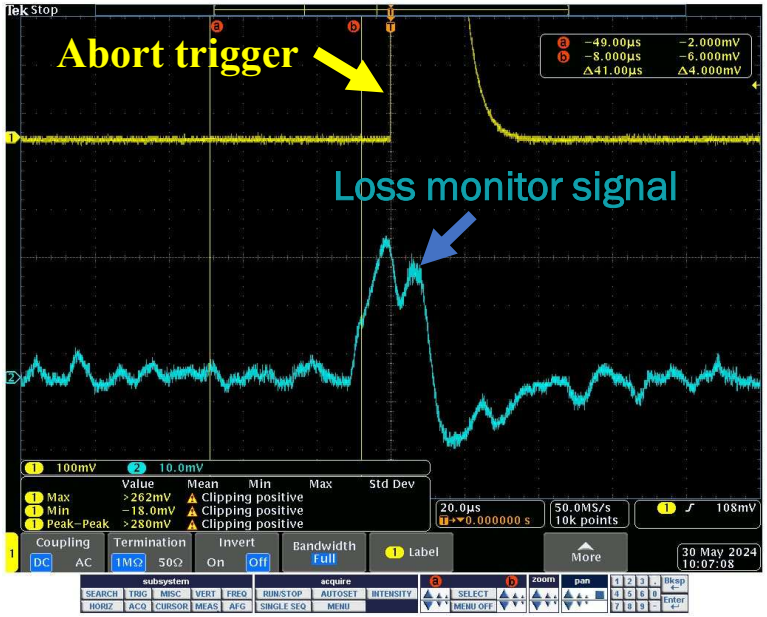


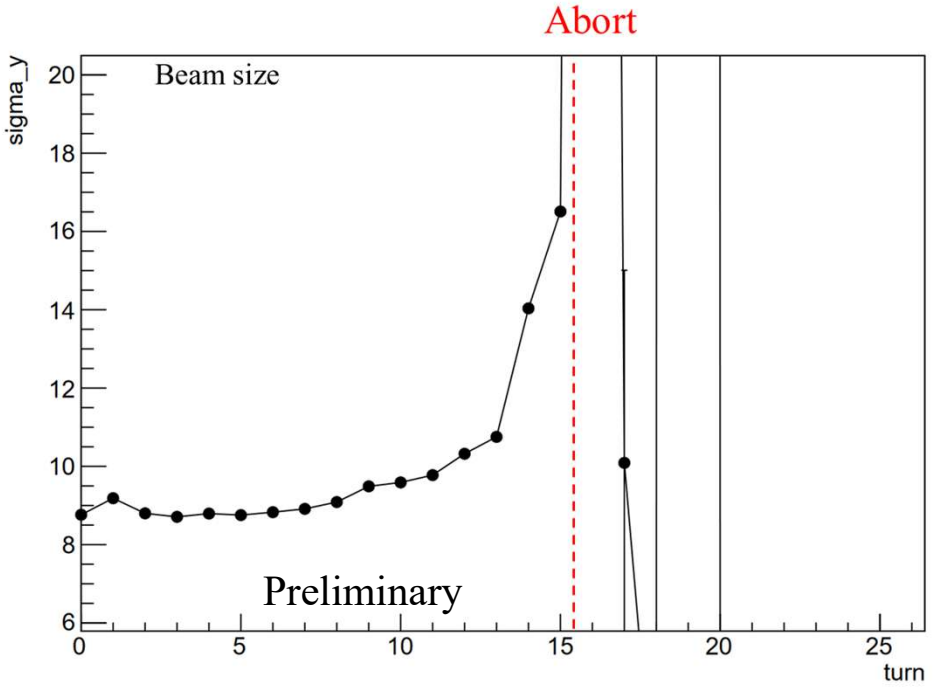
Similarities between SBL and dust event

- 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?

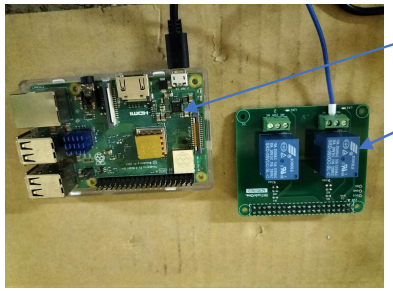
- **When the knocker study was performed at the wiggler section, losses were observed downstream of the knocker installation.**
- **An increase in vertical beam size was also observed. This beam size increase was not observed during manual abort.**

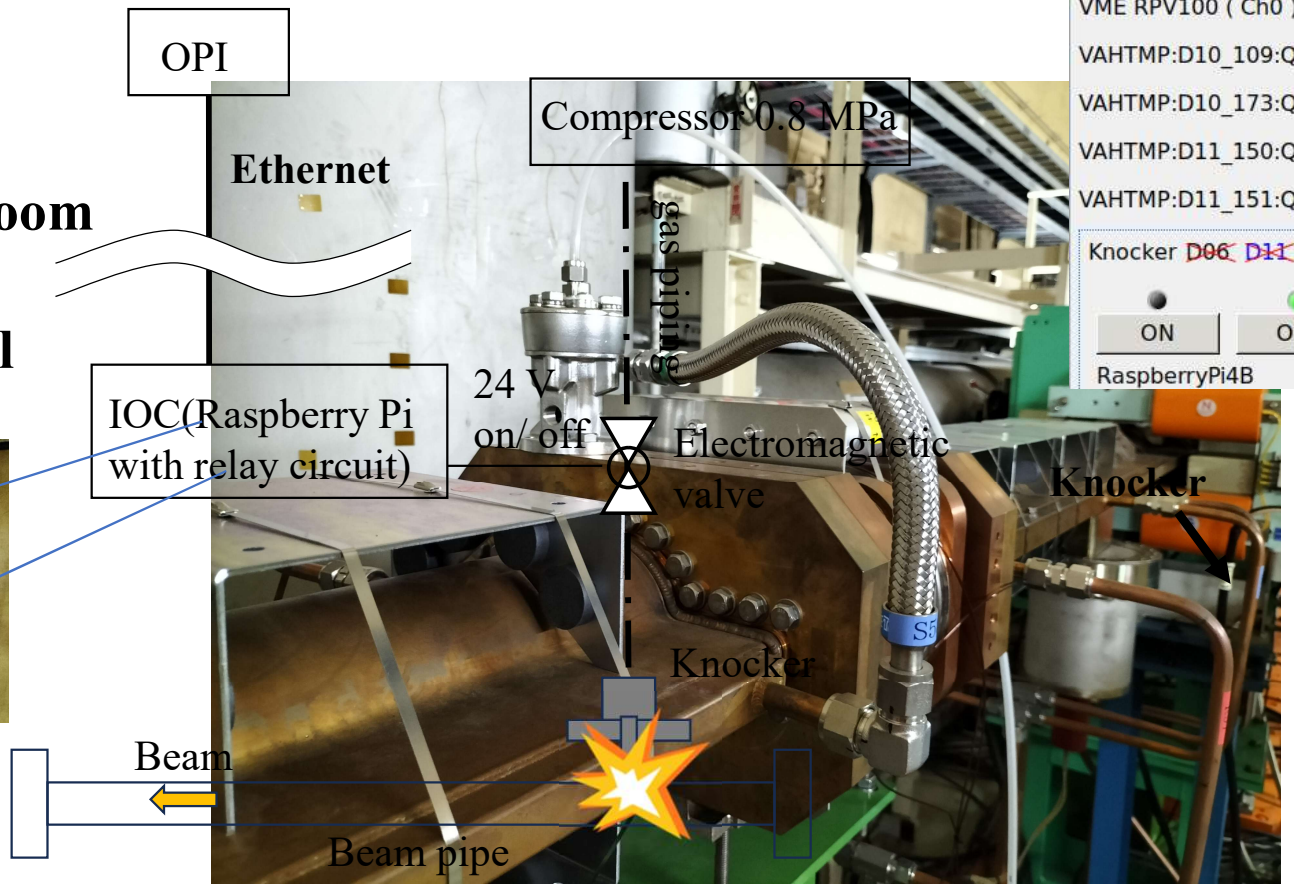




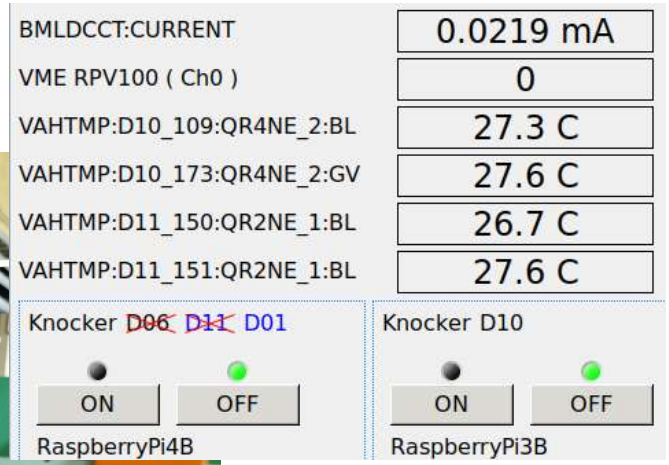
By G. Mitsuka

Introduction of knocker system



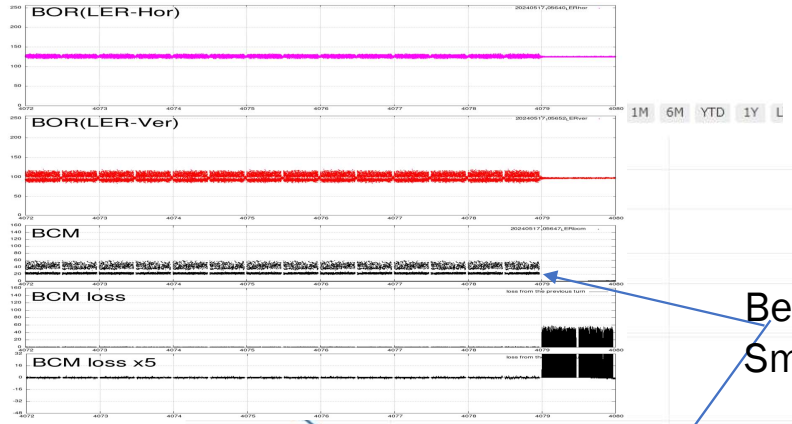


OPI



Aluminum beam pipe with grooves

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



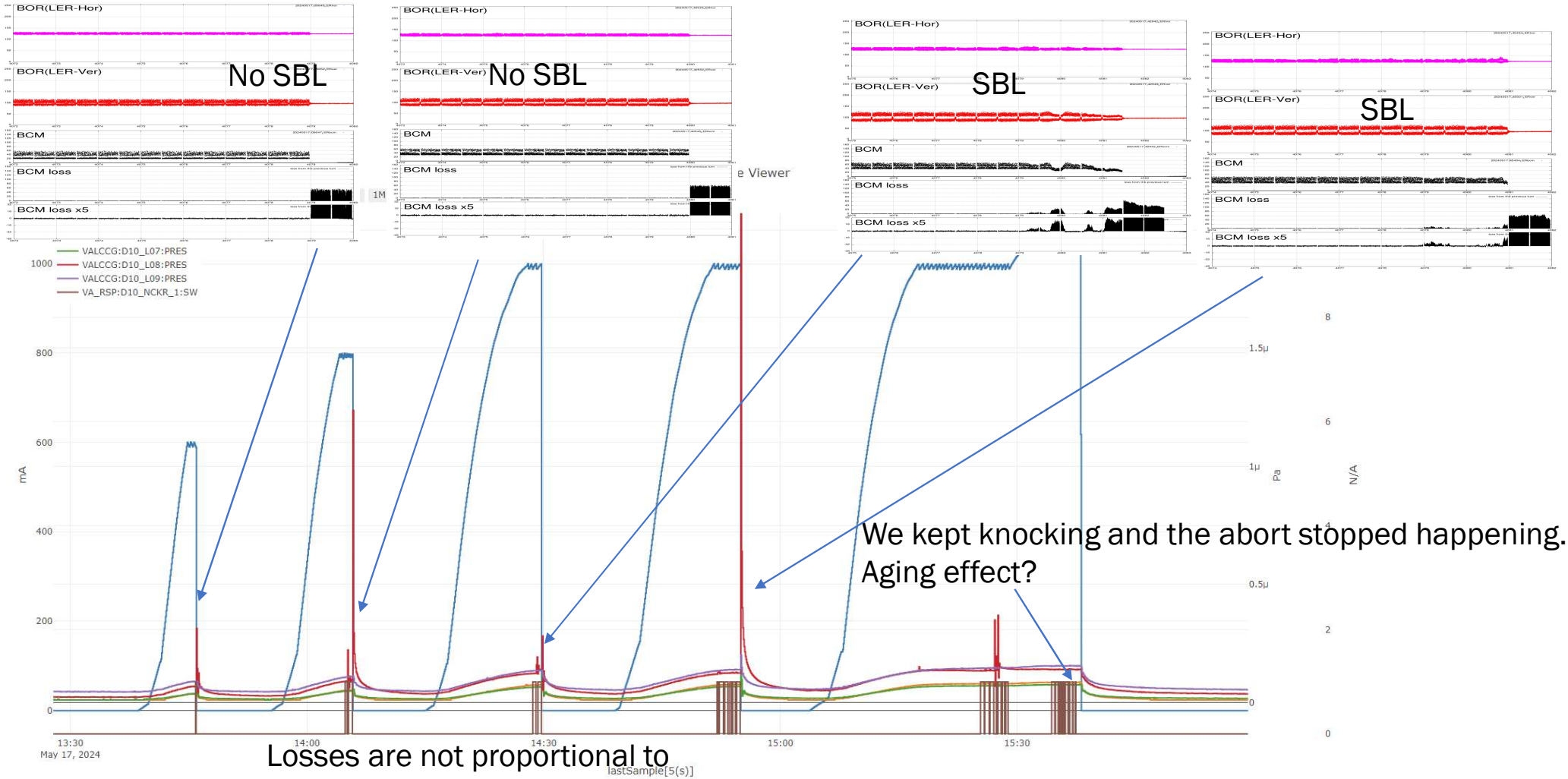
Later knocks had pressure bursts larger than the pressure burst at abort, but were not aborted.

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

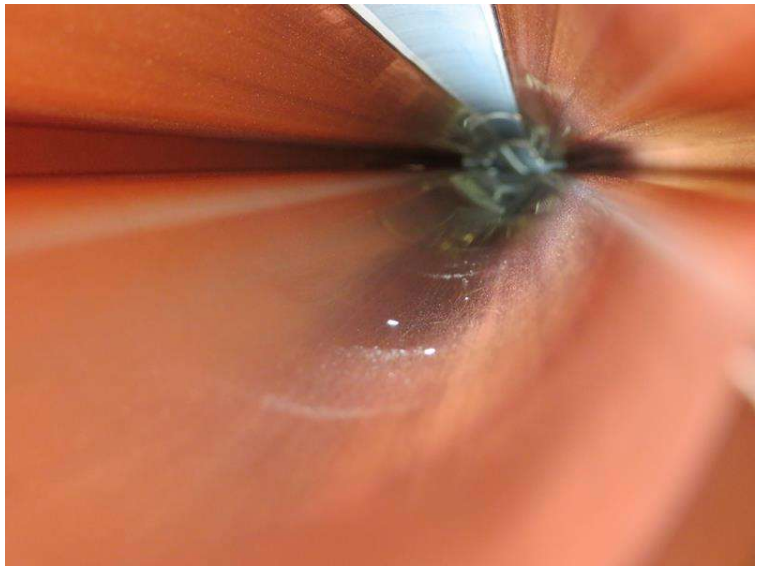


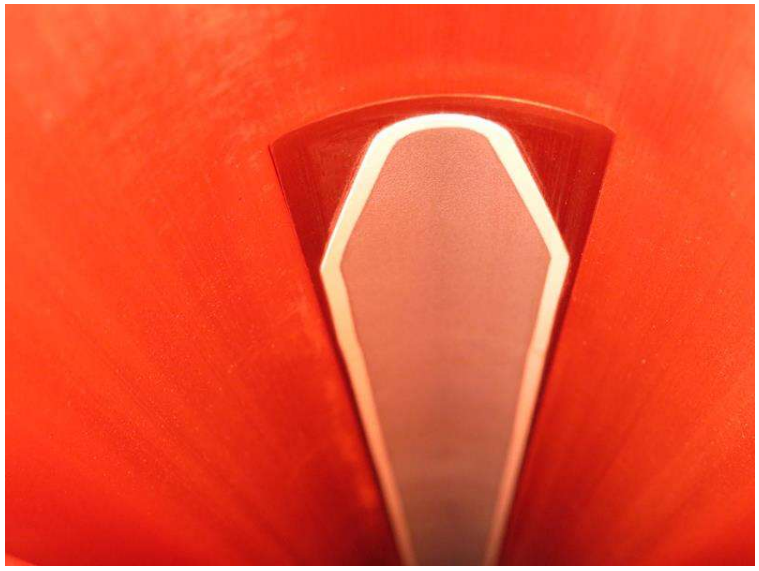
We kept knocking and the abort stopped happening.
Aging effect?

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

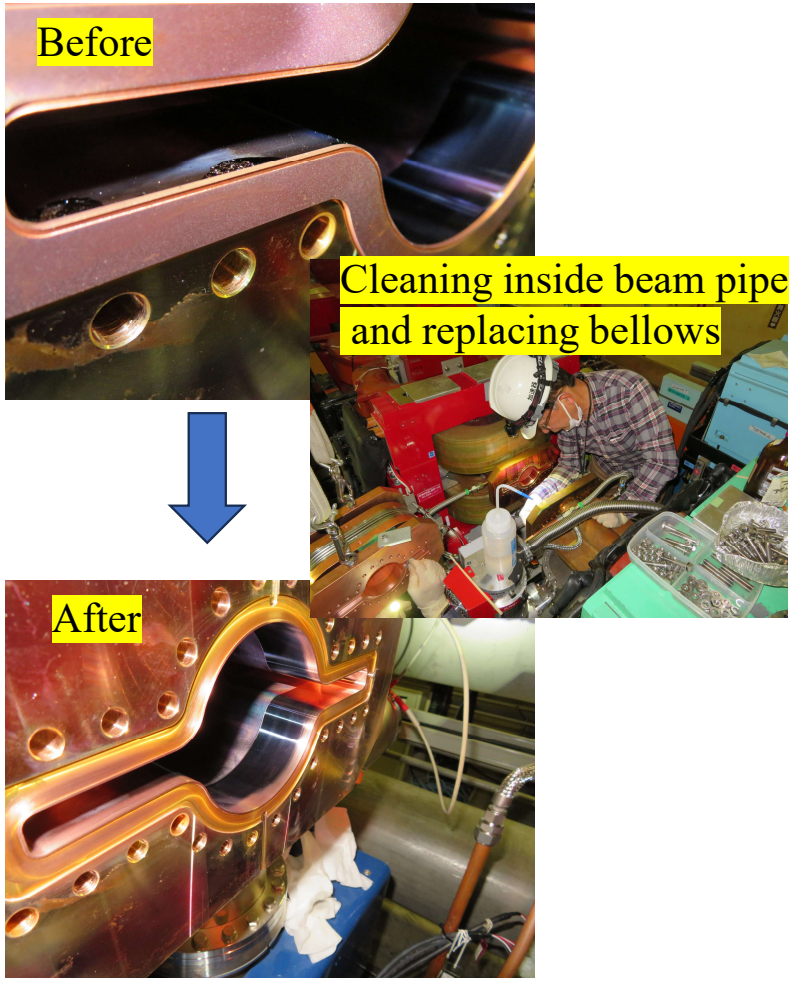
There seems to be a problem with the beam pipe with clearing electrode, so the vacuum group investigated in the experimental room with test-chamber （Chamber with electrodes taken out from tunnel at LS1).

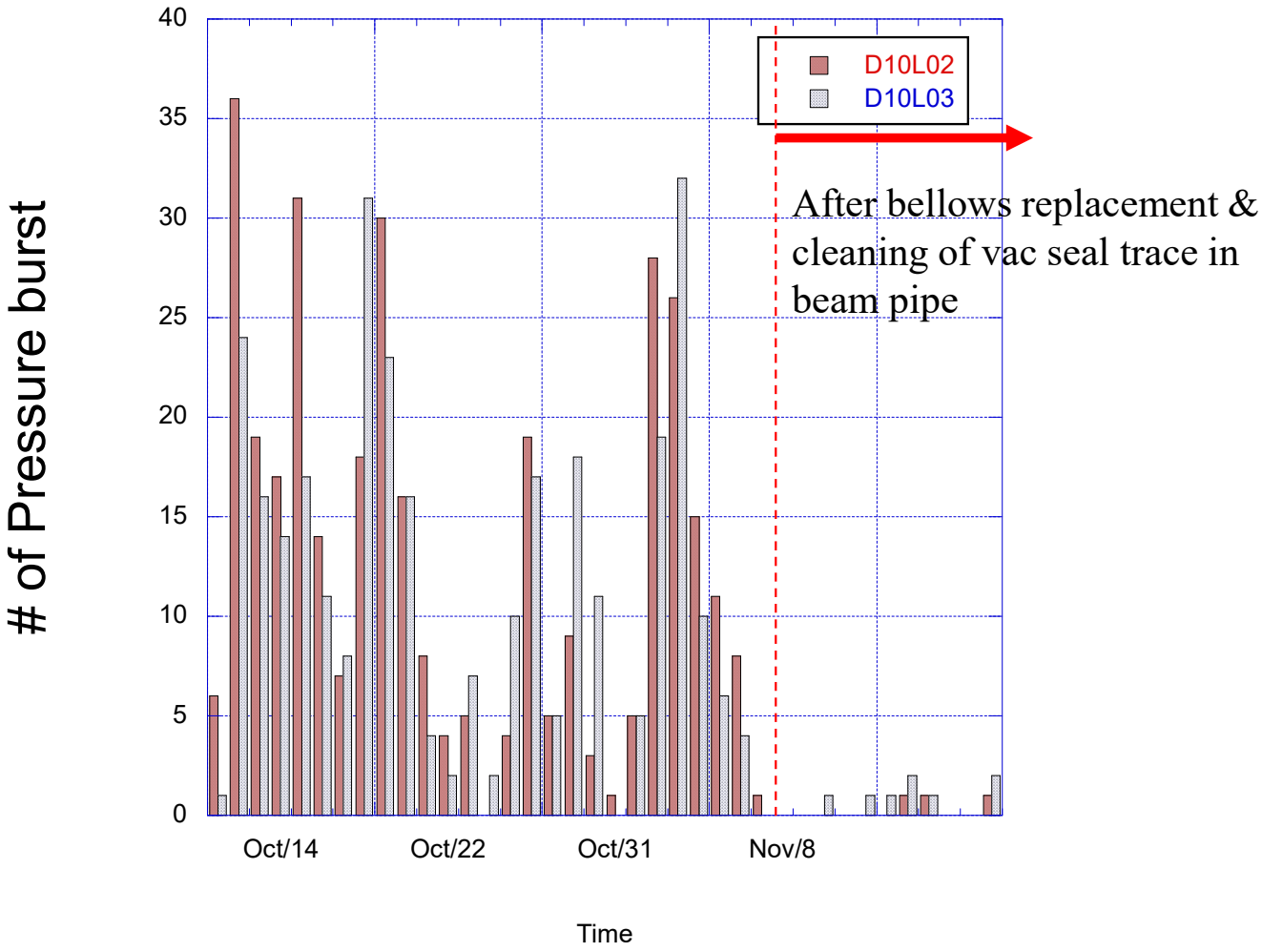
Dust from chamber gotten by knocking was sent for chemical analysis, but no tungsten was detected in the dust.





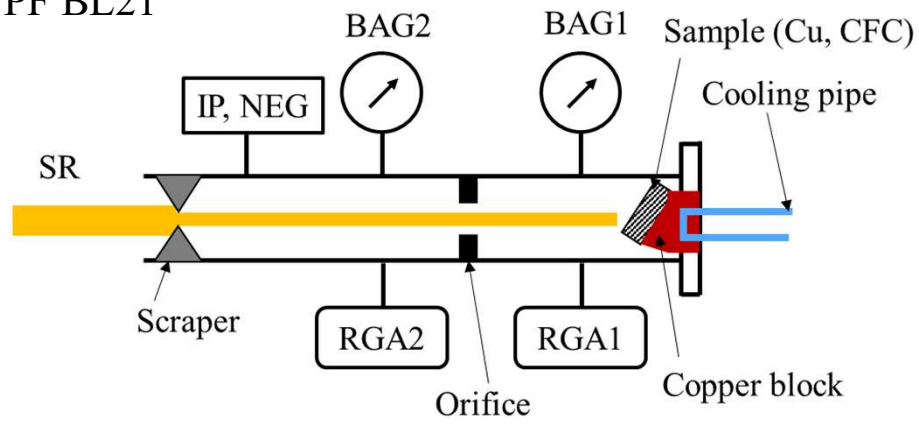
Studies and work performed during beam operation
-Bellows exchanged work and cleaning inside beam pipe



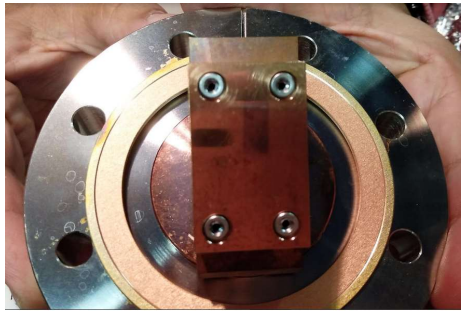


High-intensity synchrotron radiation irradiation test on vac seal coated surface. (Scheduled to be tested in the spring.)
Test to find out if multipactoring is likely to occur on vac seal coated surfaces. (Scheduled to be tested in the summer.)

High-intensity synchrotron radiation irradiation test on vac seal coated surface at PF BL21

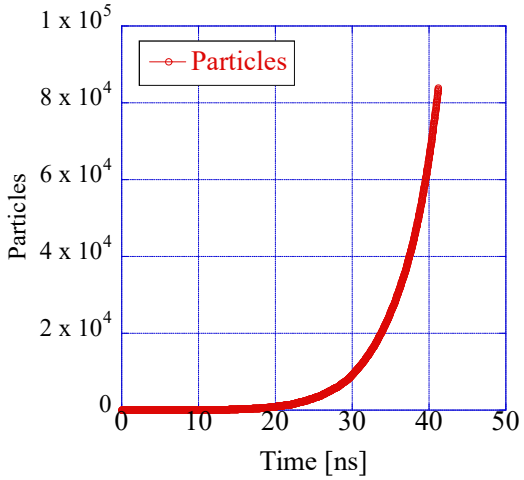


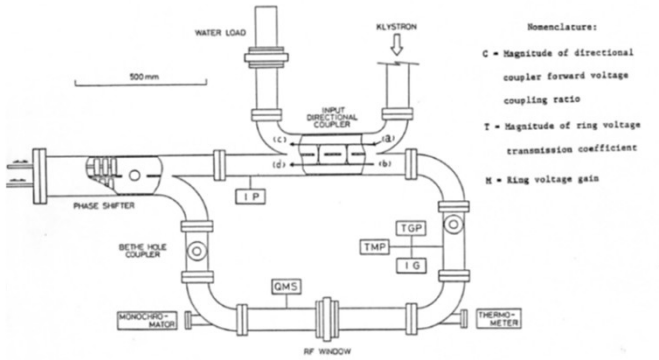
Jig fabrication for measurement has been done.

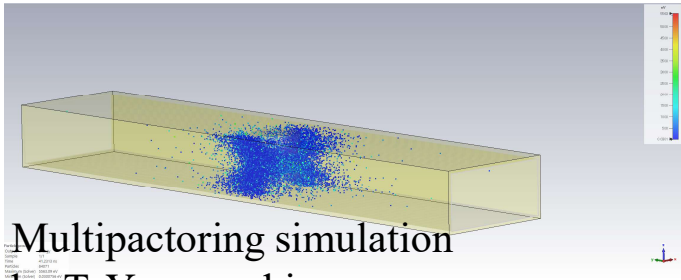


Test to find out if multipactoring is likely to occur on vac seal coated surfaces at S-band resonant ring.

Resonant Ring Design Parameters	
Freq	2856MHz
Circulated Power (Max)	300MW
Voltage (Power) Gain	4.61 (21.2)

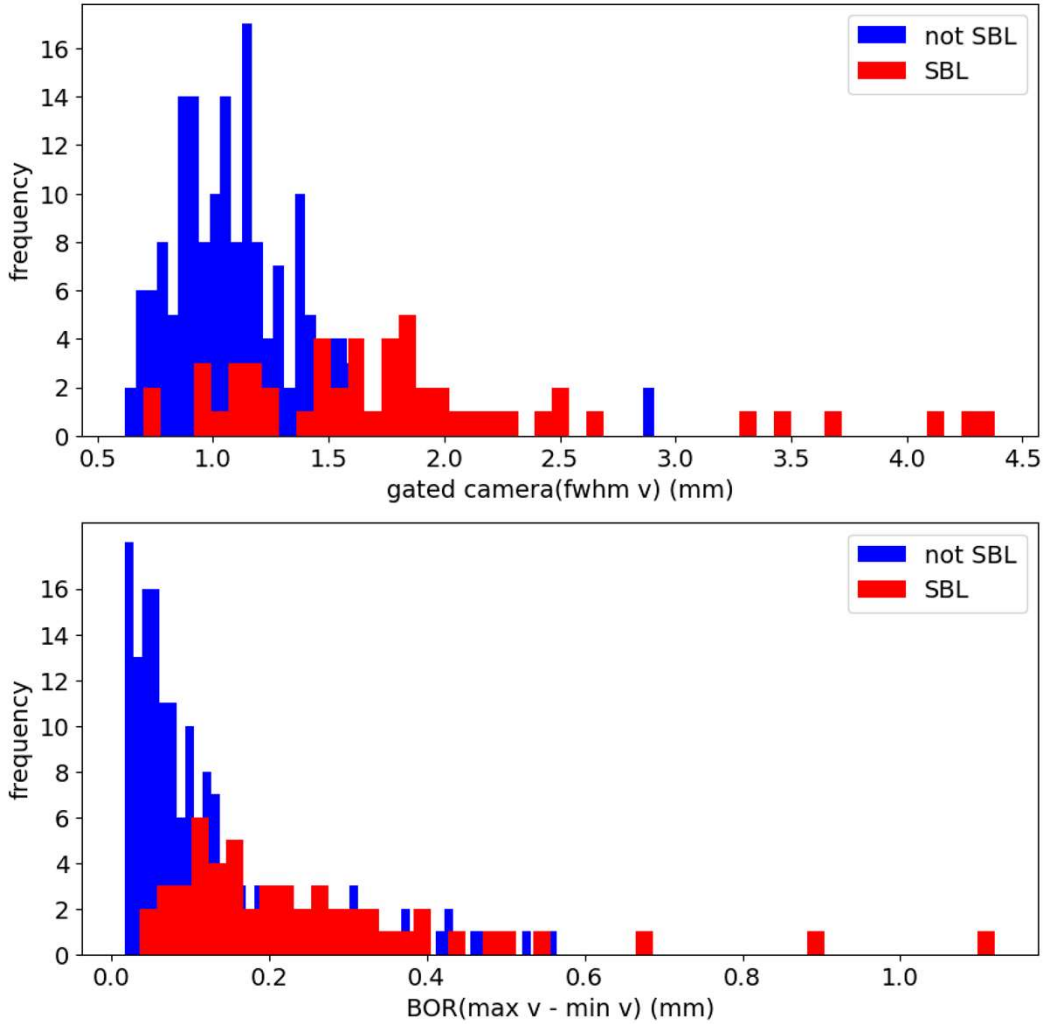






Multipactoring simulation by T. Yamaguchi

Frequency distribution



Correlation