Beam Abort Diagnosis

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2022/10/31 BPAC

Contents

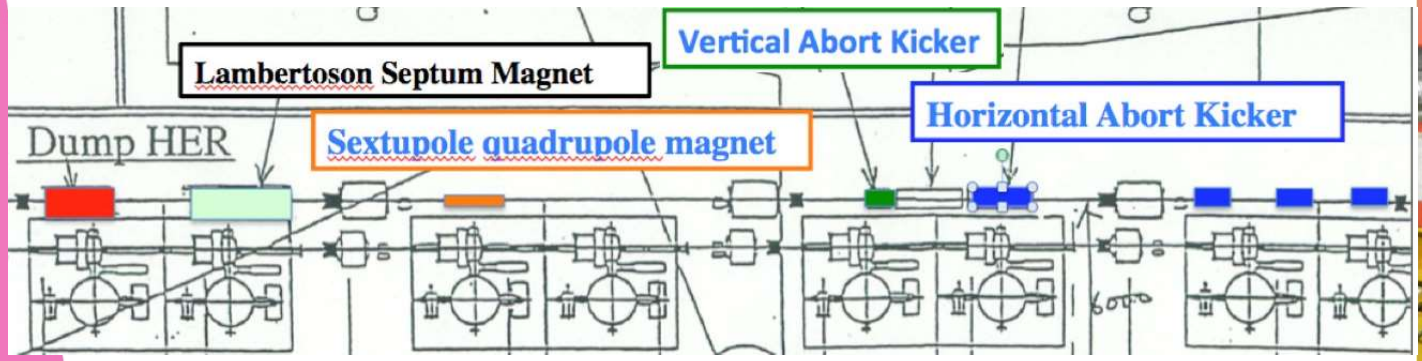
How can we protect the hardware components of the detector and the accelerator from the damage caused at high beam currents ?

↓

1. Abort the beam as soon as possible when the abnormal situation happen.
   - Improve Abort System
2. Investigate the cause of abnormalities in the beam and deal with them.
   - Abort diagnosis especially for Sudden Beam Loss

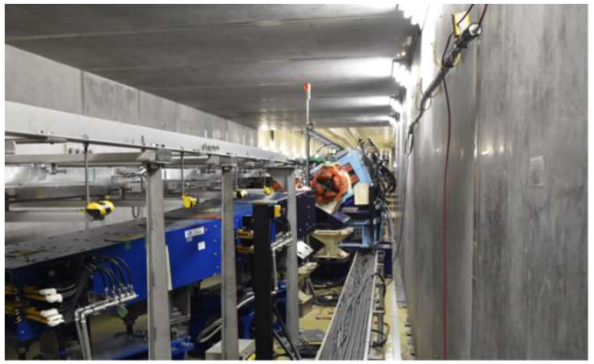
1. Abort System

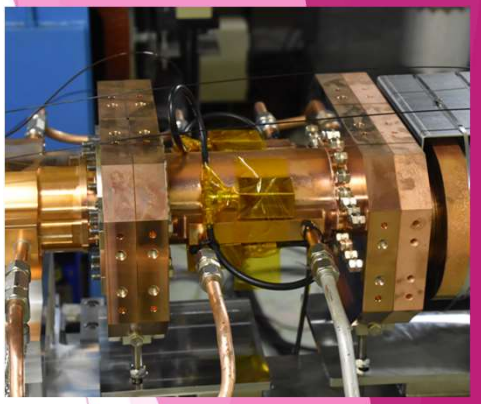
- In order to protect the hardware components against the high beam currents, we installed the controlled abort system.
- The beam is kicked by an abort kicker, taken out of the vacuum chamber through an abort window made of Ti, and throwed into a beam dump.
- Dumped beam length : one revolution time (10 μs).
- Build-up time of the abort kicker magnet : 200 ns (empty bucket space).
- Synchronization of the kicker timing and the abort gap is required for the protection of hardware.

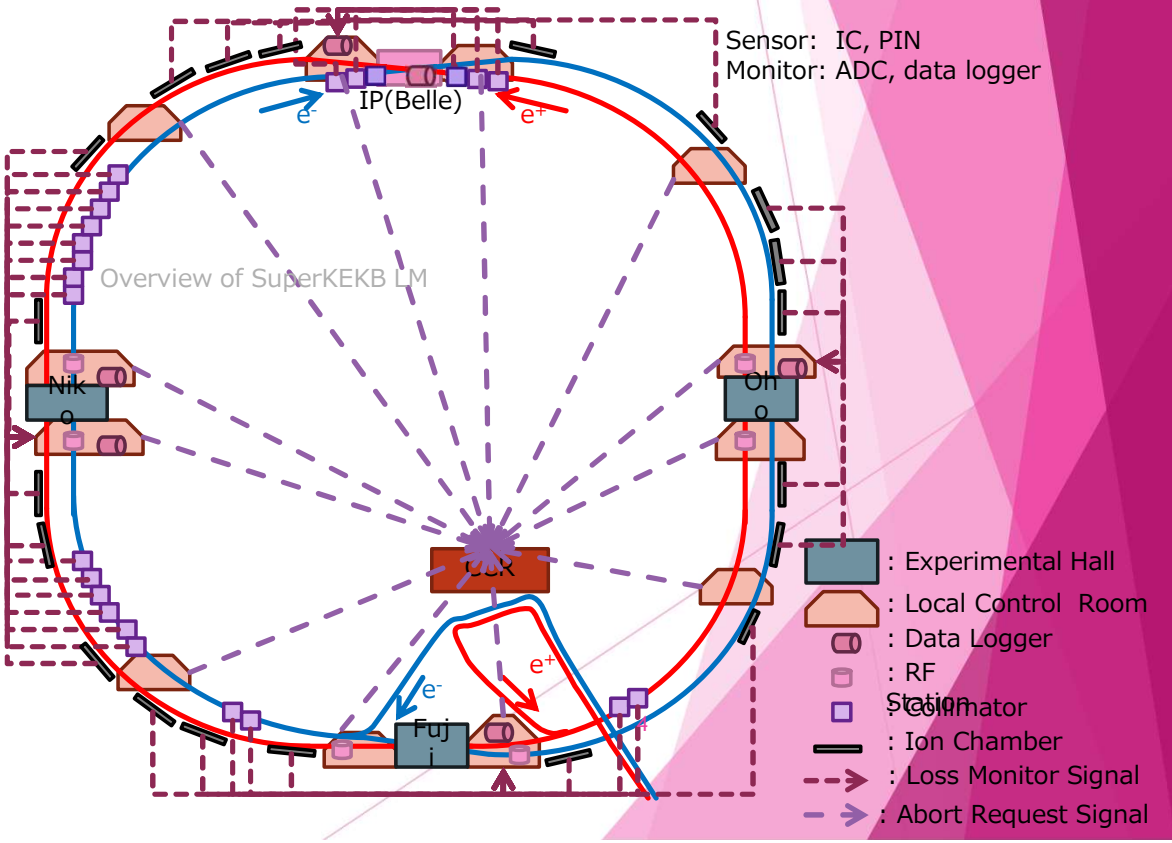


Loss Monitor System

- Measure the beam loss
- Used for
  - triggering the beam abort kicker
  - tuning and analysis of the beam operation
- No. of Sensors : 200
- Ion Chamber: Cover a wide range in space.
  - Put to cable lack of all over the tunnel to cover a wide range in space.
  - Free Air Ion Chamber (20D co-axial cable)
- PIN photo diode: Fast response and identify the ring in which the beam loss occurred.
  - Trigger generation time for beam abort in integrator : <2μs
- Optical Fiber ←New !

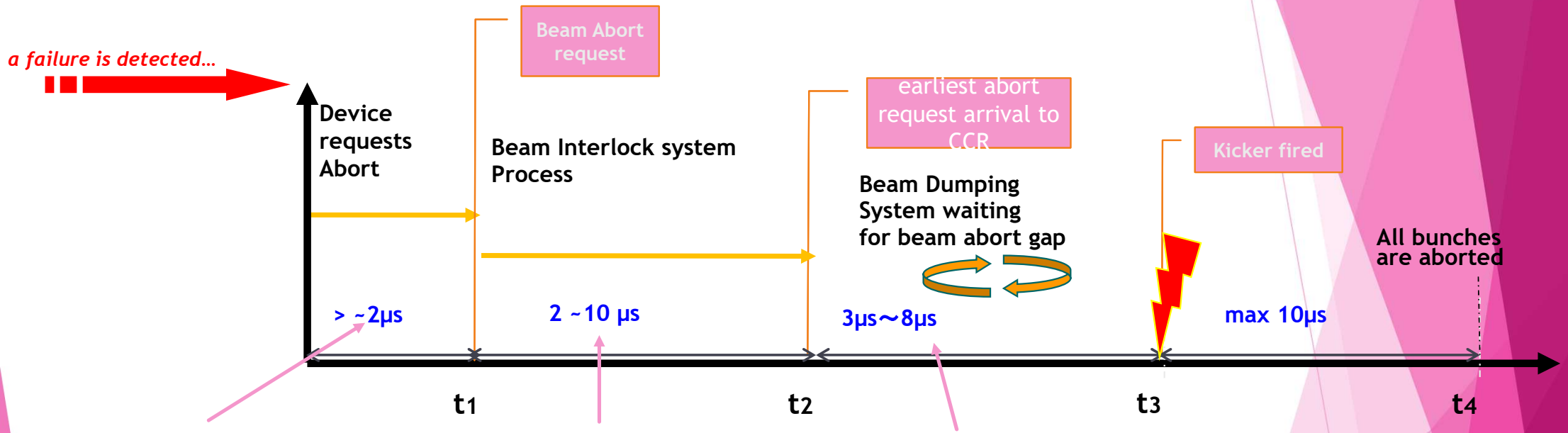






Abort Trigger Delays

We minimized abort trigger time to protect the hardware damage.



Hardware dependent

To summarize the abort request on the beam abort system.

Depends on the optical cable length from the local control room to CCR.

Synchronization of the abort request signal with revolution/2 in FPGA. : Max delay=5μs

Delay to synchronize to the abort gap(fixed delay) : ~ 0μs

Delay from CCR to kicker (400m) : 2μs

Thyratron ON :1μs

Rise time for the kicker : 200ns

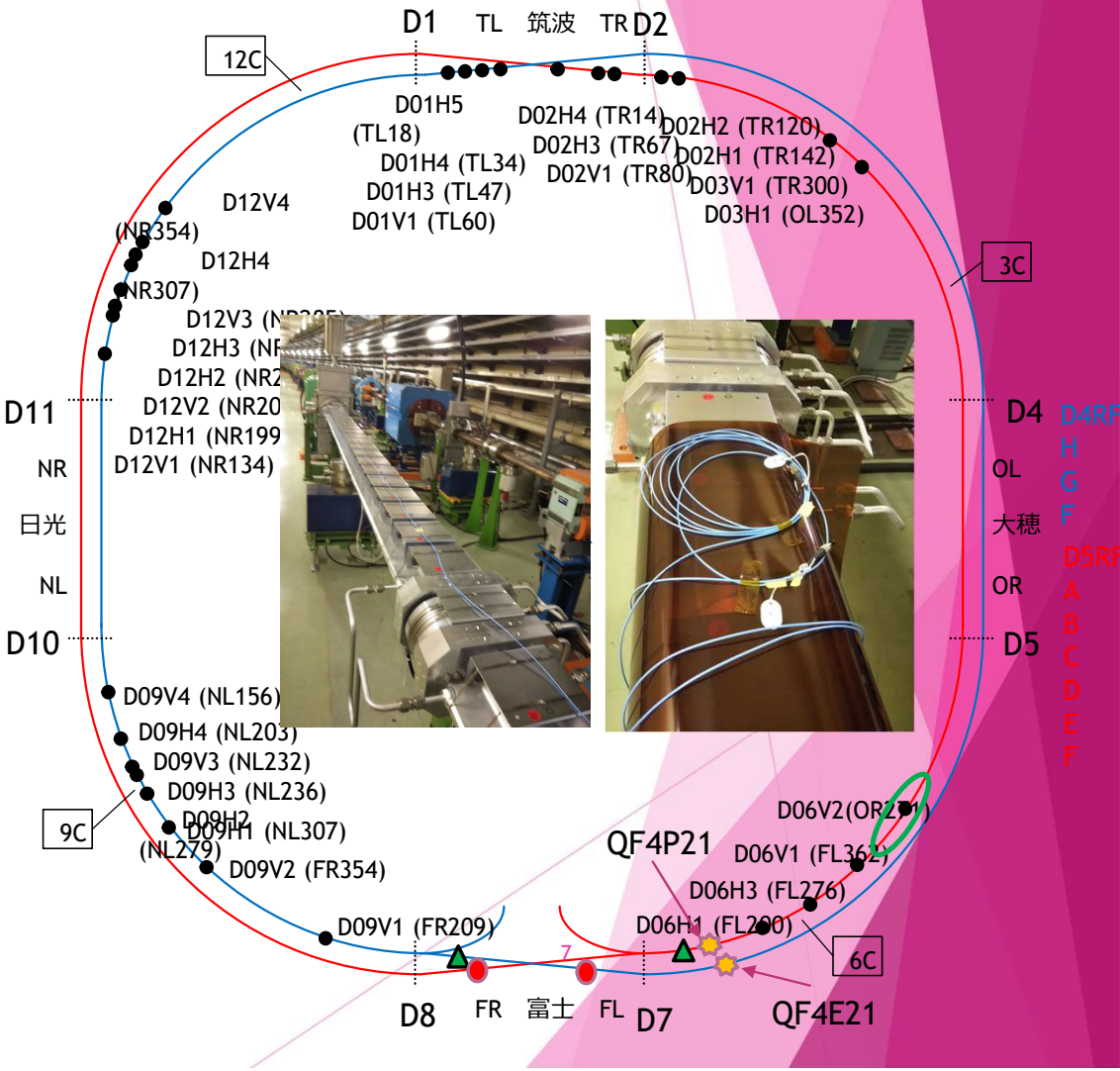
Minimum Abort Delay = 17~30μs

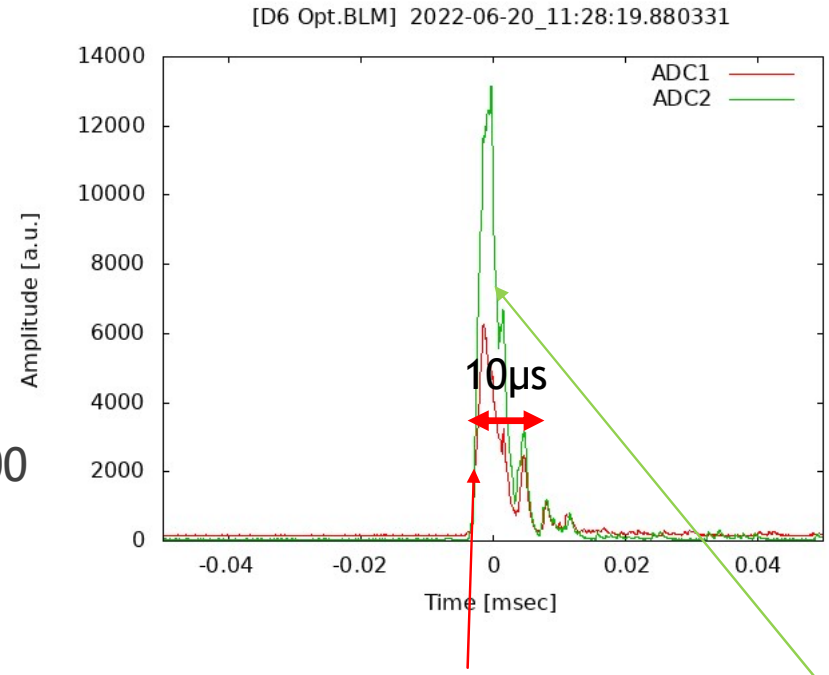
Minimize “Abort Trigger Delays”

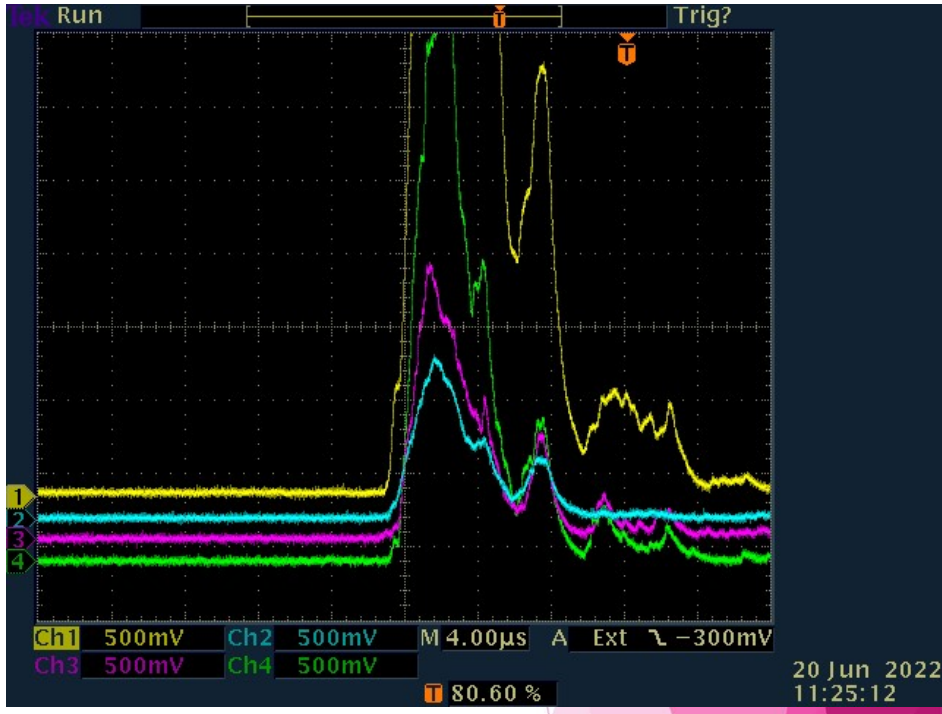
- Introduced the injection veto system to PIN beam loss monitor for collimator to set lower threshold and the abort trigger can be issued quickly.
- Changed the signal route of the loss monitor installed at the downstream of one collimator that frequently issues abort triggers.→the abort trigger can be sent out earlier.
- Introduced new loss monitor near the abort kicker.
- minimized delay to synchronize to the abort gap.
  - removed unnecessary fixed delays
  - increased the abort gap in the beam train from one to two.

New sensor : Optical fiber

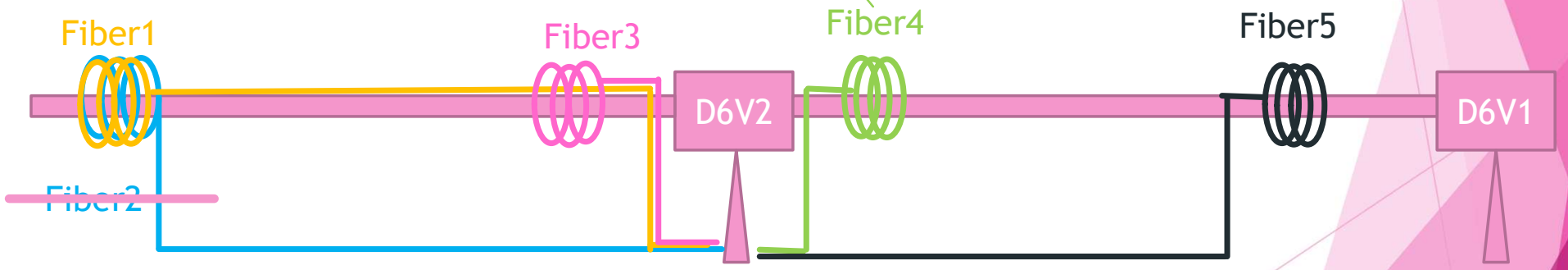
- The cause of the beam loss is unknown, but when the loss occurs, abort requested from the LM of downstream of collimator, Belle diamond, CLAWS, and also RF arc sensor.
- Since the loss monitor signal is sent to five LCRs around the ring, the cable length is not the shortest.
- In order to send abort signals at the minimum distance, a optical fiber was laid from the D6 power supply building to D6V2. After that, a single optical fiber is connected and extended upstream and downstream.
- The cable is input to PMT module and converted to electrical signals.
  - Capture/save waveform data
  - Trigger output by event detection (abort trigger)





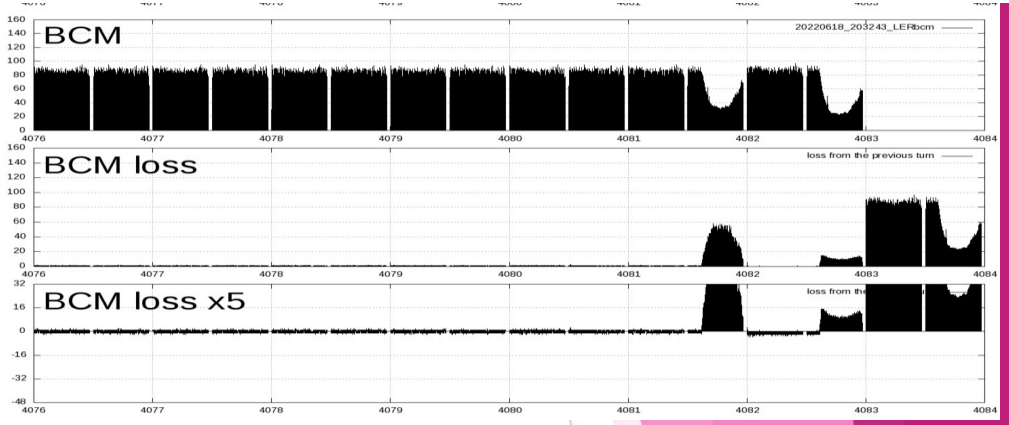


- Threshold=1000
- ADC1 wid=3us
- ADC2 wid=5us



The time to issue the abort trigger has become several μs faster.
After installing the fiber loss monitor, this abort trigger was mainly the first to fire.

2. Sudden Beam Loss



- The biggest goal of SuperKEKB is to increase luminosity, but one of the obstacles is sudden beam loss.
- The cause of the sudden large beam loss is unclear.

→ Causes collimator (and other component)damage, QCS quench, Large B.G. to Belle-II.

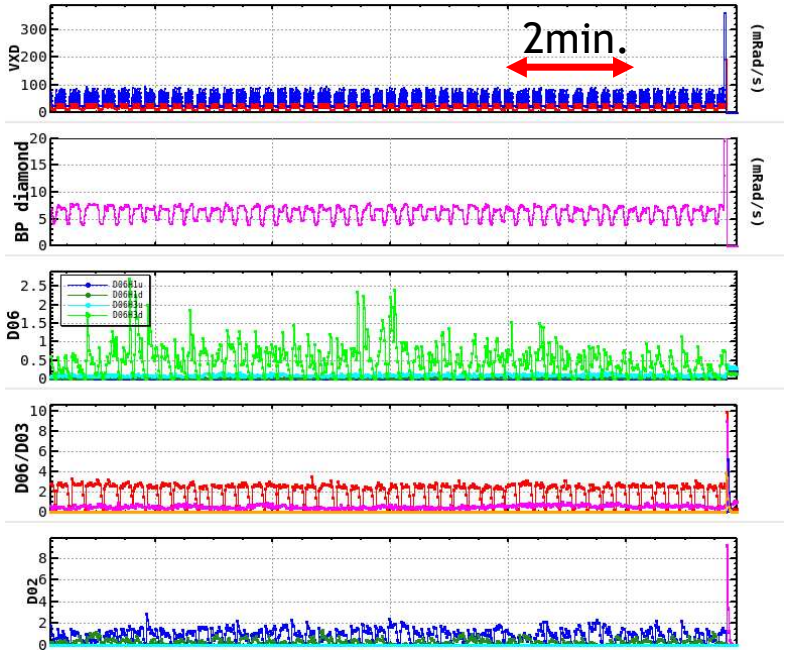
→ Cannot storage a large current since it causes beam abort.

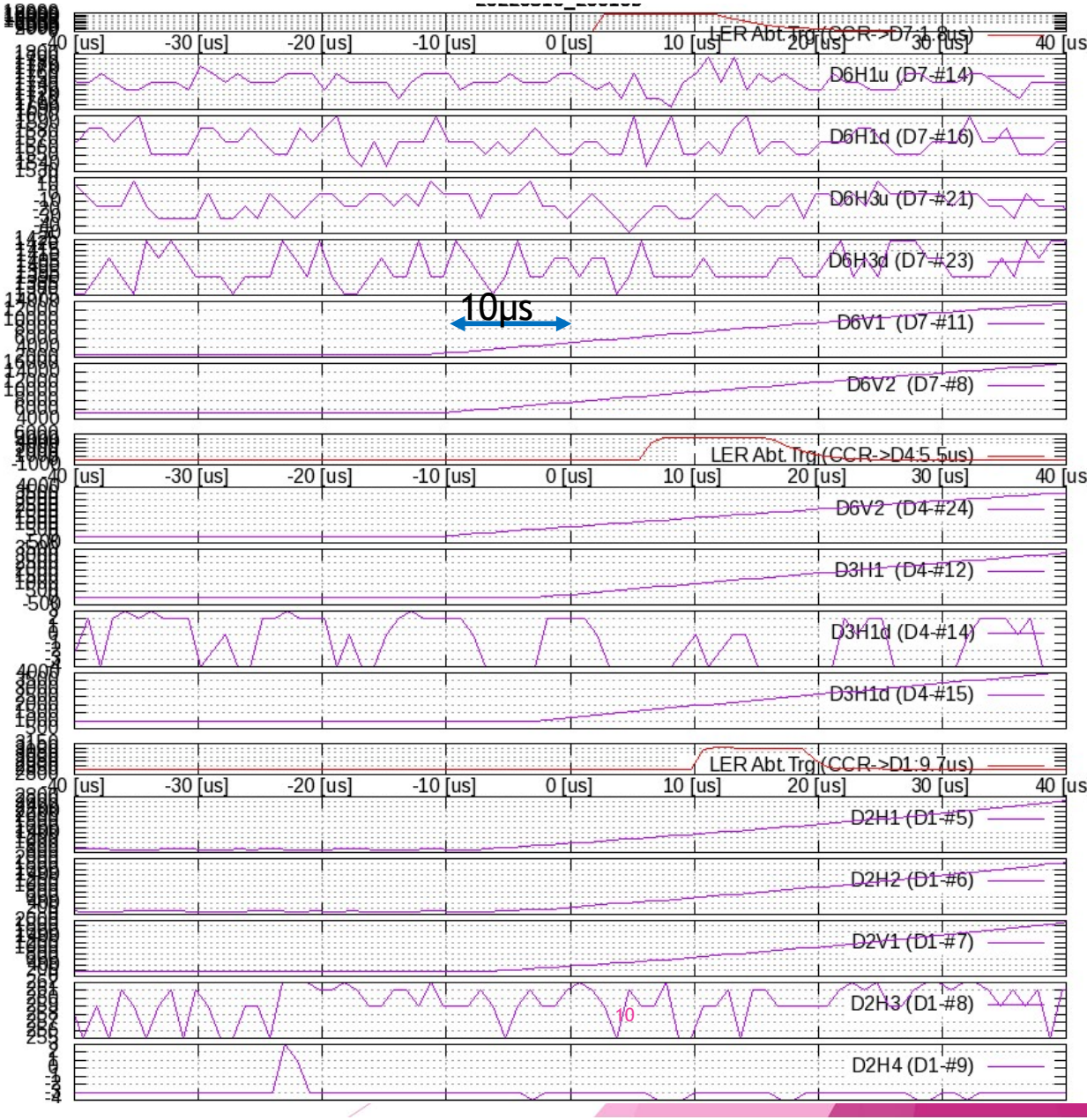
↓

- Start the international task force to investigate and resolve the cause of the **"sudden beam loss"**.

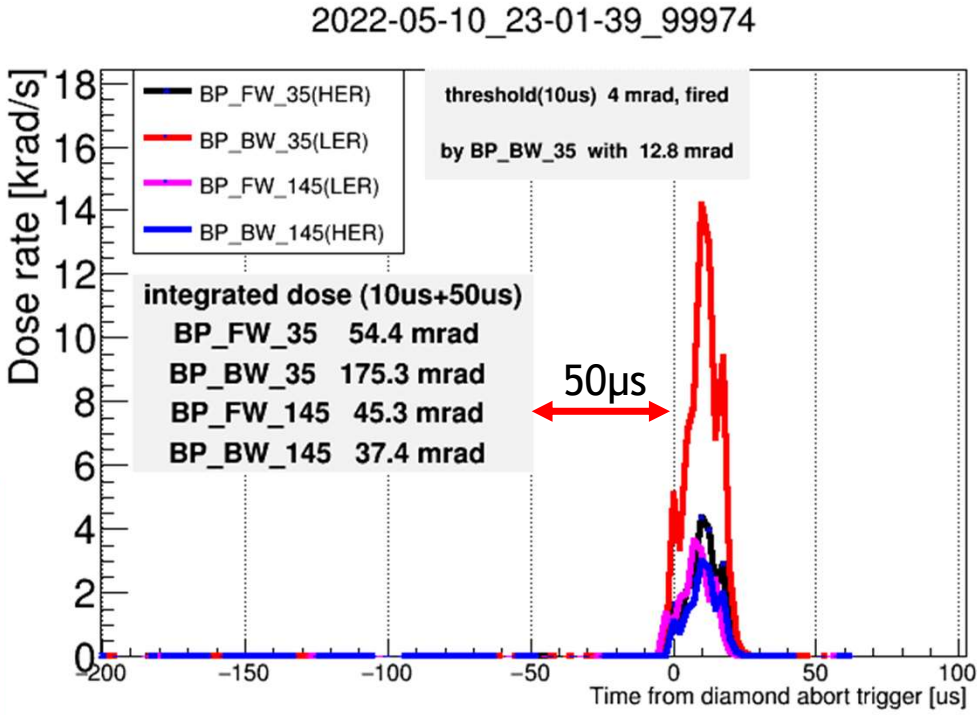
Observations : LM

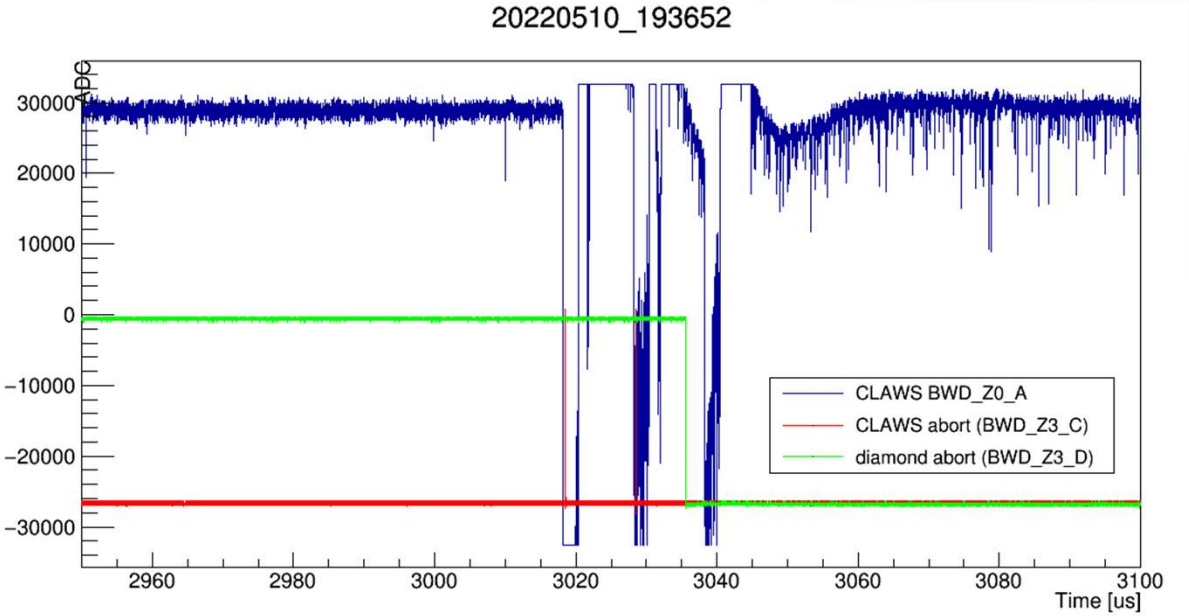
When we looked at the loss monitor when the abort occurred, which was thought to be caused by beam loss, beam loss looks started within one turn at the whole ring collimator part and Belle-II detector.





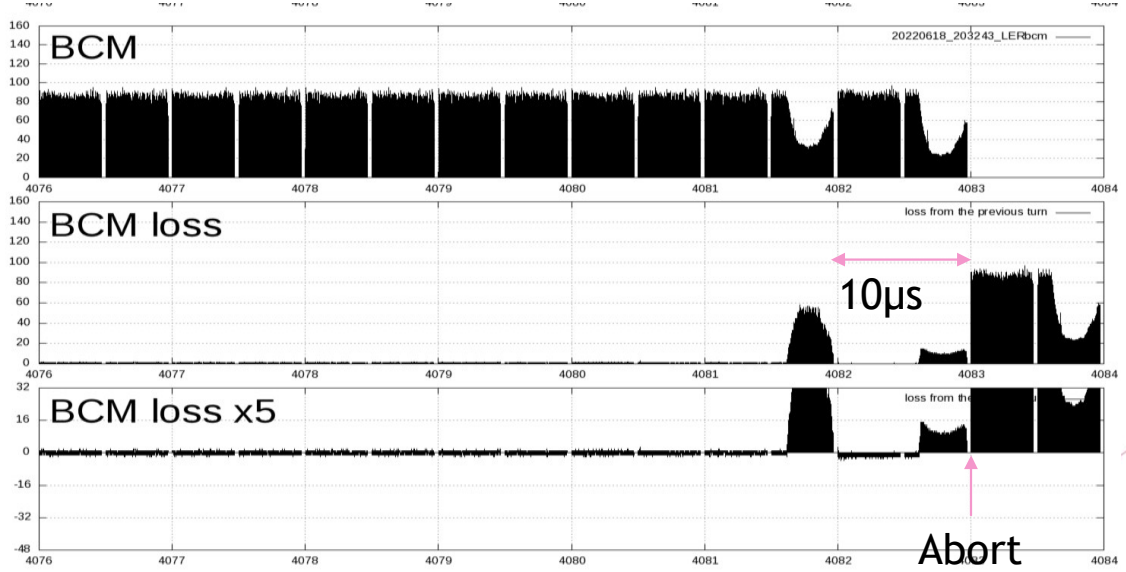
Observation : Belle dose

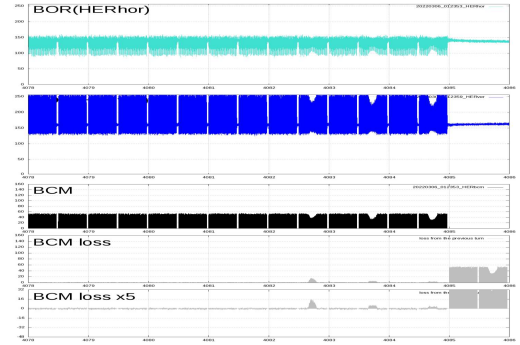


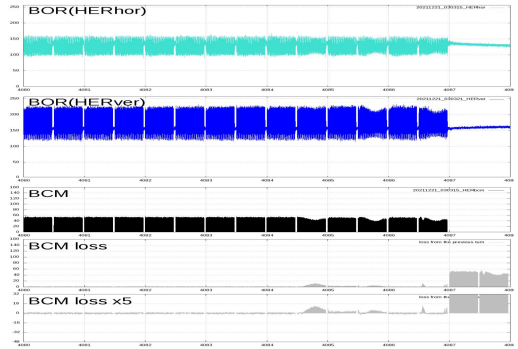


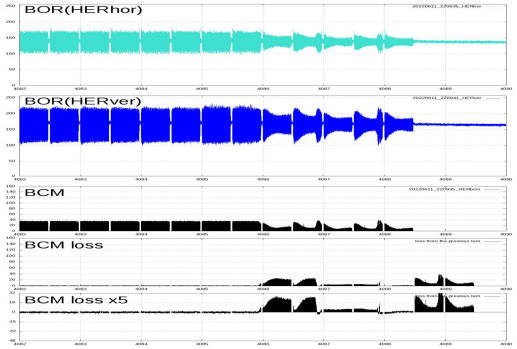
Observations : Bunch Current Monitor

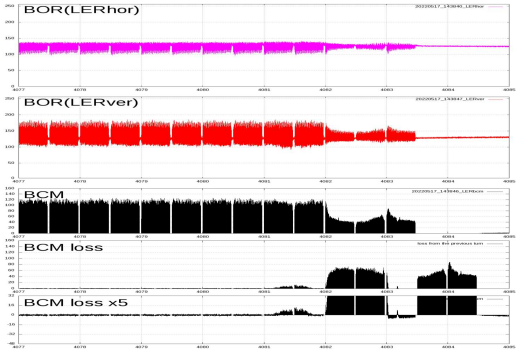
- In order to investigate where in the train the beam loss started at the moment of beam loss, we recorded the bunch current 4096 turns before the abort trigger using feedback processors .
- Beam loss has been measured by bunch current monitor (BCM) to occur suddenly on a certain turn.

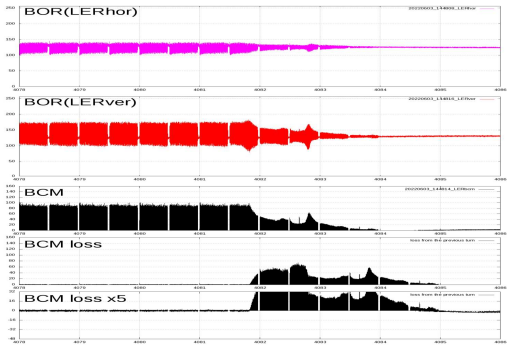


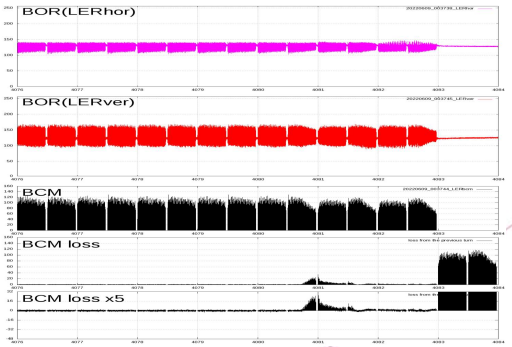








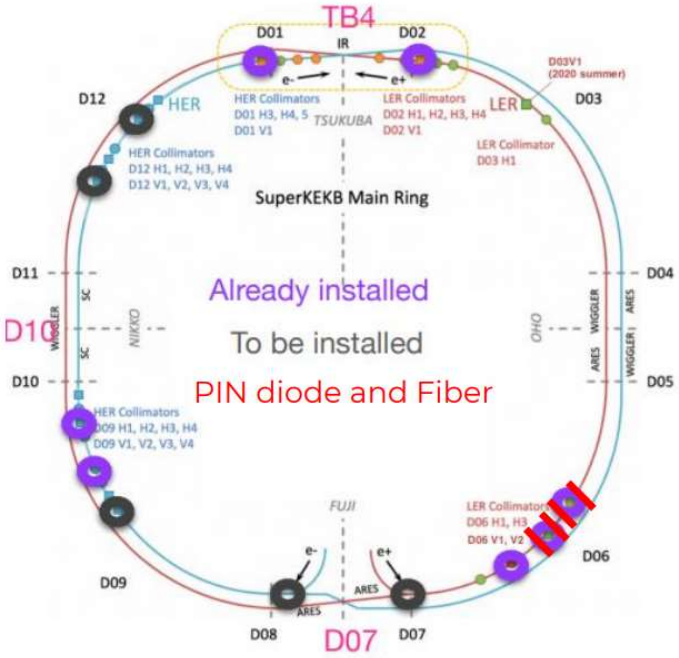


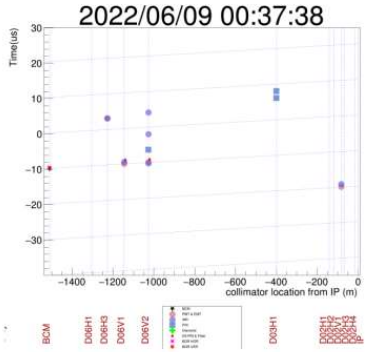


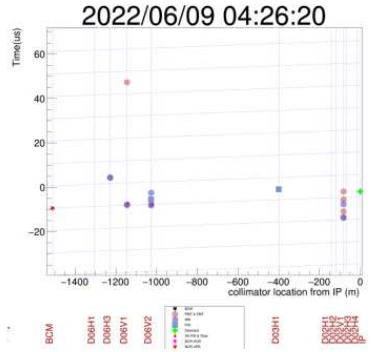
- Beam loss occurs in both HER and LER, but the damage to the hardware is particularly large when loss occurs in LER.
- We don't know if it will happen even with a single beam operation, low current beam because we haven't operated for a long time.

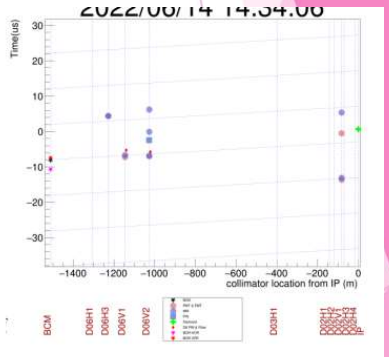
Observations : Beam Loss Timing

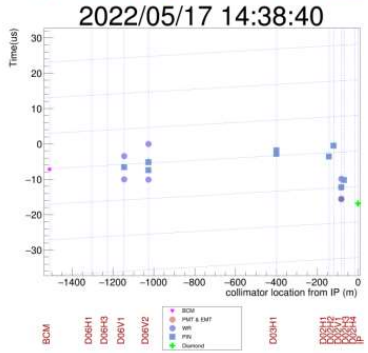
- In order to find out where in the ring the beam loss first started, we installed a loss monitor specialized for timing measurement inside the ring.
- Beam loss occurs in collimator & IR, and where it occurs first depends on collimator tuning .

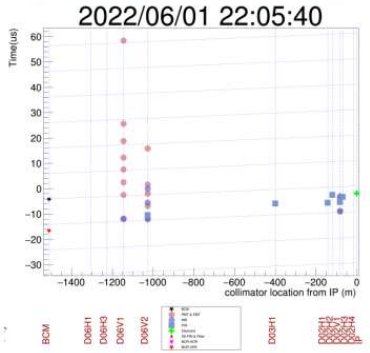


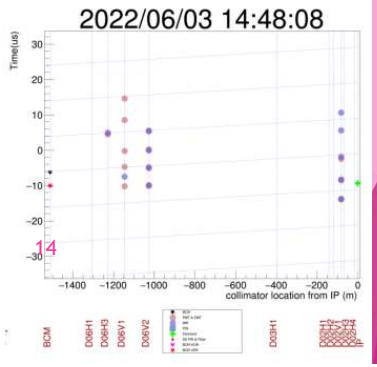








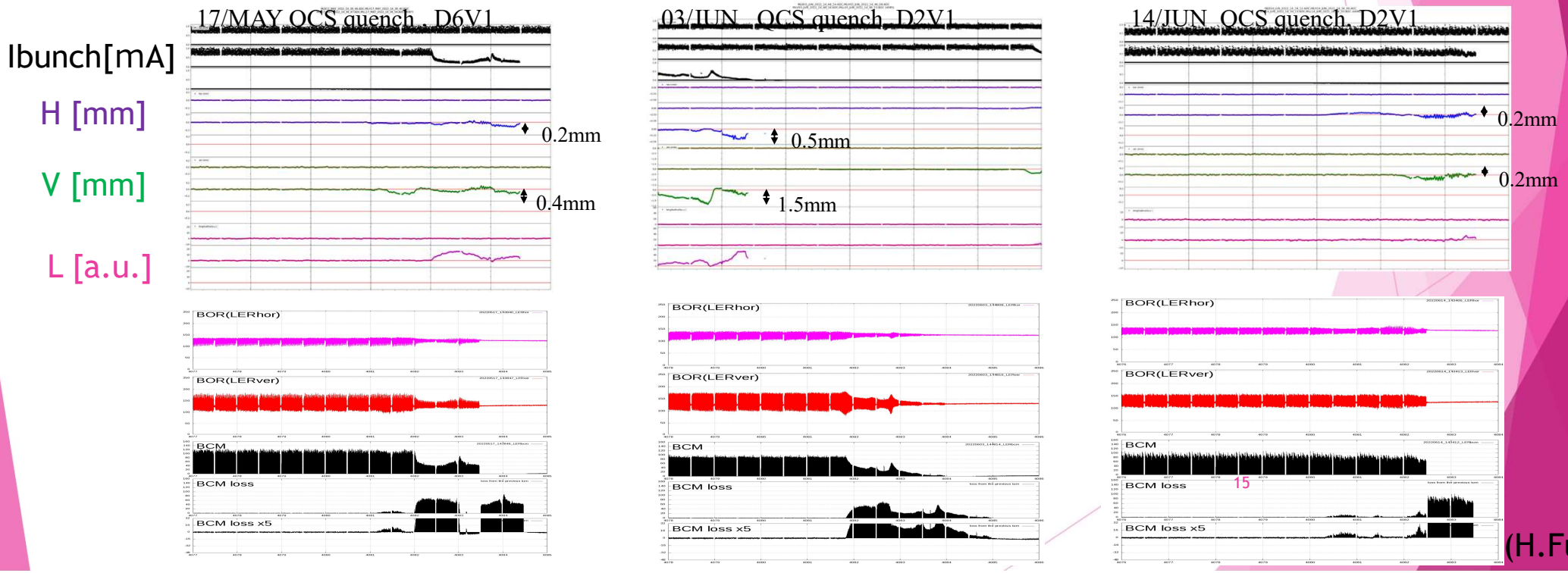




(Y.Liu)

Observations : Bunch Oscillation Recorder (BOR)

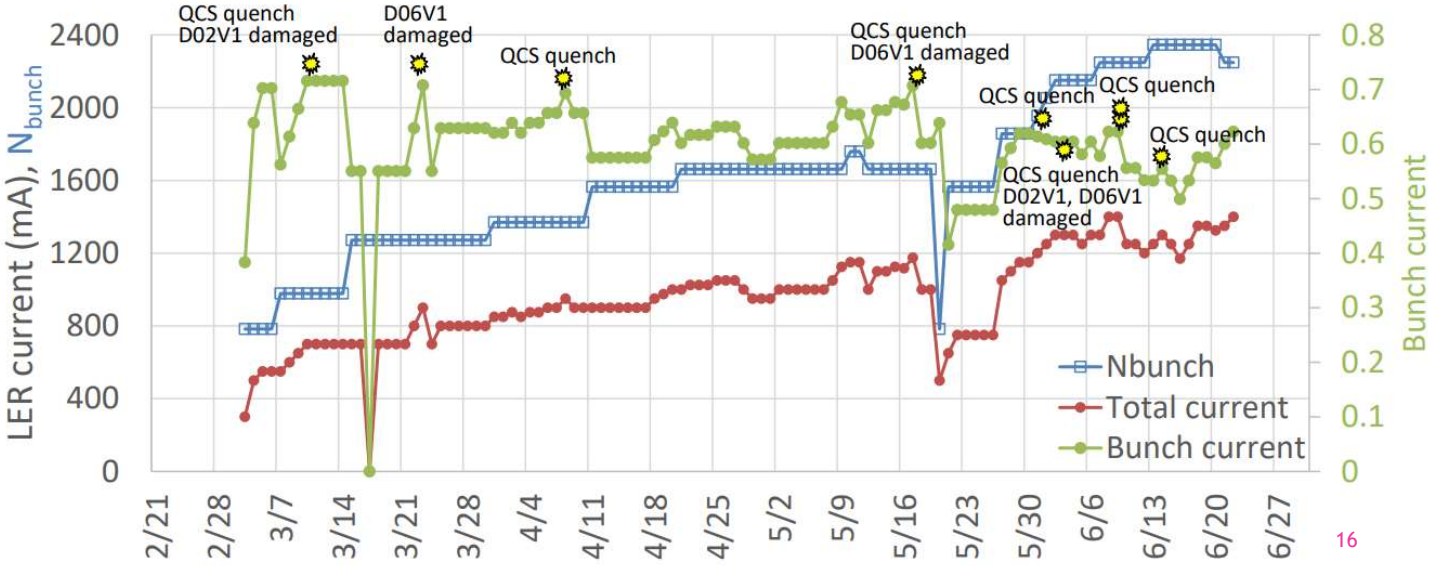
- The Bunch oscillation is measured 4096 turns before the abort trigger using feedback processors and the orbit is calculated from the data.
  - The orbit changed small ～1mm@FB position



(H.Fukuma)

Observations : Bunch Current of Operation

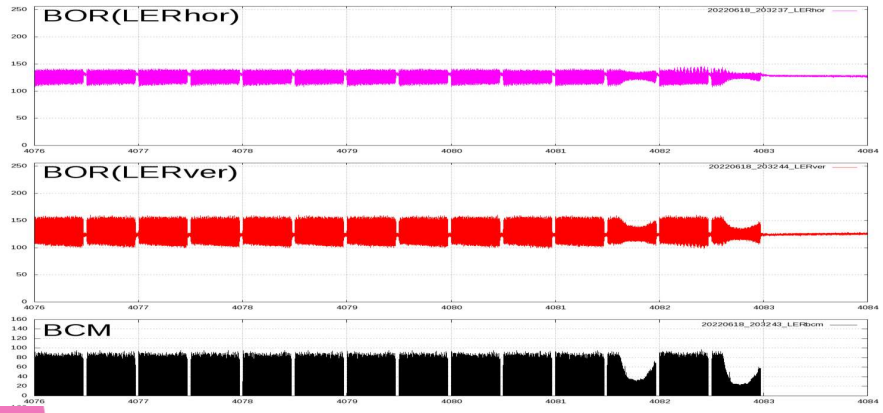
- It is likely to occur when a certain bunch current is exceeded.

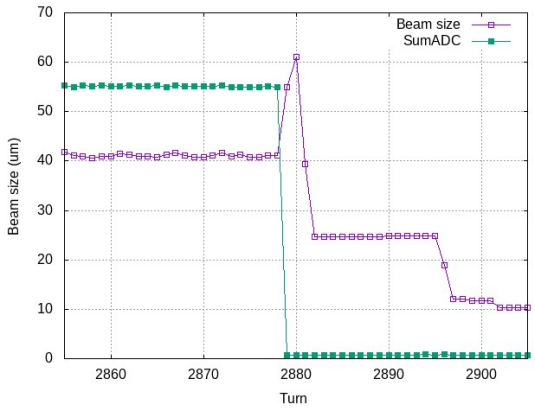


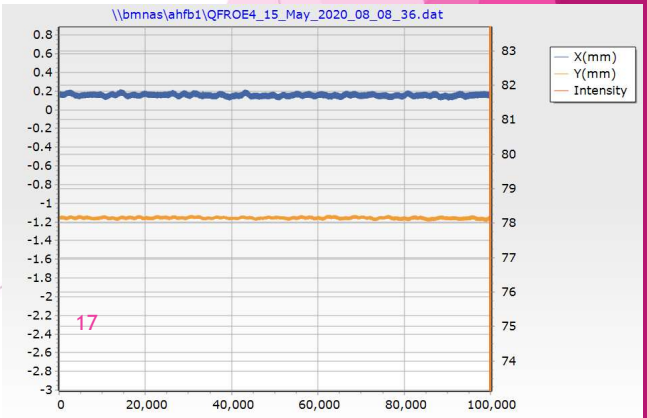
(K.Matsuoka)

Observations

- There are no signs before beam loss starting.
  - No small beam loss (beam loss monitor, BCM)
  - No oscillation (Bunch Oscillation Recorder (BOR))
  - No beam size change (X-ray monitor (XRM))
  - It is not clear if the orbit changed significantly.(Libera)

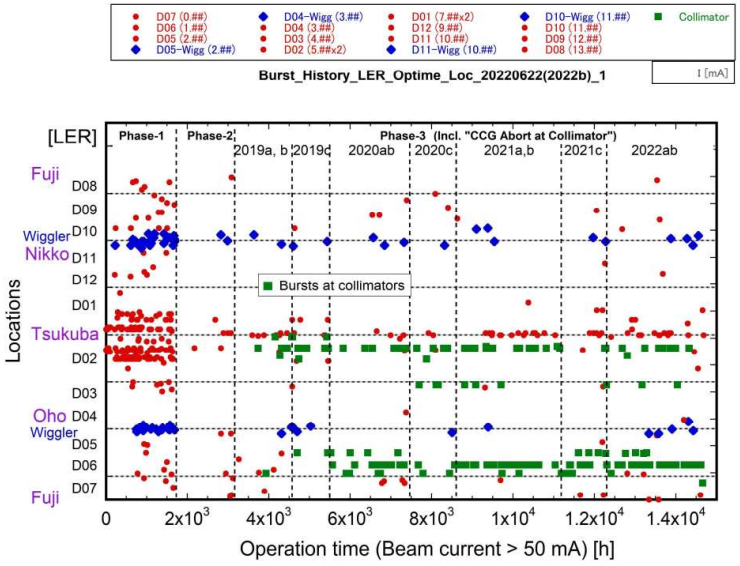


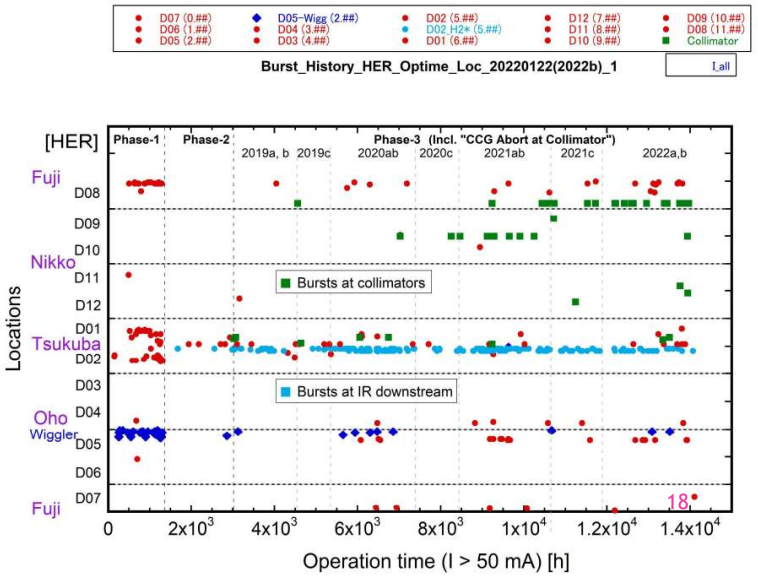




Observations : Vacuum

- Pressure bursts have been observed here and there, and it rarely occurs in the same place except in the collimator section. It may be the result, not the reason.

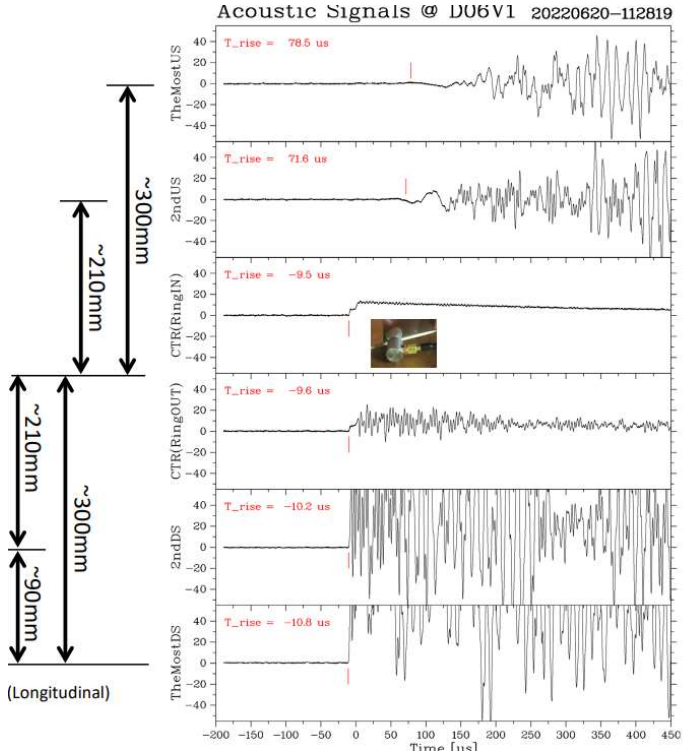


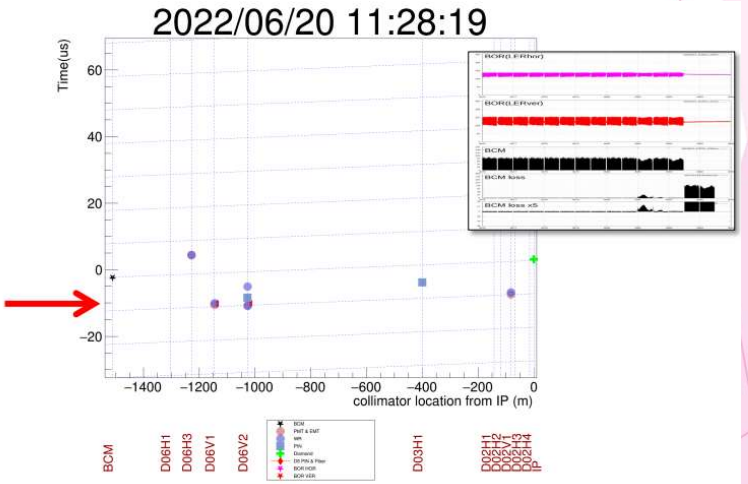


(Y.Suetsugu)

Observations : Acoustic waves

- Acoustic waves were detected at the same time with collimator beam loss.
  - We measure a few event before shutdown





Velocity of acoustic longitudinal (transversal) wave in copper: 4.65 (2.26) mm/us

This data suggests that the particle shower produced at the collimator head generated widespread acoustic wave in the downstream of the head, which propagated upstream.

(T.Abe)

Candidate of the beam loss reason

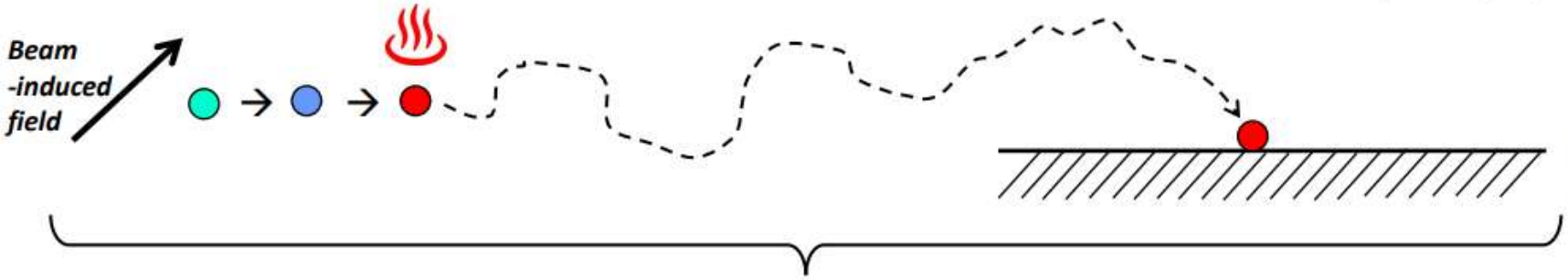
- Damage of vacuum component ： measured @ KEKB & PEP-II
  - phase changes (beam energy losses) had been observed ms ～ hundreds of μs before aborts.
    → not observed in SBL
  - abnormal temperature risings at bellows chambers had been observed and the catastrophic damages in the RF-finger had been confirmed.
- 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
  - Clean or hit the vacuum chamber to remove as much dust as possible and fixed the problem.
  - When the energy of the particles deviates greatly, the loss occurs in the horizontal collimator, so it may be possible to find out something by examining the conditions that the loss occurs in the vertical collimator in more detail.
- Fireball : Measured @ RF cavity

Physical process of the "Fireball" hypothesis, leading to fast beam loss

① A microparticle with a high sublimation point is heated by the beam-induced field.

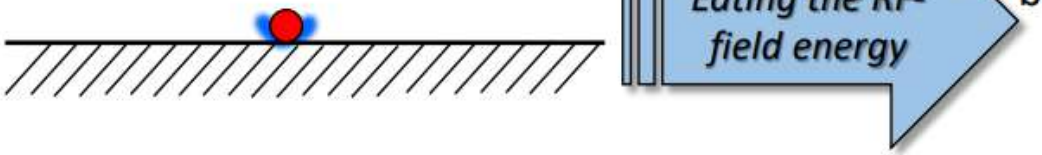
➔ **Fireball**

② The fireball touches some metal surface with a low sublimation point (e.g. copper).

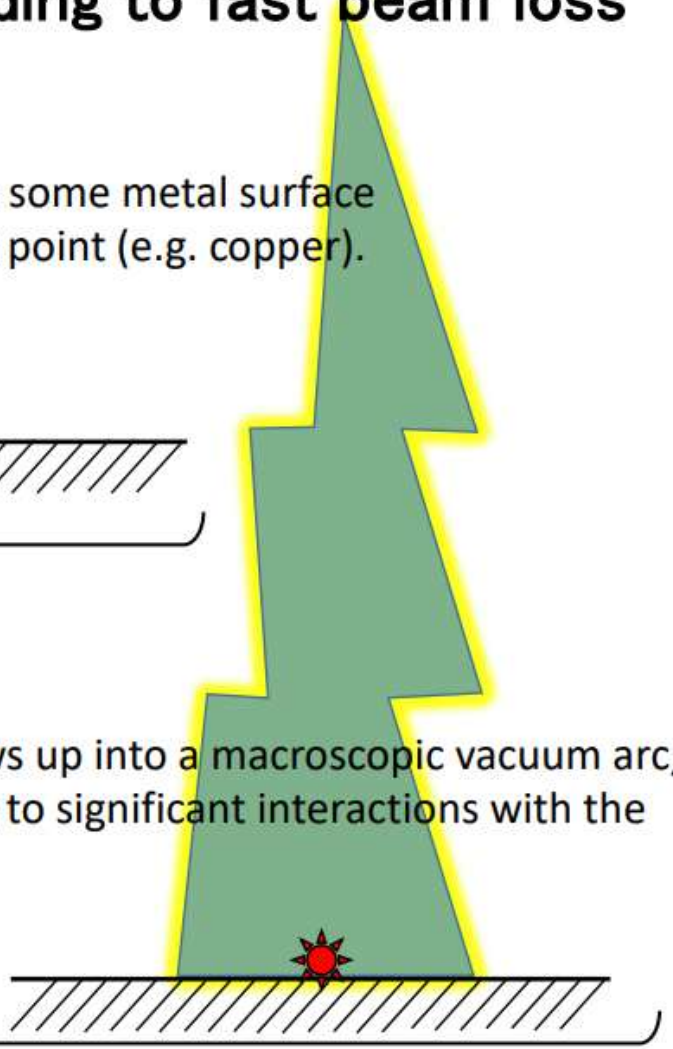


Order of ~s or longer

③ Plasma is generated around the fireball.



④ The plasma grows up into a macroscopic vacuum arc, possibly leading to significant interactions with the beam particles.



Order of ~100 ns at the fastest

(T. Abe)

Candidate of the beam loss reason

- Vertical abort kicker misfire
  - We are using the same thyratron for horizontal kicker.
- Electron cloud effect in collimator
  - In this case, SBL should be measured at LER only, but HER beam also lost.
  - Simulation of EC growth will be done.
- 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.
- 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.

Future plans

- Add new loss monitor for timing analysis and abort trigger
- Add BOR for another place on ring
- Setup acoustic sensors
- Check the temperature of vacuum component

- So far, there is no reliable way to investigate the cause of sudden beam loss

Summary

- In order to protect the hardware from dangerous beam loss, we are trying to speed up the abort trigger.
  - Increased the number of abort gap.
  - Introduce injection veto for LM.
  - Change the cable route and introduce new LM.
- One of the obstacles for luminosity increasing is sudden beam loss and the cause of the beam loss is still unclear.
  - We have been investigating with Loss Monitor, etc., and have been able to find the point where the loss started, but no phenomena that clarify the cause have been found.
  - Started the international task force to investigate and resolve the cause of the sudden beam loss.

backup

Abort kicker

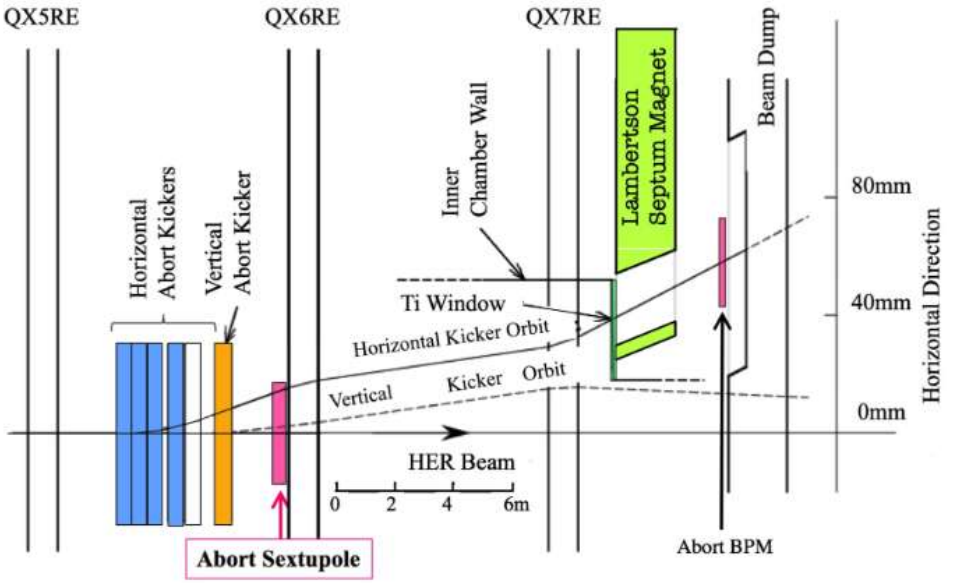
Abort Kicker is a complex of several magnets.

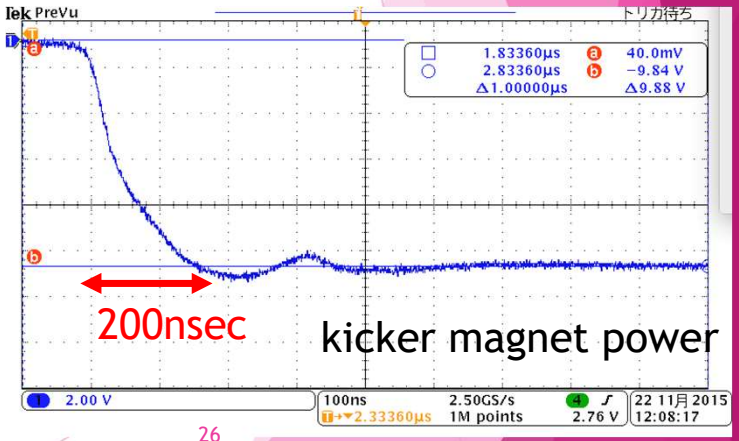
- Four horizontal magnets : extract the beam from vacuum chamber.
- DC sextupole magnet : make beam size larger by the large horizontal beta function due to the quadrupole component of the off-centered sextupole.
- A vertical magnet : sweeps the beam in the window during one revolution time.
- Lambertoson septum magnet : transport the extracted beam to the beam dump.

Dumped beam length : one revolution time (10 μs).

Build-up time of the abort kicker magnet : 200 ns (empty bucket space).

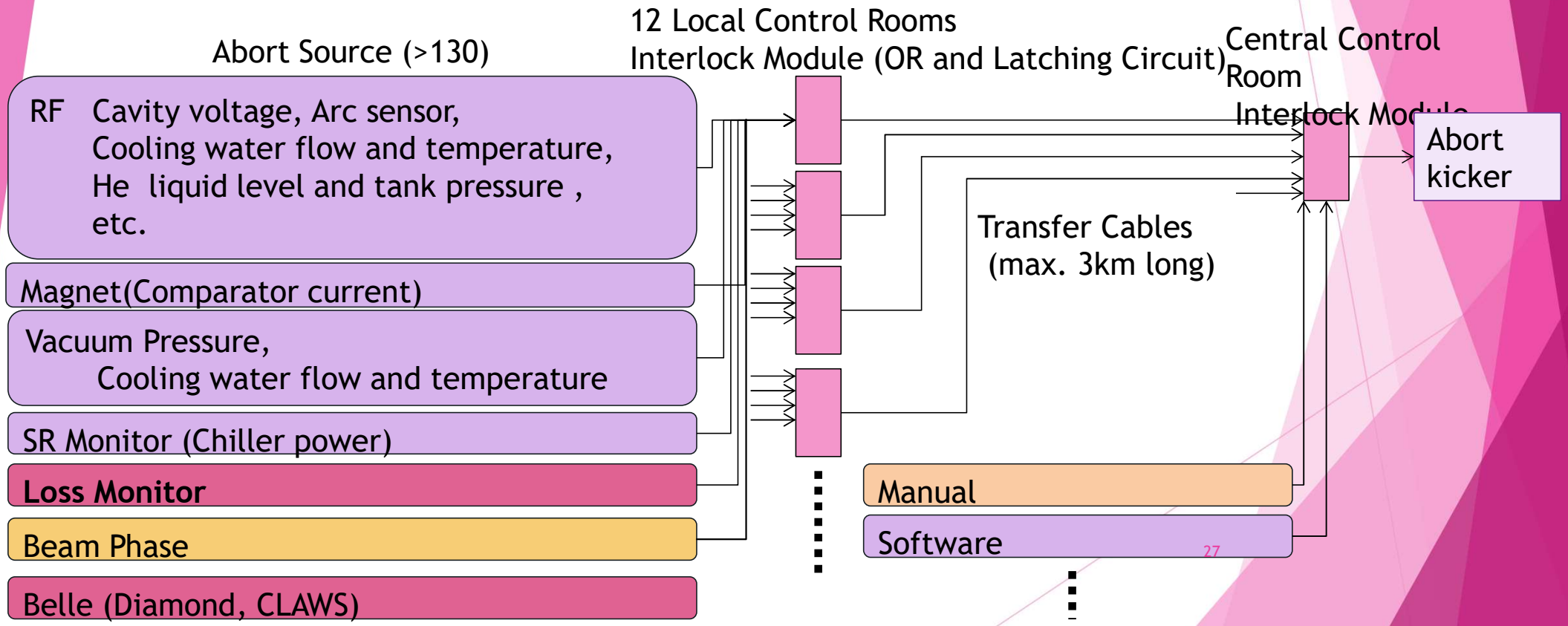
Synchronization of the kicker timing and the abort gap is required for the protection of hardware.

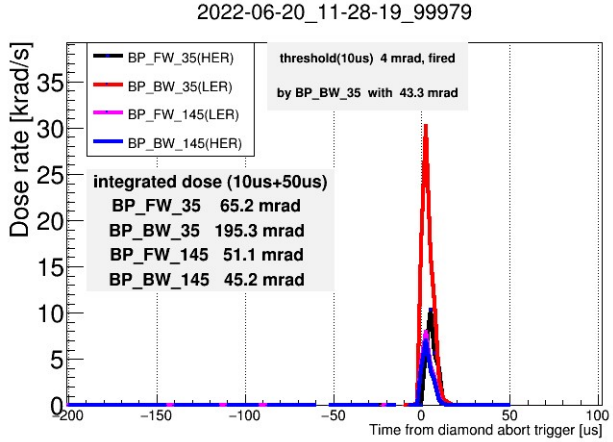


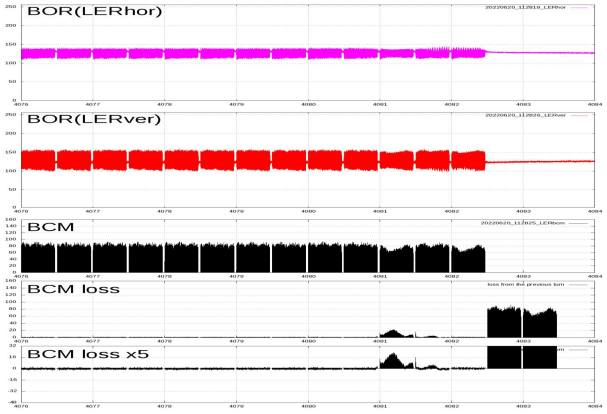


Abort Trigger

The abort request signals from each hardware component collected in 12 local control rooms. The request signals from LCRs, software abort request signals, and manual abort request signals are collected in the central control room and sent to the abort kicker within 20 μsec.







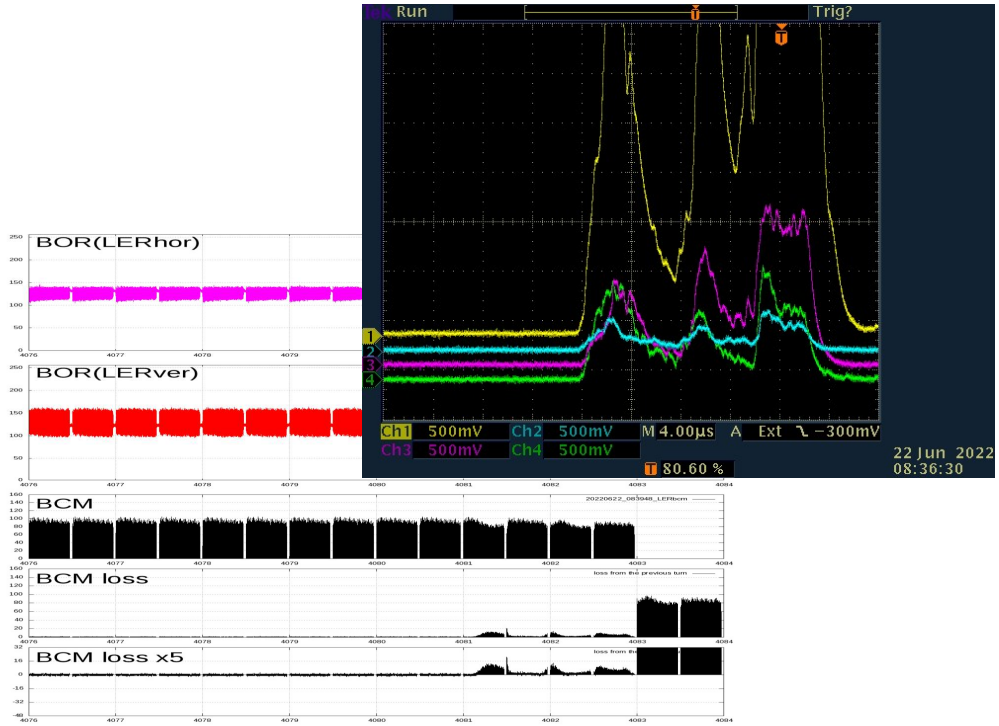
- Received @ CCB
  1. Opt.Fiber
  2. PIN from D7 (2.7us after)
  3. PIN from D4
  4. CLAWS
  5. RF 5F

RING	MESSAGE	DATE	DELTA
LER	Belle2 CLAWS	2022-06-20 11:28:19.853535900	0.000 000 000
HER	Belle2 CLAWS	2022-06-20 11:28:19.853536600	0.000 000 700
LER	COLSAFE:CCC:ABORT:CCC-7	2022-06-20 11:28:19.853539900	0.000 004 000
LER	Loss Monitor D6 (Optical Fiber)	2022-06-20 11:28:19.853540700	0.000 004 800
LER	COLSAFE:CCC:ABORT:CCC-6	2022-06-20 11:28:19.853541300	0.000 005 400
LER	Loss Monitor D4-3	2022-06-20 11:28:19.853541500	0.000 005 600
LER	RF D5-F	2022-06-20 11:28:19.853541600	0.000 005 700
LER	Loss Monitor D7-1	2022-06-20 11:28:19.853542400	0.000 006 500
LER	Loss Monitor D1-1	2022-06-20 11:28:19.853543100	0.000 007 200
LER	COLSAFE:CCC:ABORT:D7	2022-06-20 11:28:19.853544000	0.000 008 100
LER	Loss Monitor D4-2	2022-06-20 11:28:19.853544400	0.000 008 500
LER	Loss Monitor D4-1	2022-06-20 11:28:19.853545000	0.000 009 100
LER	COLSAFE:CCC:ABORT:D4	2022-06-20 11:28:19.853546600	0.000 010 700
LER	COLSAFE:CCC:ABORT:D2	2022-06-20 11:28:19.853546700	0.000 010 800
HER	COHSAFE:CCC:ABORT:D2	2022-06-20 11:28:19.853548000	0.000 012 100
LER	COLSAFE:CCC:ABORT:D5	2022-06-20 11:28:19.853548100	0.000 012 200
LER	Belle2 VXD diamond	2022-06-20 11:28:19.853550400	0.000 014 500
HER	Belle2 VXD diamond	2022-06-20 11:28:19.853551100	0.000 015 200
LER	COLSAFE:CCC:ABORT:D1	2022-06-20 11:28:19.853552600	0.000 016 700
LER	RF D5-A	2022-06-20 11:28:19.853554300	0.000 018 400
LER	RF D5-D	2022-06-20 11:28:19.853554300	0.000 018 400
LER	RF D5-B	2022-06-20 11:28:19.853554800	0.000 018 900
LER	RF D5-E	2022-06-20 11:28:19.853554900	0.000 019 000
LER	RF D5-C	2022-06-20 11:28:19.853555200	0.000 019 300
LER	RF D8-E	2022-06-20 11:28:19.853563500	0.000 027 600
LER	COLSAFE:CCC:ABORT:D8	2022-06-20 11:28:19.853563800	0.000 027 900
LER	RF D8-A	2022-06-20 11:28:19.853565400	0.000 029 500
LER	RF D8-B	2022-06-20 11:28:19.853566900	0.000 031 000
LER	COLSAFE:D7:ABORT:D7-6	2022-06-20 11:28:19.853571100	0.000 035 200
LER	RF D7-A	2022-06-20 11:28:19.853571600	0.000 035 700
HER	RF D4-F	2022-06-20 11:28:19.853572000	0.000 036 100

Received @D2

Received @CCB

Received @CCB final abort module



- Received @ CCB
  1. Opt.Fiber
  2. RF D5 (4.4us after)
  3. CLAWS
  4. PIN from D4
  5. PIN from D1

The time to issue the abort trigger has become several µs faster.

RING	MESSAGE	DATE	DELTA
LER	Belle2 CLAWS	2022-06-22 08:39:42.652924900	0.000 000 000
HER	Belle2 CLAWS	2022-06-22 08:39:42.652925300	0.000 000 400
LER	RF D5-F	2022-06-22 08:39:42.652928600	0.000 003 700
LER	RF D5-E	2022-06-22 08:39:42.652928900	0.000 004 000
LER	COLSAFE:CCC:ABORT:CCC-7	2022-06-22 08:39:42.652929300	0.000 004 400
LER	RF D5-D	2022-06-22 08:39:42.652929300	0.000 004 400
LER	Loss Monitor D6 (Optical Fiber)	2022-06-22 08:39:42.652929800	0.000 004 900
LER	COLSAFE:CCC:ABORT:CCC-6	2022-06-22 08:39:42.652930200	0.000 005 300
LER	Loss Monitor D4-3	2022-06-22 08:39:42.652930300	0.000 005 400
LER	Belle2 VXD diamond	2022-06-22 08:39:42.652932100	0.000 007 200
LER	RF D5-C	2022-06-22 08:39:42.652932300	0.000 007 400
HER	Belle2 VXD diamond	2022-06-22 08:39:42.652932500	0.000 007 600
LER	Loss Monitor D1-1	2022-06-22 08:39:42.652932500	0.000 007 600
LER	RF D5-B	2022-06-22 08:39:42.652933900	0.000 009 000
LER	Loss Monitor D4-1	2022-06-22 08:39:42.652934400	0.000 009 500
LER	COLSAFE:CCC:ABORT:D5	2022-06-22 08:39:42.652934600	0.000 009 700
LER	COLSAFE:CCC:ABORT:D2	2022-06-22 08:39:42.652935200	0.000 010 300
LER	COLSAFE:CCC:ABORT:D4	2022-06-22 08:39:42.652935600	0.000 010 700
LER	Loss Monitor D4-2	2022-06-22 08:39:42.652935600	0.000 010 700
HER	COHSAFE:CCC:ABORT:D2	2022-06-22 08:39:42.652935900	0.000 011 000
LER	RF D5-A	2022-06-22 08:39:42.652940000	0.000 015 100
LER	COLSAFE:CCC:ABORT:D1	2022-06-22 08:39:42.652942100	0.000 017 200
HER	Loss Monitor D4-4	2022-06-22 08:39:42.652954000	0.000 029 100
LER	RF D8-E	2022-06-22 08:39:42.652954400	0.000 029 500
HER	COHSAFE:D4:ABORT:D4-2	2022-06-22 08:39:42.652955000	0.000 030 100
LER	COLSAFE:CCC:ABORT:D8	2022-06-22 08:39:42.652955400	0.000 030 500
LER	COLSAFE:D2:ABORT:D2-6	2022-06-22 08:39:42.652955600	0.000 030 700
LER	RF D8-A	2022-06-22 08:39:42.652956000	0.000 031 100
LER	Loss Monitor TSUKUBA B4	2022-06-22 08:39:42.652956900	0.000 032 000
LER	RF D8-B	2022-06-22 08:39:42.652957600	0.000 032 700
HER	RF D4-F	2022-06-22 08:39:42.652958500	0.000 033 600
HER	RF D4-G	2022-06-22 08:39:42.652959000	0.000 034 100

Data Analysis : Loss Monitor Abort (Injection)

LM aborts happened at the end or start of injection.

↓

Checked Injection timings were checked.

injection kickers of upstream

injection kickers of downstream

septum magnet

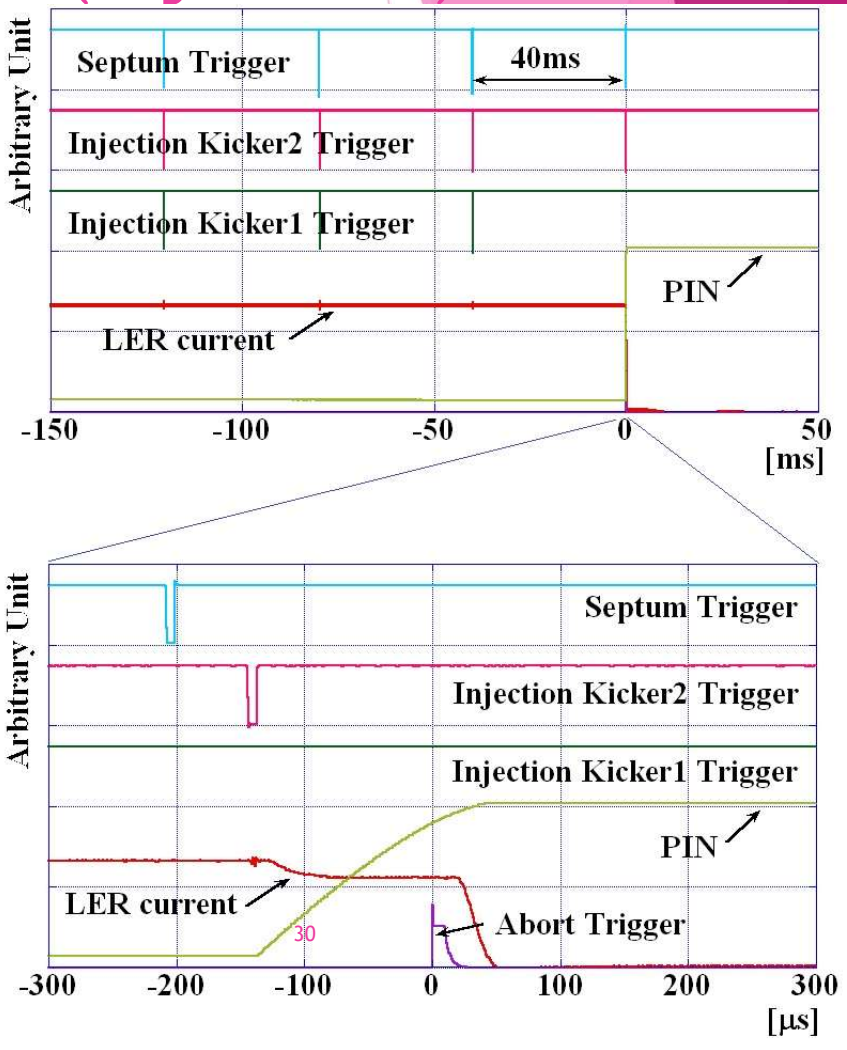
↓

The upstream injection kicker did not receive the final injection trigger.

The stored beam was kicked only by the downstream kicker⇒the beam was lost at that time.

↓

This problem was caused by injection trigger system software, and was fixed after understanding the reason.



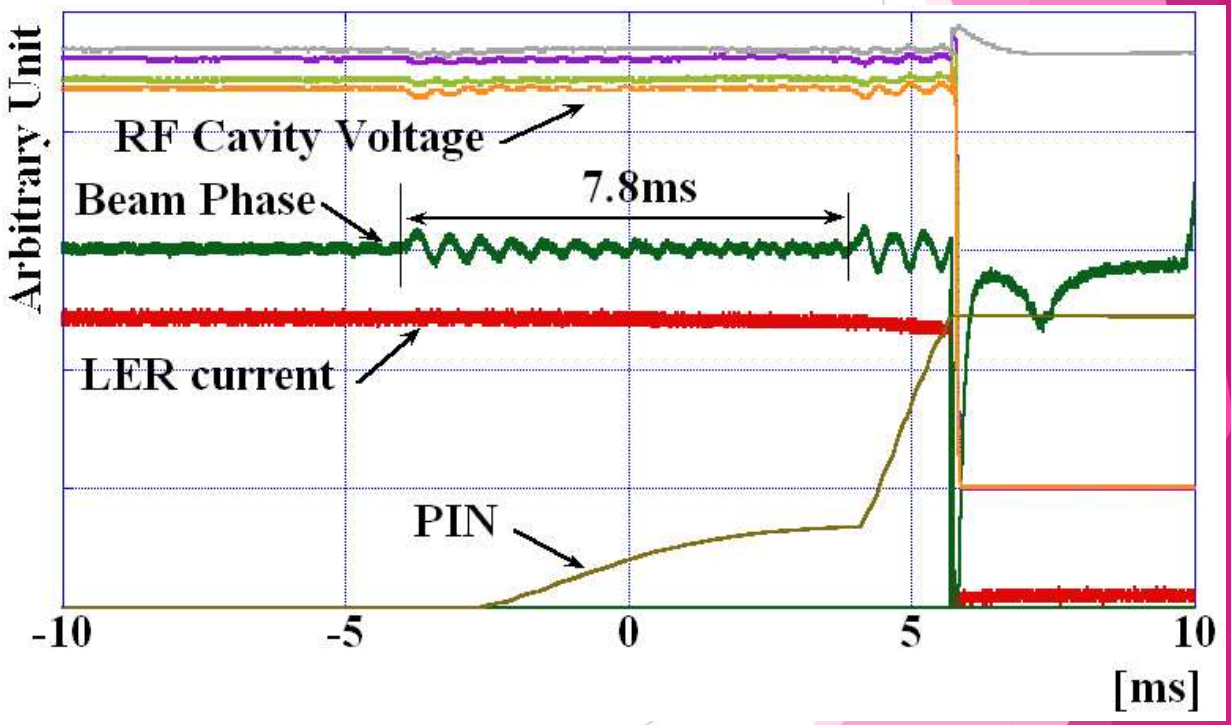
Data Analysis : Loss Monitor Abort (Vacuum)

・Beam phase oscillation & beam loss occurs.
・Vacuum pressure spikes took place somewhere.
⇒Beam was lost at a narrow aperture of the ring.

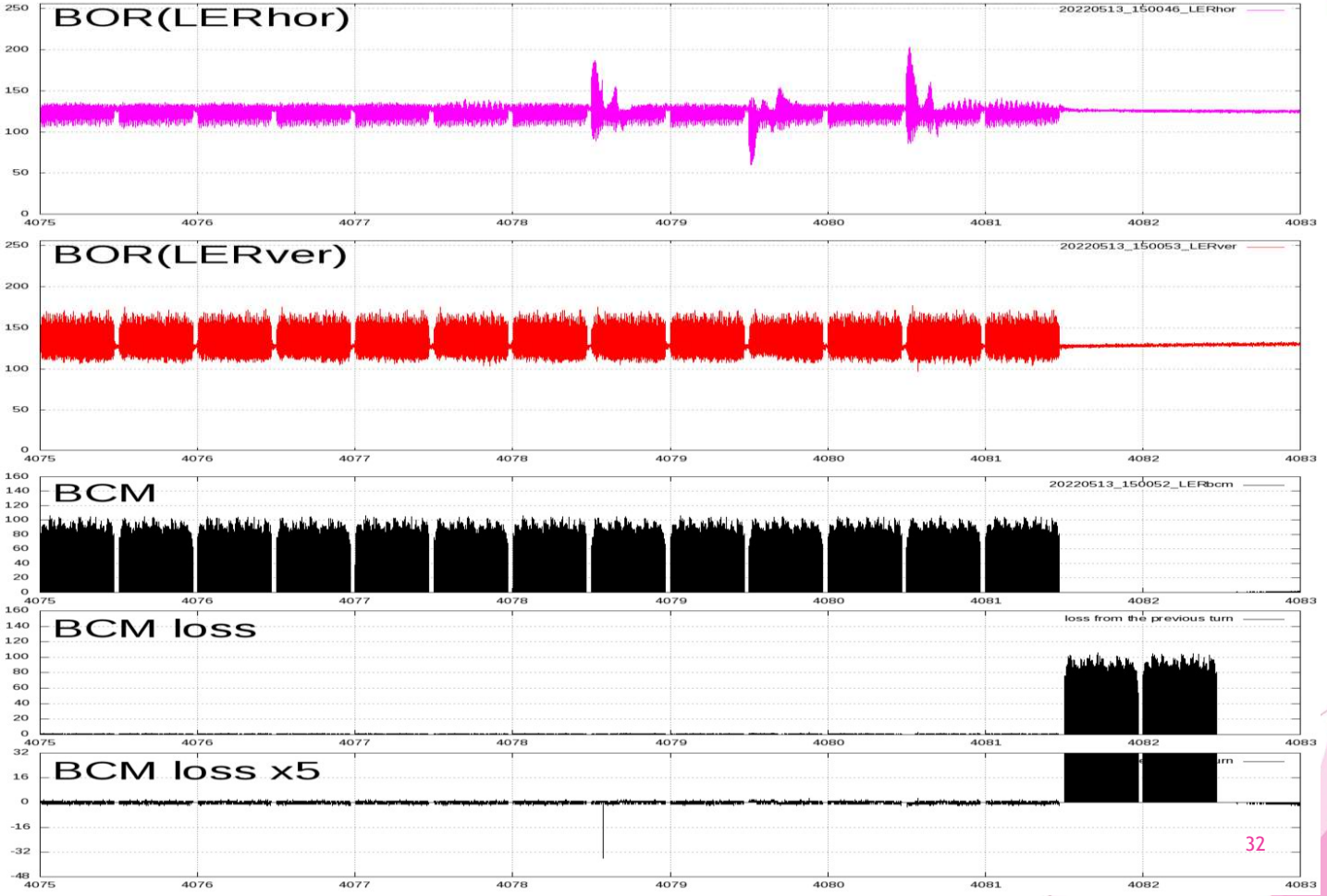
↓

Adjustment of collimators to protect the beam pipes .
⇒PINs located on collimators make abort requests.

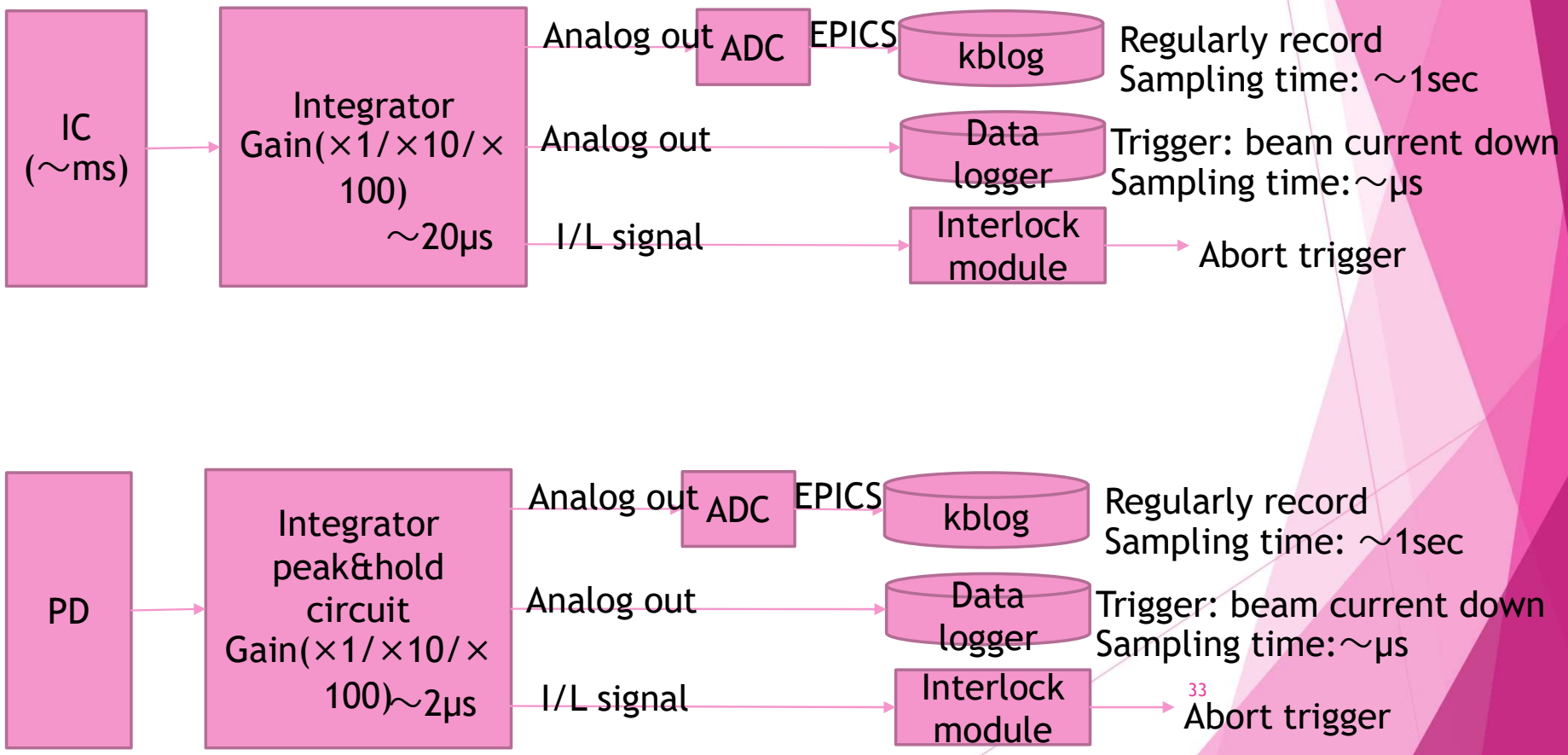
This type abort is expected to be reduced after further vacuum scrubbing.



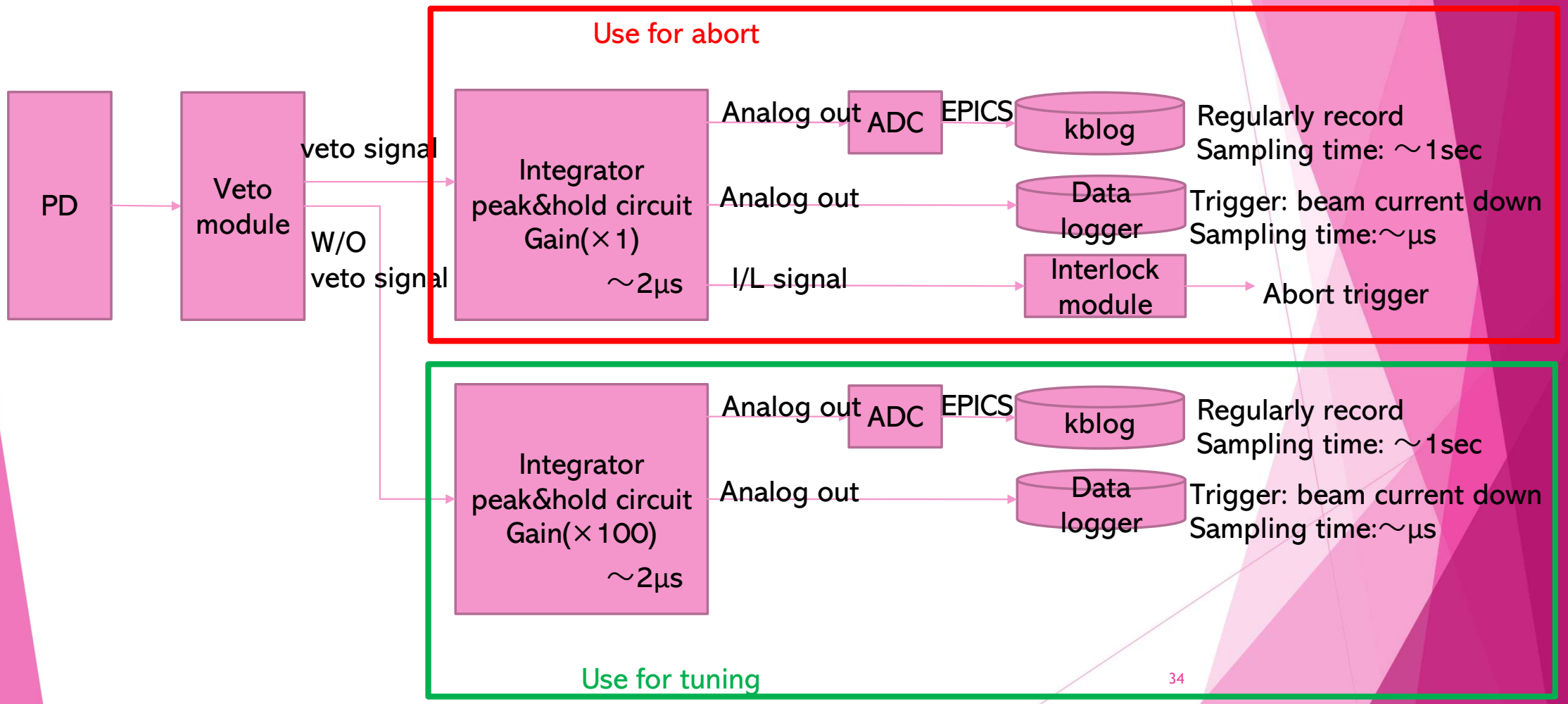
Injection related abort : BOR & BCM

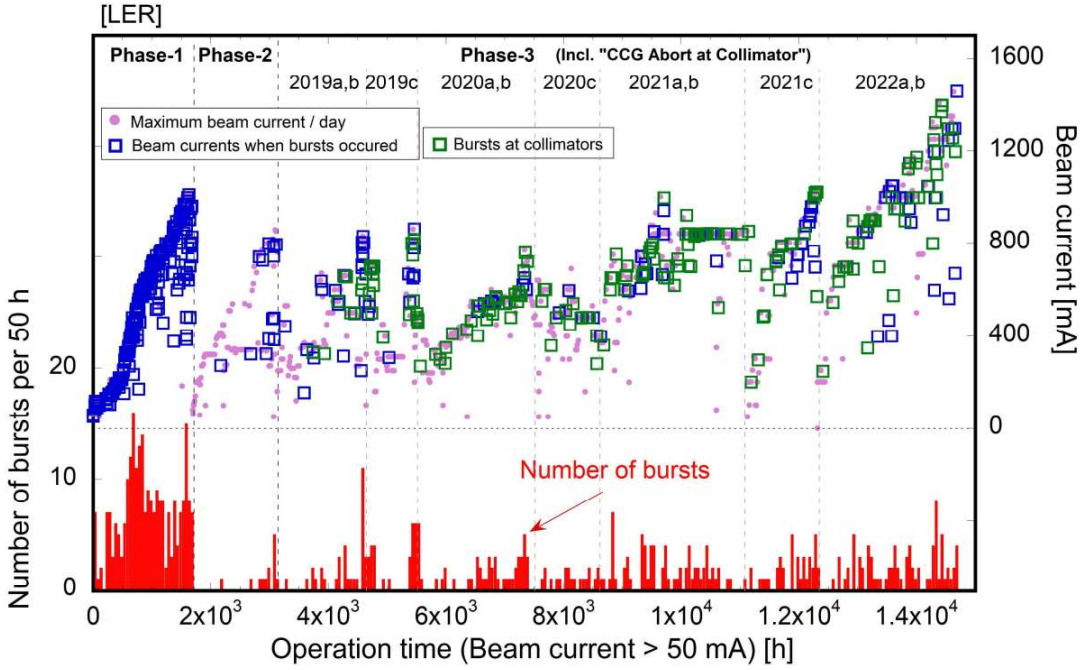


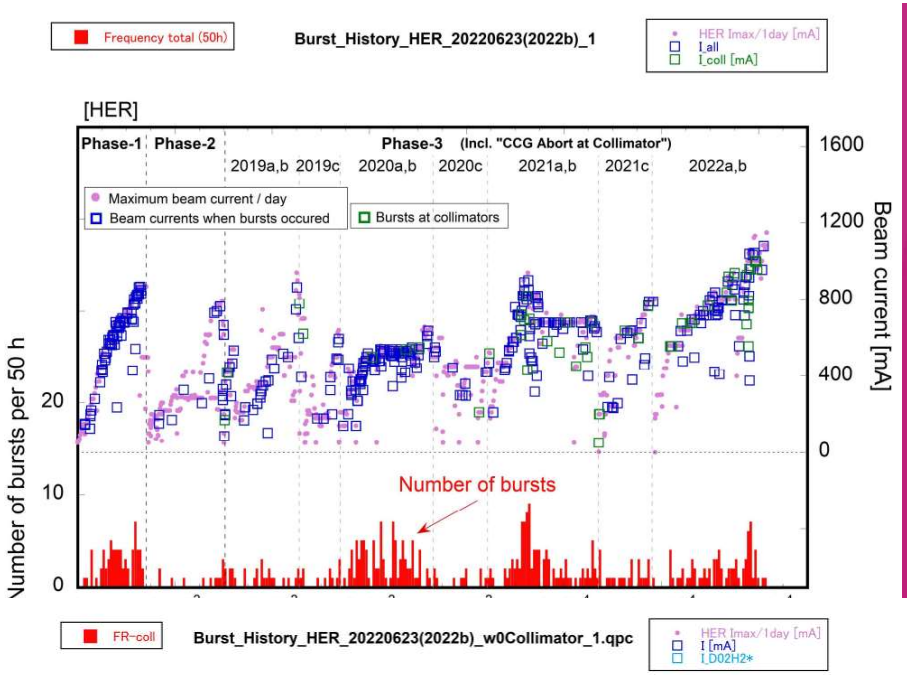
Loss Monitor Signal Flow

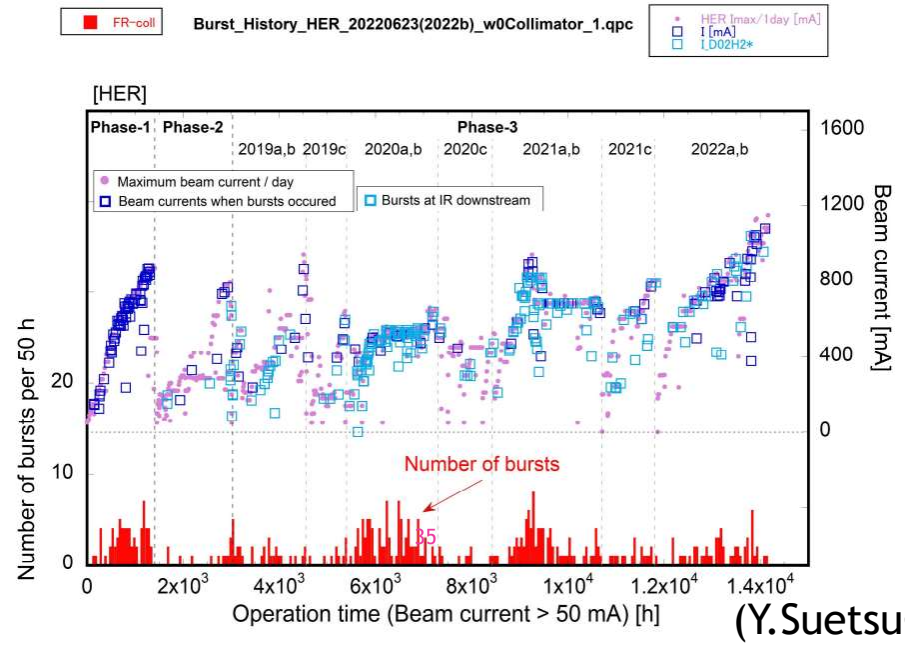


Injection veto

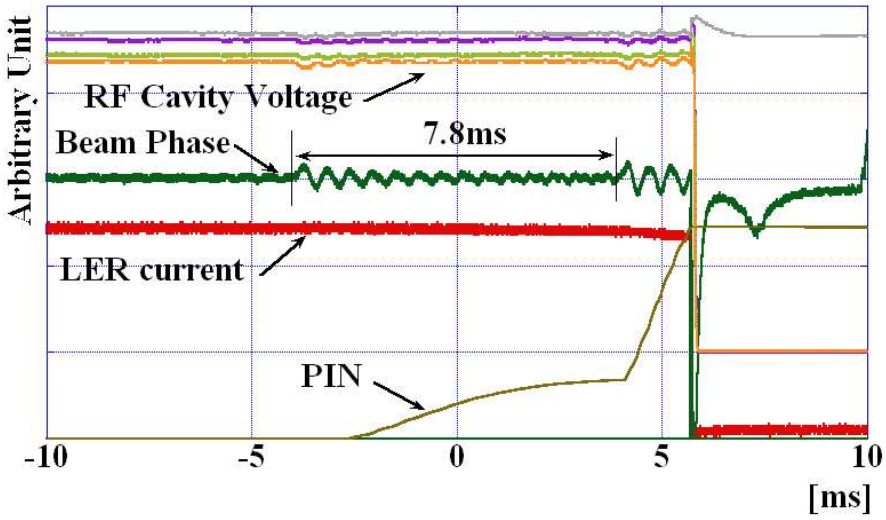


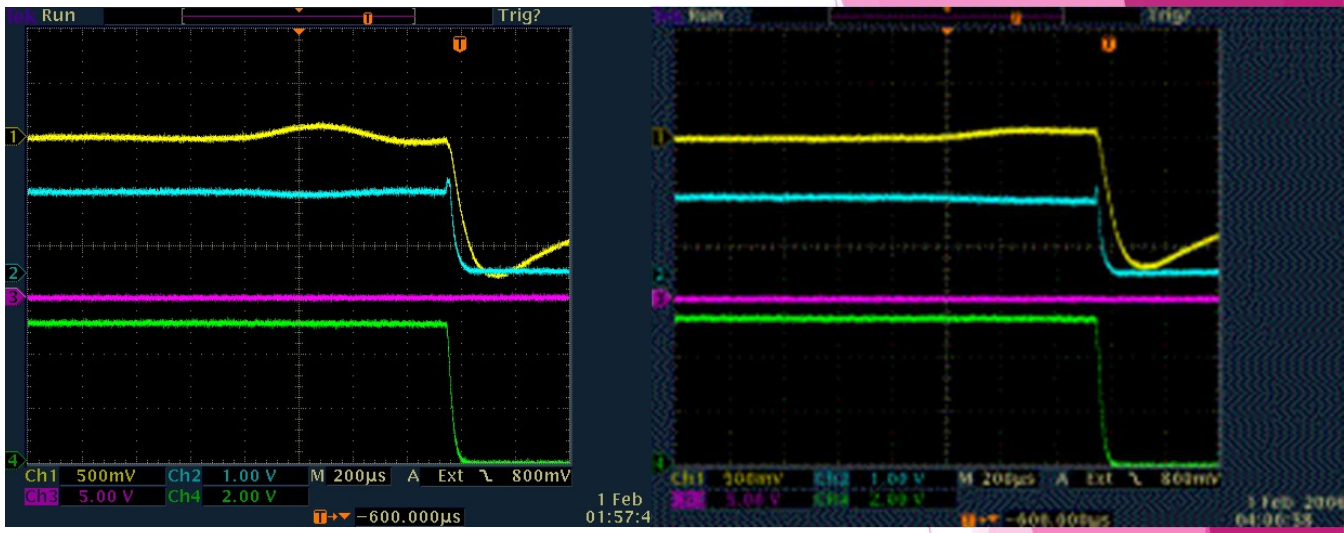

[LER]
Phase-1
Phase-2
Phase-3 (Incl. "CCG Abort at Collimator")
2019a,b
2019c
2020a,b
2020c
2021a,b
2021c
2022a,b
Maximum beam current / day
Beam currents when bursts occured
Bursts at collimators
Number of bursts
Number of bursts per 50 h
Beam current [mA]
Operation time (Beam current > 50 mA) [h]


Frequency total (50h)
Burst_History_HER_20220623(2022b)_1
HER Imax/1day [mA]
I_all
I_coll [mA]
[HER]
Phase-1
Phase-2
Phase-3 (Incl. "CCG Abort at Collimator")
2019a,b
2019c
2020a,b
2020c
2021a,b
2021c
2022a,b
Maximum beam current / day
Beam currents when bursts occured
Bursts at collimators
Number of bursts
Number of bursts per 50 h
Beam current [mA]


FR-coll
Burst_History_HER_20220623(2022b)_w0Collimator_1.qpc
HER Imax/1day [mA]
I [mA]
I_D02H2*
[HER]
Phase-1
Phase-2
Phase-3
2019a,b
2019c
2020a,b
2020c
2021a,b
2021c
2022a,b
Maximum beam current / day
Beam currents when bursts occured
Bursts at IR downstream
Number of bursts
Number of bursts per 50 h
Beam current [mA]
Operation time (Beam current > 50 mA) [h]

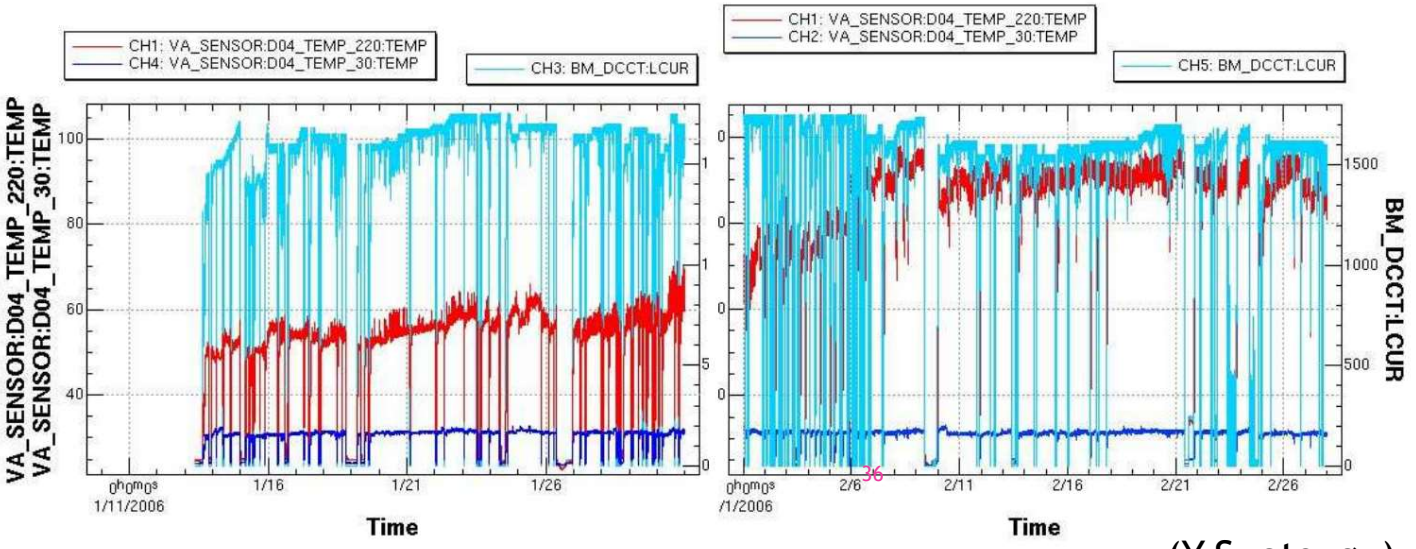
(Y.Suetsugu)





LERD04シケイン部ベローズ（内側）

(Y.Suetsugu)



(Y.Suetsugu)