Observation of sudden beam loss at SuperKEKB, and possible reasons

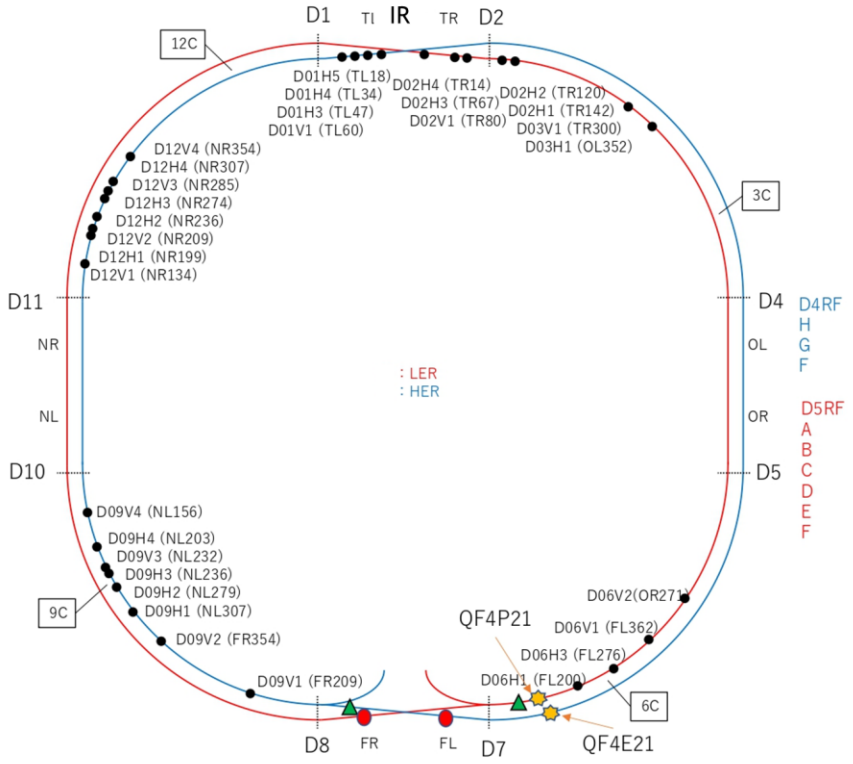
WORKSHOP ON DUST CHARGING AND BEAM-DUST INTERACTION IN PARTICLE ACCELERATORS

2023/6/13 H.IKEDA(KEK)

Contents

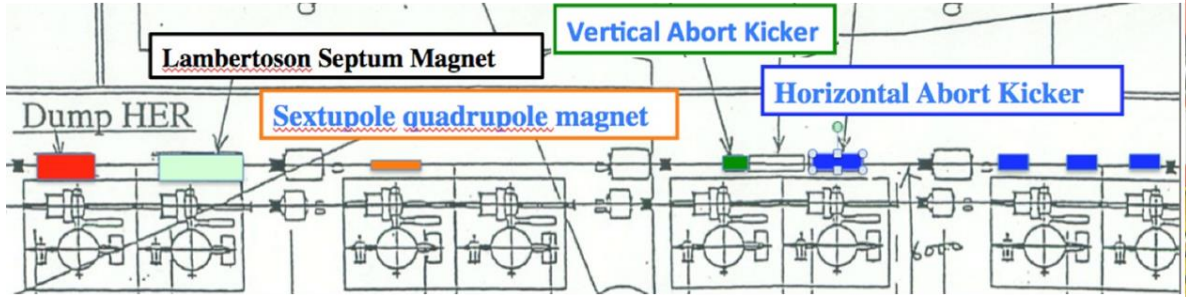
Introduction : SuperKEKB

- SuperKEKB
  - Energy : 7 GeV e- (HER) / 4 GeV e+ (LER)
  - Circumference : 3 km
  - Achieved Peak Luminosity : 4.7 $\times 10^{34}$ $cm^{-2}s^{-1}$
    - βy^* =1mm
    - Beam Currents 1.099 A (HER)/1.321 A (LER)
  - N_{bunch} = 783 ~ 2249
  - The primary goal is to achieve luminosity of $10^{35}cm^{-2}s^{-1}$ or better.
  - One of the obstacles to this goal is **sudden beam loss (SBL)**.

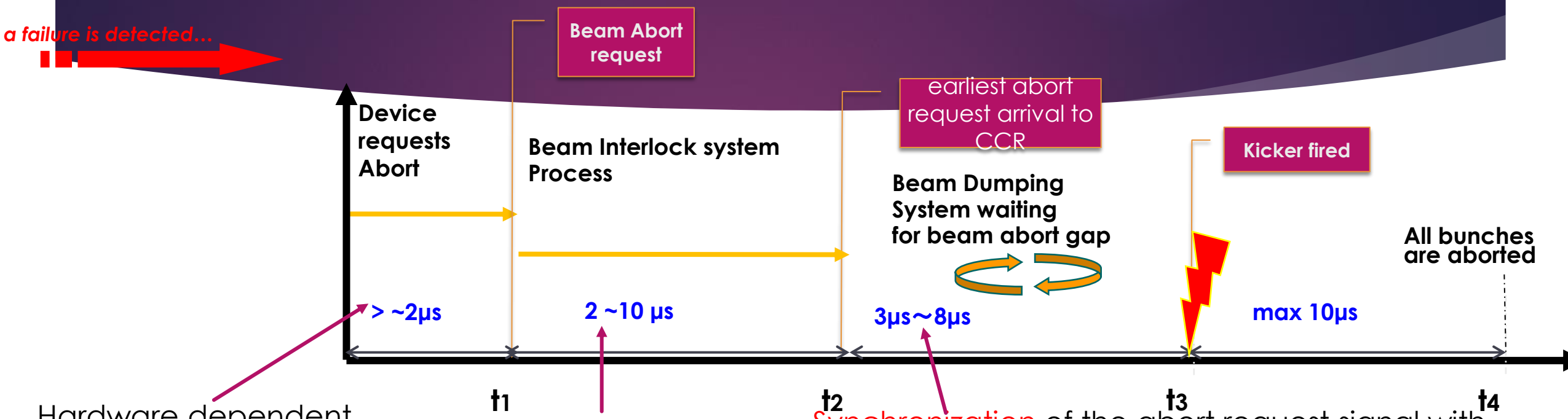


Introduction : Beam Abort System

- 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.
- We minimized abort trigger time to protect the hardware damage.



Abort Trigger Delays



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

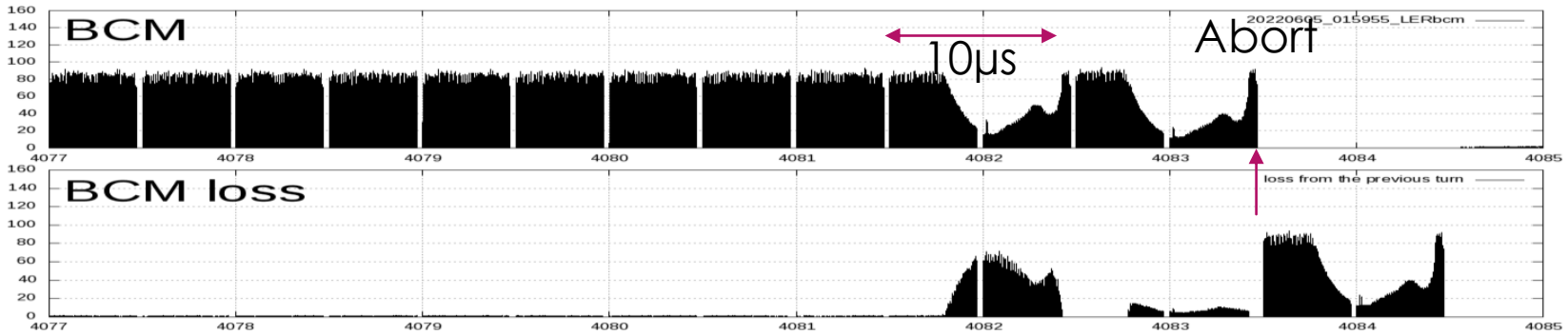
Delay from CCR to kicker (400m) : 2μs

Thyratron ON :1μs

Rise time for the kicker : 200ns

Minimum Abort Delay = 17~30μs

Introduction : What is “Sudden Beam Loss”



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

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

→ Harmful effects of SBL;

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

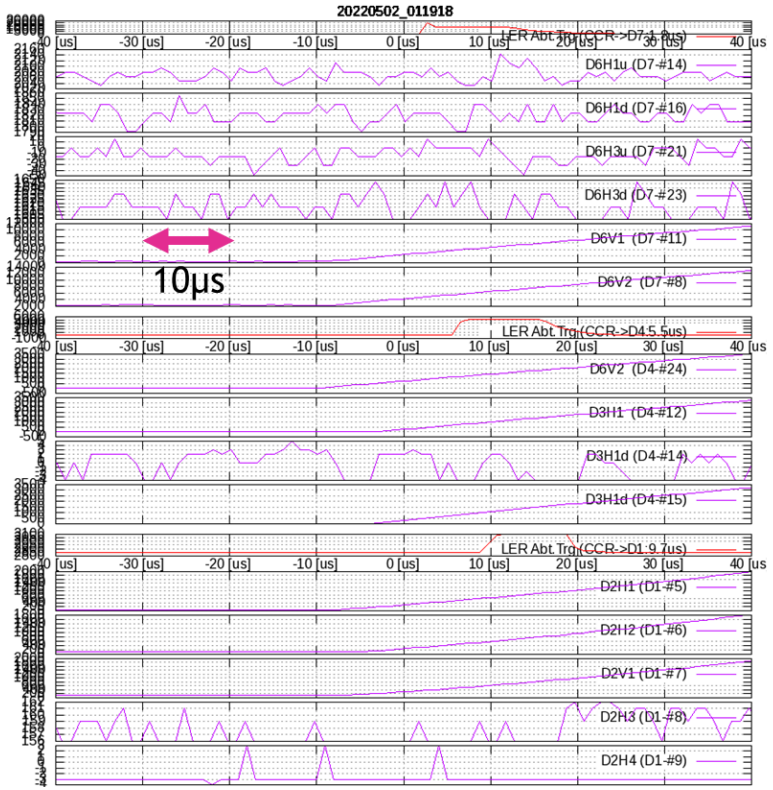
→In order to investigate and resolve the causes of SBL, a task force was established.

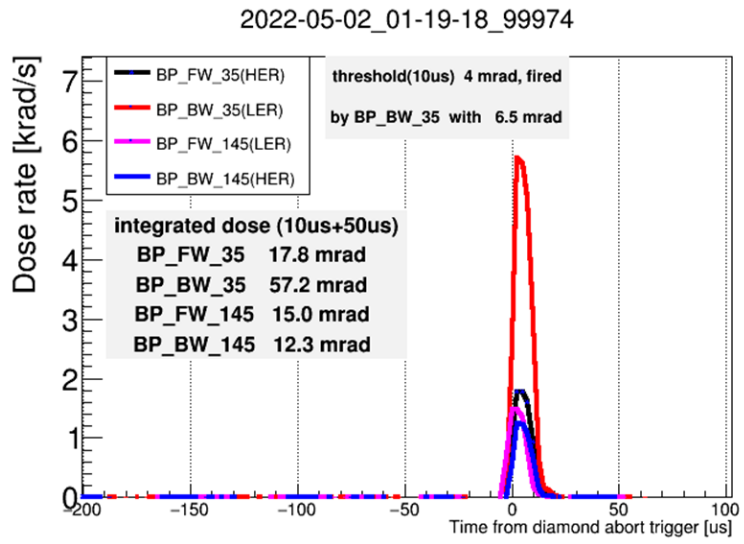
Observation : Beam Loss Monitor

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

↓

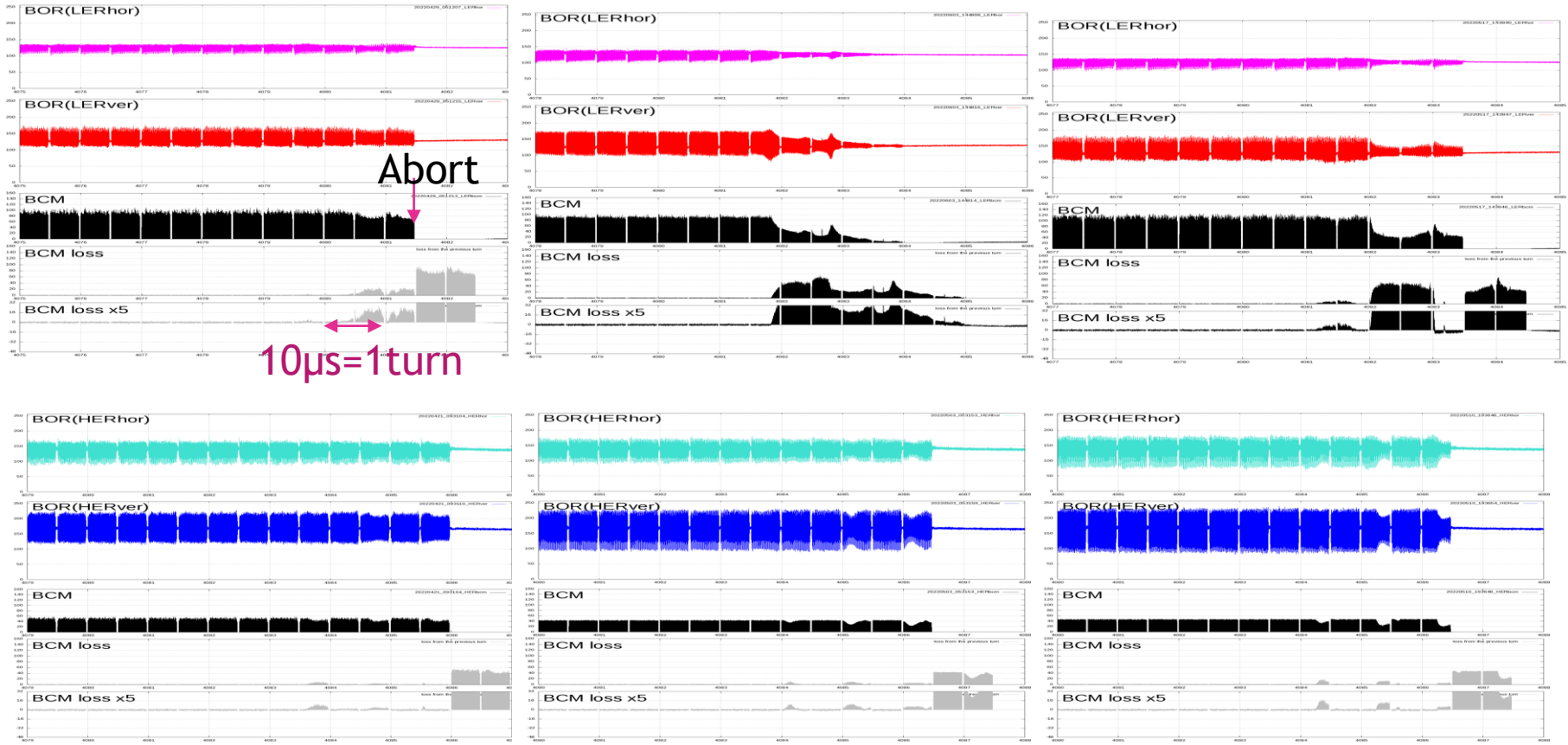
- There were many instances of sudden beam loss occurring simultaneously in the entire ring collimator section and in the Belle-II detector.



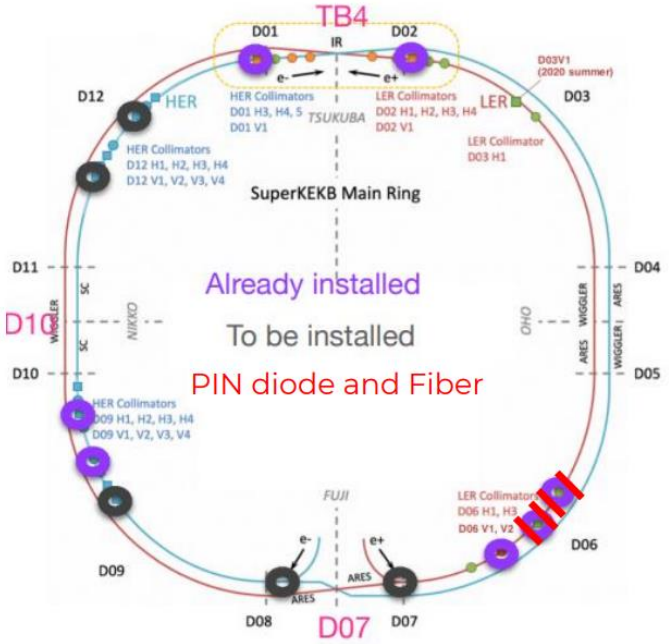


Observation :
Bunch Current monitor & Bunch Oscillation Recorder

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

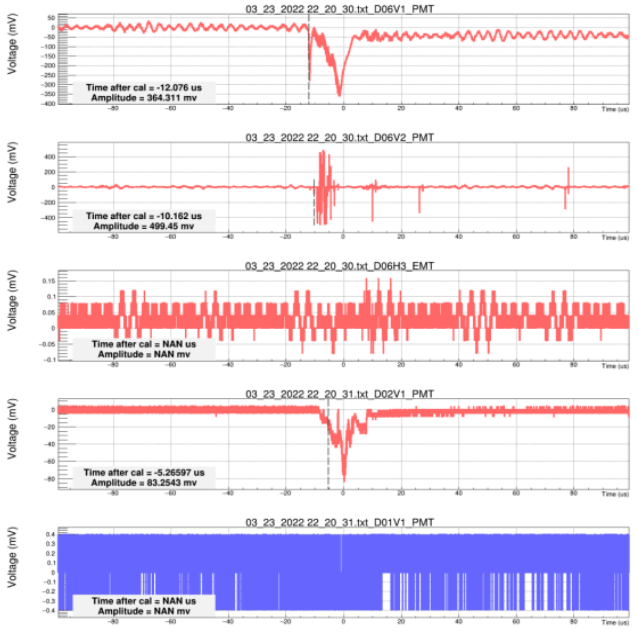


Observation :
Loss Monitor Specialized for Timing Measurements

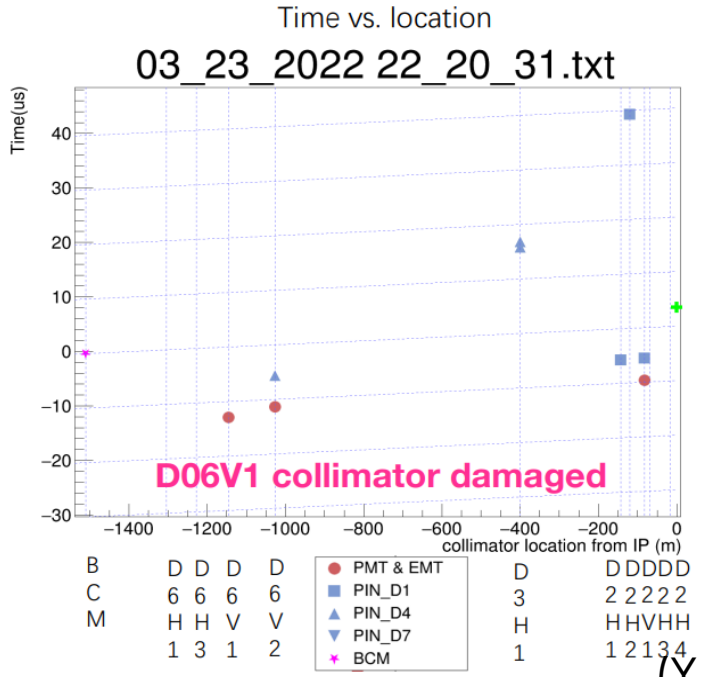


- We checked the starting point of SBL in the ring by using loss monitors specialized for position identification
- The beam loss mainly started at the D06V1 collimator (a narrow aperture to suppress background to Belle-II detector).
- When the D6 collimator was damaged and the aperture was widened,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

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



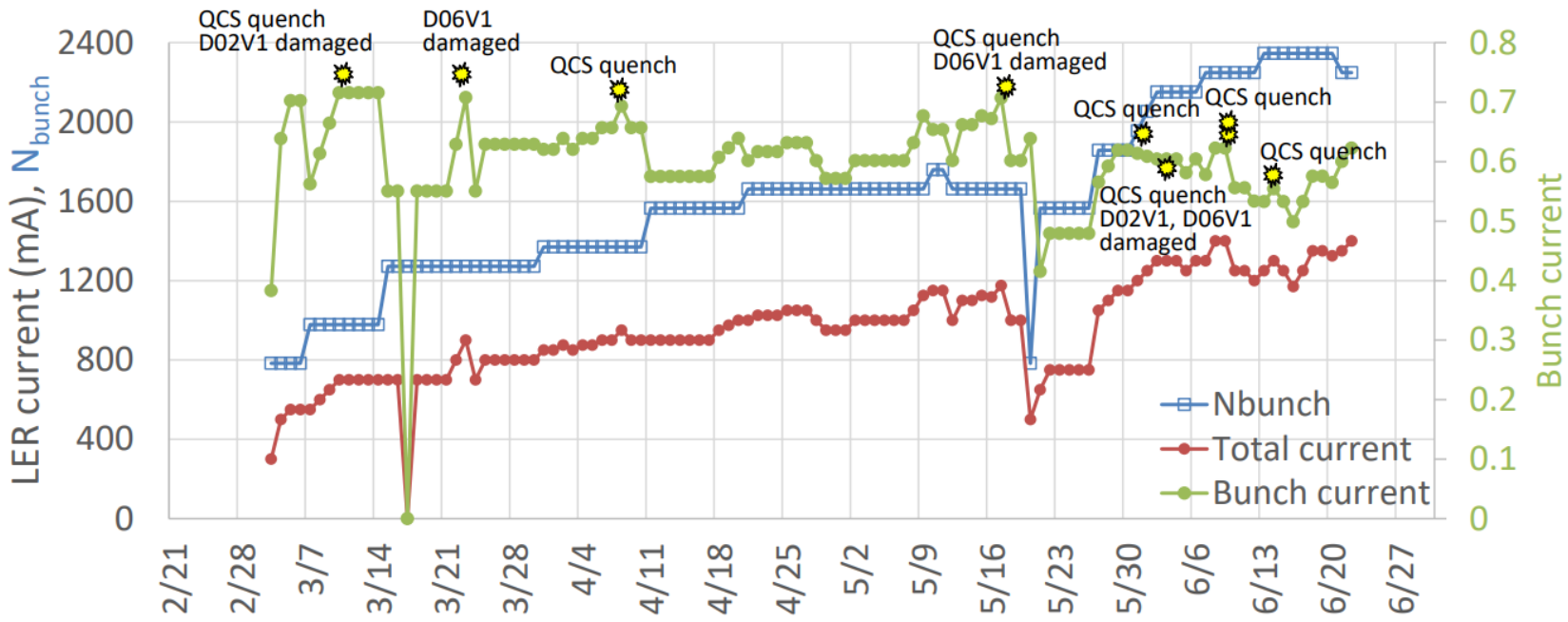
PMT & EMT



(Y.Liu)

Observation : Beam/Bunch Current Dependence

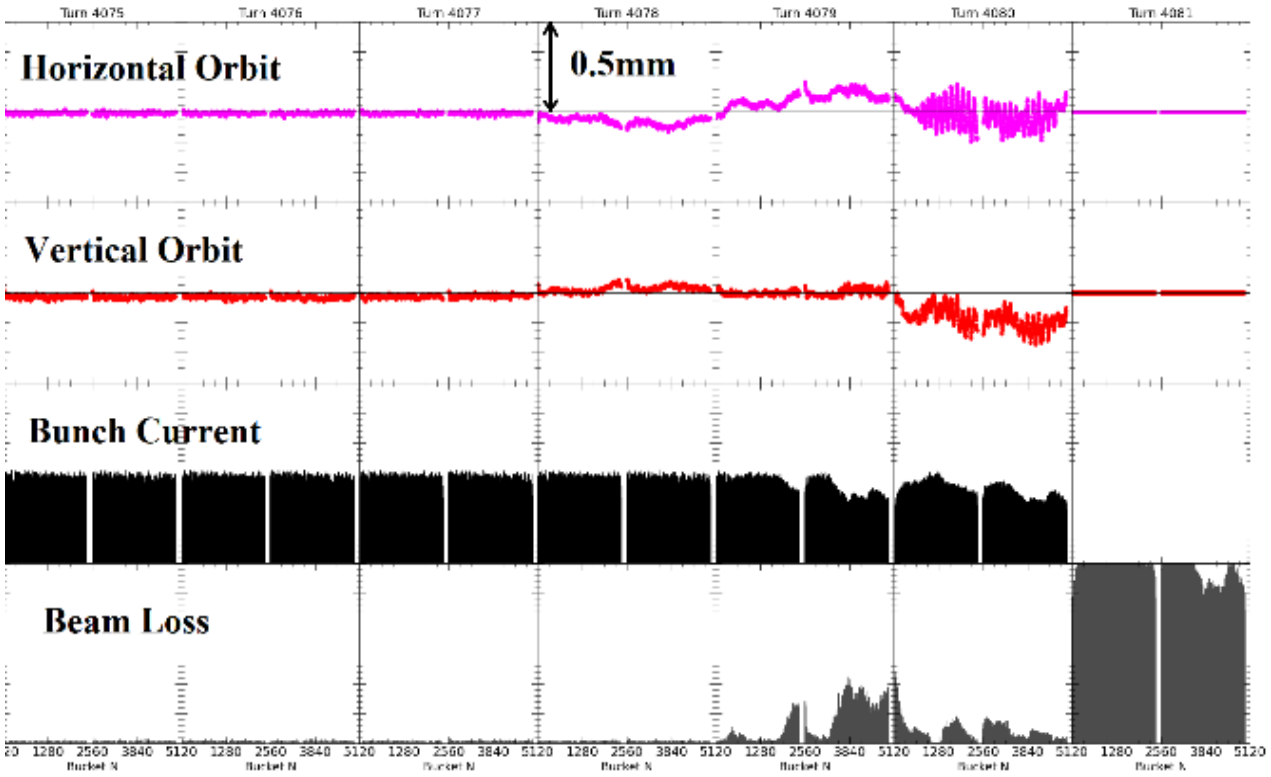
- It is likely to occur when a certain bunch current is exceeded.
- We don't know if it will happen even with a single beam or low current beam because we haven't operated for a long time.



(K.Matsuoka)

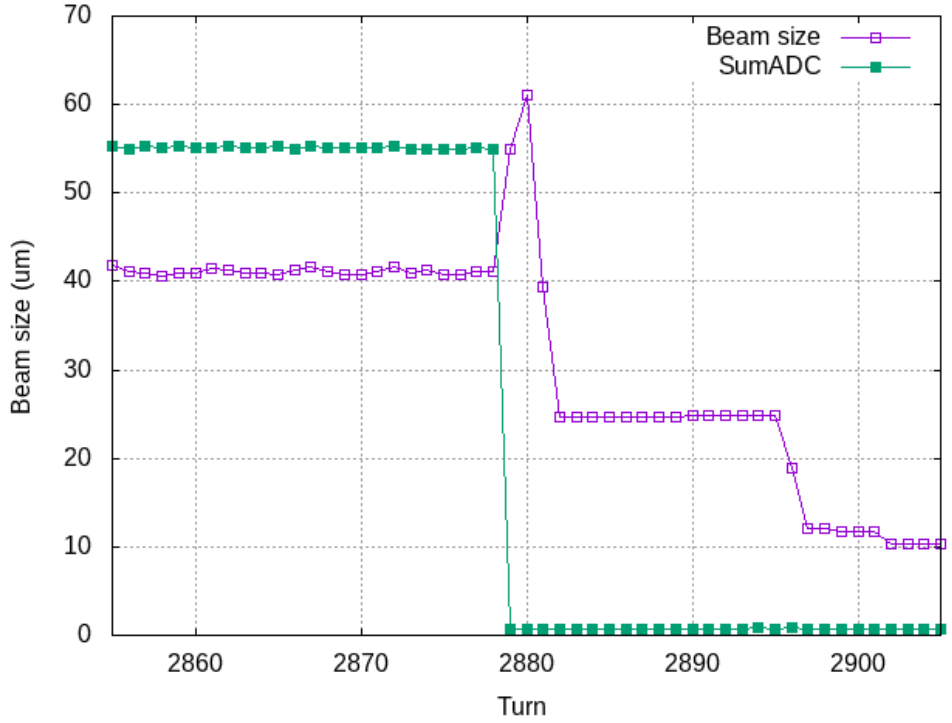
Observation : Beam Orbit

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



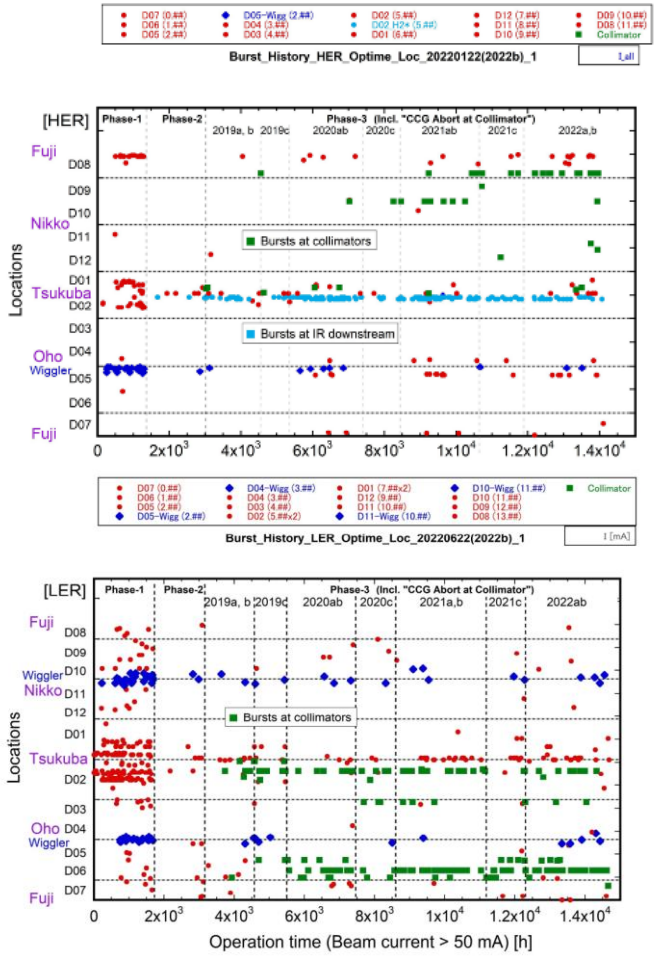
Observation : Beam Size

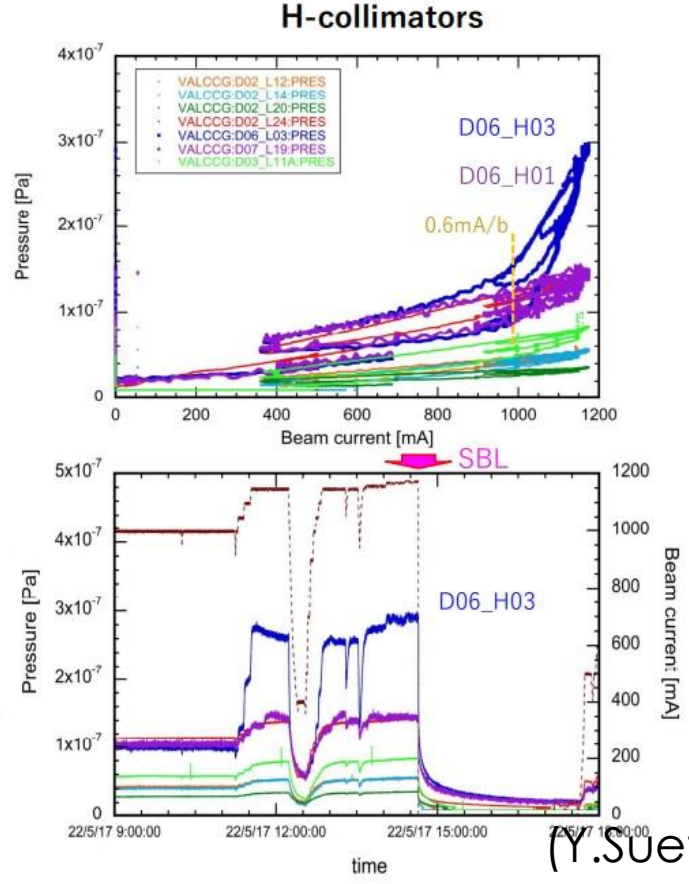
- We checked for beam size fluctuations by installing an ultra-high speed CMOS camera in the X-ray monitor to take 1μs data at 100kHz when the abort is triggered.
- There was no sign of a significant change in beam size before the SBL.



Observation : Vacuum Pressure

- Pressure bursts have been observed all over the place and rarely occur in the same place except at the collimator section.
- Regarding the pressure of D06H3 and H1 collimators there are rapid or nonlinear increase of pressure depending on the beam current.

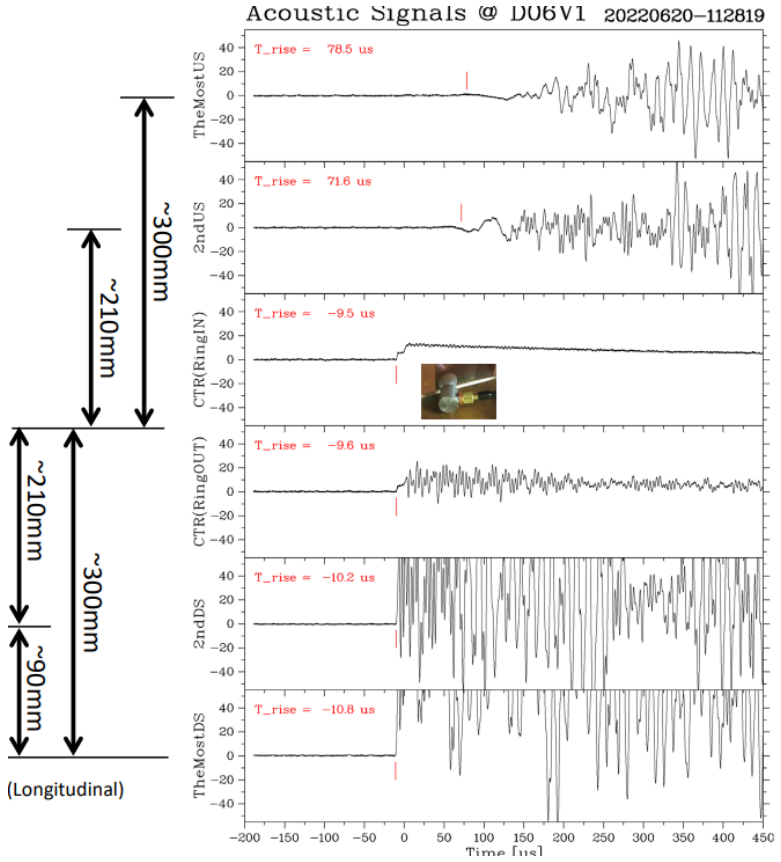


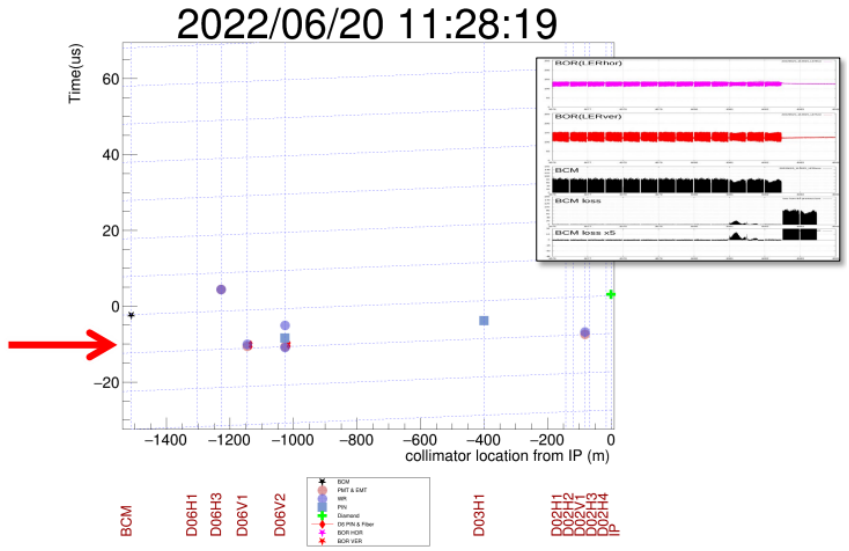


(Y.Suetsugu)

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

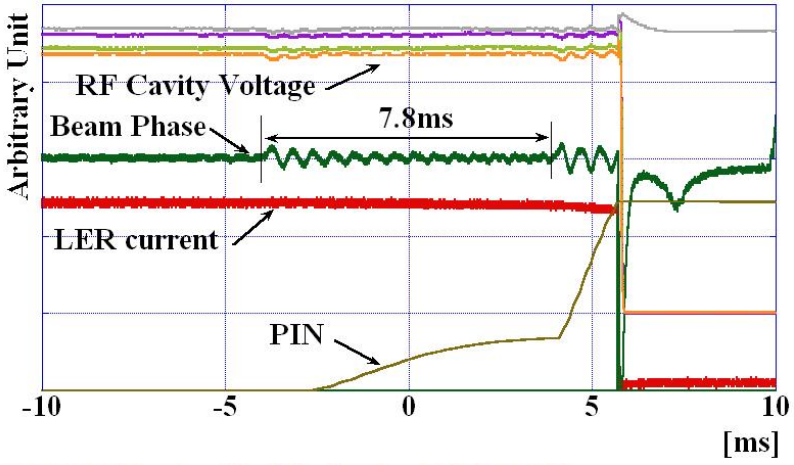
This data suggests that the particle shower produced at the collimator head generated widespread acoustic wave in the downstream of the head, which propagated upstream.

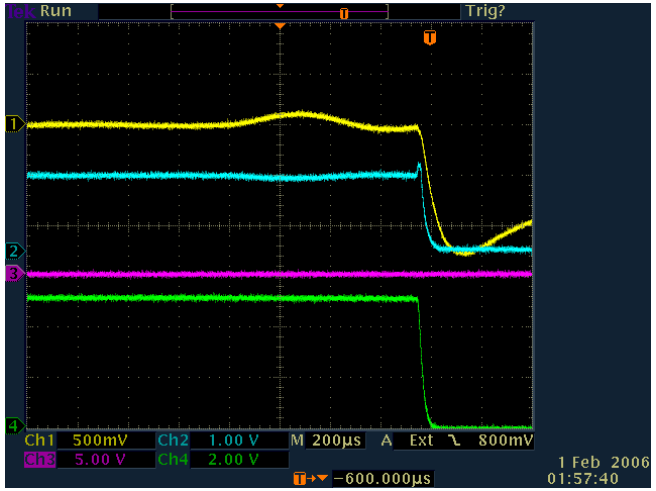
(T.Abe)

Candidate Reasons for SBL : Damage of vacuum component

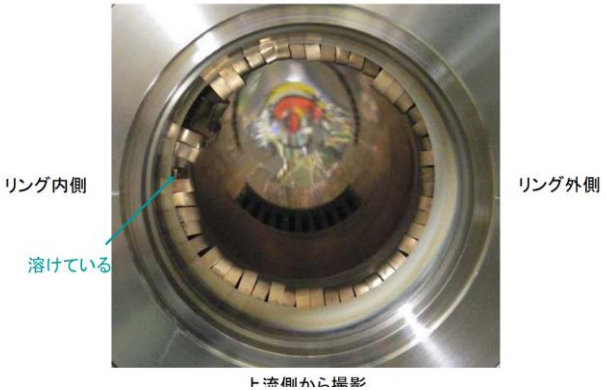
- Damage of vacuum component (RF Finger) @KEKB & PEP-II
  - Beam phase changes (beam energy losses) observed ms to several hundred μs before aborts.

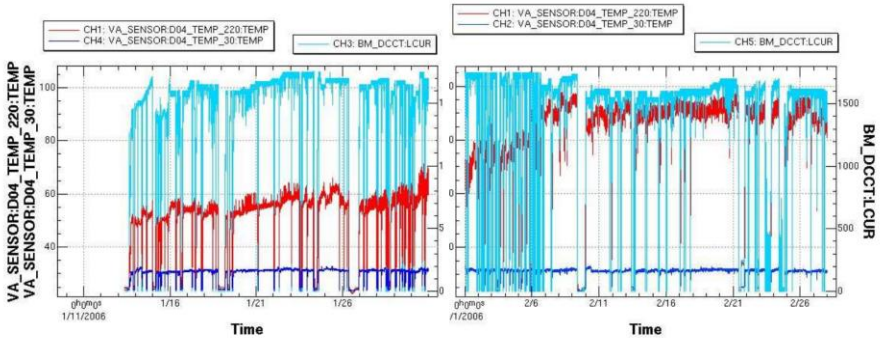
  → The time scale differs from that of SBL.
  - Abnormal temperature rise at bellows chambers had been observed and the catastrophic damages in the RF-finger had been confirmed. → We could not find that damage.





LERD04シケイン部ベローズ（内側）





(Y.Suetsugu)

Candidate Reasons for SBL : Interaction with Dust

- 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.
- For more information, please listen to the talk below.
  - **“Pressure bursts due to beam-dust interaction at SuperKEKB” (by Y.Suetsubu)**

Candidate Reasons for SBL :

- Vertical abort kicker misfire
  - We are using the same thyratron for horizontal kicker. X
- 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. X
- 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. X

Candidate Reasons for SBL : Electron Cloud

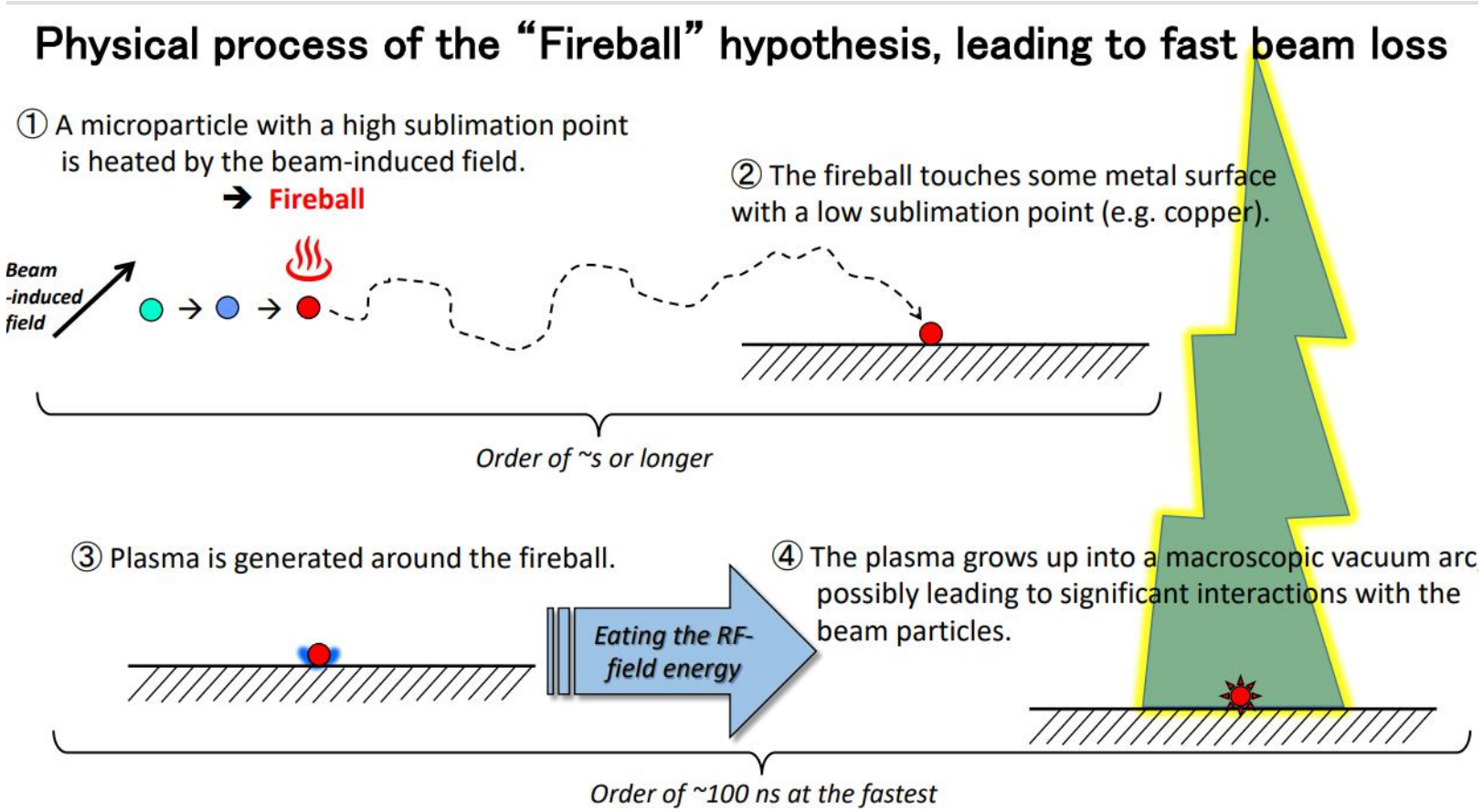
- Electron Cloud
  - SBL should be measured only in LER.→ SBL is also measured in the HER beam.
  - Curious behavior of the pressure in D06H3 collimator may suggest the formation of a discharge or electron cloud.
  - Simulations show that the electron density distribution changes with time and a maximum electron density is on the order of 1E13/m^3 to 1E14/m^3 → How this relates to SBL? △

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).
- For more information, please listen to the talk below.
  - **""Fireball" measured inside the RF cavity at SuperKEKB" (by T. Abe)**



Conclusion

- One of the obstacles to increasing SuperKEKB luminosity is sudden beam loss, the cause of which is still unknown.
- We have investigated it with several monitors, but have not found any phenomena that would elucidate the cause. D06H3 collimator may cause beam loss due to dust or plasma, but no clear mechanism causing SBL.
- The fireball is the most promising hypothesis to explain the SBL at the present time.

Future Plan

Assuming Electron Cloud or Fireball is the cause of SBL,

- Replacing damaged collimator head.
- Copper coating of collimator heads.
- Applying an external magnetic field of 40G or higher to collimator head.
- Enhancement of monitors (acoustic sensor, loss monitor, beam oscillation recorder...) .
- Simulations of plasma and beam interactions.

Announcement

- A international task force was established to investigate and resolve the causes of SBL.

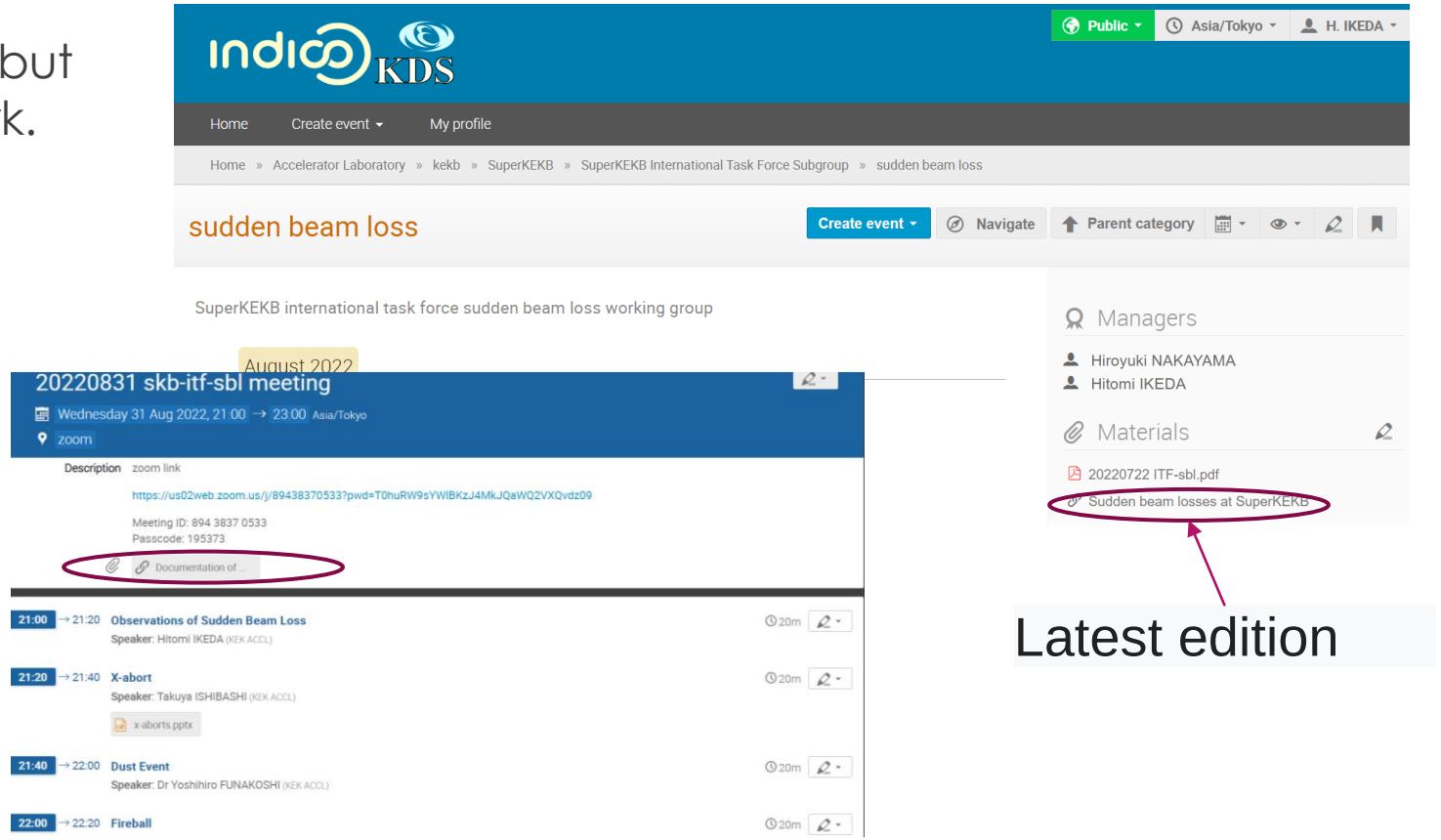
- If you are interested, please register to mailing list from

  http://www-linac.kek.jp/linac-com/skb-itf/ml/

- Would you let us know if you know the expert who may give us advice about the “sudden beam loss” ?

Document

- not summarized all observations, but it's a summary of recent hard work.
- any comment or question in the document, please leave the comment on this link or send us a mail
- The contents of the document
  - description of each sensor
  - result of timing analysis
  - Hypotheses



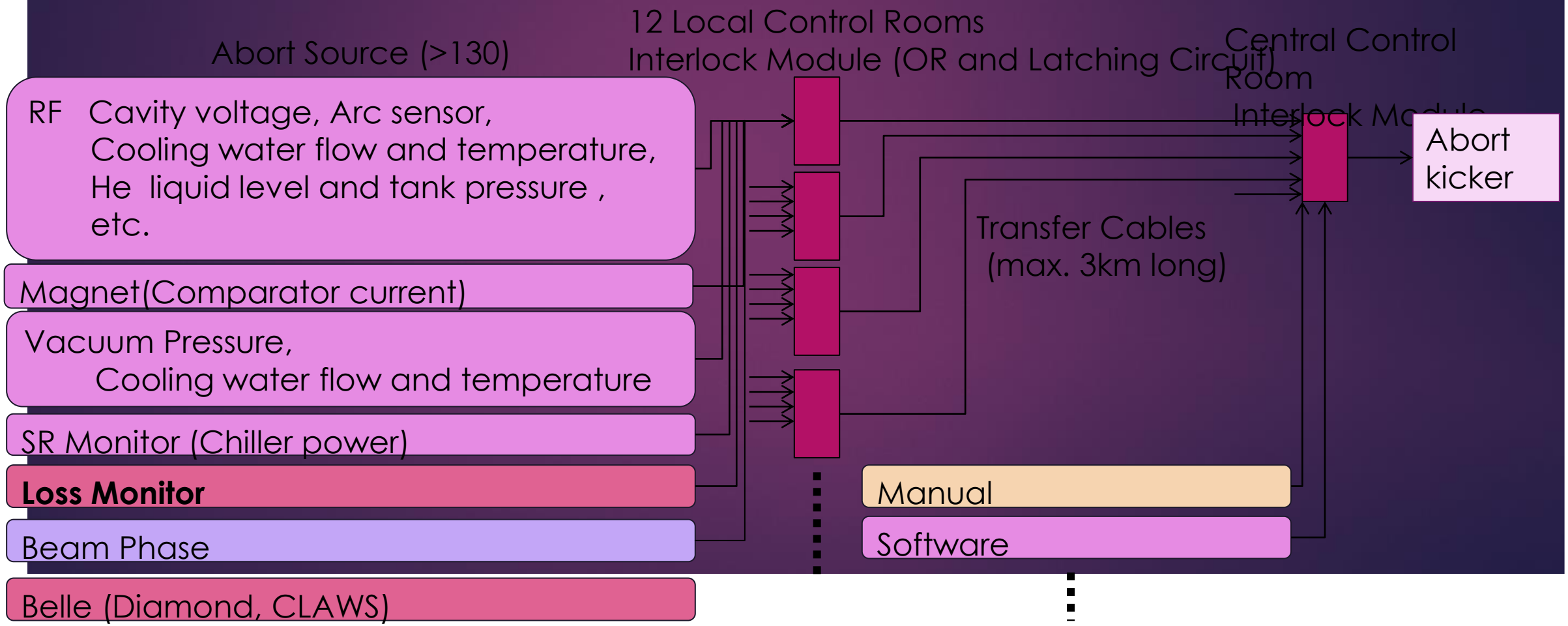
Buckup

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.

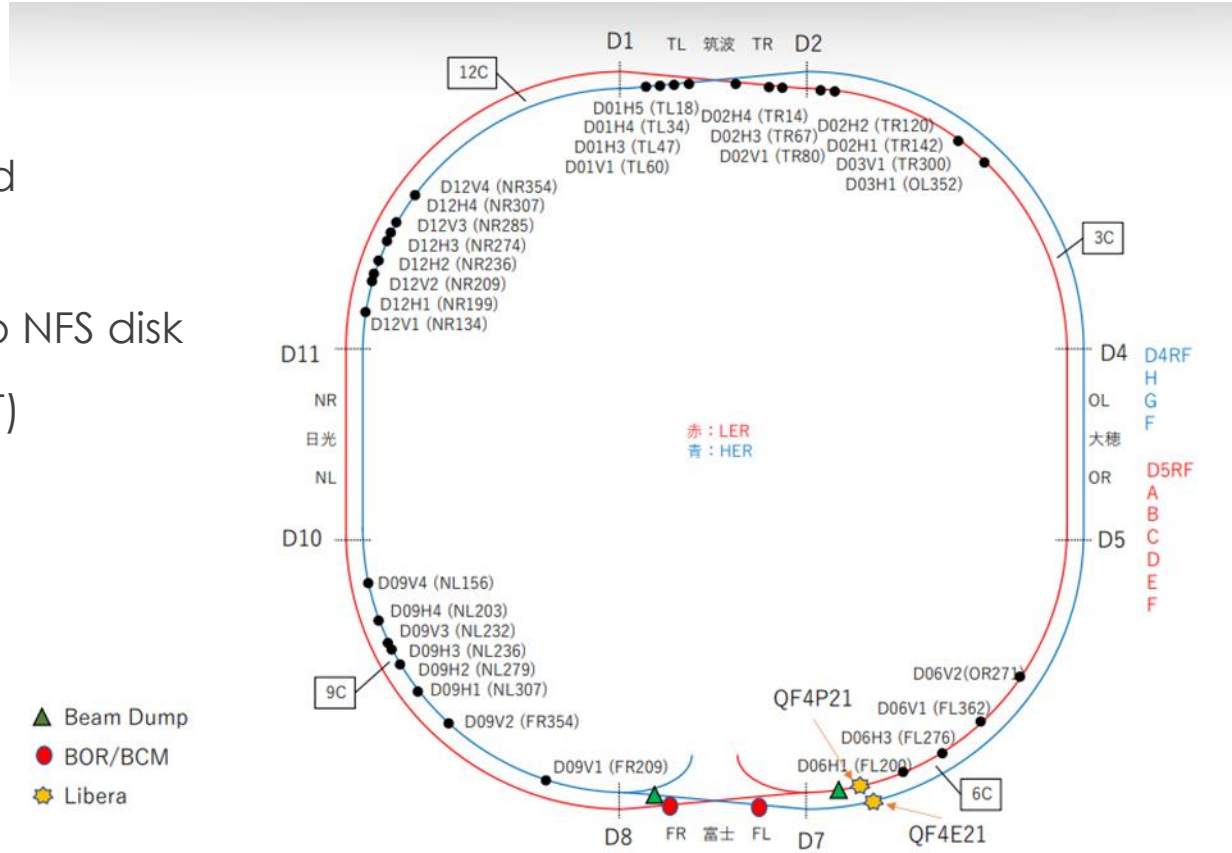
Abort Trigger

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.



Observations : Bunch Oscillation Recorder (BOR) Bunch Current Monitor (BCM)

- 18K10 ADC board
  - VME 2W form factor with BLT data transfer function
  - 8 bits resolution (MAX108 ADC)+Spartan6 FPGA card
  - 5120x4096 turns of ring memory, or 5120x1 (BCM)
  - 4.6s from 18k10 (20M) to VME CPU, 1.4s from VME to NFS disk
  - stop acquisition with (quick) beam loss event (DCCT)
  - LER Horizontal Vertical Longitudinal
  - HER Horizontal Vertical Longitudinal
  - BCM HER LER (shared memory)
  - Long BCM HER LER(5120x4096)



Beam Abort Categorization

After the categorization:

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

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

No particular correlation was found