Beam loss at SuperKEKB: an analysis with the new loss monitor system for the Belle II experiment

Michele Aversano[1],
Keisuke Yoshihara [2], Isamu Nakamura [3], Tachiro Koga [3], Shuji Tanaka [3], Hiroyuki Nakayama [3], Ichiro Adachi [3], Hiroshi Kaji [4], Hitomi Ikeda [4], Hidekazu Kakuno [5], Kenkichi Miyabayashi [6], Yu Nakazawa [3], Akane Maeda [1], Yuxin Liu [7], Aimi Kusudo [6], Kazuki Kitamura [5]

[1]Nagoya University, [2]Nagoya KMI, [3]KEK IPNS, [4]KEK Acc., [5]Tokyo Metropolitan University, [6]Nara Women's University

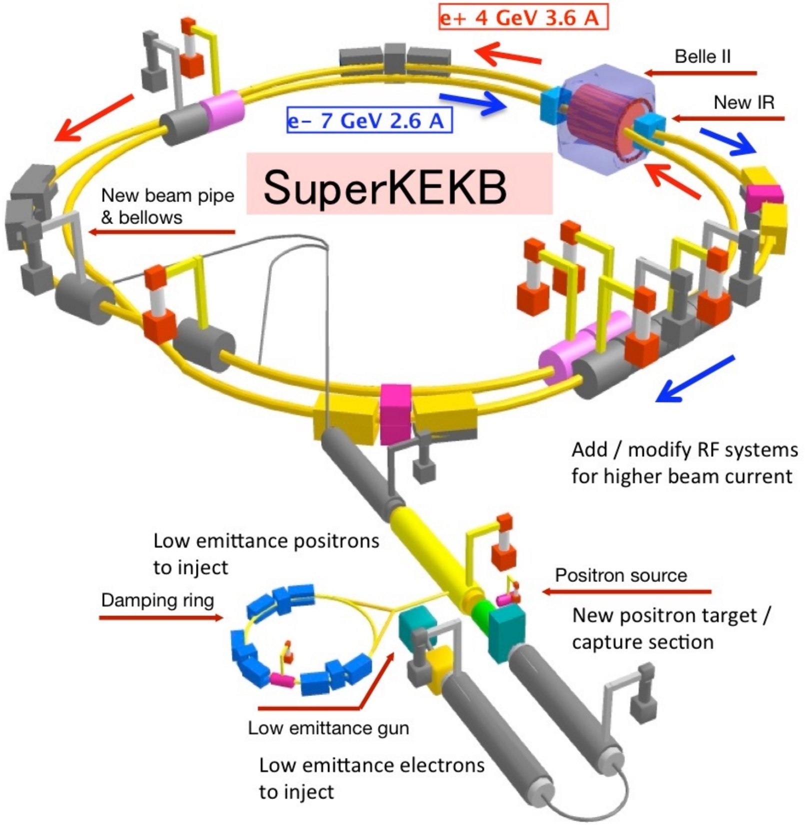
名前の発音：
ミケーレ
アヴェルサーノ

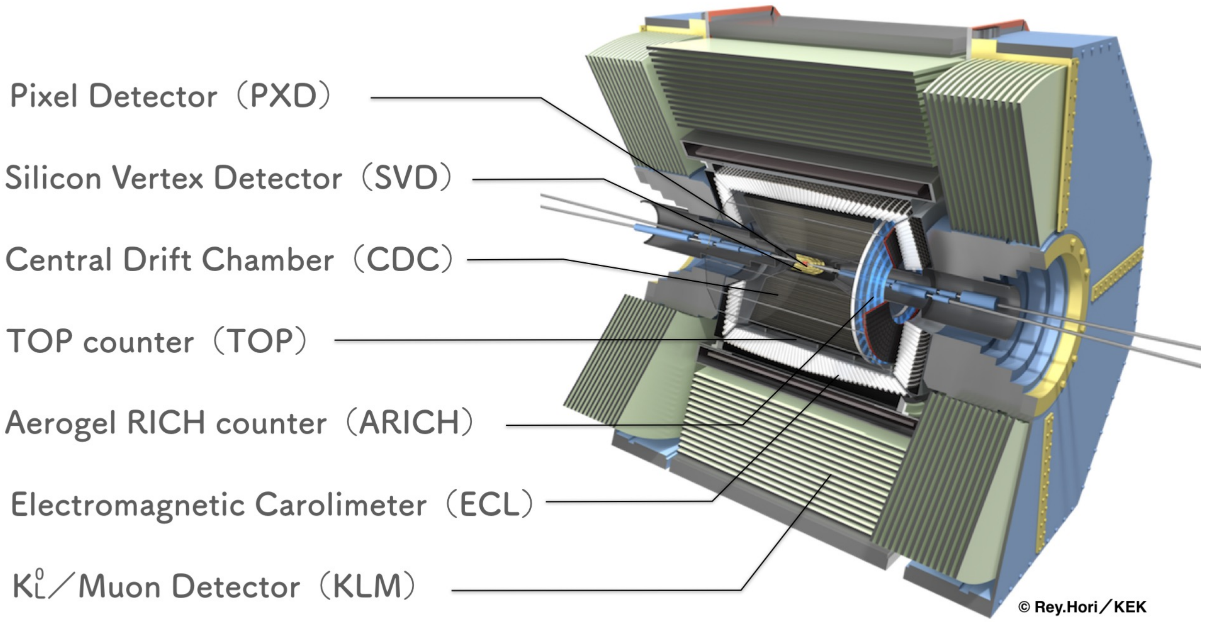
FlavorPhysicsWorkshop 2022/11/07

The Belle II Experiment and SuperKEKB accelerator

The Belle II experiment is a Particle Physics experiment designed to primarily study the properties of **B mesons**.

SuperKEKB → asymmetric collider e^-e^+(**7 GeV** and **4 GeV**) operating mainly at a center of mass energy of **10.58 GeV** →the **ϒ(4S) resonance**.





The Belle II detector is a a **general-purpose** detector.

From 2022/06/22 → Long Shutdown 1 (LS1)

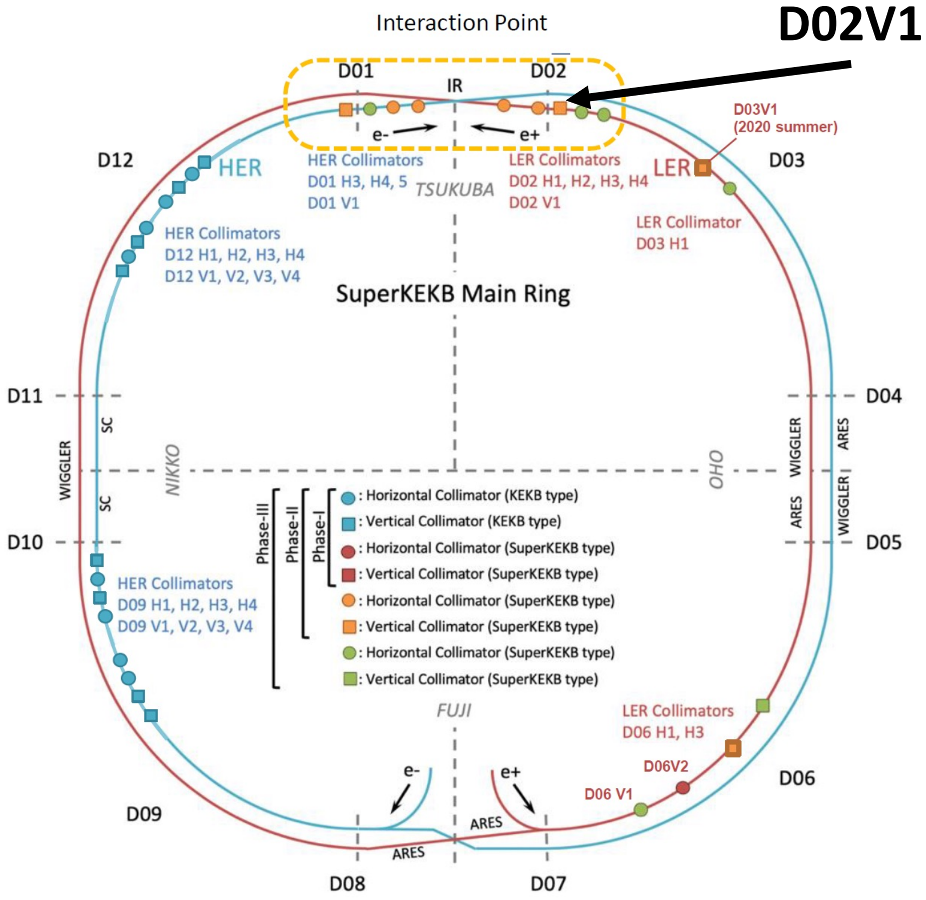
Until now:

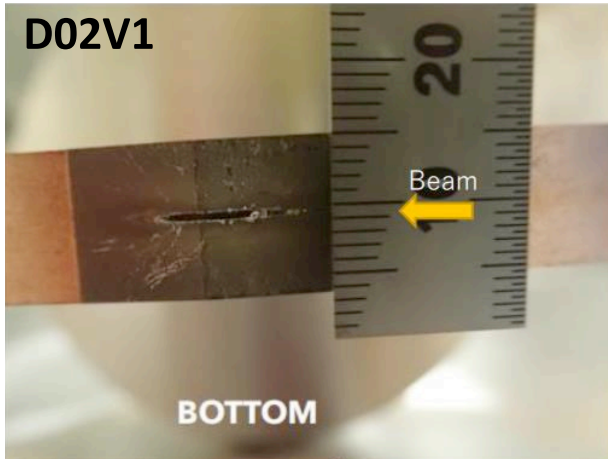
- $L_{peak} \sim 4.7 \cdot 10^{34} cm^{-2} s^{-1}$**(world record!)**
- $L_{int} \sim 424 fb^{-1}$

Sudden Beam Loss (SBL)

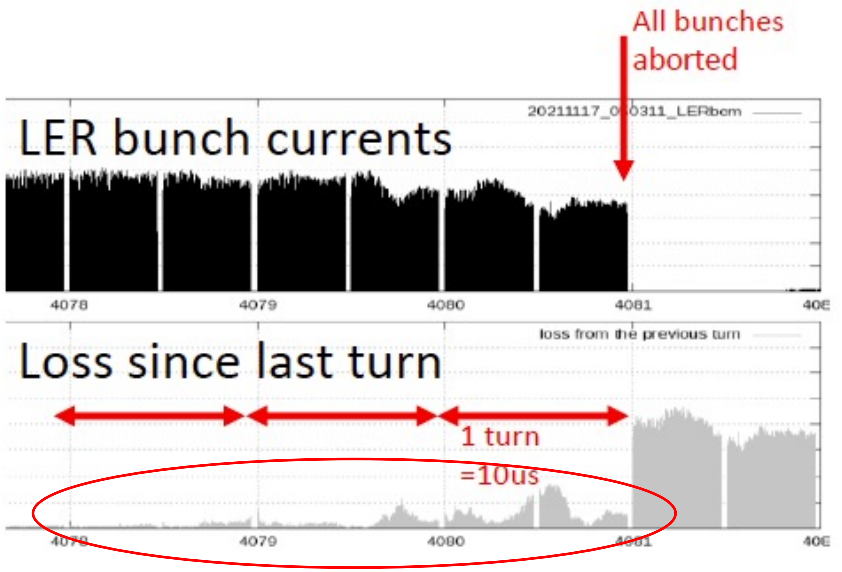
Beam becomes suddenly **unstable** → «**Catastrophic» loss** can lead to **severe damage on collimator** or **Belle II detector**

In order to get **high in luminosity** we need to **increase the beam current** → **SBL is a big limitation for operation.**





Severe damage on D02V1 collimator heads after QCS quench with high beam current.



Motivation:
investigate location of the initial loss, in order to **try understand the reason(s) of the large beam loss events.**

Collimator at SuperKEKB

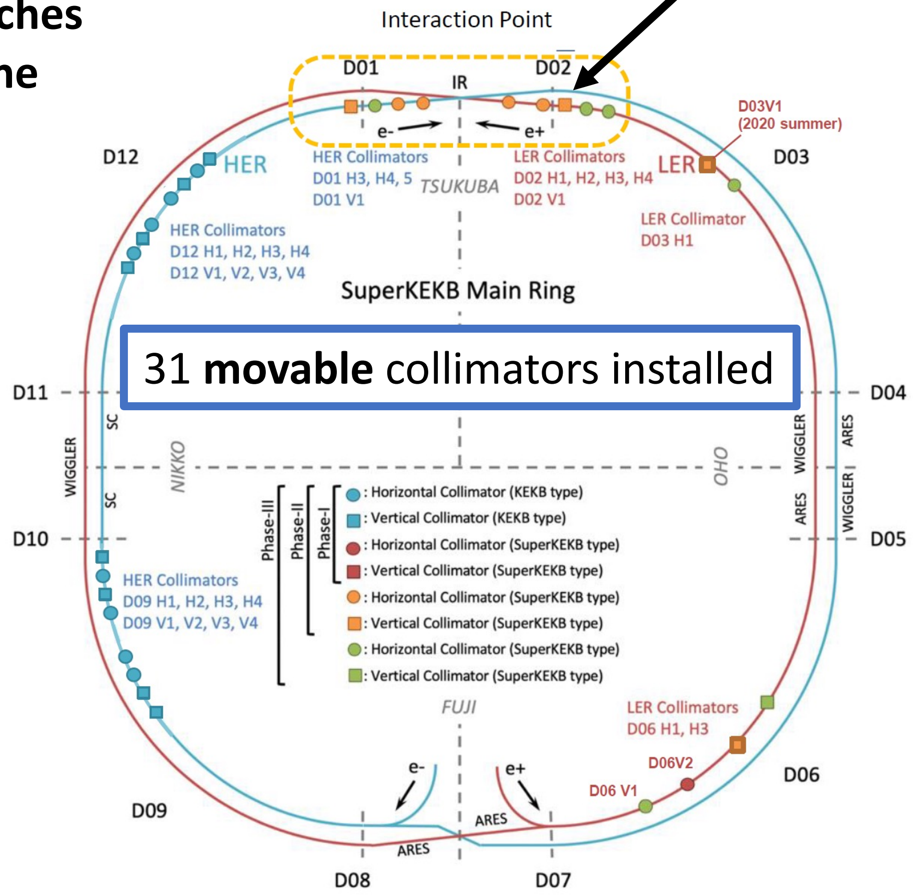
There are 2 types of collimator:

- **Horizontal (H)**
- **Vertical (V)**

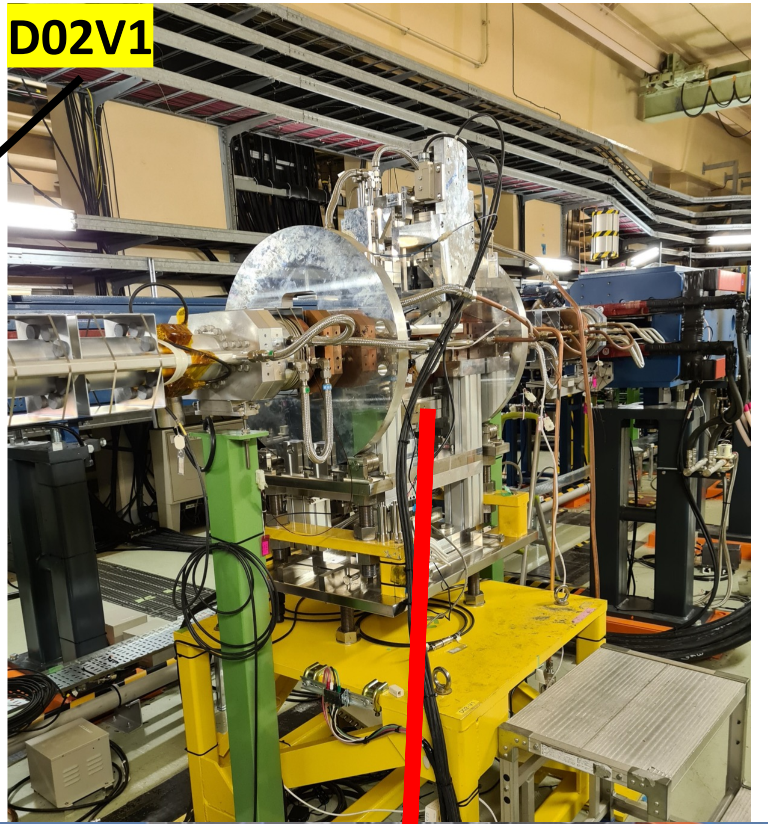
Purposes:

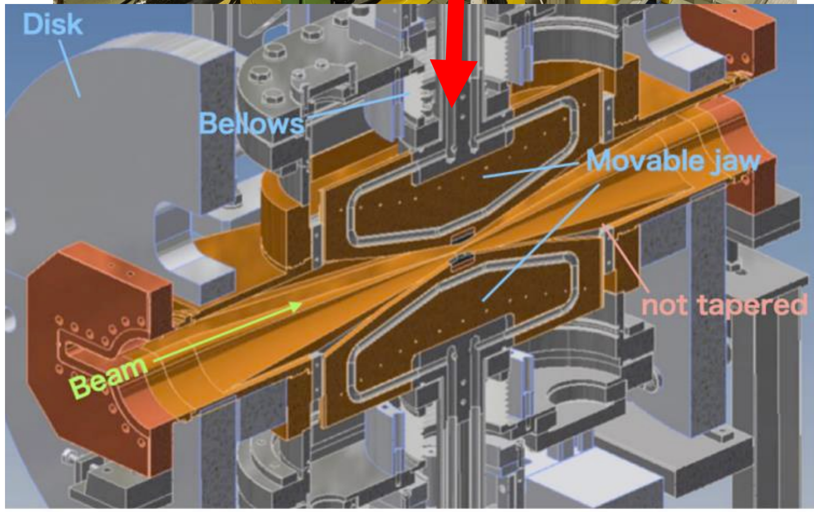
- **Shield the non-Gaussian tail in bunches**
- **Limit physical apertures locally in the ring**
- **Suppress background noise**

Narrowest part of the ring
→**most likely location for SBL.**



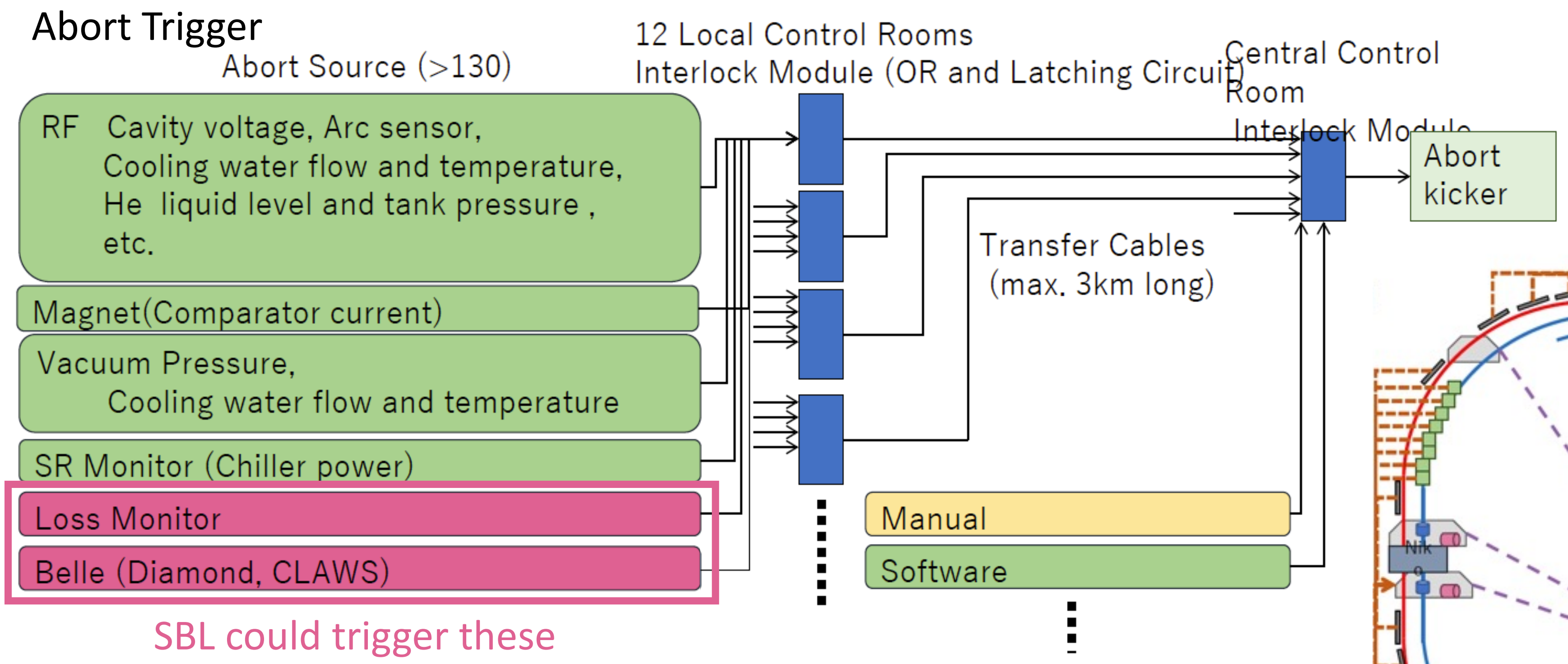
31 **movable** collimators installed

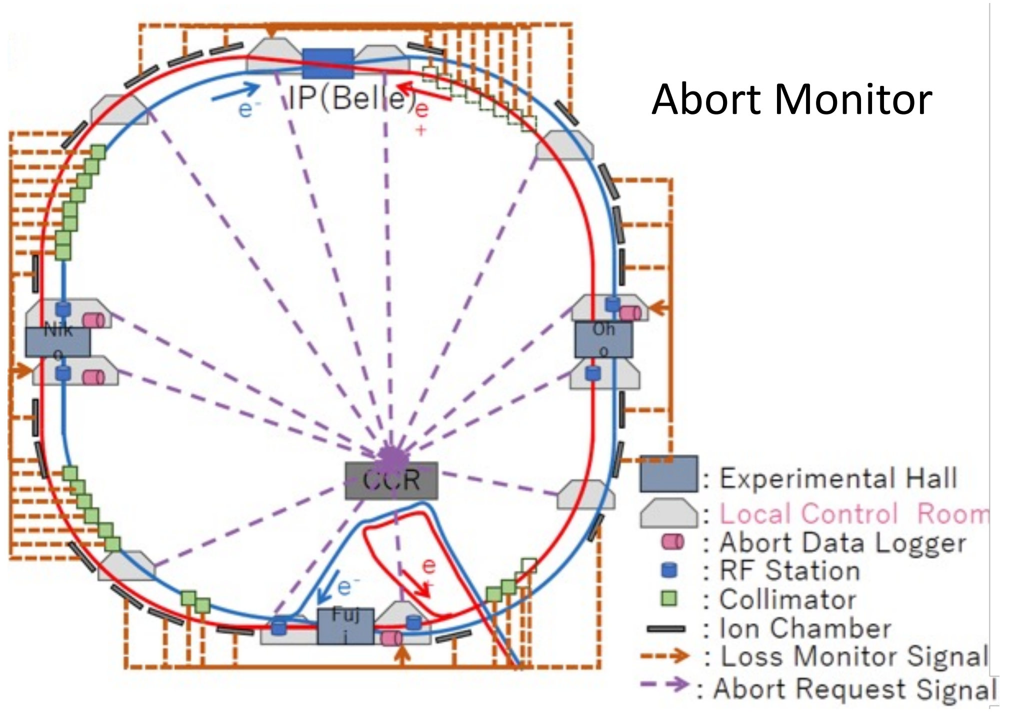




Beam Abort at SuperKEKB

In order to protect the Belle II detector and the accelerator against the high beam currents
→ we must **detect the abnormalities as soon as possible** and **the beam must be kicked out from the ring**
→ **Abort System**





→ **Kick out all beam in case high radiation detected in Belle II, beam loss detected by loss monitors or other safety issues.**

Fast Loss Monitor

In order to try to understand the cause of the loss → we add a lot of "**eyes**":

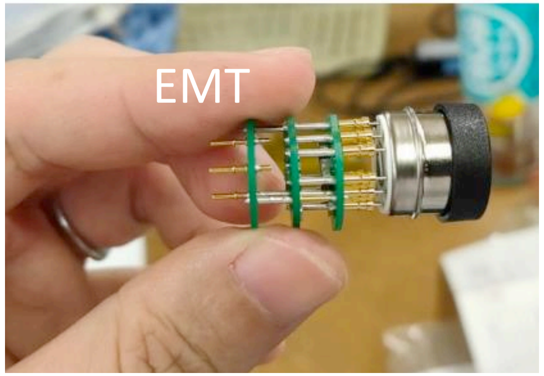
→Loss monitors + Time sync system(White Rabbit)

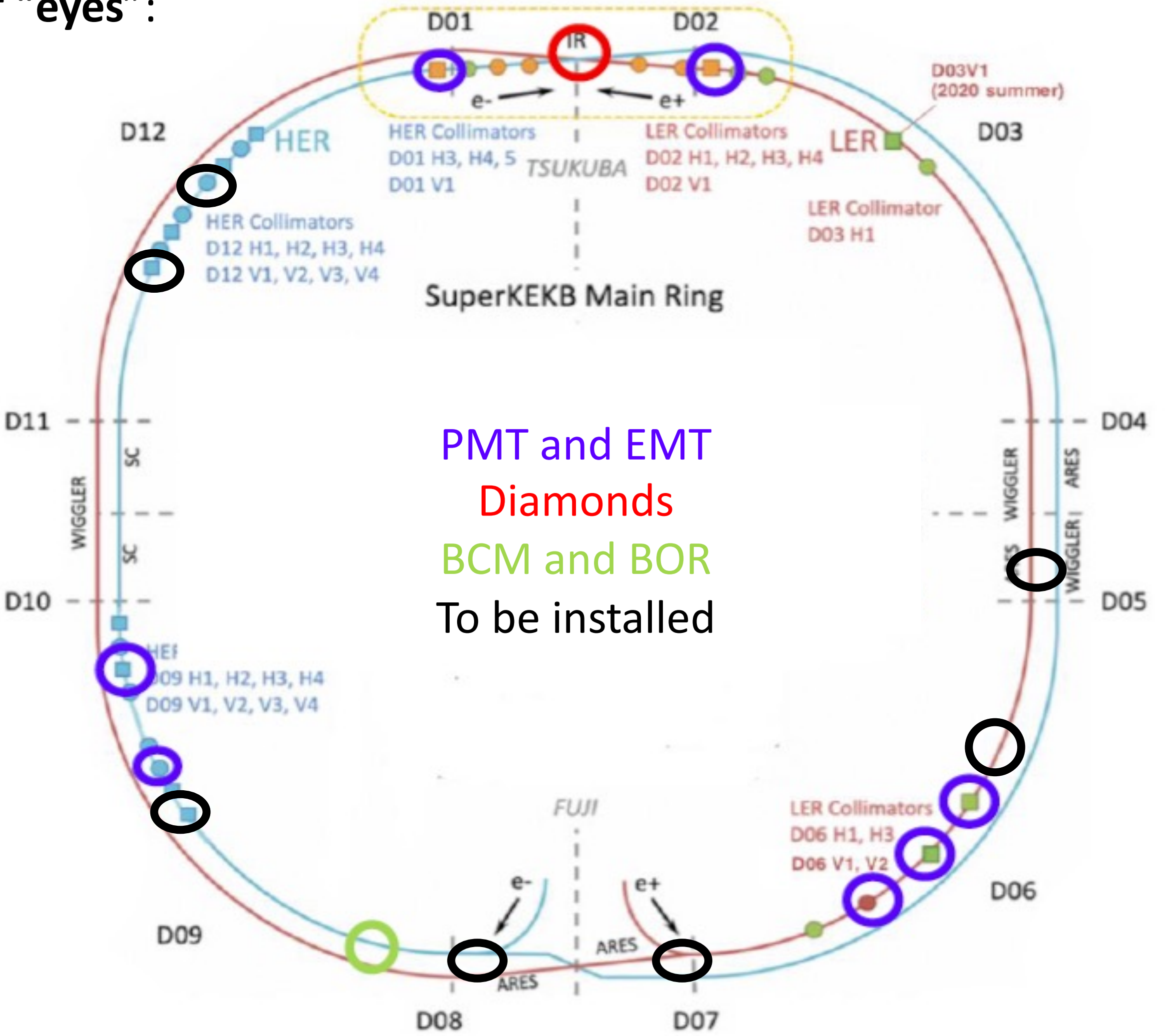
7 detectors installed from last year:

- **Pure CsI + PMT**
- **EMT**

→ good resolution $\sim 10ns$

→The plan is to install the remaining ones during **LS1.**
(loss monitors >12)





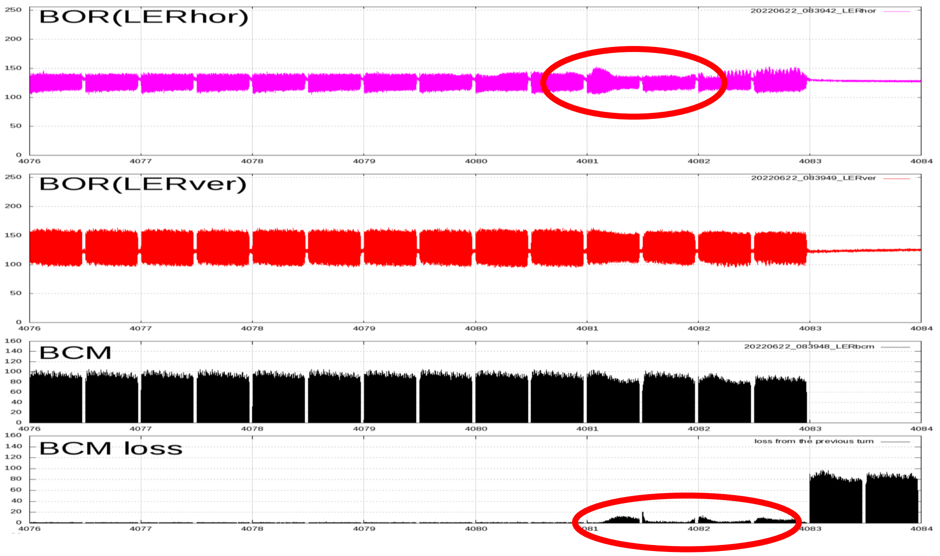
Other sensors

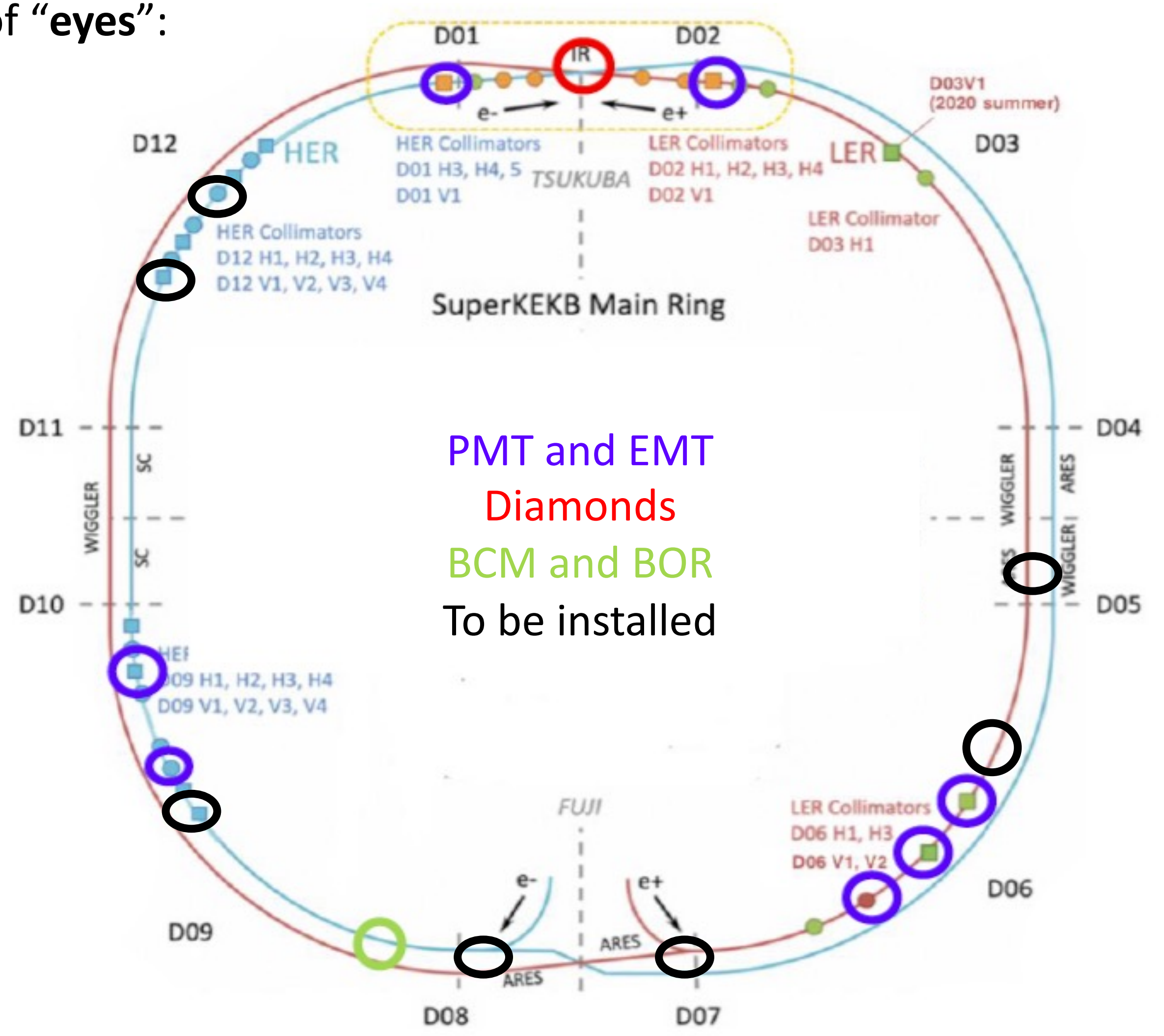
In order to try to understand the cause of the loss → we add a lot of "**eyes**":

→Loss monitors + Time sync system(White Rabbit)

We use also **other sensors:**

- **Bunch Current Monitor** (**BCM**), for beam current loss.
- **Bunch Oscillation Recorder** (**BOR**), for beam stability information.
- **Diamonds**, for radiation level at Interaction Region.





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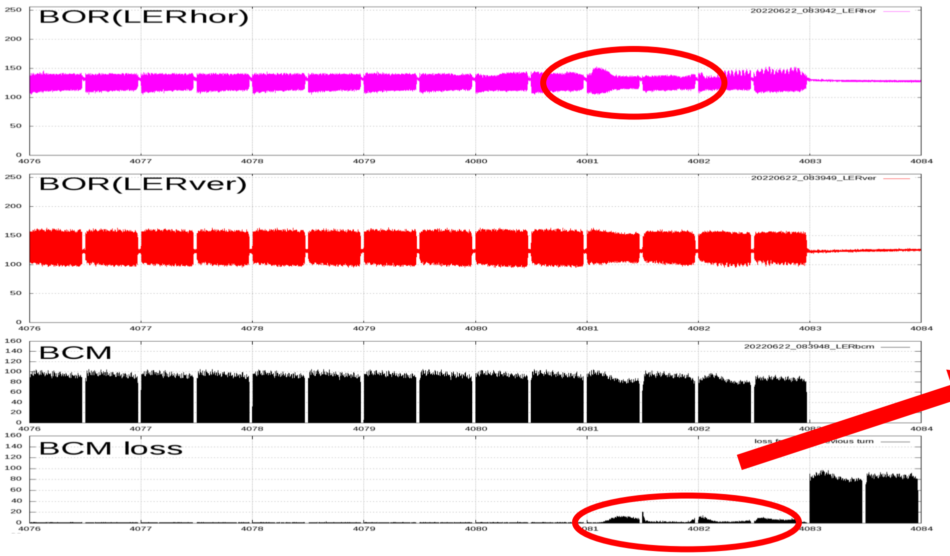
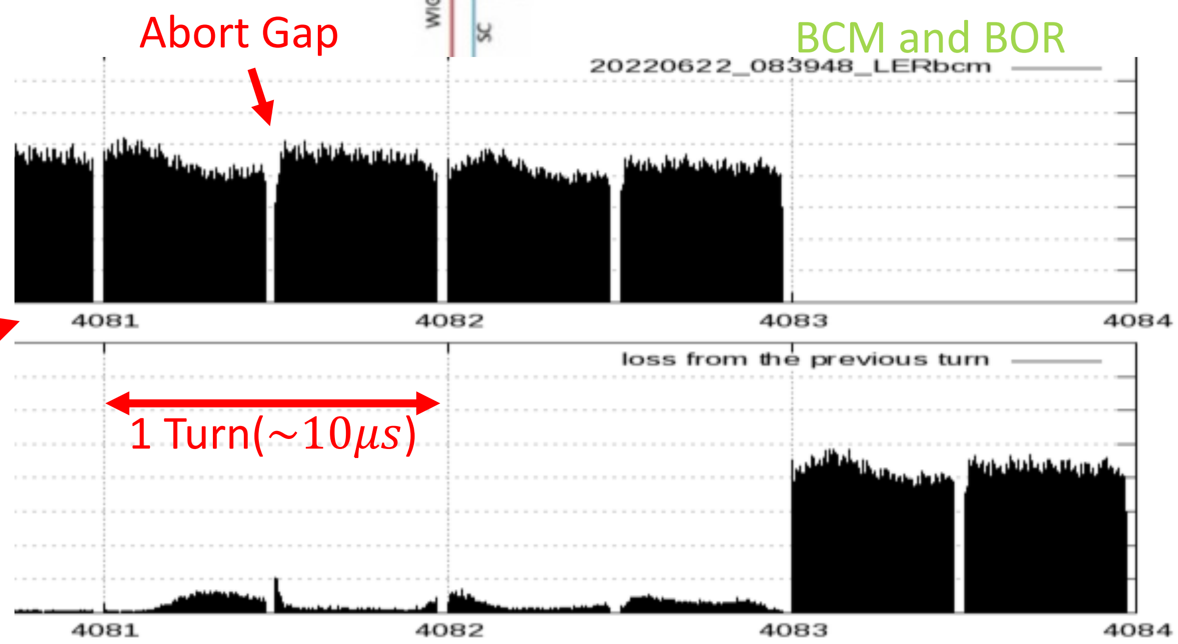
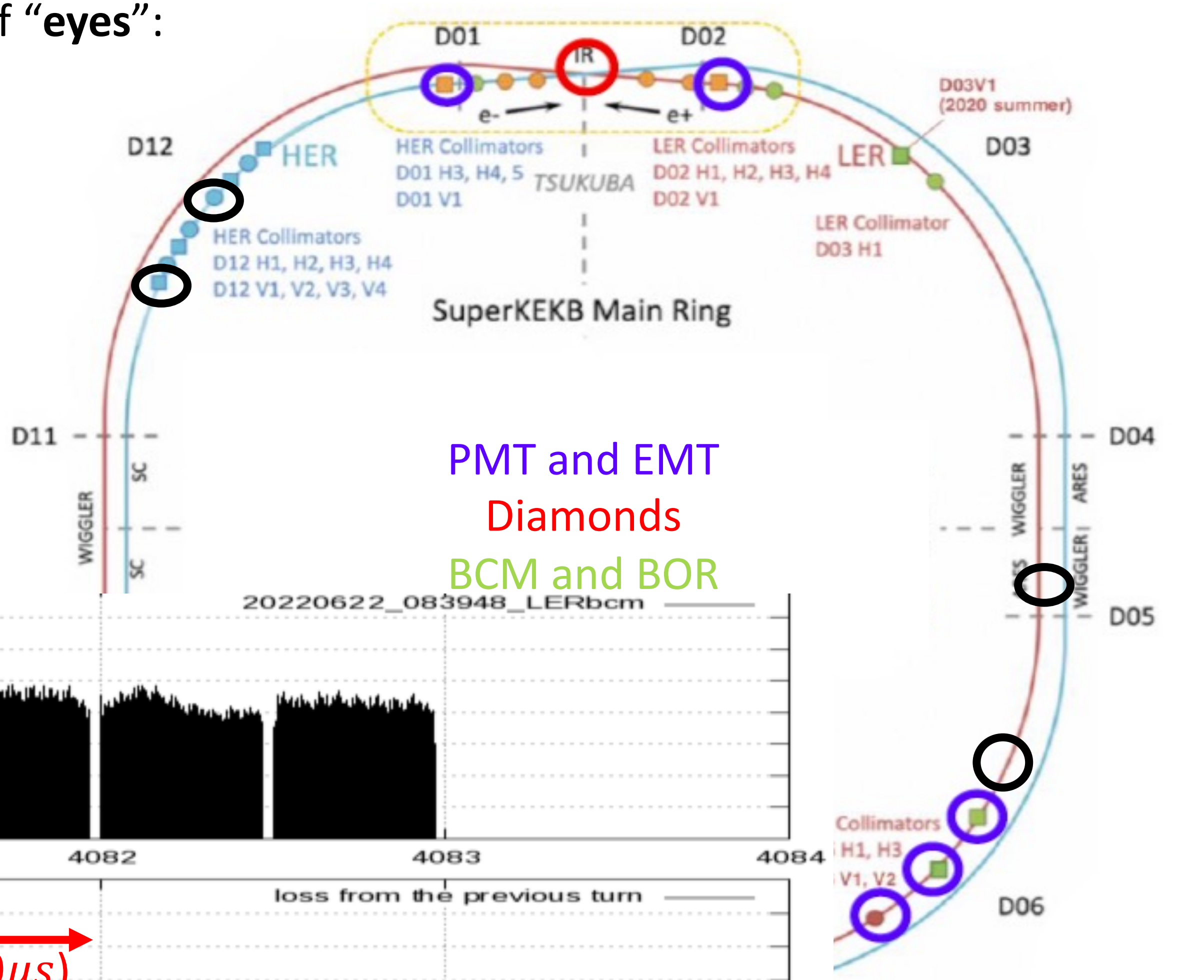




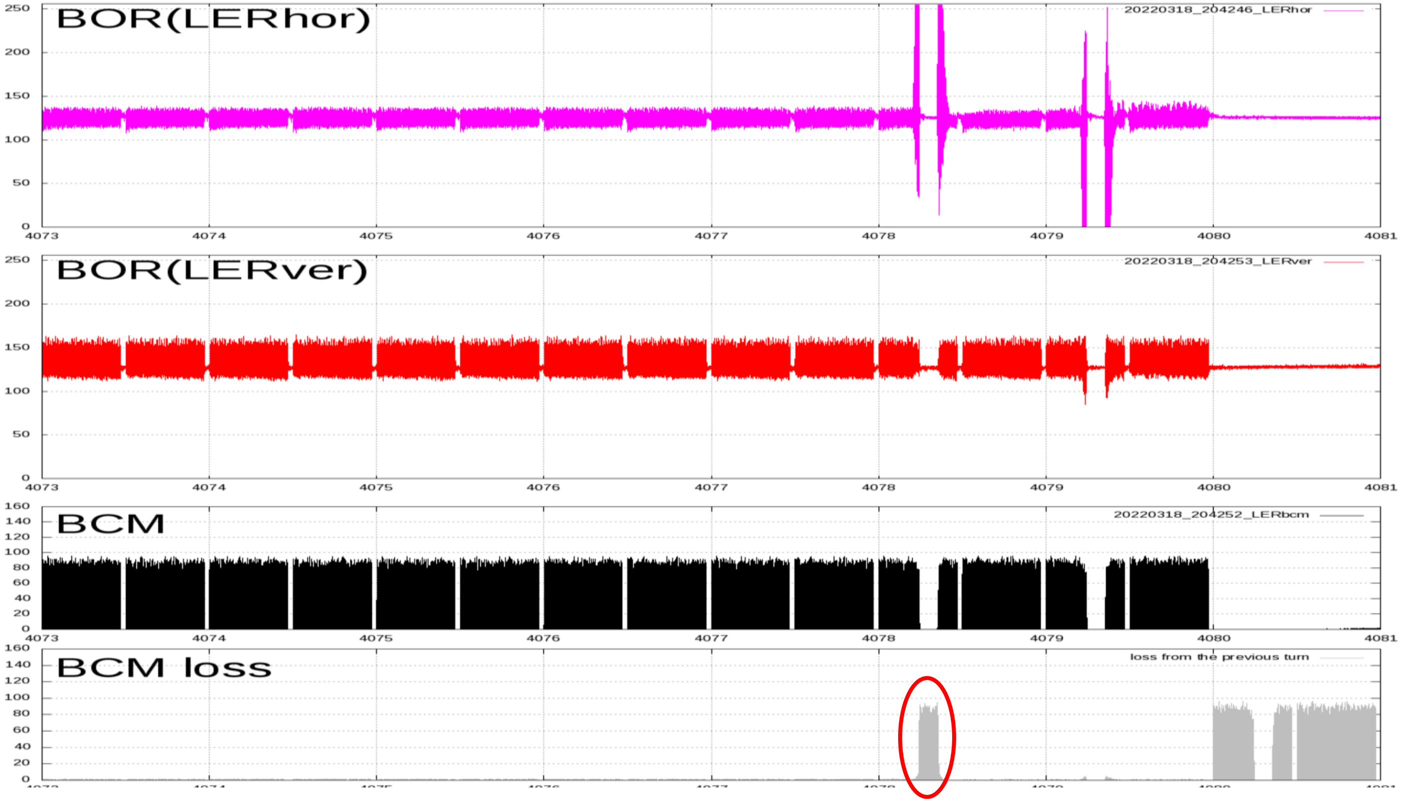


Pulse Height Comparison

This calibration is independent from the timing analysis.

In order to **compare integrated dose from different detectors**
→ a **calibration** is needed.

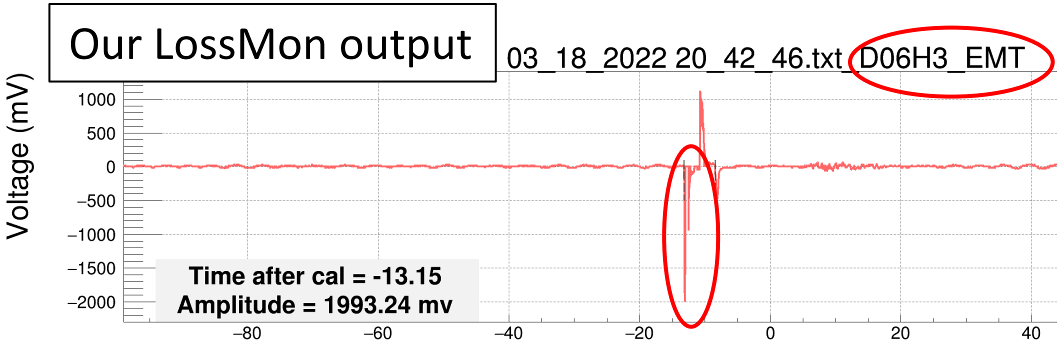
2022/03/18 20:42:52 **(D06H3 - Accidental Kicker Firing)**



→ we tried it, but it was **not possible** since the **small acceptance of our detectors.**

I used **4 events** like this and obtained **4 calibration factors for D06H3 detector**:

In the Accidental Kicker Firing, the BCM loss is all located in a particular Turn → good for calibration.

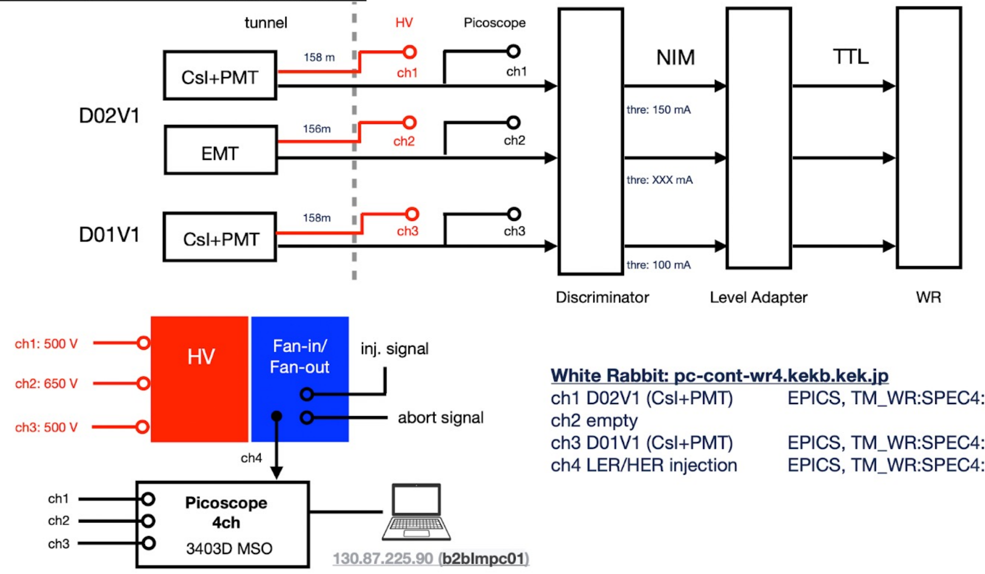


D06H3 calibration Factors (mA/mV)
0.657536109
0.06896233
0.01241349
0.0153827

The Calibration factors are too different

Readout System and Time Sync

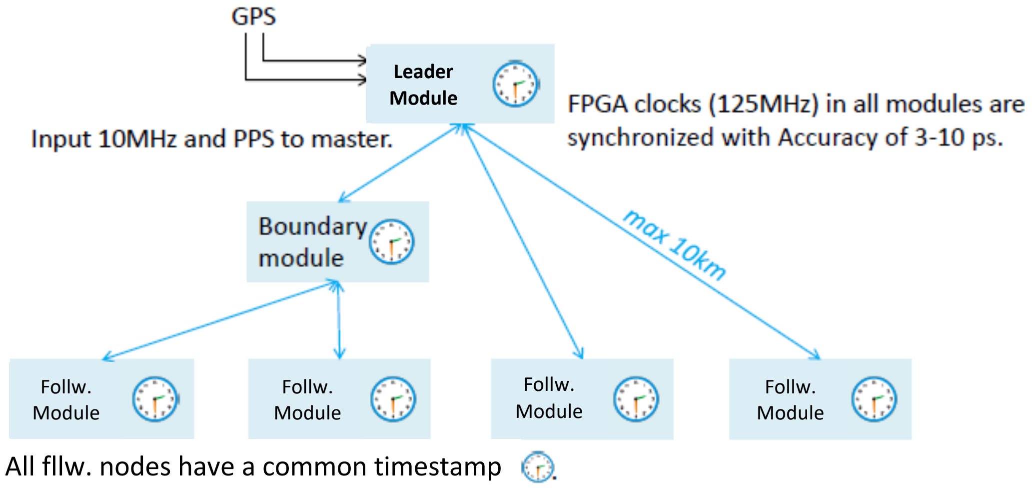
Tsukuba B4（現状）



White Rabbit: pc-cont-wr4.kekb.kek.jp

ch1 D02V1 (CsI+PMT)	EPICS, TM_WR:SPEC4:DIO:CH1:STA
ch2 empty	
ch3 D01V1 (CsI+PMT)	EPICS, TM_WR:SPEC4:DIO:CH3:STA
ch4 LER/HER injection	EPICS, TM_WR:SPEC4:DIO:CH4:STA

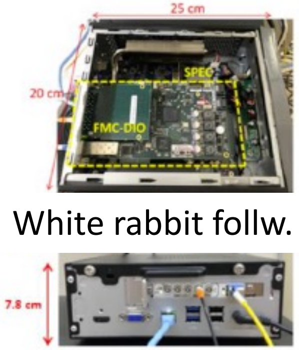
→readout system example



For our timing analysis → **White Rabbit (WR)** and **Oscilloscope:**

- WR consists of **Leader module** and **Follower modules** and can provide a **common timestamp (GPS)** with $\sim 8\ ns$ accuracy.
- Oscilloscope can provide **both timing and waveform** →triggerd by beam abort.

White rabbit leader module



White rabbit follw. module

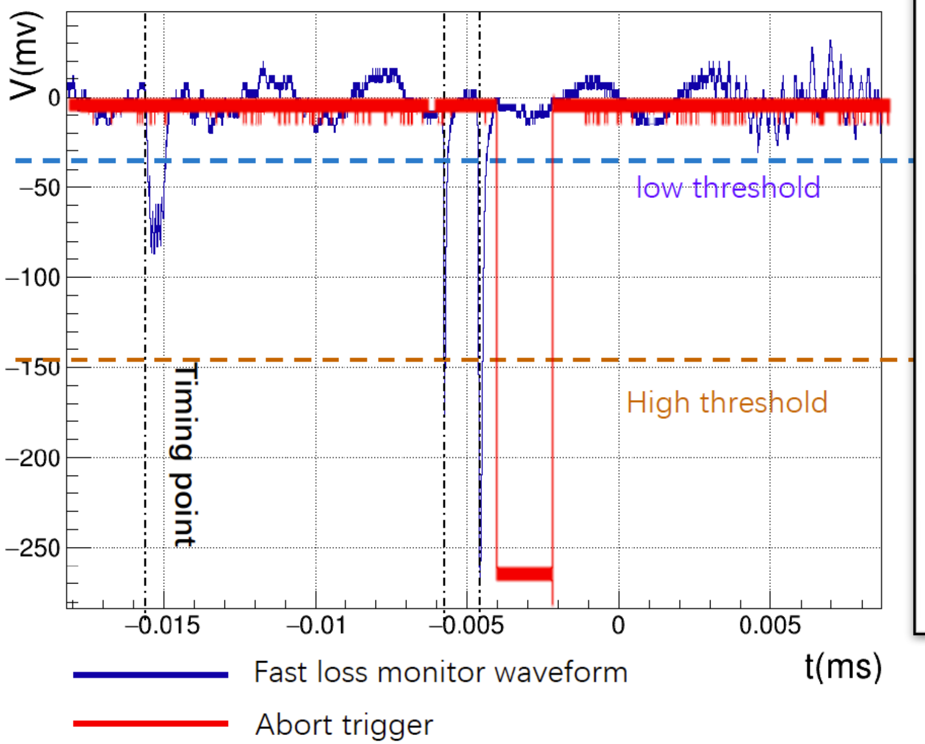
Timing Analysis

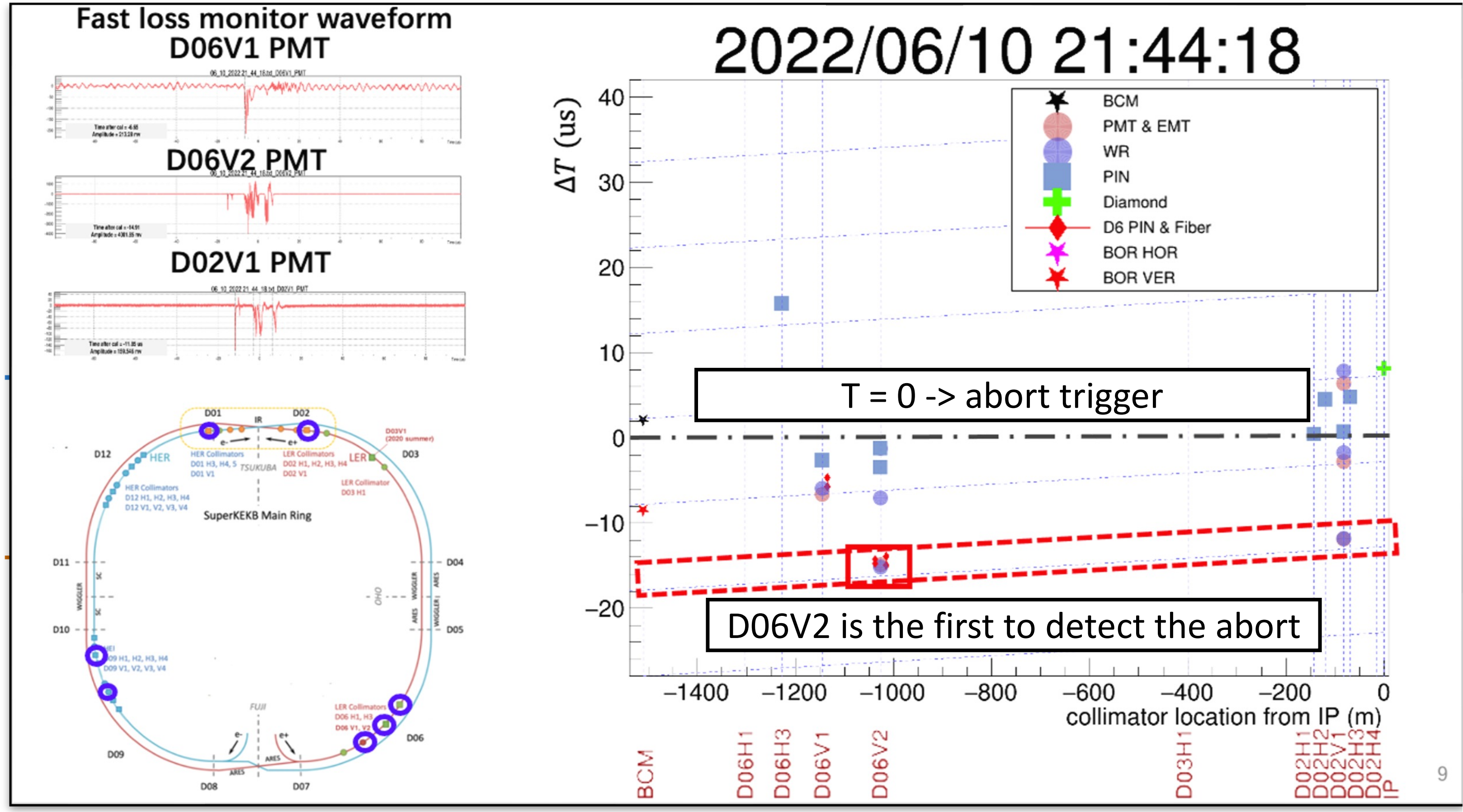
To synchronize different local systems (fast lossmon, BCM, etc.)
→ **oscilloscope** timing information and the **abort trigger** timing (**common timestamp**):

Y. Liu

$$\Delta T = T_{sensors} - T_{abortTrigger}$$

A **double threshold**, low and high, is used.

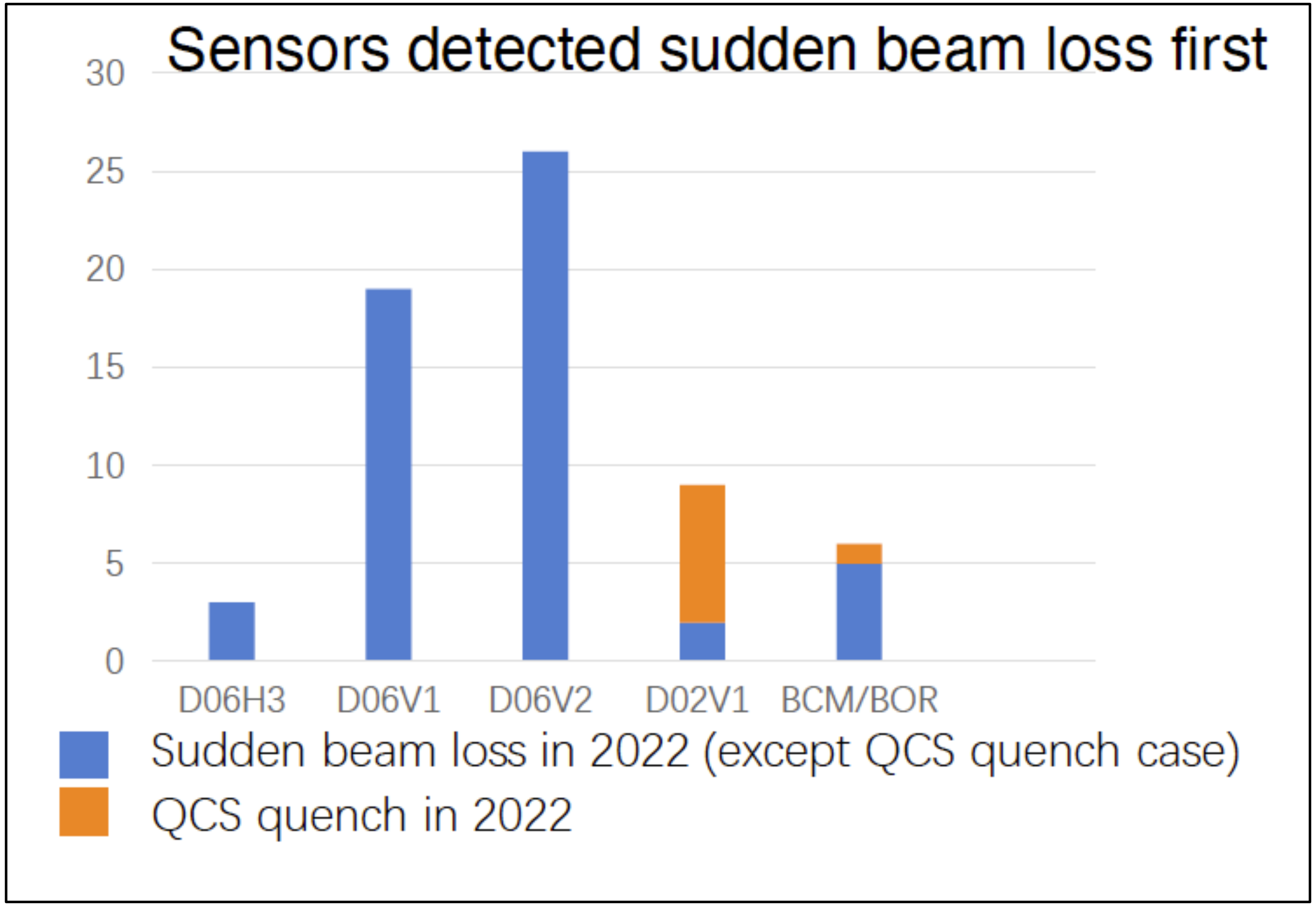




For more details -> Liu-san’s poster

SBL summary 2022

Y. Liu



- Most of the initial beam loss
  → **D06 section**

- When a **QCS quench occurs**, in most of the cases the initial beam loss
  → **D02V1**

(Vertical collimator closest to the IR)

Beam Abort Categorization

Frequent beam aborts disturb machine operation and led to a **decrease in recorded luminosity:**
having a **better understanding of the beam aborts is essential.**

→ Beam abort categorization.

SBLs are just one kind of events that cause the abort → there are other categories:

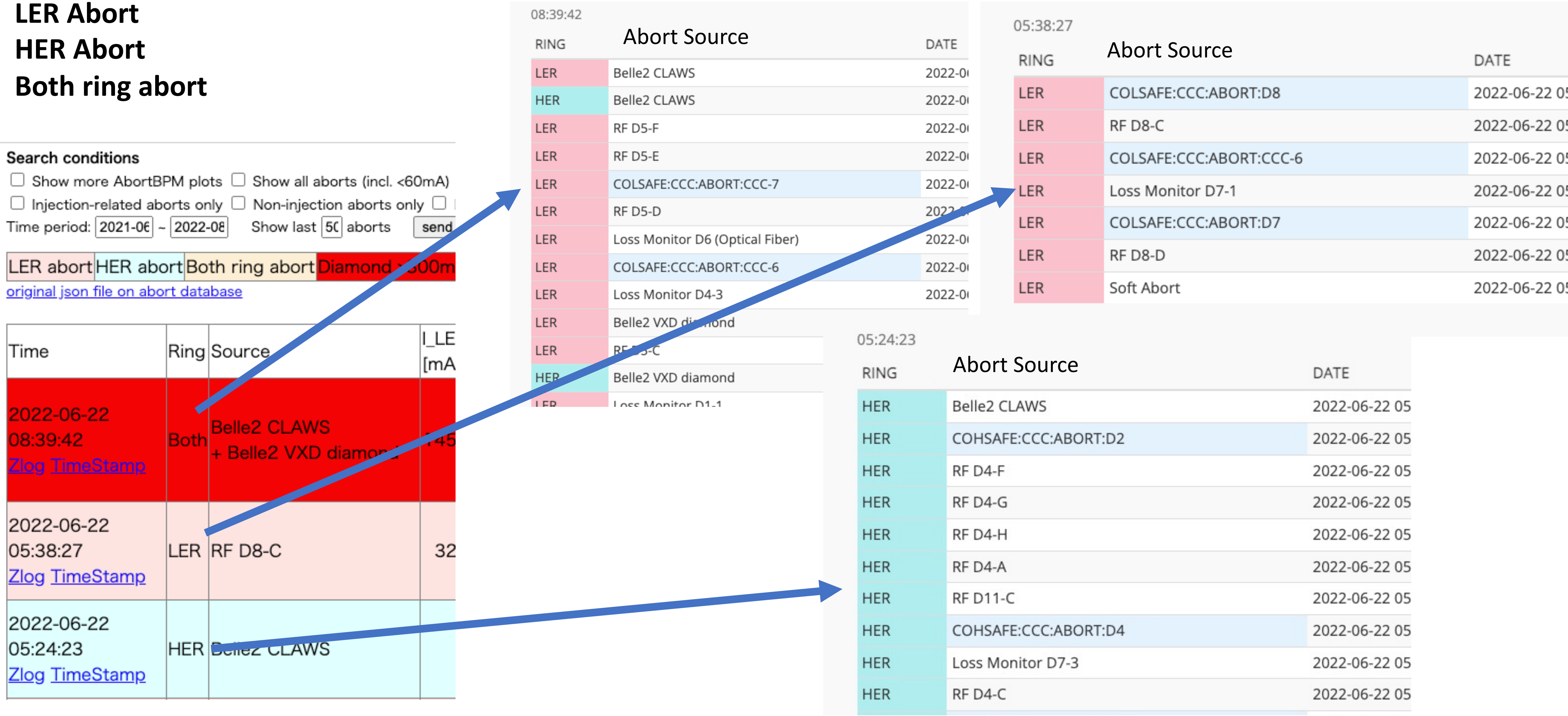
1. Injection related beam aborts (bad injection, injection trubles)
2. RF/magnet troubles
3. Vacuum Troubles
4. Earthquake
5. ….

With this study, we could also be able to find some **hidden SBL or other kind of BL that are not immediately evident**.

Beam Abort Categorization

The beam aborts could be divided in **3 categories:**

- **LER Abort**
- **HER Abort**
- **Both ring abort**



Search conditions

☐ Show more AbortBPM plots ☐ Show all aborts (incl. <60mA)
☐ Injection-related aborts only ☐ Non-injection aborts only ☐
Time period: 2021-06 ~ 2022-08 Show last 50 aborts send

LER abort | HER abort | Both ring abort | Diamond >300m

original json file on abort database

Time	Ring	Source	I_LE [mA
2022-06-22 08:39:42 Zlog TimeStamp	Both	Belle2 CLAWS + Belle2 VXD diamond	745
2022-06-22 05:38:27 Zlog TimeStamp	LER	RF D8-C	32
2022-06-22 05:24:23 Zlog TimeStamp	HER	Belle2 CLAWS	

08:39:42

RING	Abort Source	DATE
LER	Belle2 CLAWS	2022-0
HER	Belle2 CLAWS	2022-0
LER	RF D5-F	2022-0
LER	RF D5-E	2022-0
LER	COLSAFE:CCC:ABORT:CCC-7	2022-0
LER	RF D5-D	2022-0
LER	Loss Monitor D6 (Optical Fiber)	2022-0
LER	COLSAFE:CCC:ABORT:CCC-6	2022-0
LER	Loss Monitor D4-3	2022-0
LER	Belle2 VXD diamond	
LER	RF D5-C	
HER	Belle2 VXD diamond	
LER	Loss Monitor D1-1	

05:38:27

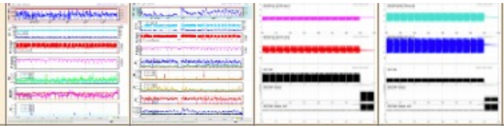
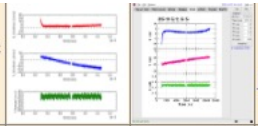
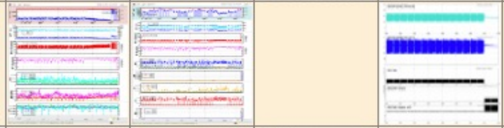
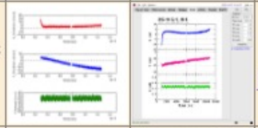
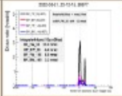
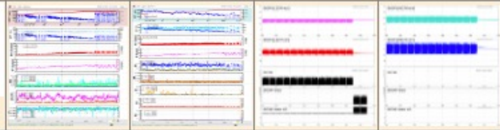
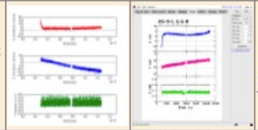
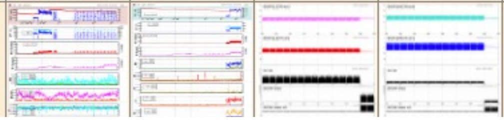
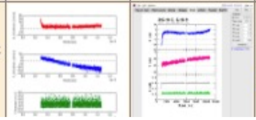
RING	Abort Source	DATE
LER	COLSAFE:CCC:ABORT:D8	2022-06-22 05
LER	RF D8-C	2022-06-22 05
LER	COLSAFE:CCC:ABORT:CCC-6	2022-06-22 05
LER	Loss Monitor D7-1	2022-06-22 05
LER	COLSAFE:CCC:ABORT:D7	2022-06-22 05
LER	RF D8-D	2022-06-22 05
LER	Soft Abort	2022-06-22 05

05:24:23

RING	Abort Source	DATE
HER	Belle2 CLAWS	2022-06-22 05
HER	COHSAFE:CCC:ABORT:D2	2022-06-22 05
HER	RF D4-F	2022-06-22 05
HER	RF D4-G	2022-06-22 05
HER	RF D4-H	2022-06-22 05
HER	RF D4-A	2022-06-22 05
HER	RF D11-C	2022-06-22 05
HER	COHSAFE:CCC:ABORT:D4	2022-06-22 05
HER	Loss Monitor D7-3	2022-06-22 05
HER	RF D4-C	2022-06-22 05

Beam Abort Categorization

We want to automatically distinguish if the **«Both» beam abort is caused by HER or LER**.

2022-06-22 04:13:32 Zlog TimeStamp	Both	Belle2 CLAWS	1413	1134	2249	116	42				not in-sync with inj.		[tkb]	D01_H02 QKALE
2022-06-22 01:48:41 Zlog TimeStamp	Both	Belle2 CLAWS	1345	1077	2249	96	182				not in-sync with inj.		[tkb]	
2022-06-21 23:12:15 Zlog TimeStamp	Both	Belle2 CLAWS + Belle2 VXD diamond	997	799	2249	43	54	 23 mRad			not in-sync with inj.		[tkb]	
2022-06-21 22:08:34 Zlog TimeStamp	Both	Loss Monitor D1-4	698	533	2249	31	37				not in-sync with inj.		[tkb]	

We want to **categorize also SBL not immediately associable to LER or HER.**

In order to do that, **I created an algorithm in order to distinguish between HER or LER aborts**.

I am looking at aborts:

- **HER and LER current > 50mA**
- **No Manual Aborts**

Beam Abort Categorization

In order of importance, the condition are:

1) Timing with the HER/LER injection.

2) Loss in the BCM.

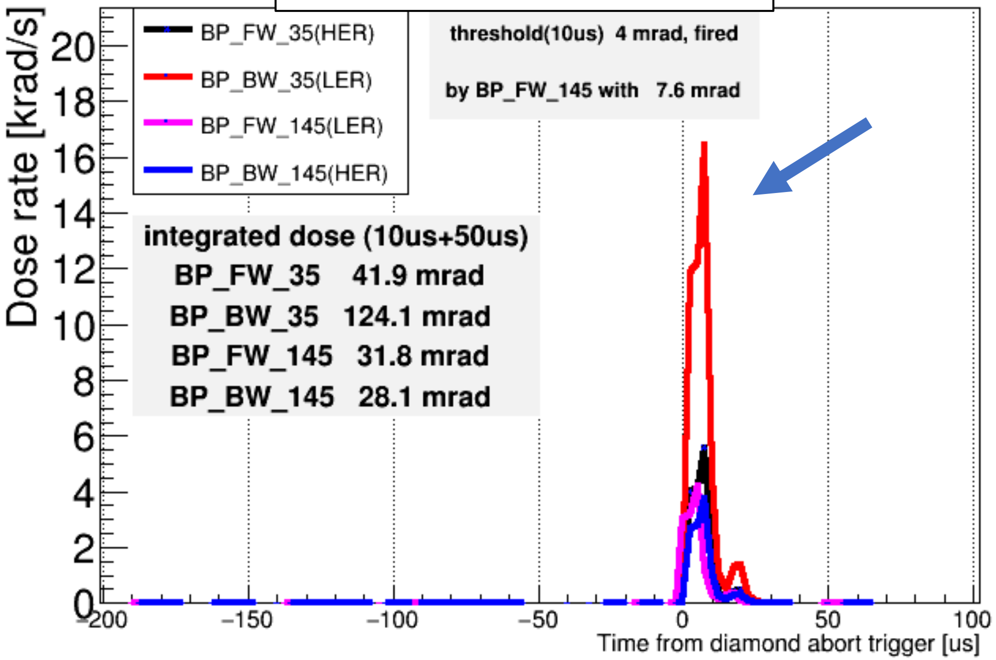
3) Highest integrated dose in the Beam Pipe Diamonds.

4) Highest spike in the Bellows QCS Diamonds.

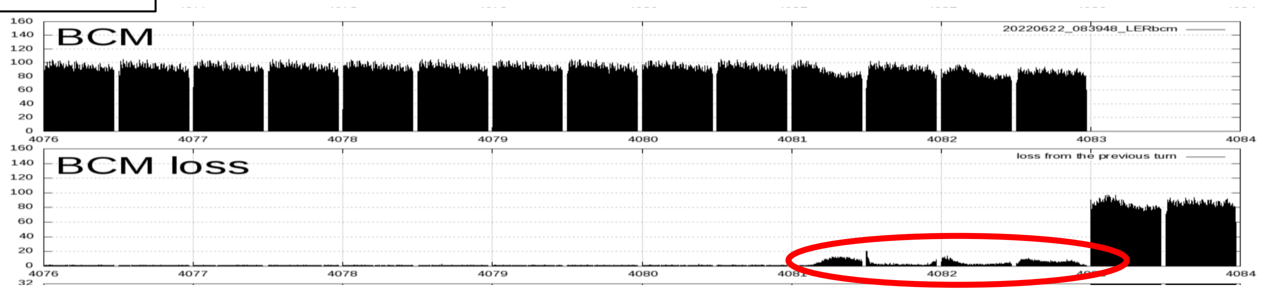
5) Highest spike in the Loss Monitors.

Bellows QCS Diamonds

Beam Pipe Diamonds



BCM



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	53
Injection Related	4	16	48	81	24	173
RF/magnet/vacuum /earthquake	7	42	39	43	31	162

Summary

- With the new installed fast loss monitor together with the existing loss monitors and beam monitors, **we can find the initial location of the SBL events**, but not compare signal from different detectors.

- In most of the cases, **the initial loss was observed around D06 section** (LER), so the cause should be around D06 or in the upstream part.
  The real cause of the SBL events is not fully understood yet.

- We manage to develop a solid **automatic beam abort categorization**, for a better understanding of the beam aborts and in order to categorize «**Both» type beam abort events** → it will be used «**online»** after LS1.

Future Plans and prospects:

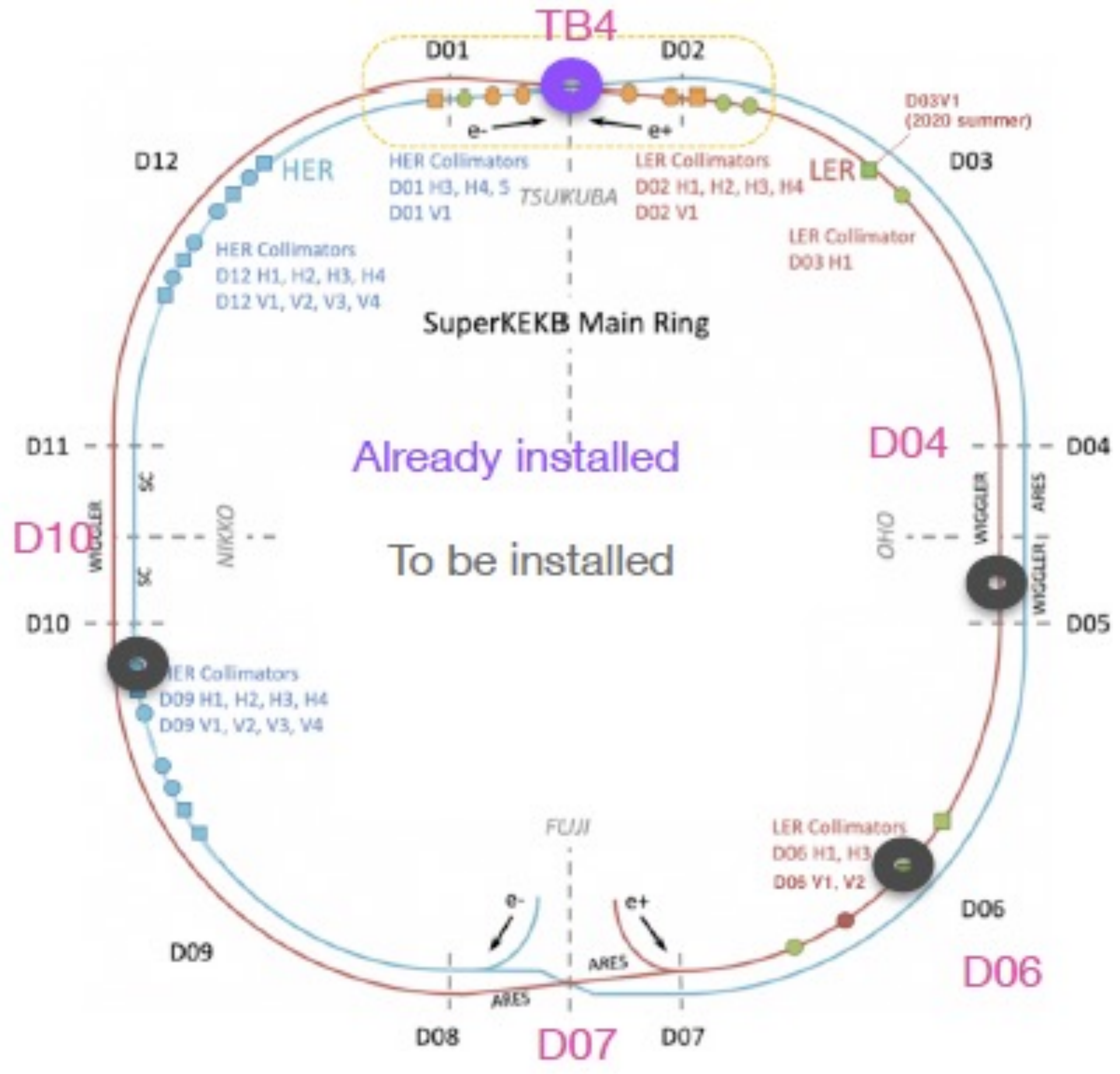
We are working **to improve the operation against SBL**.

- **Beam diagnosis system with fast loss monitors**:
  - **Installation of more sensors** in new locations during LS1 (**new LMs and CLAWS sensors**)
    → **full scale system**.

- **Abort system upgrade → fast beam abort:**
  - additional master module in D07 area.

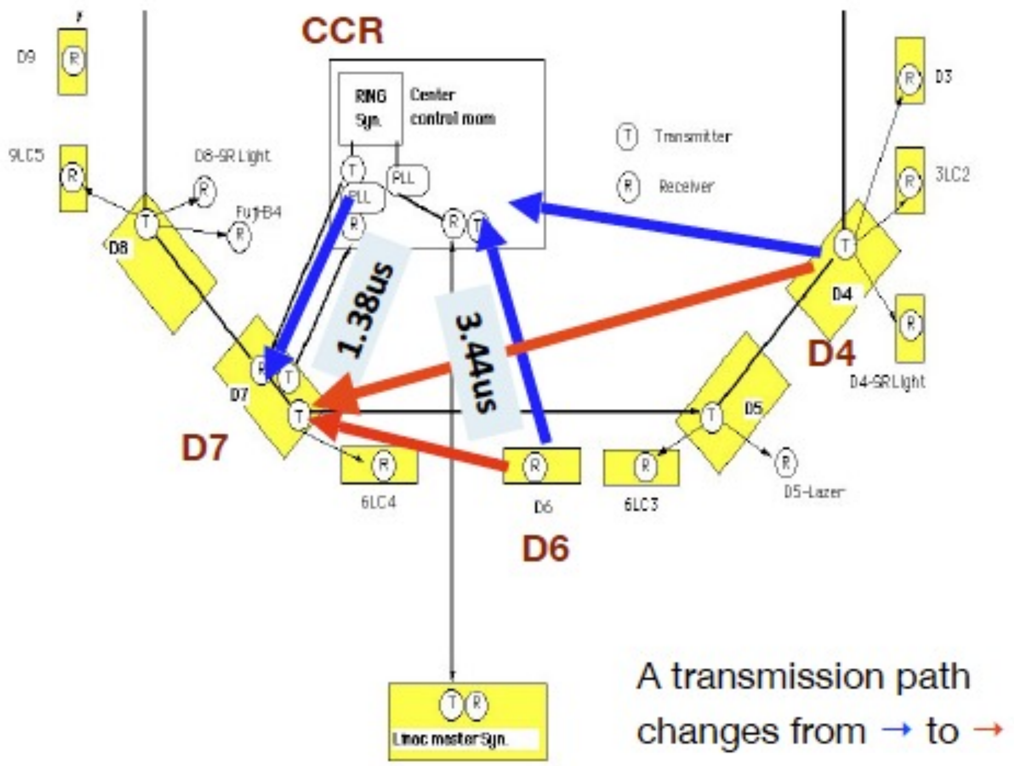
Backup

Fast sensor: CLAWS



- CLAWS has been proven as a fast abort detector during machine operation.
- CLAWS can be expanded in sensible locations such as D05 (Non-Linear Collimator), D06 and D10 sections.
- We will install them in 2 or 3 locations for monitoring while having the capability of upgrading to abort detector once the improvement is confirmed.

Shorter Abort Transmission Path



Abort request/trigger signals are sent to D07 section (location of the Abort Kicker) via CCR:

→skip CCR and send the signal directly.

- D06: $4.8\mu s \rightarrow 2.9\mu s$
- D04: $6.0\mu s \rightarrow 5.2\mu s$

To make the transmission path shorter:
- Wireless system
- Laser (x1.5 faster)

R&D studies during LS1

Beam Background at SuperKEKB

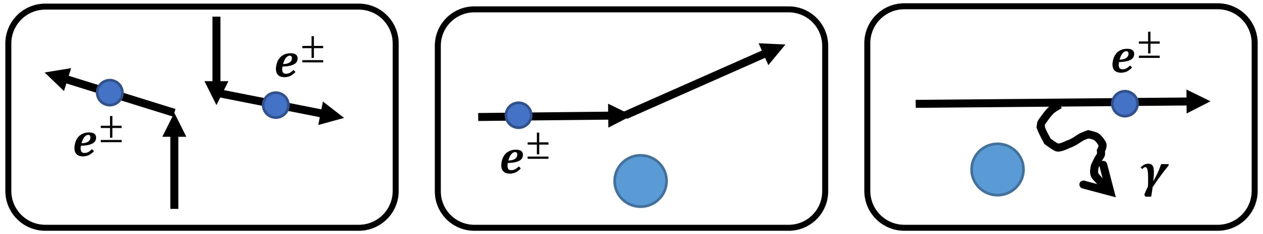
When beam particles deviate from the nominal orbit → eventually are **lost** and **hit the beam pipe**.

If this particle loss happens near the IP, generated EM showers might reach the Belle II detector

→ damage and/or fake hits.

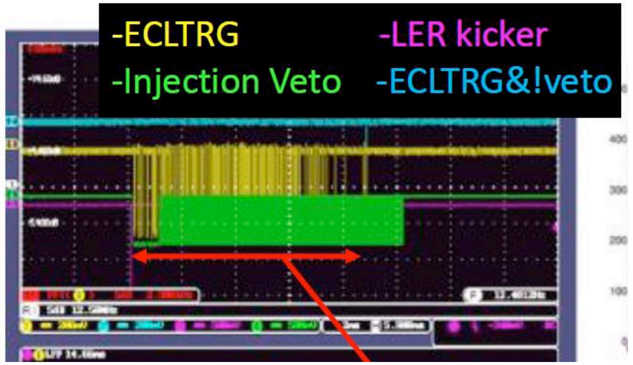
Beam BG Sources:

- **Single-beam BG (**in the single ring**)**
  - **Touschek scattering:**
    Rate $\propto (I_{beam})^2 (N_{bunches})\ (beam\ size)^{-1} (E_{beam})^{-3}$
  - **Beam-gas scattering (Coulomb/Bremsstrahlung)**
    Rate $\propto (I_{beam})(P_{beam\ pipe})$
  - **Synchrotron radiation**
    SR $\propto (E_{beam})^2 (B)^2$ (mainly HER, few keV to tens of keV) → beam pipe coated with Au layer
  - **Injection BG**
    Typical duration of injection BG: few~ten ms



Countermeasure: Horizontal collimators

Countermeasure: Vertical collimators



Injection BG Countermeasure: Injection Veto

Longer veto window → integrated luminosity is lost

Beam Background at SuperKEKB

When beam particles deviate from the nominal orbit → eventually are **lost** and **hit the beam pipe**.

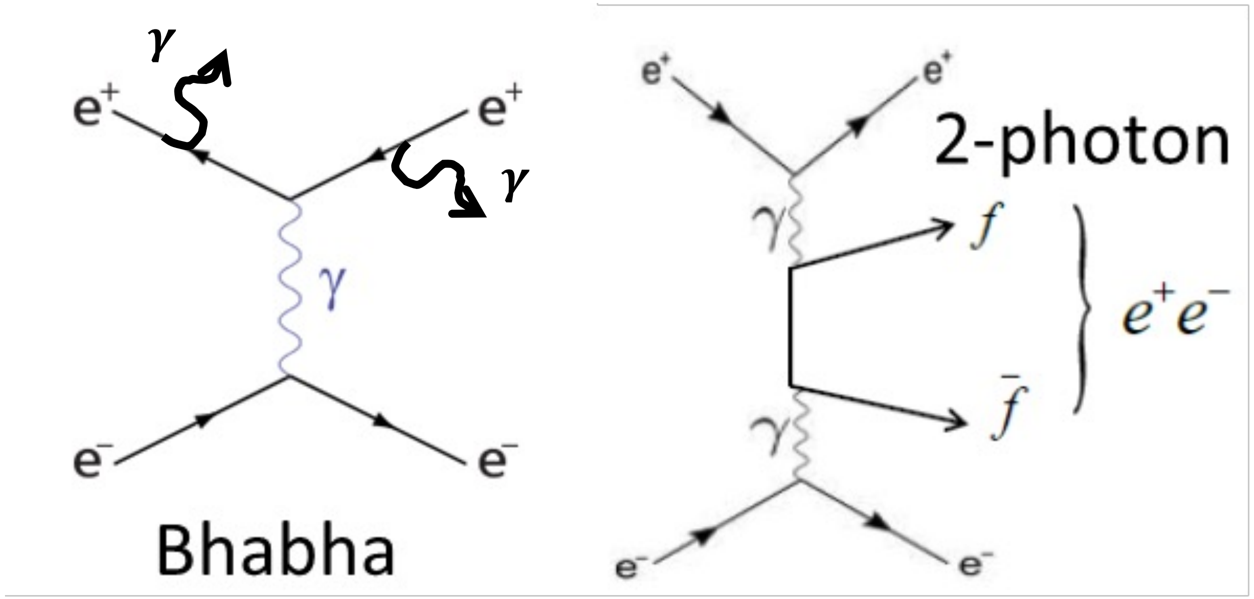
If this particle loss happens near the IP, generated EM showers might reach the Belle II detector

→ **damage and/or fake hits.**

Beam BG Sources:

- **Luminosity BG (**from e^+e^-collisions**)**
  - **Radiative Bhabha**
  - **Two-photon process, etc…**

  Rate(both) ∝ $(Luminosity)$

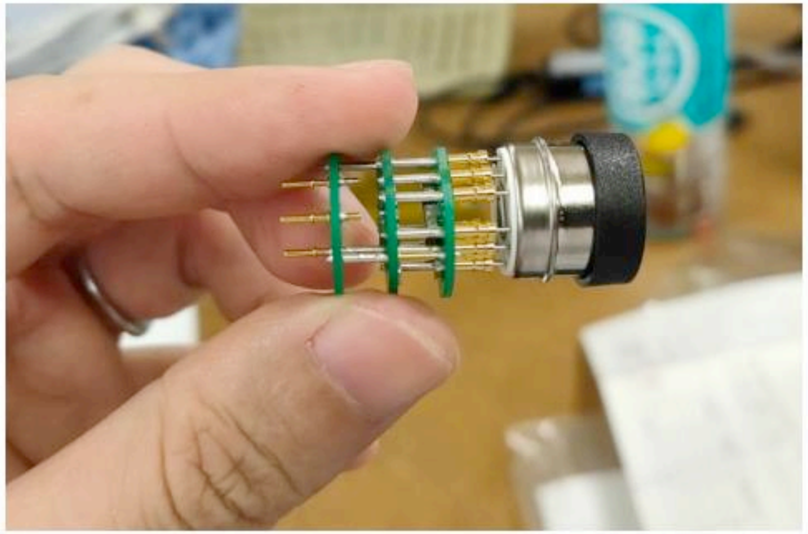


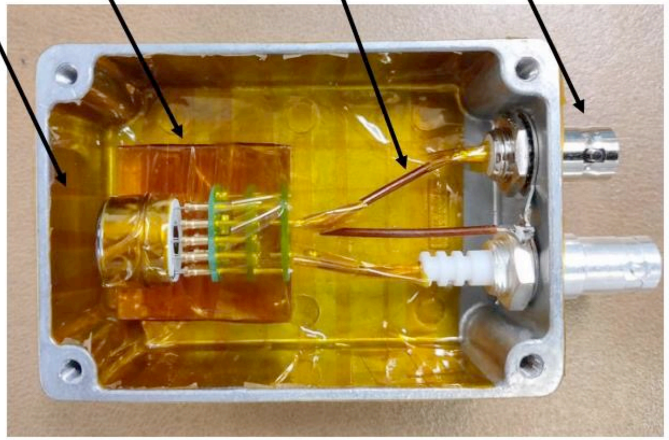
For now, Beam-gas Coulomb BG by LER is **dominant**

→Luminosity BG is currently smaller than single-beam one, but it will **dominate as the luminosity grows up**.

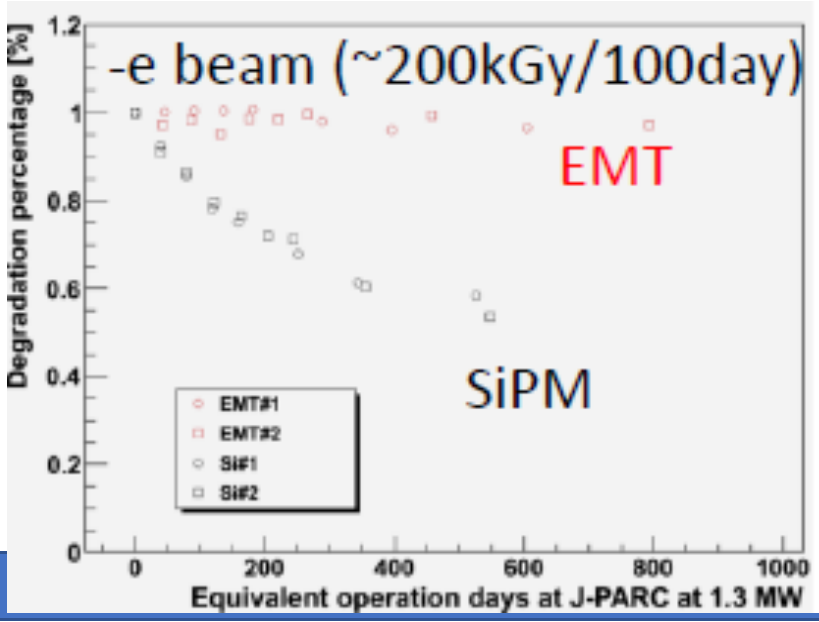
EMT

T. Koga-san

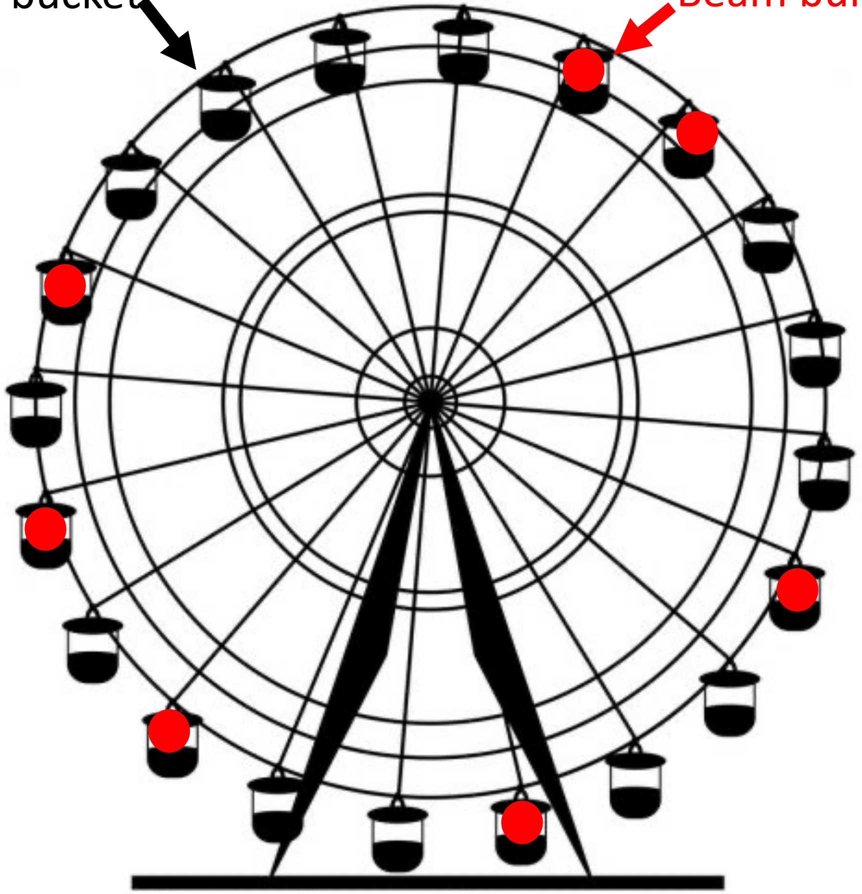




- EMT - PMT (R9980U 110) but with aluminum for photoelectric surface , known to have high radiation tolerance.
- R&D study was originally performed by T2K for muon beam monitors.



RF-Bucket and Beam Bunch



The RF-bucket can be defined in the entire ring with time and space.

We can imagine it as the a ferris wheel.

The **Harmonic Number** is the **number of RF-buckets** of the ring. The beam flights with the speed of light, so the harmonic number is uniquely defined knowing the circumference and the RF clock rate.
In the case of SuperKEKB, **RF-bucket number is 5120**.

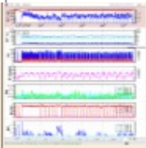
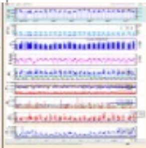
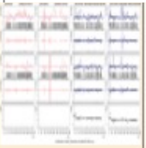
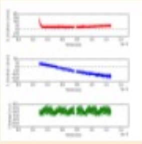
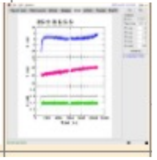
Important: **RF-bucket $\neq$ beam bunch**

RF-bucket is the container of the beam bunch.
The harmonic number is uniquely defined for each accelerator ring.

Maximun number of bunches until now: 2346

Abort Categorization: Timing with Injection

1) The first condition to be checked is the **timing with the HER/LER injection.**

Time	Ring	Source	I_LER [mA]	I_HER [mA]	Nb	Dia(L) [mRad/s]	Dia(H) [mRad/s]	Diamond abort	LossMon (L)	LossMon (H)	BOR/BCM (L)	BOR/BCM (H)	Inj(L) [us]	Inj(H) [us]	BT orbit	AbtBPM (L)	AbtBPM (H)
2022-04-28 13:32:52 Zlog TimeStamp	Both	Belle2 CLAWS	846	674	1662	39	57							-118			

I check the last injection timing for both HER and LER.

If the **difference between the abort timing and injection timing is** $-500\mu s < \Delta t < 100\mu s$
-> **in-sync with the injection**.

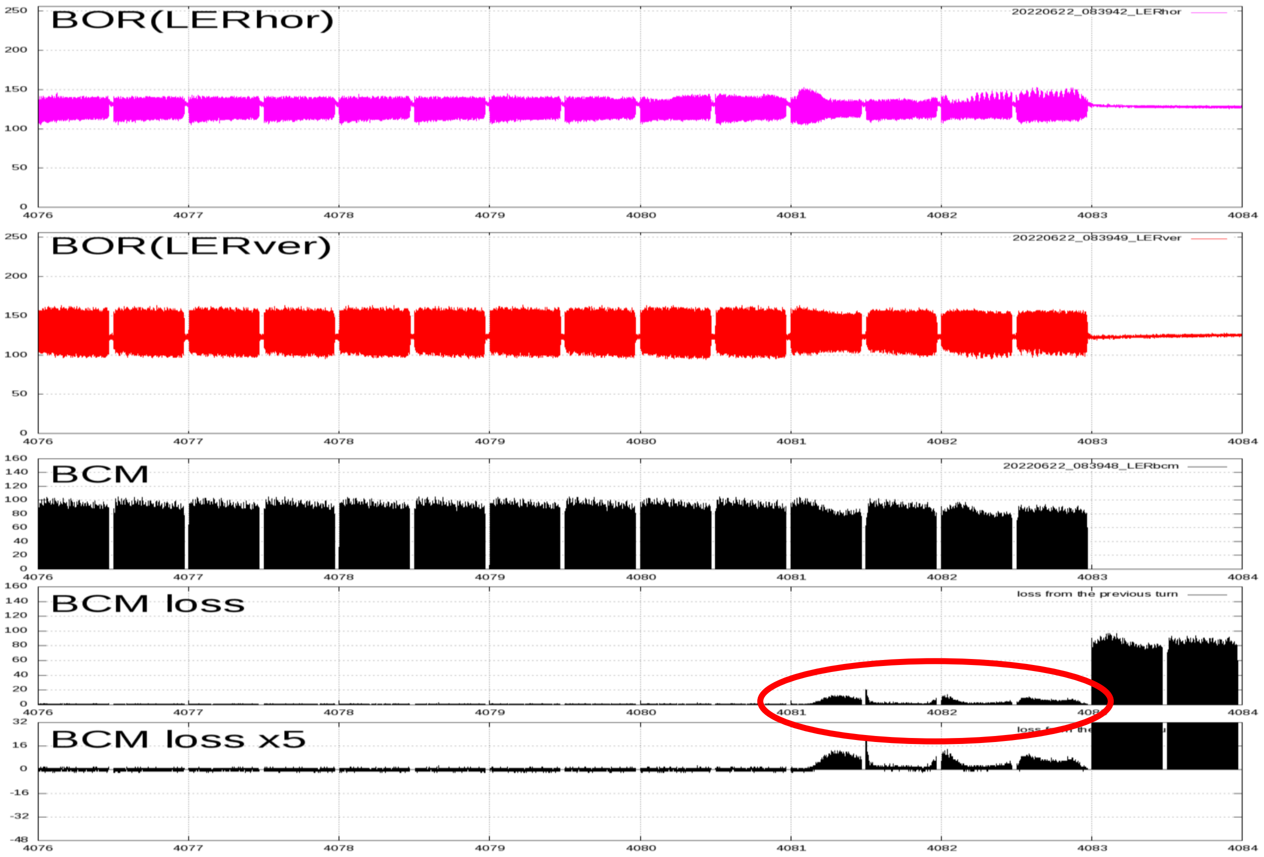
In this example, we have $\Delta t = -118\mu s$:

-> HER Abort

Abort Categorization: BCM loss

2) If the abort not in-sync with inj., the next condition to be checked is the presence of some **loss in the BCM**.

2022-06-22 08:39:42



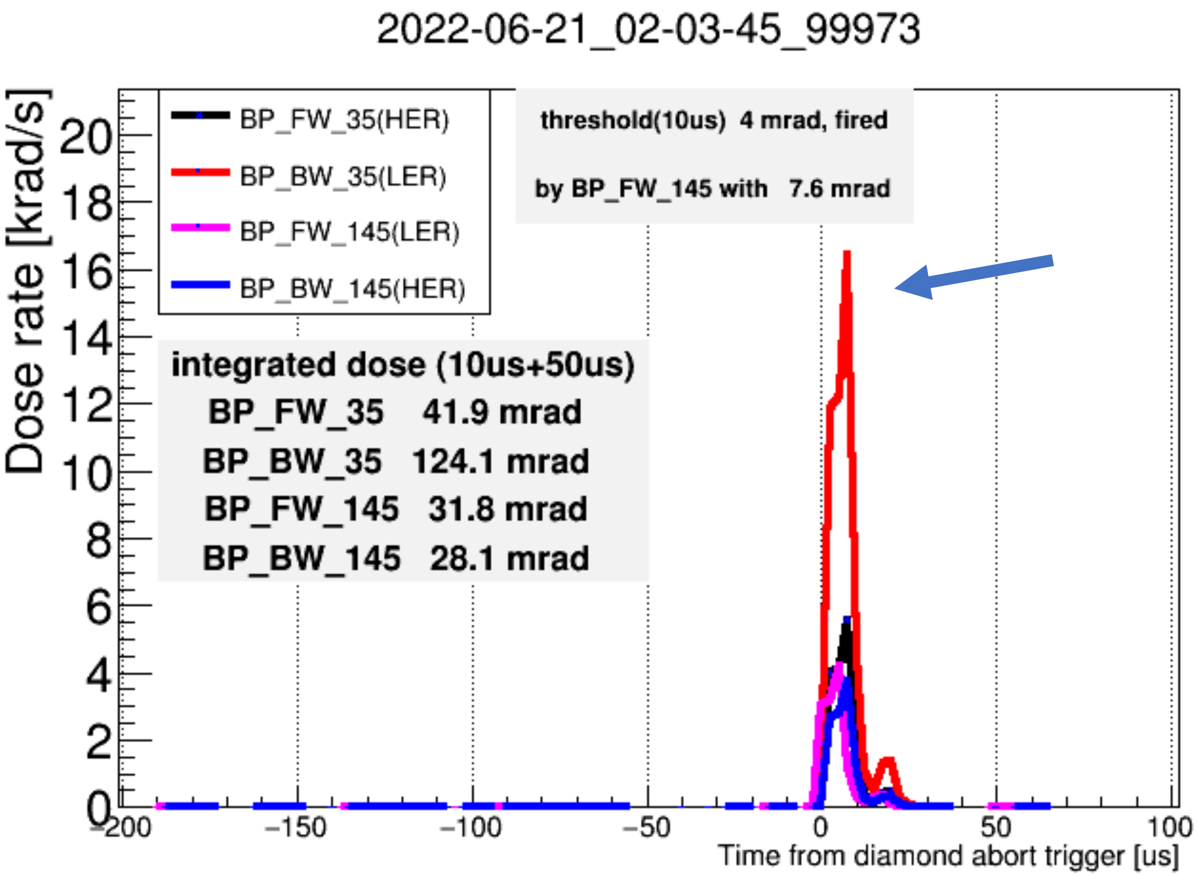
I check BCM raw data for both HER and LER.

In this example, we have loss in the LER BCM
-> LER Abort

Abort Categorization: BeamPipe Diamonds

3) If the abort not in-sync with inj. and there is no BCM loss, the next condition to be checked is **the integrated dose in the BP Diamonds**.

2022-06-21 02:03:45



I check BP Diamonds raw data for both HER and LER:

Threshold($10\mu s$) = 4 mrad

I calculate the integrated dose and select the **highest one**.

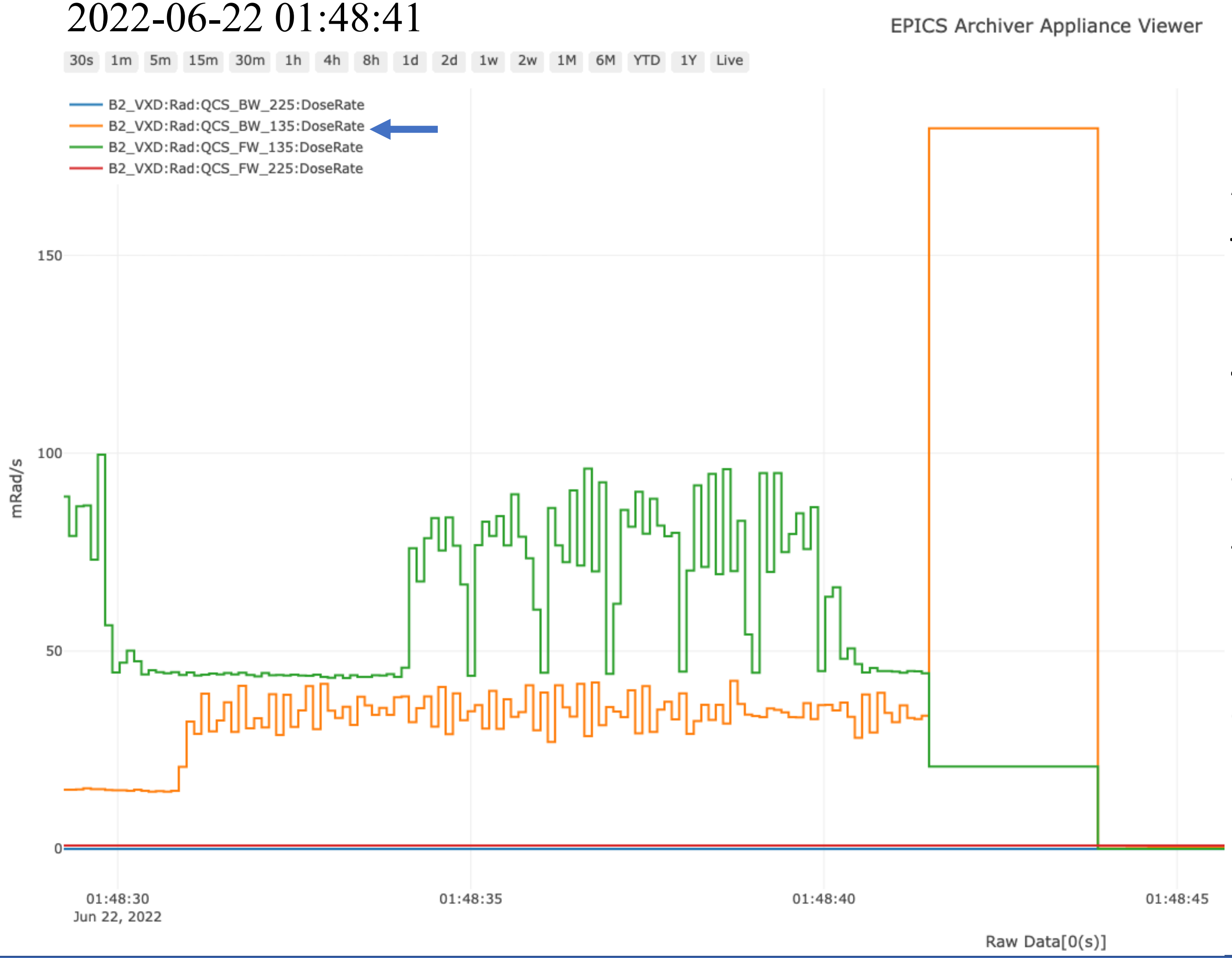
In this example, we have BP_FW_35(HER) and BP_BW_35(LER) exceeding the threshold.

I select the highest integreted dose, BP_BW_35(LER) -> LER Abort

Abort Categorization: Bellows QCS Diamonds spikes

4) If the abort not in-sync with inj. and there is no BCM loss and no BP Diamonds spikes, the next condition to be checked is the presence of **spikes in the Bellows QCS Diamonds.**

2022-06-22 01:48:41



I check Bellows QCS Diamonds raw data in EPICS Archiver for both HER and LER.

To set the Threshold, I calculate a «sort of baseline», looking at the data 30 sec before the abort.

-> Baseline = average value in 30 sec
(especially for Feb and March abort, low current -> average ~0 -> I set 5mRAd/s)

-> **Threshold = 3*baseline**

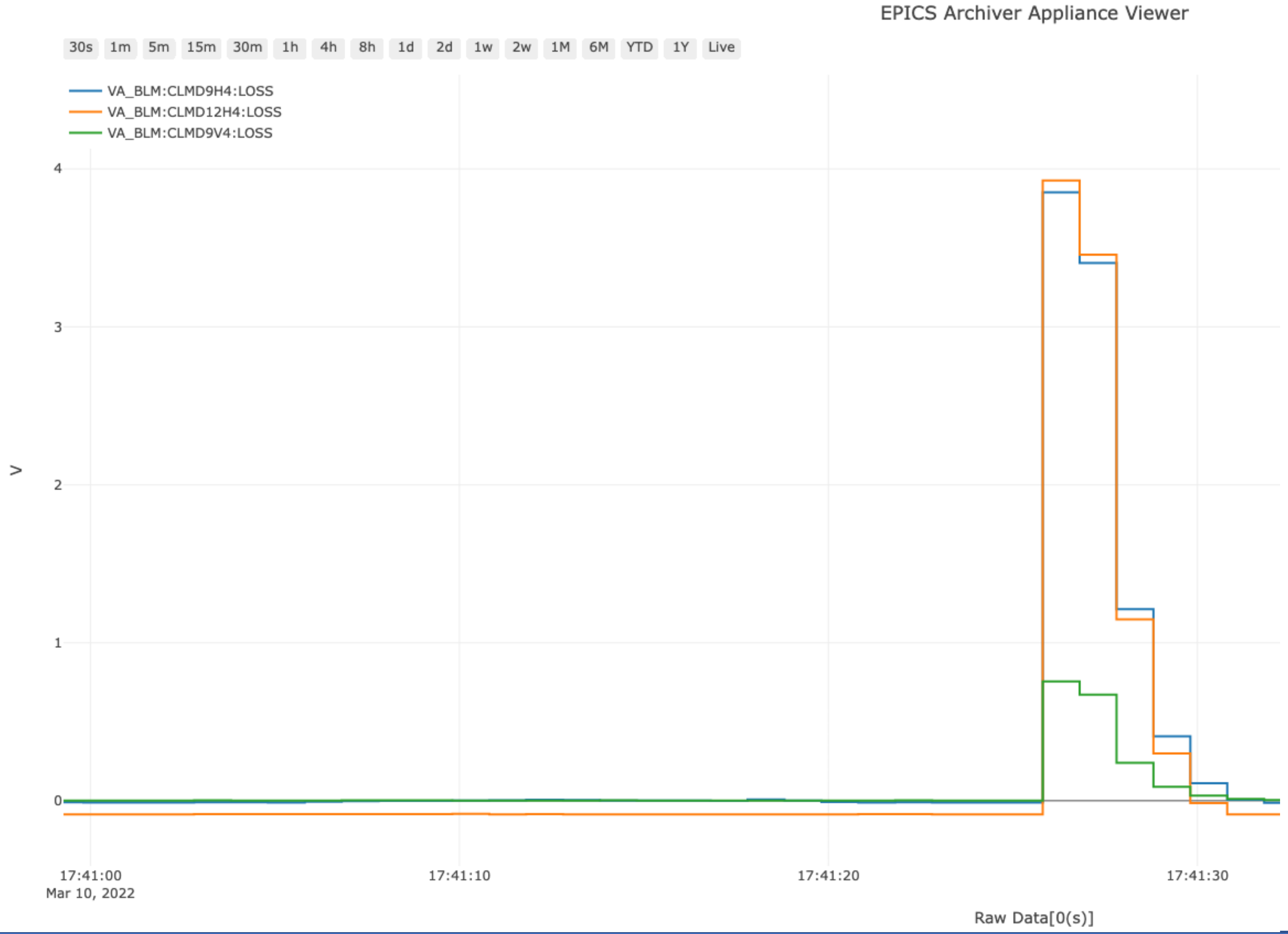
In this example, we have a clear spike in QCS_BW_135(HER):

-> HER Abort

Abort Categorization: Loss Monitors spikes

5) If the abort not in-sync with inj. and there is no BCM loss, no BP and QCS Diamonds spikes, the other condition to be checked is the presence of **spikes in the Loss Monitors.**

2022-03-10 17:41:23



I check all LossMonitors raw data in EPICS Archiver for both HER and LER.

To set the Threshold, I calculate a «sort of baseline», looking at the data 10 sec before the abort.

-> **Baseline = average value in 10 sec**
(baseline almost < 0.5, but not so noisy)

-> **Threshold = 3*baseline**

If both have spikes -> I select the one with the **highest number of spikes.**

In this example, we have spikes in D9H4(HER), D9V4(HER), D12H4(HER):

-> HER Abort