Observing sudden beam loss events using bunch-by-bunch BPMs at SuperKEKB

UTokyo, KEK, SLAC

Riku Nomaru, Gaku Mitsuka, Larry Ruckman

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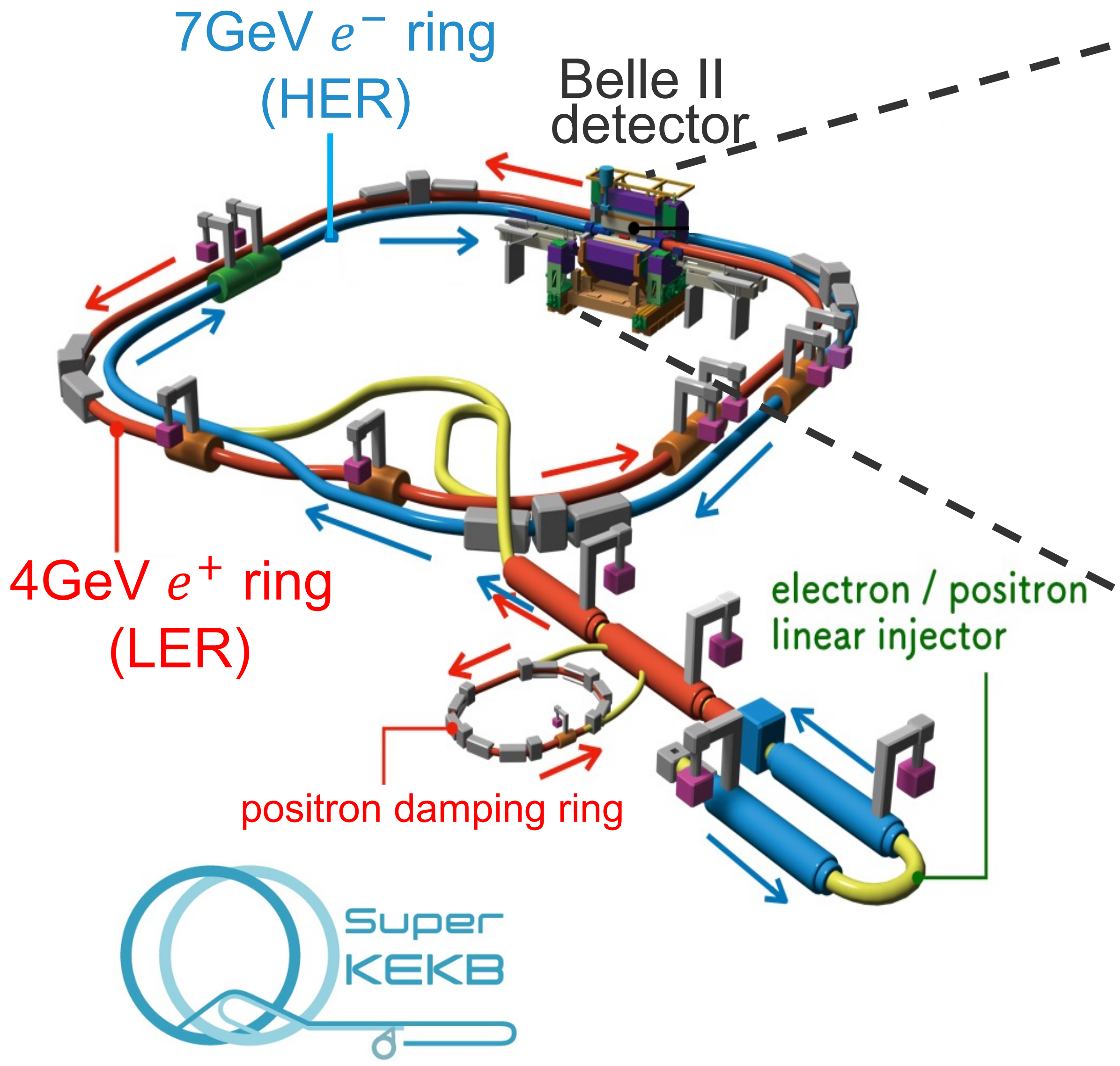
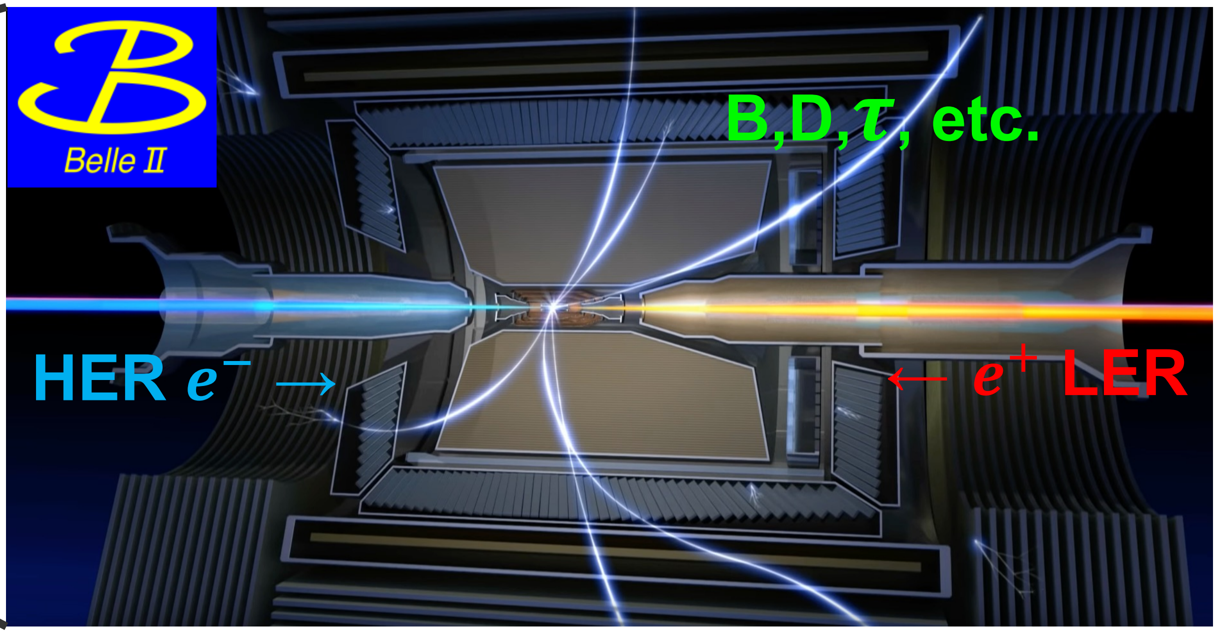
Outline

1. SuperKEKB and Sudden Beam Loss
2. Development of a new Bunch Oscillation Recorder
3. Test of Bunch Oscillation Recorder
4. Observation and study of Sudden Beam Loss
5. Summary and outlook

The SuperKEKB / Belle II experiment





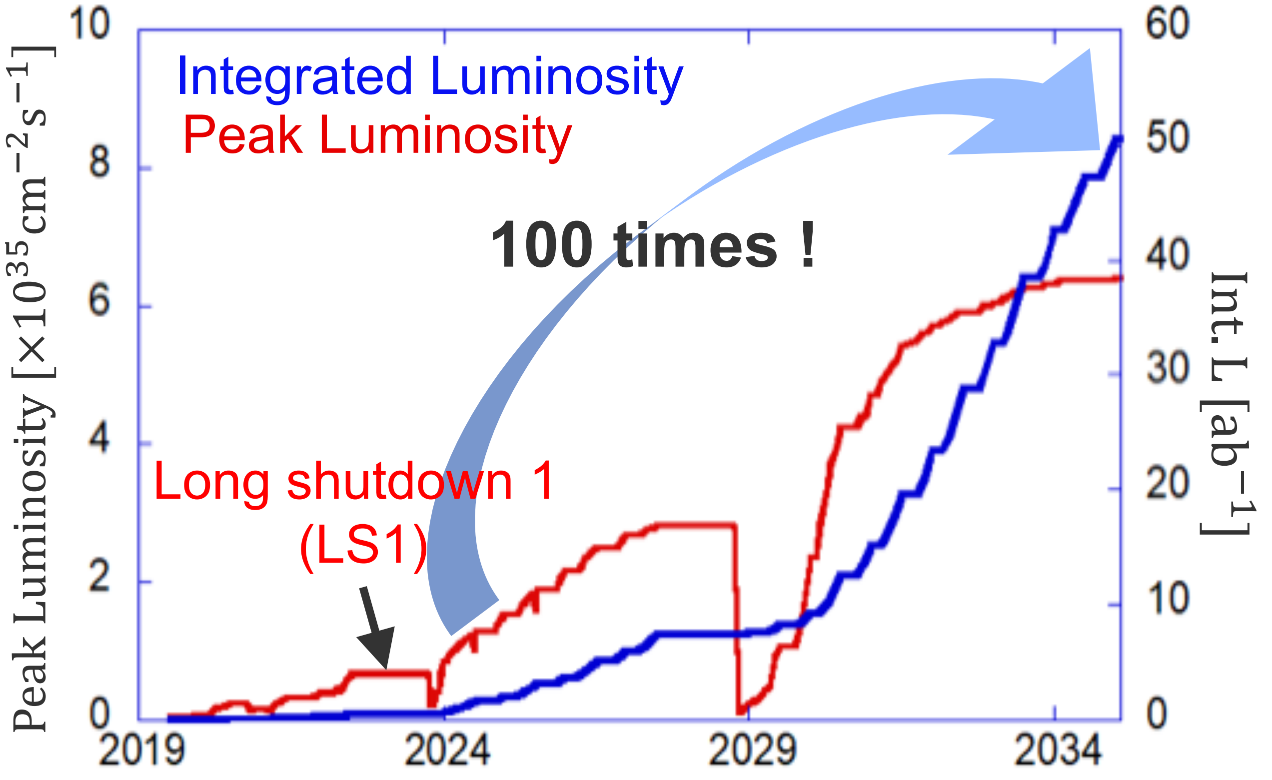
Belle II experiment is precisely measuring a large number of elementary particle reactions and searching for **new physics**

Luminosity Improvement

The number of physics events

$$N = \sigma[\mathrm{cm}^2] \int \underbrace{L[\mathrm{cm}^{-2}\mathrm{s}^{-1}]}_{\text{Luminosity}} \, dt[\mathrm{s}]$$

To improve the performance of the new physics search, the luminosity of SuperKEKB must be improved.



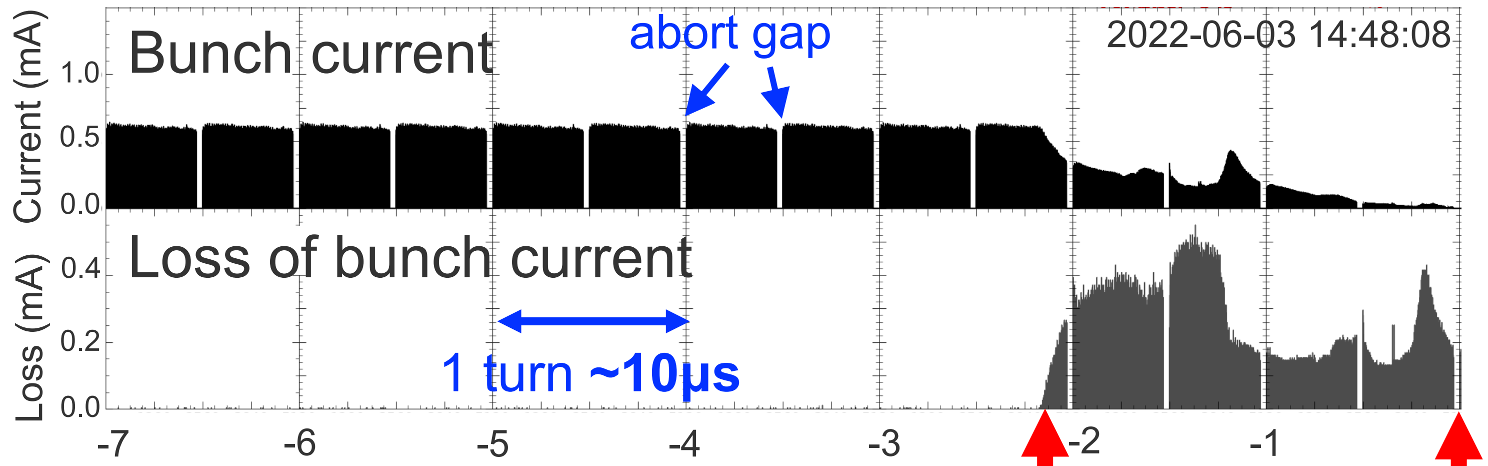
LS1 (Jun. 2022 to Feb. 2024) was over and we are now aiming for even higher luminosity.

However, <u>**Sudden Beam Loss**</u> is a major obstacle to improving luminosity

Sudden Beam Loss (SBL)

■ Ampere class beam is suddenly lost and aborted **within a few turns (tens of μs)**

Bunch-by-bunch beam current and loss observed at one point in the LER

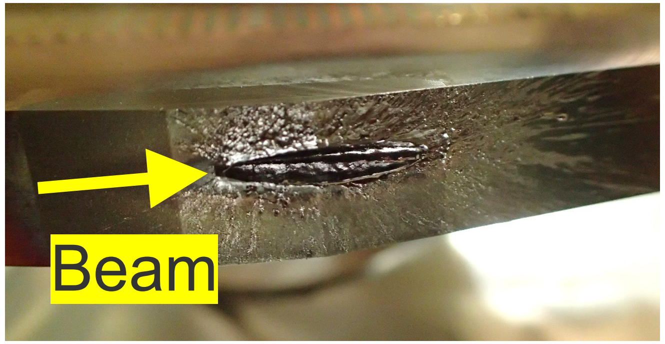


How many turns before the beam abort

Beam loss detection Abort request

Abort

Radiation from beam loss cause serious damage to the Belle II detector and collimator etc.



Vertical collimator was scraped off (LER)

Due to SBL concerns, beam current cannot be increased so that **luminosity has been stayed lower.**

Determining the cause of SBL and resolving it is an urgent task for SuperKEKB.

SBL observation before LS1

■ **Bunch Oscillation Recorder (BOR)**

Records bunch-by-bunch beam position and charge for several turns just before the beam abort.

■ Multiple BORs are needed

- Cover the betatron phase widely to avoid creating dead areas
- Determine instability source point(s)

Target

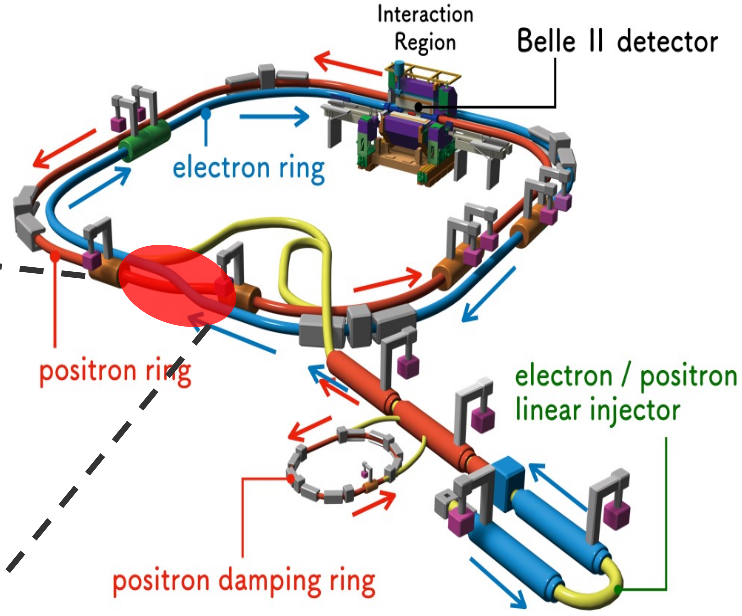
Create a BOR that is portable and has measurement accuracy equivalent to or greater than the VME-BOR (~30μm)

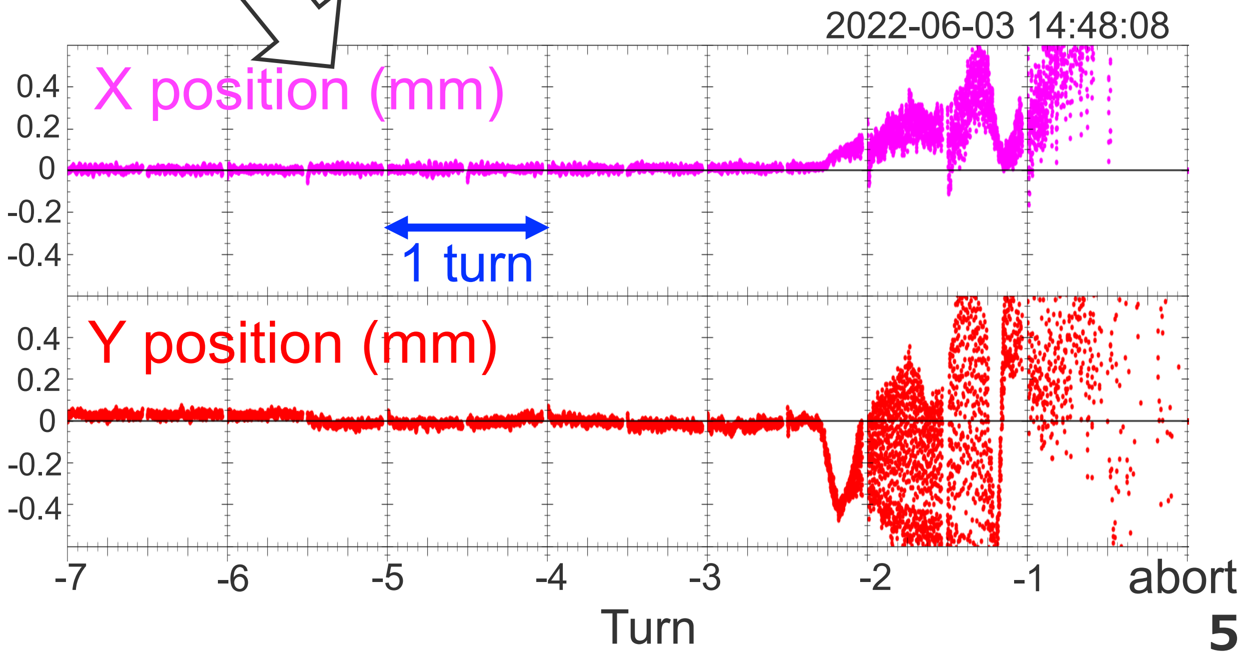
→ RFSoC, which is attracting attention in the high frequency signal field.

VME-BOR

8-bit ADC
Resolution ~30μm

[Tobiyama & Flanagan, IBIC2012]





Development of a new Bunch Oscillation Recorder using RFSoC

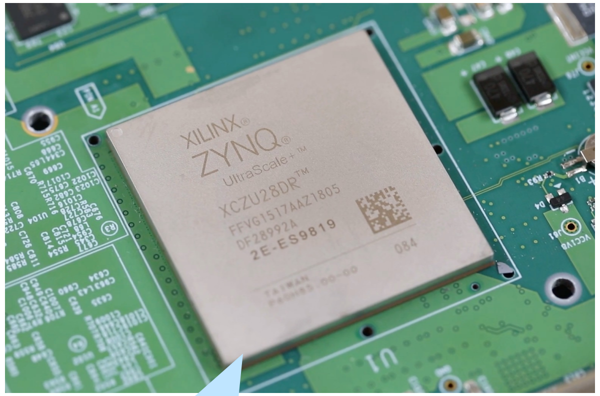
<u>RFSoC-BOR</u>

RF System on Chip (RFSoC)

by AMD/Xilinx

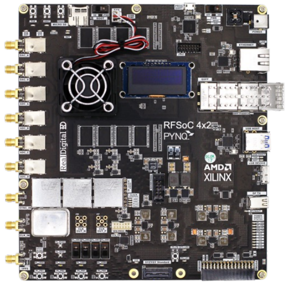
■ FPGA, CPU, ADC, and DAC all in one chip

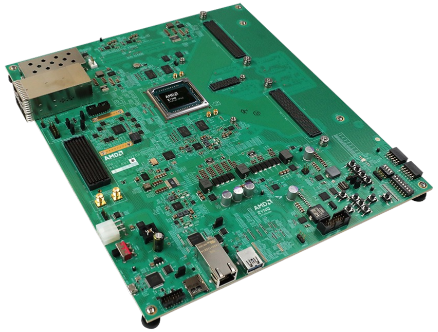
- No need to design communication with data converters
- Up to 16 channels of ADCs up to 5Gsps, 14-bit (Gen3)
- Synchronized multi-channel high-speed sampling

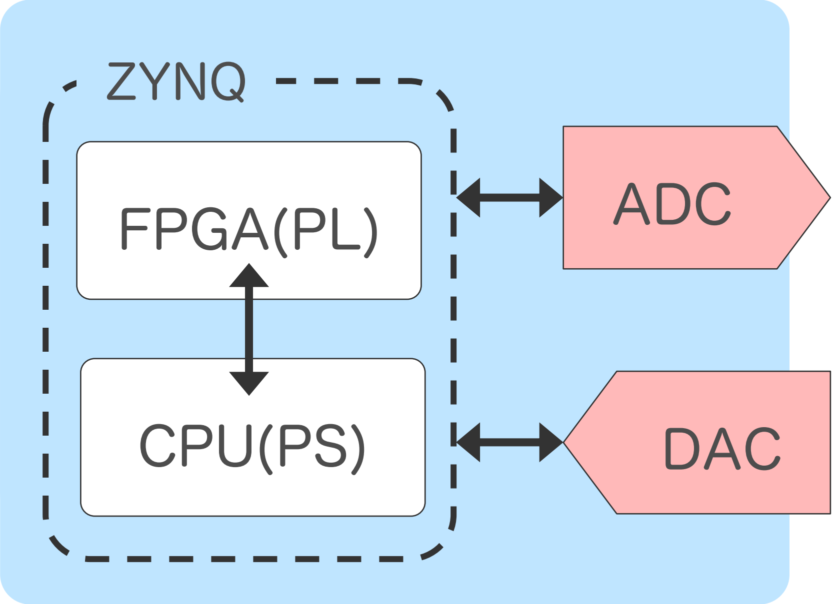


■ Benefits of using RFSoC for BOR

- We can improve ADC bit width
- Easy to carry along a ring
  →narrow down the candidate
  points of origin.
- We can develop quickly

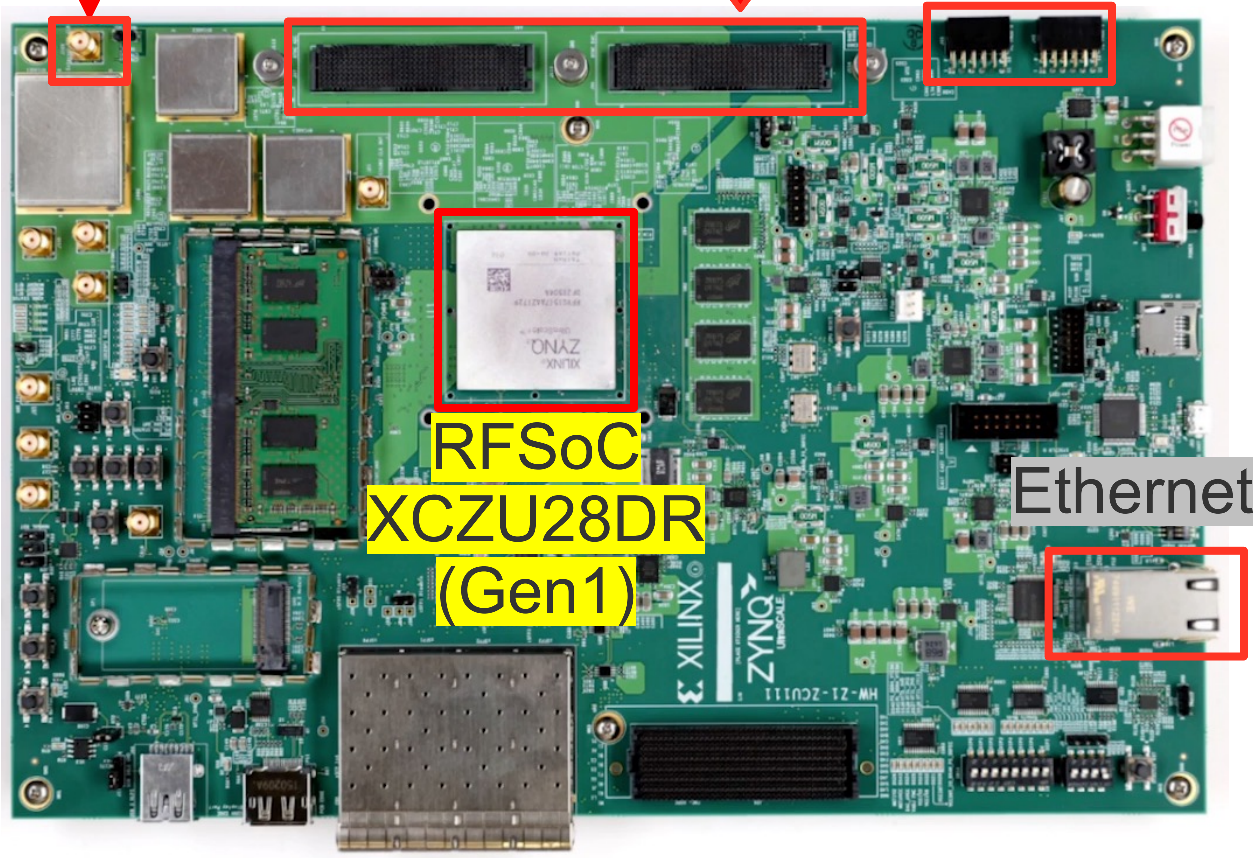




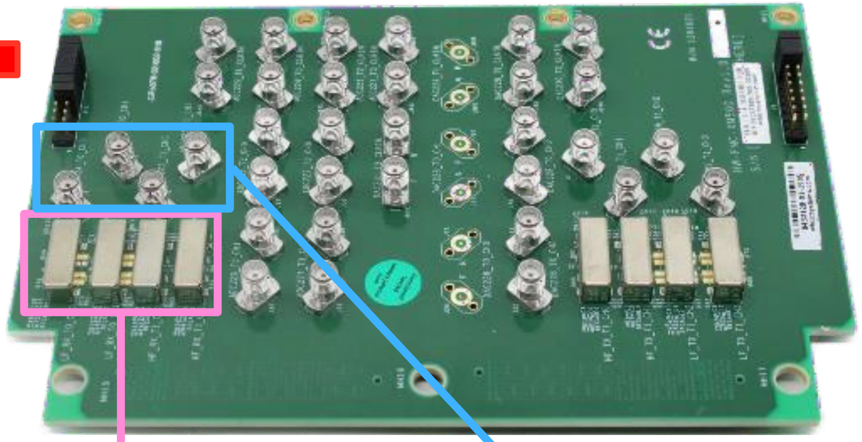


RFSoC Evaluation board, ZCU111

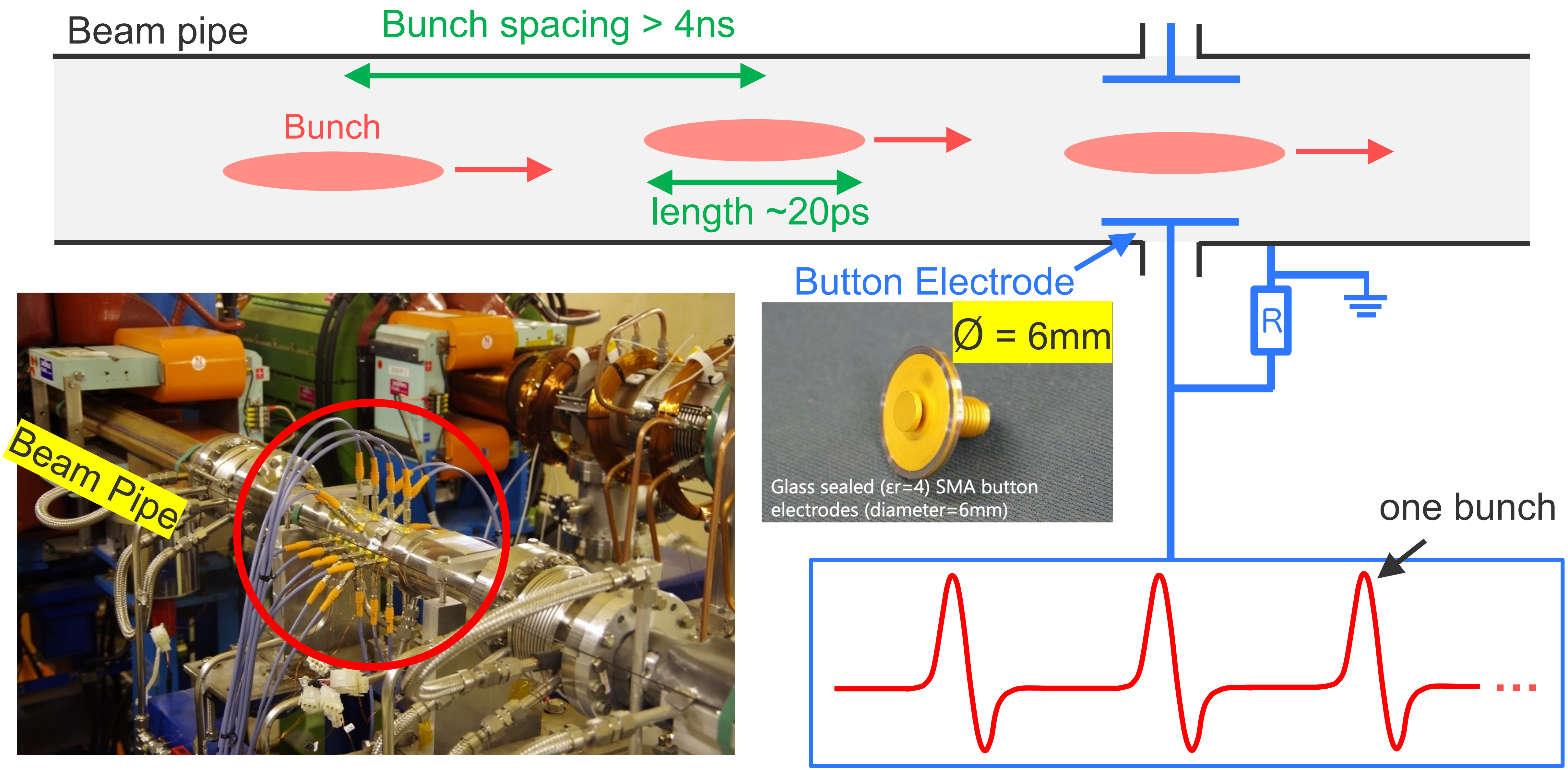
- 8 channels of 12-bit ADC (maximum of 4096Msps)



daughter board XM500

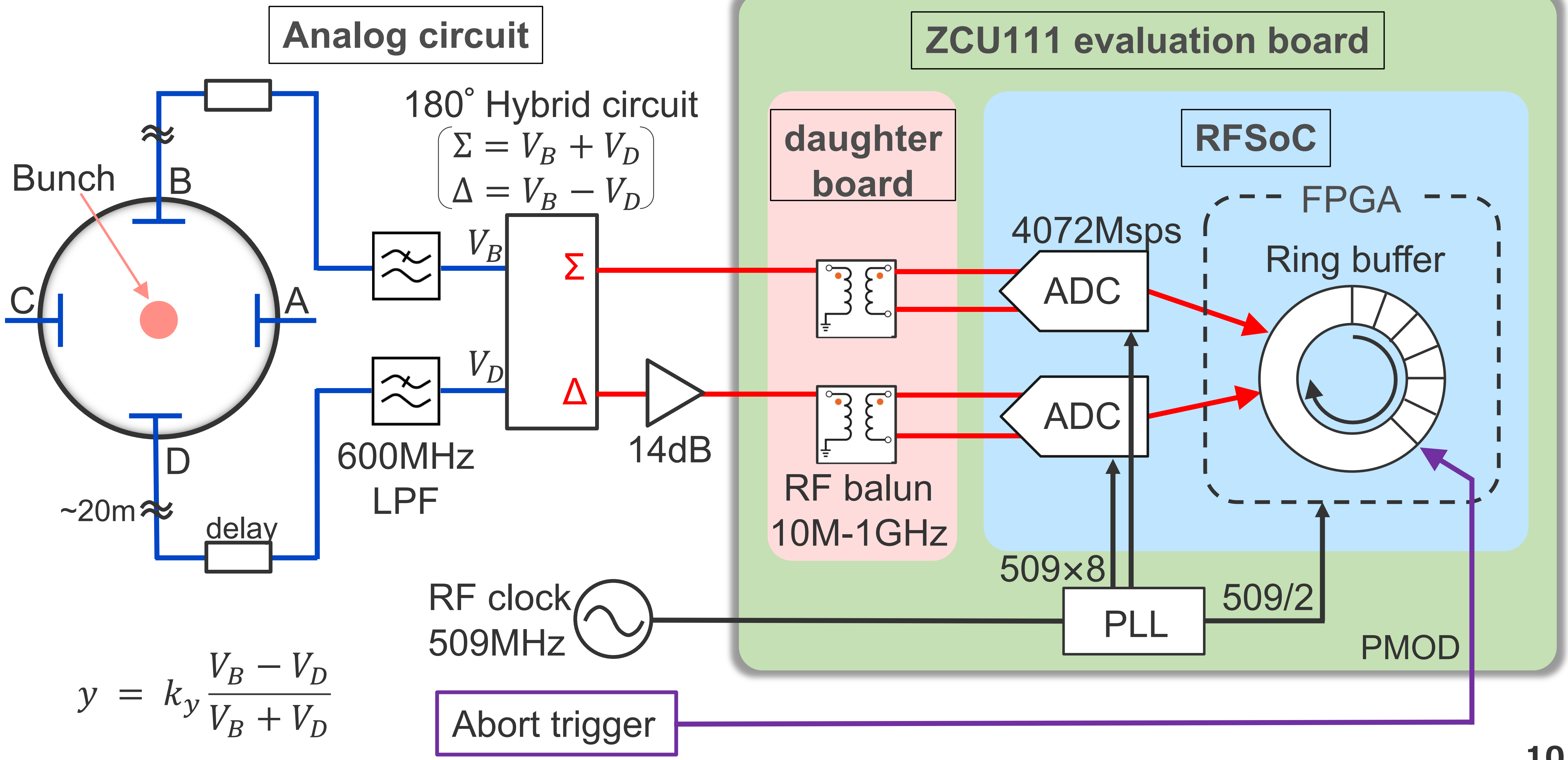


Measurement of bunch position



RFSoC-BOR circuit

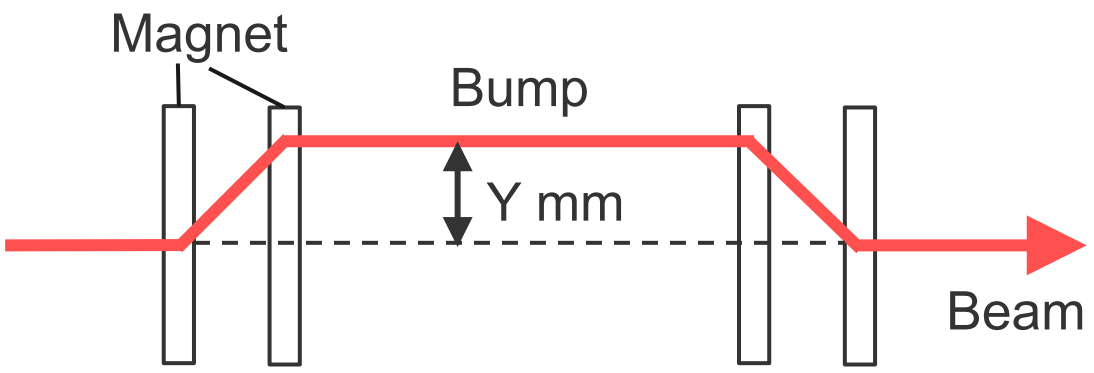
SLAC framework is used
https://github.com/slaclab/Simple-ZCU111-Example

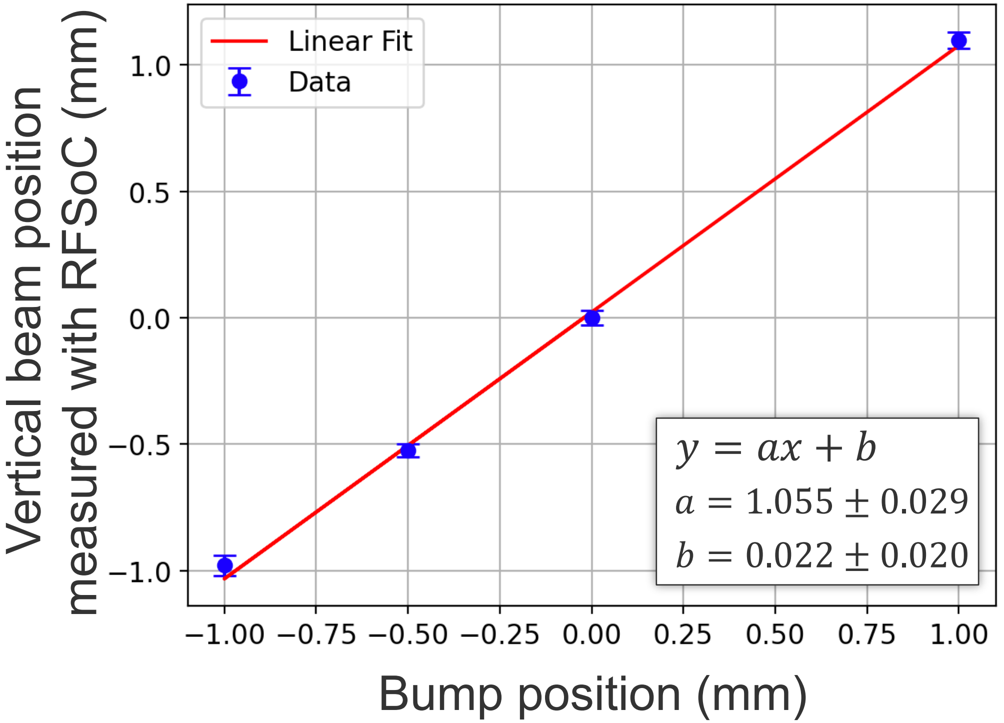


$$y = k_y \frac{V_B - V_D}{V_B + V_D}$$

Operation test of RFSoC-BOR

Evaluation of measurement resolution





- Changing the local beam bump position, measurement was performed with RFSoC.
  $y = k_y \frac{\Delta}{\Sigma}$ (k_y by boundary element method)

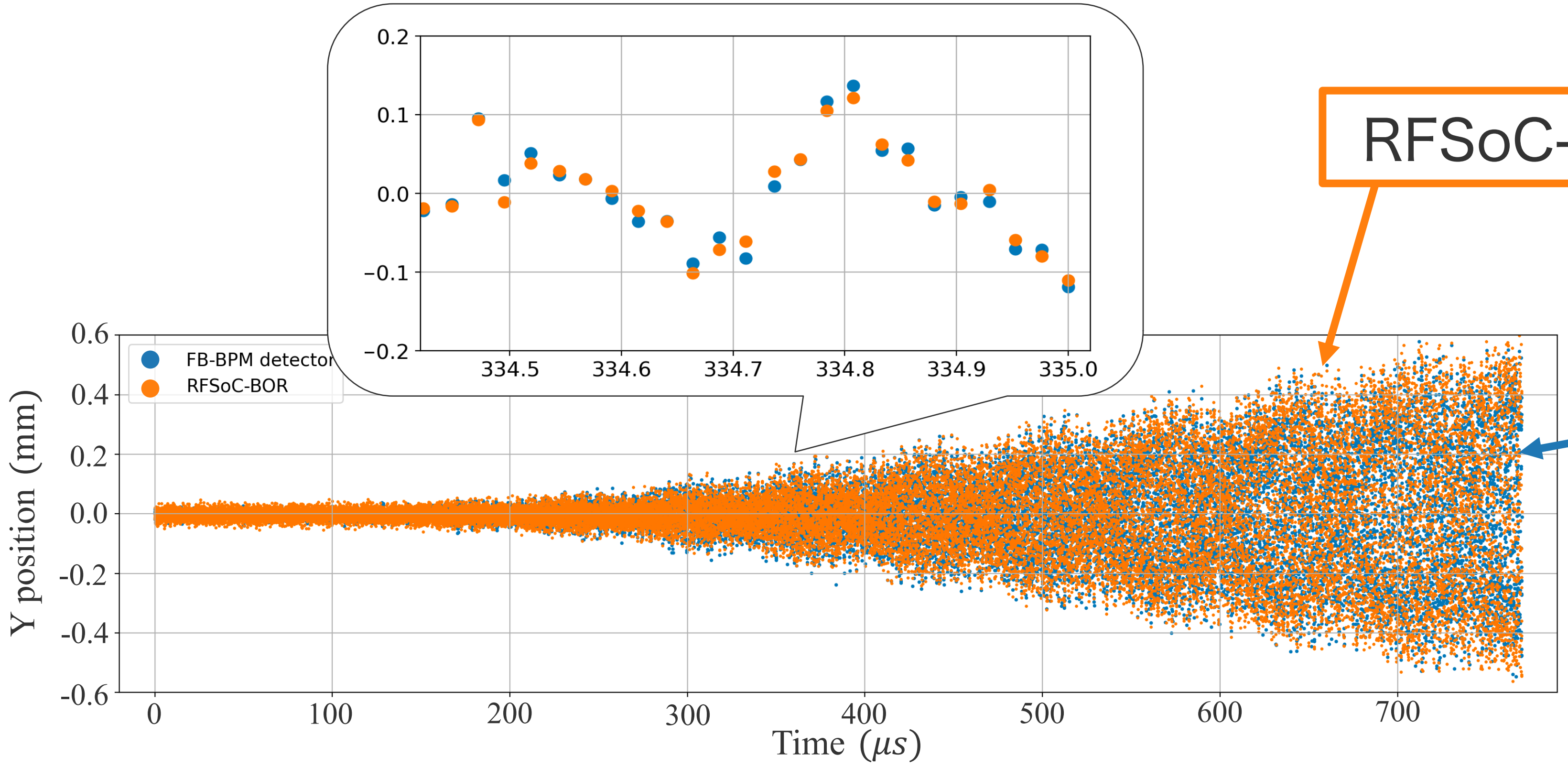
- The positions measured with RFSoC matches closely with the bump position.

- Stdev for each measurement point is approximately **30μm**

→ Achieved the target measurement resolution equivalent to that of VME-BOR

Comparison with the existing monitor

- Bunch oscillations are intentionally induced by inverting the phase of the bunch-by-bunch feedback kicker.



RFSoC-BOR

FB-BPM (iGp12)

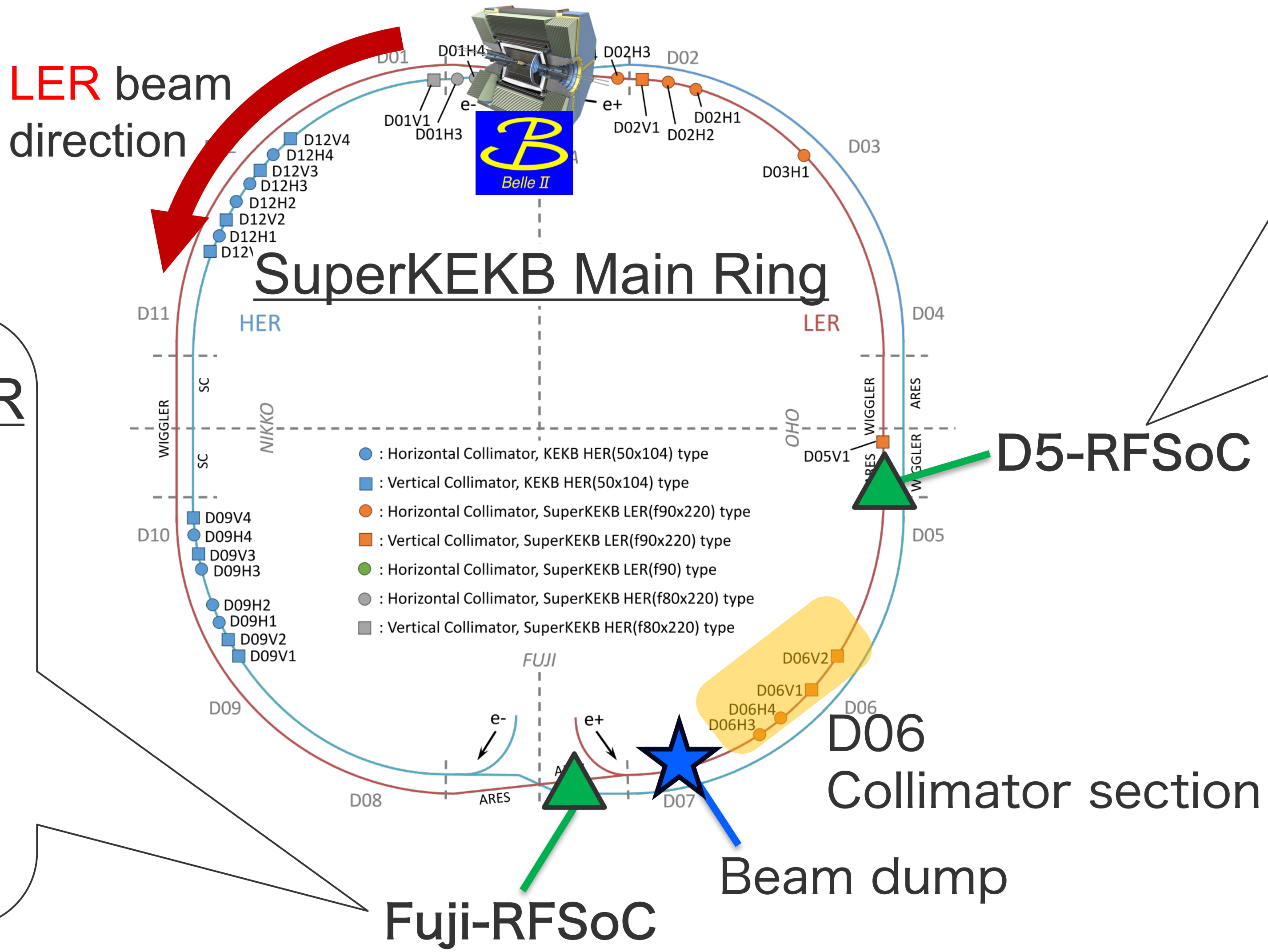
Feedback system detector (calibrated)

by Dimtel, Inc.

The magnitude of oscillation and the growth time of instability were almost the same, so the RFSoC functioned as a BOR without any problems.

Develop and install two RFSoC-BORs

- System capable of measuring bunch position and charge at multiple points



1st RFSoC-BOR

ZCU111
eval board

2nd RFSoC-BOR

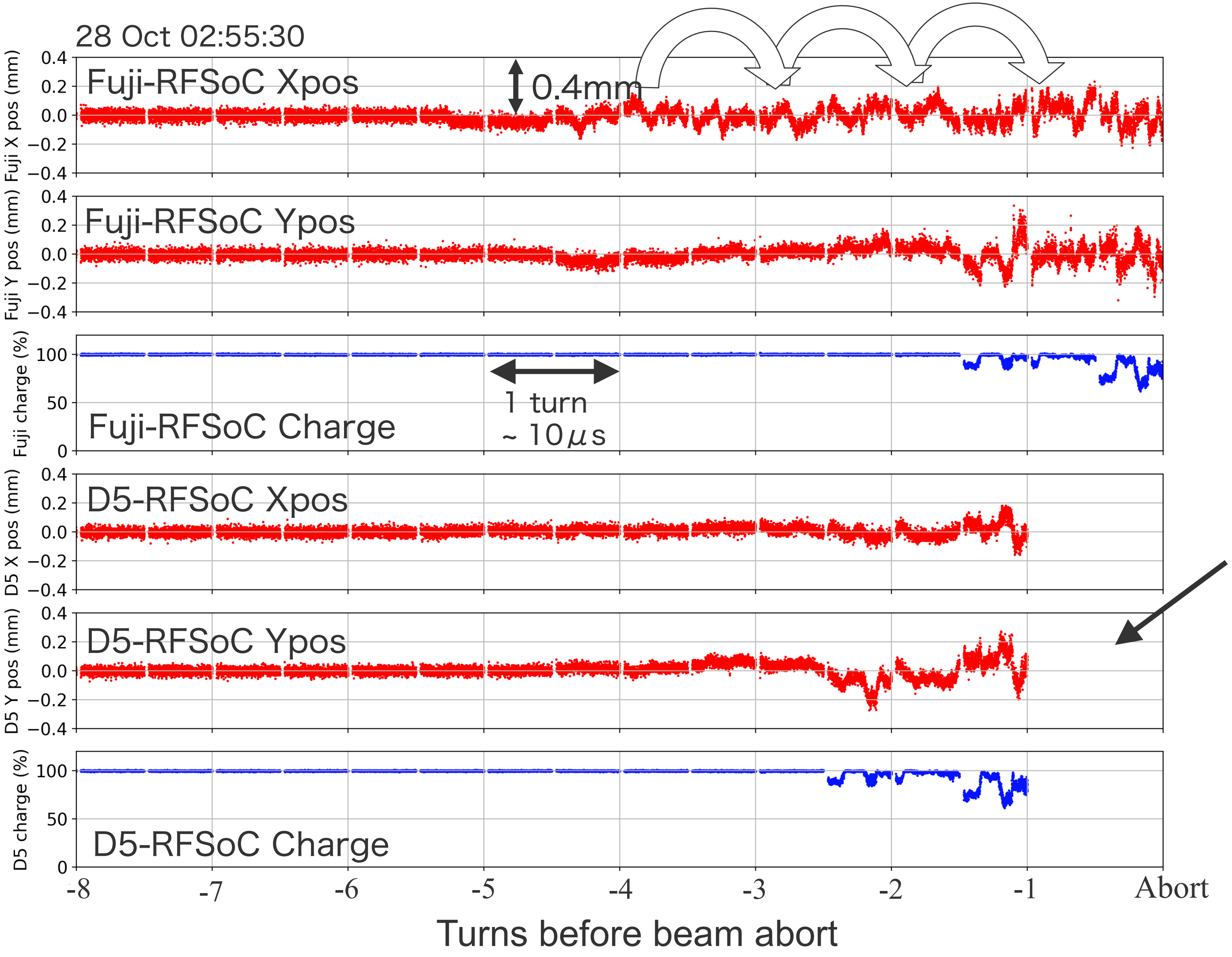
ZCU208 eval board

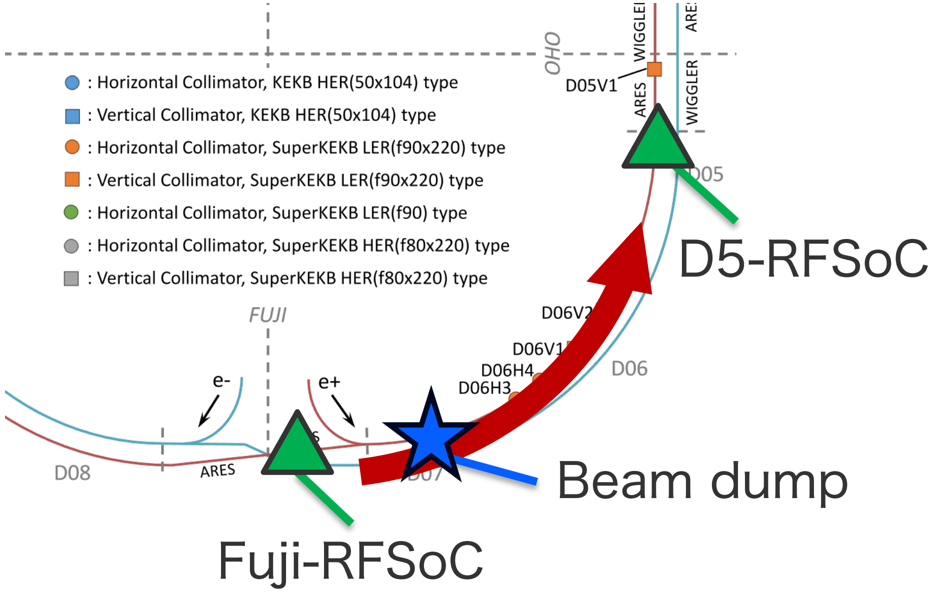
Circuit and firmware copied from Fuji-RFSoC.

Observation and study of sudden beam loss events using RFSoC-BORs

Observation of SBL using RFSoC-BORs

- Introducing the observation results of SBL events



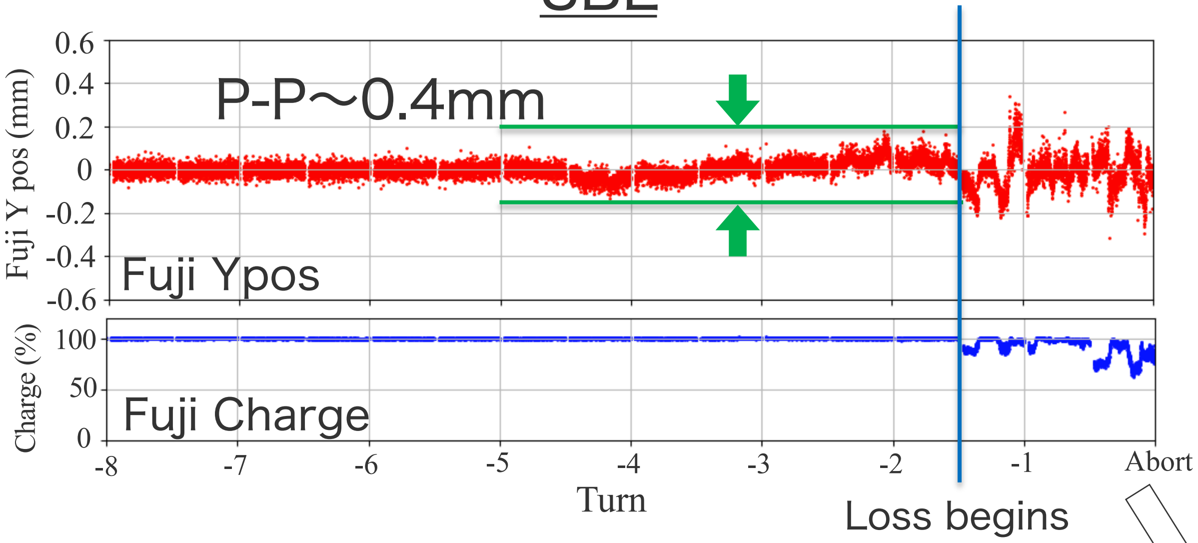


No data available as there is a beam dump immediately after Fuji-RFSoC

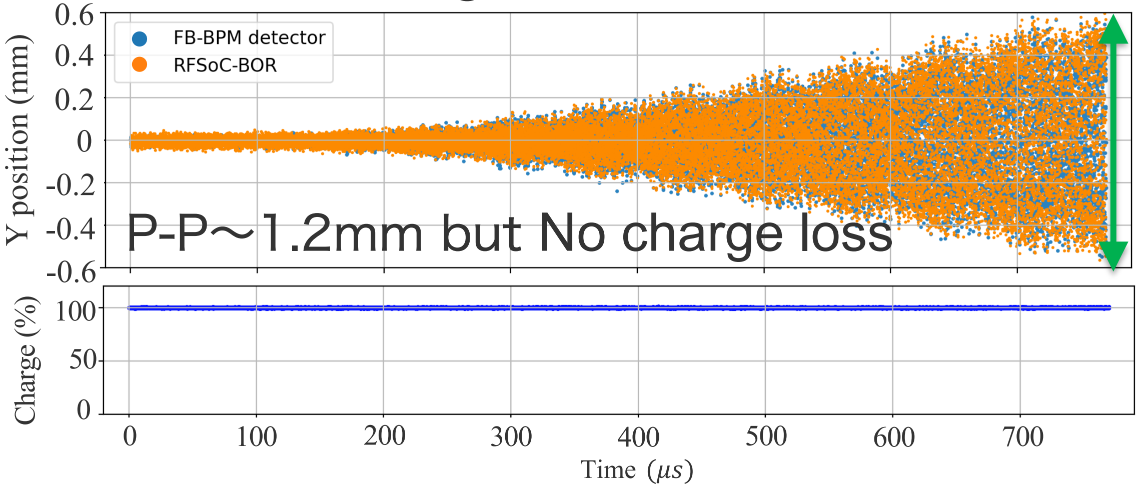
	period	Num of records
Fuji-RFSoC	October 13 to November 28	117
D5-RFSoC	October 26 to November 28	58

Bunch oscillations during SBL events

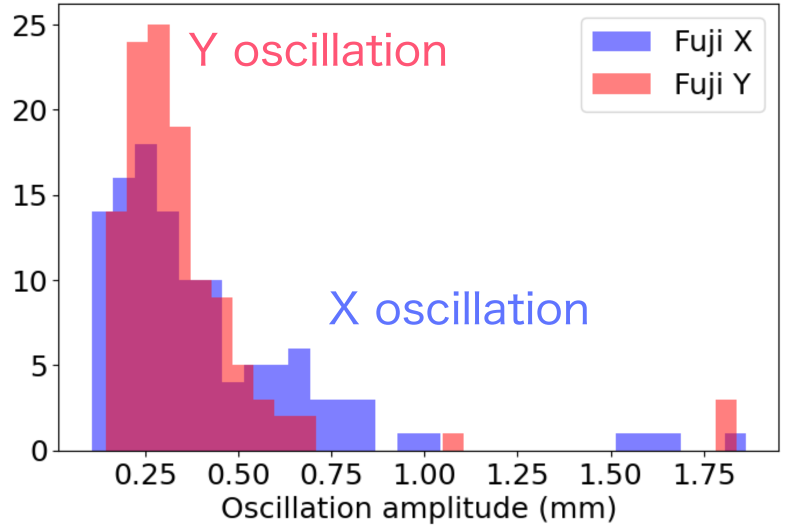
SBL



Testing with Feedback



Distribution of P-P values



Charge loss tends to occur at oscillations smaller than the physical aperture that should be allowed.

Not only position oscillation but also an increase in beam size may occur.

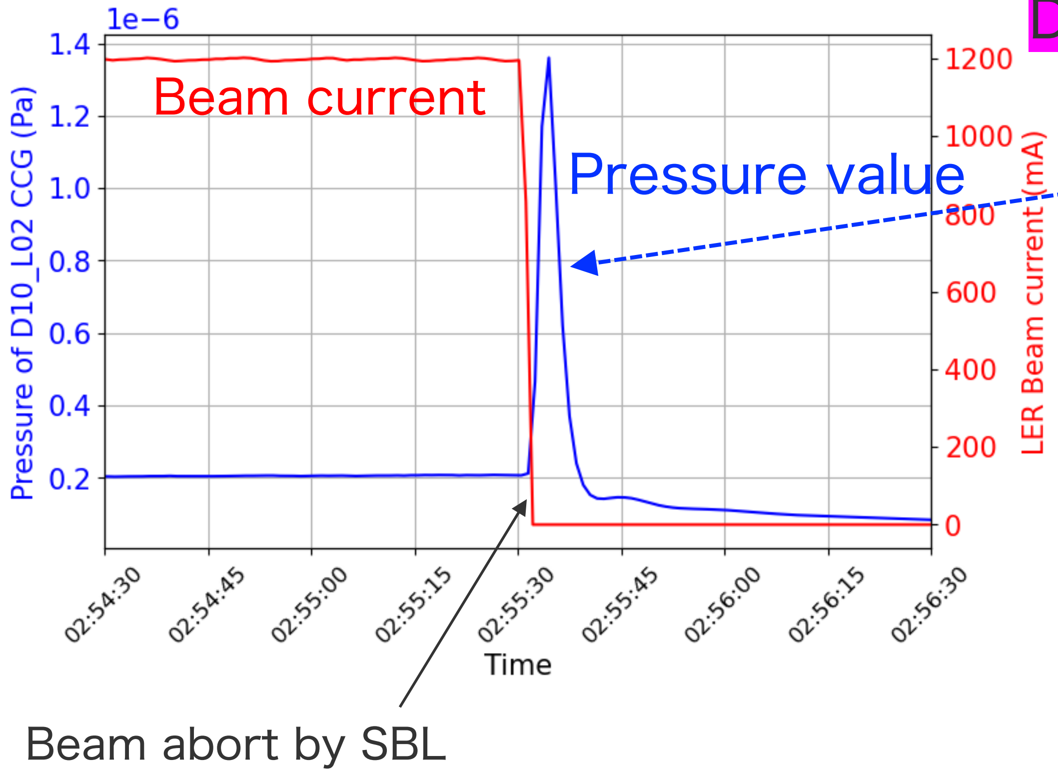
Size increase cannot be seen with BOR alone

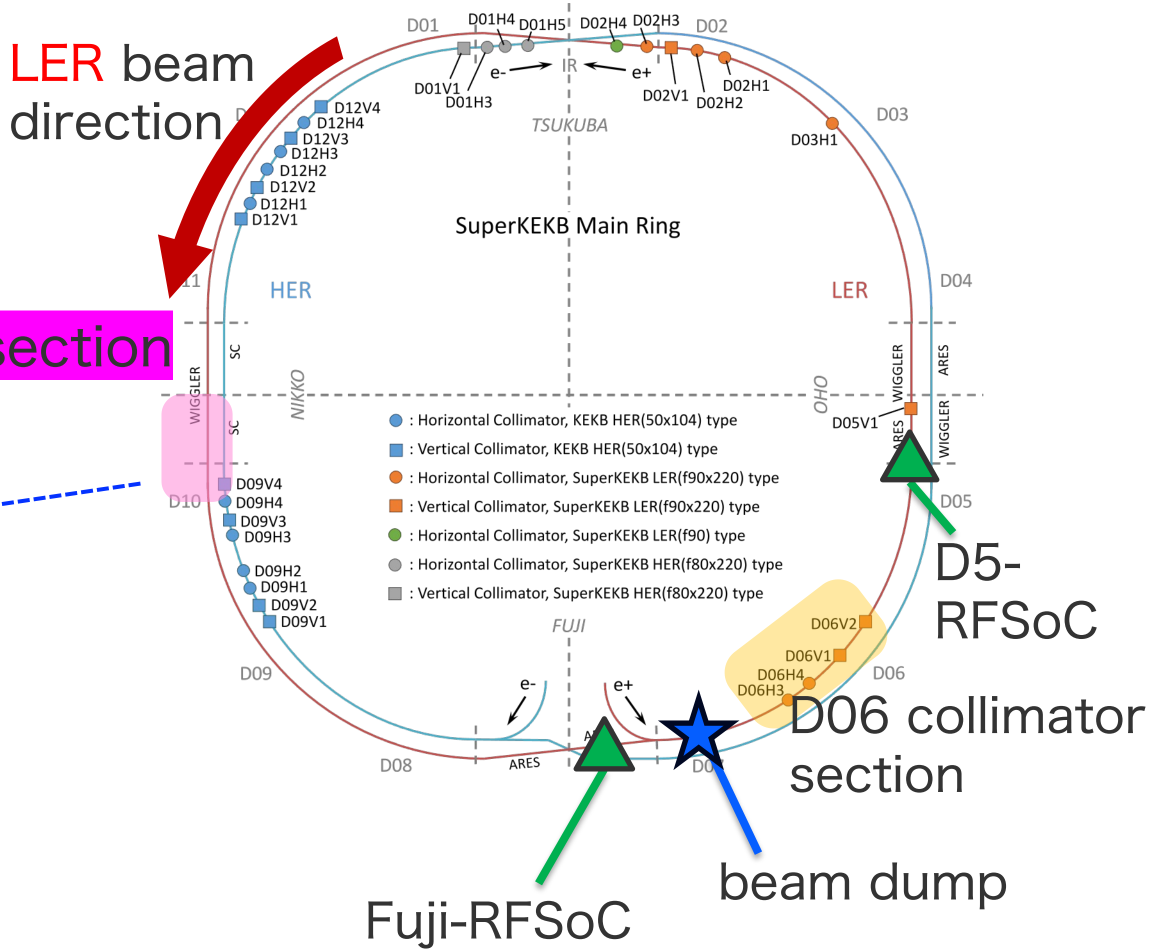
Pressure burst

■ When SBL occurs, the pressure in the chamber often rises abnormally at some point on the ring.

→ We call it “Pressure burst”

Pressure value at a certain point in the D10 section when an SBL occurs

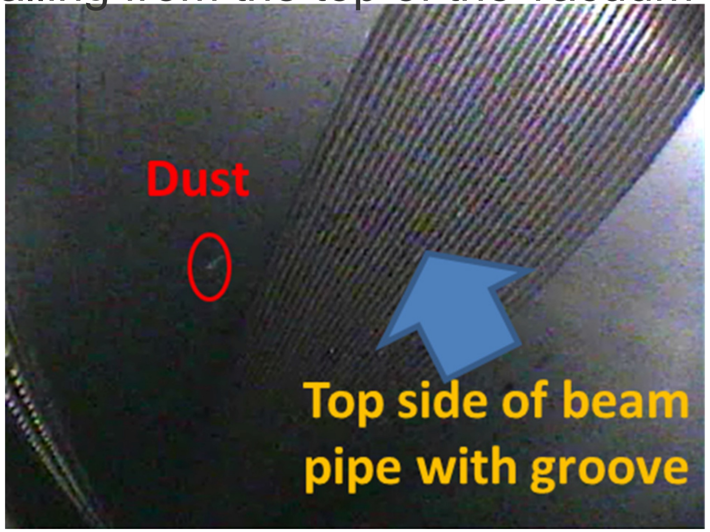




Previous studies on pressure burst

- There were also beam aborts with pressure burst events at LER in 2016
- Cause: Collision of the beam with dust falling from the top of the chamber.
  The pressure burst occurs at the location where the dust and beam collide.

Dust falling from the top of the vacuum chamber



[S. Terui et al., PASJ2017]

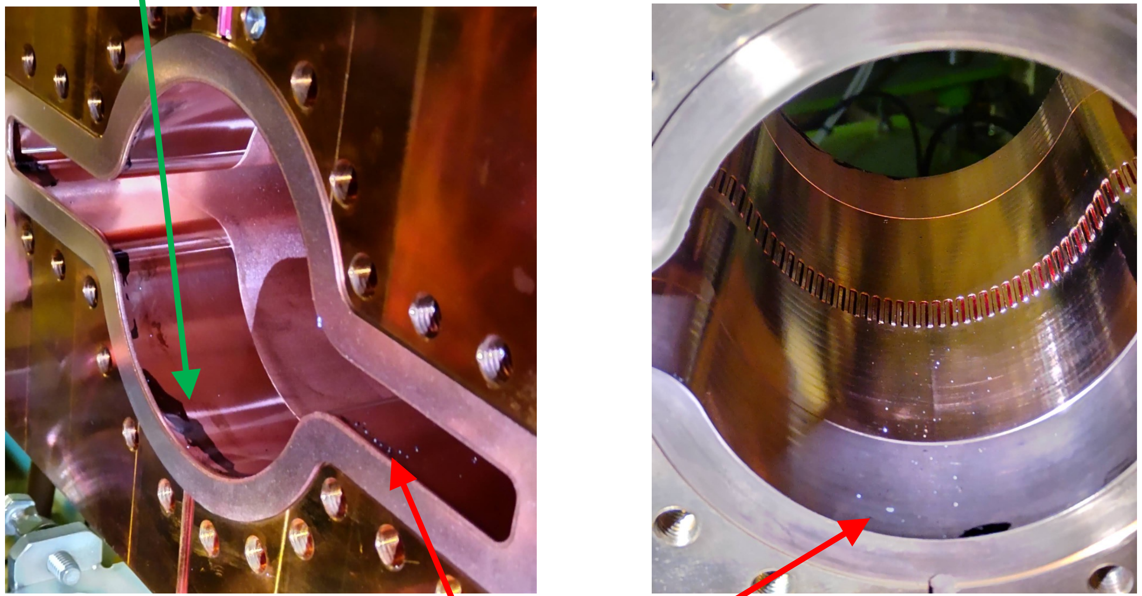
- Beam current loss over several hundred μs to about 1 ms. (slower than SBL)
- Synchrotron oscillation when the beam loses momentum due to collision with dust

Even in the case of the SBL, could the beam interact with other materials at the location where pressure burst occurs or receive kick forces that lead to fast beam loss?

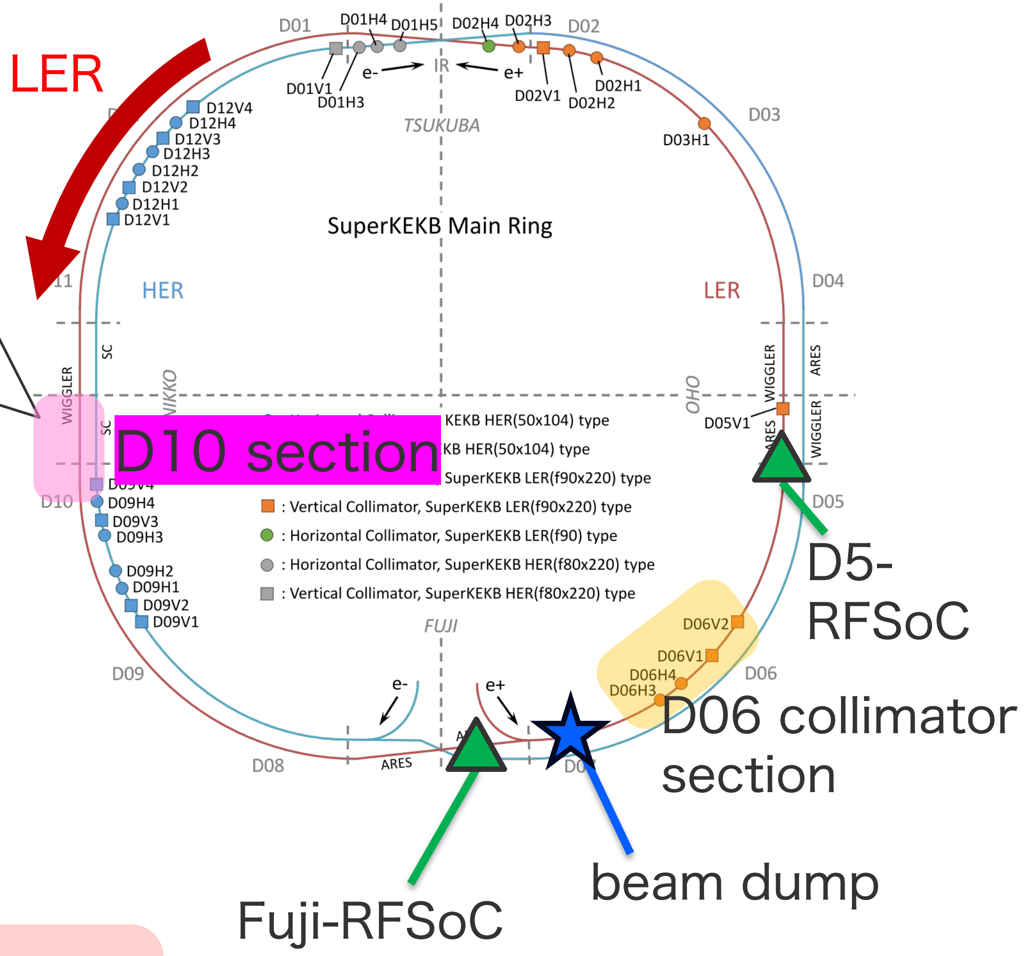
Relation between pressure burst and SBL

- SBL events with pressure bursts in D10 section occurred very frequently.

Vacuum seal
seeping into chamber

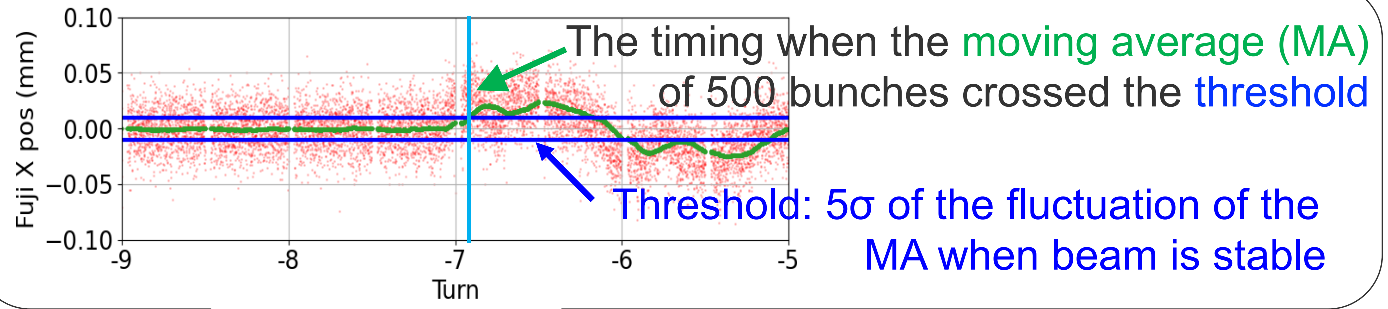


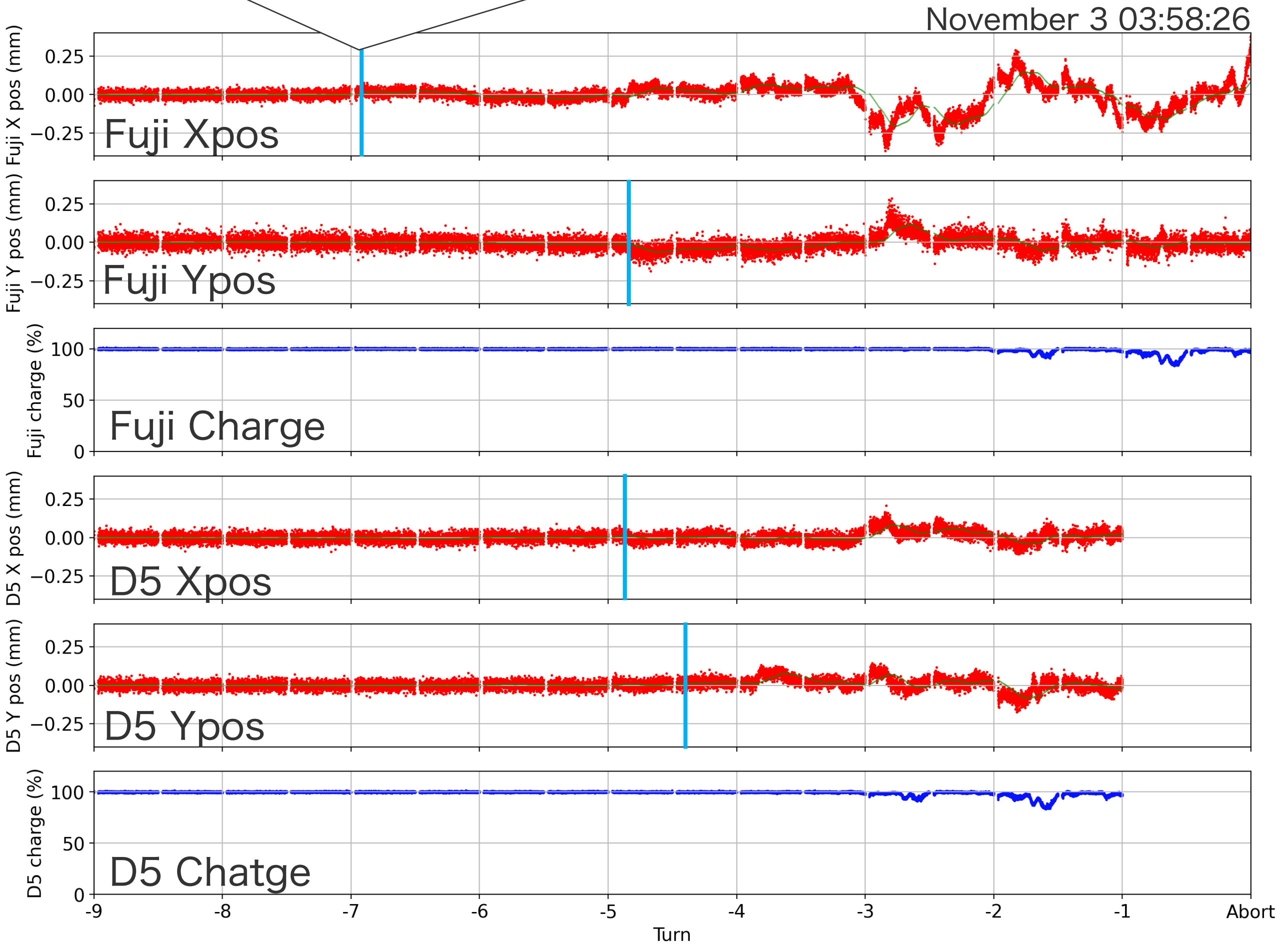
dust



It's thought that the beam received force at the D10 section

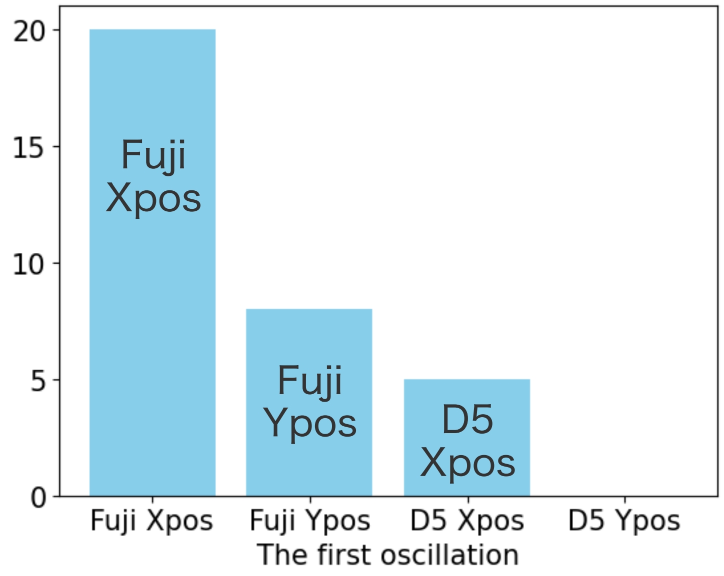
■ Focus on the timing of oscillations start





■ About 33 SBL events

Which of the X and Y pos of Fuji-RFSoC and D5-RFSoC detected oscillation first?



Fuji-RFSoC tends to detect oscillation earlier

■ Betatron Phase Difference

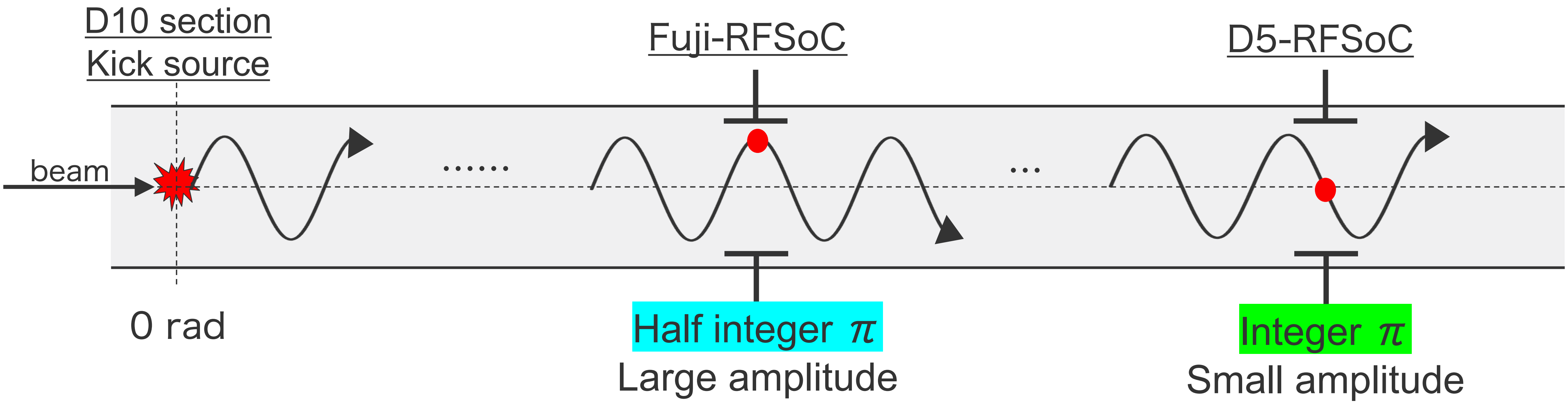
	D10 section Kick source	Fuji-RFSoC	D5-RFSoC
X betatron phase diff (rad)	0	21.40 π	40.89 π
Y betatron phase diff (rad)	0	22.56 π	42.93 π
		Half integer	Integer

Kick at point 1 → Observe at point 2

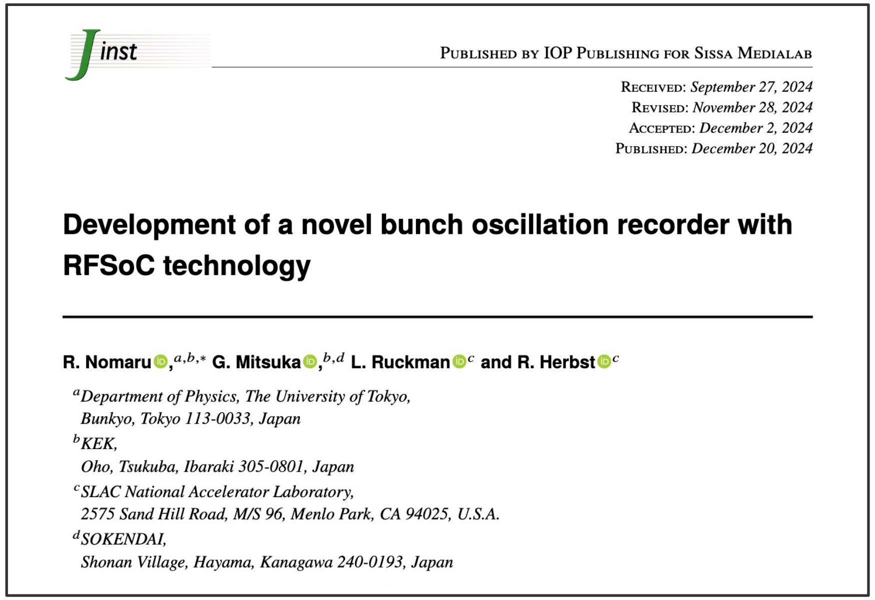
$$y_2 = \sqrt{\beta_{y1}\beta_{y2}} \sin \Psi_{12} \, \Delta y_1'$$

Phase diff between two points

Consistent with "Fuji-RFSoC tends to detect oscillation earlier"



Summary and outlook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Development of a novel bunch oscillation recorder with RFSoC technology

R. Nomaru,[a,b,*] **G. Mitsuka**,[b,d] **L. Ruckman**[c] **and R. Herbst**[c]

[a]*Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[b]*KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan*
[c]*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, M/S 96, Menlo Park, CA 94025, U.S.A.*
[d]*SOKENDAI, Shonan Village, Hayama, Kanagawa 240-0193, Japan*

- Sudden Beam Loss (SBL) is a major problem in SuperKEKB.

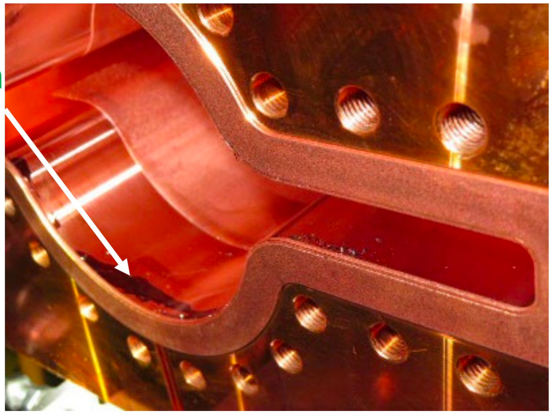
- To observe and analyze SBL in detail, we developed a new Bunch Oscillation Recorder (BOR) using RFSoC.
  - Improve accuracy through new daughter board development
  - Develop and install more BORs by taking advantage of portability

- SBL events observations were performed using new BORs.
  - Beam size increase
  - Relationship with Pressure Burst

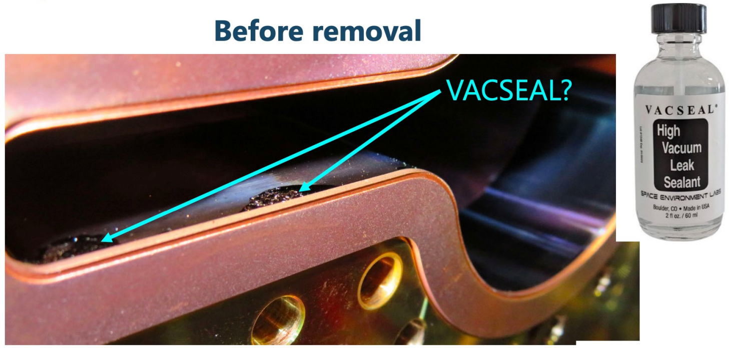
Thank you for your attention.

Back up

Black stain
VACSEAL?

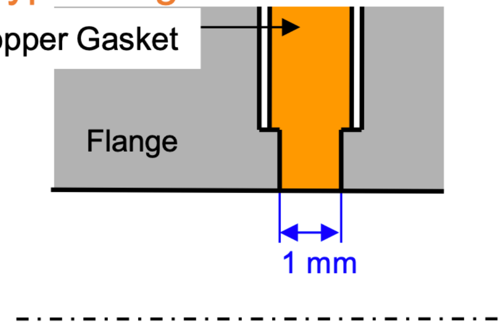


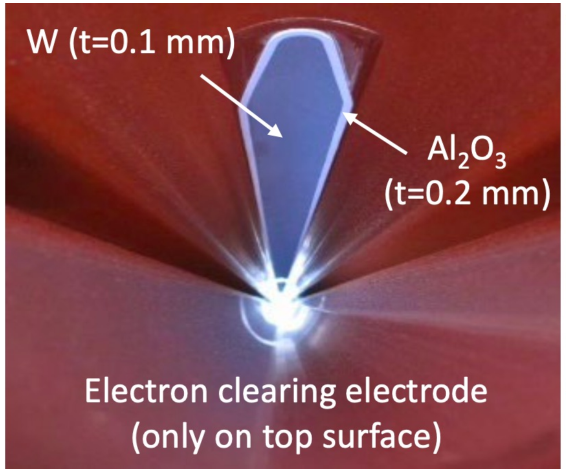
Before removal

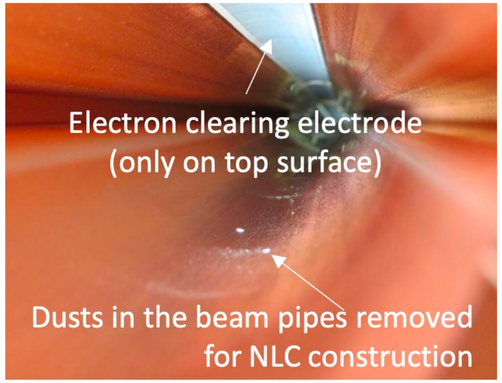


C,O,Si

MO-type flange

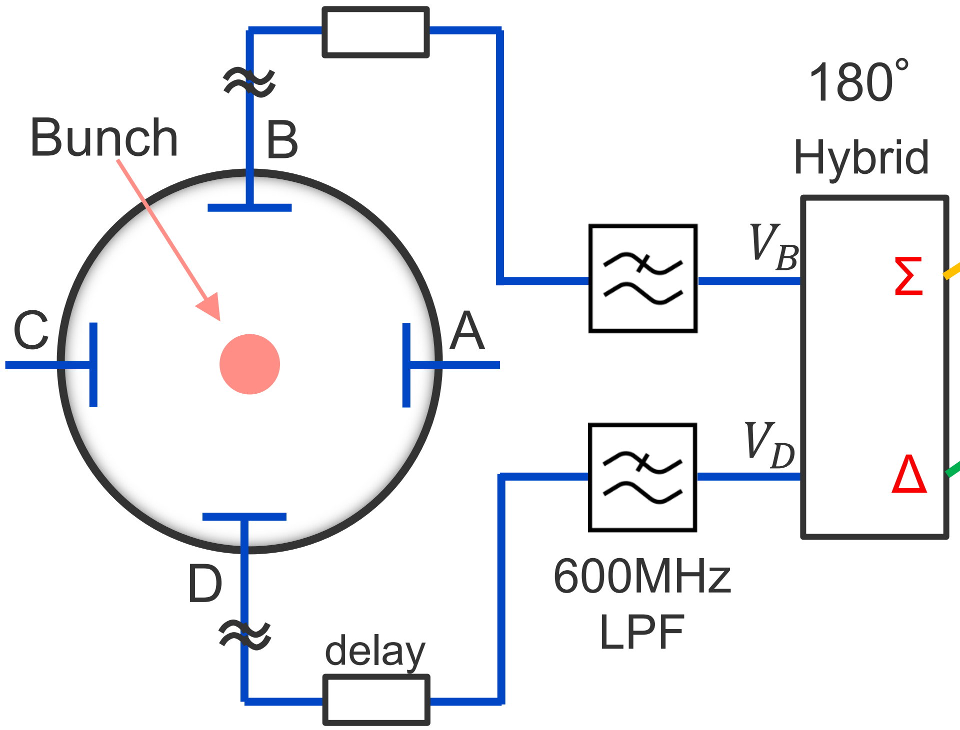




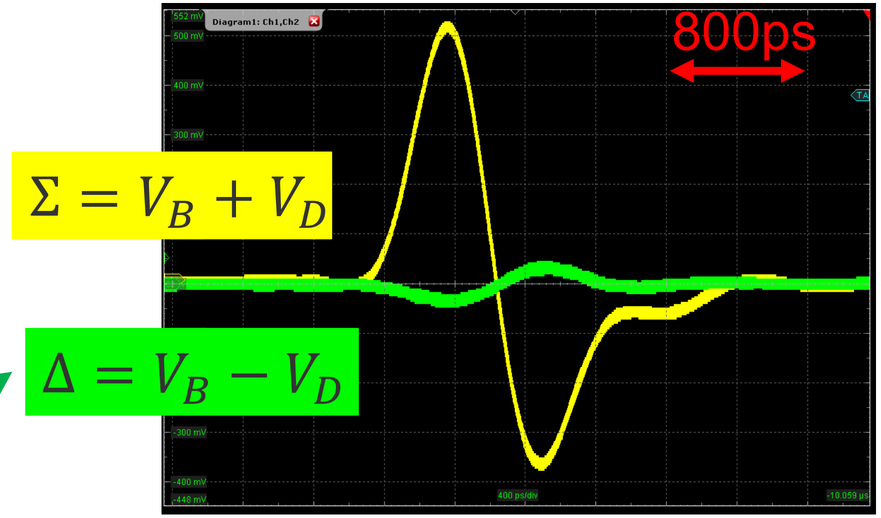


Fe, Al, O, C

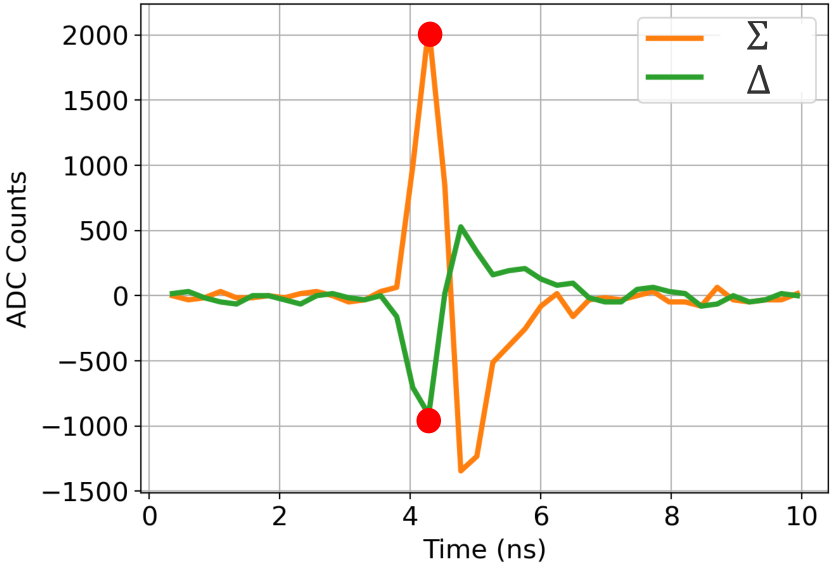
Observing waveform

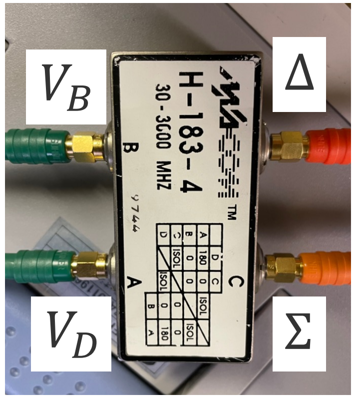


One bunch signal (oscilloscope)

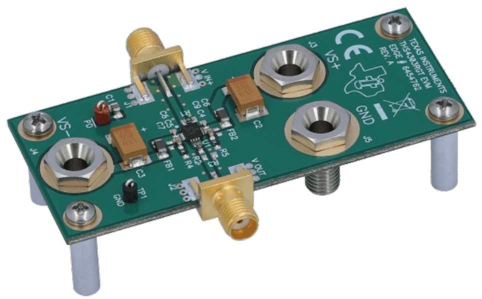


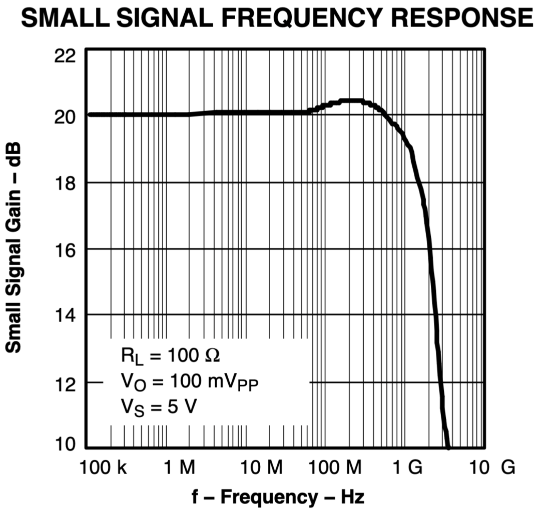
measured by RFSoC (4072Msps)



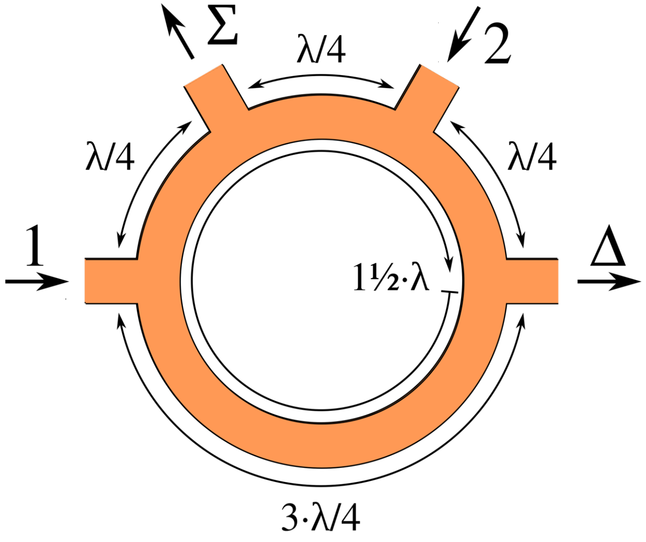


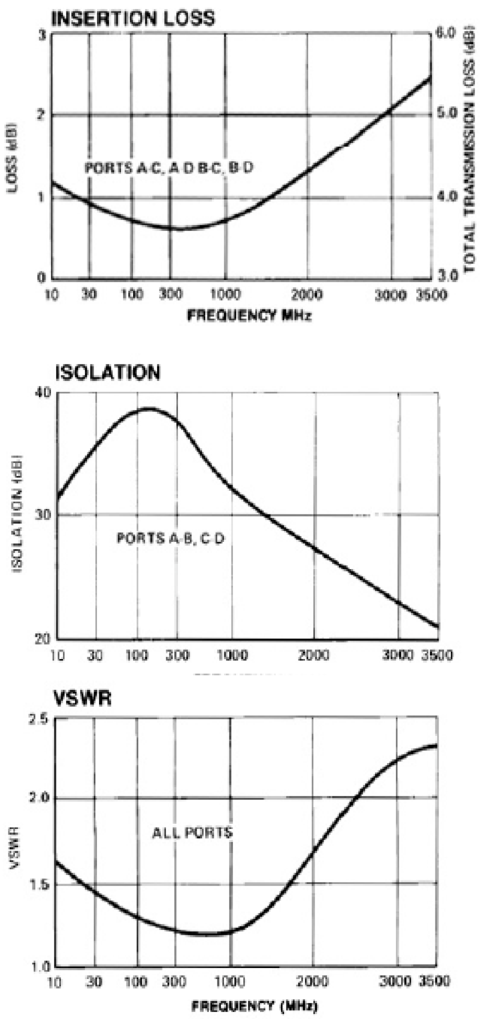
Texas Instruments
THS4303



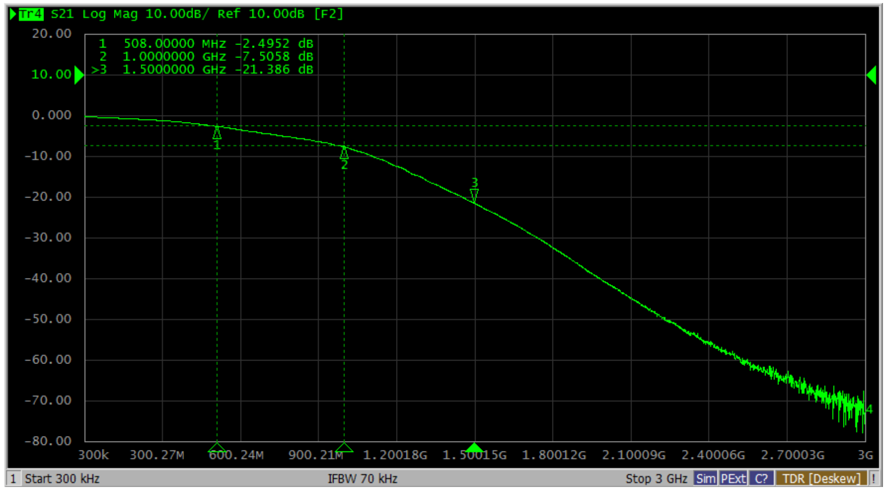


MACOM
Microwave Hybrid Junction H-183-4

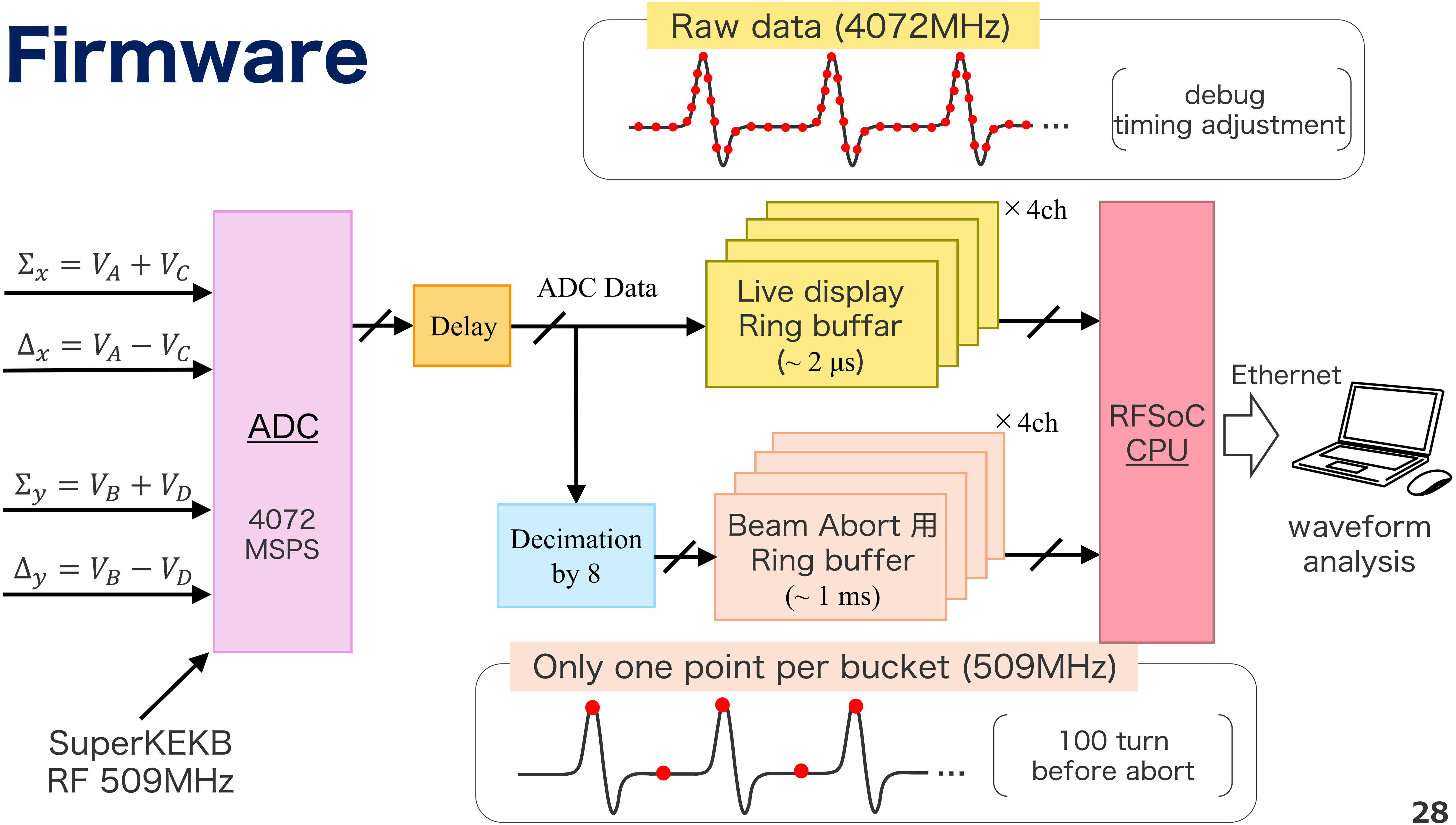




LORCH
5LP8-600B-SR



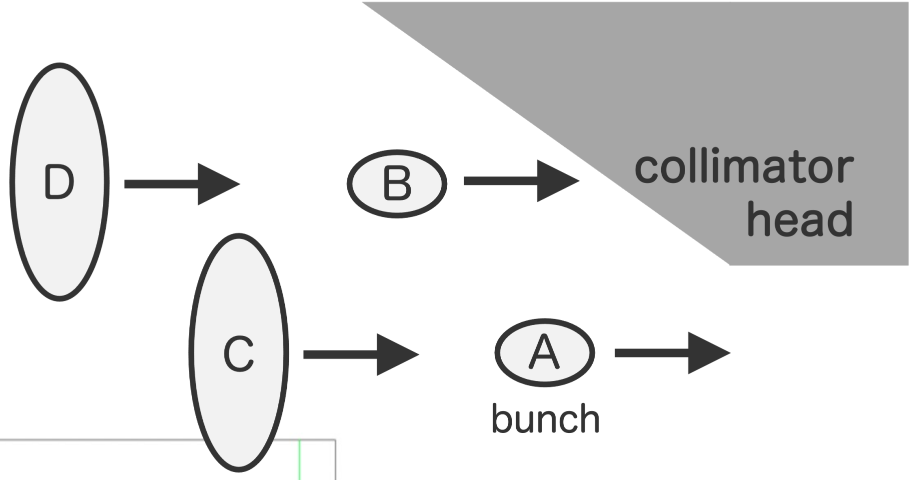
Firmware

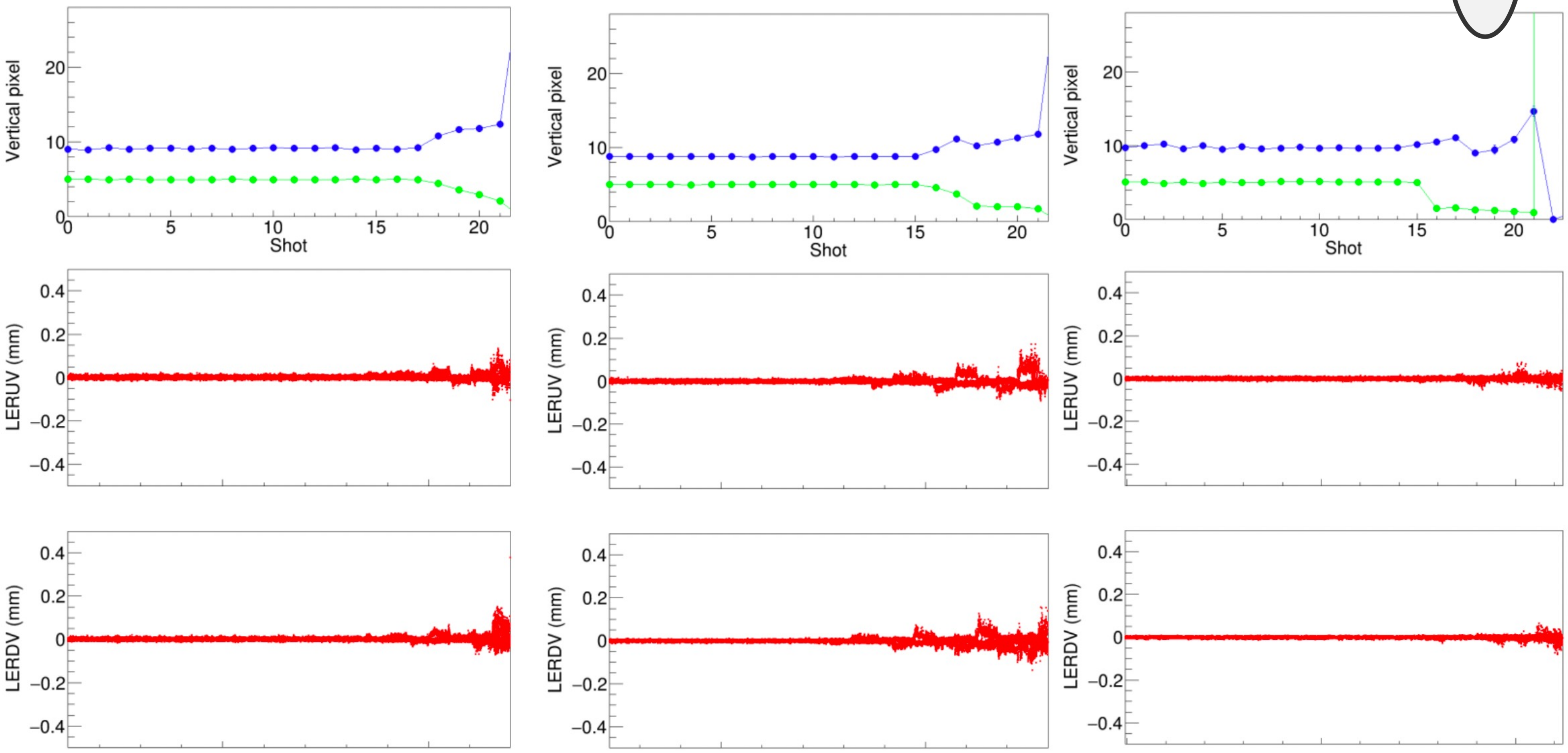


Raw data (4072MHz)
debug
timing adjustment
$\Sigma_x = V_A + V_C$
$\Delta_x = V_A - V_C$
$\Sigma_y = V_B + V_D$
$\Delta_y = V_B - V_D$
ADC
4072
MSPS
SuperKEKB
RF 509MHz
Delay
ADC Data
Live display
Ring buffar
(~ 2 μs)
× 4ch
Decimation
by 8
Beam Abort 用
Ring buffer
(~ 1 ms)
× 4ch
RFSoC
CPU
Ethernet
waveform
analysis
Only one point per bucket (509MHz)
100 turn
before abort

Beam size monitor

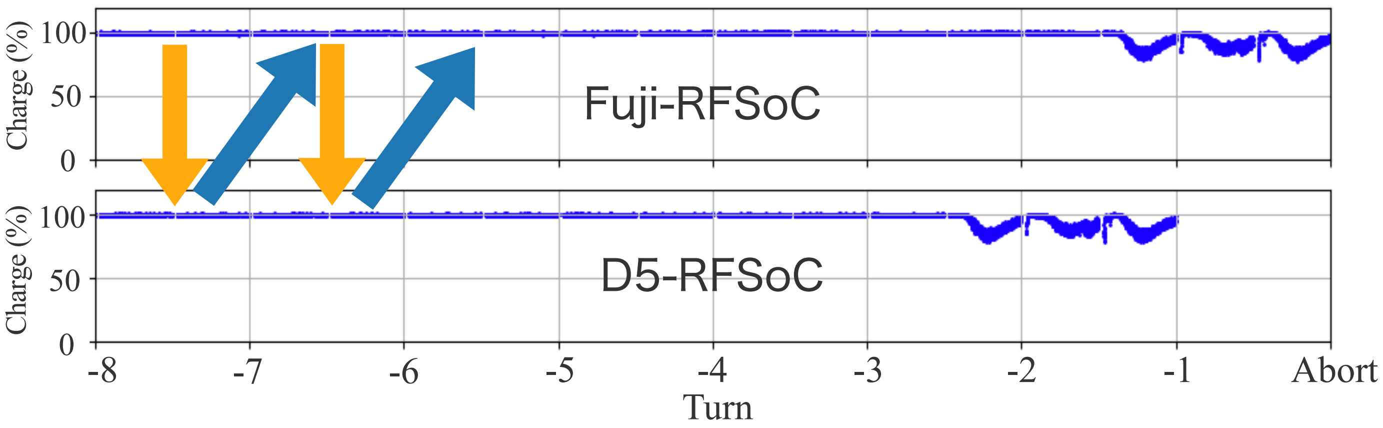
Visible light CMOS
Imaging is done once every two turns
with an exposure time of 1us.





Bunch Charge loss

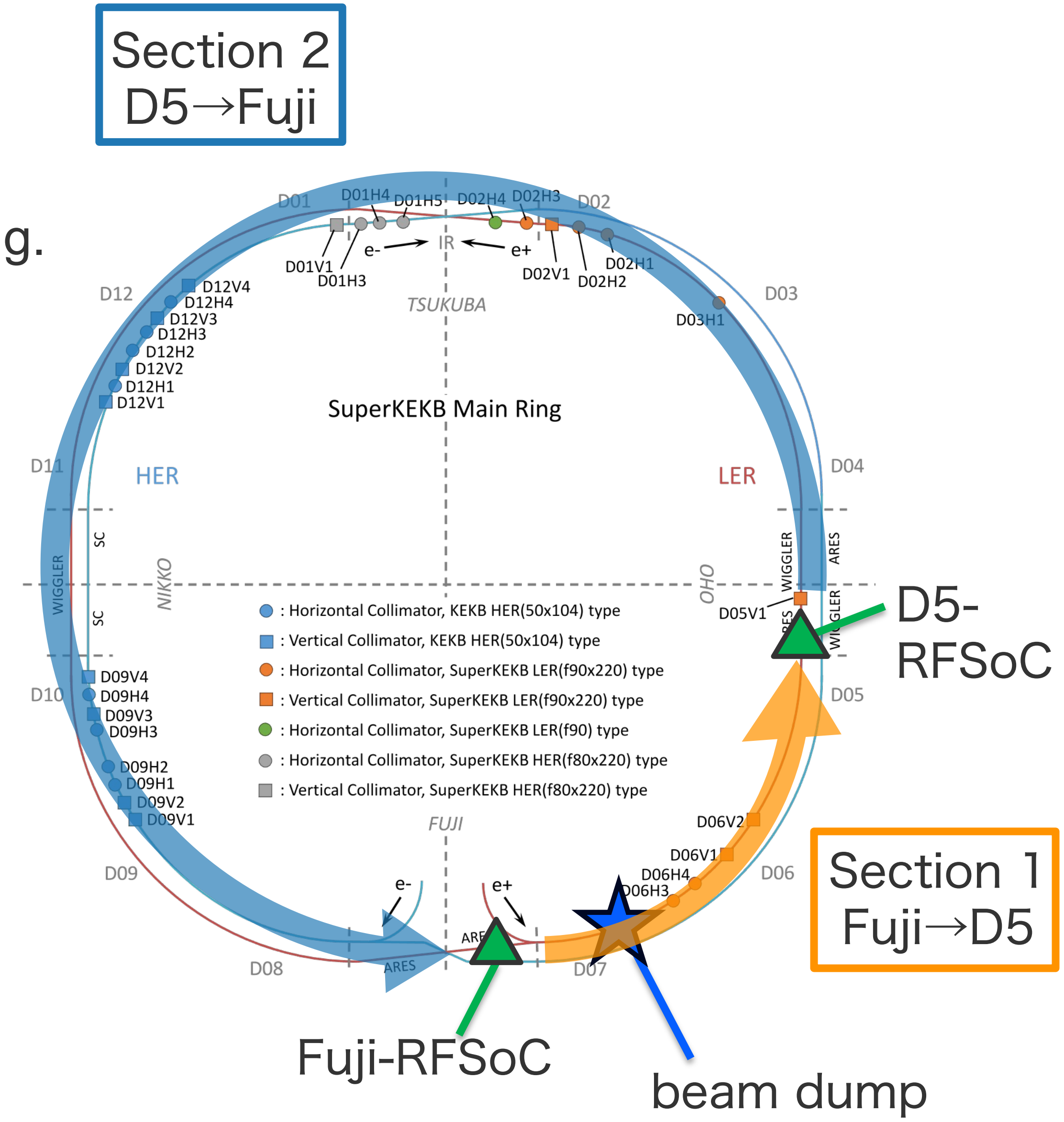
- By dividing the ring with two RFSoC-BORs, it is possible to determine where charge loss is occurring.



Time series

: Bunch moves section 1

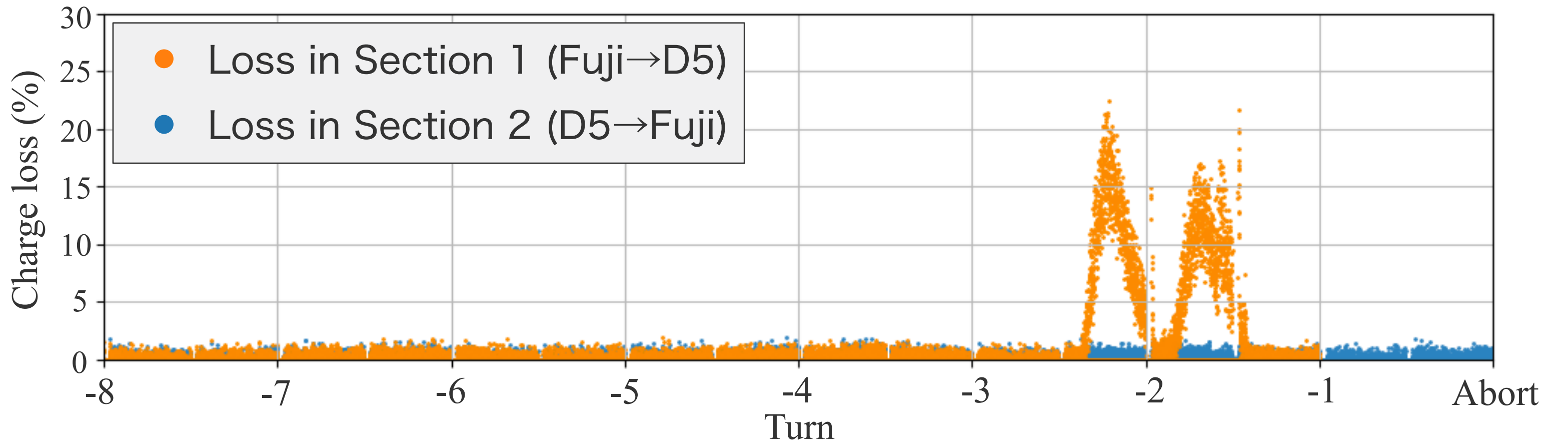
: Bunch moves section 2



- In this example, there appears to be charge loss mainly in section 1

Bunch Charge loss

- Take the difference between the bunch charges recorded by two RFSoC-BORs

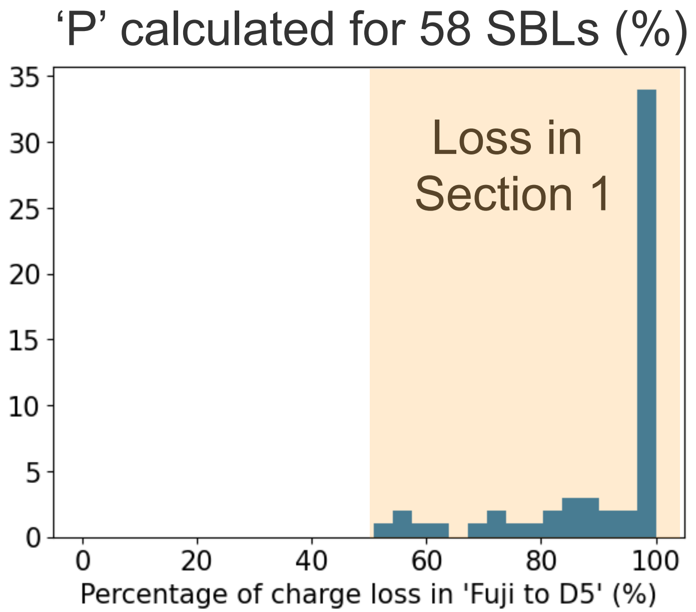


- Percentage of loss in Section 1

$$P = \frac{(\text{Total loss in section 1})}{(\text{Total loss in section 1}) + (\text{Total loss in section 2})}$$

Sum of orange points

Sum of blue points



Most of the charge loss occurred in Section 1 (Fuji→D5).
Large oscillation and beam size increase before entering D06 collimator section

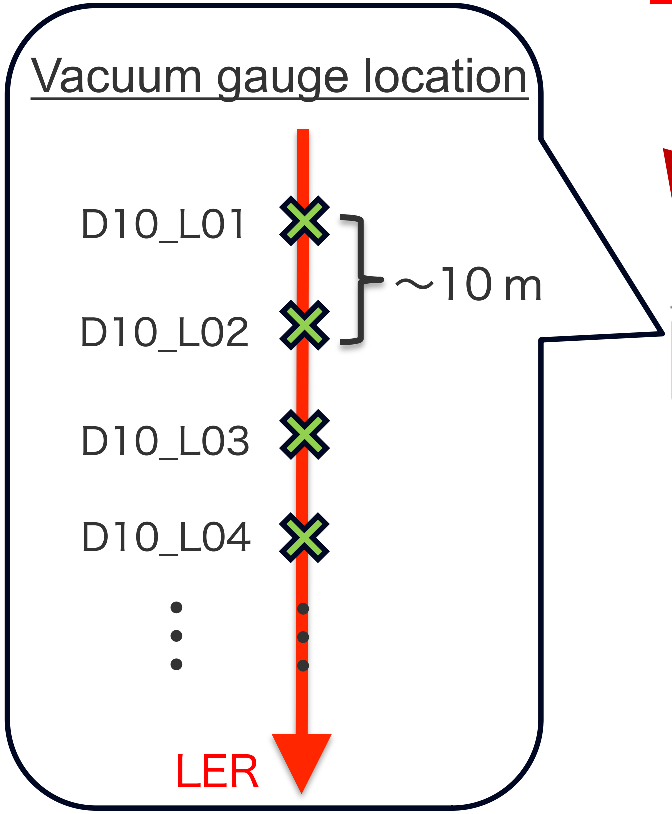
Relation between pressure burst and SBL

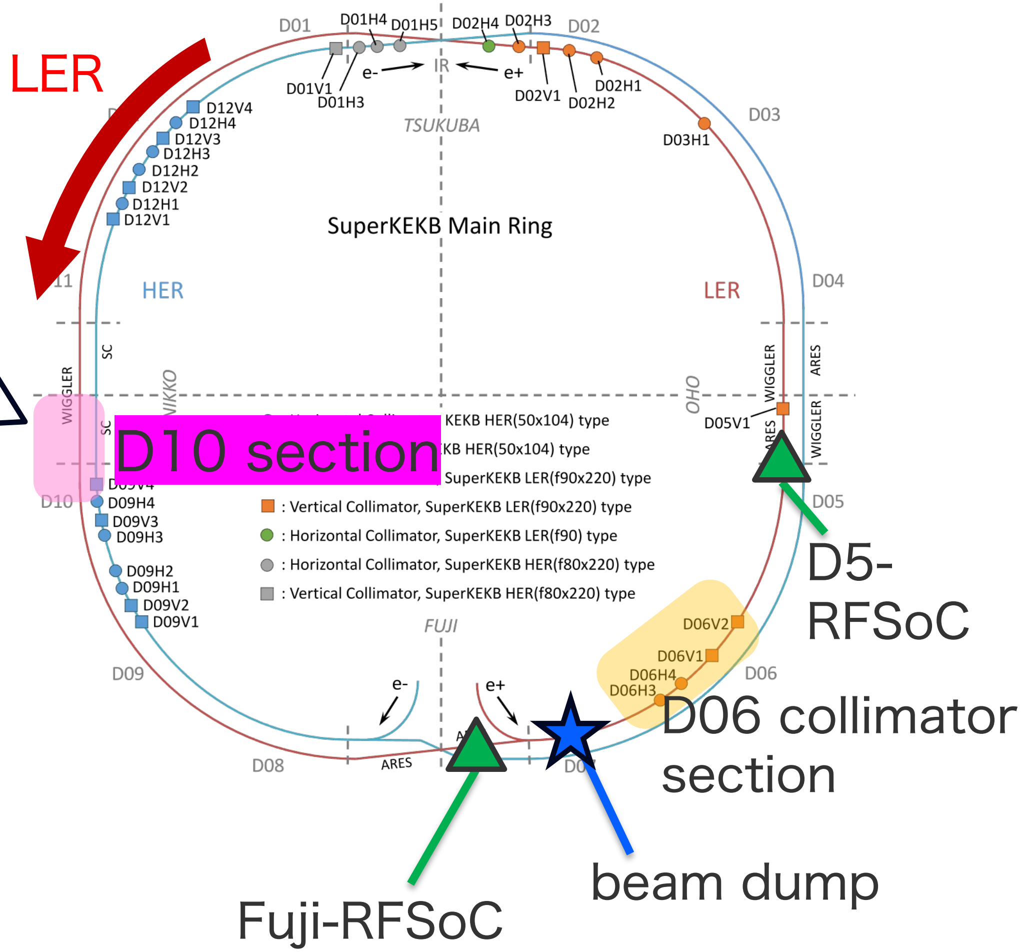
- SBL events with pressure bursts in D10 section occurred frequently.

$\beta_y^* = 1\mathrm{mm}$ operation

Location of pressure burst	Num of events
D10_L02/03	33
D10_L05	4
D10_L06	2
D10_L07	2
D10_L08	2
D02_L18	2
D06_L12	2

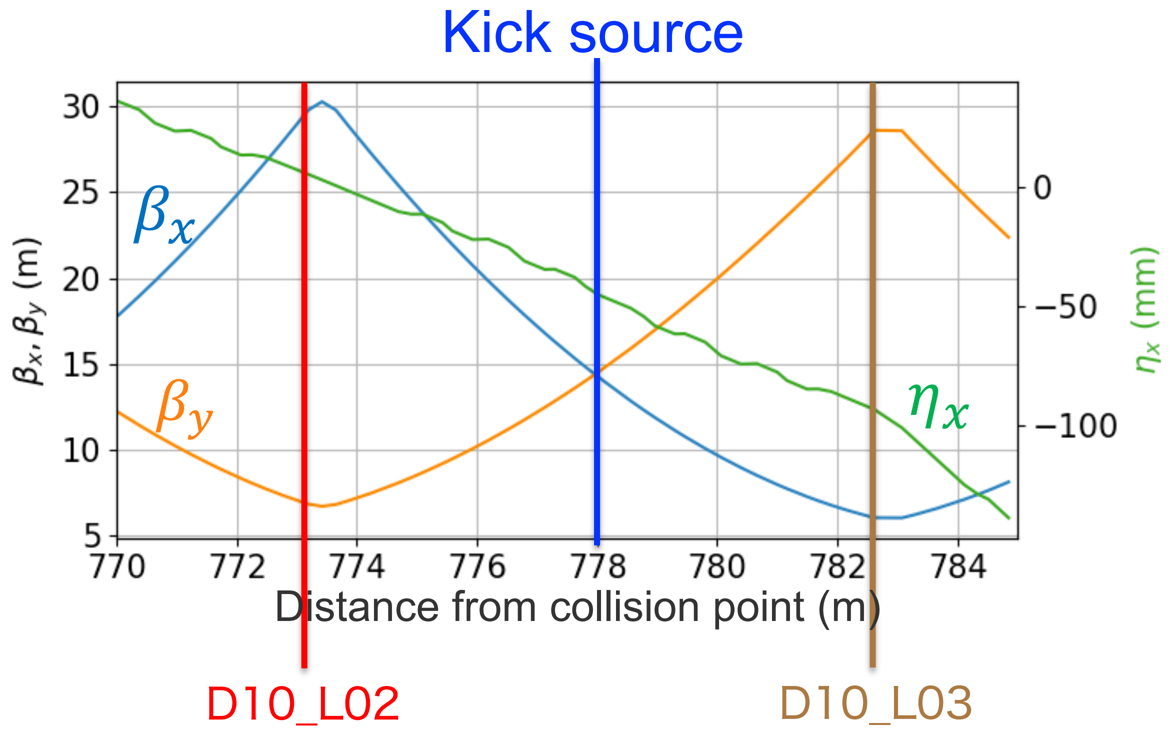
D10_L02 and L03 are grouped together because they always detect pressure bursts at the same time.





■ Beta function

$$y_2 = \sqrt{\beta_{y1}\beta_{y2}} \sin\Psi_{12}\, \Delta y_1'$$



"②Tendency to see oscillations earlier in X pos than in Y pos"

Beta functions in X and Y directions are equal at the Kick source

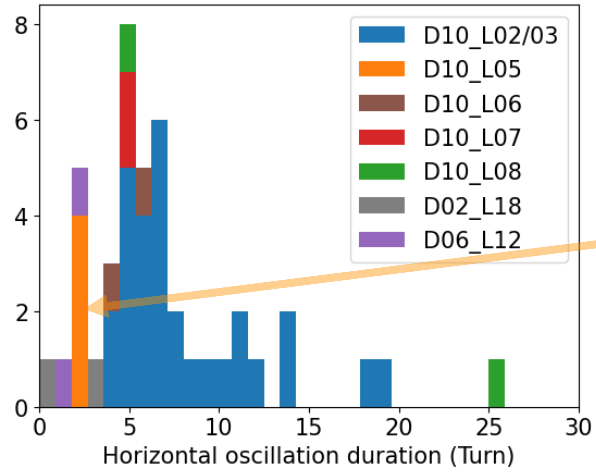
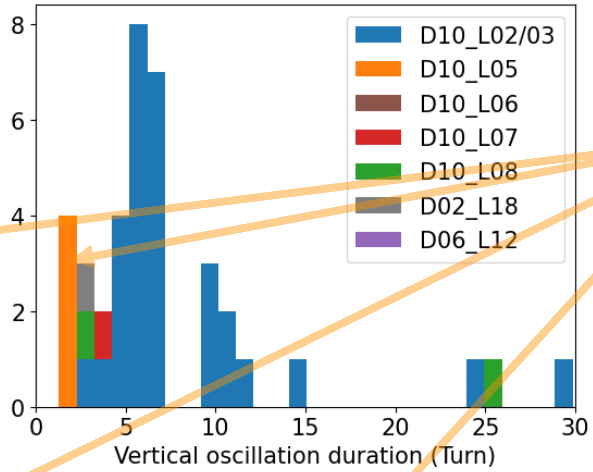
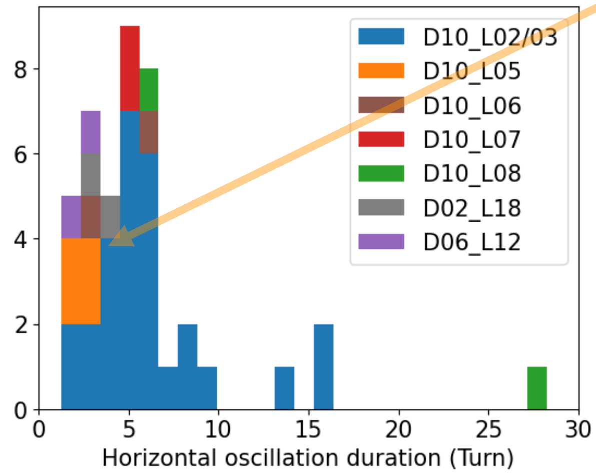
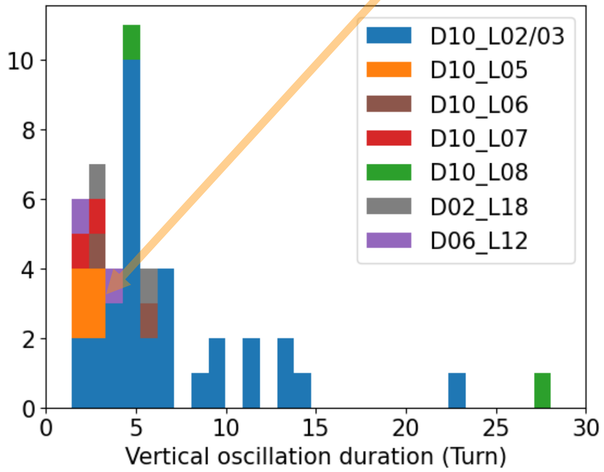
→ Possibly reflecting the nature of the kick itself that the bunch receives, rather than due to the beta function or phase difference

Also, the horizontal dispersion function is non-zero

→ If the beam loses momentum when it collides with dust, it could also cause X oscillations.

By classifying SBL events by the location of the pressure burst, we gained new insight into the process of SBL events.

Pressure burst and oscillation duration

	X oscillation duration	Y oscillation duration
Fuji RFSoC		
D5 RFSoC		

Focus on D10_L02/03 and D10_L05

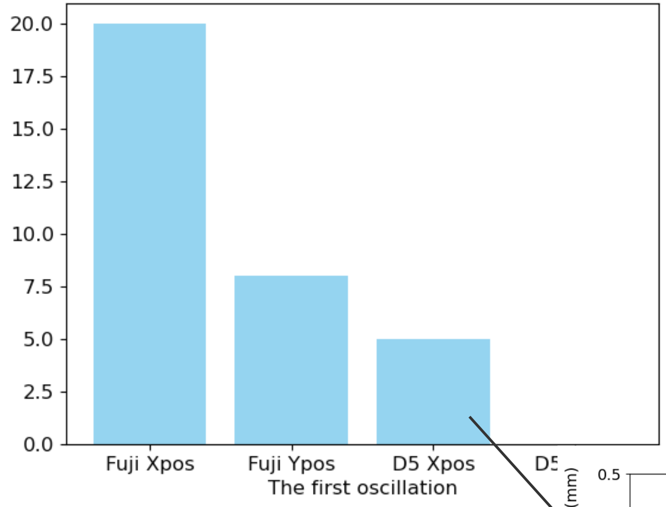
D10_L05
The oscillation duration is very short for all events.

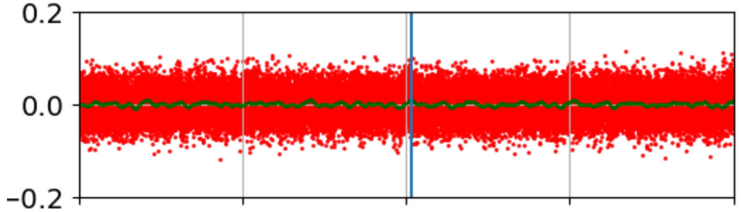
(the phase relationship is such that it will hit the D06 collimator immediately)

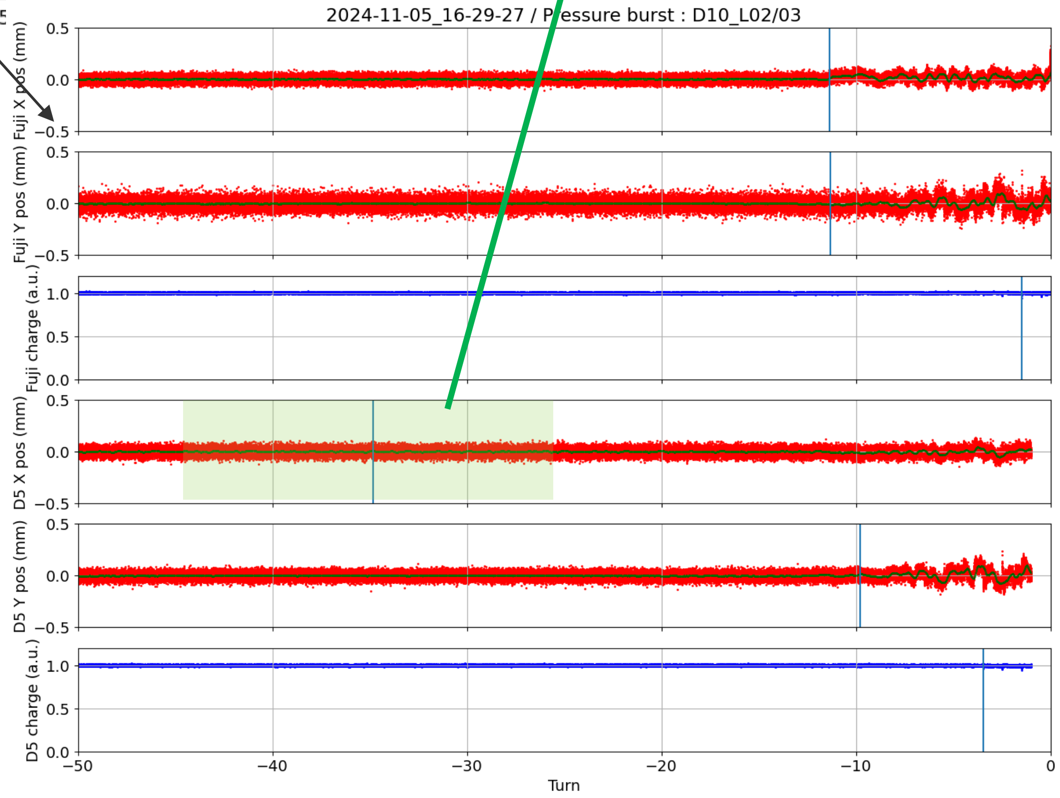
On the other hand, D10_L02/03 oscillations tend to last longer

A relationship btwn the location of the pressure burst and SBL

5σ







6σ