New physics search at the instrumentation frontier

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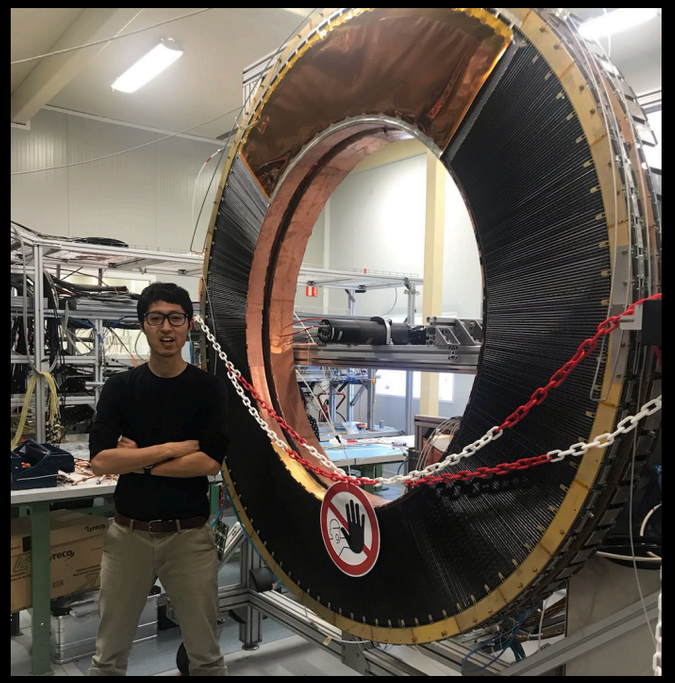
19th April 2023, Hawaii seminar

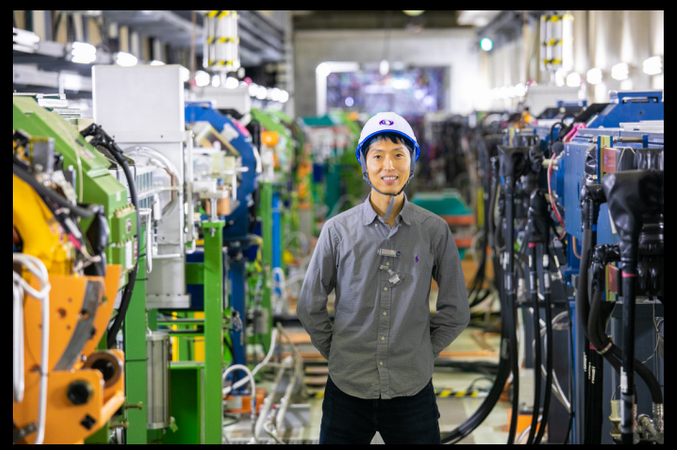
Research summary

- **J-PARC E06/E36 (2009 - 2011)**
  - Muon polarimeter (drift chamber) R&D
  - J-PARC K1.1BR beam line commissioning

- **LHC-ATLAS (2011 - 2019)**
  - Higgs search&coupling meas. (**Ph.D. thesis)**
  - SUSY searches
  - ATLAS TRT operation
  - HL-LHC silicon detector ASIC design



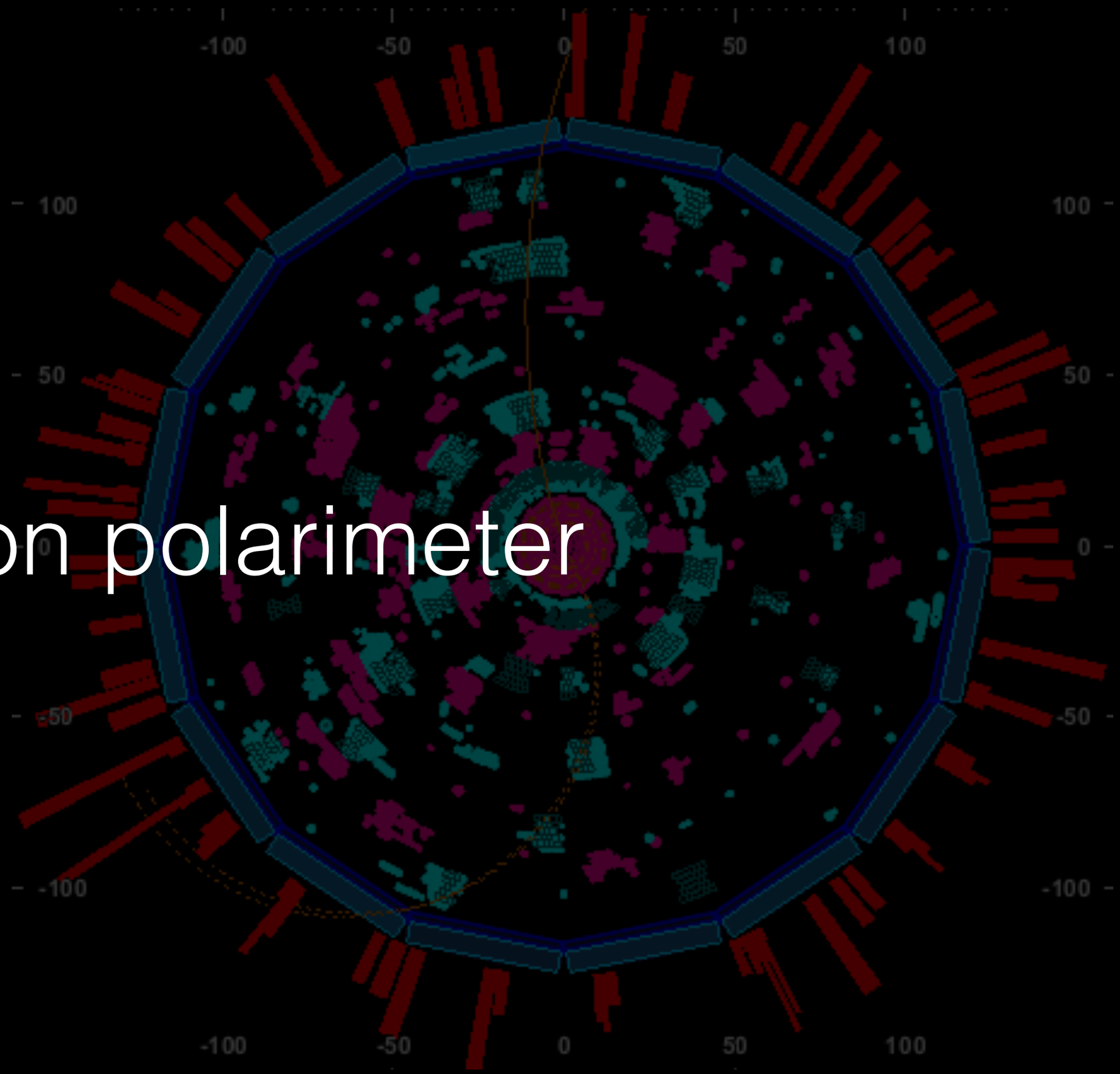
- **SuperKEKB/Belle II (2019 -)**
  - Belle II operation (KLM, collimator)
  - **Machine Detector Interface (MDI)**: interface between detector and accelerator



Outline

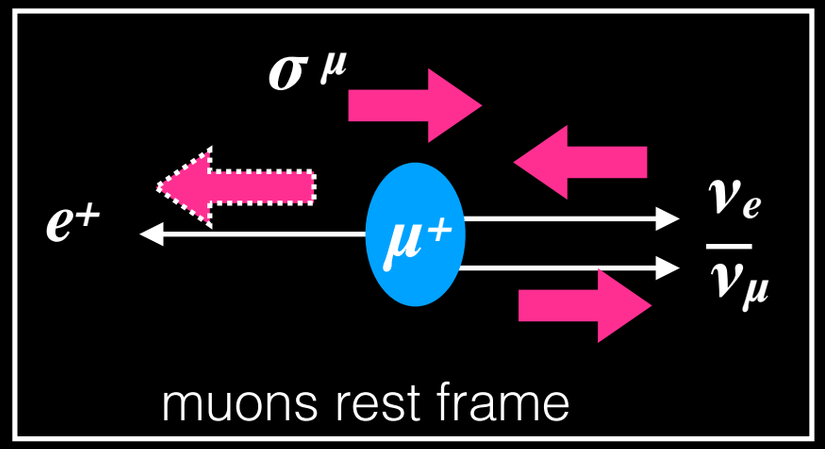
- Muon polarimeter
- LHC-ATLAS TRT
- Belle II KLM
- Sudden Beam Loss
- ALPs search

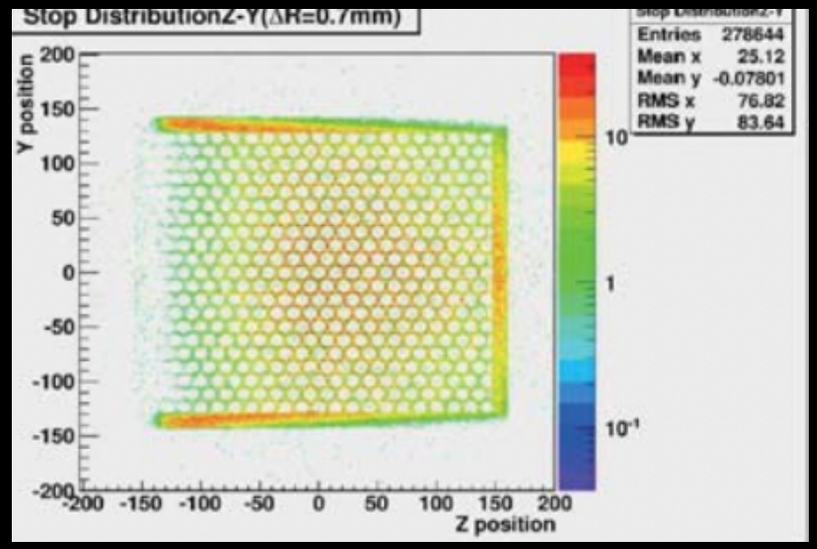
Muon polarimeter



Muon polarimeter

- **I led the development from the design to manufacturing.**
- Principle: positrons tend to be emitted in muon spin direction (due to helicity conservation)
- Requirement: sufficient material to stop incident muons while tracking positrons to determine the positron emission angle.
- Internal structure optimized with GEANT4 simulation.
- A5052 (aluminum alloy) was selected as a material after μSR testing.
- Assembly was performed at REPIC. Beam testing at TRIUMF.

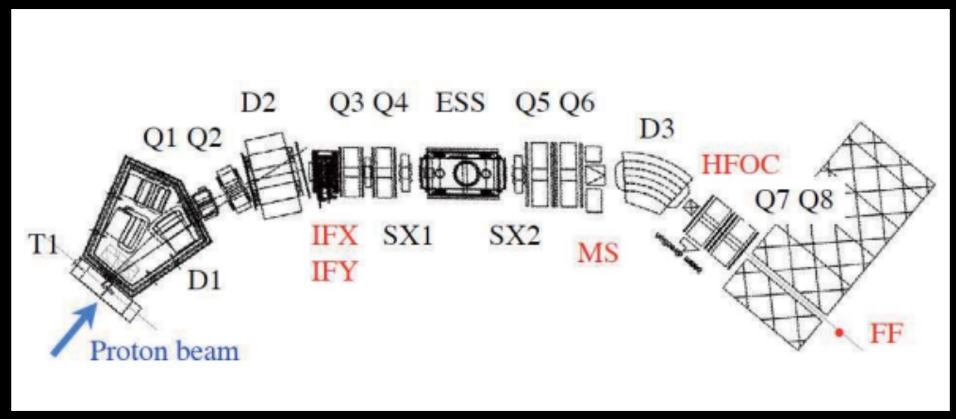


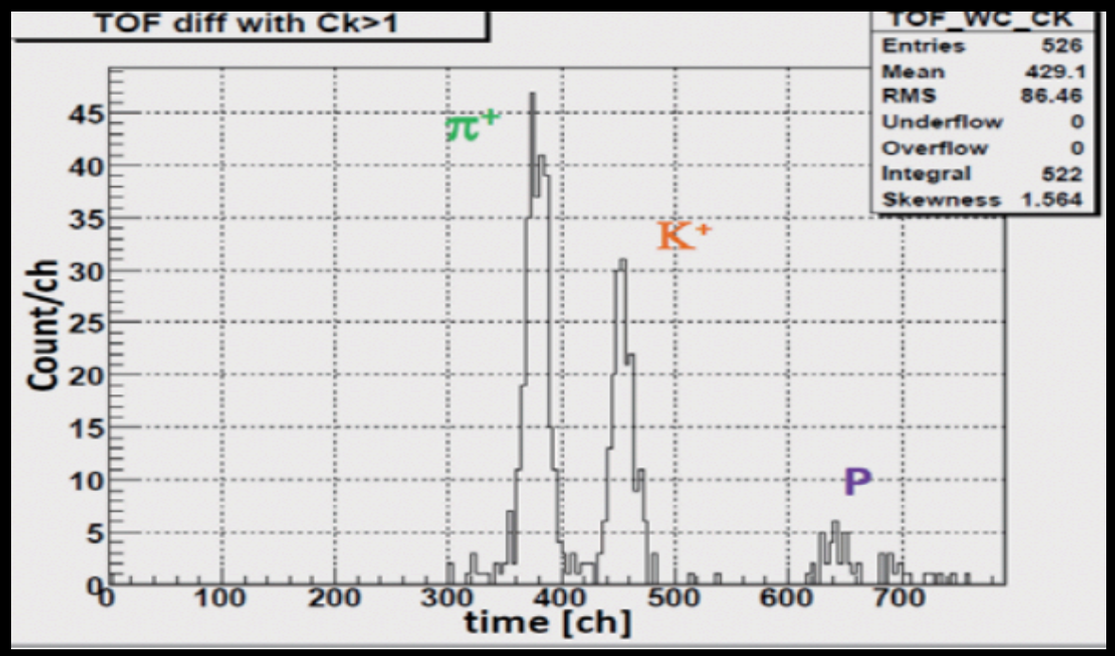


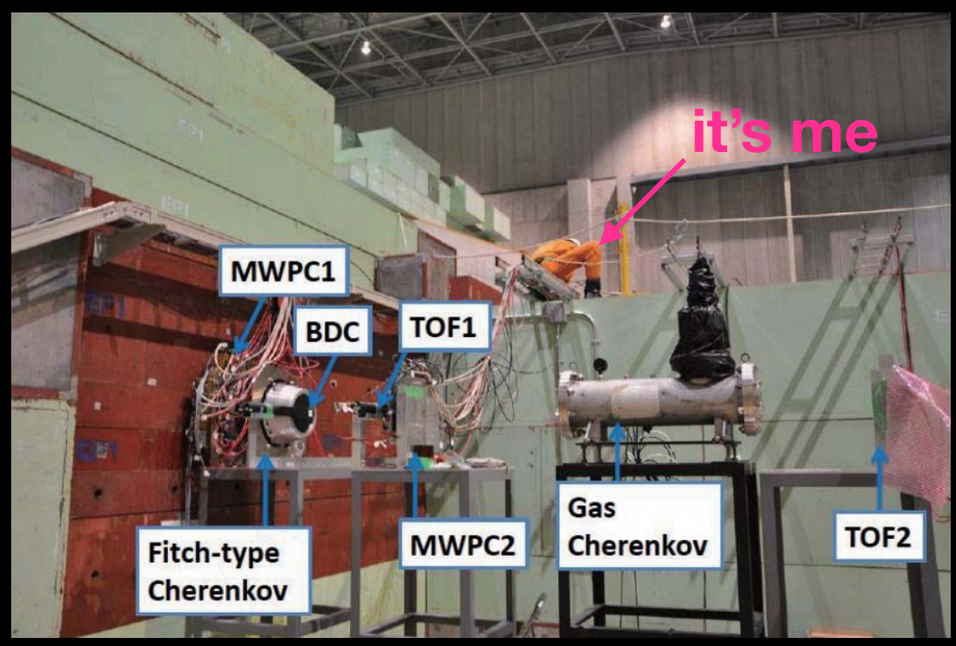
https://www.icepp.s.u-tokyo.ac.jp/papers/ps/thesis/master/kyoshihara_mthesis.pdf

Beamline commissioning at J-PARC

- The purity of kaons (against pions) was measured by utilizing various detectors (e.g. Cherenkov counters, MWPCs, TOFs)
- **I led the effort for the beam channel construction, installation and operation of the detectors and quadrupole magnets.**
- ESS (Electrostatic separator) is a key component for K/π separation.
- Trigger logic for various particles prepared for users.



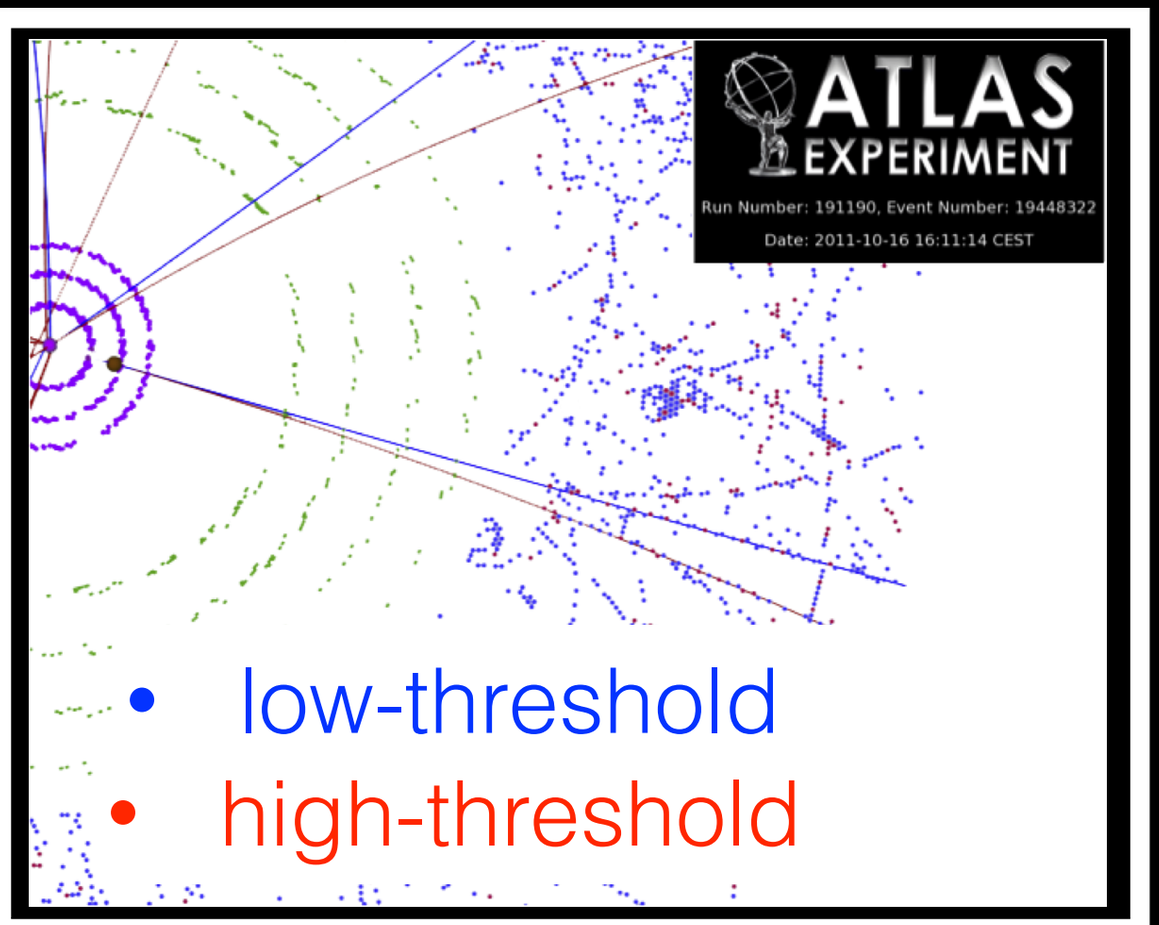


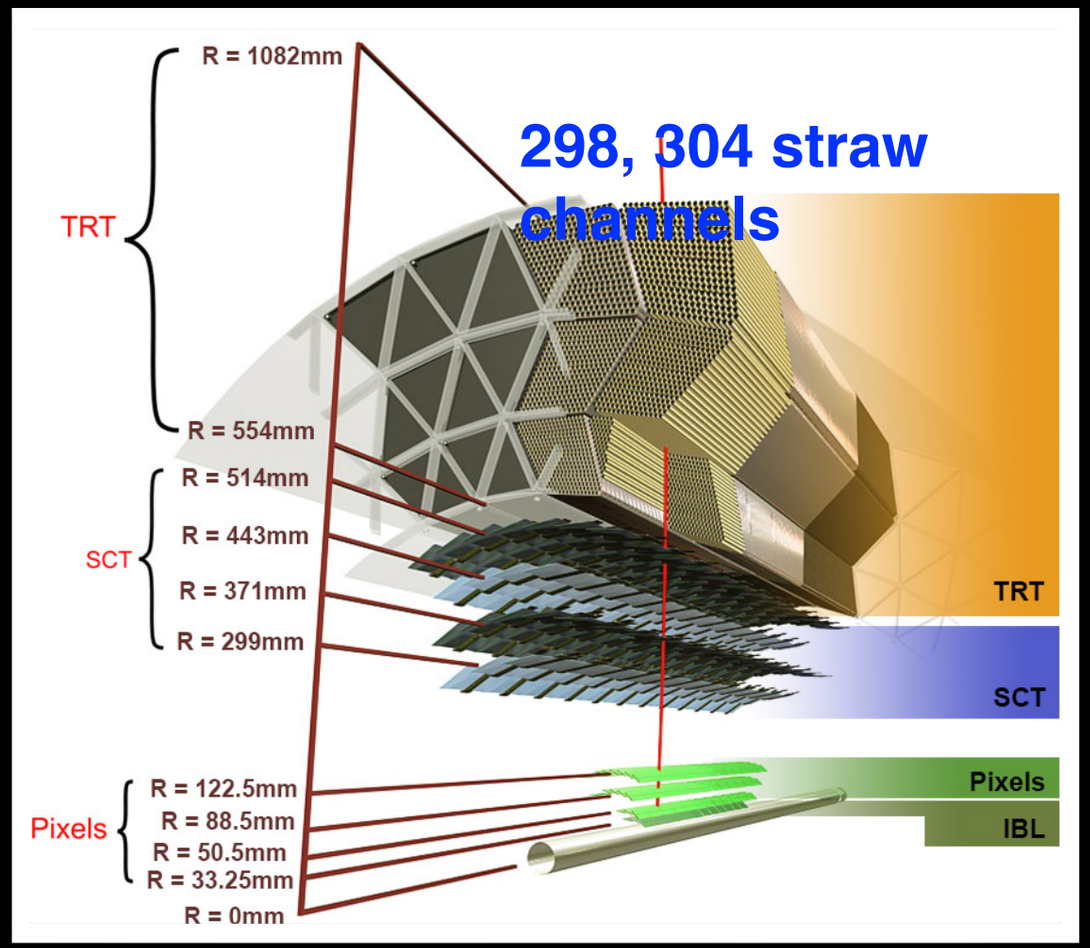


LHC-ATLAS TRT

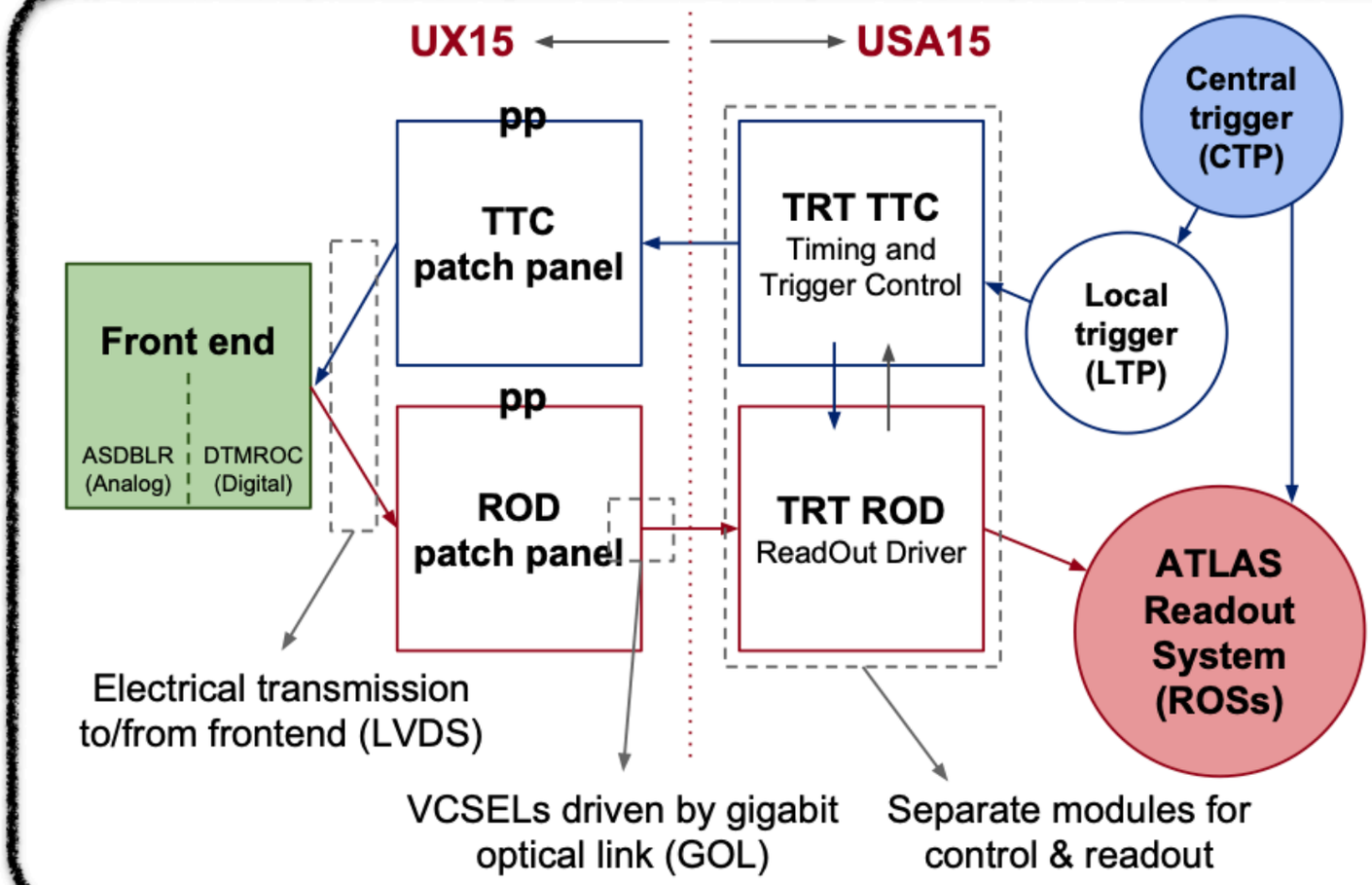
Transition Radiation Tracker

- TRT is a straw-tube tracker ($Xe+CO_2$), providing an **electron identification** (ID) against hadrons using transition radiation ($\beta\gamma \sim 1000$).
- TRT employs low threshold for tracking and high threshold for electron ID. Position resolution: <150 μm





TRT DAQ



TRT DAQ team in USA15

- On-detector FE ASIC (ASDBLR and DTMROC) communicates with PPs via electrical transmission (LVDS)
- ROD and TTC (VME) communicate with the PPs via optical links. ROD eventually sends data to the ATLAS central ROS.

Readout upgrade

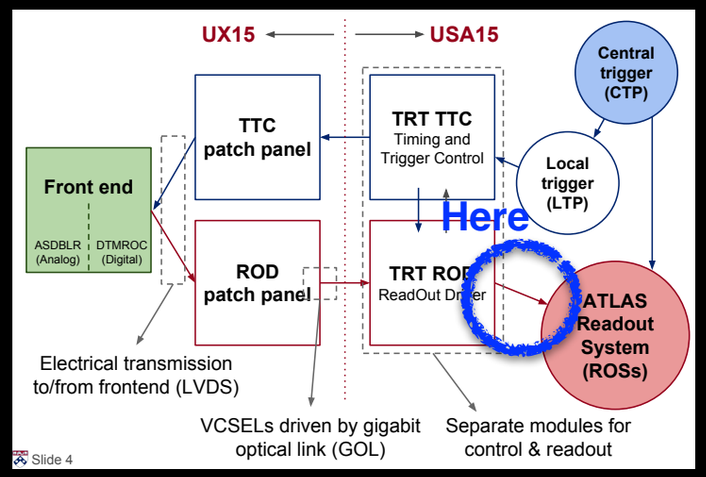
- As the luminosity increases (twice as high as designed peak luminosity as of 2018), we were forced to increase the S-Link bandwidth (data sending out to ROS):
  - **S-Link card (on ROD) upgrade** — 192 boards in total
  - Re-optimization of hash table and data compression.

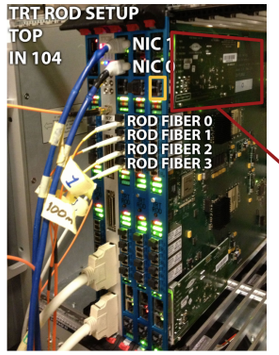
S-Link card upgrade

Clock speed: 100 →120MHz

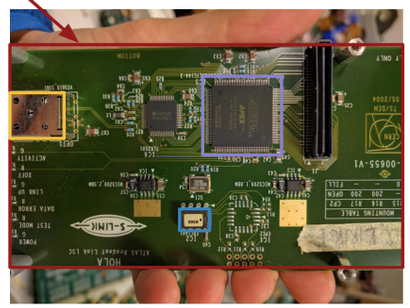
FPGA: 2.0 Gbps → 2.5 Gbps,

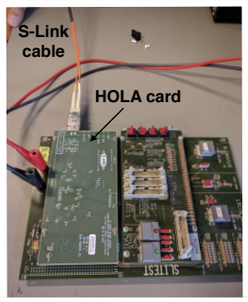
allowing for <μ>~60-65 at L1~100kHz

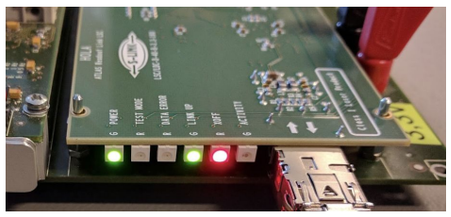




- S-Link transciever (SFP)
- HOLA Card
  - FPGA
  - Crystal



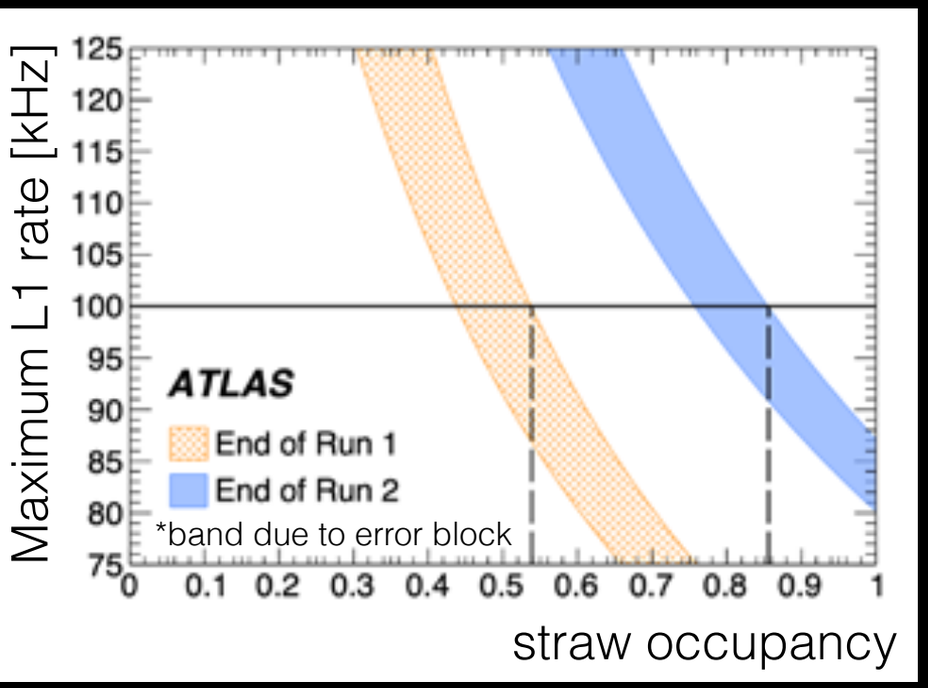




Data compression

Huffman encoding: For patterns that occur frequently, short bit stream is assigned. While for less frequent patterns, longer bit stream is assigned such that the total number of bits can be minimized.

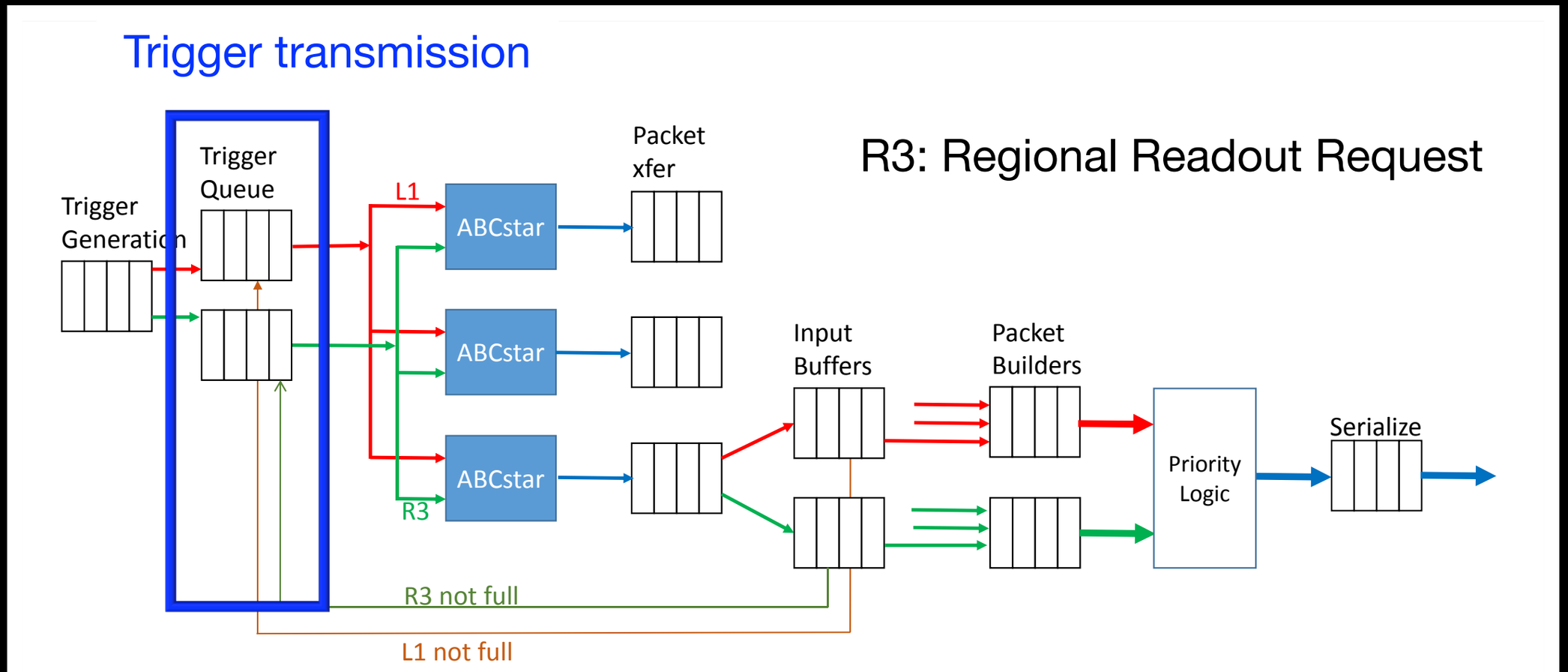
Alphabet	Probability	Tree of code	Code word
A	0.5		1
B	0.2		01
C	0.1		0011
D	0.08		0010
E	0.05		0001
F	0.04		00001
G	0.02		000001
H	0.01		000000



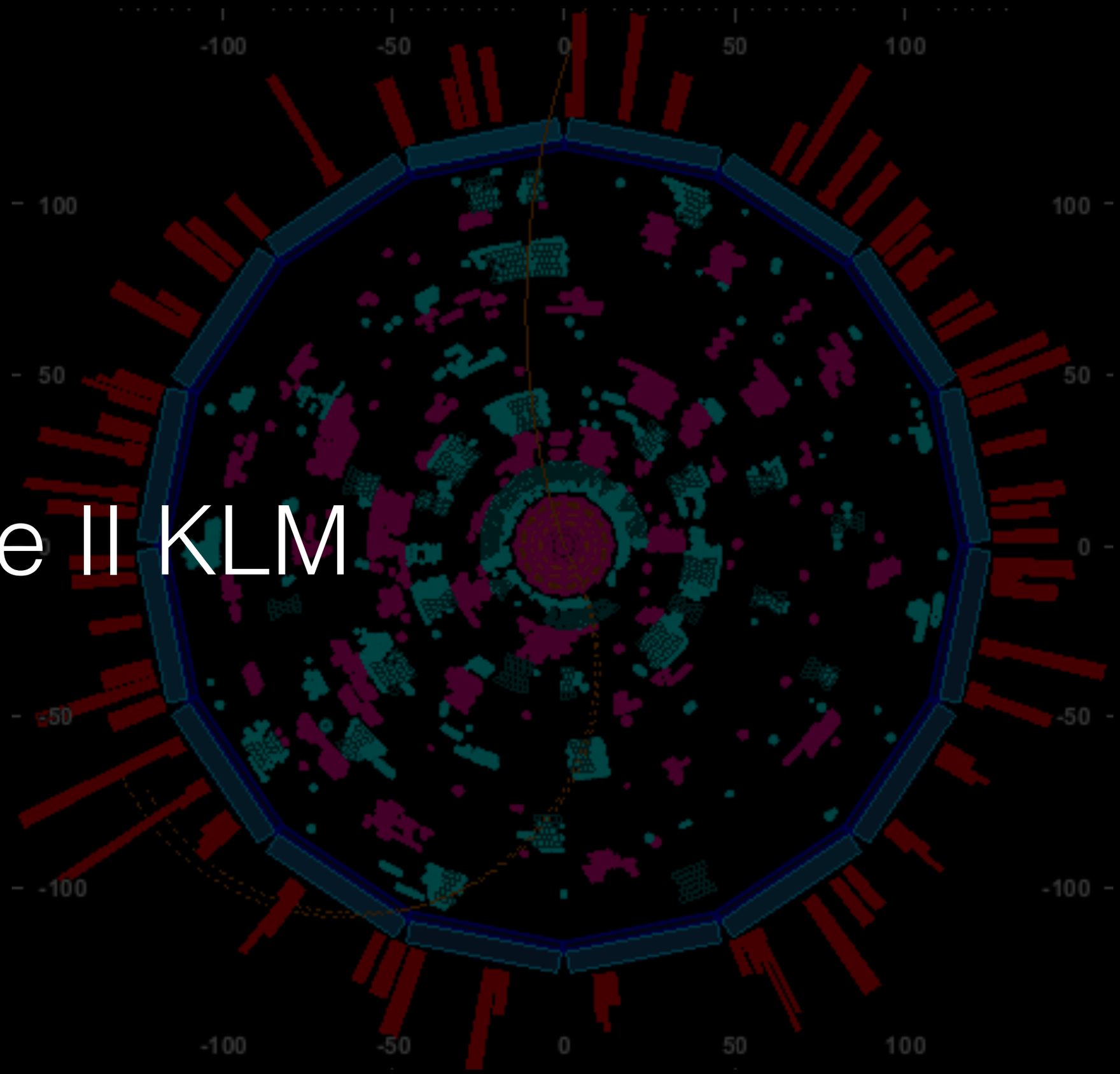
As the bit pattern depends on <μ>, the encode was optimized as <μ> changes such that the data compression is always effective. The most frequent patterns are saved on the look-up table to be able to convert immediately.

TRT → Silicon Strip detector

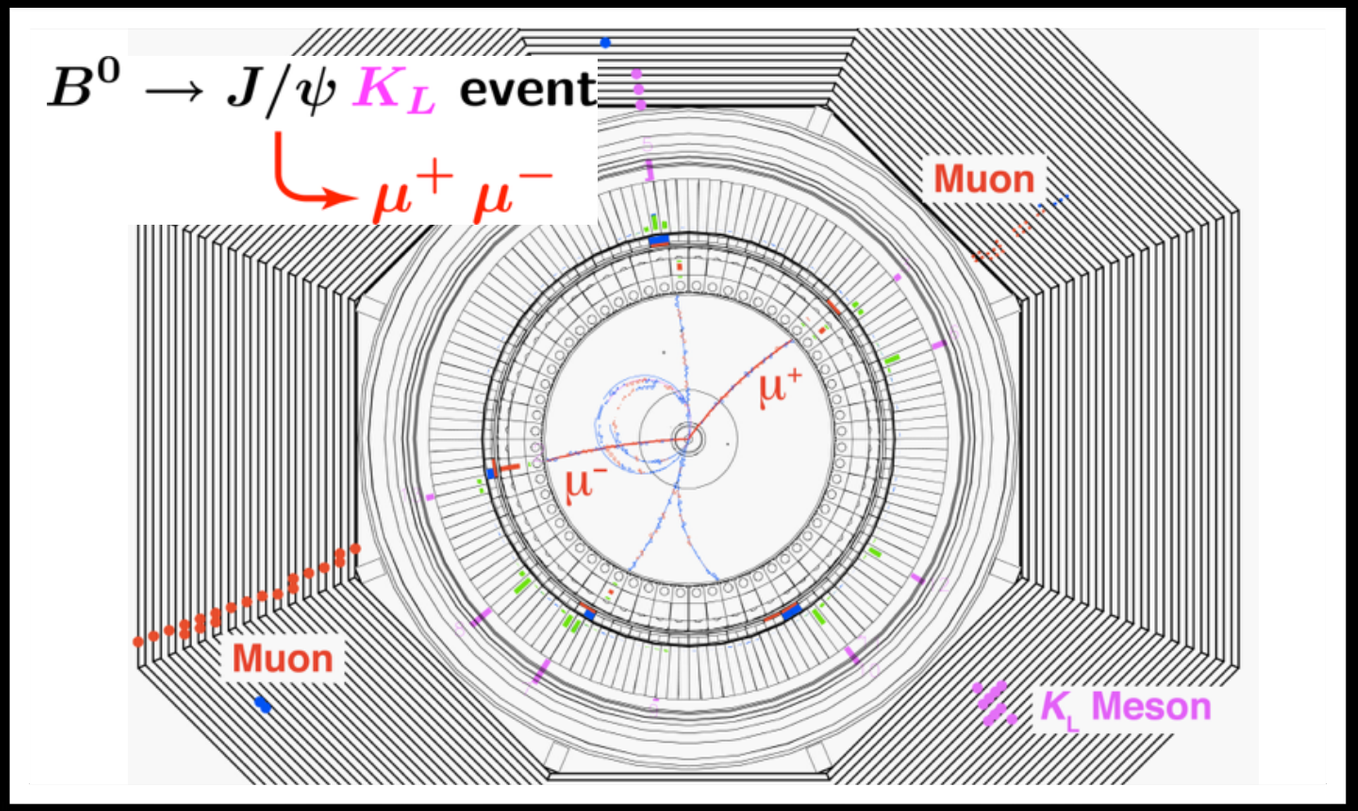
- TRT will be replaced by silicon strip detector for HL-LHC.
- I have studied behavioral modeling of the chips in hardware simulation (verilog), implementing functionalities and optimizing the data packet structure for the ABC and HCC to accommodate trigger rate and latency constraints.



Belle II KLM



KLM

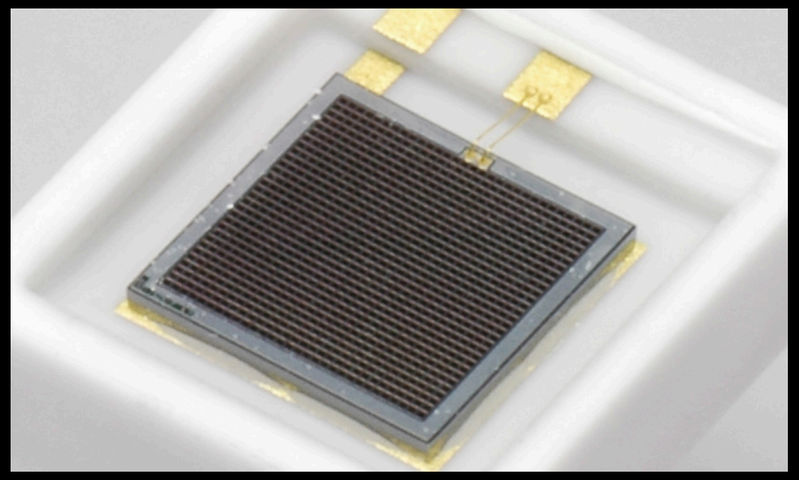


Barrel:
2 (scintillators) + 13 RPC

Endcap:
Bwd: 12 (scintillators)
+ 2 (polyethylene)
Fwd: 14 (scintillators)

- KLM consists of RPC (or scintillator) and absorber material (iron). Iron also works as return yoke.
- K_L^0 s cause hadronic shower due to strong interaction in material.
- Ionization loss when muons pass through. Pions have large multiple scattering.

Scintillator readout



40x40 pixels in an area of 1 × 1 mm^2

- **HAMAMATSU MPPC (SiPM)** operating in Geiger mode is used as scintillator readout.

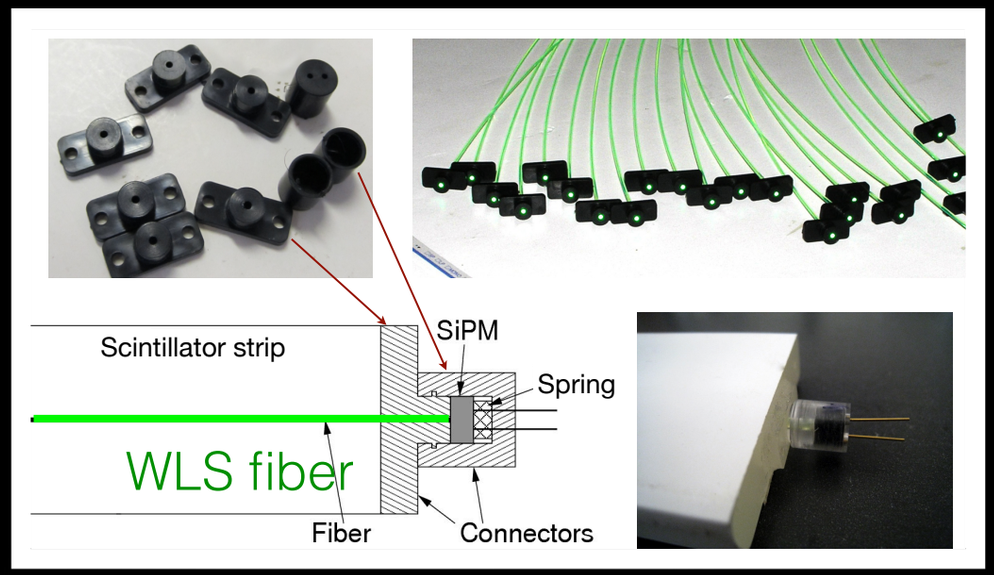
  Advantages

  - Radiation hard, Great time resolution (~10ps), Operational at magnetic field (up to ~4T), Low operational voltage (~75V)

  Drawbacks

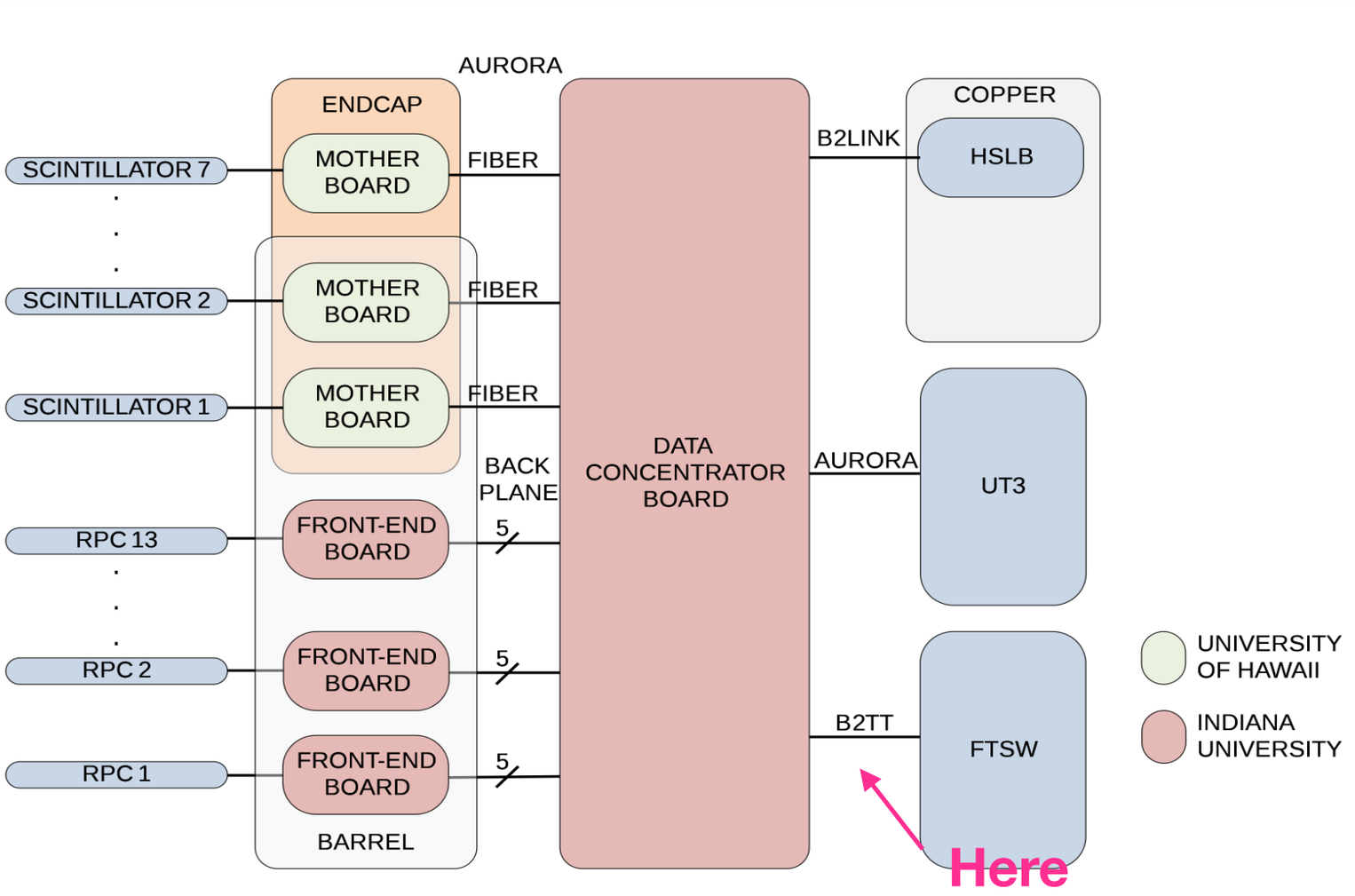
  - Relatively high dark current (~10^6Hz/mm^2). increases with radiation damage. Sensitive to ambient temperature

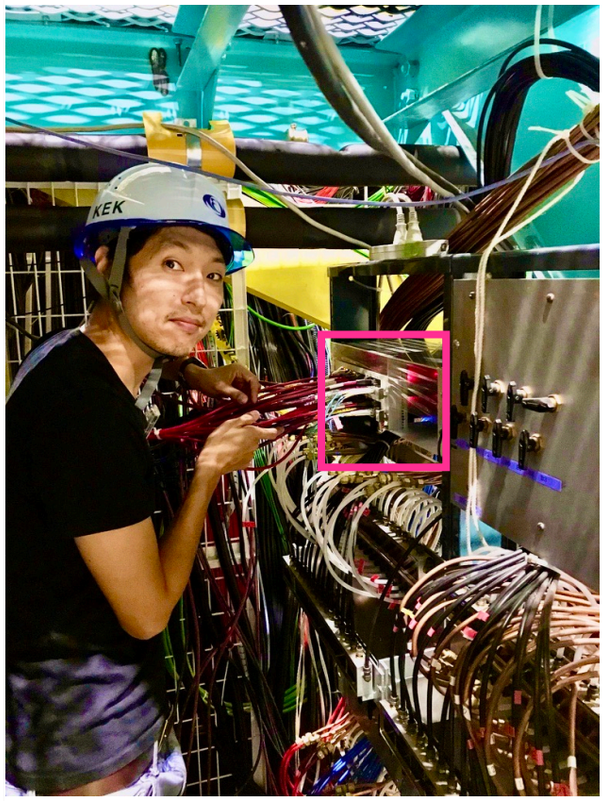
- TARGETX ASIC chip (Gary Varner) having the capability of wave form sampling



KLM operation

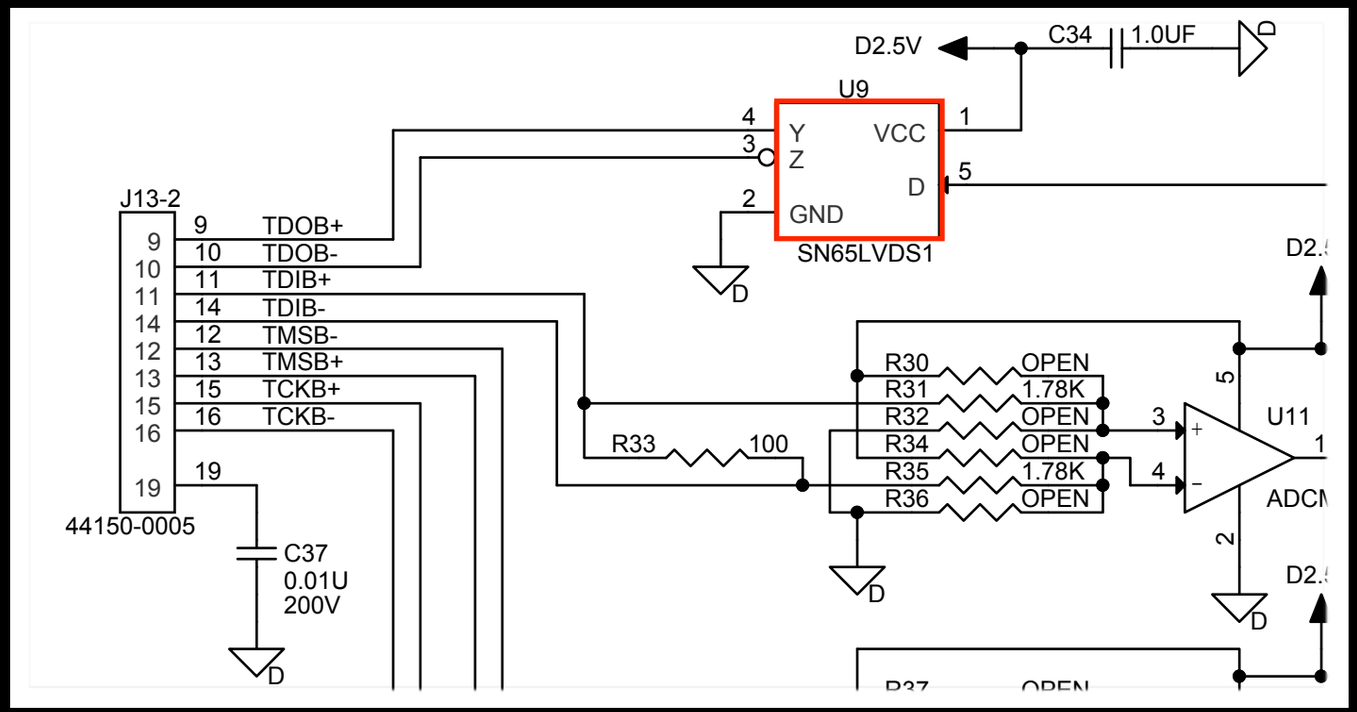
- In 2020, frequent B2TT errors (ttlost) occurred due to signal degradation with 20 m long CAT7 cable. I coordinated the local work for re-arrangement of hardwares to shorten the cable length and fix frequent errors due to B2TT.

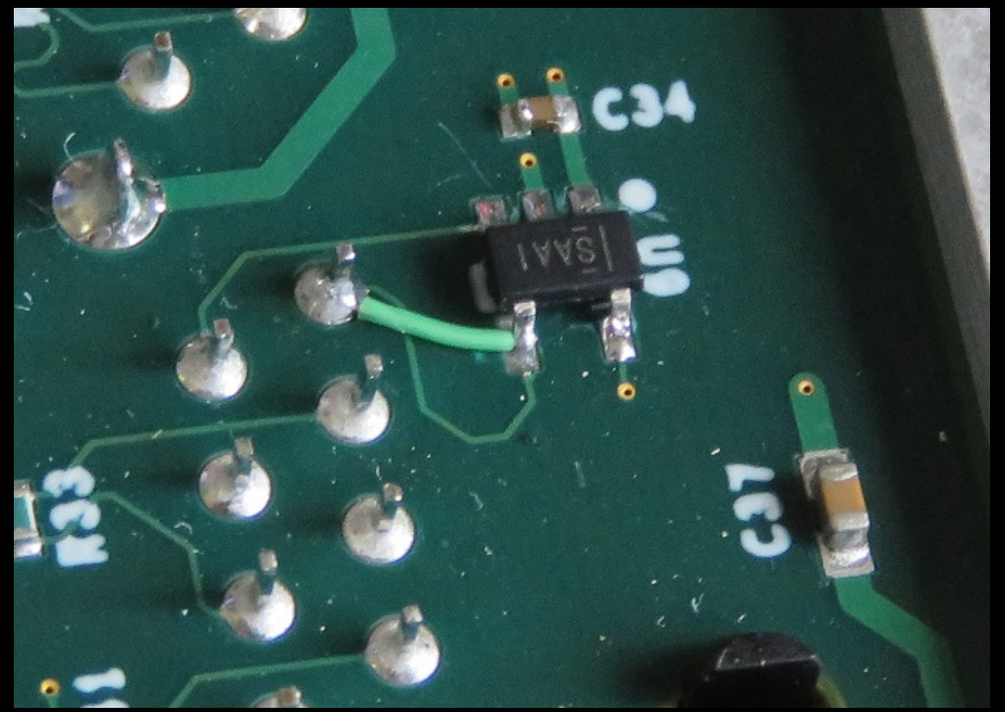




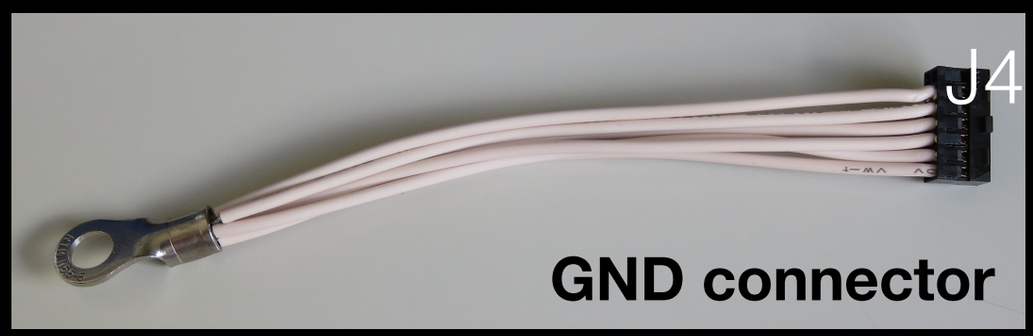
Newly installed mini-VME crate for FTSW modules

Data concentrator repair



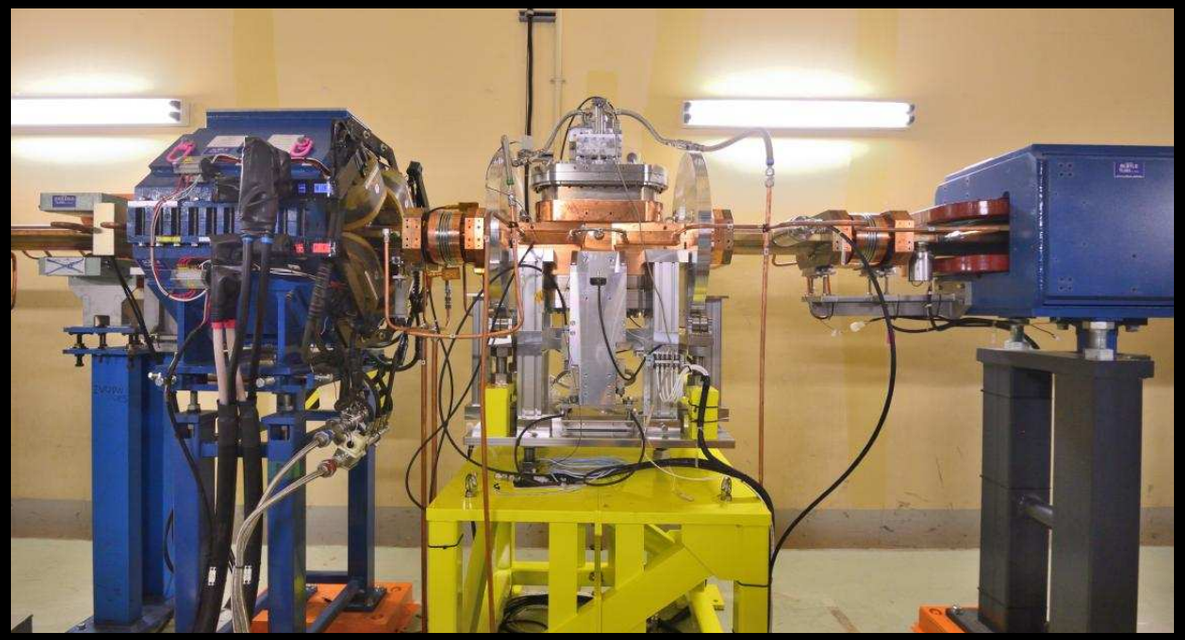


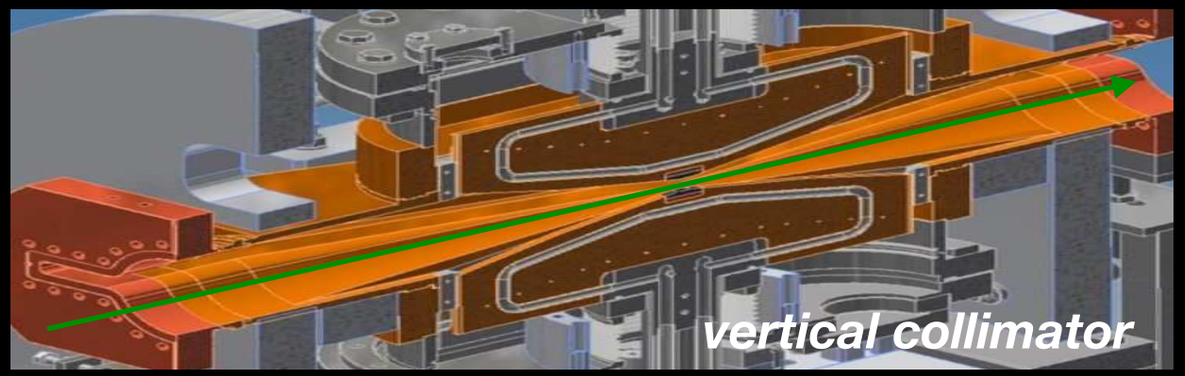
- VME backplane GND was not sufficient and LVDS transmitter chip for JTAG/B2TT was broken due to electrical surge needing chip replacement.
- I led the replacement work and fix the backplane GND with special GND cable.

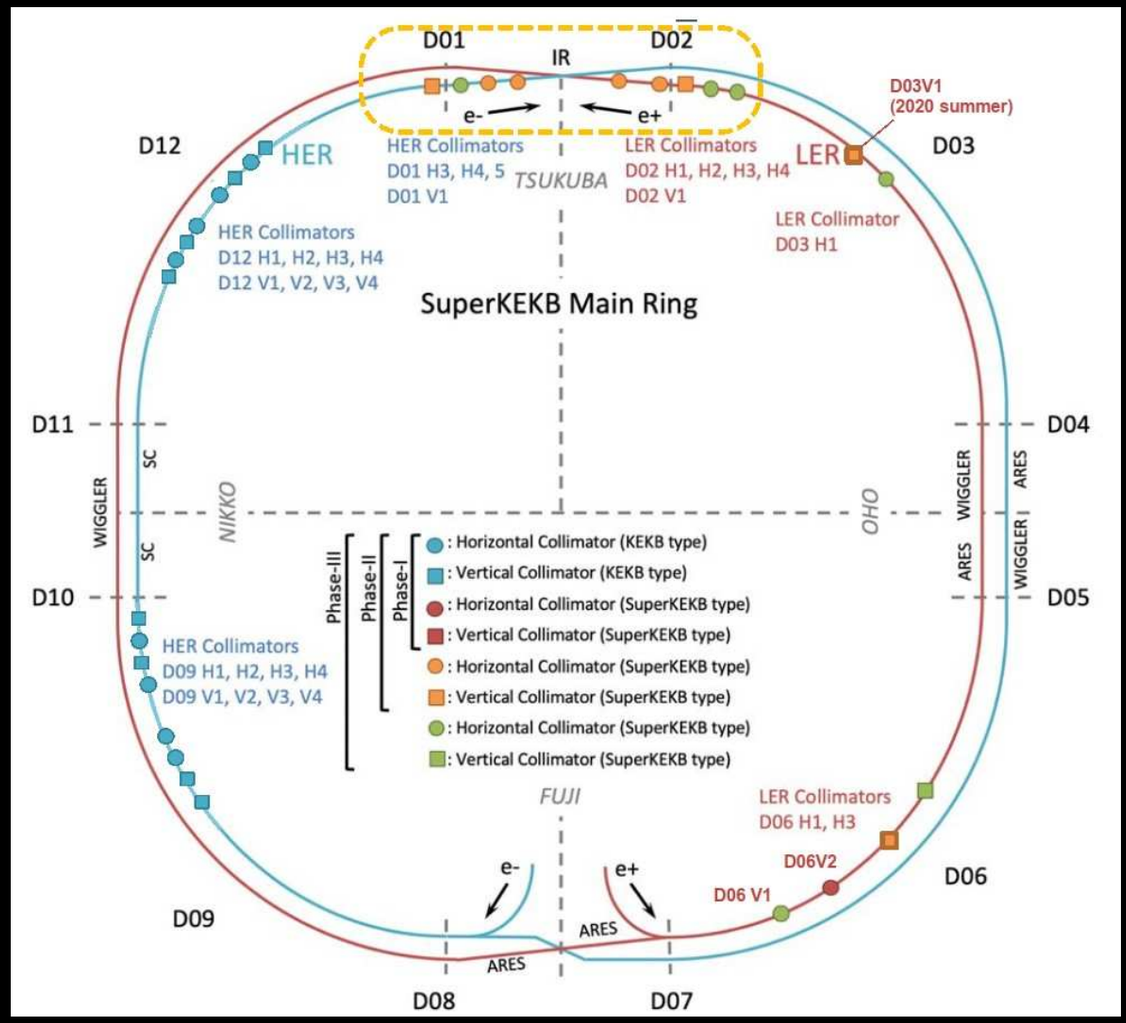


Sudden Beam Loss

Collimator system

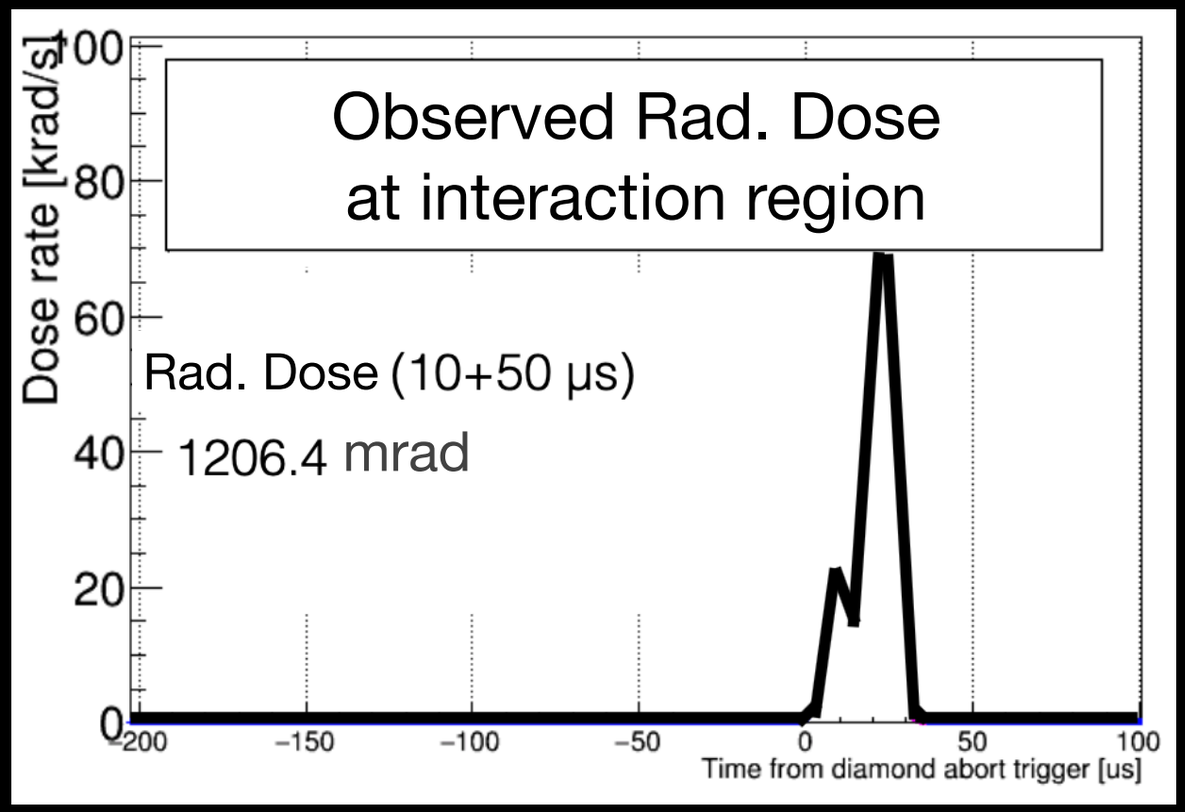


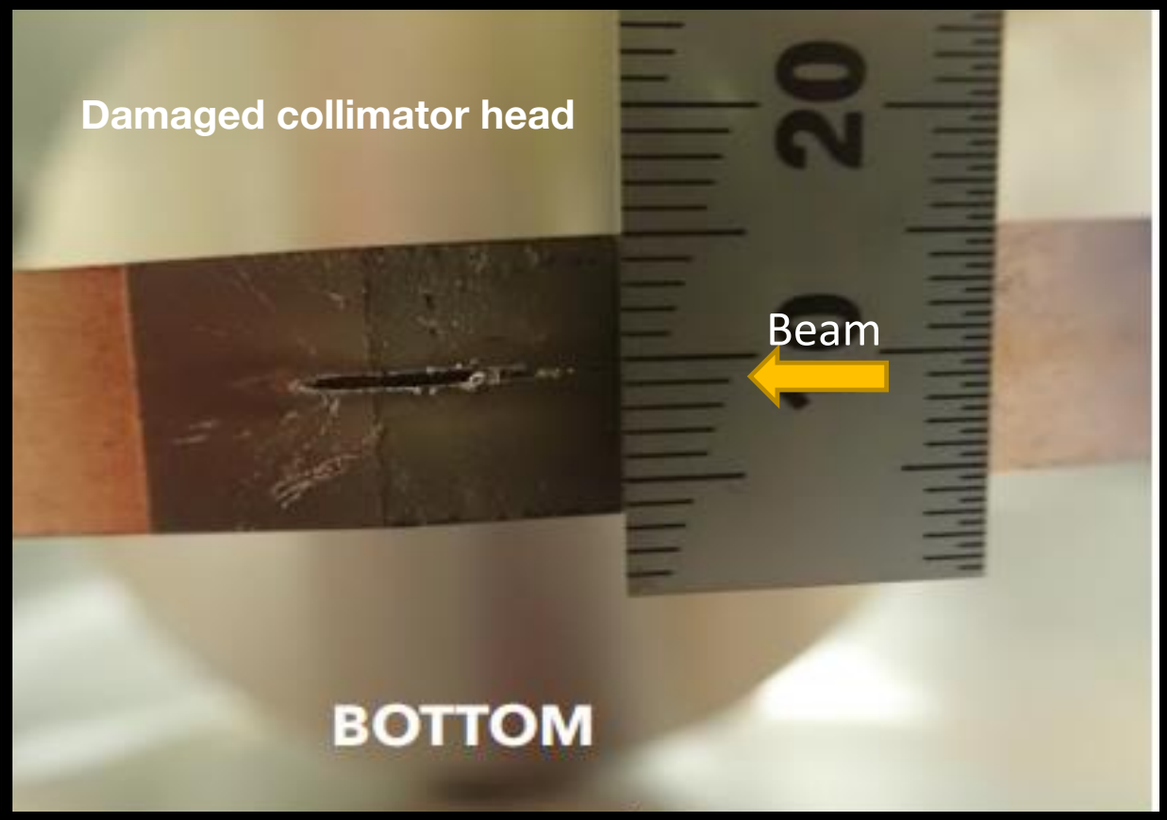




- Collimators are used to reduce the beam background.
- I have been in charge of **collimator operation and BKG control** since 2020. I also give personal training to those who take a shift.

Sudden beam loss





Stored beam is lost in only a few turns for unknown reasons.
This sometimes occurs in association with a QCS (final focus magnet) quench damaging collimator head or Belle II detector.

→ **Major limitation in machine operation**

How to tackle SBL?

I initiated the beam diagnostics and beam abort upgrade, forming a joint team with accelerator experts.

1. **Beam diagnostics** (5 students from Europe, Japan, China)
   - Identifying the location of initial beam loss
2. **Faster beam abort** (1 student from Japan)
   - Minimizing the risk of damaging hardware from SBL
3. **Verification of fireball hypothesis** (1 student from US)
   - Fireball hypothesis that can explains SBL mechanism is verified with acoustic sensors

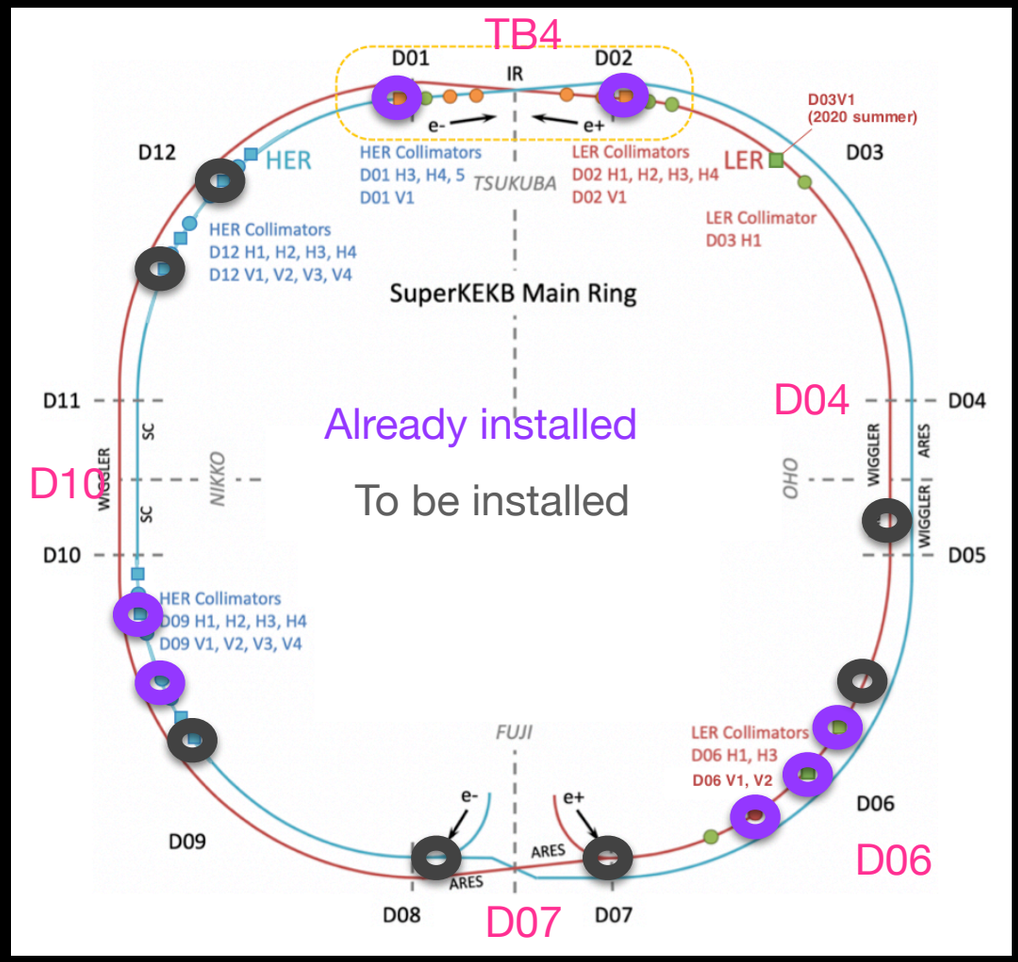
In addition, an international task force (involving CERN, SLAC, IHEP, etc) was created to tackle SBL issue and share knowledges with other labs.

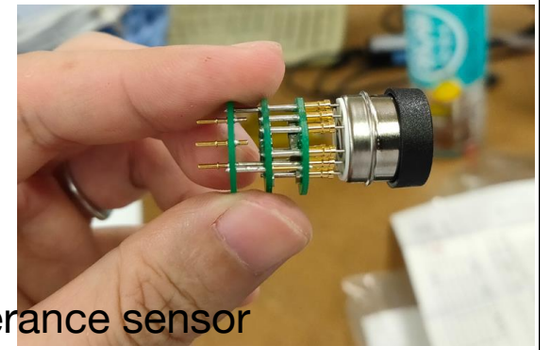
→ Good opportunity to establish a global collaboration scheme in accelerator at KEK!

Beam diagnostic system

Adding more “eyes” to find the hint for SBL!

- Fast loss monitors (CsI+PMT, EMT) installed step-by-step around collimator locations (i.e. smallest aperture in the ring) since summer 2021.



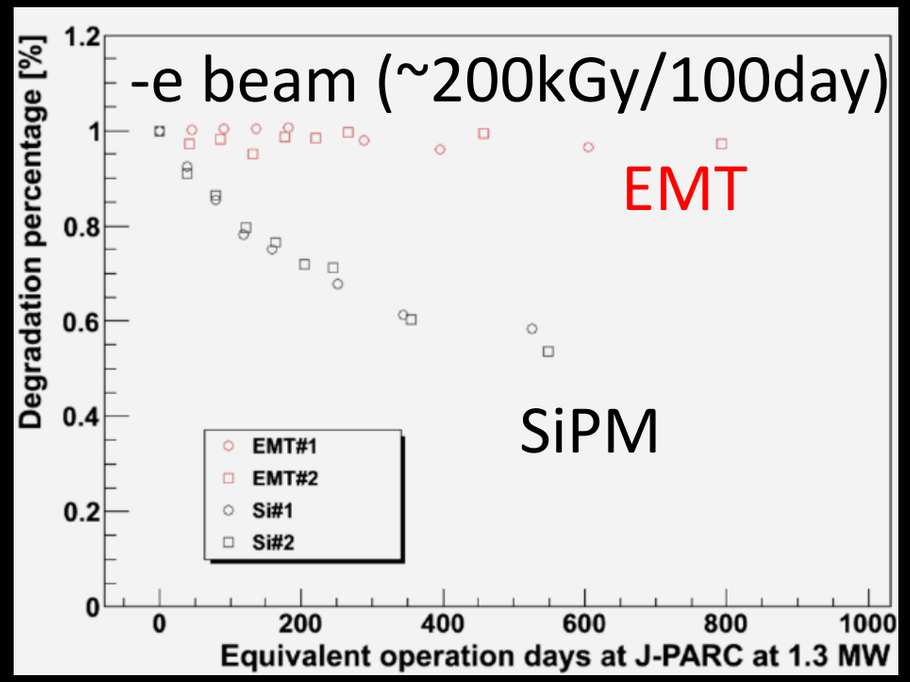


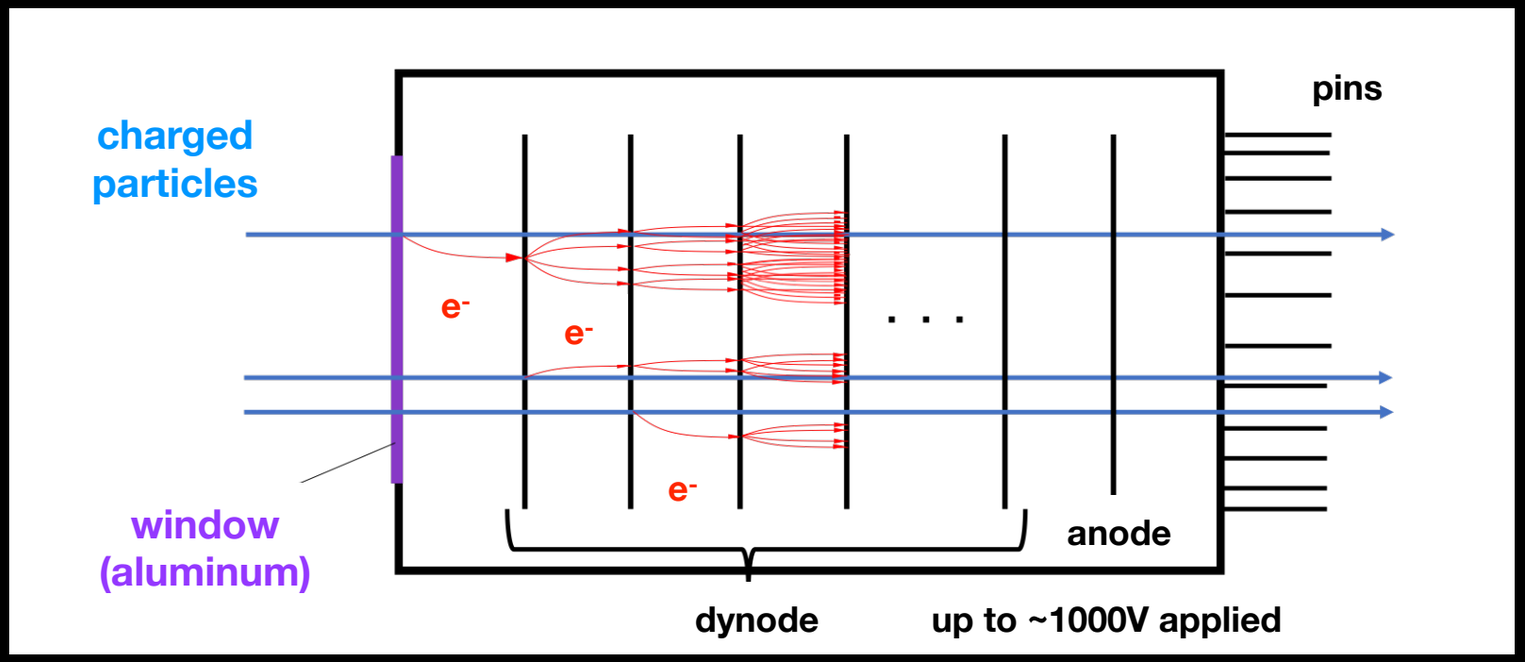
high radiation tolerance sensor

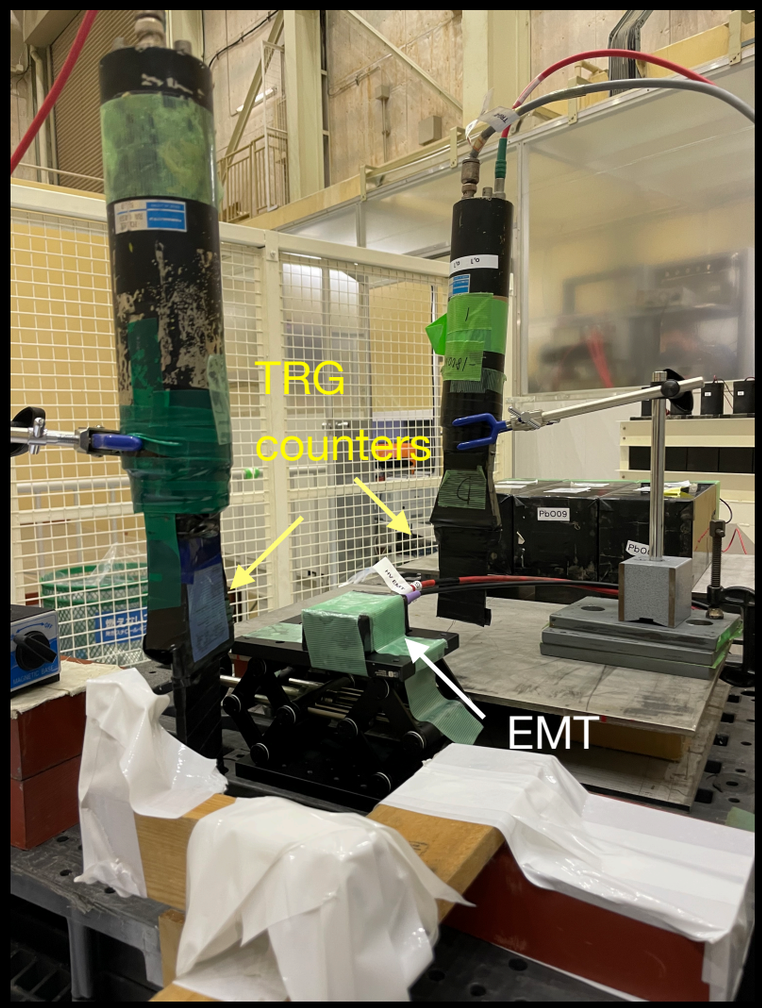
- Working on adding more sensors to be a full scale system.
- White Rabbit (referred to as WR in the following slides) introduced as time sync system.

EMT

PMT (R9880U-110): Known as **radiation hard** sensor. Similar to PMT but photocathode vapored with aluminum, originally studied at T2K as muon beam monitors. arXiv:1805.07712

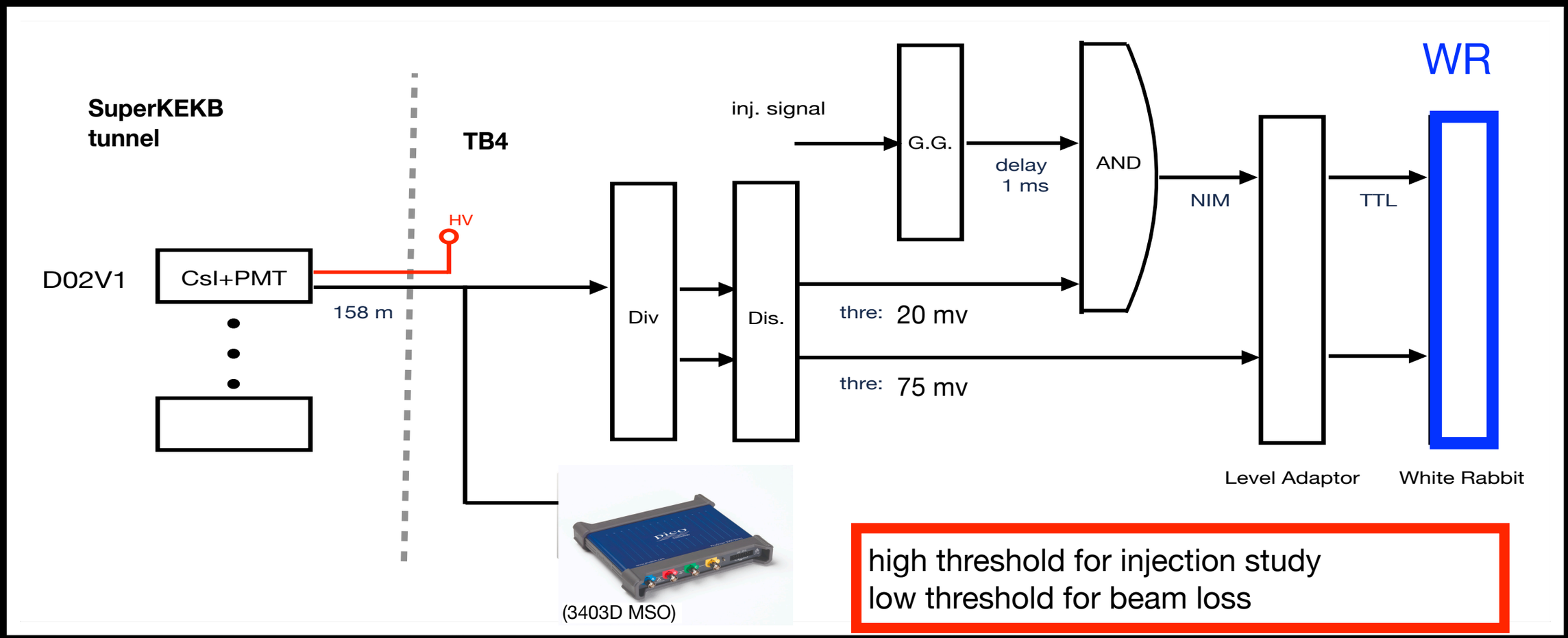






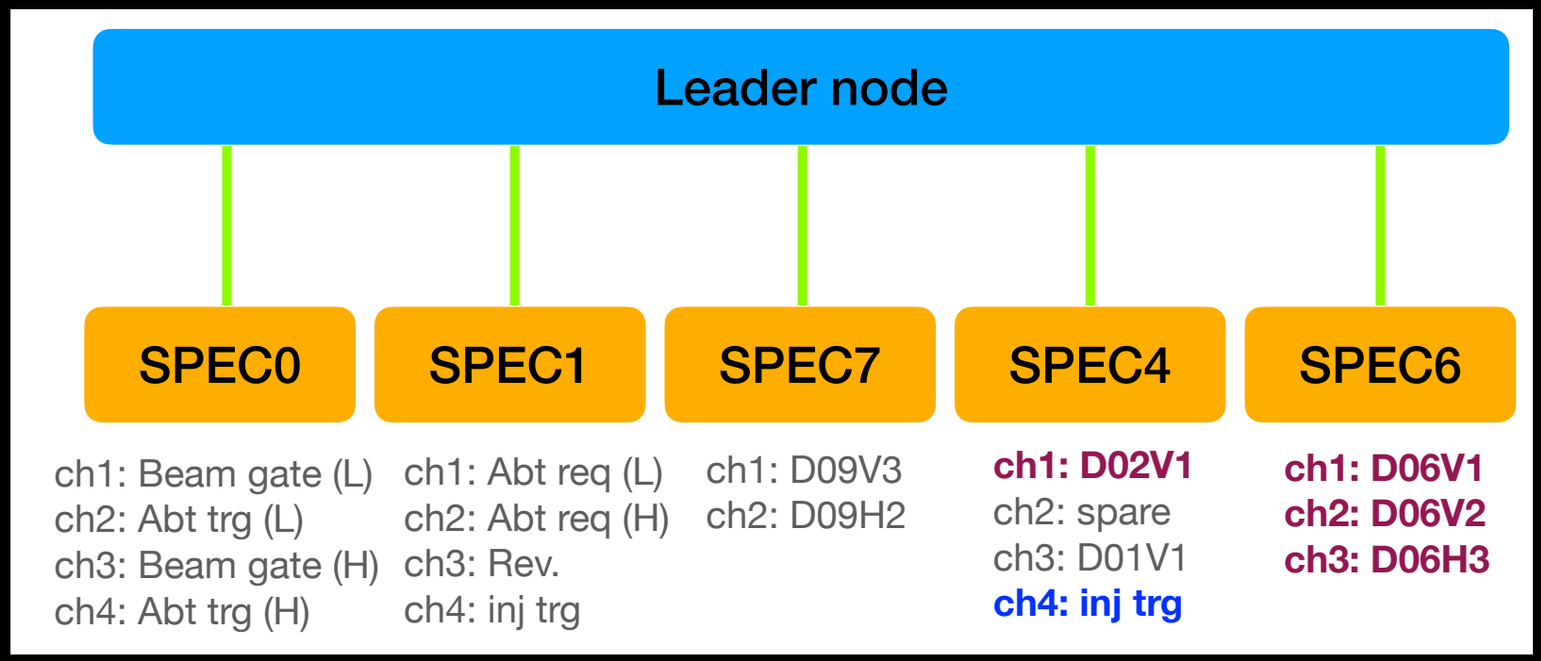
Beam test (3.5 GeV e^- beam) performed at KEK in Nov 2022 to evaluate the detection efficiency and gain curve.

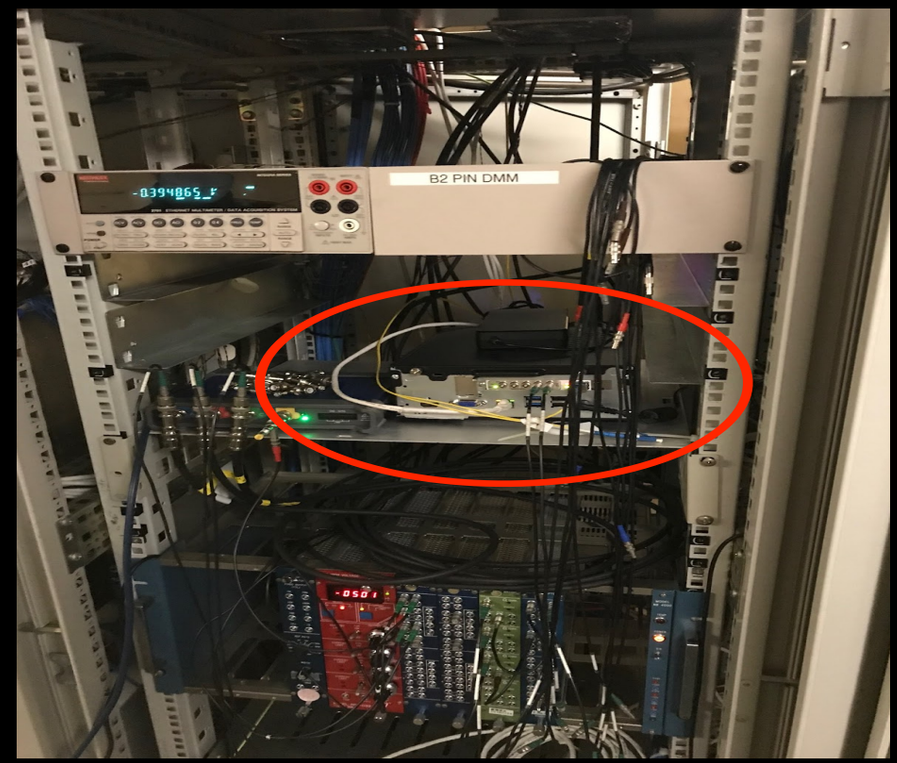
Readout system



- **WhiteRabbit (WR):**
  Distributed TDC system in sync with GPS. 125 MHz CLK sharing time stamps with other WR nodes.
- **Picoscope (USB oscilloscope):**
  Recording waveform w/ time window ±1ms wrt abort trigger timing.

WhiteRabbit

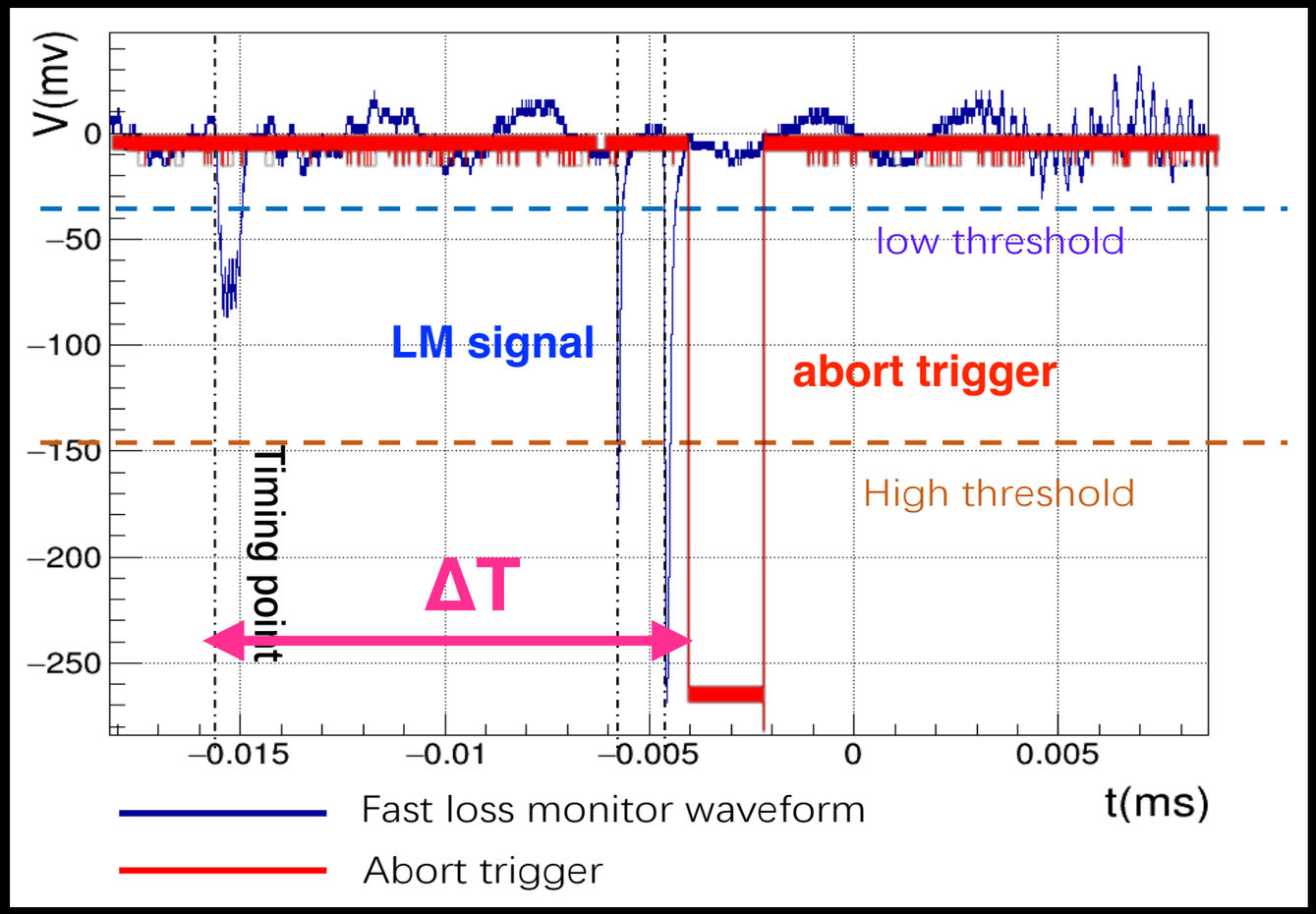


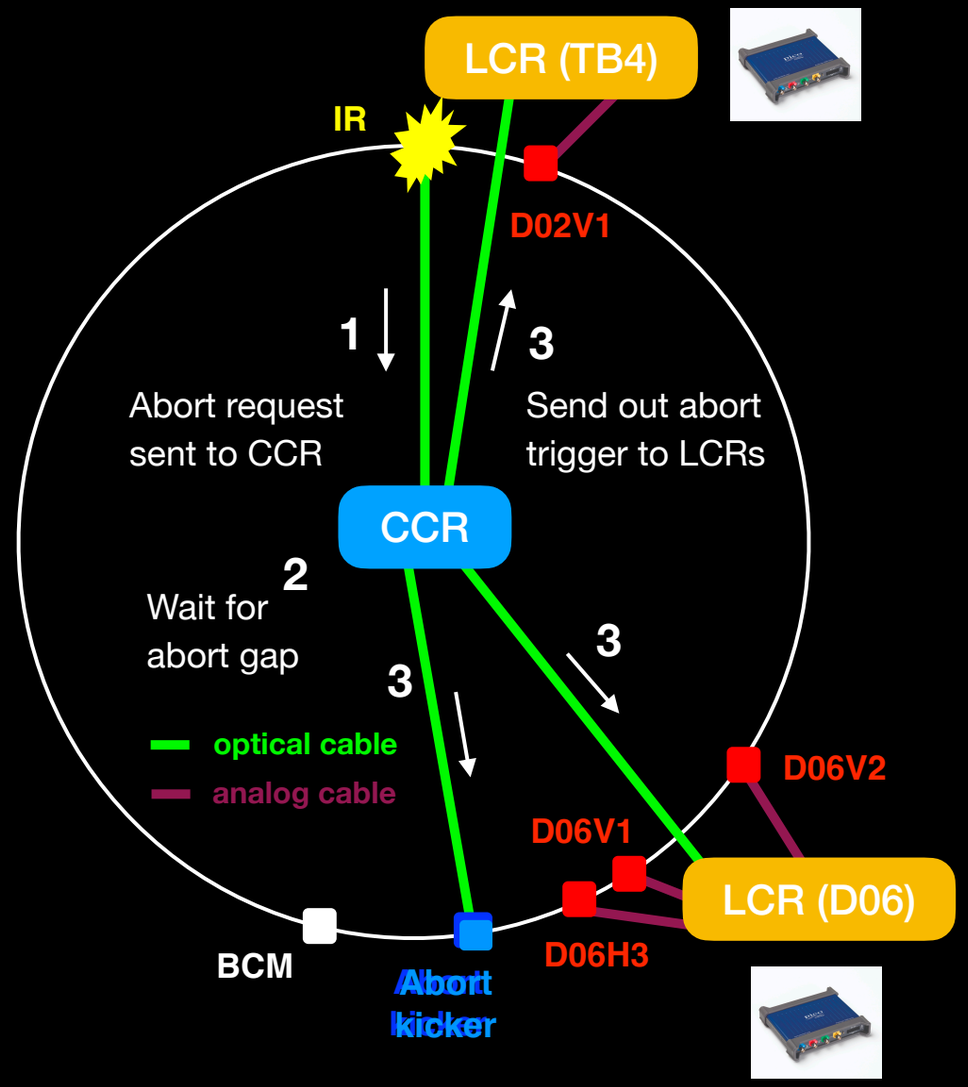


- White Rabbit (WR) is a time-synchronization system originally developed at CERN for LHC.
- FPGA clocks (125 MHz) in all modules are synchronized with 3-10 ps precision

- The system consists of leader (Master) module and follower nodes, sharing common timestamps with 8 ns accuracy.
- Bidirectional communication with a single optical cable.

ΔT measurement

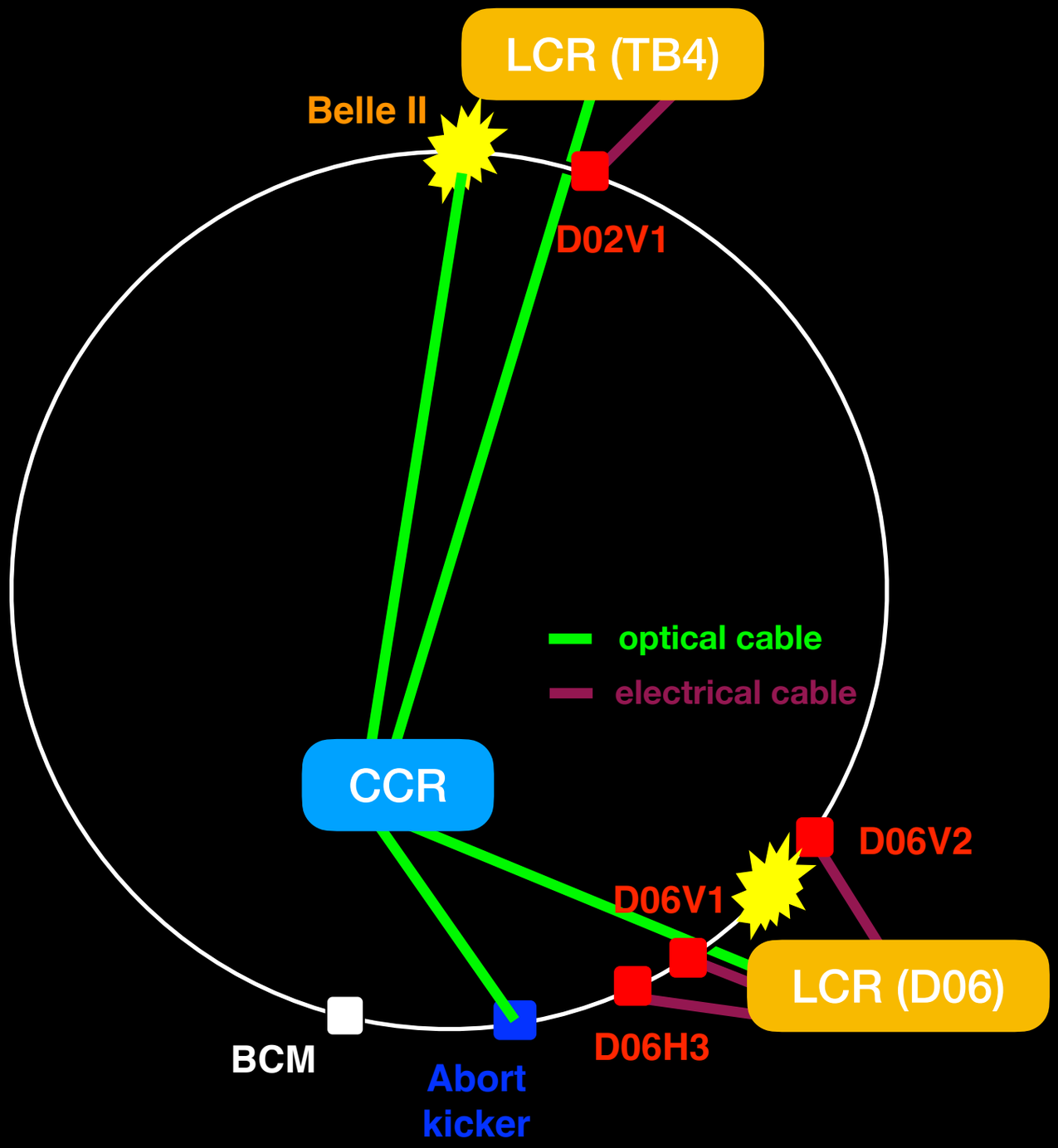




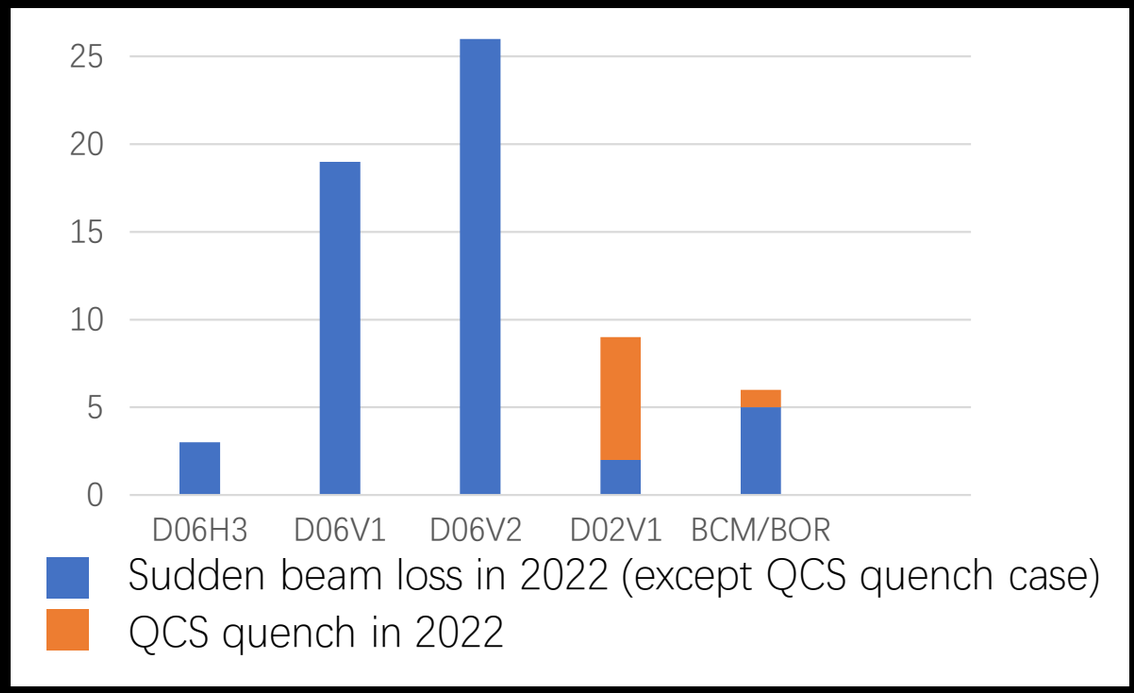
ΔT = T_{LM} - $T_{abort\ trigger}$ is measured at each sensor.

- T_{LM}: beam loss timing at each loss monitor (LM)
- $T_{abort\ trigger}$: abort trigger as a common time reference

Our findings

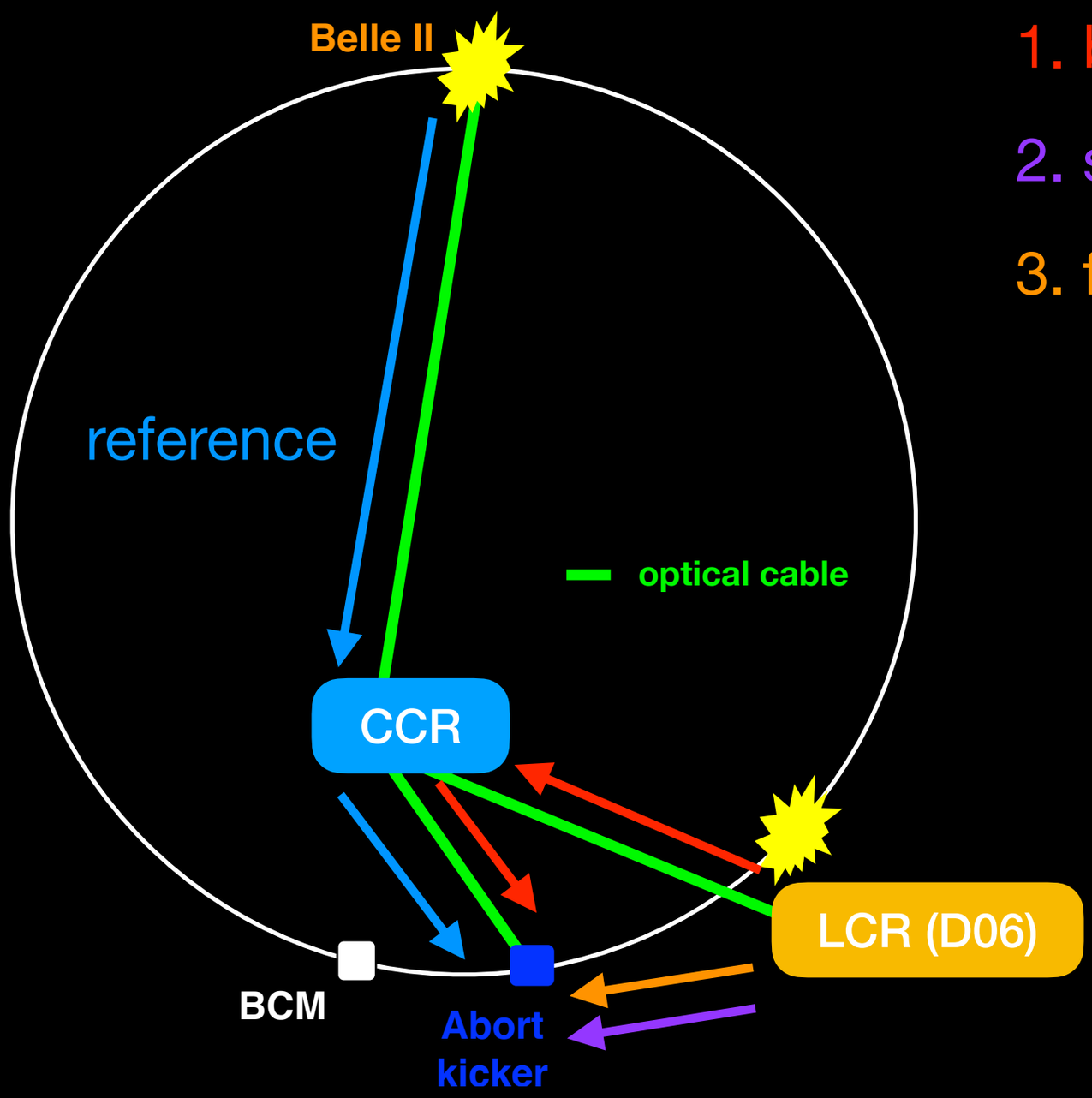


SBL events summary



Initial loss was mostly observed in the D06 section. However, the abort request was made by sensors near the Belle II

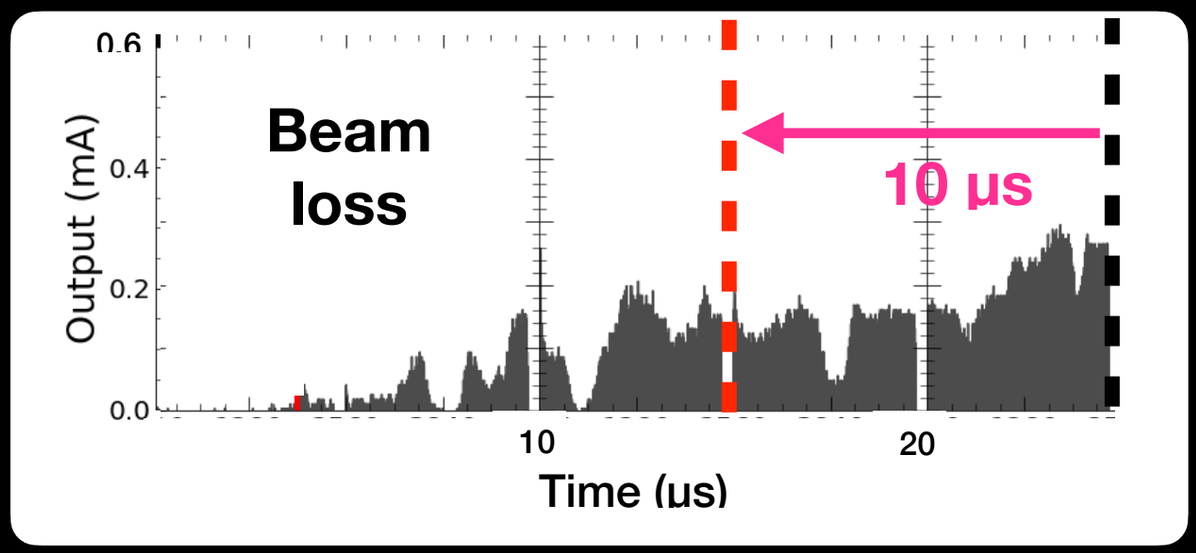
Toward faster beam abort



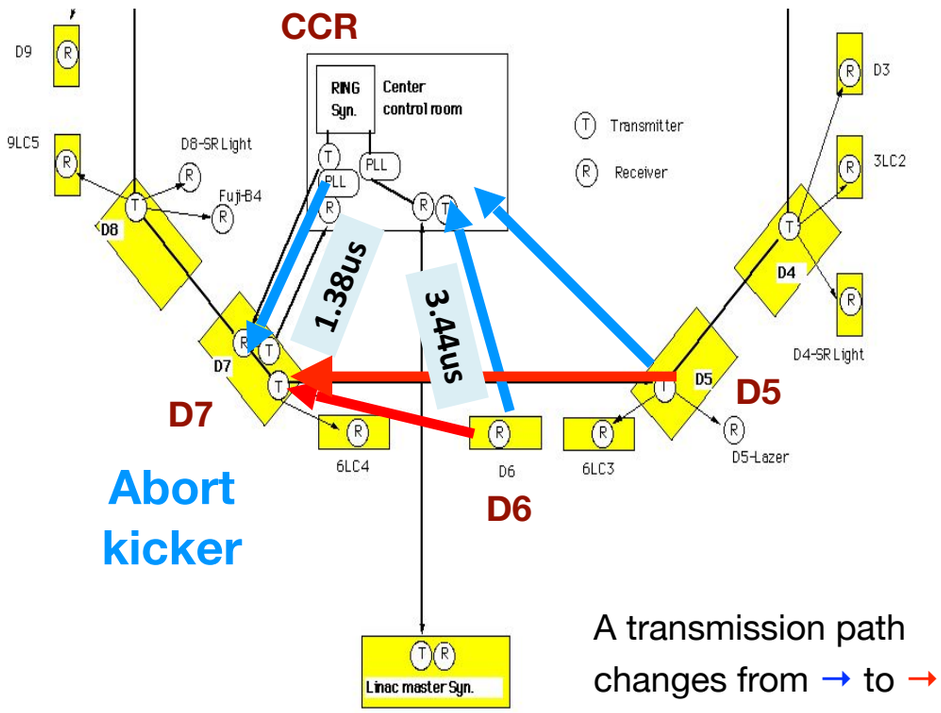
Can we improve the time by having:

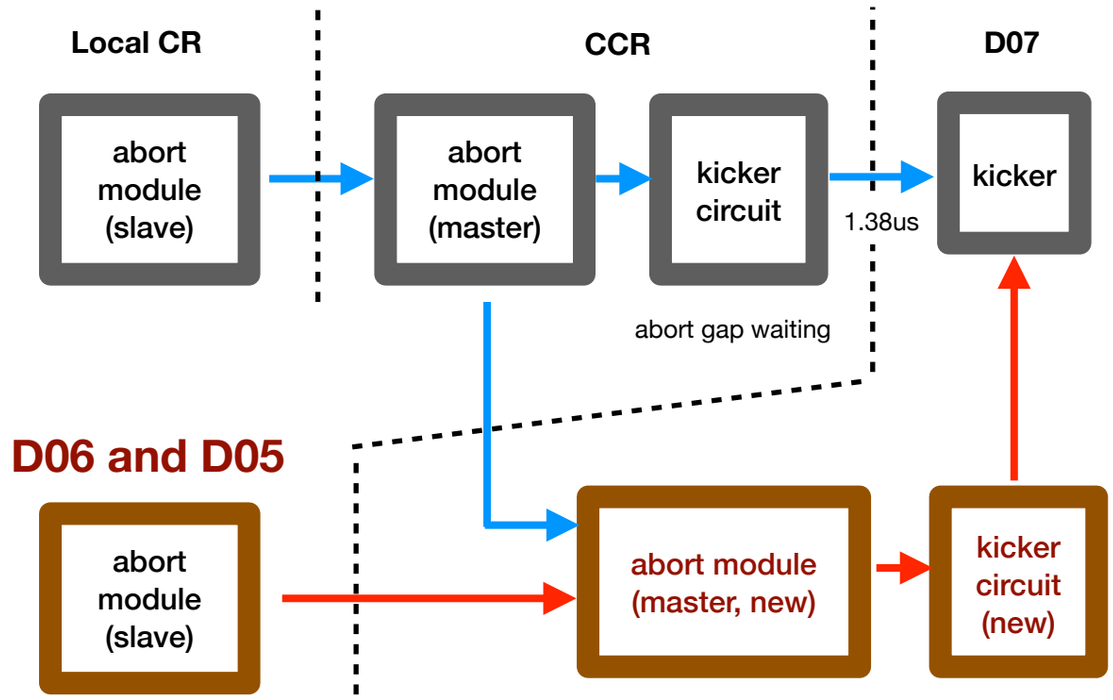
1. better sensor location
2. shorter transmission path
3. faster transmission

In 2022, we demonstrated that "better sensor location" actually gives 10 μs improvement.



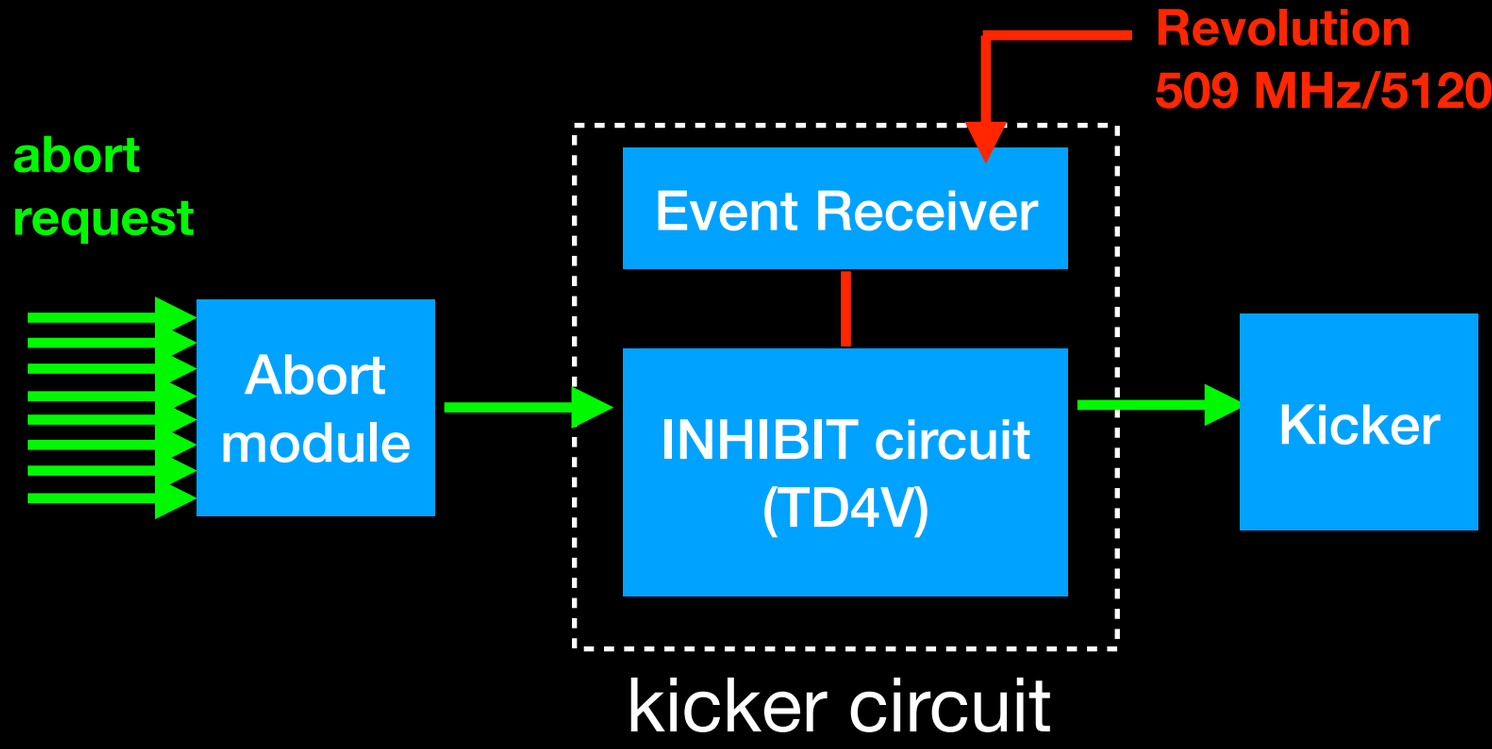
Modifications required for shorter path

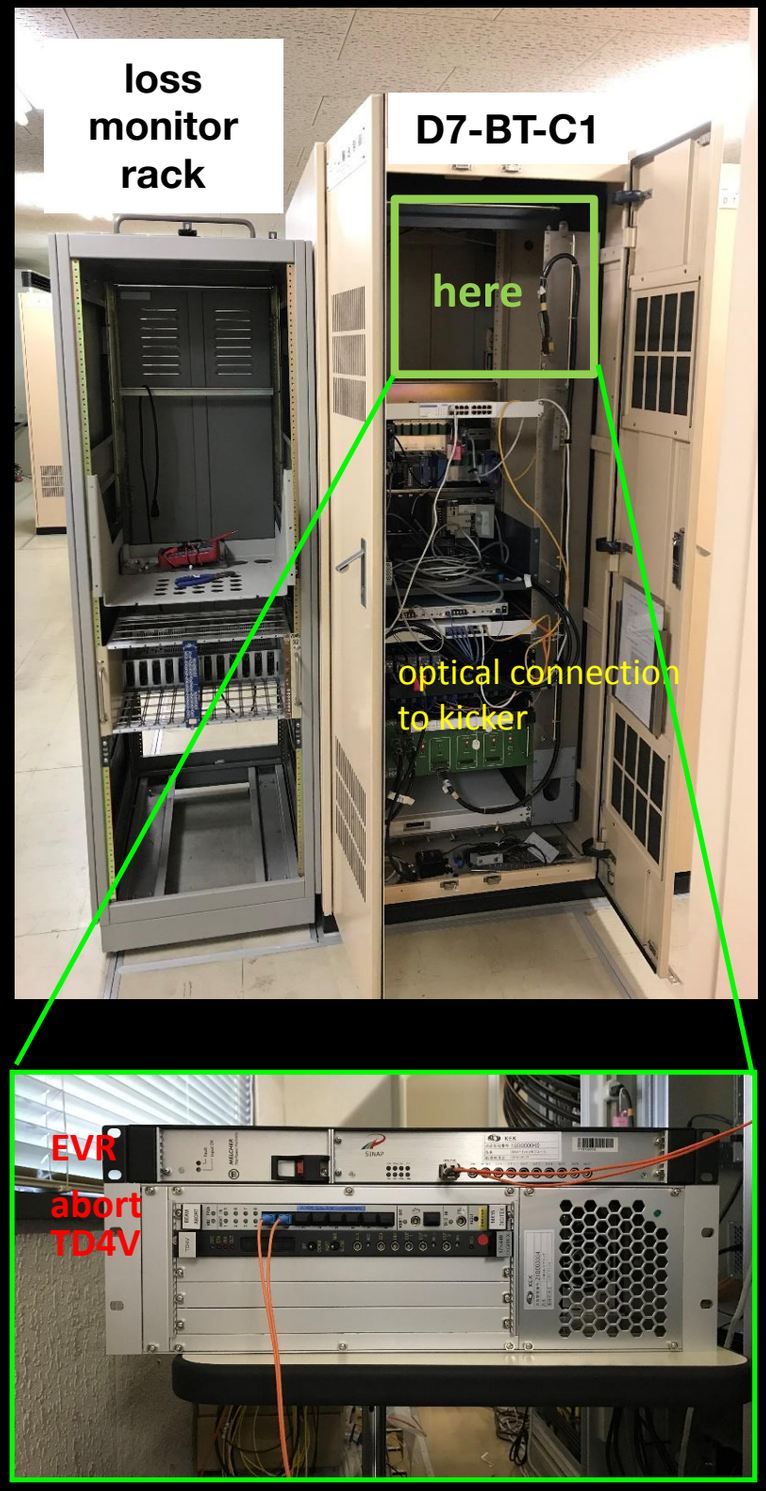




- At present, abort request signals are sent to D07 section (abort kicker) through CCR. What if the signals are directly sent to abort kicker?
  - **D06: 4.8 μs → 2.9 μs**
  - **D05: 6.9 μs → 5.2 μs**

Abort module upgrade



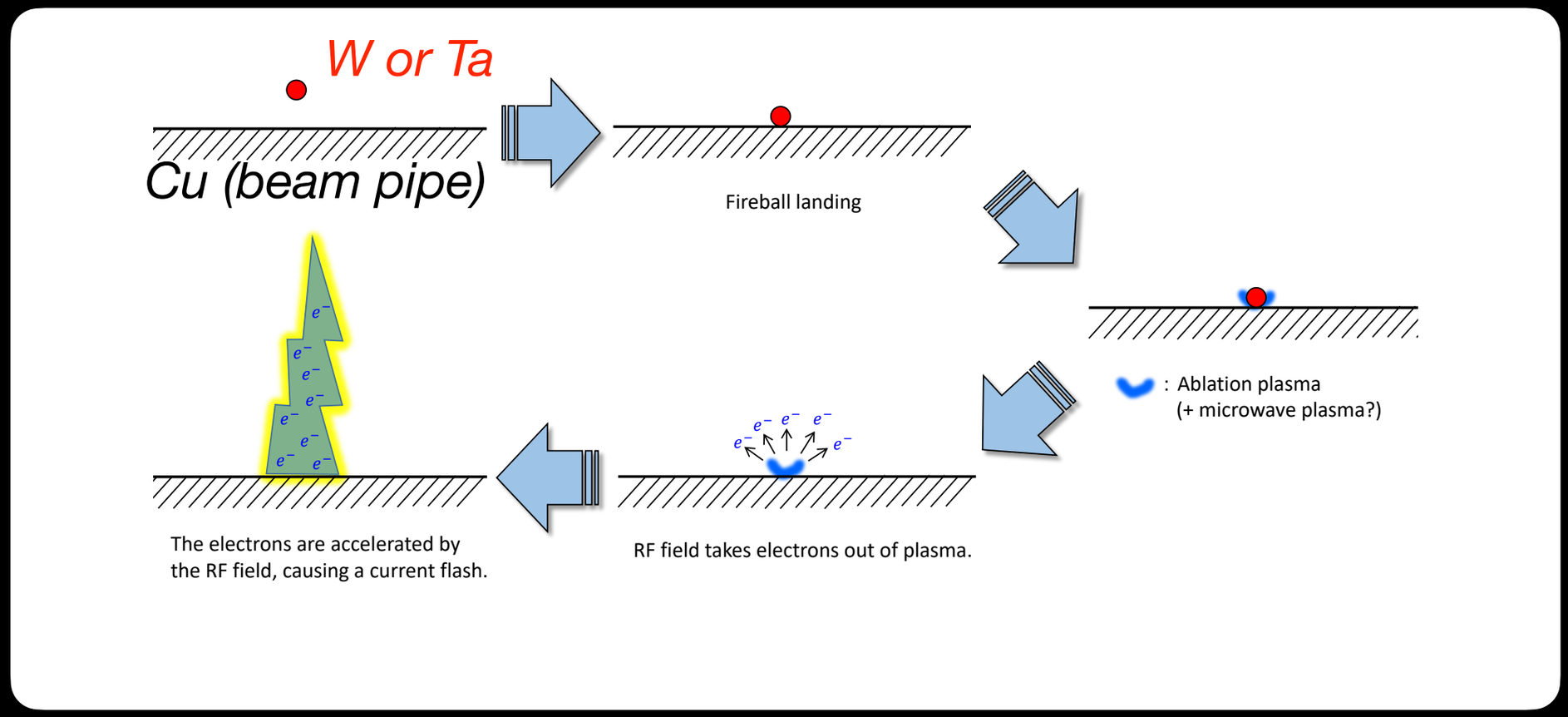


- The firmware on Event Receiver (EVR) FPGA will be updated such that two kicker circuits can be operated (CCR and D07) in parallel.
- A student can work on installation and commissioning with beam.

Fireball hypothesis

- **Fireball**: A micro particle from damaged collimator with a high sublimation point (e.g. W or Ta).

Collimator head made of W or Ta



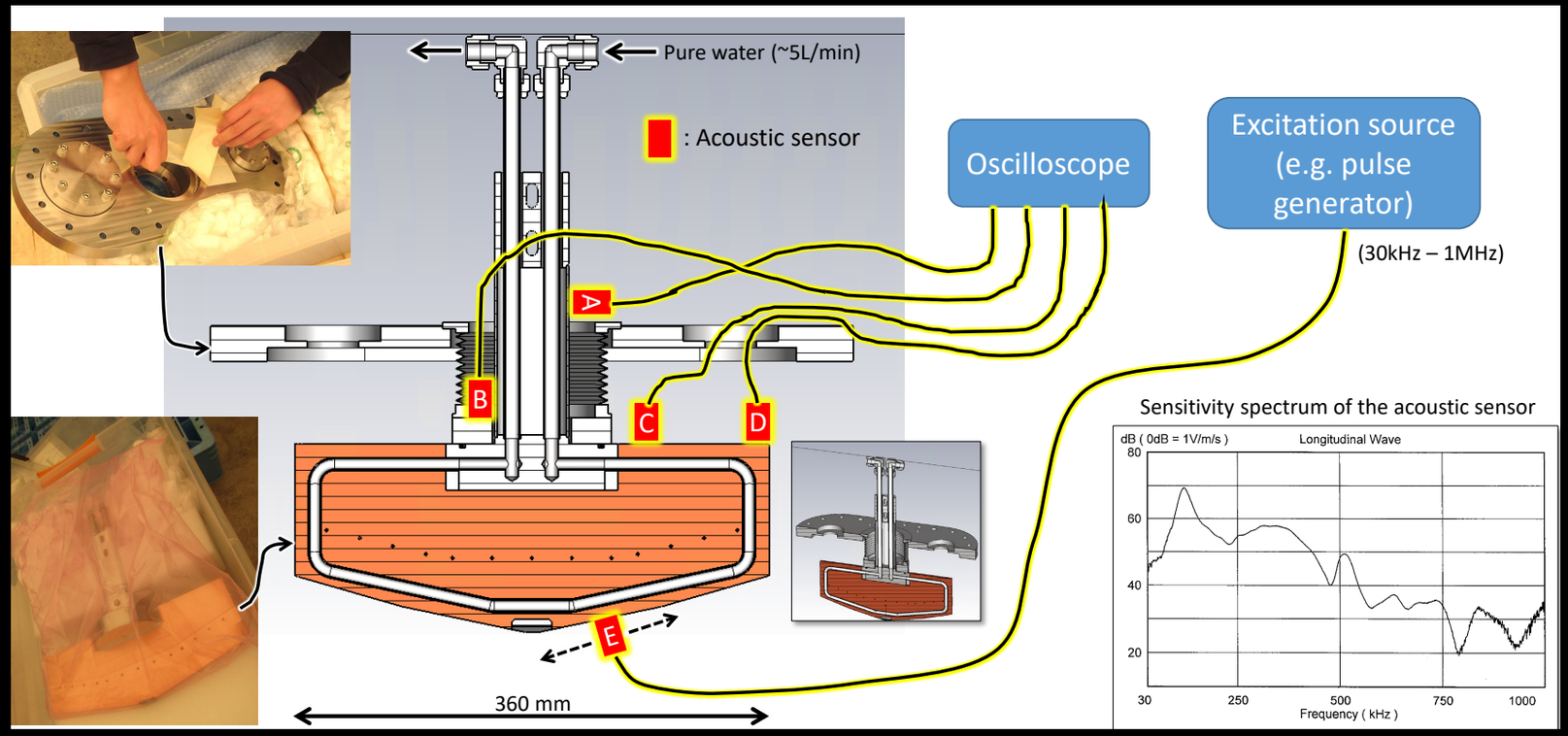
- Fireball can be heated by the beam-induced field and plasma is generated around it, growing up into a macroscopic vacuum arc, leading to significant interactions with the beam particles.

Acoustic sensor

Adding more “ears” to investigate SBL!

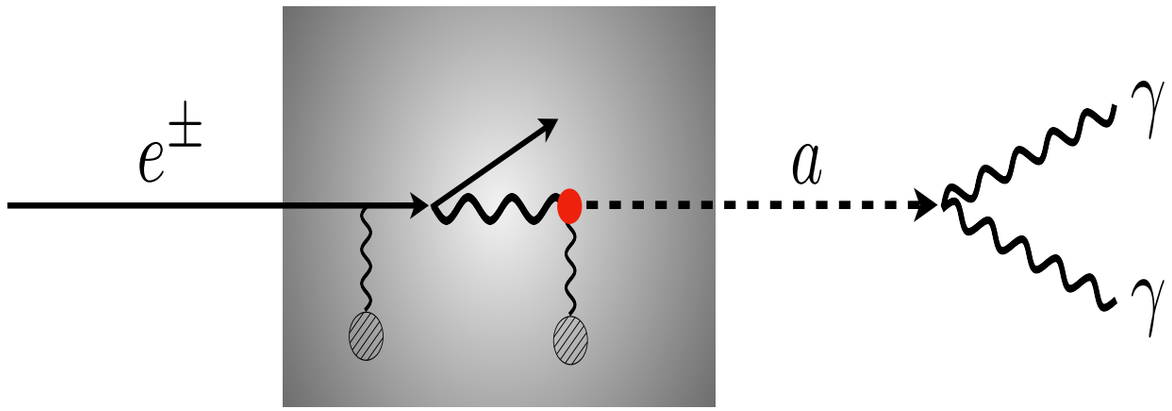
- Acoustic sensor (AE124AT) can be used to “hear” ultrasonic sound waves generated at vacuum breakdown.
- Sensors will be installed around the collimators.
  - sensor position will be optimized with the spare collimator jaw.

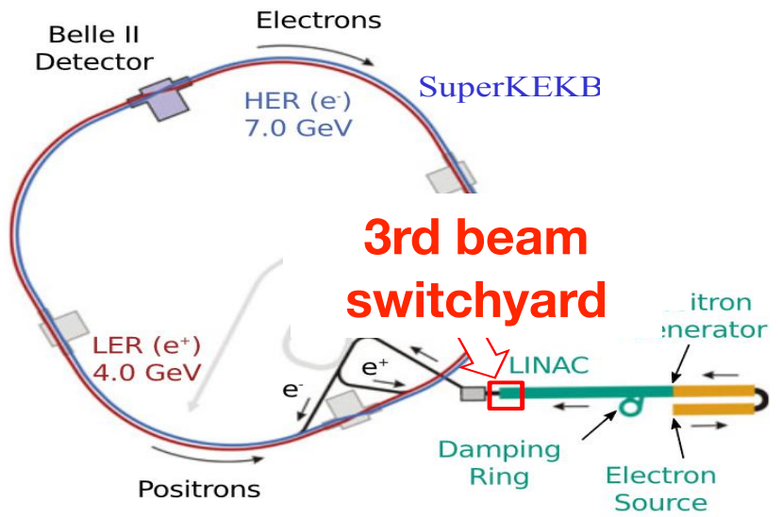
Sensitive to 30 kHz - 1 MHz



ALP search

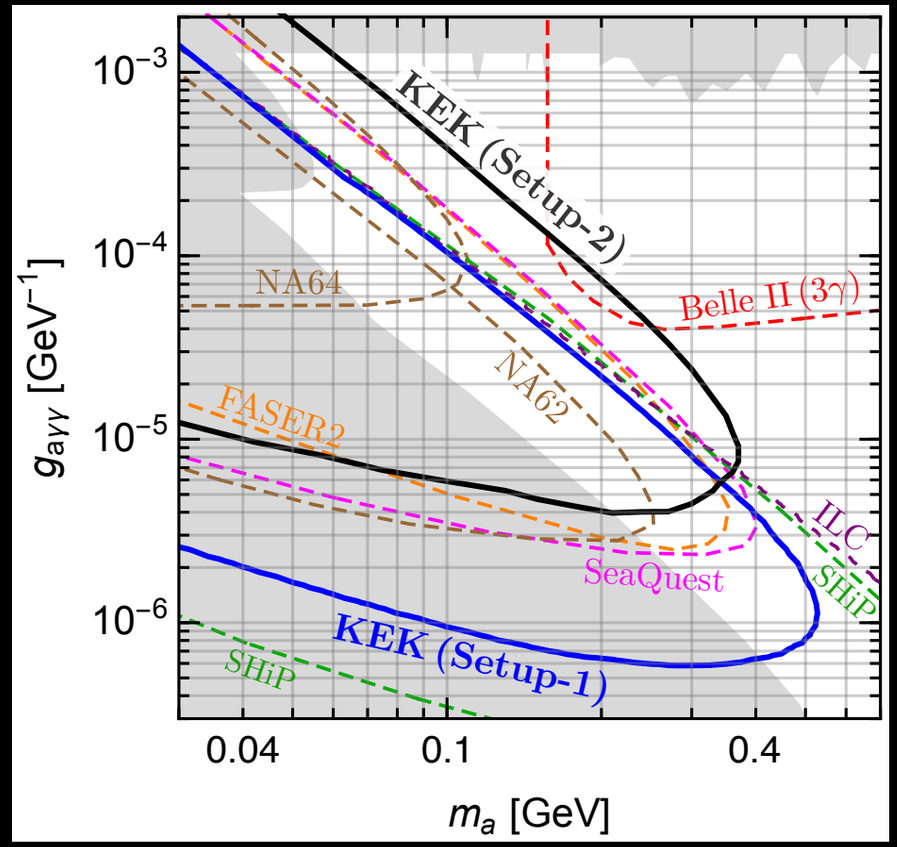
ALPs search at KEK LINAC





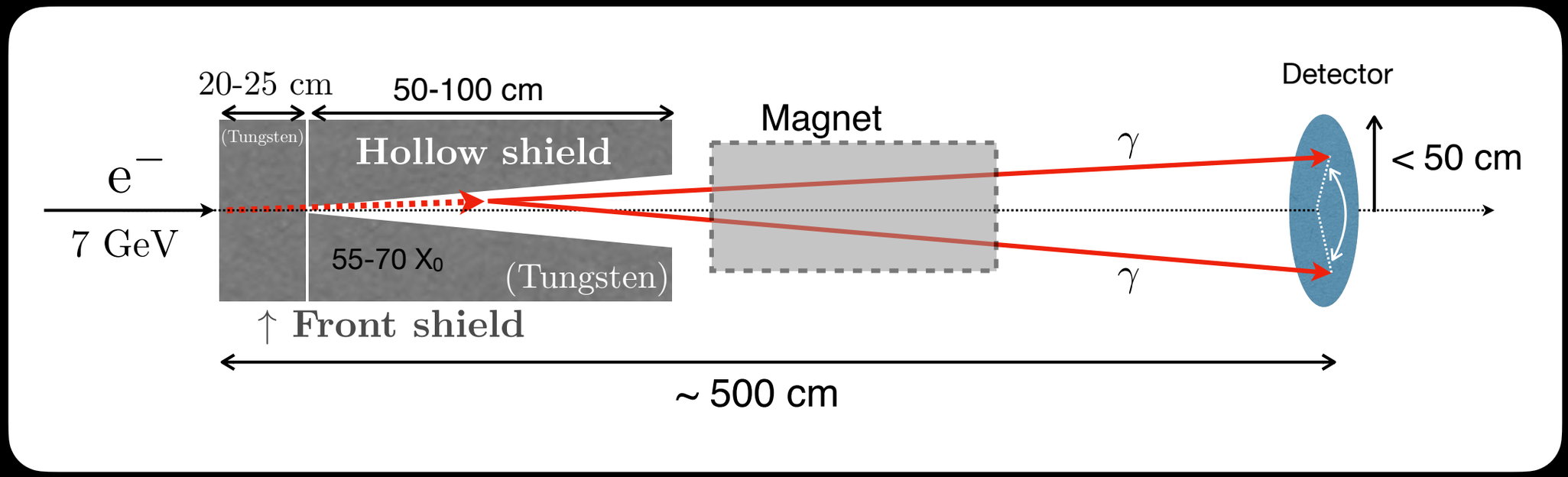
- Axion-like particle (ALP) is more general expression of axion, with the ALP mass (m_Φ) being independent of the breaking scale (f_a)

- A new beam dump experiment was proposed at the KEK LINAC, targeting an unexplored region of phase space.

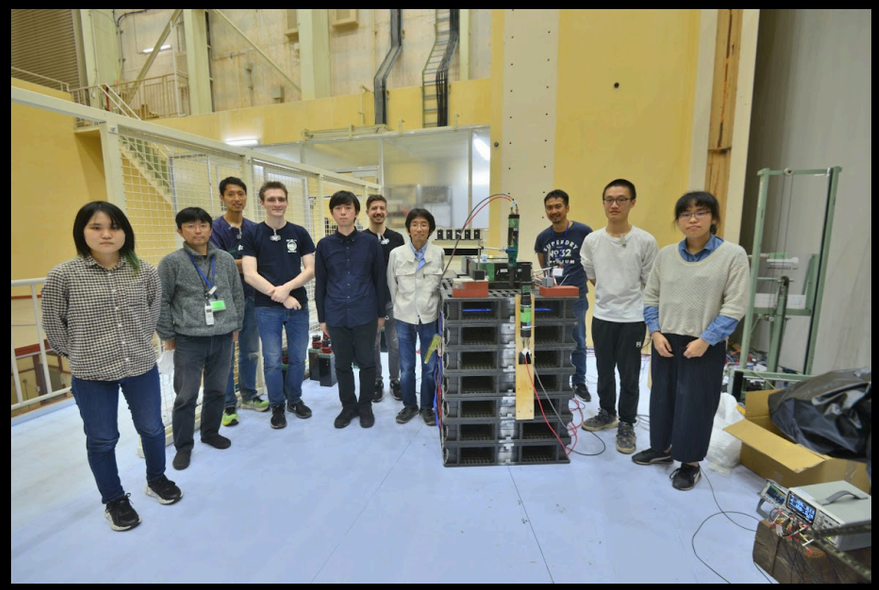


arXiv:2107.06431

ALPs search at KEK LINAC



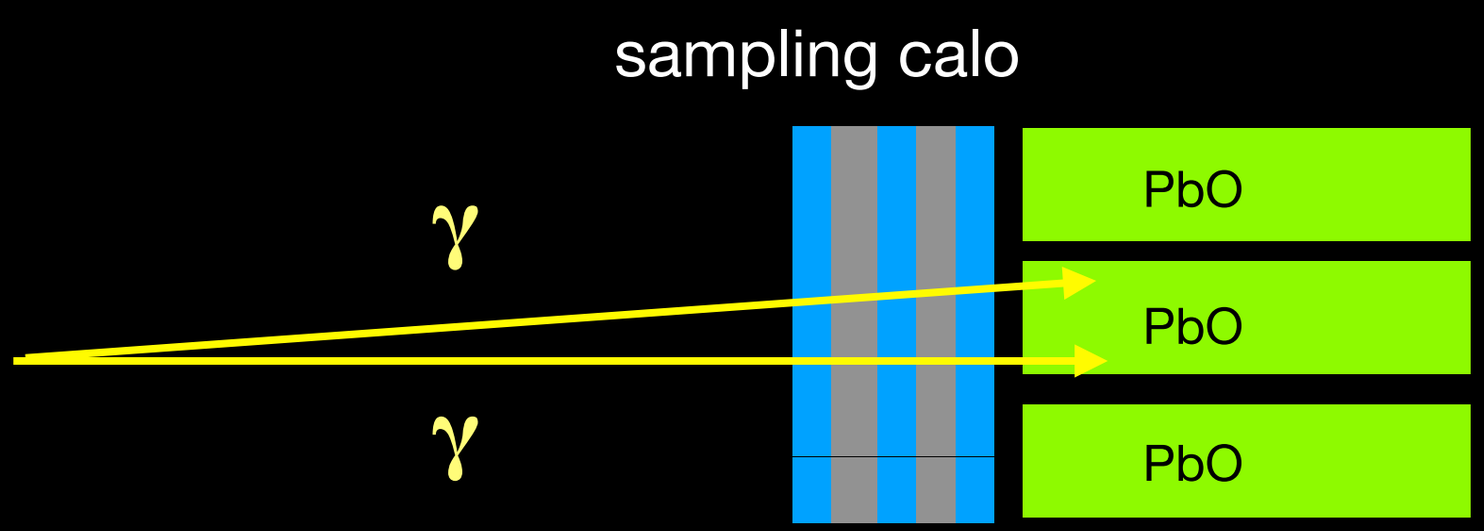
- Shorter beam dump in comparison with previous experiments
  - Large ALP acceptance while allowing for larger BKG.
  - BKG can be reduced by Hollow Shield and dipole magnet
- In 2022, I have led
  - Background study (3 students)
  - PbO calibration (6 students)
- Future: readout development
  — more hardware opportunities for students!



Test beamline at KEK

Calorimeter readout

- Segment size of 1 cm x 1 cm required for the background reduction with azimuthal angle ($\Delta\phi_{\gamma\gamma}$) cut
- Sampling calorimeter (e.g. plastic scintillator + tungsten) can be readout with SiPM.



- Electronics should have the capability to record the waveform to be able to reduce the background further. Something similar to KLM scintillator electronics?

Summary

- I have been working on various hardware projects through my career.

- I would like to propose
  - MDI projects (beam diagnostics, beam abort upgrade, fireball verification)
  - ALPs search with calorimeter readout development

- I am happy to join IDL for firmware/electronics development for UH HEP projects.

Thank you!