Belle II PID Systems

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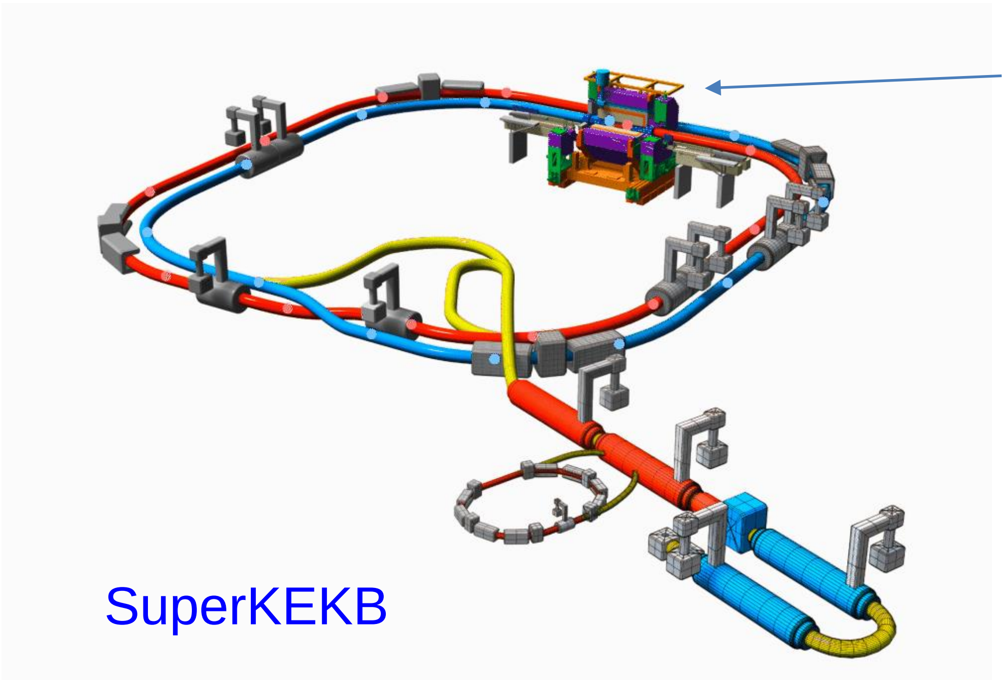
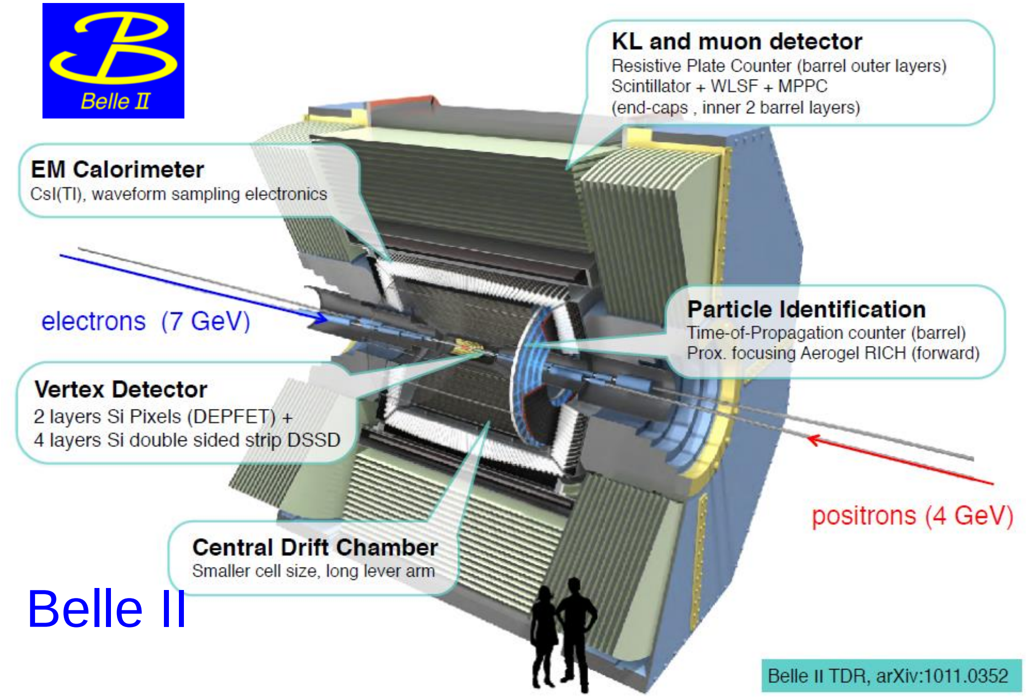
KEK

CEPC Workshop @ 復旦大學

Aug. 14, 2023

Belle II @ SuperKEKB

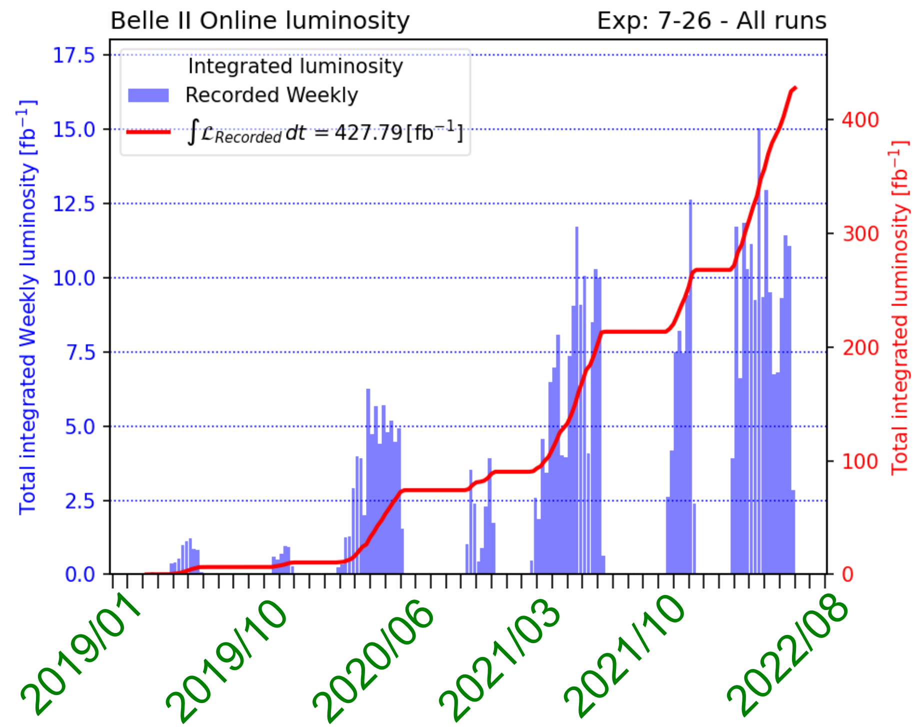


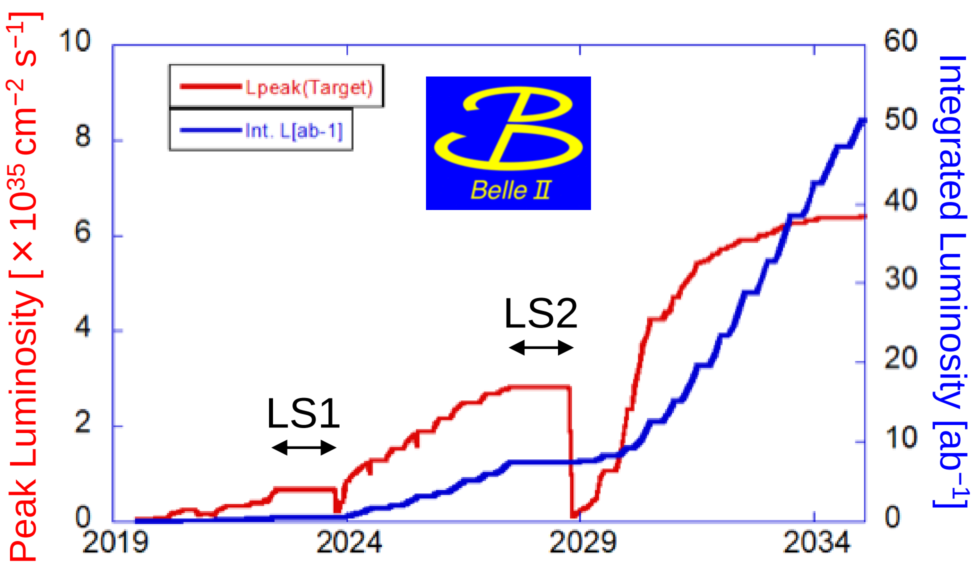


- Belle II experiment at KEK: flavor physics experiment, successor of Belle.
- SuperKEKB Asymmetric electron-positron collider: 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme to achieve high luminosity.
- Operation with full detector started in 2019.
- Now in Long Shutdown 1 (2022 Jul – 2023 Nov)
- Luminosity $4.7 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ achieved so far (aiming one order higher).
- Plan to accumulate one order larger dataset than belle (50 ab^{-1})

SuperKEKB and Belle II

- Luminosity 4.7×10^{34} cm^{-2} s^{-1} achieved (Jun 8, 2022).
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- 424 fb^{-1} of data accumulated so far.
  - ✓ Belle: 1 ab^{-1} (= 1000 fb^{-1}) in 11 years' operation.
  - ✓ Belle II target: O(10) of Belle.

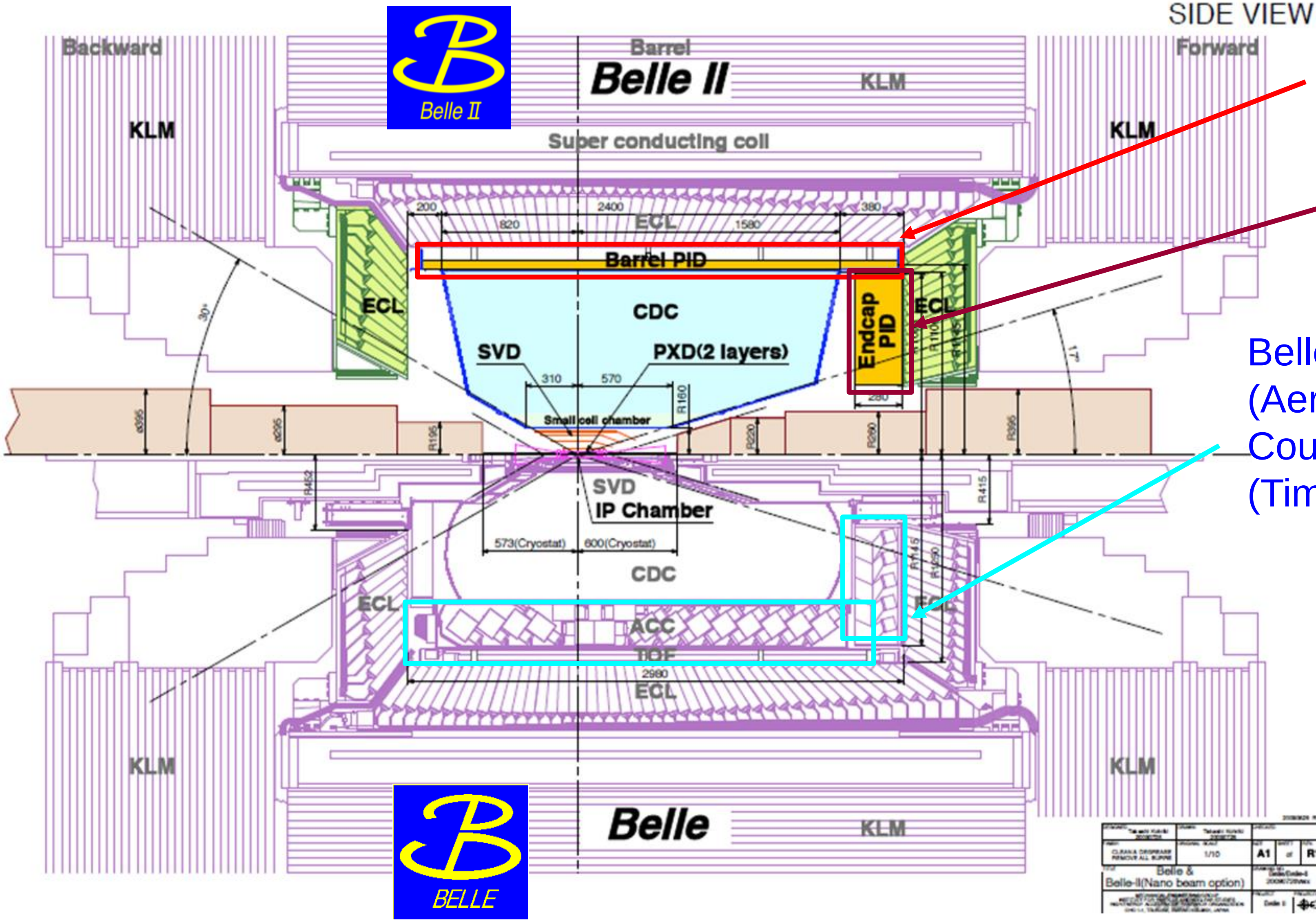




1 ab^{-1} ~ 10^9 $B\bar{B}$

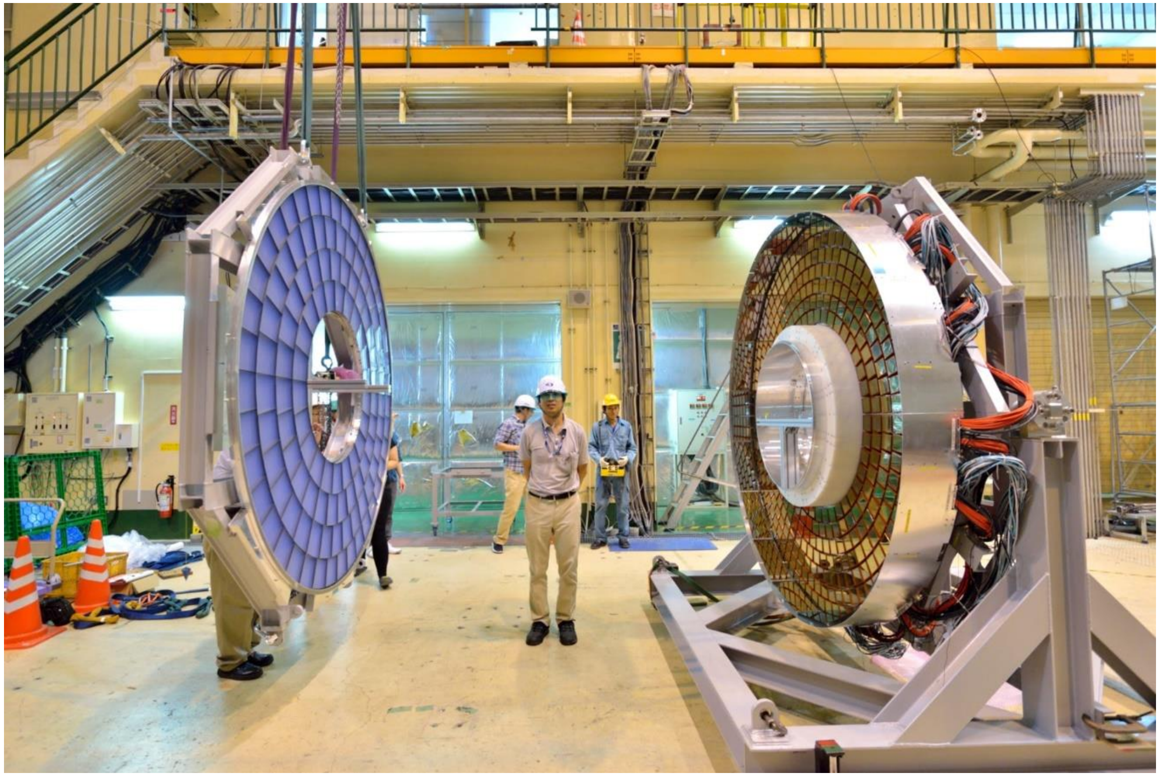
- Long shutdown (LS) 1 starts from summer 2022 to fully install PXD. Operation will be resumed in the end of 2023.

Belle II PID

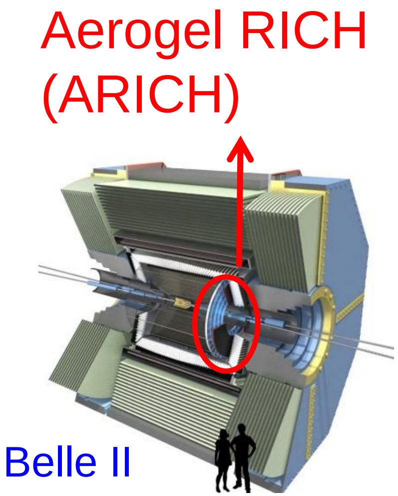


More space to VXD and CDC at Belle II

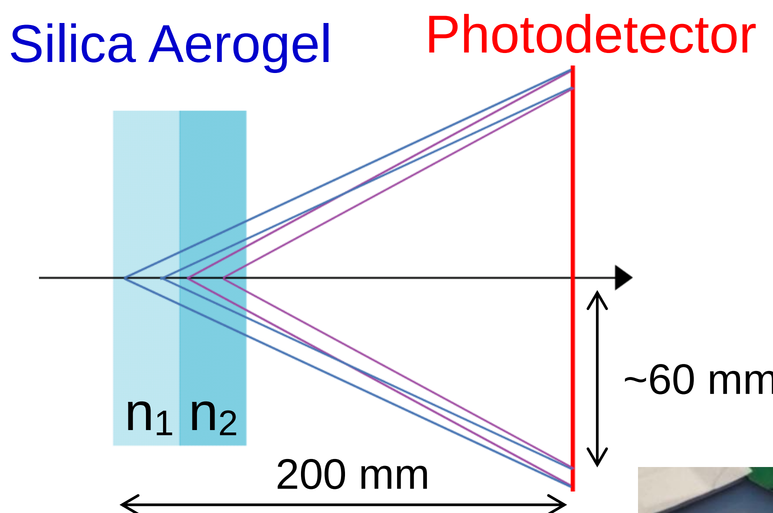
ARICH (Aerogel RICH)



Aerogel RICH



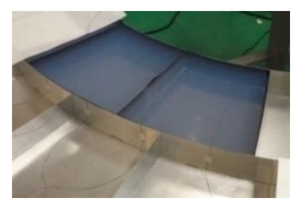
- Ring Imaging Cherenkov Counter (RICH) with aerogel radiator.
- Limited space available
  → proximity-focusing RICH.



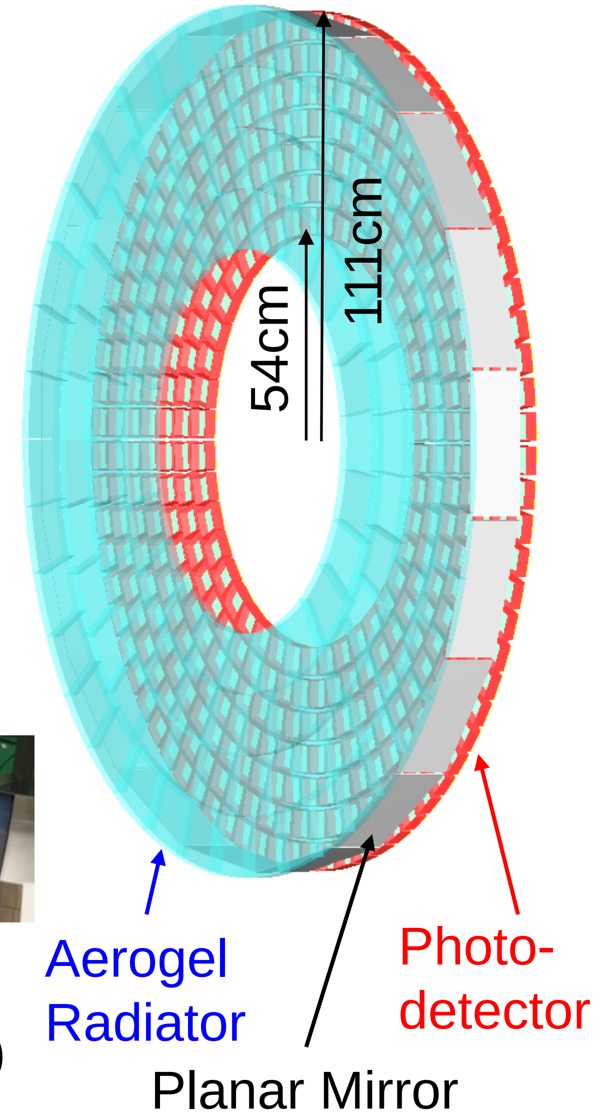
$$\cos\theta_c = \frac{1}{\beta n} = \frac{\sqrt{(m/p)^2+1}}{n}$$

performance:

$$\sigma_{\mathrm{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$



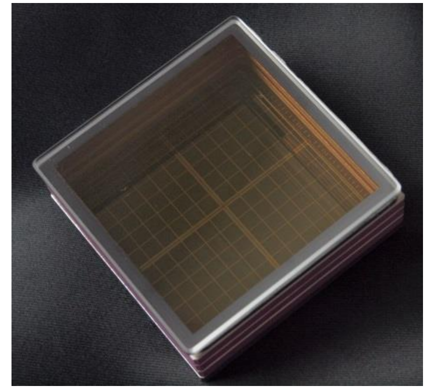
- Two layers of aerogel
  $n_1 = 1.045$, $n_2 = 1.055$
- Good transparency (~40mm)
- $\theta_C(\pi) - \theta_C(K)$ ~ 23 mrad (@4 GeV)

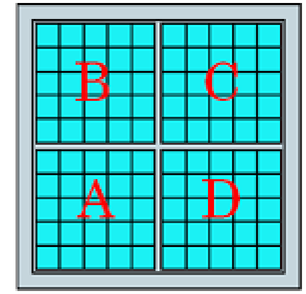


Photodetector

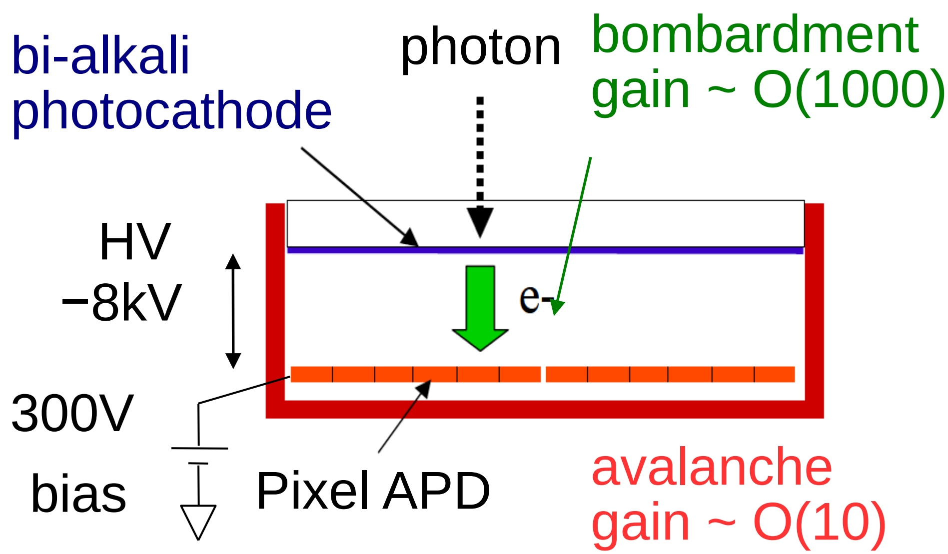
- ~5mm pixel size. Sensitive to single photon
- Large coverage (3 m^2).
- Immune to 1.5T magnetic field.
- Radiation tolerance (10^{12} cm^{-2} neutron).

⇨ HAPD (Hybrid Avalanche Photo-Detector)





□4.9 [mm]

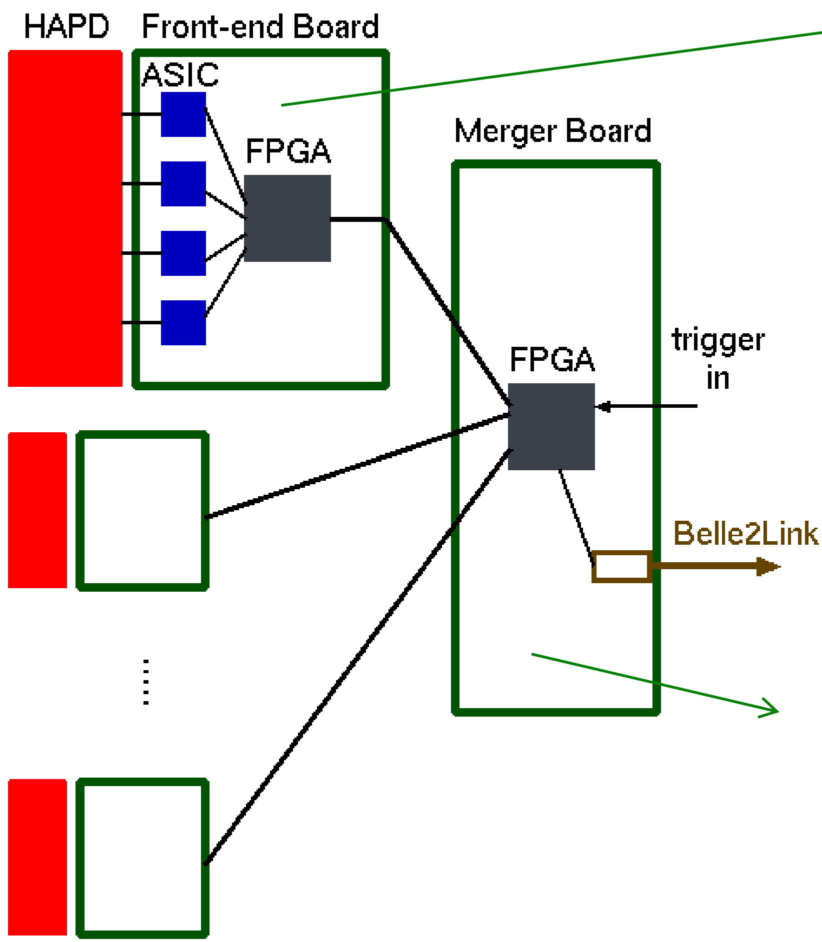


Hybrid: Vacuum tube + semi-conductor

- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip × 4).
- Gain ~ 70000.
- Peak QE ~28%
- Size 73mm × 73mm.
- Effective area 63mm×63mm (65%).

Total 420 HAPDs

Electronics



420 HAPDs + Front-end Boards
72 Merger Boards

Front-end Board

- 4 ASIC + Xilinx FPGA (Spartan6).
- ASIC : preamp + shaper + discriminator.

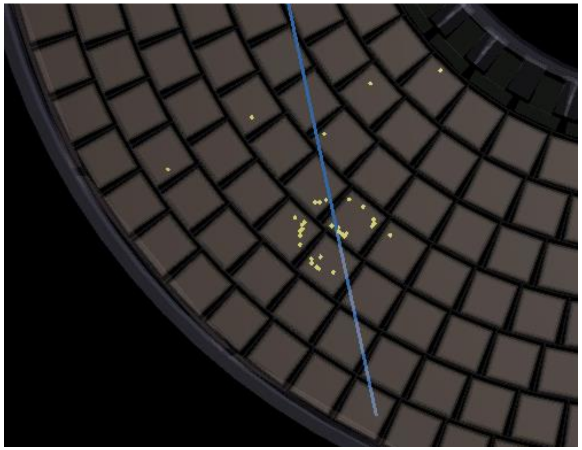
- Total 60480 channels.
  - ✓ 1-bit ON/OFF information is enough.

Merger

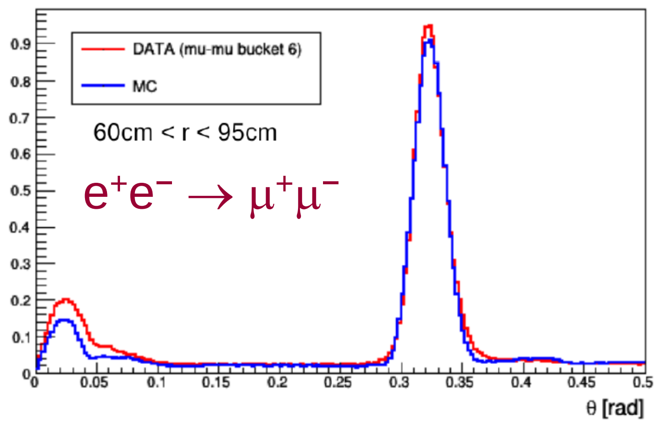
- Receive hitdata from 5-6 front-end boards.
- Zero suppression.
- Send to DAQ.

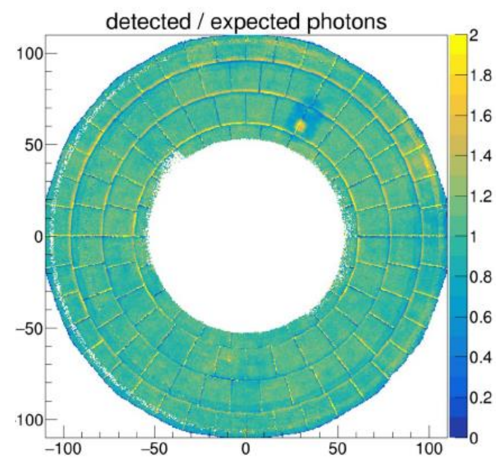
Performance

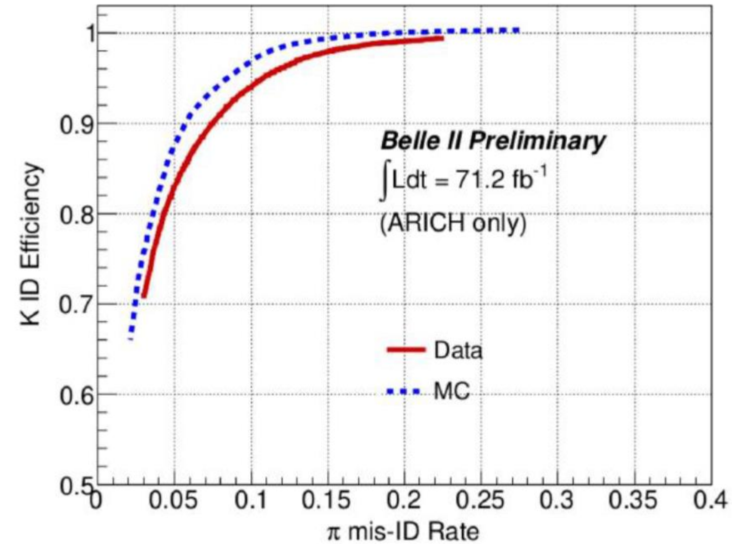
Particle Identification (PID) by ARICH is obtained from the comparison of the hit pattern and the expected PDF for different particle hypothesis.

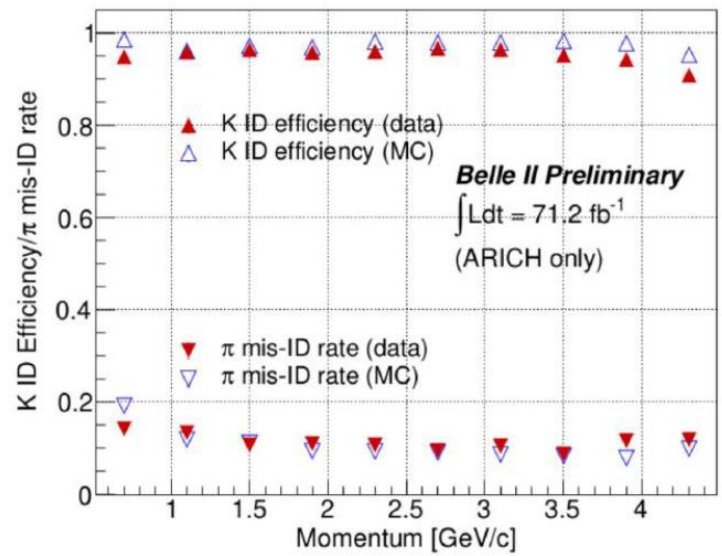


- Reconstruction procedure is rather simple.
- Many minor things to be considered (aerogel tile edge, reflection of photons inside HAPDs…)







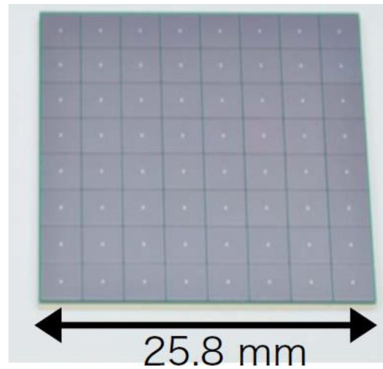


Upgrade

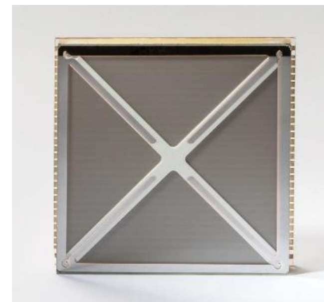
- HAPDs are expected to work for ~10 years, but additional HAPDs cannot be purchased any more → upgrade around 2030- ?
- Candidate photon sensors: MPPC (SiPM), LAPPD (MCP based detector)

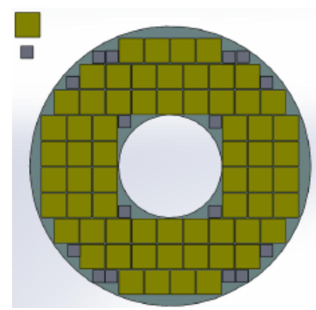
- MPPC has better performance (PDE) but has large concern on the dark count and radiation damage (>10^{12} n / cm^2 @ 1 MeV equiv. is expected.)
  - ✓ Cooling (~ −40°C ?) is necessary.
  - ✓ Readout electronics with fast timing capability (fastIC chip developed for LHCb ARICH is a candidate)
- LAPPD looks a promising option, but it is still at development stage and its performance (PDE etc.) is not so good.
  - ✓ Study just started at JSI.

64 (8 × 8) ch MPPC



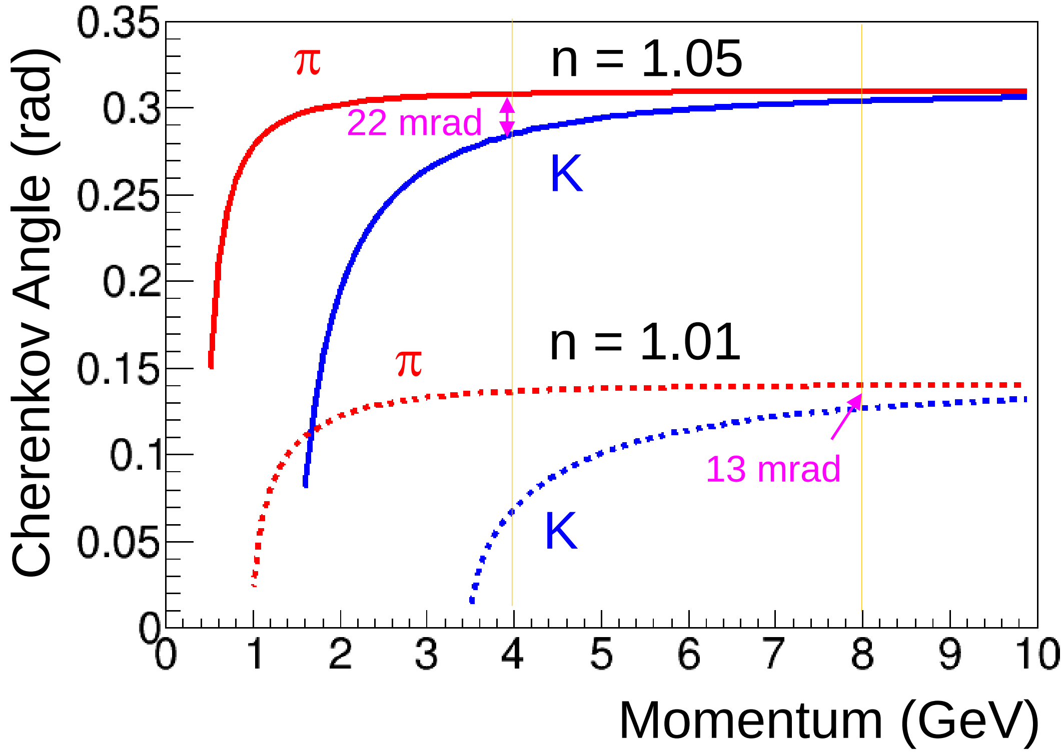
LAPPD (Large Area Picosecond PhotoDetector) : 200mm × 200mm





Momentum Range

- Belle II ARICH is optimized to 1-4 GeV (n ~ 1.05).
- If you need cover higher momentum range, you can reduce the refractive index of the aerogels.
  - ✓ Cherenkov angle gets smaller, so you need larger distance or better position resolution.
  - ✓ n ~ 1.005-1.01 is minimum; 10 GeV looks the maximum.

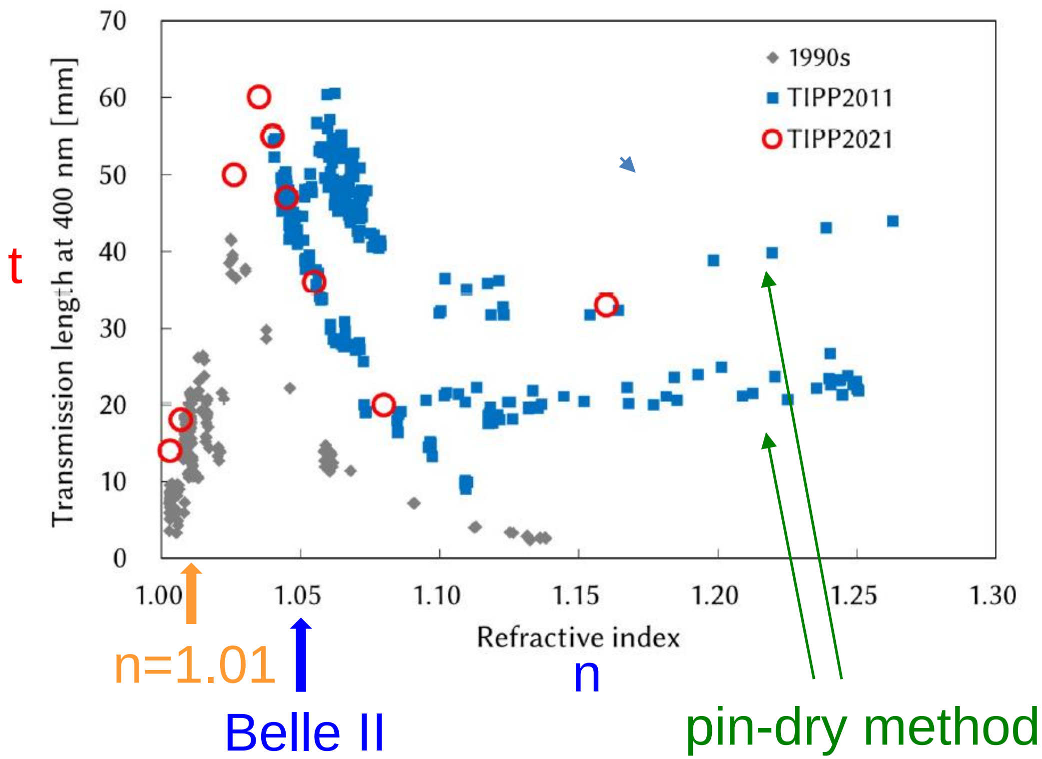


[Shown at the previous workshop]

Aerogel with Low Index

Aerogel developed at Chiba Univ. →
“Aerogel Factory” (https://www.aerogel-factory.jp/)

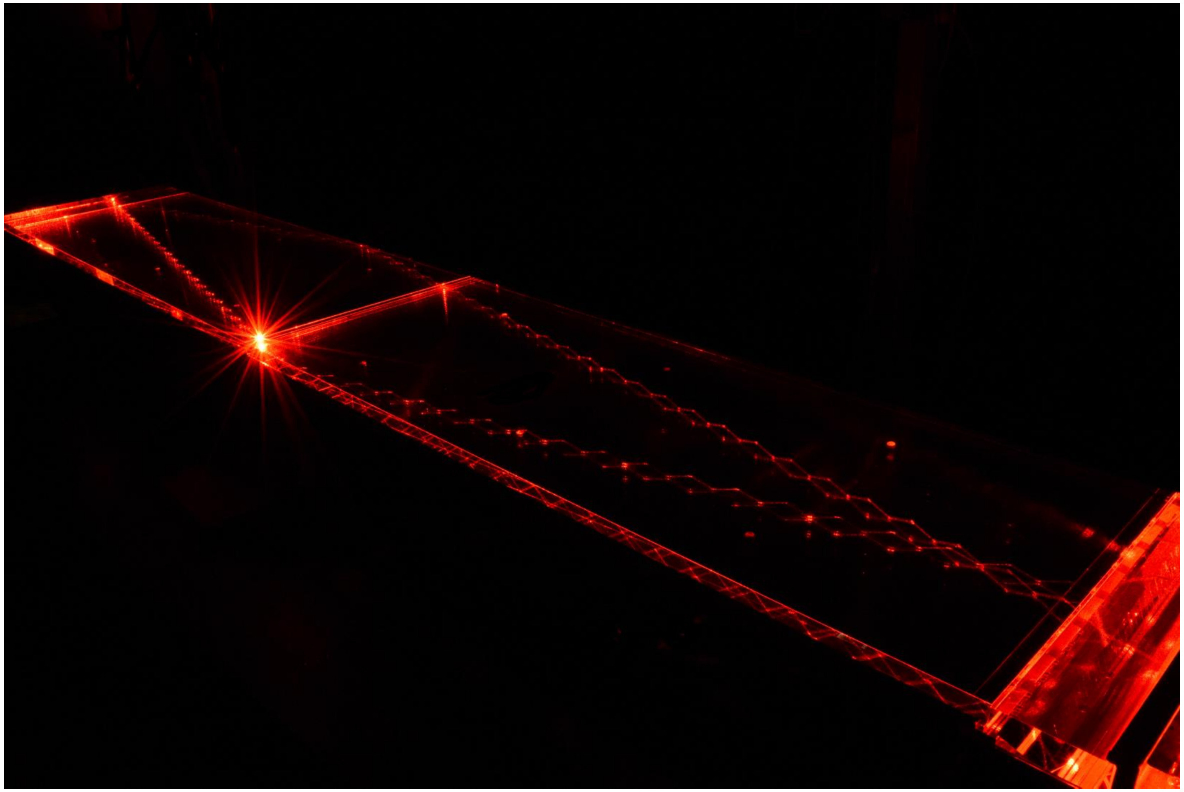
[J.Phys.Conf.Ser. 2374 (2022) 1, 012114. doi:10.1088/1742-6596/2374/1/012114]



- Transmission length (transparency) (t) is important for ARICH.
- Aerogel for Belle II ARICH: n=1.045 & 1.055, t ~ 40 mm
- t rapidly drops for lower n at n<1.04.
- n=1.02 with t~40mm will be available with small development.
- n=1.01 with t~40mm is challenging, but maybe possible with more study.
- Aerogels with n=1.003, 1.007 are under development for threshold type detector (with lower t).

The performance at higher momentum depends on the configuration, but p<10 GeV is roughly the range that ARICH can cover.

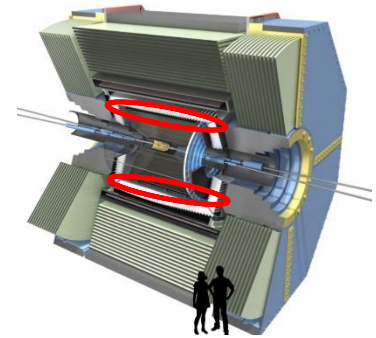
TOP (Time Of Propagation)

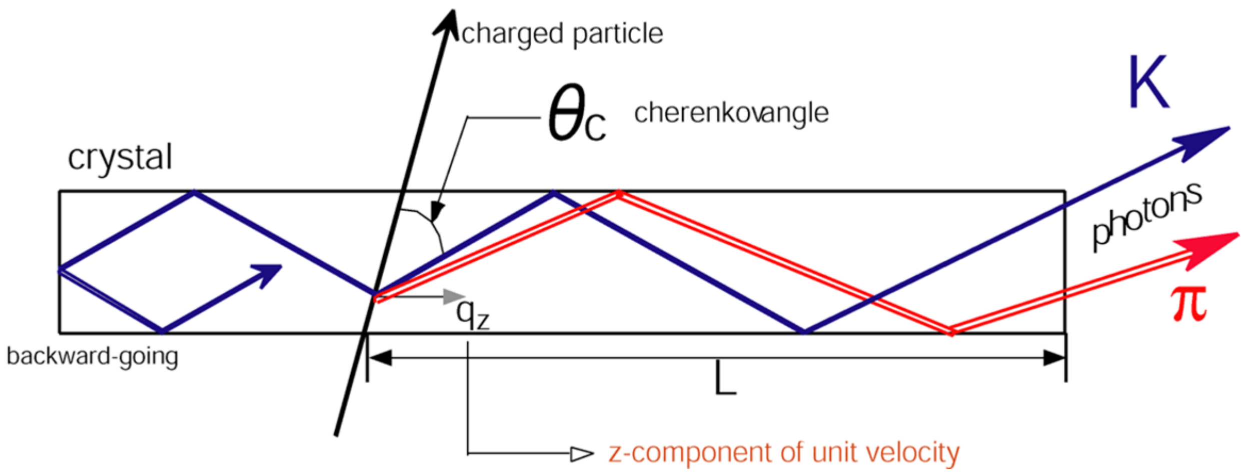


A part of the material is provided by
Kenji Inami (Nagoya)
from Belle II TOP group.

TOP

Measurement principle of TOP (Time of Propagation) Detector

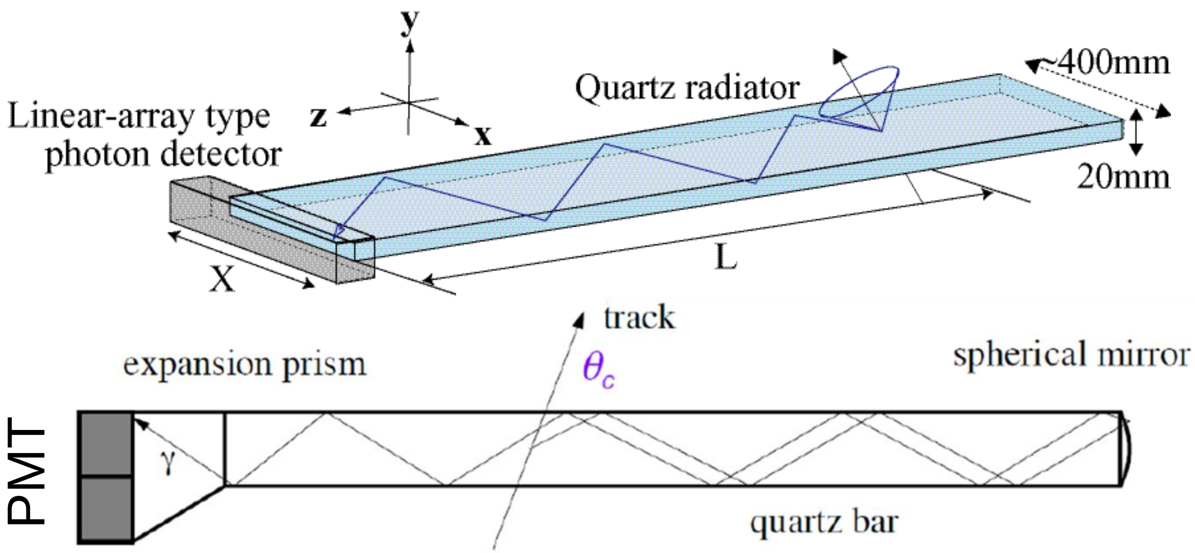




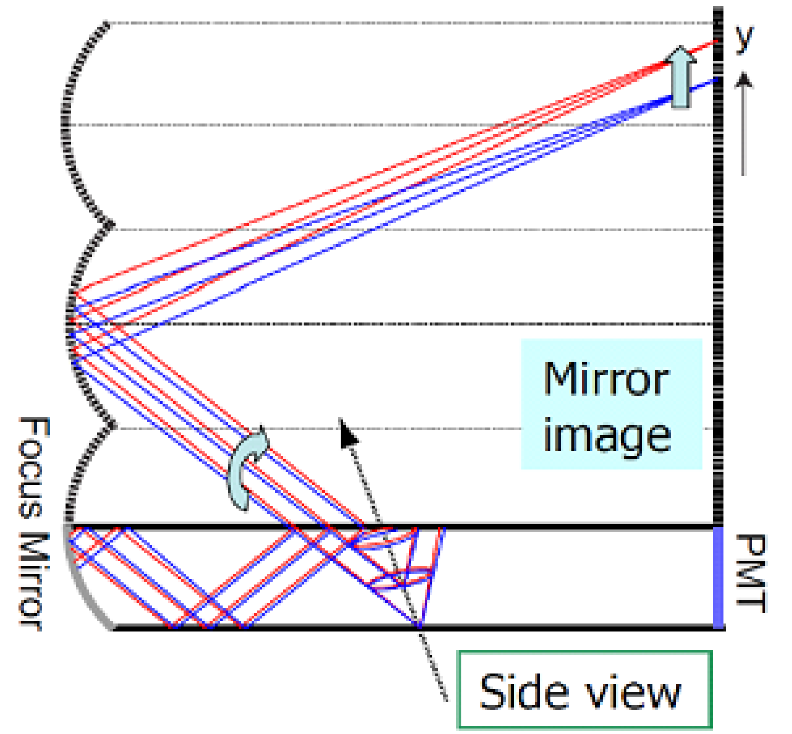
Different Cherenkov angle
→ Different photon path
→ Different time of propagation.

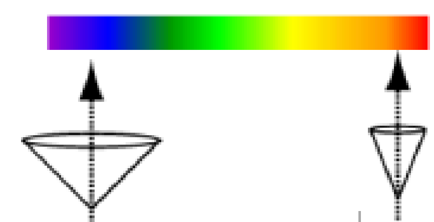
- Measure the time of propagation of K and π: need ~ 50 ps timing resolution
- Measure the position of photons, too.
- Also works as a TOF (Time of Flight) detector for low momentum particles.
  - ✓ Combination of TOF and RICH with a single device

TOP



- Very flat quartz bar
- Photo-detector with good timing resolution.
- Focus Mirror
  - ✓ Parallel photons are focused: remove the uncertainty from the bar thickness.
  - ✓ y actually differs with different θ_c (when wavelength is different).
    → Correction of chromatic dispersion
    (look at the relation of y and t)





$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$

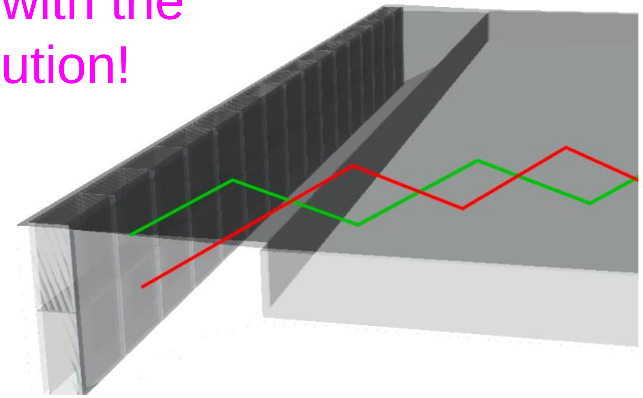
MCP-PMT

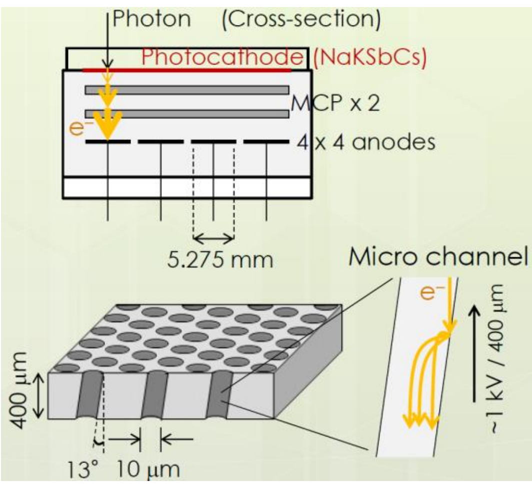
MCP (Micro Channel Plate) -PMT

- 4 × 4 channels
- NaKSbCs photo cathode; QE>24%
- TTS (Transit Time Spread)* < 40ps

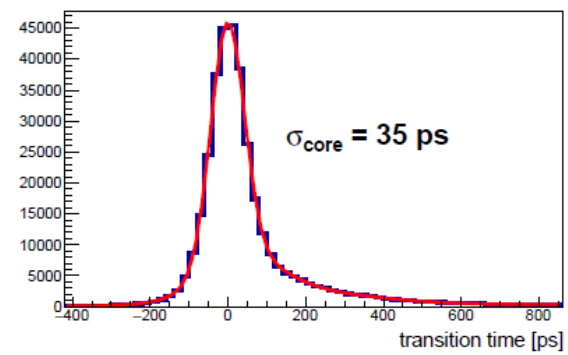
  * = Fluctuation of the signal timing for single photon input.

Photodetector with the best time resolution!



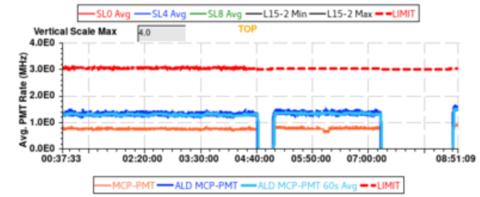


- Hamamatsu MCP-PMT's,
  4 × 4 channels, 5.5 mm pixel size
- 2 rows of 16 PMT's per module (512 pixels)
- single photon sensitivity
- excellent time resolution
- works in magnetic field

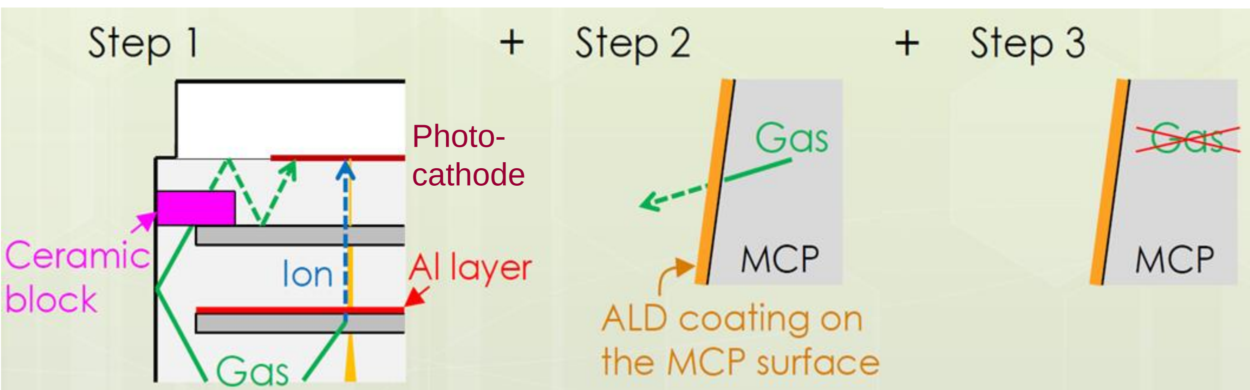


MCP-PMT

Aging problem of MCP



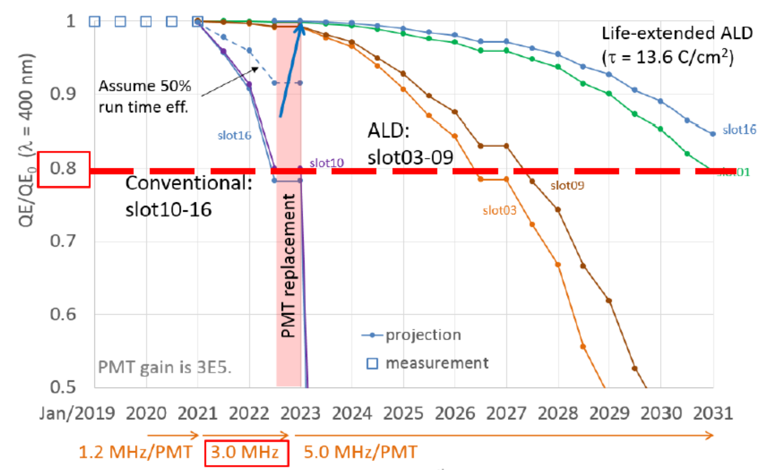
- QE drops as a function of accumulated charge.
  - ✓ The gas and ion from MCP damage the photo-cathode.
- ALD (Atomic Layer Deposition) and life-extended ALD type were developed during mass production.
- The MCP-PMT rate (~accumulate charge) is now limited to 3 MHz so that MCP-PMTs survive till the replacement.
- Replacement work was done during.



Conventional

ALD

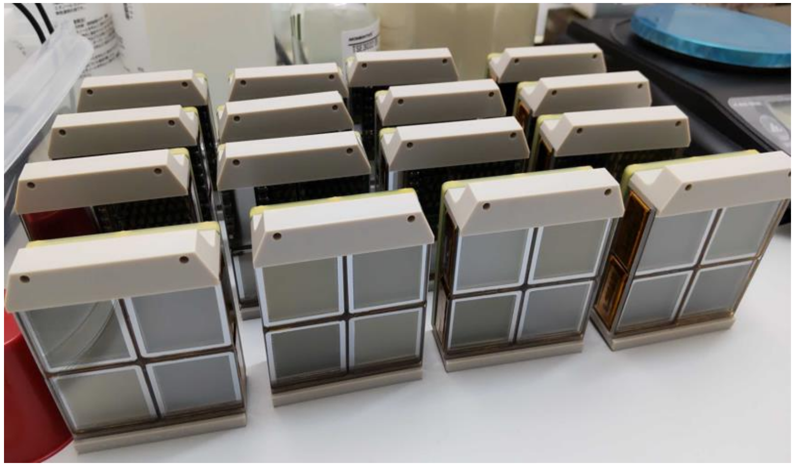
Life-extended ALD

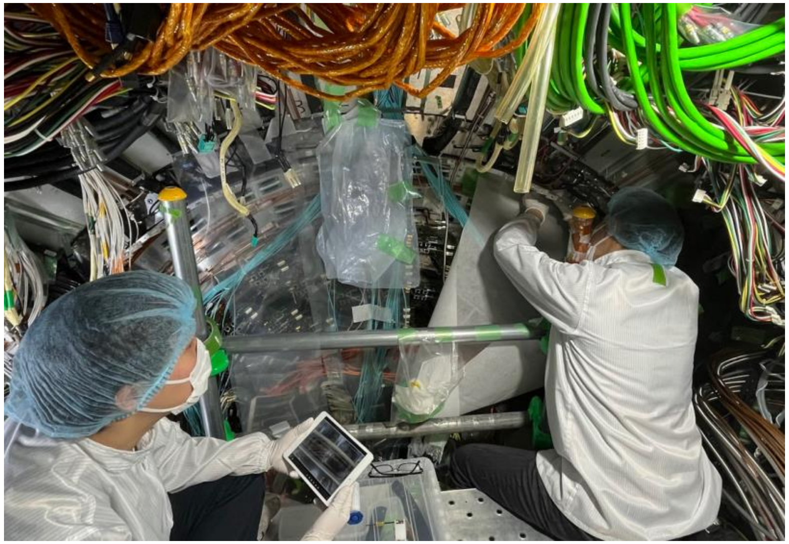


Assumption: The luminosity background follows 17th MC, scaling to the peak luminosity. IntL~870fb^{-1}, Lp~5.7x10^{34} at 2022/June and 5months operation in 2022ab.

MCP-PMT Replacement

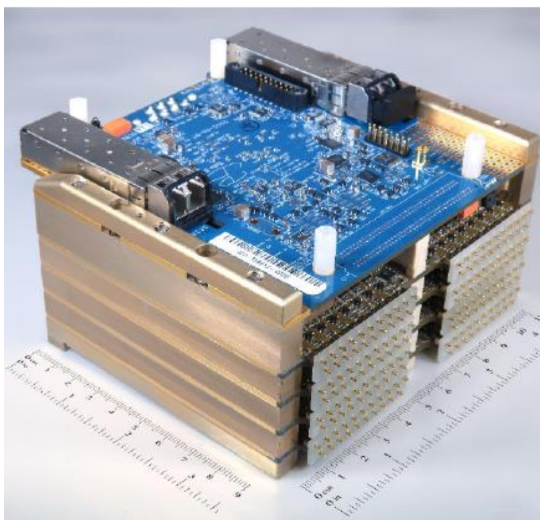
- Replaced 224 MCP-PMTs by new life-extended ALD PMTs
  - ✓ Installed to upper half of TOP modules
- Relocate lower half by best ALD and conventional PMTs
- Exchanged/repaired frontend electronics → >99.5% active channels

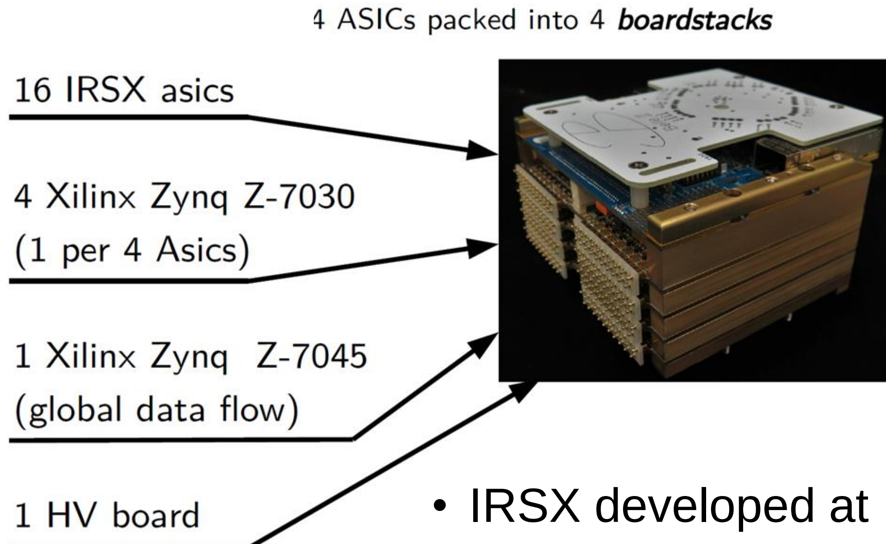




Front-end Electronics

- waveform sampling with 2.7 Gs/sec
- custom designed ASIC with 11 μs long analog ring buffer for storing waveforms
  → running continuously
- 8 channels/ASIC
- 16 ASIC's/boardstack (=128 channels)
- digitization and feature extraction (50% CFD)
- data sent-out by optical link

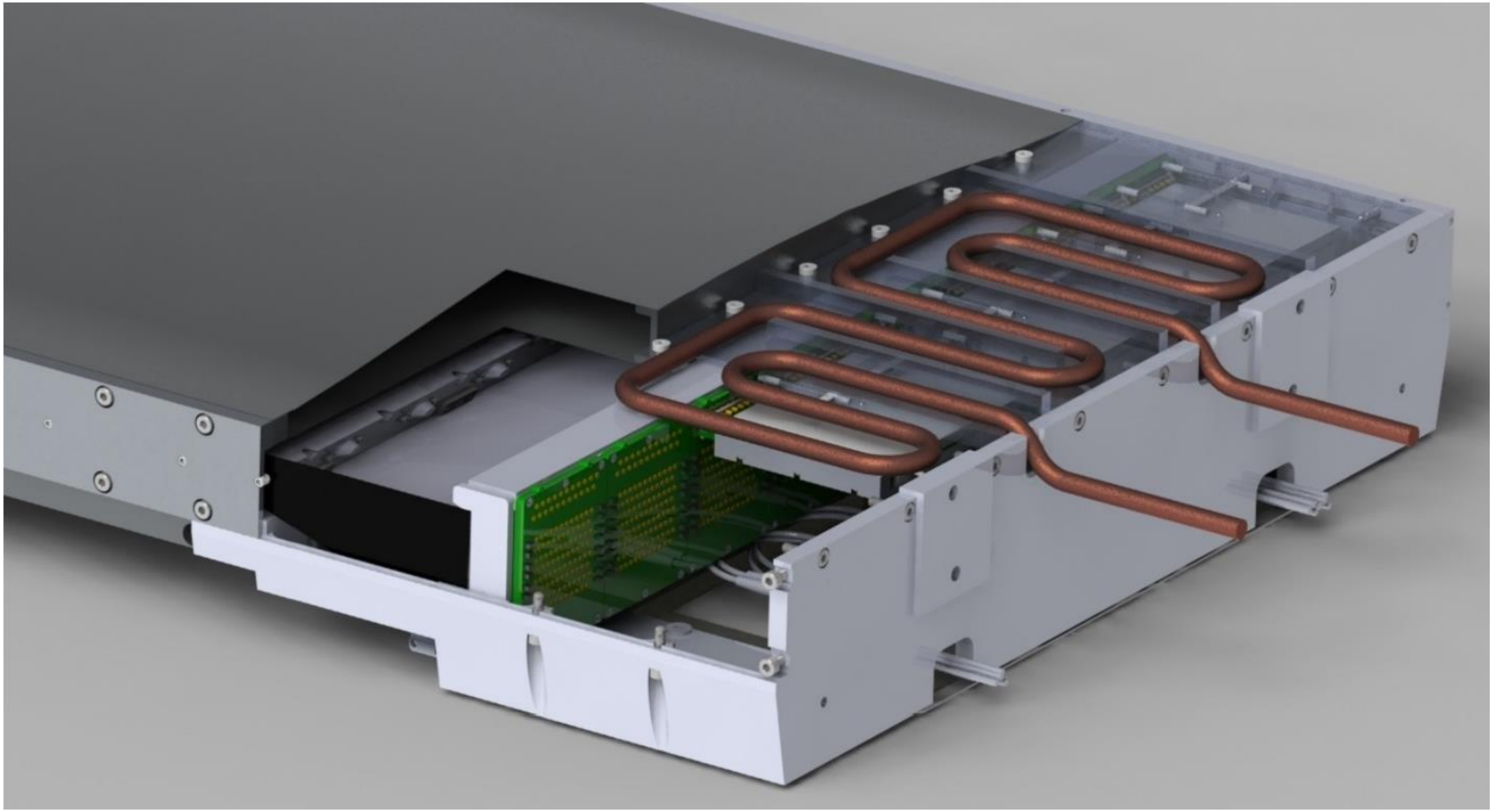




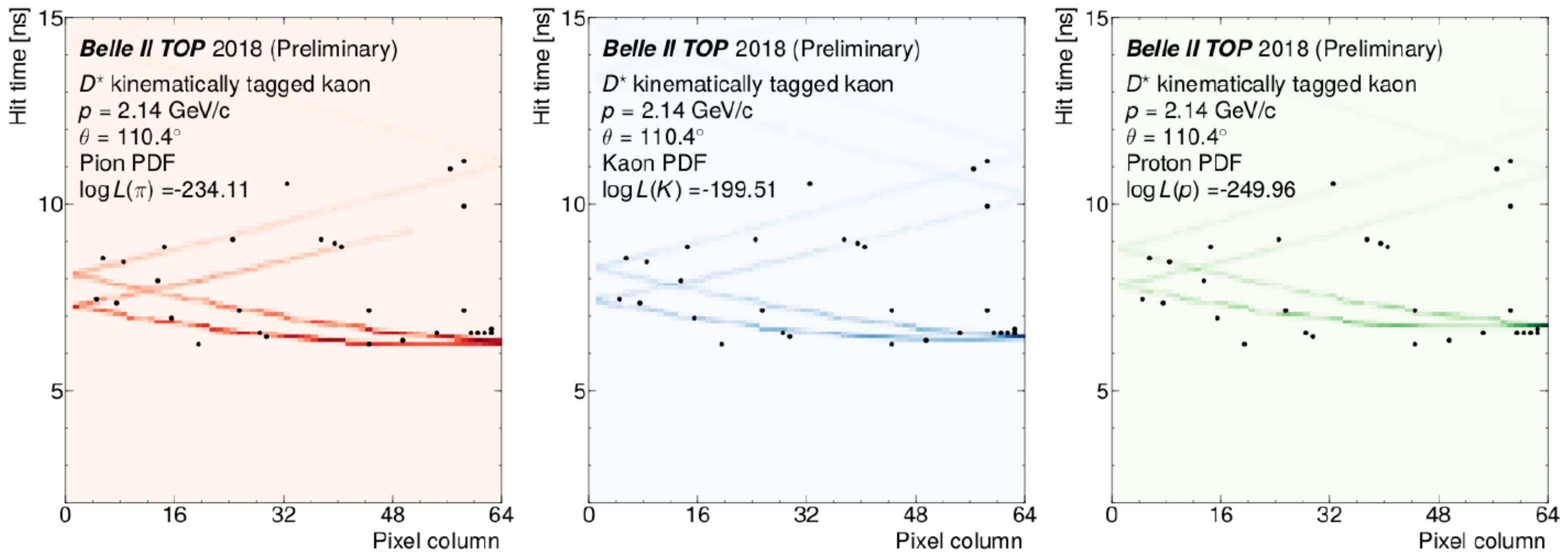
- IRSX developed at Hawaii Univ.
- Full waveform output.

TOP Module

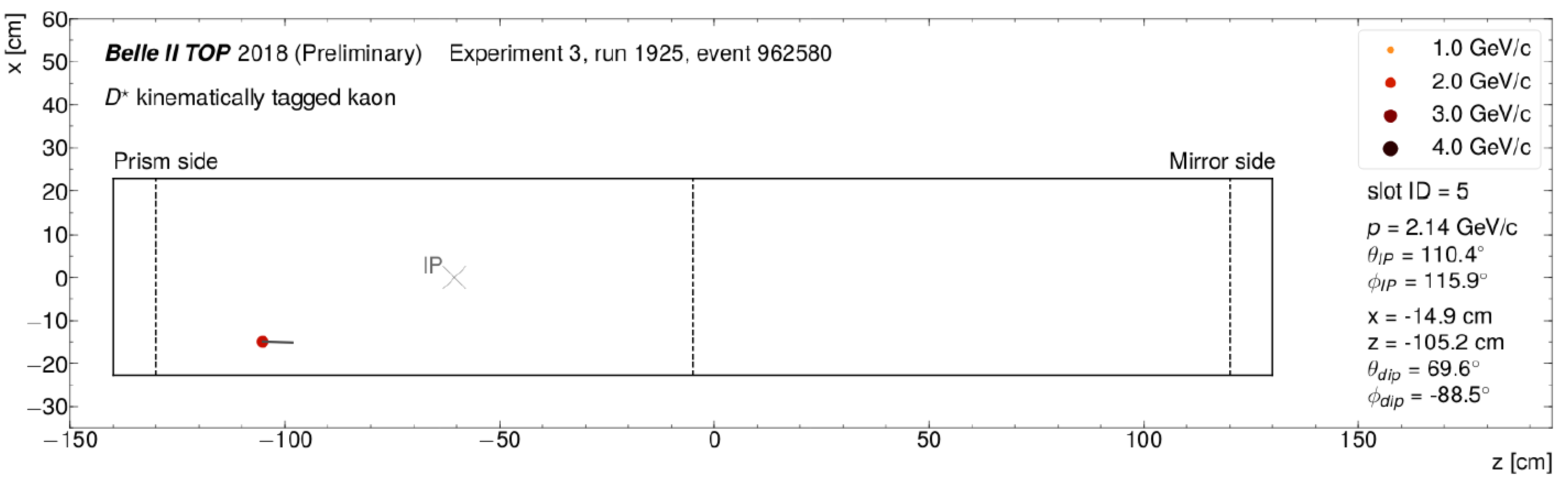
4 boardstacks per module



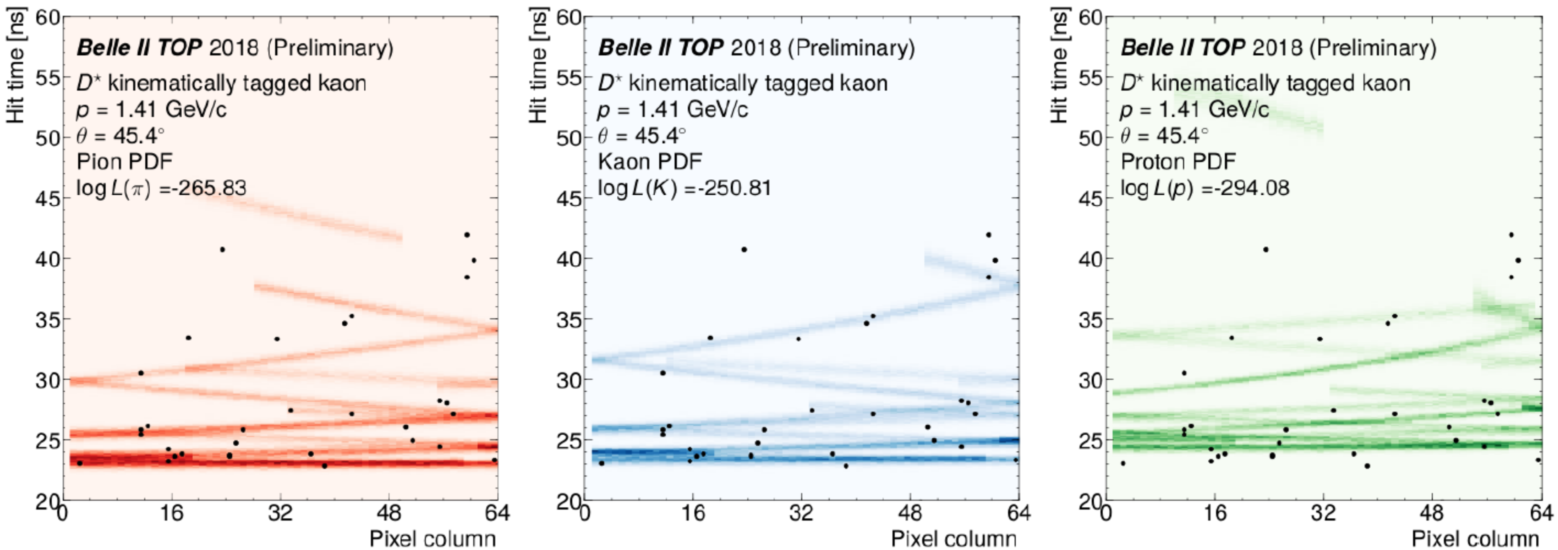
PID at TOP



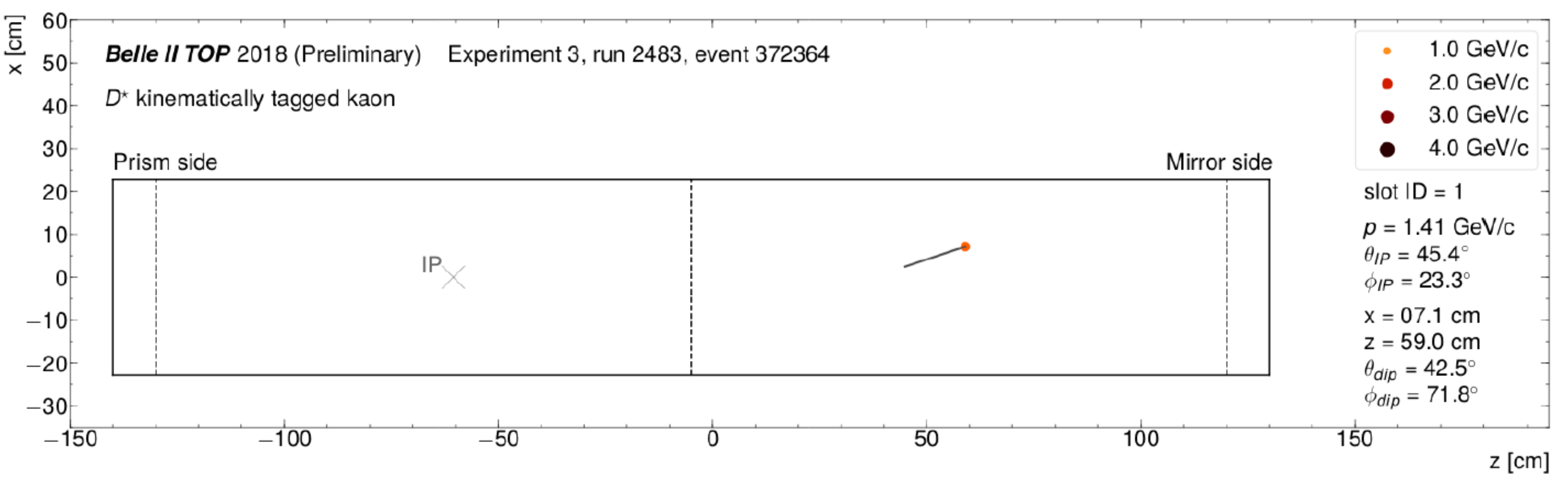
2.14 GeV kaon
(prism-facing)



PID at TOP

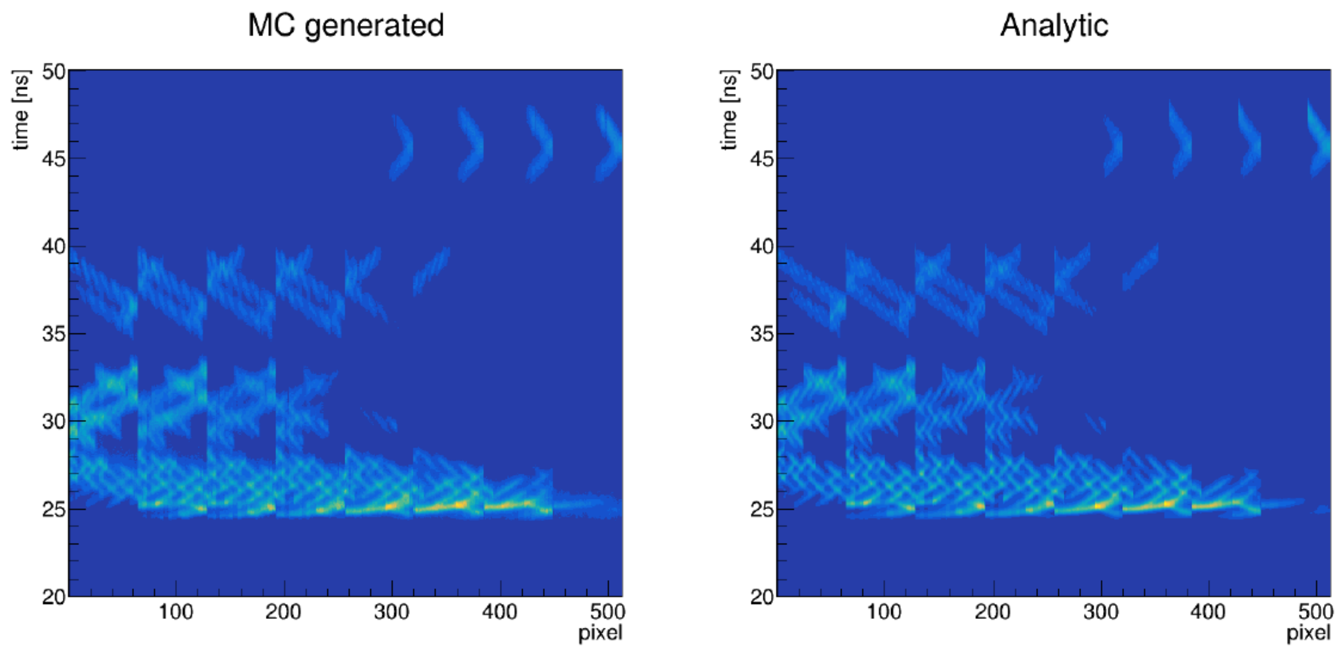


1.41 GeV kaon
(mirror-facing)

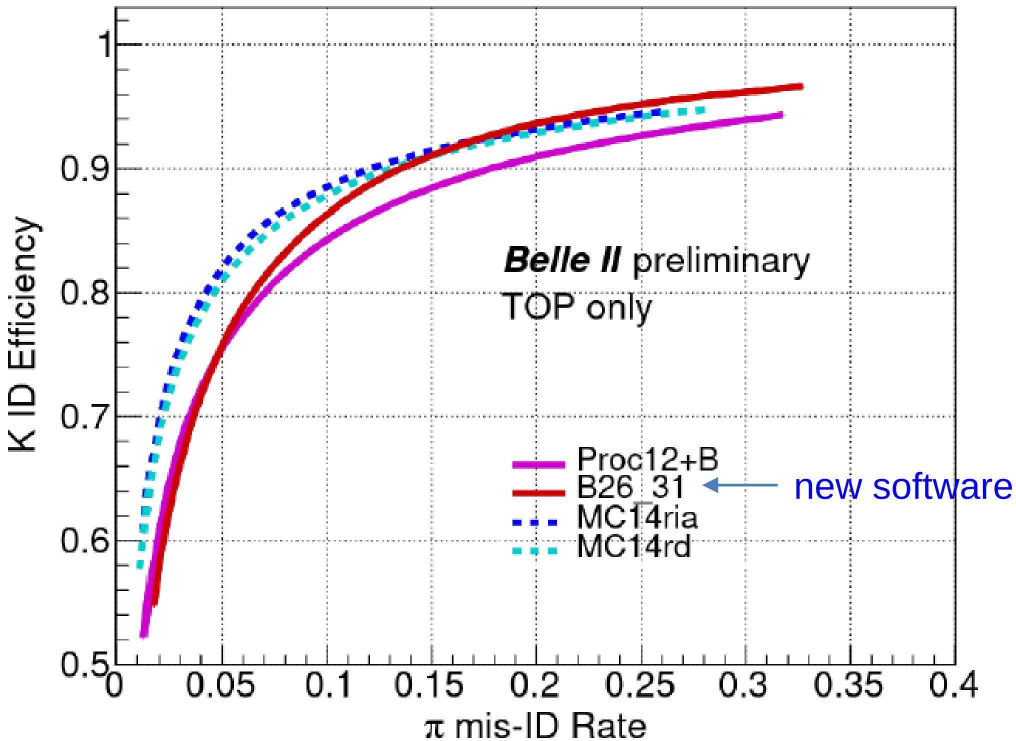


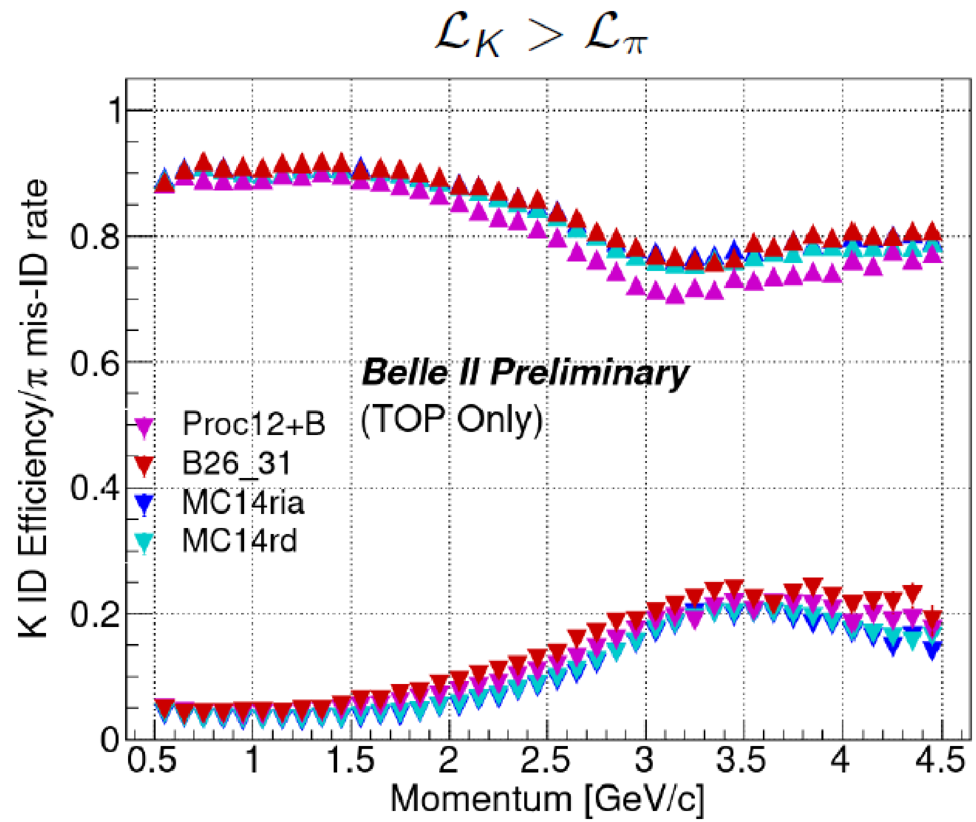
PID at TOP

- Extended likelihood method with analytically constructed PDF's to determine log likelihoods of e, μ, π, K, p, d
- PDF in a single channel described with a sum of Gaussian distr.
  - positions, widths and normalizations determined analytically according to particle impact position, angles, momentum and mass
- Method presented at RICH2010 (NIM A 639 (2011) 252-255)



PID Performance





TOP works well, but still need improvement for better performance.

- bunch-finder
- PDF reconstruction by machine learning

Future Plan and R&D

2021	2022	2023	2024	2025	~2026	2027	2028	2029	2030	~2031

Replacement of conventional MCP-PMT

Replacement of
no life-extended ALD MCP-PMT

TOP readout upgrade

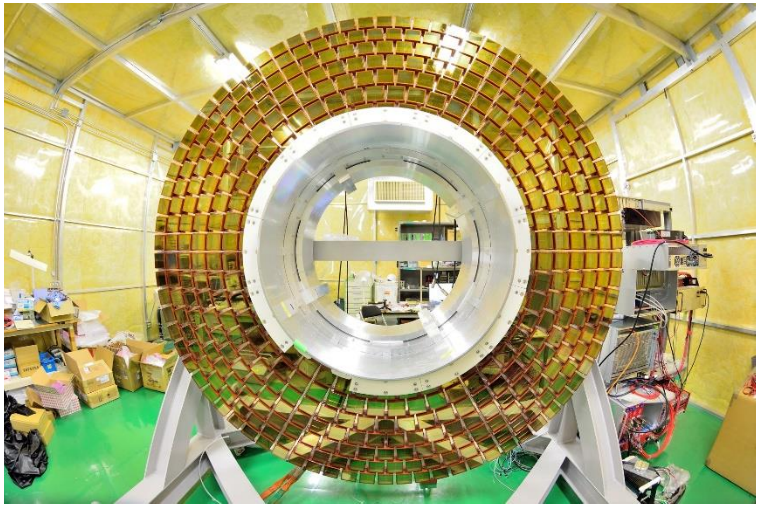
Replacement off all PMTs

TOP

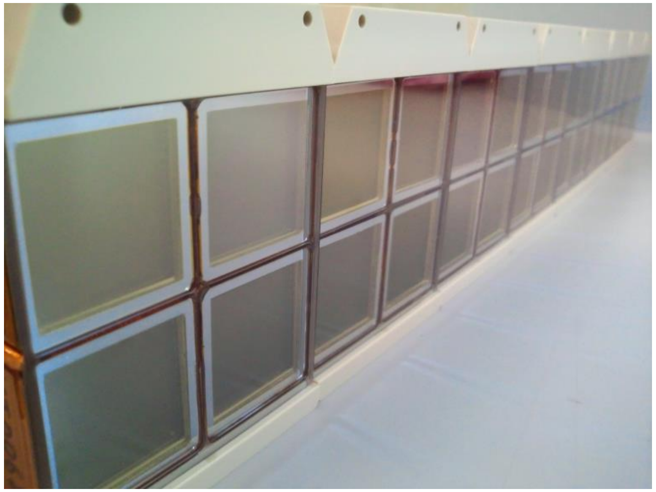
- New life-extended ALD PMTs are in production and will be replaced with remaining ALD PMTs in next long shutdown.
- Readout upgrade with higher speed and compact digitizer (new ASIC or RFSoC, Radio Frequency System on Chip)
- New photon detector option based on SiPM is in testing.
  - ✓ Need to check neutron radiation level at the detector and its tolerance of possible candidate (or new production).

Summary and Comments

- ARICH: a proximity focusing RICH detector with aerogel, in the forward endcap at Belle II.
- ARICH is running stably since 2019.
  - ✓ Simple detector.
- New photo-detectors will be a key development items for future use.
  - ✓ MPPC(SiPM): radiation ?
- For high momentum particles, aerogels with low refractive index needs to be study.



- TOP: time of propagation, in barrel region.
- State-of-the-art PID device.
  - ✓ Need more understanding
- Possible to extend to higher momentum region by putting the detector at the position with longer flight length,



Backup

Belle II Experiment

Belle and Belle II experiment:

- KEK (High Energy Accelerator Research Organization) in Tsukuba, Japan.
- Accelerator: KEKB / SuperKEKB
  - ✓ Linac + 3km ring
  - ✓ Asymmetric e^+-e^- collider
- KEKB + Belle : 1999-2010.
- SuperKEKB + Belle II : 2019-
- "B factory experiments" (produce large amount of B mesons).

KEKB

- 3.5 GeV e^+ + 8 GeV e^-.
- Max. current 2.0A (e^+), 1.4A (e^-).
- Peak lum. 2.11×10^{34} cm^{-2} s^{-1}
- Total luminosity ~1040 fb^{-1}

⇨

SuperKEKB

- 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme.
- Target luminosity
  - ✓ Total 50 ab^{-1}

SuperKEKB, Belle II Operation

2016 Feb.-Jun. : Phase 1
- SuperKEKB commissioning without Belle II detector

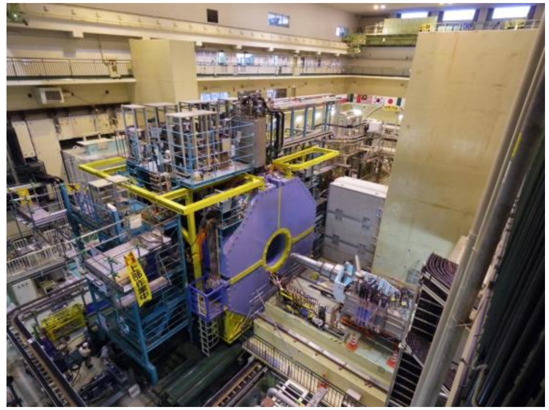
- Belle II installed in 2017. Apr.
- ARICH installed in 2017 summer.

2018 Feb.-Jul. : Phase 2
- Belle II detector without inner vertex detectors
- First collision. Commissioning of SuperKEKB and Belle II, beam background study.

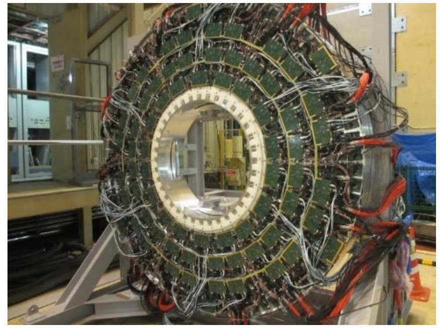
- ARICH hardware modification + re-installation

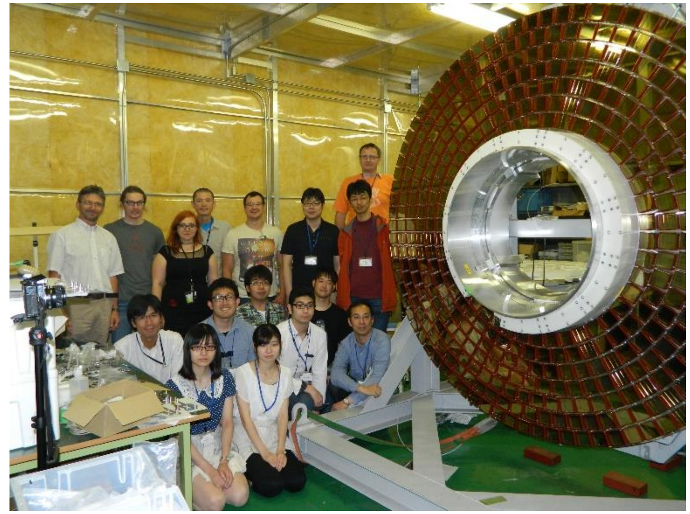
2019 Mar.- : Phase 3
- Physics run with full Belle II detector.
- 6.5 fb^{-1} accumulated in 2019 Mar.-Jul operation.
- Autumn run starts on Oct. 15.

2017/4/11



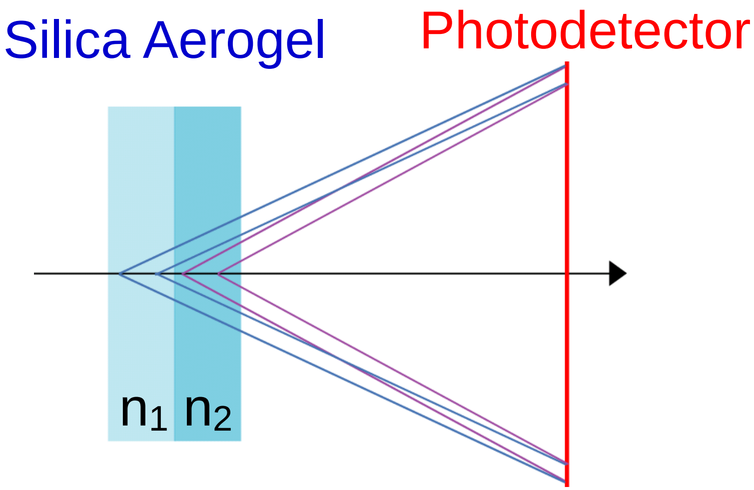
ARICH Status



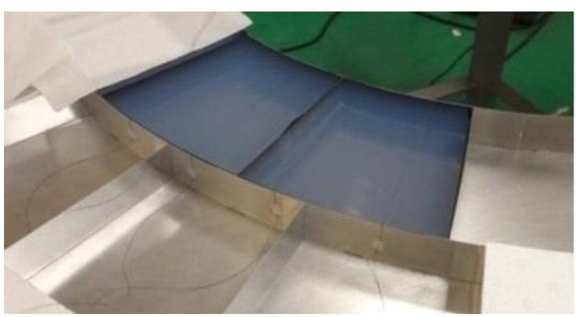


- 2017: ARICH installation to Belle II detector.
- 2018 Feb-Jun: Belle II commissioning without inner vertex detector (Phase 2).
- 2018 Sep-: ARICH hardware modification
- 2019-2022 Jun: Belle II operation with full detector (except PXD 2nd layer)
- 2022 Summer- 2023 : Long Shutdown1 LS1 (for PXD 2nd layer installation).
- 2023-: Resume operation.

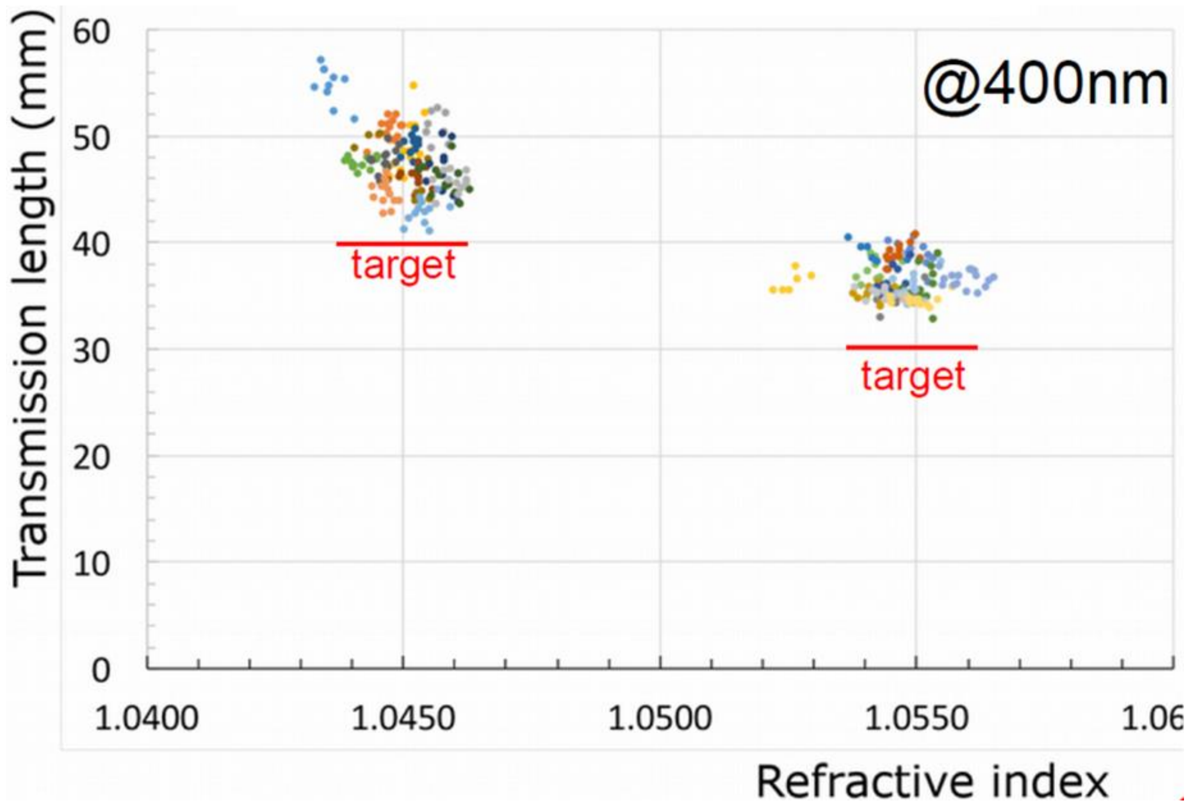
Aerogel Radiator



- n_1 = 1.045 and n_2 = 1.055
- Good transparency (~40mm)
- 248 tiles in total
  - ✓ Cut with water jet from 18cm × 18cm tile.

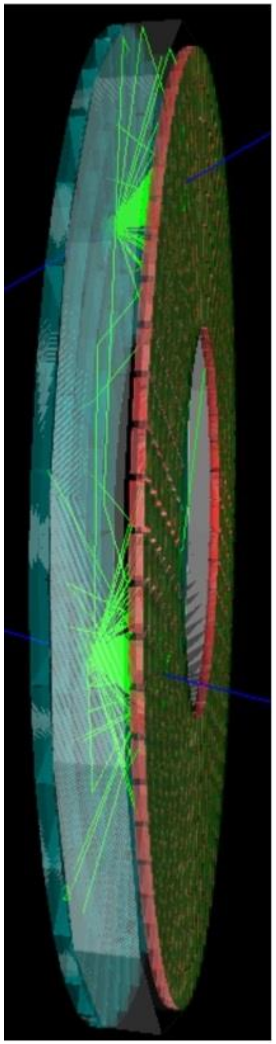


- Thicker aerogels produce more photons but make angle resolution worse.
- Two layers of aerogels with different indices.
  - ✓ Ring images overlap at the photo-detector.

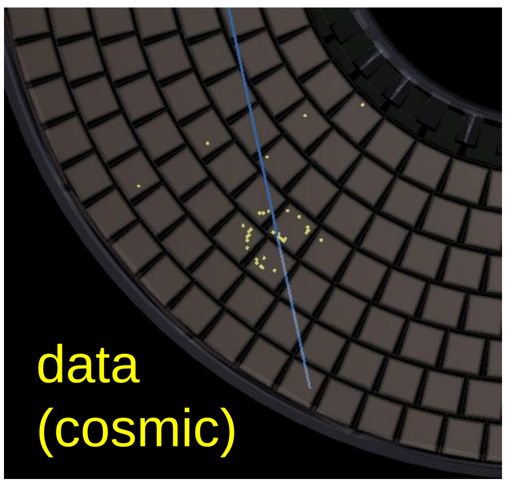


Cherenkov Angle

MC



- Rough performance can be obtained Cherenkov angle (σ_θ) and Number of photons per track ($N_{p.e.}$)
- Distribution with Bhabha sample from the commissioning run (2018).
  - ✓ $N_{p.e.}$ = 9.5 (10.4), σ_θ = 16.3 (14.7) mrad in data (MC)
  - ✓ corresponding to 4.3 σ K/π separation at 4 GeV.

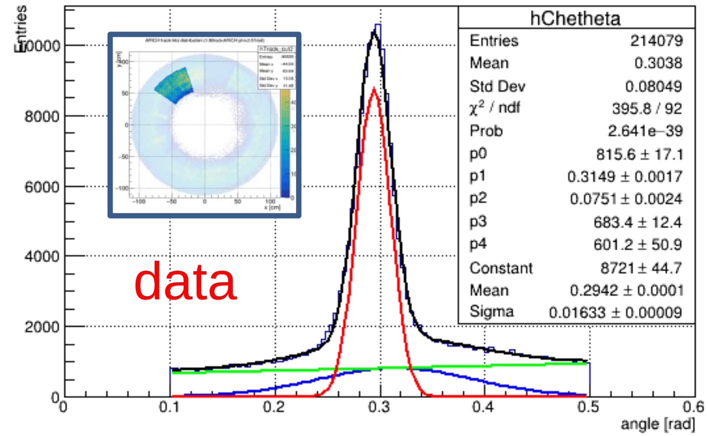


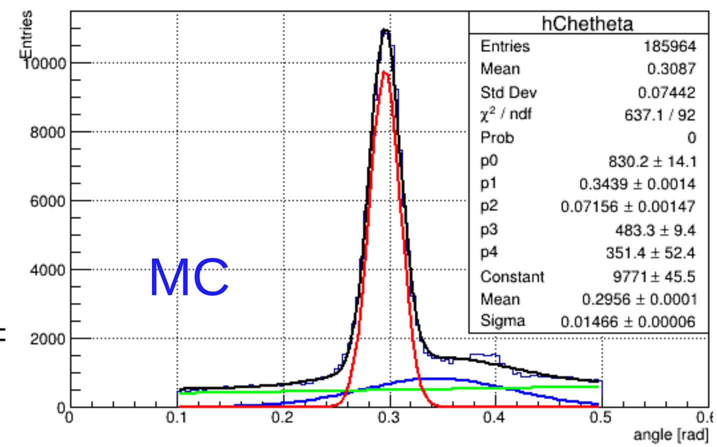
ARICH is working well

performance:

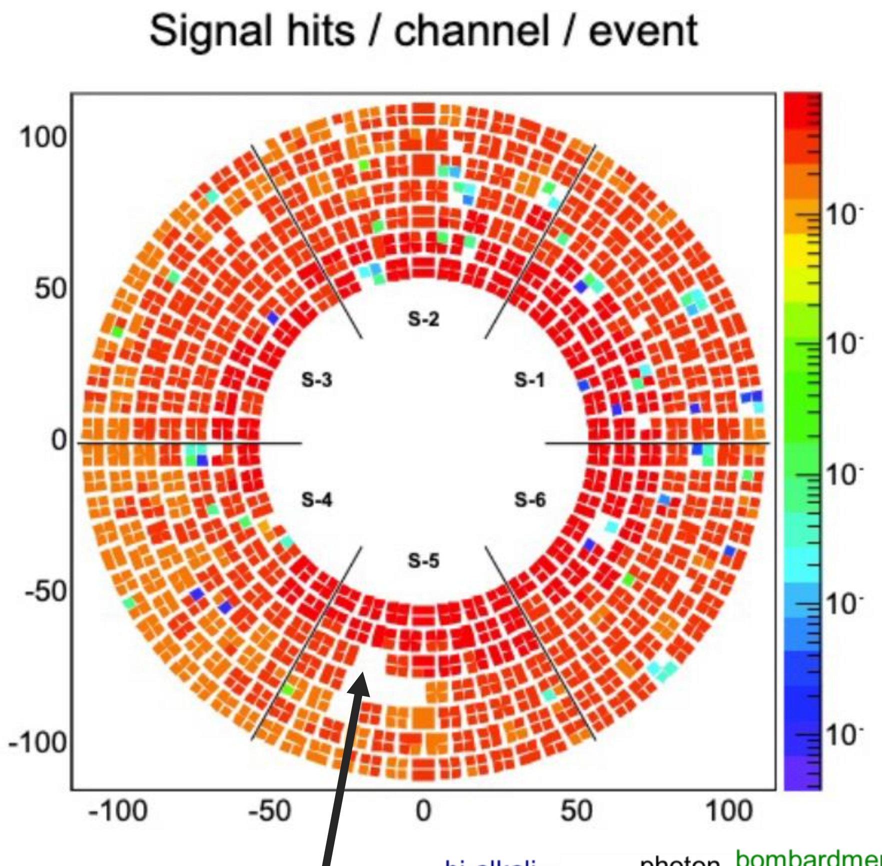
$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

Cherenkov Angle distribution (Bhabha, 2018)

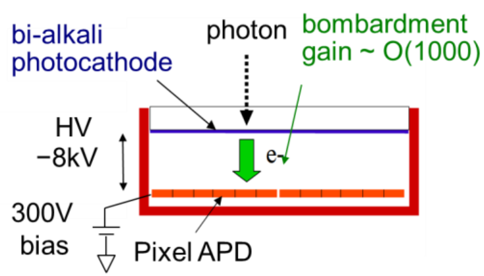




HAPDs



LV cable failure



Status of HAPD operations in 2022

- 5 HAPDs (1.2%) are off due to a problem of LV cable to the front-end electronics.
  - ✓ Fixed in 2022 summer.
- 3% of channels suffer bias (or guard) problem inside APD.
  - ✓ Typically due to sudden increase of leakage current.
- 2% of channels suffer HV problem.
  - ✓ Probably outside of HAPDs.

Total 6% dead

The effect of dead channels to PID performance is very small.

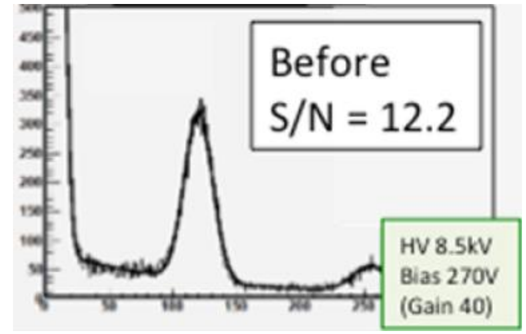
Radiation

- ARICH operation has been stable. No major problem happened in ARICH.

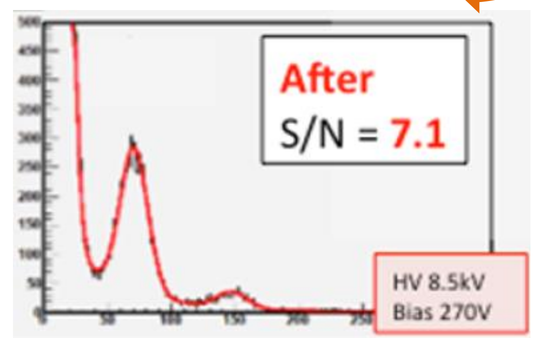
- ARICH is relatively tolerant to the beam background.
  - ✓ In general, large beam background is an issue to Belle II detector.
- One concern is the neutron radiation.

- Deterioration of HAPDs (increase of the leakage current, larger noise) due to silicon bulk damage by neutrons.
  - ✓ Tolerant to 10^{12} neutrons / cm^2 @ 1MeV equiv., assumed for to 10 years' operation.
  - ✓ Sensor performance will be gradually degraded, with a very modest effect on the PID performance.
- Single event upset in the FPGAs electronics.

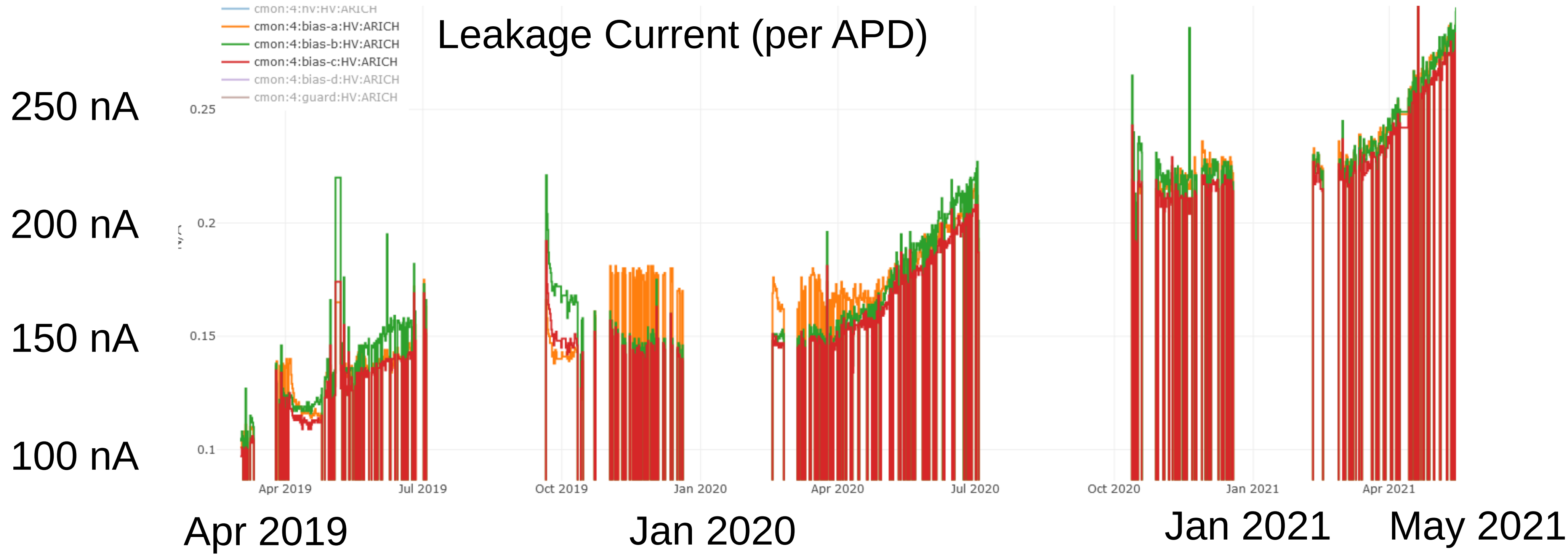
neutron irradiation test of HAPD



0.5×10^{12} n / cm^2



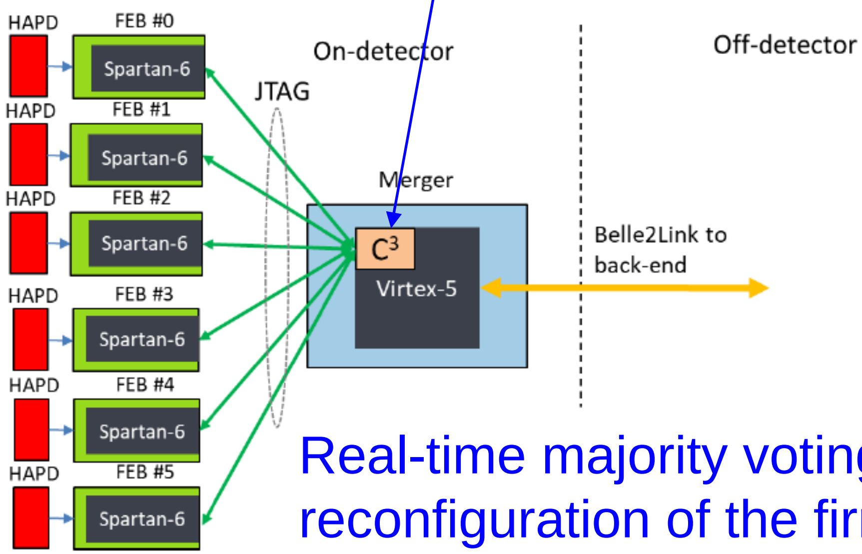
HAPD Leakage Current



- Leakage current of APD (bias) increases at ~ 10-30 nA / months.
- Estimated neutrons ~ (0.3-1) × 10^9 n / cm^2 / month; 6 × 10^9 n / cm^2 till now.
- Below the original expectation (10^{11} n / cm^2 / year or 10^{12} n / cm^2 in 10 years' operation)

SEU in the front-end

Another effect from neutrons is SEU (Single Event Upset) in the FPGAs



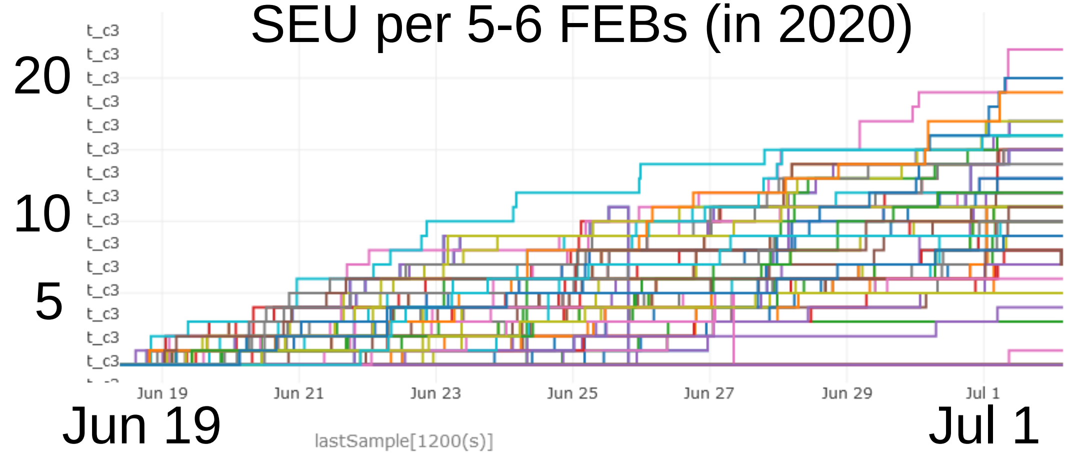
- Frequent SEUs expected at Spartan 6.
  - ✓ Boron is used as p-type dopant.
  - ✓ old estimation: 8 SEUs / h / HAPD in the firmware.
- Configuration consistency corrector (C^3) is implemented in the merger firmware.

Real-time majority voting + partial reconfiguration of the firmware.

[R.Giordano et. al. IEEE Trans. Nucl. Sci. 68, no 12, 2810 (2021) arXiv:2010.16194]

- ~0.5 SEUs / FPGA per day are detected (and fixed).
- DAQ failures possibly due to SUEs happened a few time per month. Maybe an issue in future with higher luminosity (raidiation).

SEU per 5-6 FEBs (in 2020)

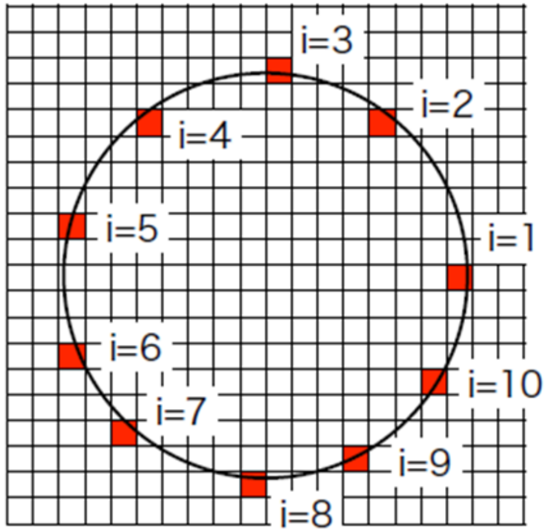


Particle Identification

Particle Identification (PID) by ARICH is obtained from the comparison of the hit pattern and the expected PDF for different particle hypothesis.

$$\ln \mathcal{L}_h = -N_h + \sum_{\text{hit } i} [n_{h,i} + \ln(1 - e^{-n_{h,i}})]$$

h: particle hypothesis (e, μ, π, K, p,..)
N_h : expected total number of hits
$n_{h,i}$: expected number of hits (probability) at pixel i



Note: ARICH has only ON/OFF information in each channel (pixel).

Likelihood ratio

$$R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

$$R_{\pi/K} = \frac{\mathcal{L}_\pi}{\mathcal{L}_K + \mathcal{L}_\pi} = 1 - R_{K/\pi}$$

Future Upgrade

This table is only for the purpose to give a rough idea. The values depend on model numbers; some values are not confirmed.

	HAPD	MPPC (SiPM)	LAPPD
Pad / Position	4.9mm × 4.9mm	3.0mm × 3.0mm	1mm resolution
PDE	~20% (QE ~ 30%)	~40%	~15% (QE ~ 20%)
Gain	7×10^4	6×10^6	$\sim 10^7$
Wavelength	200-600 nm	320-900 nm	(200-600 nm)
Dark Count	~0	~0.5 MHz	<150 Hz / s / cm^2
Operation voltage	−8kV HV + 350V bias	60V	3kV HV
Radiation damage	Tolerable at Belle II	Weak	(OK)

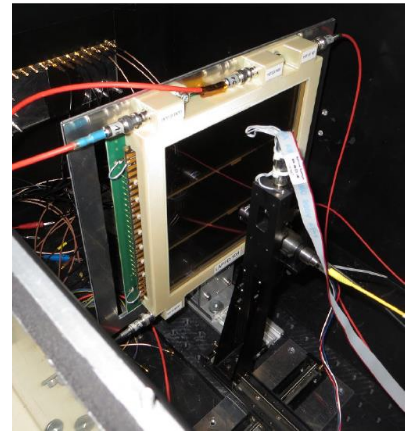
- MPPC (SiPM) has good performance, but radiation tolerance is an issue.
- LAPPD is still under development.

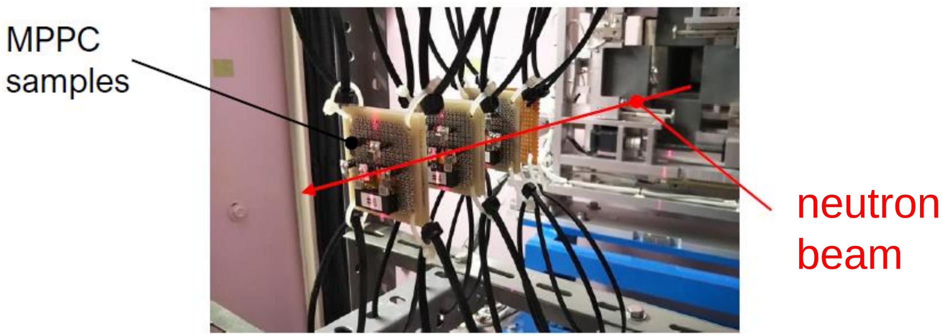
Future Upgrade

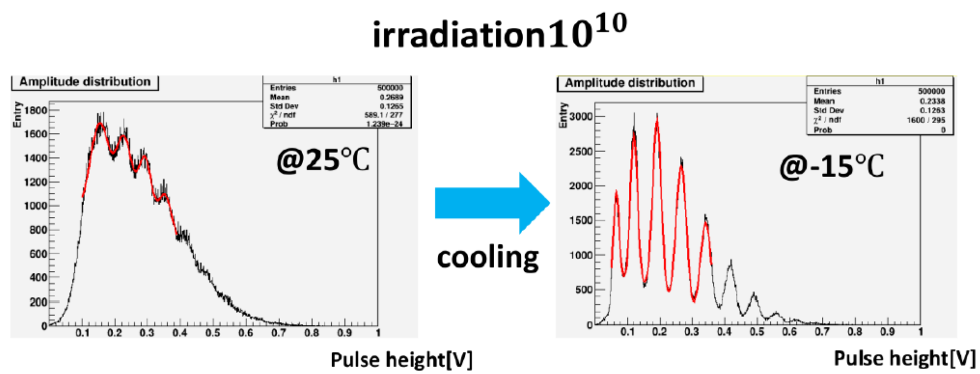
Radiation tolerance is an issue for MPPC

- Neutron irradiation test for MPPC is performed at J-PARC MLF in 2020.
- Single photon cannot be measured after 10^{10} n / cm^2 (@ 1 MeV equiv), while 10^{12} are expected for 10 years operation at Belle II.
- Cooling is necessary (but not studied yet).

test of LAPPD just started







At this stage, we still don't have clear strategy for photon detector upgrade.