ARICH Detector at Belle II

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KEK

2022 International Workshop on the High Energy Circular Electron Positron Collider

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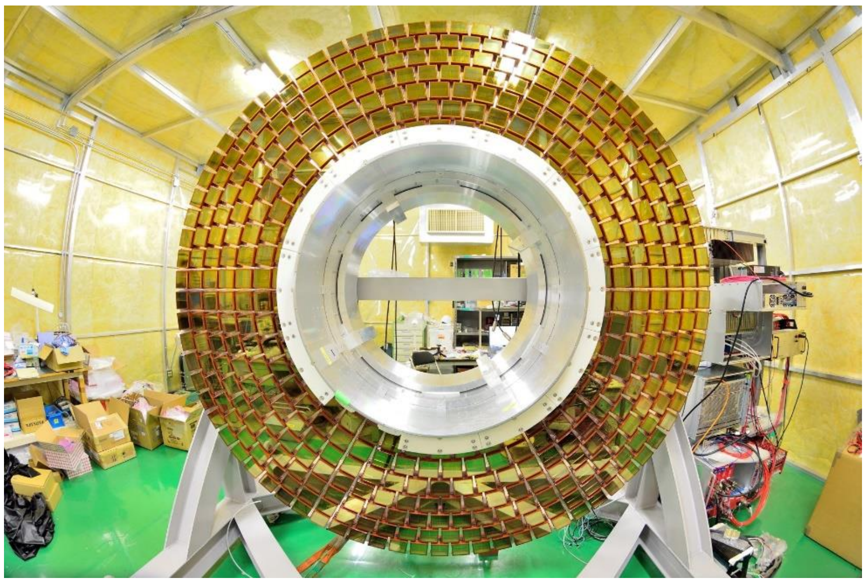
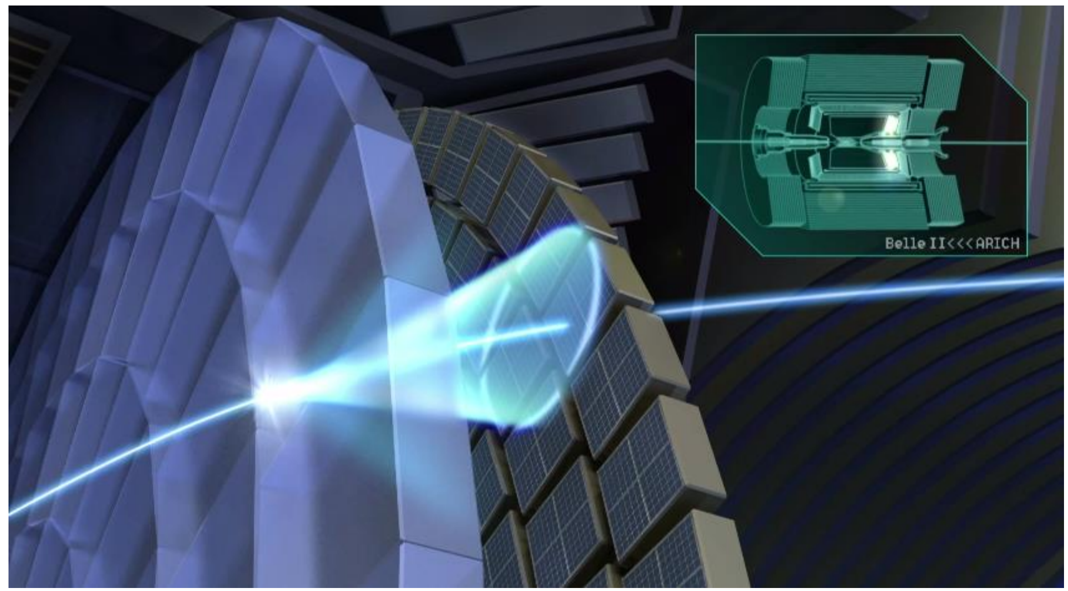
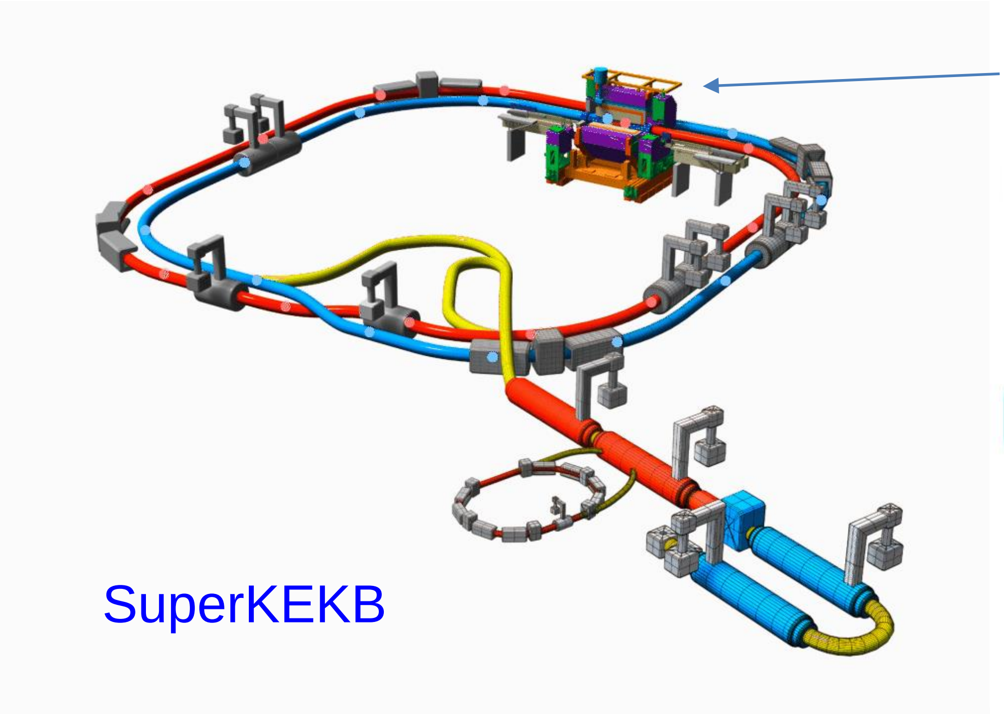
Belle II ARICH Group

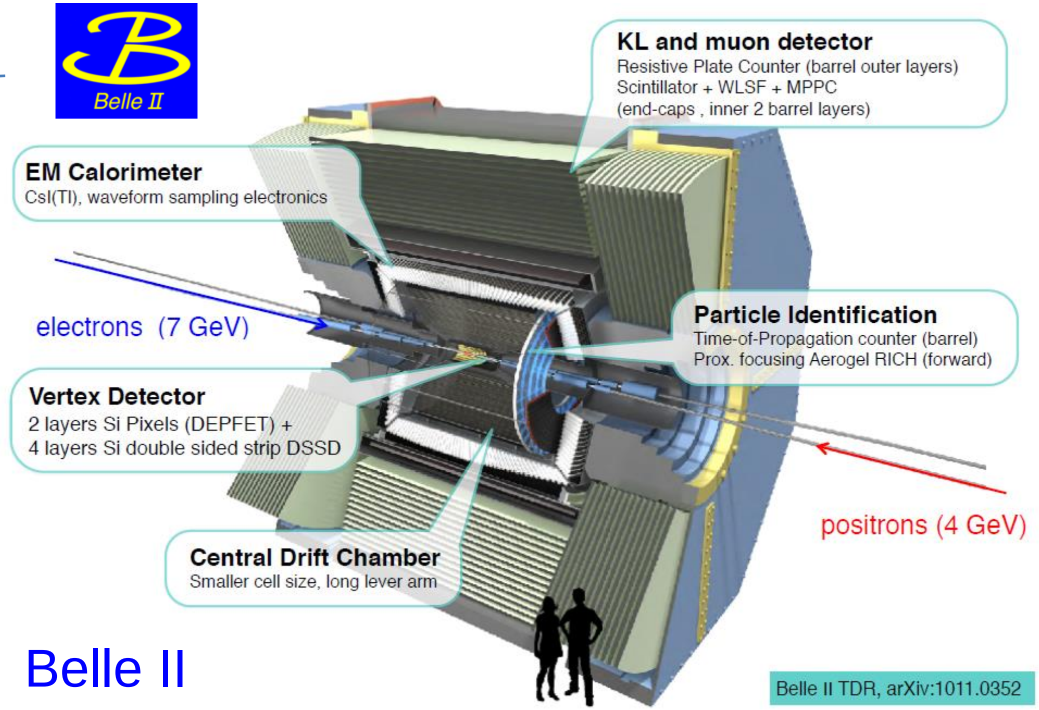
KEK, Chiba, Nagoya, Niigata, TMU, Toho (Japan)
JSI (Slovenia), LAL (France),
AANL (Armenia)





Belle II @ SuperKEKB

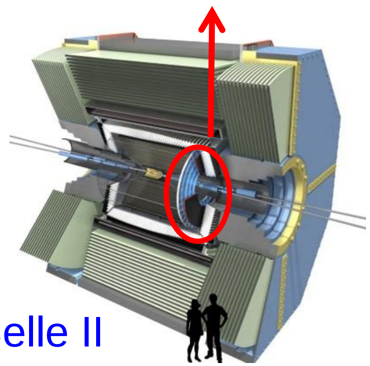




- Belle II experiment at KEK: flavor physics experiment, successor of Belle.
- SuperKEKB Asymmetric electron-positron collider: 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme to achieve high luminosity.
- Operation with full detector started in 2019.
- Luminosity 4.7×10^{34} cm^{-2} s^{-1} achieved so far (aiming one order higher).
- Plan to accumulate 50 ab^{-1} in ~10 years (50 times of Belle).

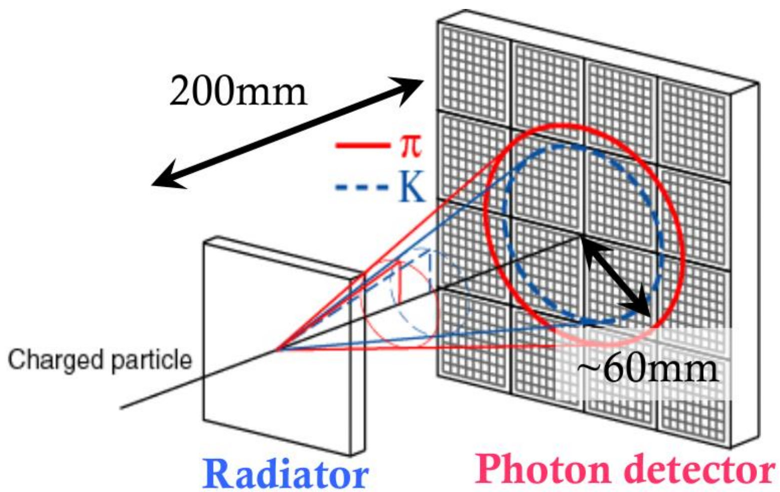
Aerogel RICH

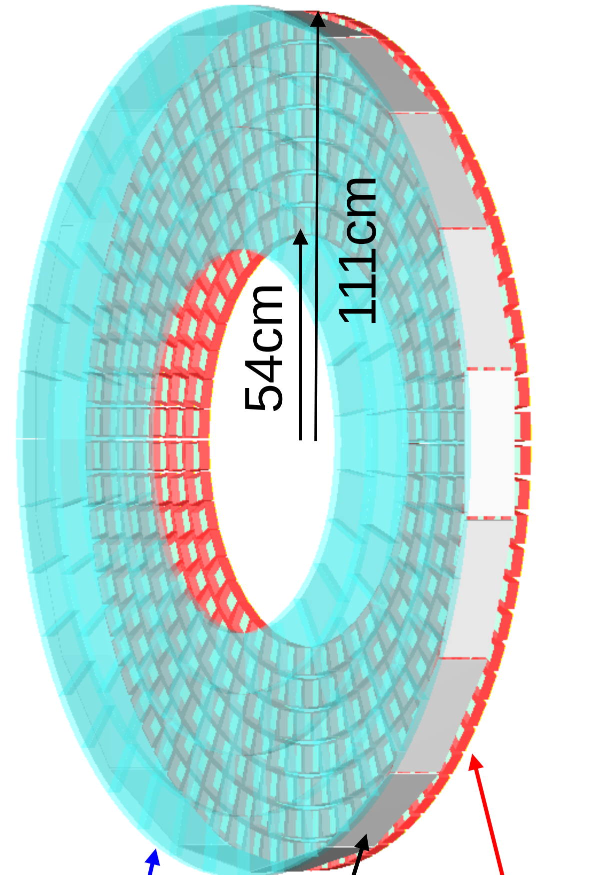
Aerogel RICH (ARICH)



- Ring Imaging Cherenkov Counter (RICH) with aerogel radiator.
- PID device at the forward endcap.
- Replace threshold type Aerogel Cherenkov Counter used in Belle.
- Limited space available
  $\rightarrow$ proximity-focusing RICH.

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



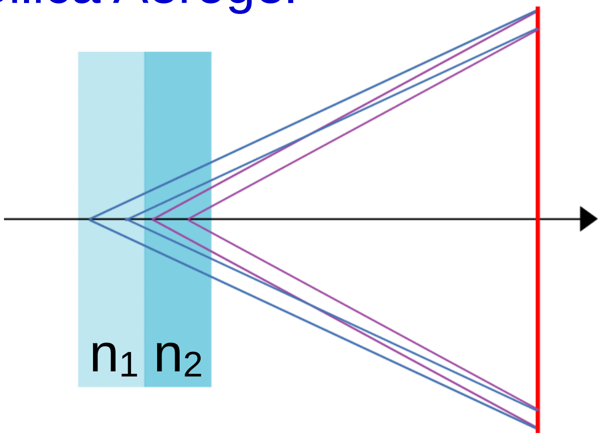


performance:

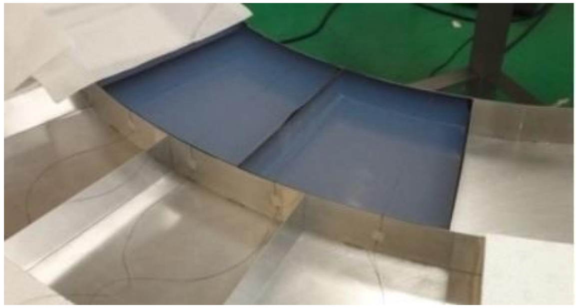
$$\sigma_{\mathrm{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

$\theta_C(\pi) - \theta_C(K) \sim 23$ mrad (@ 4 GeV; n = 1.05)

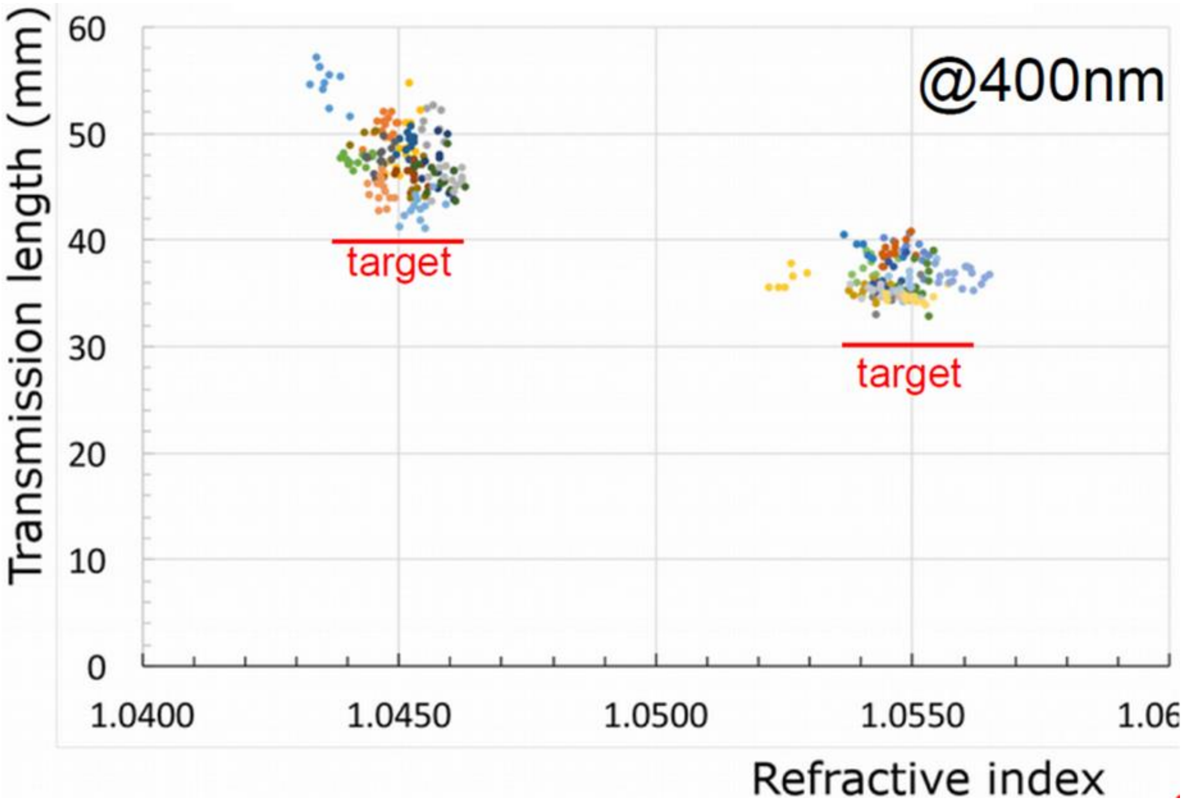
Aerogel Radiator



- 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.

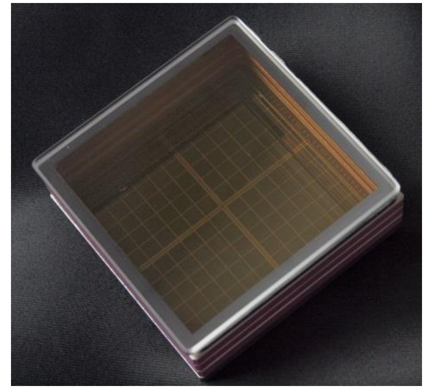


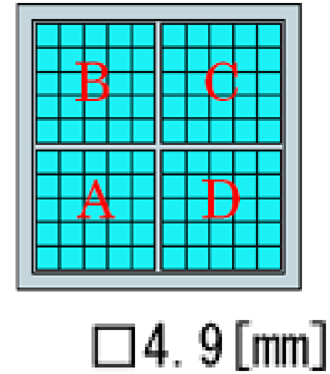
Photodetector

Photodetector

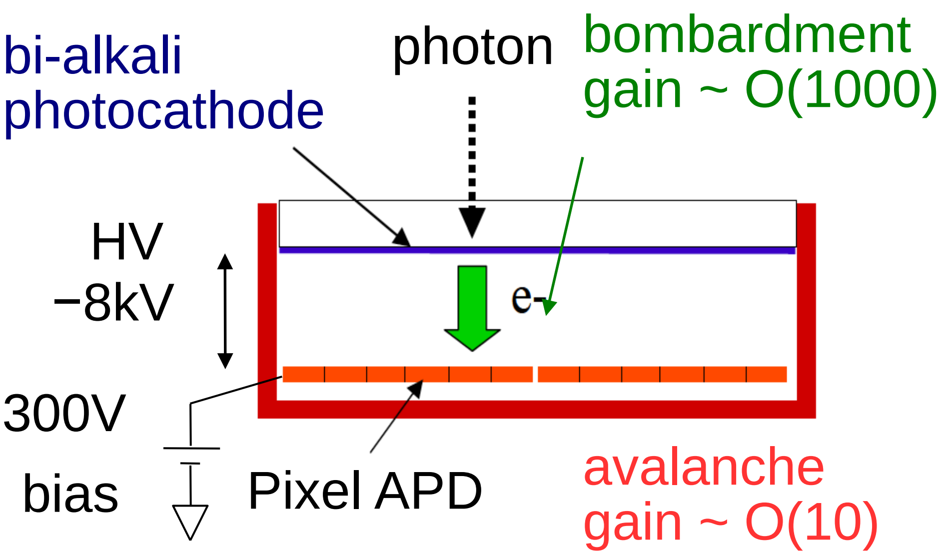
- ~5mm pixel size. Sensitive to single photon
- Large coverage (3 m^2).
- Immune to 1.5T magnetic field.
- Radiation tolerance (10^{12} cm^{-2} neutron).

⇨ HAPD (Hybrid Avalanche Photo-Detector)





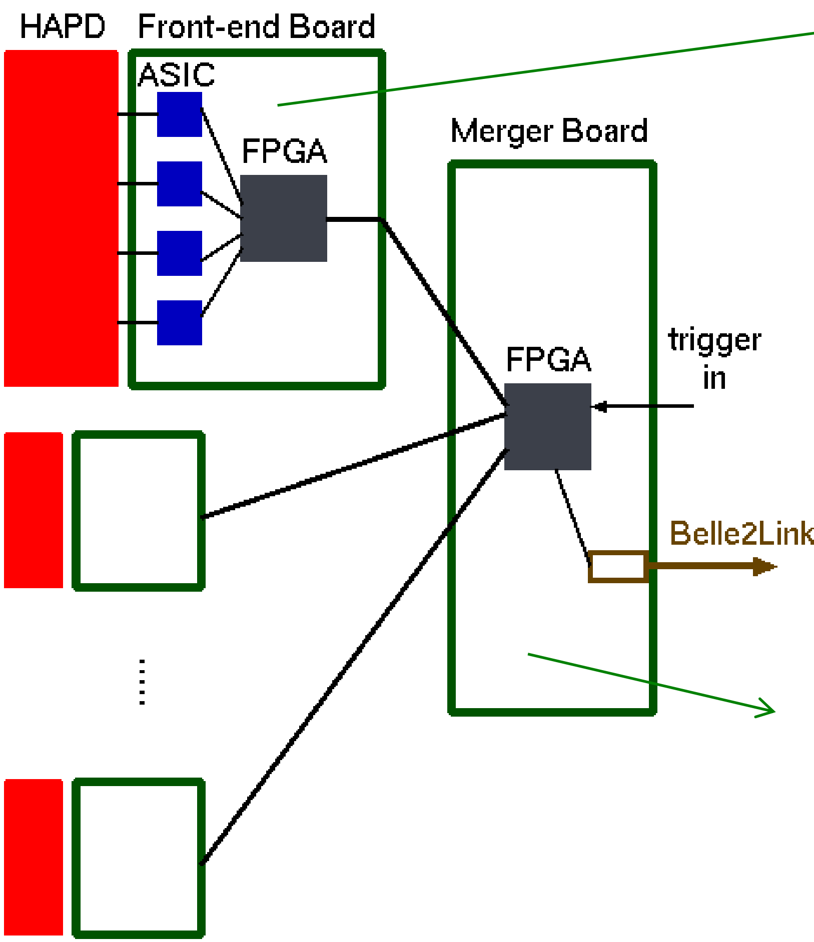
Hybrid: Vacuum tube + semi-conductor



- 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

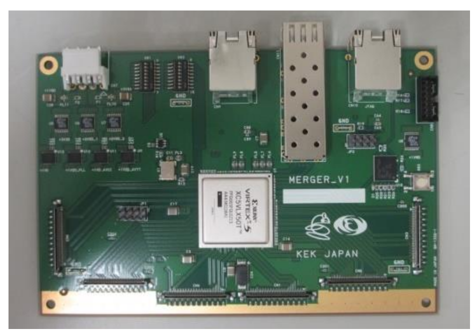


Front-end Board

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

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

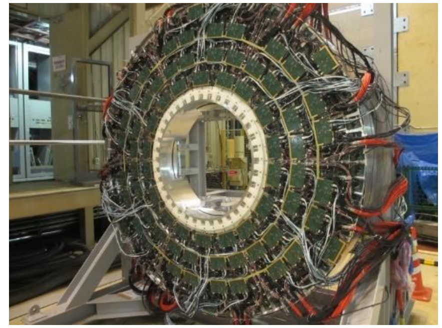
Merger

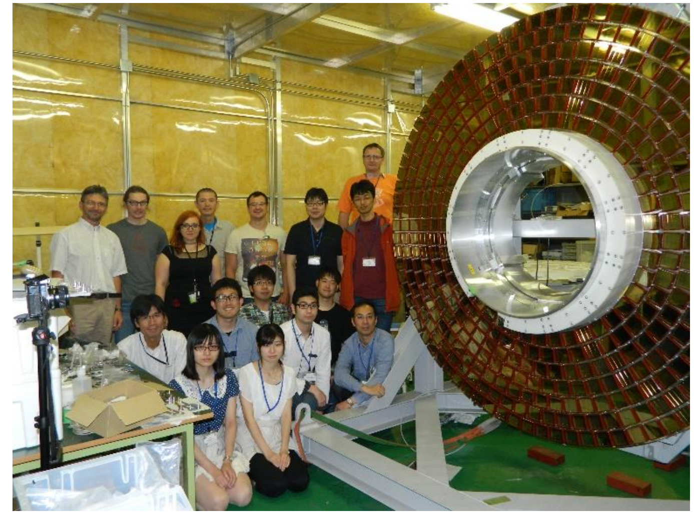


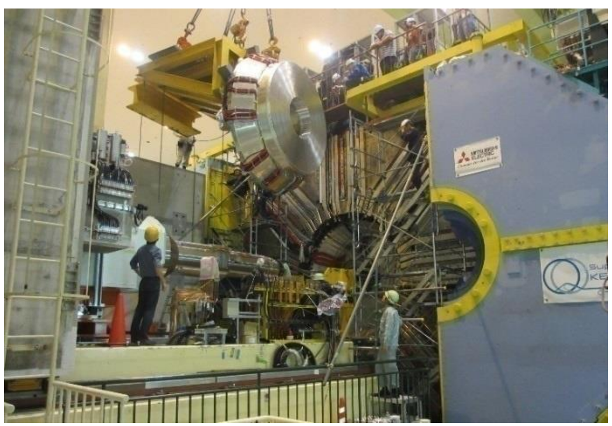
- Receive hitdata from 5-6 front-end boards.
- Zero suppression.
- Send to DAQ.

420 HAPDs + Front-end Boards
72 Merger Boards

ARICH Status



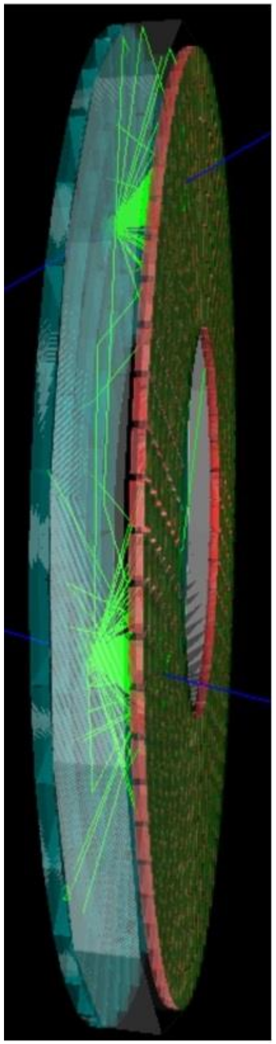




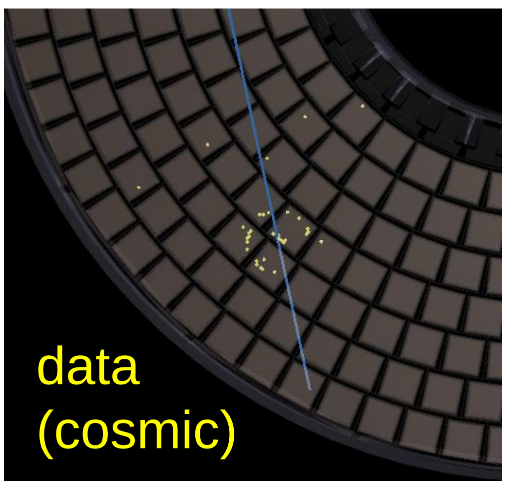
- 2017: ARICH installation to Belle II detector.
- 2018 Feb-Jun: Belle II commissioning without inner vertex detector (Phase 2).
- 2018 Sep-: ARICH hardware modification
- 2019-2022 Jun: Belle II operation with full detector (except PXD 2nd layer)
- 2022 Summer- 2023 : Long Shutdown1 LS1 (for PXD 2nd layer installation).
- 2024-: Resume operation.

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.

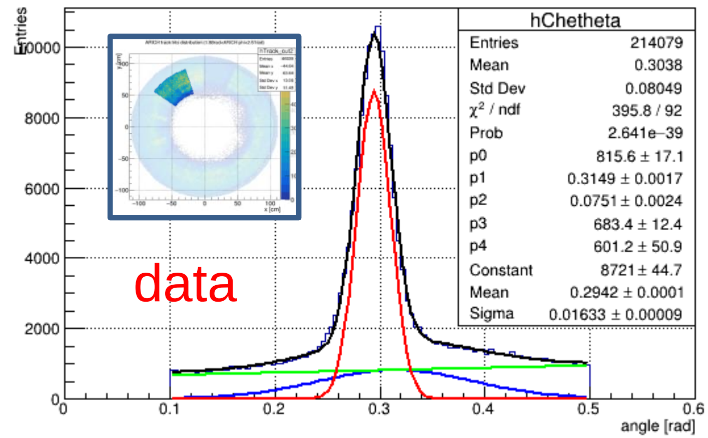


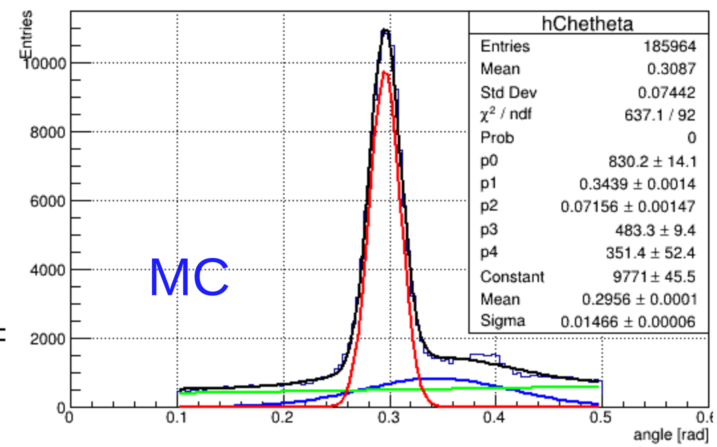
ARICH is working well

performance:

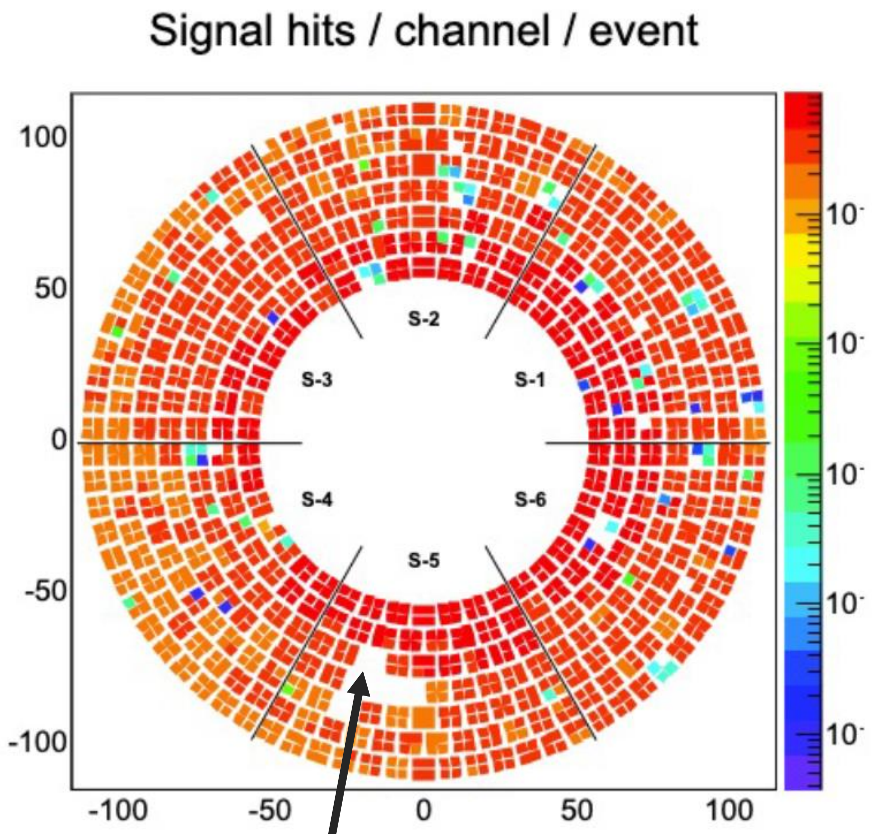
$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

Cherenkov Angle distribution (Bhabha, 2018)

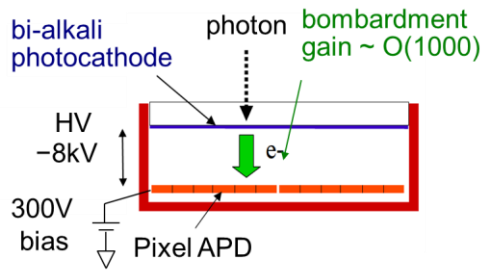




HAPDs



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.

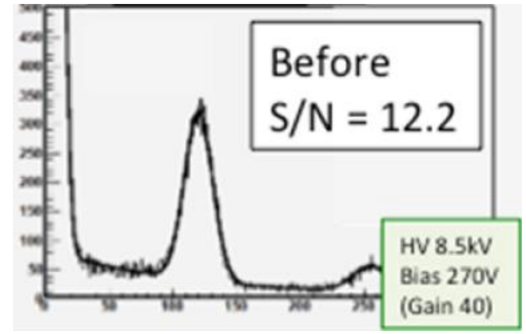
Radiation

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

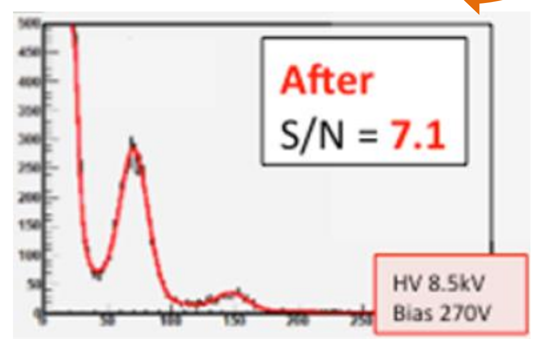
- ARICH is relatively tolerant to the beam background.
  - ✓ In general, large beam background is an issue to Belle II detector.
- One concern is the neutron radiation.

- 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.

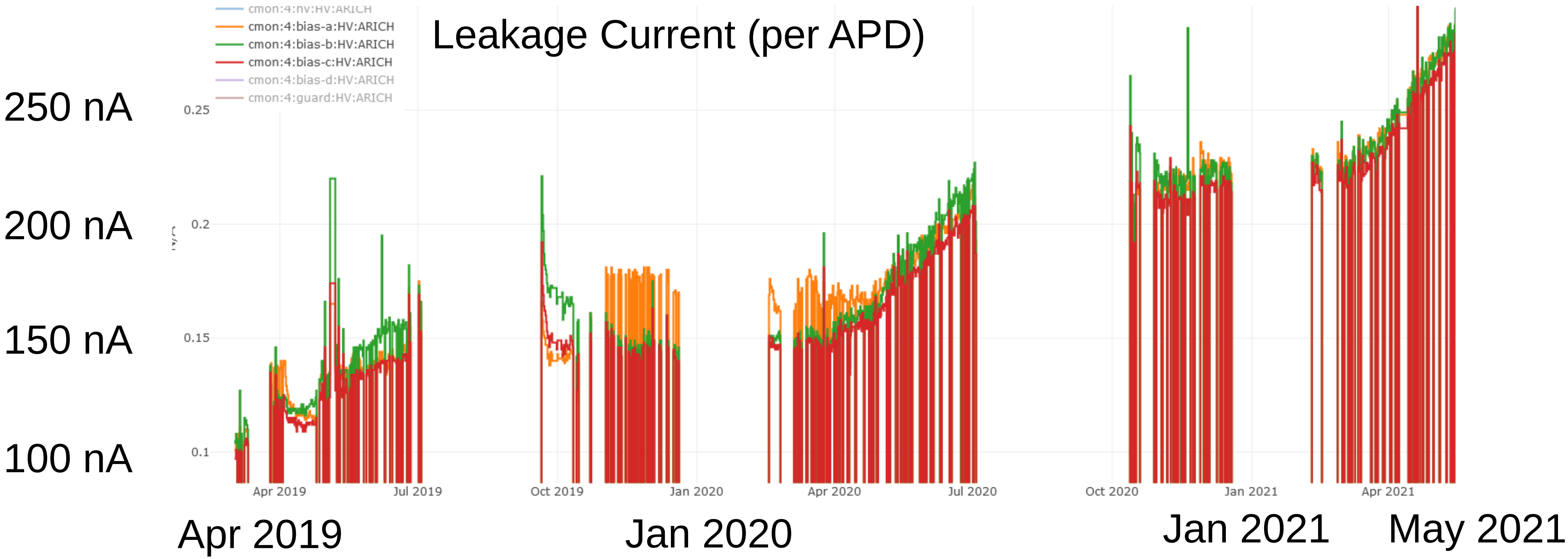
neutron irradiation test of HAPD



0.5×10^{12} n / cm^2



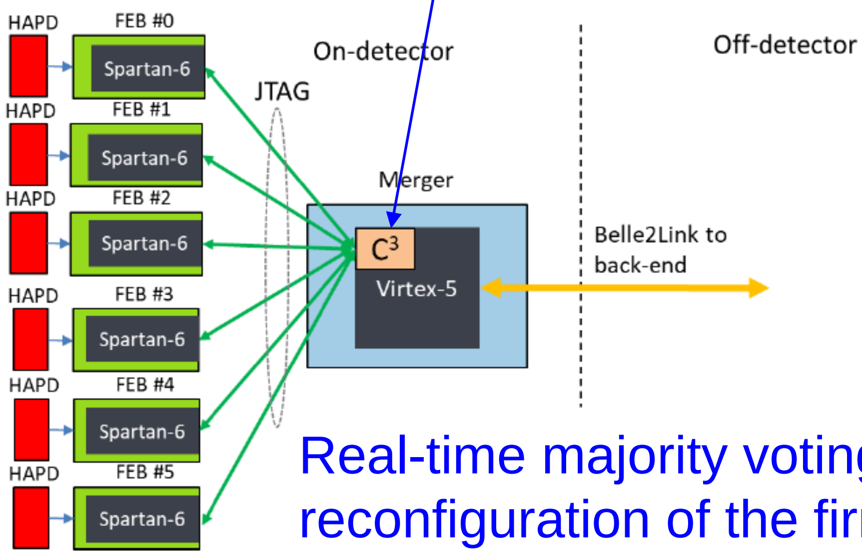
HAPD Leakage Current



- Leakage current of APD (bias) increases at ~ 10-30 nA / months.
- Estimated neutrons ~ (0.3-1) $\times$ 10^9 n / cm^2 / month; 6 $\times$ 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



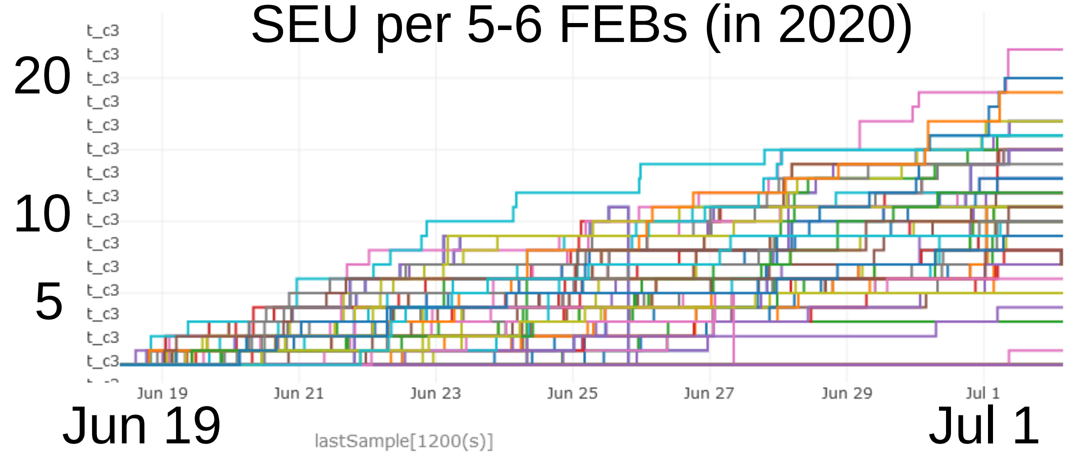
- Frequent SEUs expected at Spartan 6.
  - ✓ Boron is used as p-type dopant.
  - ✓ old estimation: 8 SEUs / h / HAPD in the firmware.
- Configuration consistency corrector (C^3) is implemented in the merger firmware.

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)

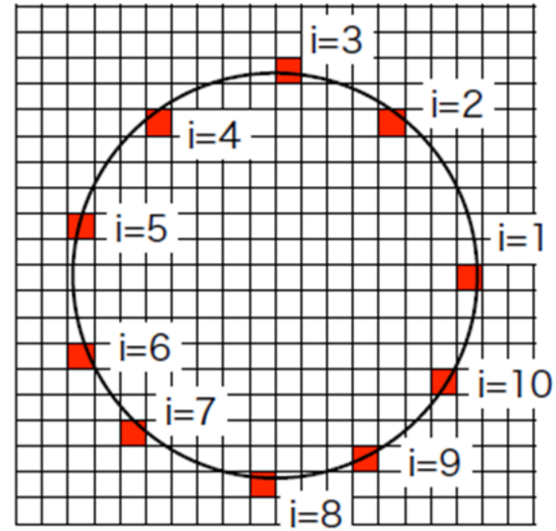


Particle Identification

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).

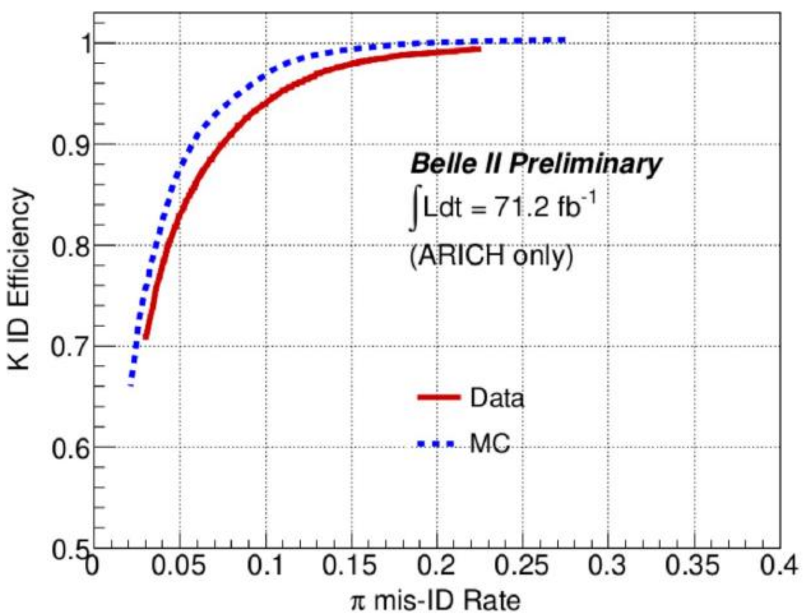
Likelihood ratio

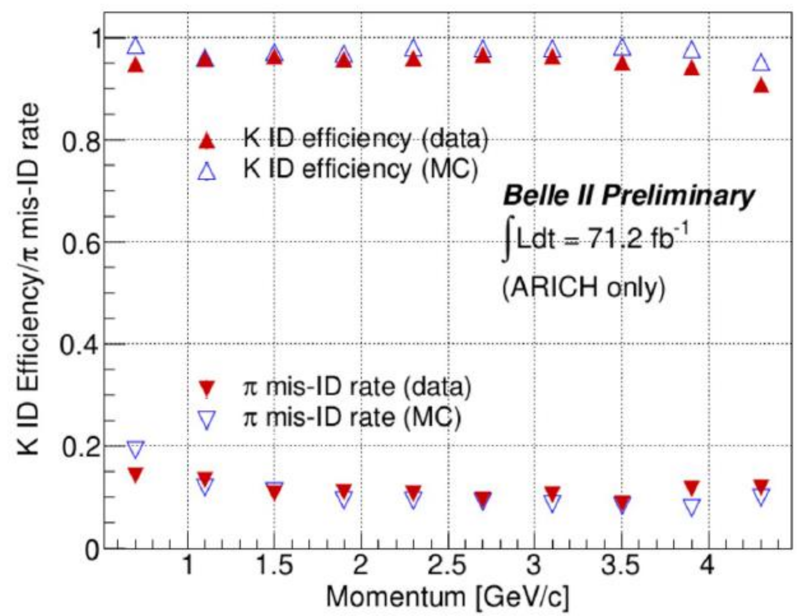
$$R_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

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

PID Performance

- although good data / MC agreement in Cherenkov angle resolution and number of photons slightly worse PID performance is observed in measured data



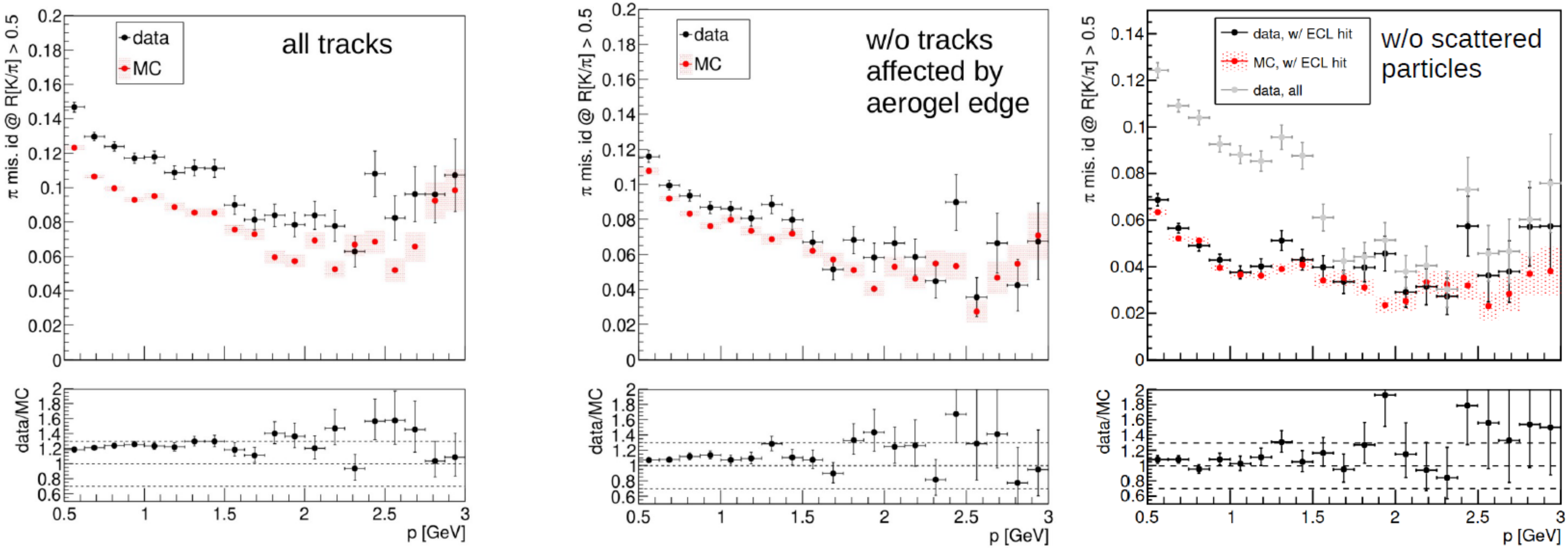


→ ~3% lower kaon id. efficiency is observed in data @ pion misid. rate of 10%

PID Performance

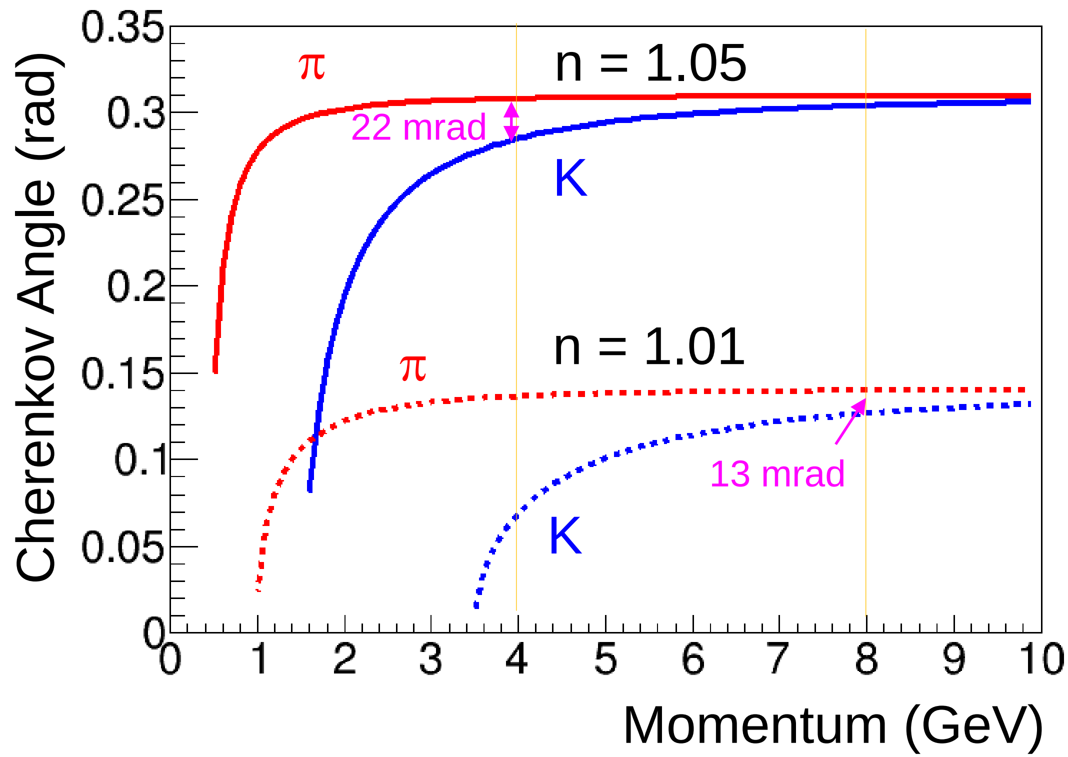
- identified sources of this discrepancy:

→ imperfect description of gaps between the aerogel tiles in the MC (photon loss)
→ misalignment of aerogel tile positions (reality w.r.t. assumed in reconstruction)
→ possible underestimate of amount of material in front of ARICH in MC
→ imperfect other alignments (global, mirrors)



Momentum Range

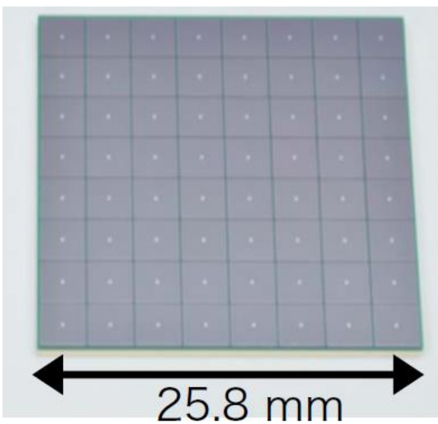
- Belle II ARICH is optimized to 1-4 GeV (n ~ 1.05).
- If you need cover higher momentum range, you can reduce the refractive index of the aerogels.
  - ✓ Cherenkov angle gets smaller, so you need larger distance or better position resolution.
  - ✓ n ~ 1.005-1.01 is minimum; 10 GeV looks the maximum.



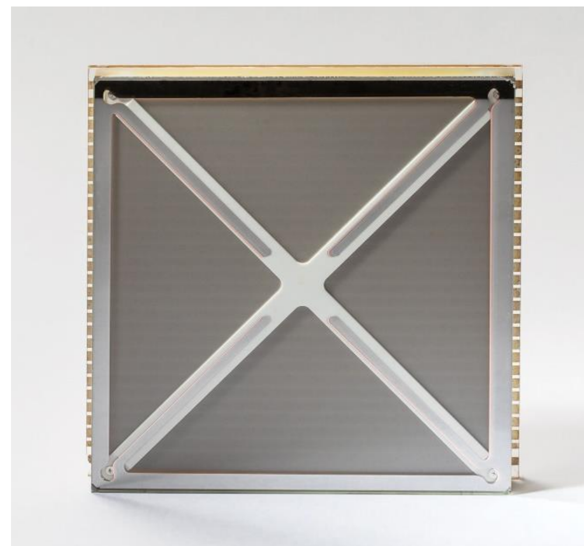
Future Upgrade

- HAPDs are expected to continue to work during 10 years operation at Belle II.
- Additional HAPDs cannot be purchased.
  - ✓ Hard (inconvenient) to treat −8kV HV + 350V bias
- Possible upgrade of photo-detectors around 2030 (?)
- Candidates: HAPD, MPPC (SiPM), LAPPD (MCP based detector)

64 (8 × 8) channel MPPC



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



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)

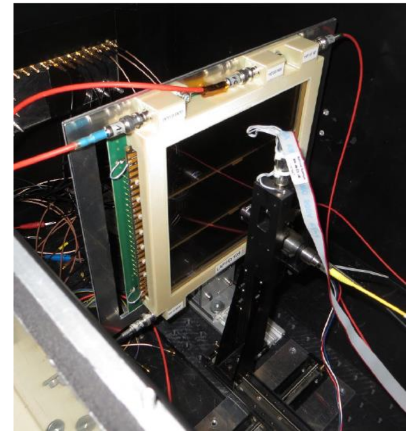
- MPPC (SiPM) has good performance, but radiation tolerance is an issue.
- LAPPD is still under development.

Future Upgrade

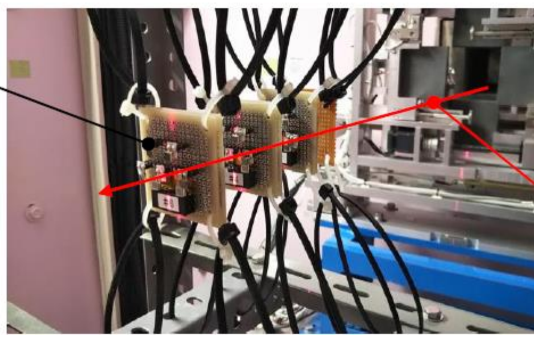
Radiation tolerance is an issue for MPPC

- 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

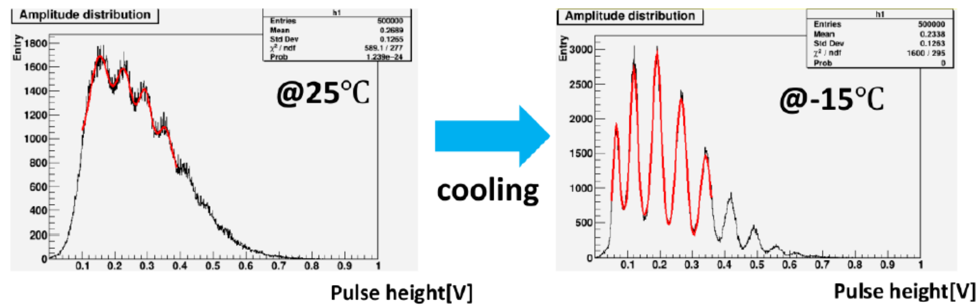


MPPC samples



neutron beam

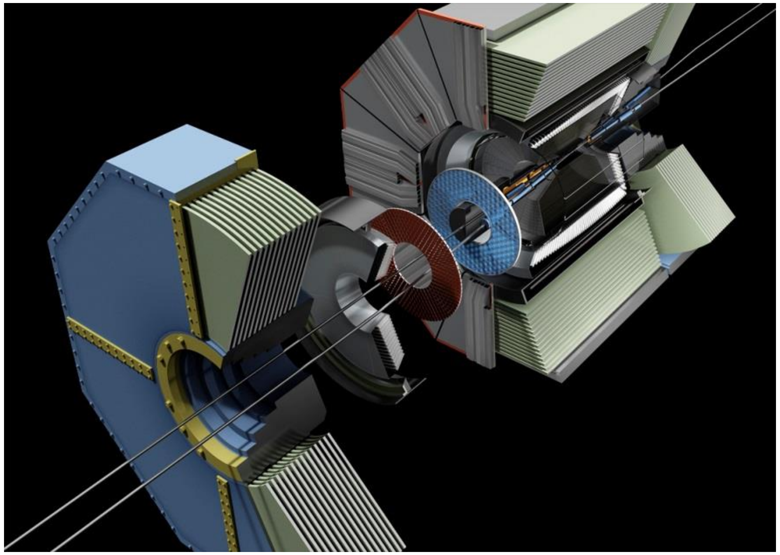
irradiation10^{10}

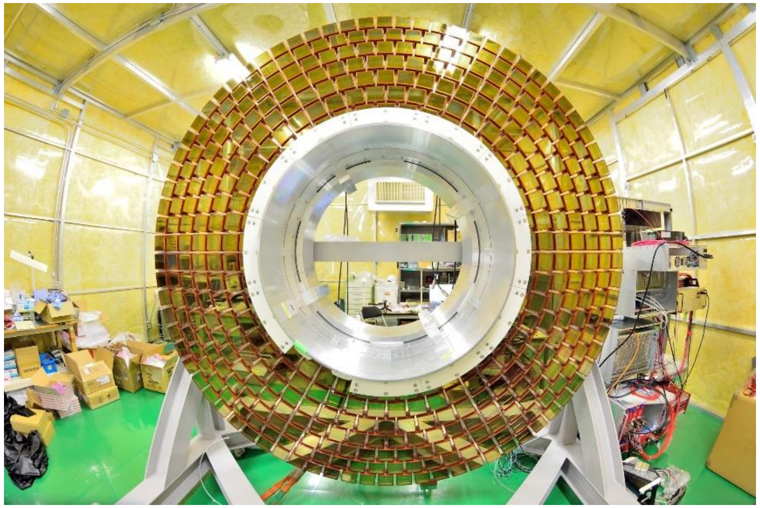


At this stage, we still don’t have clear strategy for photon detector upgrade.

Summary

- ARICH: a proximity focusing RICH detector with aerogel, for the PID in the forward endcap at Belle II
- ARICH is running stably since 2019 (start of Belle II physics run).
- Damage of HAPDs by neutrons are anticipated, but the fluence of the neutrons are well below the tolerable level.
  - ✓ SEUs in FPGAs are also managed by the auto-correction mechanism.
- Initial performance of the ARICH is estimated. Good separation is obtained.
- Other photon-detector candidates are under study for future upgrade.





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}

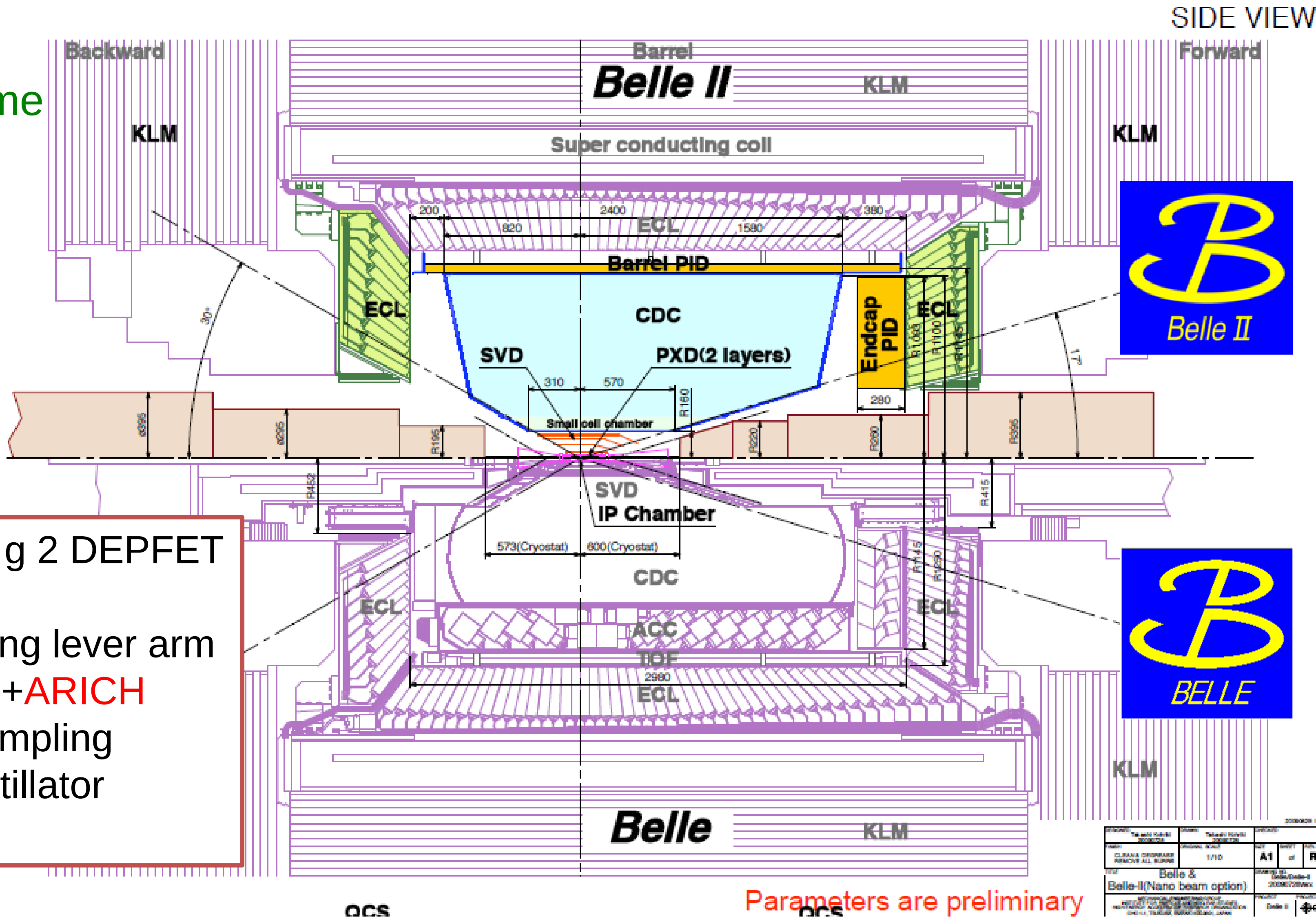
➡

SuperKEKB

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

Belle II

- At least, the same performance as Belle in higher luminosity.
- Better performance if important for physics

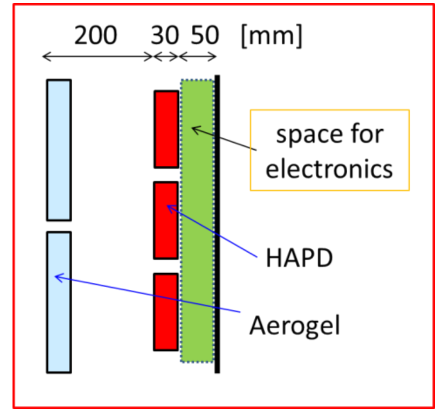


SVD: 4 DSSD lyrs g 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling
KLM: RPC → Scintillator +SiPM (end-caps)

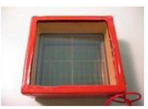
Parameters are preliminary

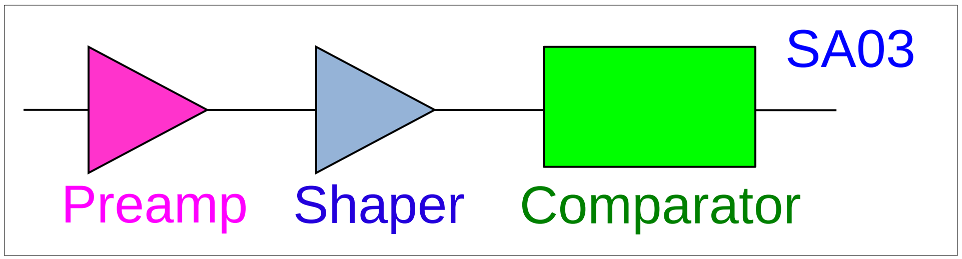
Electronics

- Total 60000 channels.
  - ✓ 1-bit ON/OFF information is enough.
- High-gain, low-noise.
- Only 5 cm available behind HAPD

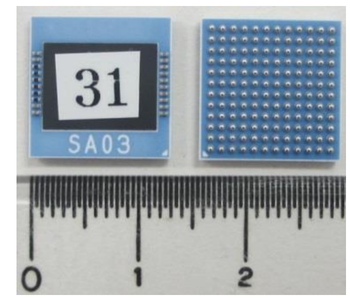


➡ ASIC (SA03)





FPGA for readout



- CMOS 0.35 μm process @ TSMC and X-FAB.
- 36 ch / chip (i.e. 4 ASIC for one HAPD).
- Variable gain (3.1-12.5 V/pC) and shaping time (100-200ns).
- Common threshold but adjustable offset (16-bit; for each channel).
- DICE (Dual Interlocked CEll) register to be tolerant to SEU.
- Mass production done at X-FAB.

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

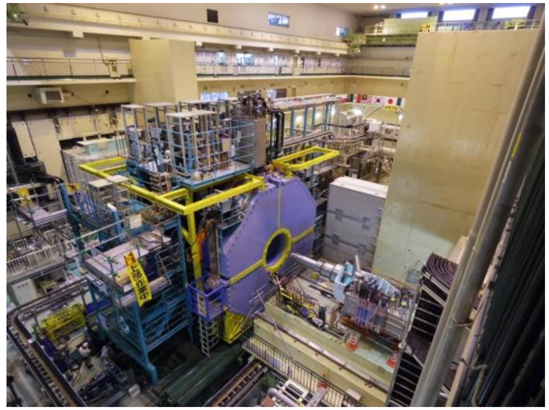
- Belle II detector without inner vertex detectors
- First collision. Commissioning of SuperKEKB and Belle II, beam background study.

- 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



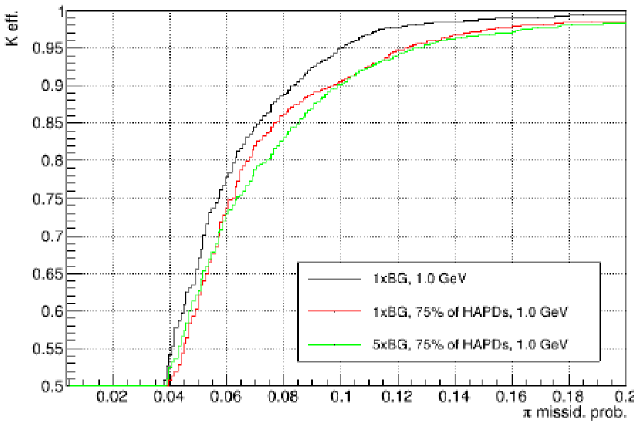
Simulation with more broken HAPDs

All HAPD alive + beam background with full luminosity

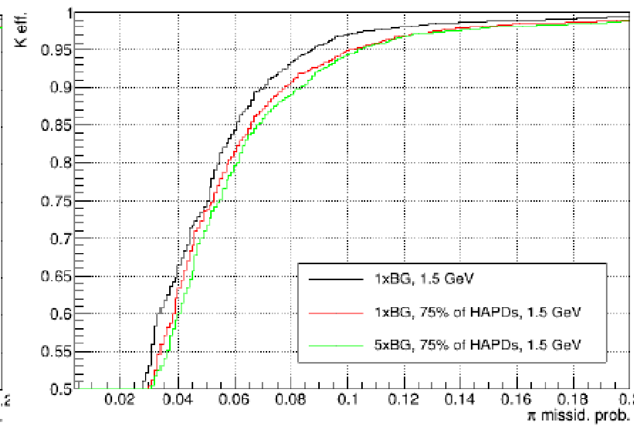
25 % of HAPD randomly dead + beam background with full luminosity

- effect of broken HAPDs (full HAPD dead). Disabled 25% of HAPDs, randomly distributed over the detector plane

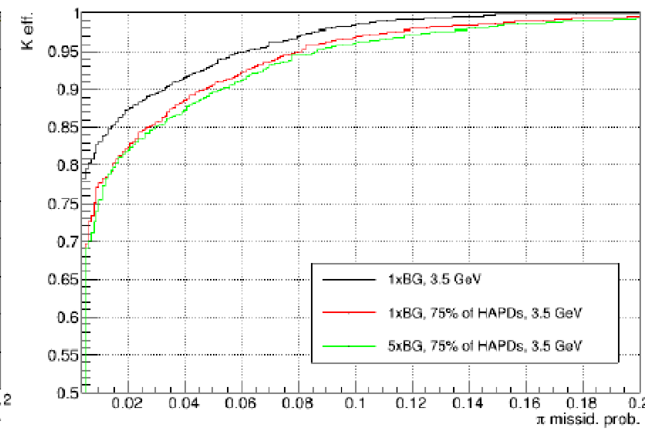
1.0 GeV



1.5 GeV



3.5 GeV



- ~5% drop in efficiency, again this is largely independent of background photon hit level

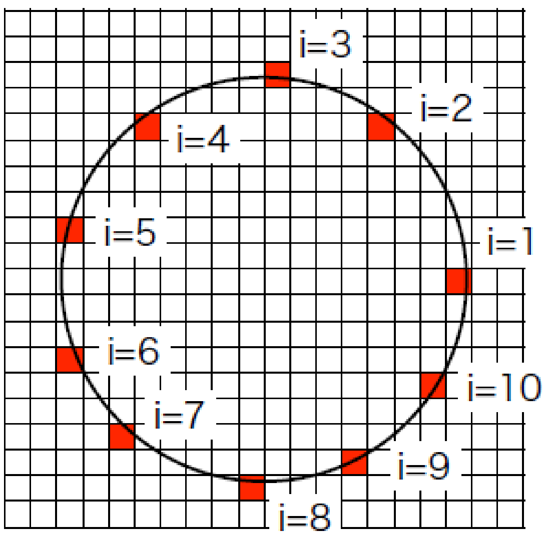
→ background photons are not serious problem for performance (at least up to 10xBG)
→ operation with 75% of HAPDs seems still reasonable

Likelihood Calculation

各トラックに対して、候補粒子(π、K、μ、e、p、d)のlikelihoodを計算

Likelihoodの計算方法

1. トラックから25 cmの領域内のヒットに対して、チェレンコフ角度(θ_{Ch})を計算
2. 候補粒子毎の期待される検出光子数を算出(A)
3. $0.1[\mathrm{rad}] < \theta_{Ch} < 0.5[\mathrm{rad}]$のヒットに対して、ヒットのlikelihood($\ell_i^h$)を計算(B)
4. AとBから候補粒子毎のlikelihood($\mathscr{L}^h$)を算出



期待されるチェレンコフリング

$$\ln \mathscr{L}^h = -N^h + \Sigma[\ell_i^h + \ln(1 - e^{-\ell_i^h})]$$

h : 候補粒子　　i : ヒット番号

N^h: 候補粒子hの期待される検出光子数

ℓ_i^h : i番目のヒットのlikelihood

粒子識別はlikelihoodの比を用いて行う

K/π 識別の例 : $\dfrac{\mathscr{L}^K}{\mathscr{L}^K + \mathscr{L}^\pi}$

MPPC (SiPM)

MPPC samples	Pixel pitch (um)	gain	Pixel number/ 1ch	Effective photosensitive area(mm^2)	Spectral response	PDE(%)	Fill factor (%)	Vbr	Vop	dark count (kcps)	dark current (nA)	Terminal capacitance (pF)
– S13361-3050AE-08	50	$1.7 * 10^6$	3584	3 * 3	320-900 (450)	40	74	53 ± 5	Vbr + 3	500 (1500)	100-300	320
– S13361-3075AE-08	75	$4.0 * 10^6$	~1600	3 * 3	320-900 (450)	40	82	53 ± 5	Vbr + 3	500 (1500)	400-500	320
– S14160-3010PS	10	$1.8 * 10^5$	90000	3 * 3	290-900 (460)	18		38	Vbr + 5	700	20-30	530
– S14160-3015PS	15	$3.6 * 10^5$	40000	3 * 3	290-900 (460)	32		38	Vbr + 4	700	50-60	530
– S14160-3050HS	50	$2.5 * 10^6$	3531	3 * 3	270-900 (450)	50	74	38	Vbr + 2.7		600-1800	500