The TOP Detector for the Belle II Experiment

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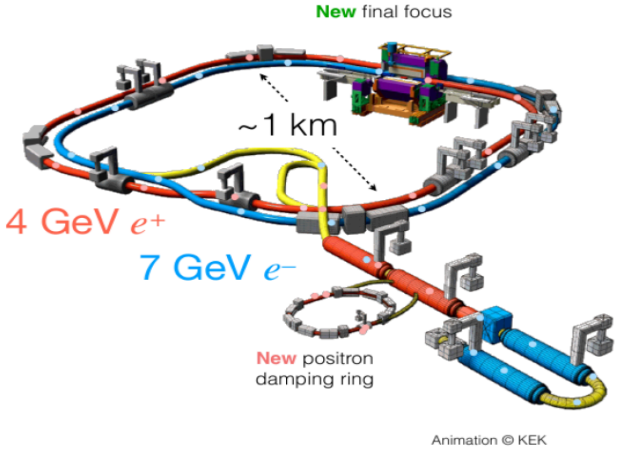
on behalf of the Belle II TOP group

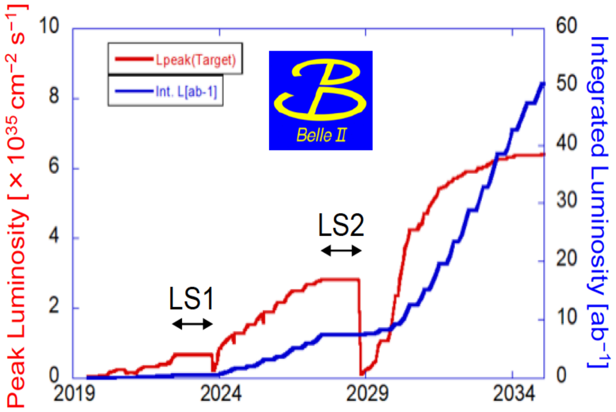
International workshop on the high energy Circular Electron-Positron Collider (CEPC), Nanjing, China

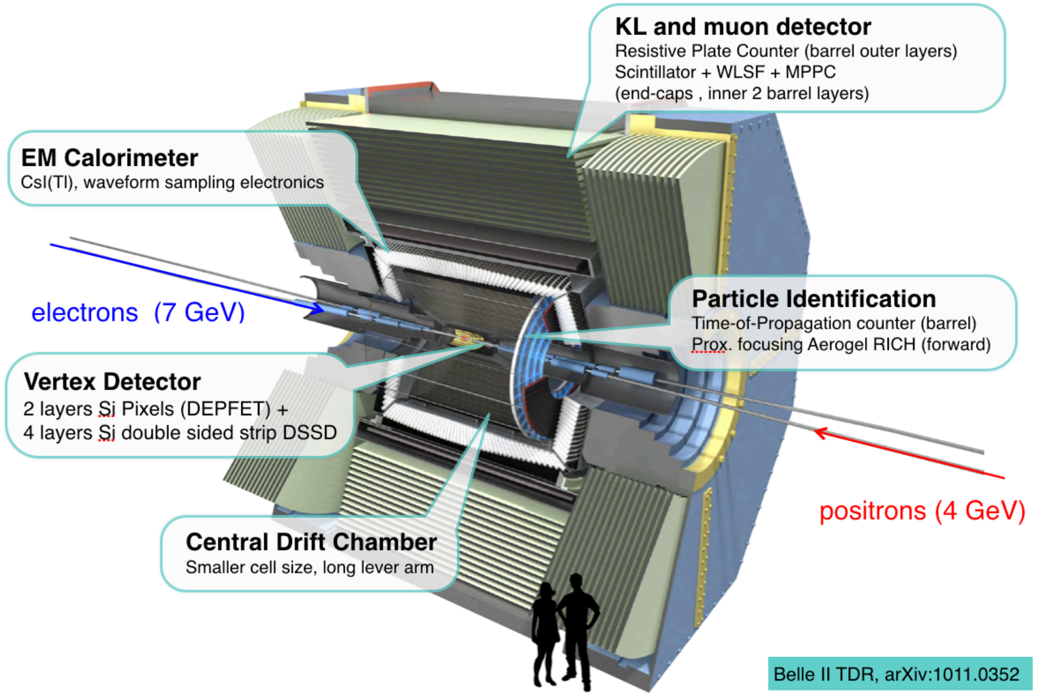
Oct. 23-27, 2023

SuperKEKB and Belle II

Tsukuba @ Japan







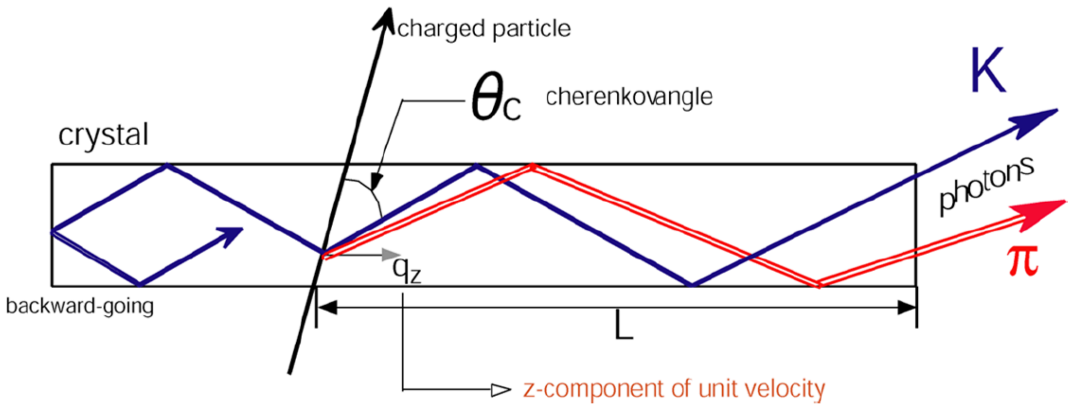
- SuperKEKB: asymmetric e^+e^- collider. B factory, also charm and τ factories.
- Nano beam scheme to achieve high luminosity.
- Record peak luminosity $4.7{\times}10^{34}cm^{-2}s^{-1}$ (target 6 x $10^{35}cm^{-2}s^{-1}$).
- Now in a Long Shutdown 1 (LS1, Jul.2022 – Nov.2023).

- Silicon detectors for vertex measurement
- Drift chamber for p and dE/dx measurement
- TOP and ARICH counters for particle identification
- EM Calorimeter (ECL) for e^+ and γ reconstruction
- KLM detector for K_L and μ detection

TOP counter: concept

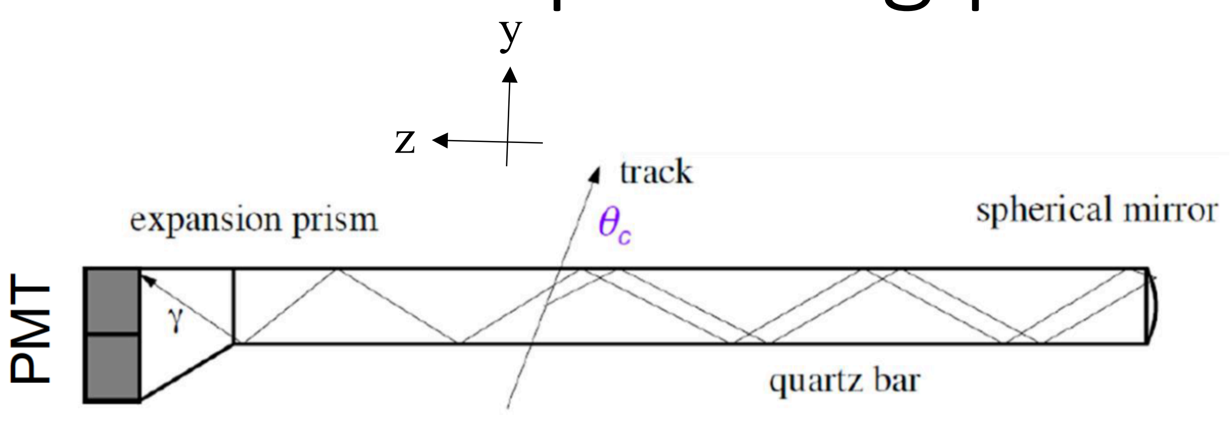
- Physical requirement: hadron separation in momentum range 1-5 GeV/c.
- Very limited space between drift chamber and calorimeter in Belle II barrel: a conventional Ring-imaging Cherenkov (RICH) detector does not fit.
- Imaging **Time Of Propagation (TOP)** counter: instead of reconstructing the full ring image, measure time of propagation of Cherenkov photons.
- Different Cherenkov angle: different photon path which means different time of propagation and different position of photons.
- Collision timing is well known, also can measure time of flight.

side view of TOP counter

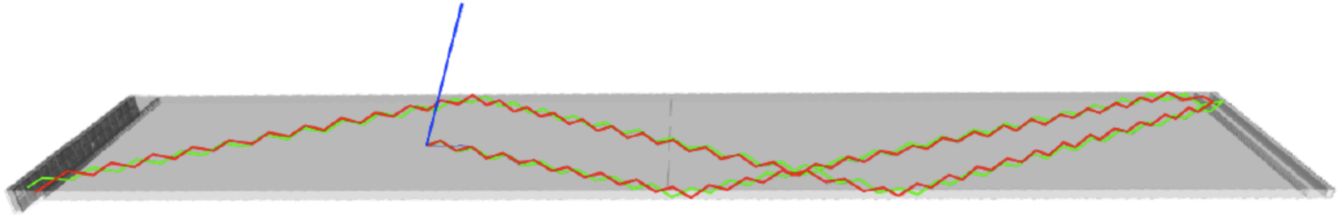


TOP counter: operating principle

20 to 40 photons per charged track are detected

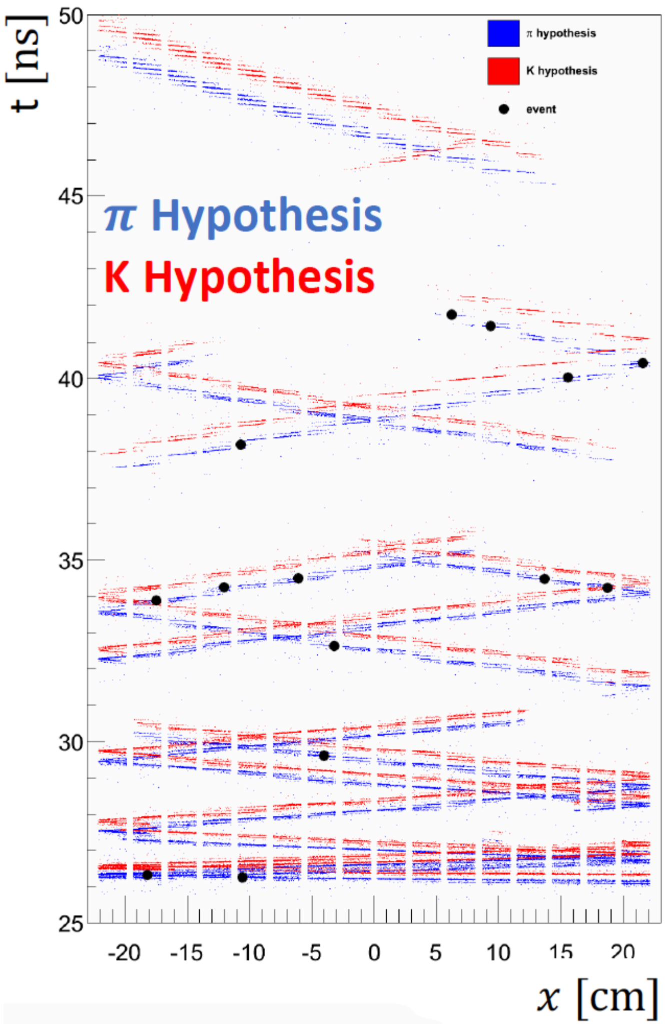


- Cherenkov photons transported to the photon sensors by means of total internal reflections (DIRC).
- π and K have different Cherenkov angle θ_c according to $cos\theta_c = 1/n\beta$. Thus different γ hit positions and arrival times. For $p = 3\ GeV/c$, $\Delta\theta_c = 0.65$ degrees, that is $\Delta t = 68\ ps$ per m.
- Two-dimensional information about the Cherenkov ring by measuring the time-of-arrival and the position of photons at photon sensors.

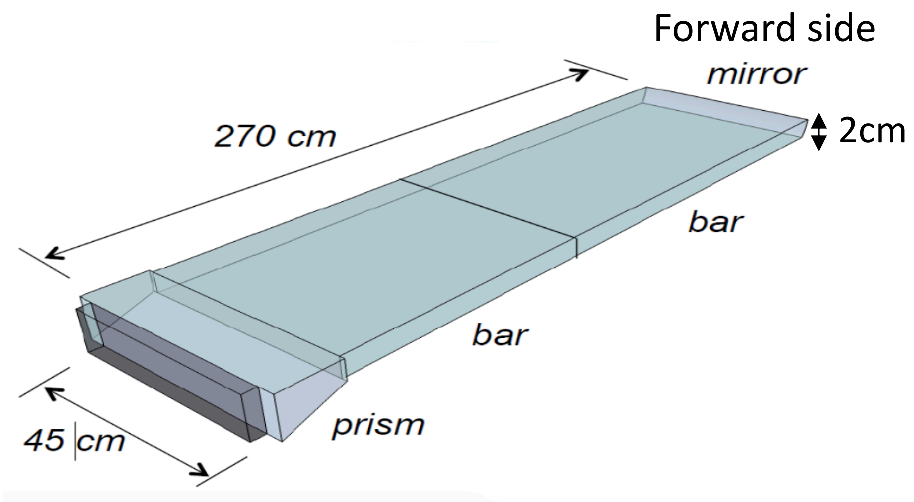


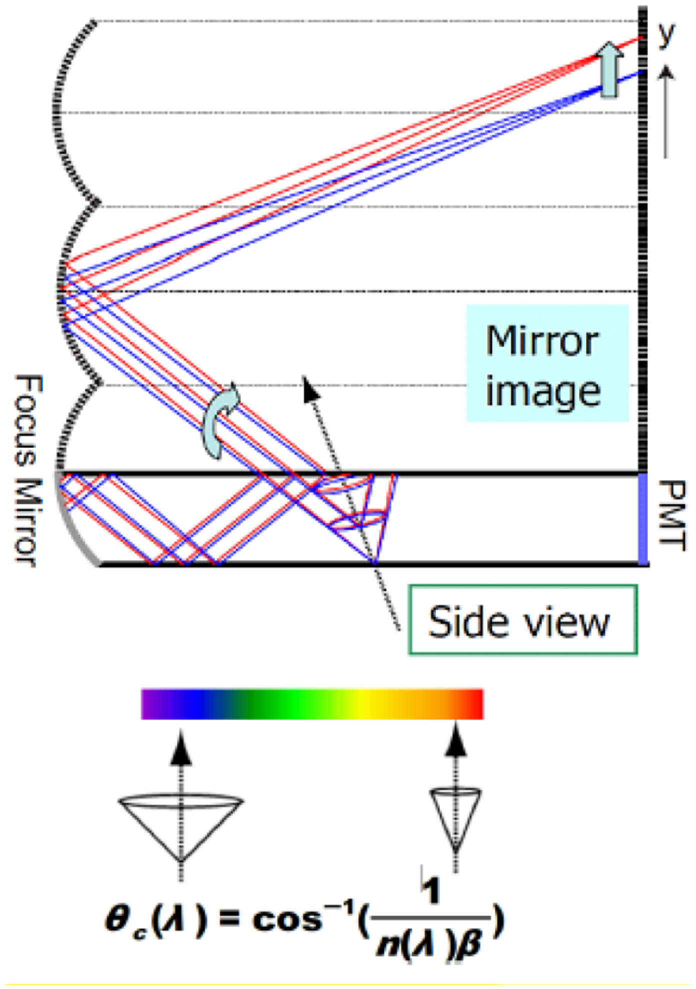
Nominally 100-150 reflections off large top and bottom faces

MC simulation



Optical components: synthetic fused silica (quartz)

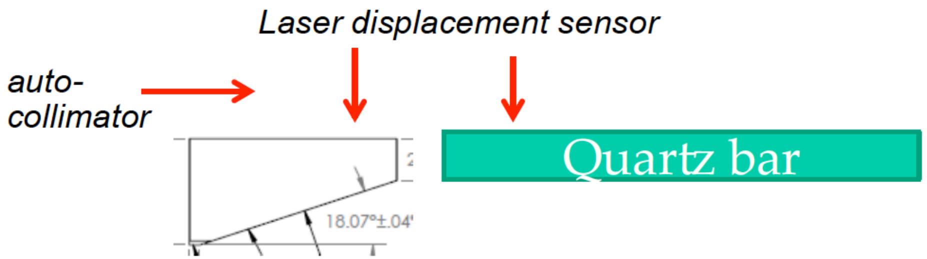




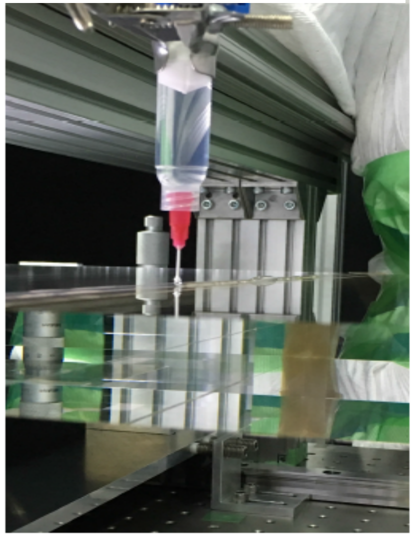
- Quartz bars: medium to generate Cherenkov radiation and to transport photons to PMTs at the end.
- Focus mirror: spherical mirror to focus Cherenkov photons onto PMTs; focal length is 3.25 m
  - parallel rays are focused to a single point: removes the bar thickness.
  - non-parallel rays are focused to different points: allows to make a correction for chromatic dispersion.
- Prism: to expand the image of Cherenkov cone, improving resolution and reducing ambiguities.

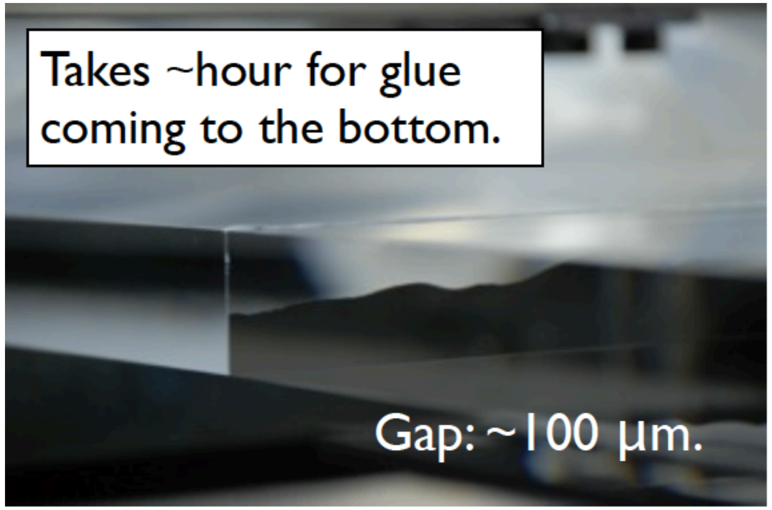
Gluing optics

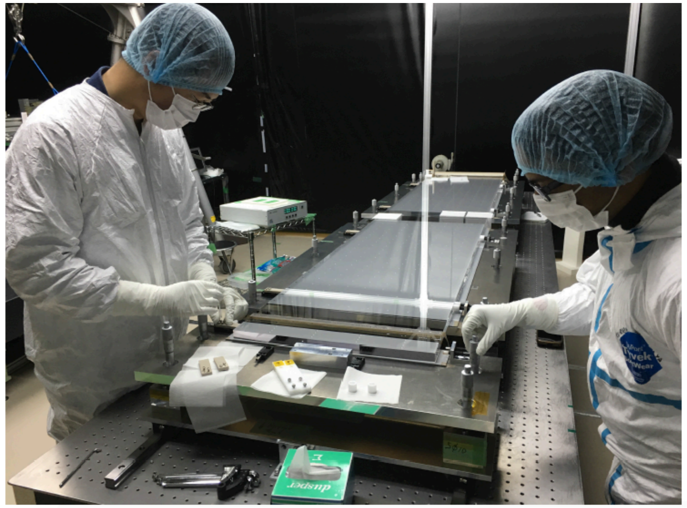
- 3 places need gluing: bar to bar; bar to prism; bar to mirror
- Alignment and gluing:
  - adjust surfaces positions using laser displacement sensor and micrometers
  - adjust surfaces angles using auto collimator and micrometers
  - insert shims, tape joint and repeat steps 1,2
  - apply epoxy (EPOTEK 301-2) to joint



Put glue using dispenser.

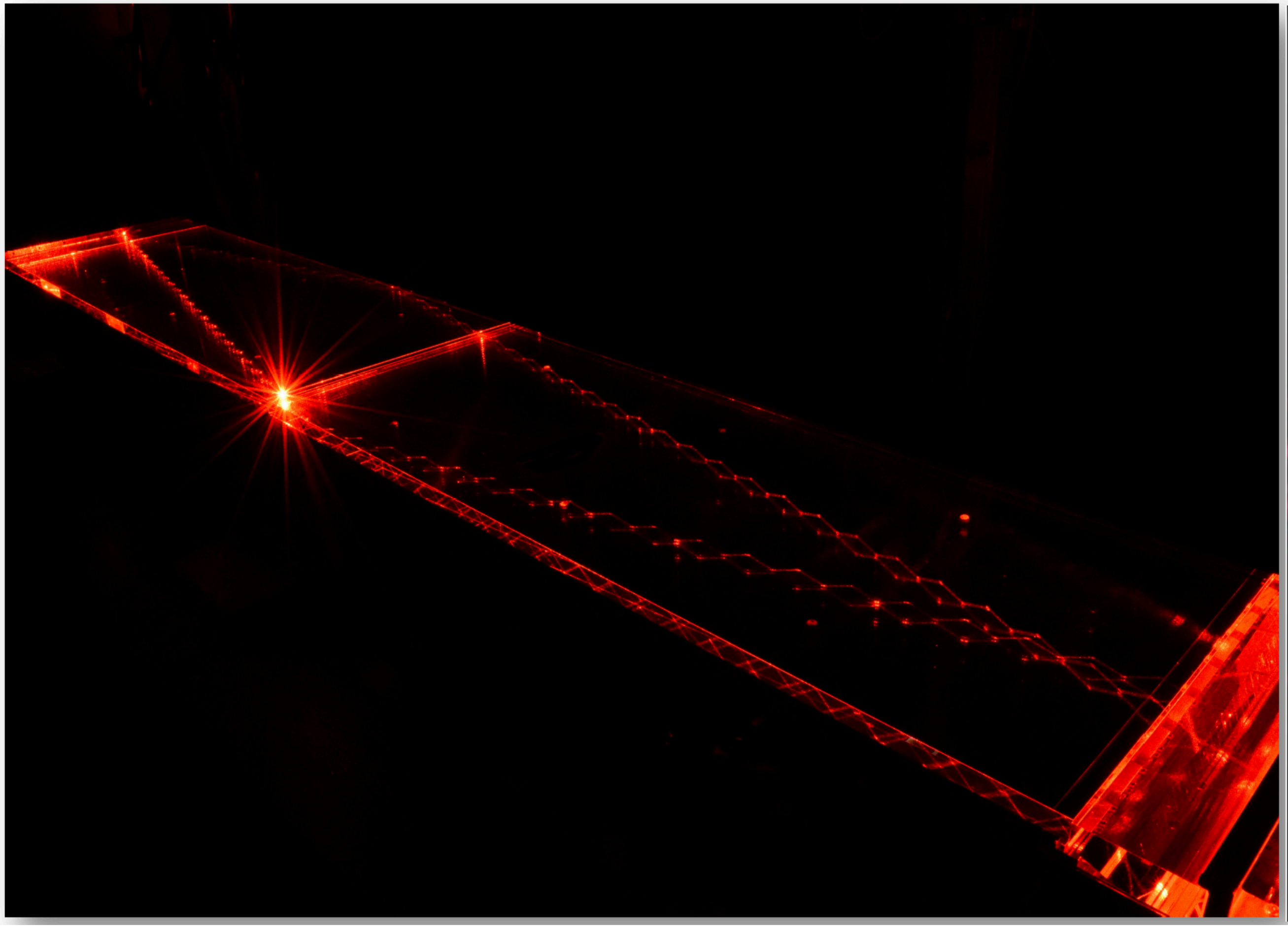


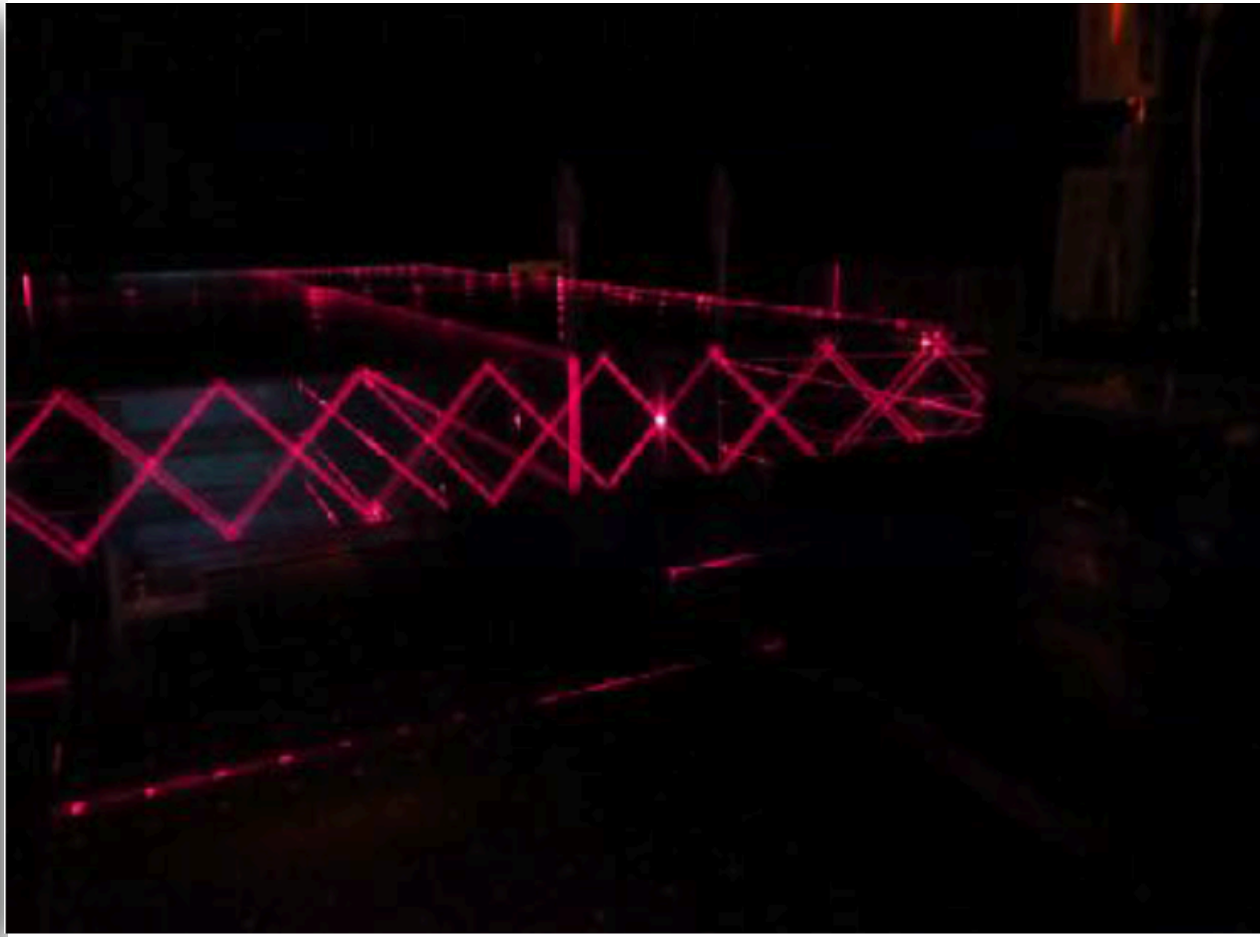




Light path in the quartz bar

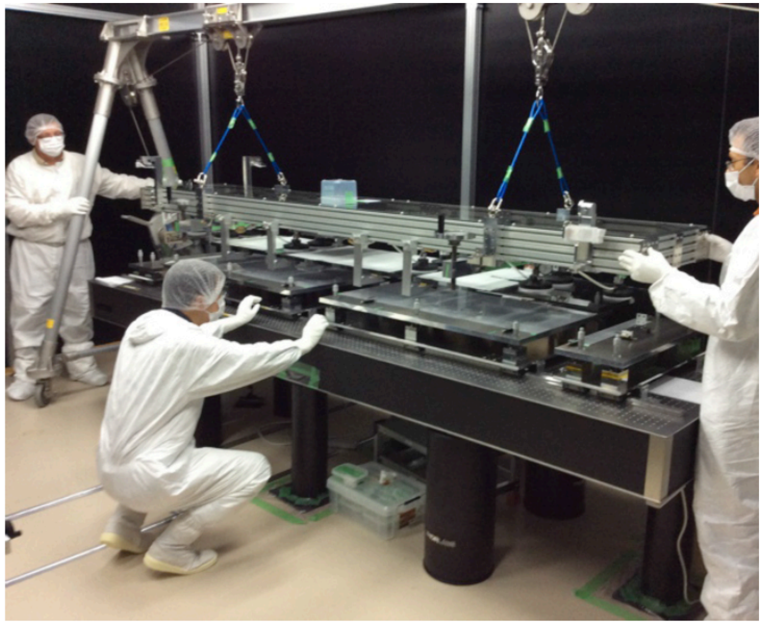
Long time exposure with laser input from prism end.



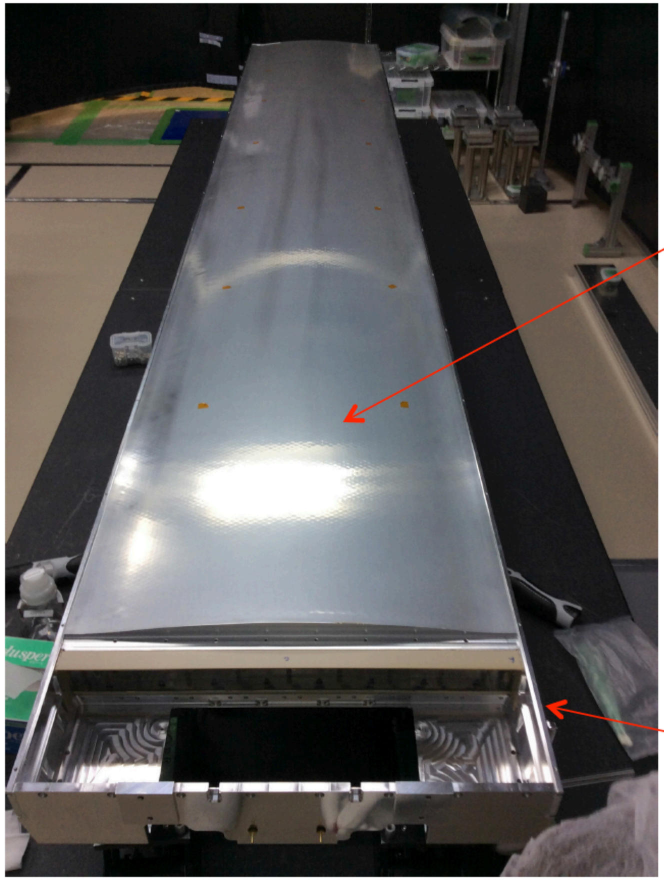


Quartz Bar Box (QBB) assembly

- Vacuum-based lifting jig is used to move fully glued optics to QBB assembly table.

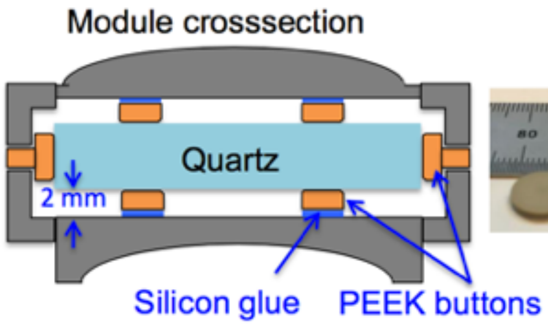


- Box is made of aluminum honeycomb panels (low mass).



top honeycomb panel

Prism Enclosure: provides access for PMTs and readout electronics



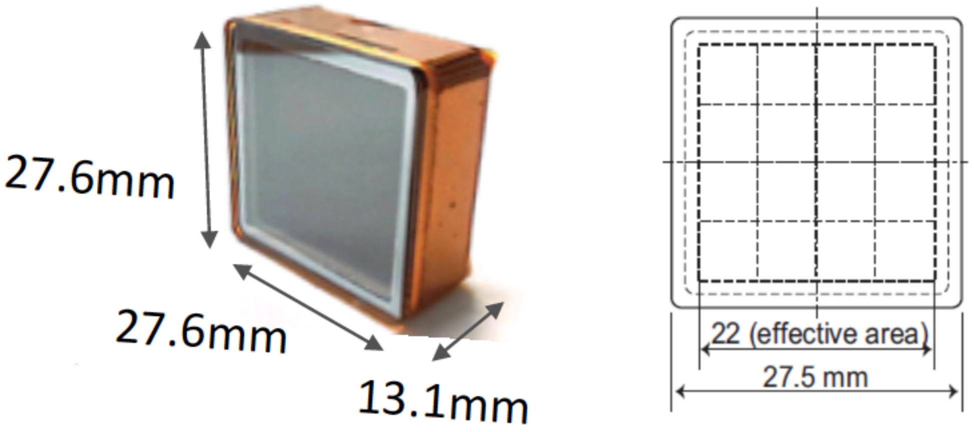
- Support quartz bar with PEEK buttons.

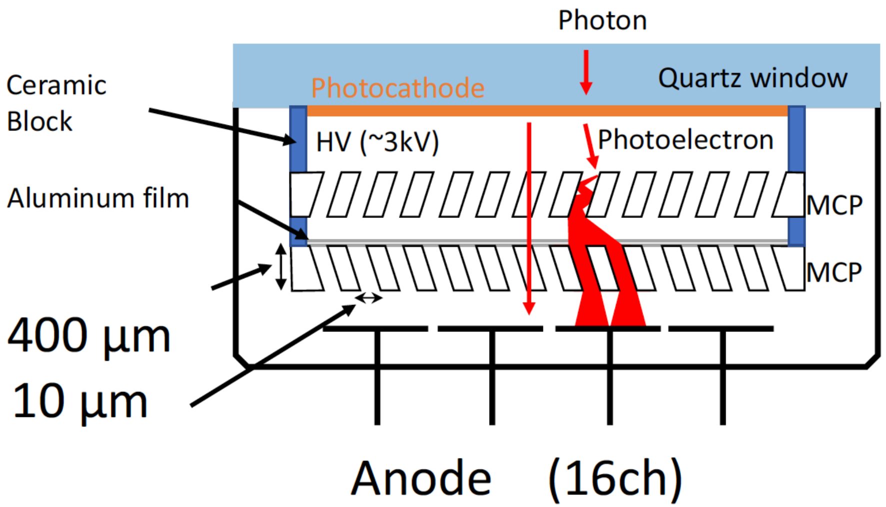
TOP readout: requirements

- Goal < 100ps single optical photon time resolution
- Sensor requirements:
  - single photon efficiency
  - <50ps single photon time resolution
  - ~few mm spatial resolution
  - operation in 1.5T B-field
- Electronics requirements:
  - 30kHz trigger rate
  - digitization w/o deadtime
  - <50ps electronics time resolution
  - <30ps clock distribution jitter
  - 8192 readout channels

Photon detection: Hamamatsu MCP-PMTs

- Photomultiplier tube with micro channel plates (MCPs) amplifying electrons.





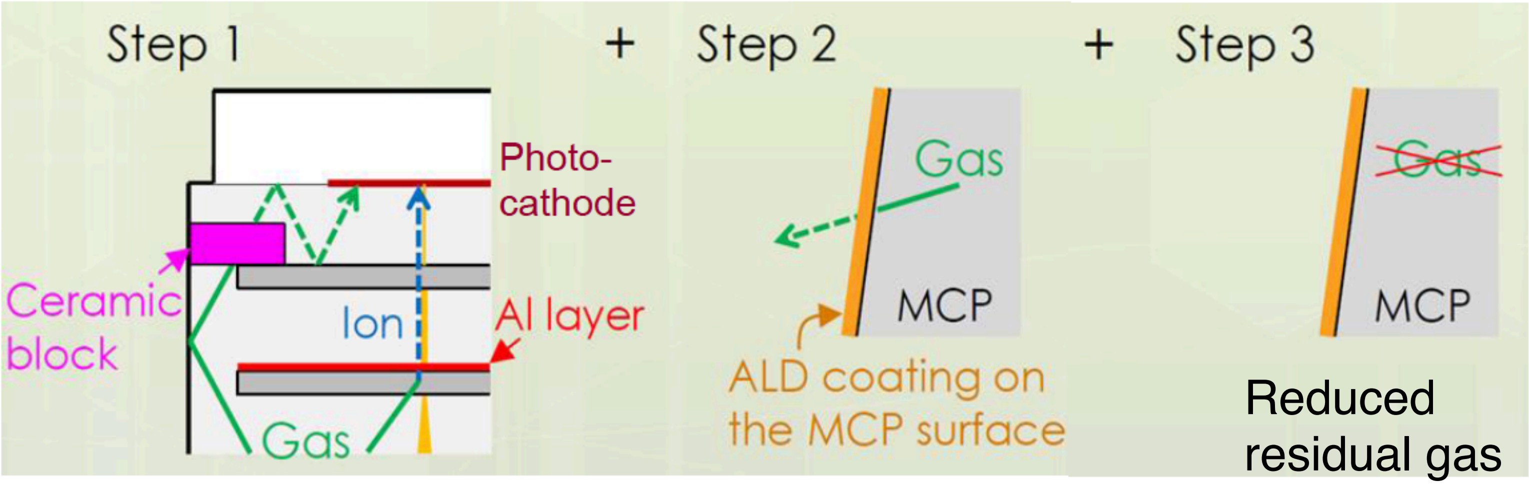
- >5years R&D effort at Nagoya University
- developed in collaboration with Hamamatsu
- high gain to detect single photon
- excellent timing: TTS (Transit Time Spread) < 40ps
- good Quantum Efficiency (QE)
- good segmentation: 4 x 4 channels, 5.5 mm pixel size
- works in magnetic field

Performance for Single Photon	
Average time resolution	34.3 ps
Gain (Nominal)	3×10^5
Average quantum efficiency (QE) at the peak wavelength	29.3 %

JPS Conf. Proc. 27 011020 (2019)

MCP-PMT aging

- QE drops as a function of accumulated charge
  - The gas and ions from MCP damage the photo-cathode
- ALD (Atomic Layer Deposition) and life-extended ALD type were developed during mass production. Thus, three types PMTs are installed on the detector.
- Replacement of conventional MCP-PMTs was done during LS1. Also exchanged/repaired frontend electronics leads to >99.5% active channels.



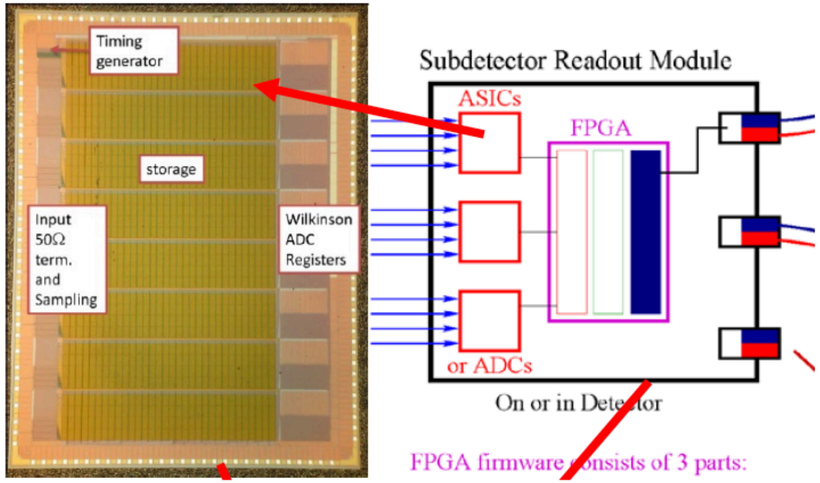
Conventional ALD Life-extended ALD

Type	Lifetime
Conventional	$1.1\ \mathrm{C/cm^2}$ (Average)
ALD	$10.4\ \mathrm{C/cm^2}$ (Average)
Life extended ALD	$>13.6\ \mathrm{C/cm^2}$

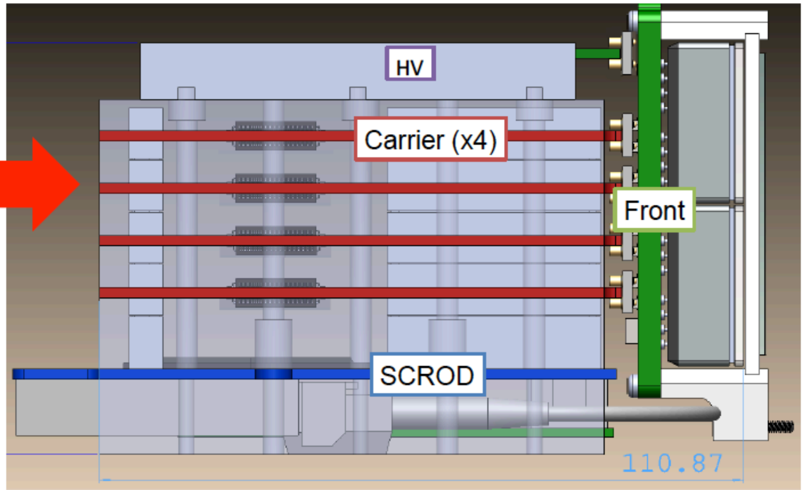
Front-end electronics

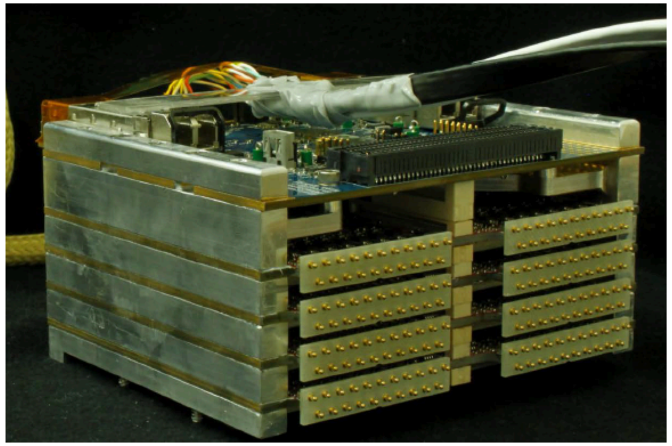
NIM A 941, 162342 (2019)

Front-end electronics based on a custom 8-channel waveform-sampling ASIC.

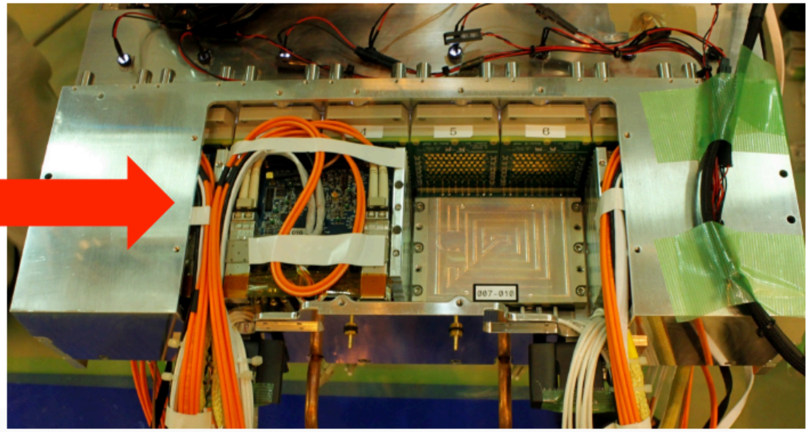


ASICs are mounted in “Carrier boards”, and 4 carriers + controller (SCROD) = 1 boardstack





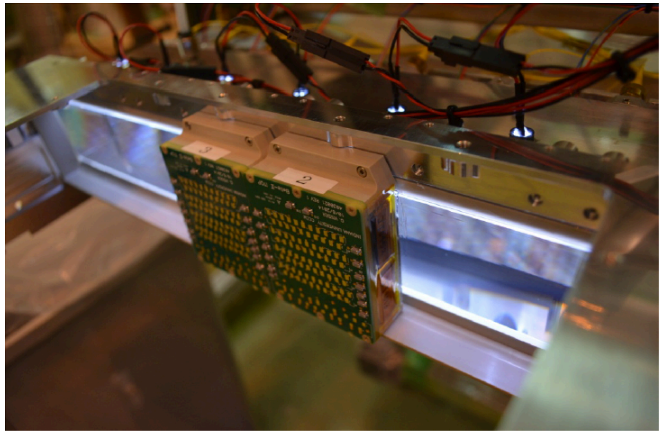
4 boardstacks + 4 HV boards per TOP module



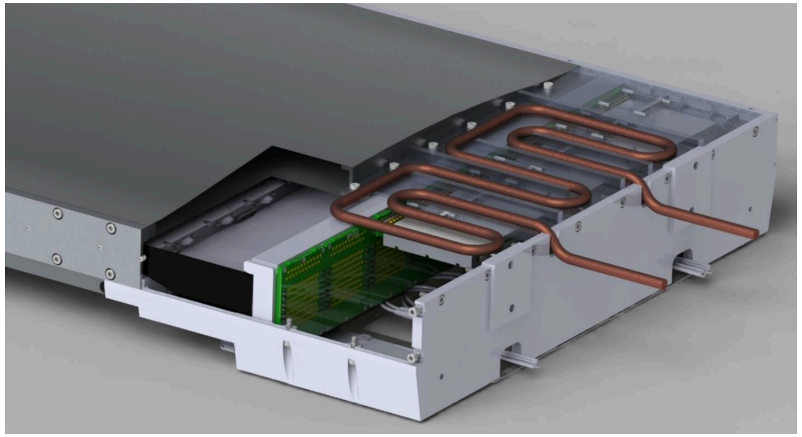
data sent out by optical links

TOP module assembly & installation

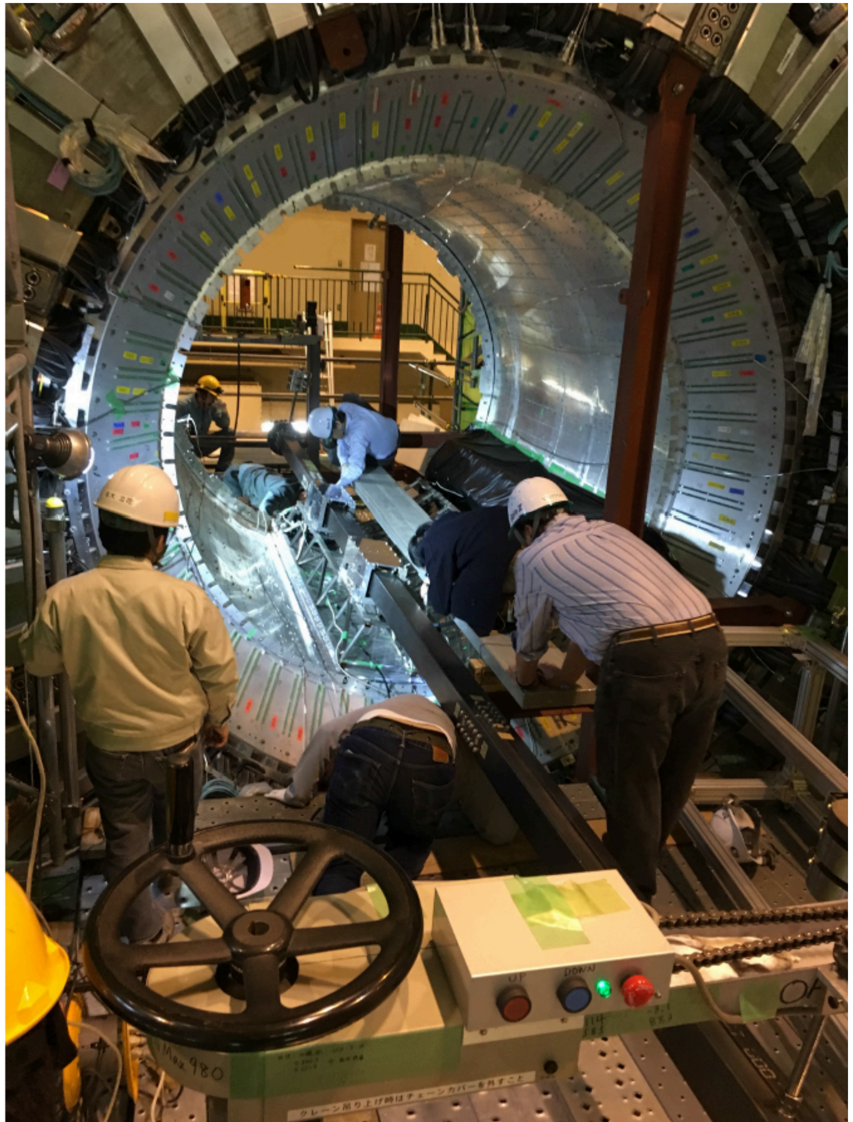
PMT modules mounted to prism with a “cookie” (+oil)



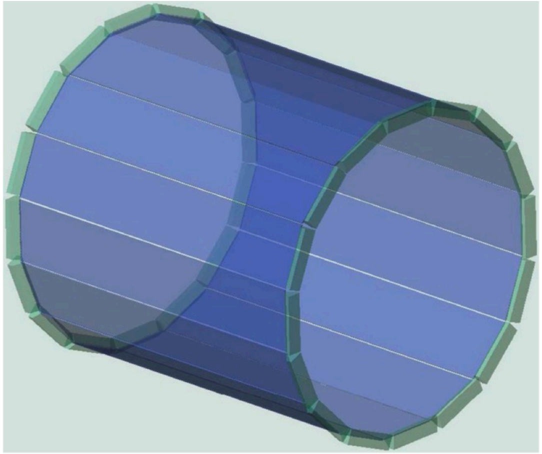
one TOP module with 4 boardstacks and 16 x 2 =32 PMTs



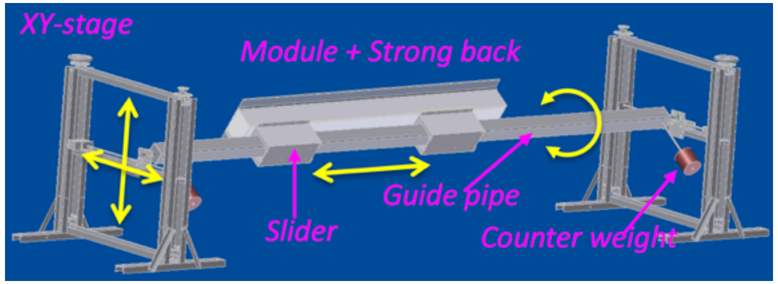
Installing one of 16 modules.



TOP geometry: 16 TOP modules arranged around IP at R = 120cm

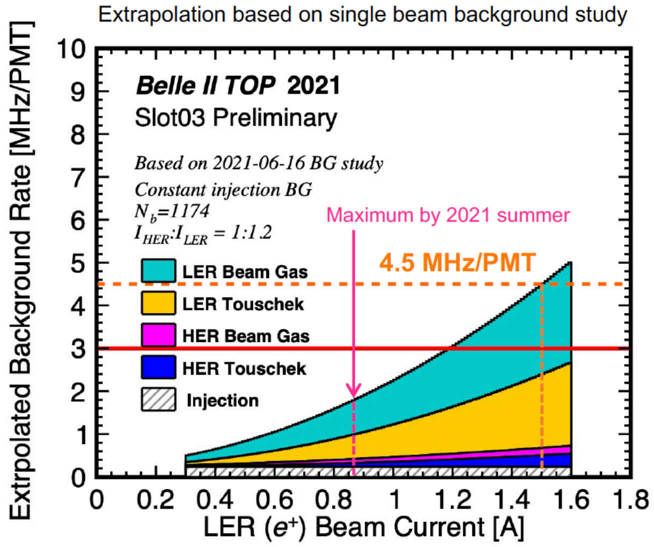


The “jig” used to put TOP modules on the detector

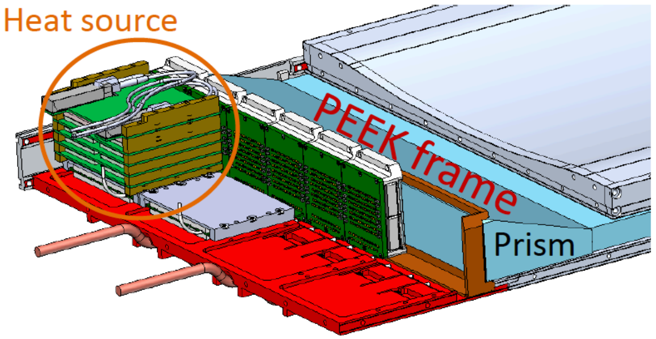


Operation experiences

- Aging problem of conventional PMTs
  - PMTs seem to age faster in the detector than expected.
  - during LS1, conventional PMTs are replaced with life-extended ALD PMTs.
- Beam background
  - beam backgrounds are much higher than expected.
  - background bursts (from beam injections etc.) sometimes cause readout deadtime.
- Single Event Upset (SEU)
  - cause processing system (PS) on electronics boards lock-up and corrupt data taking;
  - auto SEU correction is equipped and moving PS functionality to readout PC.
- PMT rotation in magnetic field
  - PMT tube is made of Kovar alloy which is ferromagnetic.
  - fixed by shimming; residual issues have marginal effects on TOP performance.
- Prism support (PEEK) frame partially separates from prism
  - seems due to the optically polished prism surface.
  - keep monitoring; minimize temperature fluctuations to reduce thermal stress.

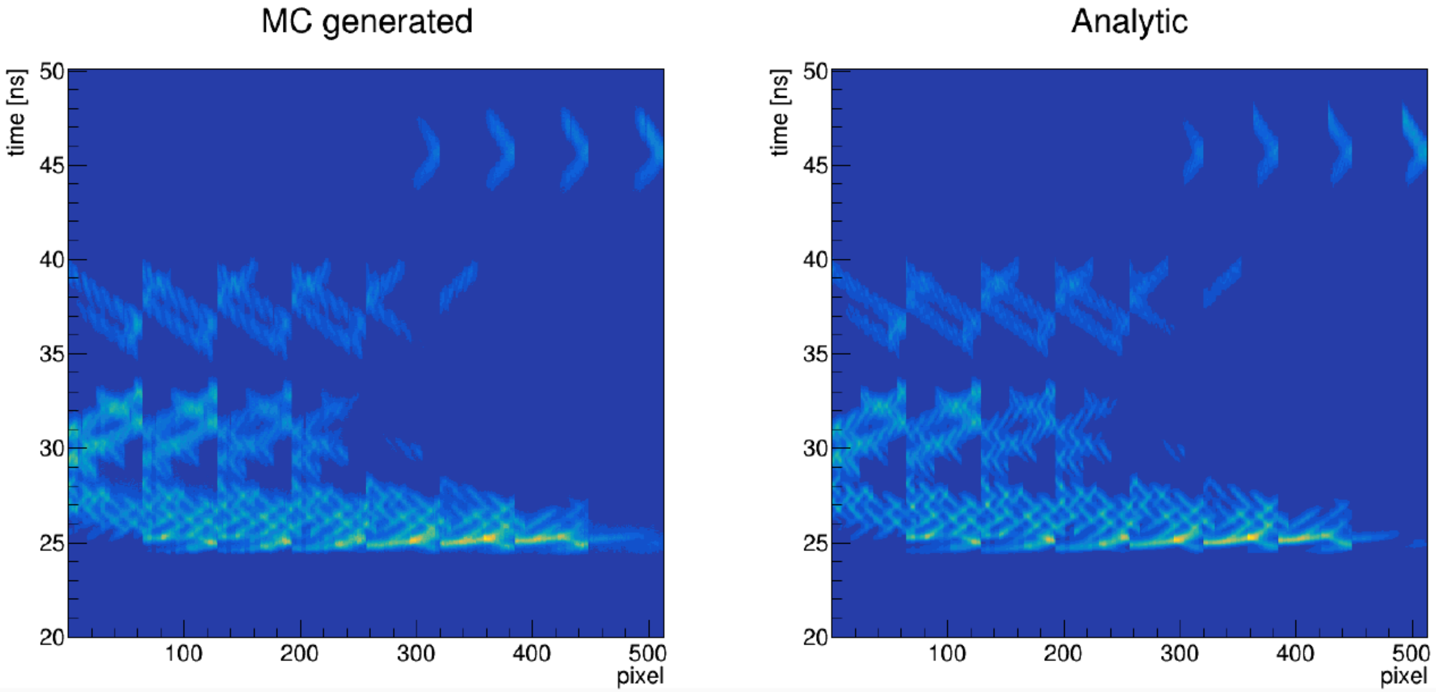


PEEK frame is glued to prism using EP21LV-LO epoxy, which is widely used in industry.



PID algorithm at TOP

- Extended likelihood method with analytically constructed PDFs to determine log likelihoods of e, μ, π, K, p, d.
- PDF in a single channel described with a sum of Gaussian distributions.
  - positions, widths and normalizations determined analytically according to particle impact position, angles, momentum and mass.

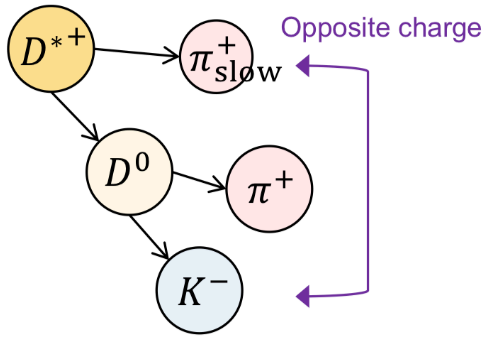


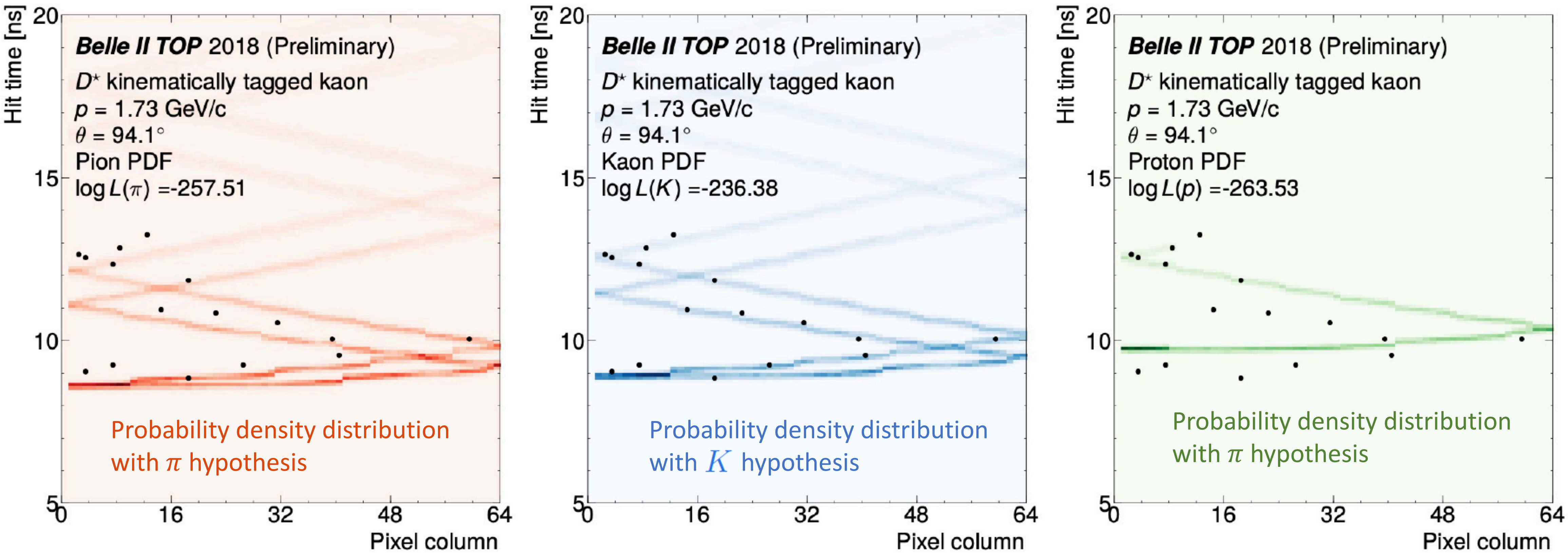
32PMTs per TOP module, 16 pixels per PMT; 32x16=512.

Method presented at RICH2010, NIM A 639 (2011) 252.

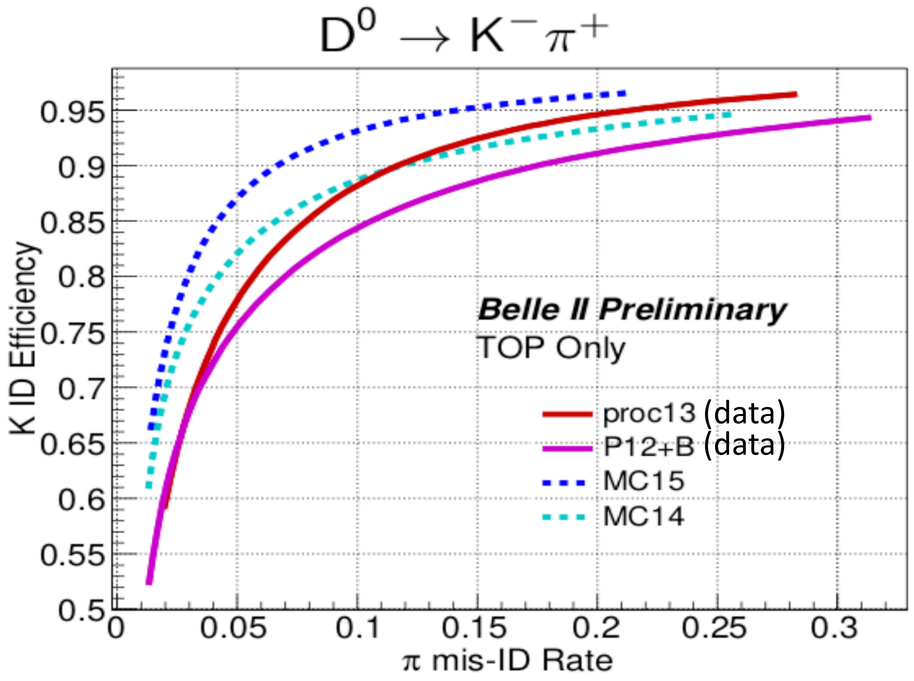
Photon hit patterns in real data

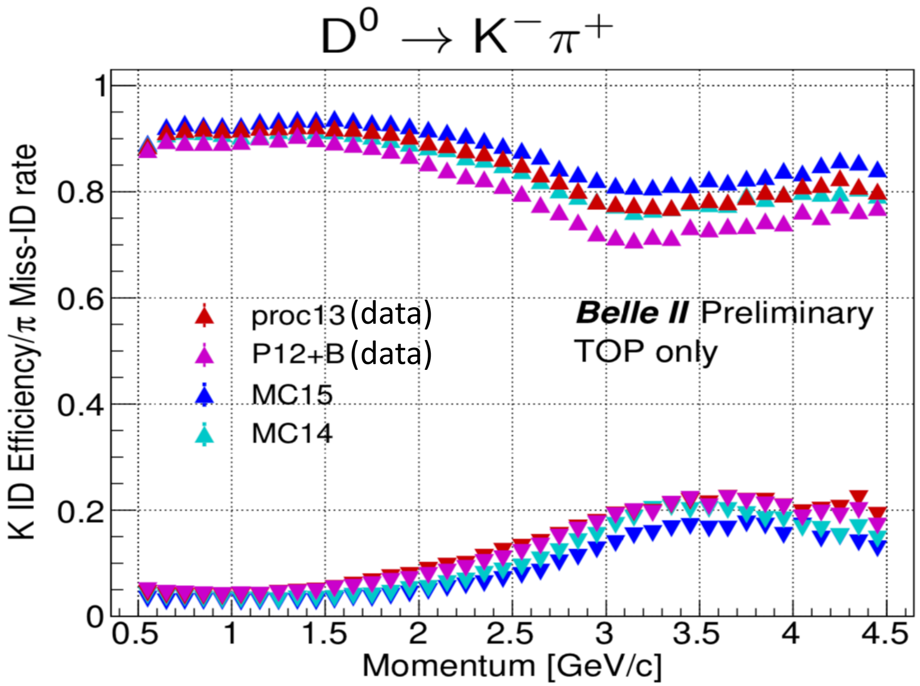
A kaon candidate track tagged in $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+_{slow}$ using $\pi^+{}_{\text{slow}}$.





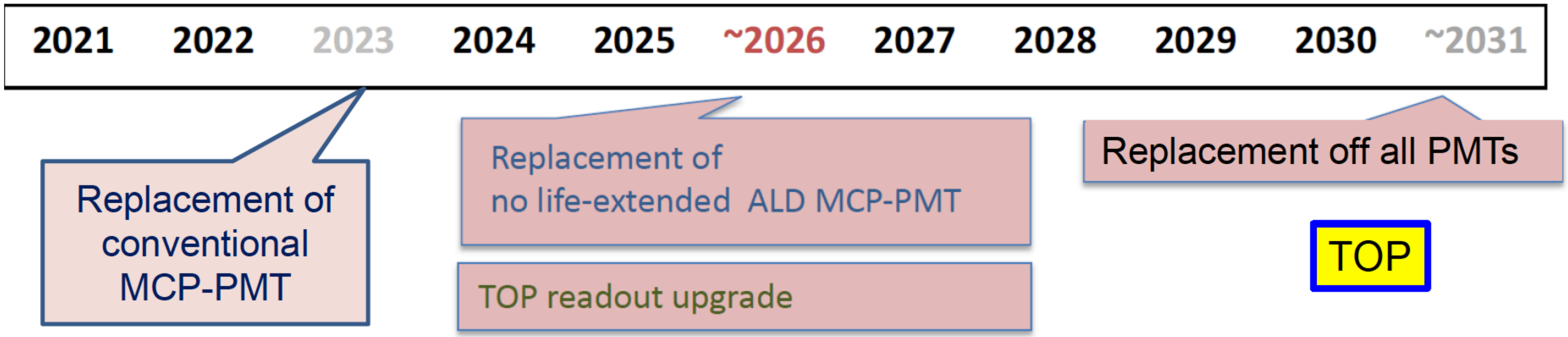
TOP PID performance





- PID performance of the TOP counter has been increasing with each new software release/reprocessing
  - improvements in detector calibration, PDF modeling and bunch-crossing time determination.
- TOP works well, further improvements being explored, e.g., more accurate bunch finder.

TOP detector upgrade plan and R&D



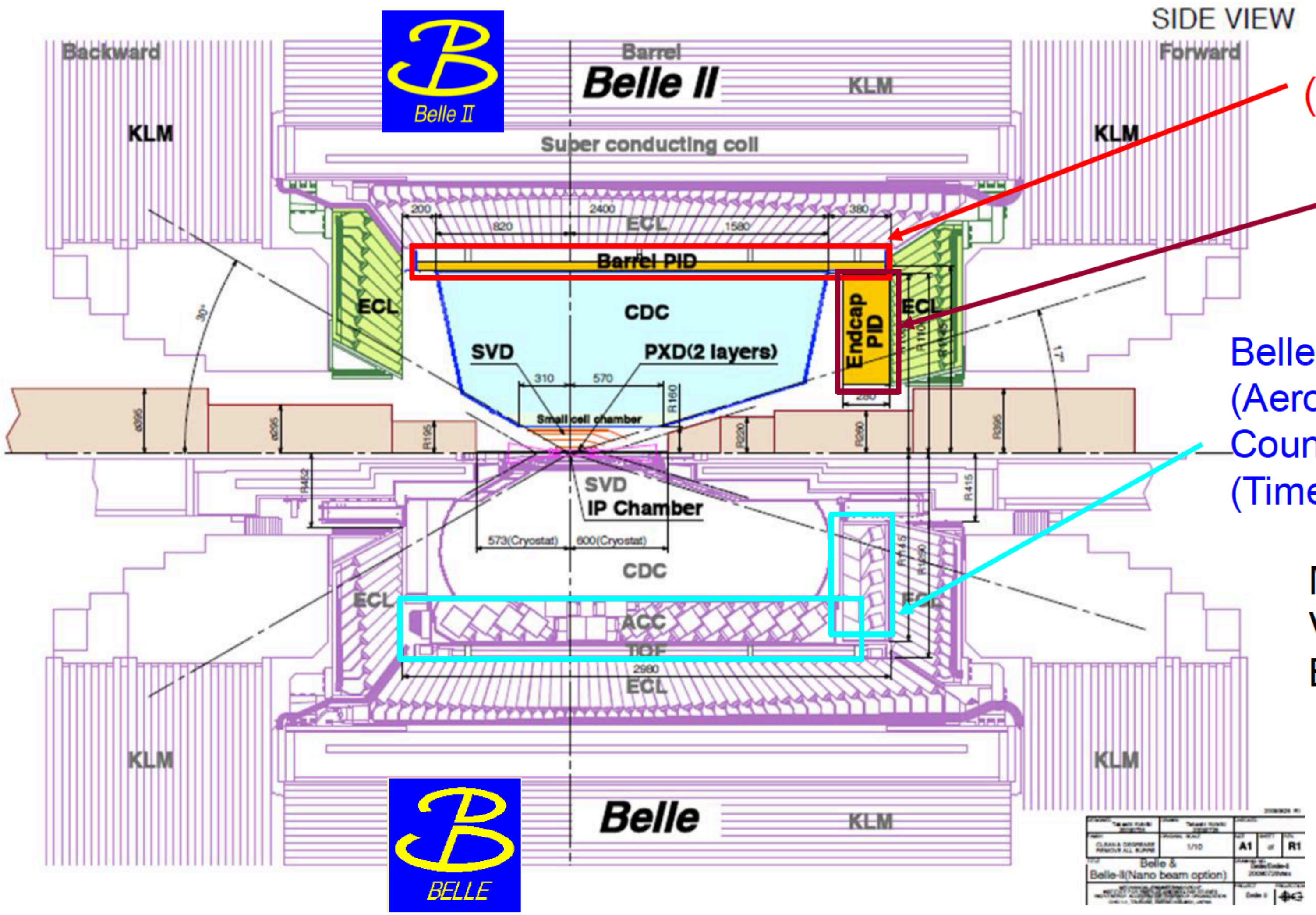
- New life-extended ALD PMTs are in production and will replace ALD PMTs as they reach their end of life in next long shutdown.
- Possible readout upgrade with higher speed and compact digitizer (new ASIC or RFSoc, Radio Frequency System on Chip) being studied.
- New photon detector option based on SiPM is in testing
  - Need to check neutron radiation level at the detector and its tolerance.

Summary

- The TOP counter at Belle II is a new type of Cherenkov detector
  - utilizes total internal reflection of Cherenkov photons produced in quartz bars
  - strong requirements on photon sensors and readout electronics
- TOP is performing well in Belle II data taking.
- Further efforts are on-going to improve performance on data taking and PID.
- We are now in a long shutdown. Replaced PMTs and exchanged/repaired frontend electronics; preparing for Run2 starting from 2024.

Extra

Belle and Belle II



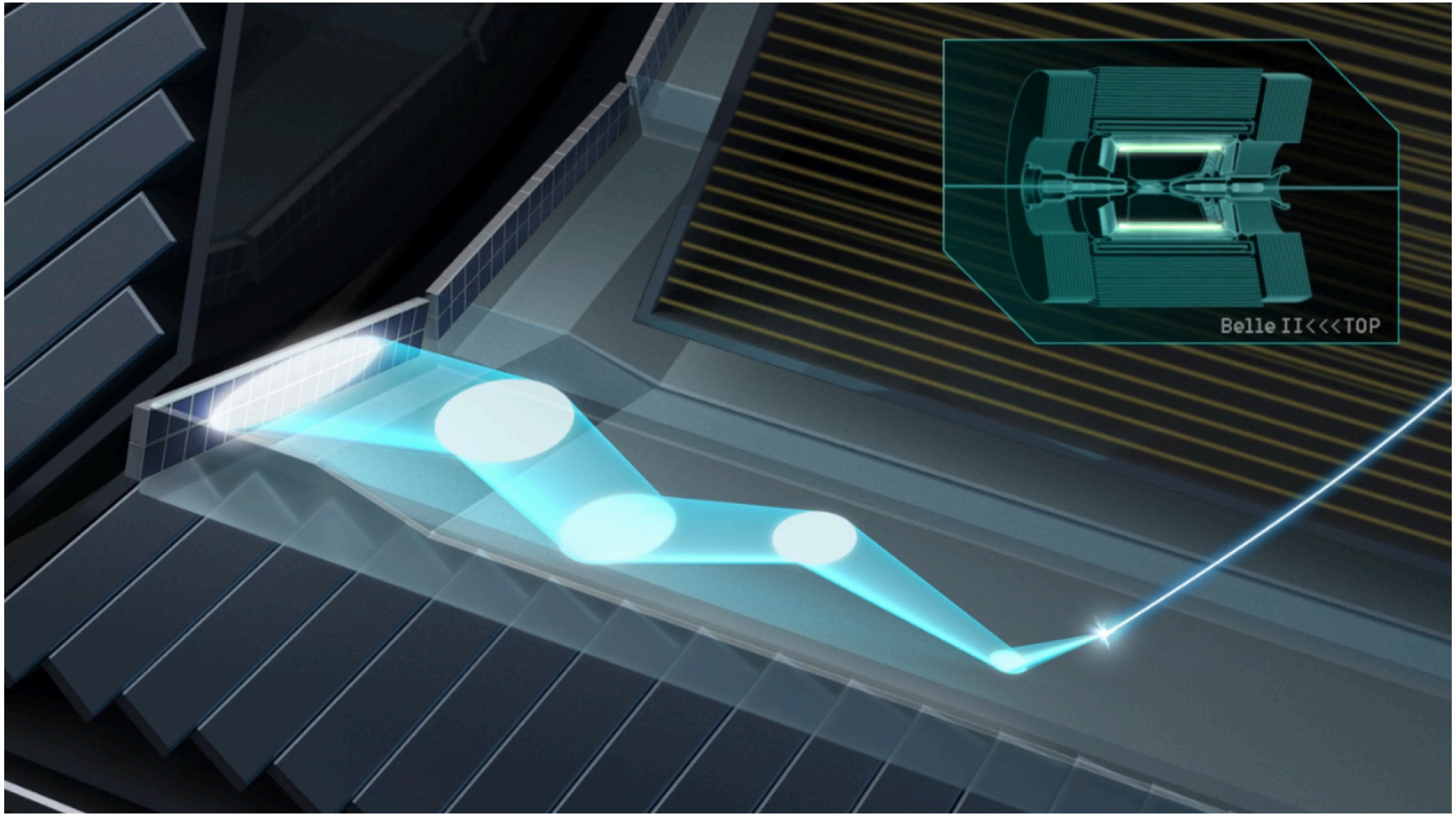
TOP (barrel)

ARICH (forward endcap)

Belle equipped ACC (Aerogel Cherenkov Counter) and TOF (Time Of Flight)

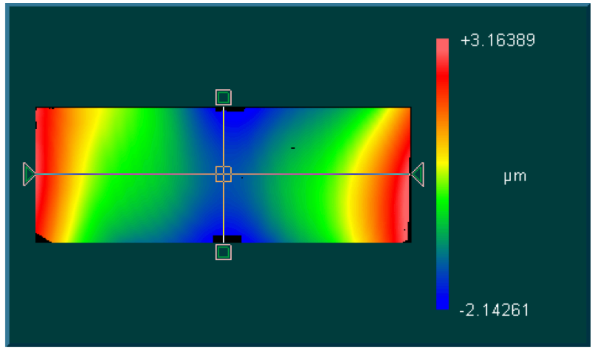
More space to VXD and CDC at Belle II

TOP counter



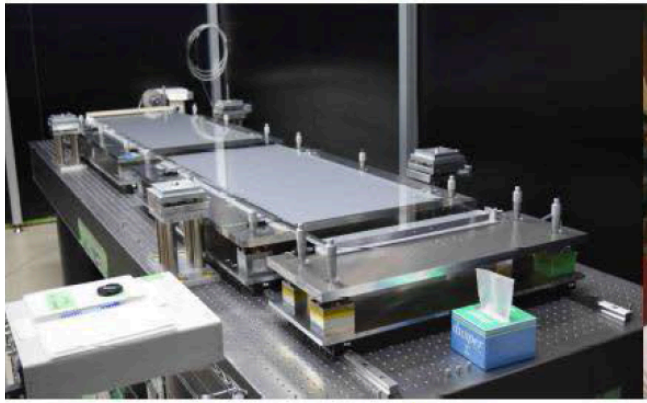
Fabricating quartz bars: flatness is critical

- Acceptance test:
  - Bars: chip inspection, bulk transmittance, internal surface reflectrance.
  - Mirrors: chip inspection, reflectivity position of optical axis, focal point and focal length, spherical aberration, astigmatism
  - Prisms: chip inspection, transmission, angle of tilted surface.
- Surface flatness, surface roughness, parallelism, perpendicularity and chamfer specs were qualified by vender.



(S1 Surface Flatness)

Module assembly



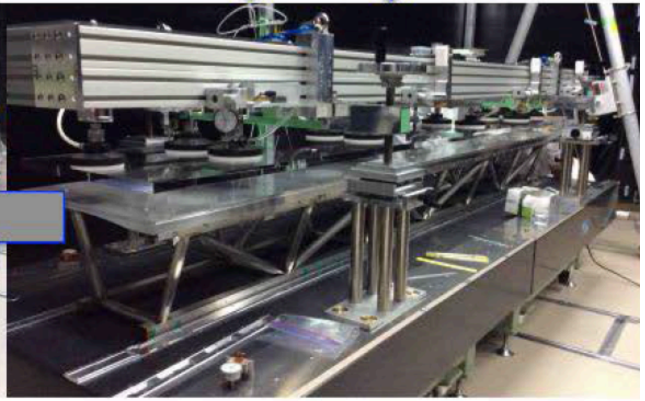
Optics: alignment, gluing, curing and aging (~2 weeks).

Enclosure: gluing CCDs and LEDs, integrating fiber mounts.

QBB: strong back flattening, button & enclosure gluing.

Put on a cart. PMT and front-end integration, performance check.

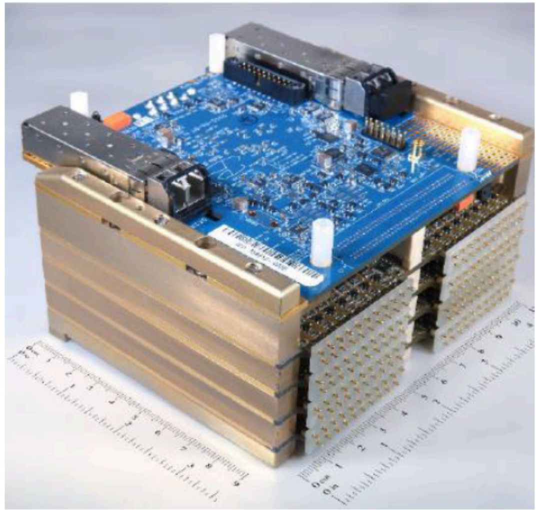
QBB assembly and gas sealing.



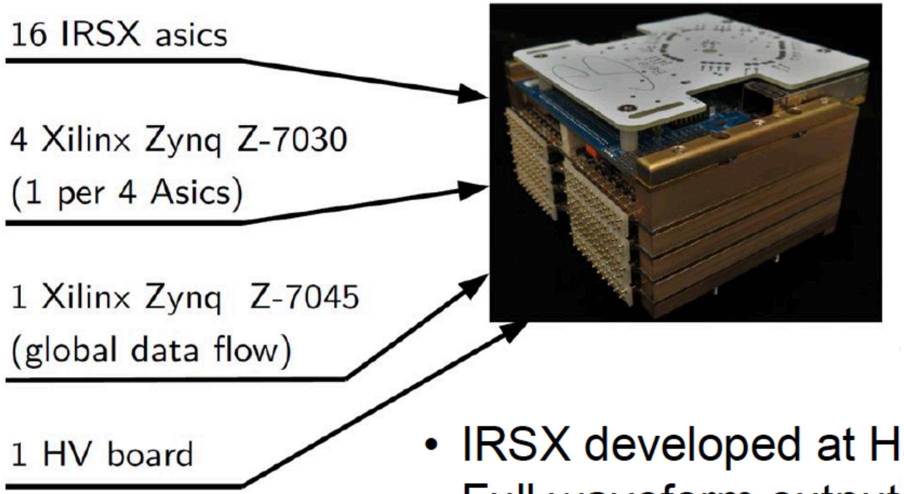
Move optics to QBB using the "lifting jig".

TOP frond-end electronics

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



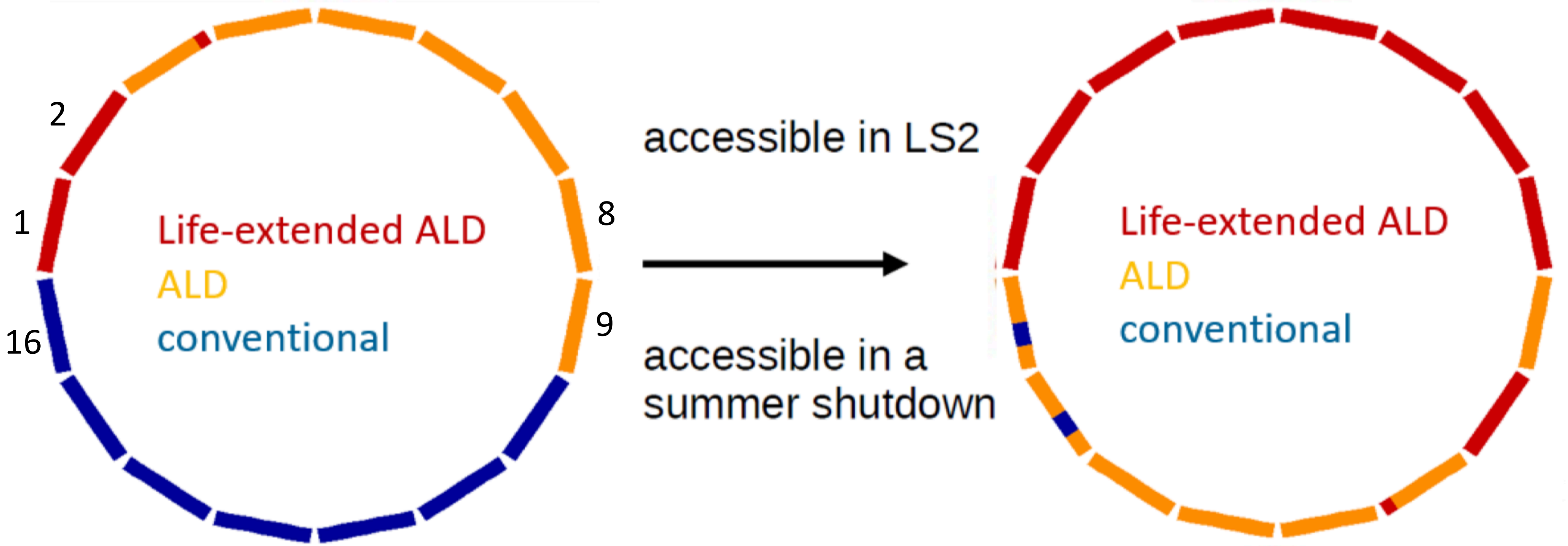
4 ASICs packed into 4 ***boardstacks***



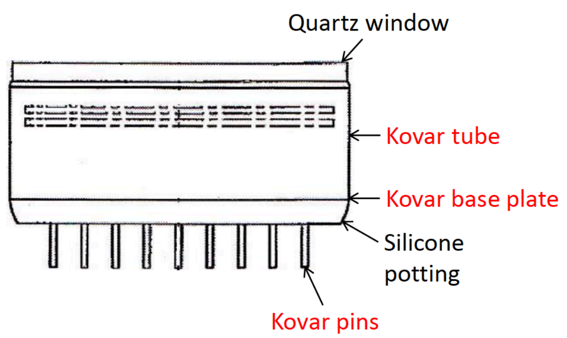
- IRSX developed at Hawaii Univ.
- Full waveform output.

PMT replacement

Viewed from backward to forward



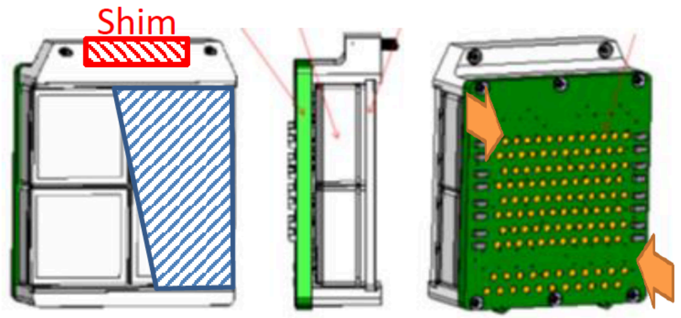
two PMT rotation problems



- The housing of the MCP-PMT is made of Kovar alloy (29Ni-16Co-Fe), which has almost the same coefficient of thermal expansion as glass and is ferromagnetic.

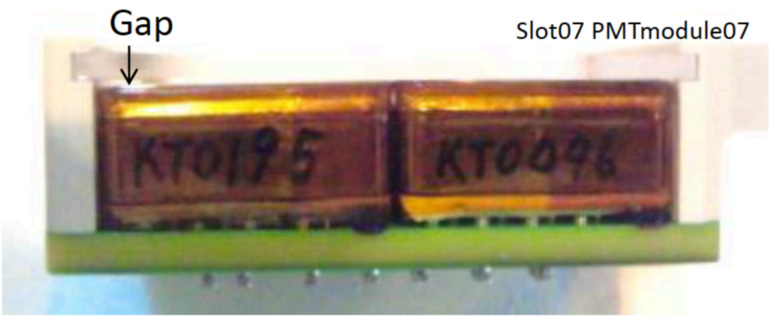
Rotation of PMT module

- Large effect on photon transmittance due to bubbles of the optical oil on the Si cookie
- Has been fixed in situ by shimming



Rotation of PMT

- Effect only for photons of larger incident angles than ~43° if the peel-off surface is clear.
- Wil be fixed if necessary after phase 2



Particle idenfification at Belle II

slide from Marko Staric

- Almost any detector component involved
  - SVD and CDC: energy losses (dE/dx)
  - TOP: Cherenkov imaging in barrel region
  - ARICH: Cherenkov imaging in forward region
  - ECL: energy deposits
  - KLM: penetrating power (trajectory length)

  mostly hadron ID   mostly lepton ID

- All these components provide log likelihoods for e, μ, π, K, p, d
- Combined by summing over detector components:
  - $\log \mathcal{L}_h = \sum_{\mathrm{det}} \log \mathcal{L}_h^{\mathrm{det}}, \quad h = \{e, \mu, \pi, K, p, d\}$
- Particle selection with either
  - binary PID: $P_{h/h'} = \frac{\mathcal{L}_h}{\mathcal{L}_h + \mathcal{L}_{h'}}$
  - global PID: $P_h = \frac{\mathcal{L}_h}{\sum_{h'} \mathcal{L}_{h'}}$

SVD	silicon vertex detector
CDC	central drift chamber
TOP	time-of-propagation counter
ARICH	proximity focusing aerogel RICH
ECL	electromagnetic calorimeter
KLM	K_L and muon detector