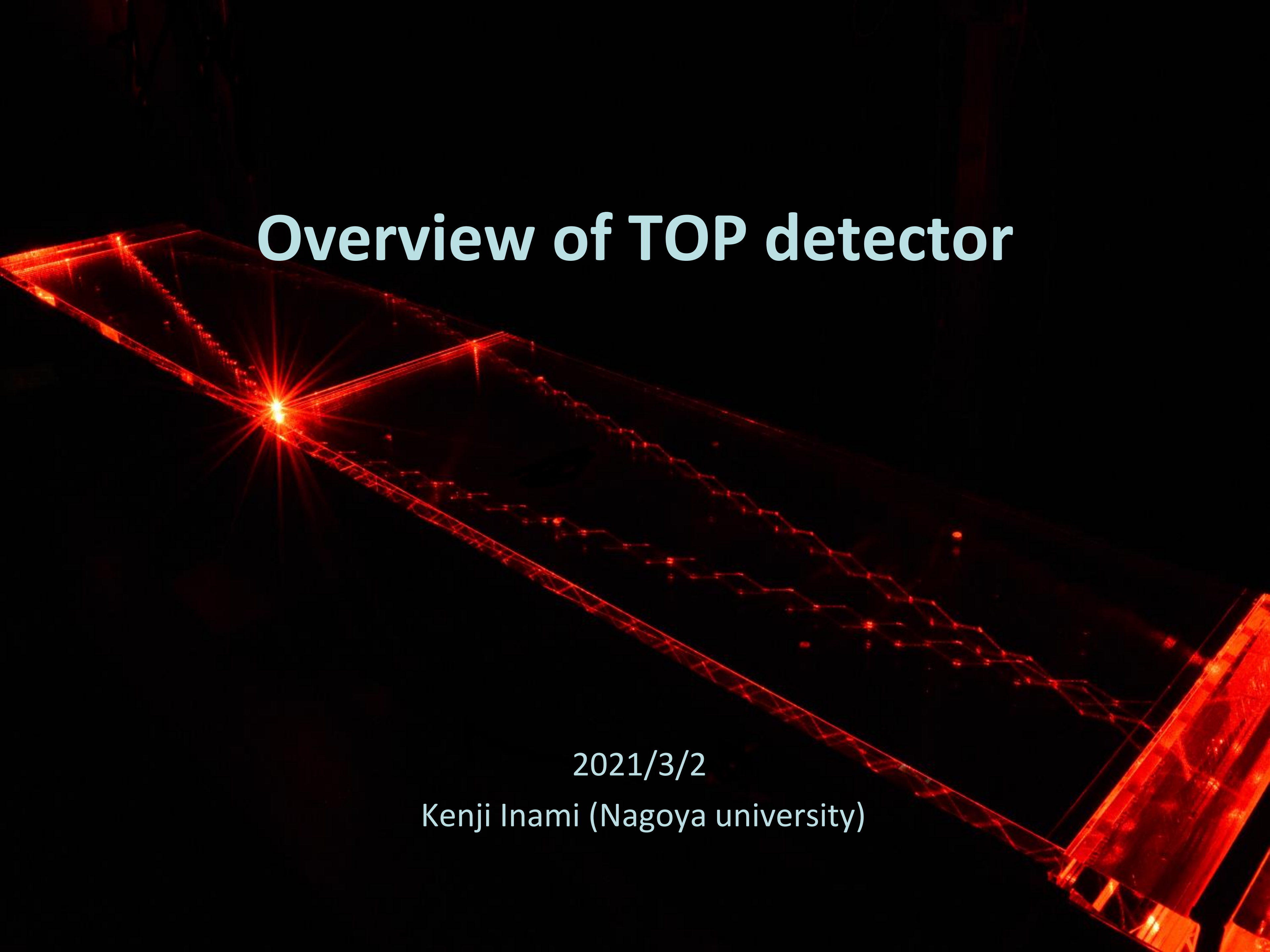
Overview of TOP detector

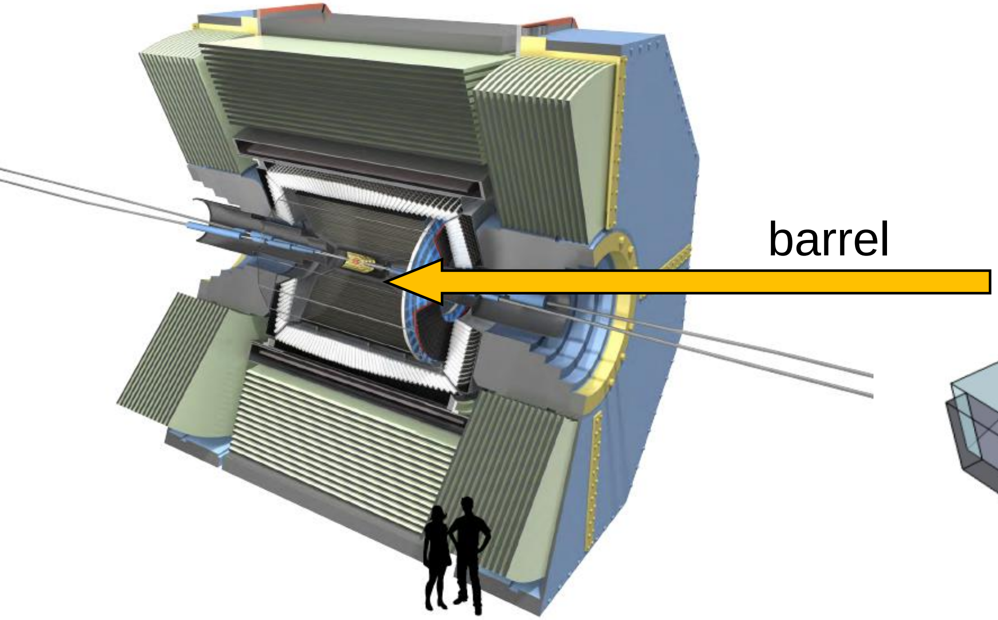


2021/3/2

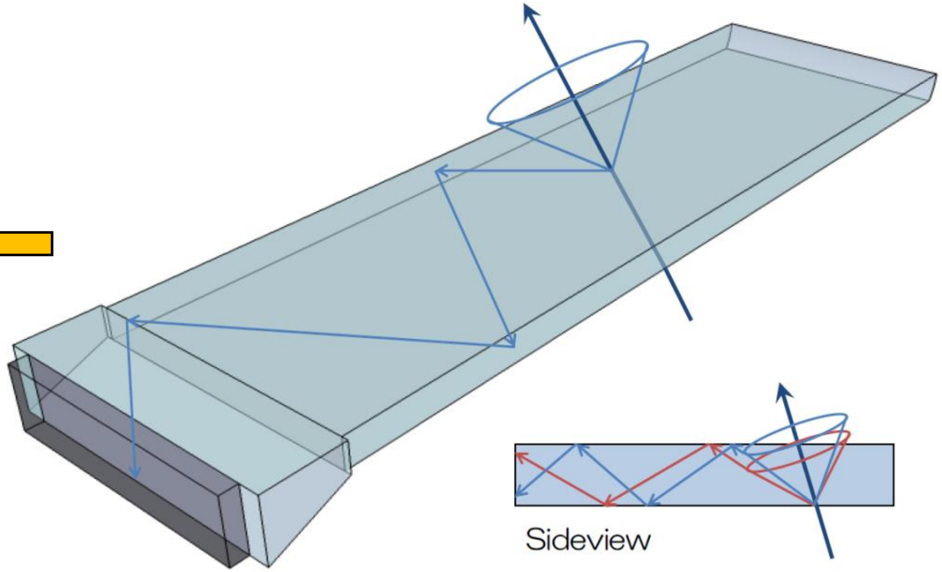
Kenji Inami (Nagoya university)

Belle II TOP detector

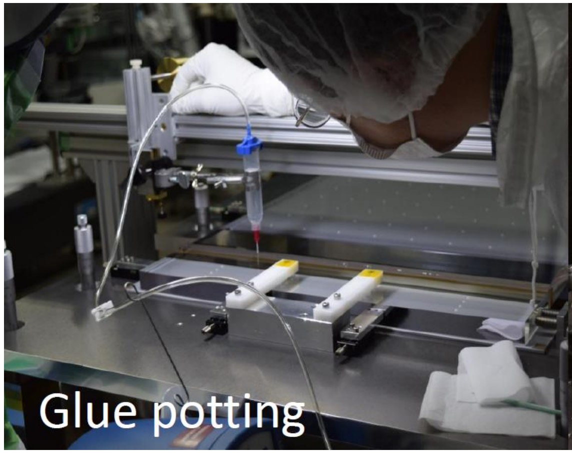
- Belle II experiment
  - Higher luminosity B-factory experiment; x50 integrated luminosity from Belle
- Particle identification; Ring Imaging Cherenkov detectors
  - A fake rate for K/π separation 2-5 times smaller than Belle
- TOP detector measures Cherenkov light arrival time/position precisely, then reconstructs particle velocity.
- 16 TOP modules are located in the barrel region outside of tracking device.

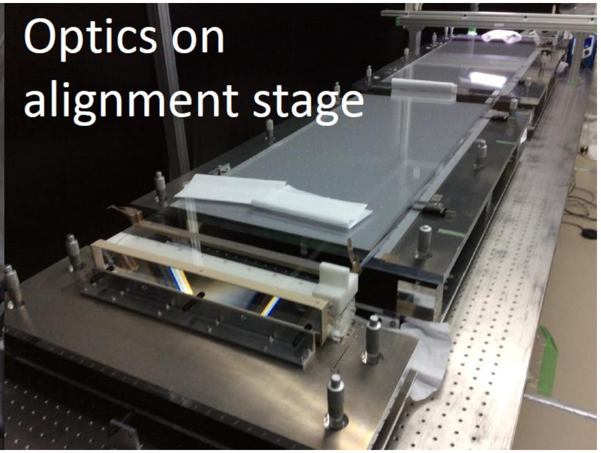


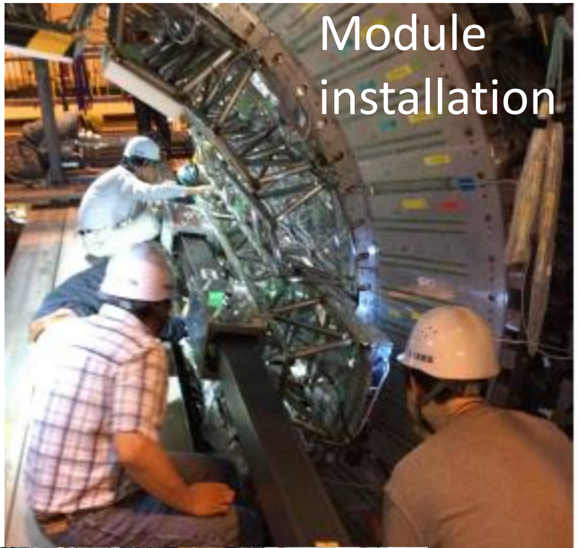
TOP（Time-Of-Propagation）detector

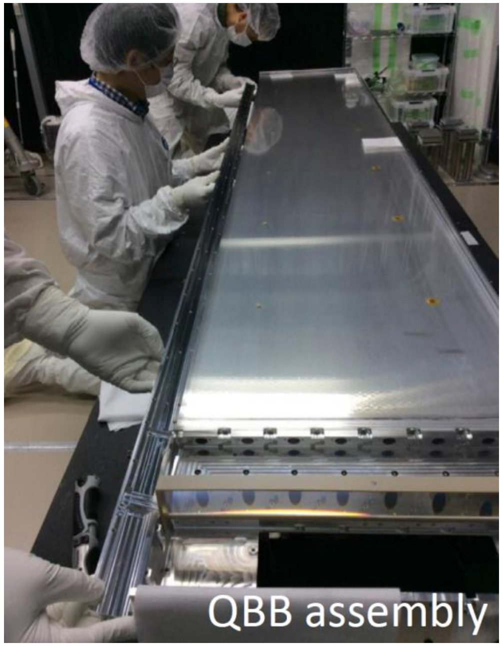


Module construction/installation


Glue potting

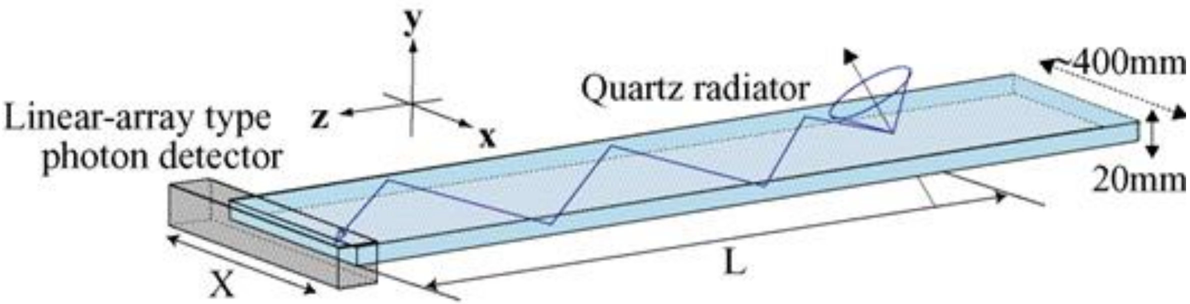

Optics on alignment stage


Module installation

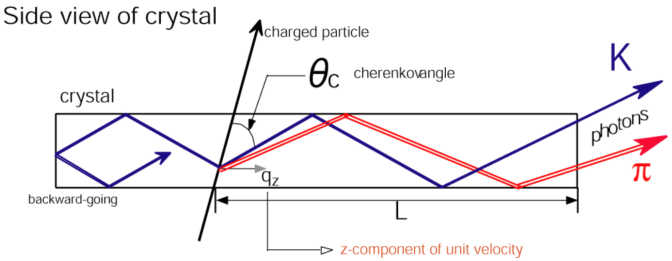

QBB assembly

Basic concept

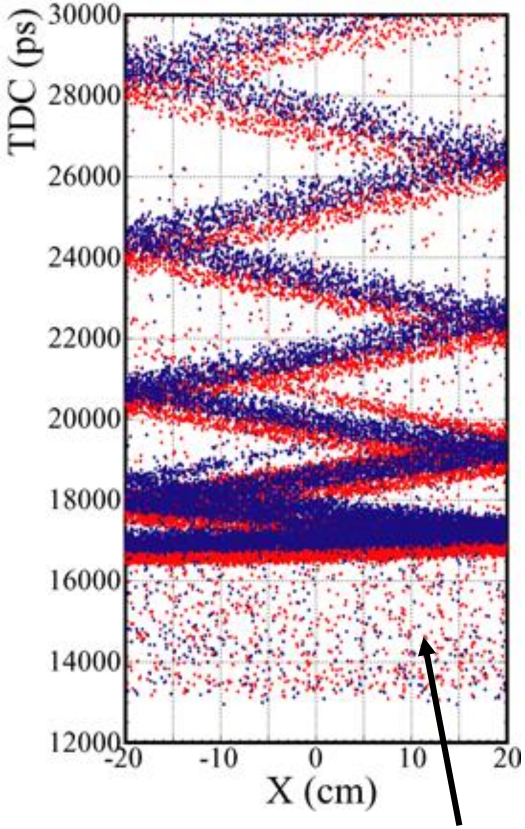
- Cherenkov ring imaging using timing information
- Very compact, suitable for detector geometry.
- Key technologies:
  - Single photo detection with precise timing
  - Accurately polished quartz bar



$$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$



Simulation
2GeV/c, θ=90 deg.
~20photon/track



δ-ray,
had. int.

Difference of path length → Difference of time of propagation (TOP)

~150-200ps from TOP + TOF from IP

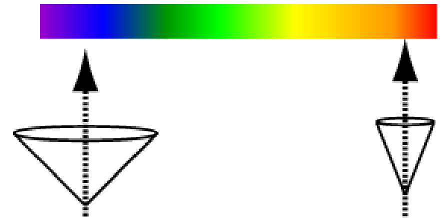
with precise time resolution (σ~40ps) for each photon

Focusing mirror + 3D imaging

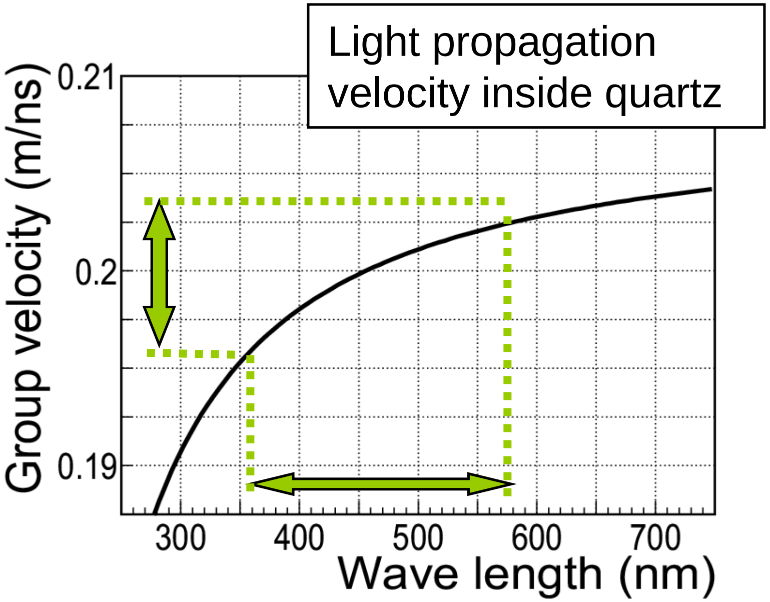
- Chromatic dispersion smears the TOP by ~100ps.
- Use λ dependence of Cherenkov angle to resolve chromaticity

➔ Focusing system to measure θ_c

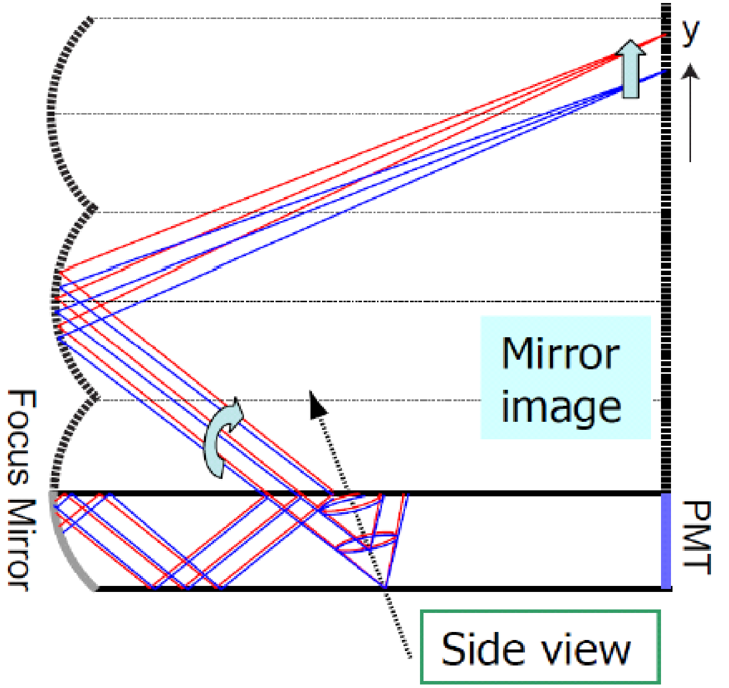
  - $\lambda \leftarrow \theta_c \leftarrow$ y position
  - Reconstruct ring image from 3D information (time, x and y).
  - Long focusing length enlarges y difference.
    - $\Delta\theta_c$~5mrad → Δy~14mm for 2.5m length



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



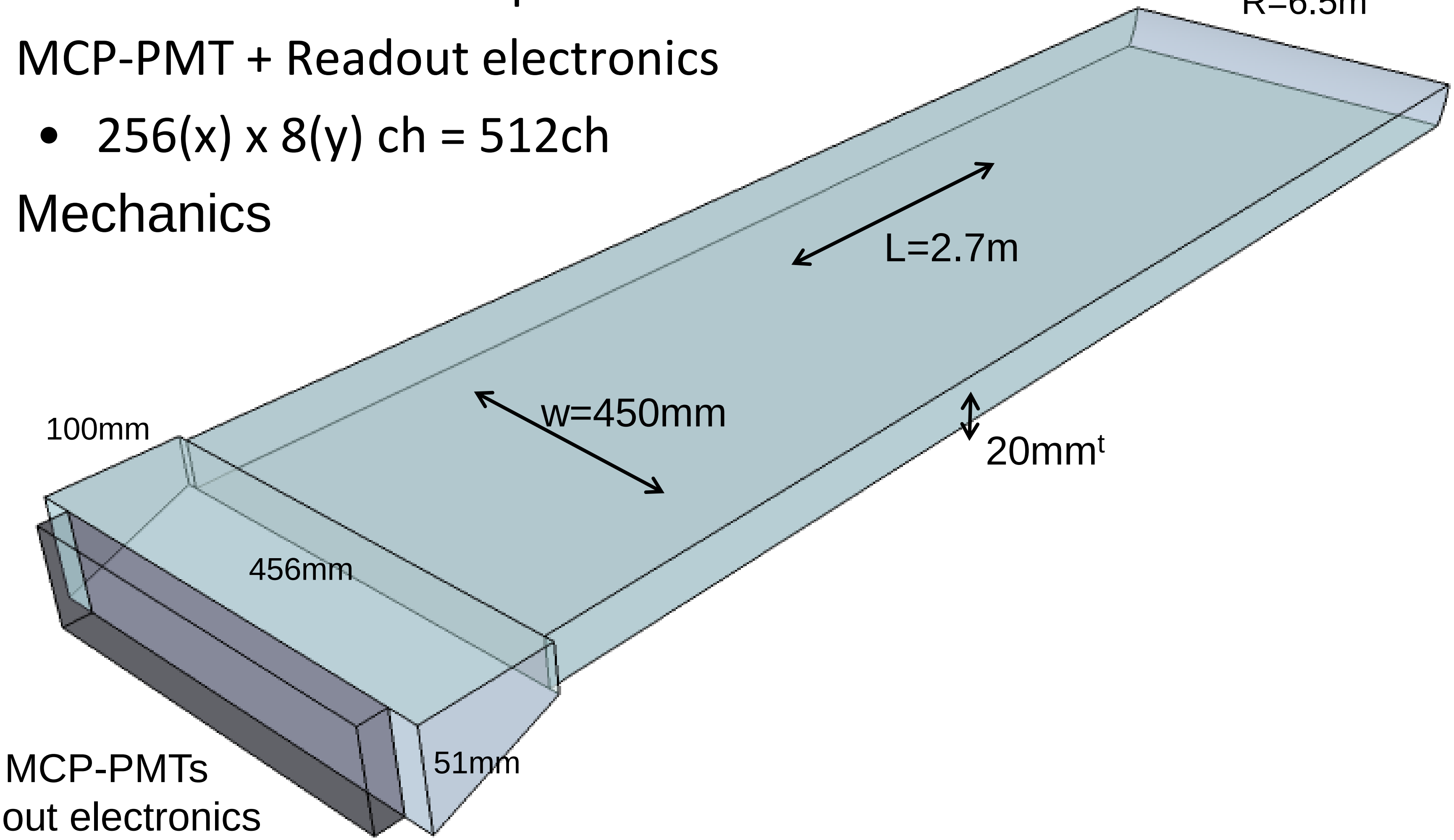
Light propagation velocity inside quartz



Side view

TOP detector for Belle II

- Quartz radiator
  - With mirror and expansion block
- MCP-PMT + Readout electronics
  - 256(x) x 8(y) ch = 512ch
- Mechanics

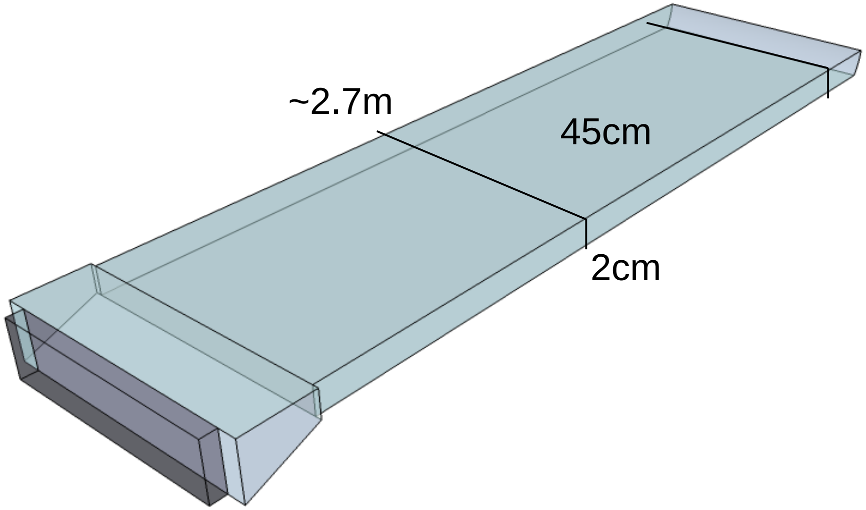


16x2 MCP-PMTs
Readout electronics

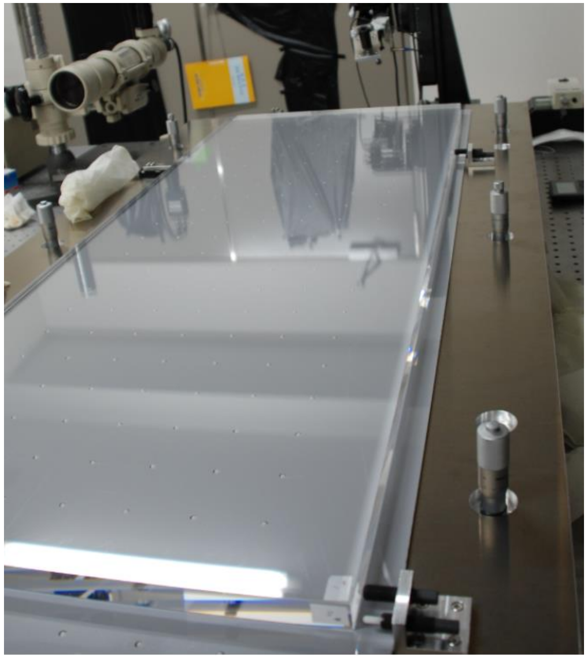
Quartz radiator

- Quartz bar (1.25m x 45cm x 2cm) x2
  - ~maximum size of polishing
- Focusing mirror (R=6.5m)
- Expansion block

→ Glue each other



- Production
  - Quartz bars made by Zygo (US) and Okamoto optics (Japan)

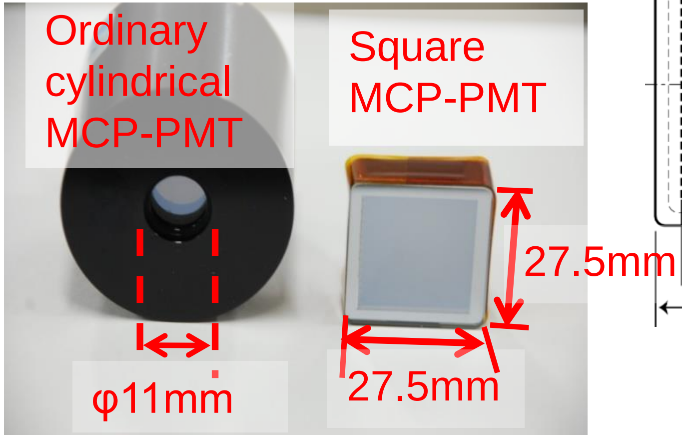


Quartz radiator requirements

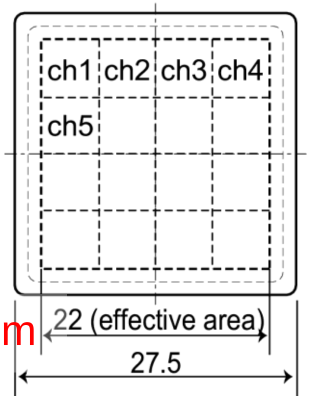
- Quartz material; Corning 7980 class 0, grade D or better
  - DIN58927 class 0 material has no inclusions (inclusions ≤0.01 mm diameter are disregarded).
  - Grade D (or superior) material having index homogeneity of ≤3 ppm over the clear aperture of the blank. This is verified at 632.8 nm according to the supplier brochure.

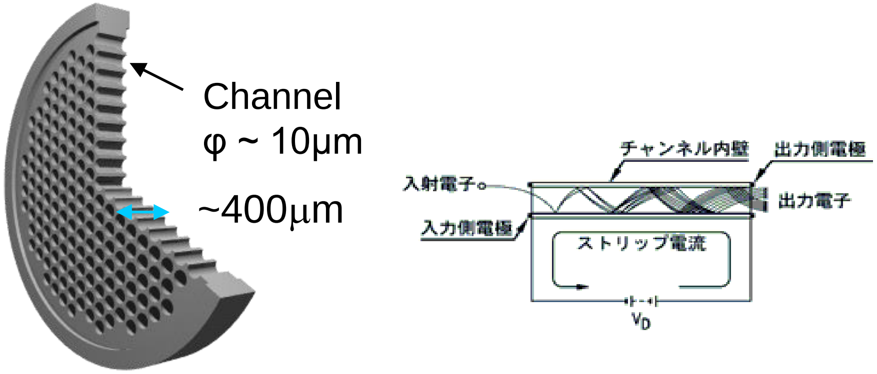
- Need high quality surface polishing
  - Roughness: 0.5nm (to keep total reflectance)
  - Flatness: $<10\lambda$ ($6.3\mu m$) over full aperture (to keep ring image)
  - Edge chamfer: <0.2mm
    - Allow small tip area

Square-shaped MCP-PMT



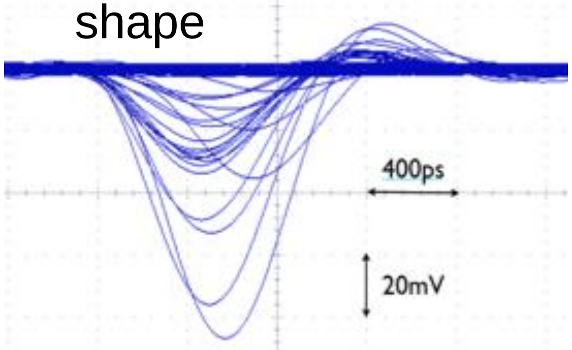
Co-development with Hamamatsu Photonics K.K.





MCP(Micro channel plate)

Typical signal shape

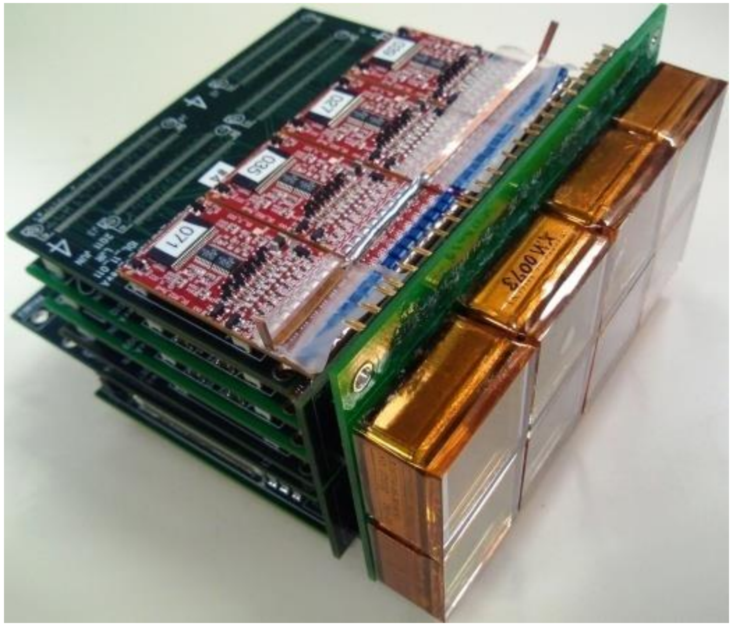


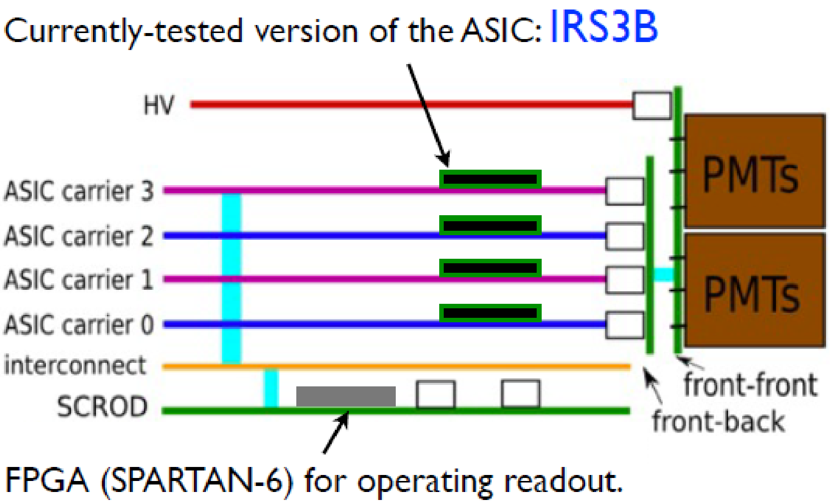
Single photon irradiation

Catalog spec	
Photo-cathode	Enhanced multi-alkali (>28% QE at peak)
MCP Channel ϕ	10μm
MCP bias angle	13°
MCP thickness	400μm
MCP layers	2
Al protection layer	On 2nd MCP
Anode channels	4 × 4
Sensitive region	64%
HV	~ 2500 – 3500 V

Readout electronics (prototype)

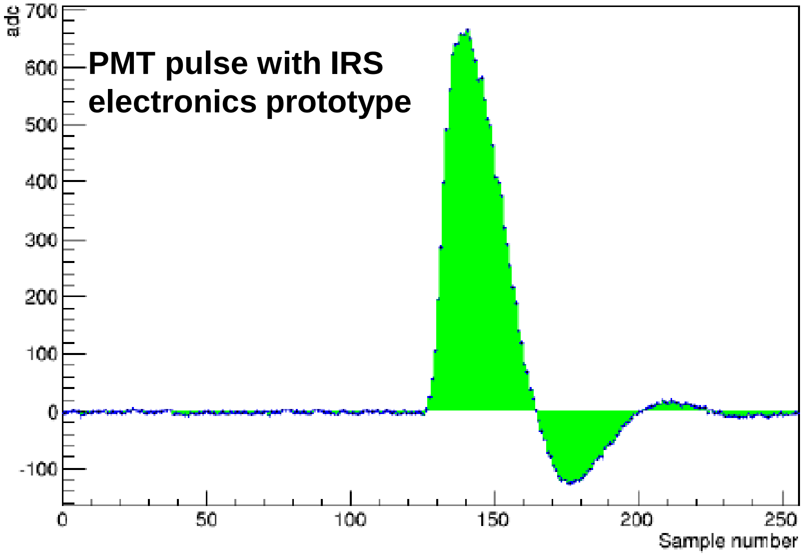
- MCP-PMT signal is readout by newly developed “IRS” series of ASICs.
    - Waveform sampling
        - Clear signal read out by ASIC.
    - High density, multi-hit buffering
        - 512ch / module, 30kHz trigger rate
    - Clock jitter measured with test pulse is about 20ps.





Currently-tested version of the ASIC: IRS3B

FPGA (SPARTAN-6) for operating readout.



PMT pulse with IRS electronics prototype

Prototype R&D

PMT issues under the high hit rate

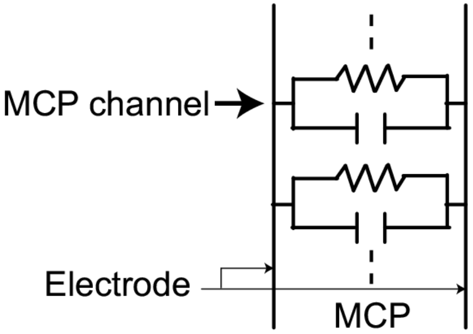
- Timing performance degradation
  - Gain drops when MCP current is saturated due to many electron multiplication in the channel.

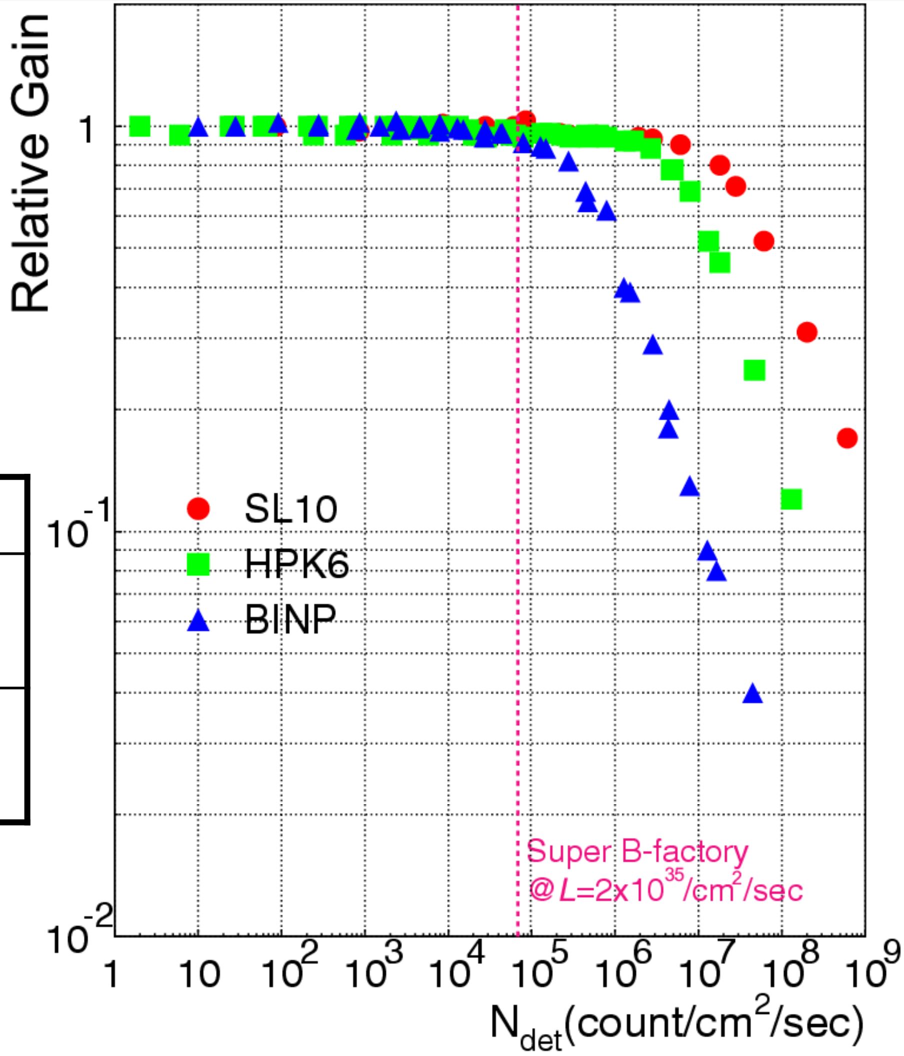
- Photocathode aging
  - Electron multiplication causes out gas and ion feedback to photocathode.
  - Photocathode QE degrades

Rate dependence

- Gain drop for high rate
  - $>10^5$ count/cm^2/s
  - Due to lack of elections inside MCP holes
  - Dep. on RC variables

	SL10	HPK6	BINP
MCP resistance ($M\Omega$ cm^2)	96	143	380~1000
MCP capacitance (pF/cm^2)	16	31	24~39



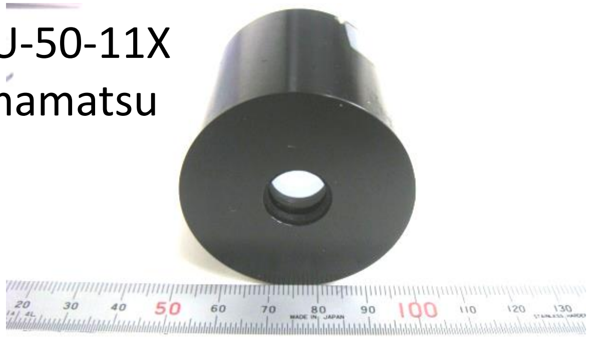


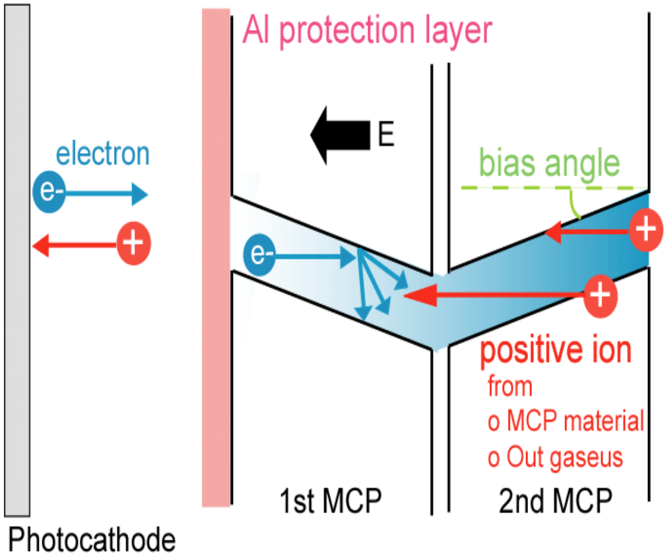
[SL10: Square-shaped MCP-PMT for TOP]

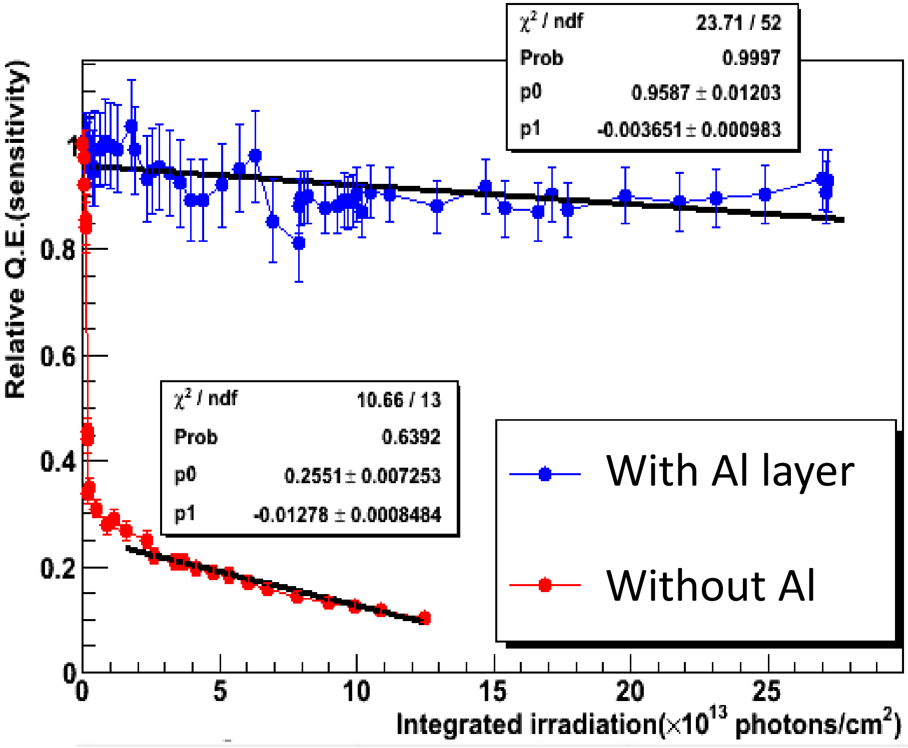
Aging of photocathode

- Round-shape MCP-PMTs
  - With and without aluminum layer on MCP
    - Protect feedback ions
  - Obtain sufficient lifetime, by putting Al on MCP
  - TTS is stable, if gain>~10^6

R3809U-50-11X
by Hamamatsu



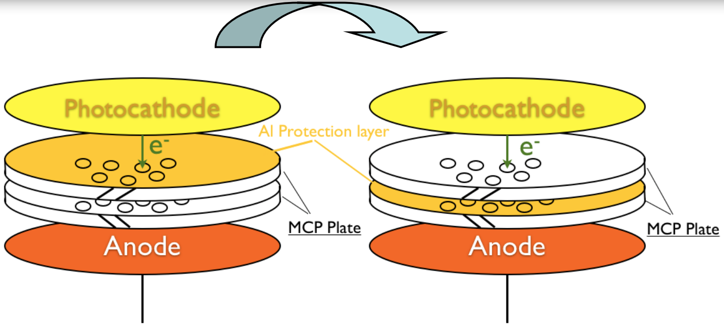




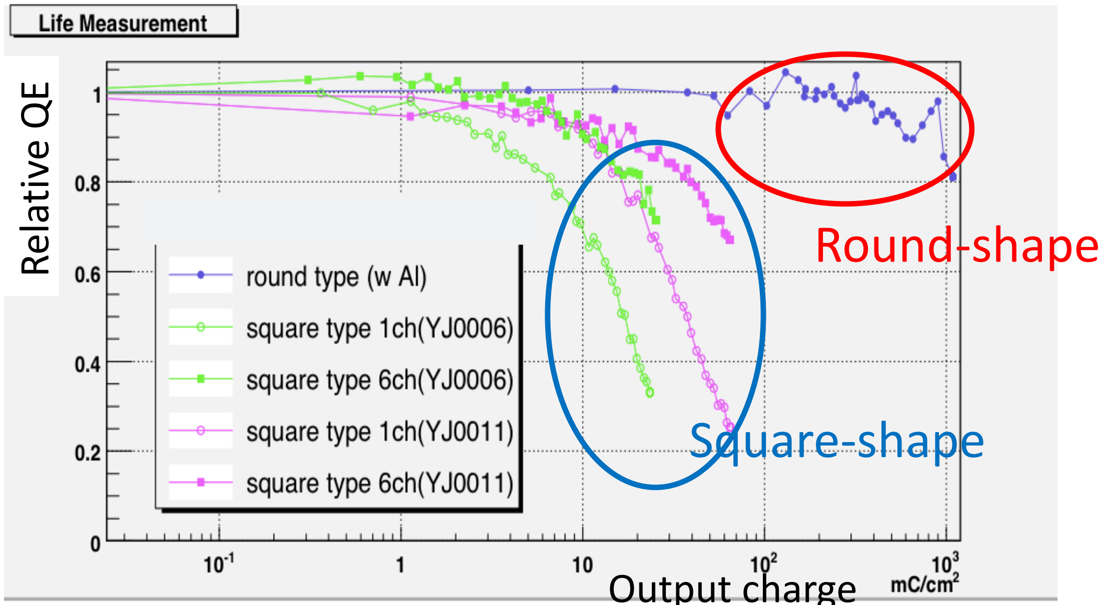
Nucl. Instr. Meth A564, 204 (2006)

Lifetime for square-shape MCP-PMT

- Improvement for square-shape MT
  - With Al layer on MCP
  - Al protection layer on 2nd MCP
    - Recover collection efficiency (35%→60%)
    - Expect small effect to lifetime
      - Because of 1/10^3 smaller number of electrons in 1st MCP compared to 2nd MCP
- Tested first prototype

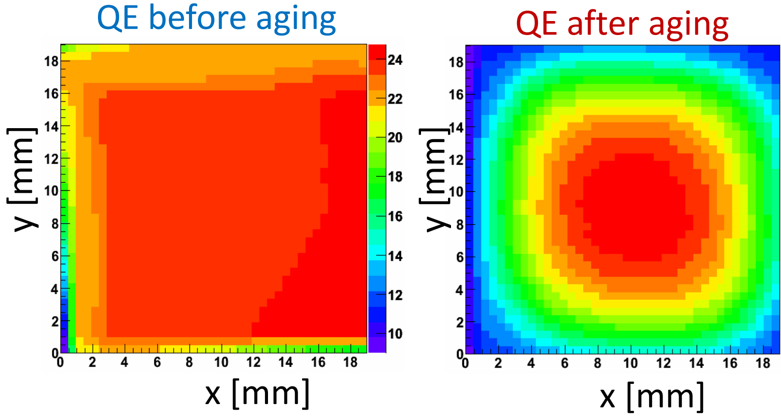


Measured PMT	YJ0006	YJ0011
Al protection layer	1st MCP	2nd MCP
Initial gain (× 10^6)	0.41	1.1



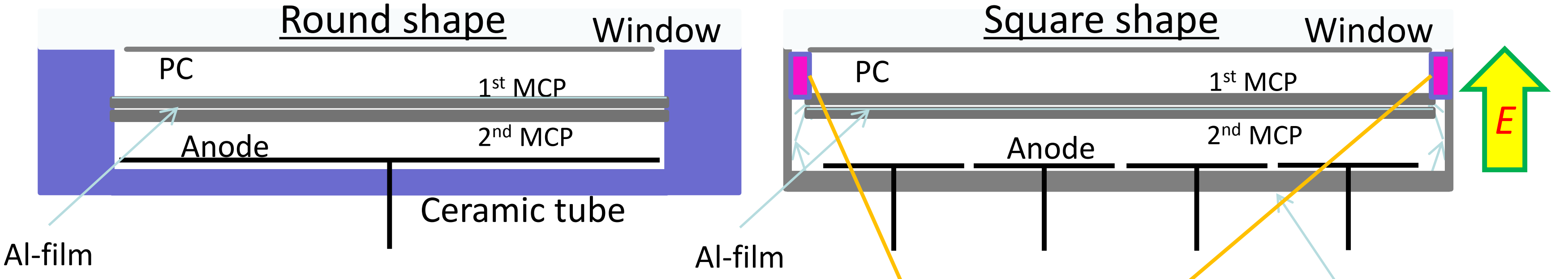
The QE drop becomes more significant toward the edges.

– Related to the structure?



Cause of aging

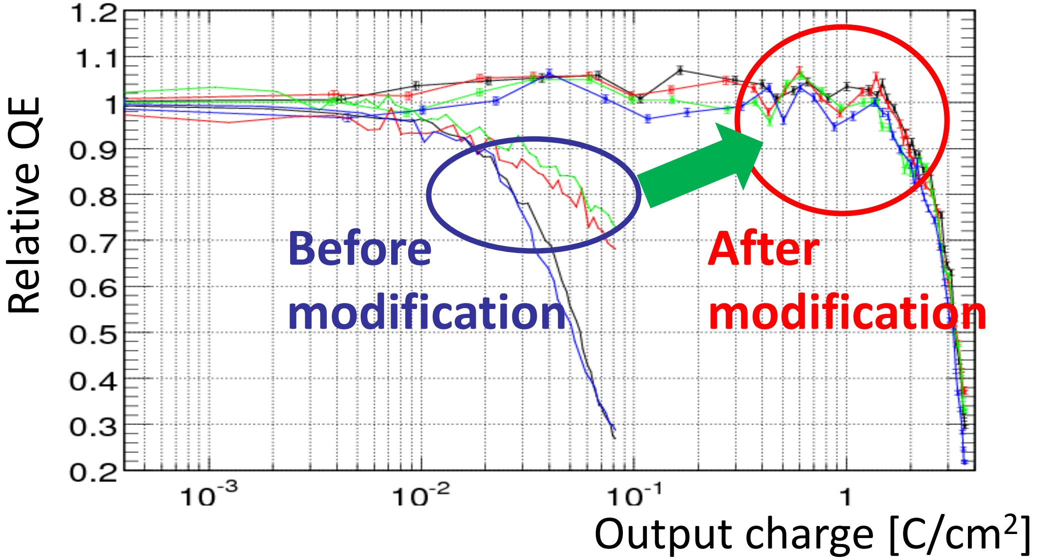
- Difference of inner structure btw round-shape and square-shape MCP-PMTs



- Neutral gas from 2nd MCP can pass through side gap.
  - We suspected that neutral gas through side gap causes QE degradation.
- Ceramic insulator added to block the path

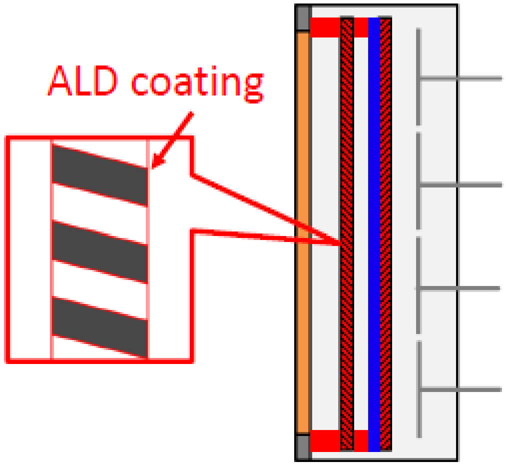
- Lifetime is significantly improved

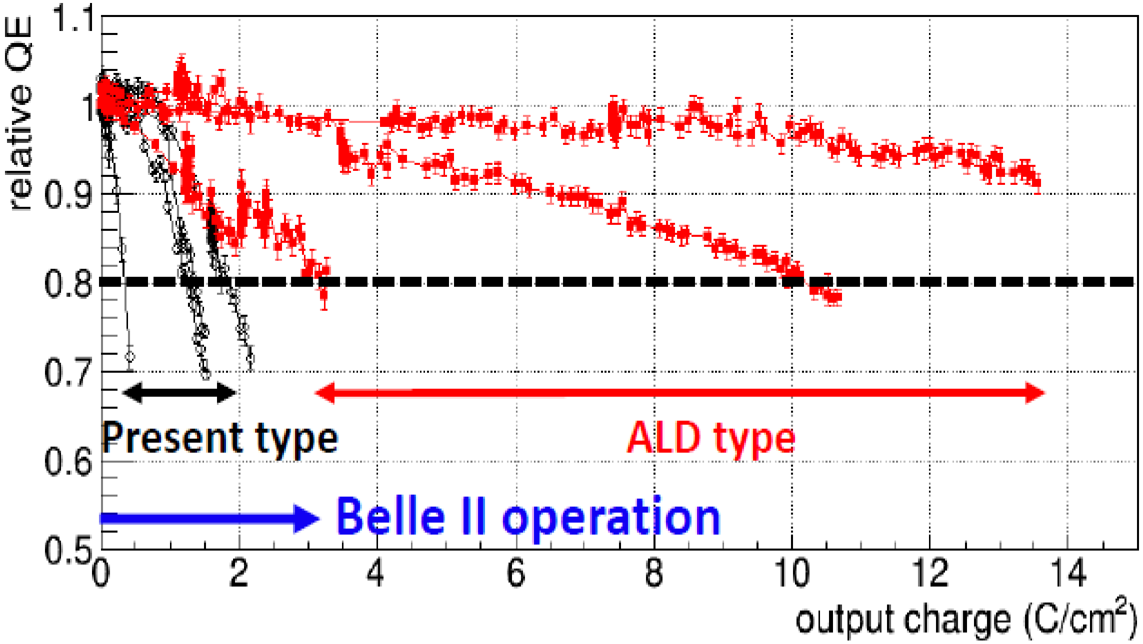
Nucl. Instr. Meth. A629, 117 (2011)



ALD coated MCP-PMT

- During mass-production, we noticed lifetime improved PMTs are needed along with the progress of BG sim.
- ALD (Atomic layer deposition) technique applied to MCP production.
  - Higher gain compared with conventional type
  - Less outgas/ion emission for same gain operation
- Tested ALD MCP-PMT ➔Confirmed improved lifetime



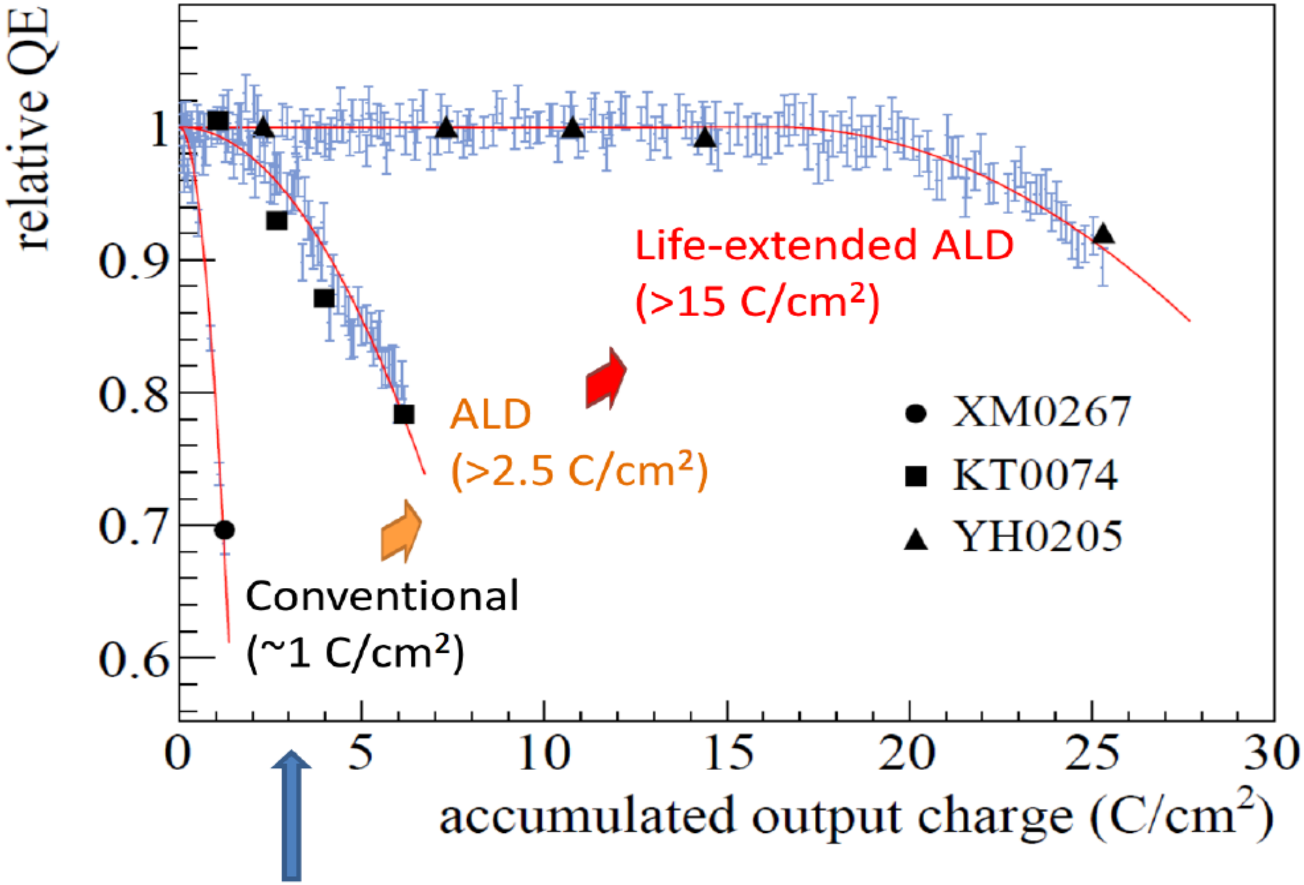


Nucl. Instr. Meth. A766, 148 (2014)

Further improvement for aging

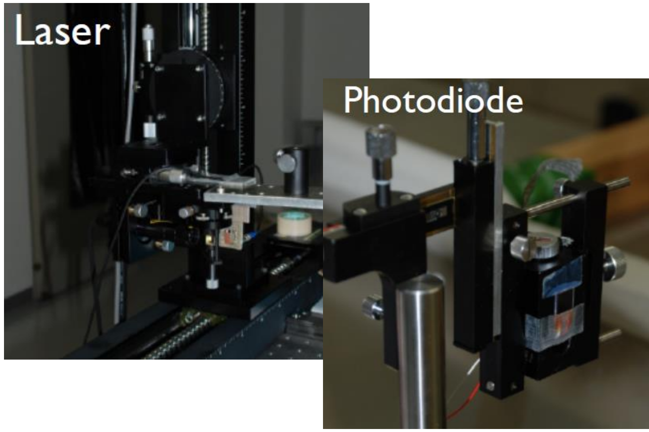
- Further improved PMTs developed with Hamamatsu.
  - Several production method tested (secret recipe…)

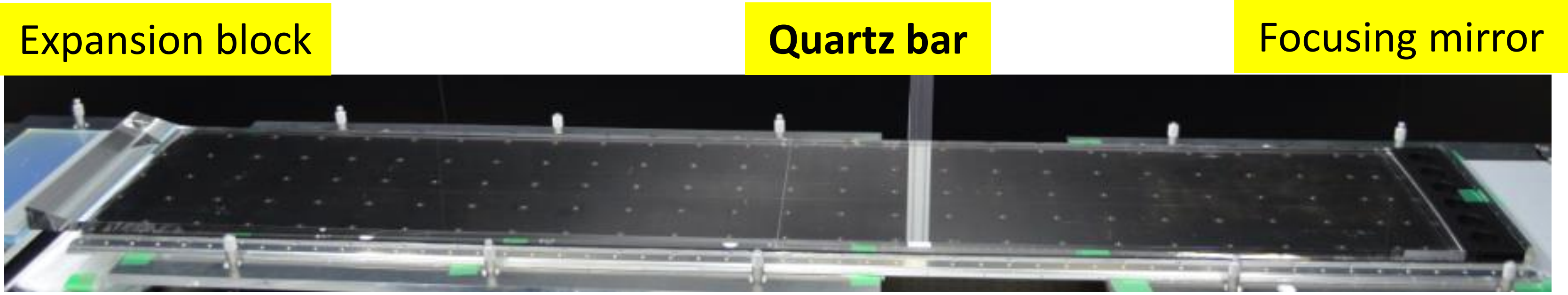
Photocathode lifetime improvements



Quartz radiator production R&D

- Polished surface meets our requirements.
  - Roughness: 0.44nm
  - Flatness: 4.9, 5.1μm for 1.2m
- Quality confirmed by our laser system
  - Internal surface reflectance: 99.92~99.97%
  - No evidence of striae
- Gluing quartz bars and mirror
  - Built optical stage to align precisely
  - Relative angle < 0.1mrad, Displacement < 100μm

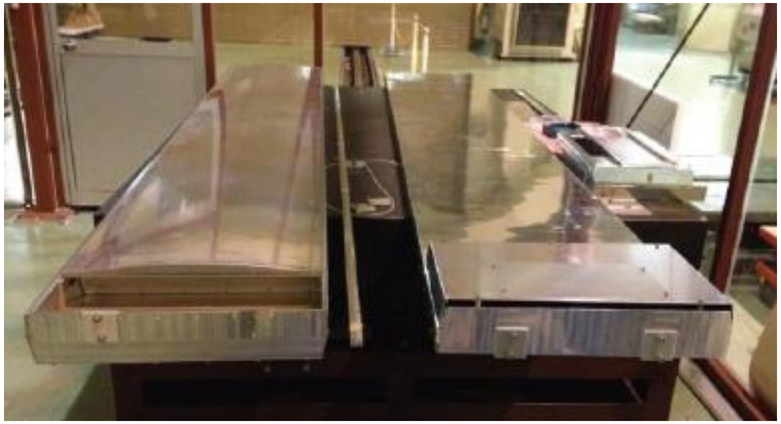


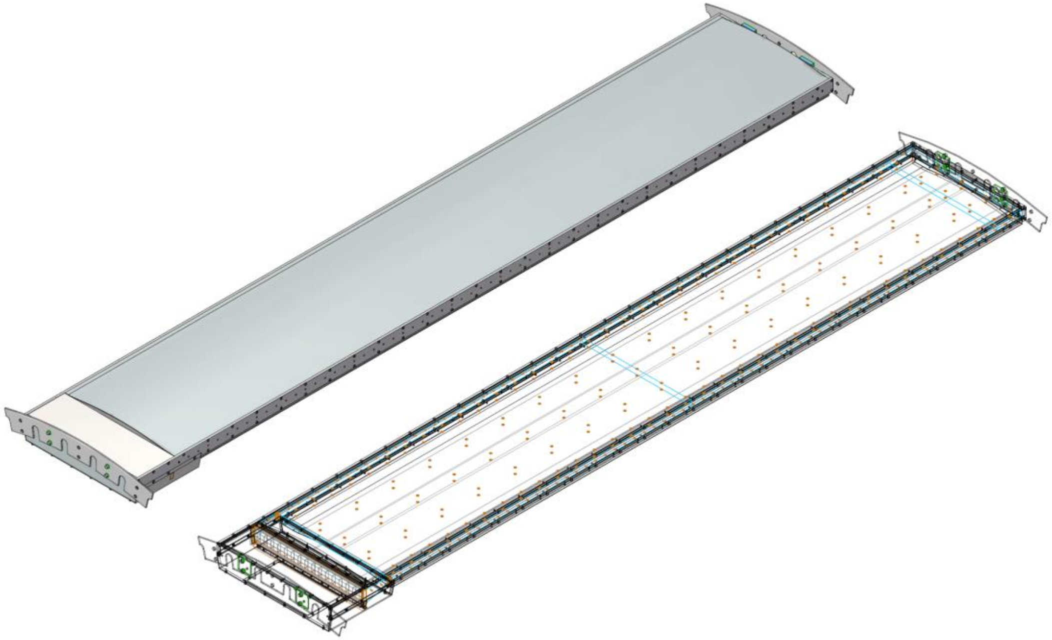


Mechanics development

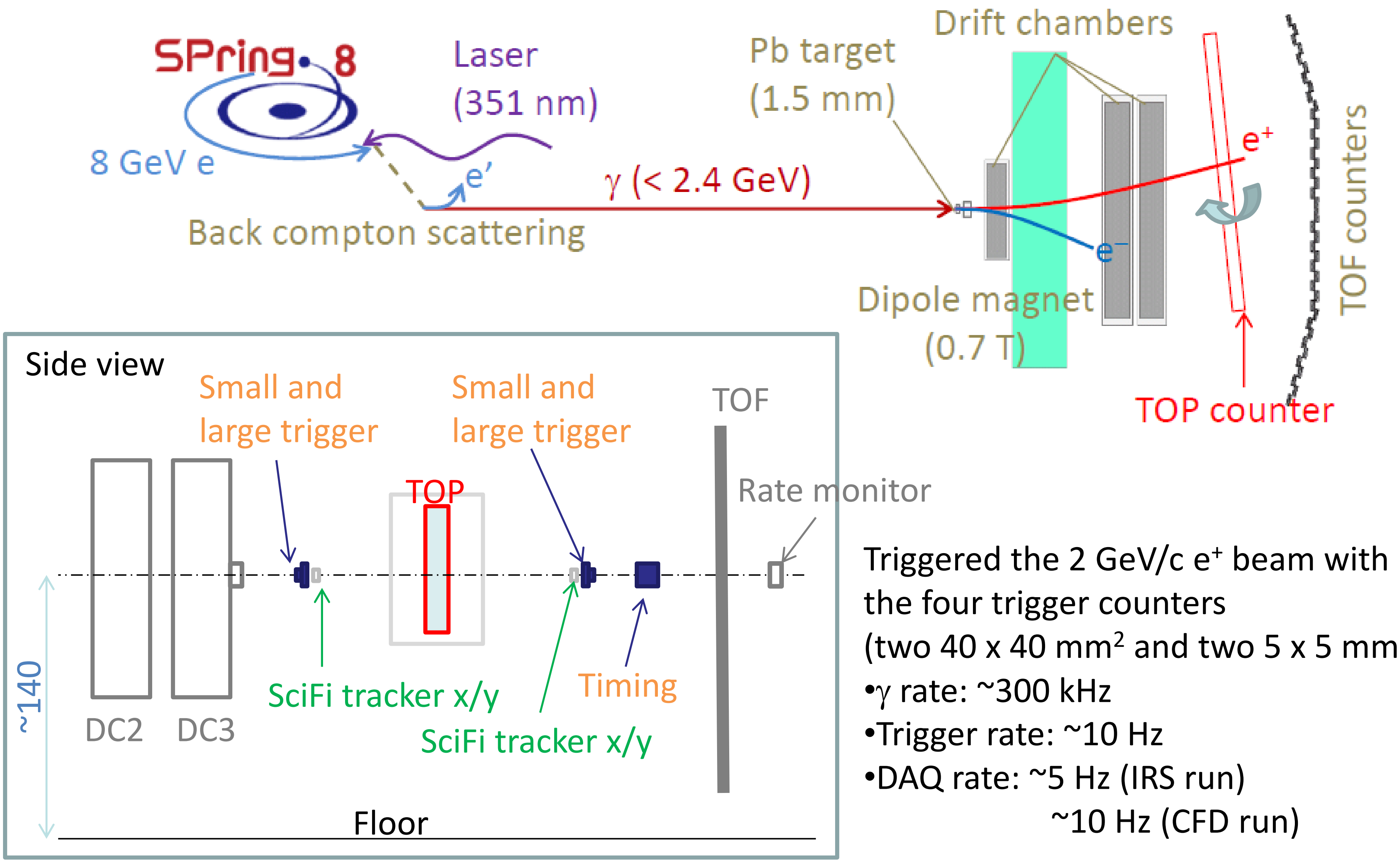
- Quartz bar box and readout support
  - Honeycomb panels (low mass)
    - + side rails, + readout cover
  - Quartz radiator is supported with PEEK buttons, to allow the total reflection
- Rigid support required for the final system
  - Connect to adjacent modules
  - Round shaped honeycomb panel

QBB prototype with
Round shaped panel and normal panel





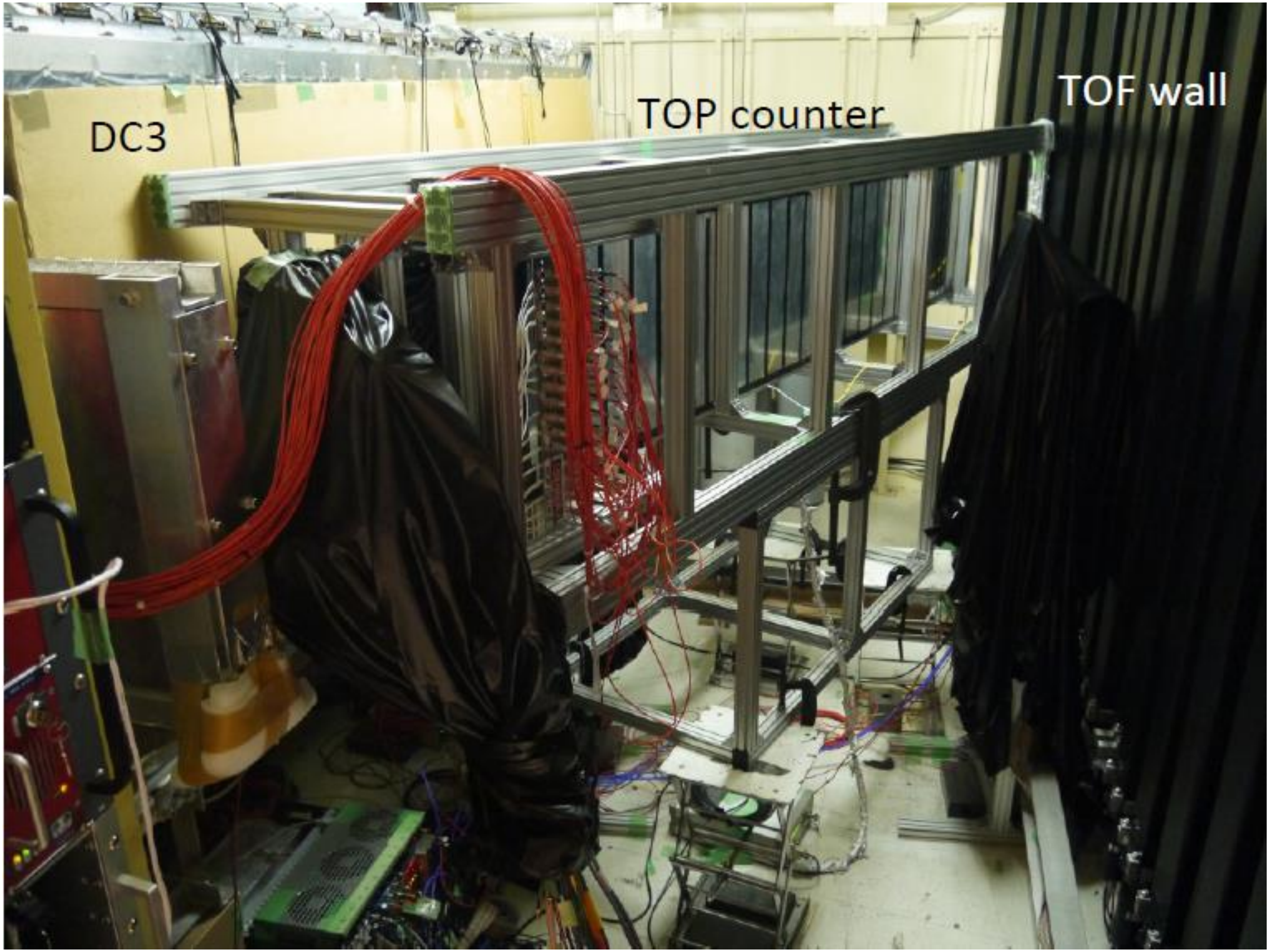
Beam test at Spring-8 LEPS



Triggered the 2 GeV/c e$^+$ beam with the four trigger counters (two 40 x 40 mm^2 and two 5 x 5 mm^2)

- γ rate: ~300 kHz
- Trigger rate: ~10 Hz
- DAQ rate: ~5 Hz (IRS run)
  ~10 Hz (CFD run)

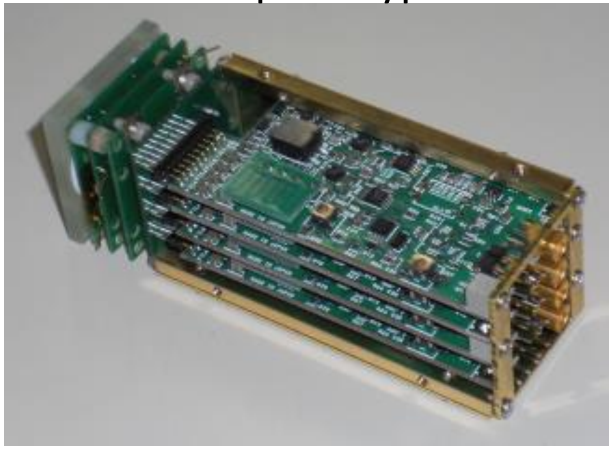
TOP detector in LEPS beam line

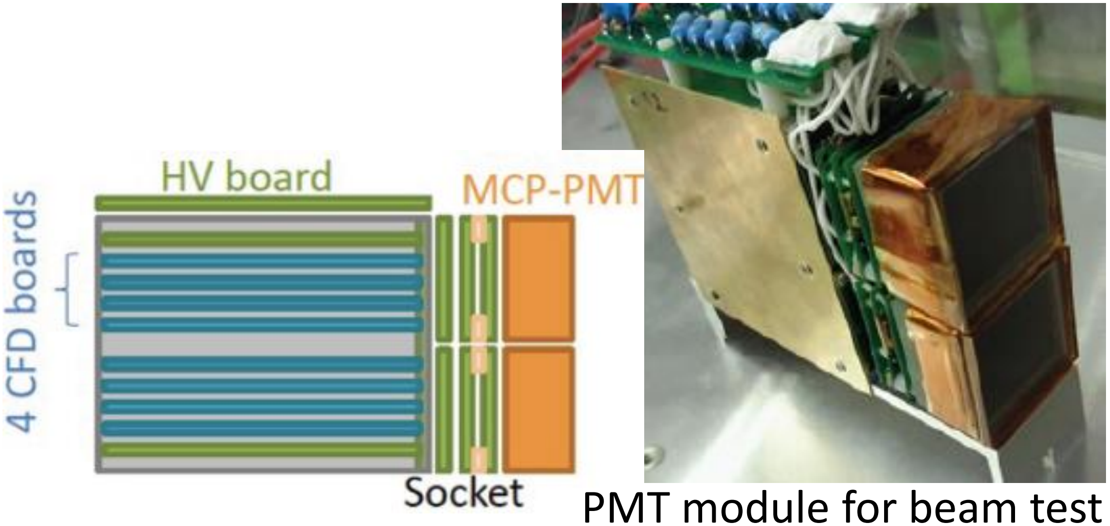


CFD readout for beam test

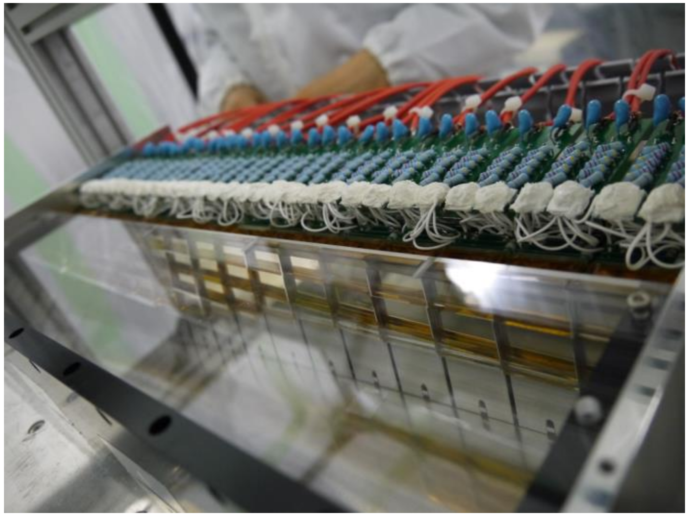
- CFD readout
  - Used already at previous beam tests
  - 1x4 readout.
    - 4-channels are combined (128ch/module).
  - Suitable back-up for beam tests.
- Good resolution (~40ps for single photon)
  - With MCP-PMT and CAEN VME TDC (V1290A)
  - Confirmed by laser

CFD module prototype





PMT module for beam test



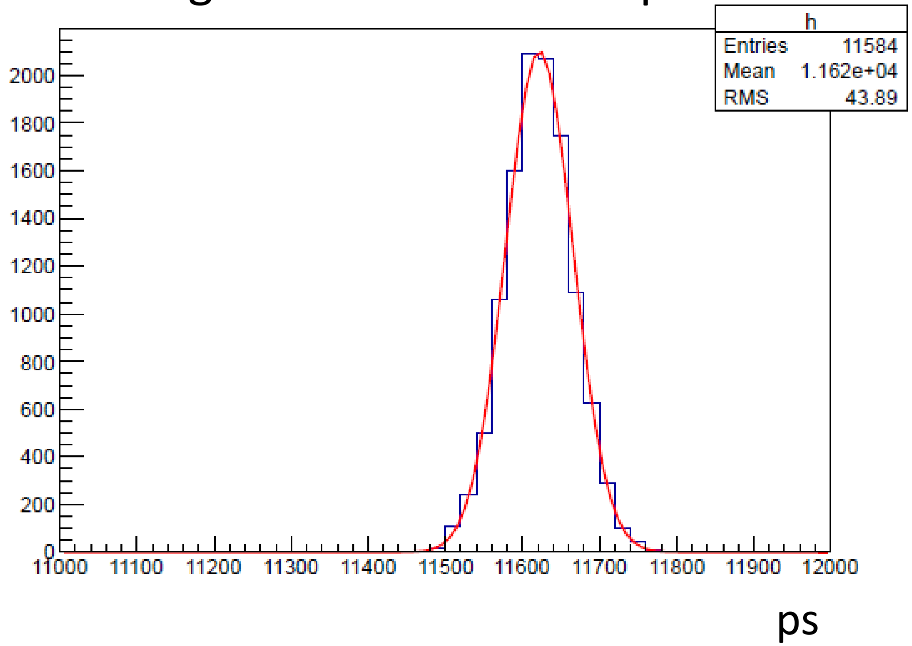
PMT modules mounted

Beam timing

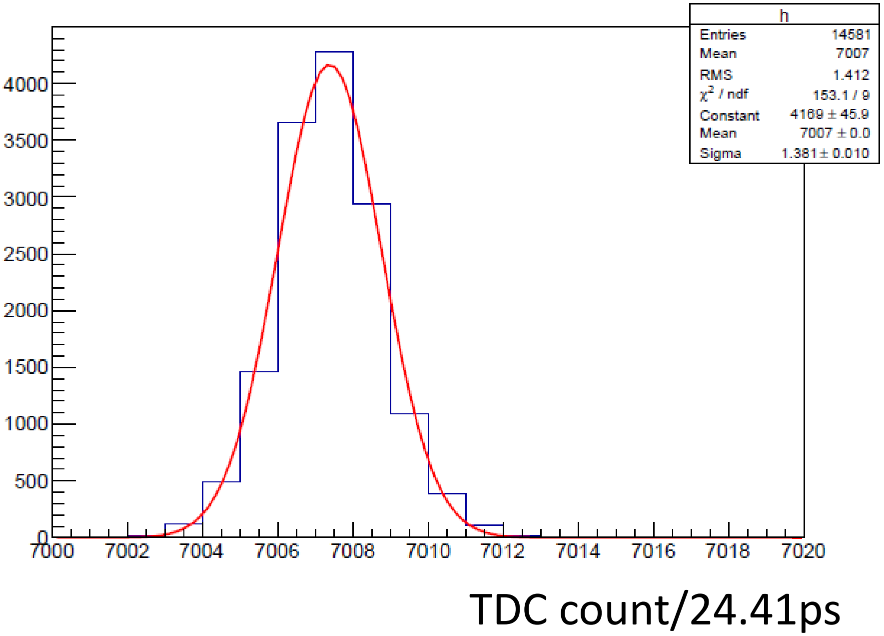
- RF clock from accelerator
- Timing resolution was confirmed with timing counter.
  - T_0 resolution : ~40ps
  - RF digitization resolution: ~24ps

10mm$^{\phi}$ quartz + MCP-PMT

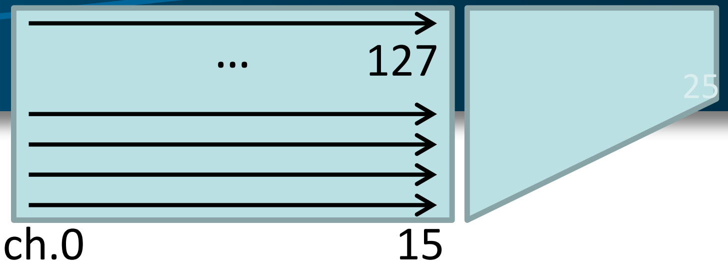
Timing counter - RF: σ=44ps



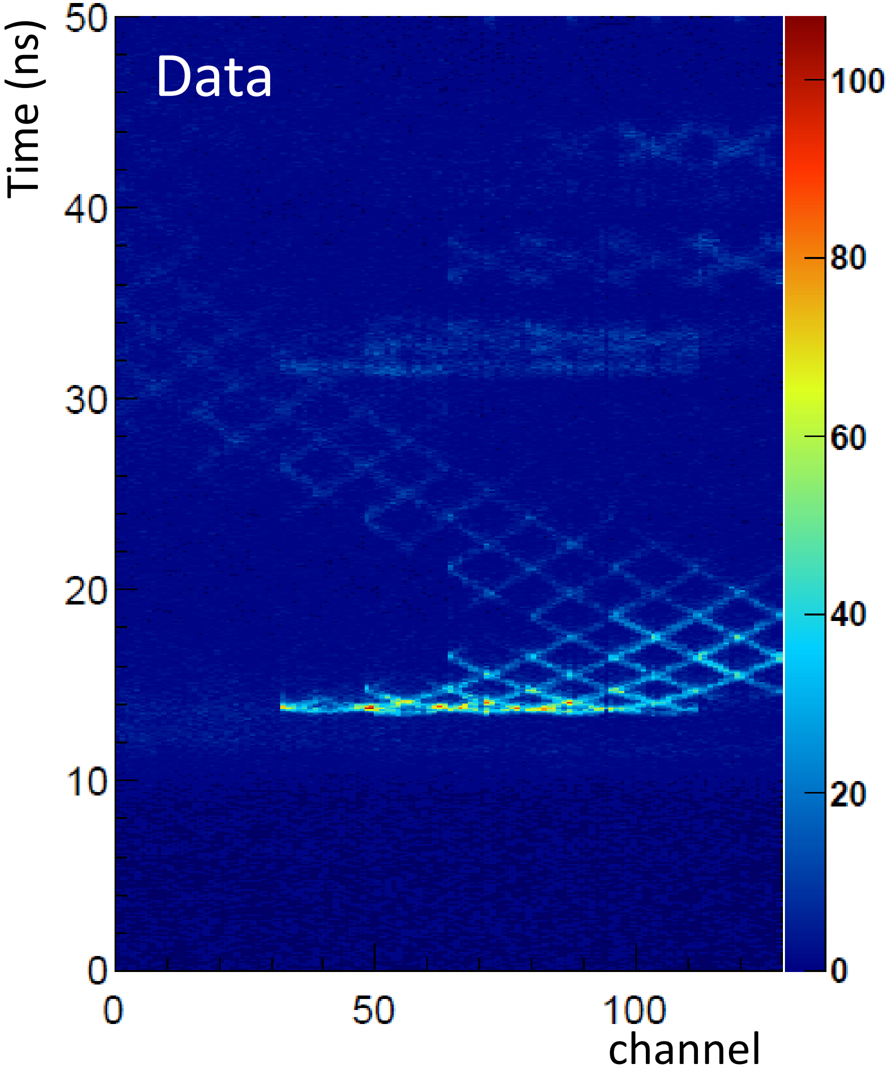
Two RF clock difference: σ=34ps/sqrt(2)

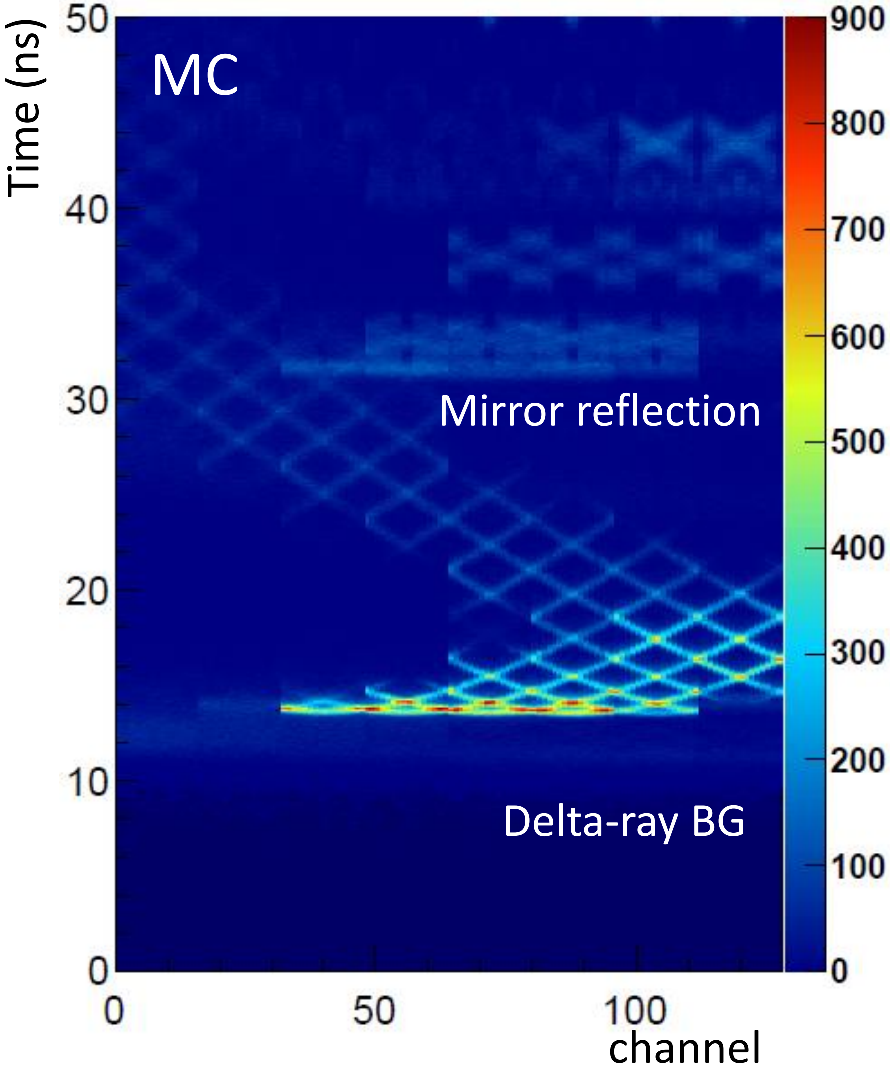


Ring image



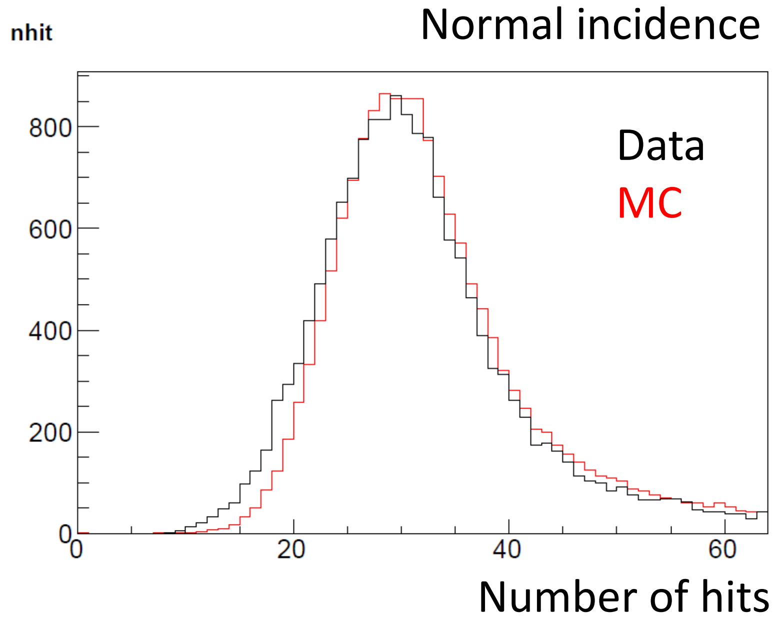
- Normal incidence, CFD readout

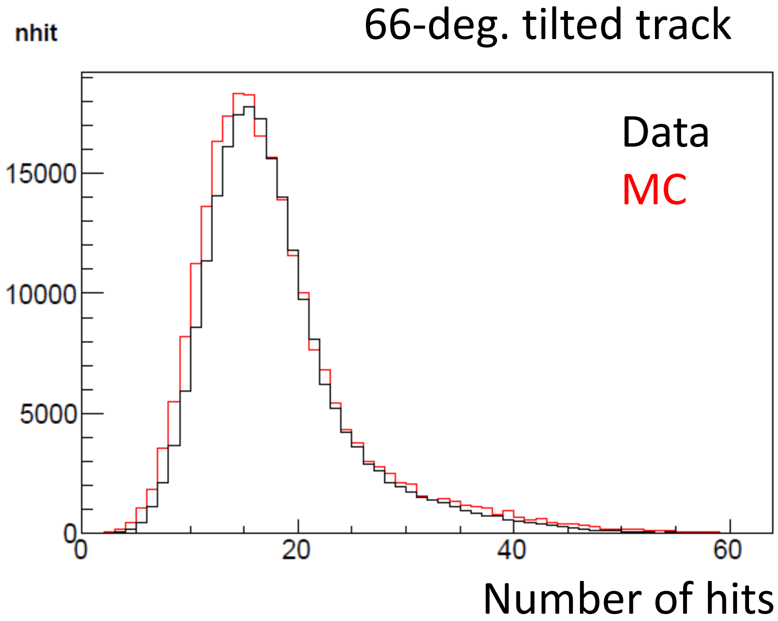




Number of detected photons per event

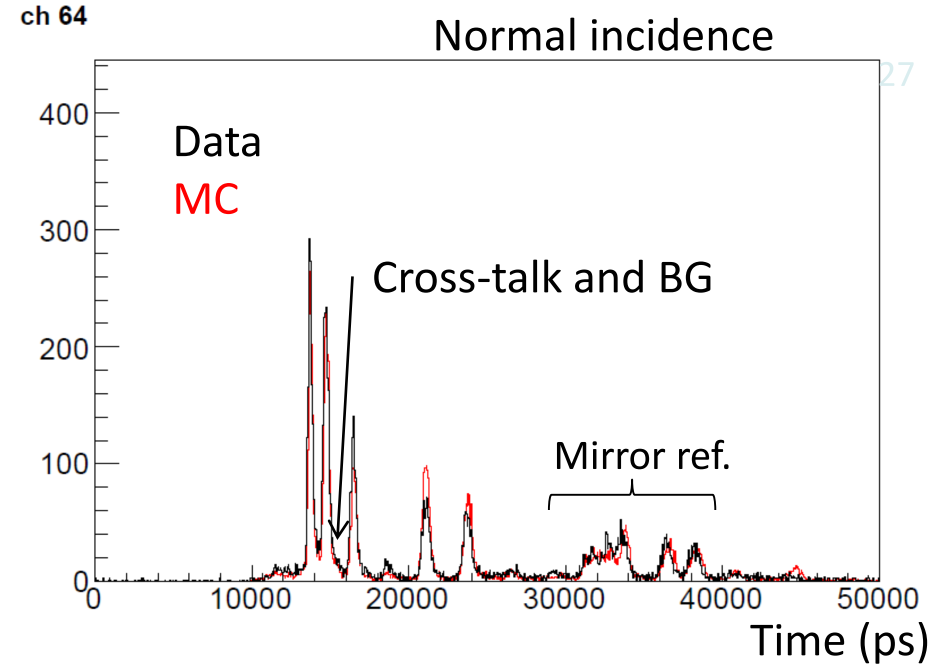
- Number of hits was obtained as expected.
  - Peak: 25 hits for normal incidence, 15 hits for tilted track
  - Considering path length, photon acceptance, QE (av. 29% at peak), cross-talk/charge sharing (~13%), etc.
  - Tail component is due to the delta-ray and shower tracks in the front of TOP detector (trigger and Scifi tracker) and TOP radiator itself.

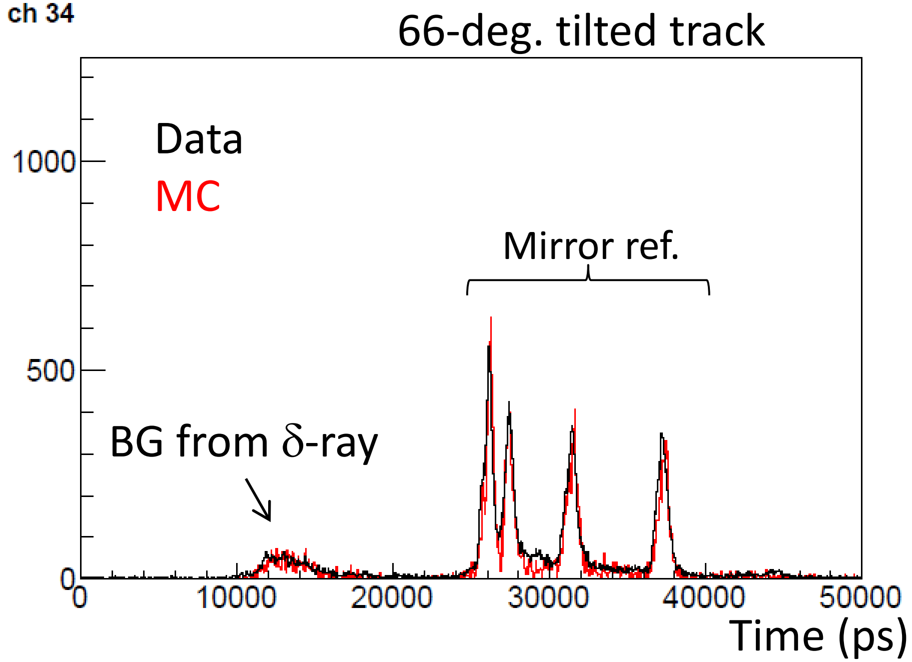




TDC distribution

- Good agreement between data and MC expectation.
  - Background component (especially for the data before first peak)
    - Due to delta-ray/showering tracks by the electron beam interaction with the material in front of detector.
  - Tail component
    - Reproduced by cross-talk hits and background



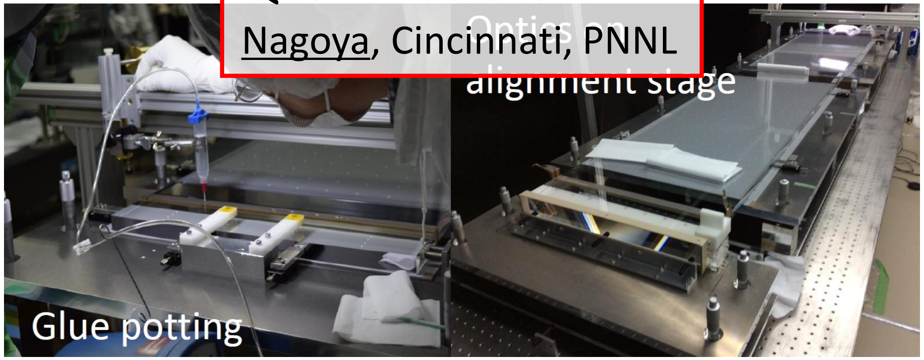


Production

Detector components

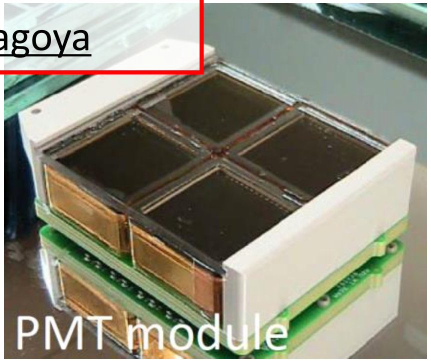
Quartz radiator

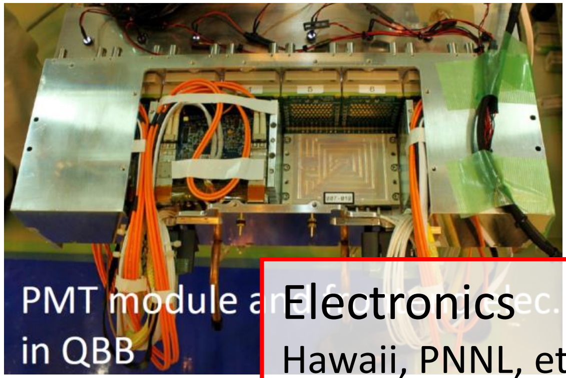
Nagoya, Cincinnati, PNNL



MCP-PMT

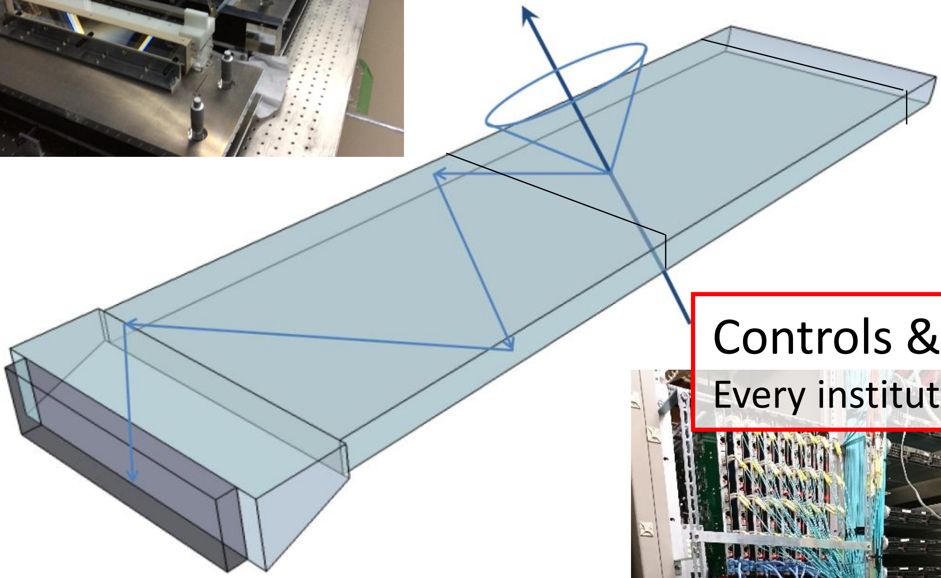
Nagoya





Electronics

Hawaii, PNNL, etc.



Commissioning, calibration

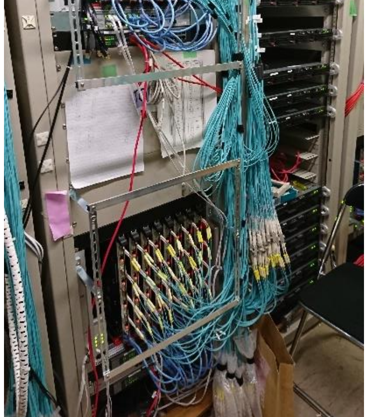
Every institutes

Mechanics

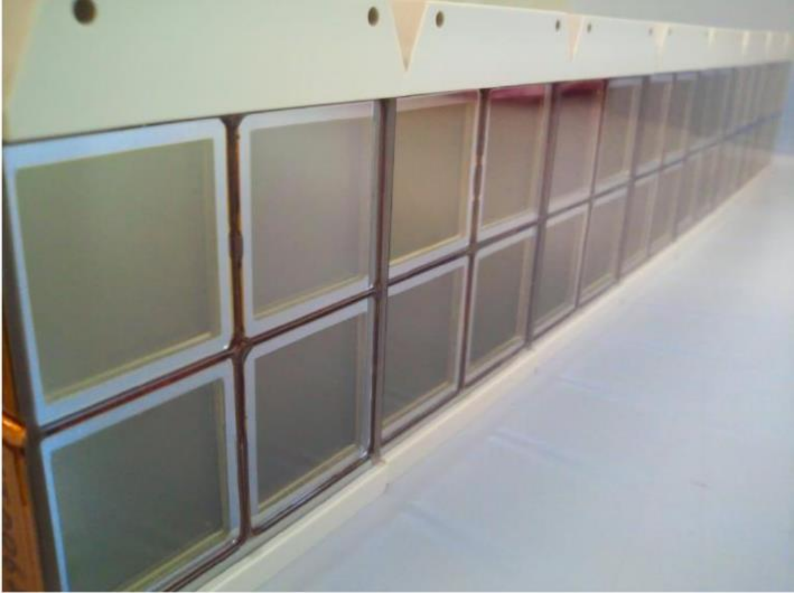
Nagoya, KEK, Hawaii

Controls & calibration system

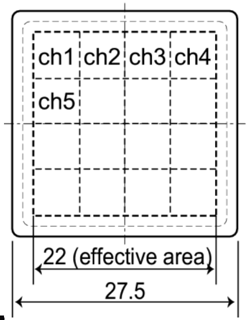
Every institutes



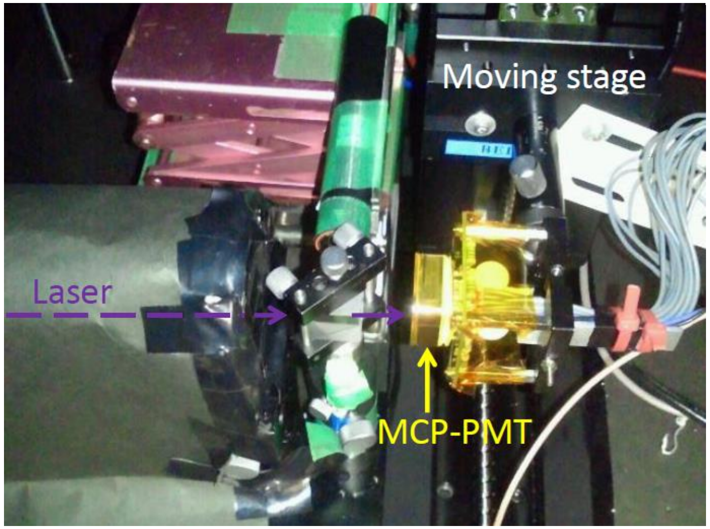
PMT mass production



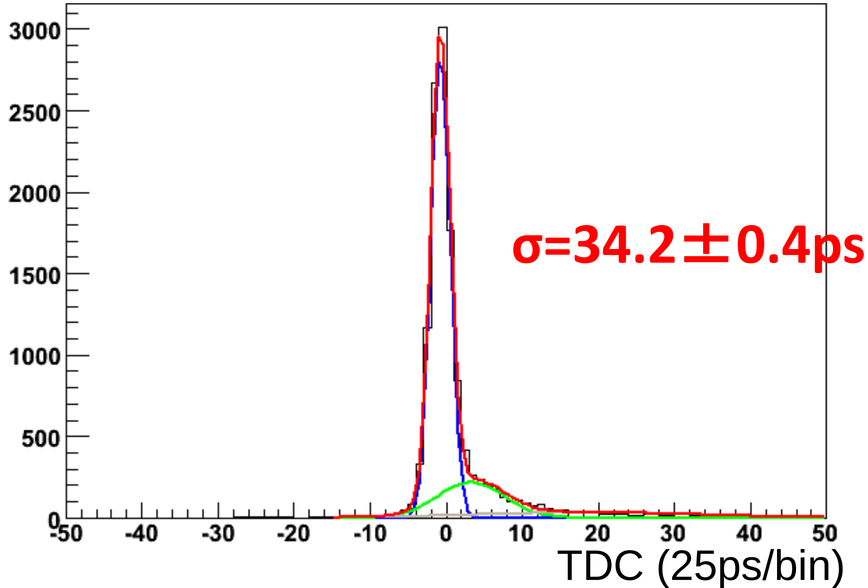
- MCP-PMT produced by Hamamatsu
  - Checked basic gain-HV curve
- Acceptance test at Nagoya university
  - Time resolution for single photon and gain
  - Scan all channel and HV
  - Quantum efficiency scan



- Pulse laser test



Time resolution for single photon

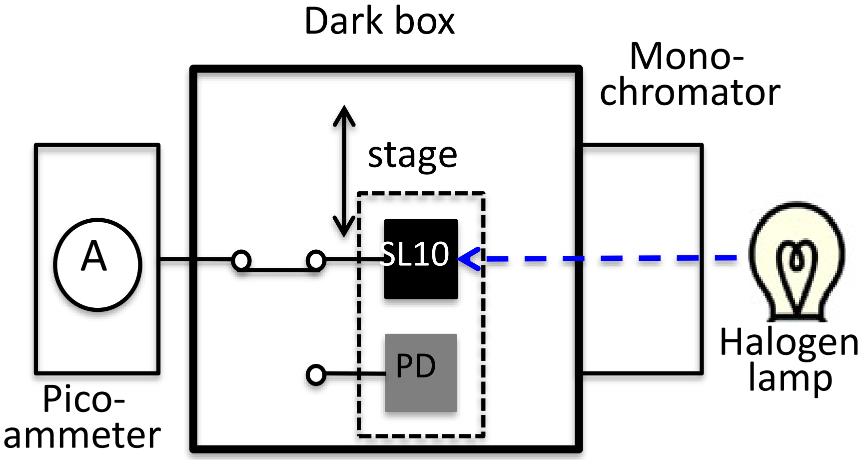


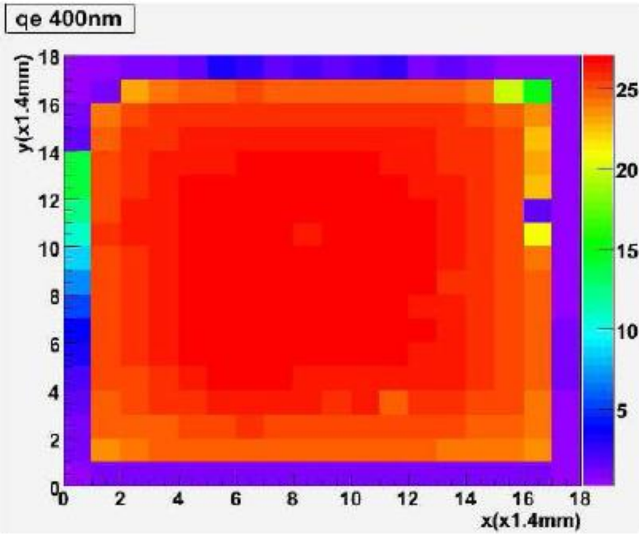
Photocathode efficiency

- Quantum Efficiency (QE)
  - With a reference photodiode.

    $QE_{PMT} = [I_{PMT} / I_{PD}] * QE_{PD}$

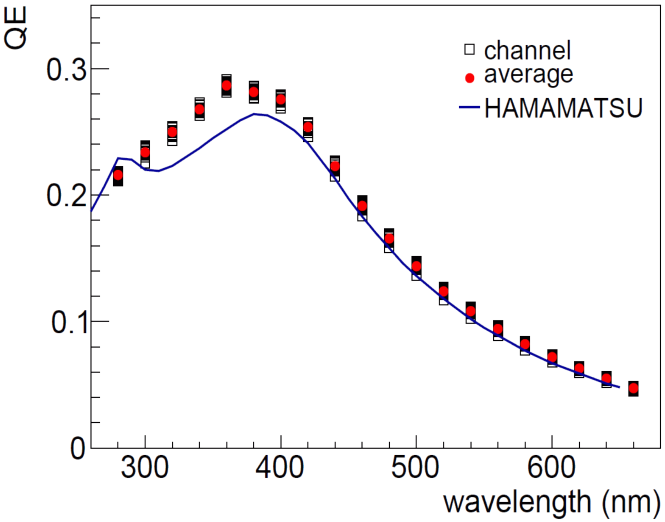
    I_{PMT}: photo-current between the p.c. and the front surface of the 1st MCP.
  - 2D scan on the PMT window.
  - λ scan: 350-700 nm is our interest.



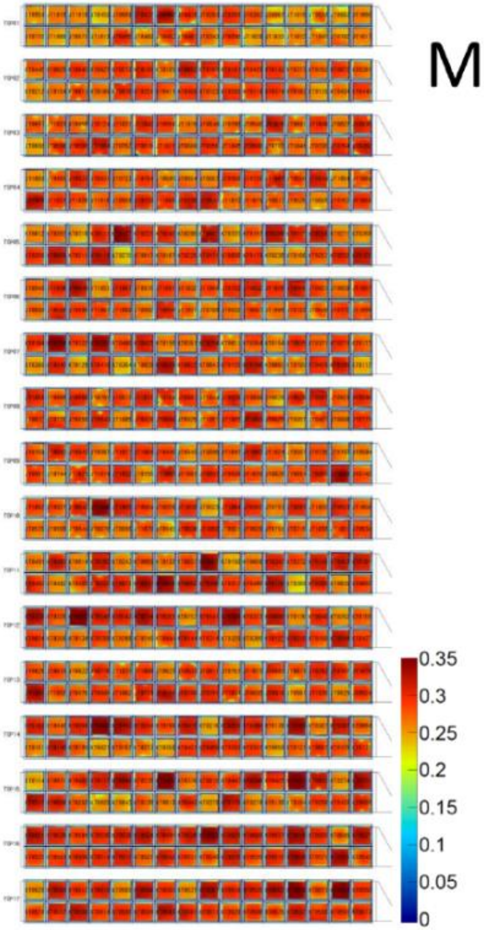


Photocathode improvement

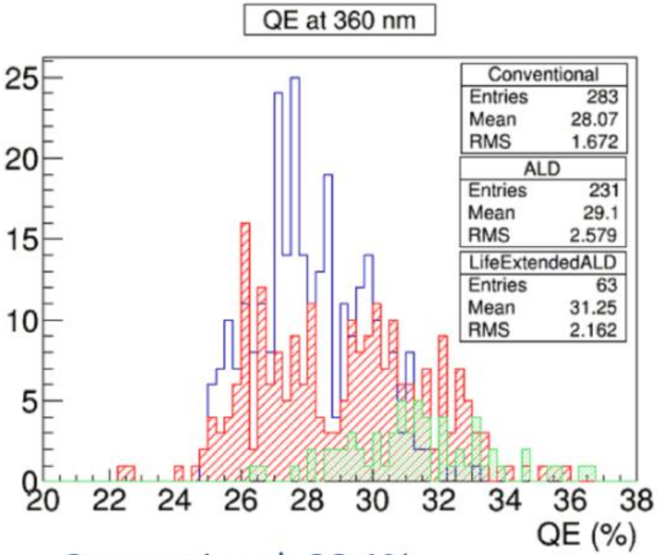
- Apply super-bialkali technique to multi-alkali photocathode
  - Major photocathode cathode for Hamamatsu MCP-PMT
  - QE improved during mass production



QE peaks around 360 nm



Measured QE



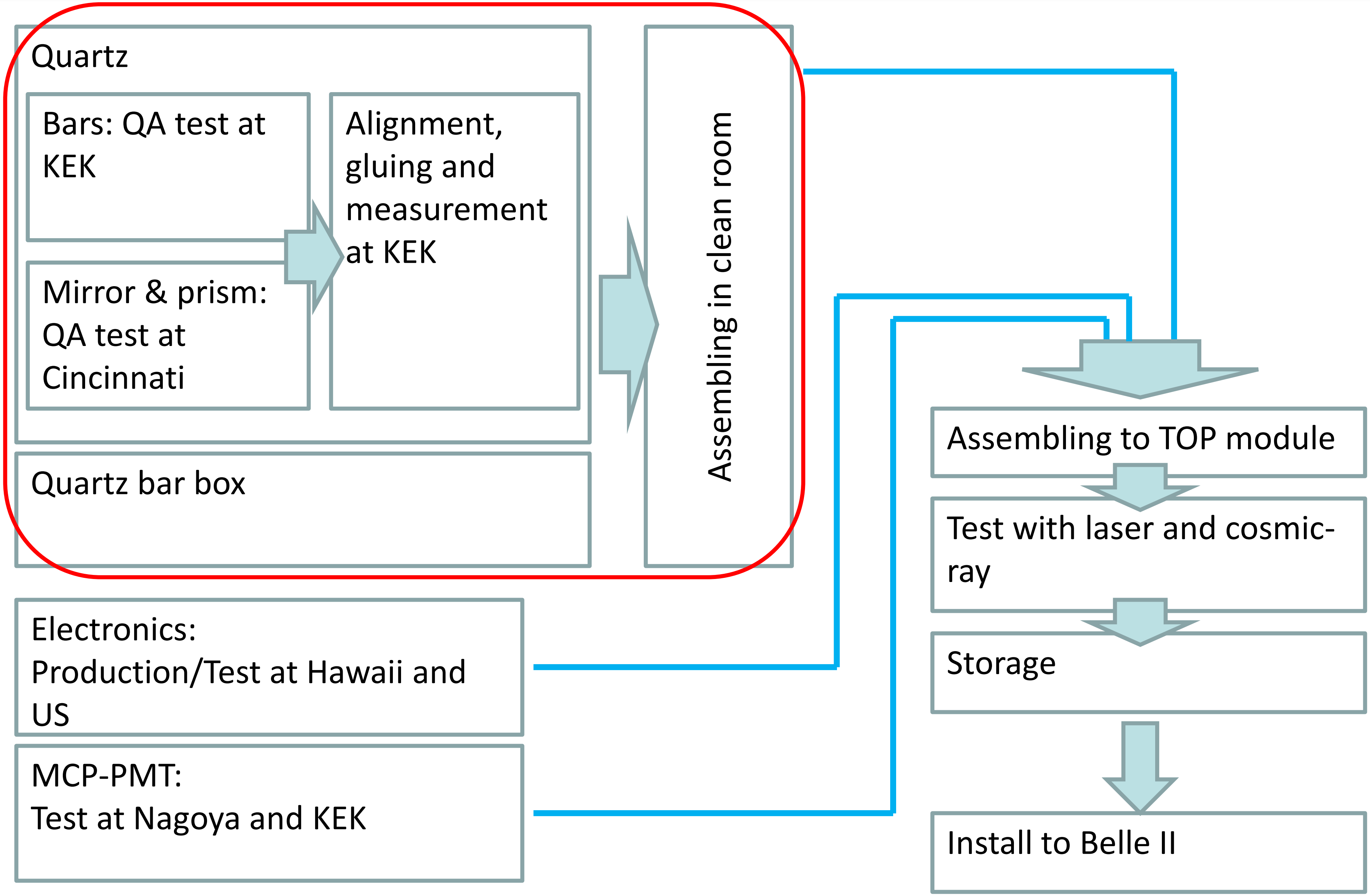
Conventional: 28.1%

ALD: 29.1%

Life-extended ALD: 31.3%

QE difference among PMTs ≈ ±10%

Construction flow overview



Quartz

Bars: QA test at KEK

Mirror & prism: QA test at Cincinnati

Alignment, gluing and measurement at KEK

Quartz bar box

Assembling in clean room

Electronics: Production/Test at Hawaii and US

MCP-PMT: Test at Nagoya and KEK

Assembling to TOP module

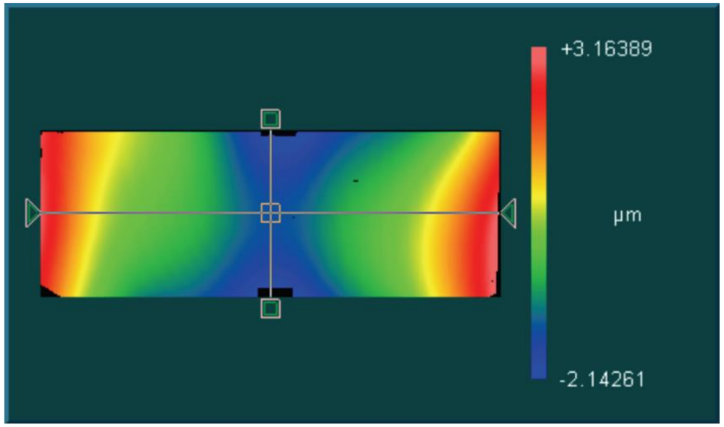
Test with laser and cosmic-ray

Storage

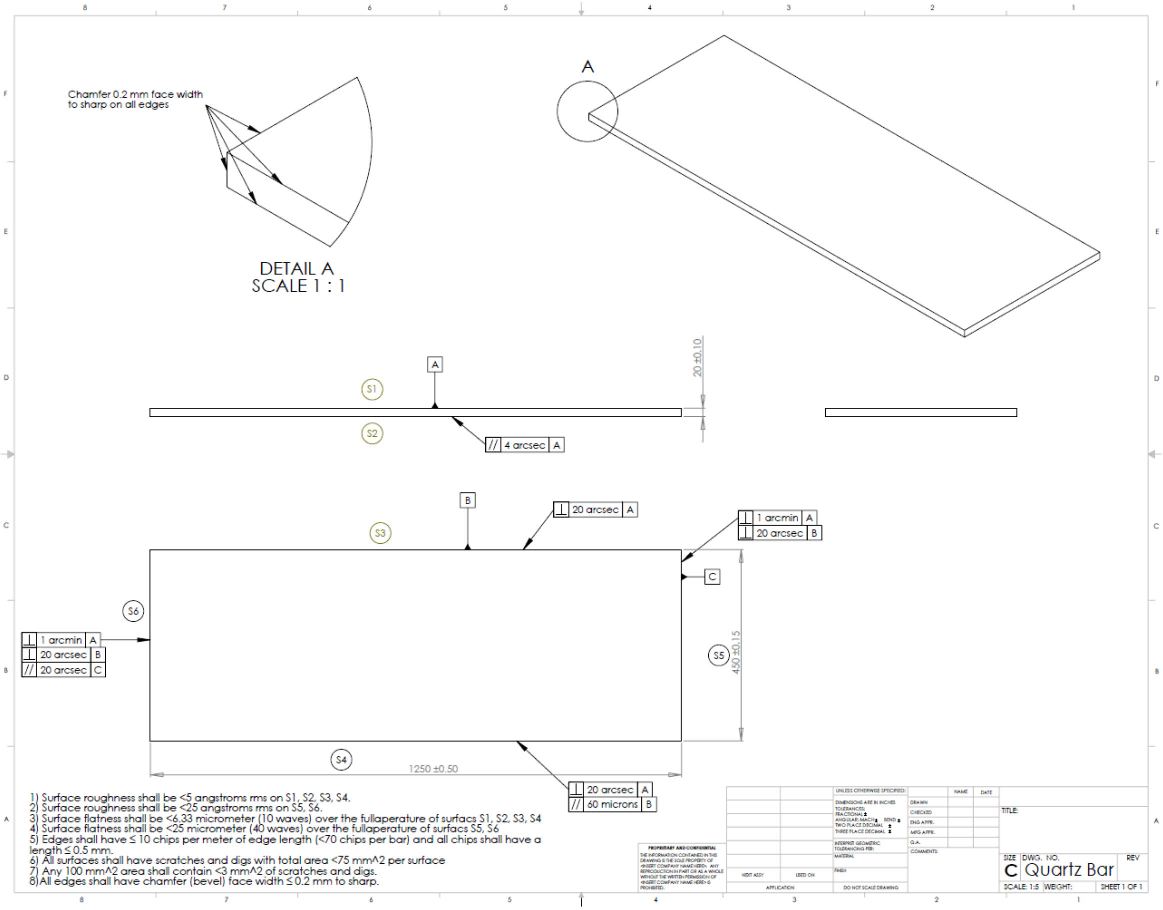
Install to Belle II

Quartz bar

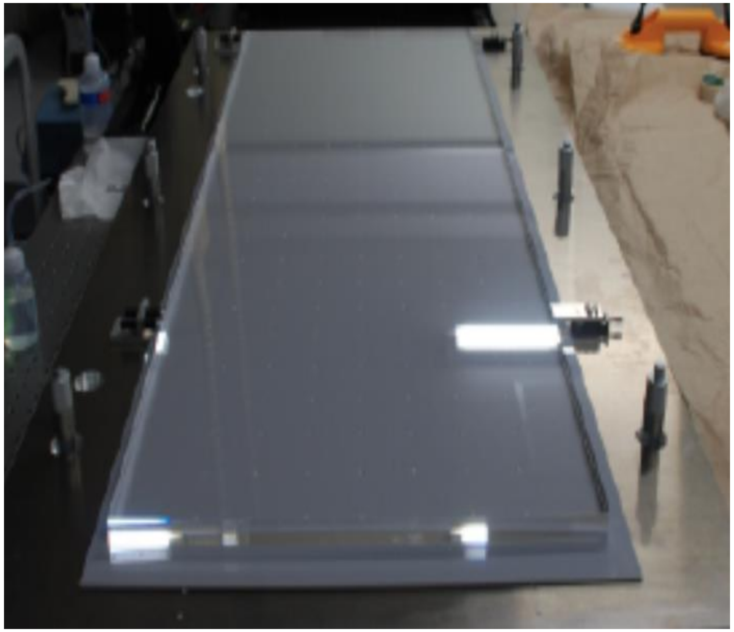
- Prototype production by Okamoto-optics.
- Most of production bars by Zygo
  - Because of production rate



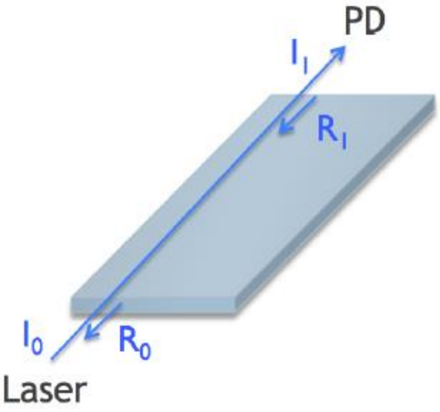
Interferograms of one of the bar surfaces from metrology report



1) Surface roughness shall be <5 angstroms rms on S1, S2, S3, S4.
2) Surface roughness shall be <25 angstroms rms on S5, S6.
3) Surface flatness shall be <6.33 micrometer (10 waves) over the fullaperature of surfacs S1, S2, S3, S4
4) Surface flatness shall be <25 micrometer (40 waves) over the fullaperature of surfacs S5, S6
5) Edges shall have ≤ 10 chips per meter of edge length (<70 chips per bar) and all chips shall have a length ≤ 0.5 mm.
6) All surfaces shall have scratches and digs with total area <75 mm^2 per surface
7) Any 100 mm^2 area shall contain <3 mm^2 of scratches and digs.
8)All edges shall have chamfer (bevel) face width ≤ 0.2 mm to sharp.

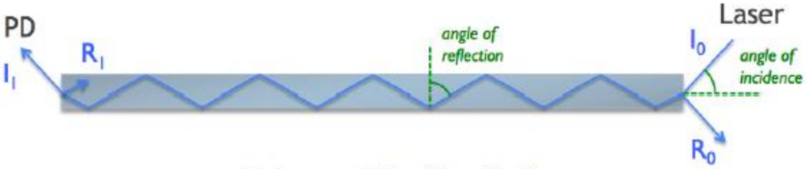


Acceptance test (bar)



Bulk Transmission

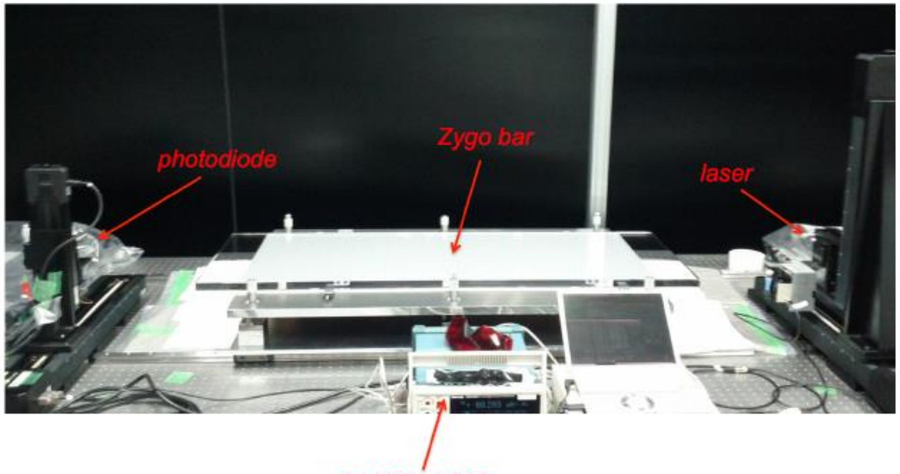
$$I_0(1-R_0)\,\tau\,(1-R_1)=I_1$$



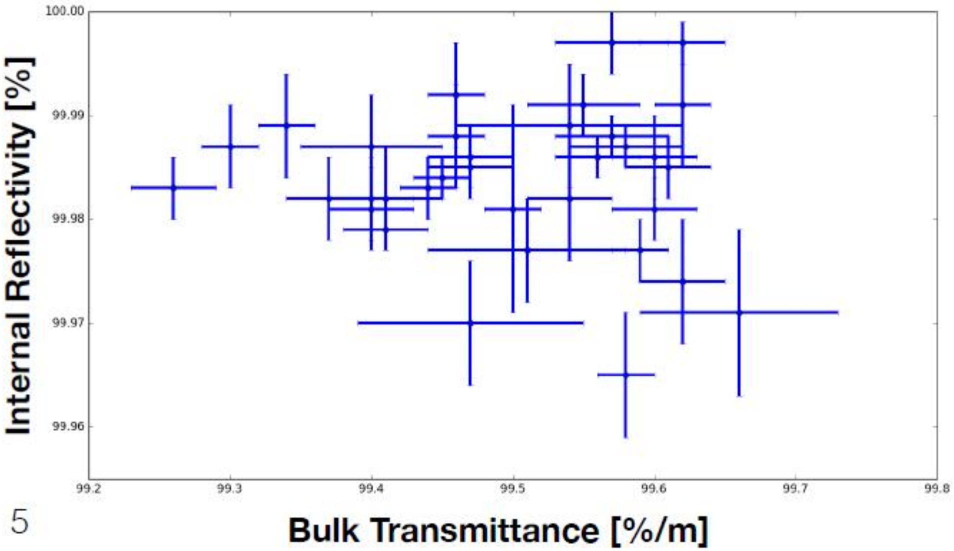
Internal Reflectivity

$$(I_1 - R_1) = (I_0 - R_0)\cdot\alpha^N\cdot\exp\left(-\frac{L}{\Lambda}\cdot\sqrt{1+(Nh/L)^2}\right)$$

Requirement:
Bulk Transmittance: > 98.5 %/m
Internal Reflectivity: > 99.9 %



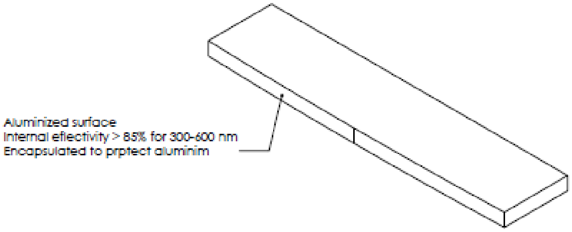
control system
(software runs as Python scripts)



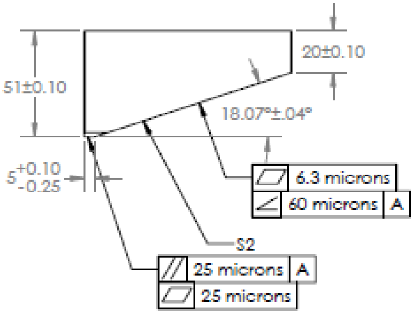
5

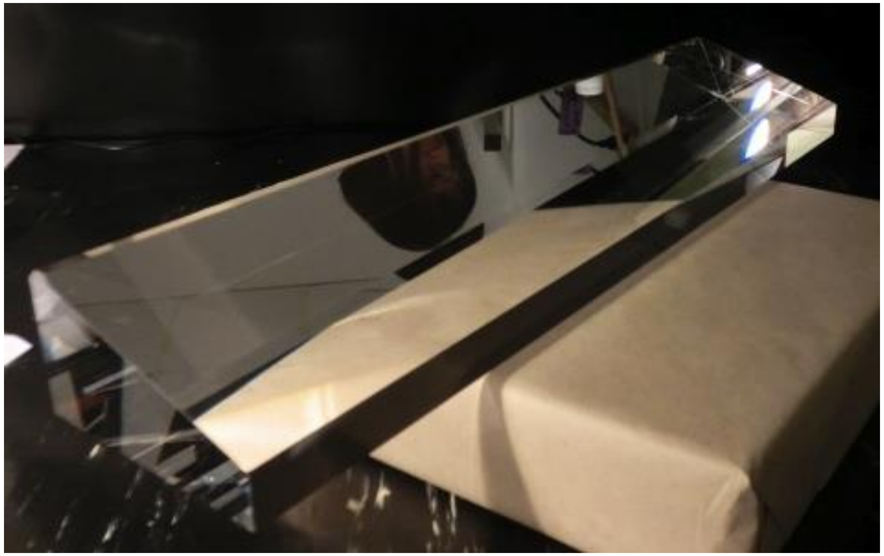
Mirror and expansion prism

- Mirror by Exelis
  - Spherical mirror (R=6.5m)
    - Aluminized
    - Peak at the edge



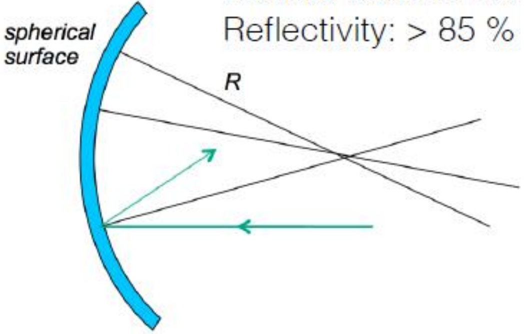
- Prism by Zygo

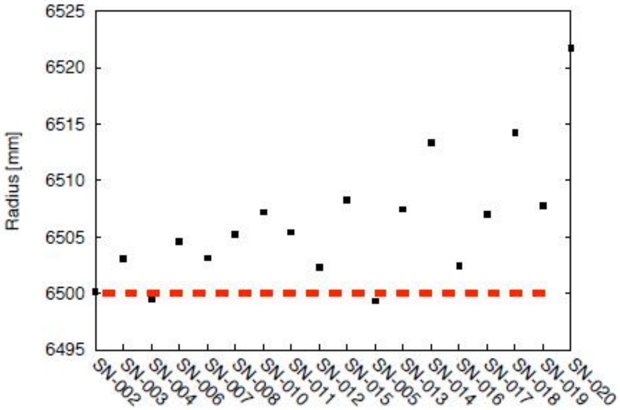


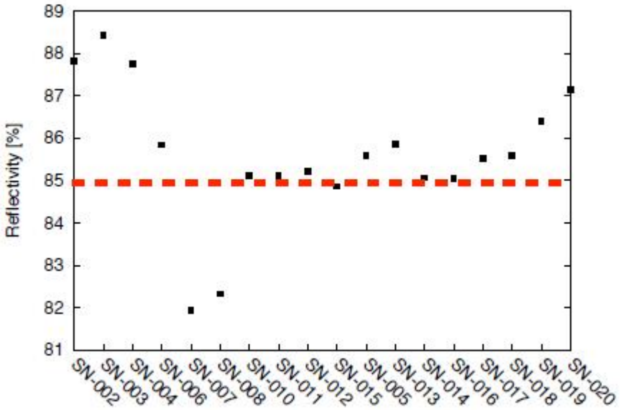


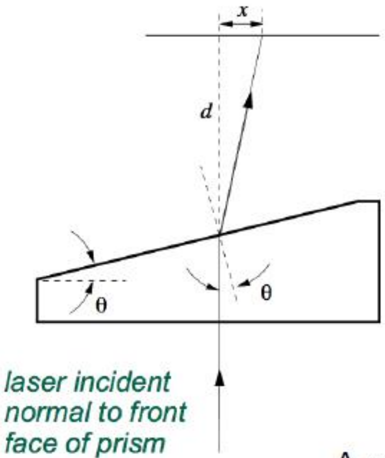
Acceptance test (mirror and bar)

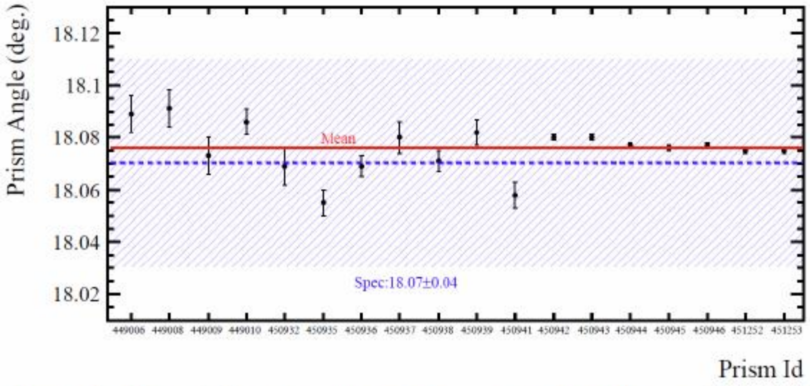
Specification
Radius: 6500 ± 100 mm
Reflectivity: > 85 %

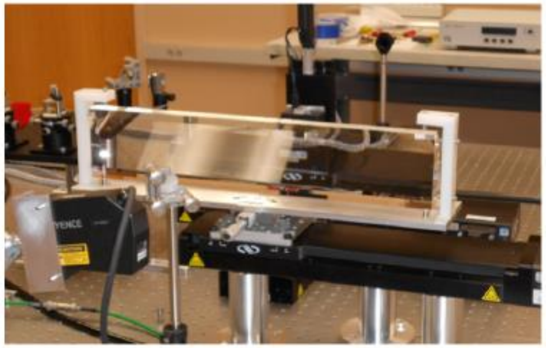










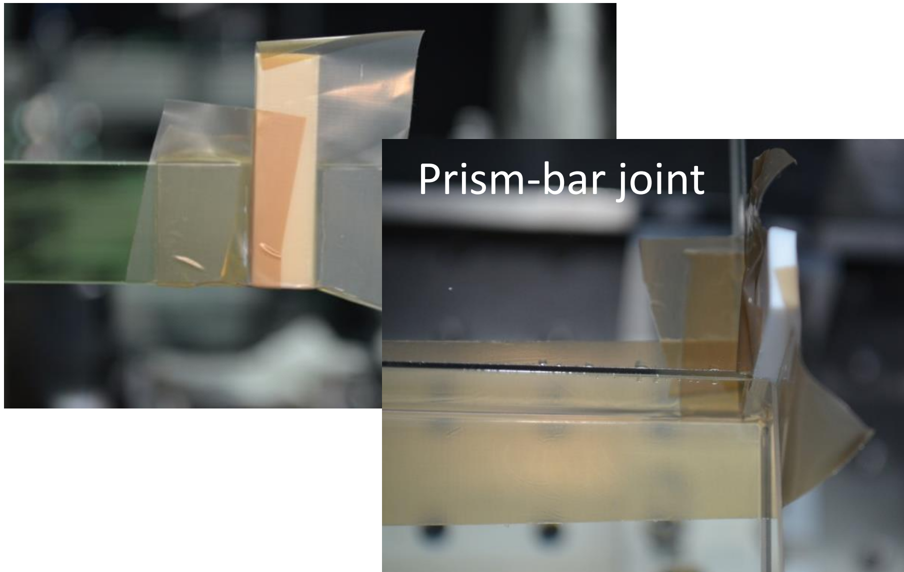


Angle of tilted face: 18.07 ± 0.04 deg (± 144 arcsec)

Gluing with taping method

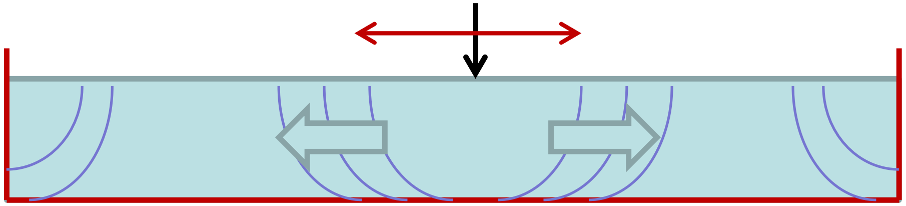
- Used EPOTEK 301-2 glue
  - Need to keep joint stable by fully cured (~2 days)
- Put tape under and side of quartz to keep the glue in the gap.
  - Remove tapes and clean up after fully cured (2~3 days after)
- Chose softer Teflon tape
  - Easy to fix the leakage around the edge
- Teflon block and tape for prism part
  - Difficult joint due to the difference of width; Prism (456mm), bar (450mm)
  - After several ways, finally no leakage happened
- Enabled to align/tune after taping by using soft tape

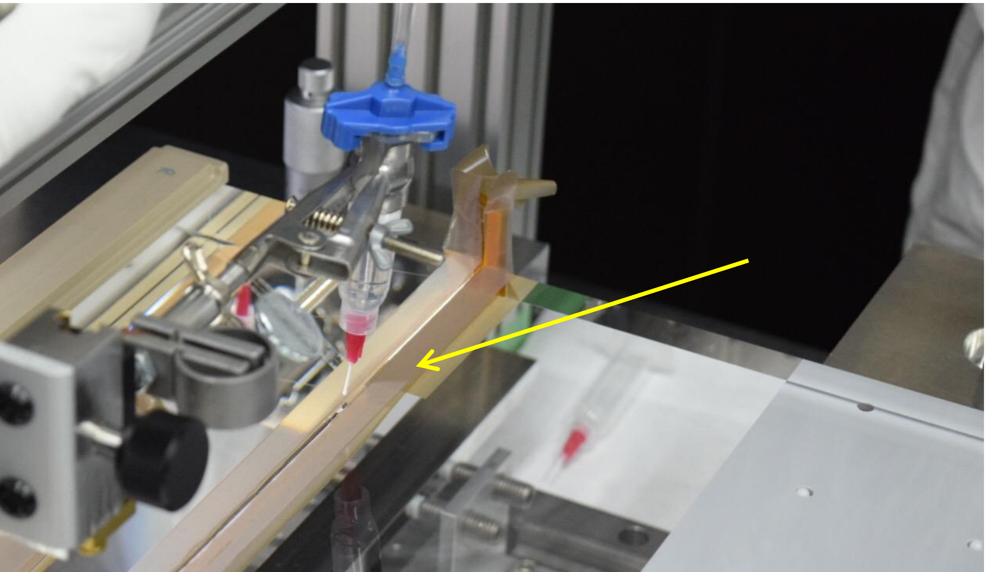

First gluing

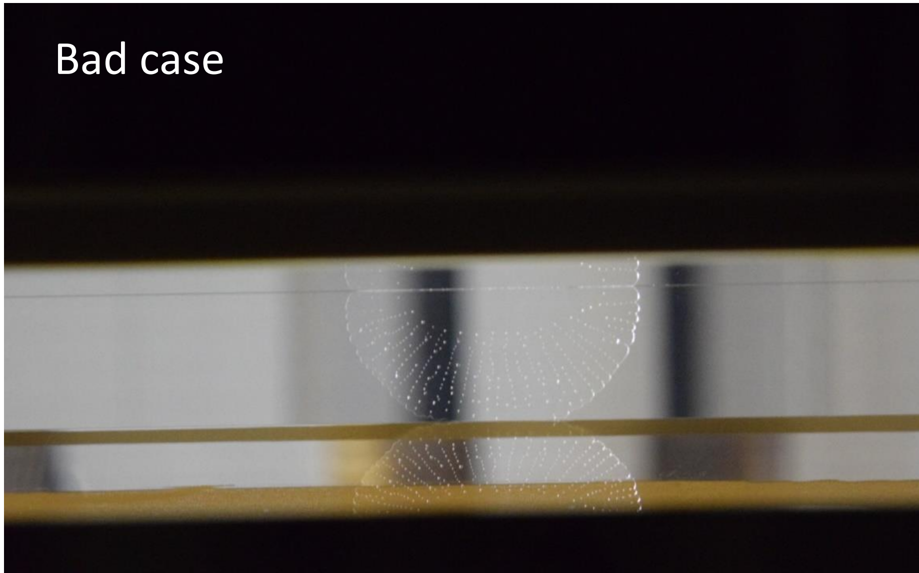

Prism-bar joint

Glue flow

- Pot glue at the center of joint
- Move dispenser head forward following glue front.
  - Not to include air bubble
- Fill up the gap by glue (~one hour)
- If there are many bubbles, remove joint, clean surface carefully and retry again.

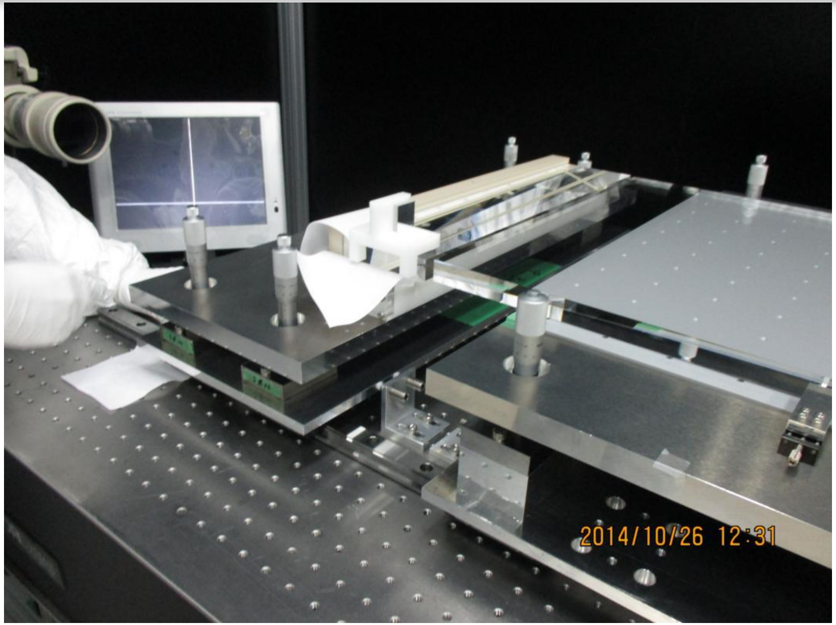




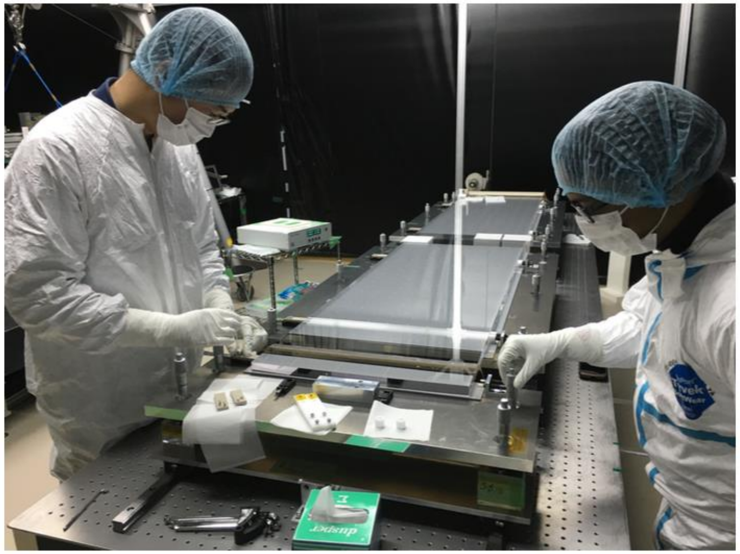


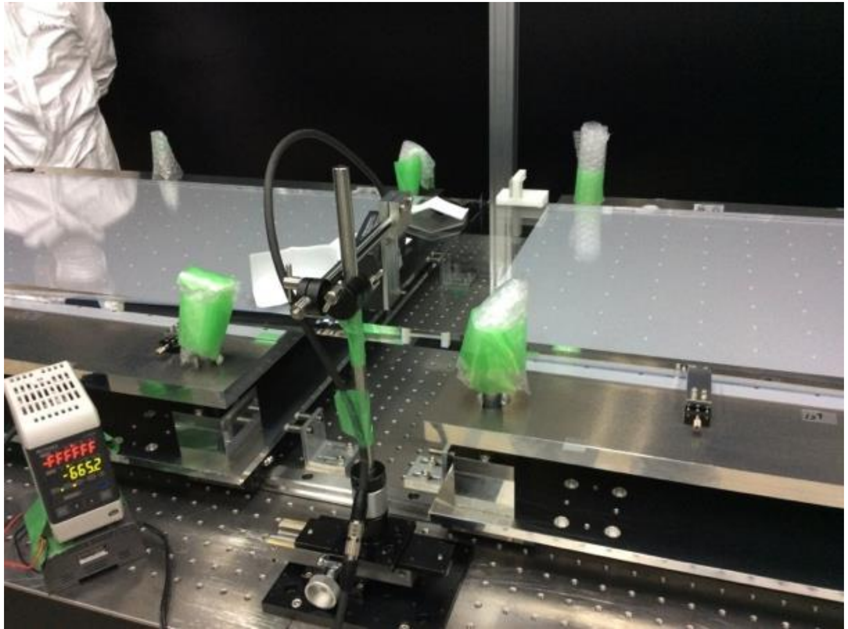
Bad case

Quartz alignment



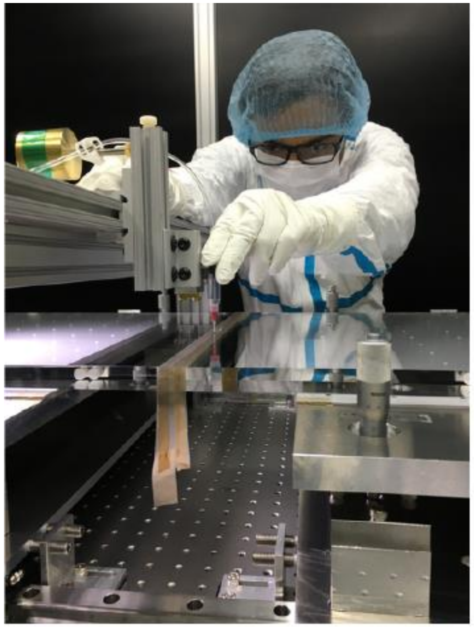
- Optics joints are cleaned carefully, then aligned by gluing stage
    - Quartz position is tuned by micrometer heads at stage corners and side.
    - Relative angle and height are measured using autocollimator (~10arc-sec, ~0.05mrad) and laser displacement sensors (~20micron), respectively.
    - Gap between parts tuned using plastic film (t~50μm)

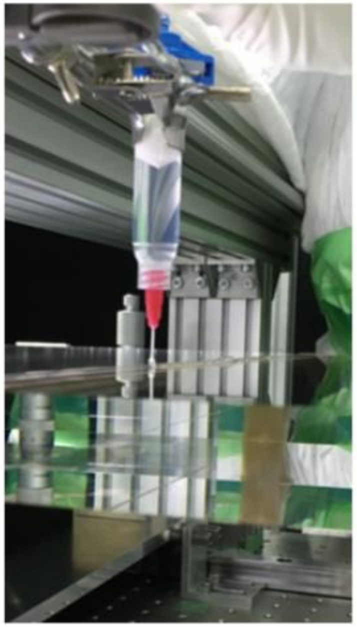


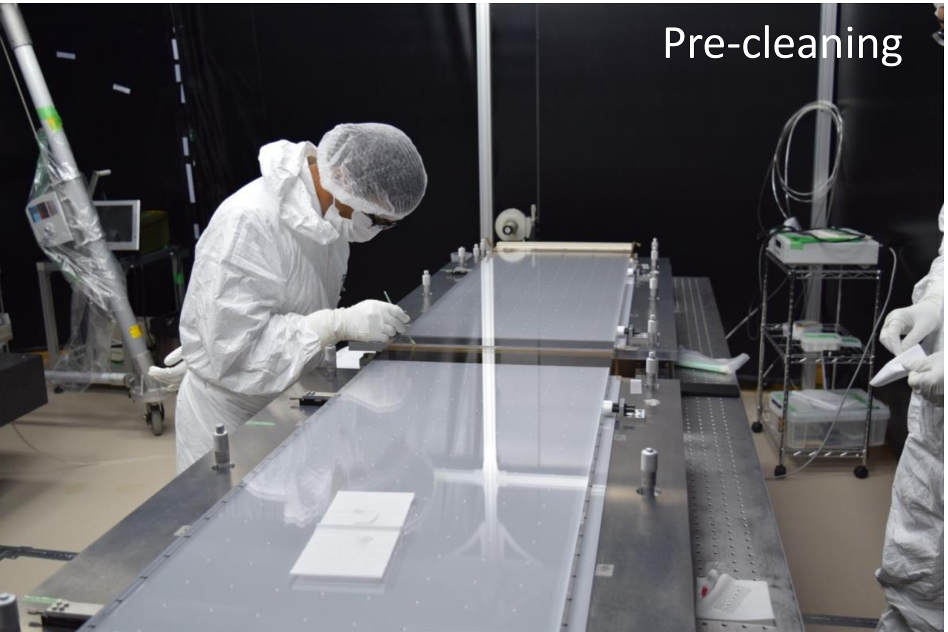


Gluing of modules

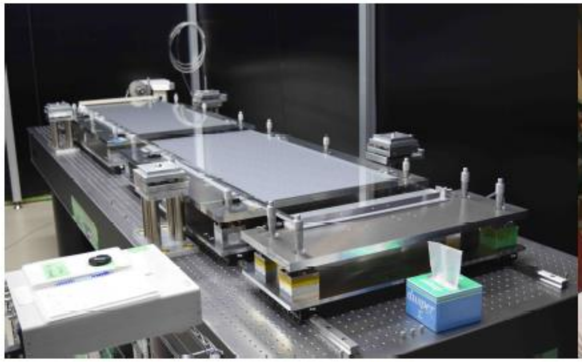
- Put tapes after the alignment
- Pot EPOTEK301-2 glue on the gap
- Pre-cleaning of glue excess
- Clean excess glue after fully cured and final inspection of quartz shape



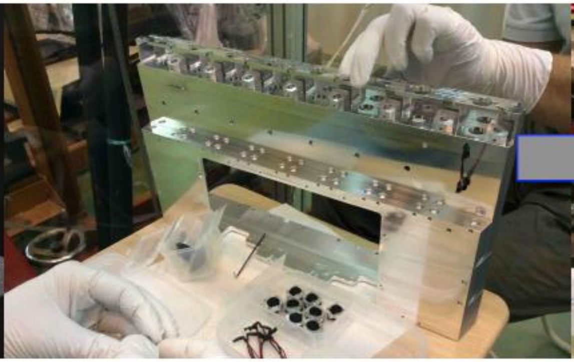




Assembling



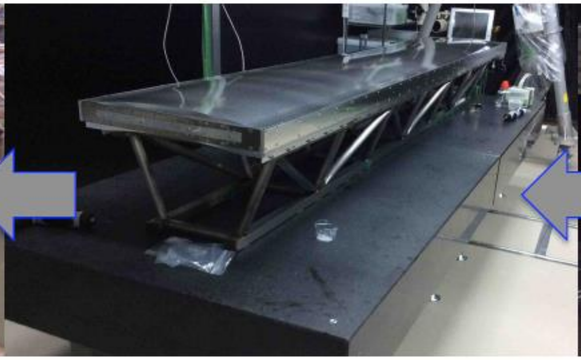
Optics: alignment, gluing, curing and aging (~2 weeks).



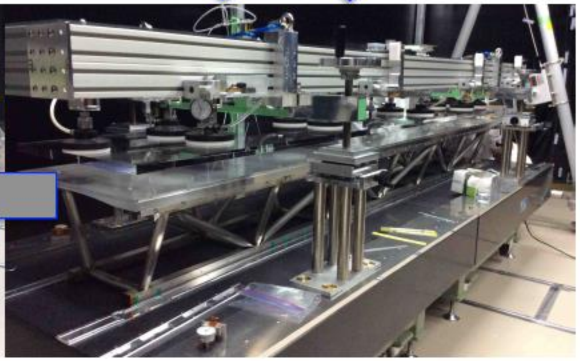
Enclosure: gluing CCDs and LEDs, integrating fiber mounts.

QBB: strong back flattening, button & enclosure gluing.

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



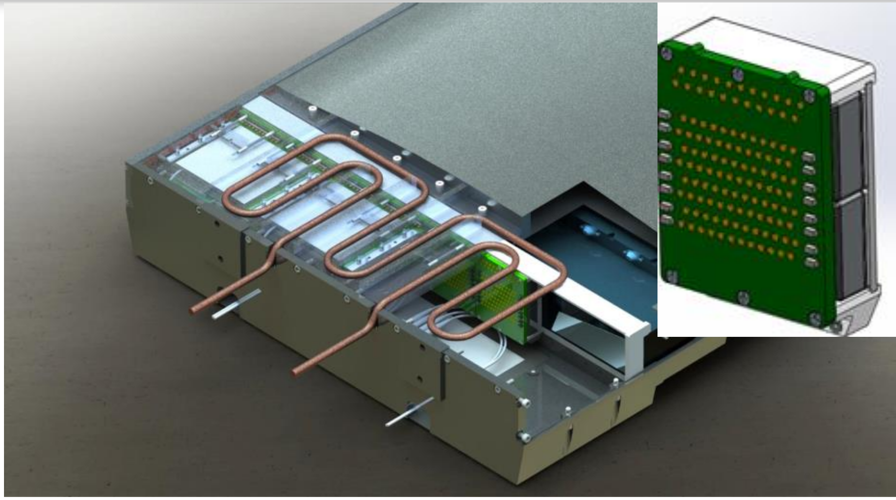
QBB assembly and gas sealing.

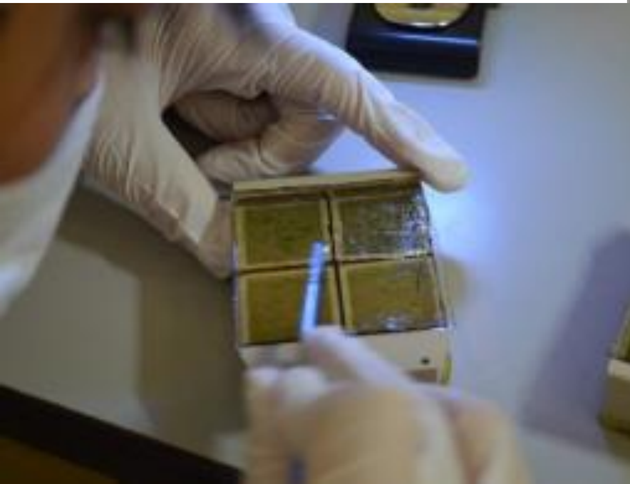


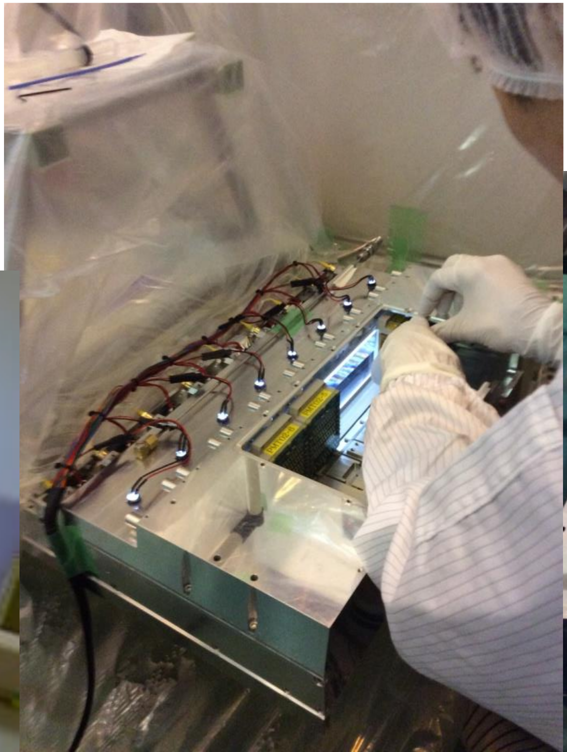
Move optics to QBB using the “lifting jig”.

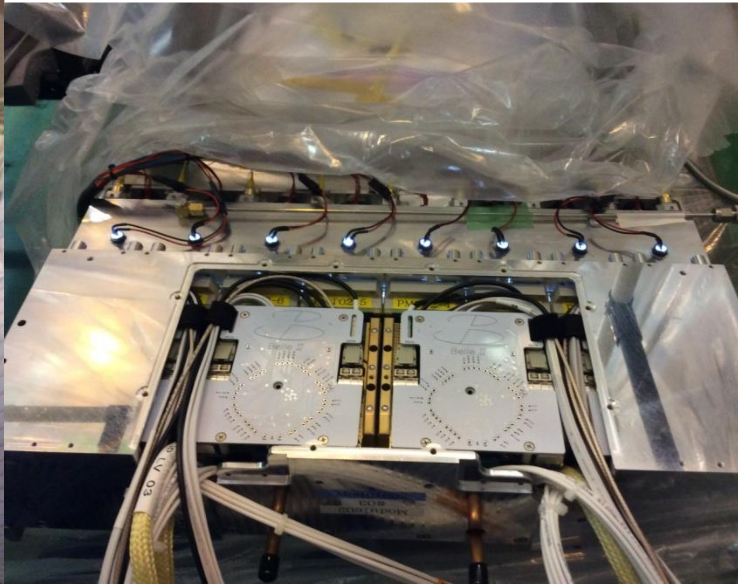
PMT/HV/Frontend assembly

- Tested PMTs assembled to PMT modules
  - Produce optical cookies
- Install into TOP module
  - PMT modules
  - HV/Frontend electronics from US







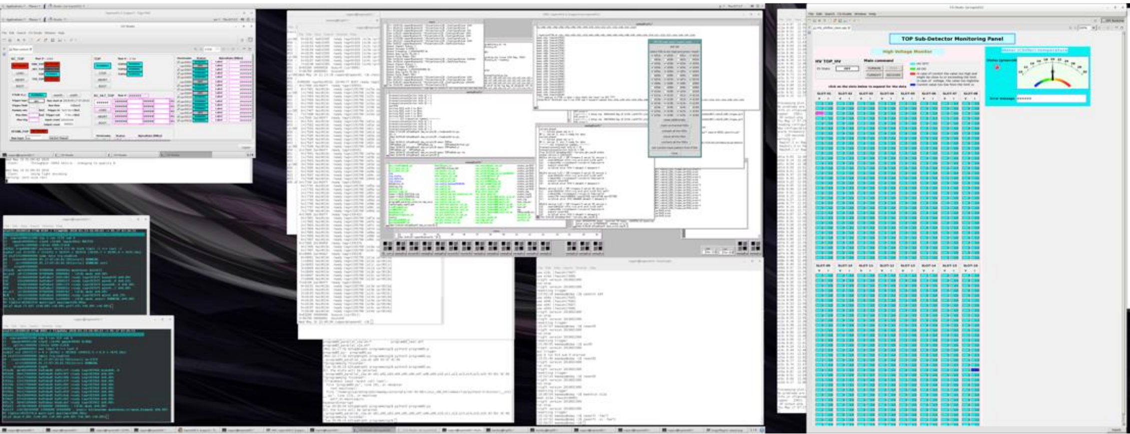


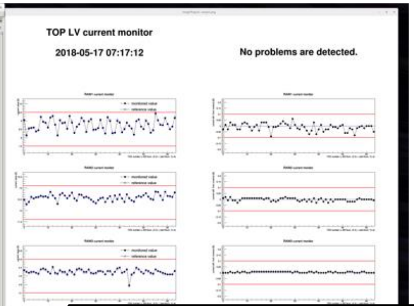
TOP installation

- 16 modules using special frames

Operation

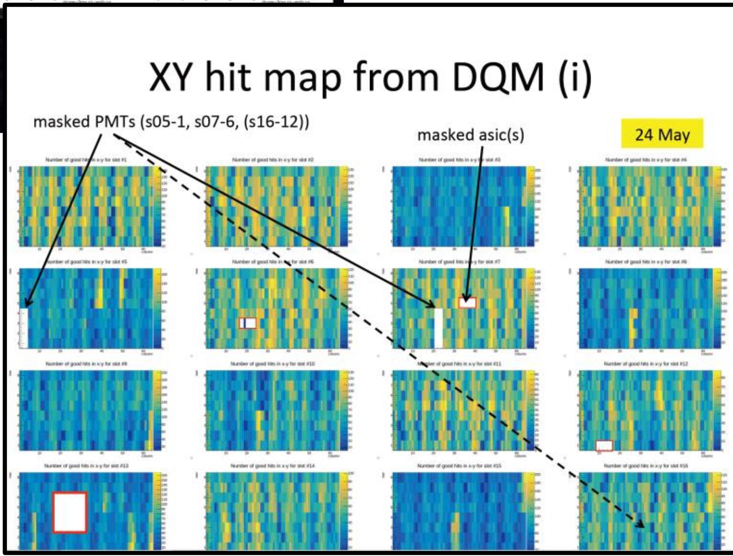
- Operate TOP subsystem as the expert
  - Manage operation of DAQ, HV/LV control, laser
  - Manage many requests on system setting, firmware revision, data type, etc…
  - Communicate / negotiate with many people; TOP member, run coordinator, DAQ and other subsystem experts




TOP LV current monitor

2018-05-17 07:17:12

No problems are detected.

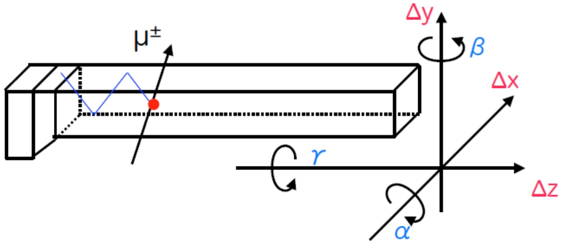

XY hit map from DQM (i)

Calibration

- Important part to realize targeted PID performance
- Timing calibration (and geometrical alignment)
    - Using cosmic-ray and mu-pair events
    - Scan timing origin (similar with likelihood fit)
    - Stable for one year operation

Calibration constants

$$\hat{p} = (\overbrace{\boxed{\Delta x, \Delta y, \Delta z,}}^{\text{Translation}}\ \underbrace{\boxed{\alpha,\ \beta,\ \gamma,}}_{\text{Rotation}}\ \underbrace{t_0}_{\text{Time offset}})$$

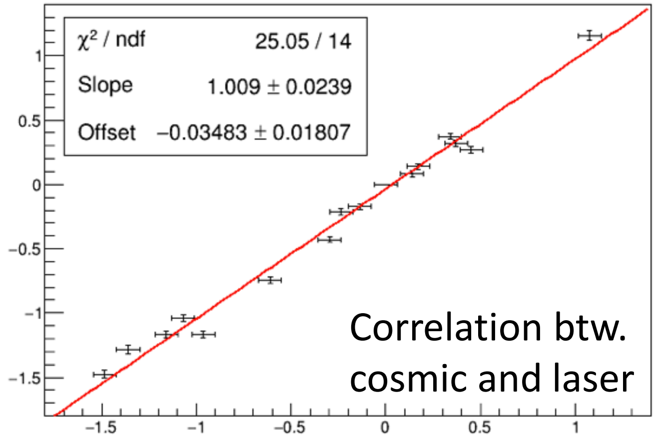


Likelihood : product of Probability Density Function (PDF)

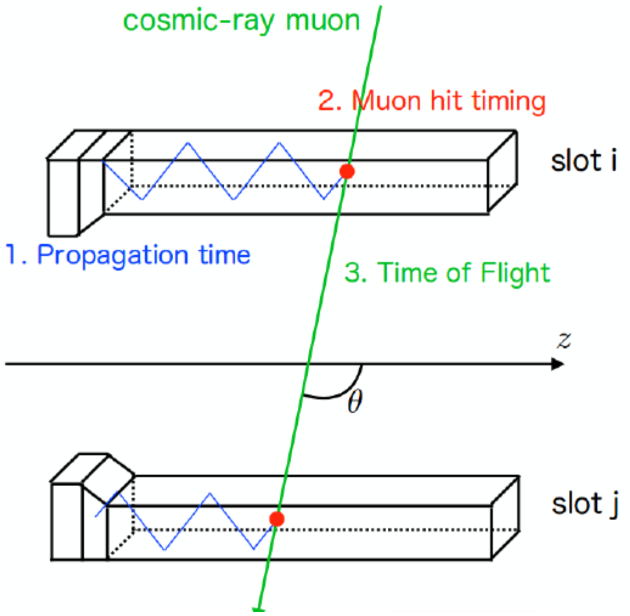
PDF of muon

$$\boxed{\mathcal{L}_\mu(\hat{p})} = \prod_{\text{photon}} \boxed{f_\mu(t_{\text{photon}},\ x_{\text{photon}};\ \hat{p})}$$

Timing calib.

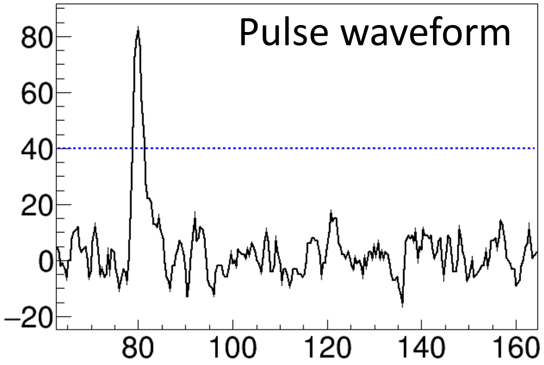


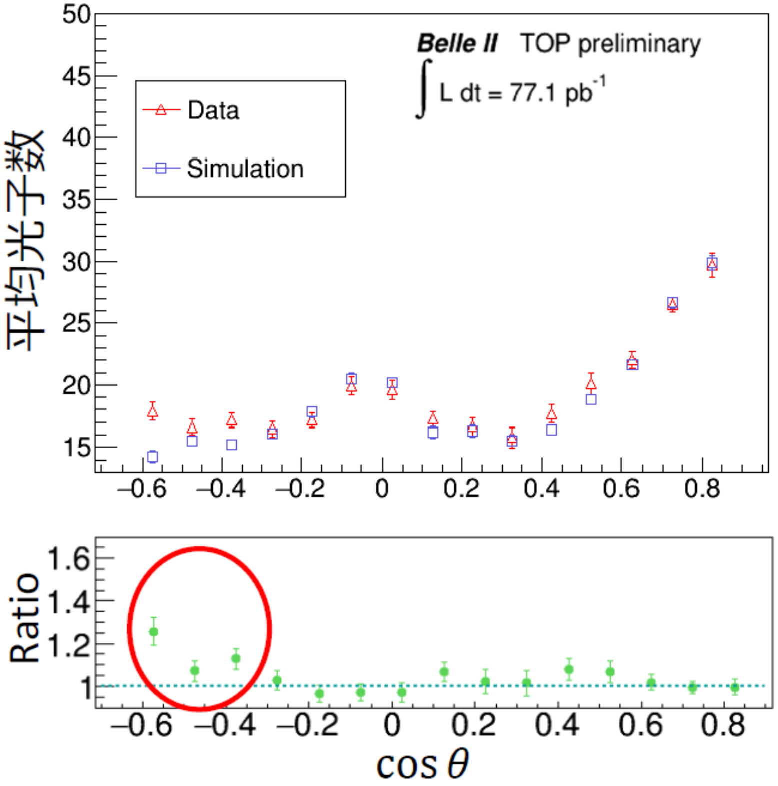
Correlation btw. cosmic and laser



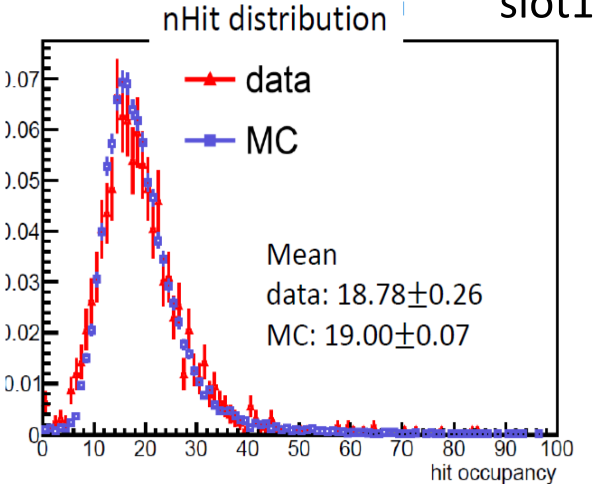
Photon hit/gain evaluation

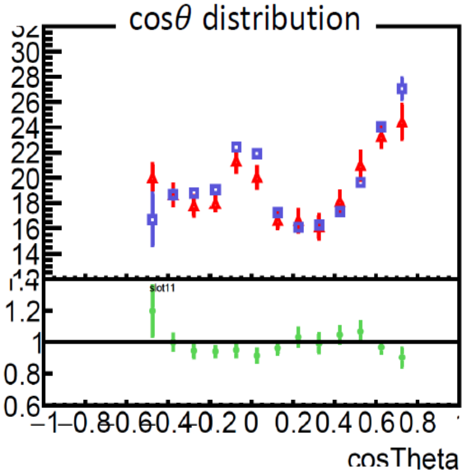
- Hit efficiency → PID performance
- Gain → Stability and PMT lifetime
- Good hit selection
  - Cross-talk, noise reduction
- Gain evaluation / HV calibration
- Number of hits evaluation
  - Evaluate hit efficiency, electronics performance, background → MC tuning
  - Good agreement with the expectation, although small discrepancy still exists.



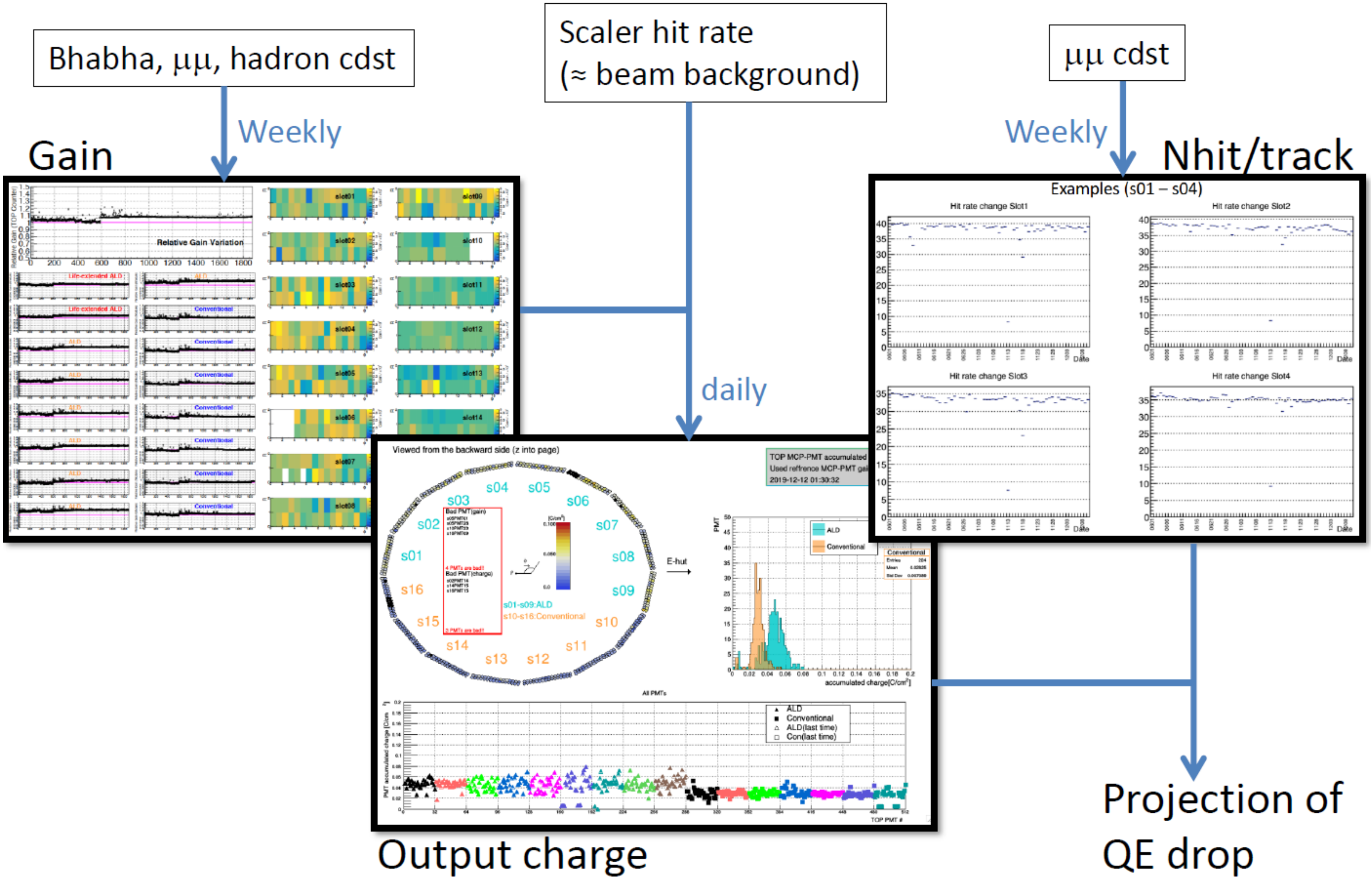


slot11





PMT monitoring



Bhabha, μμ, hadron cdst

Scaler hit rate
(≈ beam background)

μμ cdst

Weekly

Weekly

daily

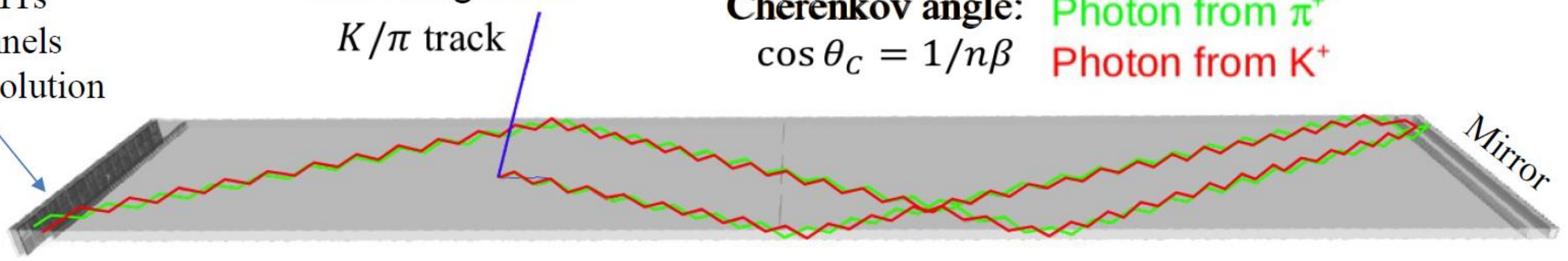
Gain

Nhit/track

Output charge

Projection of
QE drop

TOP ring image



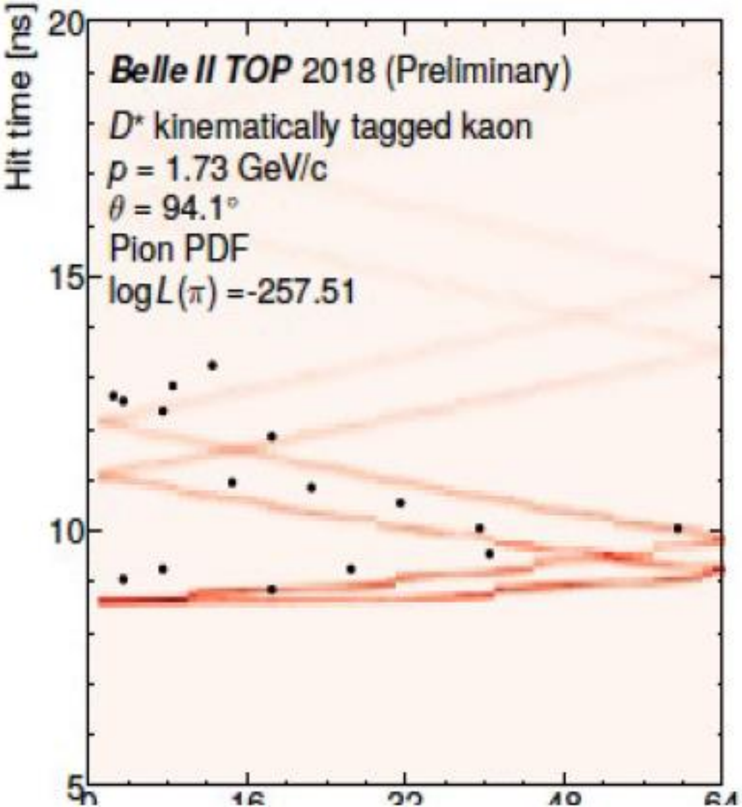
MCP-PMTs
512 channels
50 ps resolution

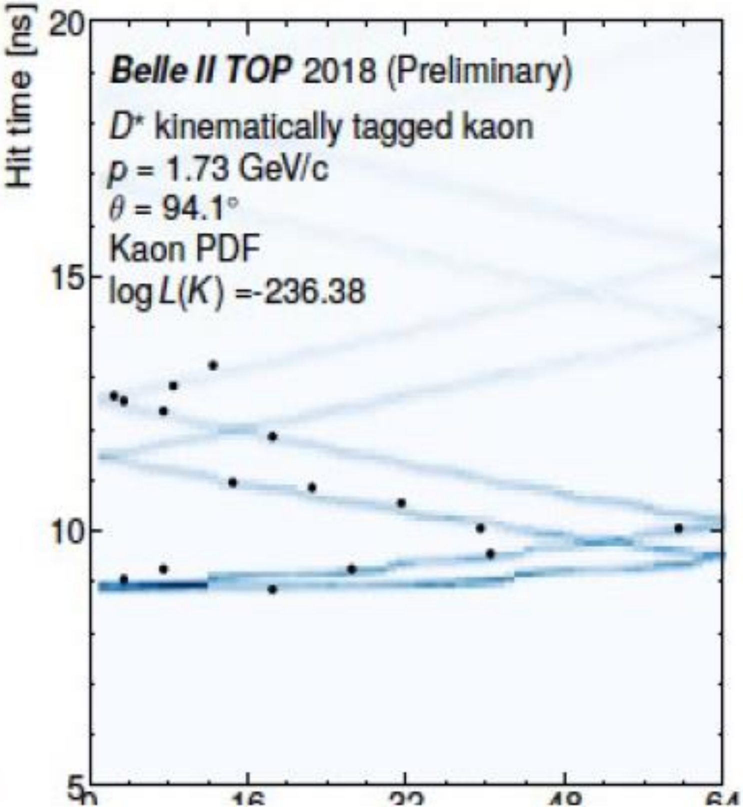
Incoming track
K/π track

Cherenkov angle: $\cos\theta_C = 1/n\beta$

Photon from π^+
Photon from K^+

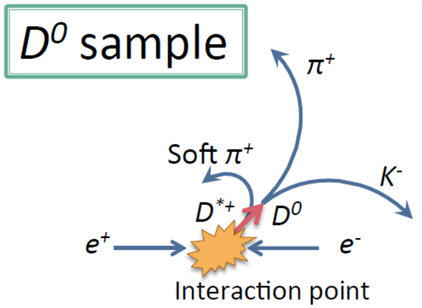
Bar length = 2600 mm, width = 450 mm, thickness = 20 mm

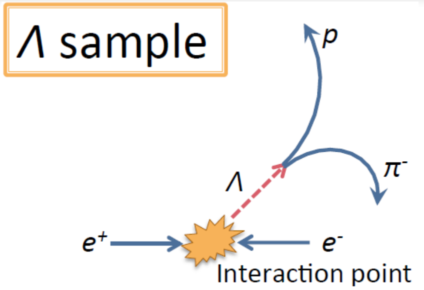




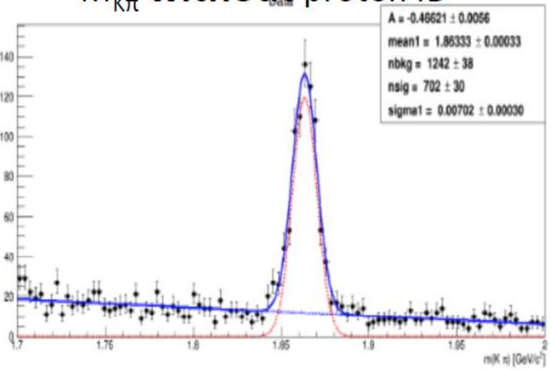
PID performance

- Performance check
  - D* and Lambda samples
  - Well defined results
  - Need more data, but less performance compared with MC expectation
- Trial to improve PID performance using Machine learning

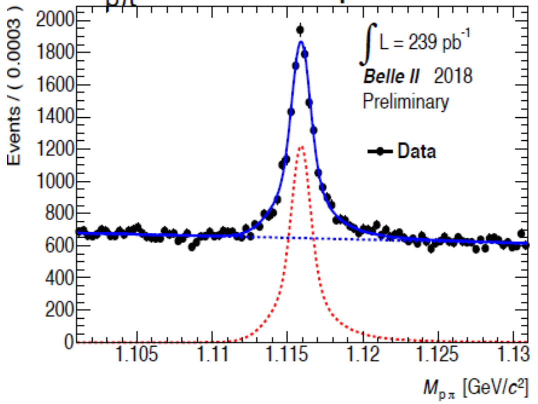




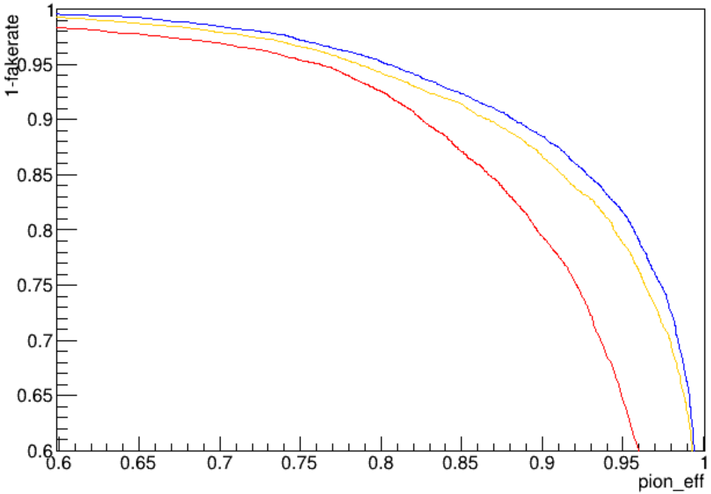
$M_{K\pi}$ **without** proton ID



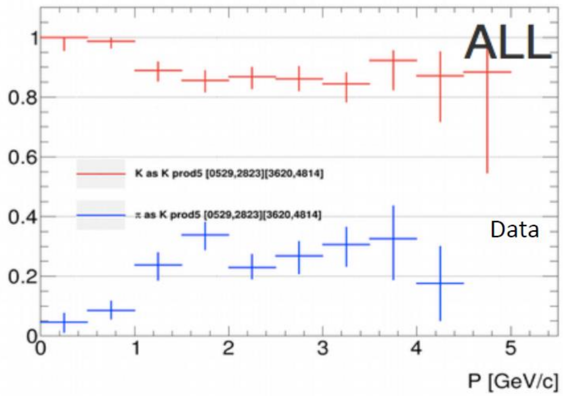
$M_{p\pi}$ **without** proton ID



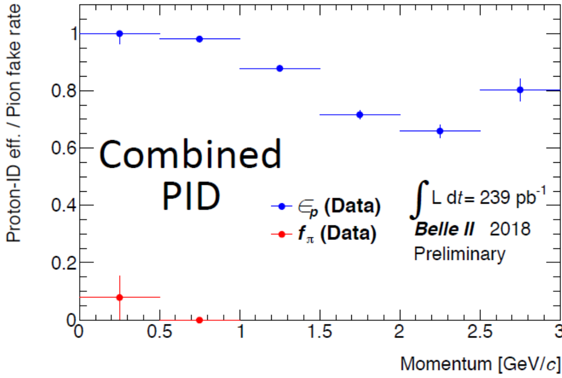
Roc_curve(2.5 < momentum < 3.0)



***K*-ID** performance at **Belle II**



Proton-ID performance at **Belle II**



Summary

- TOP detector
  - Utilizes Cherenkov photon timing
  - High quality quartz + MCP-PMT + high timing-resolution electronics
- Developed TOP prototype and test with beam
  - Quartz production and assembling procedure worked well.
  - Beam test data shows good agreement with MC
    - Ring images, number of detected Cherenkov photons, timing information as well as background levels are in agreement with expectations.
- Production/installation finished successfully
  - PMT mass production and quartz radiator assembly system
- Belle II experiment started.
  - Operation is stable. Calibration is still on-going.
  - Performance looks OK, although need more calibration/software development to improve the performance.