Design and performance study of the TOP counter

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for the Belle II TOP group

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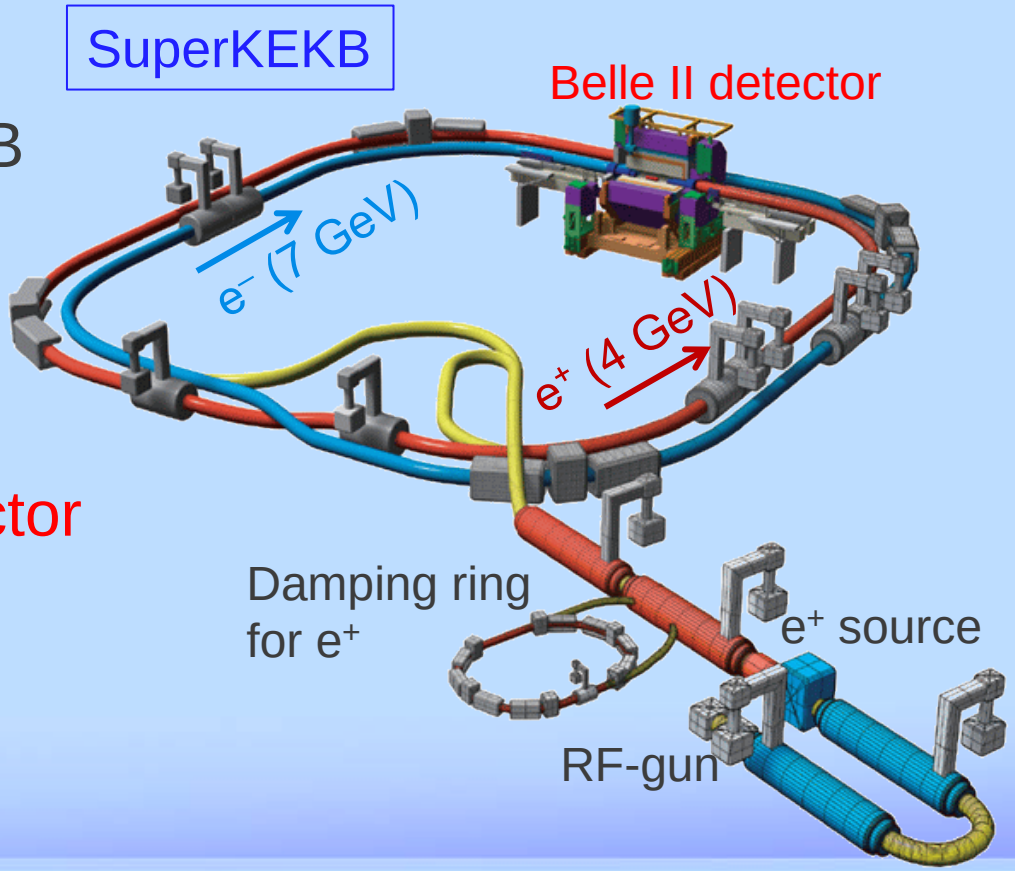
- Summary

The Belle II experiment

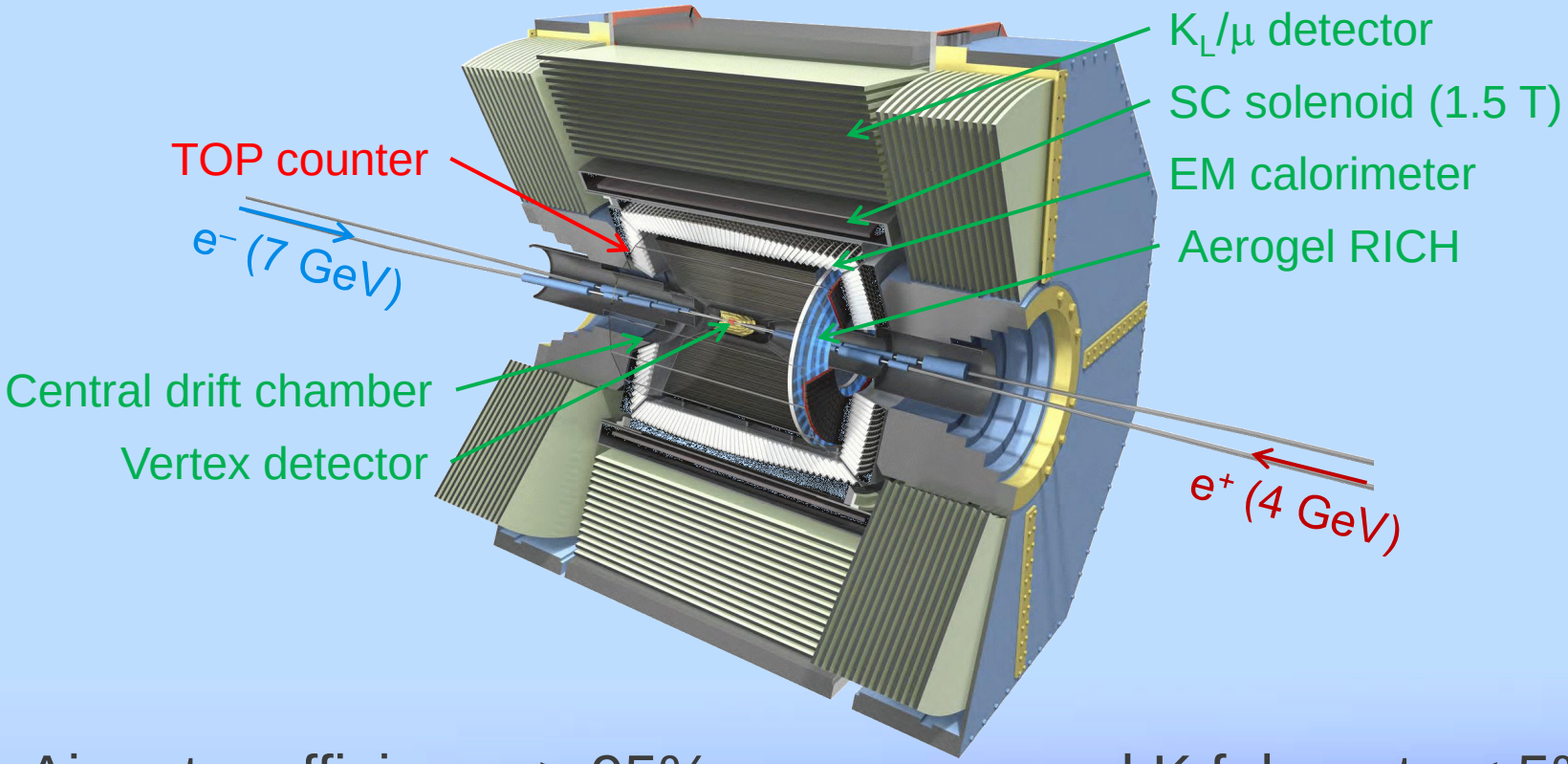
- Elucidate new physics beyond the Standard Model through precise measurement of rare B and τ decays at Super-KEKB.

- Luminosity: x40 of KEKB
  → 8 x 10^{35} $cm^{-2}s^{-1}$
- Statistics: x50 of Belle
  → 50 ab^{-1}
- Upgrade the Belle detector
  → Belle II



PID in Belle II

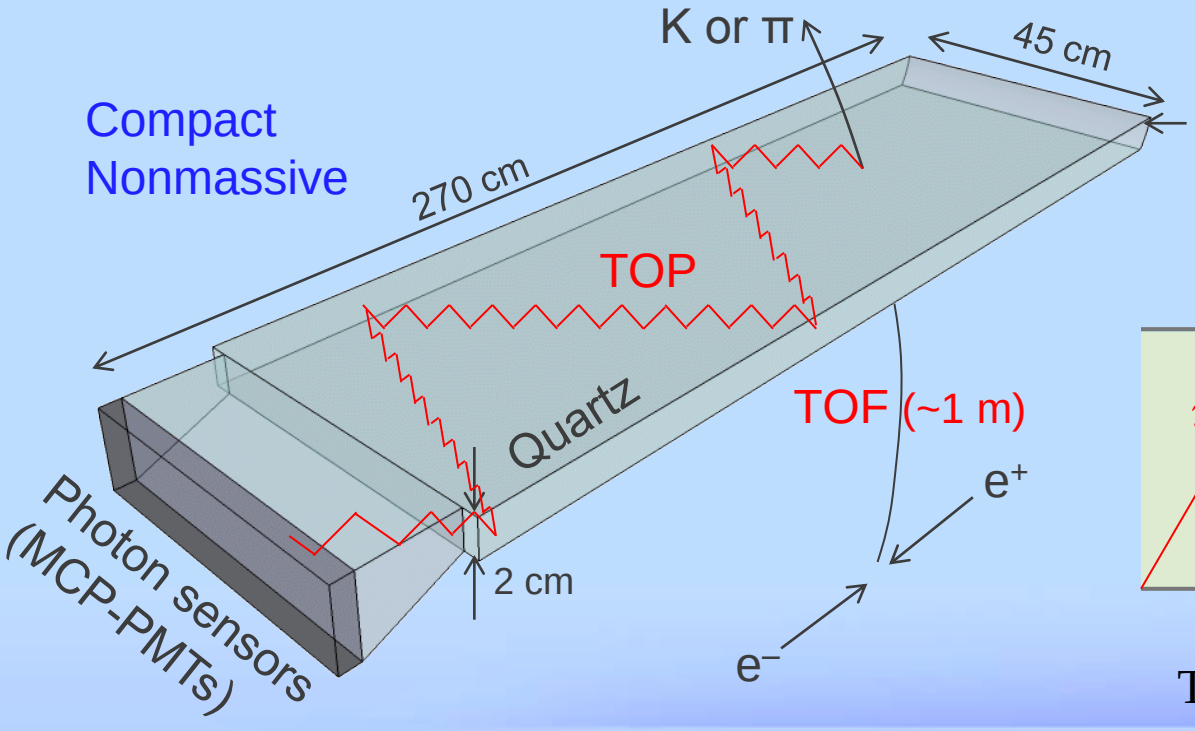
- K/π identification is a key issue for the B physics.
- Also important to reduce the mass of the PID detector for the outer calorimeter.

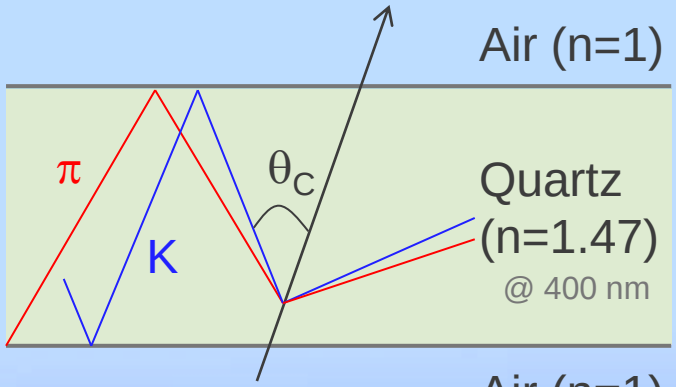


Aim at π efficiency > 95% (89% in Belle) and K fake rate < 5% (12% in Belle) with a new detector, TOP counter.

TOP (Time Of Propagation) counter

- Ring imaging Cherenkov detector.
  - The Cherenkov photons travel in the quartz bar as they are totally reflected on the quartz/air boundaries.
  - Measure Δ(TOF+TOP) to identify K/π.

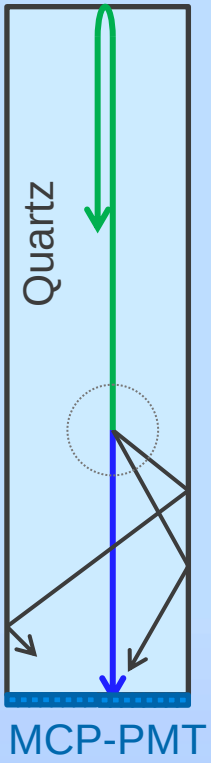


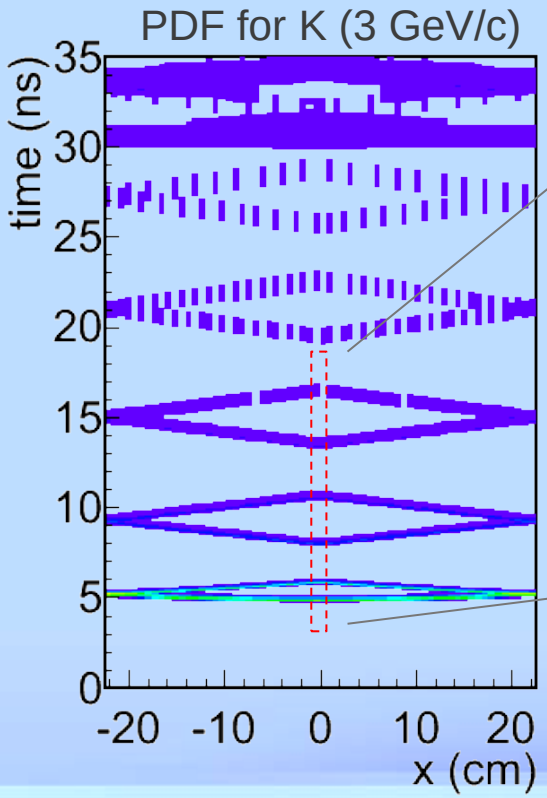


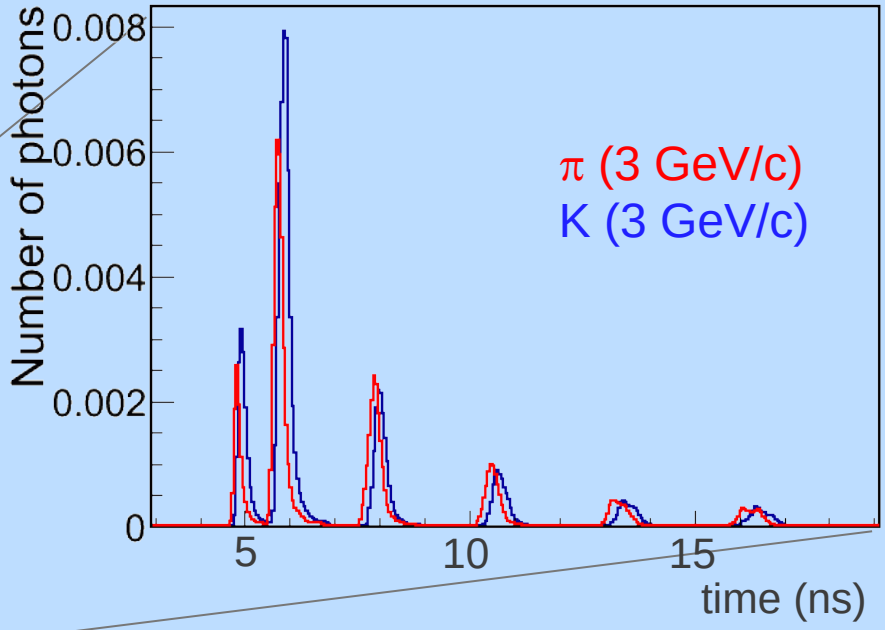
$$\mathrm{TOP} \propto \cos\theta_C = \frac{1}{n\beta}$$

TOP counter

- Measure the hit timing of ~20 Cherenkov photons.
- Hit timing difference between 3 GeV/c K and π
  - ΔTOF ~ 50 ps/m
  - ΔTOP ~ 75 ps/m



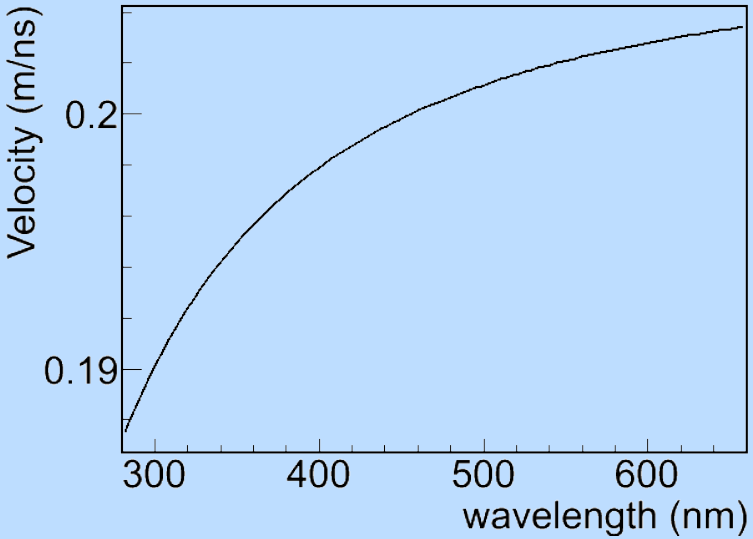


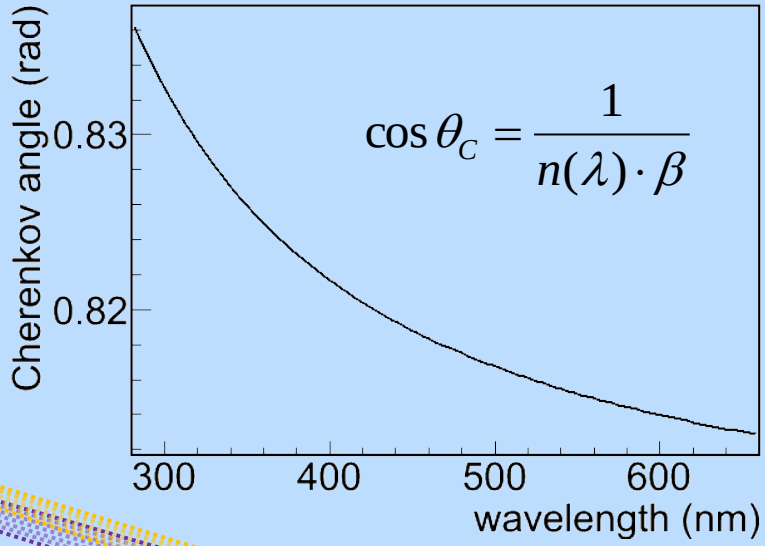


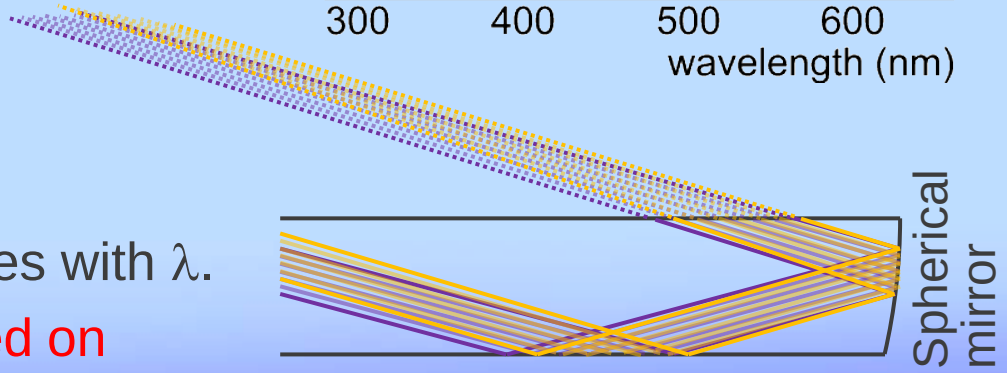
To distinguish K/π, the 'ring' image has to propagate undistorted along the bar and measured with good timing resolution (~50 ps).

Chromatic dispersion

- The photon velocity in the quartz varies with the wavelength (chromatic dispersion) → worsen the time resolution.
- The spherical mirror (r = 5 m) suppresses the deterioration of the time resolution.





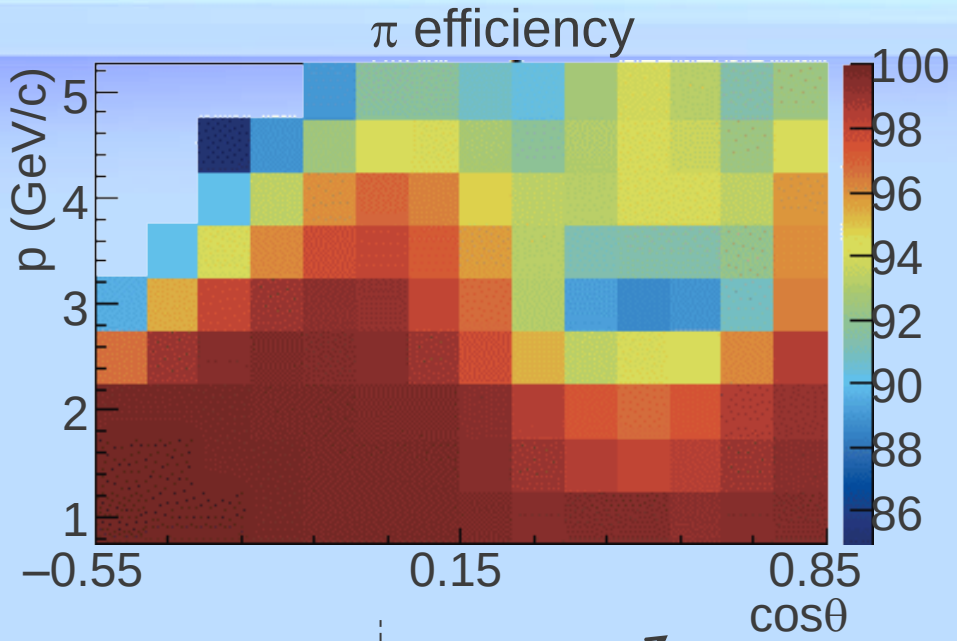


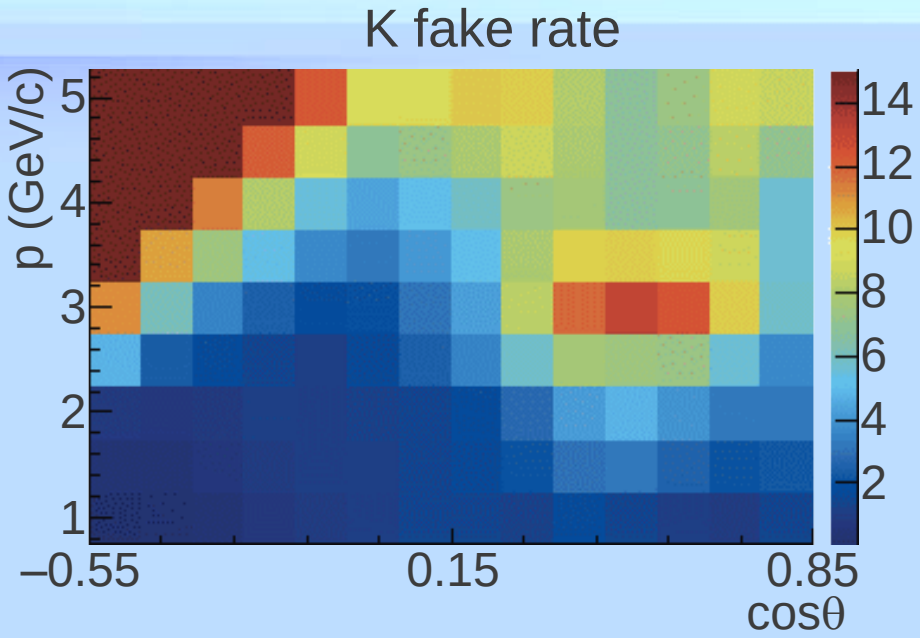
Incident angle to the mirror varies with λ.

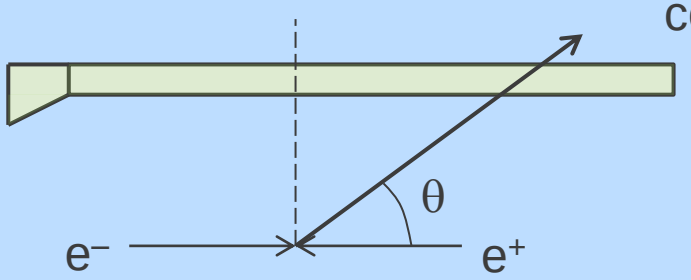
→ Light of different λ is focused on different points on the focal plane.

→ Correction of the chromatic error.

Expected performance







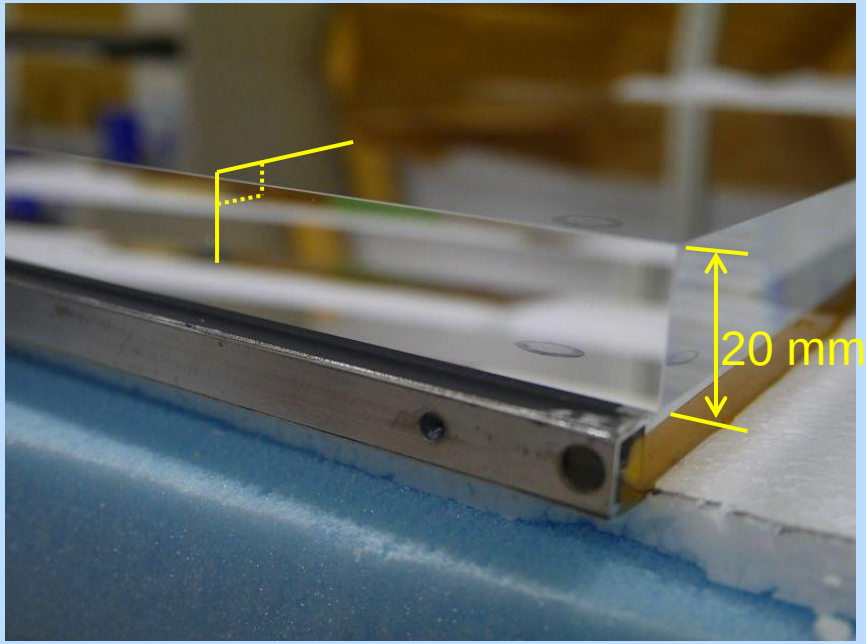
Benchmark channels

	Efficiency	**Fake rate**
B → ππ	~95%	~6%
B → ργ	~98%	~3%

Quartz

- The quality of Cherenkov ring image has to be maintained after ~100 reflections on the quartz surface.

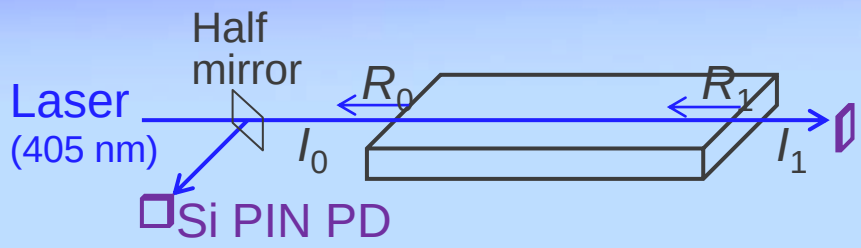
Requirements (for the largest surfaces)	
Length	1250 ± 0.50 mm
Width	450 ± 0.15 mm
Thickness	20 ± 0.10 mm
Flatness	< 6.3 μm
Perpendicularity	< 1 arcmin
Parallelism	< 4 arcsec
Roughness	< 5 Å (RMS)



Polished by a company to meet the requirements.
The bulk transmittance and the surface reflectance are measured in our construction bench to check the quality.

Quality check of the quartz bars

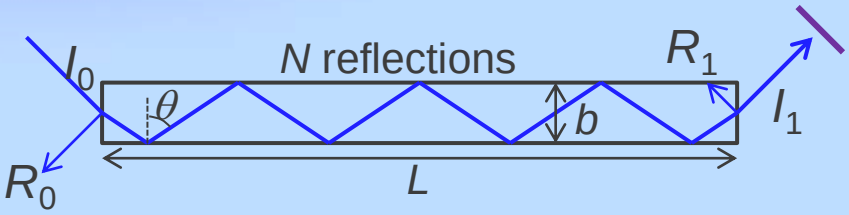
- Bulk transmittance (τ)



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

PD — Calculated using Fresnel equations — PD

- Surface reflectance (α)



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

PD — Fresnel — Loss by bulk transmit — Fresnel — PD

Measured τ (av. of 7×5 points)

- Suprasil-P710: 99.44%/m
- Corning 7980 0D: 99.35%/m

Measurement error: ±0.17%/m

Measured α ($56^o \le \theta \le 70^o$)

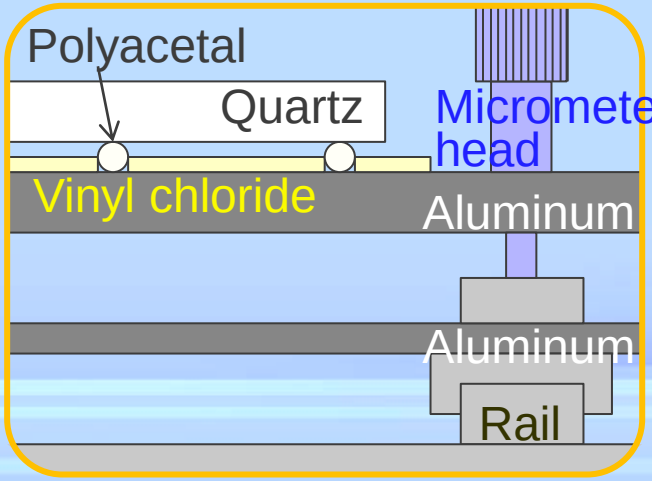
- Suprasil-P710: 99.92–99.98%
- Corning 7980 0D: 99.92–99.97%

Measurement error: +0.02/–0.01%

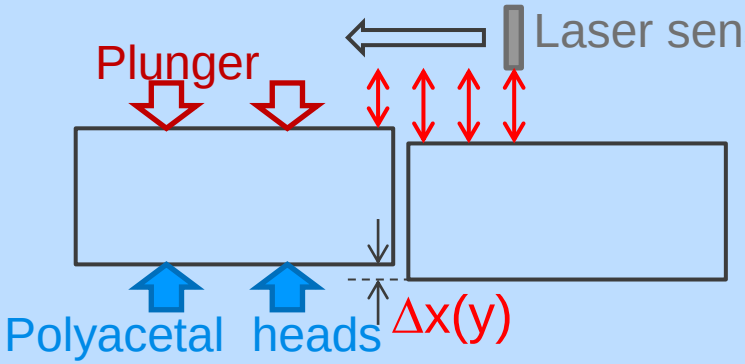
The quartz quality can be measured precisely in our bench, and both the samples meet the requirement (τ > 98%/m, α > 99.90%).

Gluing the quartz bars

- Need to glue the two quartz bars w/ $\Delta\theta < 0.2$ mrad and $\Delta x,y < 100$ μm.



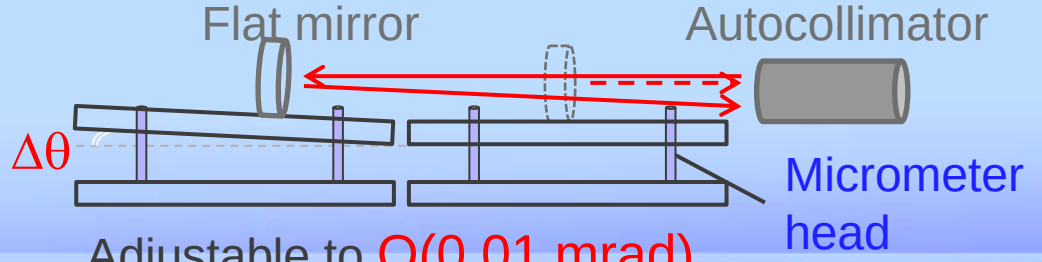
Adjustment of the relative position



Adjustable to O(10 μm)

Measurement precision: ±5 μm

Adjustment of the relative angle

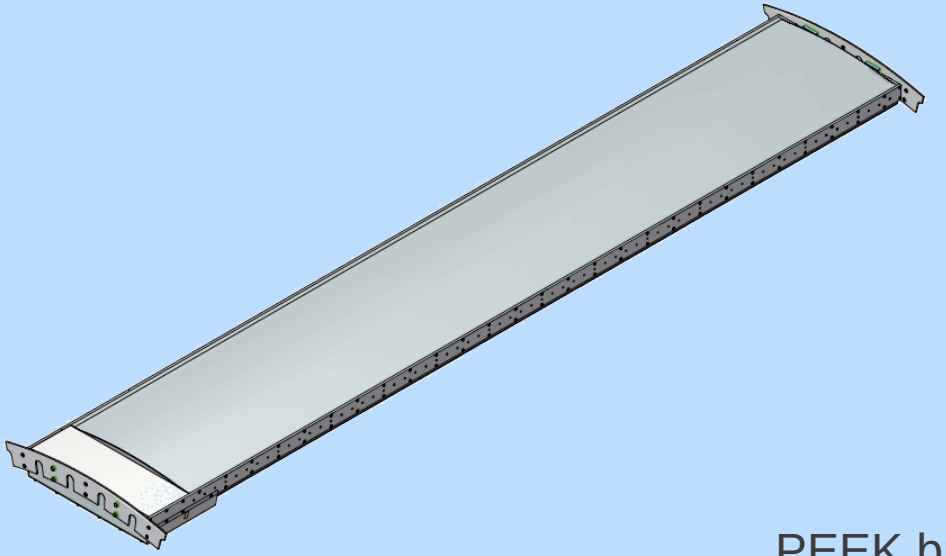


Adjustable to O(0.01 mrad)

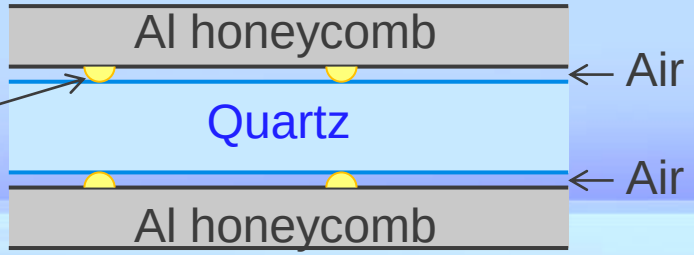
Measurement precision: ±0.01 mrad

Quartz bar box

- Made of aluminum honeycomb panels.
  → Low mass
- Support the quartz with PEEK buttons.
  → Enable the total reflection on the quartz surfaces.



PEEK button

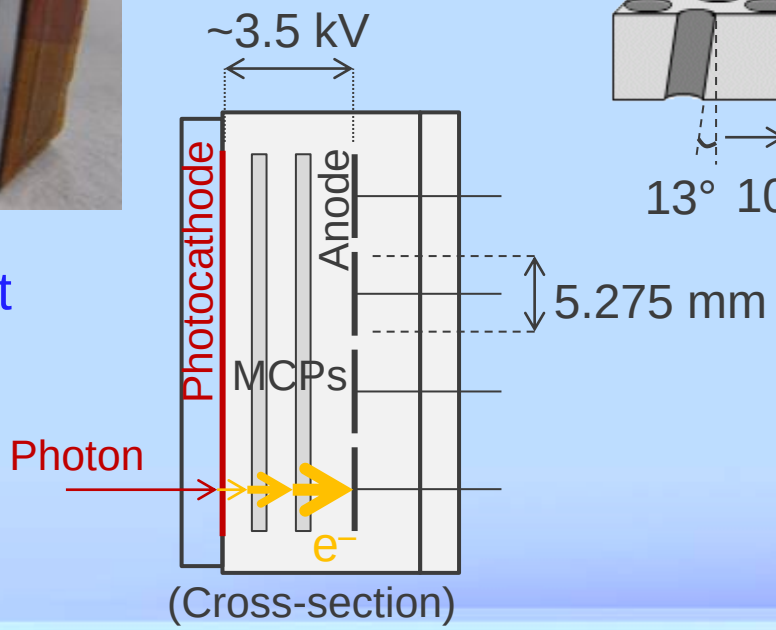


MCP-PMT (Micro Channel Plate PMT)

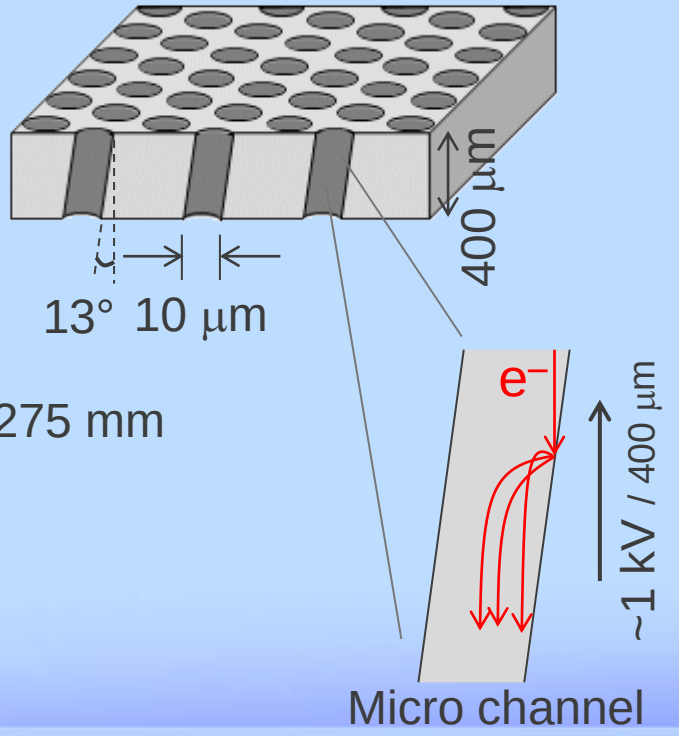
- Developed at Nagoya in collaboration w/ HAMAMATSU Photonics.
- 32 MCP-PMTs per TOP module, 512 PMTs in total.
  - 4 x 4 channels per PMT

MCP-PMT

Compact

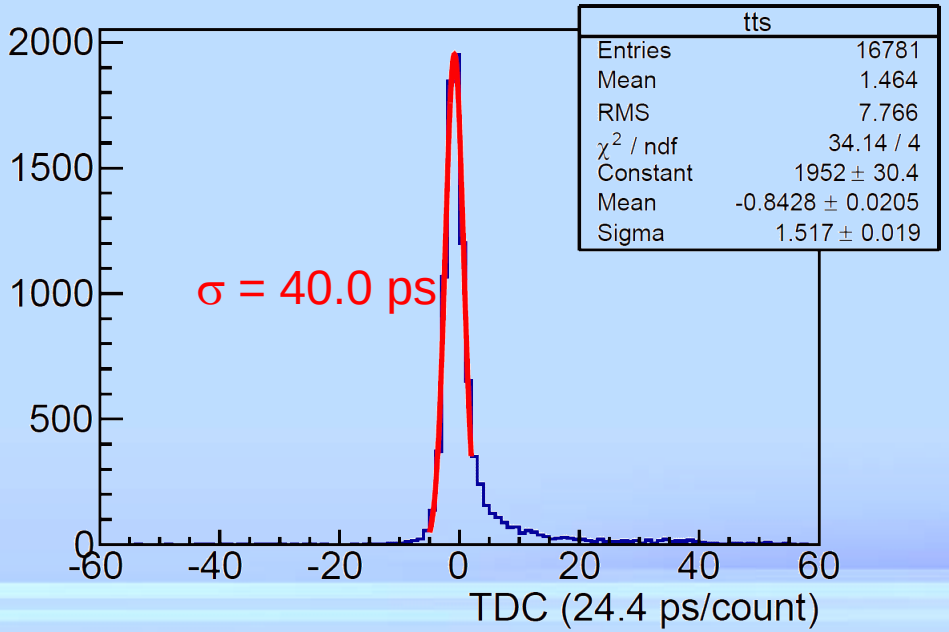


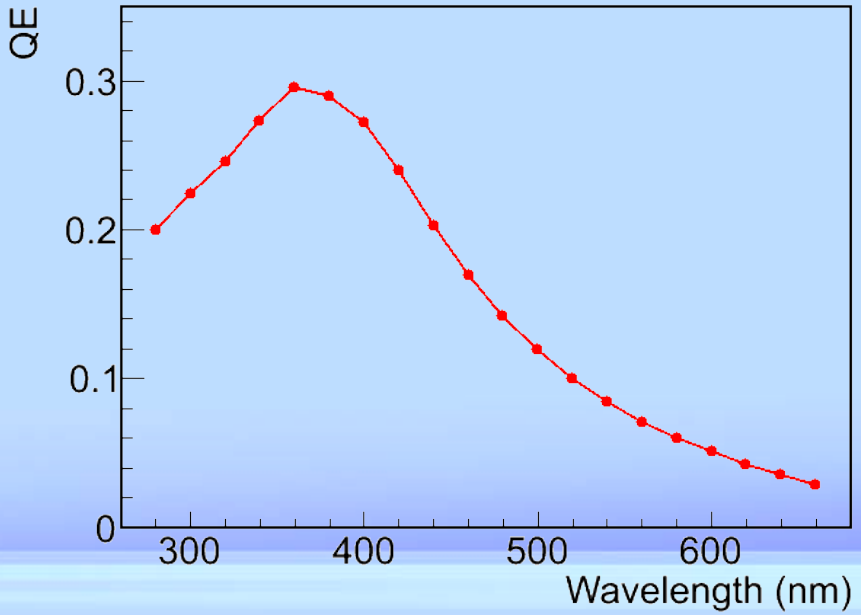
Micro Channel Plate (MCP)



Specification of the MCP-PMT

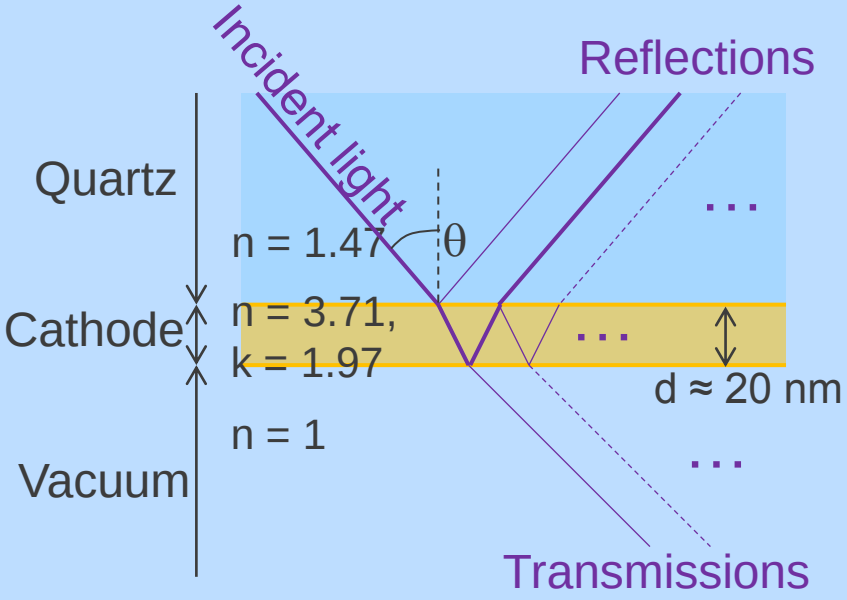
- Square shape, small dead region (active area: 69.4%)
- NaKSbCs photocathode; QE ≥ 24% (28% on average) at 380 nm
- Collection efficiency: 50~55% (≈ MCP aperture ratio)
- 2 x 10^6 gain at ~3.4 kV → Capable of detecting single photon.
- Transit Time Spread (TTS): ~40 psec
- Dark noise rate < 100 kHz
- Work in 1.5 T



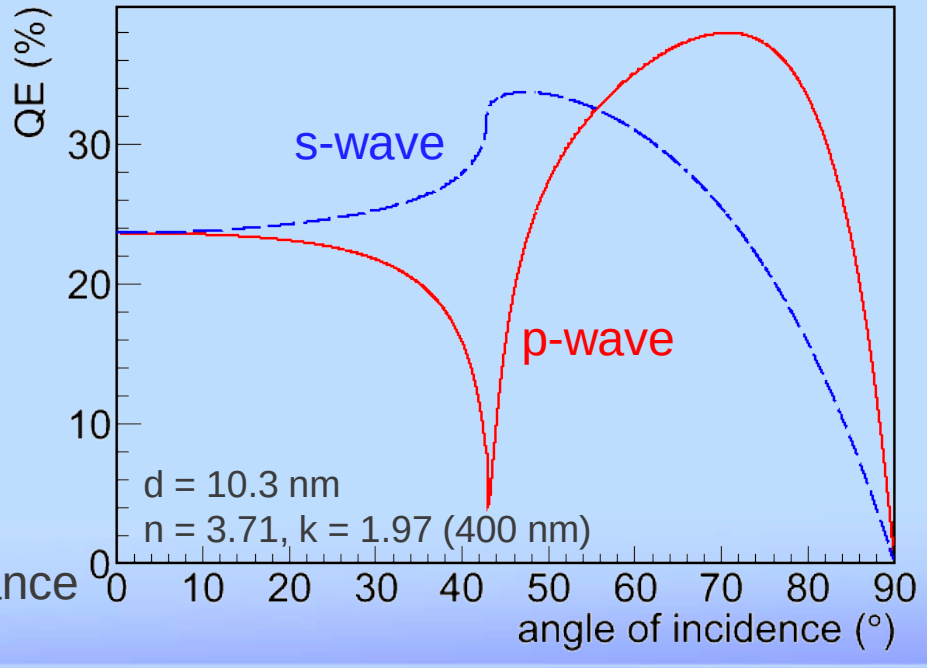


Angle/polarization dependence of QE

- QE depends on the photon incident angle and polarization.
  - TOP counter detects photons at various angles ($\theta \gtrsim 40°$).
  - Cherenkov light is linearly polarized.



QE ∝ Absorbance
= 1 – reflectance – transmittance

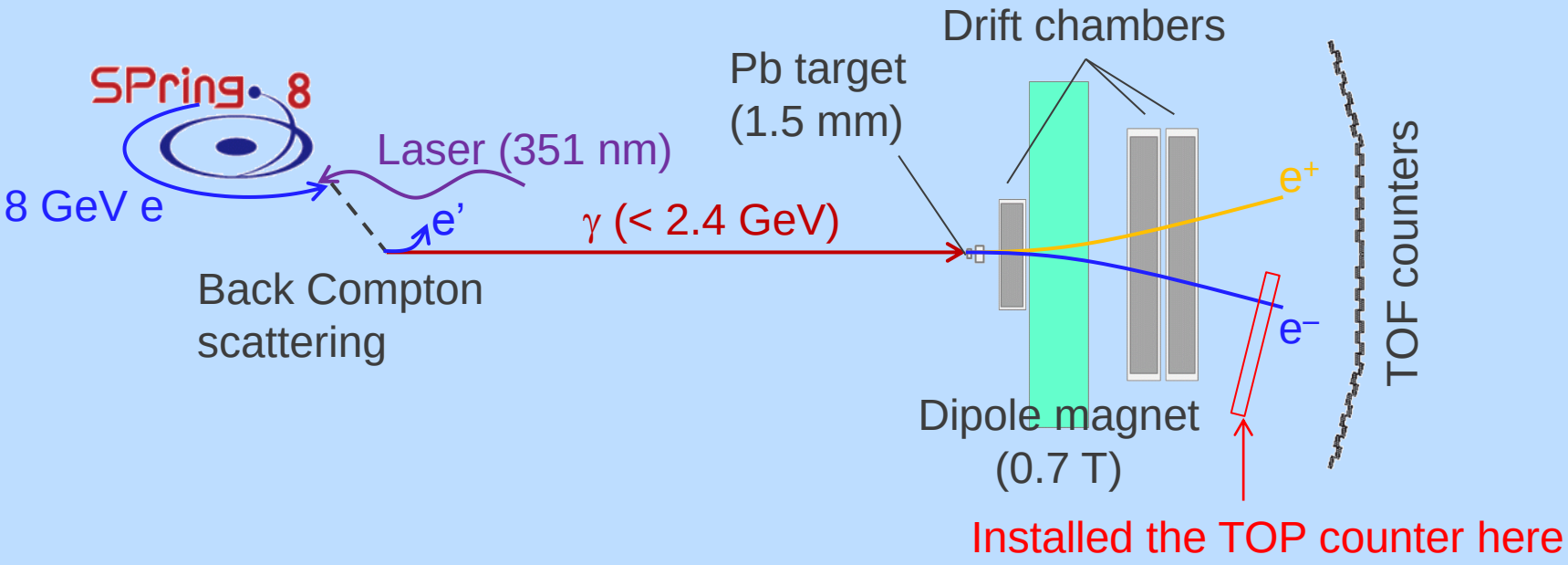


n, k and d are measured by ellipsometry.
→ Calculate the reflectance and transmittance using Fresnel equations.

Need to take this QE dependence into account.

Beam test at LEPS/SPring-8

- R&D for all the key components of the TOP counter almost finished.
- Evaluated the TOP counter performance with ~1.2 GeV electron beam at LEPS (Laser Electron Photon beamline at SPring-8).



The tracking information is available from the LEPS spectrometer.
The beam timing is obtained from the accelerator RF.
Supported by the LEPS collaboration.

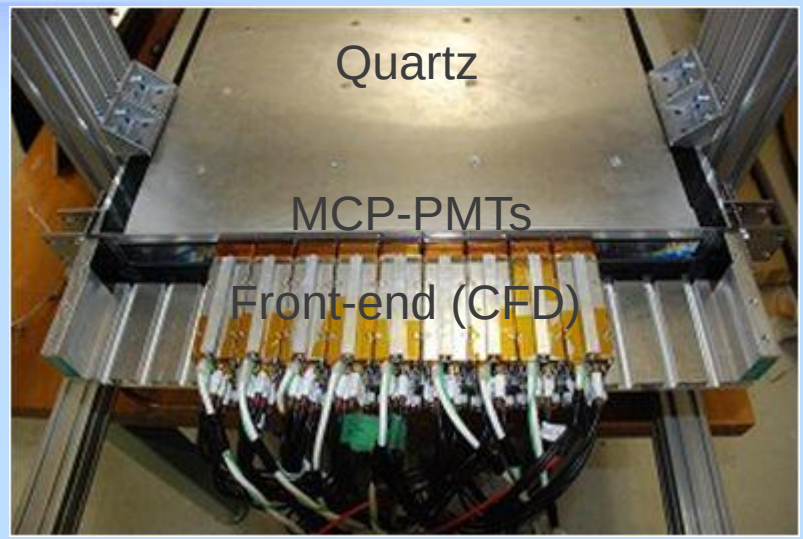
TOP prototype for the beam test

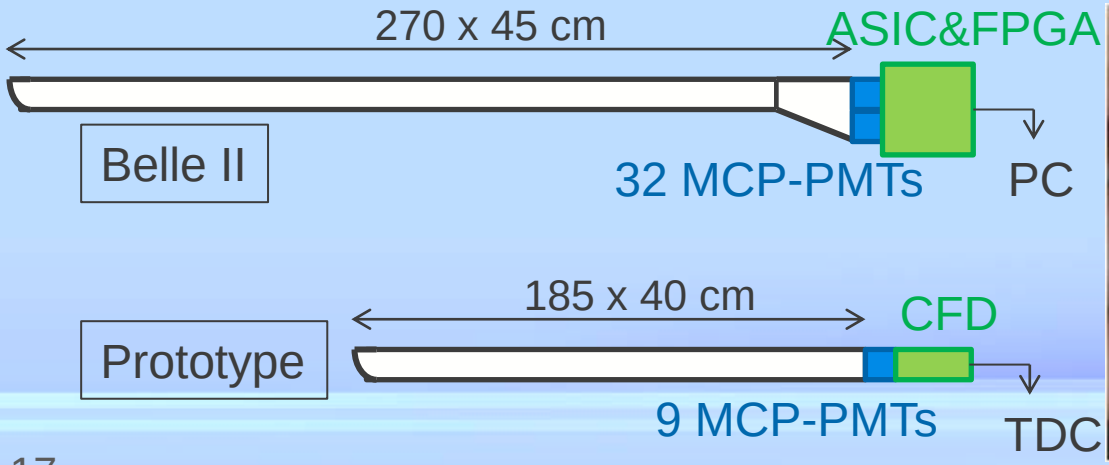
- Check if the ring image can be obtained as expected with the small prototype counter.
  - Smaller quartz bar
  - Fewer number of MCP-PMTs
  - Readout for performance verification:

    CFD (Constant Fraction Discriminator)

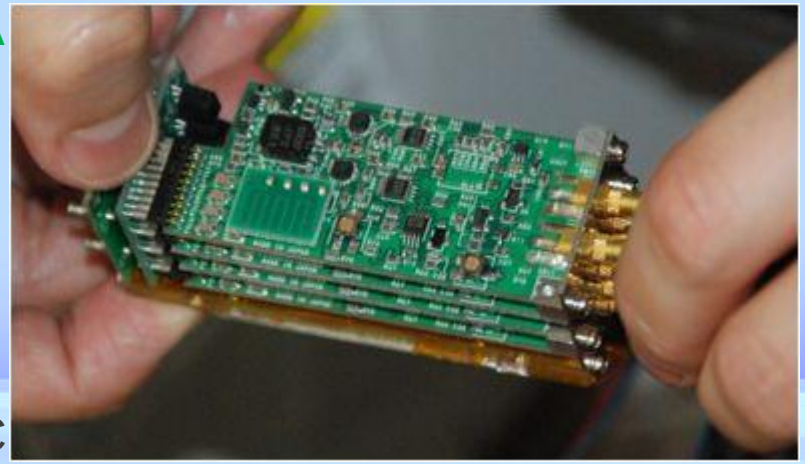
    VME TDC

TOP prototype



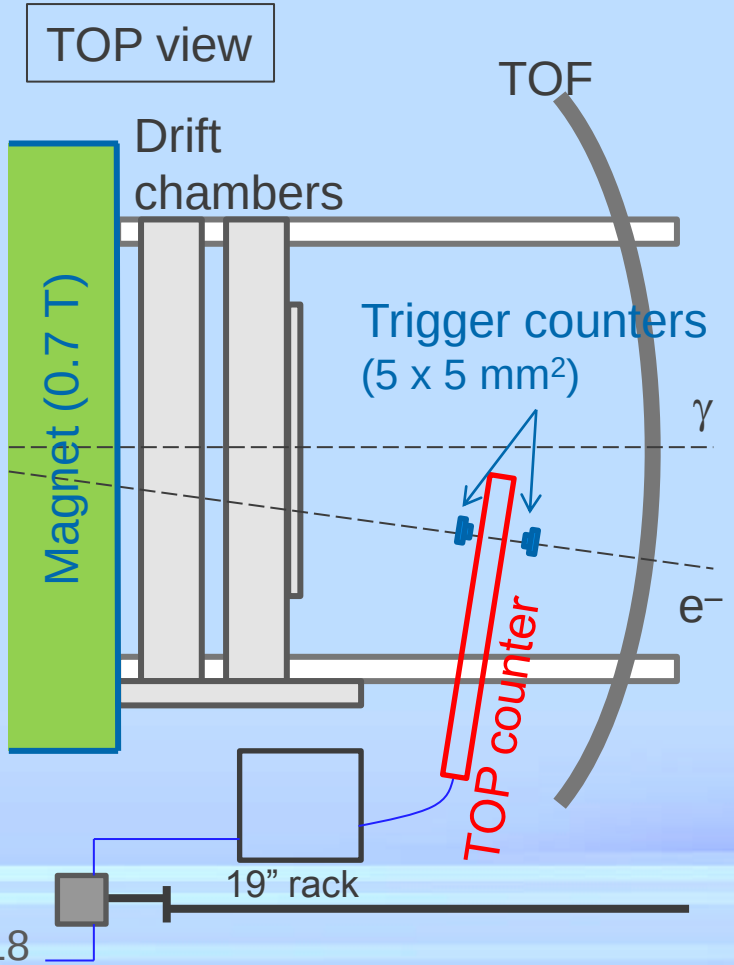


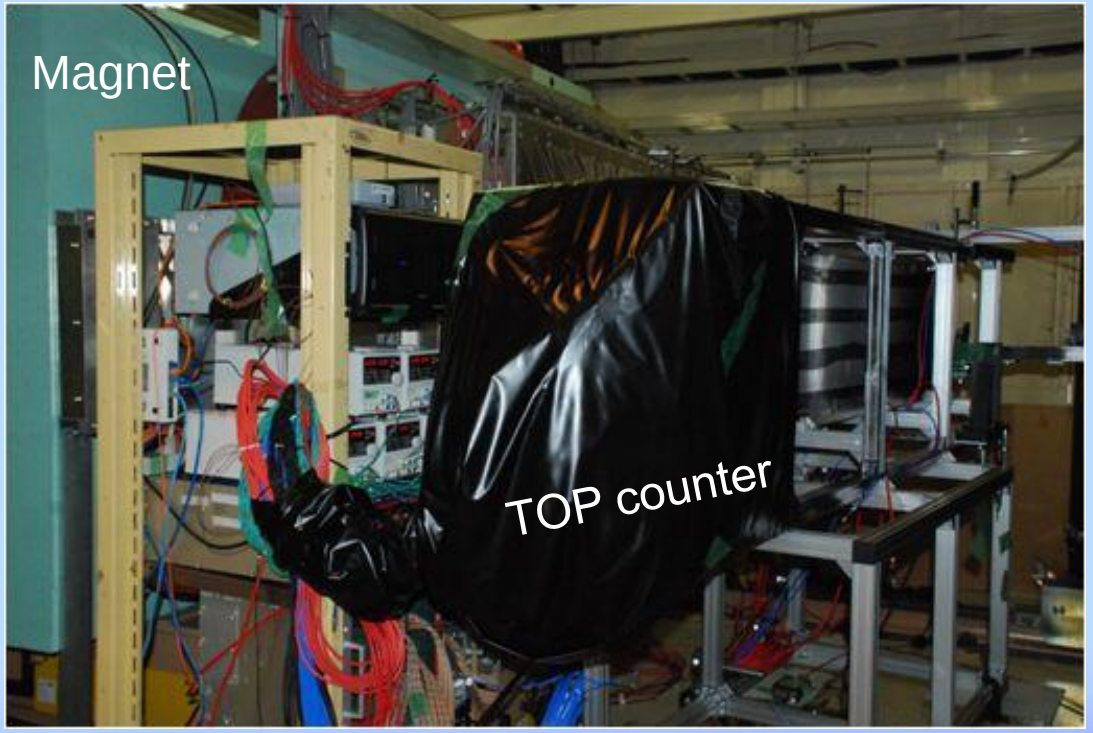
Front-end (CFD)



Setup of the beam test

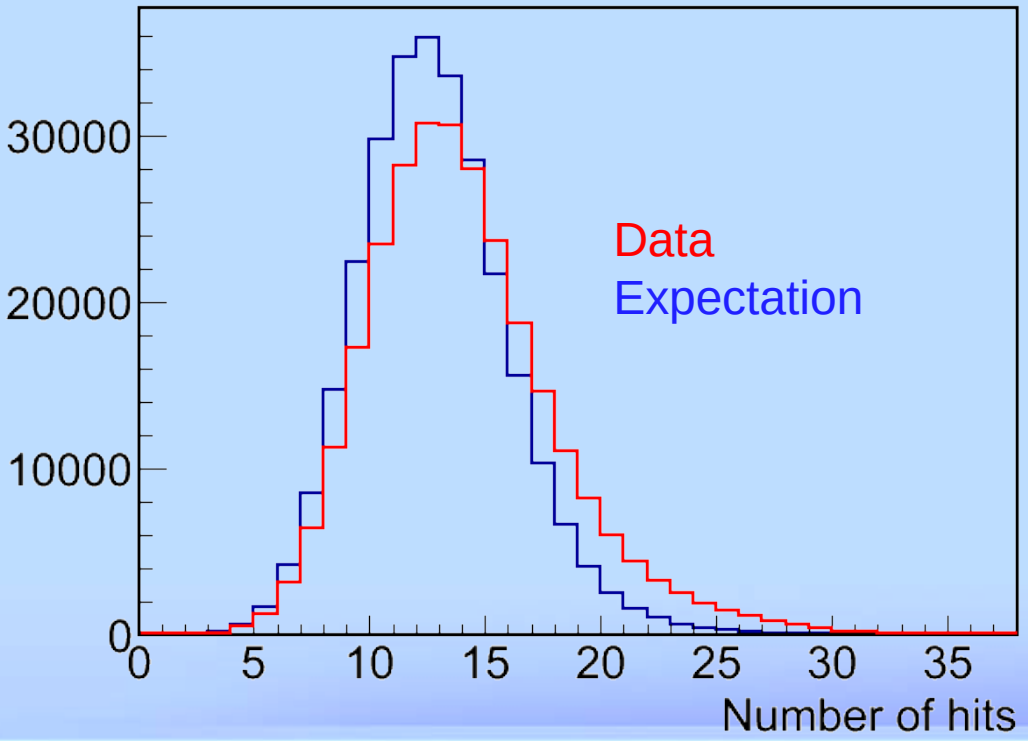
- Trigger the ~1.2 GeV electrons.
- They pass through the TOP counter perpendicularly.



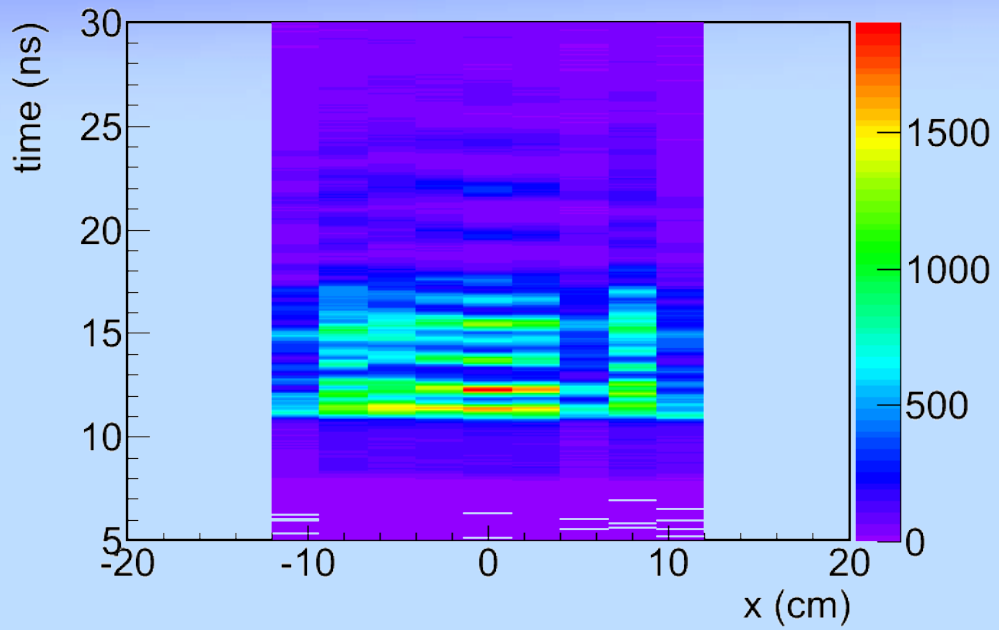


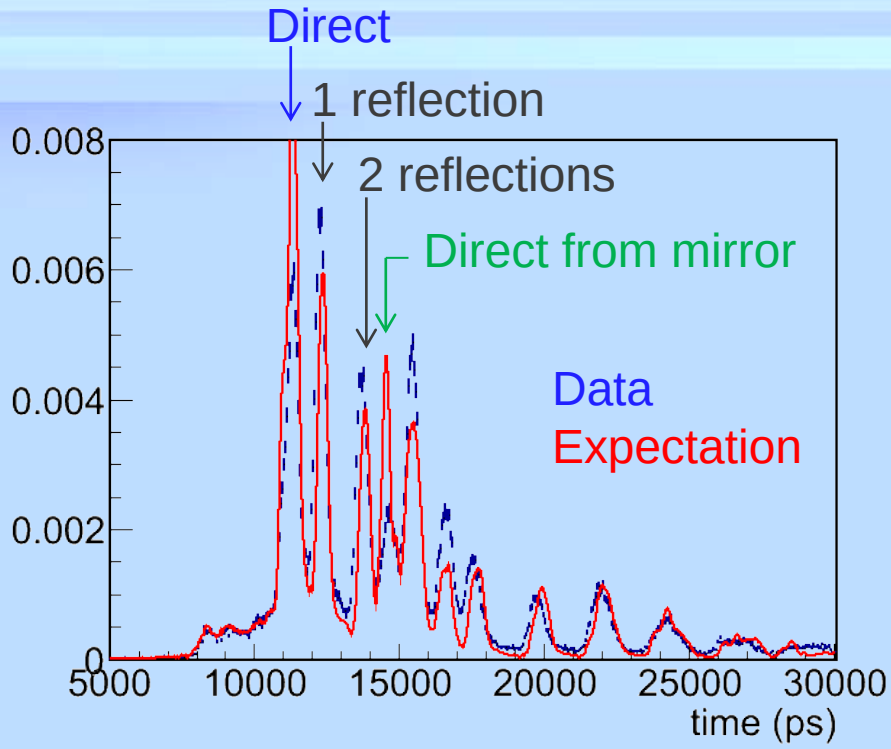
Num. of detected photons / event

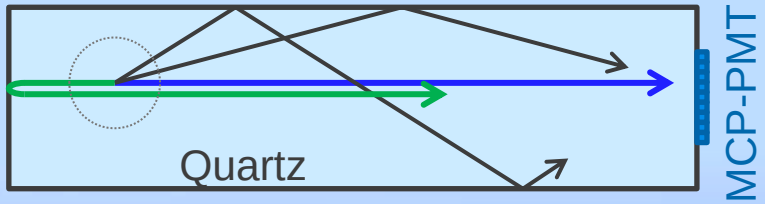
- Data: 13.54 photons/event on average
- Expectation: 12.34 photons/event on average
  - Including ~3 photons from the EM shower background



Ring image



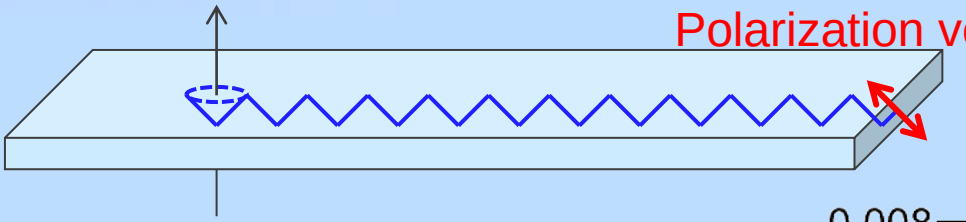


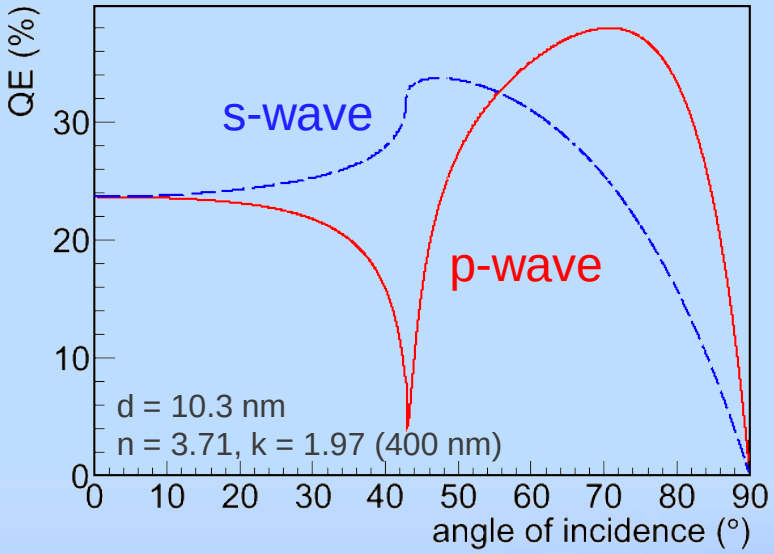


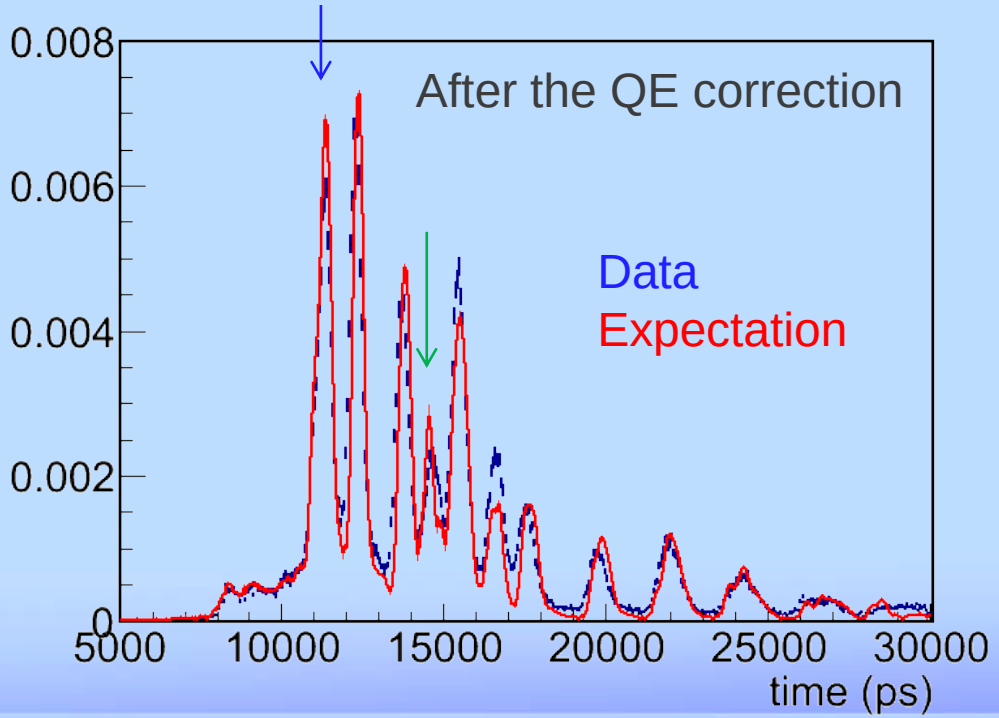
Large discrepancy for the peaks by the photons not reflected on the quartz sides.

Effect of the polarization

- The direct photon is ~100% p-polarized and their angle is ~40° relative to the MCP-PMT photocathode.







The ring image was obtained as expected.

Mass production status and plan

- Production of the 16 TOP counters is ongoing.
  - The first two quartz bars will be delivered soon.
  - About half of the 512 MCP-PMTs were delivered.
- It is time to test the real TOP counter.
  - Next beam test at LEPS in April.
  - Each assembled TOP counter will be tested in a cosmic ray test stand.
- Installation of the TOP counter into the Belle II detector starts in March 2015.
- Belle II physics run starts in 2016.

Summary

- A novel ring imaging Cherenkov detector, TOP counter, has been developed for the K/π PID in Belle II.
  - Important to propagate the ring image as it is.
    - Confirmed that the quartz bar can be polished and glued to meet the stringent requirements.
  - Need good timing resolution
    - Detect single photon with ~40 ps resolution by MCP-PMT.
- Prototype TOP counter was tested at LEPS/SPring-8.
  - The QE dependence on the photon incident angle and polarization is specifically important.
  - The ring image was obtained as expected.
- Mass production of the TOP counter is ongoing.
  - To be installed in March 2015.