The (i)TOP Detector for the Belle II Experiment

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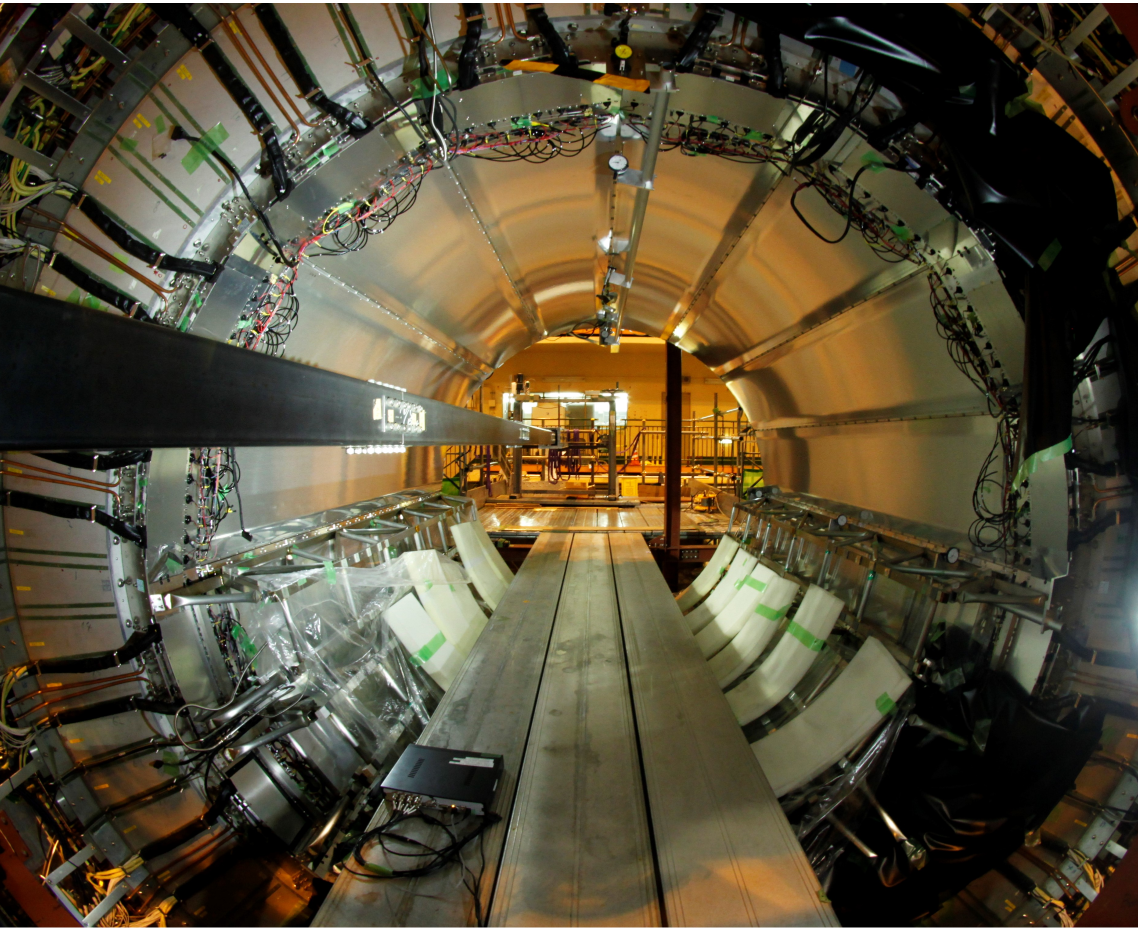
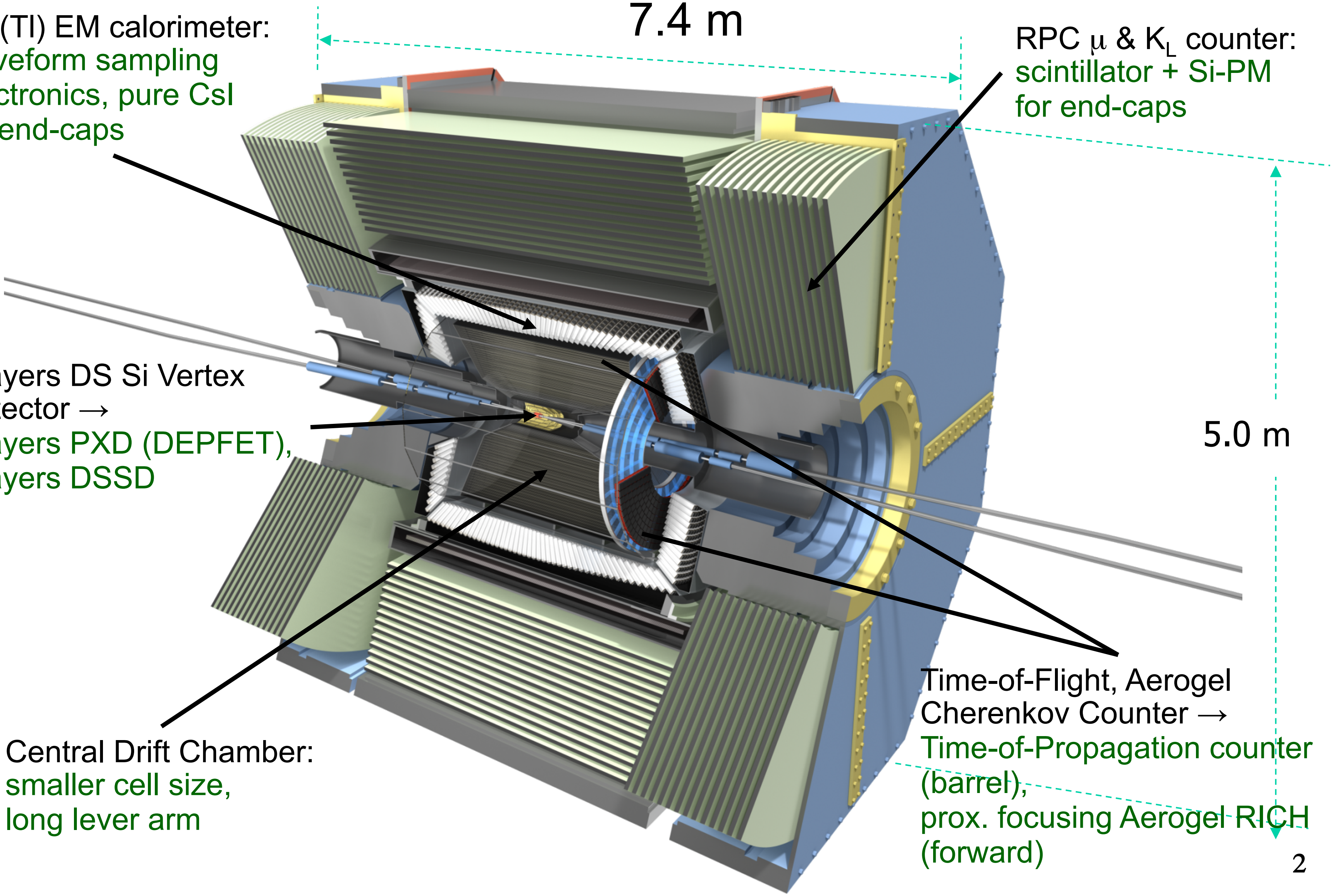


- *overview*
- *optics*
- *mechanical & electronics*
- *first commissioning results*
- *expected performance*

The Belle II Detector



CsI(Tl) EM calorimeter:
waveform sampling electronics, pure CsI for end-caps

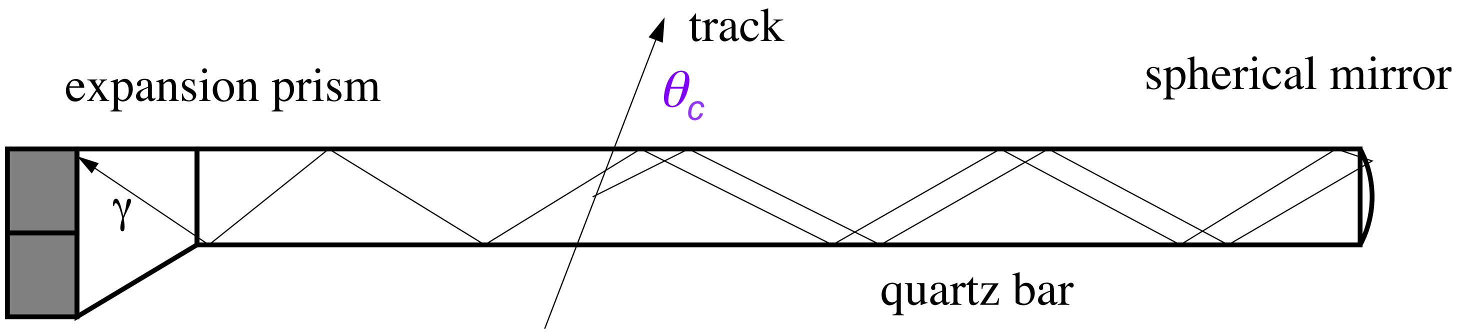
RPC μ & K_L counter:
scintillator + Si-PM for end-caps

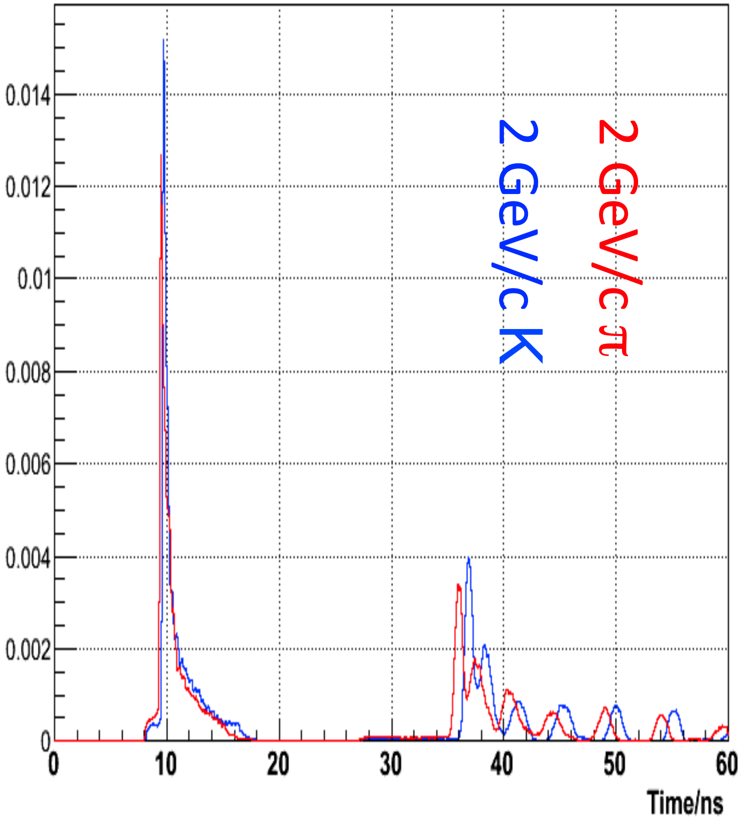
4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET), 4 layers DSSD

Central Drift Chamber:
smaller cell size, long lever arm

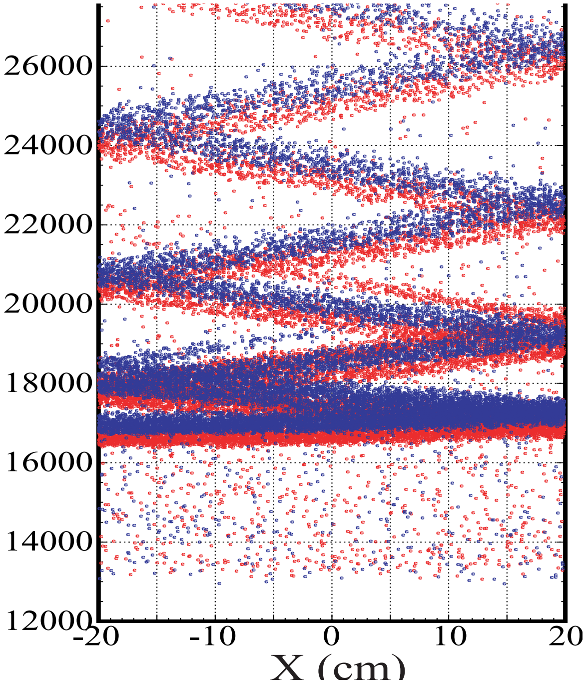
Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)

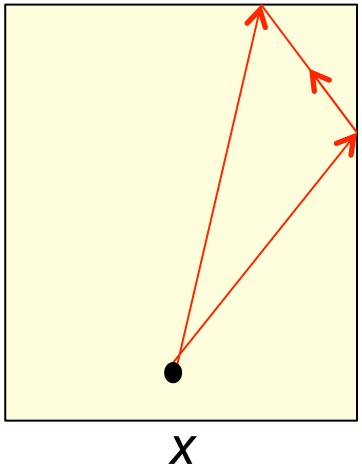
iTOP Principle of Operation



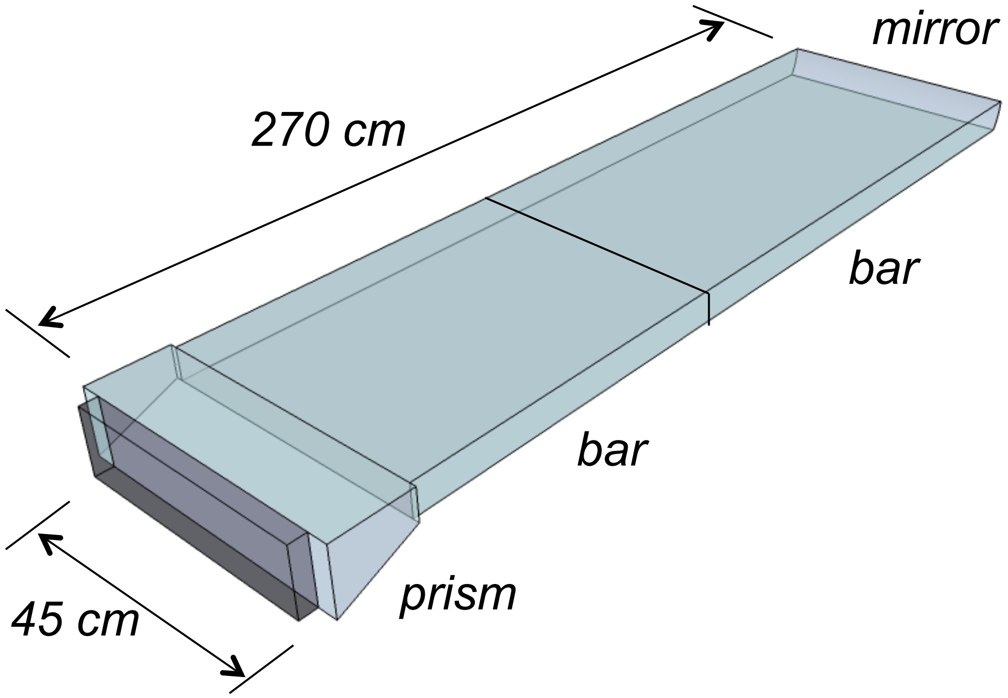


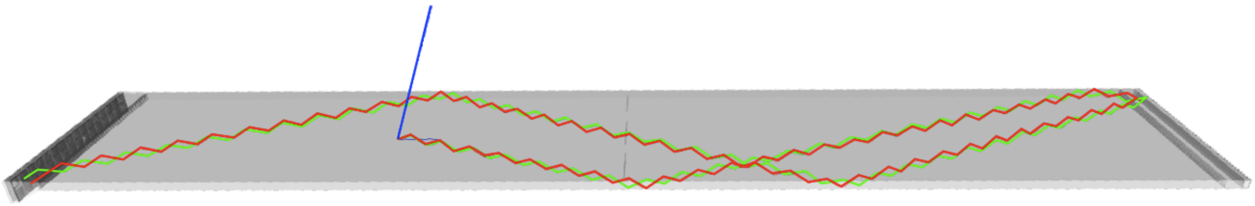
π and K have different θ_c according to cos $\theta_c = 1/n\beta$ ⇒ different γ hit positions and arrival times. For p=3 GeV/c, $\Delta\theta_c$ = 0.65 degrees → Δt = 68 ps per m





Optical Components: synthetic fused silica (quartz)





Nominally 100-150 reflections off large top and bottom faces

Bars: medium to generate Cherenkov radiation. Two bars of dimensions 2 x 45 x 125 cm^3 are glued together to make a "long bar" of length 2.5 m.

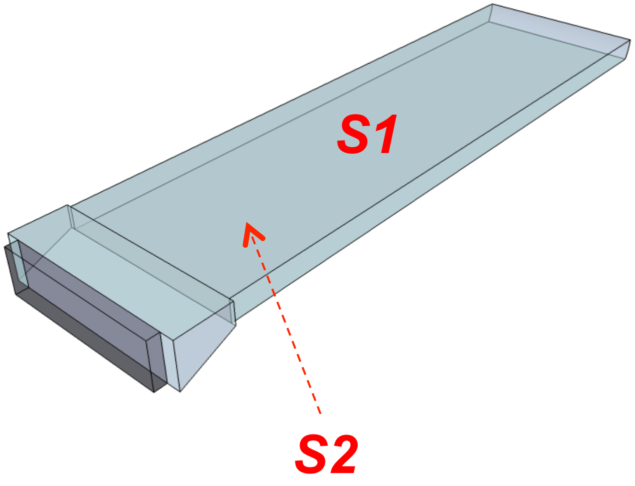
Mirror: to focus Cherenkov photons onto PMTs, thus improving imaging. Dimensions are 2 x 45 x 10 cm^3. Mirrors are spherical with focal length of 3.25 m.

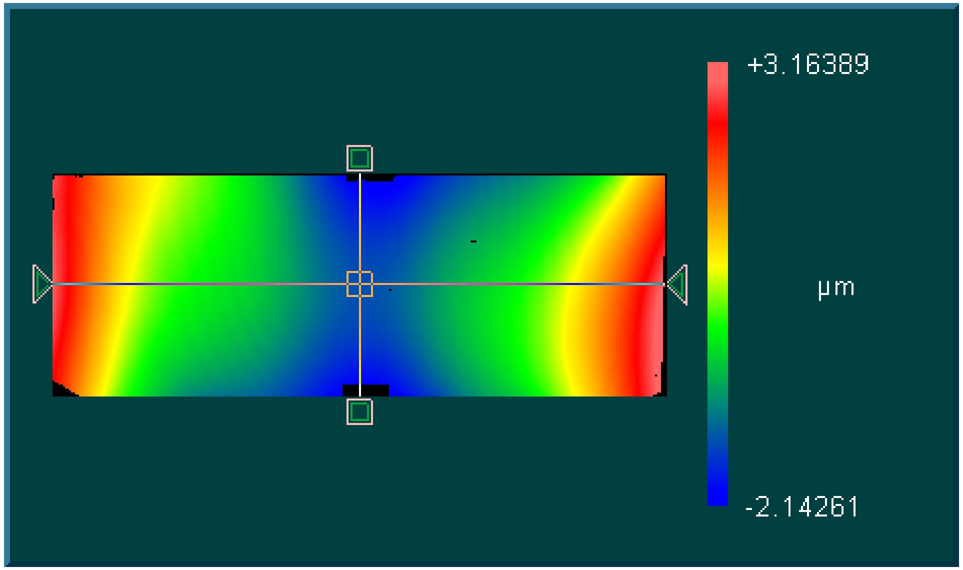
Prism: to expand the image of Cherenkov cone, improving resolution and reducing ambiguities. Dimensions are 2 x 45 x 10 cm^3; angle of tilted fact is 18.1 degrees.

Fabricating quartz bars: flatness is critical

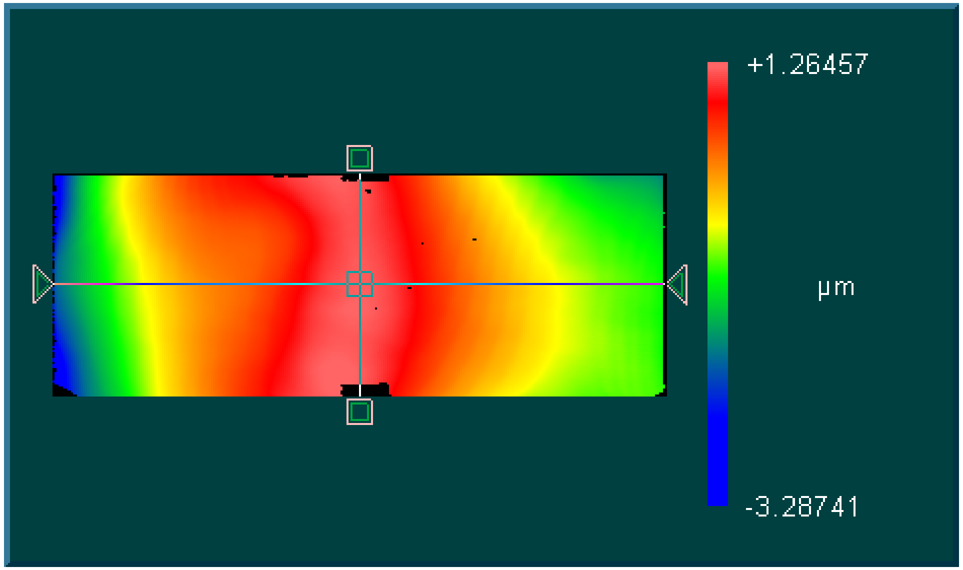
Interferograms from metrology report:

***S1** peak-to-peak: 5.3 μm (< 6.3 μm)*
***S2** peak-to-peak: 4.6 μm (< 6.3 μm)*



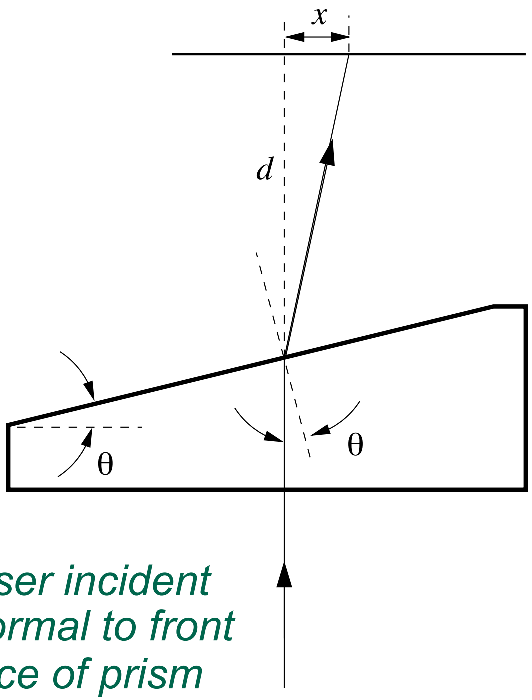


(S1 Surface Flatness)



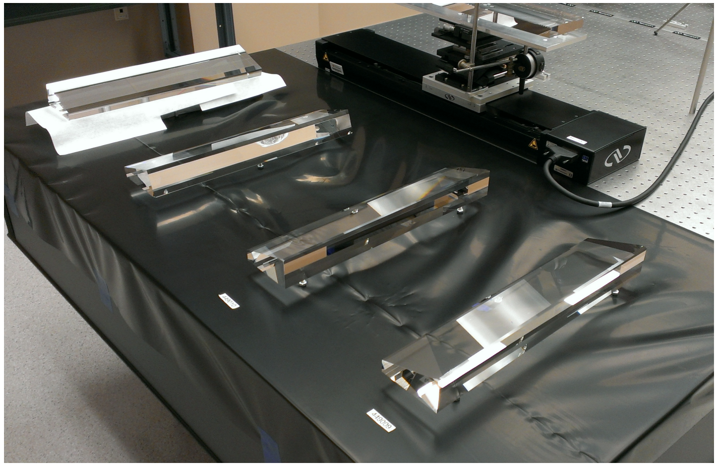
Quality control: measuring prism tilted face

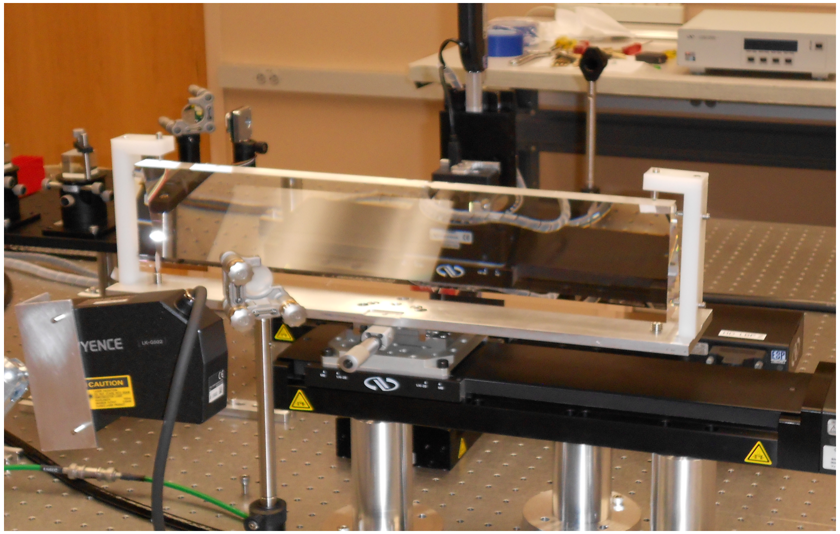
Angle of tilted face. Specification: 18.07 ± 0.04 deg. (±144 arcsecs)



laser incident normal to front face of prism

$$\theta = \tan^{-1}\left[\frac{\alpha}{n_{\mathrm{qtz}}\sqrt{1+\alpha^2}-1}\right] \qquad \text{for } \alpha \equiv \frac{x}{d}$$

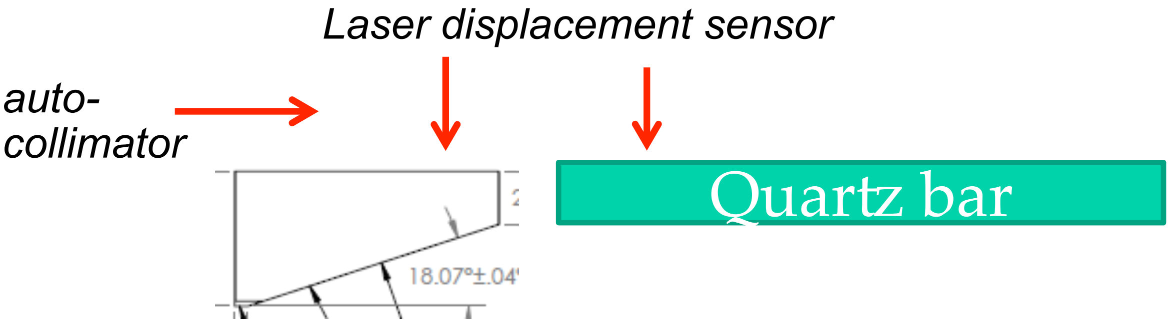




Gluing Optics

3 types:

- bar to bar
- bar to prism
- bar to mirror



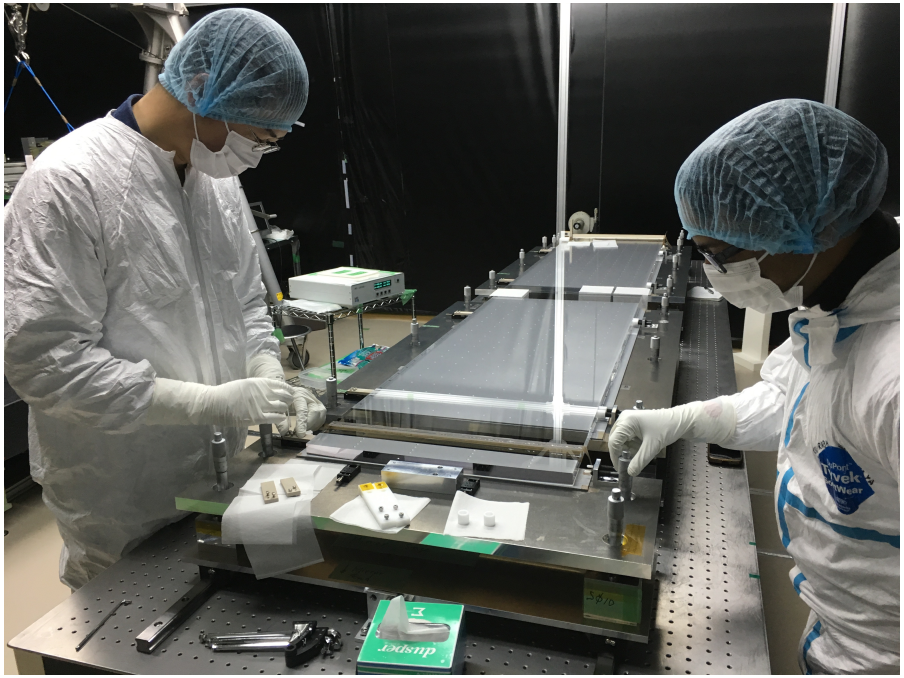
Laser displacement sensor

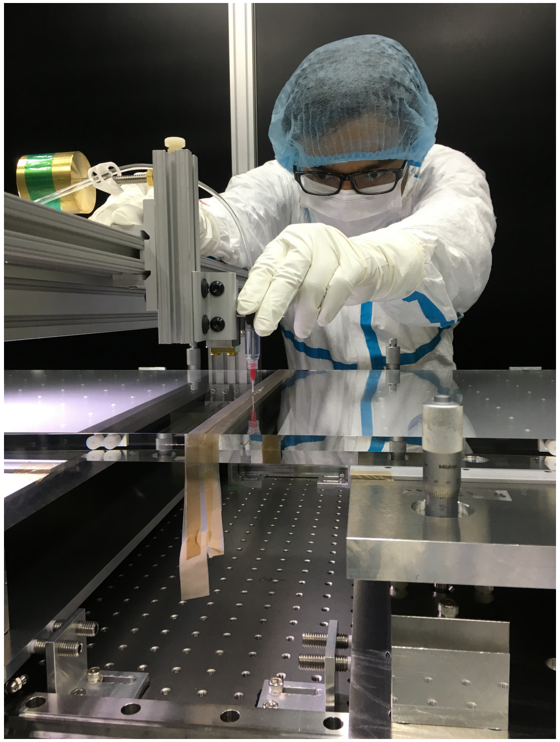
auto-collimator

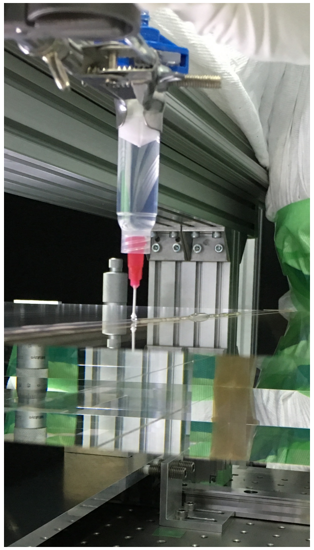
Quartz bar

Alignment and Gluing:

- *adjust surfaces positions using laser displacement sensor and micrometers*
- *adjust surfaces angles using autocollimator and micrometers*
- *insert shims, tape joint and repeat steps 1, 2*
- *apply epoxy (EPOTEK 301-2) to joint*

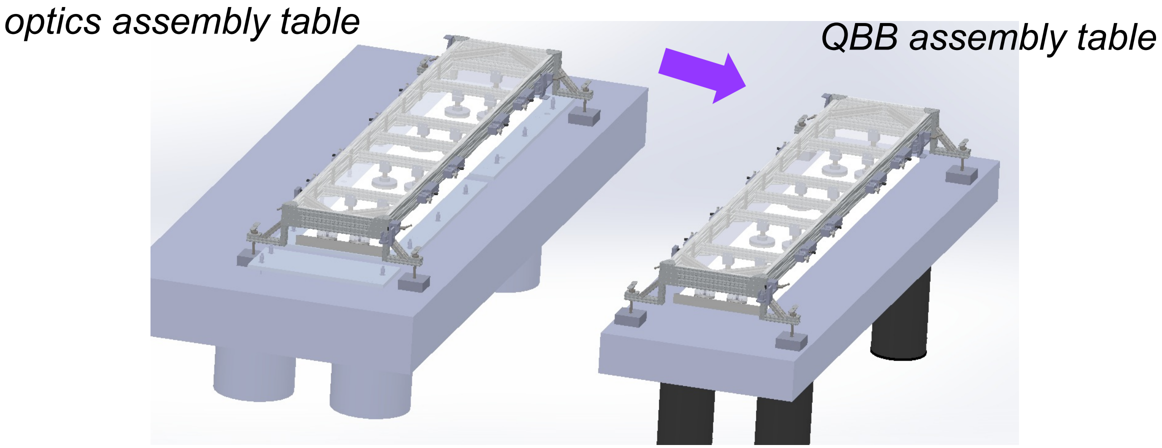


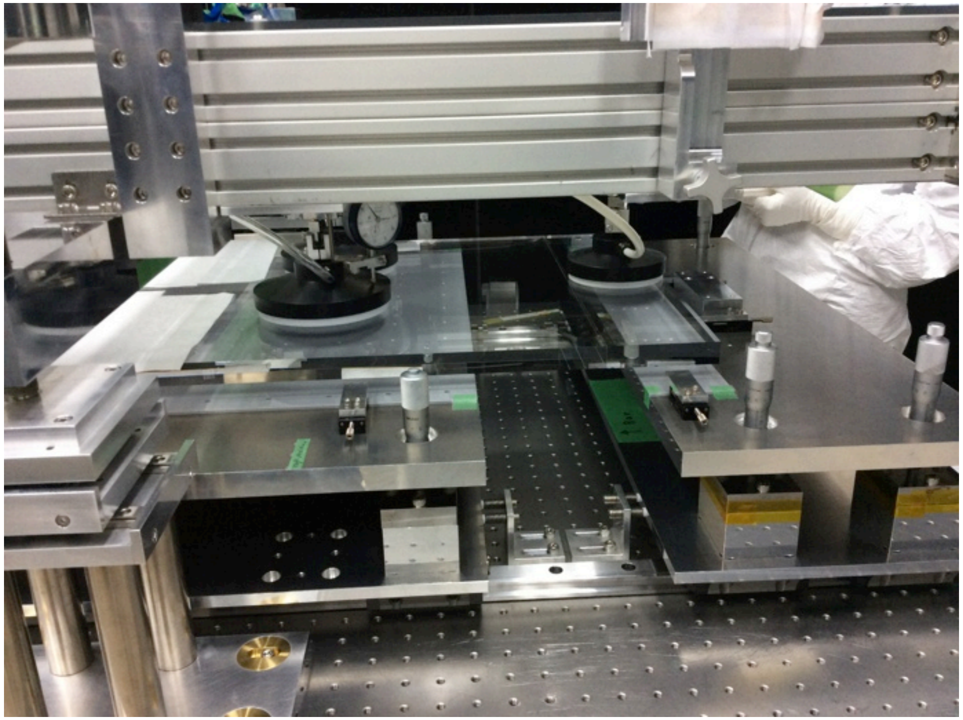


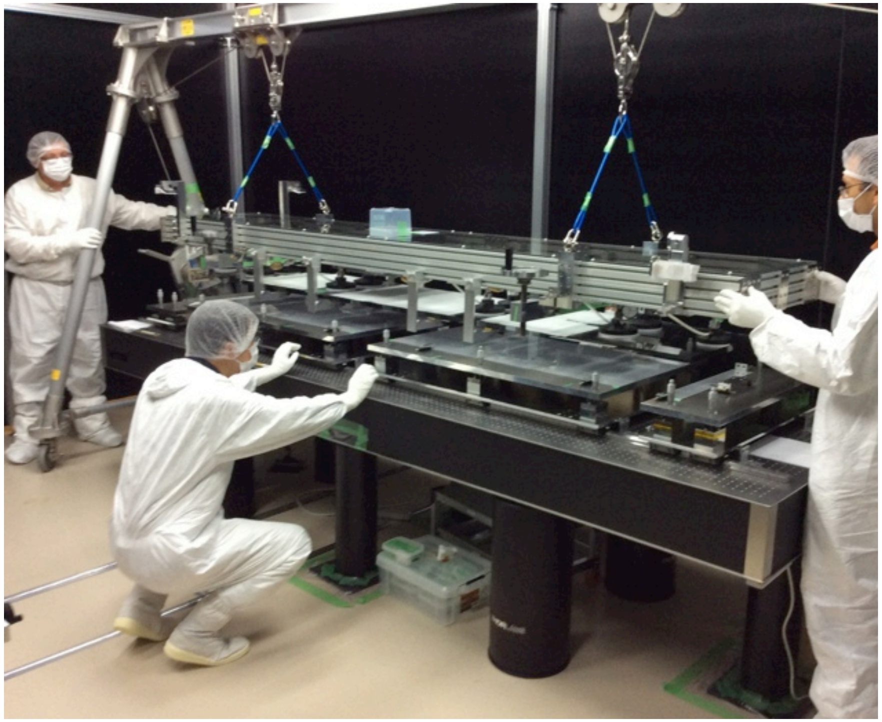


Moving Optics to Quartz Bar Box (QBB)

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



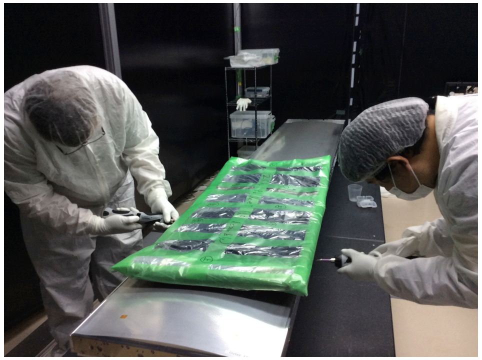




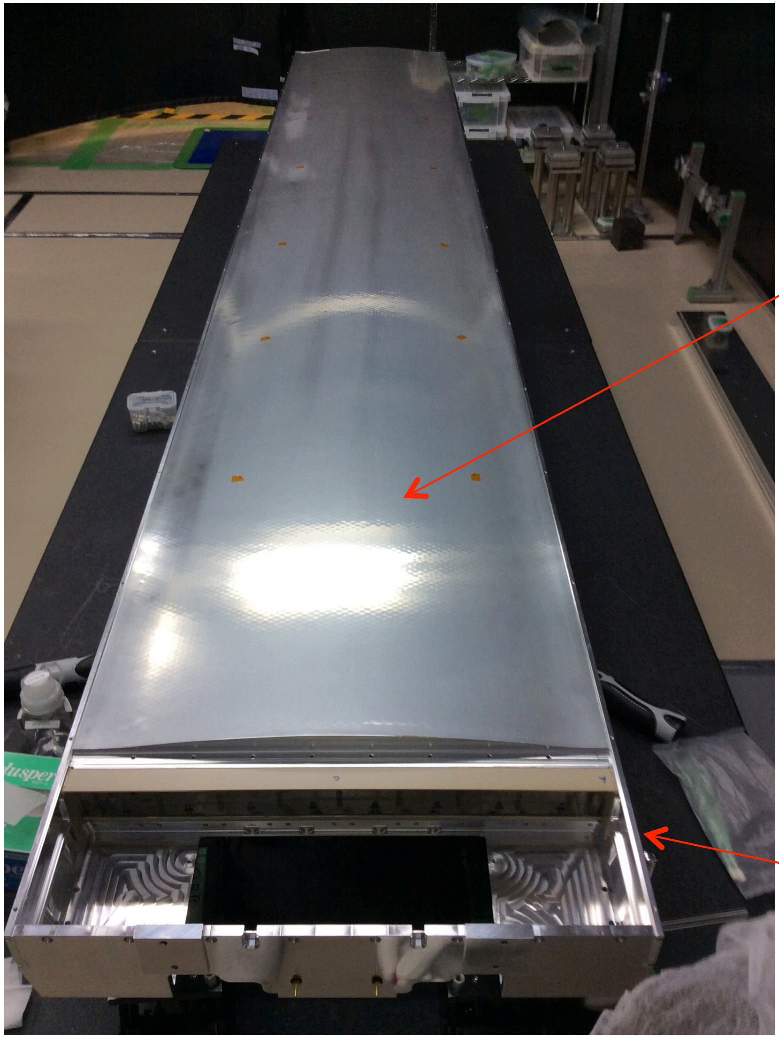
QBB Assembly

Quartz Bar Box is built up around optics:

Fixing outer honeycomb panel to side rails with panel preloaded (to load buttons)



Sealing outer honeycomb panel to PEEK frame

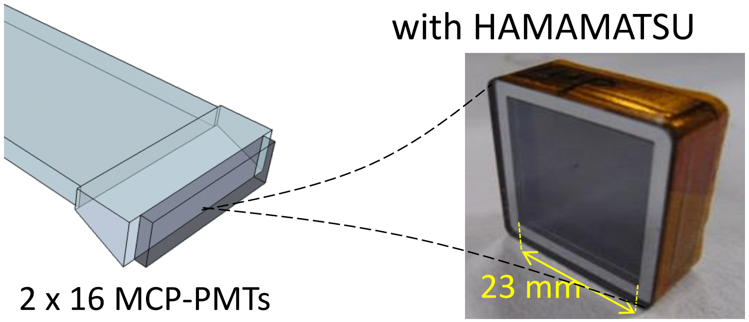


top honeycomb panel

Prism Enclosure: provides access for PMTs and readout electronics

Photon Detection: Hamamatsu PMTs

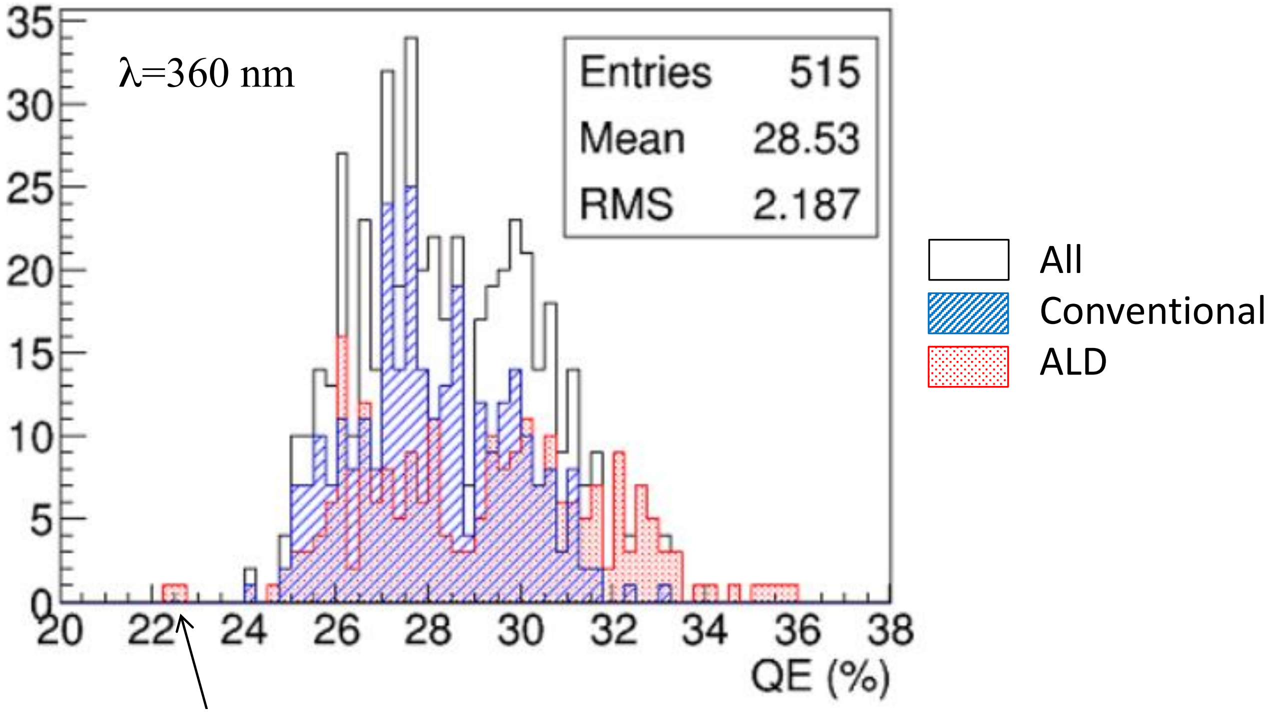
Developed in collaboration with HAMAMATSU



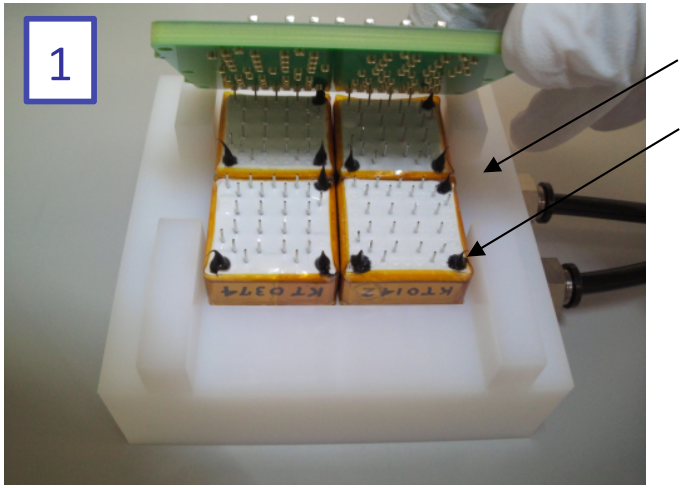
Hamamatsu SL-10 Multi-Channel-Plate PMTs:

- *>5-year R&D effort at Nagoya University*
- *high gain to detect single photons*
- *excellent timing: TTS < 50 ps*
- *good QE: 28% on average*
- *good segmentation: 16 anodes/tube: 5.3 x 5.3 mm^2*
- *works in a 1.5 T magnetic field*

- *All PMTs tested; those with QE < 24% are rejected*
- *32 tubes/module x 16 modules = 512 tubes needed (8192 channels)*
- *"Conventional" PMTs have lifetimes 0.3-1.8 C/cm^2 ⇒ will need to be changed @ ~20 ab^{-1} (44% of tubes). Next geeration (ALD) PMTs are satisfactory.*



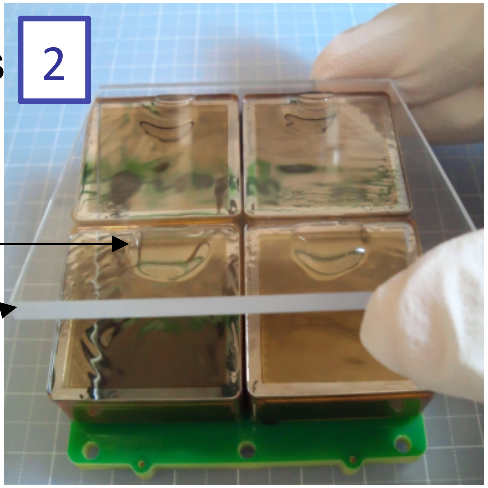
PMT Module Assembly

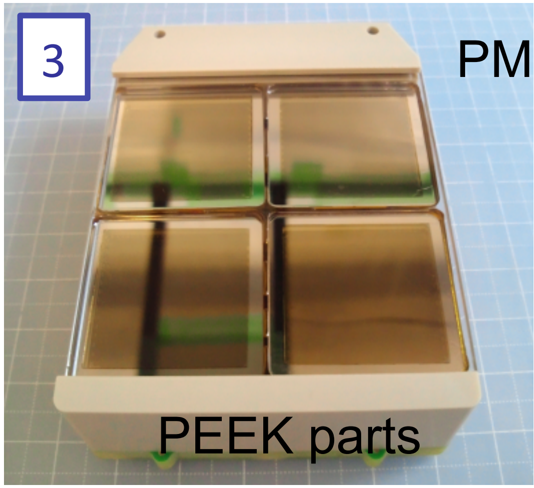


Vacuum chuck to align the PMT faces

RTV silicon rubber to hold the PMTs

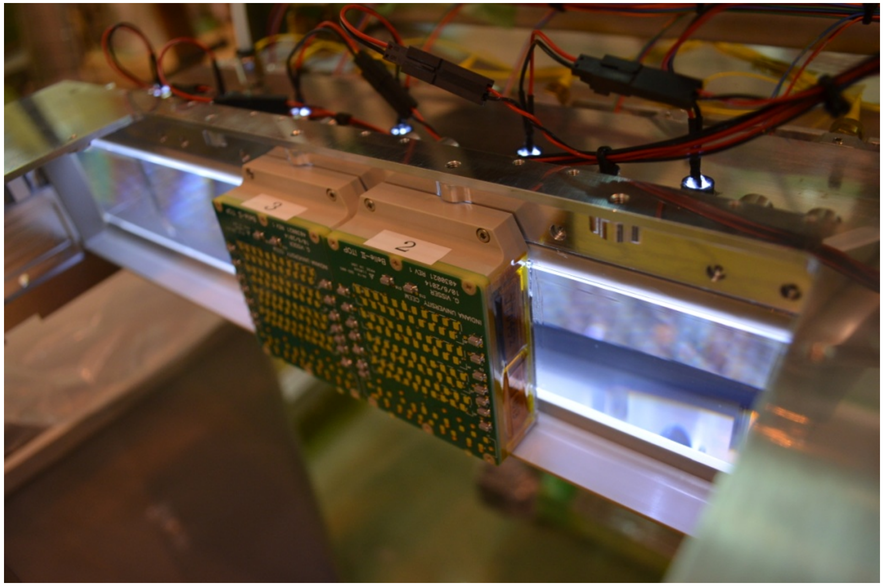
Silicon rubber TSE3032 (before curing) to be filled between the PMTs and the wavelength cut filter





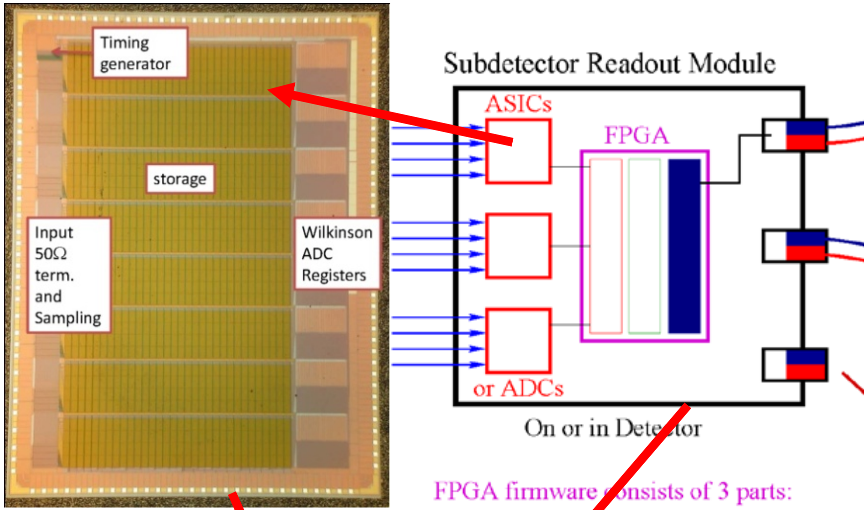
PMT module completed

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

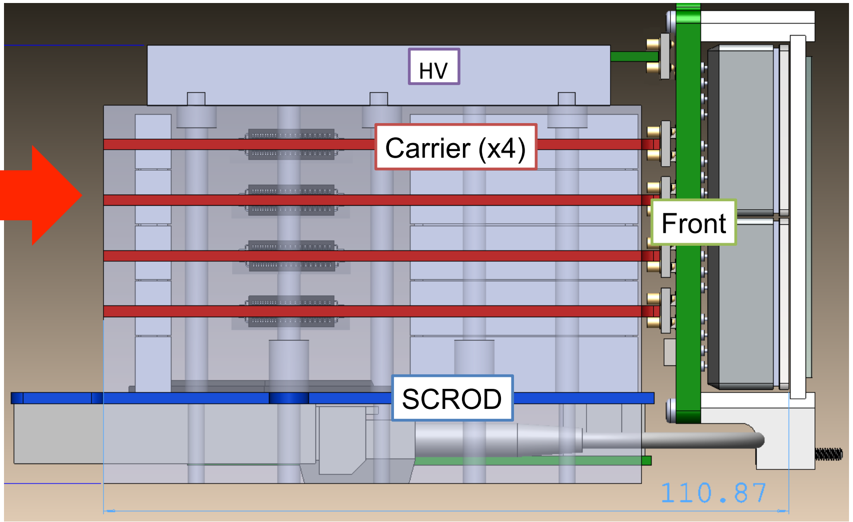


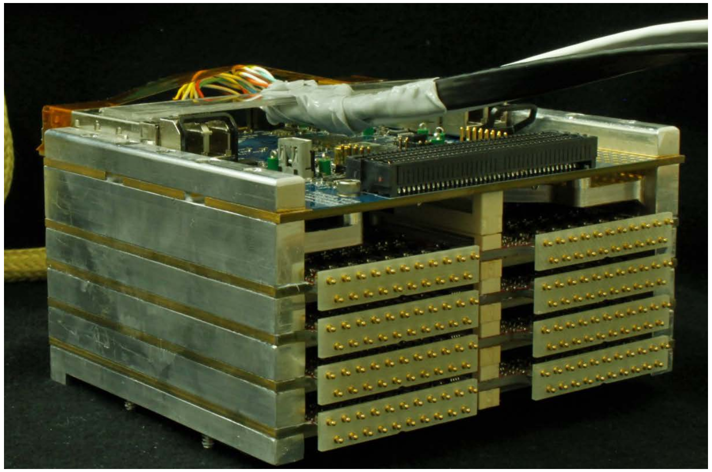
Front-end electronics

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

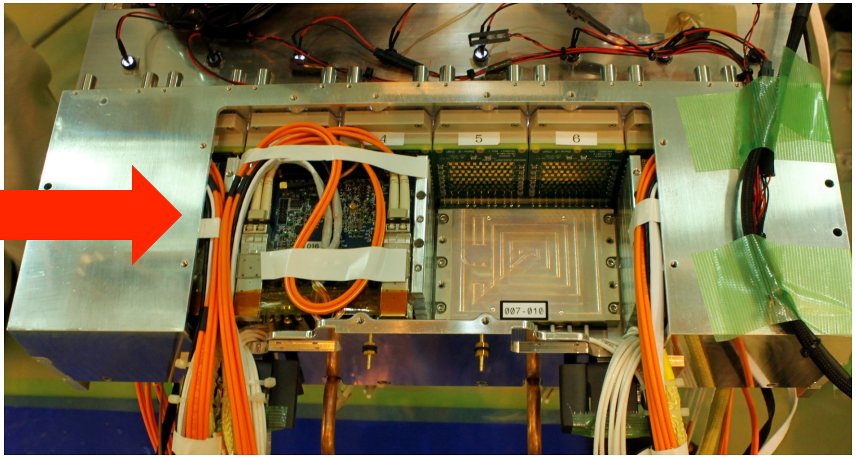


ASICs are mounted in "Carrier boards," and 8 Carriers + controller/HV/connector boards = 1 boardstack:



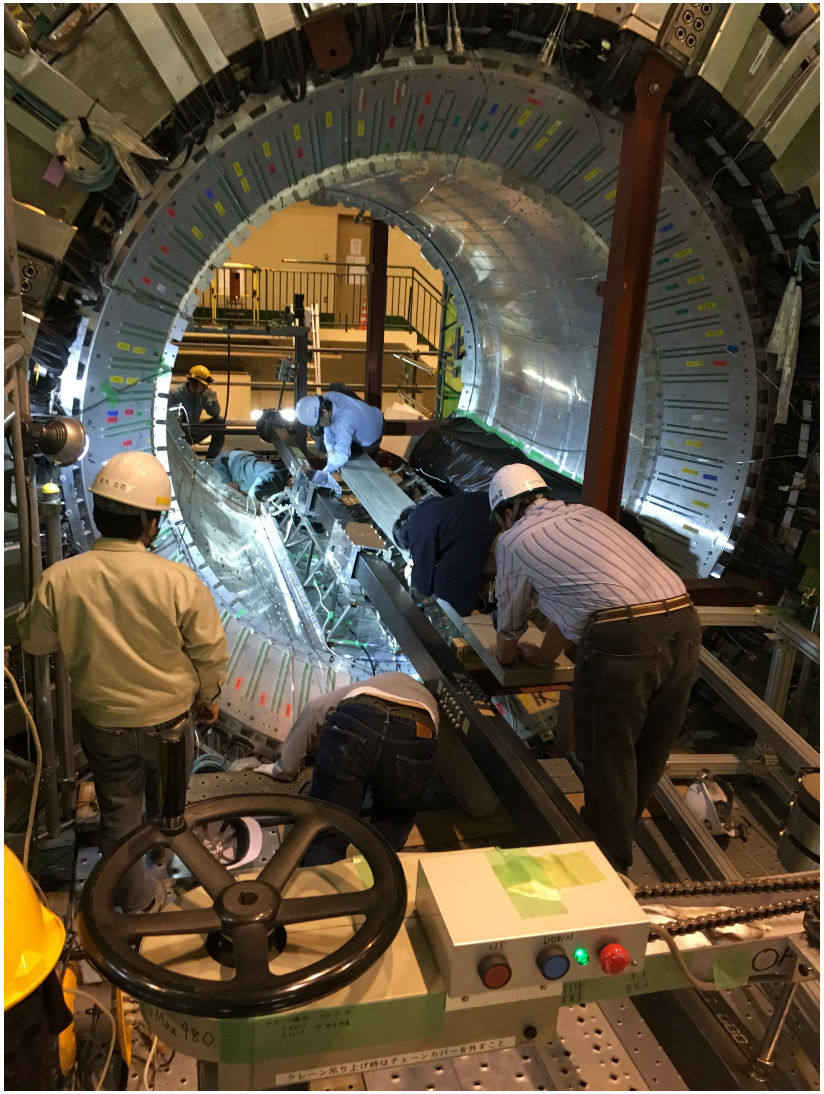


4 boardstacks per module:

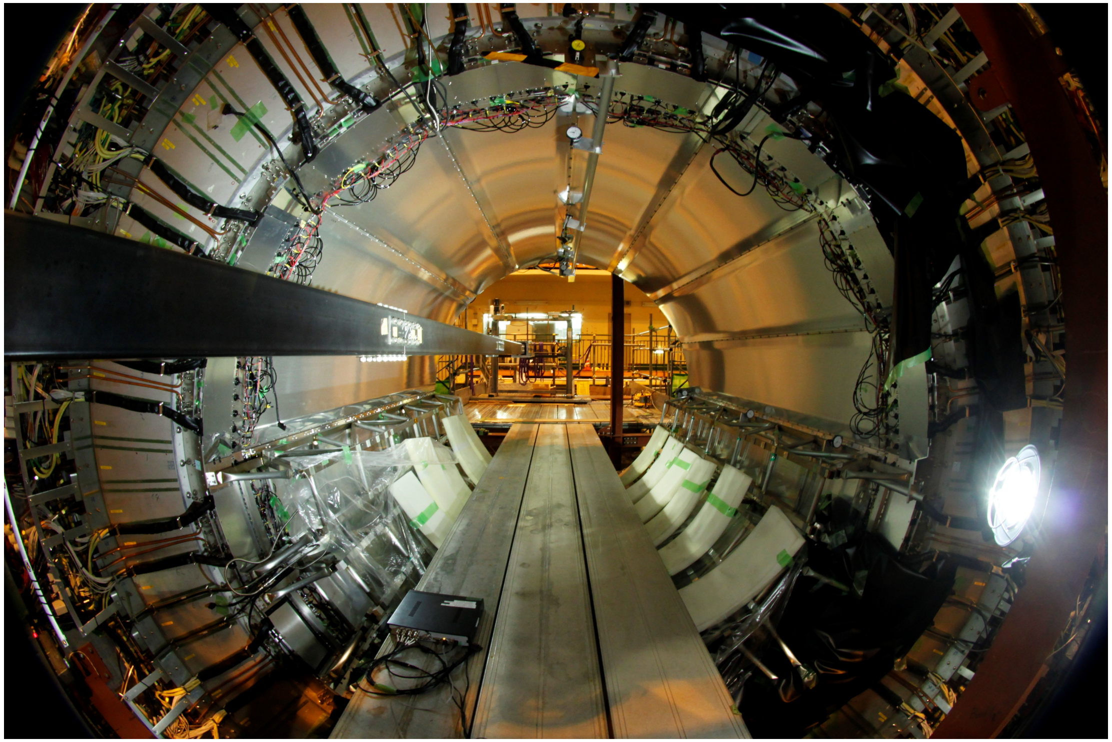


Installing Modules in the Magnet

Installing one of 16 modules into "Roman arch" configuration:



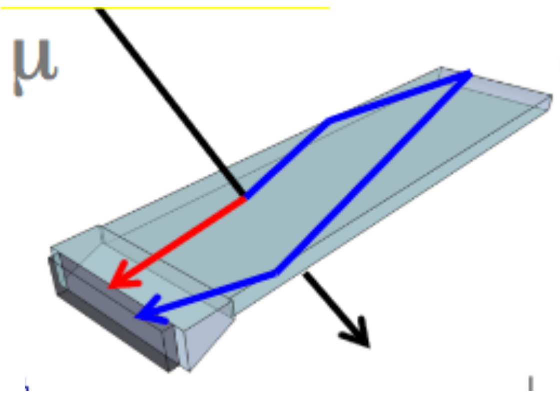
All 16 modules installed:

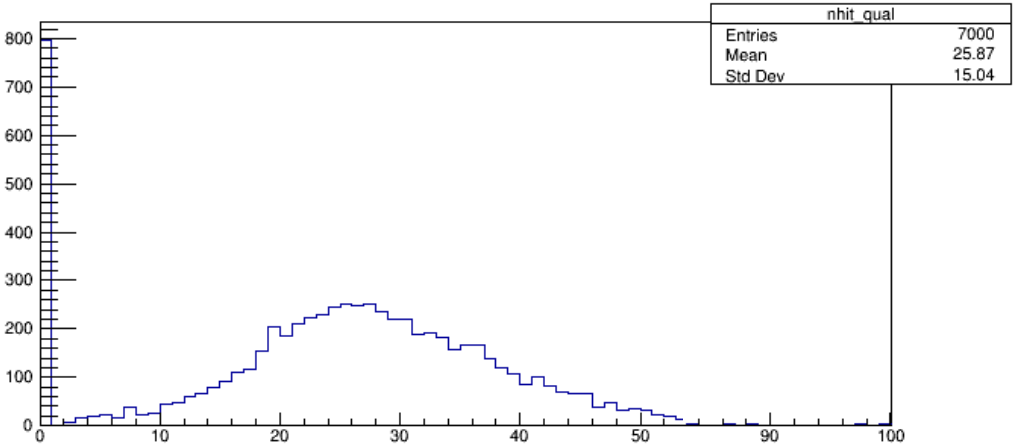


First commissioning results (data)

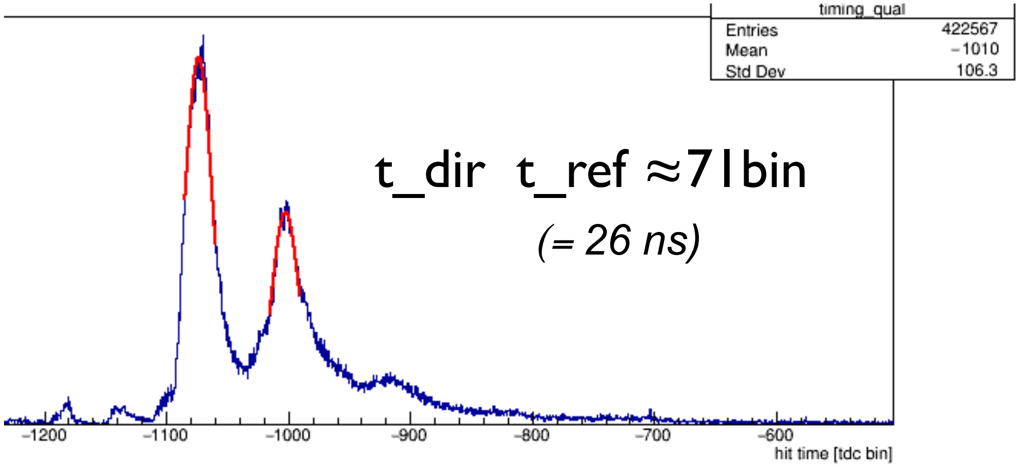
Test modules with cosmic rays, using simple scintillator paddle trigger:

(no tracking yet available, but will be very soon)





number of photon hits



t_dir t_ref ≈71bin

(= 26 ns)

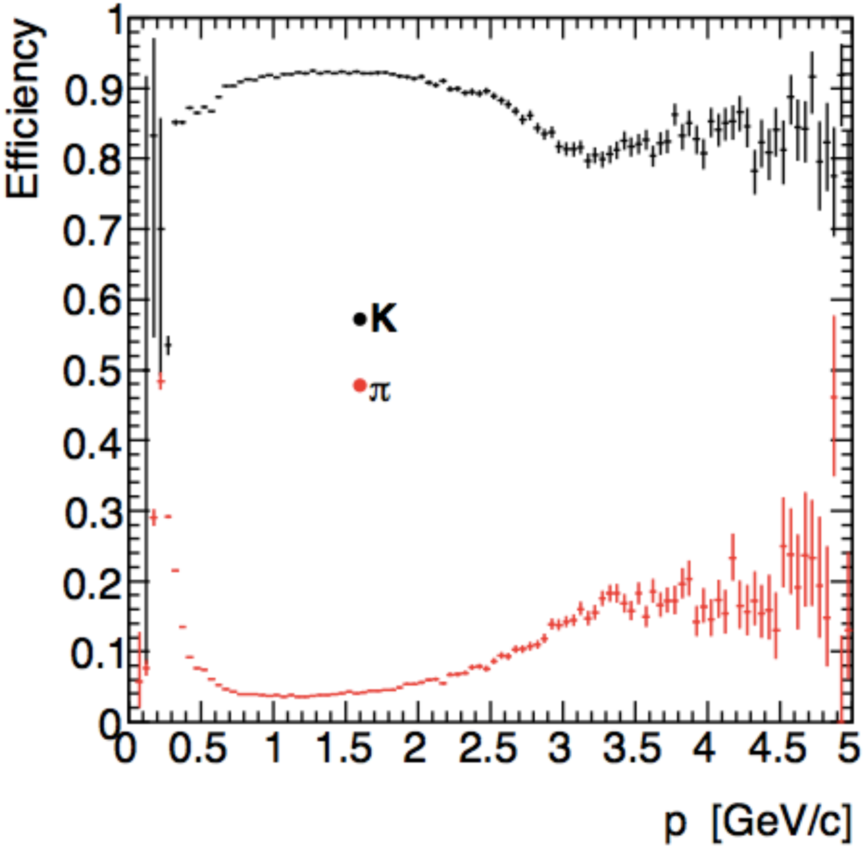
photon hit time

Both distributions are in reasonable agreement with MC simulations; other slots look similar

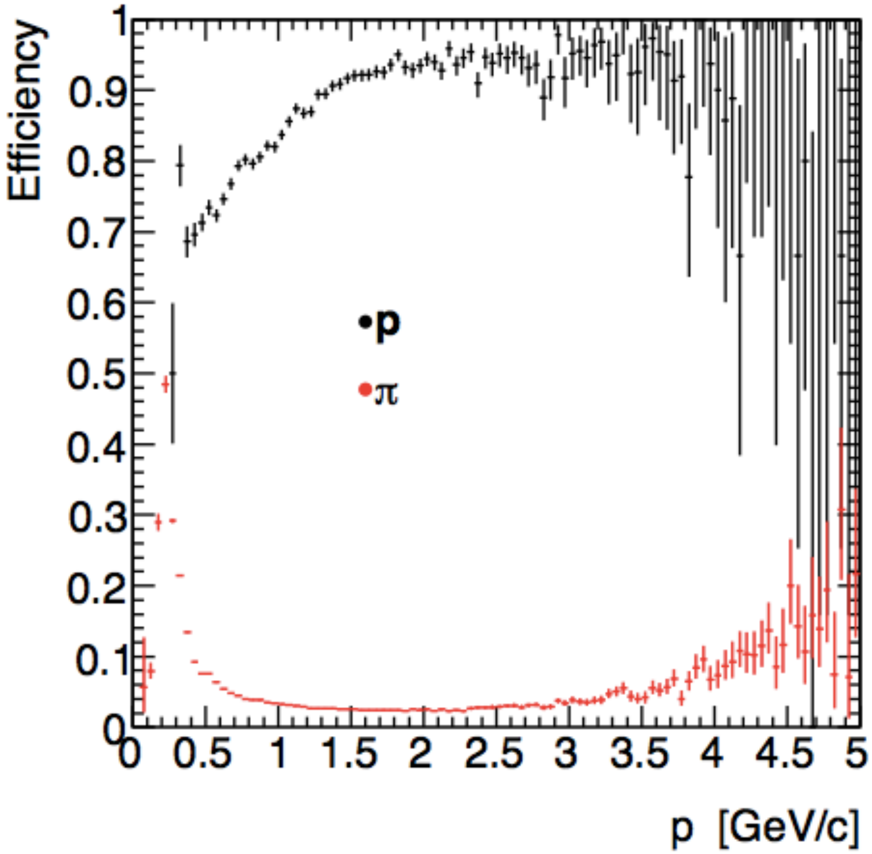
Expected Performance I

Monte Carlo simulation: $e^+e^- \to c\bar{c}$ (generic):

$\mathcal{L}(K/\pi) > 0.50$



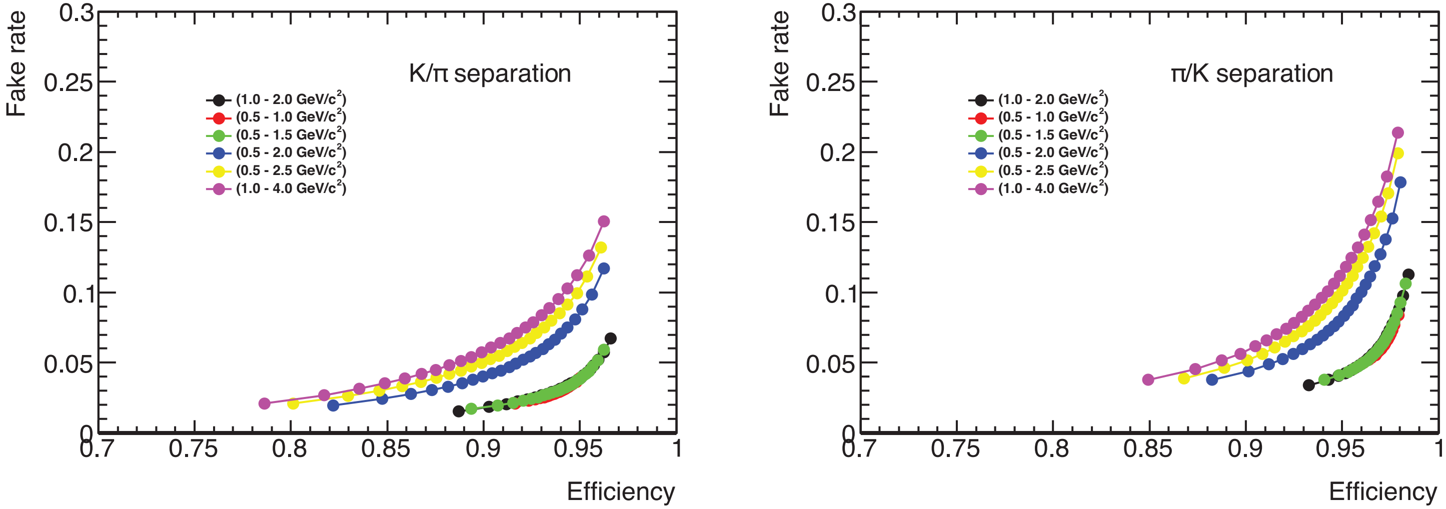
$\mathcal{L}(p/\pi) > 0.50$



Expected Performance II

Monte Carlo simulation: $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$:

MC5 sample



Cut	Efficiency (BGx1)	Fake Rate (BGx1)
K_PIDk > 0.001	98.2%	26.9%
K_PIDk > 0.110	95%	10.9%
K_PIDk > 0.552	90%	5.5%
K_PIDk > 0.835	85%	3.4%
pi_PIDpi > 0.003	99%	34.7%
pi_PIDpi > 0.344	95%	12.1%
pi_PIDpi > 0.827	90%	6.2%
pi_PIDpi > 0.959	85%	4.0%

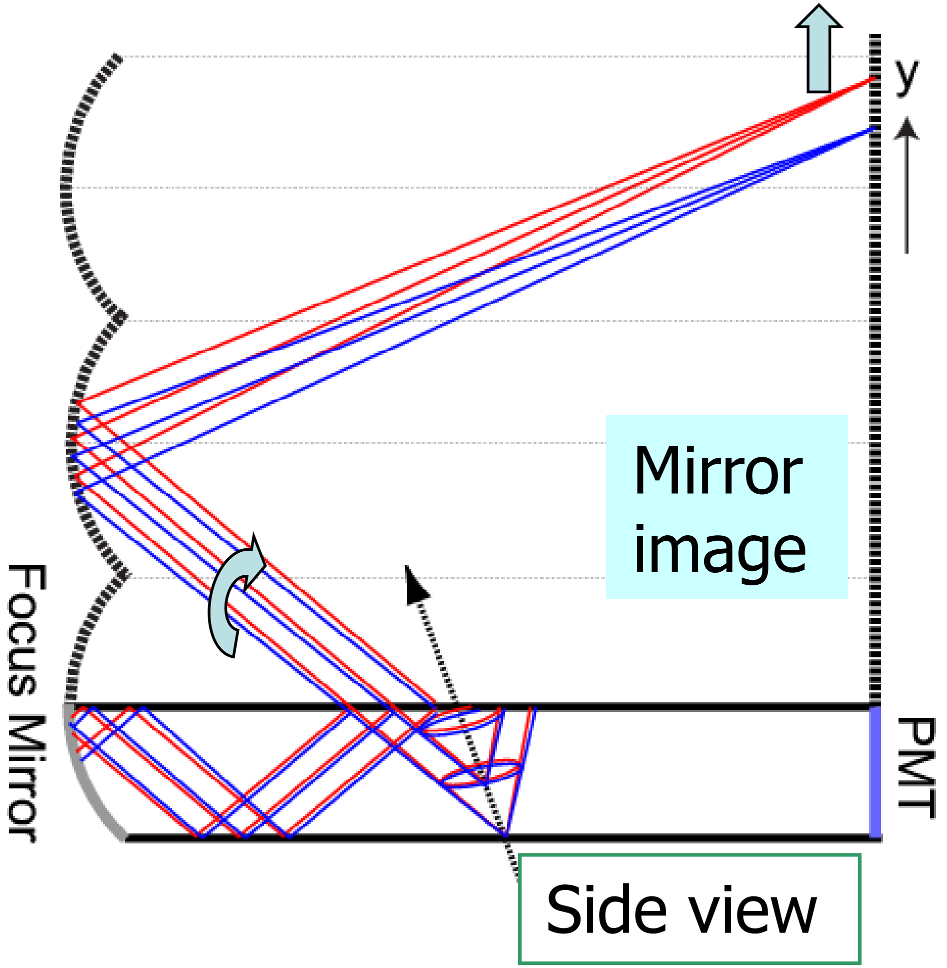
Summary

- *A new type of particle identification detector has been built: a Time-of-Propagation counter with imaging. The construction took approximately 18 months.*
- *The detector is now fully installed in the Belle II solenoid. Electronics are cabled, and detector is being commissioned with cosmic rays.*
- *We are uncovering issues with interfacing to the data acquisition system, and issues with firmware running in the front-end readout boards. These are being debugged.*
- *We expect performance similar to or better than that achieved in Belle, but at much higher luminosity and background rates.*
- *The Belle II experiment is scheduled to take first commissioning data in 2017, and first real data in 2018. All detector systems are (more-or-less) on schedule.*

Extra

Extra Slides

Principle of Focusing Mirror



Mirror does two tasks:

- *parallel rays get focused to a single point*
  ⇒ *removes bar thickness*
- *non-parallel rays are focused to different points*
  ⇒ *possibly allows to make a correction for chromatic dispersion.*

Limiting issue: chromatic dispersion

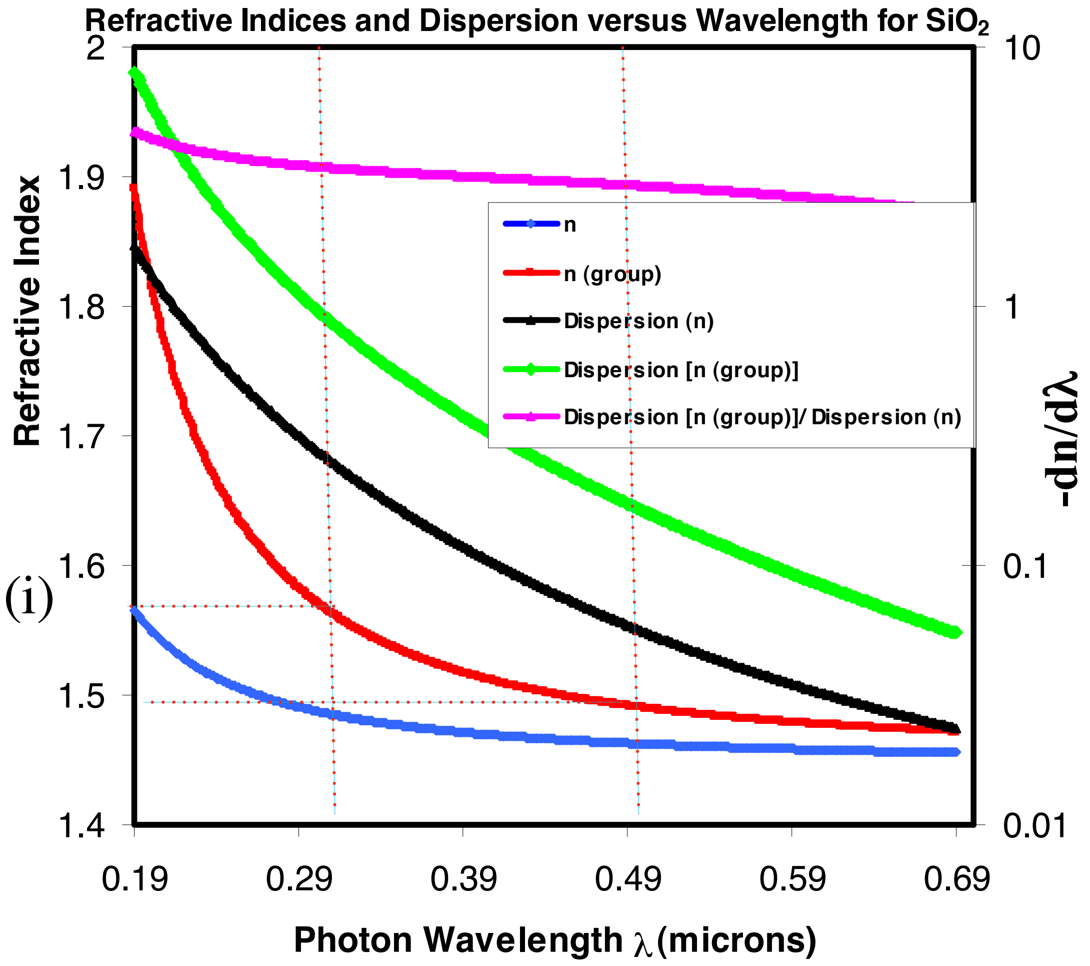
$$v = \frac{c}{n} \left\} \begin{array}{l} \text{phase velocity : n} = \sqrt{\dfrac{\epsilon\mu}{\epsilon_0\mu_0}} \\ \text{group velocity : n}_\text{g} > \text{n} \end{array} \right.$$

$$n_g(\lambda) = n(\lambda) - \lambda\left(\frac{dn}{d\lambda}\right)$$

From λ = 300-500 nm:

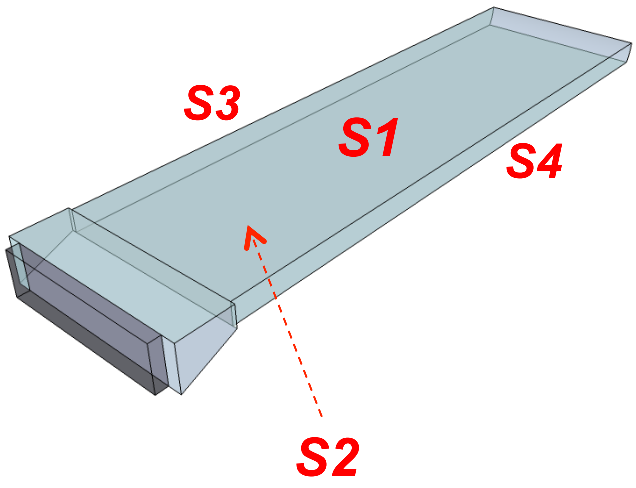
- *n_g ranges from1.50-1.56; a 4% effect = 4x larger than the 1% difference of π/K Δt*
- *n ranges from1.46-1.49 (Corning 7980 data sheet)*

⇒ *ultimate limit to performance of this type of detector (a long TOP counter)*



Fabricating quartz bars: metrology report

Final metrology report:

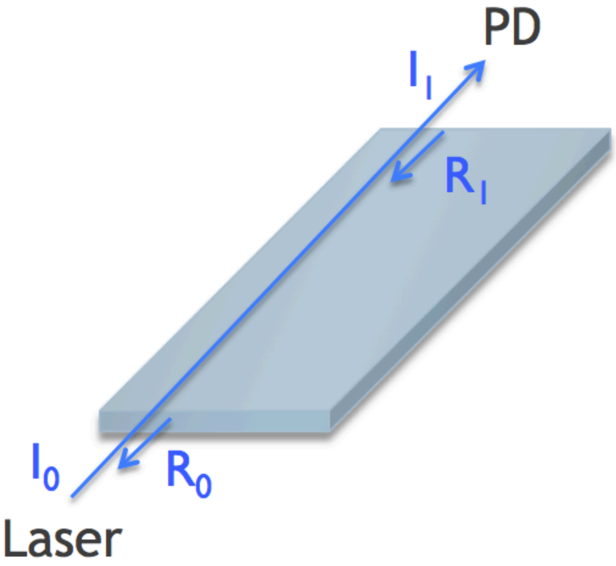


Tolerance	Specification	Measurement	Pass	Fail
S1 Datum A Flatness	≤ 6.3µm	5.31	x	
S1 Local Flatness over 200mm Area	≤ 1.8µm	Max 0.564	x	
S2 Flatness	≤ 6.3µm	4.6	x	
S2 Local Flatness over 200mm Area	≤ 1.8µm	Max 1.01	x	
S3 Datum B Flatness	≤ 6.3µm	0.48	x	
S4 Flatness	≤ 6.3µm	0.47	x	
S5 Datum C Flatness	≤ 25µm	2.47	x	
S6 Flatness	≤ 25µm	2.753	x	
S1 Parallel S2	≤ 4 arcsec	1.2	x	
S1 Perpendicular S3	≤ 20 arcsec	4.0	x	
S1 Perpendicular S4	≤ 20 arcsec	5.0	x	
S1 Perpendicular S5	≤ 1 arcmin	0.083	x	
S1 Perpendicular S6	≤ 1 arcmin	0.083	x	
S3 Parallel S4	≤ 60µm (10 arcsec)	4.8 arcsec	x	
S3 Perpendicular S5	≤ 20 arcsec	8.0	x	
S3 Perpendicular S6	≤ 20 arcsec	6.0	x	
S5 Parallel S6	≤ 20 arcsec	10.0	x	
Surface Roughness S1	≤ 5 Å rms	4.1	x	
Surface Roughness S2	≤ 5 Å rms	4.4	x	
Surface Roughness S3	≤ 5 Å rms	4.2	x	
Surface Roughness S4	≤ 5 Å rms	3.65	x	
Surface Roughness S5	≤ 25 Å rms	9.52	x	
Surface Roughness S6	≤ 25 Å rms	9.05	x	
Length	1250 ±0.50mm	1250.3	x	
Width	450 ±0.15	450.10	x	
Thickness	20 ±0.10	20.055	x	

Testing Bars (transmission, internal reflection)

Step a:

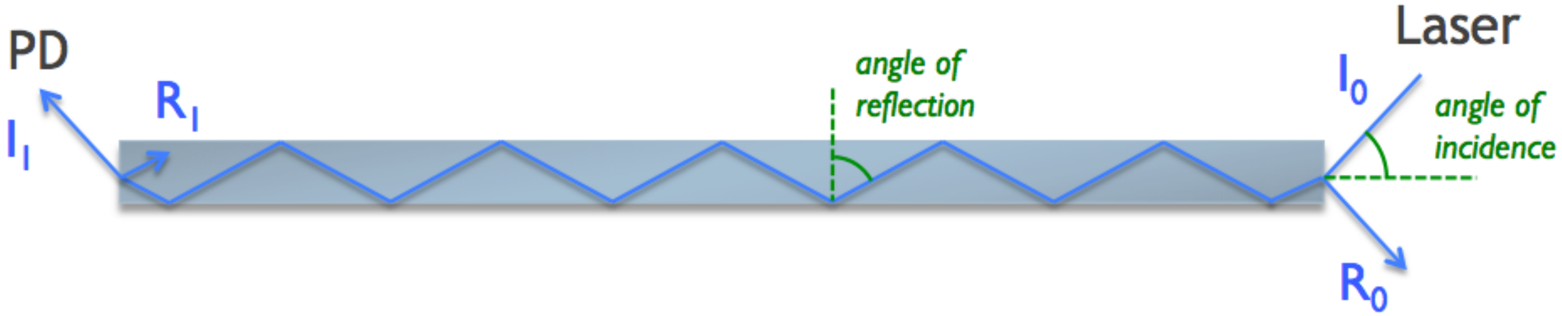
Measurement of bulk transmission of bars and coefficient of total internal reflection. (R_0, R_1 calculated via Fresnel equations)



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

Step b:

Measurement of coefficient of total internal reflection of bars [SLAC-PUB-9735 (2003)]



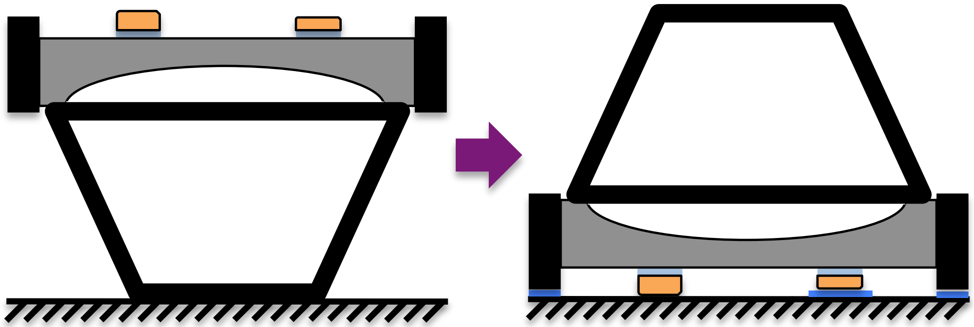
$$(I_1 - R_1) \;=\; (I_0 - R_0)\cdot\alpha^N\cdot\exp\left(-\frac{L}{\Lambda}\cdot\sqrt{1+(Nh/L)^2}\right)$$

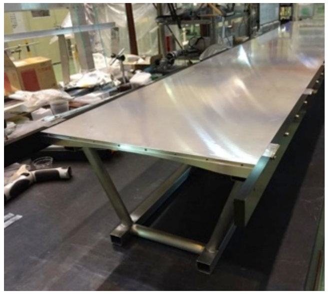
N is the number of reflections inside bar, Λ is the attenuation length of quartz (>1000m @ λ=530 nm), L is bar length (125 cm), h is bar height (2.0 cm). R_0 and R_1 are measured or calc. via Fresnel eqs.

Gluing buttons to honeycomb panels

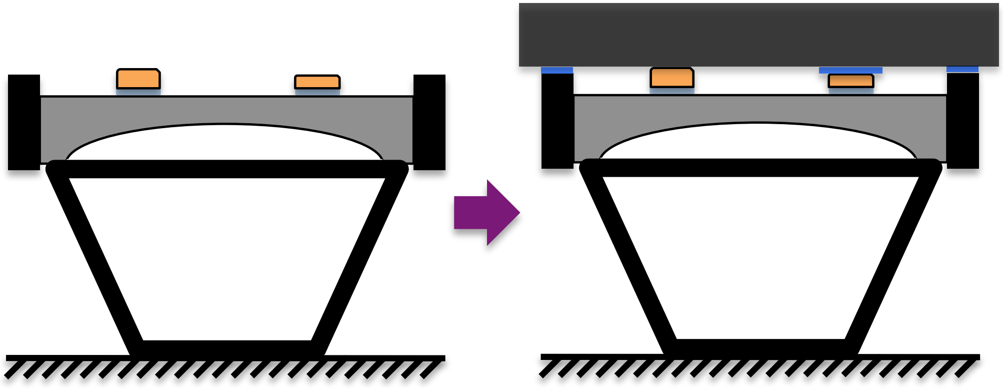
Button heights must match quartz profile:

Module 01-02

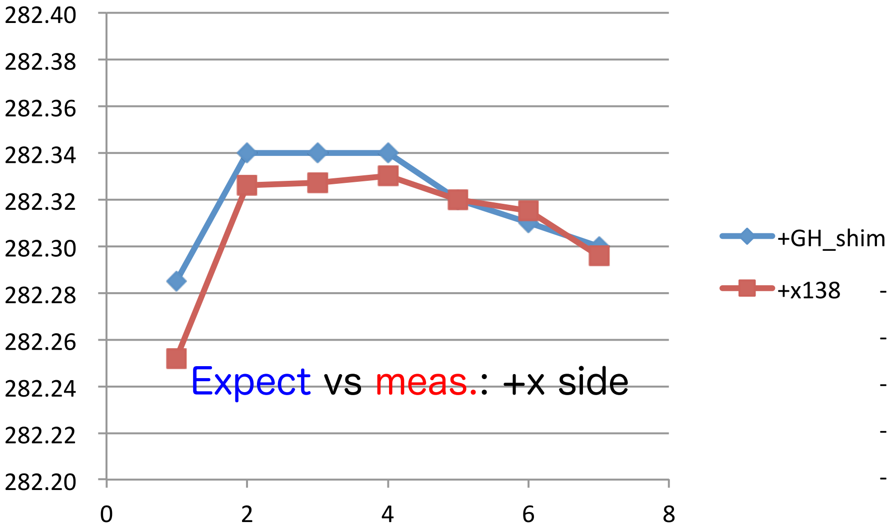


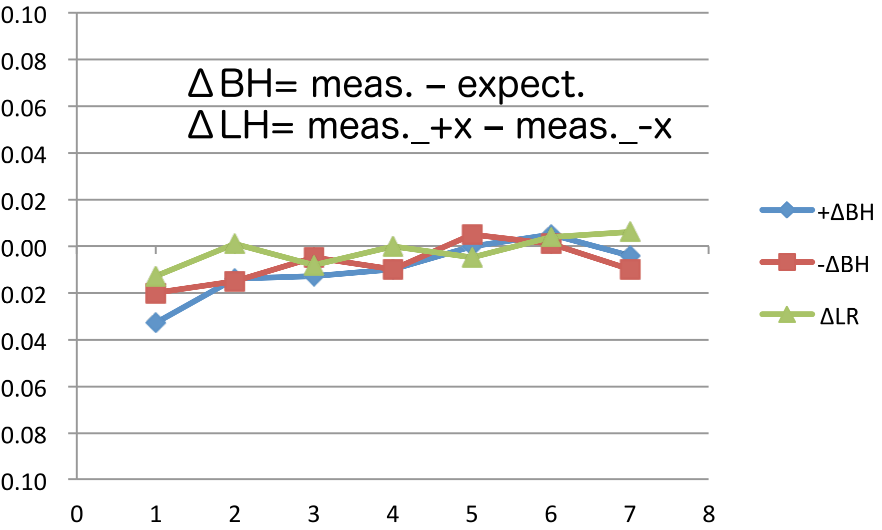


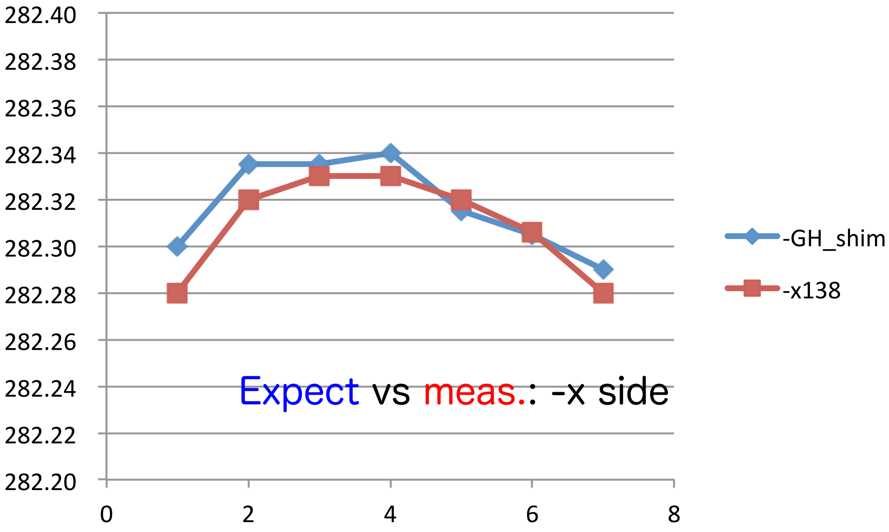
Module 03-

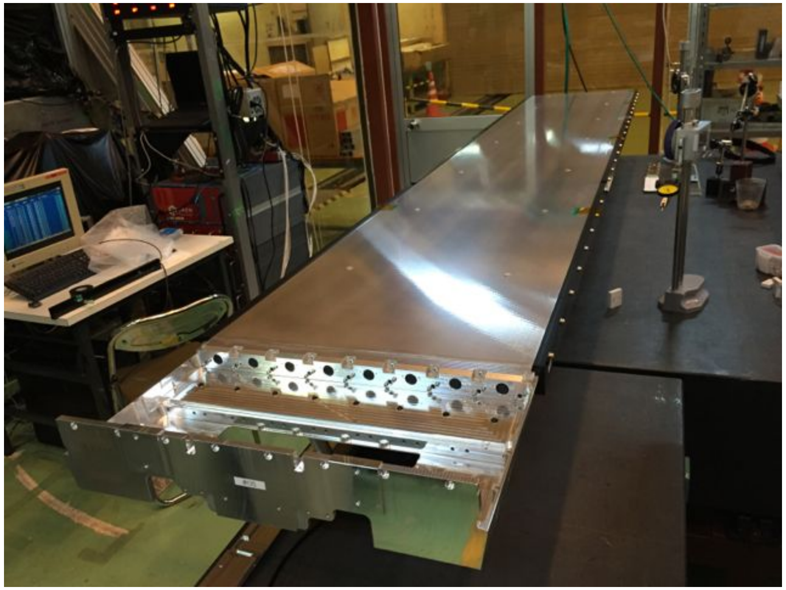


Measuring button heights (must match quartz profile)



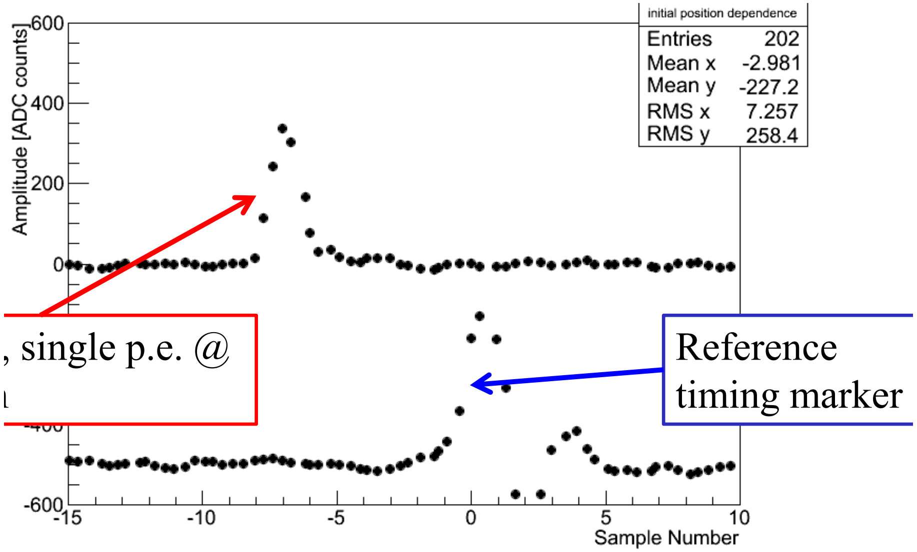






Front-end electronics: testing boardstacks

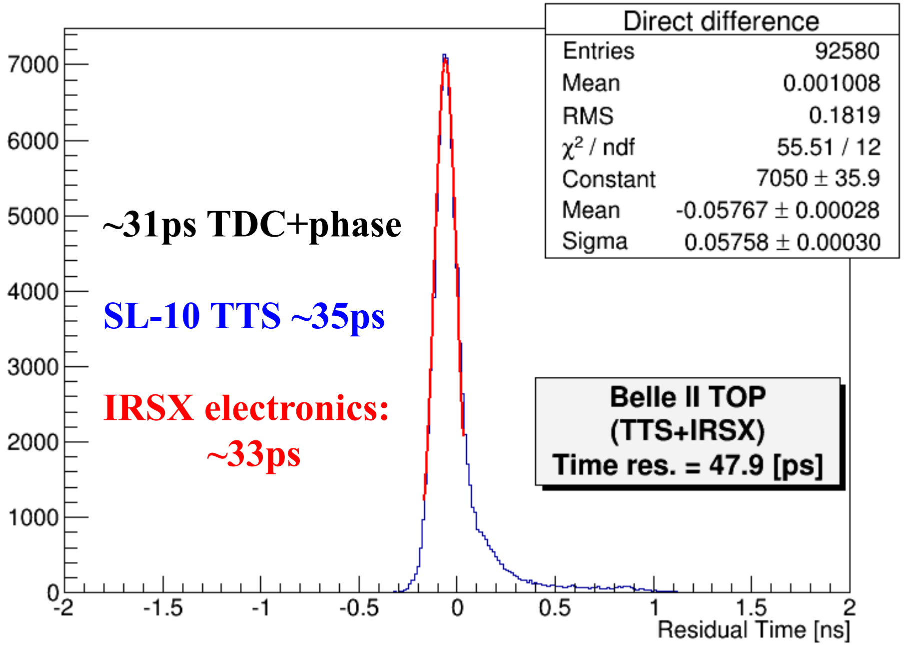
Test PMT channels with laser, record single photon hit times, calculate time difference w/r/t reference pulse, plot residuals w/r/t known time difference:



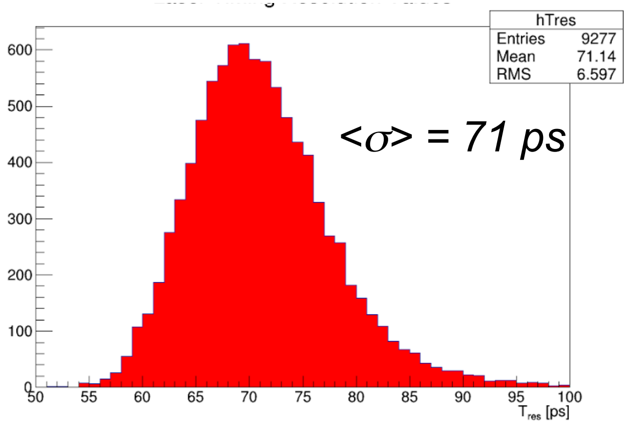
, single p.e. @

Reference timing marker

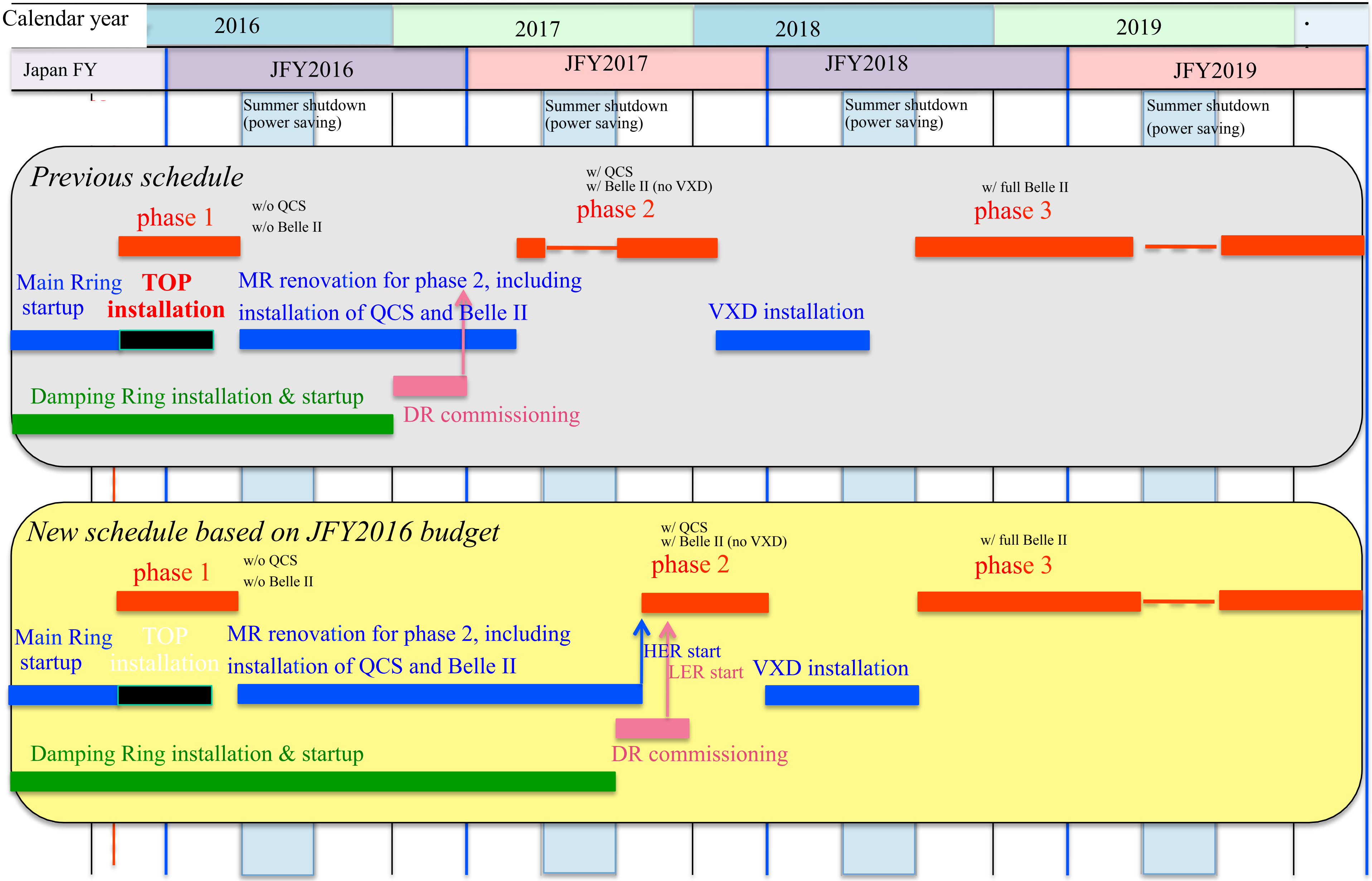
Residuals (typical):



Testing all boards, excellent yield:



Super-KEKB and Detector schedule



Calendar year: 2016, 2017, 2018, 2019

Japan FY: JFY2016, JFY2017, JFY2018, JFY2019

Summer shutdown (power saving)

Previous schedule

phase 1 — w/o QCS, w/o Belle II

phase 2 — w/ QCS, w/ Belle II (no VXD)

phase 3 — w/ full Belle II

Main Rring startup

TOP installation

MR renovation for phase 2, including installation of QCS and Belle II

VXD installation

Damping Ring installation & startup

DR commissioning

New schedule based on JFY2016 budget

phase 1 — w/o QCS, w/o Belle II

phase 2 — w/ QCS, w/ Belle II (no VXD)

phase 3 — w/ full Belle II

Main Ring startup

TOP installation

MR renovation for phase 2, including installation of QCS and Belle II

HER start

LER start

VXD installation

Damping Ring installation & startup

DR commissioning