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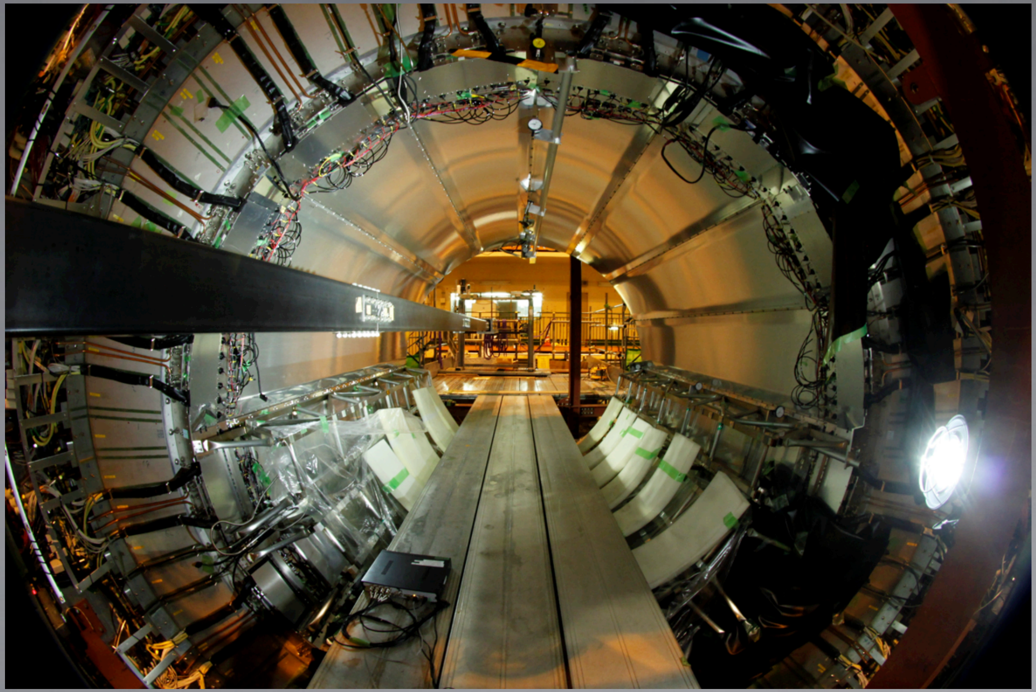
The Belle II imaging Time-of-Propagation (iTOP) Detector



James Fast
Pacific Northwest National Laboratory

RICH 2016, 5-9 September 2016
Bled, Slovenia

Outline

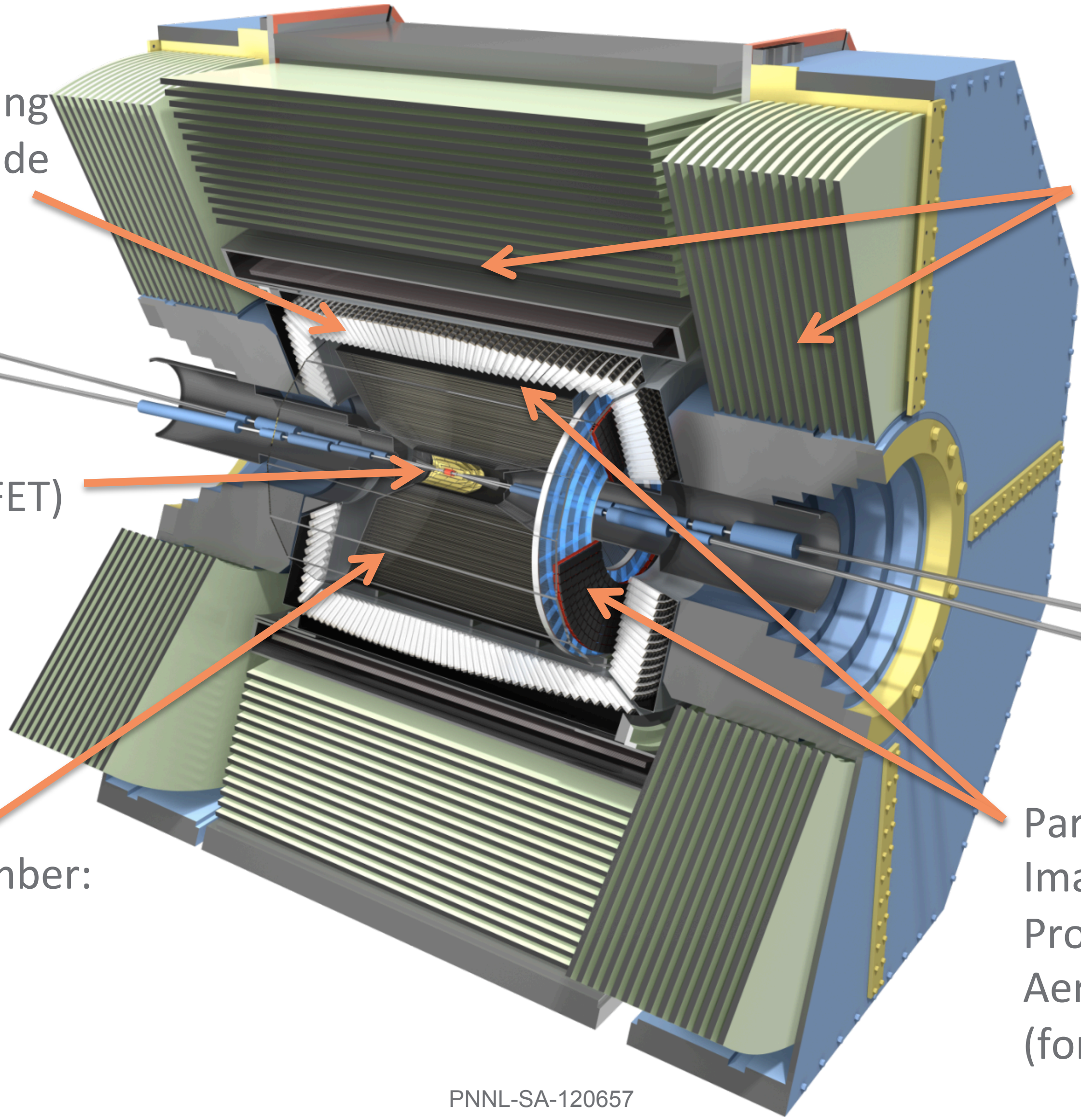
- Belle II Upgrade
- iTOP operating principle
- Optics (focus on this element in this presentation)
- Photodetectors (covered in detail by Matsuoka-san Tuesday)
- Frontend readout electronics (element of talk by Gary Varner Friday)
- Assembly and installation (covered in detail by Suzuki-san Friday)
- Some preliminary cosmic ray results

- Also at RICH 2016:
- Alignment (Marko Staric Tuesday)
- Calibration (Umberto Tamponi – poster session)

Belle II detector overview

EM calorimeter:
waveform sampling
Electronics upgrade

Muon/K_L:
Plastic scintillator
+ Si-PM replacing
RPCs in inner two
barrel layers and
All of end-caps

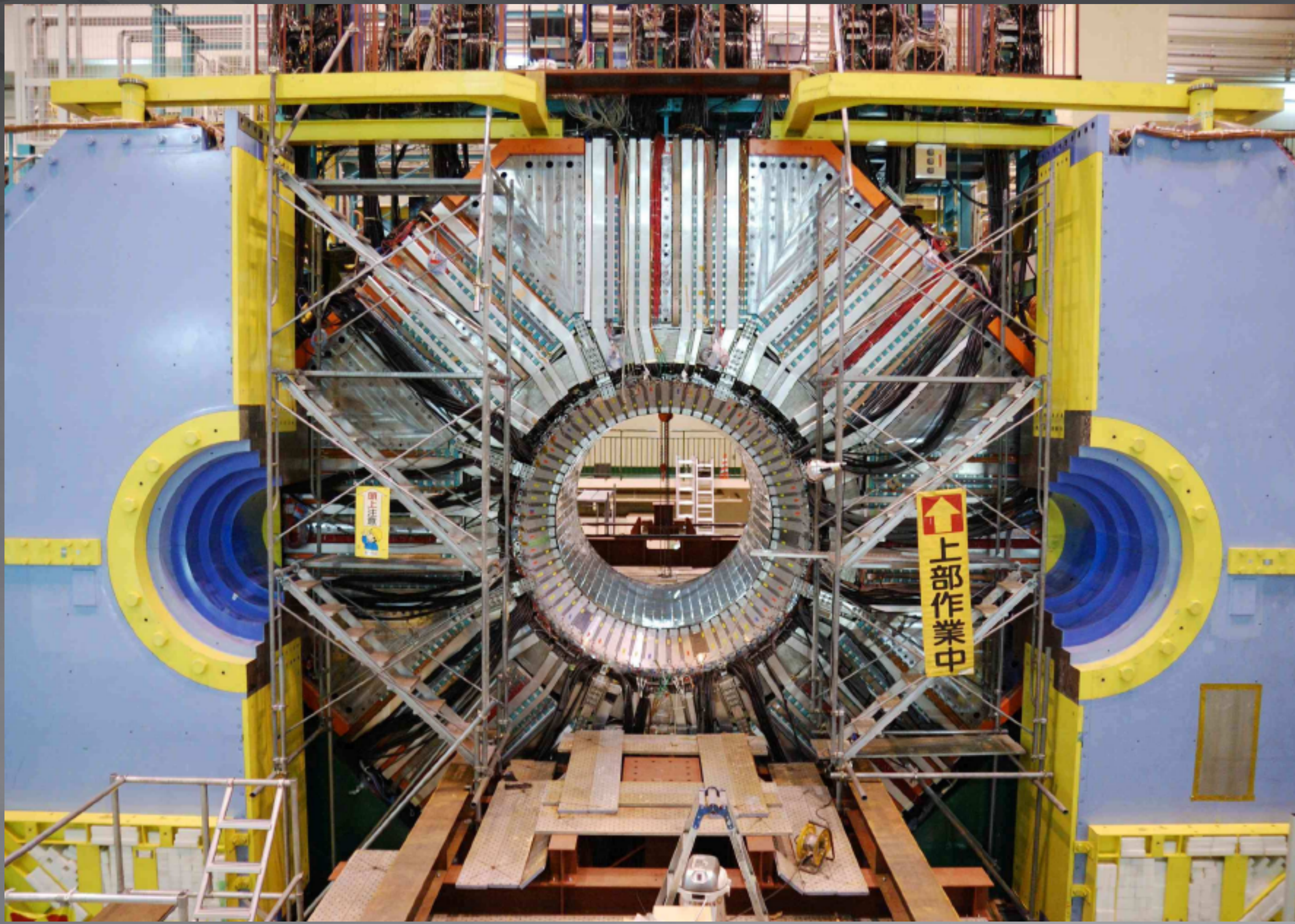


Inner tracking:
2 layers PXD (DEPFET)
4 layers DSSD

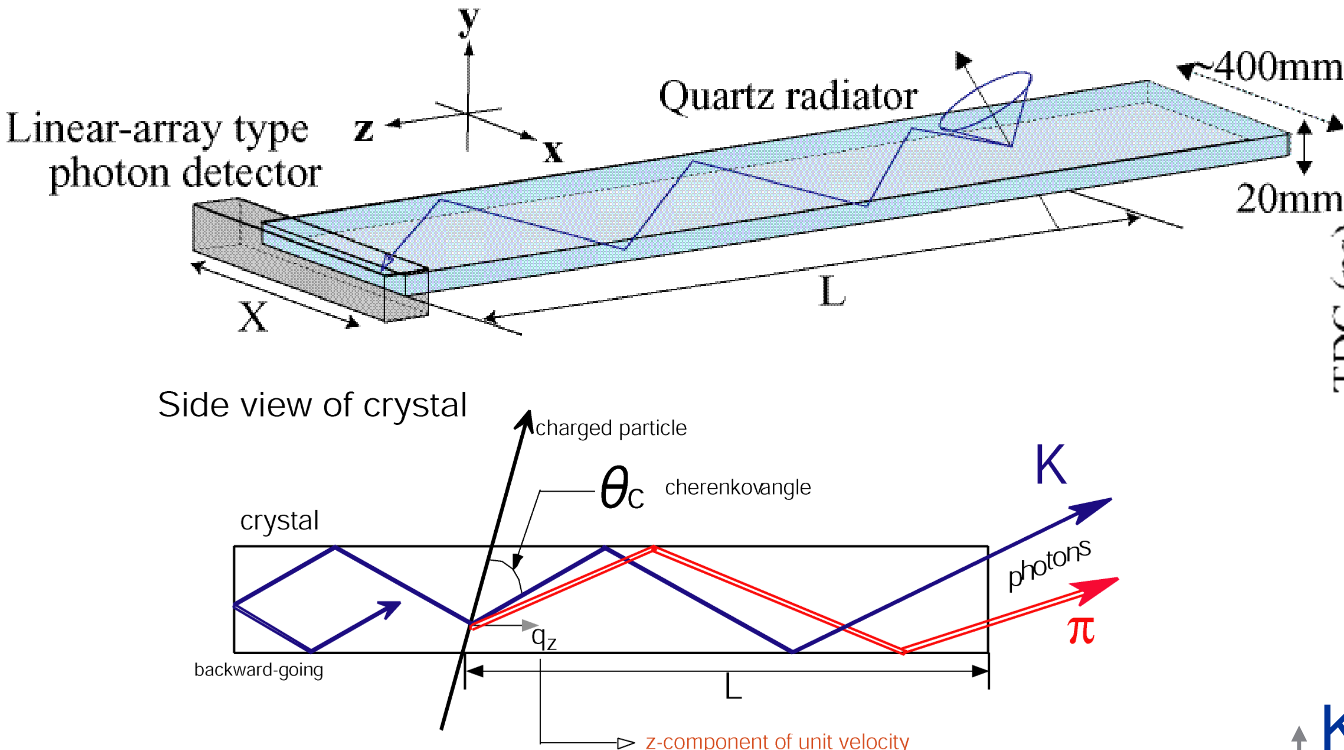
Central Drift Chamber:
smaller cell size
long lever arm

Particle ID:
Imaging Time-of-Propagation (barrel)
Aerogel RICH
(forward)

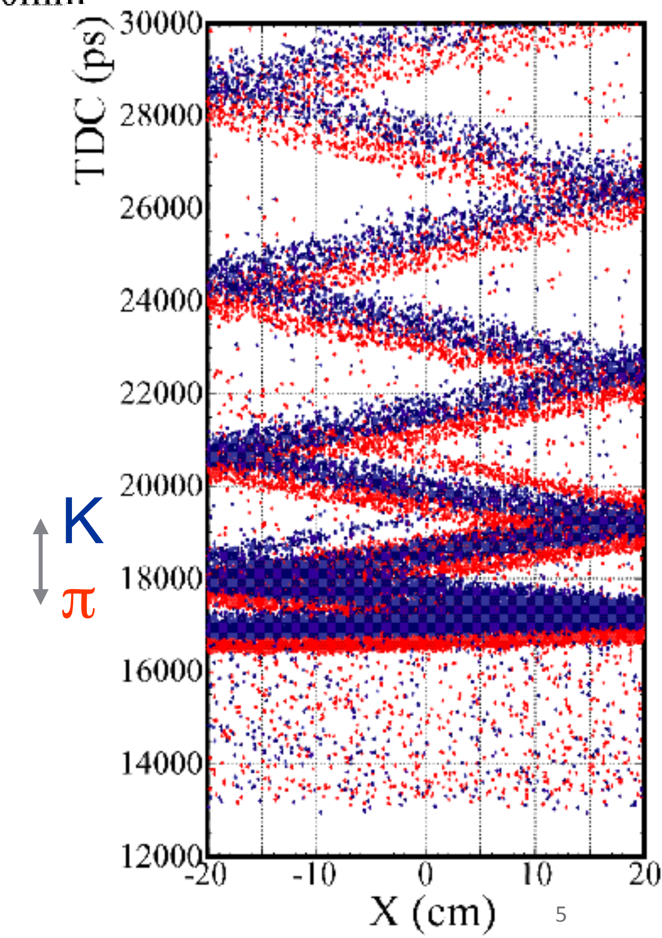
Belle detector in 2011 – ready for upgrade



iTOP counter operating principle



Simulation
2GeV/c, θ=90 deg.



Different opening angles for the same momentum

- Measure x-y position (5 mm) of photons (imaging)
- Measure precise (40 ps) time of arrival of photons (time-of-propagation); TOF from IP works additively

Quartz optics

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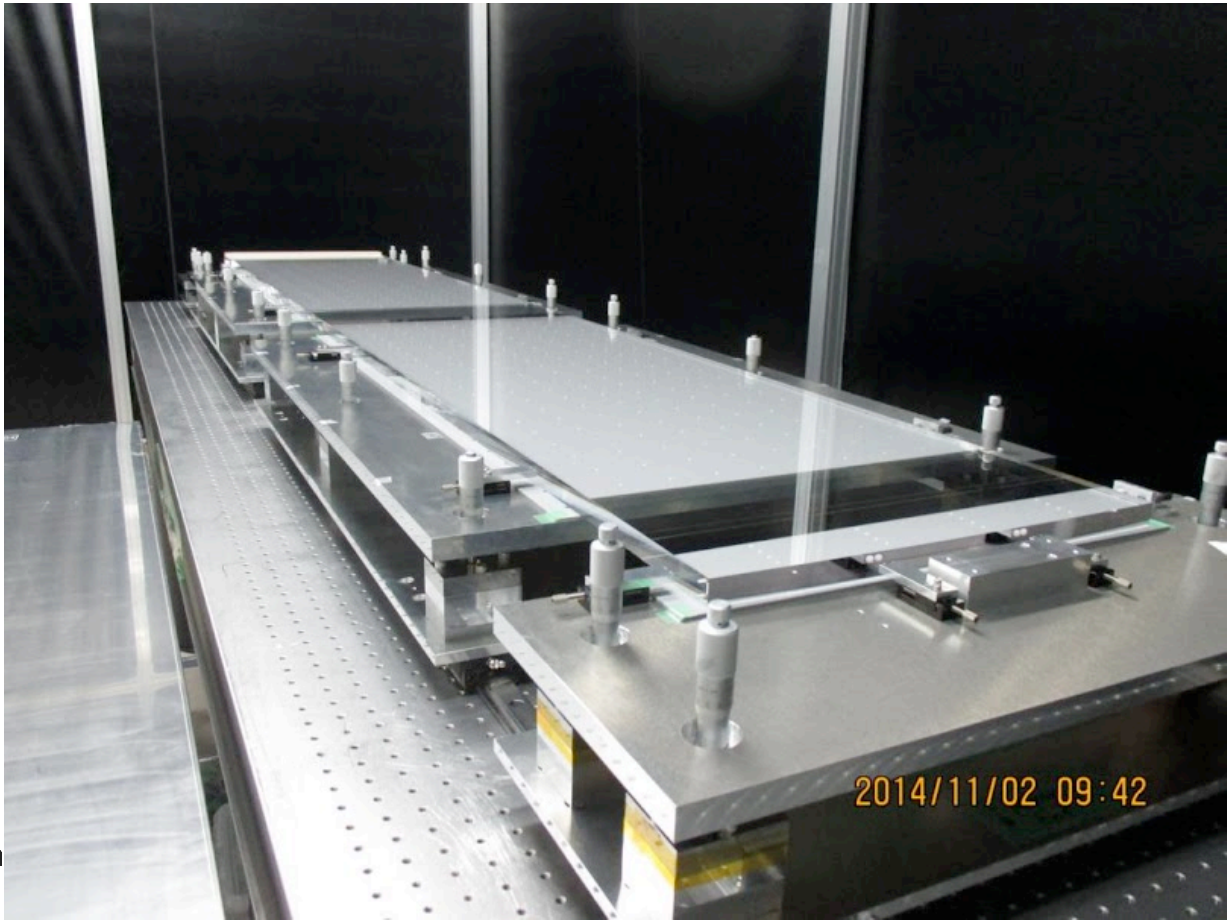
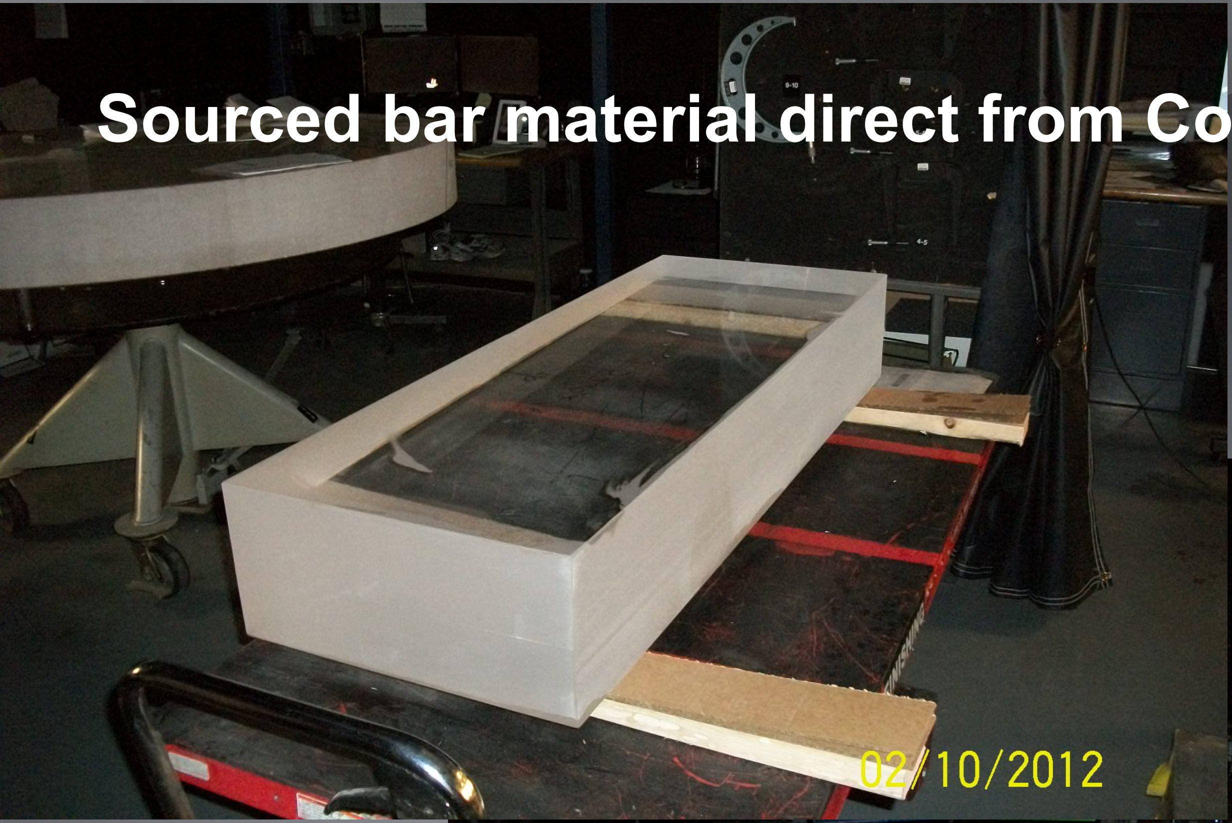
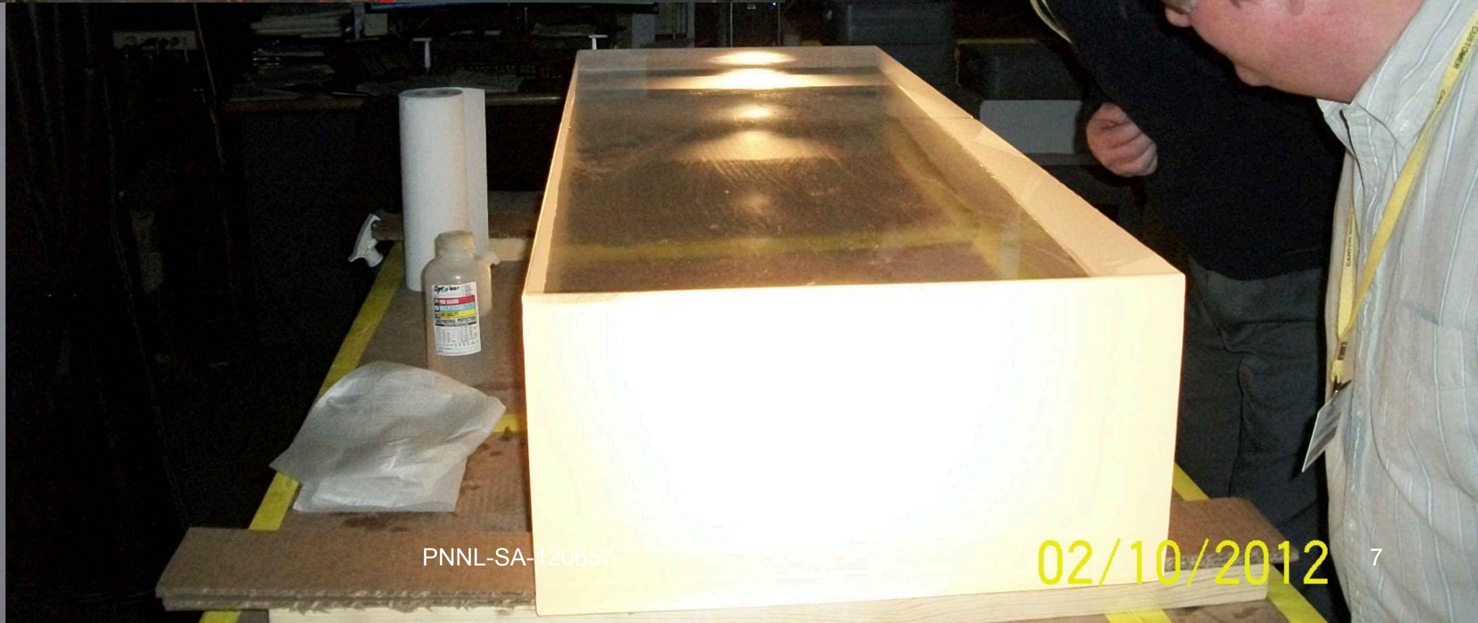
- Bars:
  1250 x 450 x 20 mm^3
  two bars per module
- Mirrors:
  100 x 450 x 20 mm^3
- Prisms:
  100 mm long, 456 x 20 mm^2 at bar face expanding to 456 x 50 cm^2 at MCP-PMTs
- Material: Corning 7980
  - DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
  - Grade F (or superior) material having index homogeneity of ≤5 ppm over the clear aperture of the blank; verified at 632.8 nm
  - Birefringence / Residual strain ≤1 nm/cm



Sourced bar material direct from Corning

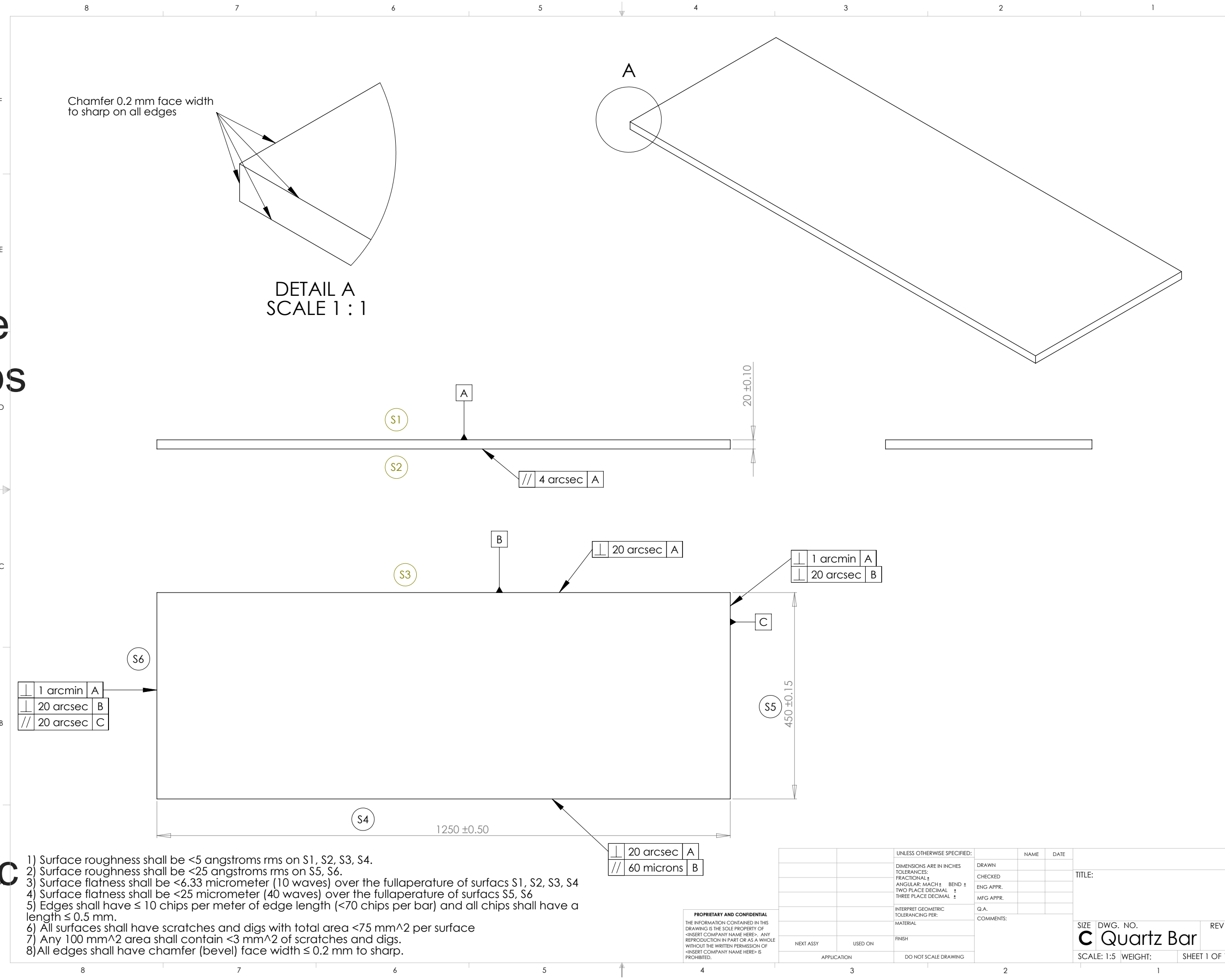


High quality quartz from Corning is a byproduct of the National Ignition Facility optics program

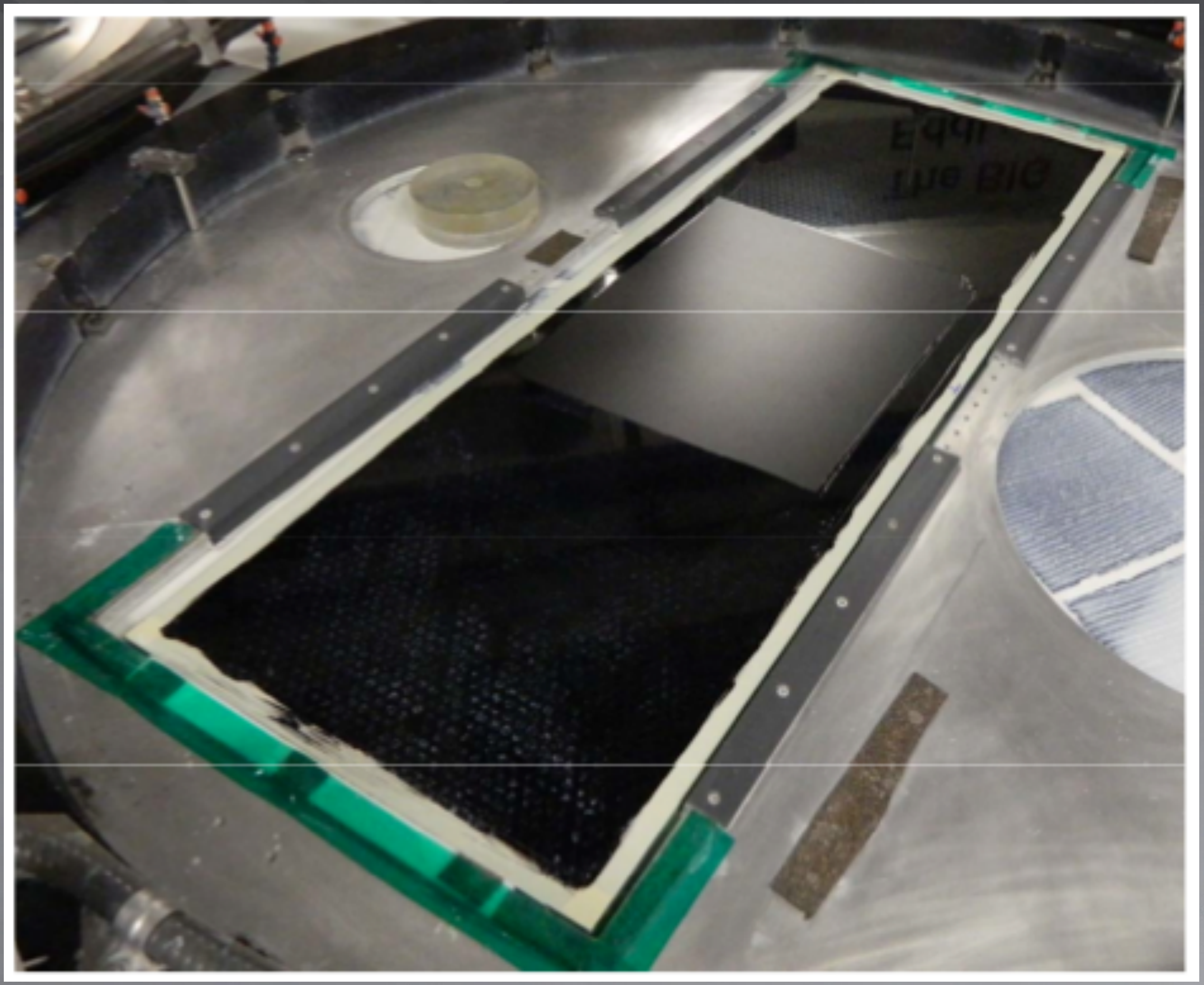


Challenging specification

- All chamfers (bevels) of edges shall have face width ≤ 0.2 mm to sharp.
- Each bar shall have total area of all chips ≤ 25 mm2. Bars should have ≤ 20 chips total on all edges.
- Large surfaces flat to <6.3 microns (10 waves).
- Large surfaces parallel to <4 arcsec (24 micron runout over 1.25 meter)



First bar in process at Zygo



Finished bar in final inspection at Zygo

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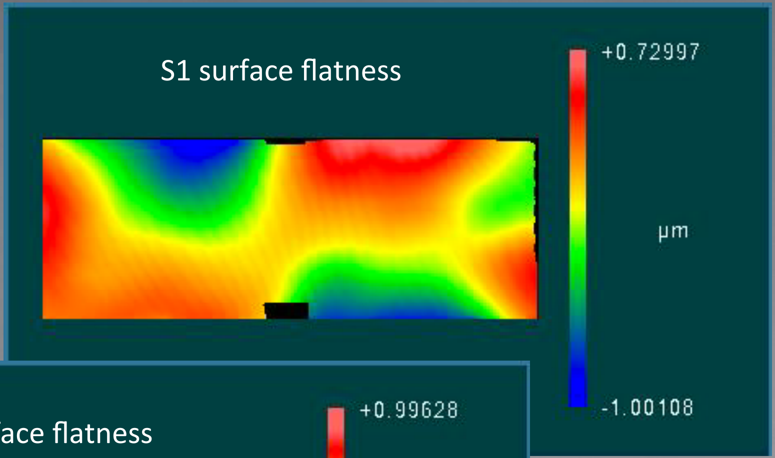
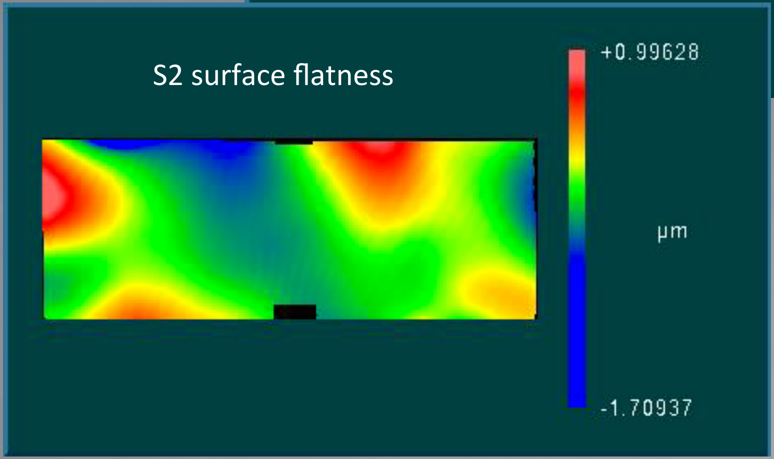
Bar production and quality

- Worked with two vendors
  - Okamoto optics failed to meet schedule and quality
    - dropped after initial preproduction prototypes
  - Zygo completed remaining parts with very high quality “just on time”
    - Proprietary shaping techniques were critical to success

Tolerance	Specification	Measurement	Pass	Fail
S1 Datum A Flatness	≤ 6.3µm	1.731	x	
S1 Local Flatness over 200mm Area	≤ 1.8µm	0.678 Max	x	
S2 Flatness	≤ 6.3µm	2.706	x	
S2 Local Flatness over 200mm Area	≤ 1.8µm	1.462 Max	x	
S3 Datum B Flatness	≤ 6.3µm	2.952	x	
S4 Flatness	≤ 6.3µm	1.472	x	
S5 Datum C Flatness	≤ 25µm	1.425	x	
S6 Flatness	≤ 25µm	2.633	x	
S1 Parallel S2	≤ 4 arcsec	≤ 1.4	x	
S1 Perpendicular S3	≤ 20 arcsec	≤ 5	x	
S1 Perpendicular S4	≤ 20 arcsec	≤ 3	x	
S1 Perpendicular S5	≤ 1 arcmin	≤ 0.083	x	
S1 Perpendicular S6	≤ 1 arcmin	≤ 0.05	x	
S3 Parallel S4	≤ 60µm (10 arcsec)	≤ 7 arc sec	x	
S3 Perpendicular S5	≤ 20 arcsec	≤ 5	x	
S3 Perpendicular S6	≤ 20 arcsec	≤ 5	x	
S5 Parallel S6	≤ 20 arcsec	≤ 10	x	
Surface Roughness S1	≤ 5 Å rms	3.064	x	
Surface Roughness S2	≤ 5 Å rms	3.045	x	
Surface Roughness S3	≤ 5 Å rms	4.035	x	
Surface Roughness S4	≤ 5 Å rms	3.127	x	
Surface Roughness S5	≤ 25 Å rms	13.887	x	
Surface Roughness S6	≤ 25 Å rms	16.991	x	
Length	1250 ±0.50mm	1250.37	x	
Width	450 ±0.15	450.08	x	
Thickness	20 ±0.10	20.09	x	





Bar transmission/reflectivity summary

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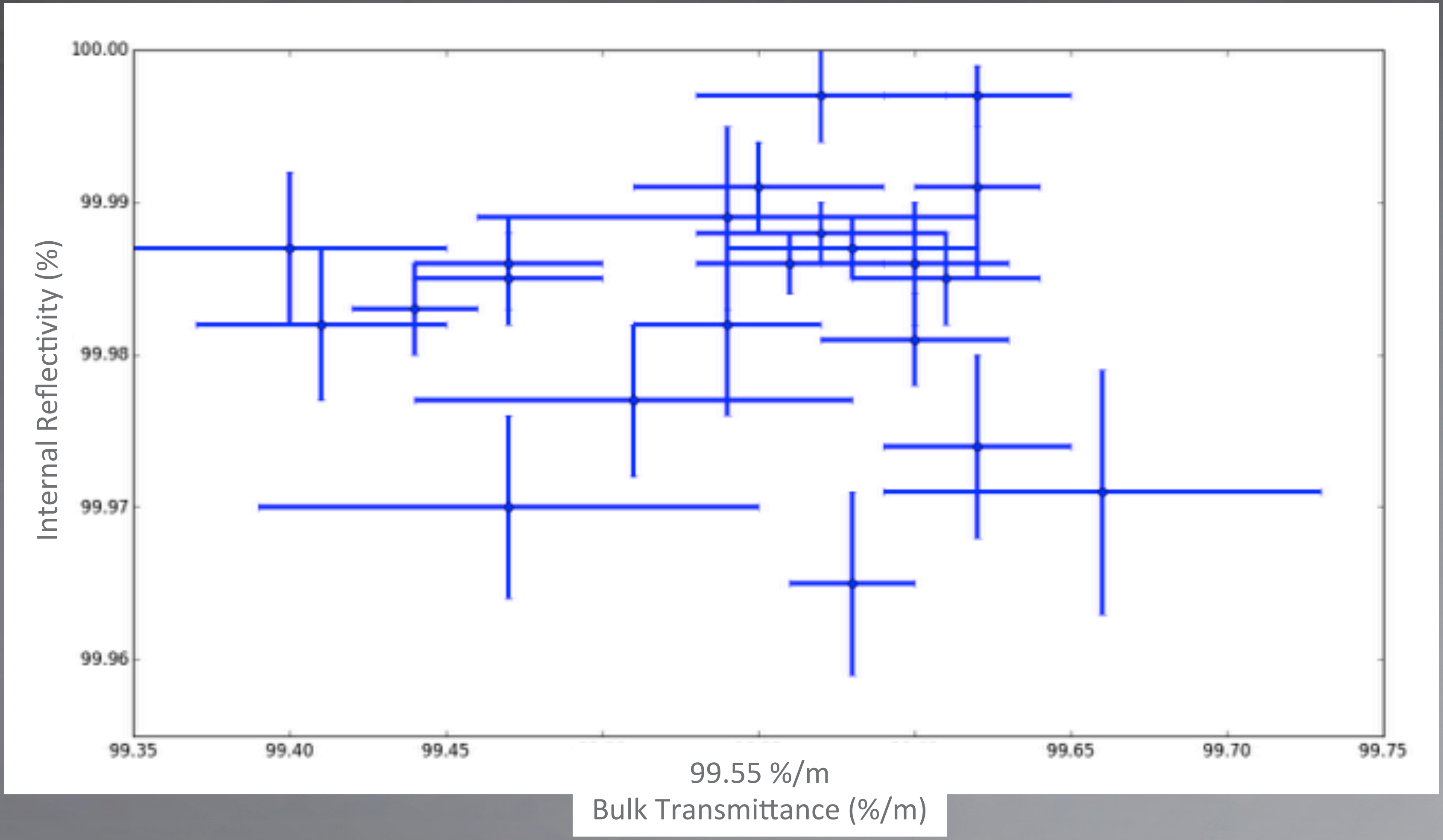
Laser wavelength: 405 nm
Avg. Bulk Transmission: (99.55 ± 0.07) %/m
Avg. Internal Reflectivity: (99.984 ± 0.008) %

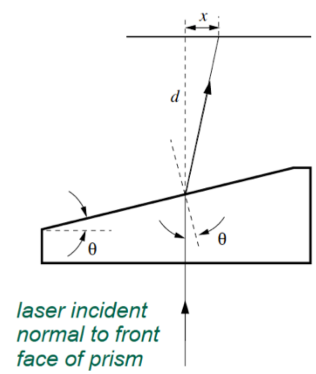


Prism production

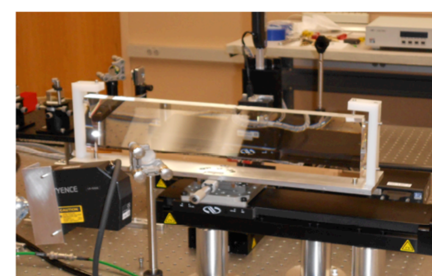
- Zygo made all production prisms
  - All were of high quality, meeting all specifications

Acceptance testing of prisms and mirrors performed at U. Cincinnati

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

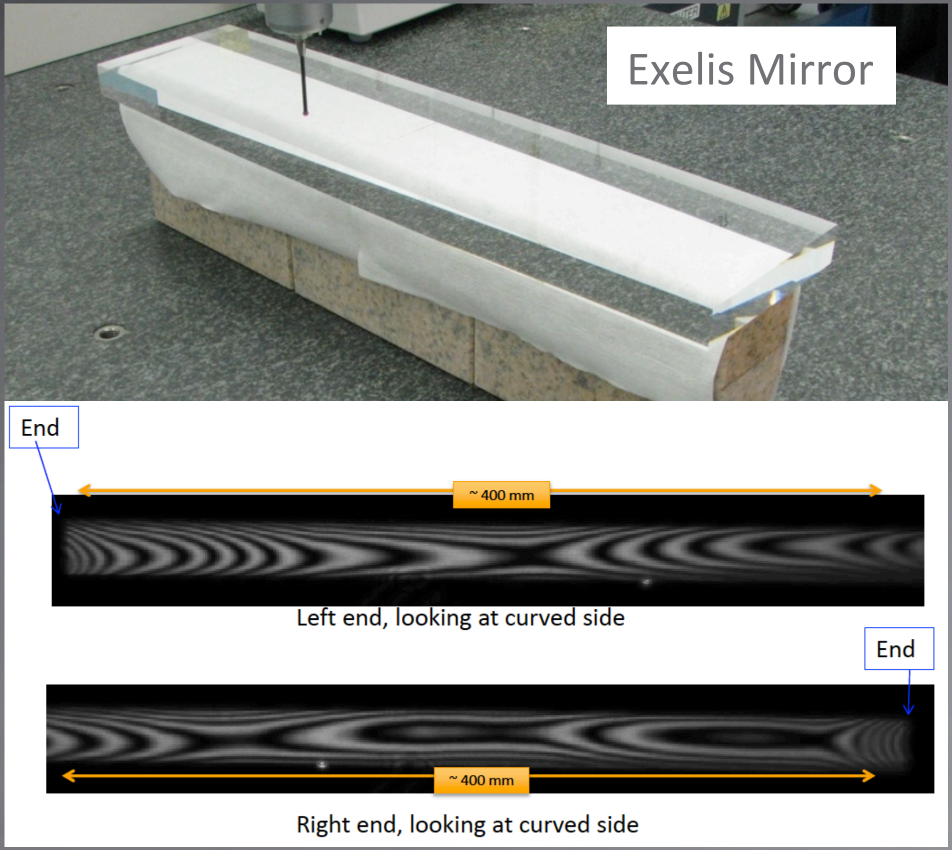


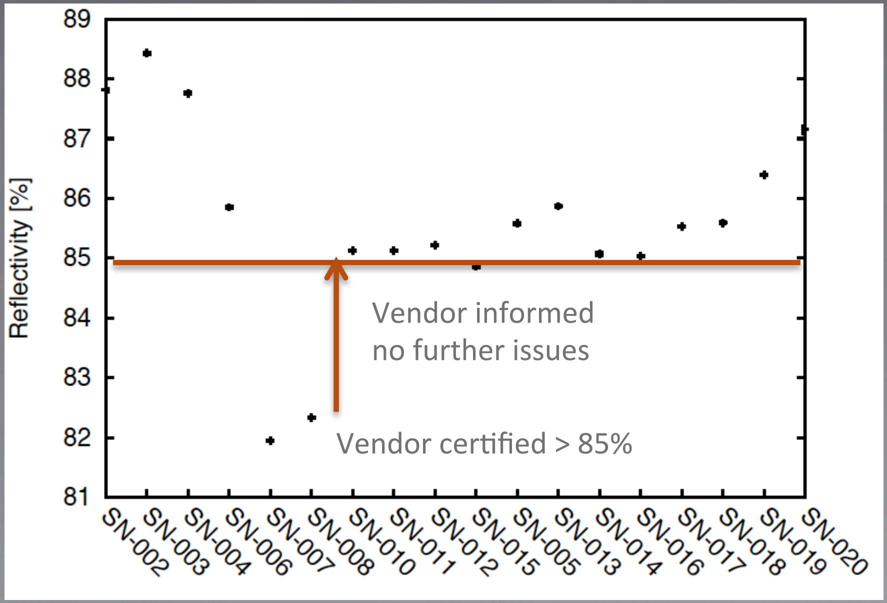
$$\theta \;=\; \tan^{-1}\left[\frac{\alpha}{n_{\text{qtz}}\sqrt{1+\alpha^2}-1}\right] \qquad \text{for } \alpha \equiv \frac{x}{d}$$



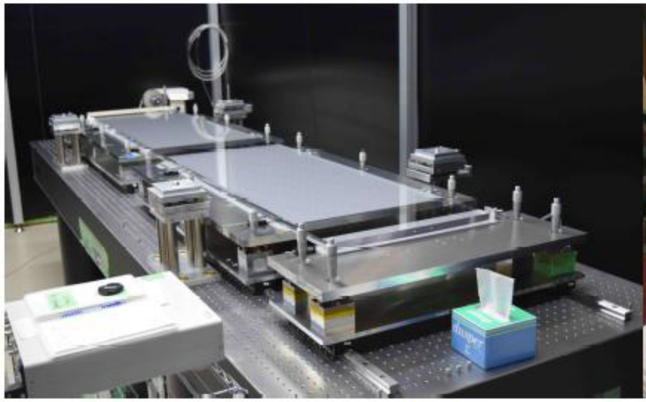
Mirror production

- All mirrors were made by Exelis (formerly ITT)
  - High-end vendor for satellite optics – very high QA/QC standards
  - Very responsive to quality issues – no recurrences once notified of issues





Module production process

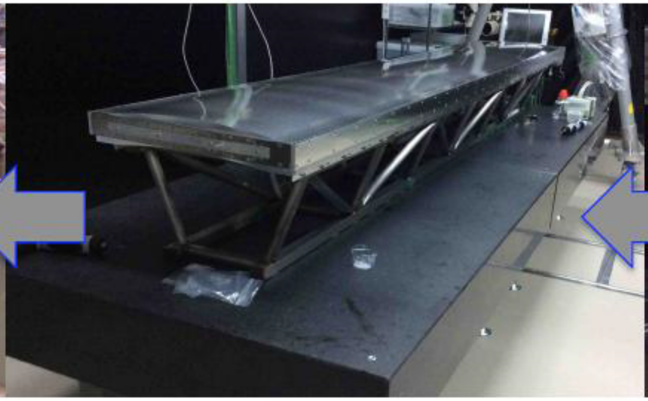


Optics: alignment, gluing, curing and aging (~2 weeks).

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”.

Photodetectors: Hamamatsu MCP-PMTs

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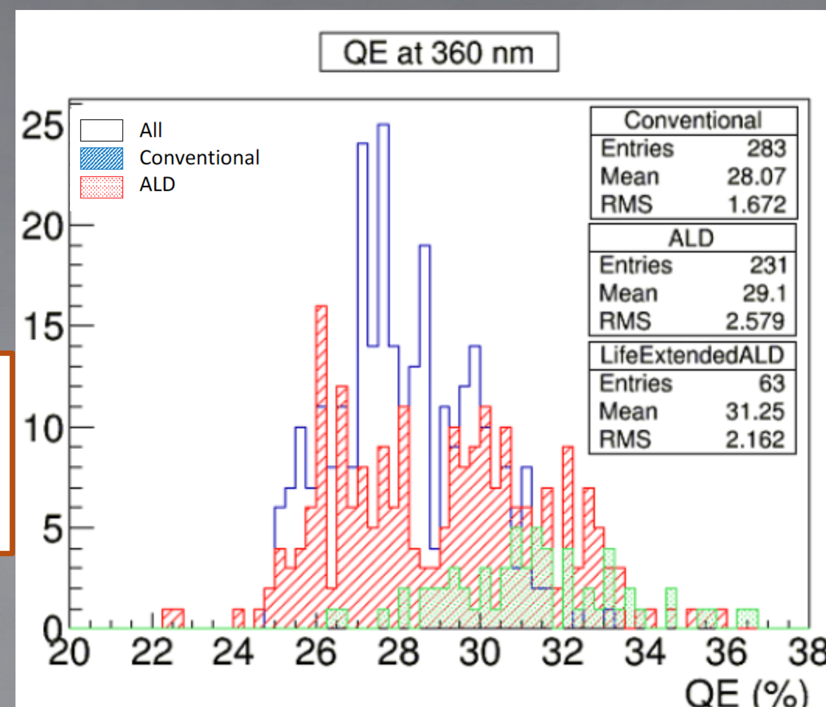
- Developed over >5 year R&D collaboration with Nagoya University
- >2 years production cycle to supply Belle II with 512 + spares
  - Midway through ALD technique was adopted in production by HPK
  - Lifetime extended from 0.3-1.7 C/cm^2 (~20 ab^{-1} exposure) to >2.5 C/cm^2
- Tubes with low QE, high gain variation or other issues returned to HPK

R-10754: 4 x 4 anodes
27.6 x 27.6 mm^2
23.0 x 23.0 mm^2 active

QE Requirements:
>24% at peak λ
>28% average over all devices



MCP-PMT modules

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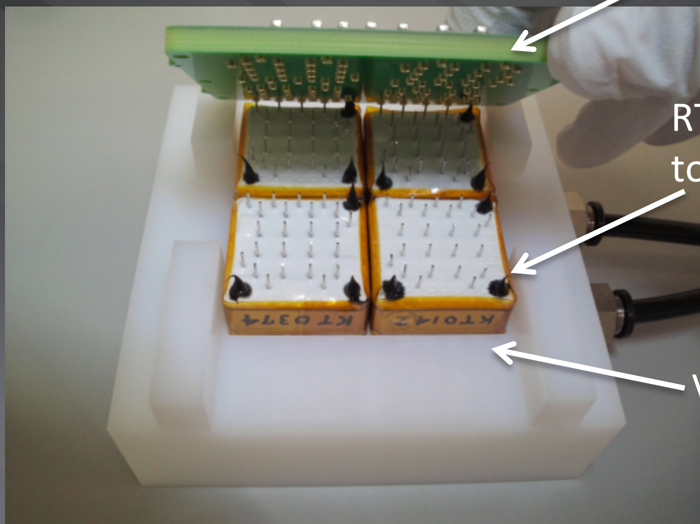
Front board (signal/HV routing, HV filtering)

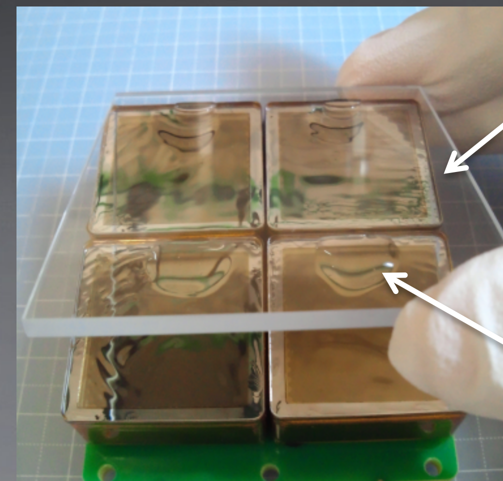
RTV to fix MCP-PMTs to front boards

Vacuum chuck

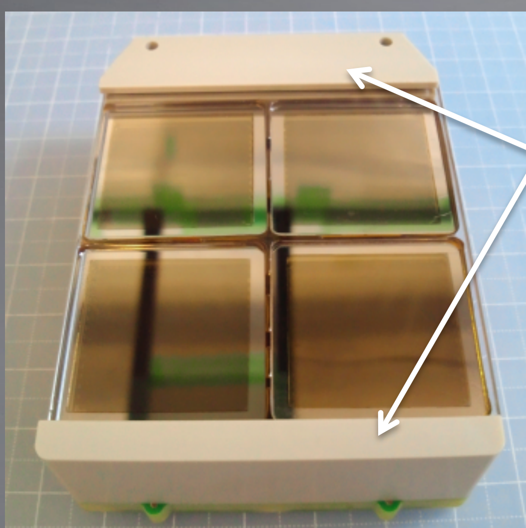


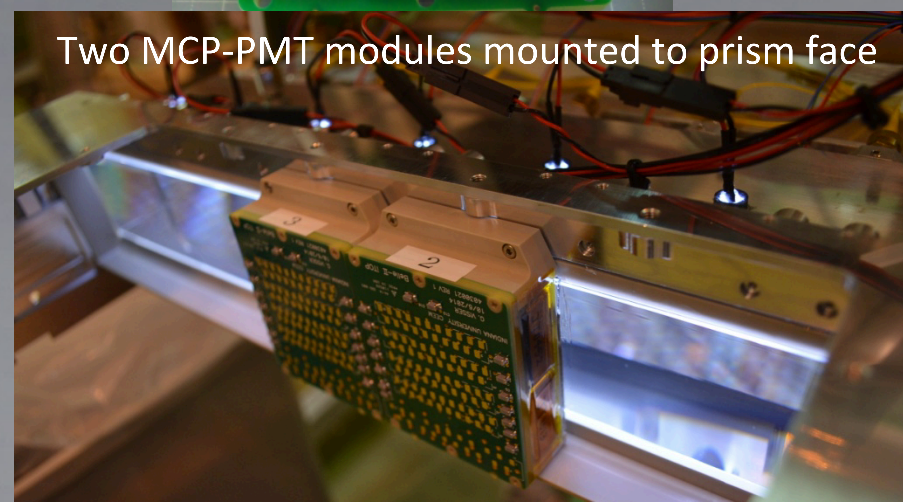
340 nm wavelength filter

Optically matched silicon cast in place



PEEK parts precisely locate wavelength filter relative to front board



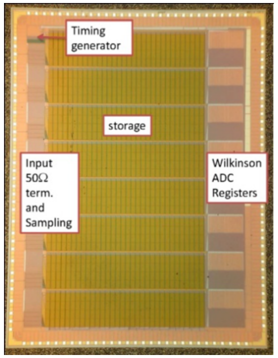


Two MCP-PMT modules mounted to prism face

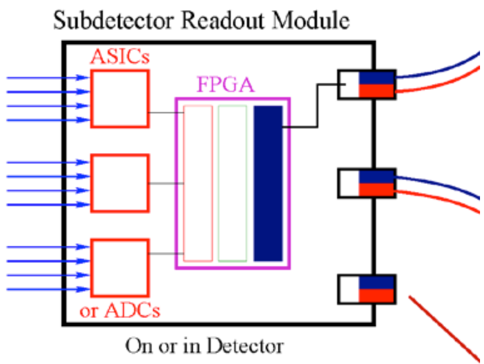
Removable optical coupling is made using a soft cast silicone cookie with a drop of optical oil to make a “bubble free” contact

Frontend readout electronics

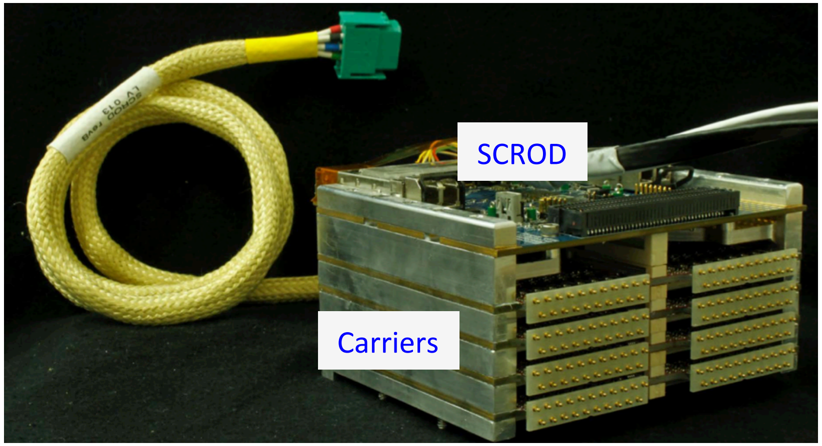
8k channel waveform sampling ASIC



Carrier boards:
4 ASICS + Xilinx FPGA

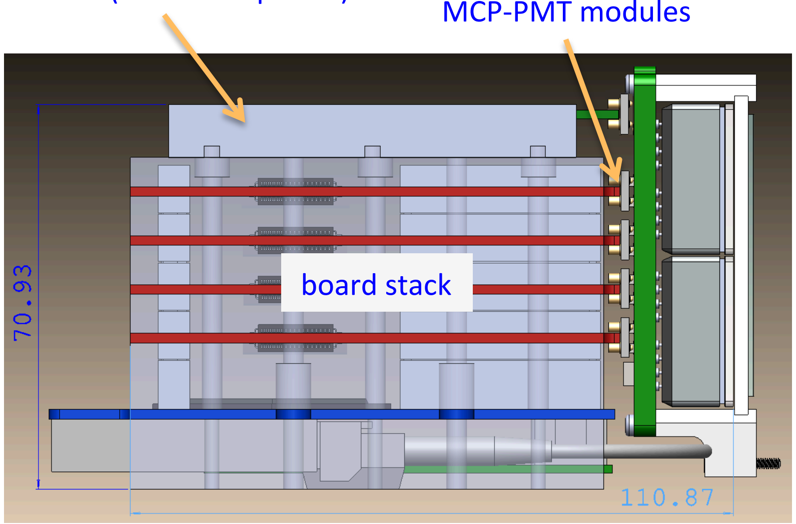


Board stack: 3 Carriers + SCROD
SCROD: master FPGA, fiber transceivers, clock, power

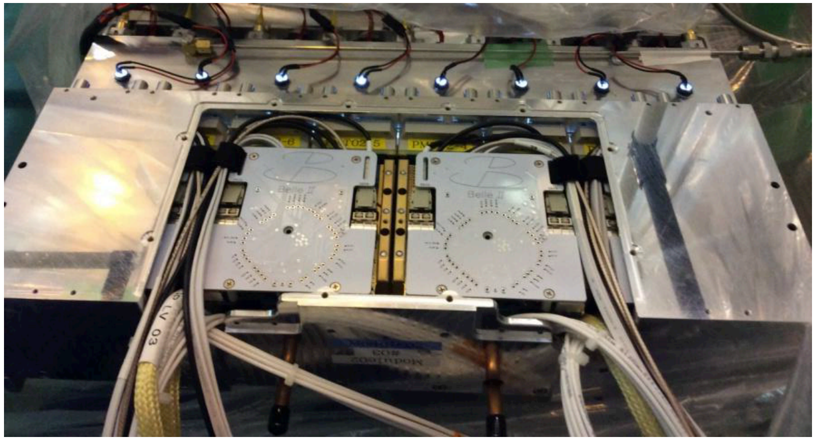


HV board (MCP-PMT power)

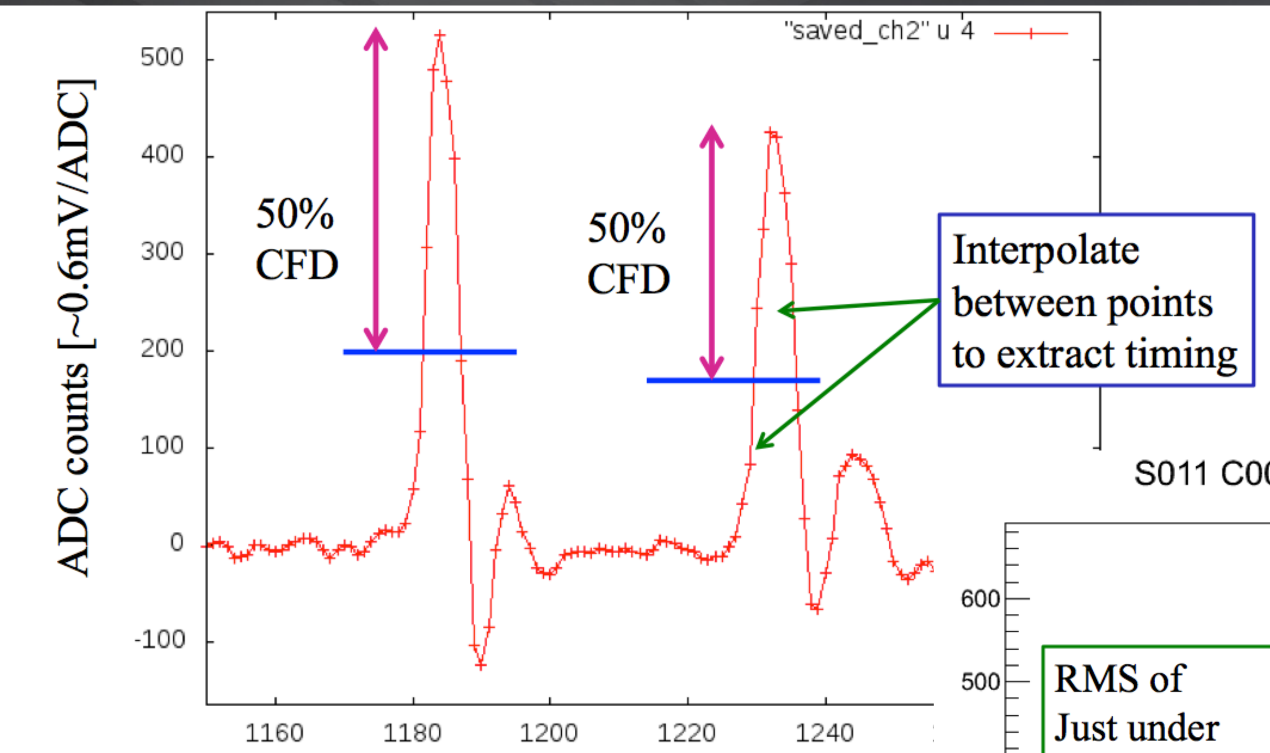
POGO pin connections to MCP-PMT modules

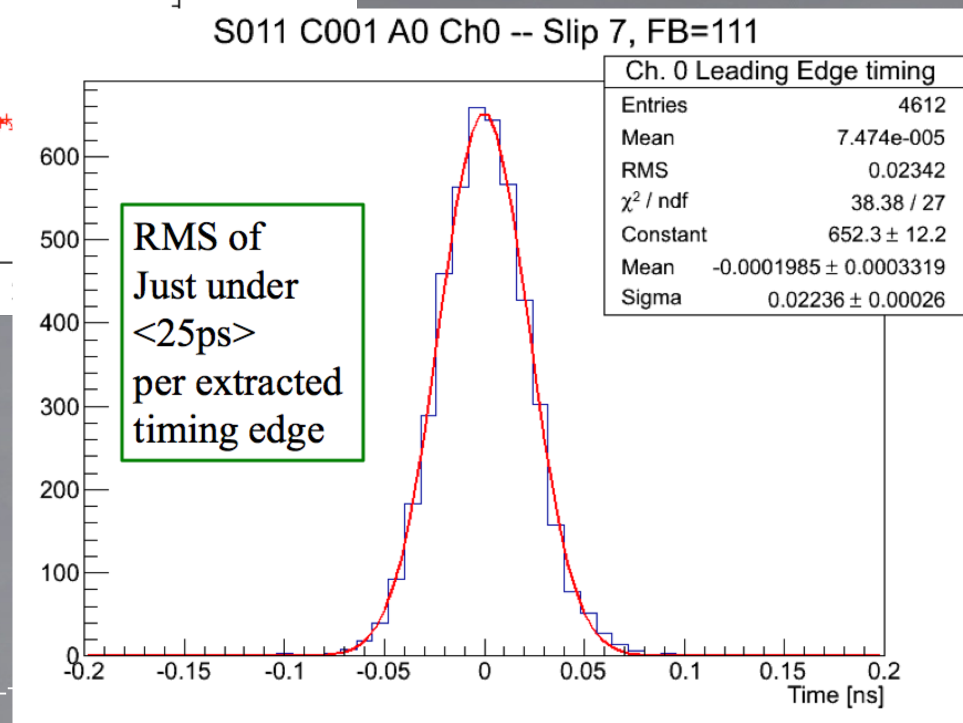


Four board stacks service each iTOP module

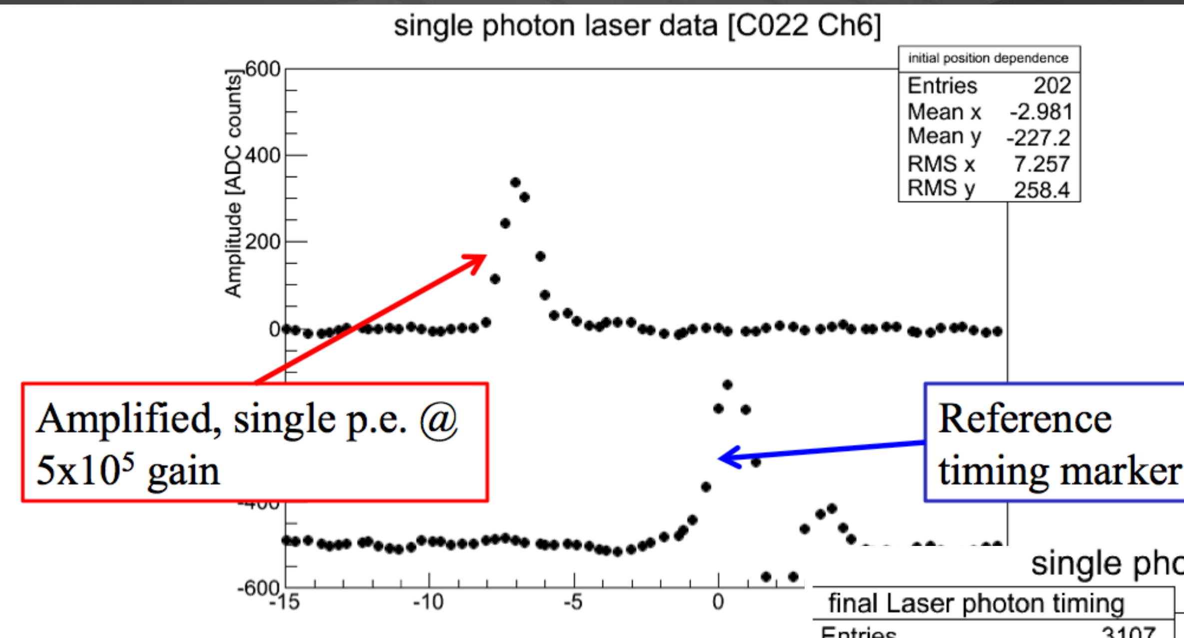


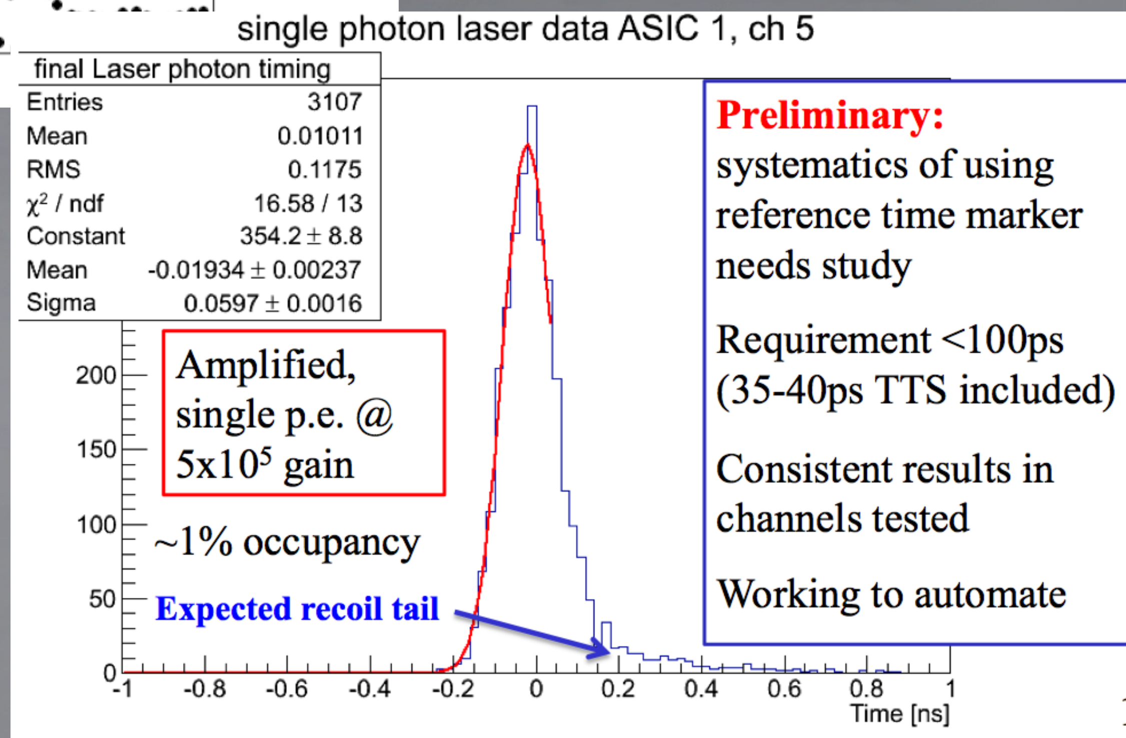
Fast pulse timing verification





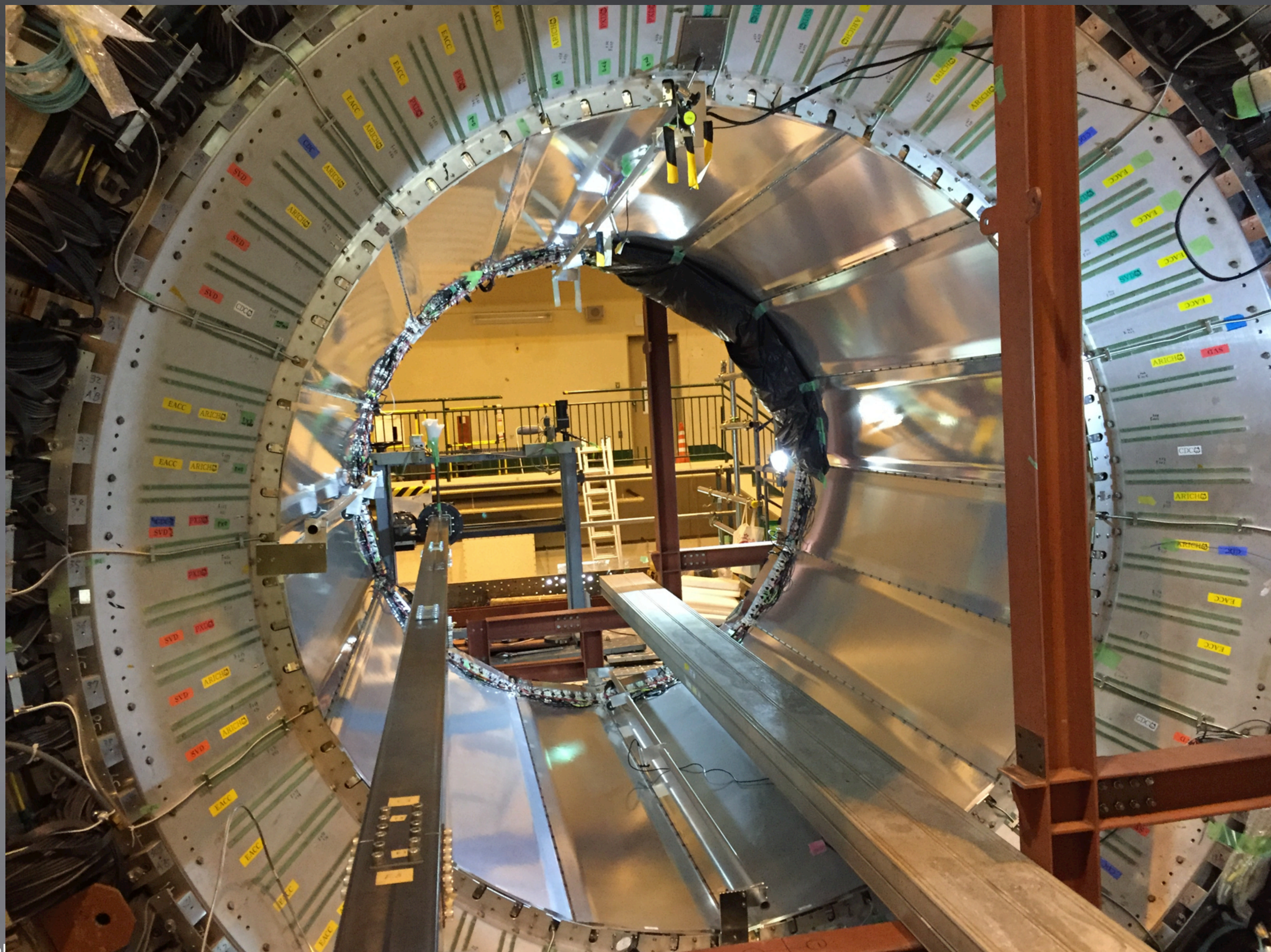
Single photon signal timing





Installation

Installation completed…



…but much left to do be done

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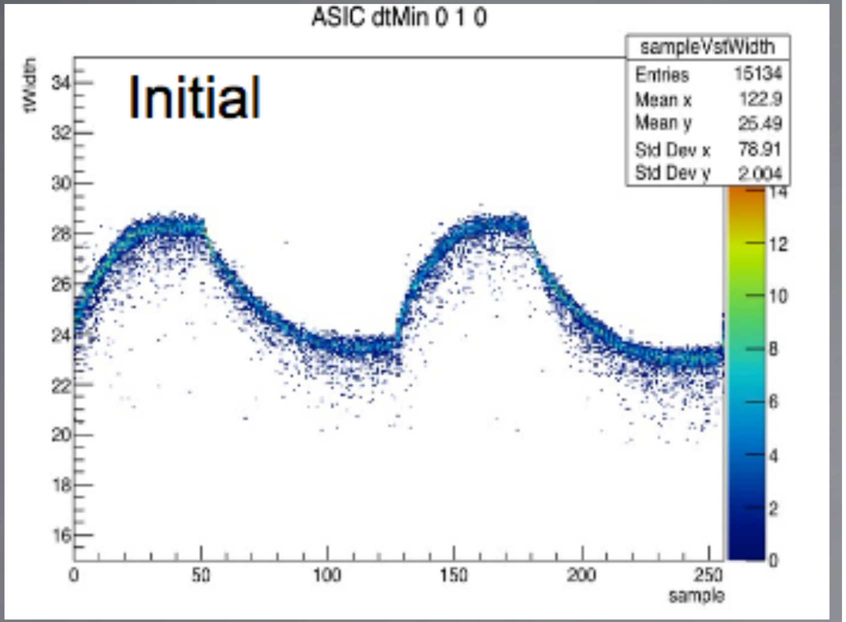
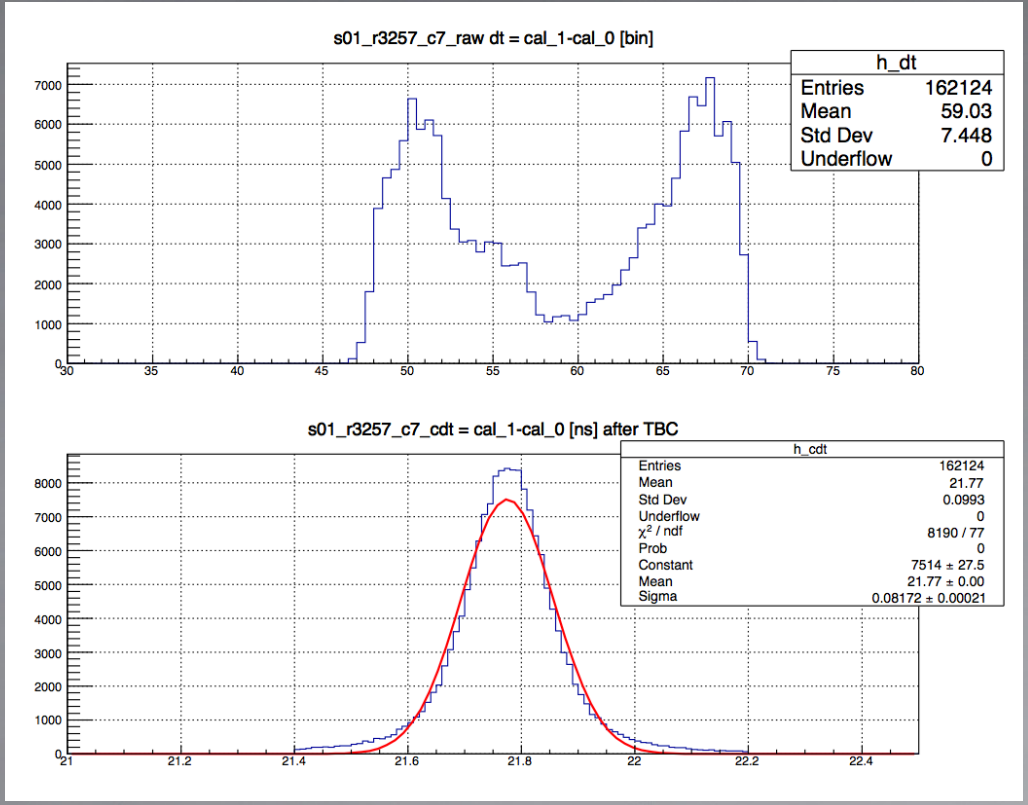
- Extensive post installation tests
  - Laser, cosmic ray muon
  - Have until October 10 to validate everything is OK before CDC is installed
- Still work to do on firmware
  - Feature extraction, on-the-fly pedestals
- Calibration, gain, efficiency
  - Sample time calibration essential to achieve required timing performance
- Get ready for physics
  - Does the data we see match, in detail, the simulations?
    - We need tracking and alignment to do this analysis
  - Tune Monte Carlo response to match data
    - Ideally we want to understand the physics/optics leading to differences and correct at a fundamental (optics/physics) level rather than using ad-hoc empirical "fudge factors"

Time base correction

- ASIC uses a delay line so each "time" increment depends on the chemistry of that particular region of that particular ASIC
- Every "time interval" (127 per ASIC, 8k total) must be calibrated
  - Currently achieving 70-85 ps double-pulse resolution, so ~50-60 ps single hit
  - Up to 100 ps is fine for physics





In situ cosmic ray tests – reasonable results

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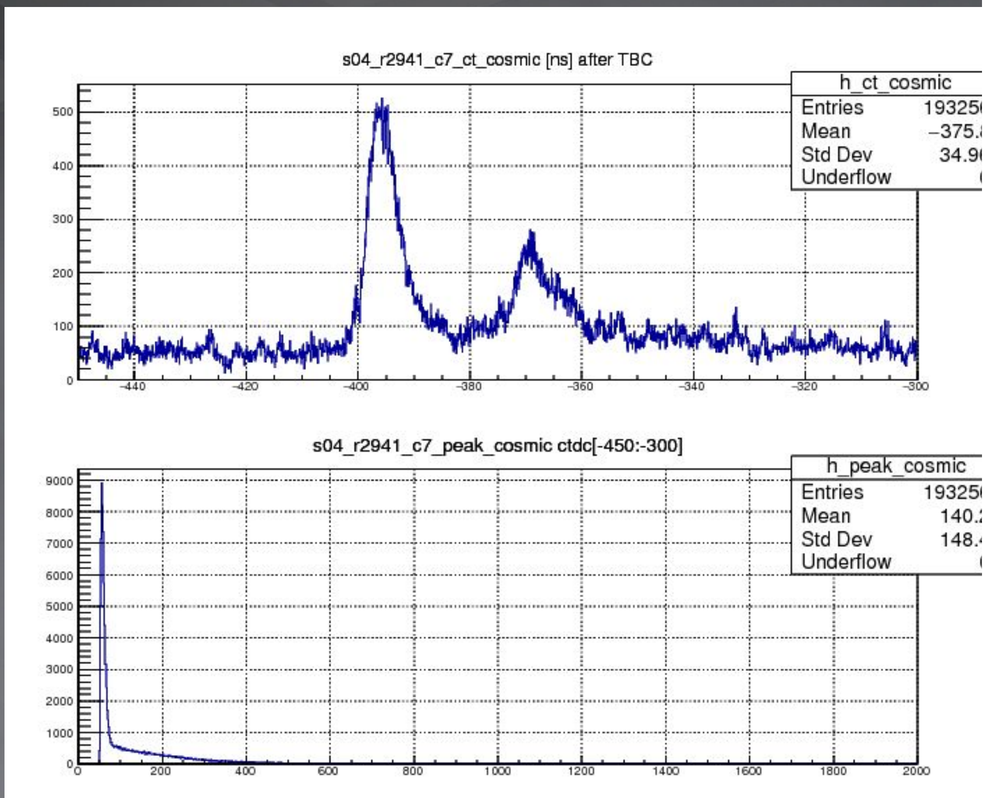
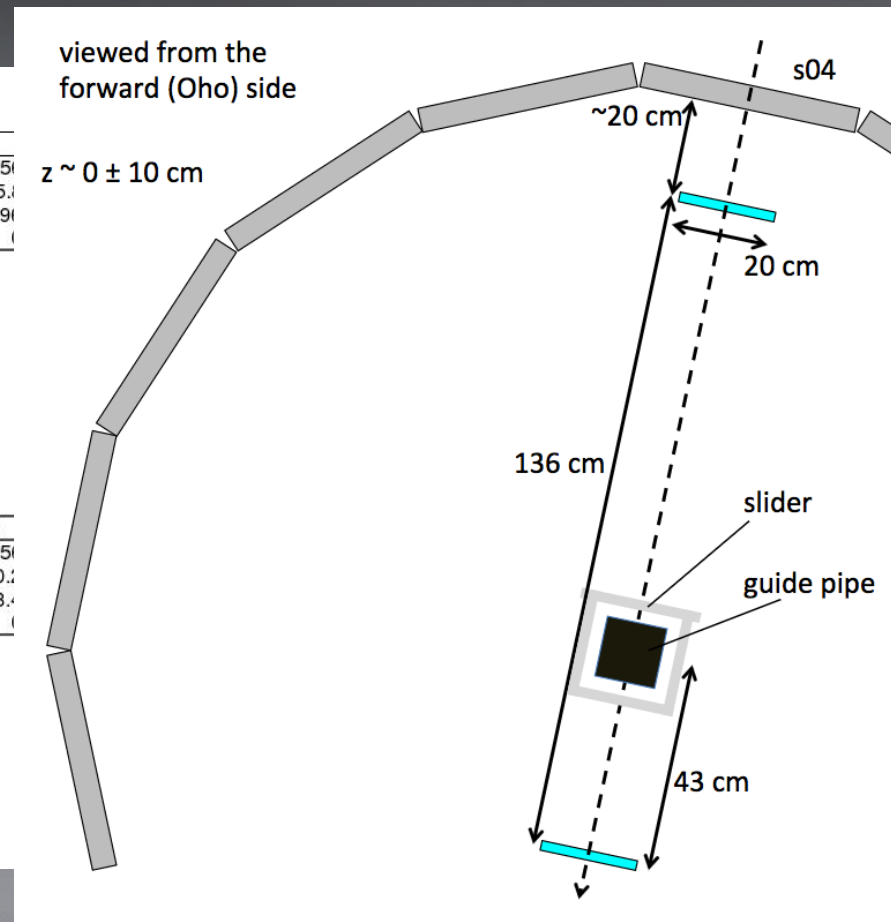
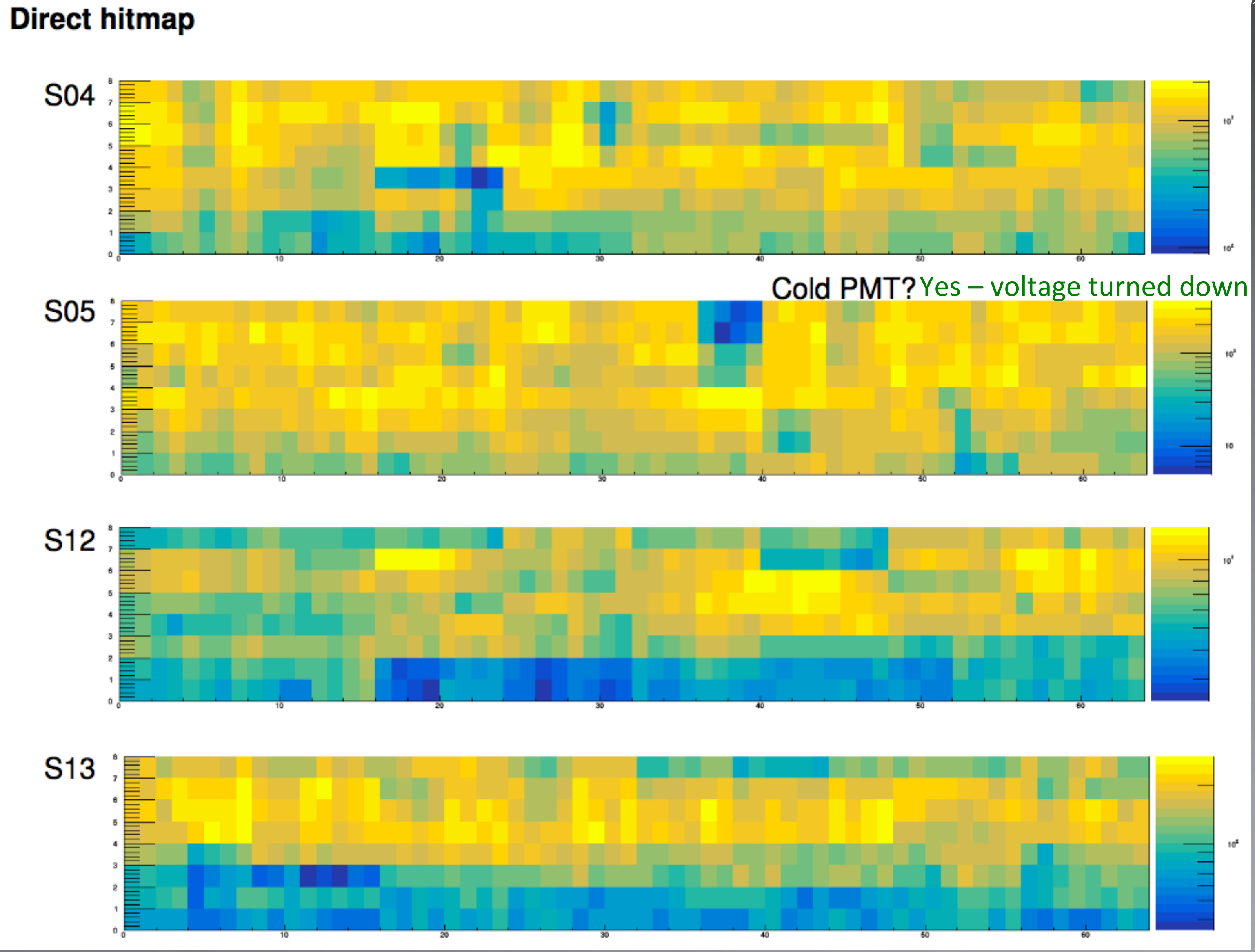


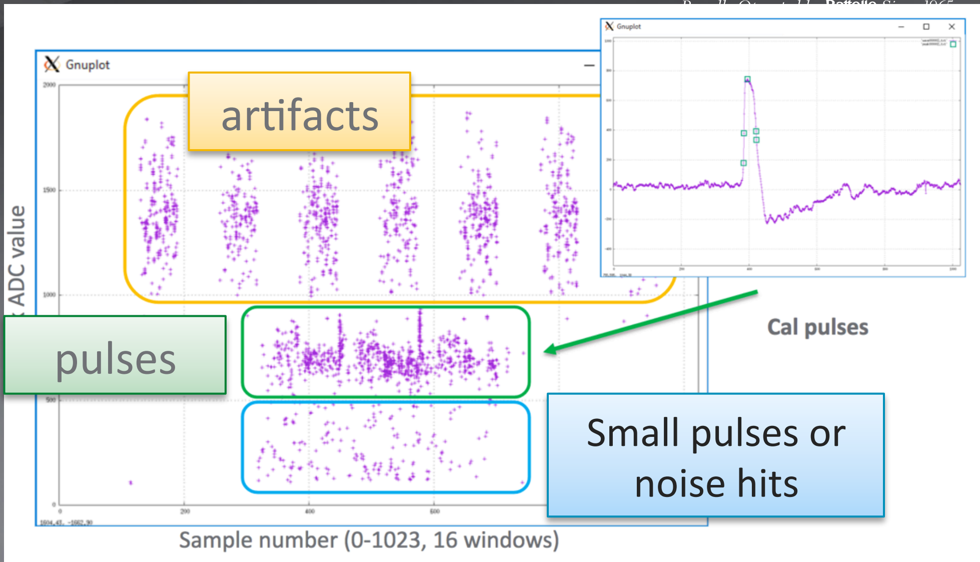


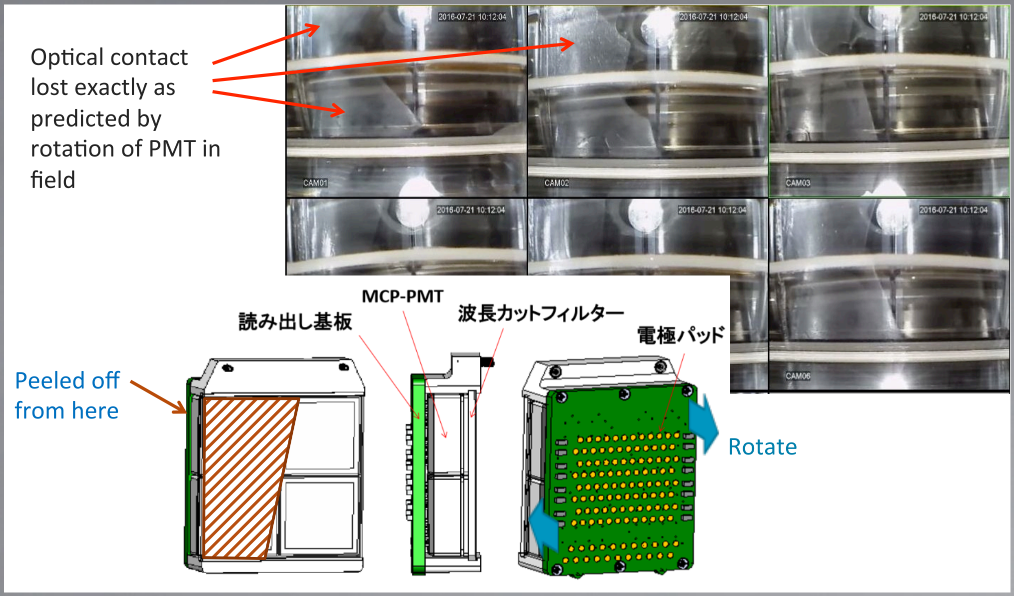
Hit maps from *in-situ* cosmic ray tests



Some of the remaining issues

- DAQ Integration still not where we need it to be
  - iTOP firmware is just reaching point where we can use feature extraction and ROI modes
  - Full DAQ integration being done in parallel with commissioning
  - Still have many “features” in data
- MCP-PMT materials are more magnetic than expected
  - Large torque in B-field is breaking optical coupling to prism and electrical contacts
  - Repairs (shimming) underway, but no time to do long-term stability tests





Summary

- Belle-II Detector upgrade is underway to provide improved performance at x40 luminosity; iTOP provides the essential particle identification in the barrel region needed to carry out the physics
- iTOP is fully assembled and installed; undergoing commissioning
  - Optics, MCP-PMTs and readout all met specifications
  - Integration went well; mechanics are sound; no installation issues
  - Much remains to do on system-level integration/test/commissioning
- SuperKEKB Phase 1 commissioning was completed in 2016
  - "first physics" expected in 2018 - so we have some time to sort out issues