multi-PMT Photon Detectors for Hyper-K and Beyond

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TRIUMF Science Week
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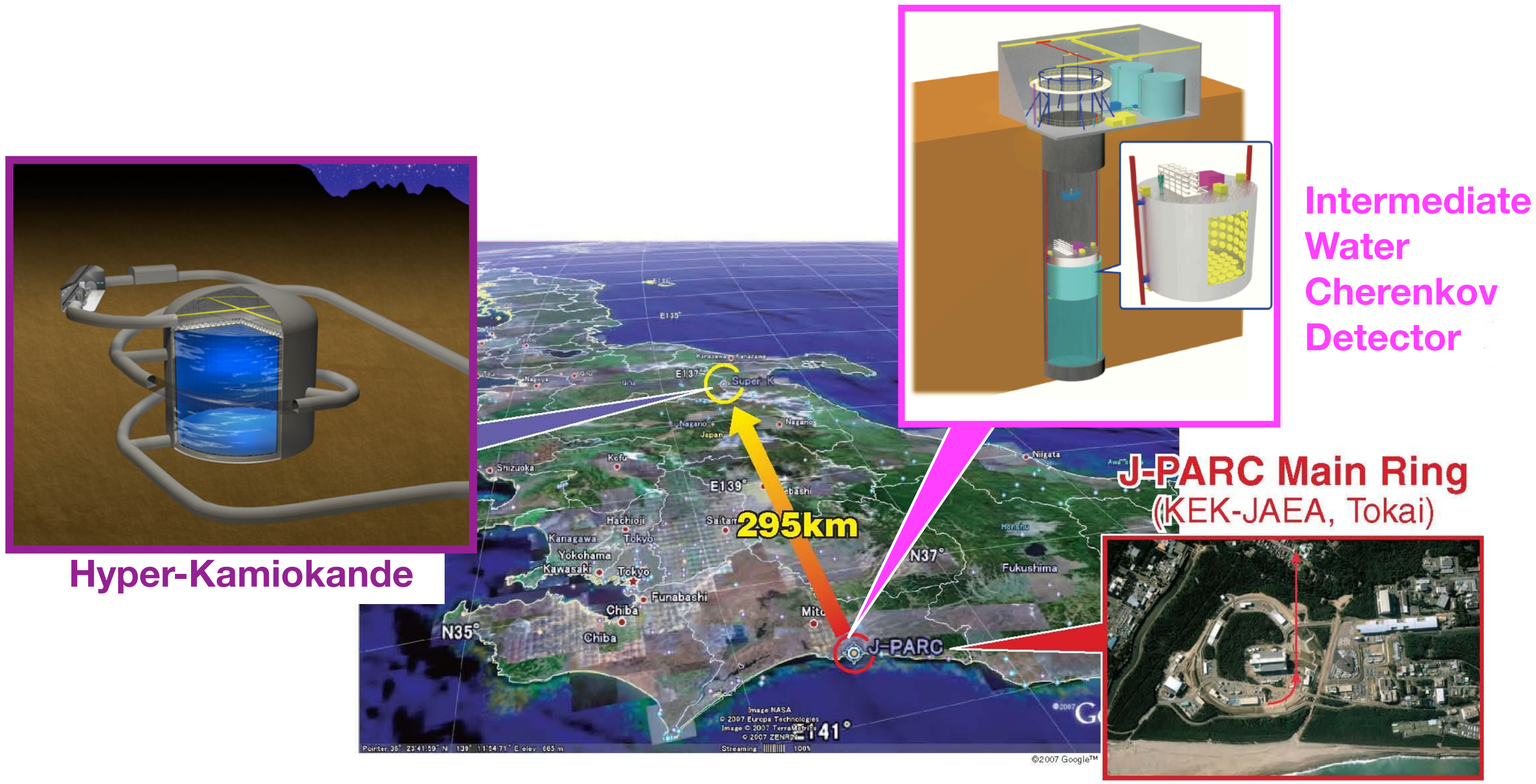
Discovery, accelerated

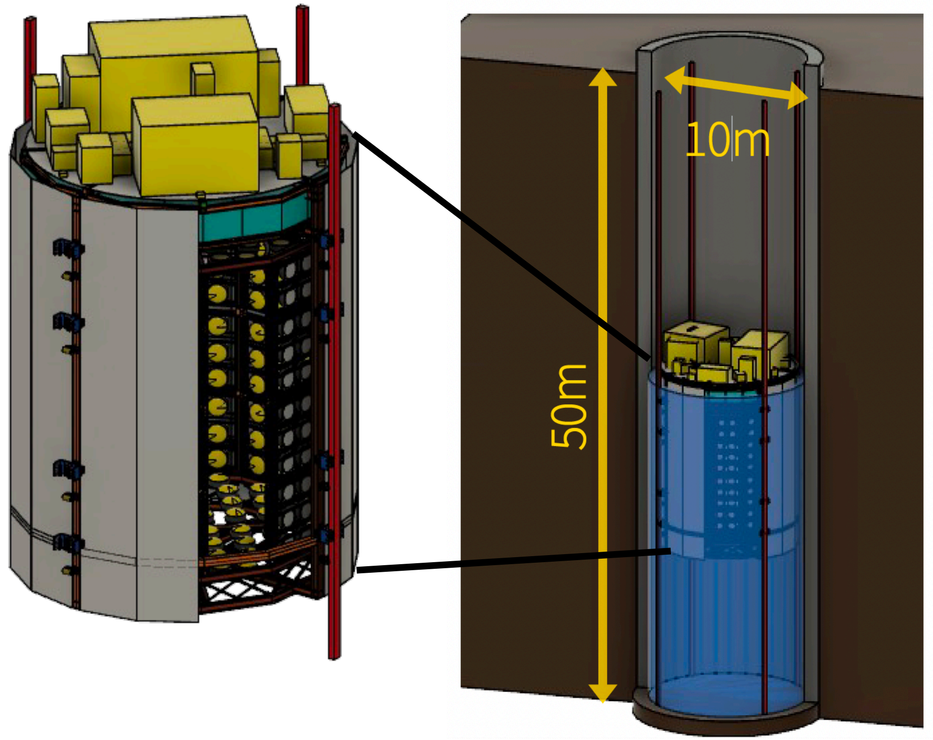
Hyper-Kamiokande

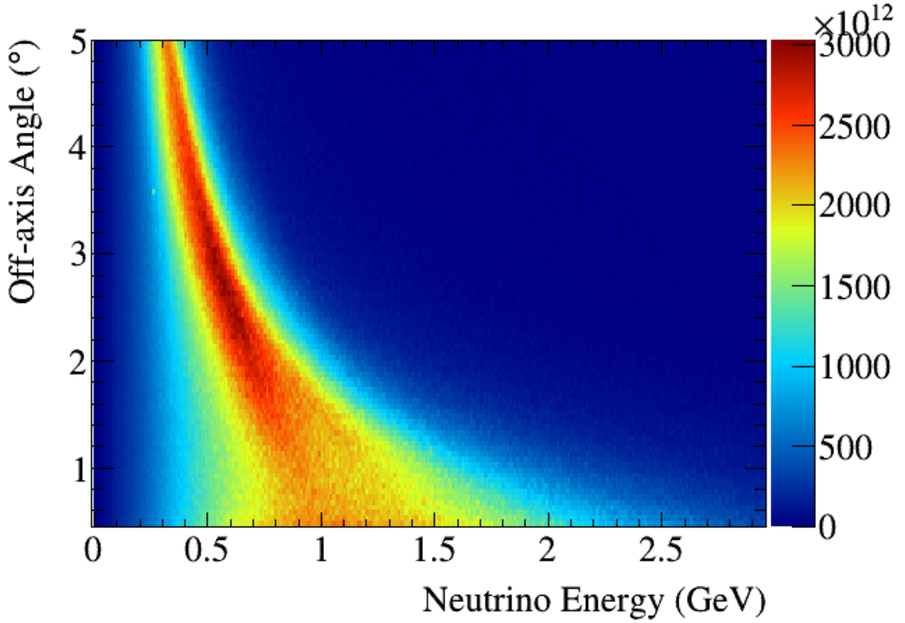


- Next-generation long baseline neutrino experiment in Japan
- Accelerator produced neutrinos from 1.3 MW proton beam and neutrino beam line at J-PARC
- 187 kton fiducial mass Hyper-Kamiokande detector
- New Intermediate Water Cherenkov Detector (IWCD) located near J-PARC

IWCD

- 300 ton active region neutrino detector
- Located about 1 km from the neutrino source at J-PARC
- Able to move in the neutrino beam to probe different neutrino energies
- Measurements of neutrino-nucleus scattering in order to control systematic uncertainties
- Detector is small compared to Super-K or Hyper-K -> impacts the choice of photosensor

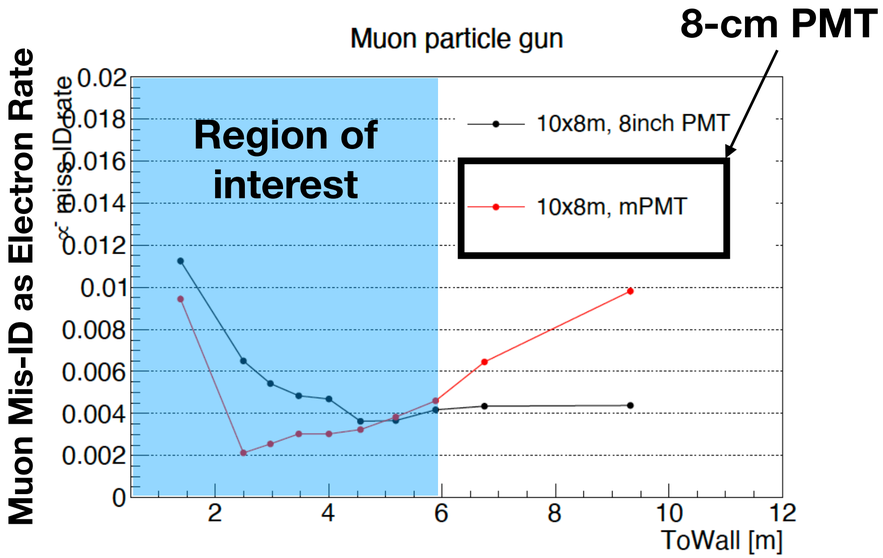




Photon Detector for Hyper-K and IWCD

- Super-Kamiokande uses large 50-cm diameter PMTs
- Around the time time of Hyper-K development: 8-cm diameter PMTs have a similar cost per photo-cathode area as 50-cm PMTs
  - Smaller PMTs require more cables, electronics channels etc.
  - Provide better timing and spatial resolution, less sensitive to geomagnetic field
- Careful consideration of 8-cm diameter PMTs, especially for IWCD since size is smaller
  - Need the improved timing and spatial resolution
  - How to mitigate challenge of cabling for ~10,000 PMTs

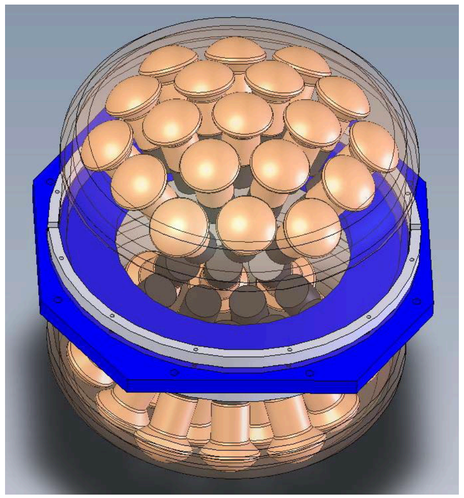
Super-K PMT



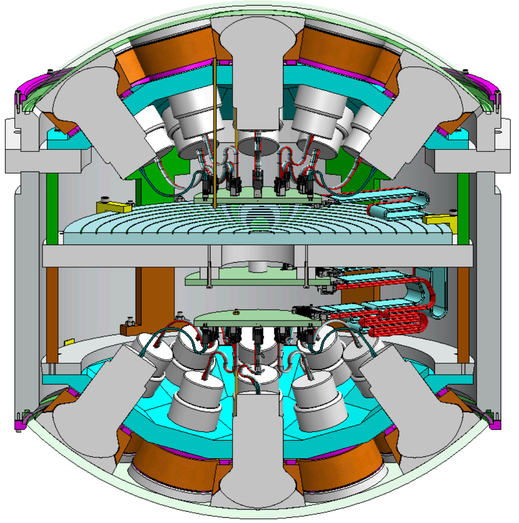
multi-PMT Concept

- Concept adopted for neutrino telescopes experiments (KM3NeT, IceCube upgrades, P-ONE)
- Photosensors, high voltage, digitization electronics all housed in a single vessel that operates in the detector water (ice)
- Early concepts for Hyper-K and IWCD:

~2016



~2017



- Early concepts where very much conceptual!
- Original idea to have photosensors on both sides to view both inner and outer detectors
- At the start, technology readiness level = 1

mPMT Project at TRIUMF

- Development and implementation of the mPMT concept for IWCD and Hyper-K has been led through collaboration of TRIUMF Hyper-K group and the SciTech department
  - Collaboration with partner institutes in Canada (UVic, Carleton, URegina, UWinnipeg, York, BCIT) and International partners in Poland and Italy
- Key TRIUMF personnel (significant number of co-op students have worked on the project):

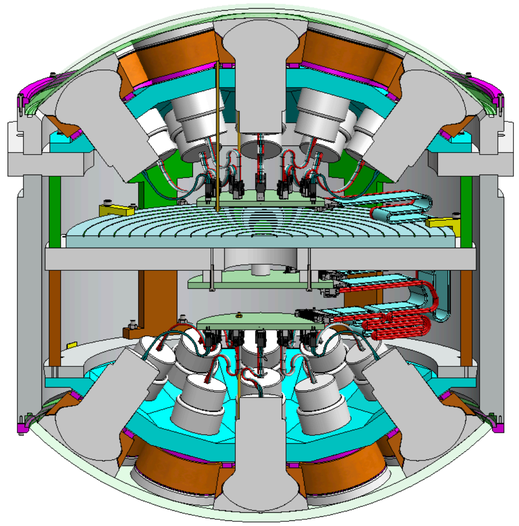
SciTech Department	Postdocs, Graduate Students, Techs	Scientists
T. Lindner	M. Gola	P. de Perio (now at Kavli IPMU)
D. Bishop	R. Akutsu	M. Hartz
Y. Linn	J. Rimmer	A. Konaka
M. Constable	T. Yu	X. Li
P. Lu	M. Scott	H. Tanaka (now at SLAC, Stanford)
R. Henderson	T. Feusels	
R. Maharaj	S. Cuen-Rochin	
P. Margatek		
B. Smith		

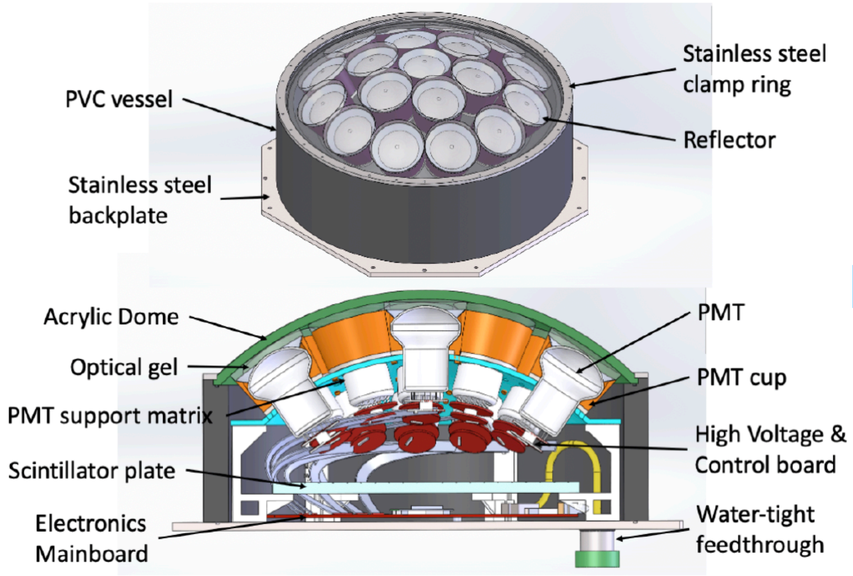
- Dedicated funding has including:
  - 2018 RTI to design and build mPMT prototypes
  - 2019 RTI to complete a pilot production of 30 mPMTs to be operated in a test experiment (at CERN)
  - 2020 CFI-IF to build 250 mPMTs for IWCD
  - 2023 CFI-IF to build 200 mPMTs for Hyper-K

Development Challenges

- Understood from the beginning that multi-PMTs should generally use established equipment, components and materials
- Challenges in project arise from:
  - Production and sourcing of components at feasible cost while compatible with operation in ultra-pure water
  - Integration of components into module accounting for optical coupling, heat removal, cable routing, etc.
    - Mechanical, optical, electronics and firmware development in coordination required
  - Reliable operation over 10+ year timescale
  - Repeatable and efficient assembly procedure (building >400 modules)
  - Testing capabilities to ensure proper operartion of assembled modules
- A practical challenge arises from collaboration with international partners in Poland and Italy

Evolution of the Concept & Application

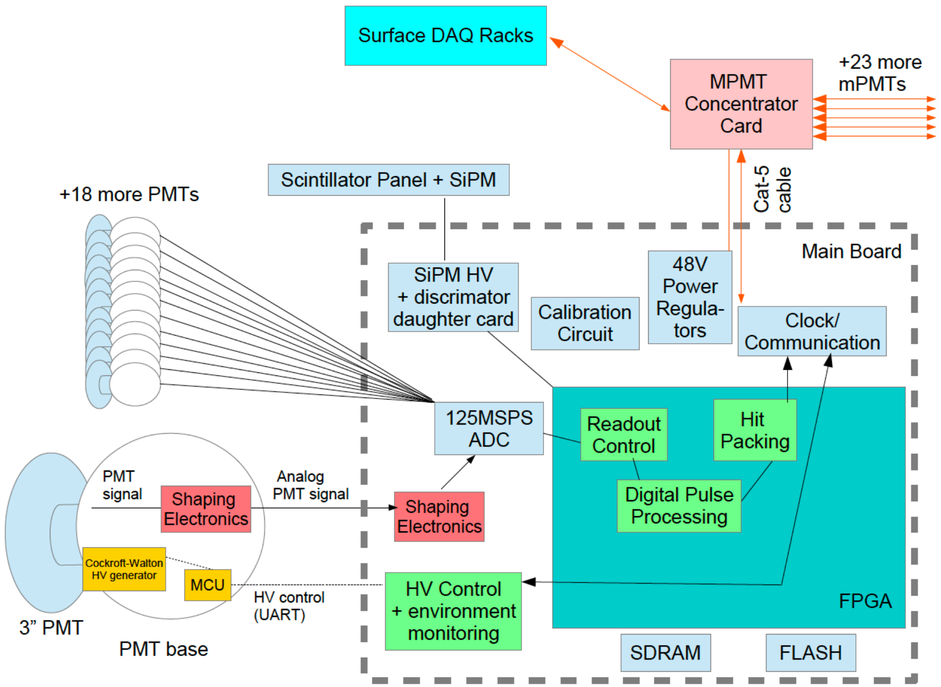




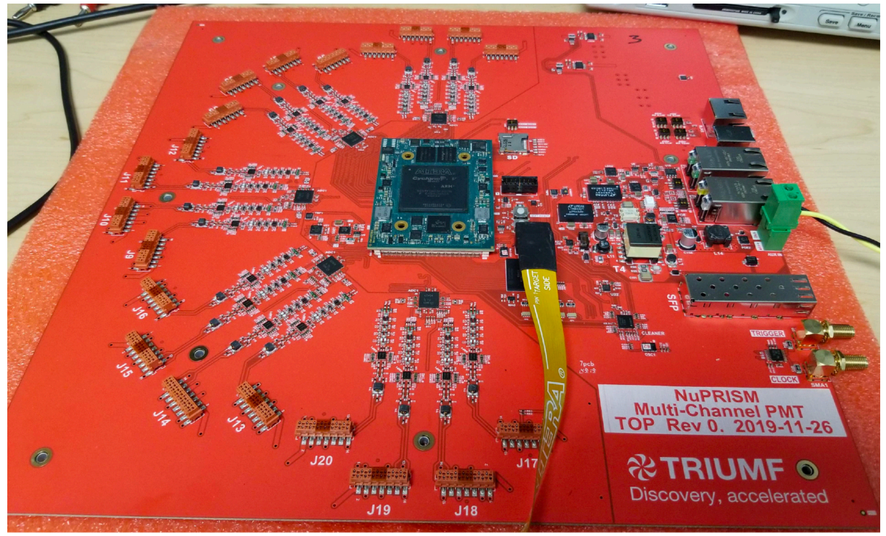
- Found more economical to have separate photosensors for outer detector (requires less photocoverage)
- PVC was chosen as material for cylindrical section due to easy commercial availability at required dimensions
- Internal scintillator was dropped from design since additional capability did not justify increase in cost and complexity
- LEDs internal to module added for timing calibration (pulsed) and photogrammetry beacons (constant)
- mPMT as primary photon detection system for Hyper-K was too expensive compared to 50-cm diameter PMTs
  - TRIUMF development focused primarily on mPMT for IWCD

Electronics

- 125 MSPS FADC digitizer main board with 20 channels to handle 19 mPMTs in each model
  - Primarily developed by TRIUMF SciTech Electronics and DAQ groups
- Shaping/amplification electronics developed in collaboration with Warsaw University of Technology (WUT)
- Onboard FPGA for readout control, digital pulse processing and hit packing
- Communication and power over a Cat-6 cable using PoE protocol
- Each PMT has a control Cockcroft–Walton HV board and control board
  - Developed by WUT, based on initial design by INFN

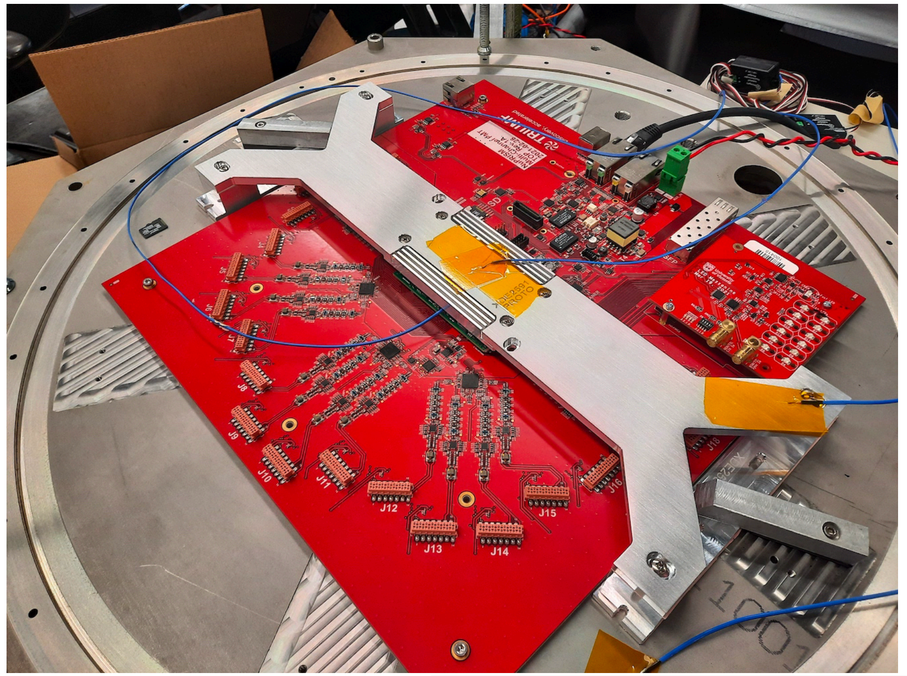


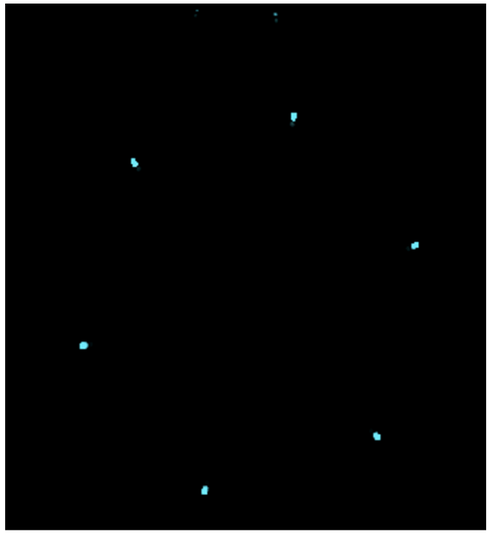
Main Board



Further Development and Integration

- LED mezzanine card was developed and added to the main board
  - Constant current LEDs used as beacons for photogrammetry position calibration
  - Pulsed LEDs allow for timing and single p.e. calibration in the detector
- Heat removal was an important consideration
- Heat sink design and installed to transfer heat to back plate where is can be dissipated into the water
- Careful planning of cabling inside module was necessary





Picture of beacon LEDs with photogrammetry camera in test setup at U. Winnipeg

Firmware Development

- TRIUMF electronics development group also has been a leader in developing firmware and software for the mPMT mainboard.
- Development of the overall firmware build environment, including the configuration of petalinux on the SoC's hard processor.
- Development of the initial ADC readout scheme, including support for software and hardware triggering, as well as LED flashing.
- Implementation and testing of the modbus communication between the mainboard and PMT bases.
- Diagnosis and fixes for many subtle timing and configuration problems seen during 100 board production.

Assembly Methods

In-situ gel application much less labour intensive:

Tasks	Ex-Situ Time (min.)	In-Situ Time (min.)	FTE Minutes (ex-situ)	FTE Minutes (in-situ)	Remarks
Backplate Preparation	60	60	120	120	2 FTEs
PMT Gelling/PMT Gluing	120	90	360	270	3 FTEs
Detector Closing	90	90	180	180	2 FTEs
Moulds Cleaning	120	NA	360	NA	3 FTEs
Total Time	390	240	1020	570	2-3 FTEs

Ex-situ gel application allows for replacement of single PMTs

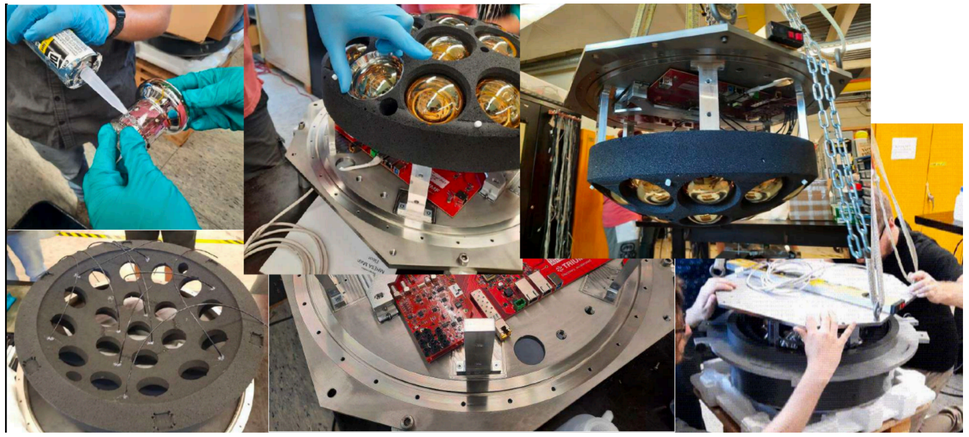
TRIUMF experience is key input for design decision by collaboration

- Optical gel couples PMT to acrylic dome of module
- Two methods developed:
  - Optical gel pre-applied and cured for each PMT before assembly (ex-situ application)
  - PMTs are installed in position relative to dome before gel is applied and cured (in-situ application)

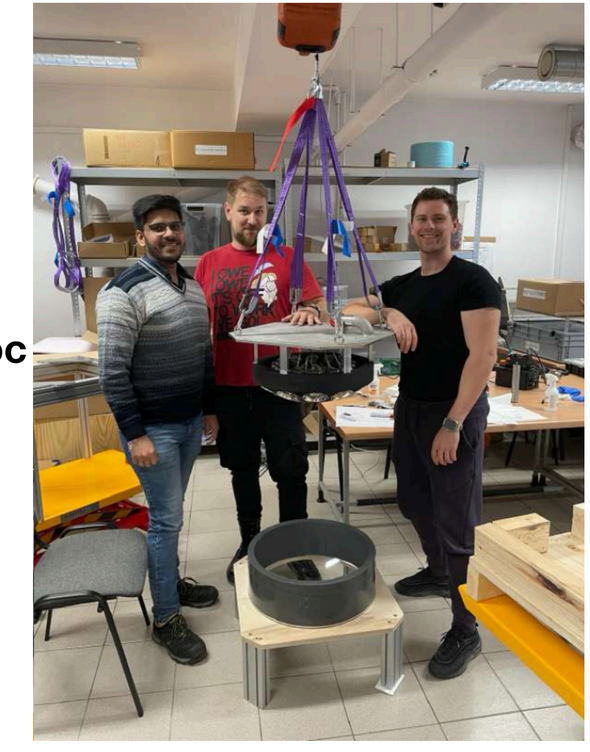
Pilot Production

- Completed a pilot production of 50 mPMTs at TRIUMF and WUT in Poland
- Assembly method for ex-situ gelling was primarily developed at TRIUMF and optimized in collaboration with WUT
- Design and assembly method for in-situ gelling was collaboration between TRIUMF and Carleton
- TRIUMF postdoc M. Gola led assembly work at TRIUMF and traveled to Warsaw to teach the in-situ gelling assembly method (lower right)
- Generally successful pilot production with some problems on the QC for the main board
  - For the upcoming 300 board production will need to develop more rapid and robust electronics QC setup.

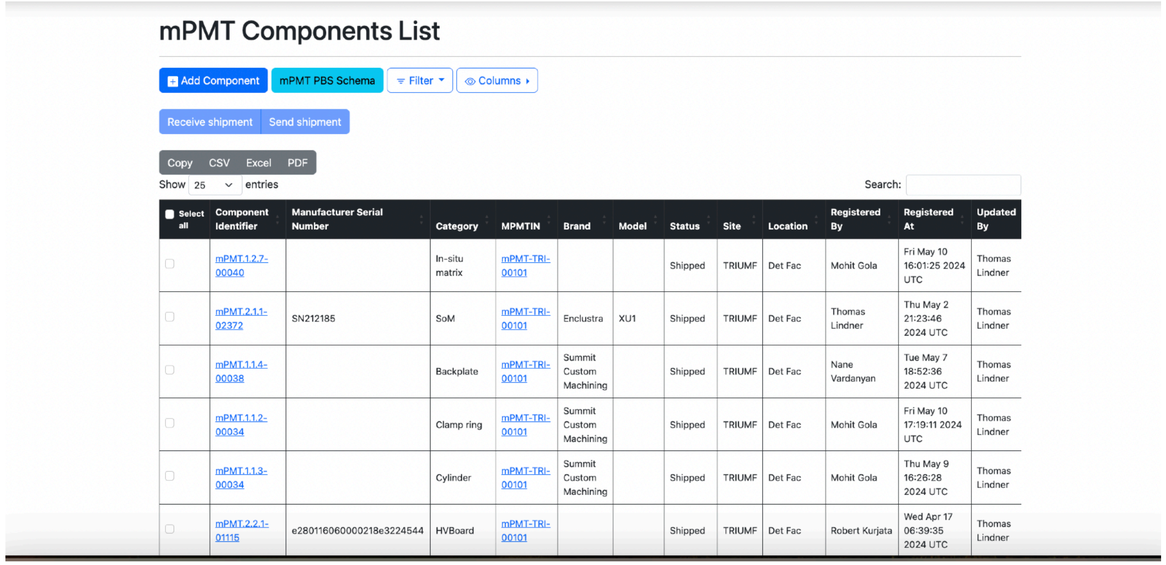
Assembly of mPMT at TRIUMF



TRIUMF Postdoc M. Gola



Construction Database



mPMT Components List

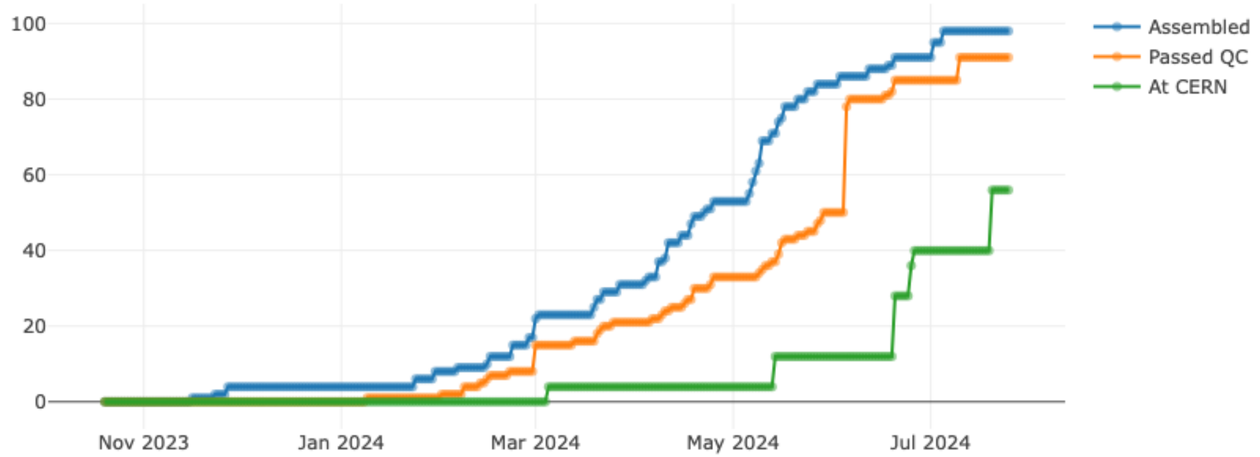
Add Component | mPMT PBS Schema | Filter | Columns

Receive shipment | Send shipment

Copy | CSV | Excel | PDF

Show 25 entries Search:

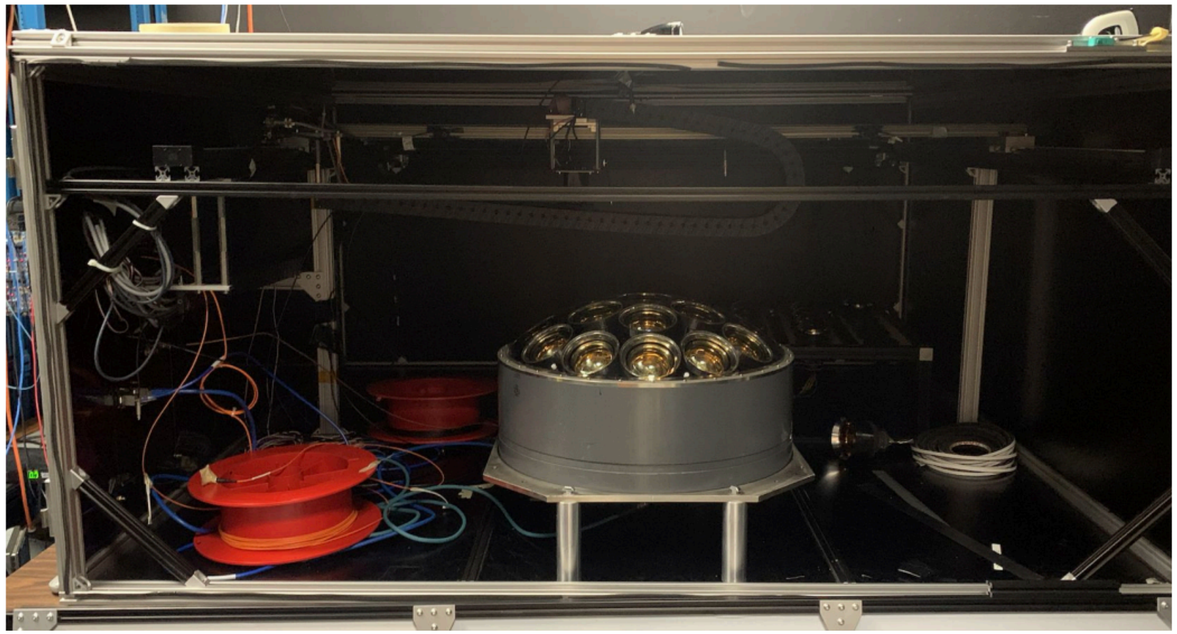
Select all	Component Identifier	Manufacturer Serial Number	Category	MPMTIN	Brand	Model	Status	Site	Location	Registered By	Registered At	Updated By
	mPMT.1.2.7-00040		In-situ matrix	mPMT-TRI-00101			Shipped	TRIUMF	Det Fac	Mohit Gola	Fri May 10 16:01:25 2024 UTC	Thomas Lindner
	mPMT.2.1.1-02372	SN212185	SoM	mPMT-TRI-00101	Enclustra	XU1	Shipped	TRIUMF	Det Fac	Thomas Lindner	Thu May 2 21:23:46 2024 UTC	Thomas Lindner
	mPMT.1.1.4-00038		Backplate	mPMT-TRI-00101	Summit Custom Machining		Shipped	TRIUMF	Det Fac	Nane Vardanyan	Tue May 7 18:52:36 2024 UTC	Thomas Lindner
	mPMT.1.1.2-00034		Clamp ring	mPMT-TRI-00101	Summit Custom Machining		Shipped	TRIUMF	Det Fac	Mohit Gola	Fri May 10 17:19:11 2024 UTC	Thomas Lindner
	mPMT.1.1.3-00034		Cylinder	mPMT-TRI-00101	Summit Custom Machining		Shipped	TRIUMF	Det Fac	Mohit Gola	Thu May 9 16:26:28 2024 UTC	Thomas Lindner
	mPMT.2.2.1-01115	e280116060000218e3224544	HVBoard	mPMT-TRI-00101			Shipped	TRIUMF	Det Fac	Robert Kurjata	Wed Apr 17 06:39:35 2024 UTC	Thomas Lindner



- A custom construction database was prepared to track all mPMT components and assembled mPMT information
- All QC information stored in the database
- Web interface and identification and tagging of parts with QR codes

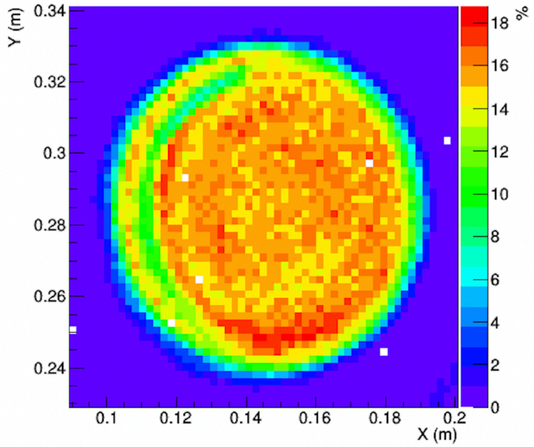
mPMT Testing

- Dark box built with motorized stages to scan pulsed light source over mPMTs or single PMTs
- Used to study aspect of photon detection such as effect of reflectors
- QA for PMTs after bases are soldered
- QA for mPMTs after assembly

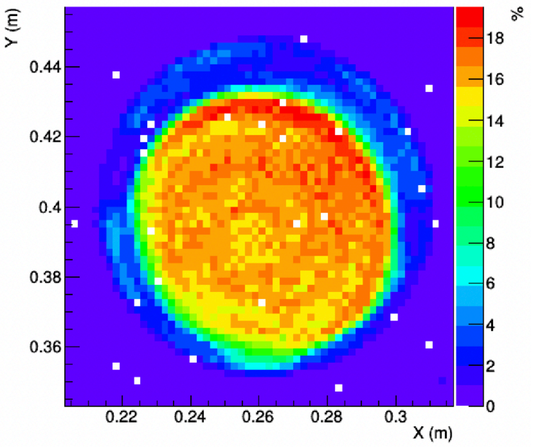


Photon Detection Rate

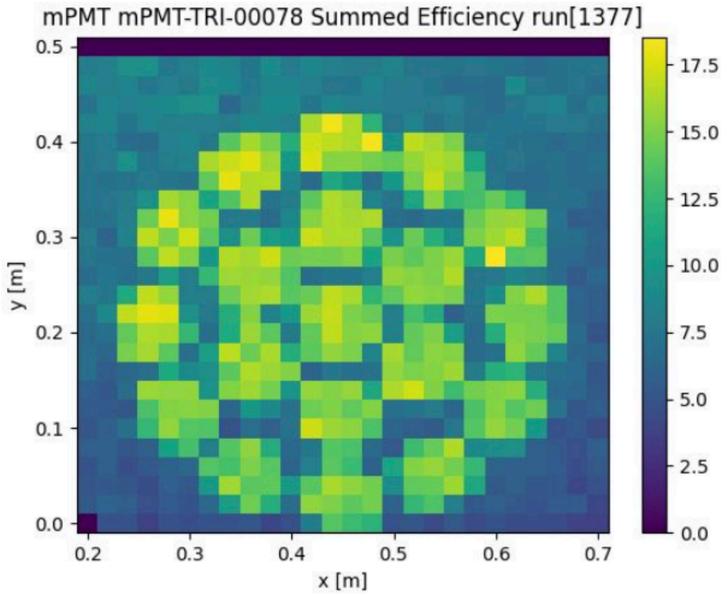
With Reflector



Without Reflector

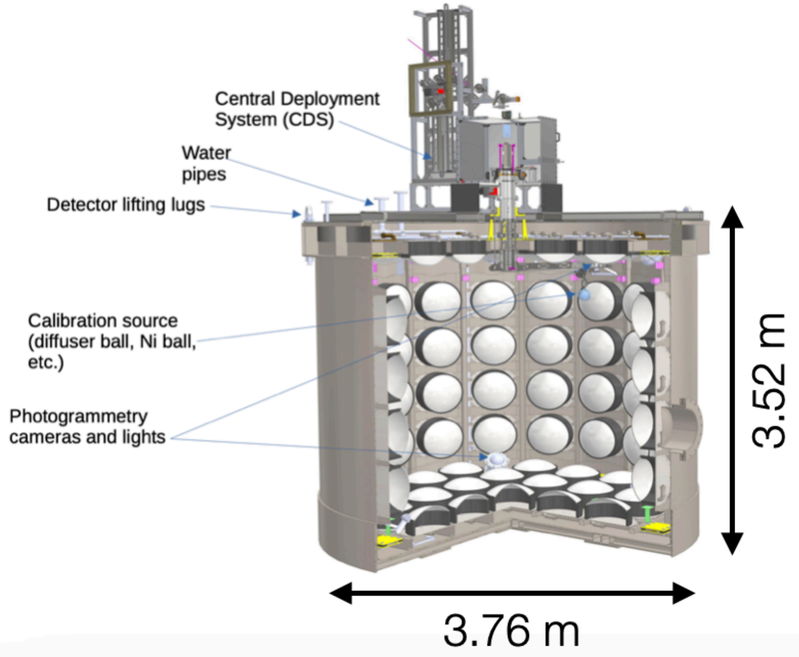


Scan of Assembled mPMT

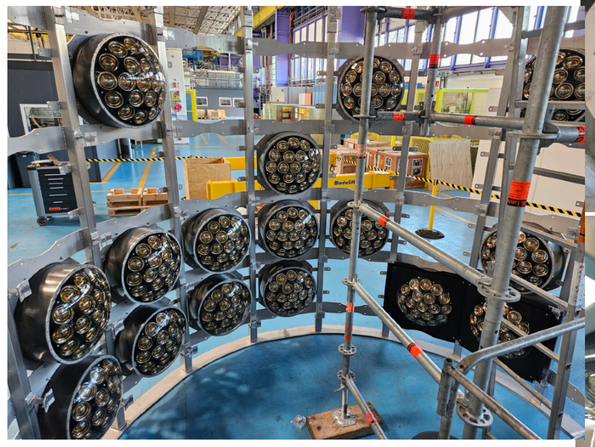


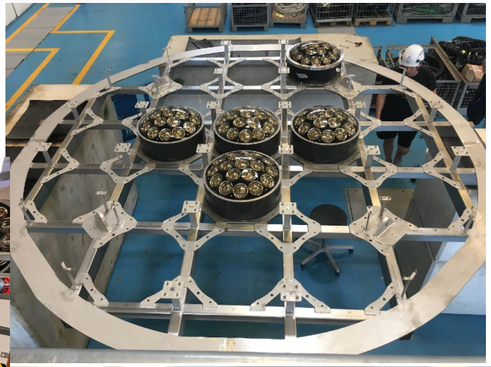
mPMTs Ready to Ship

Application in WCTE



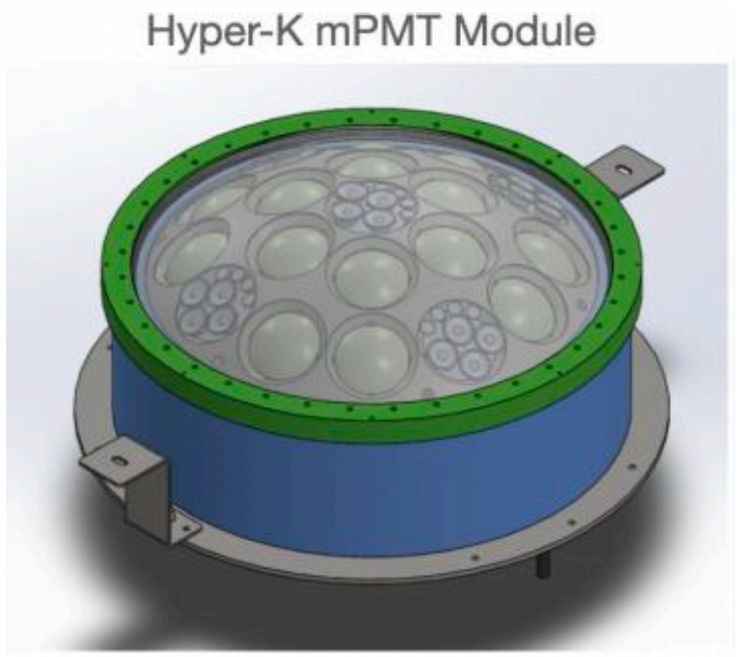
- Initial installation and operation of mPMTs in Water Cherenkov Test Experiment (WCTE) at CERN
- Will operate in T9 test beam line from October 2024
  - Injection of μ, π, e, p, γ at momenta of 200-1200 MeV/c
- 50 mPMTs built at TRIUMF being installed now
- Operation of WCTE from Oct. 2024 to ~June 2025
  - Beam in Oct.-Dec. 2024 and at beginning of 2025 beam operations
- Based on WCTE experience, mPMT design for IWCD will be optimized and finalized
- After WCTE, at TRL 7 or 8 - implementation and operation





mPMTs in Hyper-K Detector

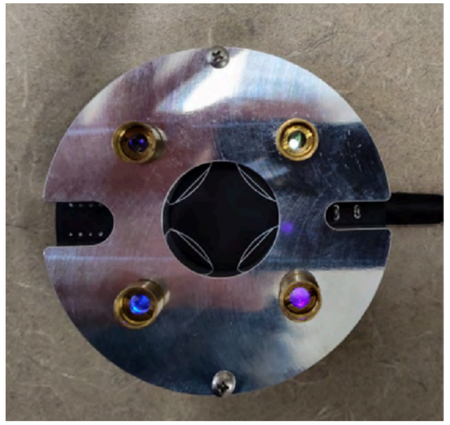
- Result of mPMT development by TRIUMF and collaborators → mPMT cannot compete with the Hamamatsu 50-cm diameter PMT for the main Hyper-K photon detection system
- 10,000 50-cm diameter PMTs will be installed in the Hyper-K detector as the main photon detection system
- Is there still a need for mPMTs in Hyper-K detector? Yes, they can play a role in calibration!

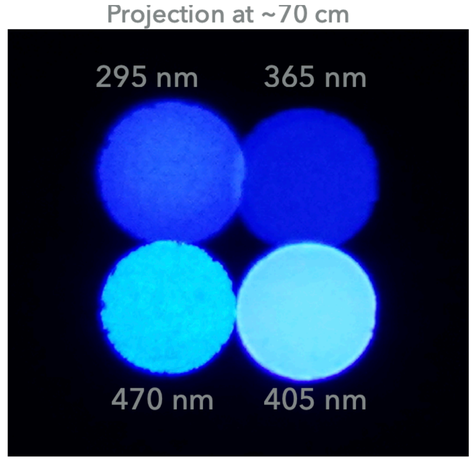


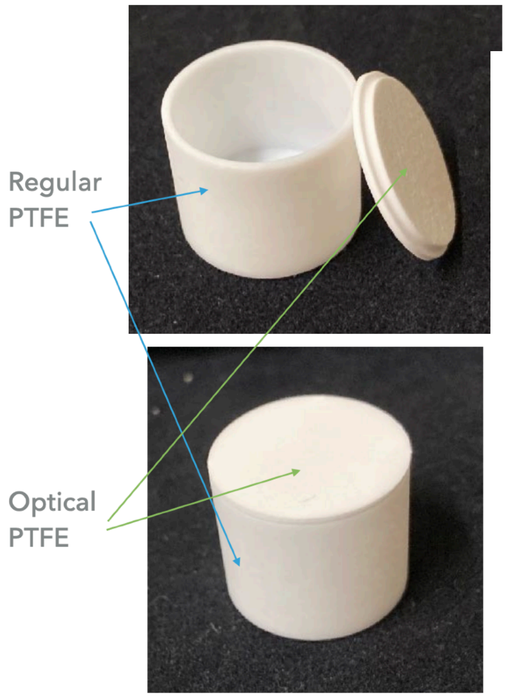
- 5 PMTs are replaced with boards containing diffuse and collimated pulsed LED light injectors
  - Collimated light to study photon scattering in water
  - Diffuse light for in-situ measurement of 50-cm PMT angular dependence
- mPMT itself provides measurements that can be compared to 50-cm PMT
  - Well understood angular dependence with insensitivity to magnetic fields

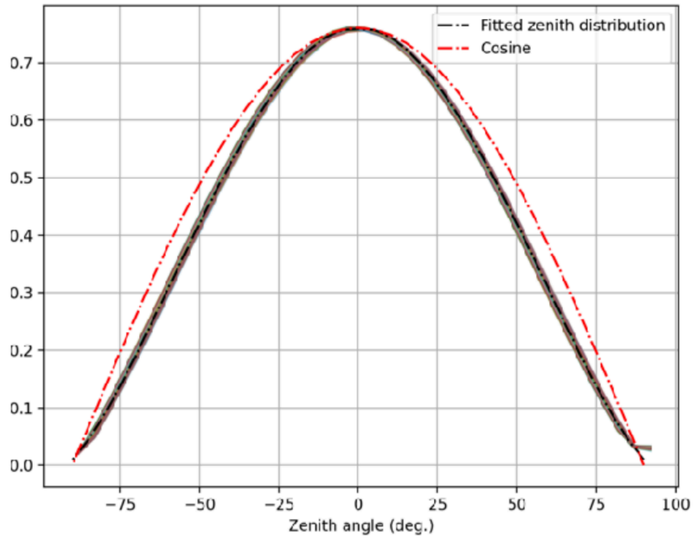
Ongoing Developments

- Carleton U. team is leading the development of the Hyper-K mPMT in Canada
- Development of pulsed LED circuit at U. Victoria by N. Braam
  - Same LED driver being used in water quality monitor project at TRIUMF (A. Konaka)
- TRIUMF is involved in the development and testing of collimators and diffusers (X. Li, P. Lu)
- Four modules built in Italy without the LED light sources will be operated in WCTE from this October









Summary

- The development of the mPMT for IWCD has been a Canadian-led project with a major role played by TRIUMF
- Since ~2016, have moved from TRL of 1 to first large-scale deployment in WCTE this autumn
- The mPMT has been further developed as a calibration device for Hyper-K
- Canada will build ~250 mPMTs for IWCD and 200 for Hyper-K
- mPMT project for IWCD and Hyper-K naturally connects to other experiments such as neutrino telescopes
  - Use the same or similar photomultiplier tubes
  - Calibration methods and LED-based light injectors are common needs