Development of Optical Modules Based on WLS Plates and PMTs for Cherenkov Detectors

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WLS/PMT Modules

Module = PMT + WLS-plate for Cherenkov light collection

- increase light collection efficiency
- Allow use of smaller PMTs
- Less expensive than more PMTs

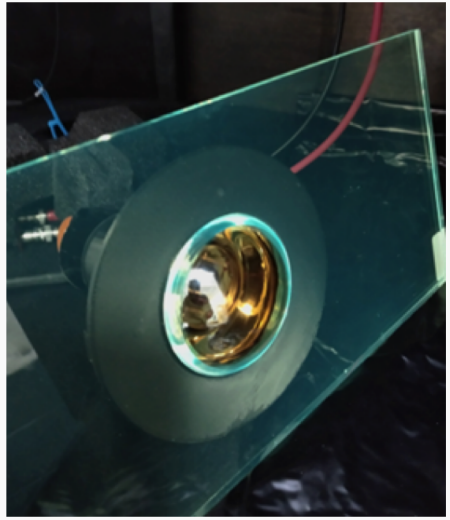
PMT at R&D

- 3-inch (8 cm) Hamamatsu R14374

WLS-plates at R&D

- Manufacturer: Kargin Polymer Research Institute, Dzerzhinsk, Russia
- Base: PMMA (acrylic glass)
- Chemistry: Bis-MSB, EJ286, BBQ, **POPOP and PPO + POPOP** (concentration is given in mg/L)

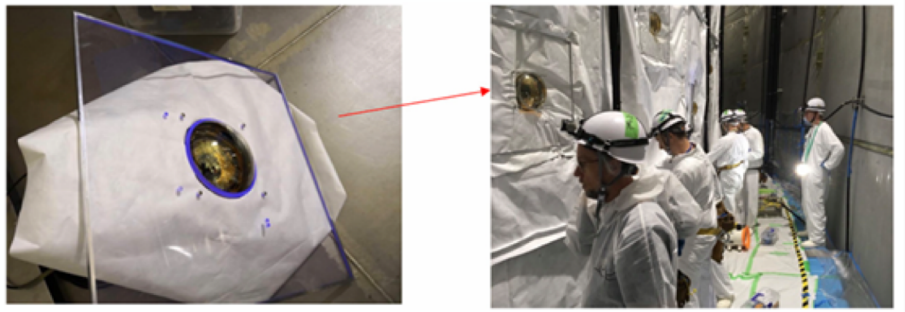






Optical modules for water Cherenkov detectors

The concept for such optical modules was proposed in 1987. They were used in the SuperKamiokande outer detector and are planned for use in HyperKamiokande. The use of these modules in other experiments involving the detection of Cherenkov light is also being discussed



WLS/PMT modules at SuperKamiokande

WLS Plate proposal from 1987

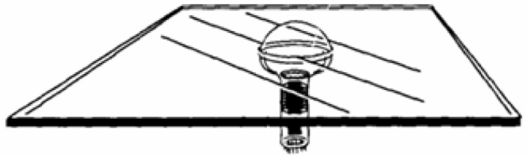
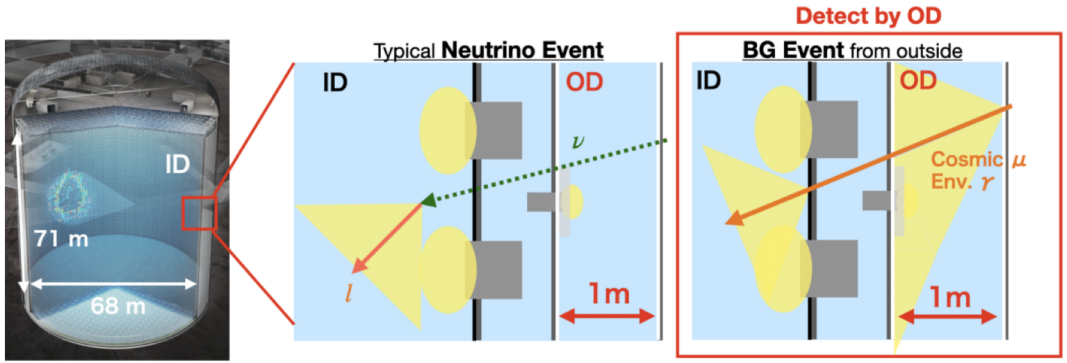


Fig. 1. Photomultiplier tube with waveshifter plate.

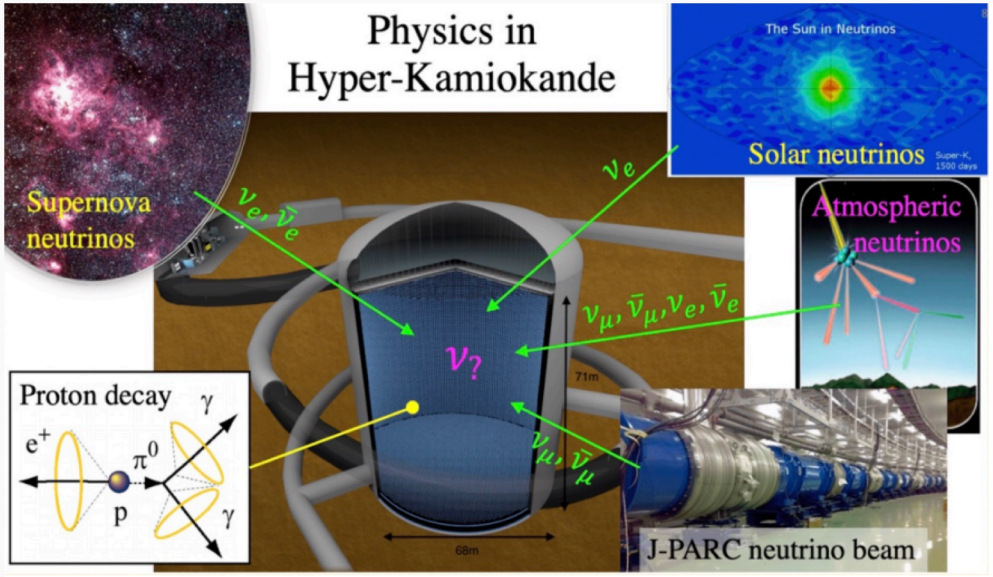
In their present application, waveshifter plates increase the mean singles rate in the counters by about 2 kHz. Some other compounds which have fluorescence spectra comparable to those of bis-MSB (notably BBOT and BBQ) generate mean noise increases as small as 0.4–1 kHz, although the light collection enhancement which they achieve is only 70–80% of that reported here. Nevertheless, for low noise applications one of these compounds may be preferable.

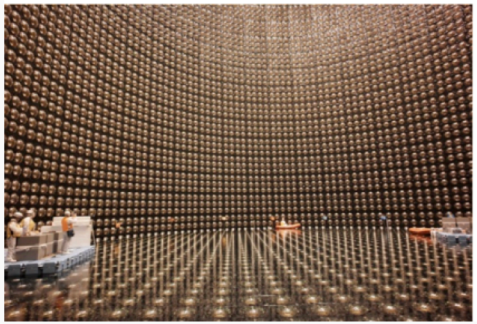


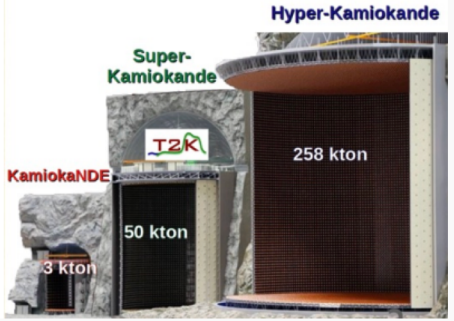
Scheme of Outer Detector HyperKamiokande

HyperKamiokande

- The largest water Cherenkov tank ever under construction in Kamioka, Japan
  - Data-taking start expected in 2028
- Rich physics program, within 10 years aim for
  - Accelerator neutrinos from J-PARC (T2K beam)
    - searching CPV
    - Atmospheric + beam neutrinos for MO
  - Solar neutrinos
    - >5σ for D/N asymmetry
    - “Upturn” region in vacuum→ MSW
    - hep neutrinos
- SN neutrinos
  - Discriminate between models
- Proton decay
  - Reach > 10^{35} years
- BSM, NSI, steriles

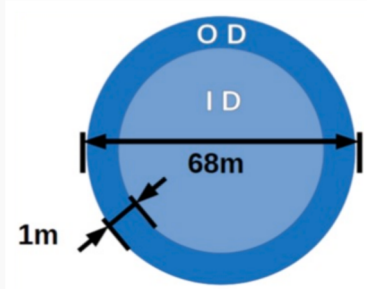




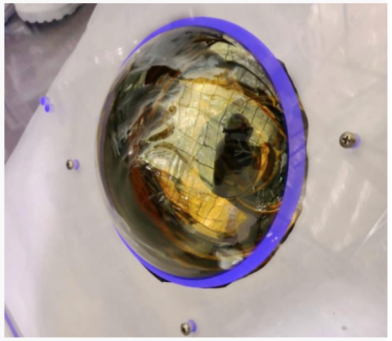


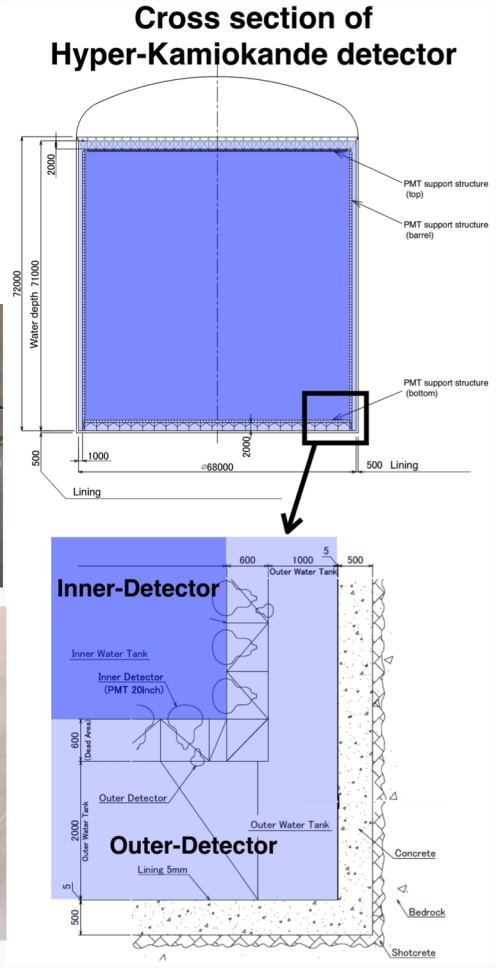
Outer Detector

- Optically separated ID and OD
- Challenges (wrt SK)
  - Shallower overburden 1000m → 600m
  - Larger HK volume
    - Cosmic rate 2Hz → 45 Hz
  - Narrower OD region
    - 2.6/2.7m → 1/2m (caps)
- Performance requirements
  - **Veto inefficiency 10^{-6}**
  - ~4m accuracy of muon exit/ entrance positions
  - Provide passive backgrounds shield
  - **Low radioactivity** < 10mBq (ID&OD)
  - Thermal power < 1W per channel
  - **Longevity and enough redundancy**→ operation for decades + high-cost of draining and intervention
- Light-collection
  - **3.6k** 8 cm PMTs
  - **Tyvek coverage on walls**
  - **WLS plates**









Selection of additives

- **Double fluor** to accept Cherenkov light in wide spectral range 250-400 nm
- **Bis-MSB**: **lower re-emission efficiency than POPOP**. Bis-MSB advantage to dissolve in a base material. Manufacturer tests: total polymerization times in PMMA with POPOP and bis-MSB is about the same
- **PPO fluor** with high concentration 10 g/L shows shorter attenuation length wrt 3 g/L, and lower light signal Published data indicate the flat light signal dependence on PPO concentration in range 3-7 g/L
- **POPOP** concentration of 50 mg/L gives advantage in short UV range 250-320 nm, while with POPOP concentration of 200 mg/L signal gain in long UV range 320-400 nm
- **The optimum dopant composition was found to be: 50 mg/L POPOP + 3 g/L PPO ?!**



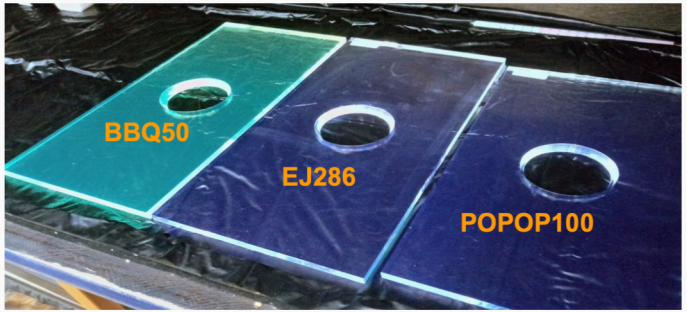
Fast UV LED light sources from PicoQuant
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

Tests with LED source in air and water

WLS plates	BBQ 50	BBQ 100	bis-MSB 50	bis-MSB 100	POPOP 100	POPOP 200	POPOP 400	POPOP 100 PPO 10000	POPOP 800 PPO 5000	EJ286
FOM	2.91	3.34	3.81	3.83	4.38	4.64	3.80	5.89	4.60	3.34

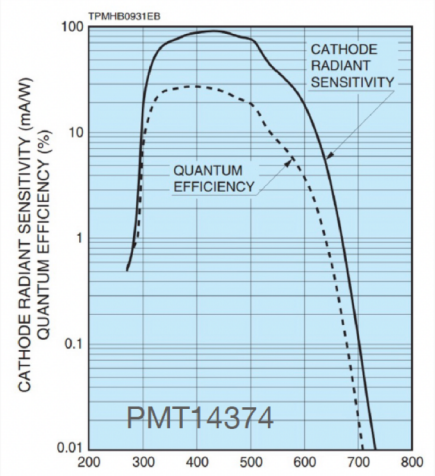
$$FOM = 0.45*R.L.Y._{(250\text{-}300nm)} + 0.32*R.L.Y._{(300\text{-}350nm)} + 0.23*R.L.Y._{(350\text{-}400nm)}$$

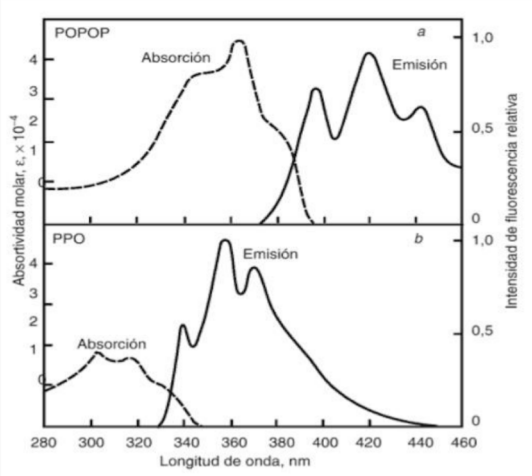
- 0.45, 0.32 and 0.23 — fractions of emitted Cherenkov light spectrum within a range
- R.L.Y. — measured relative light yield (fraction of photons converted in photoelectrons) for a range

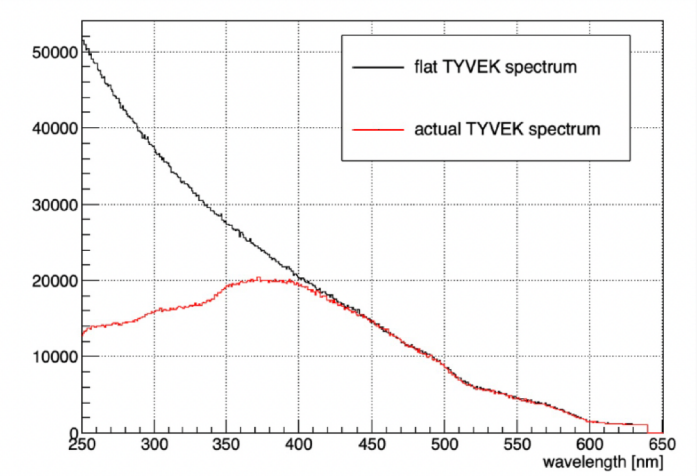


Selection of additives

- WLS works where we have short UV to be shifted and re-emitted to region of higher PMT efficiency
- First PPO+POPOP-based design is optimized for < 400 nm light collection
- But Cherenkov spectrum gets modified after reflections: Tyvek presence and properties define the resulting spectrum
- If short UV portion is significantly decreased then **POPOP without PPO** chemistry composition may be optimal

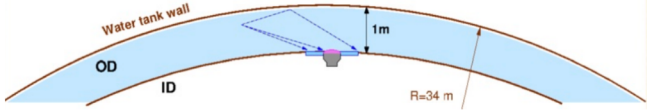


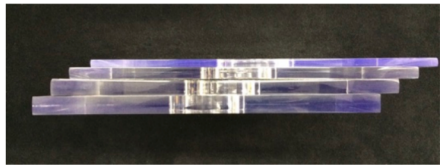


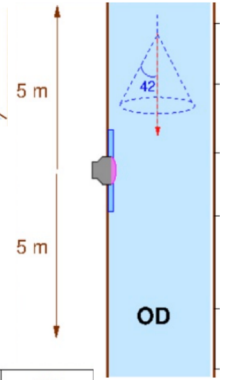


WLS-plates geometry

Based on the simulation and measurement results, the optimal plate thickness is **7 mm**

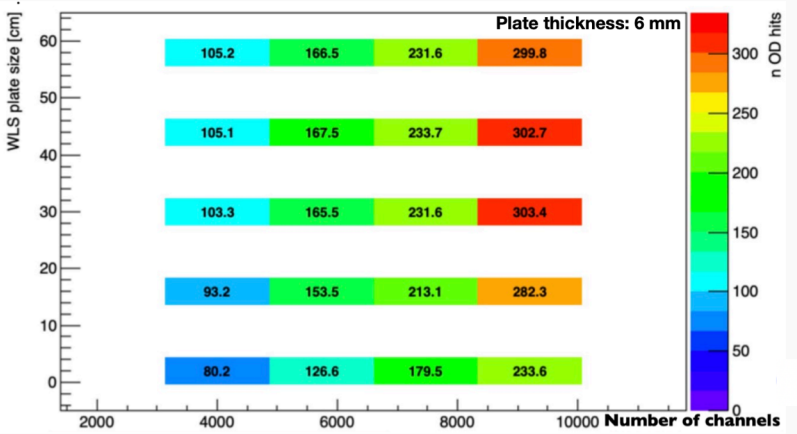


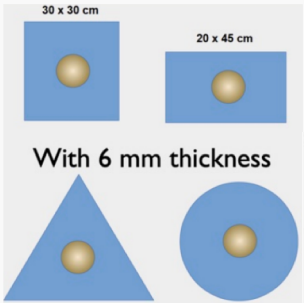




WLS plate thickness	4 mm	6 mm	8 mm	10 mm	13 mm	16 mm
Detection efficiency	2.8%	3.0%	2.8%	2.8%	2.7%	2.3%

Simulation of the OD response to cosmic muons showed that increasing the size of the WLS plates beyond **30 × 30 cm²** does not lead to an increase in the efficiency of the OD



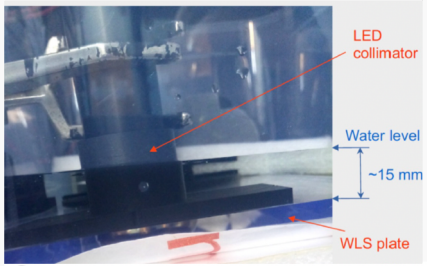


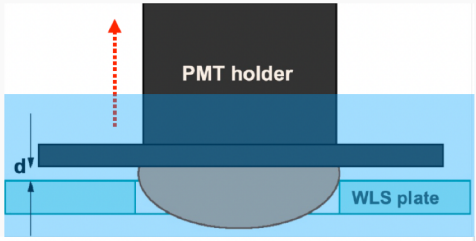
Square, triangular, and rectangular plates showed similar results. Round shape reduces light collection by 40%

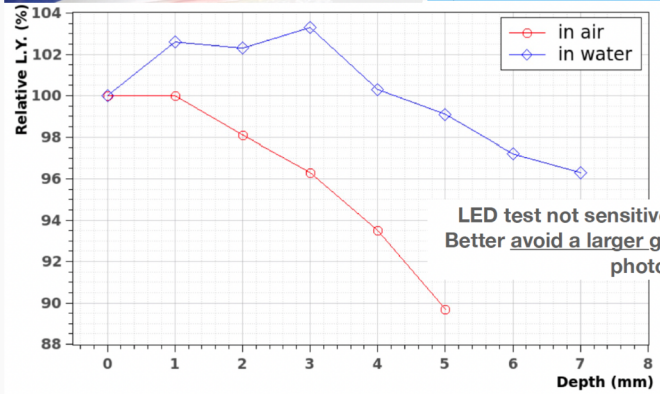
7 x 300 x 300 mm³

Shapes	Square 30x30 cm	Rectangle 20x45 cm	Rectangle 15x60 cm	Triangle	Circle
Relative light signal	100 %	99 %	97 %	99 %	62 %

WLS-plates geometry





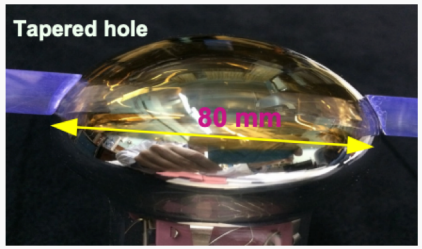


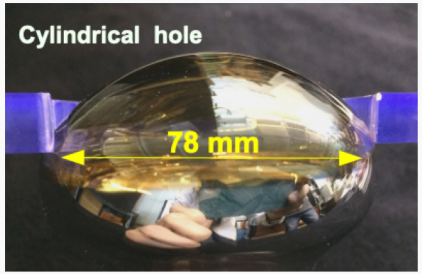
- **d - seat depth**

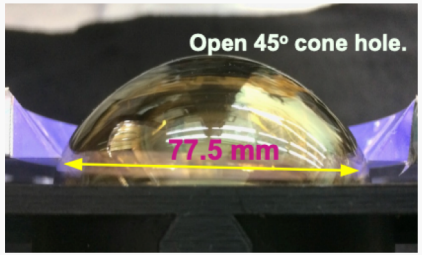
LED test not sensitive to direct light on PMT
Better avoid a larger gap so not to obscure the photosensor

PMT Seat Depth

- 100% at 0 mm, i.e. a direct contact between PMT and plate
- Signal signal remains stable with PMT raised up to 1 mm above the plate at air
- In water no signal drop up to few mm → aim at **~1 mm gap** in the final mount

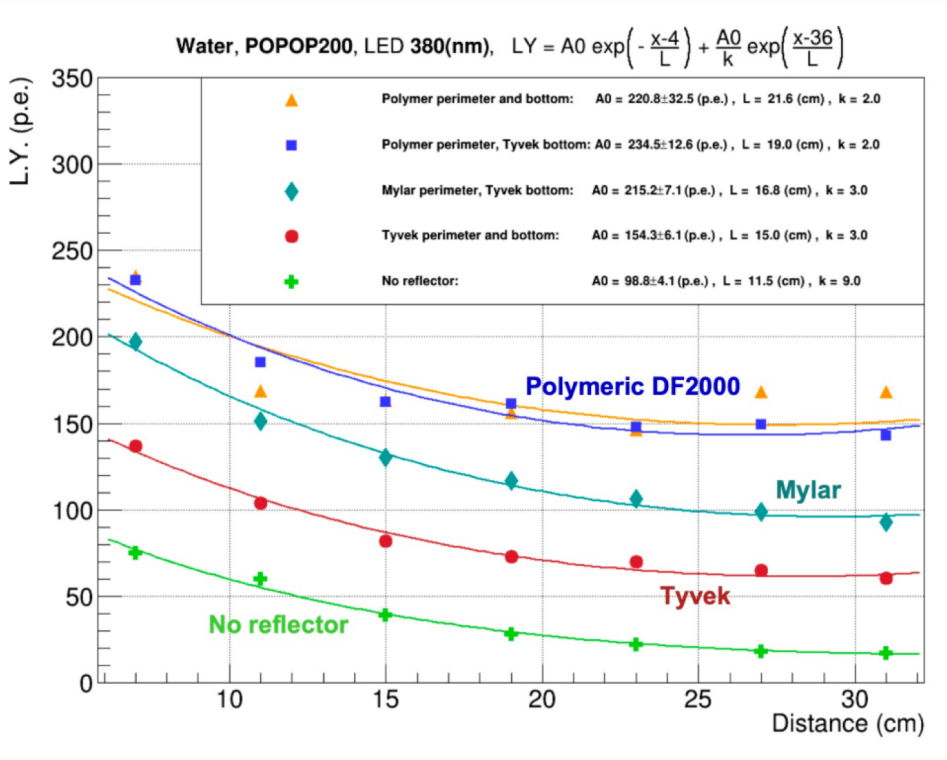


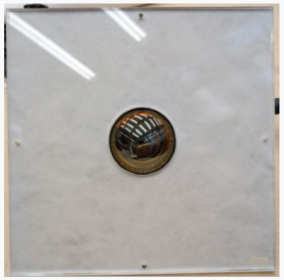


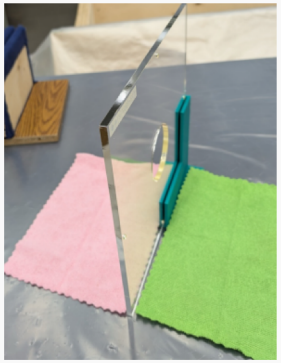


- **Tapered hole**
  - Match PMT hemispherical surface
- **Cylindrical hole**
  - Ease manufacturing ↓ cost
  - Photocathode open and Cherenkov photons not blocked
  - Less reflections back for reemitted photons
- **Open hole**
  - Enhance direct photon detection
  - Similar performance to cylindrical shape based on simulation of PMT-WLS plate in a water tank

Reflector for WLS-plates







The cladding reflector around plate edges was tested in water for 3 materials :

1) **Tyvek** (diffuse reflector);
2) **aluminized Mylar** (mirror reflector);
3) **polymeric film 3M DF2000MA** (mirror reflector).

Main results:

1) **Mylar increases** light signal almost by ~ **30%** comparing with Tyvek. The attenuation length becomes **~17 cm**.

2) **Polymeric film** increases light signal **more than 2 times** comparing with Tyvek. The attenuation length becomes **~20 cm**.

3) Bottom reflector under a WLS plate has little effect on light collection, the light gain is limited to **~10%**.

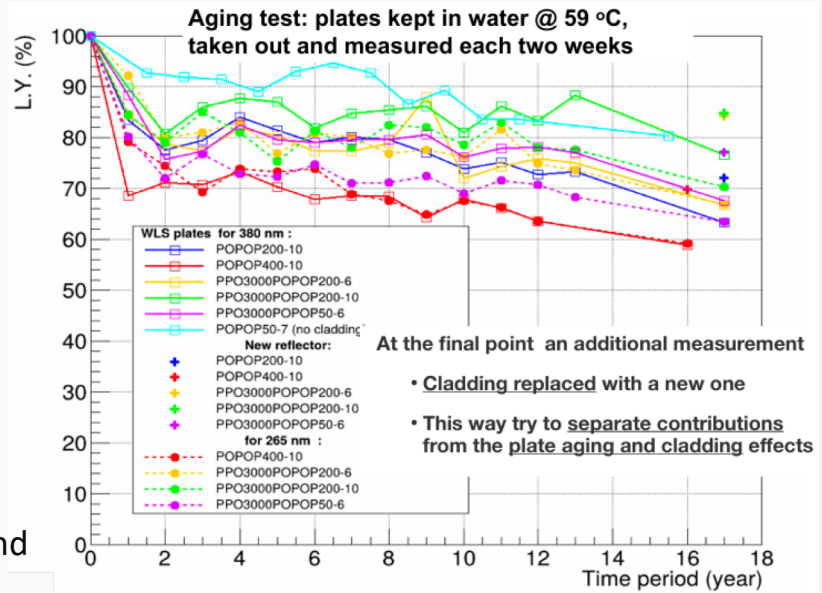
However, the bottom reflector creates the total reflection environment to collect visible photons (Cherenkov and re-emitted) on PMTs.

Accelerated Aging

Average aging rate in % per year

WLS plates	POPOP200 10 mm	POPOP400 10 mm	POPOP200/ PPO3000 6 mm	POPOP200/ PPO3000 10 mm	POPOP50/ PPO3000 6 mm	POPOP 50 7 mm No cladding	Average rate of aging
From 1st till last point with new cladding. 17 years	1.65	1.89	0.94	0.90	1.36	1.27	1.33
From 3d till last point with used cladding. 15 years	0.95	1.24	0.8	0.27	0.54	0.85	0.78

Second raw of aging rate excludes the first month of heating. In a such way we remove the temperature shock on the cladding.



- Aging rate <2%/year well consistent with expectations
- Gradual signal drop likely caused by **aging of PMMA** and not the fluor
- Cladding aging is negligible. Mechanical connection robust after the whole heating cycle*

*Aging test caveat: initial signal drop **after the first 4 weeks** of heating: cladding degradation ← air bubbles under the reflector tape

Tested plates:

POPOP200	— 10 mm thick	(blue)
POPOP400	— 10 mm thick	(red)
PPO3000/POPOP200	— 6 mm thick	(yellow)
PPO3000/POPOP200	— 10 mm thick	(green)
PPO3000/POPOP50	— 7 mm thick	(purple)
POPOP50	— no cladding, 7 mm thick	(light blue)

Production of WLS-plates

Polymerisation
(Example of a smaller plate)

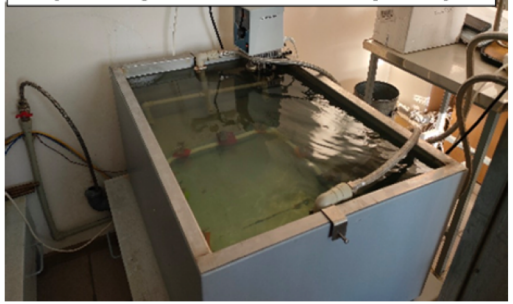
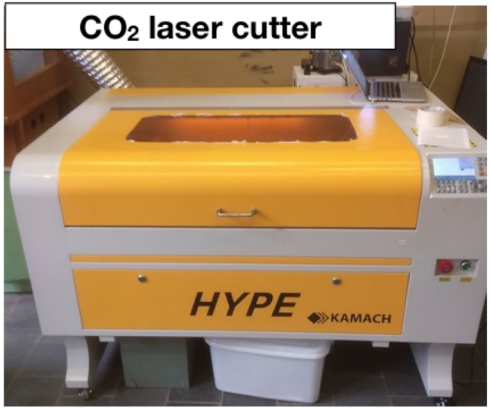


Plate billets



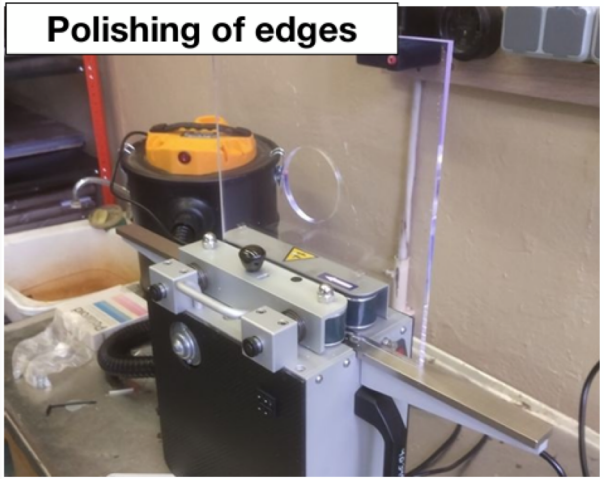
CO_2 laser cutter



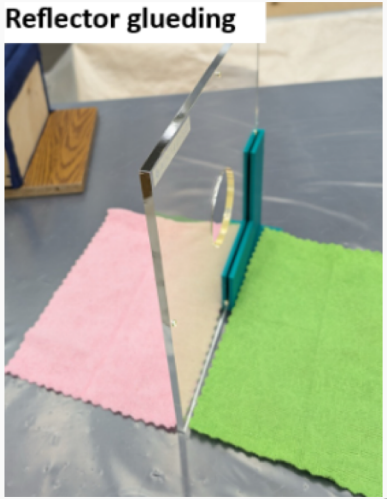
Plates and holes cutting



Polishing of edges

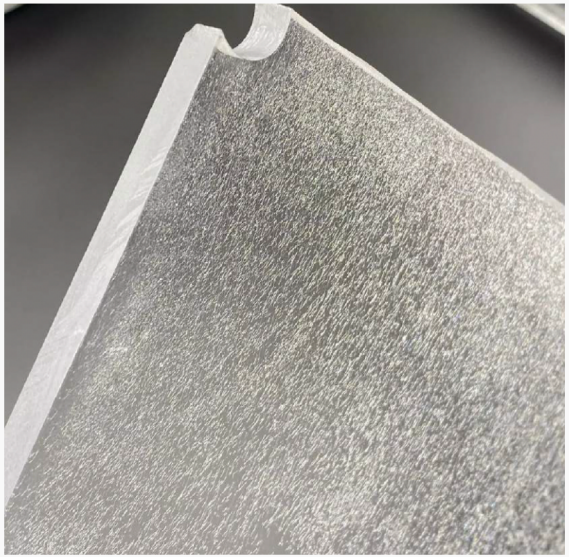


Reflector glueding

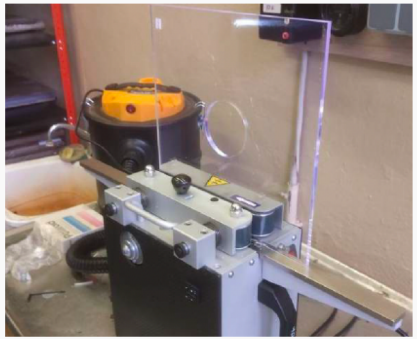


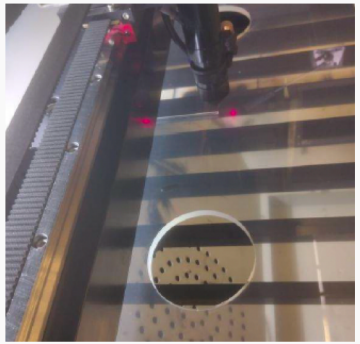
Crazing in Plexiglass

- Mechanical and/or temperature impacts on acrylic glasses can cause crazing
  - Crazing continues to grow in time after the initial impact
  - Crazing or "silver" (microcracks) formation
- Does not involve mechanical cracks but rather a change in the optical properties in the outer surface









- Can develop with time and deteriorate mechanical and optical properties of the plexiglass items
- Cutting of central holes is the main “suspicious” procedure as no additional manufacturing is involved afterwards and the surface remains intact after large temperature gradient

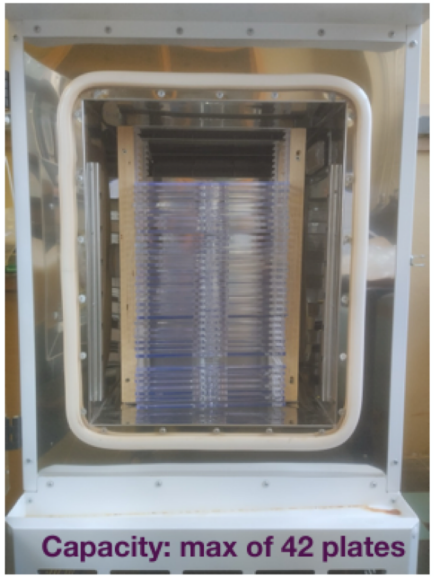
Crazing in Plexiglass

- Recommended procedure: annealing
  - Smooth heating up to 80 °C
  - 5-6 h exposure at 80 °C ← at least 0.5h/mm
  - Smooth cooling down to room temperature

WLS plates	POPOP50 12 pcs	POPOP800 5 pcs
Average L.Y. change	+ 0.4 %	- 3.5 %

Light signal with 380 nm LED + PMT before and after annealing

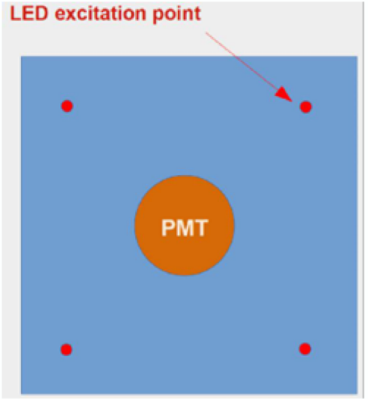


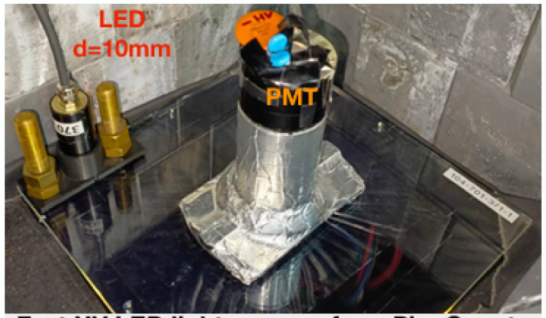


- Procedure during plates production
  - Plates put inside a heater in the morning
  - Slow heating up; then ~5-6 h exposure at 80 °C
  - Heater turned off, plates cool down overnight

Light signal checks

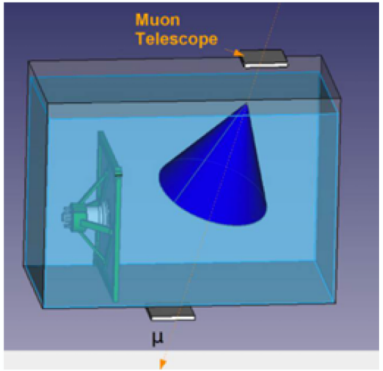
Two main methods to check WLS+PMT module performance

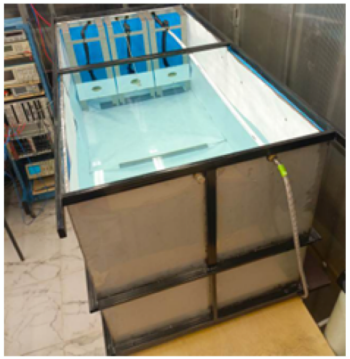




Fast UV LED light sources from PicoQuant
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

Infant-K setup to test PMT+WLS plate modules with Cherenkov light





- **PicoQuant sub-nanosecond LEDs**
- **Infant-K 110 litres + 2 tonnes Toddler-K**

- Collimator d=10 mm
- WLS plate performance at a known wavelength
- Additional setup to immerse a plate into water
- Average the results with LED at different positions

- Water Cherenkov test detectors
- Cosmic trigger, controllable muon range
- Direct and reflected Cherenkov light
- Option to put Tyvek on walls

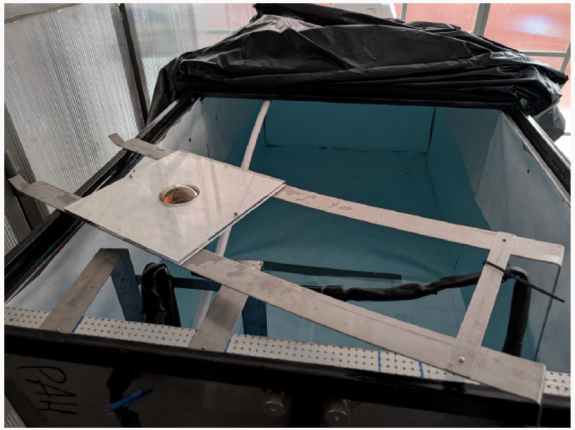
Toddler-K

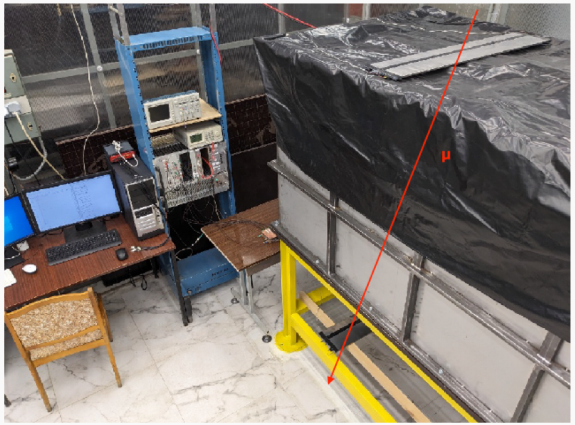
- Three-modules setup
- Full PMT+WLS OD modules
- Walls covered with (removable) Tyvek (1082D) panels
- Cosmic triggers to enhance direct and reflected Cherenkov light

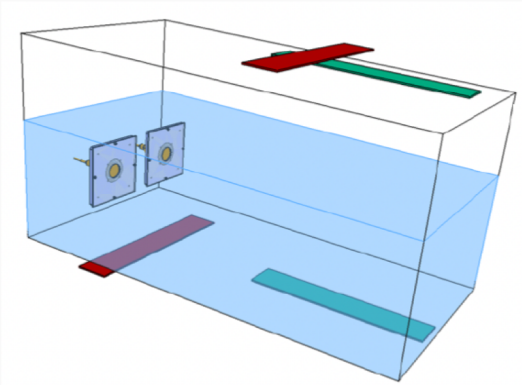
Two triggers:

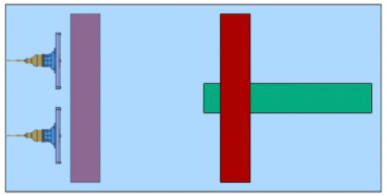
- Tyvek reflected light
- Direct Cherenkov light

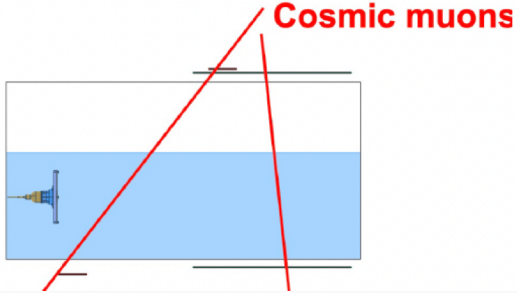




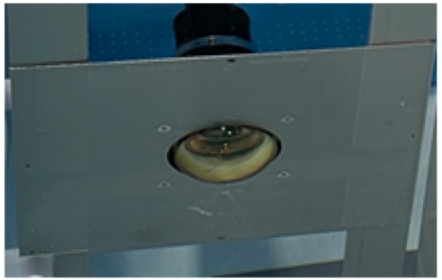




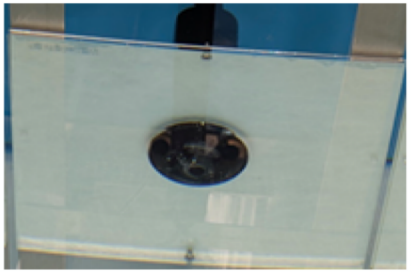




Light signal



Bare PMT



Plate+PMT+cap



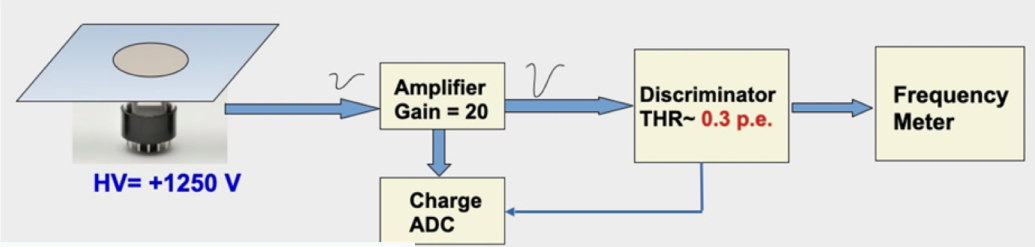
Plate+PMT

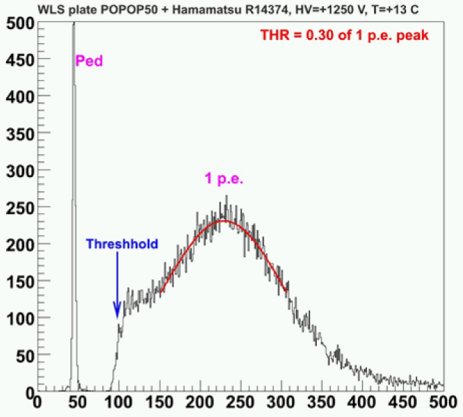
Toddler-K Setup with Cosmic Muon Trigger, Reflected Light 1082D Tyvek on Walls Plates with Edge Reflector 3M DF2000MA and Tyvek at Back Side PMT: Hamamatsu R14374				
Plate	Signal, PMT, p.e.	Signal, Plate, p.e.	Total Light Increase	Rel. Signal
POPOP400 (12.23)	26.3	33.5	×2.27	100%
POPOP50 (05.26)		**31.9**	**×2.21**	**95%**
POPOP50 (2024 best)		32.2	×2.22	96%
POPOP50 (2024 "average")		30.7	×2.17	92%
POPOP50 (2024, rejected)		24.8	×1.94	74%
PPO3000+POPOP50 (2023)		25.5	×1.97	76%

> x2 increase in the collect light with WLS plate

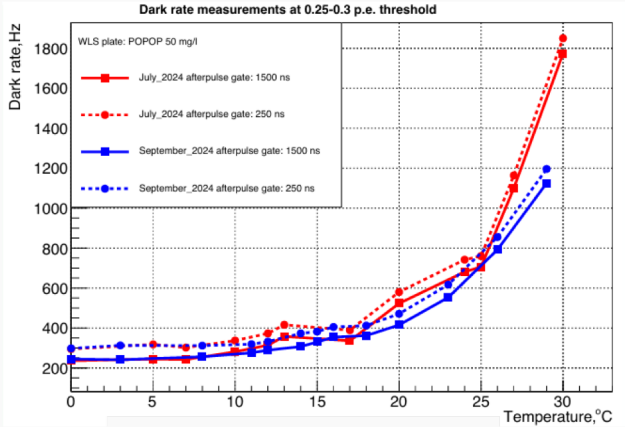
Dark rate

- Measurements inside a dark box and **inside a thermostat**
- 0–30 ^{o}C settings
- Not a precise control: ~2-3^{o}C spread over the box
- Threshold adjusted based on the 1 p.e. ADC spectrum
- Discriminator gate to suppress “after-pulses”: 250 ns mostly
- Plates measured with 3M DF2000MA edge reflector





1 p.e. ADC distribution: threshold adjusted to ~0.3 p.e.



POPOP50 plate measured twice

- *Discriminator gates: 250 ns and 1.5 μs*
- *Two measurements separated by 30 days with the plate kept in darkness in between*

Dark rate for Different plates

- Dark rate is an important parameter affecting capabilities of the detector to suppress backgrounds
- There are different contributors to the total rate
  - PMT itself
  - Reflections from the plate
  - Ambient radiation
  - Some (chemical) processes in the plate itself

Contributors to dark rate of PMT+WLS module. Threshold: 0.25-0.3 p.e. Temp: ~13-14 °C. R14374.

WLS Plate	Dark Rate, Hz
Bare PMT	200
Reflected PMT photons	50
Background in lab	100
Originated in WLS plate	150
Total POPOP400	**500**

Dark-rate measurements of PMT+WLS module. Threshold: 0.25-0.3 p.e. Temp: ~13-14 °C. Hamamatsu R14374. Dead time to suppress afterpulses: 250 ns.

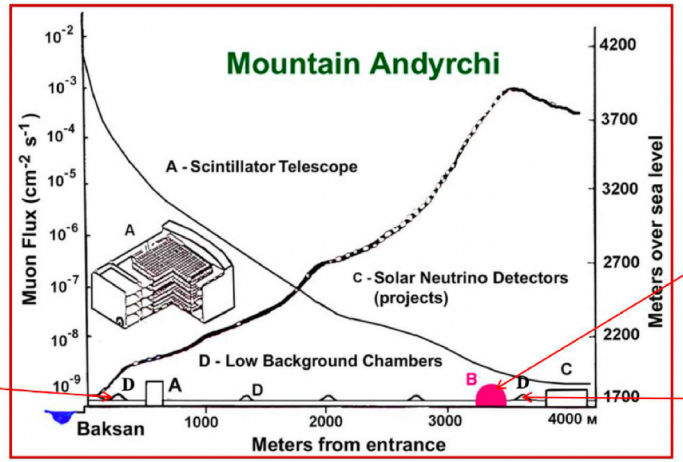
WLS Plate	Dark Rate, Hz
Bare PMT	200
POPOP800	750
POPOP400	500
POPOP200	400
POPOP50	350
POPOP50/PPO3000	650

Dark-rate measurements of PMT+WLS module. Threshold: 0.25-0.3 p.e. Temp: ~13-14 °C. Hamamatsu R14374. Dead time to suppress afterpulses: 250 ns.

WLS Plate	Dark Rate, Hz
Bare PMT	200
PMMA w/o WLS	250
POPOP50	350
POPOP400	500

Radiopurity Checks and Baksan Laboratory

- Radiopurity checks were done in INR Baksan underground laboratory in Caucasus mountains
- Site of SAGE Ga-Ge solar neutrino exp. and Baksan Scintillator Telescope



Chamber D NICA used for measurements 660 m.w.e.

Global Intensity
$(3,0\pm0,15)\cdot10^{-9}$ μ cm$^{-2}\cdot$ s^{-1}
~ 4800 m.w.e.

SAGE/BEST

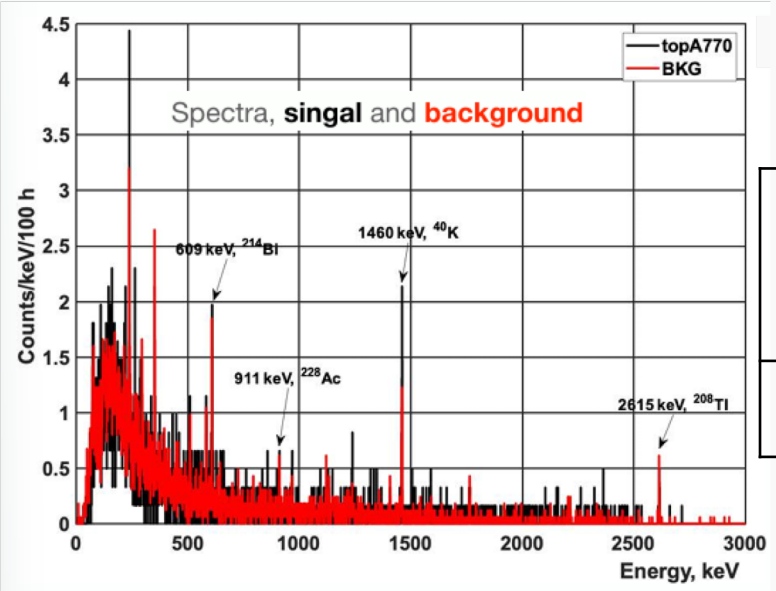
Low background Chamber D

Schematic view of a section of the Andyrchy slope along the adit (write scale) and dependence of underground muon flux on the laboratory location depth (left scale).





Plates Radiopurity



Sample POPOP400 measured ~600 hours

Sample	Isotopes			
	^{226}Ra(^{214}Bi)	^{228}Ac(^{232}Th)	^{40}K	^{208}Tl
	Activity			
POPOP 400	**≤ 3 mBq/kg (90% C.L.)**	≤ 5.4 mBq/kg (90% C.L.)	20±10 mBq/kg	≤ 1.5 mBq/kg (90% C.L.)

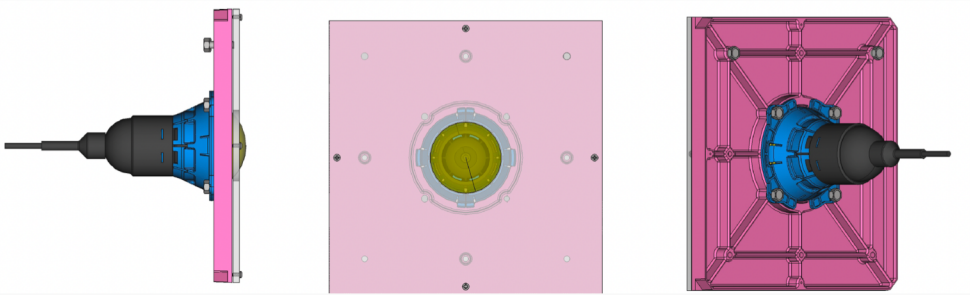
Rn emanation at background level

Sample type

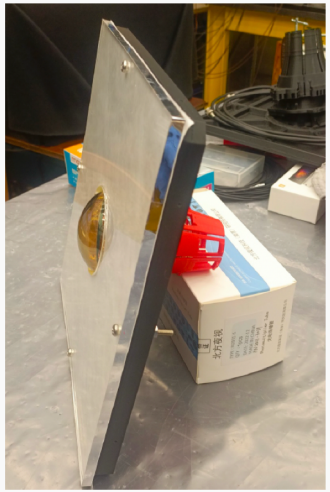
Mass, g	Size, mm	Composition	Structure	Shape
450	100x100x38	$(C_5O_2H_8)_n$	Solid	Squared

Optical modules R&D for HyperK

- PMMA based WLS plates
  - Fluor concentration: **POPOP 50 mg/l**
  - Manufacturer: Kargin Polymer Research Institute (Dzerzhinsk, Russia)
  - Plate size: **7x300x300 mm³**
  - Holes for PMTs: cylindrical, 78 mm diameter
  - PMT primary option: 3-inch Hamamatsu R14374
  - Cutting/polishing: CO2 laser cutting and polishing machine for edges
  - Reflector: **polymeric film 3M DF2000MA**, adhesive side + **Tyvek at the back side**
  - Dark rate: **less 400 Hz** (13 °C expected inside Hyper-K)
- **>x2** increase in light collection







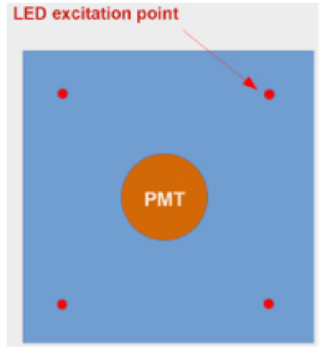
Summary

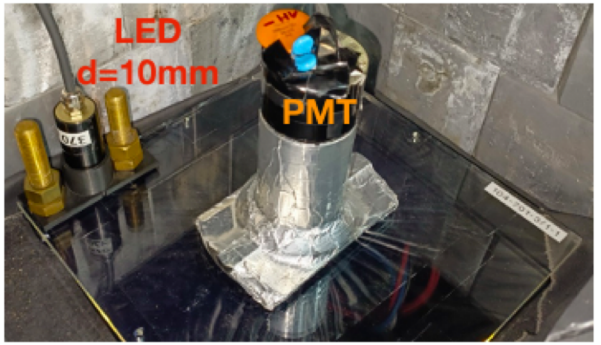
- Using WLS-plates in combination with PMTs makes it possible to **more than double** light collection
- For **POPOP50** plates **dark rate less than 400 Hz**
- WLS-plates **aging** rates **less than 2%:**
- Using **polymer film** reflector on edges of WLS-plates makes it possible to **double the light collection**
- Modules have **low level of self-radiation** and can be used at low-background experiments
- Assembly of such optical modules for the HyperKamiokande OD is scheduled to begin in **October 2026**

Backup

Light signal

Tests with LED

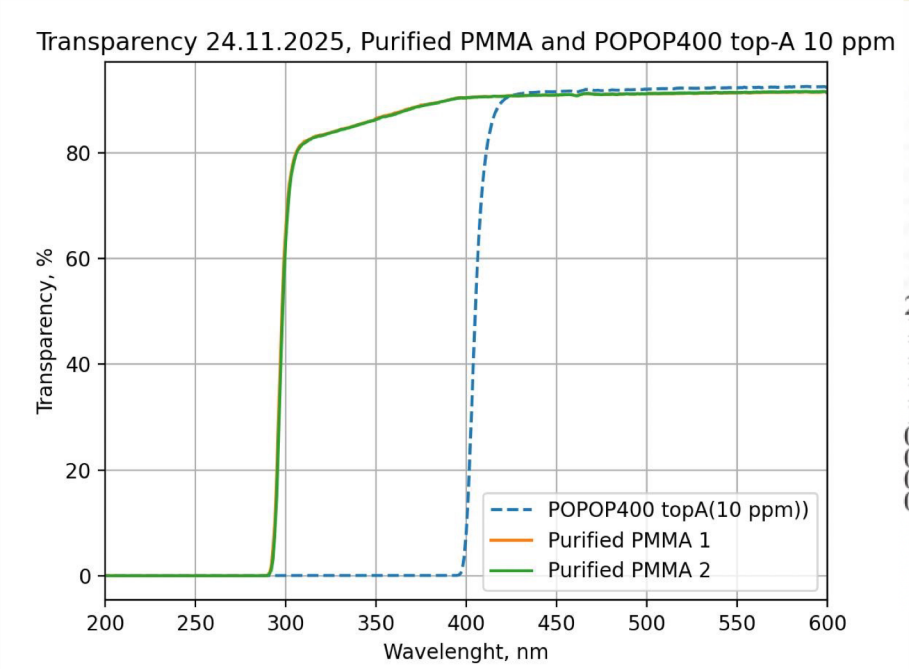


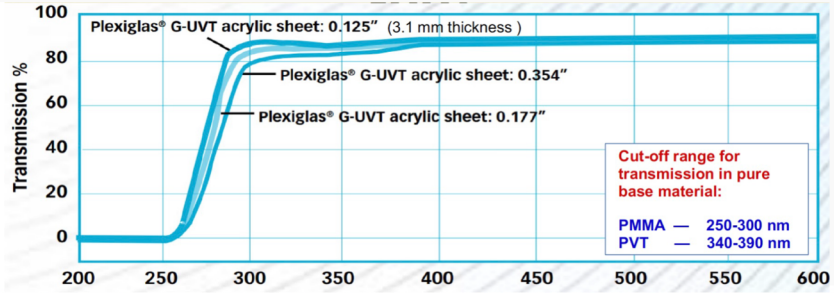


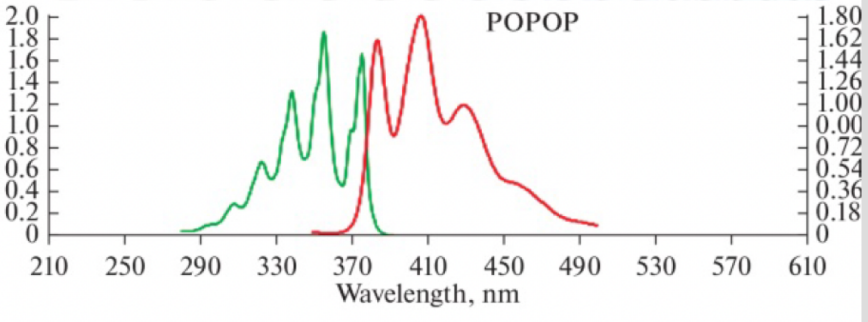
LED wavelength	265 nm	315 nm	380 nm	405 nm
POPOP 800 (2 plates)	100 %	100 %	100 %	100 %
POPOP 400 (5 plates)	96 %	112 %	114 %	107 %
POPOP 50 (4 plates)	71 %	71 %	79 %	42 %
POPOP 50 — PPO 3000 (4 plates)	95 %	54 %	70 %	35 %
KURARAY B-2 (1 plate)	63 %	86 %	100 %	115 %

WLS-plates: base

Produced batches w/o fluors and made sure the base matrix is of a good quality and well-transparent for our needs







Performance of WLS-plates

Dark Rate

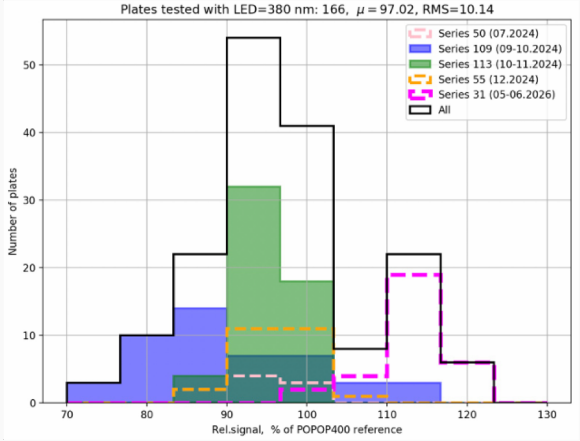
Dark rate @ 0.3 p.e. and 14-15°C PMT: Hamamatsu R14374 with edge reflector 3M DF2000MA POPOP50 plate (7.5 ppm top-A, new polymerisation) **Production date: 07.05.2026**	
Measurement date	Rate, Hz
25.05.2026	1180
29.05.2026: after annealing	850
16.09.2026	**392**

Dark-rate measurements of PMT+WLS module. Threshold: 0.25-0.3 p.e. Temp: ~13-14 °C. Hamamatsu R14374. Dead time to suppress afterpulses: 250 ns.	
WLS Plate	Dark Rate, Hz
Bare PMT	200
POPOP800	**750**
POPOP400	**500**
POPOP200	400
POPOP50	**350**
POPOP50/PPO3000	650
Kuraray B-2	350

Reference measurements back in 2024

Light signal

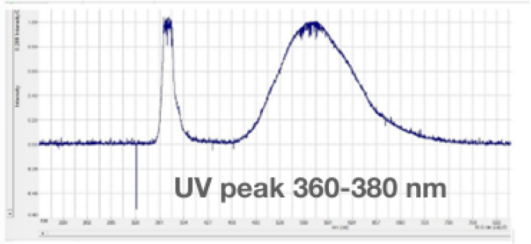
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Plate	Signal, PMT, p.e.	Signal, Plate, p.e.	Total Light Increase	Rel. Signal
POPOP400 (12.23)	26.3	33.5	×2.27	100%
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POPOP50 (2024 "average")		30.7	×2.17	92%
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PPO3000+POPOP50 (2023)		25.5	×1.97	76%

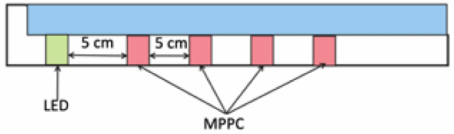


Fast QA Tests with MPPC

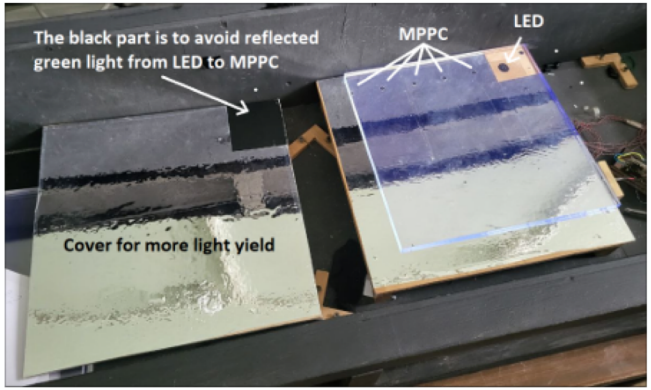
- Use a test-bench with MPPCs and a LED source

Effect signal/no signal		
	UV-LED	Green-LED
With POPOP and PPO	+	-
Without POPOP/ PPO	-	-





LED is aligned with MPPCs to avoid direct green light hitting MPPCs



Only re-emitted light from UV component of LED hits MPPCs

PDE for Hamamatsu MPPC S13081-050C (top)
Quantum efficiency for Hamamatsu R14374 (bottom

