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Development of PMT/WLS optical modules for Cherenkov detectors

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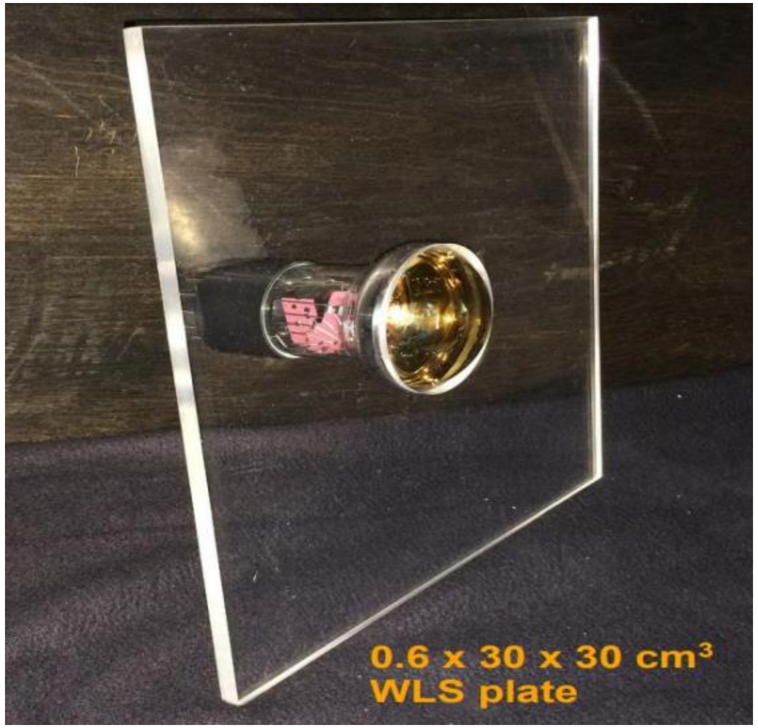
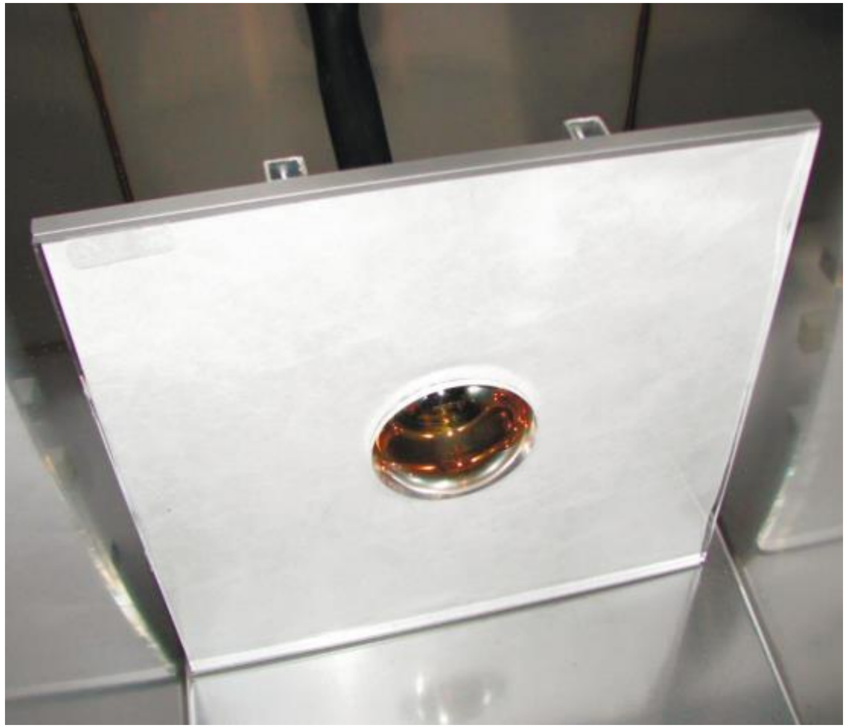
PMT/WLS OPTICAL MODULES

- WLS plate (wavelength shifting) with PMT (photomultiplier tube) - optical module for Cherenkov detectors: WLS plate increases useful surface of detector for light collection and absorbs Cherenkov's light then reemits it in sensitivity part of PMT spectrum.
- WLS plates in report are made from PMMA (polymethylmethacrylate, known as acrylic glass) with WLS dopants at "Kargin's Polymers Institute", Dzerzhinsk, Russia.
- Such optical modules can be used in water Cherenkov detectors like a component of veto-systems.



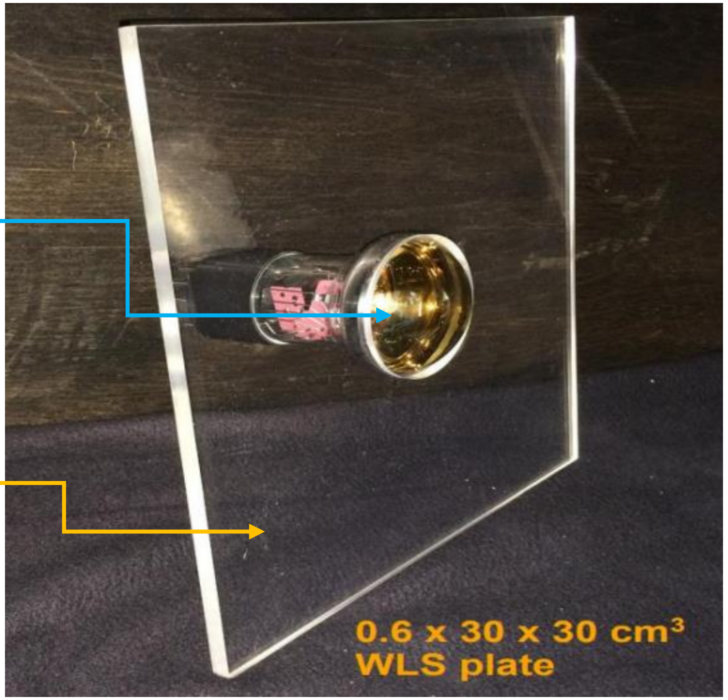


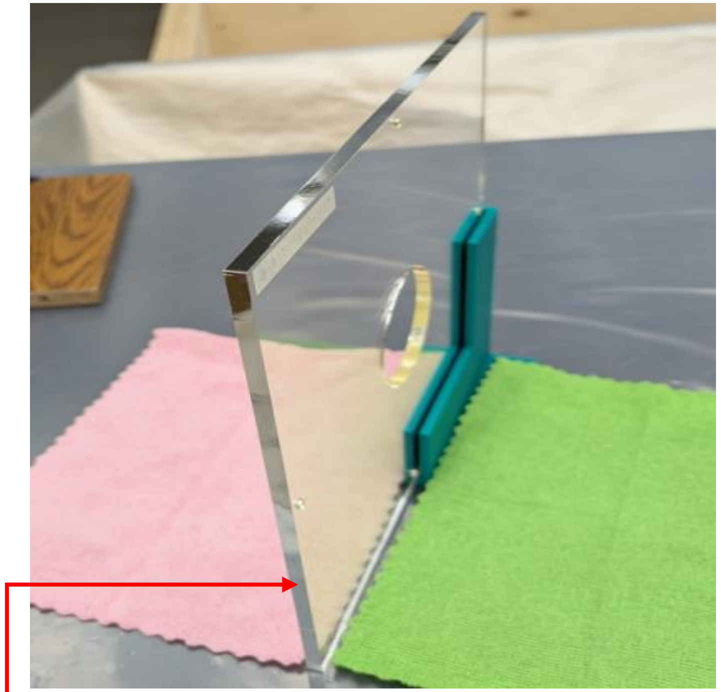
WLS/PMT optical module without reflector (left) and with reflector on back side (right)

MODULE STRUCTURE

PMT/WLS OPTICAL MODULE

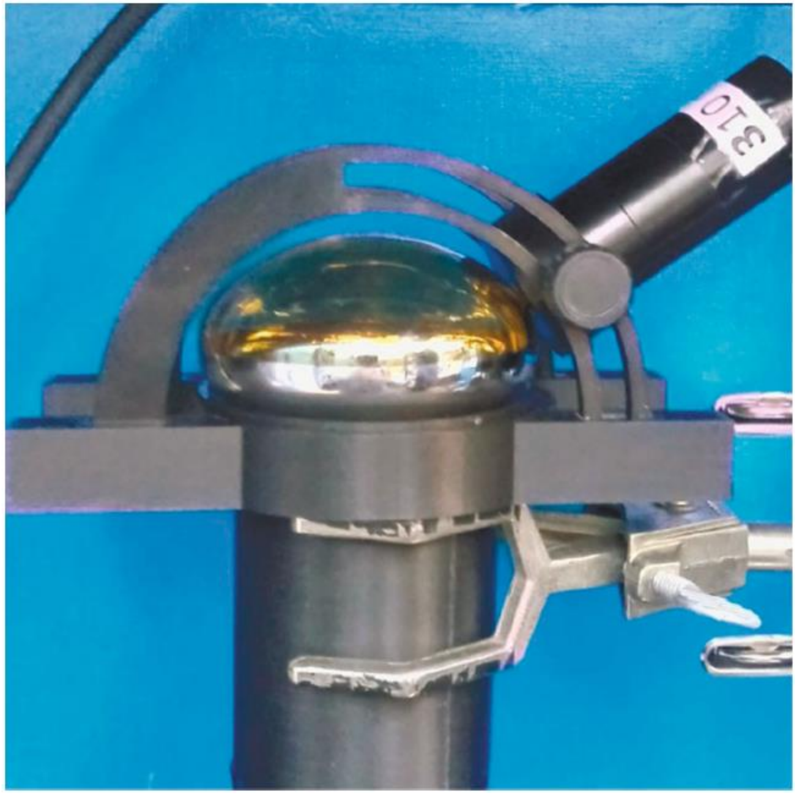
- **PMT**
- **WLS** plates
- Reflector



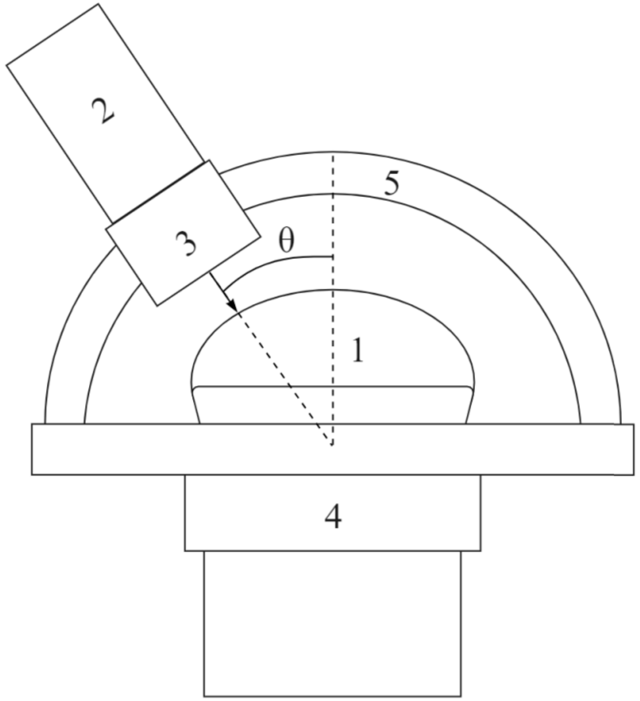


PMT STUDY

- Cathode sensitivity is important characteristic for PMT and WLS plate optical connection. There was comparison of two main candidates for usage in optical modules: **Hamamatsu R14374** and **NNVT 2031**. Both of them have identical specification:
- **3" PMT with 72 mm diameter of photocatode sensetive area.**
- The sensitivity area of photocathode corresponds for cathode diameter less than ⌀72 mm due to specification. Special device was developed for cathode sensitivity research. It provides measurements of light yield with azimuthal and polar coordinates variation.



Device for cathode sensitivity measuring.



Schematic illustration of device for cathode sensitivity study:

1. PMT
2. LED
3. Collimator ⌀ 1 mm
4. Graduated azimuthal ring
5. Arcs for polar angle θ variation and rotation-platform for azimuthal angle φ variation

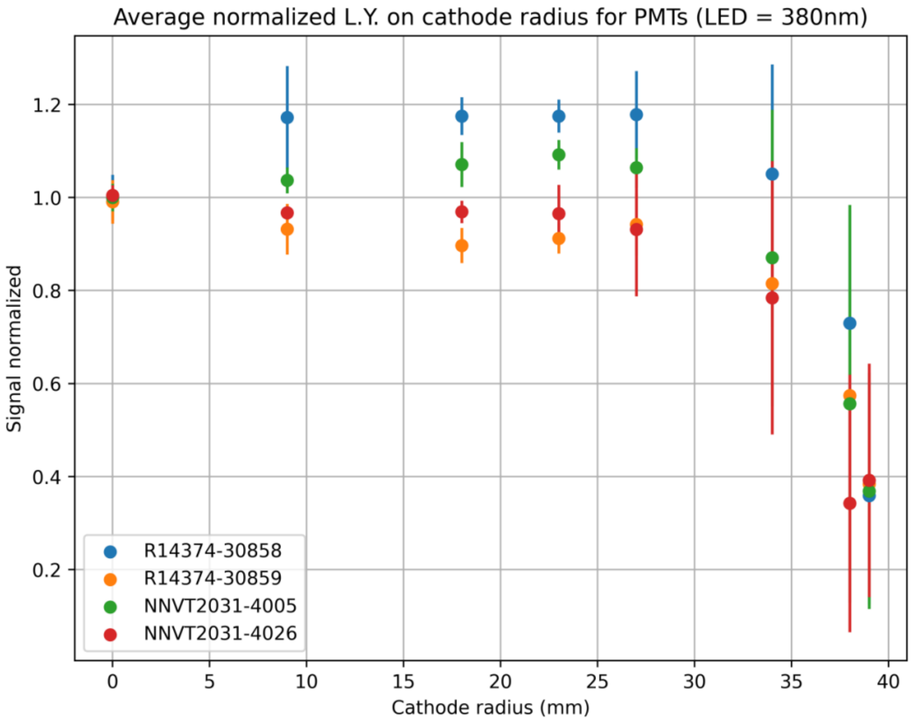
CATHODE SENSITIVITY

*Stroke Y. et al. Physics of Atomic Nuclei. 88 (2025) 3, 482-488

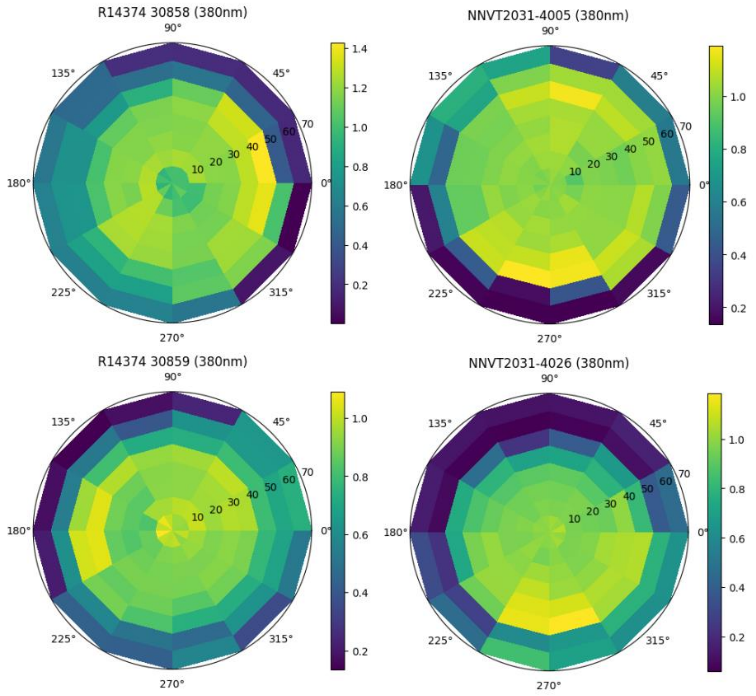
Varying the polar and azimuthal angles made it possible to construct heat maps of the tested photomultipliers. The sensitivity of the cathode was estimated based on heat maps. Result of the test for LED 380nm:

- The signal becomes significantly weaker when LED moving into the area outside the manufacturer's specified photocathode diameter (⌀72 mm).
- R14374 has more stable cathode sensitivity, especially in contact area with PMT.

Results for the signal averaged over the cathode radius show that R14374 does not differ from NNVT 2031 in the sensitivity area (less than 36 mm of the cathode radius) and is quite stable. The less sensitive area starts from a cathode radius of 34 mm, and the reduction level is about 60%.

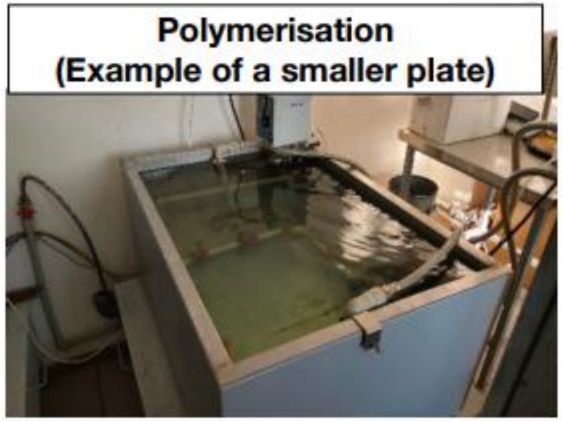


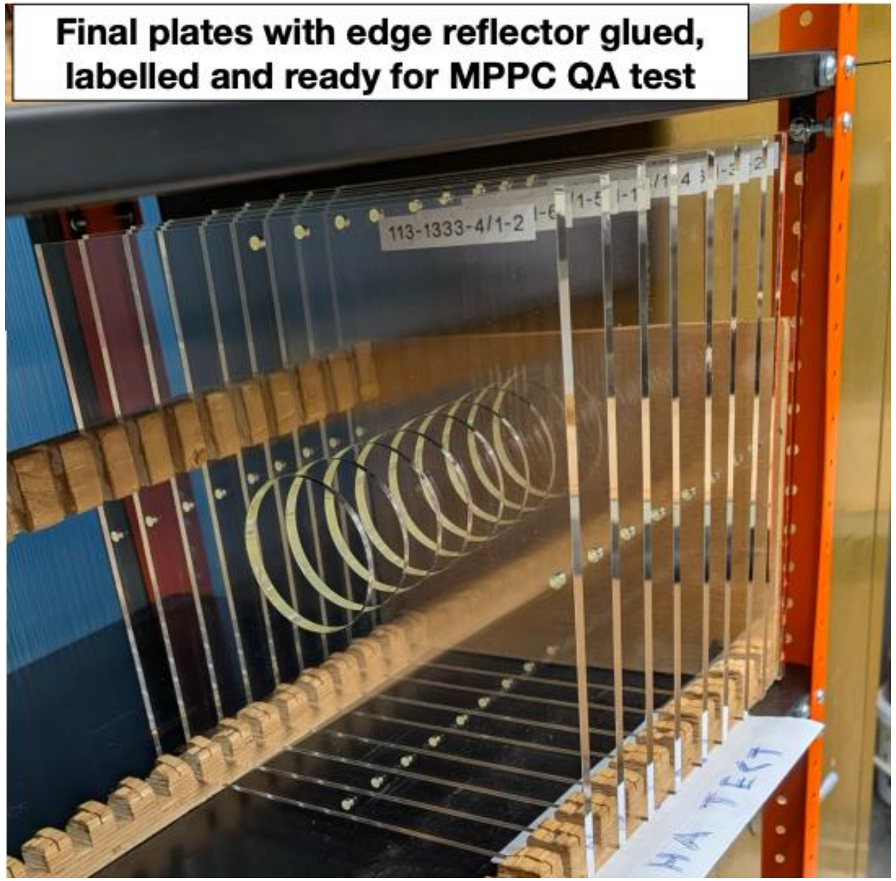
Average signal for cathode radius.

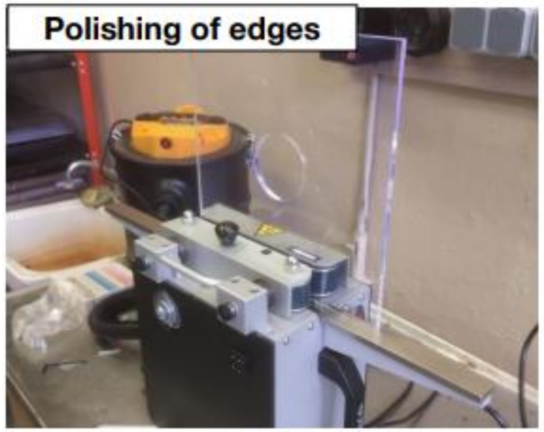


Cathode sensitivity heatmaps: left side – R14374; right side – NNVT 2031

WLS plates manufacturing

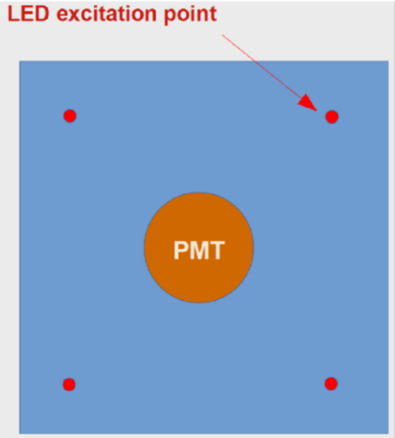


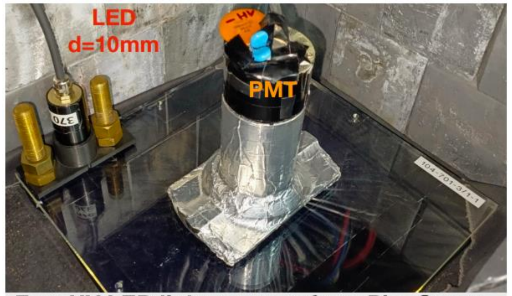




STUDY OF WLS PLATES

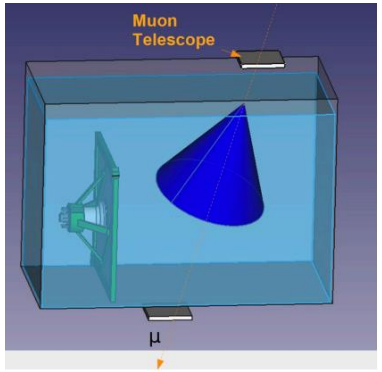
PicoQuant sub-nanosecond LEDs
- Collimator d=10 mm
- WLS plate performance at a known wavelength
- Additional setup to immerse a plate into water
- Average the results with LED at different positions

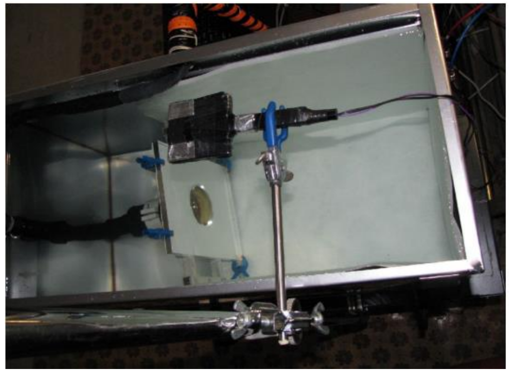




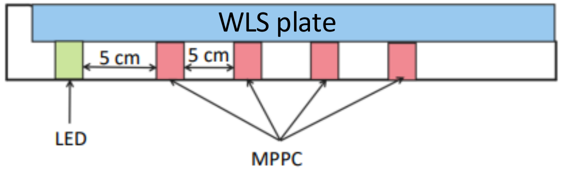
Fast UV LED light sources from PicoQuant
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

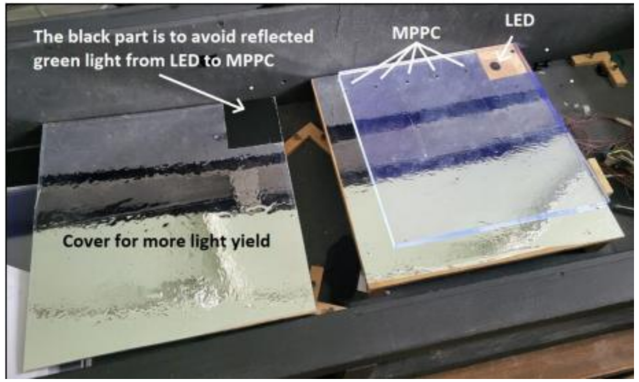
Infant-K water detector
- 110 litres of distilled water
- Cosmic trigger, muon range ~45 cm
- Direct and reflected light Cherenkov light
- Option to put Tyvek on walls





Test-bench with MPPCs and UV LED for QA
- Not a high-precision test of the WLS plate performance
- UV LED and MPPC readout from plate surface is not a PMT inside the central hole and Cherenkov light
- Sensitive to the presence of the fluors → a quick QA check



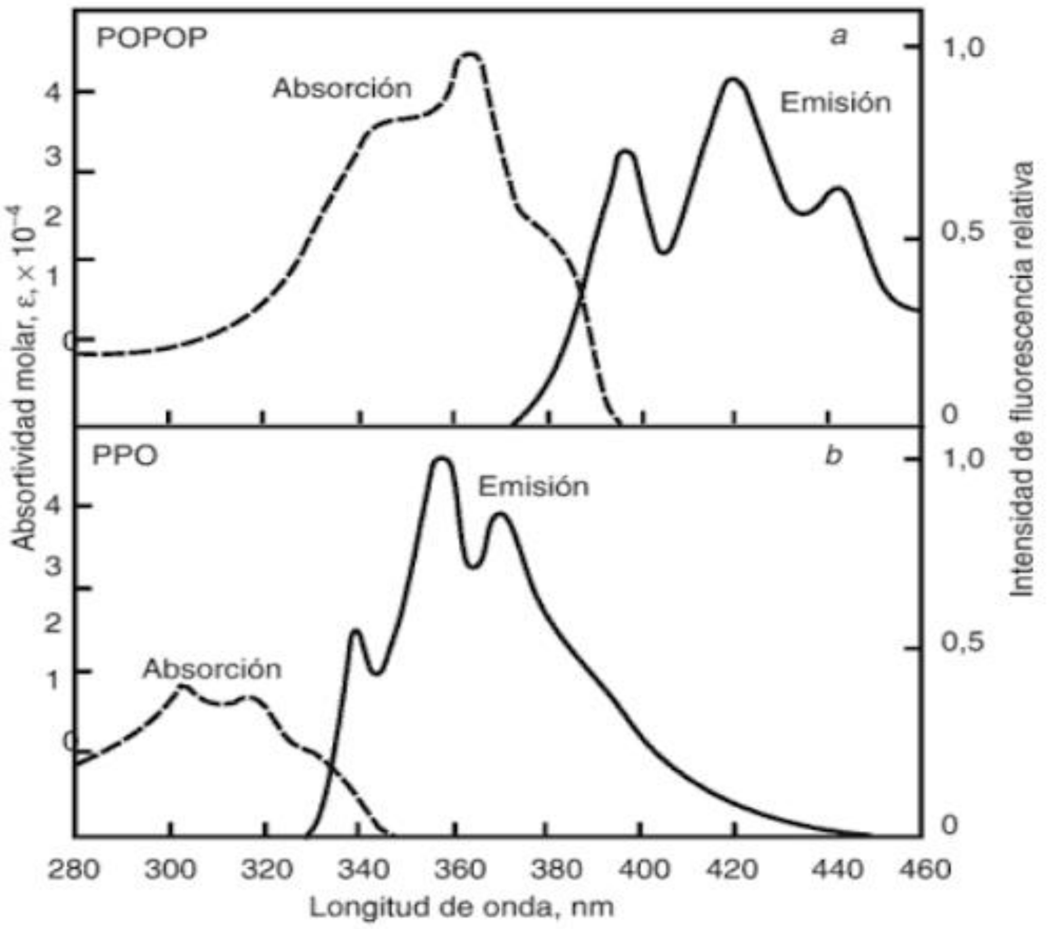


WLS DOPANTS

Based on the results of previous studies, it was decided that the additives POPOP and PPO, and their combinations, have the greatest potential for use. PPO (2,5-diphenyloxazole) and POPOP (1,4-bis[2-(phenyloxazolyl)]-benzene) are the primary dopant and secondary wavelength shifter. In particular, POPOP interacts well with the long-wave UV component, and PPO with the short-wave component.

The following system was used to label the plates: first the name of the dopant is indicated, then its concentration [mg/L]. For example PPO3000POPOP50 means WLS plate with 3000 mg/L concentration of PPO and 50 mg/L concentration of POPOP

WLS dopant	PPO	POPOP
Adsorption spectrum, nm	290÷330 peak: 300	250÷390 peak: 360
Emission spectrum, nm	320÷410 peak: 340÷380	380÷510 peak: 360



Absorption and emission spectra of wavelength-shifting additives POPOP and PPO

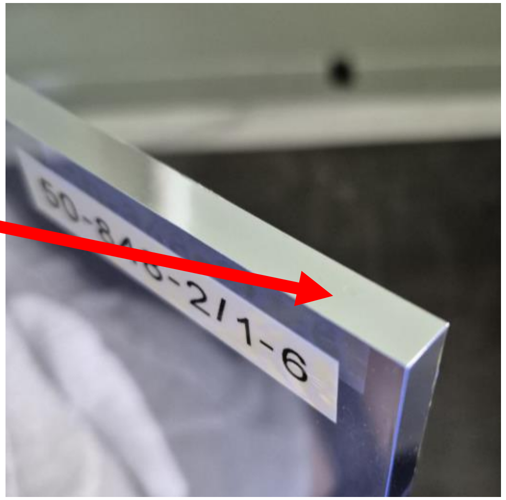
REFLECTORS

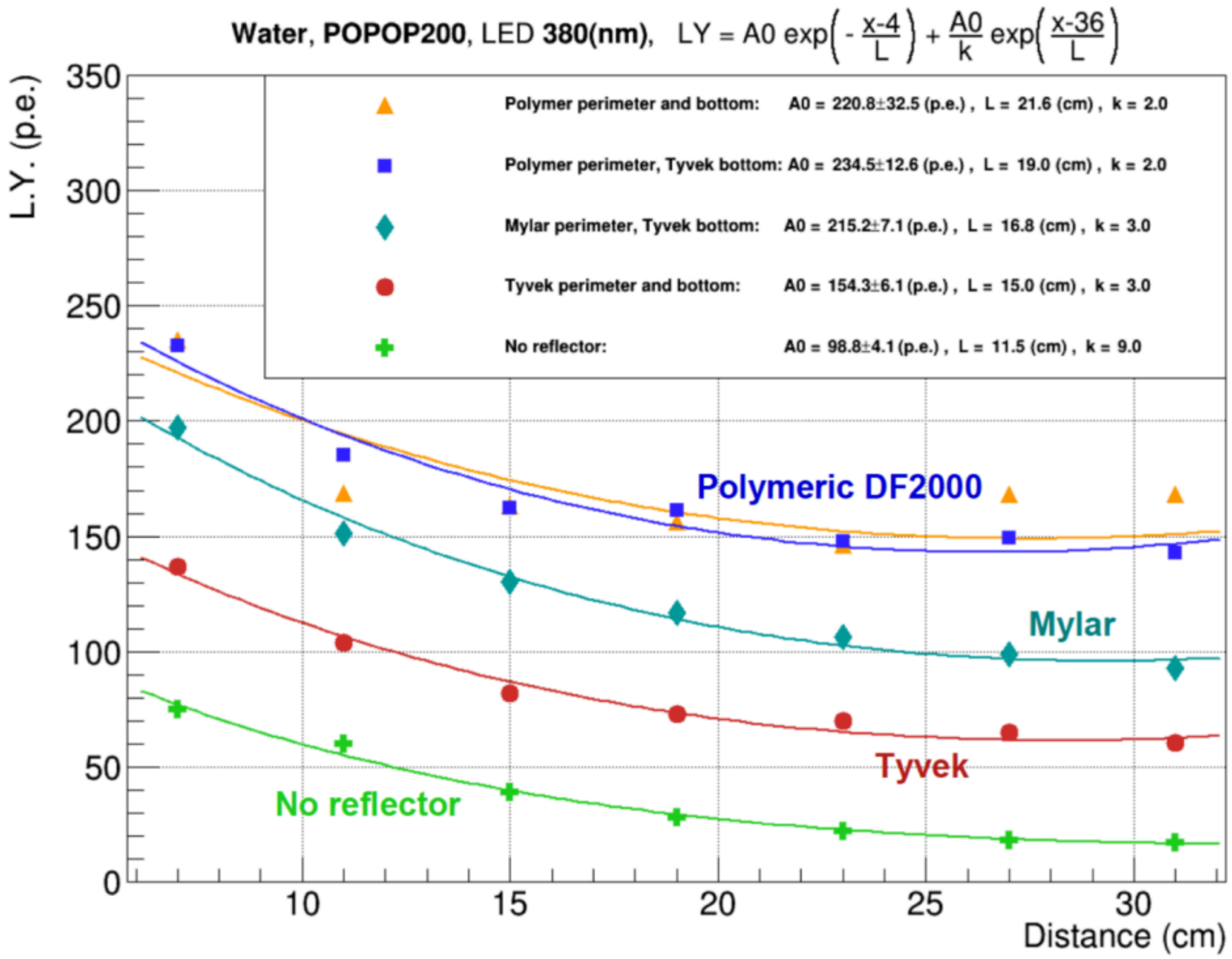
Three types of reflectors were tested:

- **Tyvek** (polymer, diffusion reflector)
- **Mylar** (aluminized film, mirror reflector)
- **3D DF2000MA** (polymer film, mirror reflector)

The most effective combination of reflectors is Polymer Perimeter 3D DF2000MA and Tyvek bottom (**increase of L.Y by 2 times** compared to plate without reflectors)

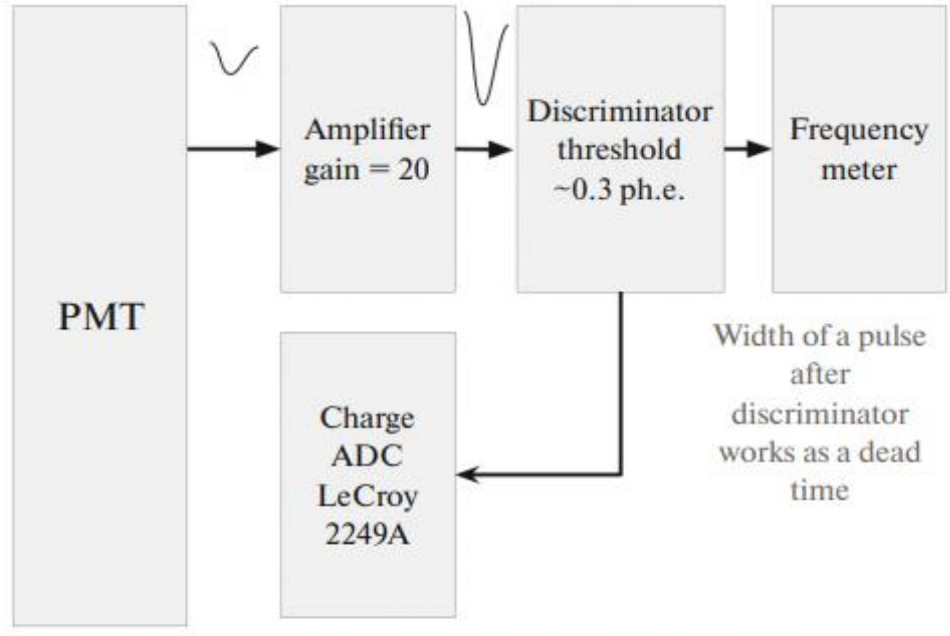
Reflector on the edge of WLS-plate helps to keep photons into the plate.





DARK RATE

To create detectors based on PMT/WLS optical modules, it is crucial to evaluate their dark counting, as this can be critical for the selection of rare events. All measurements were carried out with a ~0.3 p.e. threshold in an isolated volume with a constant set temperature.



Measurements were made in temperature controller volume

Dark Rate measurements of PMT/WLS optical module. Threshold: 0.25÷0.3 p.e. Temp: 13÷14°C. PMT: Hamamatsu R143473. Dead time to suppress afterpulses: 250 ns

WLS Plate	Dark Rate, Hz
Bare PMT	200
POPOP800	750
POPOP400	500
POPOP200	400
POPOP50	350
POPOP50PPO3000	650

Contributions to Dark Rate of PMT/WLS optical module for POPOP400 plate. Threshold: 0.25÷0.3 p.e. Temp: 13÷14°C. PMT: Hamamatsu R143473.

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

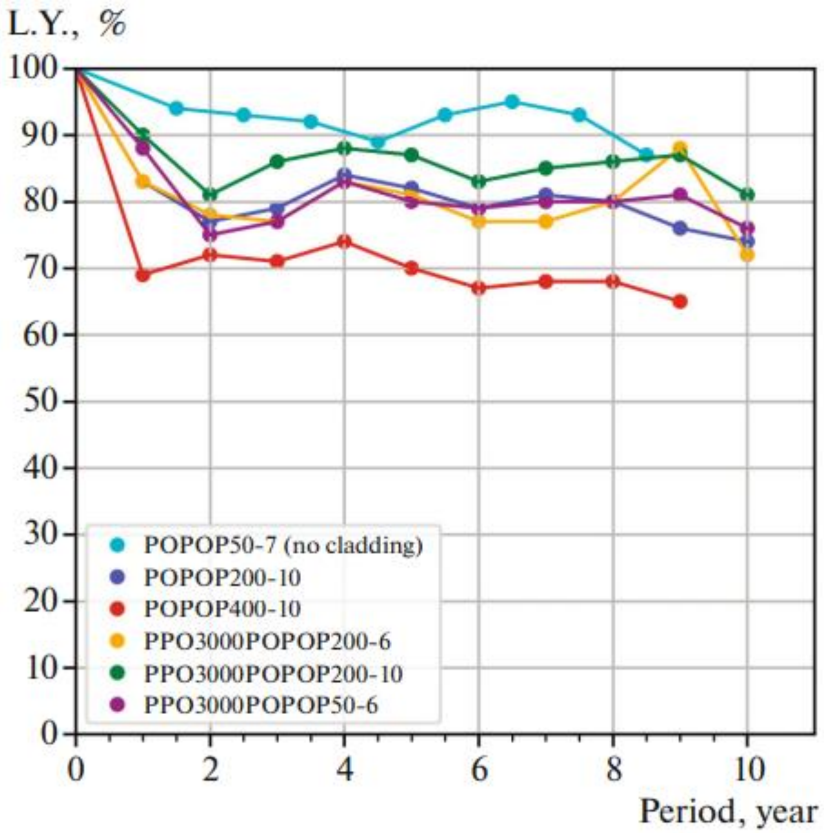
WLS PLATES AGING

Information about aging of WLS plates is important for long time experiments. All plates were tested in special thermal camera with a temperature of 59°C. 2 weeks in camera is equal one year at 13°C in a real detector. Reflector - 3D DF2000MA on plate's perimeter. All results are presented relative to a reference plate that was not subjected to accelerated aging .

All plates are practically stable after the first year. The possible reason for LY reduction during the first year is glue in reflector and air bubbles under the reflector tape which affect the optical contact.

Excluding this fact the aging of plates (reduction of LY) is **<u>less than < 2%/year</u>**.

Thermostatic oven and stainless steel container with distilled water



Dependence of relative light yield on equivalent aging time

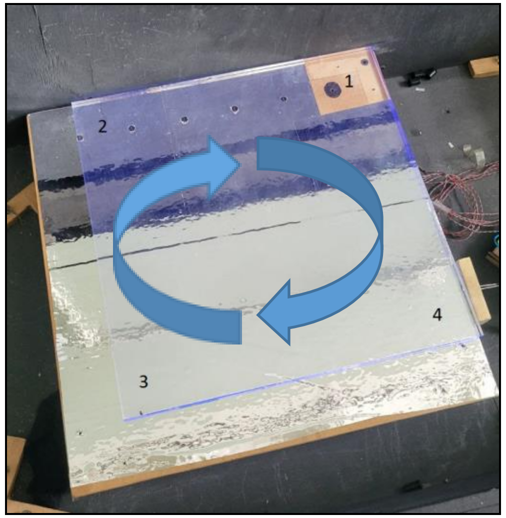
Quick tests

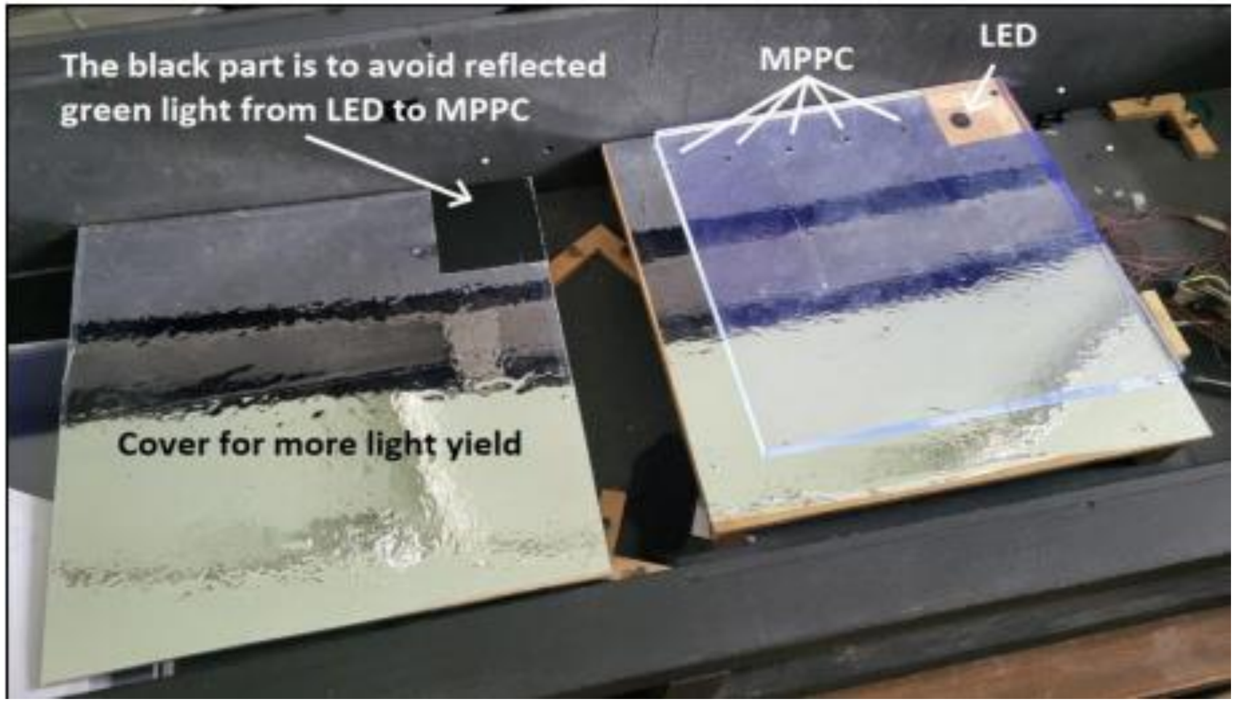
A method for fast tests of WLS-plates quality is needed during mass production to quickly respond to changes in the quality of the produced plates.

QA procedure for a WLS plate:

- Testing plate is placed on the stand and covered with the lid so that black square is above the diode
- Data is collected in one minute
- Plate is rotated 90^{o} and the measurements are repeated
- Each plate is measured in 4 positions, after which results are averaged
- Then a next plate is being tested

Total: 5-10 minutes for a plate





CHERENKOV LIGHT TESTS

Light source: **reflected Cherenkov light** from cosmic muons

Plates:

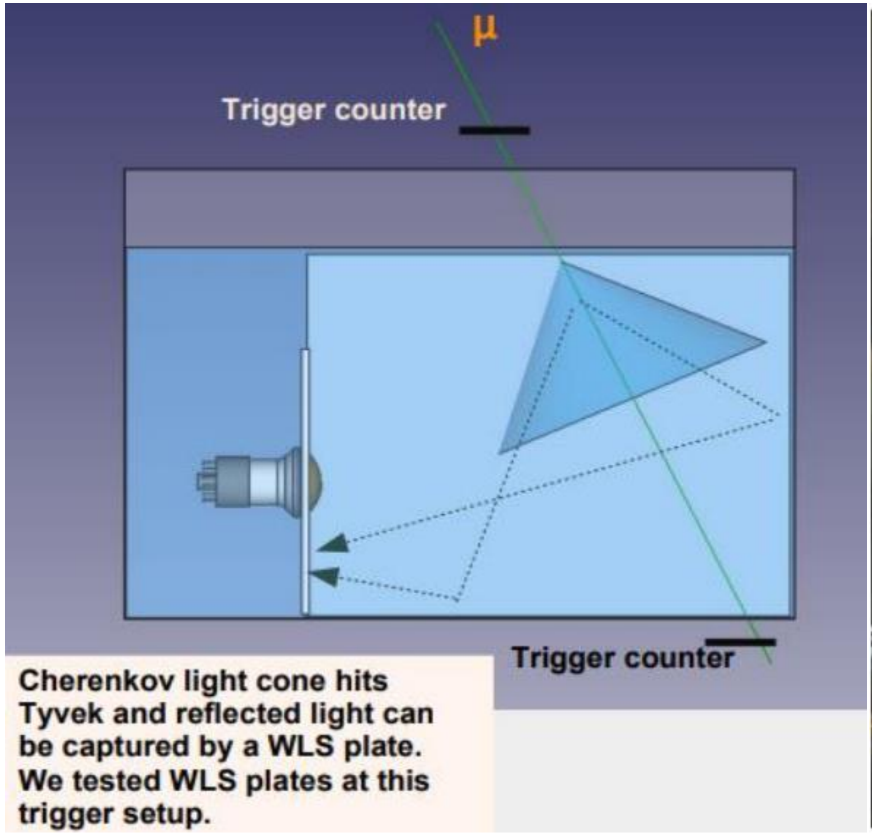
- Double fluor: **PPO3000-POPOP50**
- Single fluor: **POPOP50, POPOP100, POPOP200, POPOP400, POPOP800**

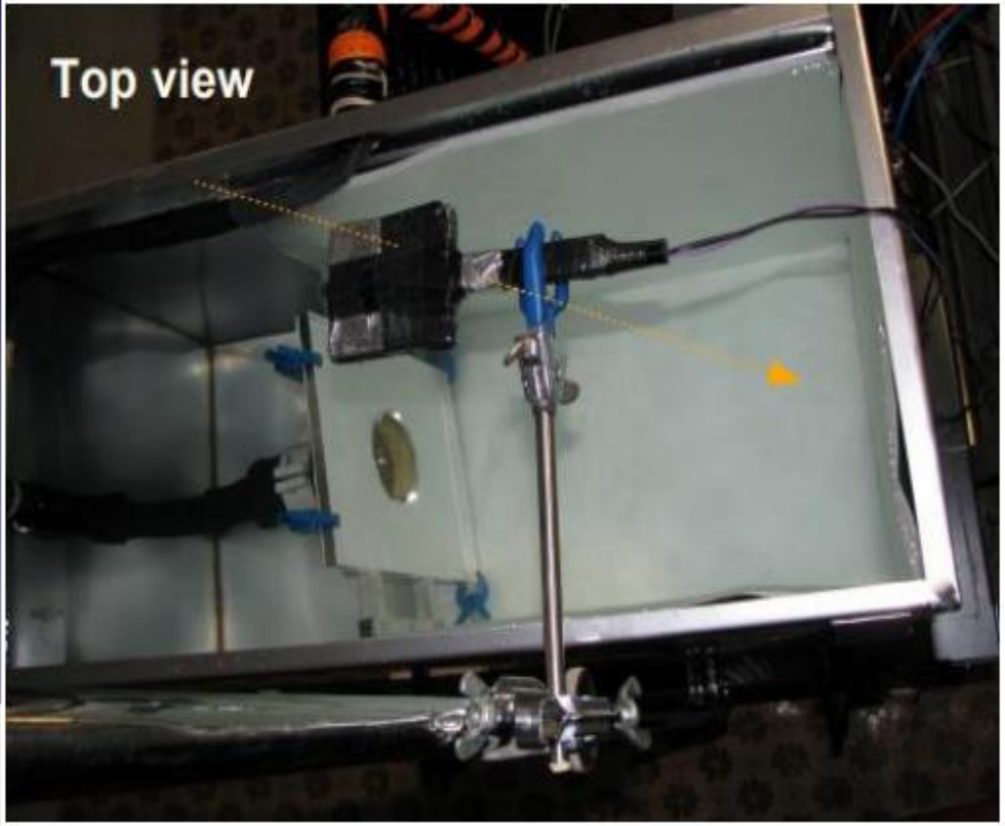
PMT : **Hamamatsu R14374**

Reflector:

- **Tyvek**, 190 µm thickness on back side of plate
- **3D DF2000MA** polymer film on perimeter

Water: **distilled for industry purposes**

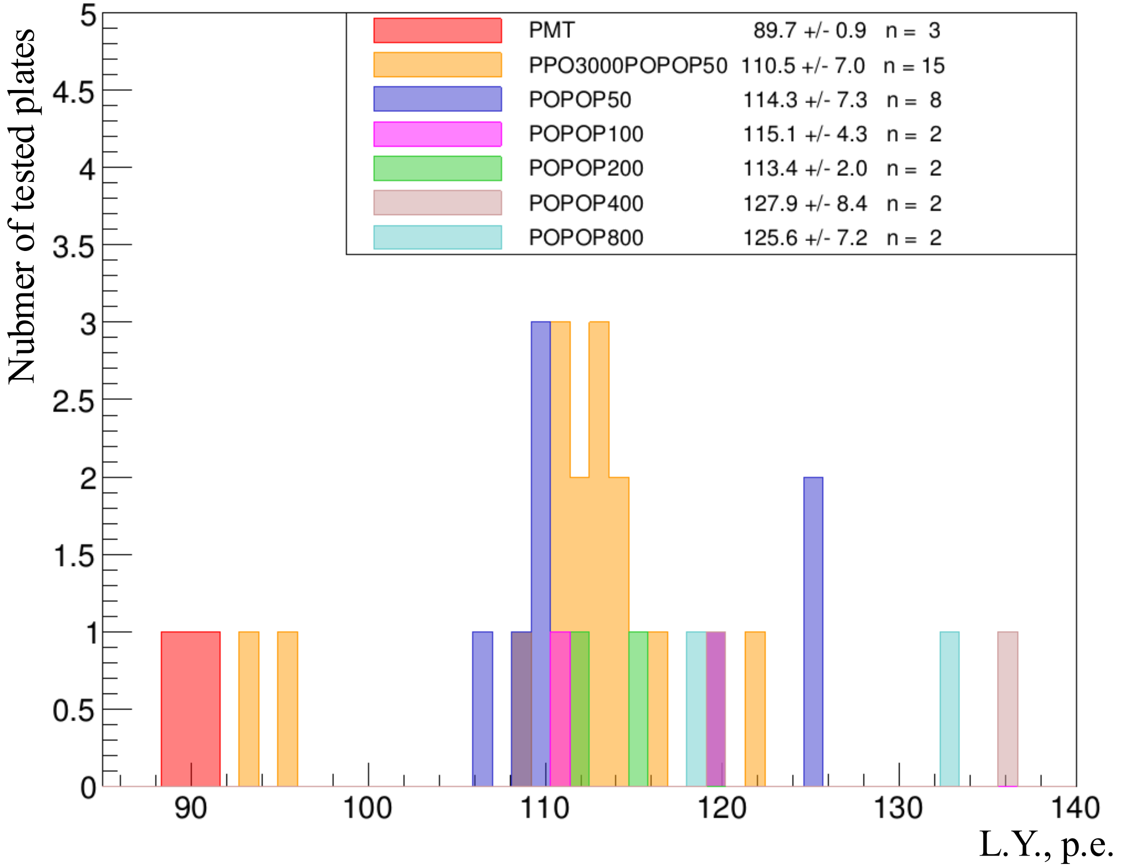




CHERENKOV LIGHT RESULTS

	TOTAL L.Y., p.e.	WLS plate contribution to total L.Y., p.e.	Detection efficiency increasement
PMT	89.7	-	1.00
PPO3000 POPOP50	200.2	110.5	2.23
POPOP50	204.0	114.3	2.27
POPOP100	204.8	115.1	2.28
POPOP200	203.1	113.4	2.26
POPOP400	217.6	127.9	2.43
POPOP800	215.3	125.6	2.40

By using WLS plates, we achieve an increase in light intensity of 2.2÷2.4 times



Results of tests with Cherenkov light. Light yield of plates is indicated excluding the contribution of the PMT

CONCLUSION

The main results of PMT/WLS plates optical modules for Cherenkov detectors development:

- Hamamatsu R14374 has better cathode surface than NNVT 2031. Non-sensitivity area starts from **34 mm** cathode radius. The signal decrease level in non-sensitivity area is nearby **60%** for both PMTs
- 3D DF2000MA film on perimeter increases the light yield by **2 times** compared to plate without reflector
- Degradation of light yield of WLS plates is **less than 2%/year.**
- A method for quality assurance during mass production of plates has been developed and tested.
- WLS plate **POPOP400** shows the best performance.
- By using WLS plates, detection efficiency of Cherenkov light in increased by **2.2÷2.4 times**.

Thank you for your attention!

BACKUP

BACKUP

●R14374

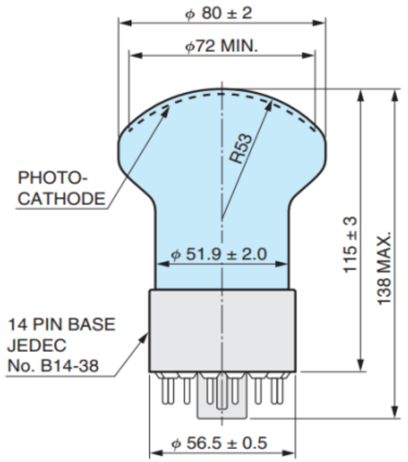


Figure 1: Typical spectral response

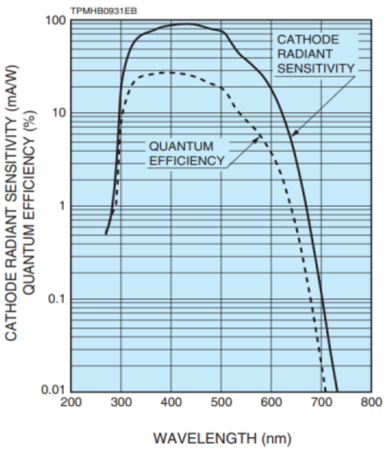
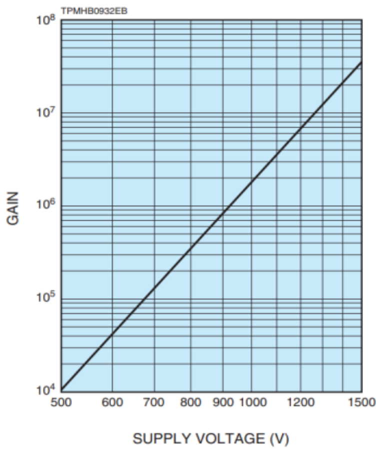
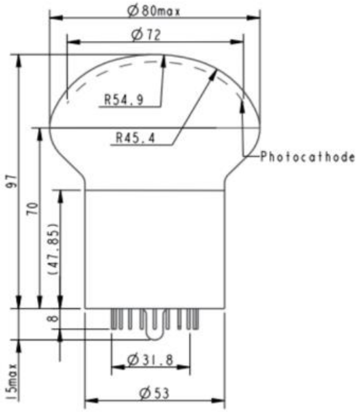
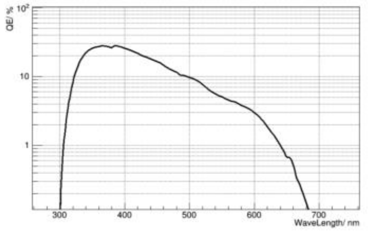


Figure 2: Typical gain

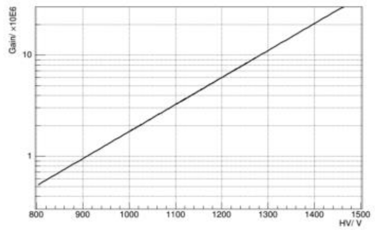




N2031光电倍增管结构图
N2031 PMT structure



典型光谱响应曲线
Typical spectral response curve



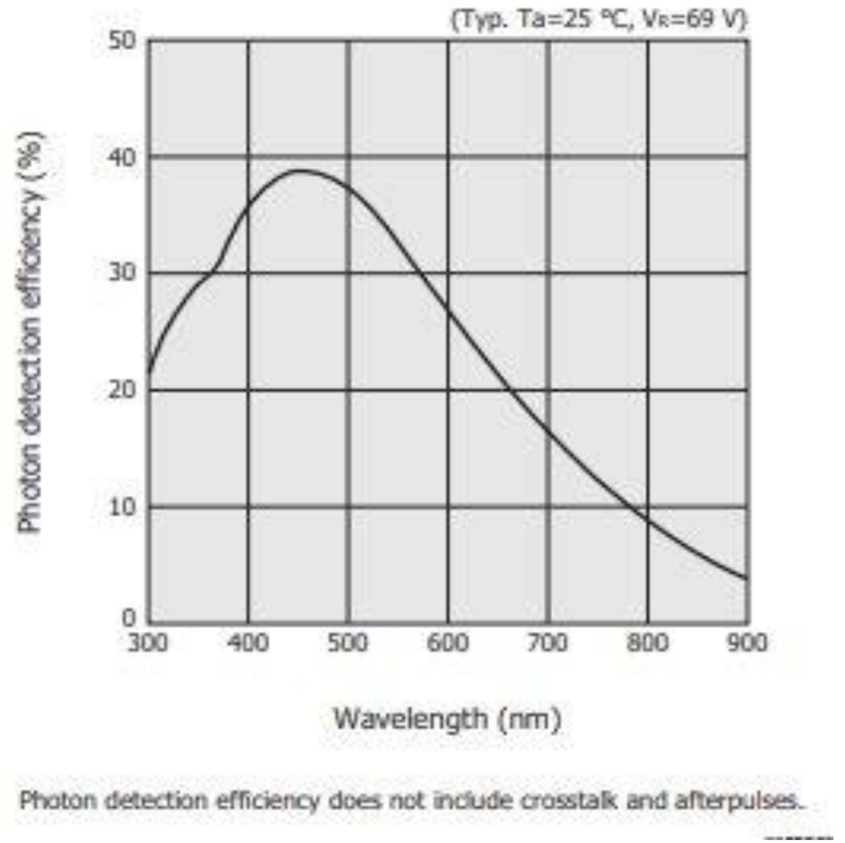
典型增益曲线
Typical gain curve

Hamamatsu R14374 and NNVT N2031 PMT characteristics

BACKUP

MPPC characteristics

MPPC series	Hamamatsu S13081-050CS
Pixel size [mkm]	50
Number of pixels	667
Active aria [mm^2]	1.3×1.3
Working voltage [V]	53-55
PDE [%]	35
Dark rate [kHz]	90
Gain	1.5×10^6



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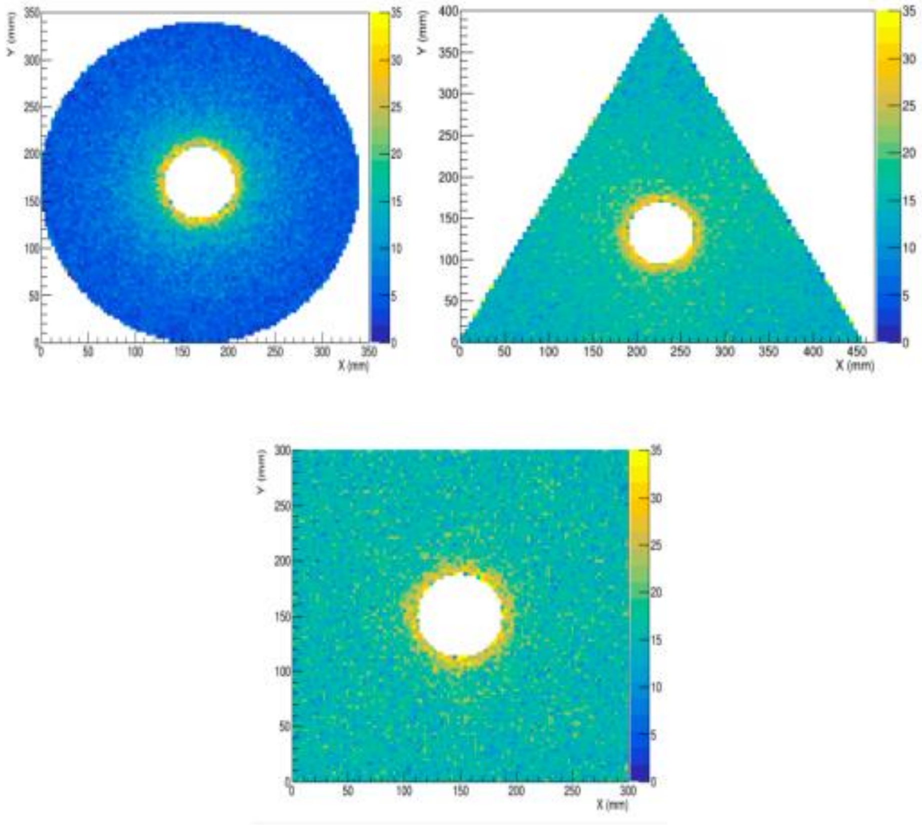

Results of light collection modeling for plates of various shapes