Preparatory Study of Photomultiplier Tubes of 10-inch and 3-inch Diameter for KM3NeT Underwater Neutrino Telescope

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KM3NeT collaboration

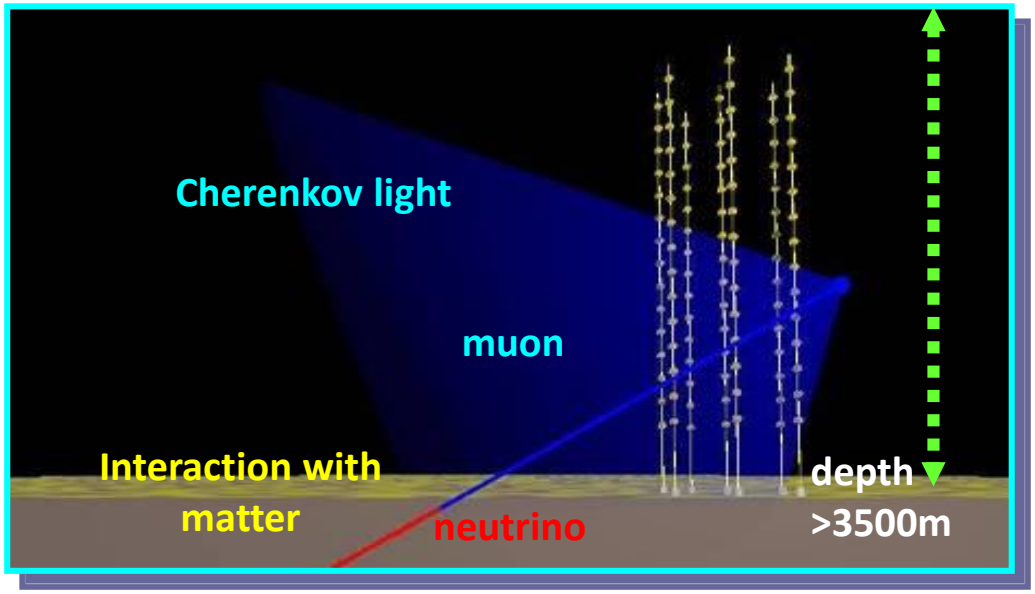
KM3NeT Neutrino Telescope

High energy neutrinos can produce in water secondary charged particles. An underwater neutrino telescope tracks the Cherenkov light emitted by HE muons in water instrumenting a big volume of water with light detectors (PMTs).

KM3NeT www.km3net.org consists of a new infrastructure at the deep-sea site of Capo Passero, Sicily, Italy at 3500 m of depth :

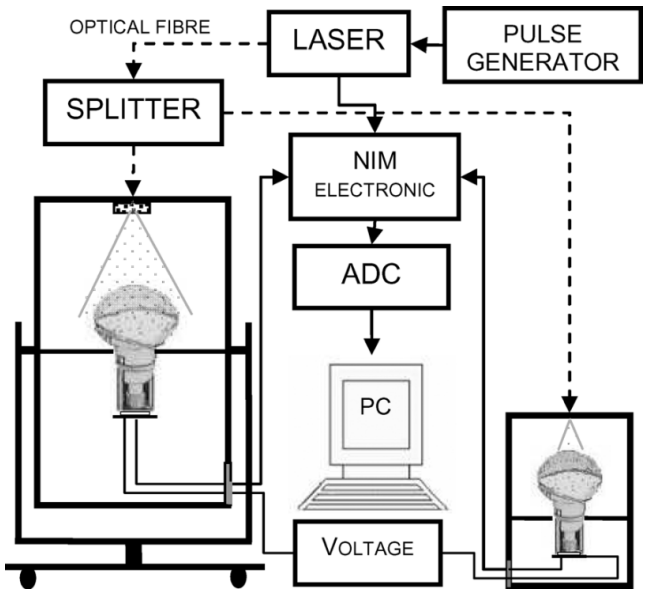
- **8 towers (13-inch Optical Module (OM) with 10-inch PMT)**
- **24 strings (17 inch Digital Optical Module (DOM) with 31 3-inch PMTs (multiPMT)**

OM with 10-in. PMT

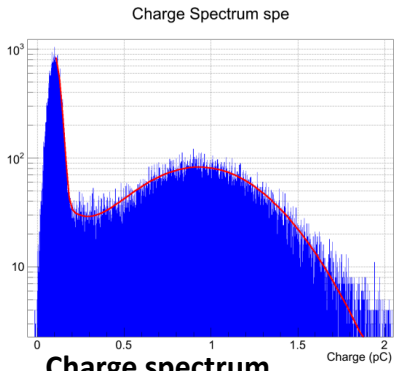


DOM with 3-in. PMTs

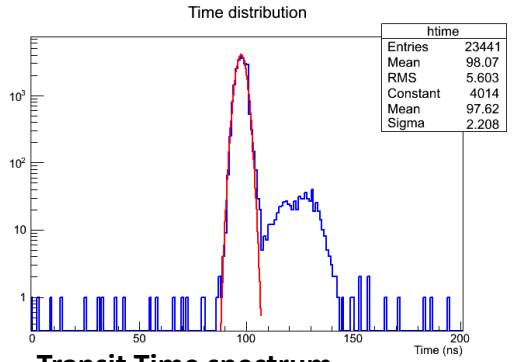
Measurements of PMTs properties



- **Nominal Voltage**
- **Dark count rate**
- **Gain**
- **Peak to valley ratio**
- **Transit Time Spread**
- **Fraction of spurious pulses**



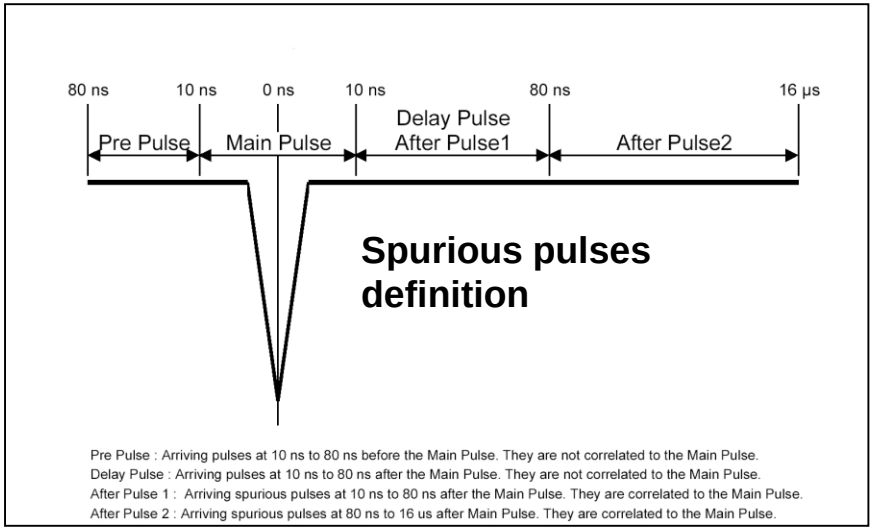
Charge spectrum



Transit Time spectrum

Main facility:

- **A pulsed laser source attenuated in s.p.e. condition**
- **Light pulses conducted by means of optical fibres**
- **Optical diffuser produces homogeneous illumination**
- **Charge measurements made by NIM QDC 7422 Silena**
- **Time measurements made by NIM 7072T FAST**
- **Le Croy waverunner 2GSample/s Digital oscilloscope**



R7081 10-inch PMT by Hamamatsu

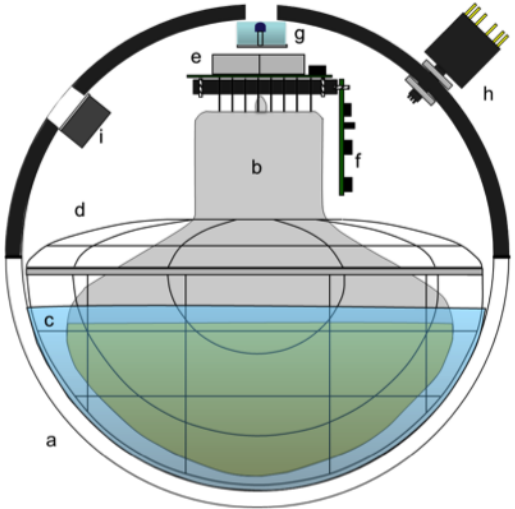
- Large Are PMT mushroom shape
- 10 stages
- 10-inch bialkali photocathode
- typical surface of 500 cm ^{2}
- quantum efficiency of about 25% at 400 nm

750 10-inch PMTs were tested for KM3NeT project

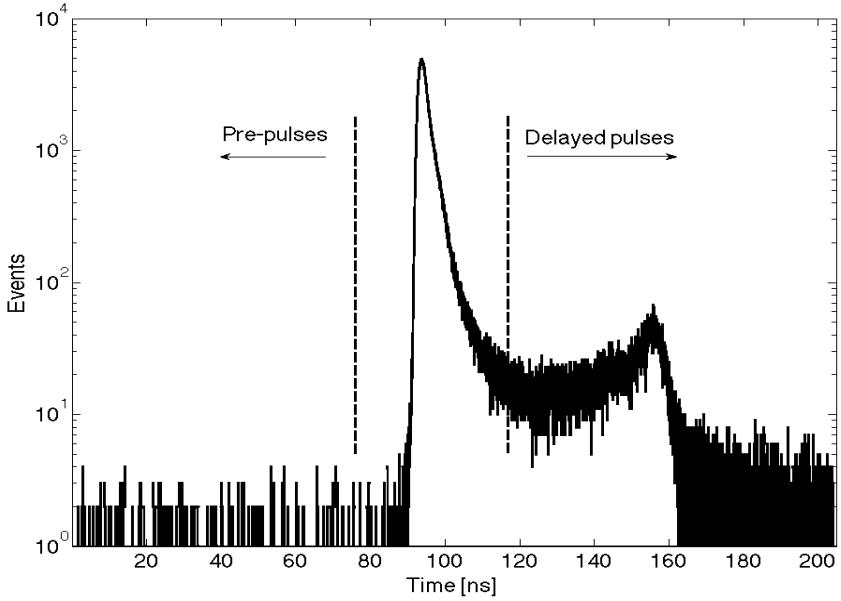
→See results in poster ANIMMA 2015 #298 by E.Leonora

Parameter	Mean values measured	Value Ranges measured
Voltage at Gain 5E7 [V]	1648	1460 ÷ 1900
Dark Count rate [Hz]	1128	274 ÷ 13200
P/V ratio	3.2	1.76 ÷ 4.5
TTS FWHM [ns]	2.4	1.98 ÷ 3.85
Pre-Pulse [%]	0.18	0.04 ÷ 2
Delayed Pulse [%]	5.65	4 ÷ 10.8
Type 1 after pulse [%]	0.47	0.05 ÷ 4.71
Type 2 after pulse [%]	7.3	3.1 ÷ 16.5

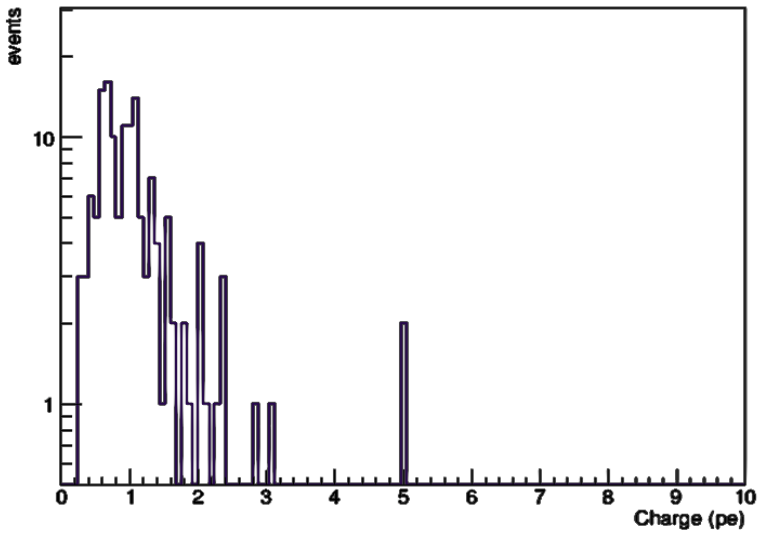
PMT is assembled inside a 13-inch glass vessel, forming the Optical Module



10-inch PMT pre- and delayed pulses charge



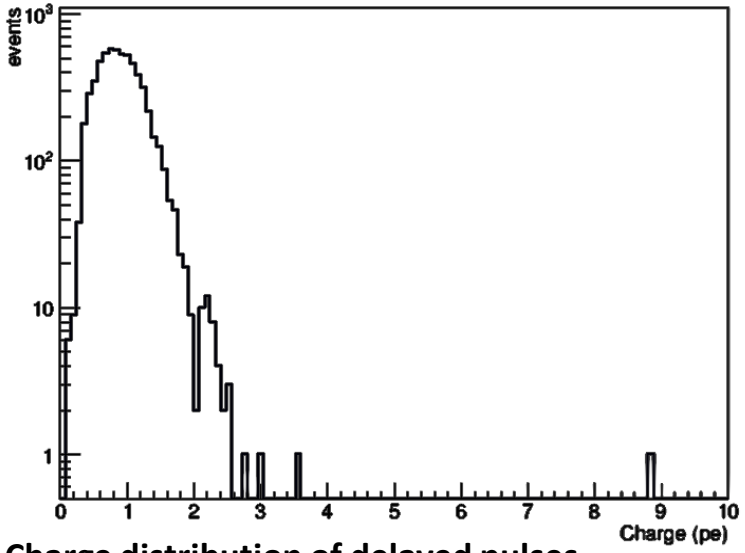
Time distribution for pre- and delayed pulses



Charge distribution of pre-pulses

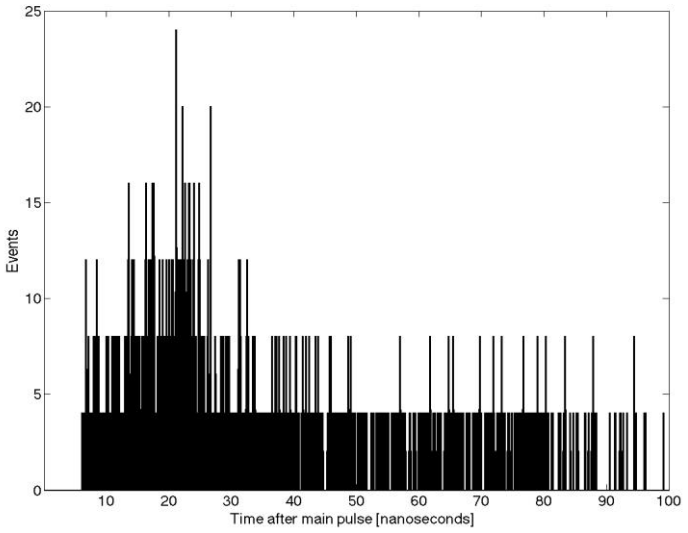
- **Pre-pulses have charge slightly lower than 1 pe**
- **Delayed pulses have a charge distribution mainly of single photoelectron (s.p.e.).**

More on 10-inch R7081 PMTs in **E. Leonora, et all. IEEE TNS, VOL. 61, N. 4, DOI: 10.1109/TNS.2014.2322655**

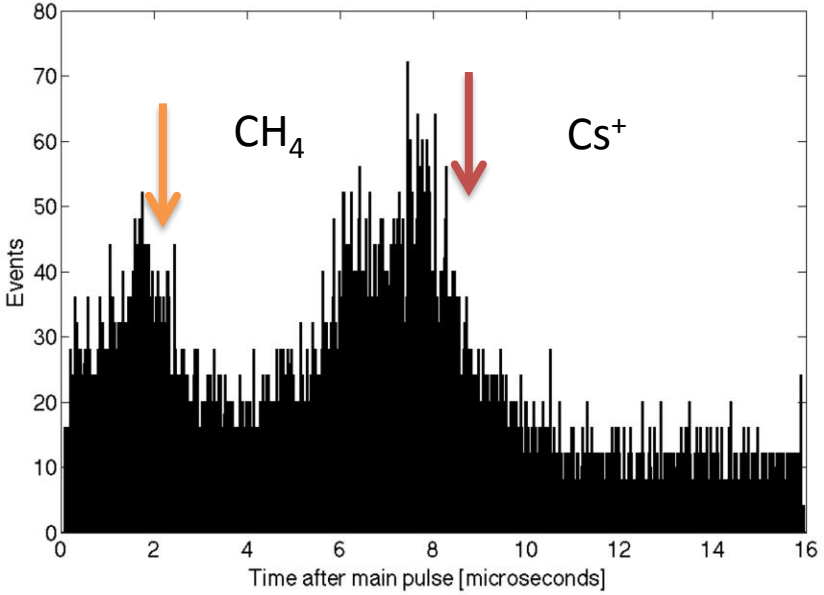


Charge distribution of delayed pulses

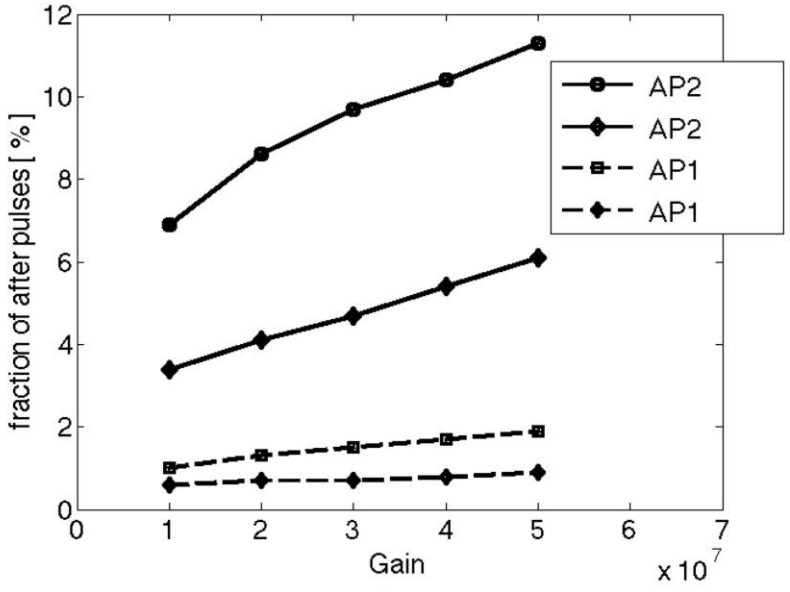
10-inch PMT type 1 and 2 after pulses



Time distribution of AP1



Time distribution of AP2



Fraction of AP1 and AP2 vs. gain

A peak around 2 μs produced by Methane (CH_4) ions

A structure between 6-8 μs due to Caesium (Cs) ions.

(Other possible candidates are Hydrogen (H), Helium (He) and cathode materials such as Potassium (K) and Antimony (Sb))

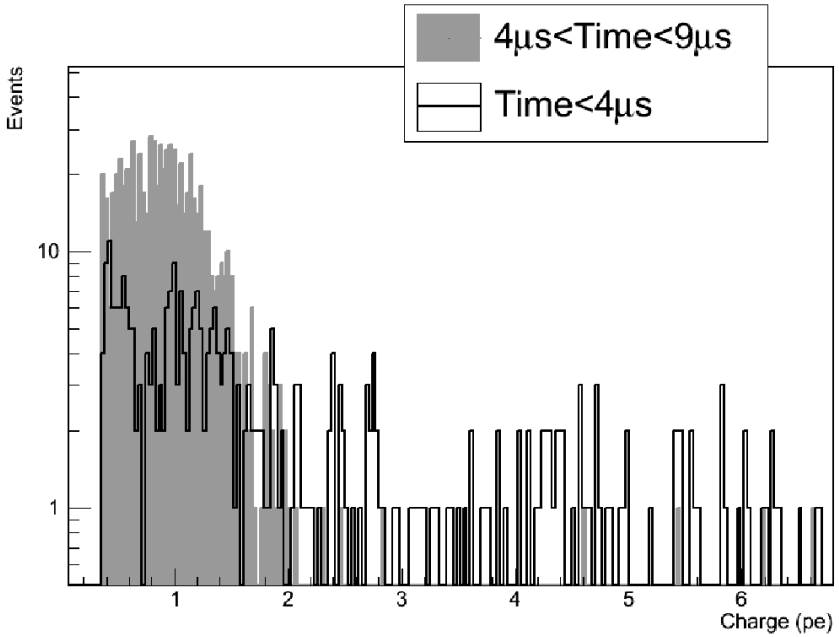
AP1 have a mean charge of 1 pe

AP2 have a mean charge of 1.5 spe

AP1 and AP2 fractions decrease with the gain

Multiple type 2 afterpulses

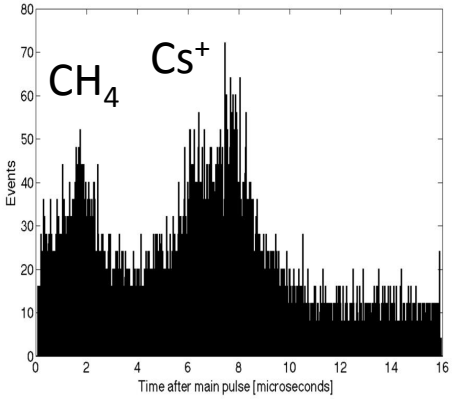
Charge distribution of AP2 in different time ranges.



In black there is the peak corrensponding to CH_4^+ while in gray there is the Cs^+ peak.
High charged AP2 are due mainly to CH_4^+

For single AP2 the mean charge is about 1,5 pe

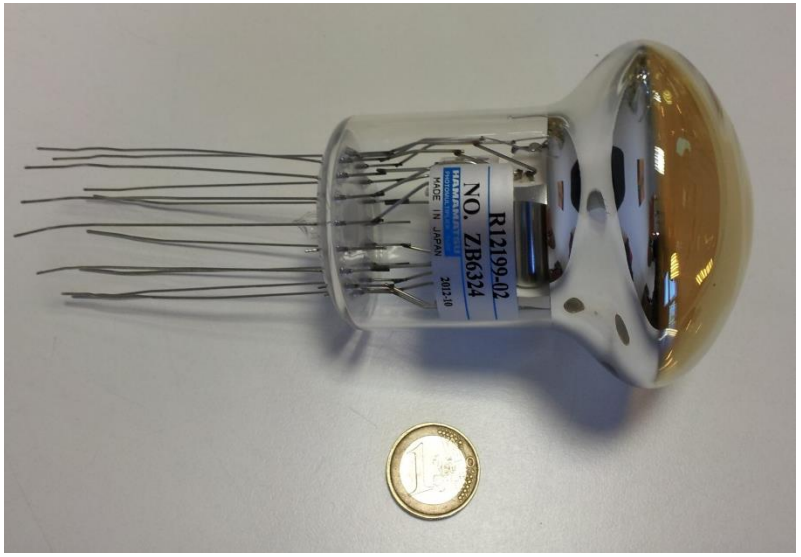
In multiple AP2 events, charge per pulse increases up to 3 pe with the increasing of the numbers of after pulses



N° AP2	Fraction (%)	Mean Charge (pe)
1	8,37	1,5
2	2,59	1,3
3	0,87	1,9
4	0,46	2,9
5	0,21	2,5
6	0,15	2,5
7	0,10	2,6
8	0,08	2,6
9	0,05	2,3
10	0,03	2,3

R12199-02 3-inch PMT by Hamamatsu

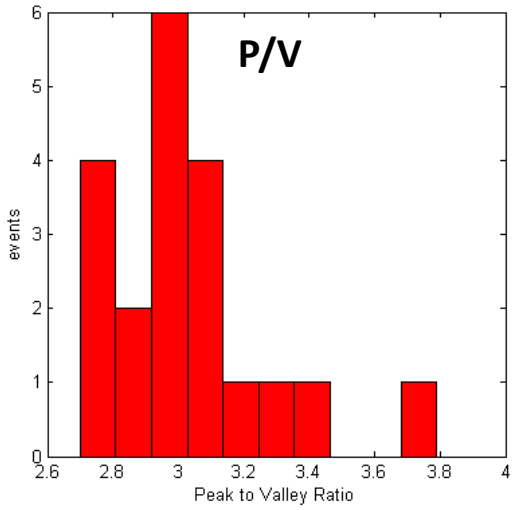
- **Mushroom shape**
- **3 inch bialkali photocathode**
- **quantum efficiency of about 25% at 400 nm**
- **10 stages**

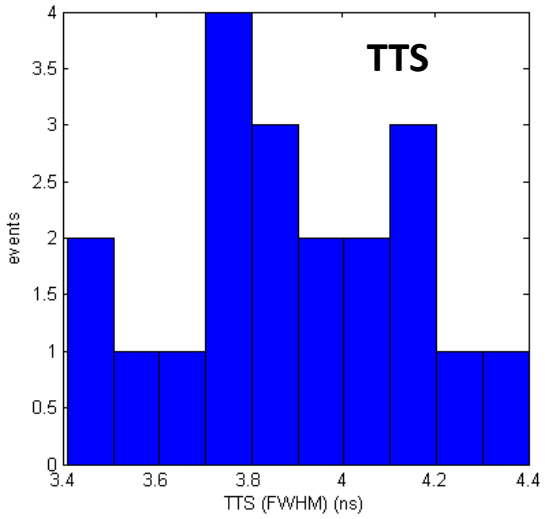


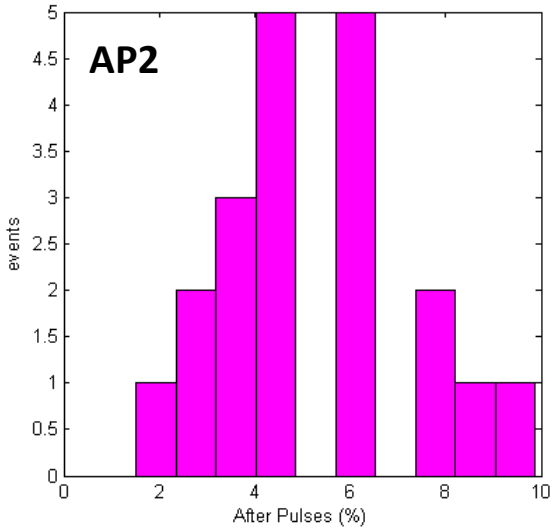
31 3-inch PMTs into a17” glass vessel make a multiPMT optical module or DOM (Digital Optical Module)

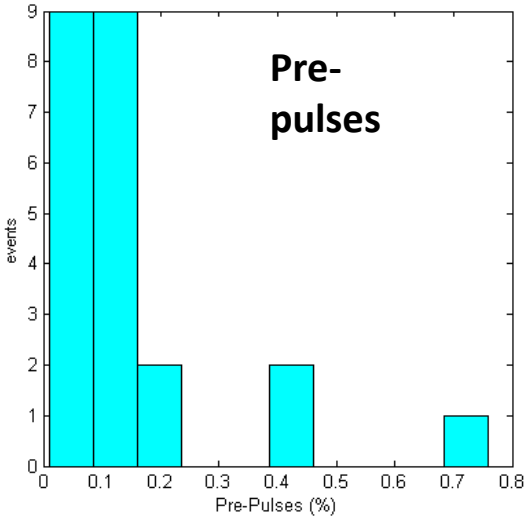
3-inch PMT main properties

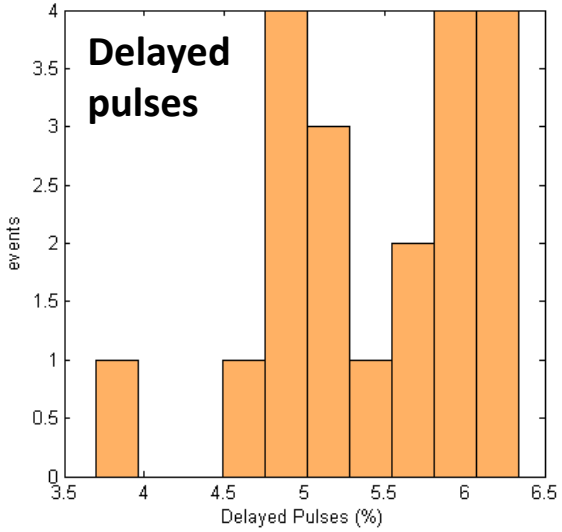
A batch of 20 PMTs by HAMAMATSU 3-inch R12199-02 tested in INFN-Catania laboratory







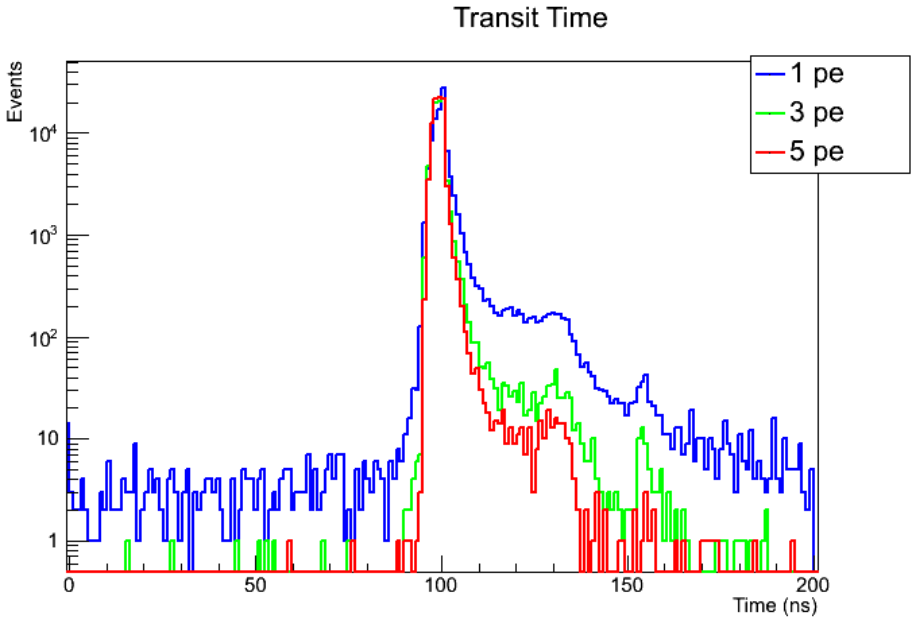


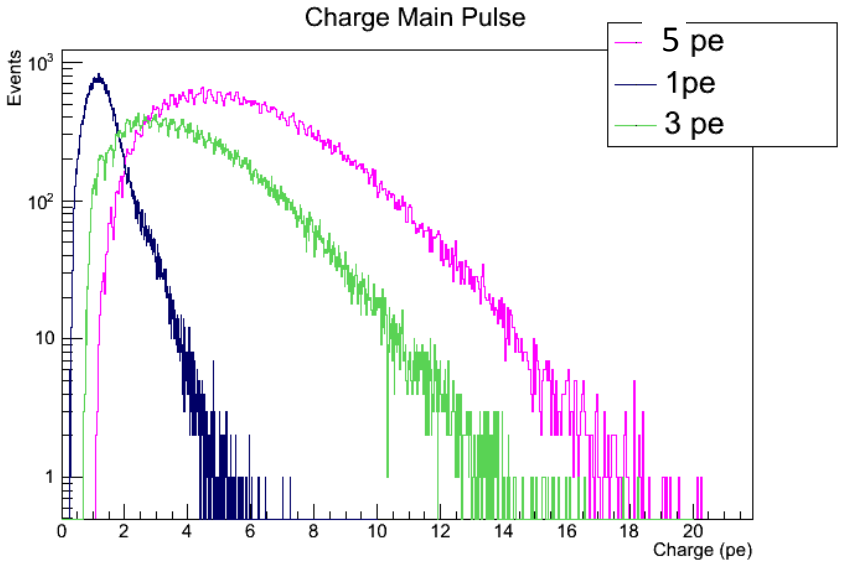


Parameter	Mean value
DC rate (Hz)	650
P/V ratio	3.1
TTS [ns]	3.9
Pre-pulses [%]	0.15
Delayed Pulses [%]	5.8
Type 2 after pulses [%]	4.15

3-in. PMT characterization (1, 3, 5 pe)

Mean charge PMT response set to 1, 3 and 5 photoelectron (pe)





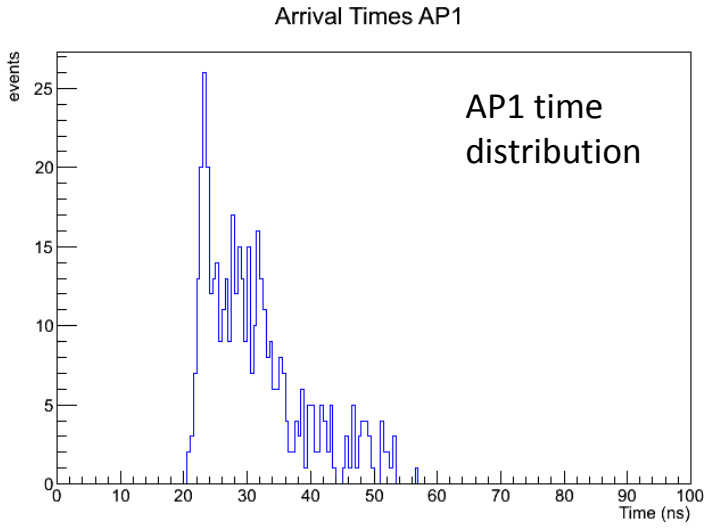
conditions	TTS (ns) FWHM
1 pe	4,0
3 pe	3,0
5 pe	2,8

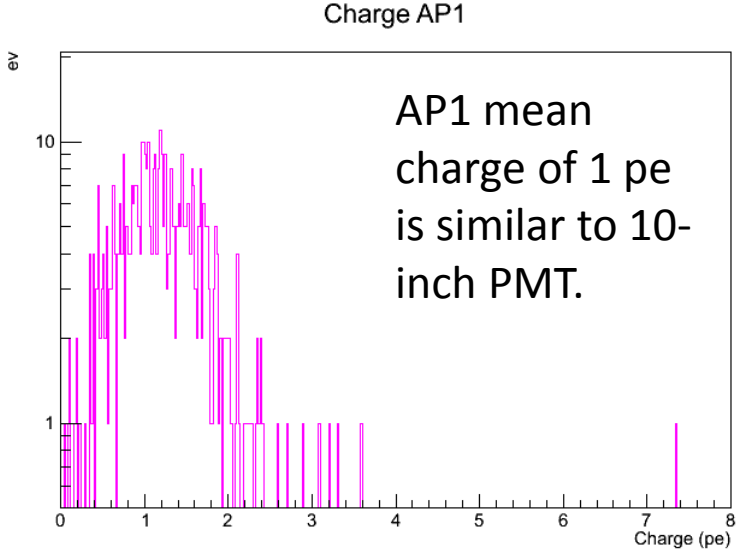
Changing PMT conditions from 1 to 5 pe TTS is reduced such as fraction of pre-pulses and delayed pulses

conditions	Pre-pulses	Delayed pulses
1 pe	0,3 %	6,40 %
3 pe	0,01 %	1,14 %
5 pe	0,002 %	0,47 %

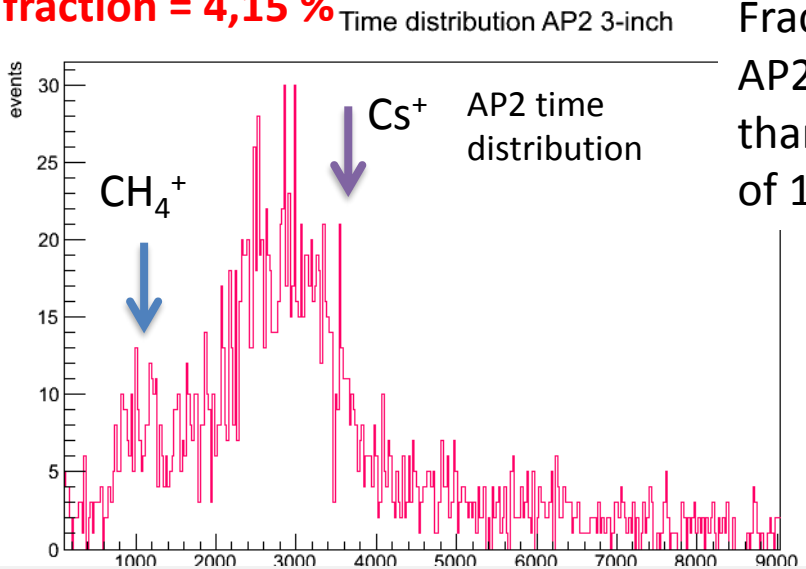
3-in. PMT type 1 and 2 afterpulses

AP1 fraction = 0,11 %

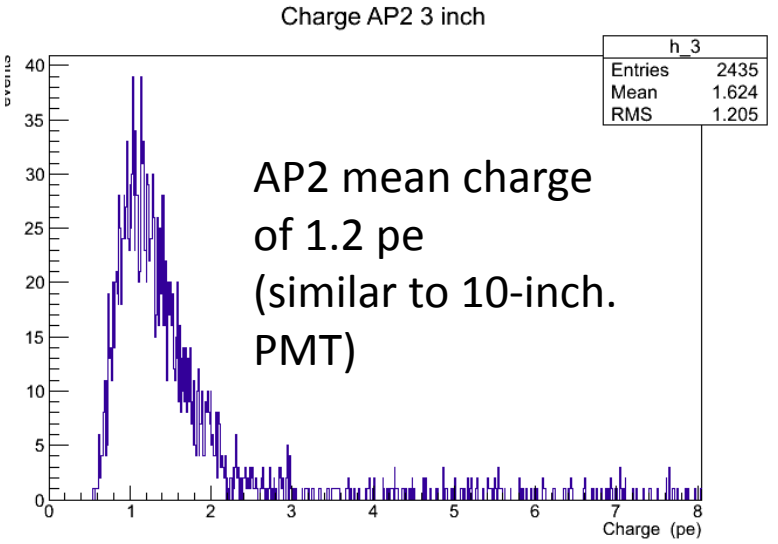




AP2 fraction = 4,15 %



Fraction of AP2 lower than that of 10 inch.

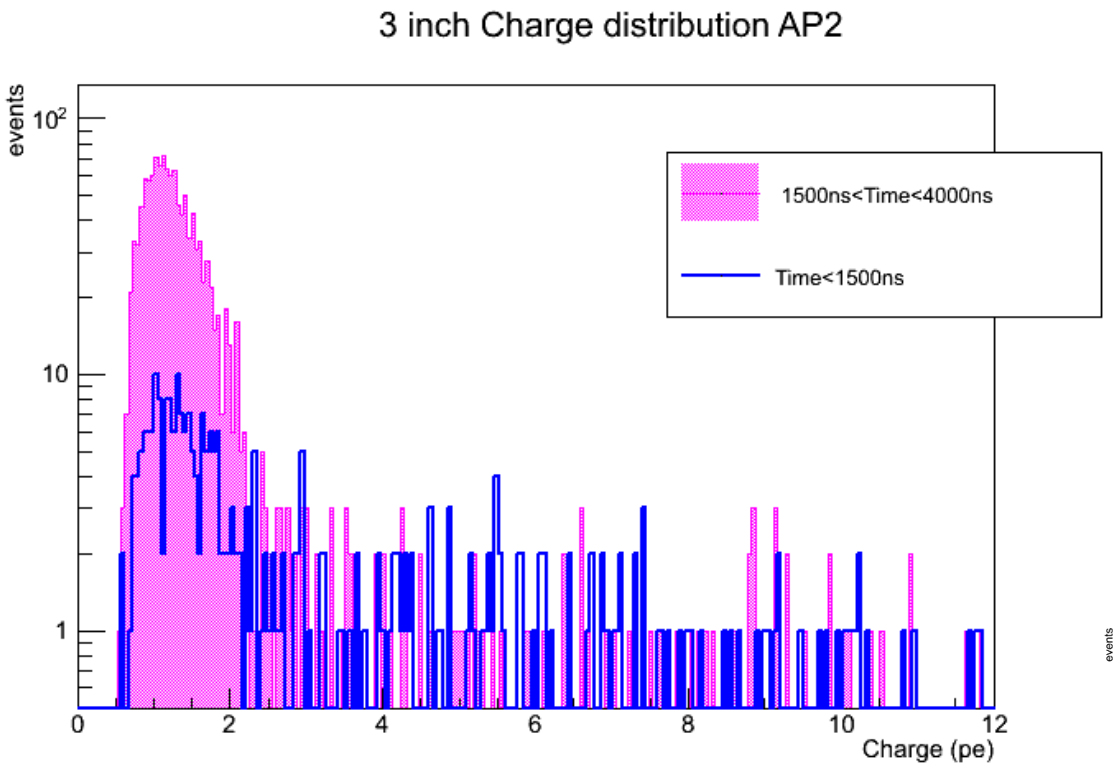


Two peaks at ~1μs and ~3μs (CH_4^+ and Cs^+) (time difference with 10-inch due to the geometry).

3-inch multi-afterpulses type 2

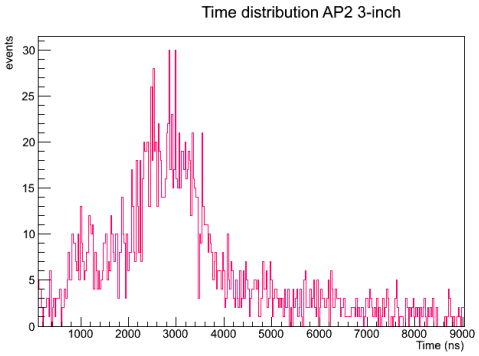
Differently to 10-inch PMT, in 3 inch PMT the multiple AP2 have a charge mainly of 1 pe. Multiple AP2 show lower fractions in confront of 10-inch PMT

Number of AP type 2	Fraction (%)	Mean Charge (pe)
1	3,81%	1,20
2	0,25%	1,21
3	0,07%	1,18
4	0,025%	1,22



magenta area there is CH_4 (arrival time lower than 1.5µs) while in blue there is Cs (with arrival time between 1.5µs and 4µs) .

Time-Charge correlation has the same behaviour ot 10-inch with an higher charge due to the CH_4^+ ions.

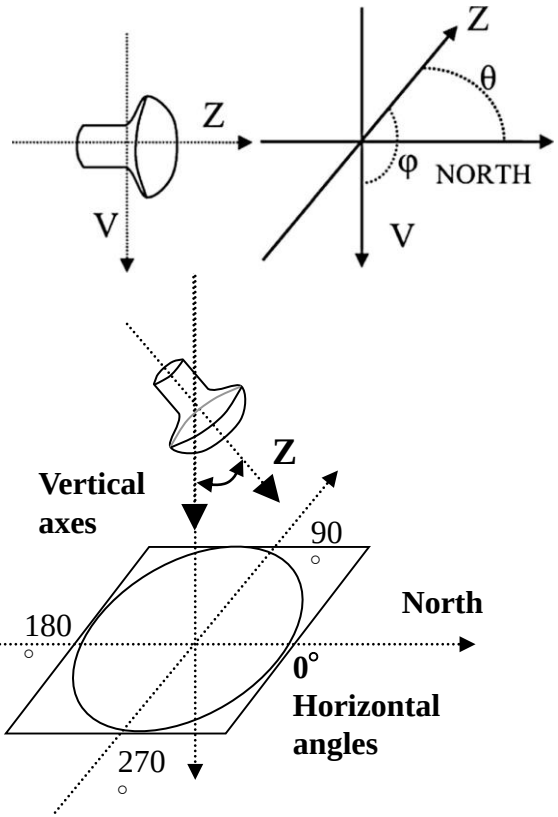


Influence of Earth's magnetic field

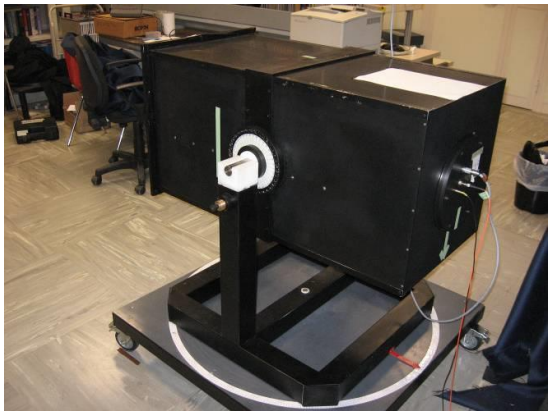
For all projects where PMT orientation is critical, the variations on characteristics due to the Earth's magnetic field must be investigated

Influence of Eart's magnetic field on large area 10-inch PMT and 3-inch PMTs was studied under KM3NeT design study

A dark box (1x0.5x0.5 m) able to rotate with respect to vertical axis and to change its inclination was made. No magnetic materials were used in its construction



The main parameters of the PMT were measured changing the orientation of the tested PMT with the Earth's magnetic field

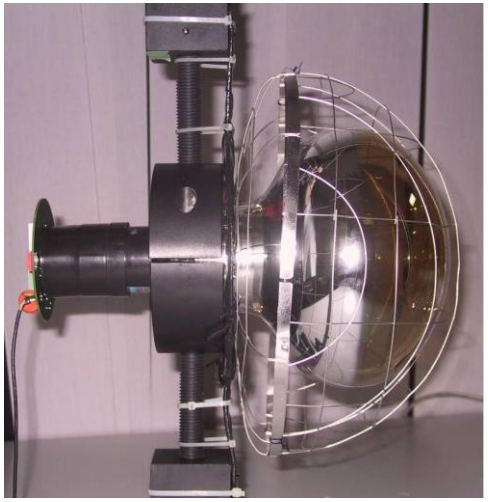


Measurements and conditions

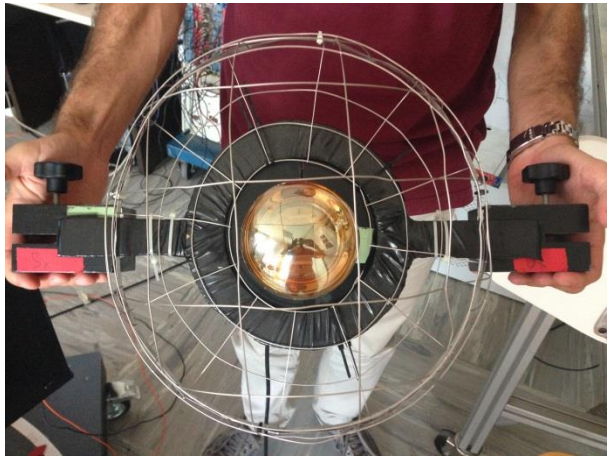
Tests on two 3-inch PMTs in 3 inclinations:
50° upwards (Tilt = +50°) ; 50° downwards (Tilt = -50°); horizontal (Tilt = 90°)
Tests on one 10-inch PMT in 3 inclination:
Vertical downwards(0°) ; horizontal (90°) ; 50° vertical downwards (-50°)

All measurements were made on PMTs un-shielded and repeated with a mu-metal cage as magnetic shield.

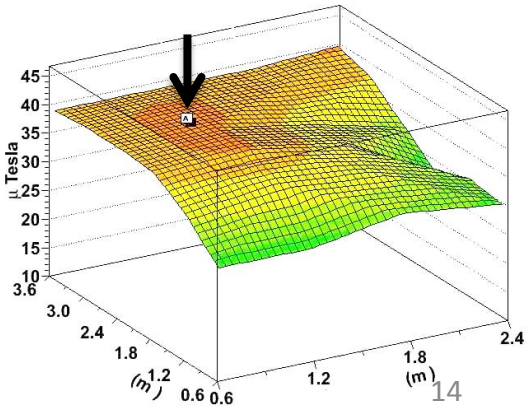
Characteristics of the cage:
- a hemispherical part
- a flat part
- wire of 1 mm of diameter
- pitch of 68 x 68 mm
- **average shielding Factor measured ≈ 4**



Cage surrounding the 10-in.

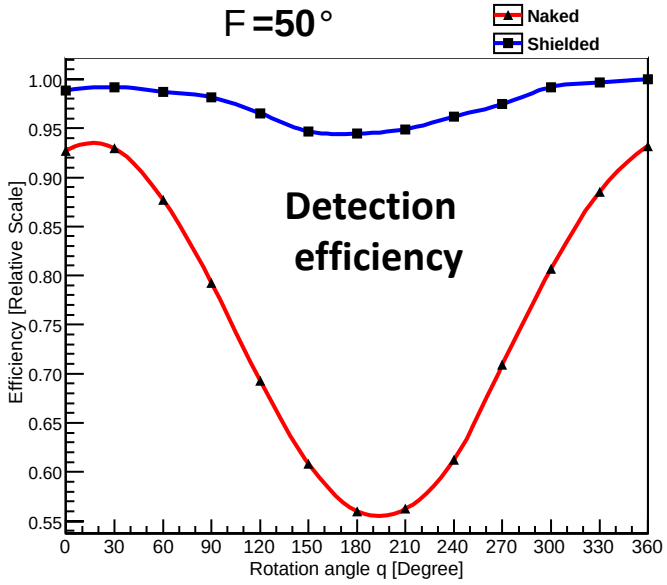


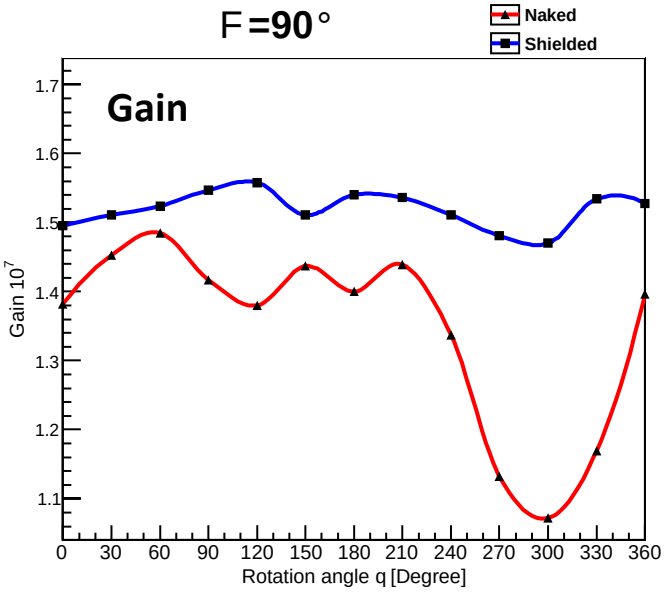
Cage surrounding the 3-in.



Magnitude and uniformity of the Earth's magnetic field were measured in the place of the test:
- B≈ 40 μTesla
- Uniformity over 1 meter area

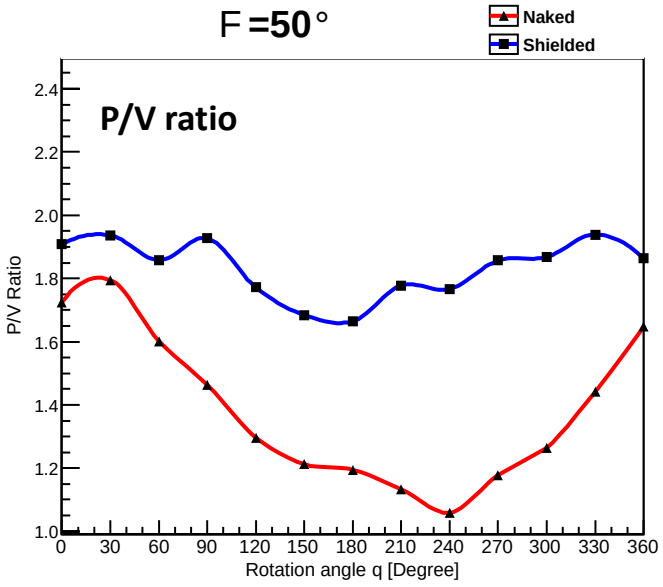
Effects of Earth's magnetic field on 10-inch PMT.
Measurements at different inclination for detection efficiency, Gain, PV ratio and TTS

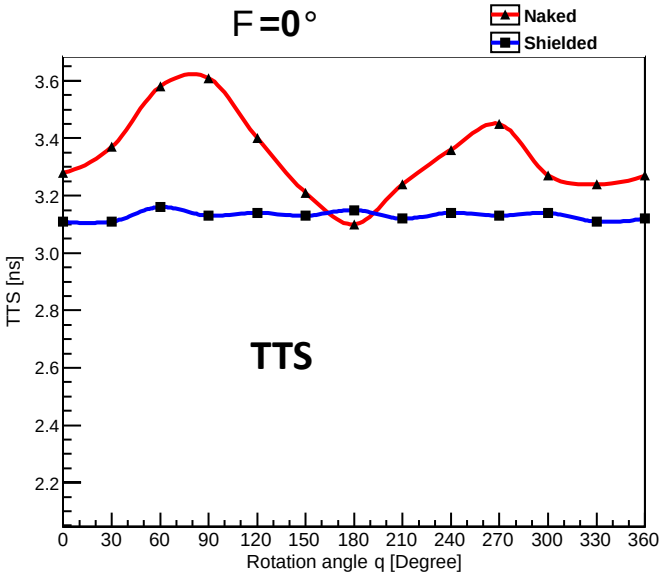




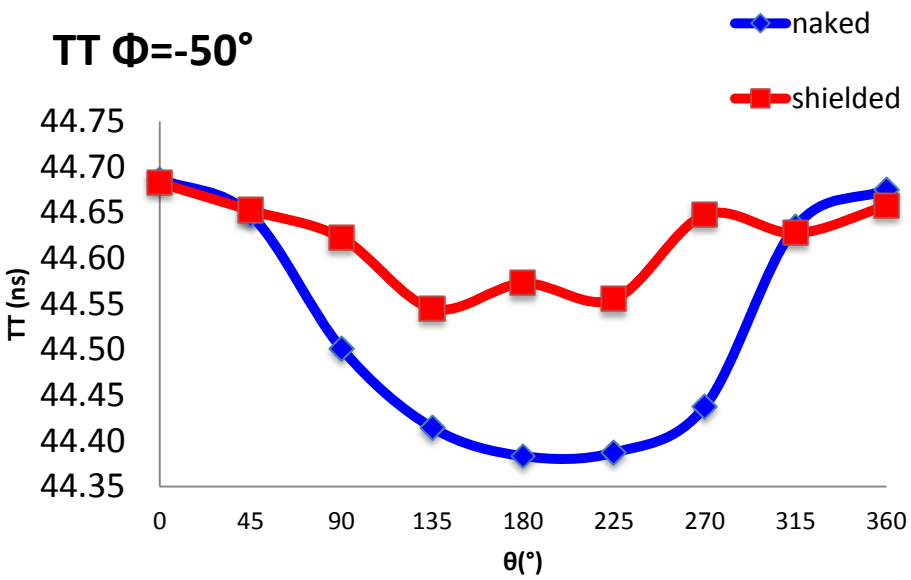
Red line: PMT naked

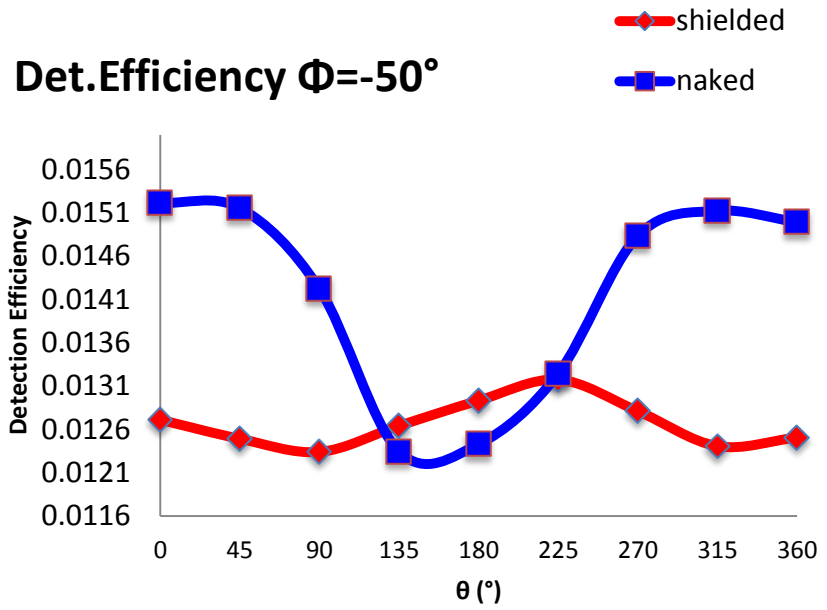
Blu line: PMT shielded

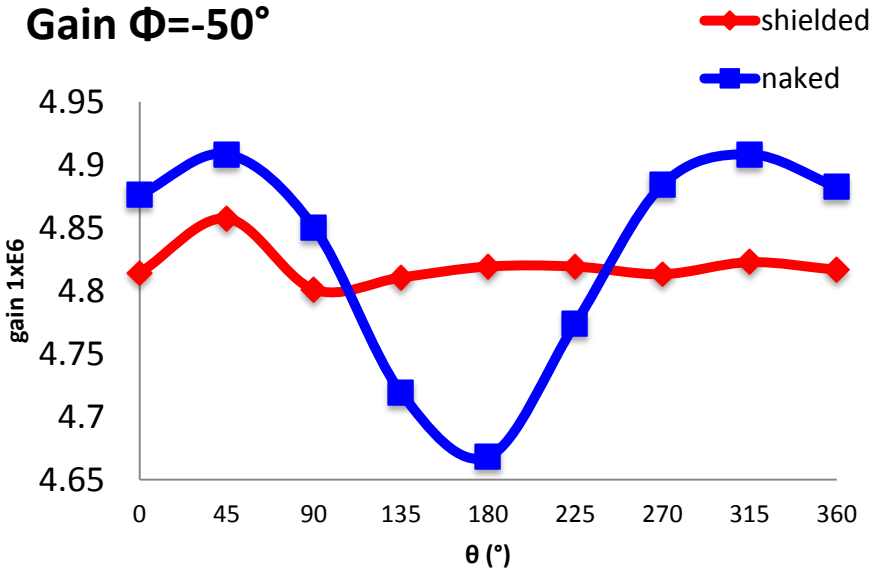


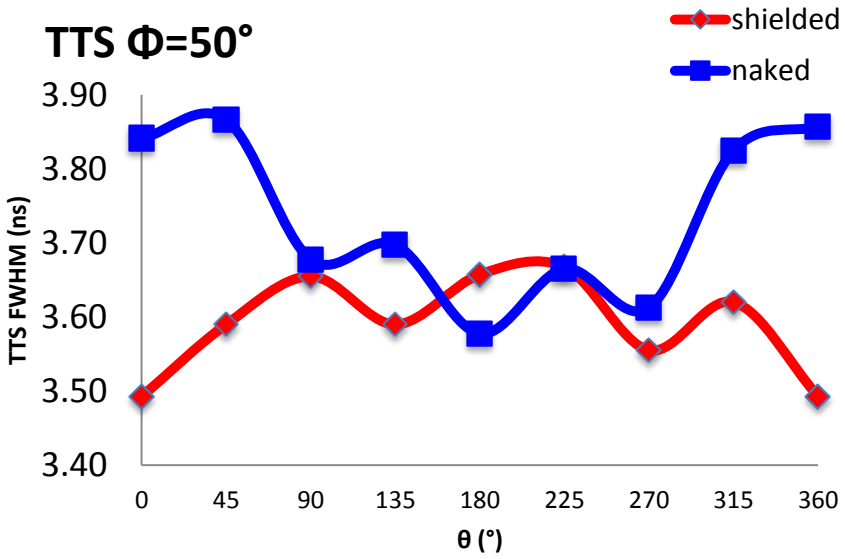


Effects of Earth's magnetic field on 3-inch PMT.
Measurements at different inclination for detection efficiency, TTS ,TT and Gain









	Naked	Shielded	Naked	Shielded	Naked	Shielded	Naked	Shielded
maximum variation on 360° horizontal rotation variation is % of difference of the maximum and minimum values divided by the maximum								
tilt	**0° (vertical down)**		**50° down**		**90° (Horizontal)**		**140° up ward**	
Det eff.								
PMT 10”	20.8 %	6.1%	39.9%	5.6%	14.7%	1.7%		
PMT 3”			23.3%	6.7%	11.9%	6.8%	12.0 %	10.0 %
tilt	**0° (vertical down)**		**50° down**		**90° (Horizontal)**		**140° up ward**	
Gain								
PMT 10”	16.3%	6.6%	28.6%	6.7%	27.8%	5.6%		
PMT 3”			5.1%	1.8%	3.0%	1.6%	4.1%	2.8%
tilt	**0° (vertical down)**		**50° down**		**90° (Horizontal)**		**140° up ward**	
TTS								
PMT 10”	14.1%	1.6%	10.5%	4.0%	9.7%	5.5%		
PMT 3”			3.3%	1.5%	4.0%	1.7%	8.1%	5.0%
TT								
Max. Variations below 0.6% for both naked 3” and 10” PMTs								

Conclusions

10 inch (spe conditions)	3 inch (spe conditions)
TTS (FWHM) ~ 3 ns (in 3 pe and 5 pe conditions it decrease)	TTS (FWHM) ~ 4 ns (in 3 pe and 5 pe conditions it decrease)
Pre-pulses are slightly lower than 1 pe Delayed pulses are mainly of 1 pe charge. In 3 pe and 5 pe, fractions are lower than 1pe	Pre-pulses are slightly lower than 1 pe Delayed pulses are mainly of 1 pe charge. In 3 pe and 5 pe, fractions are lower than 1 pe
Type 1 after pulses charge mainly is of 1 pe	Type 1 after pulses charge mainly is of 1 pe
Type 2 afterpulses charge mainly of 1.5 pe.	Type 2 afterpulses charge mainly of 1.2 pe.
Temporal peaks at 2μs and 8μs (CH_4^+ and Cs) First peak with an higher charge contribution in confront of the second	Temporal peaks at 1μs and 3μs (CH_4^+ and Cs) First peak with an higher charge contribution in confront of the second
Multiple AP2 with a mean charge up to 3 pe	Multiple AP2 with a lower statistic than 10-inch and mean charges of about 1,2 pe
High influences of Earth's magnetic field on PMT parameters. A magnetic shield is mandatory	The impact of magnetic fields was considerable smaller than 10-inch PMTs. A magnetic shield is not mandatory.