Test and Calibration of a large 3” Hamamatsu PMT sample

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NEPTUNE
New and Enhanced Photosensor Technologies for Underground/underwater Neutrino Experiments
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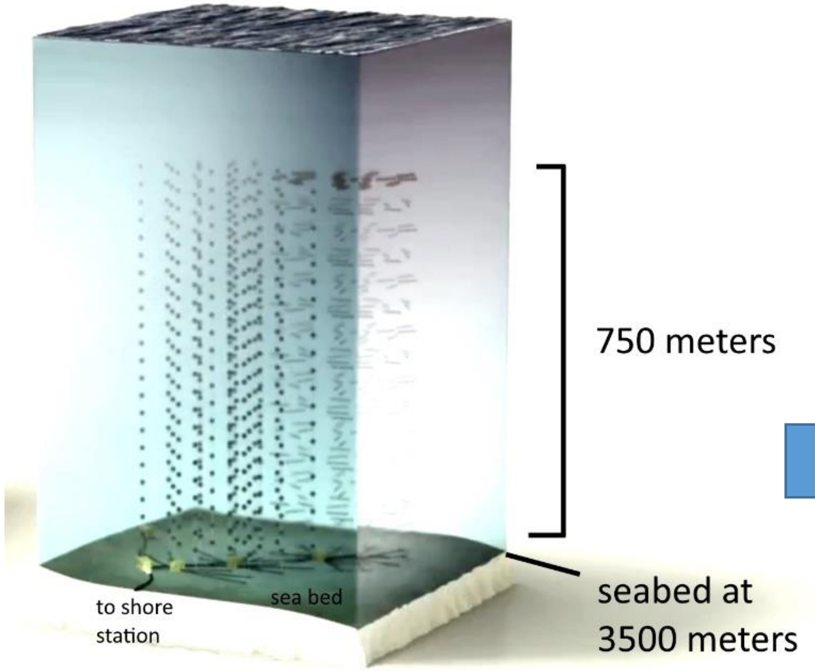
KM3NeT
INFN
Istituto Nazionale di Fisica Nucleare

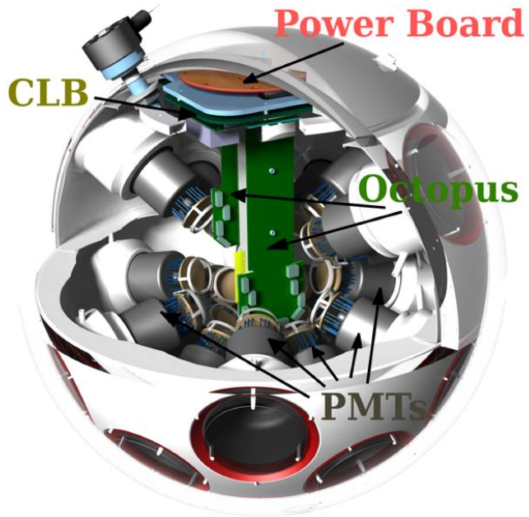
Introduction

KM3NeT



Once completed ≈ 345 Dus
18 DOMs/DU

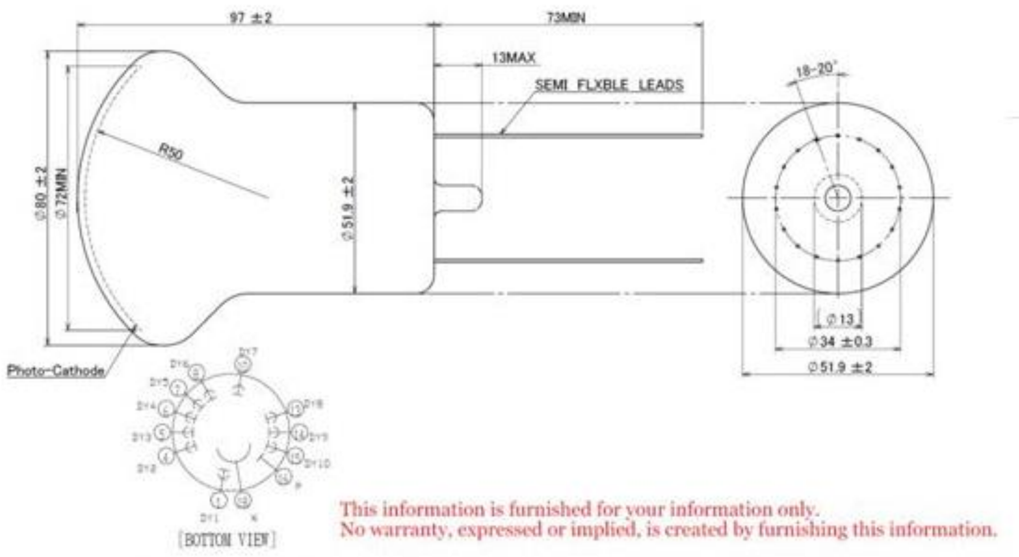
6210 DOMs
31 PMTs/DOM



192510 PMTs!!!

KM3NeT FASE 1 PMTs

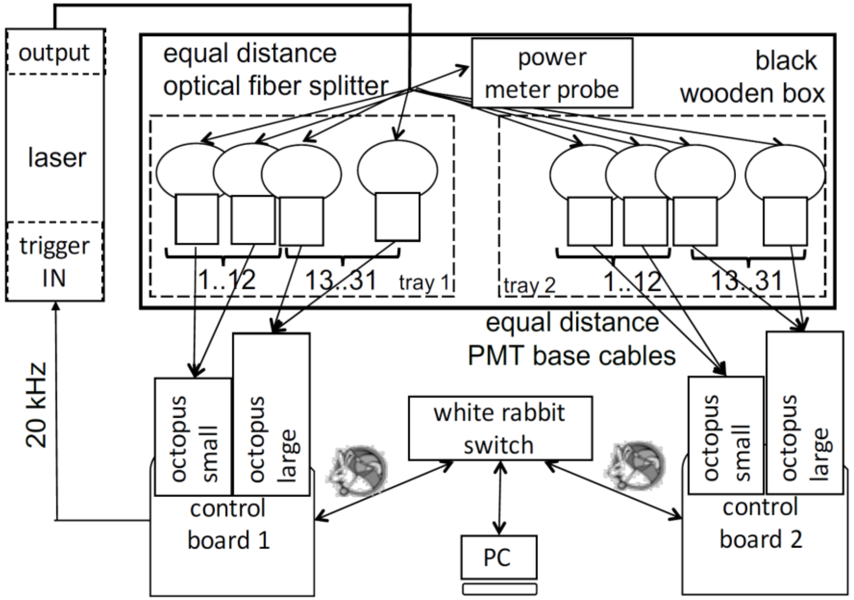
Hamamatsu R12199-02



- 3 inch bialkali photocathode
- 10 Dynode stages (Gain 3 x 10^6)
- Nominal operation voltage: -900 ÷ -1300 V
- TTS (Transit Time Spread FWHM) ≈ 3 ns
- Dark Counts ≈ 500 cps

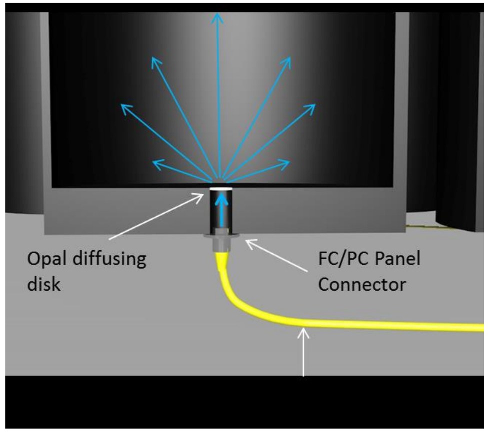
[Photomultipliers for the KM3NeT optical modules - KM3NeT Collaboration Nucl.Instrum.Meth. A695 (2012) 313-316]

The DarkBox



≈7000 PMTs tested at Napoli Using the «DarkBox» facility

- 62 PMTs tested in parallel
- 2 tests per day
- HV tuning
- Dark count measurement
- Spurious pulses
- Transit time and TTS



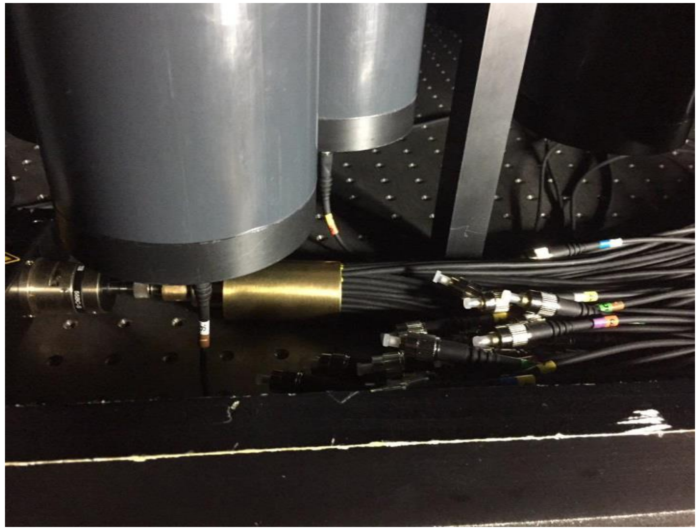
[C. M. Mollo et al., JINST 11 (08), T08002 (2016)]

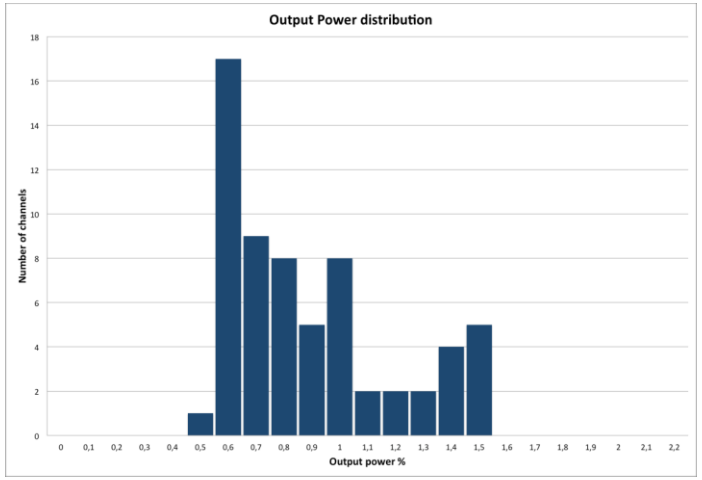
The DarkBox: optics

Laser source

PiLas Mod. EIG2000DX	
Repetition rate (internal trigger)	50 Hz – 1 MHz
Repetition rate (external trigger)	Single shot – 1 MHz
External trigger input	TTL & VAR upt 120 MHz
External trigger pulse width	Typ. ≥ 4 ns
Synchronization output pulse width	typ. ≥ 4 ns for external triggering 50% duty cycle for internal oscillator
Typical jitter between synchronization trigger output and optical signal	typ. ≤ 4 ps
Warm-up time	< 5 minutes
LASER head	Wavelength 405 +/- 10 nm, spectral width < 7 nm, pulse width (FWHM) typ < 45 ps

Optical splitter





Power meter

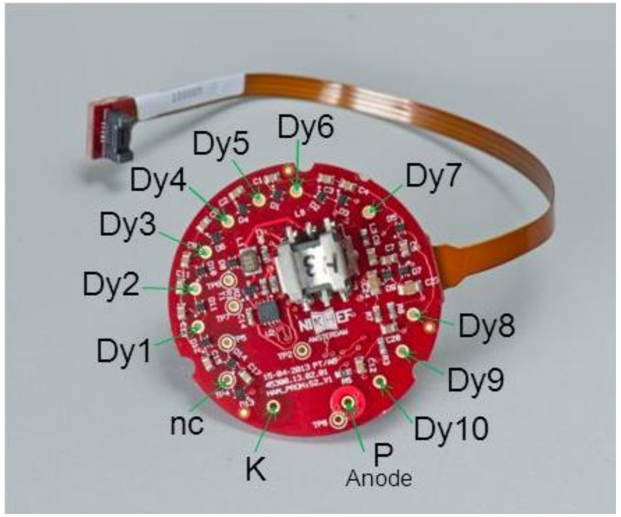
Newport Mod. 2936-C	
Full-Scale Current	2.5 nA – 25 mA
Resolution	10 fA
Accuracy	0.2%
SNR	100 dB
Bandwidth	1.2 Hz – 400 kHz
Minimum Power Resolution	11 fW

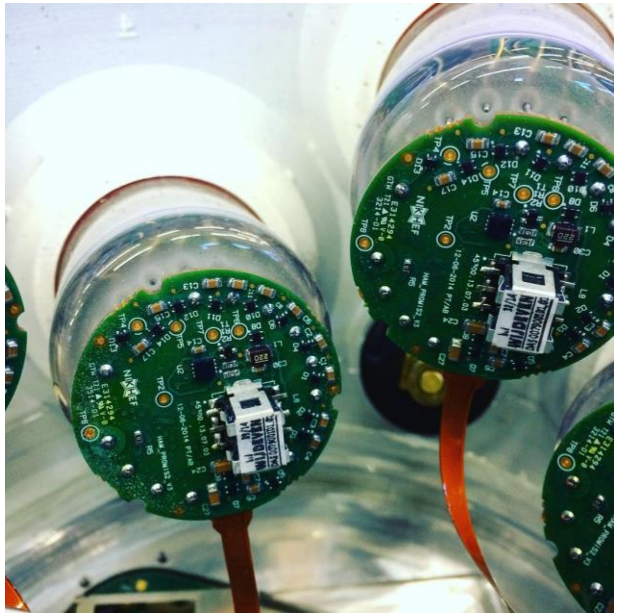
Newport Mod. 918D-SL-OD3	
Material	Silicon
Spectral Range	400 to 1100 nm
NEP (detector noise equivalent power)	0.55 pW/√Hz

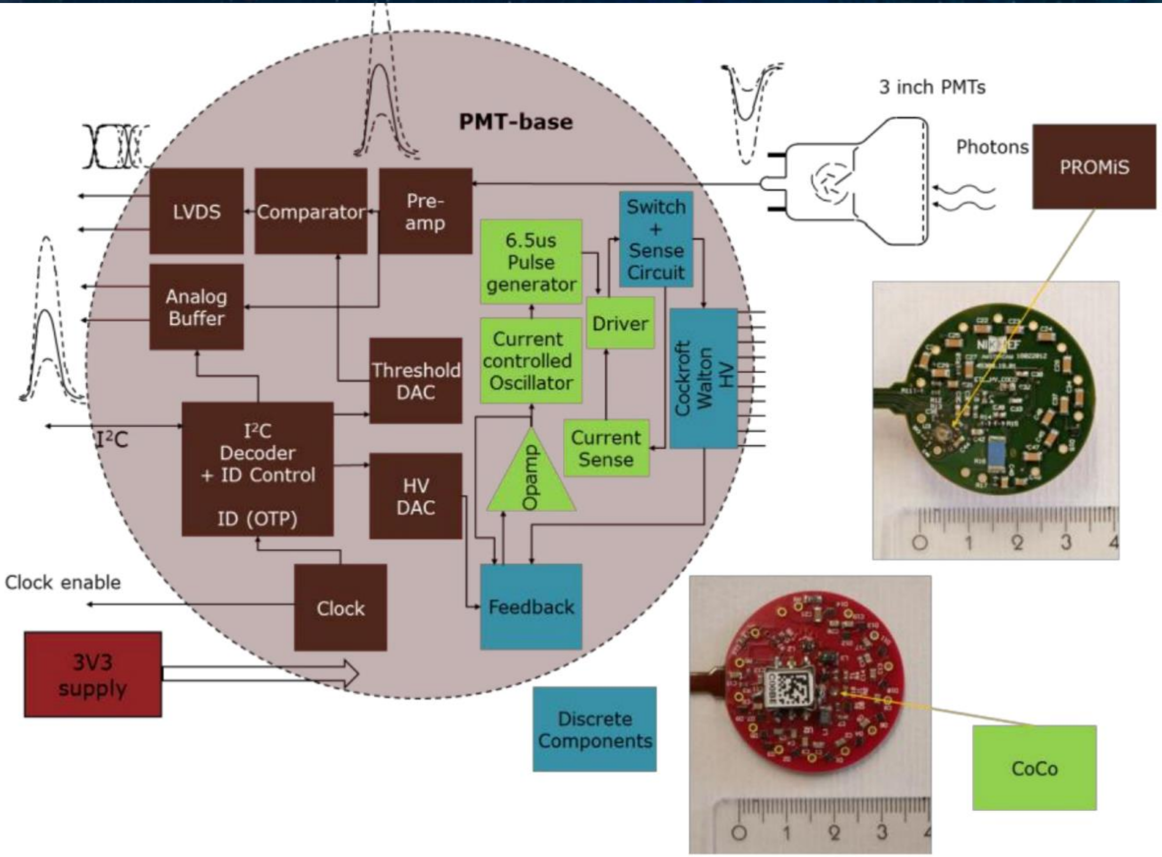
[C. M. Mollo et al., JINST 11 (08), T08002 (2016)]

The DarkBox: electronics

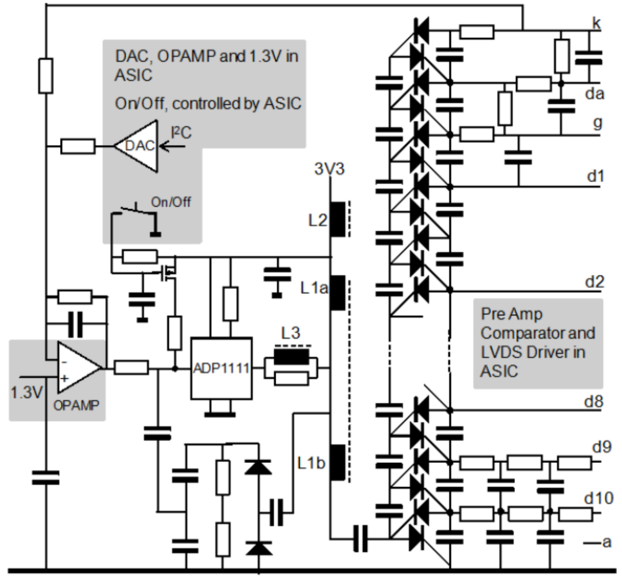
Designed at Nikhef



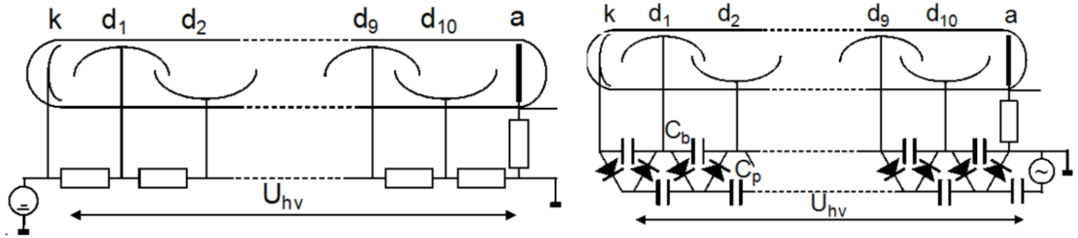




Cockroft -Walton



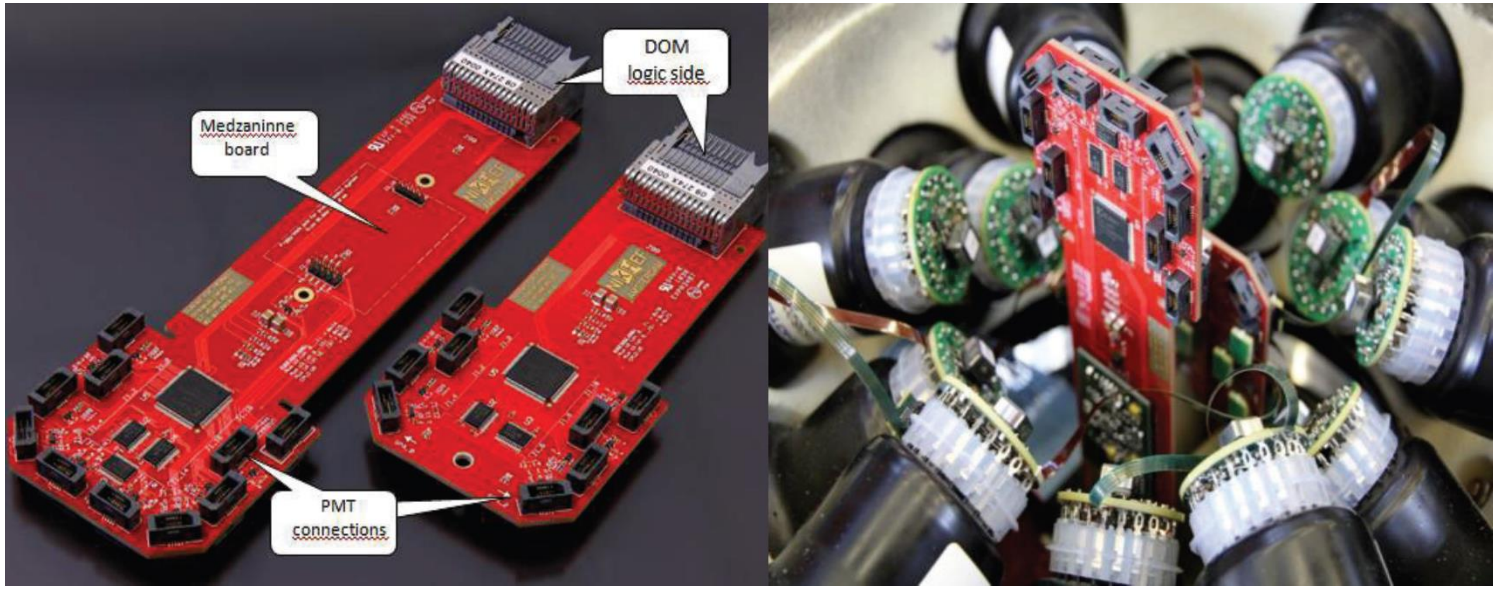
Power consumption: 3.3 mW

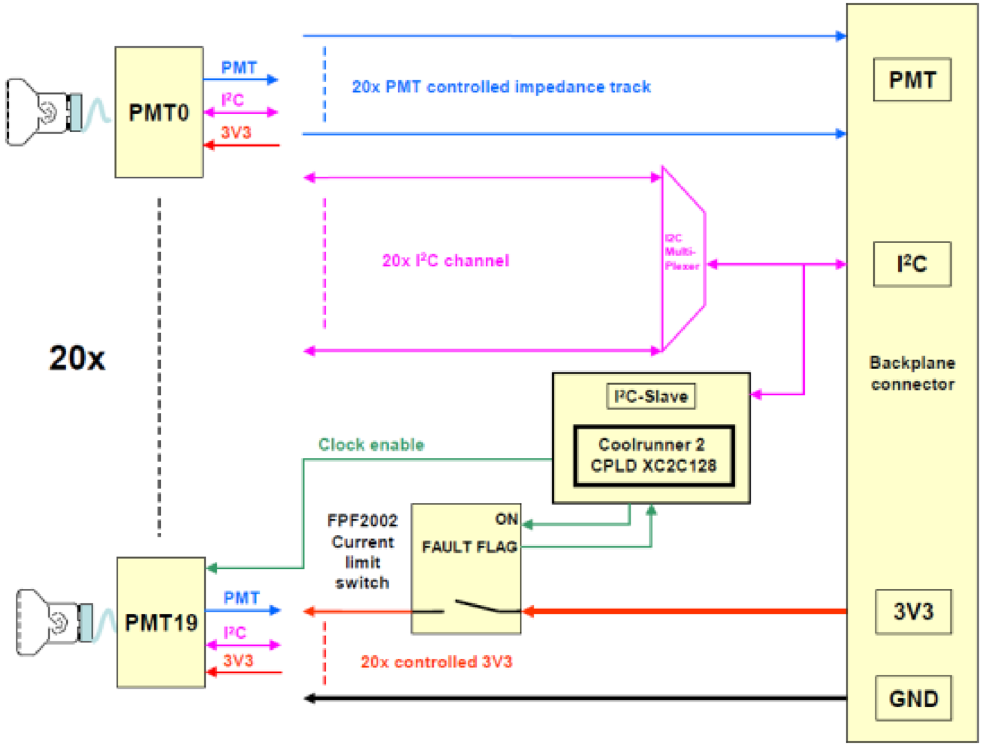


[P. Timmer, "Very low power, high voltage base for a PhotoMultiplier Tube for the KM3NeT deep sea neutrino telescope", Proceeding to the TWEPP, Aachen (2010)]

31 x 3.3 mW = 102.3 mW compared to 31 x 50 mW = 1.55 W

The DarkBox: electronics



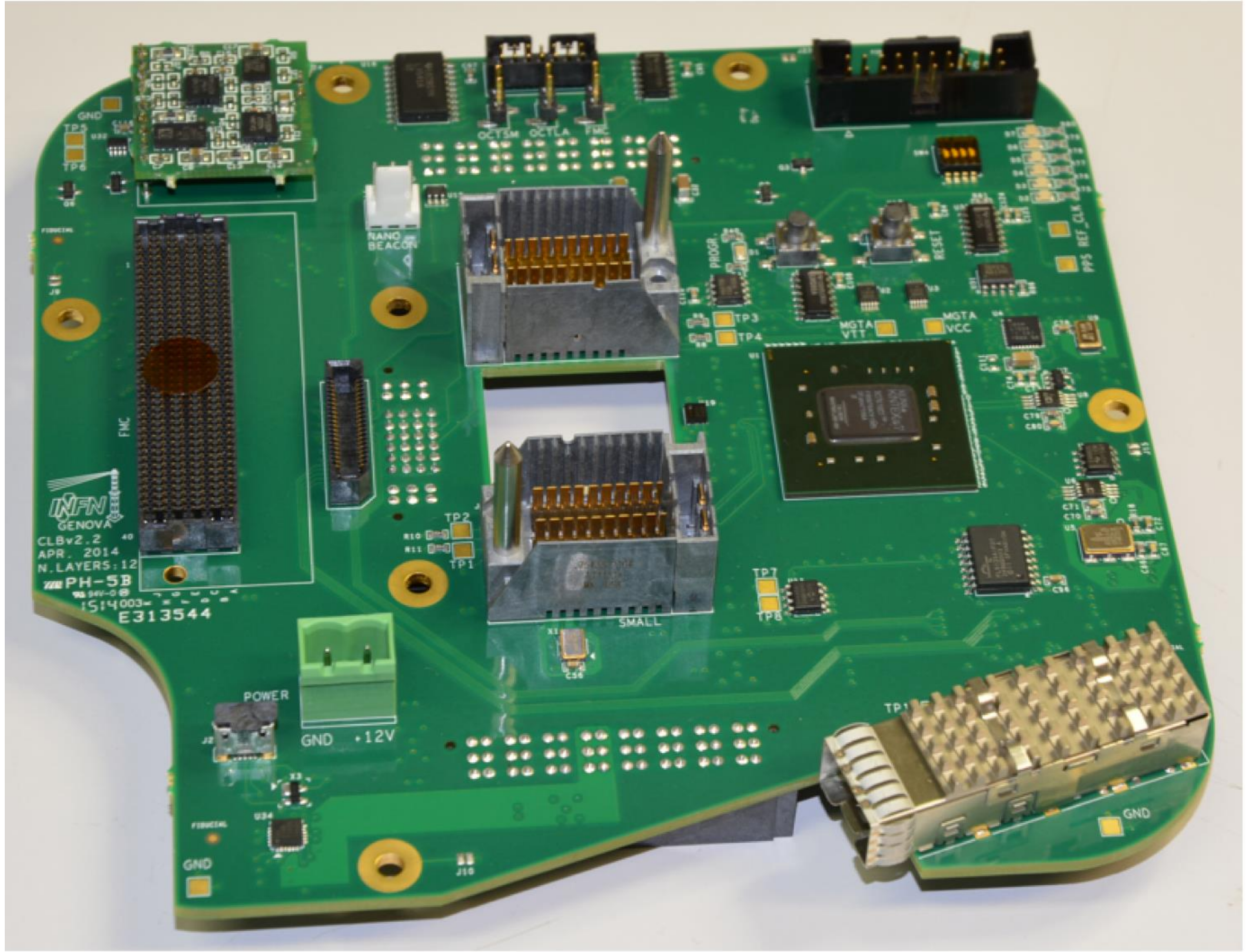


The Octopus V4 boards acts as a hub inside the DOM. It merges all the PMT signal connections, controls the power supply and re-directs the I^{2}C communication.

block diagram octopus large

At one side the Octopus V4 board is connected to the PMT's and the piezo element. It distributes the power, clock enable and I^{2}C communication to the PMT's and piezo element. It acts as in input for the differential signal from the PMT's and piezo element.
At the other side the Octopus V4 board is connected to the CLB. The power and de I2C bus are delivered from the CLB to the Octopus V4 board. The differential signal is delivered to the CLB.

The DarkBox: electronics



CLB power consumption: < 4.5 W
Total DOM power consumption about 7.5 W

The CLB main components:

- Xilinx Kintex-7 FPGA (XC7K160TBG676) is the core of the board, used to measure the arrival time and the pulse width of the 31 PMT discriminated signals with 1ns resolution
- Tunable oscillators (20 MHz and 25 MHz base frequencies) for White Rabbit PTP core
- 512 Mbit Quad SPI Flash Eprom
- PMT interface (31 x) through Octopus boards connectors
- SFP laser module housing with heatsink
- Temperature & Humidity sensor
- Compass & Tilt meter
- NanoBeacon (calibration LED Flasher) Interface
- Acoustic AES interfaces for Hydrophone and Piezoelectric acoustic sensors
- Expansion industry standard FMC High Pin Count connector
- Debugging: Serial to USB converter (2 x), Standard Header 20 pin connector, High density connector for batch production testing, Dip-Switches & LEDS

In the FPGA two microprocessor systems based on LM32 soft processor are implemented:

- White Rabbit Precision Time Protocol engine: implement 1ns time synchronization and transfer data to shore station;
- Configuration and slow control: handles all the devices inside the DOM, manage housekeeping data and implement debug ports.

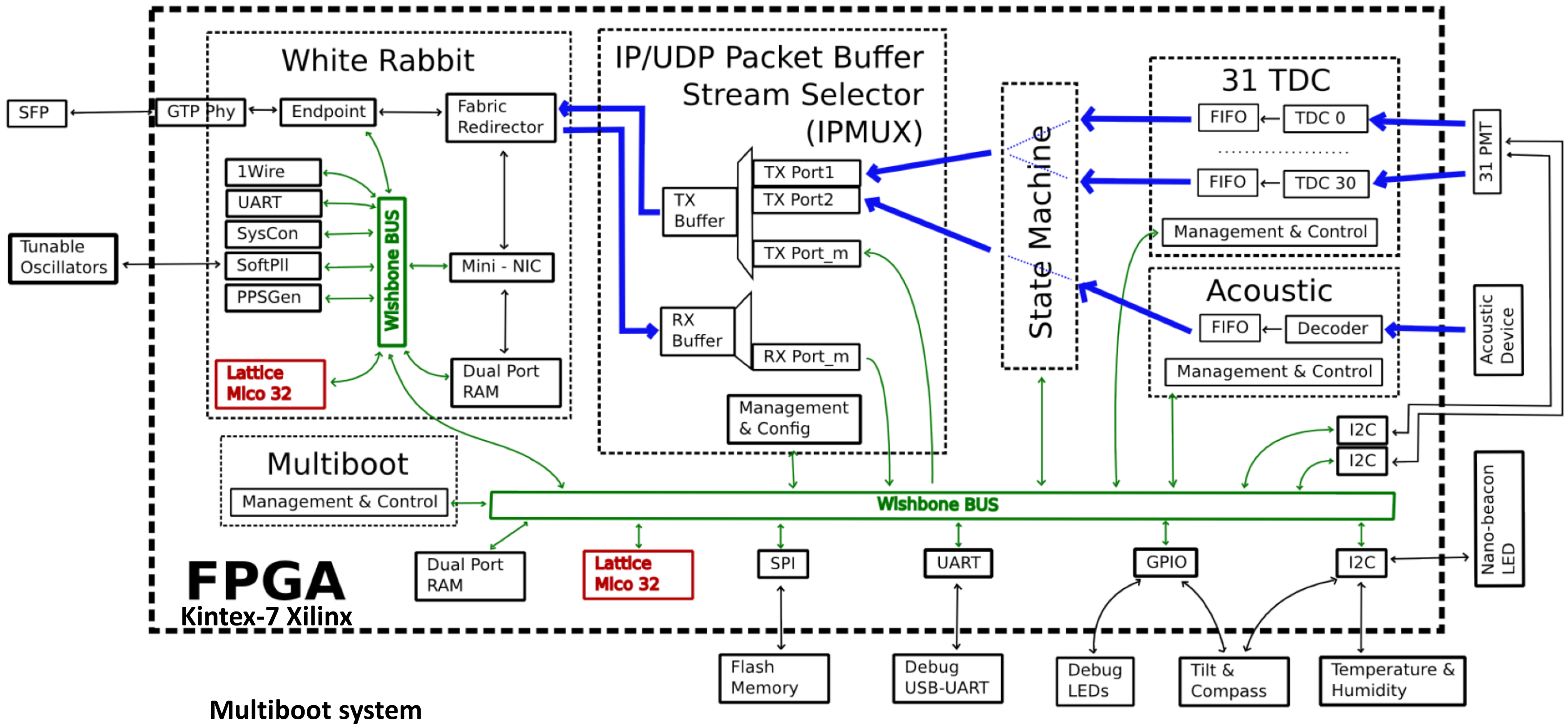
[P. Musico, “The central logic board for the optical module of the KM3NeT detector,” Proceedings of TIPP, Amsterdam, 2014]

The DarkBox: electronics

White Rabbit PTP core for time Synchronization and Ethernet over optical fibres.

IP/UDP (ethernet) packet Creation
Multiple streams
(PMTs, acoustic, monitoring)
.

High-Speed TDCs
LVDS inputs from PMTs
Hit time and ToT. 800ps/√12 resolution



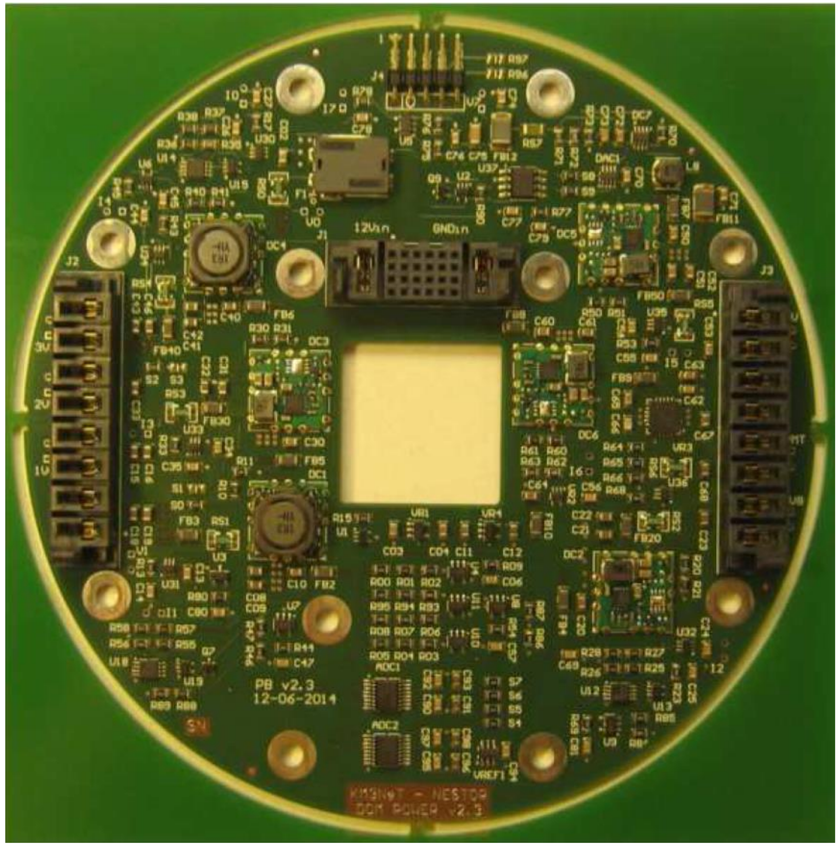
Multiboot system
Fail-safe reprogramming

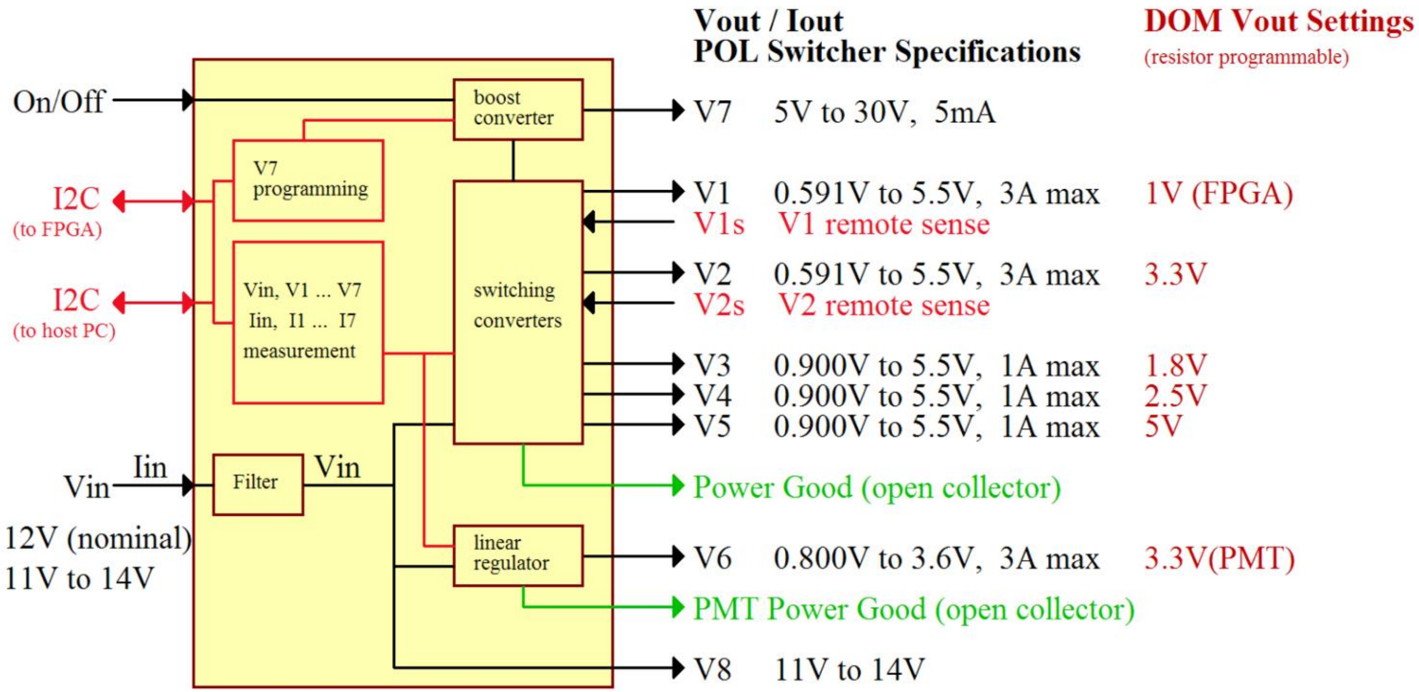
I2C communication
HV and thresholds, Compass/tiltmeter, Led Flasher
Temperature/Humidity

The CLB integrates the White Rabbit Protocol (White Rabbit is a fully deterministic Ethernet-based network for general purpose data transfer and synchronization), which allows to synchronize all the KM3NeT DOMs within 1 ns resolution. The data provided by the PMT bases are collected and distributed to the CLB by the Octopus Boards. It also contains the electronic and photonic components for an optical serial link to the shore. All necessary DC power is provided by the Power Board.

[D. Real, “The electronics readout and data acquisition system of the KM3NeT neutrino telescope node,” Proceedings of the VLVnT, Stockholm, 2013]
[White Rabbit Project: https://www.ohwr.org/projects/white-rabbit/wiki/Wiki]

The DarkBox: electronics





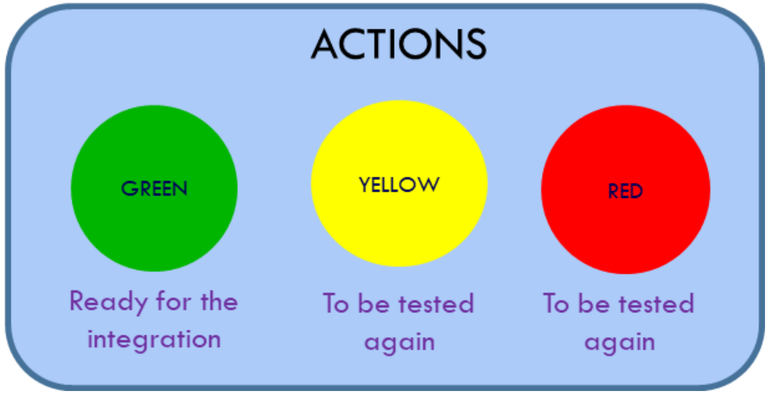
The PB rail voltages were specified at 1V, 1.8V, 2.5V, 3.3V, 3.3V(PMT) and 5V with expected loads ranging from 1W to 2.3W. They are derived from the 12V bus using step-down switching regulators. Due to the low noise and ripple requirement in driving the electronics of the PMTs, the 3.3V(PMT) rail is derived from a linear regulator (TI TPS74401) driven by a switching regulator that converts the 12V bus to an intermediate 3.8V rail in order to minimize the dropout voltage and heating of the 3.3V linear regulator.

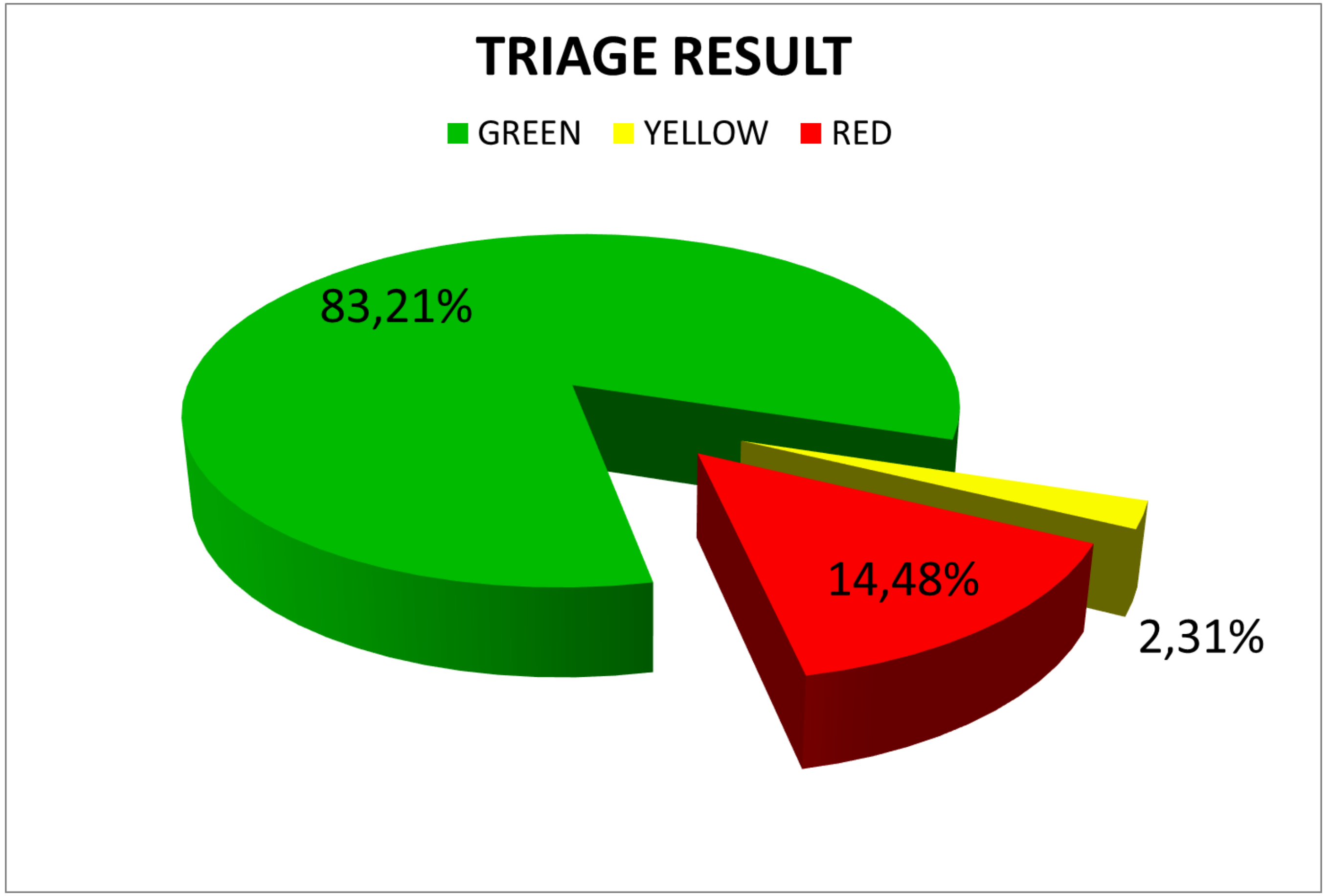
[KM3NeT Coll. (A. Belias et al.) , “Design and development of the Power Converter Board within the Digital Optical Module in KM3NeT”, PoS TIPP2014 (2014) 188]

First round of test

6960 PMTs tested

TRIAGE

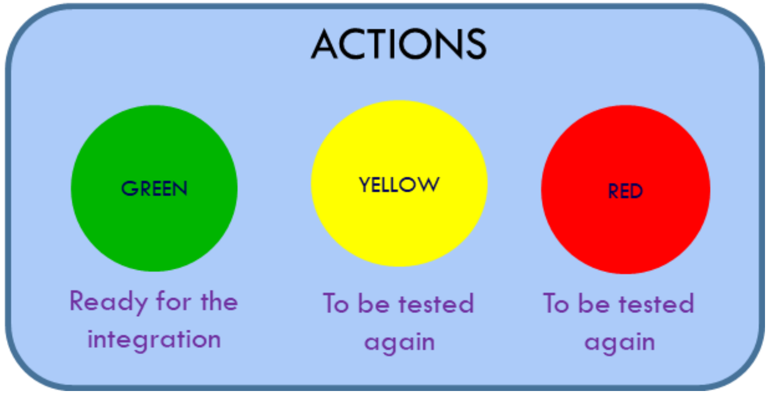


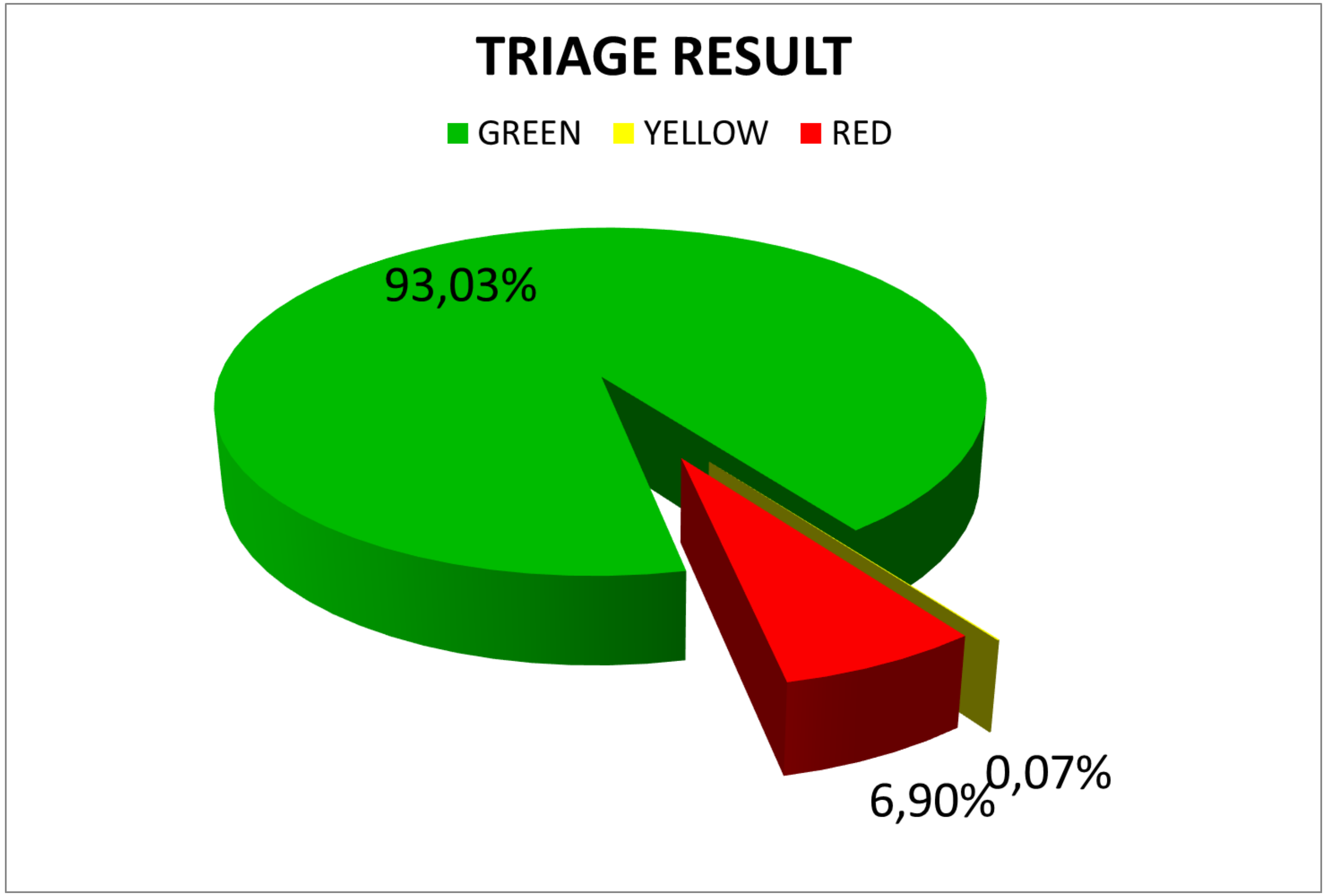


Second round of test

6960 PMTs tested

TRIAGE



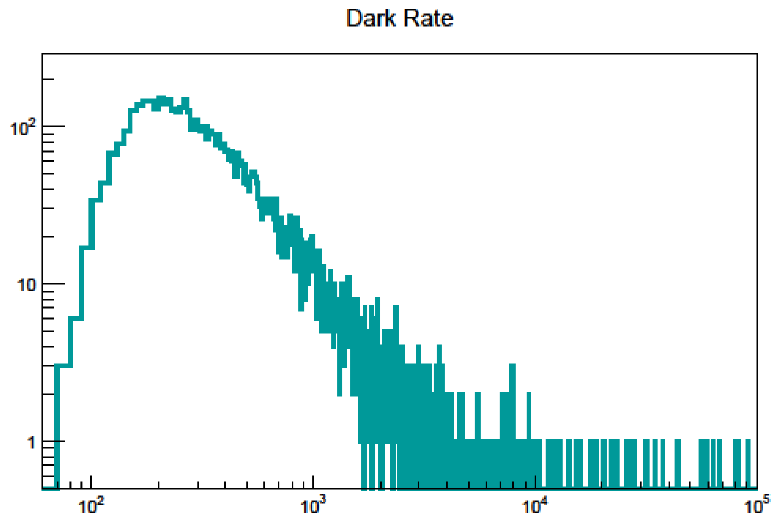


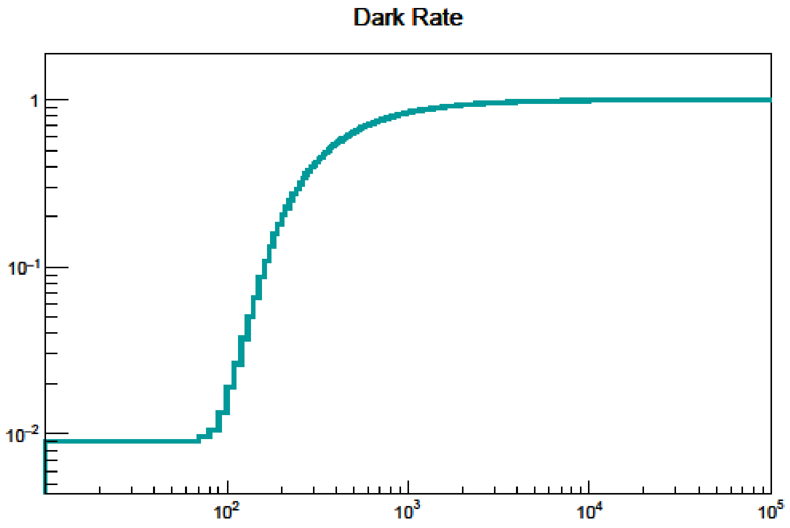
RED PMTs recovered: 53,03%
YELLOW PMTs recovered: 96,87%

Final results

Dark counts @ 20°C and 0.3 spe threshold

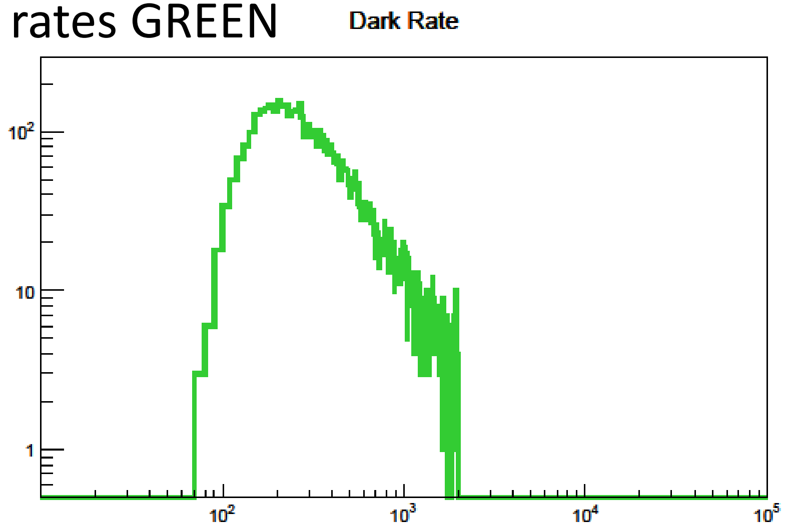
Dark rates ALL

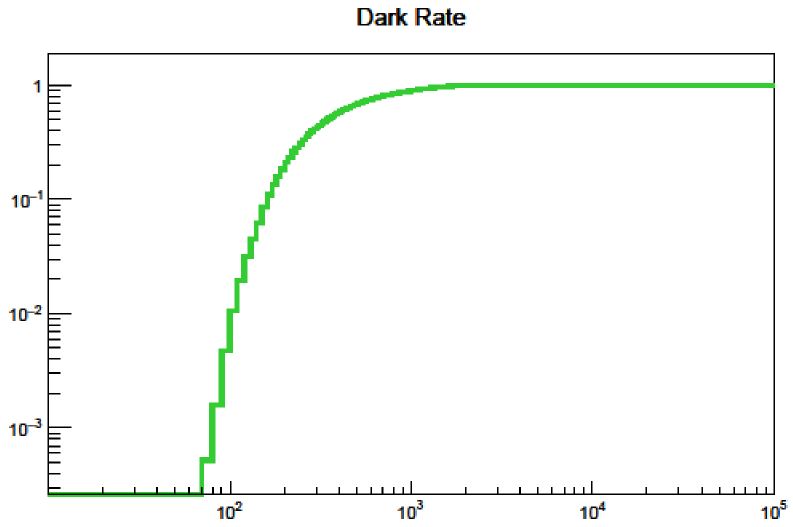




85% < 1070 cps
89% < 1490 cps
95% < 2630 cps
98% < 5460 cps
99% < 9130 cps

Dark rates GREEN

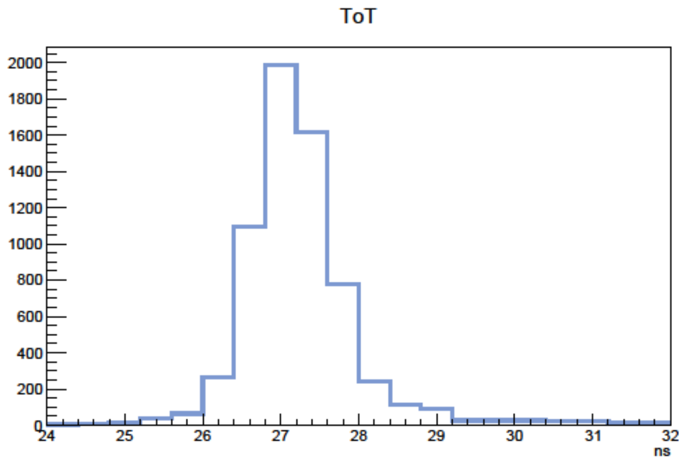


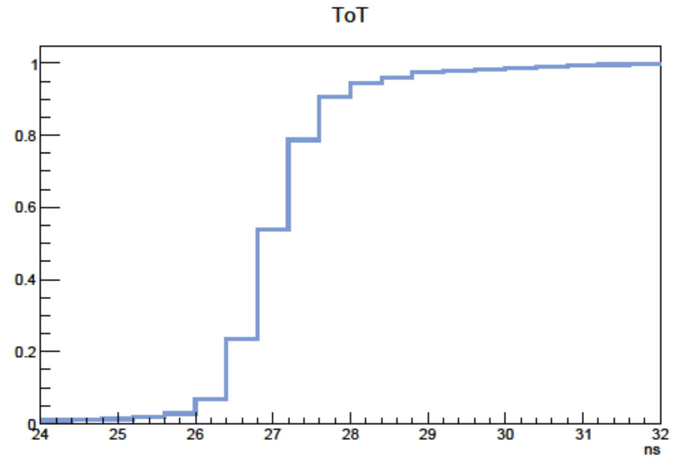


85% < 850 cps
90% < 1030 cps
95% < 1360 cps
98% < 1680 cps
99% < 1840 cps

Final results

ToT ALL

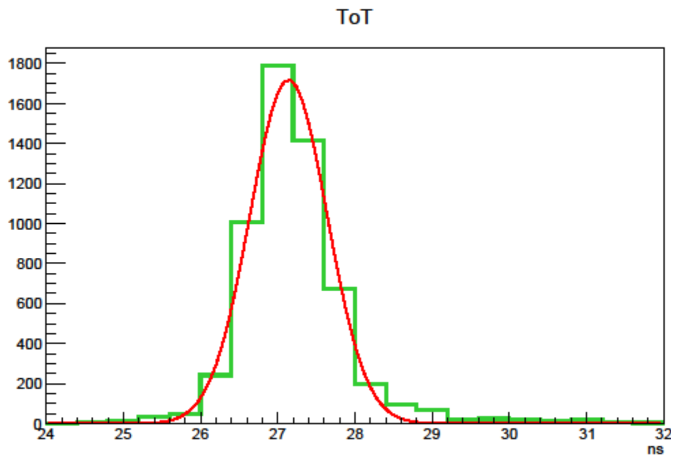


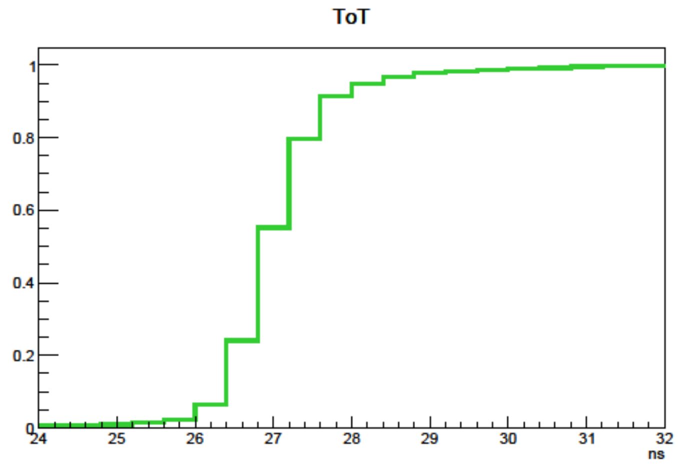


ToT: 27.1 ± 0.5 ns

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	1.95545e+03	3.31033e+01	2.36070e-01	6.42487e-06
2	Mean	2.71566e+01	6.59424e-03	6.03524e-05	-1.76085e-02
3	Sigma	4.99883e-01	5.54941e-03	2.07381e-05	1.03240e-01

ToT GREEN





ToT: 27.1 ± 0.5 ns

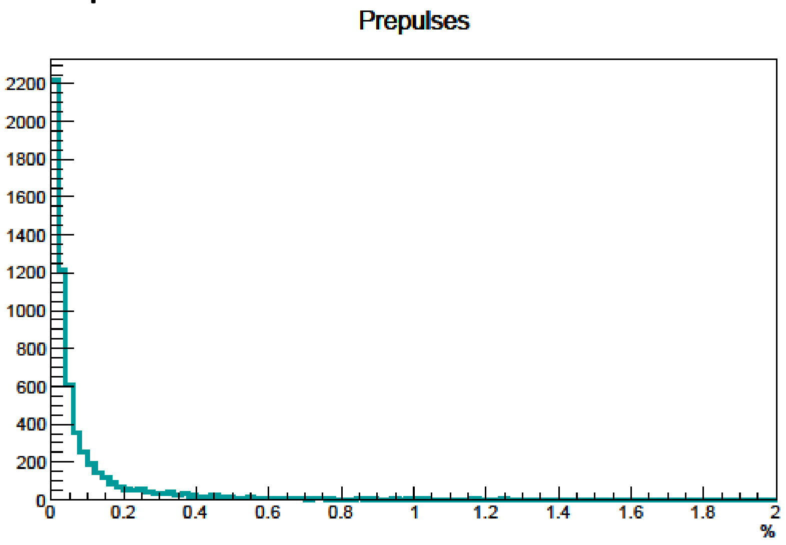
NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	1.71977e+03	3.09572e+01	2.01156e-01	1.38358e-06
2	Mean	2.71399e+01	7.01510e-03	5.84667e-05	-3.08259e-03
3	Sigma	4.99847e-01	5.87814e-03	2.03997e-05	1.25413e-02

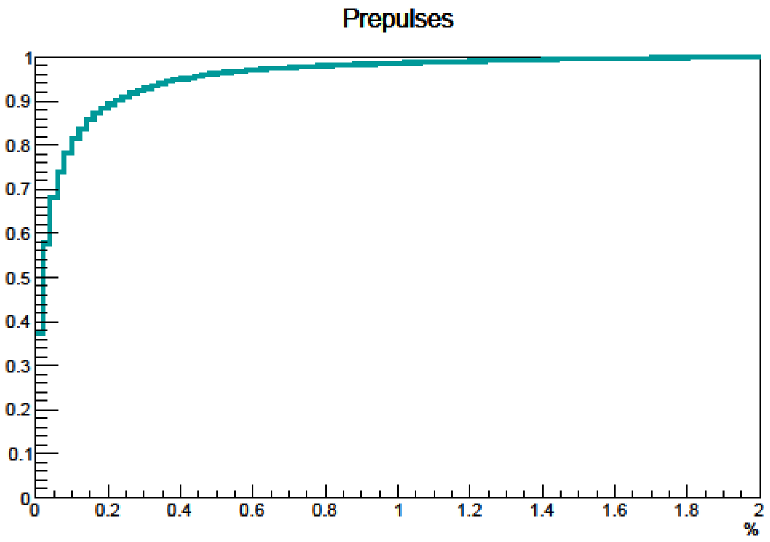
Final results

Prepulses between -60 ns and -10 ns:

- 1% typ. (97,8%)
- 1.5% max. (98,8%)

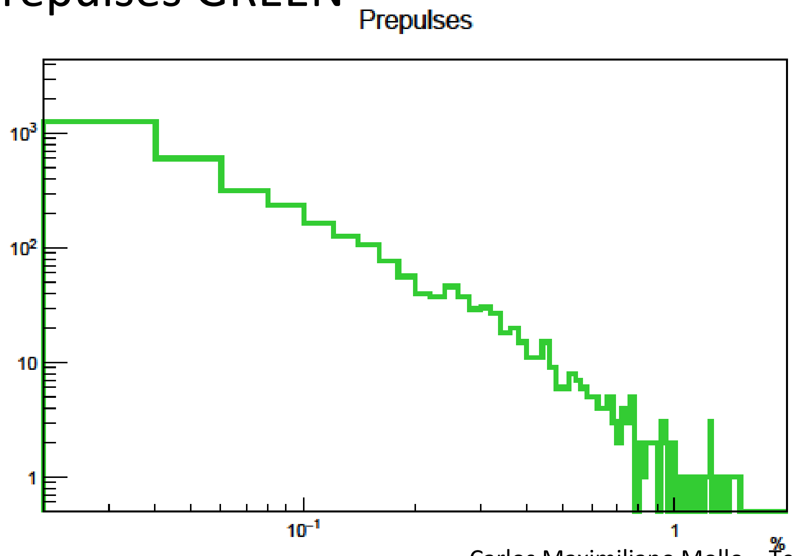
Prepulses ALL

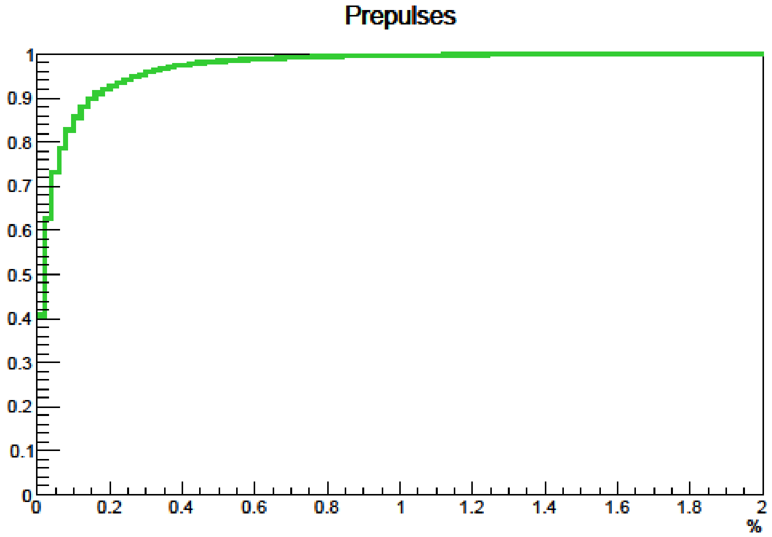




85% < 0.16 %
91% < 0.24 %
95% < 0.42 %
98% < 0.82 %
99% < 1.20 %

Prepulses GREEN





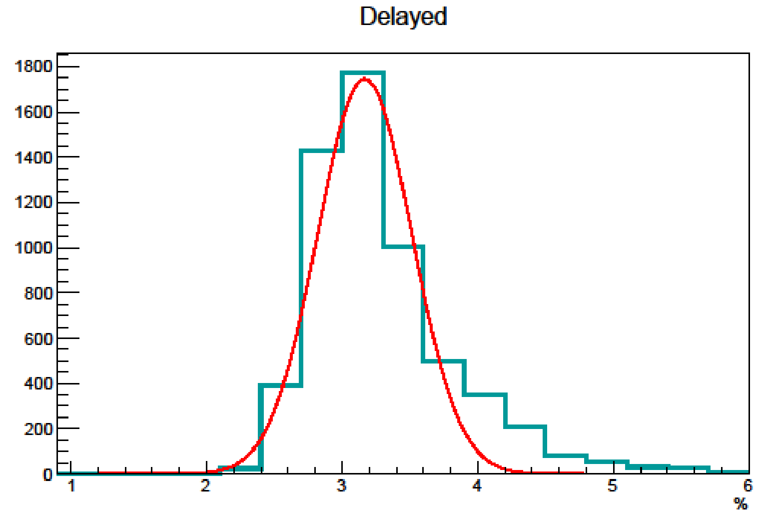
85% < 0.12 %
91% < 0.18 %
95% < 0.30 %
98% < 0.48 %
99% < 0.66 %

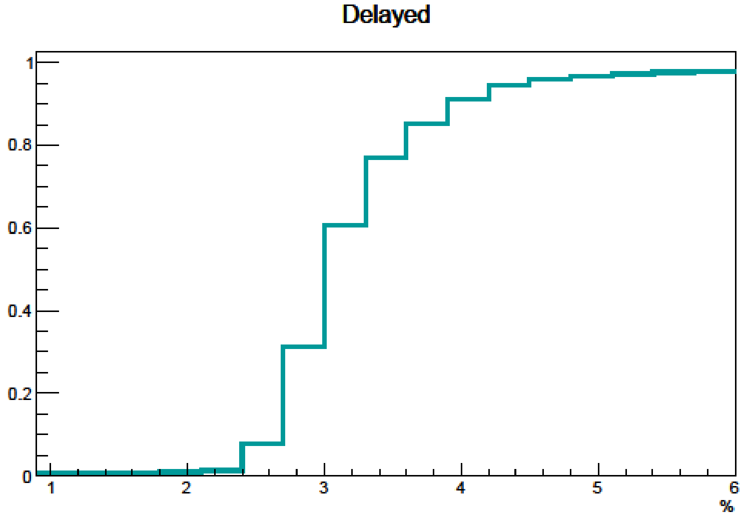
Final results

Delayed pulses between 15 ns and 60 ns (i.e. pulse arriving late with no pulse at correct time):

- 3.5 % typ. (73,5 %)
- 5.5 % max. (98,5 %)

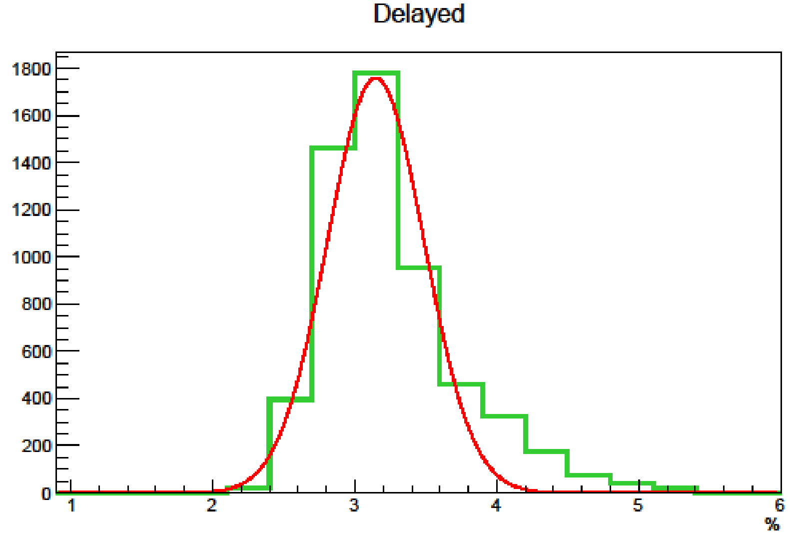
Delayed Pulses ALL

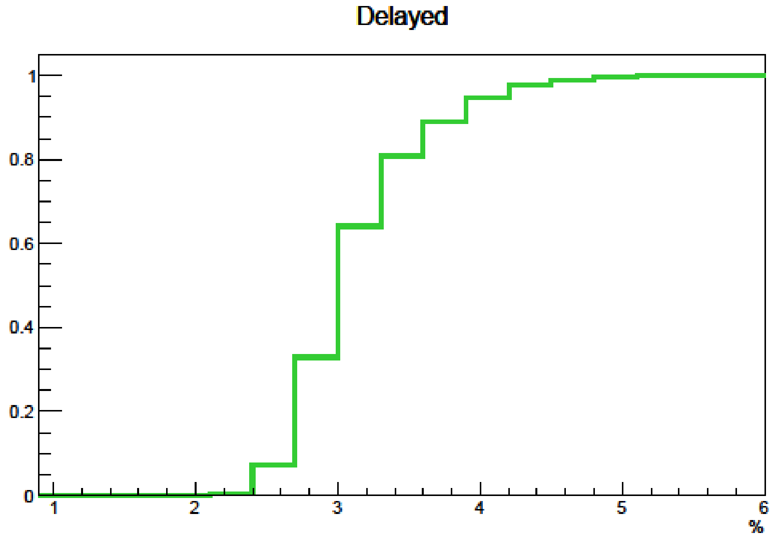




Delayed pulses: 3.2 ± 0.3 %

Delayed Pulses GREEN





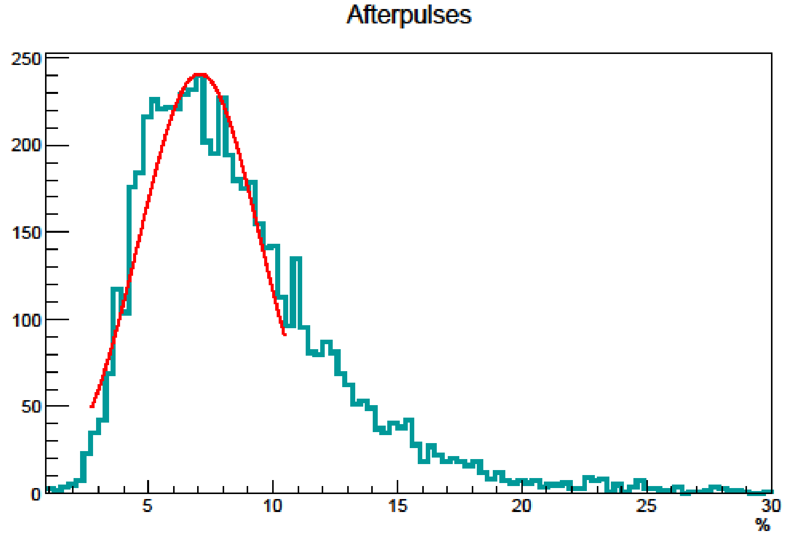
Delayed pulses: 3.1 ± 0.3 %

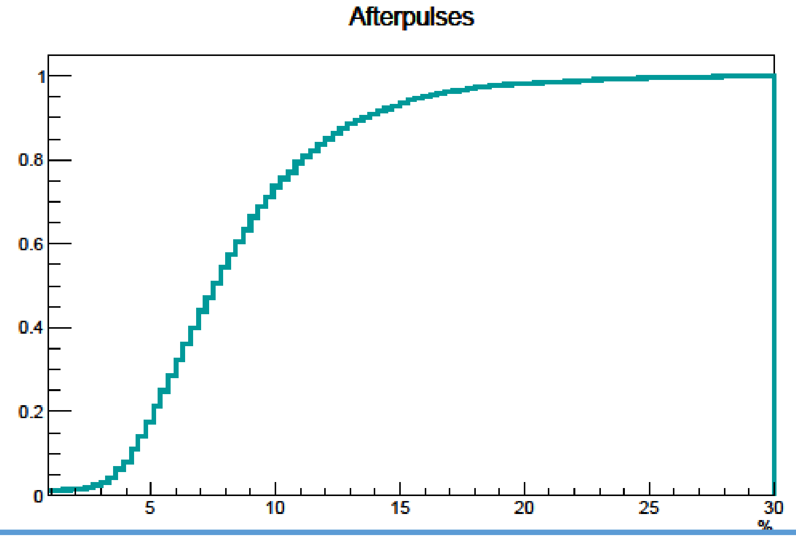
Final results

Afterpulses ALL

Late after-pulses between 100 ns and 10 us:

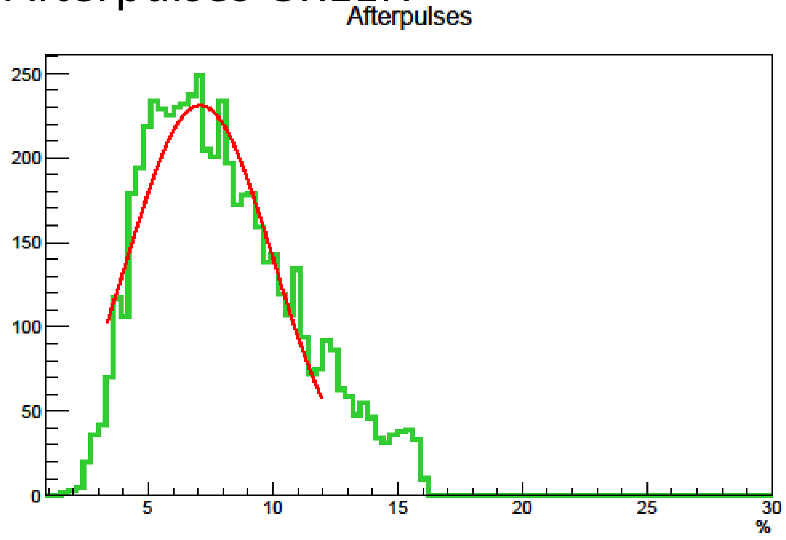
- 10 % typ. (71,4 %)
- 15 % max. (92,4 %)

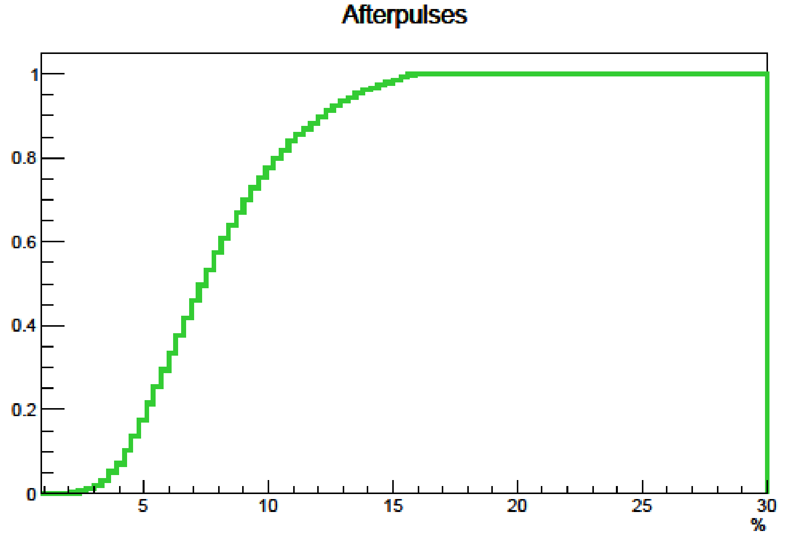




Afterpulses: 7.1 ± 2.4 %

Afterpulses GREEN

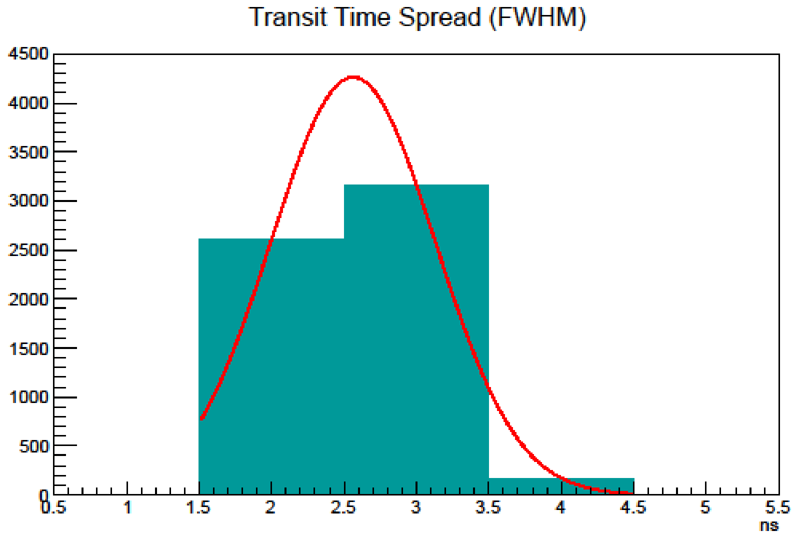




Afterpulses: 7.1 ± 2.9 %

Final results

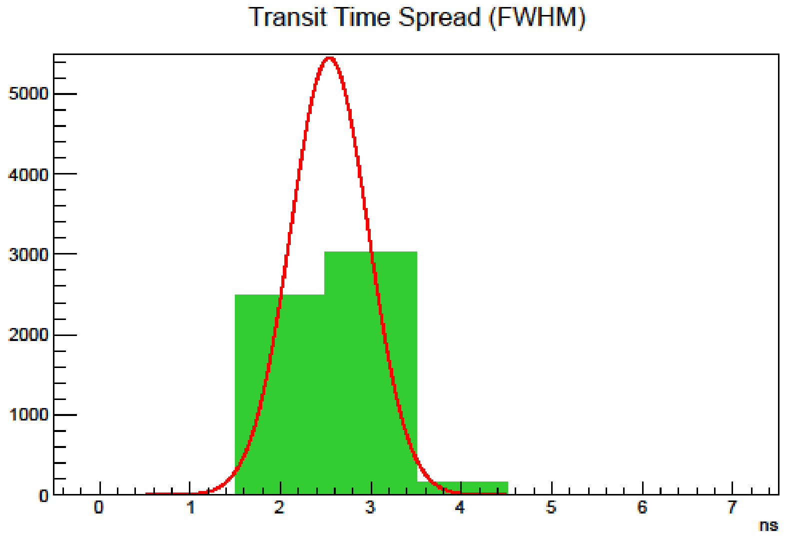
TTS ALL



TTS: 2.6 ± 0.6 ns

NO	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	4.26268e+03	7.78017e+01	2.70070e-02	4.80071e-07
2	Mean	2.56299e+00	7.87677e-03	7.68896e-06	1.12190e-03
3	Sigma	5.66615e-01	7.87494e-03	1.74721e-06	2.52584e-03

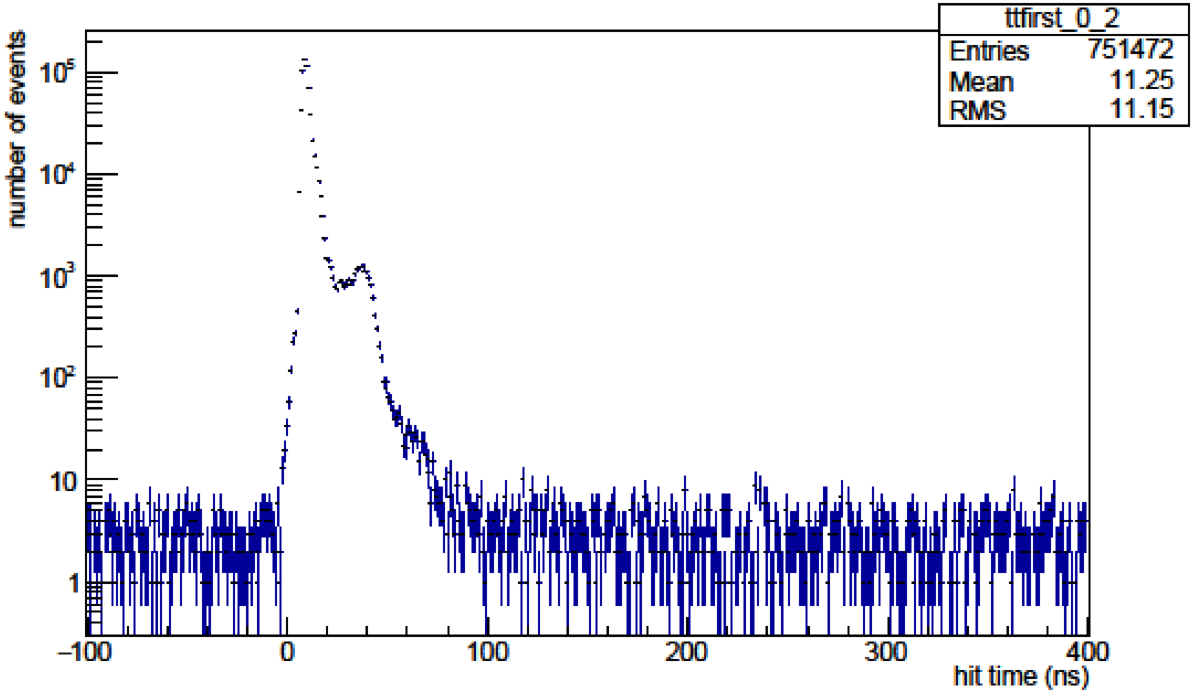
TTS GREEN



TTS: 2.5 ± 0.4 ns

NO	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Constant	5.45648e+03	1.72582e+02	4.34001e-01	-3.25981e-06
2	Mean	2.54206e+00	6.27925e-03	2.88585e-05	1.39497e-02
3	Sigma	4.28361e-01	8.68543e-03	1.41196e-05	-1.24344e-02

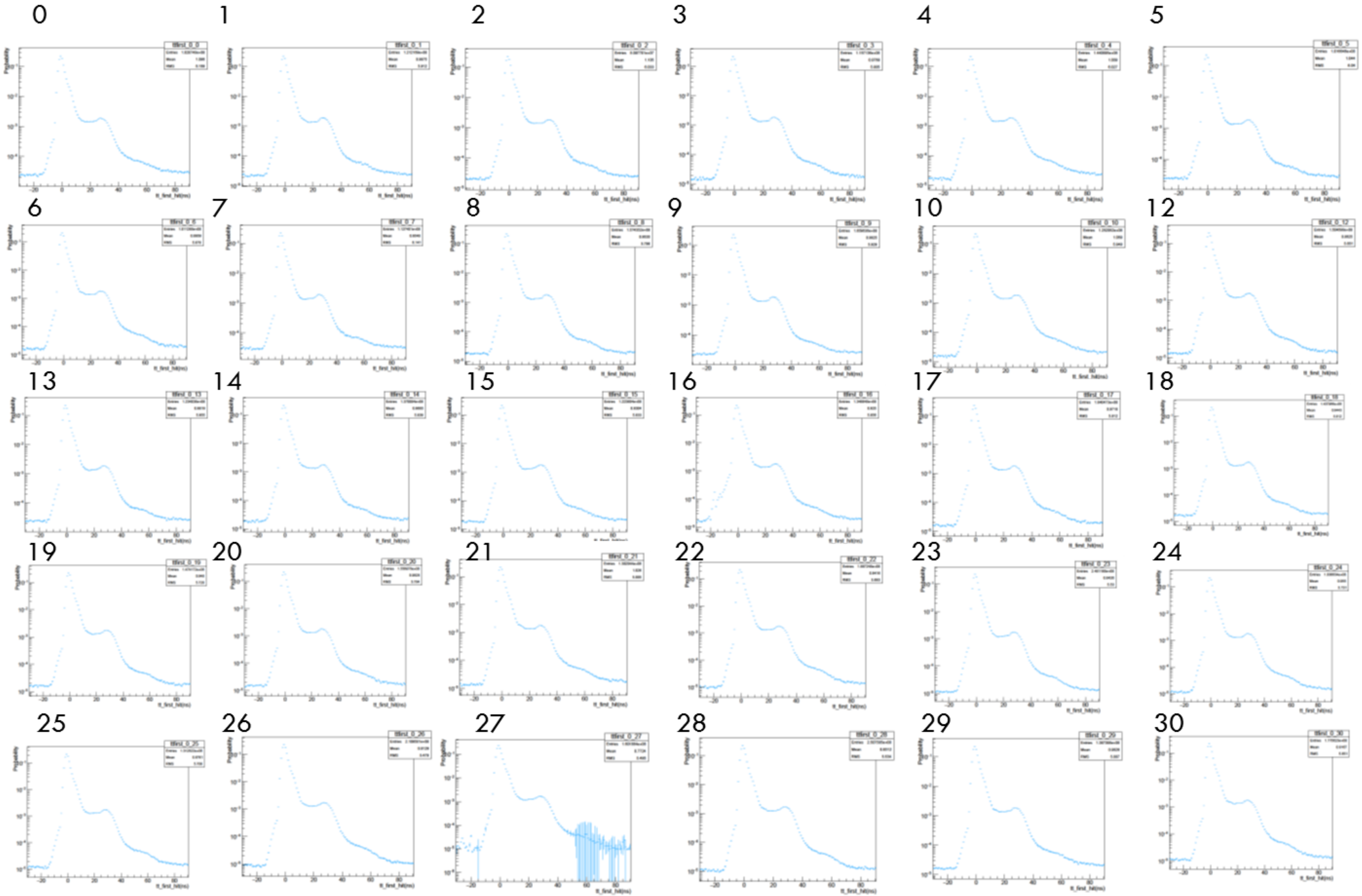
First hits distribution



We can have a distribution that contains info from all PMTs

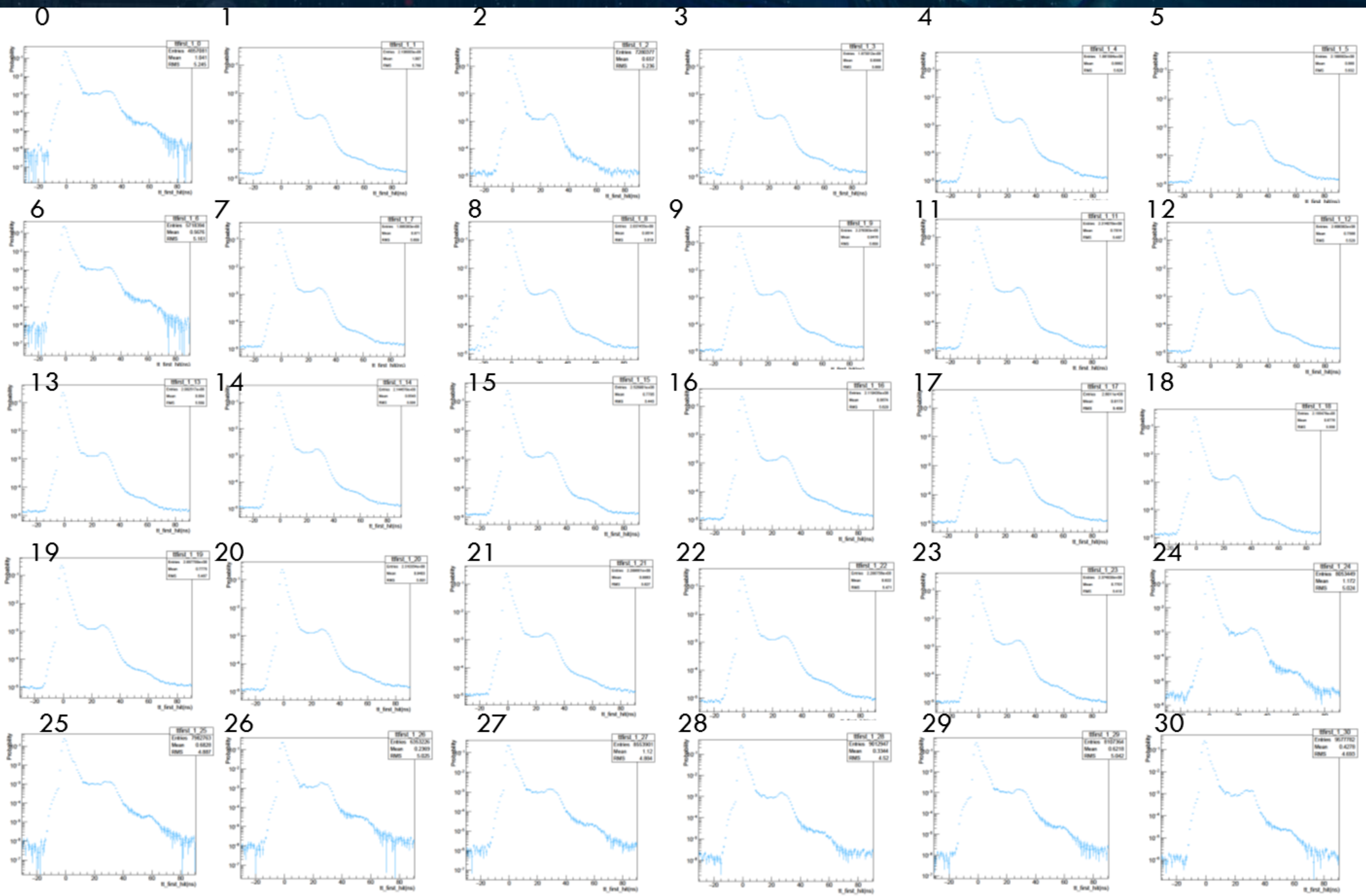
average of all normalized and shifted distributions

First hits distribution by channel (tray 0)



Channel 11 not used.

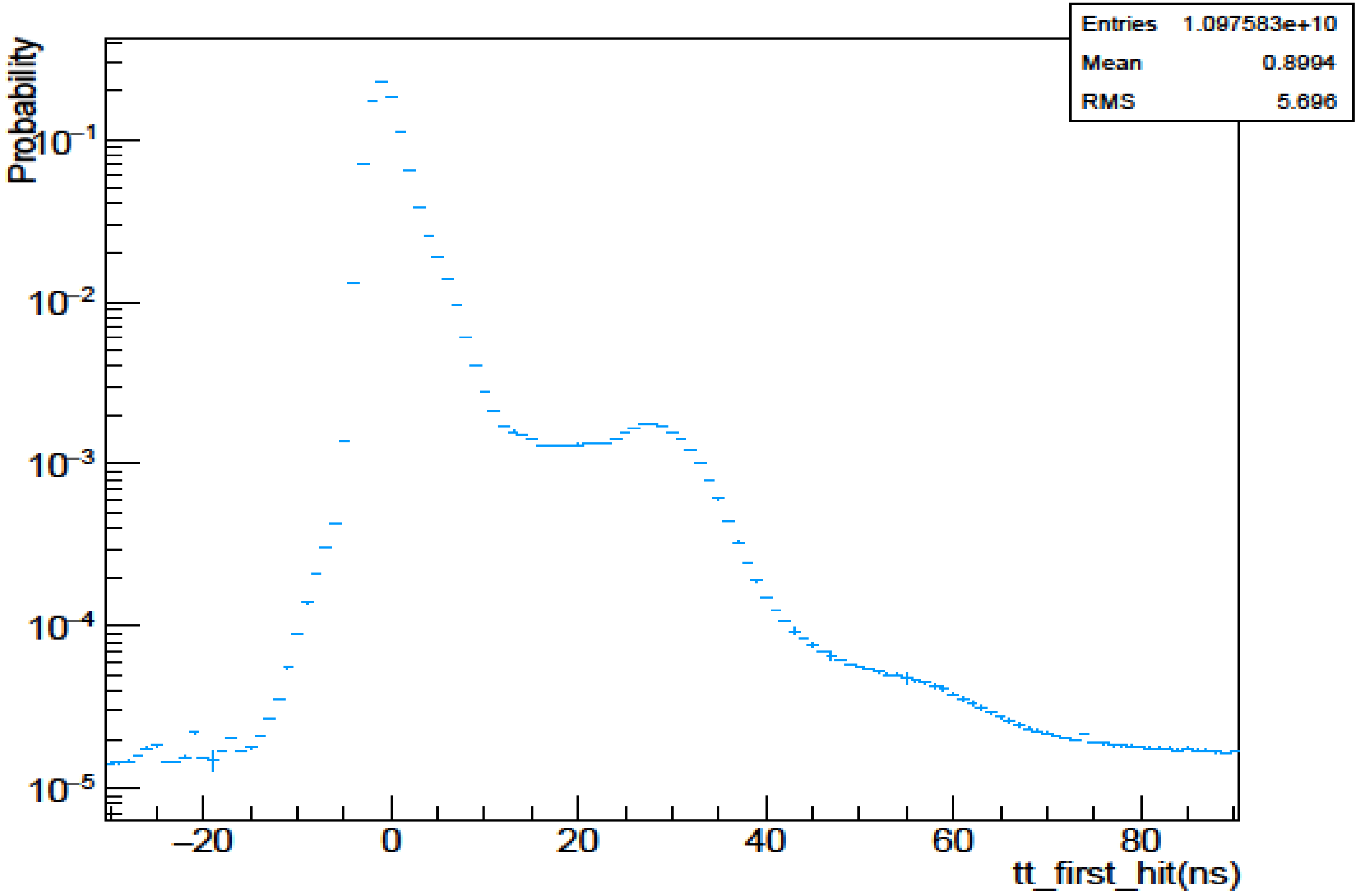
First hits distribution by channel (tray 1)



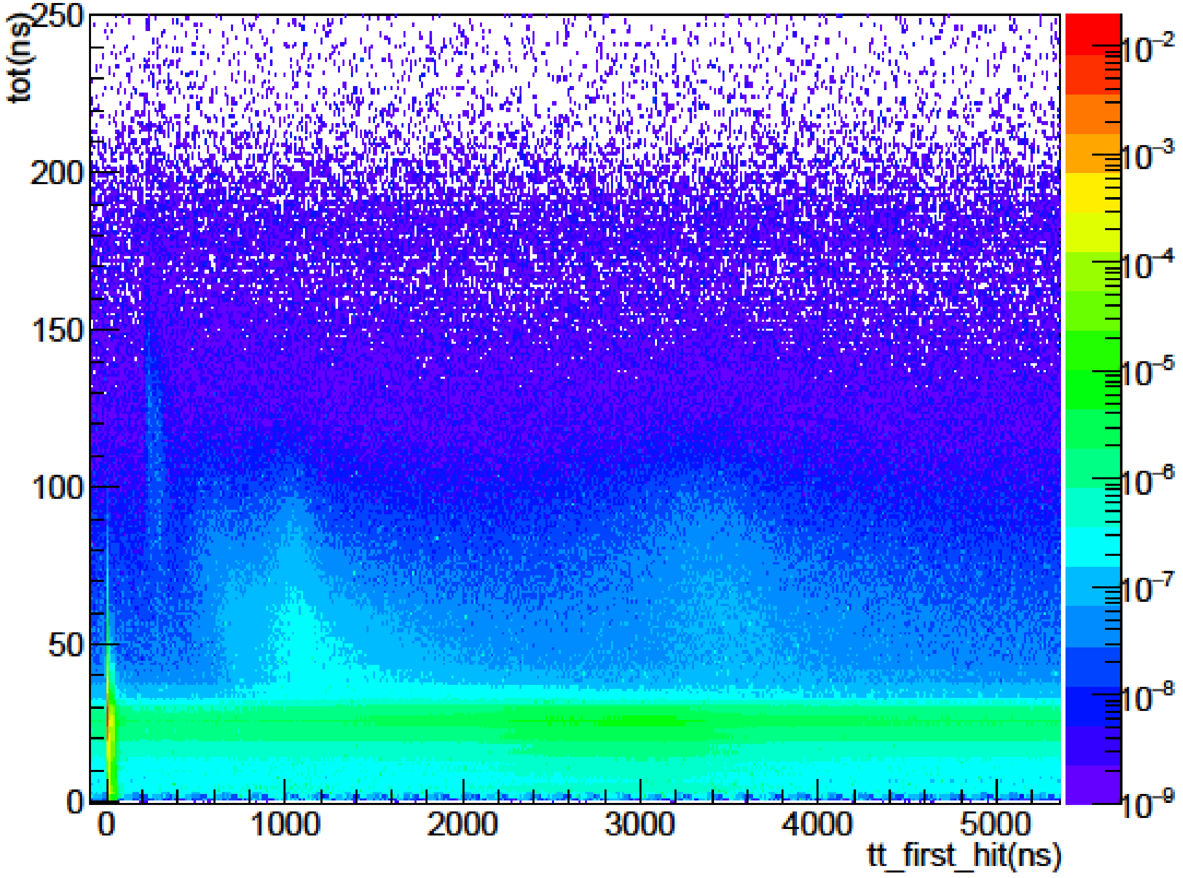
Channel 10 not used.

First hits distribution for all channels

Average histogram of all 6960 PMTs

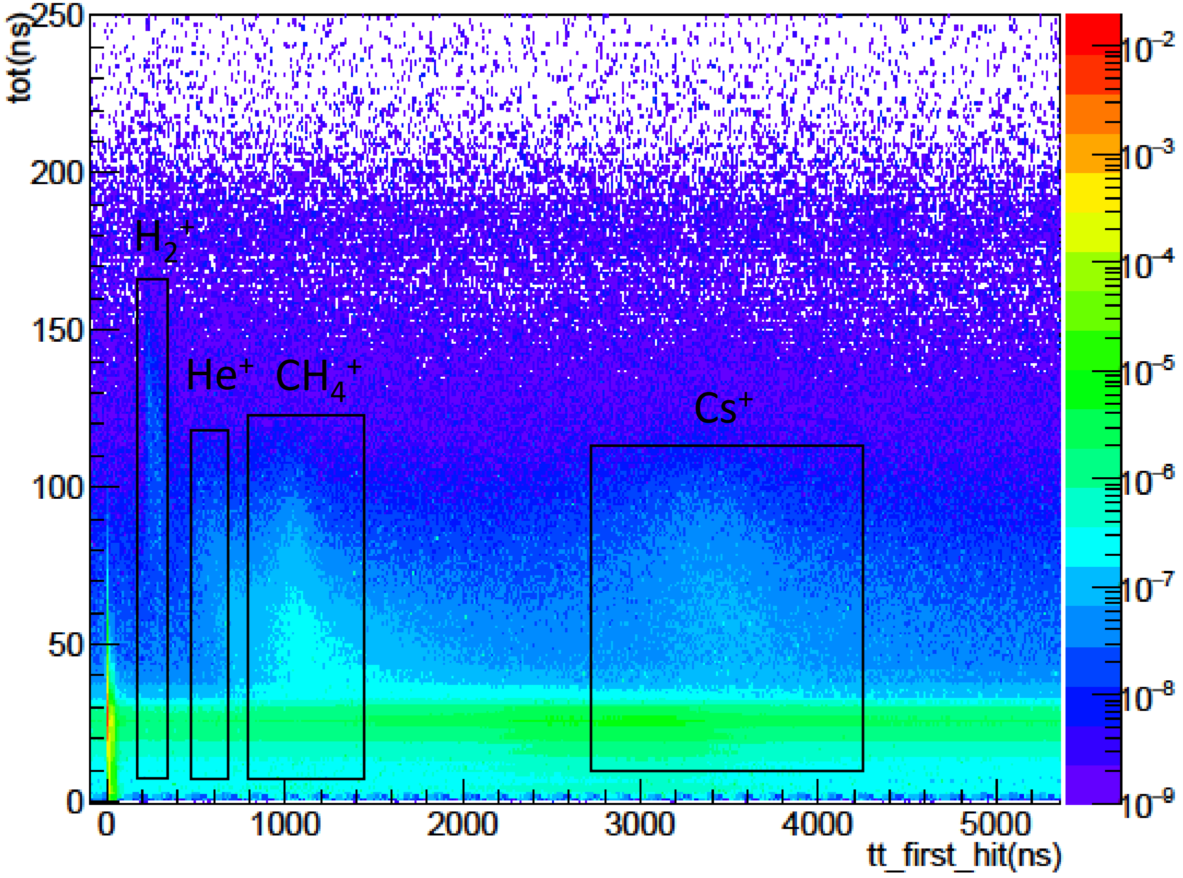


After pulses identification



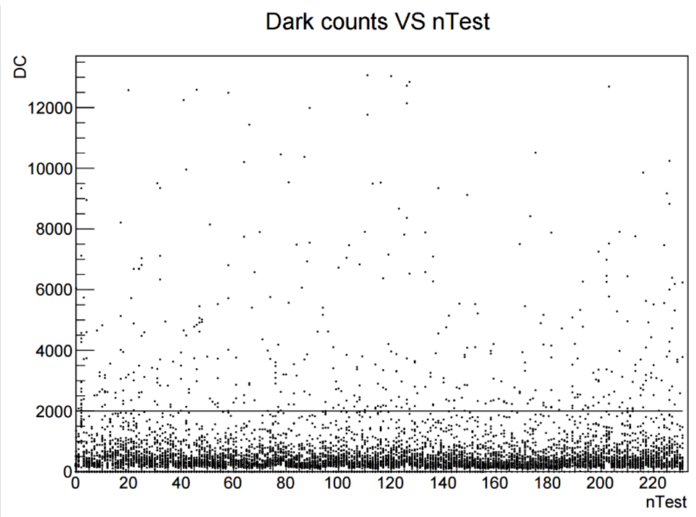
afterpulse source	duration (typ.)
luminous reactions	20 to 100 ns
ionization of residual gases:	
- in the electron-optical input system	H_2^+: 0.3 µs
	He^+: 0.4 µs
	CH_4^+: 1 µs
- in the electron multiplier	1 to several µs, e.g. 3 µs for Cs^+

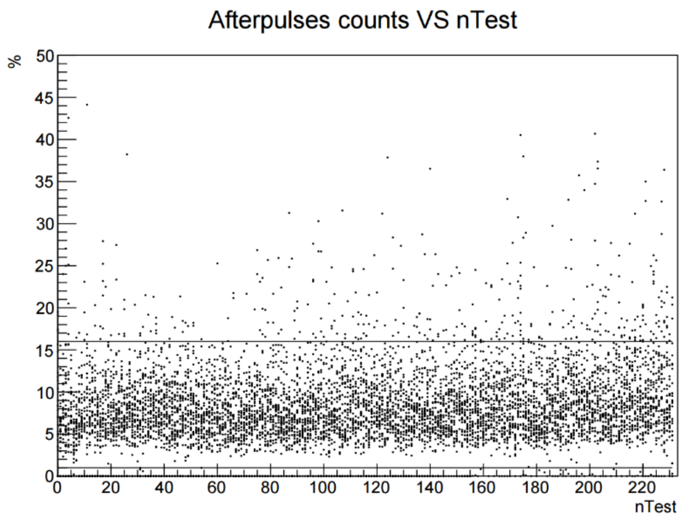
After pulses identification

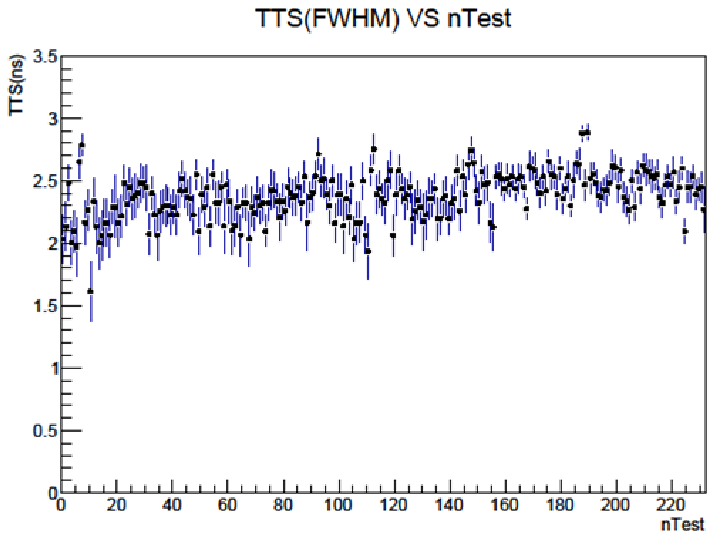


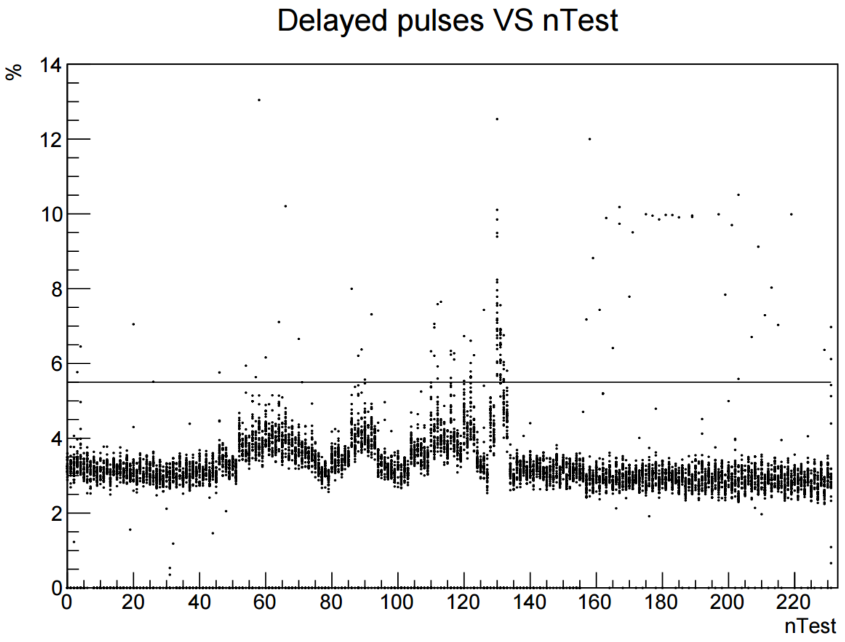
afterpulse source	duration (typ.)
luminous reactions	20 to 100 ns
ionization of residual gases:	
- in the electron-optical input system	H_2^+: 0.3 μs
	He^+: 0.4 μs
	CH_4^+: 1 μs
- in the electron multiplier	1 to several μs, e.g. 3 μs for Cs^+

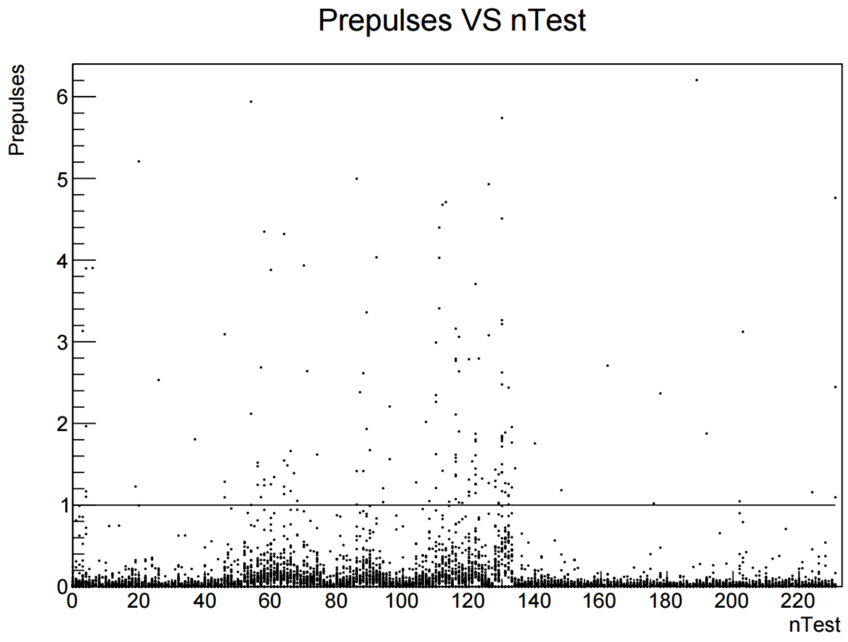
Performances monitoring



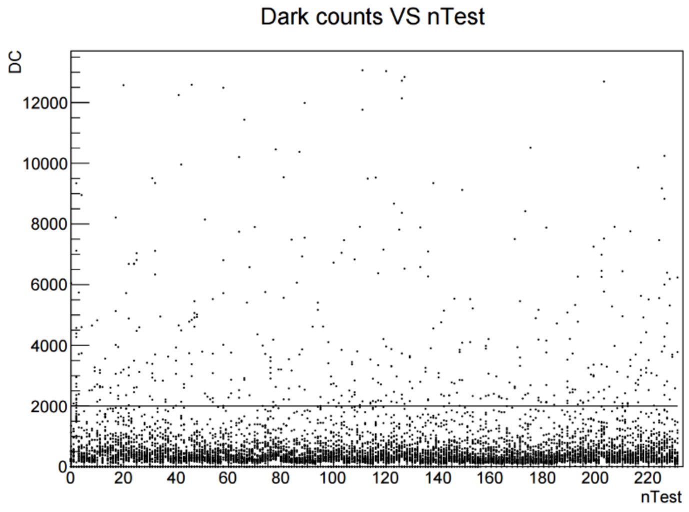


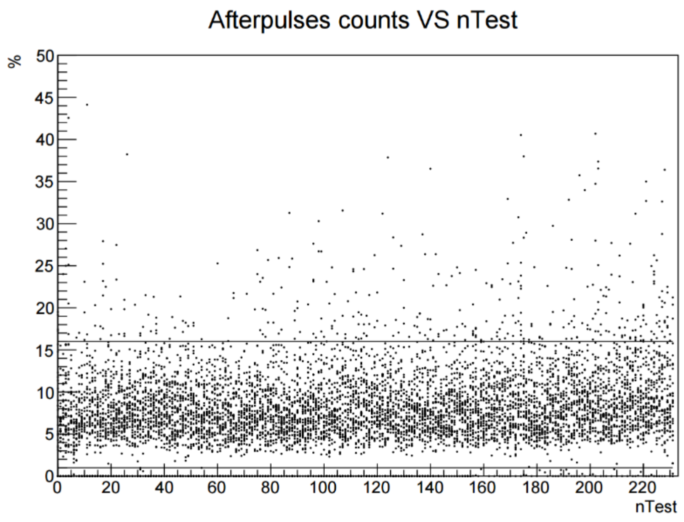


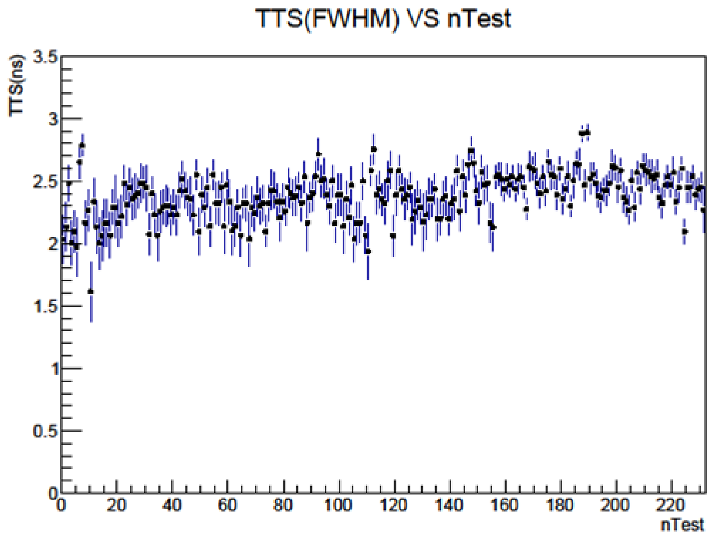


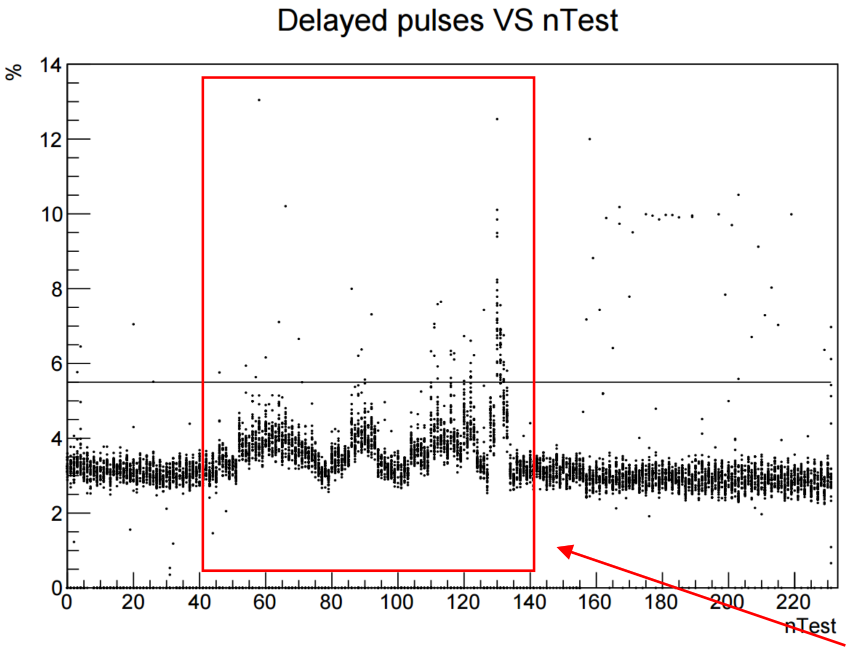


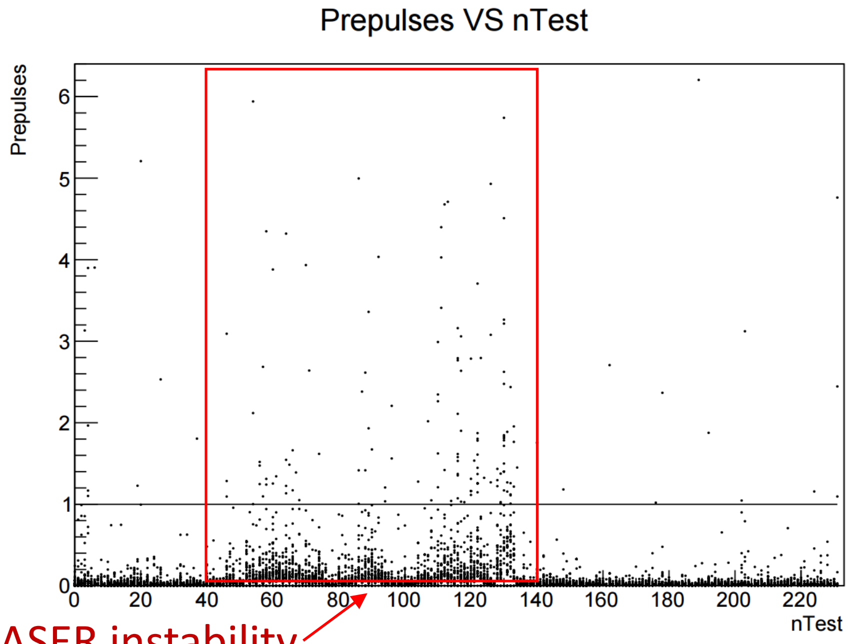
Performances monitoring











LASER instability

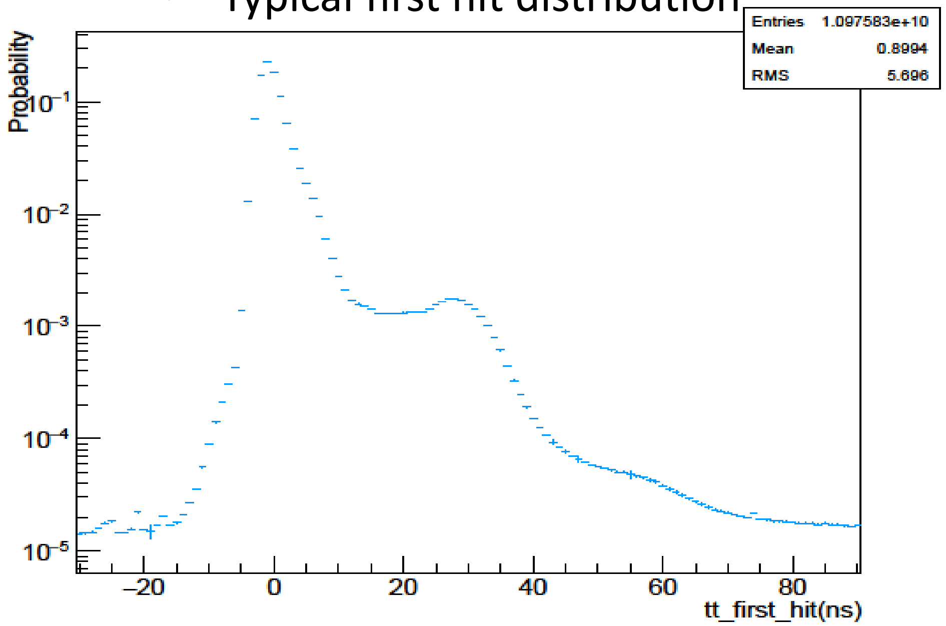
Conclusions

- All 6960 PMTs tested, RED and YELLOW PMTs re-tested: 93% of all PMTs are GREEN the other 7% was sent to Hamamatsu to be replaced.
- Two years to test all PMTs (improvements and maintenance included)

- After these tests we got precious info for the calibration.

- typical prepulses: 0.2%
- typical delayed pulses: 3.1 %
- typical Afterpulses: 7.1 %
- typical Dark Rates: 250 cps
- typical TTS: 2.5 ns

- Typical first hit distribution



[KM3NeT Coll. , "Characterisation of the Hamamatsu photomultipliers for the KM3NeT Neutrino Telescope", 2018 JINST 13 P05035]