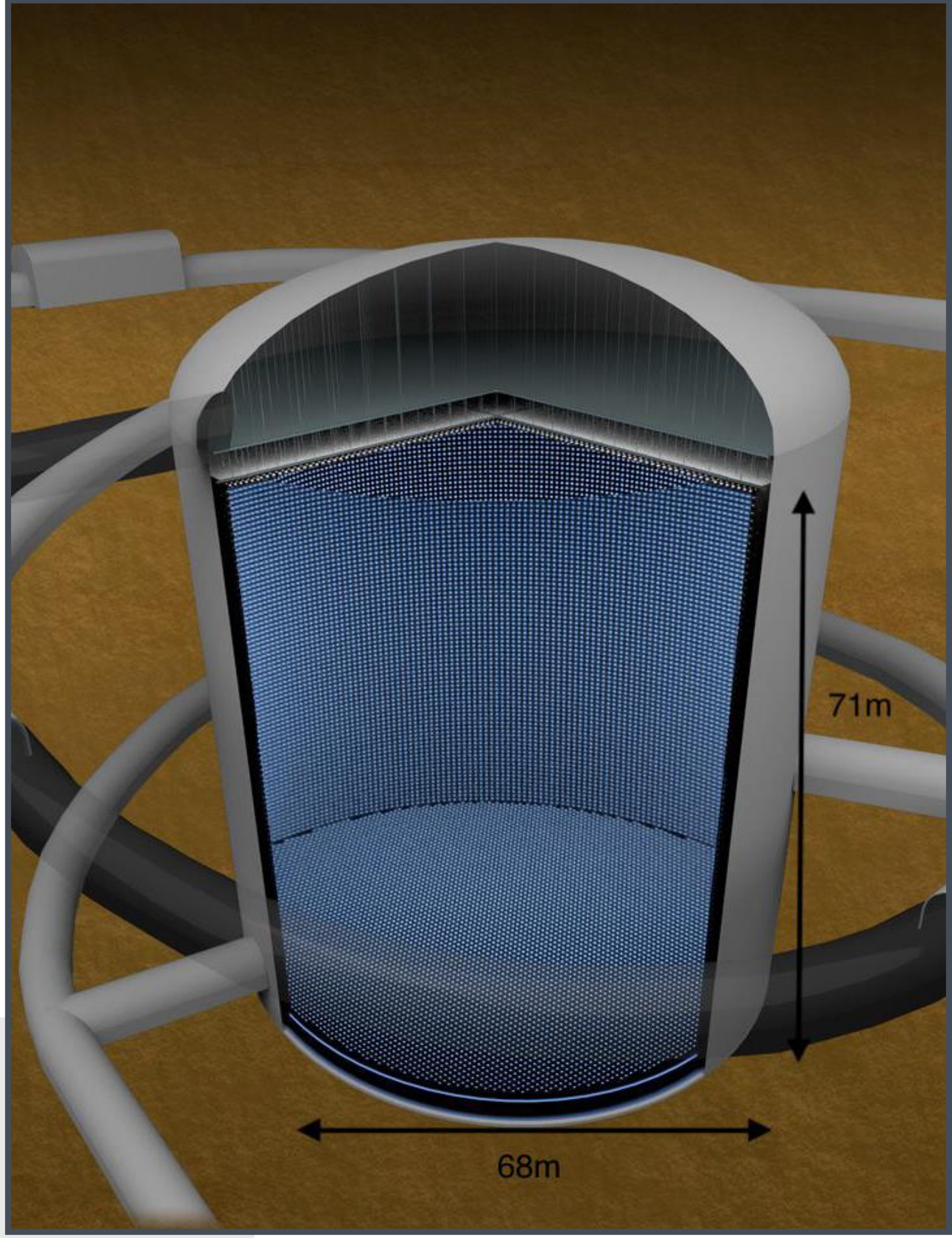
3" PMTs for Hyper-Kamiokande mPMTs

Aurora Langella (INFN Sez. Di Napoli, Università degli studi di Napoli "Federico II")

On behalf of the FD2-WG of the Hyper-Kamiokande Collaboration

Phose2023 – Workshop on "Photodetectors and sensors for particle identification and new physics searches" , 22/11/23

Table of contents



Hyper-Kamiokande

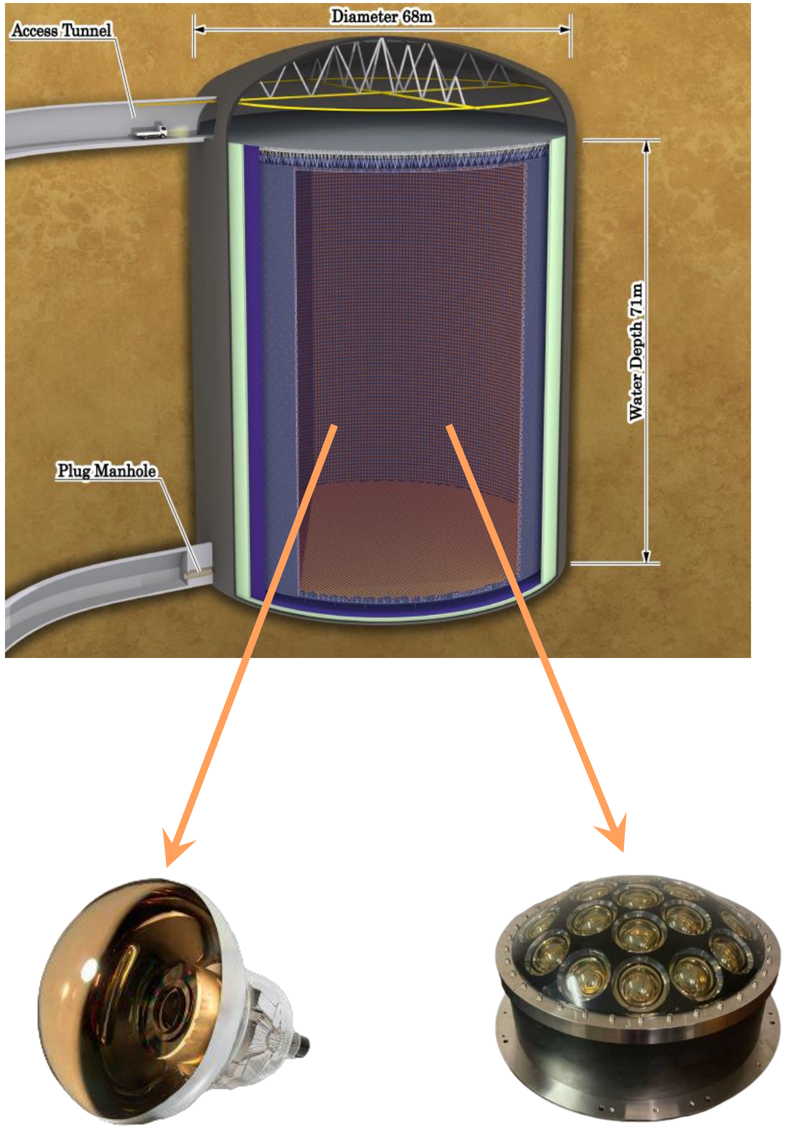
Hyper-Kamiokande

Hyper-Kamiokande (Hyper-K, HK) is to be the next generation of large-scale water Cherenkov detectors. It will adopt the successful strategies used to study neutrino oscillations in Super-Kamiokande, K2K and T2K.
Main improvements will be:

- Larger detector for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

Construction began in may 2021 and data taking will start in 2027.
The Hyper-K Far Detector (HK-FD) will be charachterized by:

Cylindrical tank: Φ 68 m and H 71 m
Fiducial volume: 0.19Mtons; × 8 SK → HK-FD
Baseline design: 20% photo-coverage with
20’000 20” B&L PMTs and about 1000 multi-PMT.



20” B&L PMT

multi-PMT

The multi-PMT module

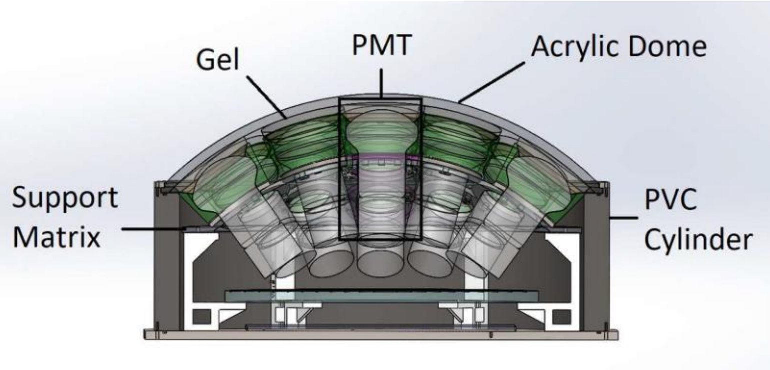
The muPMT option

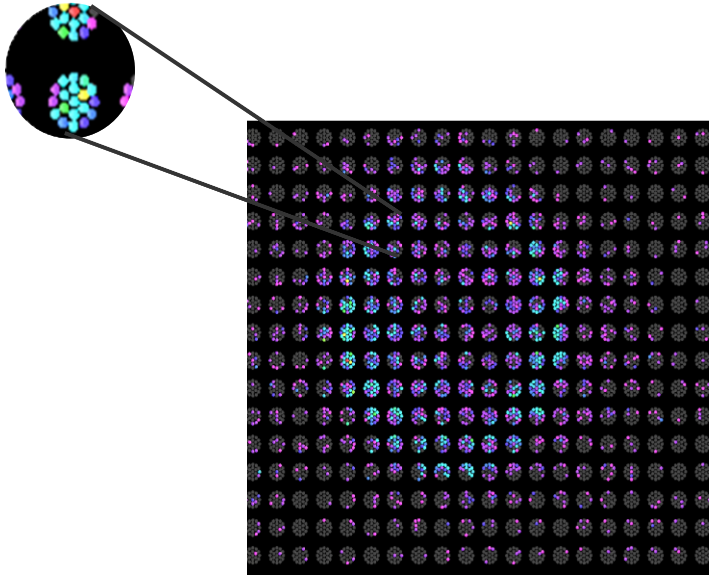
The multi-PMT (mPMT) was first designed for the KM3NeT experiment. A new design, optimized for HK requirements, has been realized. It consists of 19 3" PMTs inside a vessel, each one with a different orientation.

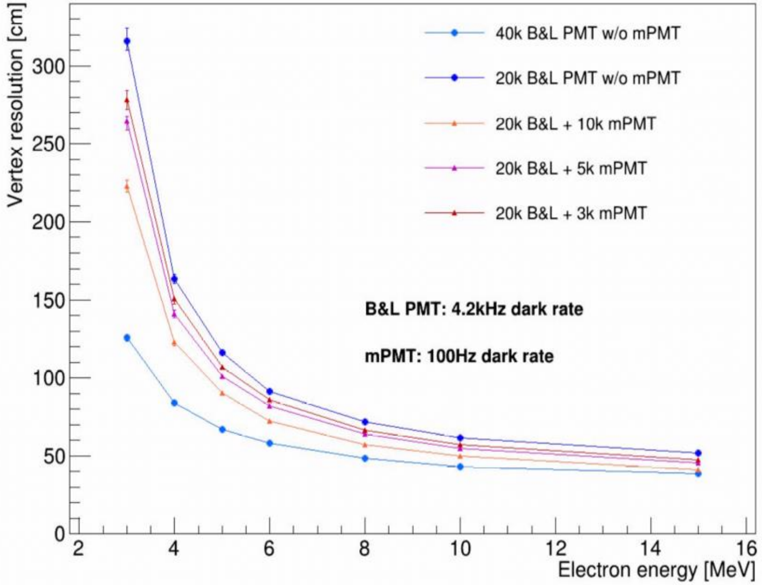
The mPMT has several advantages as a photosensor module:

- Increased granularity;
- Superior photon counting;
- Improved angular acceptance;
- Extension of dynamic range;
- Intrinsic directional sensitivity;

→ Better vertex resolution







What performance do we need?

What performance do we need?

1

Good timing characteristics

Good timing characteristics can lead to a better vertex reconstruction and separation of two continuous signals. This means an enlargement of the fiducial volume as well as a reduction of systematic uncertainties.

What performance do we need?

1

Good timing characteristics

Good timing characteristics can lead to a better vertex reconstruction and separation of two continuous signals. This means an enlargement of the fiducial volume as well as a reduction of systematic uncertainties.

2

Low intrinsic background (e.g. dark rate, RI contamination, intrinsic light emission)

Low intrinsic background allows to improve the low energy detection (MeV to tens of MeV).

What performance do we need?

1

Good timing characteristics

Good timing characteristics can lead to a better vertex reconstruction and separation of two continuous signals. This means an enlargement of the fiducial volume as well as a reduction of systematic uncertainties.

2

Low intrinsic background (e.g. dark rate, RI contamination, intrinsic light emission)

Low intrinsic background allows to improve the low energy detection (MeV to tens of MeV).

3

Low power consumption

This requirement is driven by water circulation requirements and its temperature stability, otherwise the water quality could be compromised.

3” PMT prototypes

3” PMT prototypes

Several manufacturers like Hamamatsu Photonics K.K., ET Enterprises Ltd. and HZC Photonics Ltd. have developed 3" PMTs that can be used in the mPMT module.

HAMAMATSU
PHOTON IS OUR BUSINESS

海南展创光电技术有限公司
HZC PHOTONICS

ET Enterprises
electron tubes

3” PMT prototypes

I

Several manufacturers like Hamamatsu Photonics K.K., ET Enterprises Ltd. and HZC Photonics Ltd. have developed 3" PMTs that can be used in the mPMT module.

II

These PMTs have been characterized and tested for compliance with the Hyper-K requirements by different institutes.

HAMAMATSU
PHOTON IS OUR BUSINESS

ET Enterprises electron tubes

海南展创光电技术有限公司
HZC PHOTONICS

3” PMT prototypes

I

Several manufacturers like Hamamatsu Photonics K.K., ET Enterprises Ltd. and HZC Photonics Ltd. have developed 3" PMTs that can be used in the mPMT module.

HAMAMATSU
PHOTON IS OUR BUSINESS

ET Enterprises electron tubes

海南展创光电技术有限公司
HZC PHOTONICS

II

These PMTs have been characterized and tested for compliance with the Hyper-K requirements by different institutes.

III

We found that the best solution in terms of performance for the HK-FD mPMT is the Hamamatsu R14374 3” PMT.

HAMAMATSU
PHOTON IS OUR BUSINESS

3’’ PMT electronics

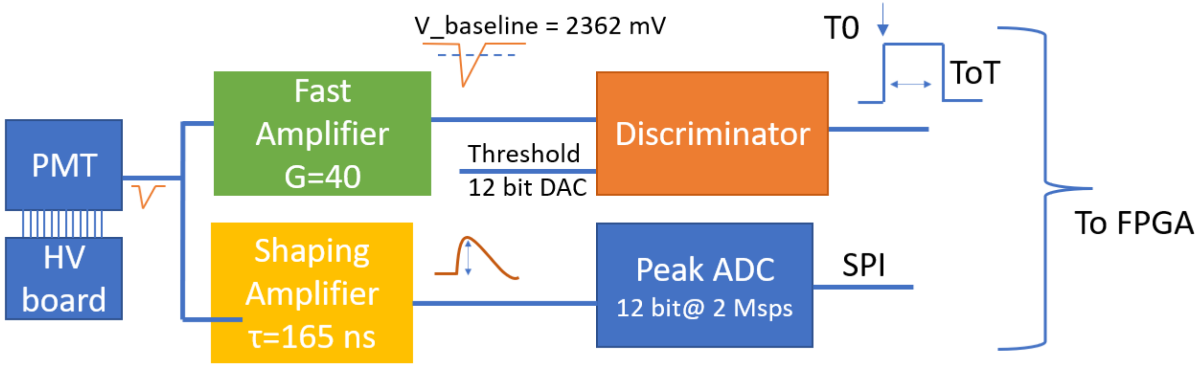
For the electronics of the HK-FD mPMT, we opted for a custom solution, designed by the Hyper-K Collaboration.

Each PMT will be connected directly to an HV active board based on a Cockcroft-Walton circuit. An anode grounding scheme will be adopted.

Data are processed and acquired from a Front-End Board connected to the HV board and an FPGA that processes and sends out the data of all the PMTs inside the mPMT module.

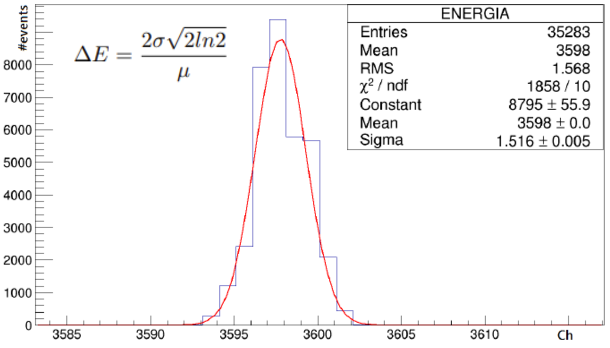
HV board

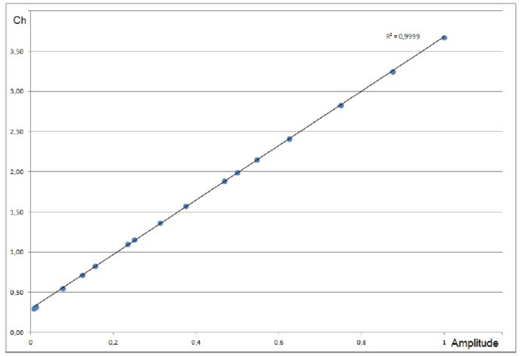
FE board

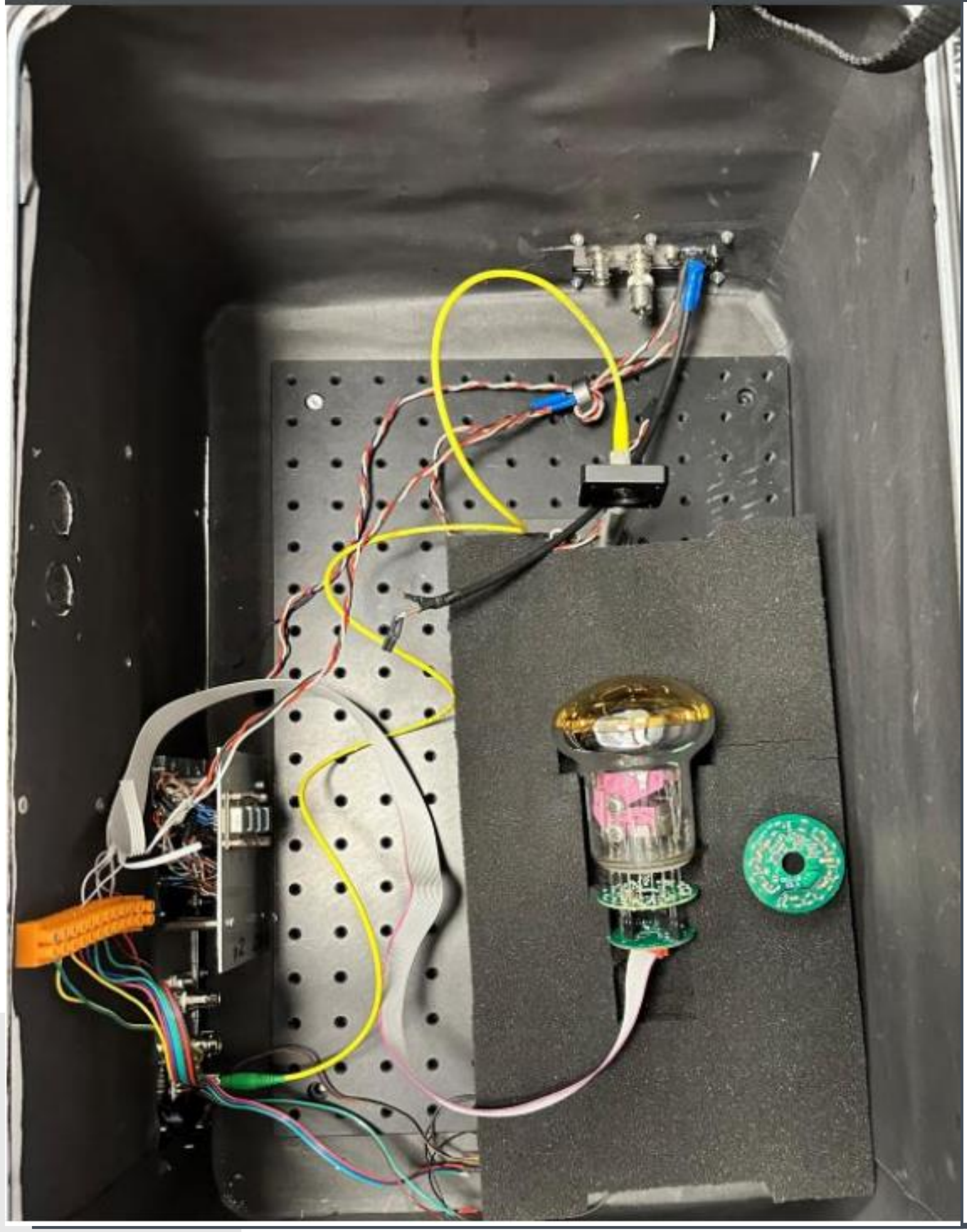


Electronics requirements
Timing resolution: less than 500 ps for 1 pe; about 200 ps for large p.e. pulses.
Charge resolution: 0.1 pe for signals up to 10 pe
Dynamic range: about 70 p.e.
Power Consumption: less than 4 W per mPMT module.
Reliability: at least 10 years.

Charge spectra acquired by the FEB and linearity plot. Signal was generated using a pulser. Both confirm the fulfillment of the requirements



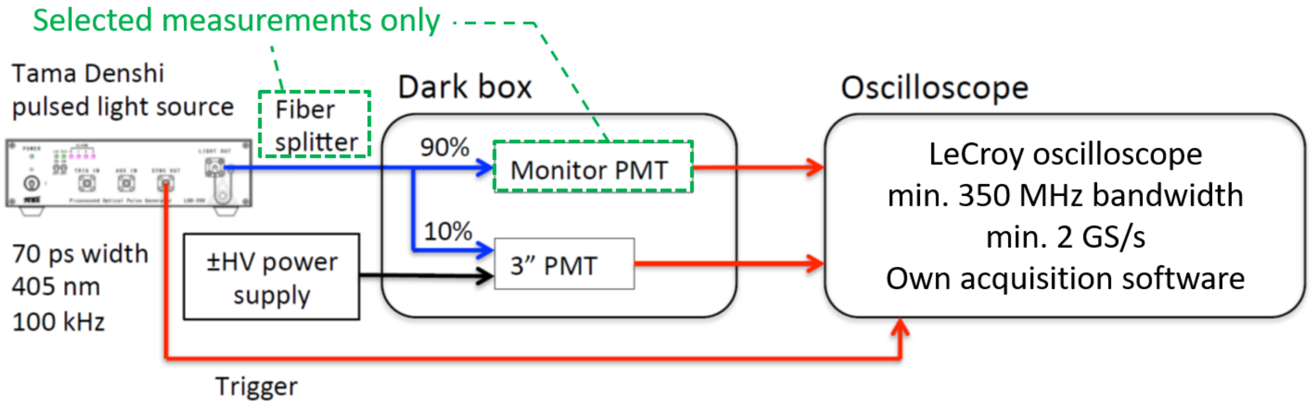




Characterization of Hamamatsu R14374 3’’ PMT

Measurements setup

1) Gain, TTs and efficiency measurements of the PMTs were done with the setup shown in Figure. The light source is collimated by a diffuser and a 14.05 cm diameter lens.

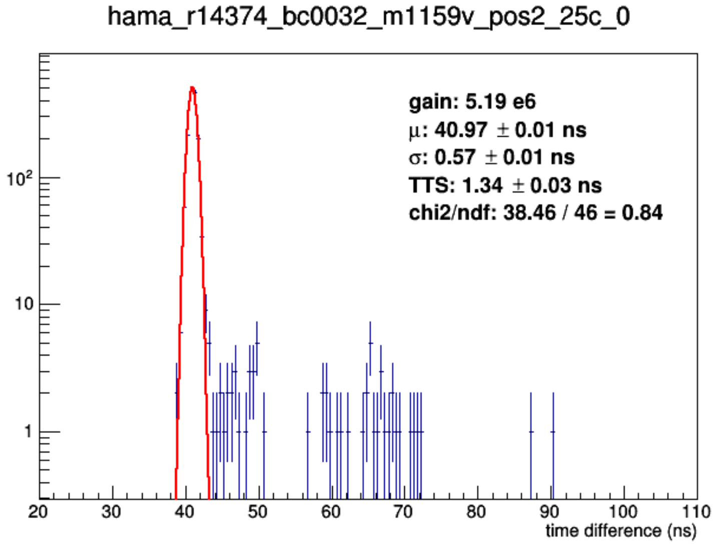


2) Linearity, resolution and afterpulses measurements were performed using a similar test stand but with the following setup:

- Laser PILAS DX + PIL044-FC (picosecond laser)
- Power supply CAEN3*V6533 + VME8010 up to 18 independent channels for each dynode
- Light splitter 10:90 (DUT:REF) + reference detectors: PMT H10720 (linearity measurements), APD430A2 (afterpulse smeasurements)
- Oscilloscope LeCroy Wavesurfer 4000HD (BW limit = 250 MHz)
- Light diffuser –evenly illuminated surface of the photomultiplier

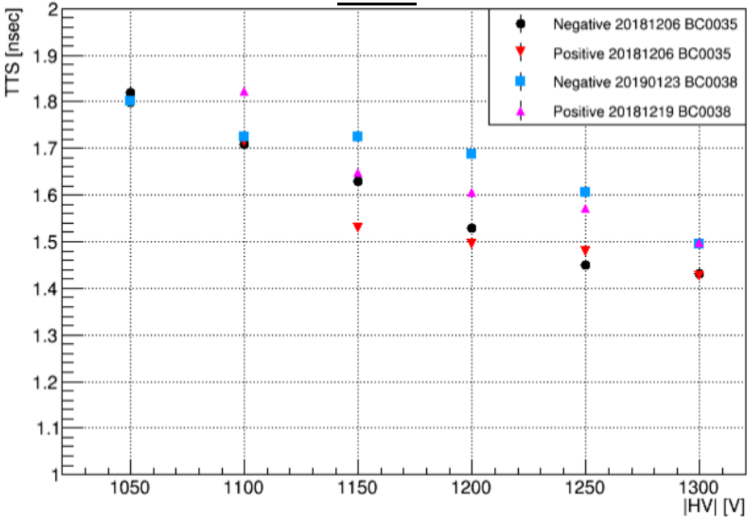
3) Dark rate measurements were performed using the HK-FD mPMT electronics. In this case, no oscilloscope is required as the FPGA presents a special feature that calculates the number of trigger in a second.

Transit Time Spread



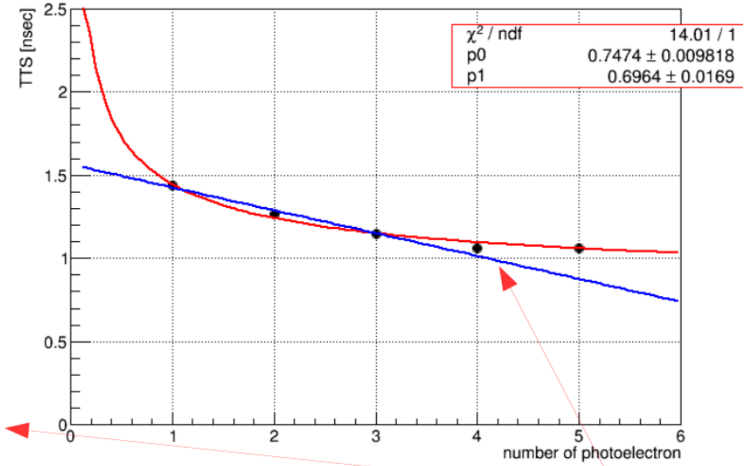
PMT	TT	TTS (FWHM)
BC0032	40.97 ns	1.34 ns
BC0036	45.88 ns	1.52 ns

TTS



The behaviour of TTS as a function of the HV shows that operating with the anode grounding scheme doesn’t impact much on TTS

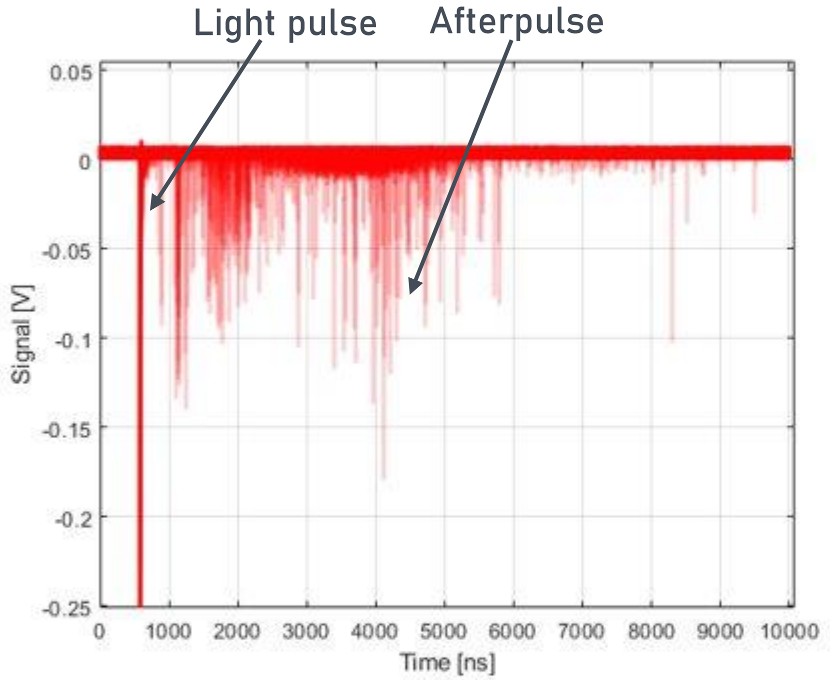
TTS wrt p.e

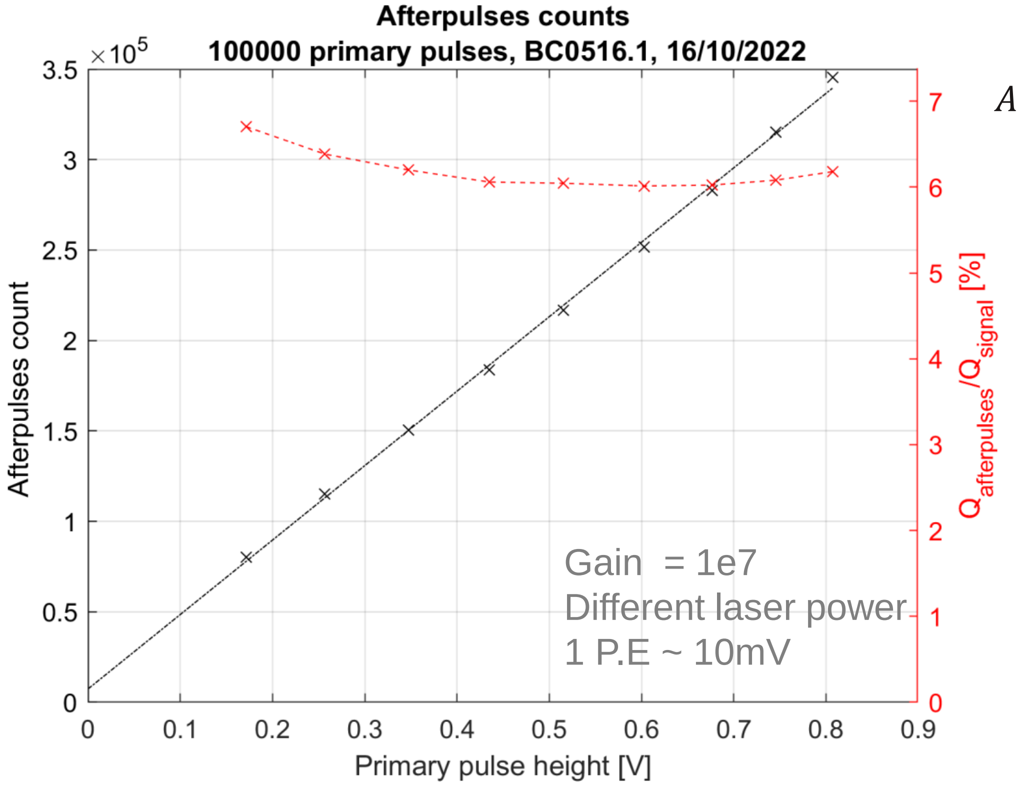


Approximating the TTS variation as 1/√p.e. is reasonable.

Afterpulses

- Recording ~10^6 waveforms (10 µs) with time step = 2ns
- Searching for pulses > 0.5 P.E., min. 75ns after main pulse
- Different laser settings
- Recording amplitude and delay
- Measurements for gain = 5e6 and 1e7





Afterpulses dependency on primary pulse height

$$AP_{rate}(\%) = \frac{Q_{afterpulses}}{Q_{tot}}$$

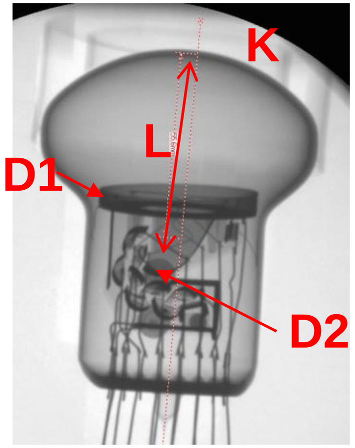
Afterpulses rates are about 6% with a gain of G = 1e7

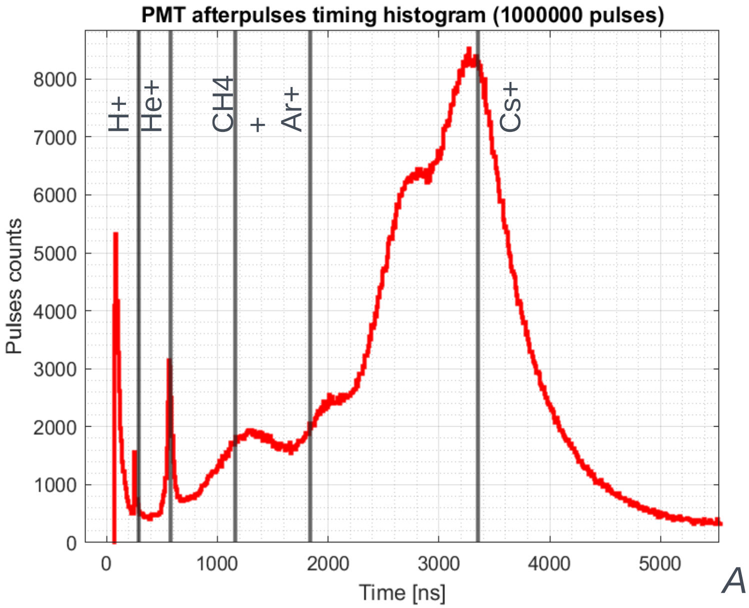
Afterpulses

An investigation has been conducted to determine the origin of afterpulses

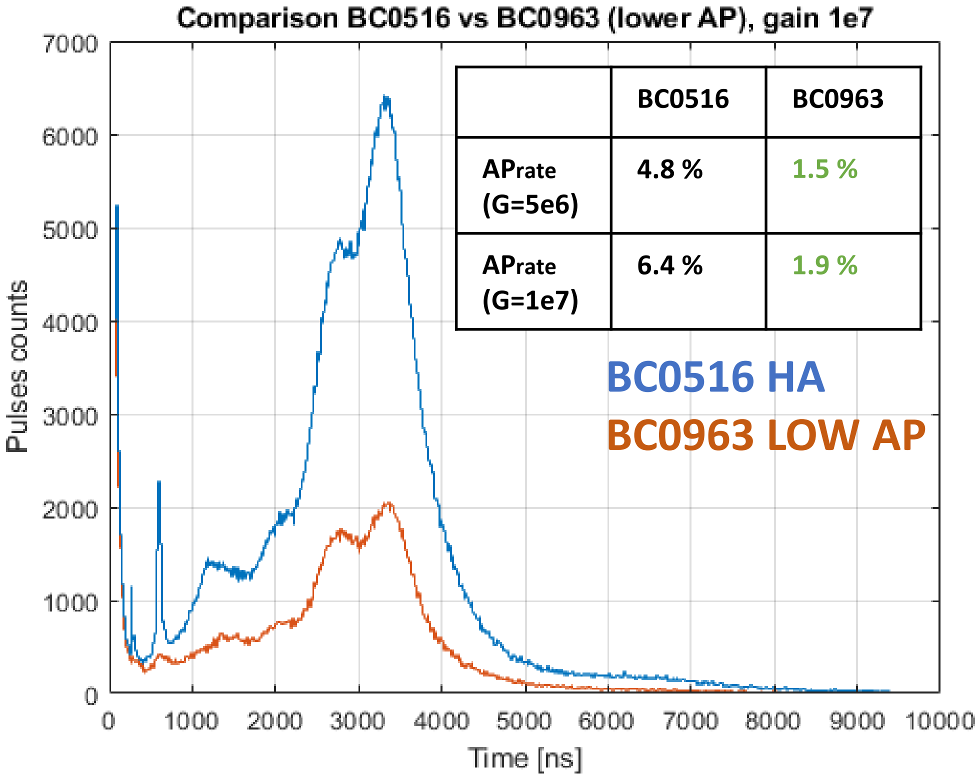
Afterpulse arrival time calculation: $t = \frac{\pi}{4}\sqrt{\frac{2m}{qV_0}}L$

We considered as distance half-way between the first two dynodes (afterpulses from further dynodes are very rare)



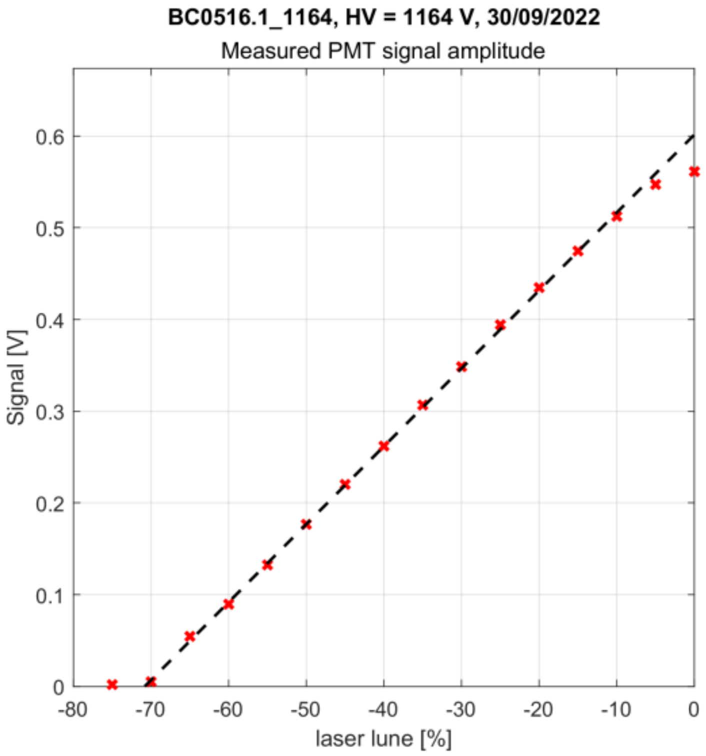

PMT afterpulses timing histogram (1000000 pulses)

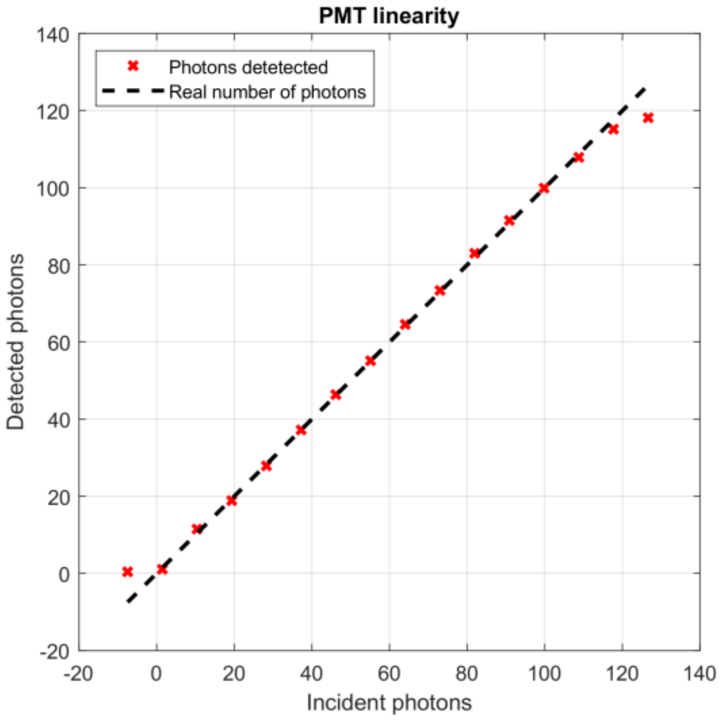
To further reduced the aferpulses we discussed with the manufacturer and they provided a new R14374 PMT with lower afterpulses

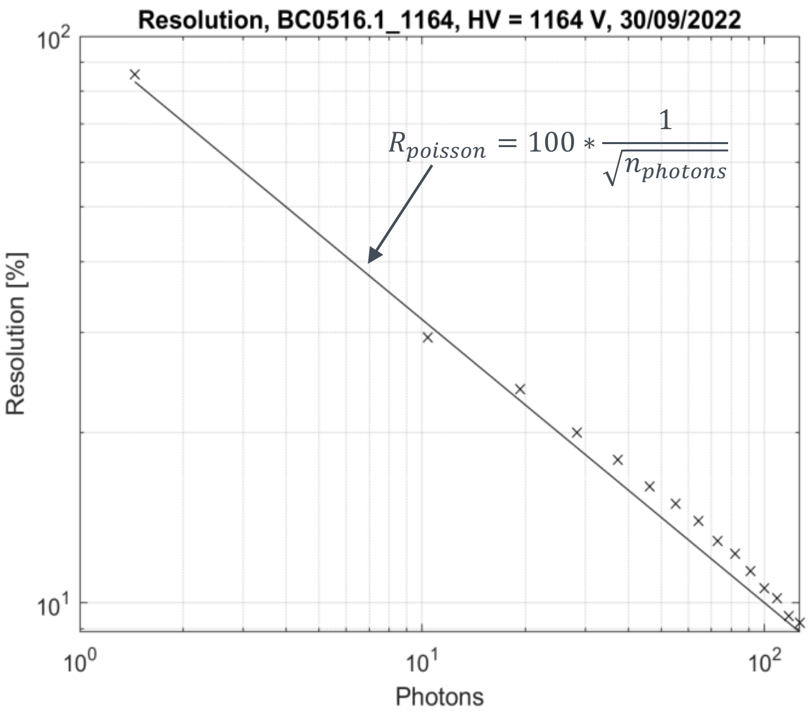

Comparison BC0516 vs BC0963 (lower AP), gain 1e7

	BC0516	BC0963
APrate (G=5e6)	4.8 %	1.5 %
APrate (G=1e7)	6.4 %	1.9 %

PMT linearity and resolution







→ Good linearity up to 100 photons

Resolution is defined as $R = 100 * \frac{std(amplitudes)}{mean(ampliudes)}$

Dark noise rate

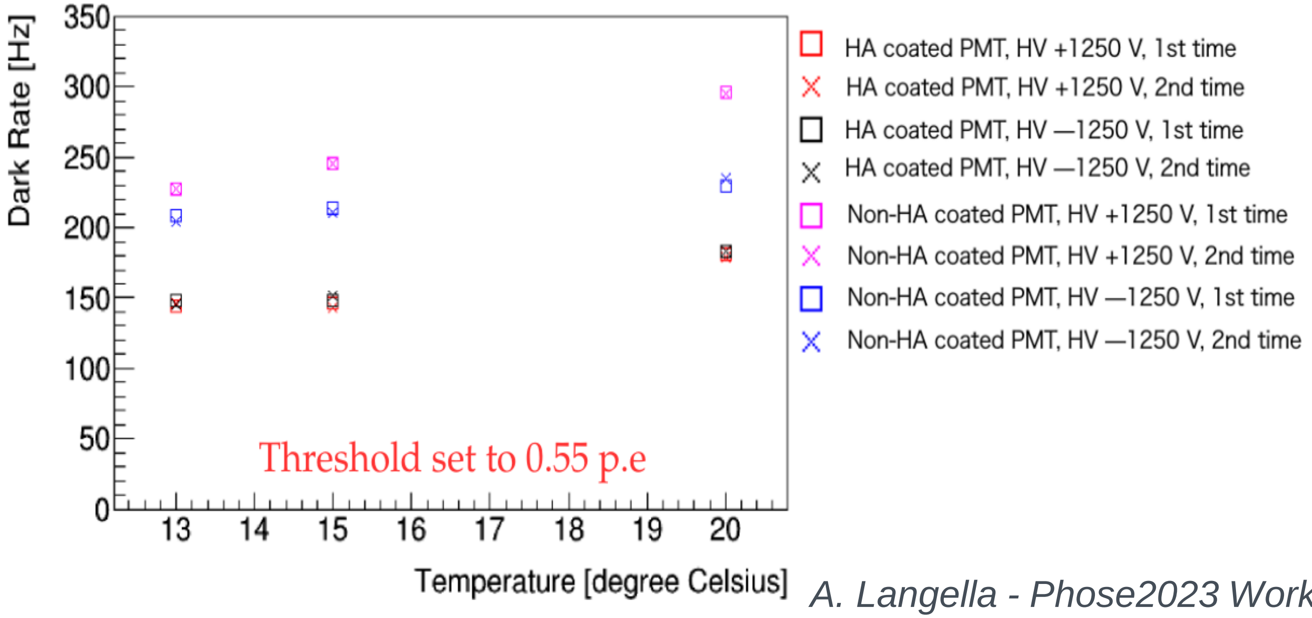
One of the main consequences of the anode grounding scheme is an increase of the dark noise rate. To prevent this, we opted to use a coating to protect the PMTs. We tested several coating and the best results to be:

- HA coating: standard coating provided by Hamamatsu Photonics K. K.
- DCB: specialist black opaque modified alkyd conformal coating

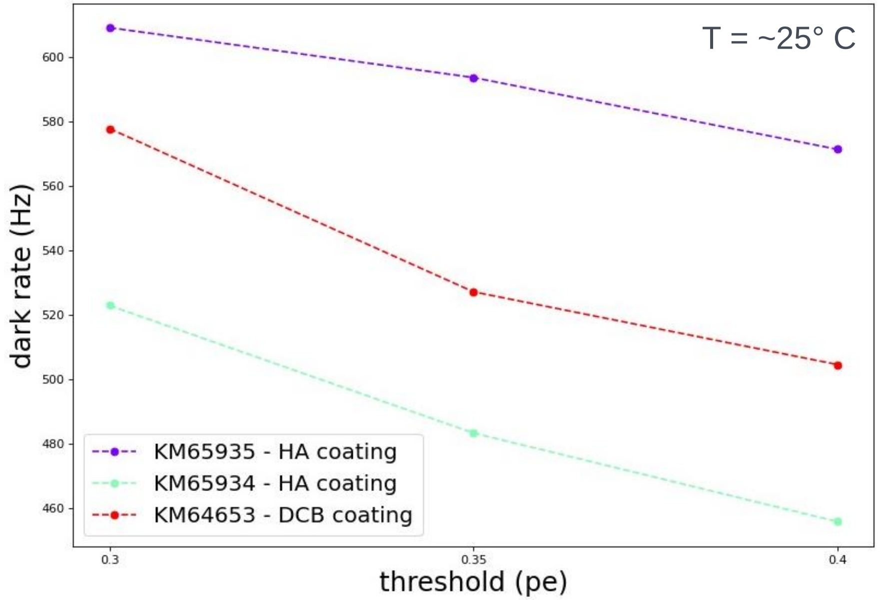
DCB and HA-coating have similar insulative properties, but we choose to adopt the DCB as it allows to coat at the same time the PMT and the HV board.


HA coating


DCB coating

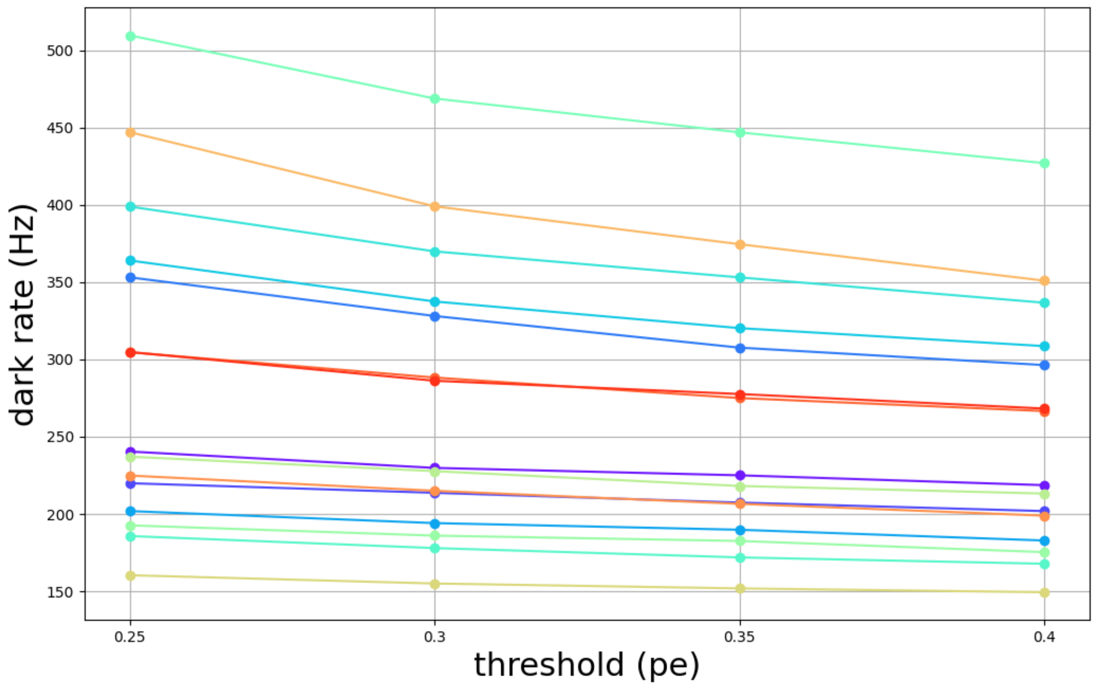


A. Langella - Phose2023 Workshop

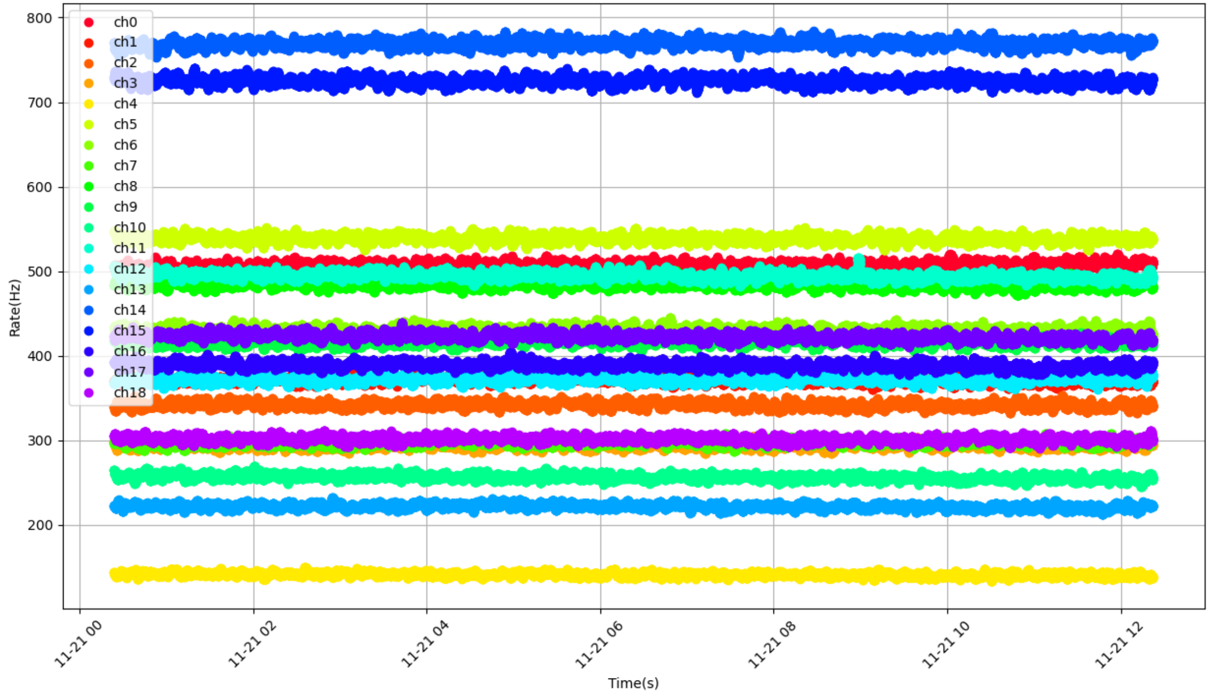


Dark noise rate

Dark rate vs threhsold



Dark rate stability (12 hrs)



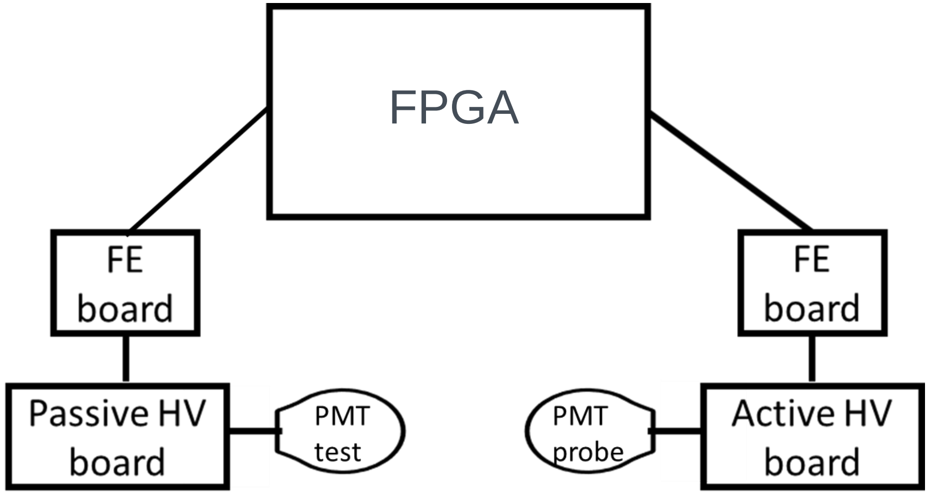
- Different R14374 3” PMTs samples coated with DCB equipped with HK-FD mPMT electronics.
- Dark rate was measured at room temperature.

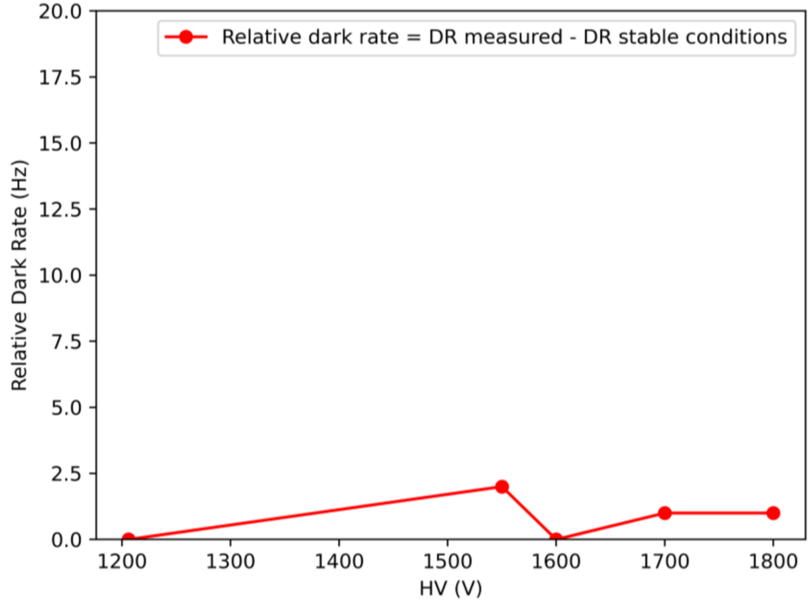
PMT light emissions

Another source of background for PMTs could comes from intrinsic light emissions from the PMT itself.
In most cases, these emission can appear as:

1) Intermittent high-intensity light emission, also known as flashers. Long-term dark rate measurements on the R14374 samples didn't show any intermittent light emission.

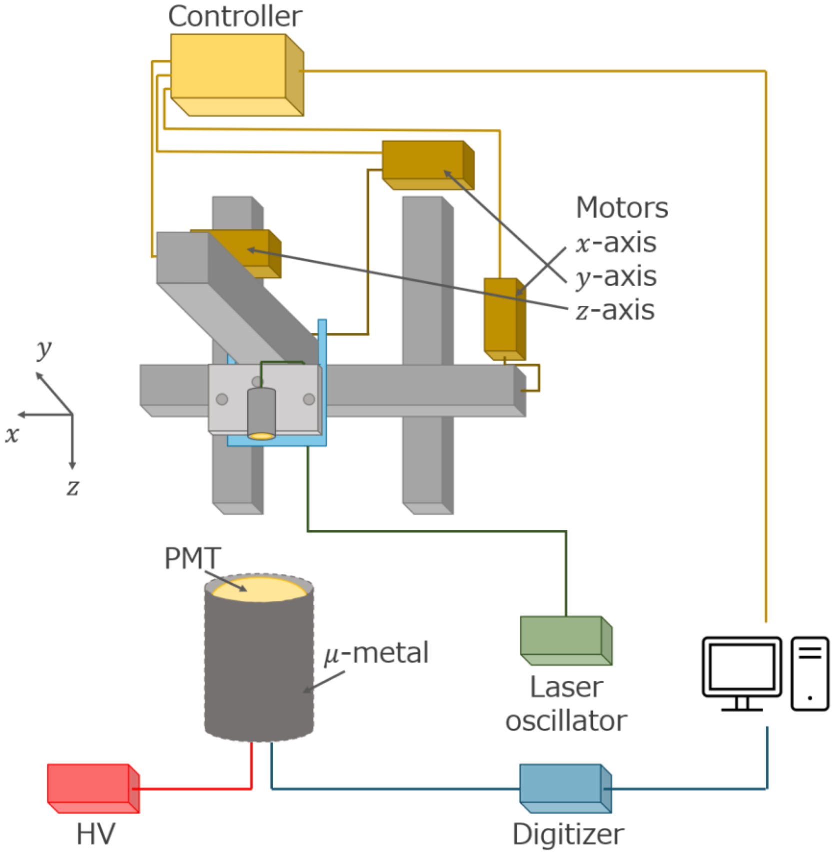
2) Constant emission of low-intensity light. Based on 10.1088/1748-0221/16/08/P08033, **this strongly depends on the HV settings**. We check whether our PMTs could be characterized by these micro-light emission using the setup shown. The main goal was to verify if, by placing 2 pmts window-to-window, the dark count rate of one PMT (PMT probe) varies with respect to its stable value (PMT test off) when the voltage supplied to the PMT being tested (PMT test) is in increased. Further investigation has been performed. Done also a test using the coincidences betweend two PMT probes.
No emissions were observed.

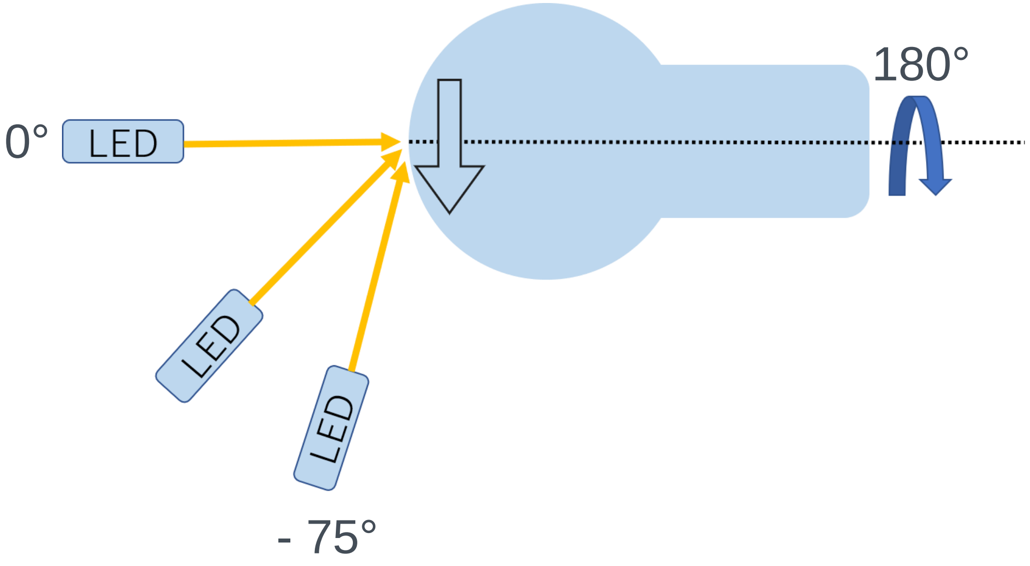




Position and angular dependecy

Using a movable laser system which can illuminate a different position on the photocathode, main PMT characteristics as a function of the position on the photocathode were measured. Same setup has been used to test the angular dependecy, both respect to the light incident angle and respect to the first two dynodes orientation. Gain was set to 1x10^7.



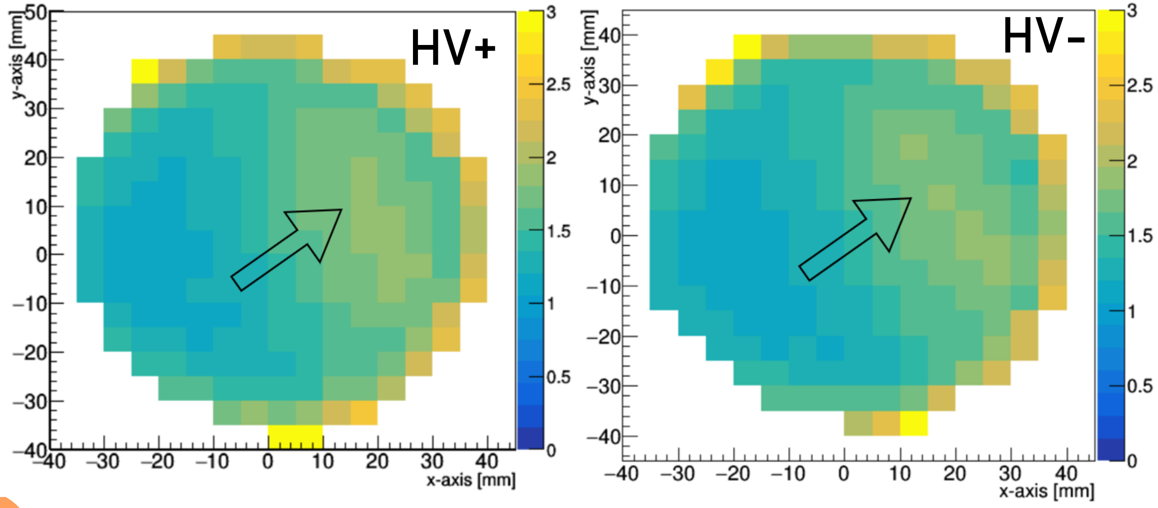


Position and angular dependecy

Using a movable laser system which can illuminate a different position on the photocathode, main PMT characteristics as a function of the position on the photocathode were measured. Same setup has been used to test the angular dependecy, both respect to the light incident angle and respect to the first two dynodes orientation.

→ TTS

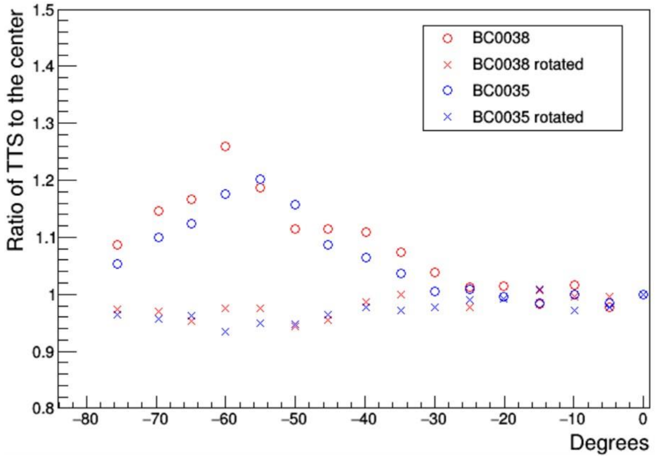
Position dependecy



TTS is about 30% smaller at the first dynode side and about 20% larger at the second dynode side than that at the center.

The arrow shows the dynode orientation from the first dynode to the second dynode of the PMT.

Angular dependecy



TTS maximizes at around 60° while it is uniform within ±5% after rotation

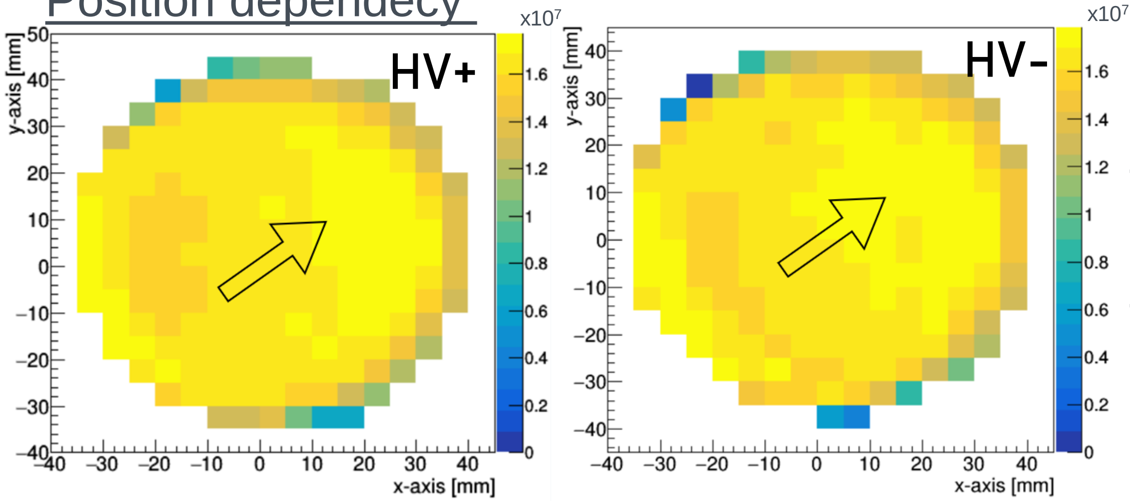
On x-axis it is reported the incident angle of the laser with respect to the center of the photocatode. The cross points refer to the rotation of the photocatode of 180°.

Position and angular dependecy

Using a movable laser system which can illuminate a different position on the photocathode, main PMT characteristics as a function of the position on the photocathode were measured. Same setup has been used to test the angular dependecy, both respect to the light incident angle and respect to the first two dynodes orientation.

→ Gain

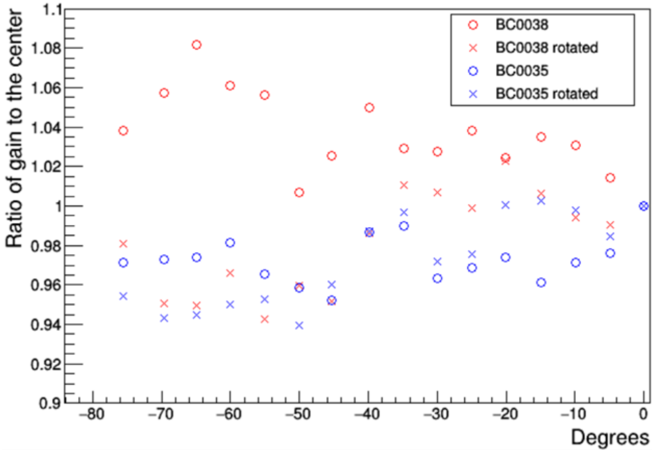
Position dependecy



Gain is about 10% higher at the arrow head which corresponds to the second dynode side.

The arrow shows the dynode orientation from the first dynode to the second dynode of the PMT.

Angular dependecy



Gain is uniform within 10% regardless of the incident angle and rotation of the PMT.

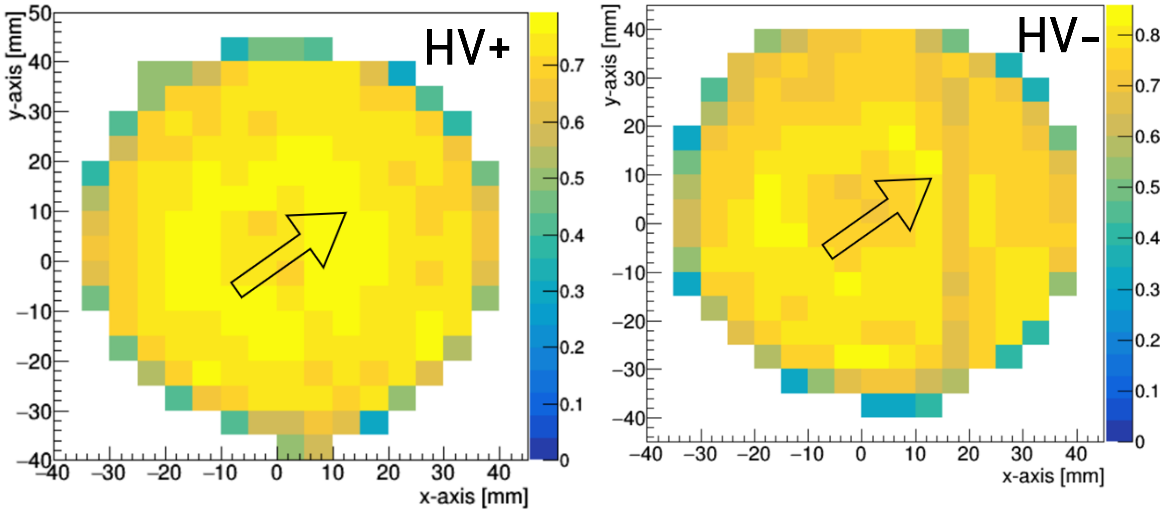
On x-axis it is reported the incident angle of the laser with respect to the center of the photocatode. The cross points refer to the rotation of the photocatode of 180°.

Position and angular dependecy

Using a movable laser system which can illuminate a different position on the photocathode, main PMT characteristics as a function of the position on the photocathode were measured. Same setup has been used to test the angular dependecy, both respect to the light incident angle and respect to the first two dynodes orientation.

→ Efficiency

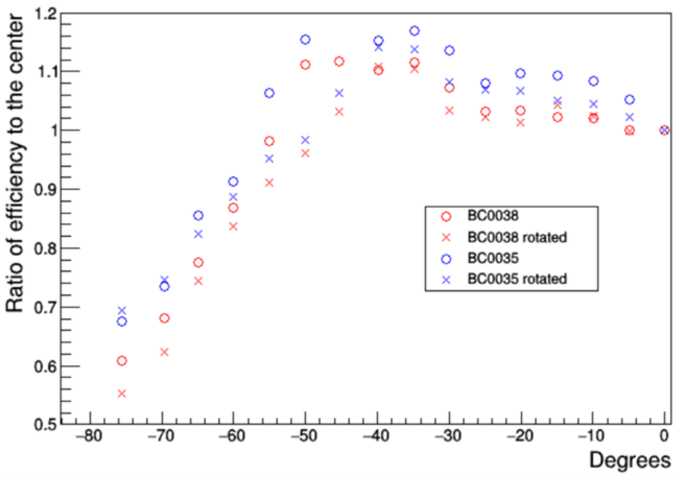
Position dependency



The efficiency is uniform on most of the photocathode within ±20%. There is no correlation between the QE and the dynode orientation.

The arrow shows the dynode orientation from the first dynode to the second dynode of the PMT.

Angular dependecy



Efficiency drops rapidly when the incident angle is larger than 50°.

On x-axis it is reported the incident angle of the laser with respect to the center of the photocatode. The cross points refer to the rotation of the photocatode of 180°.

PMT magnetic field dependency

The characteristics of PMTs are modified by the Earth's magnetic field. However, due to reduced drift length for electrons compared to 20" PMTs, this effect is expected to be considerably smaller for 3" PMTs.

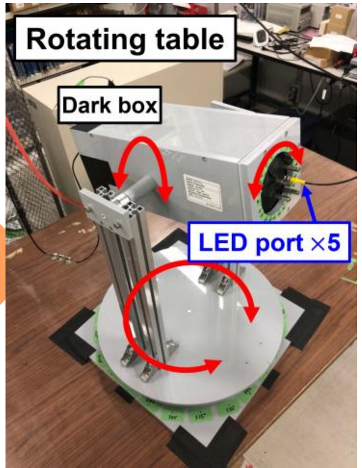
Tests were performed immersing a PMT in a uniform magnetic field and using LEDs.

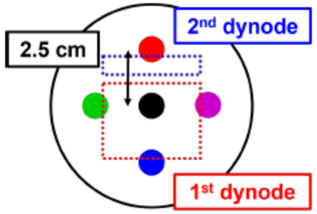
→Efficiency is stable within ±2%

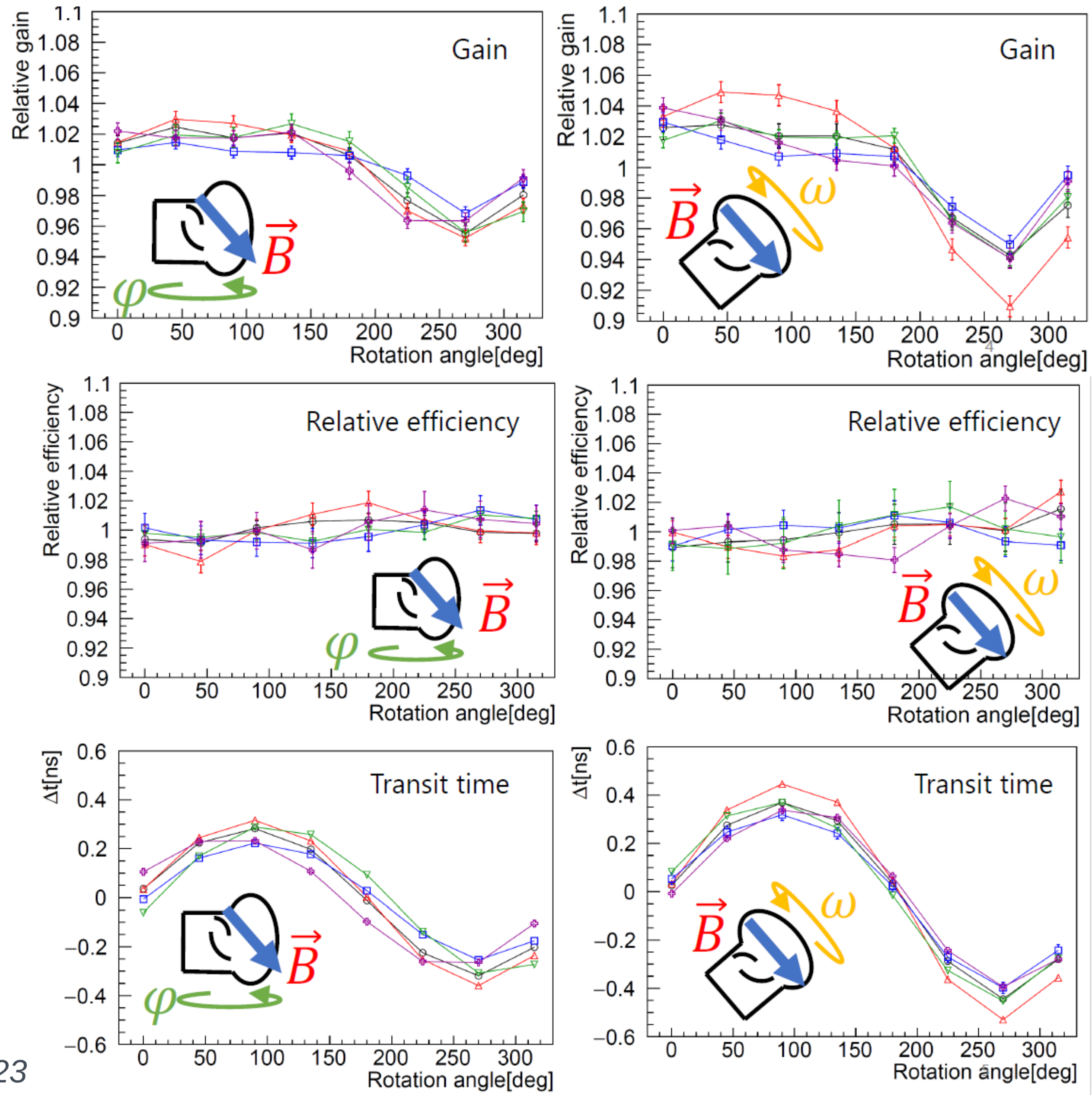
→ Gian and TT change by ±10% and ±1 ns

but these can be monitored by calibration

Tank compensation coils will be installed, to reduce variations due to orientation.







Summary & conclusions

I. A multi-PMT module is a photo-detection system equipped with 19 3” PMTs and it will be used for the Hyper-K Far Detector project. Its major requirements are related to timing characteristics and low intrinsic background, in order to improve the low energy detection, event recontruction and calibration in Hyper-K.

II. Several 3” PMT prototypes have been tested and we found the best option to be the Hamamatsu R14374 3” PMT. A custom electronics has been developed by the Hyper-K collaborators.

III. We tested many samples of Hamamatsu R14374 and work along with the manufacturer to produce a prototype that fully match our requirements. In particular TTS is about 1.5 ns, AP rate about 1.5% and dark rate on average is 300 Hz at room temperature.

IV. We verified that using an anode grounding scheme doesn’t affect main PMT characteristics.

V. Position and angular dependency demonstrated that the relative position between the first two dynodes must be taken in consideration. Thus, we decided that all PMTs will have same orientation.

VI. R&D phase for 3” PMTs is now completed and we are starting the procurement for the construction of FD mPMTs. First mPMT prototypes are now being used as test stand for the 3” PMTs.

Acknowledgments

I want to thank the whole Hyper-K FD2-WG that partecipated to the extensive measurements campaign and in particular those who helped and realized the work that I presented today:

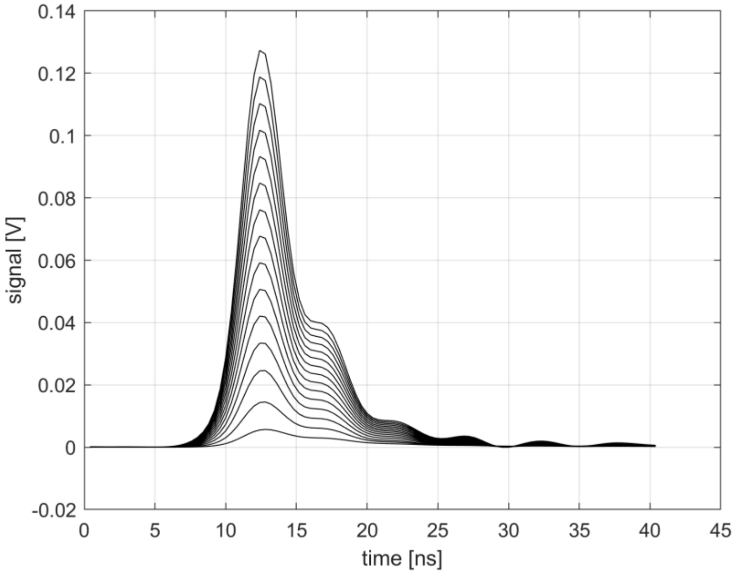
G. De Rosa, A. Di Nola, K. Dygnarowicz, A. Fiorentini, C. Fujisawa, M. Hartz, M. Inomoto, M. Ishitsuka, N. Izumi, S. Izumiyama, T. Kinoshita, M. Kuze, L. Lavitola, T. Lidner, P. Lorens, Y. Maekawa, J. Marzec , H. Morikawa, S. Nakanishi, Y. Nishimura, M.Nurek, B. Quilain, B. Piotrowski, A. Rychter, I. Sashima, Y. Yamaguchi and M. Ziembicki

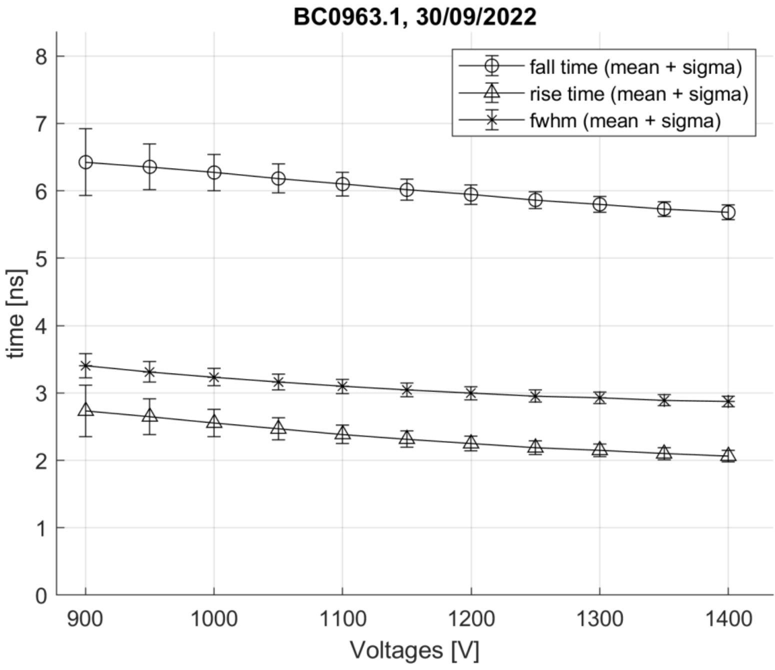
Thank you

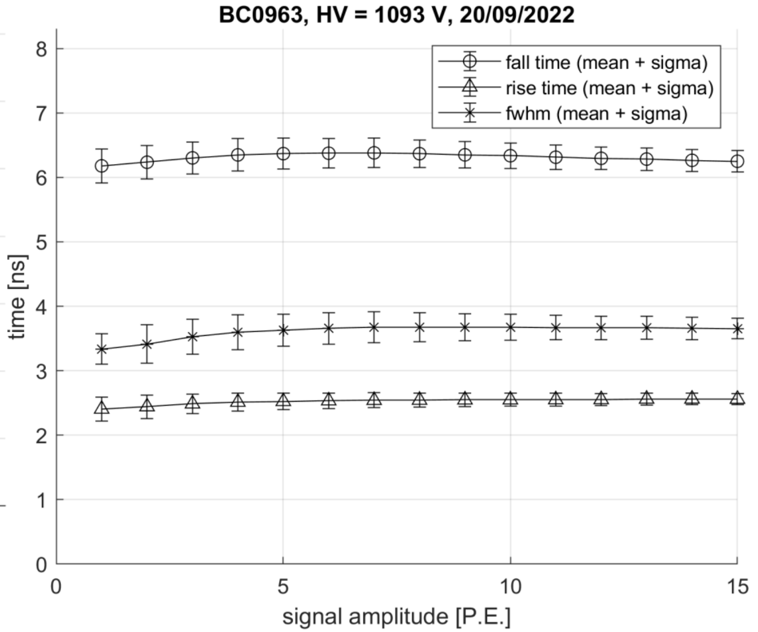
Backup slides

Pulse shape measurements

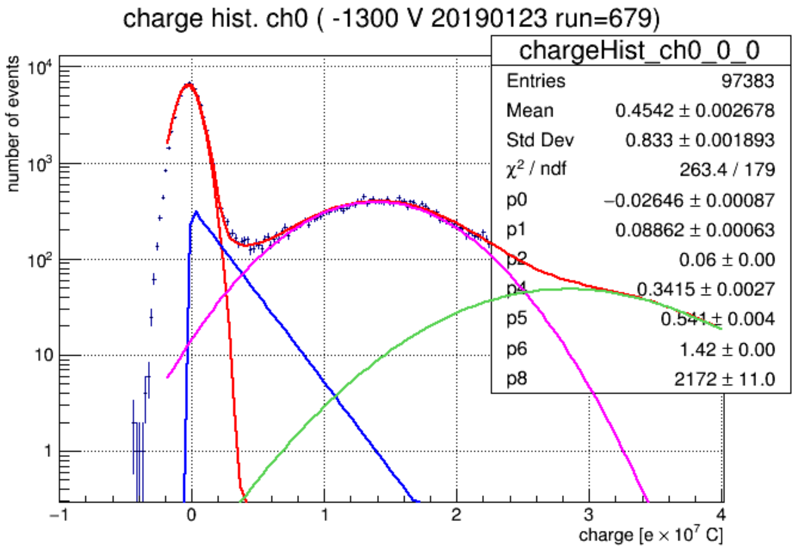
- Signal shape measurement for BC0963
- Oscilloscope BW limit set to 250 MHz
- Calculation of rise/fall time and FWHM
- Pulse shape dependency:
  - on HV with ~1PE signals
  - on signal amplitude with HV set for nominal **gain 1e7**

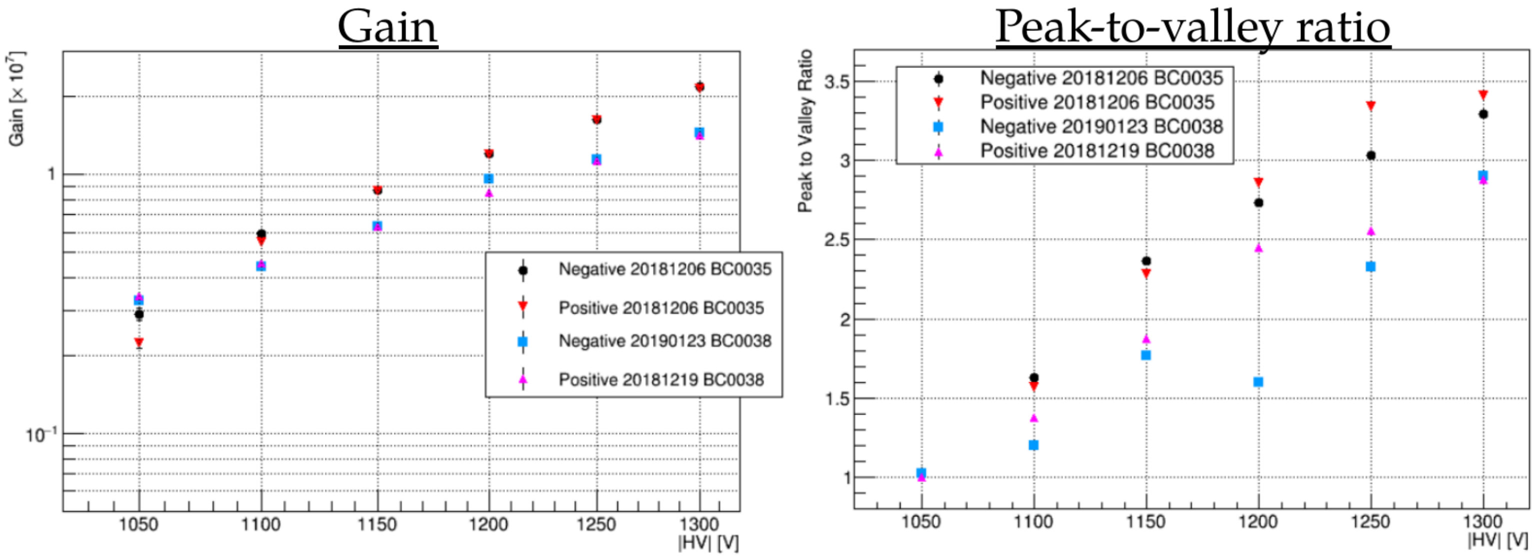



BC0963.1, 30/09/2022


BC0963, HV = 1093 V, 20/09/2022

Gain and peak-to-valley ratio





Gain and Peak-To-Valley ratio of the Hamamatsu R14374 as a function of the highvoltage, for 2 PMTs and in both positive and negative HV modes, at 25°C.