Study of After-pulse of Fast Timing MCP-PMT and Its Performance in Magnetic Fields

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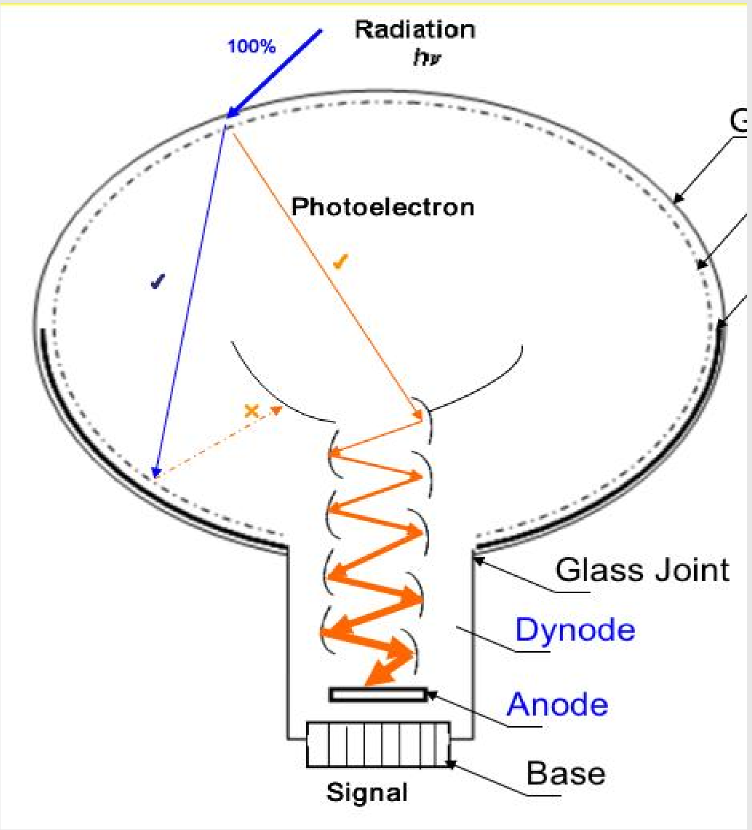
Outline

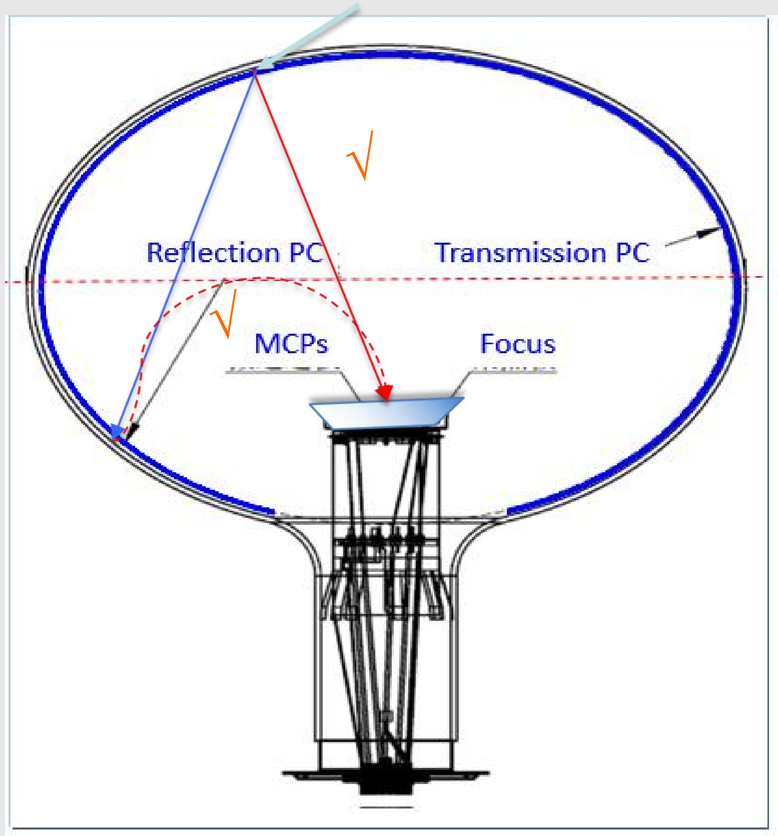
- **1. After-pulse measurement of different types of PMTs**
  - 1.0 The PMT and the Afterpulse
  - 1.1 Afterpulse of 20-inch LPMT
  - 1.2 Afterpulse of FPMT
- **2. Study on Performance of FPMT in Magnetic Fields**
  - 2.1 Changes in Gain of FPMT in Magnetic Fields
  - 2.2 Changes in Timing Performance of FPMT in Magnetic Fields

1.0 The PMTs and the Afterpulse----(1) LPMT

Totally 20000 20" PMTs were used for JUNO, including both Dynode PMTs and MCP-PMTs.

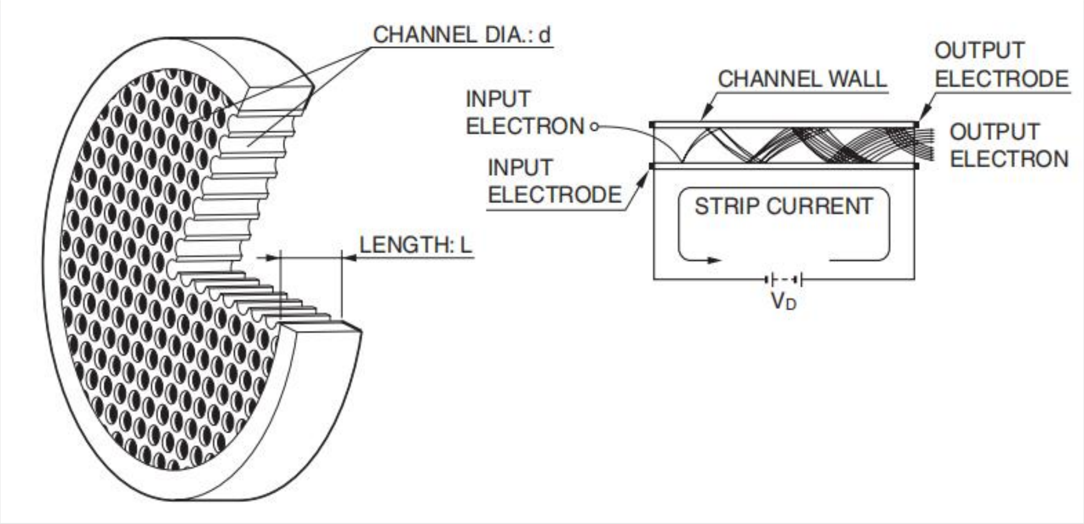


- The 20-inch Dynode PMT



- The 20-inch MCP-PMT

1.0 The PMTs and the Afterpulse----(2) FPMT



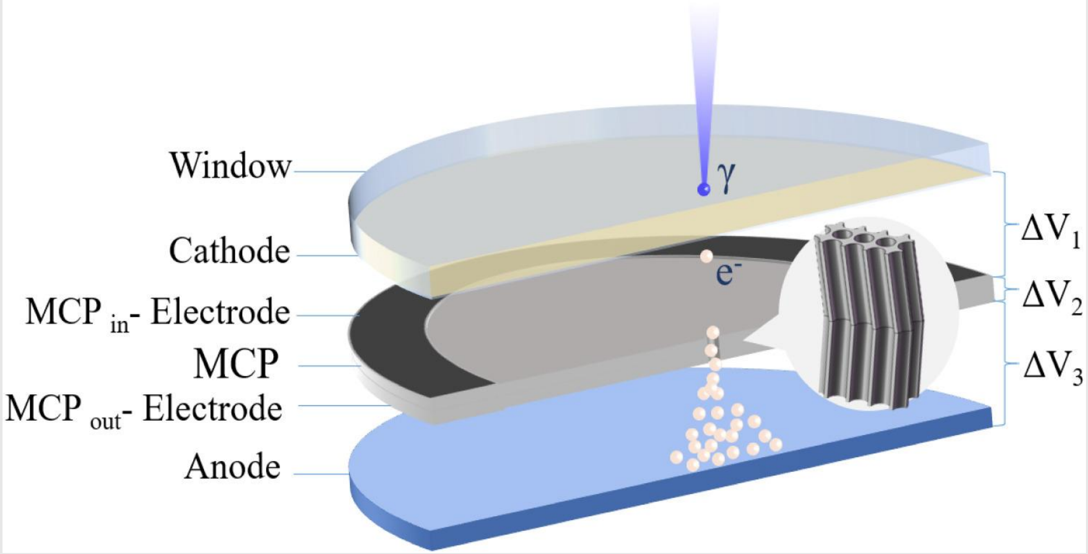
Performance of the Fast-timing MCP-PMT:

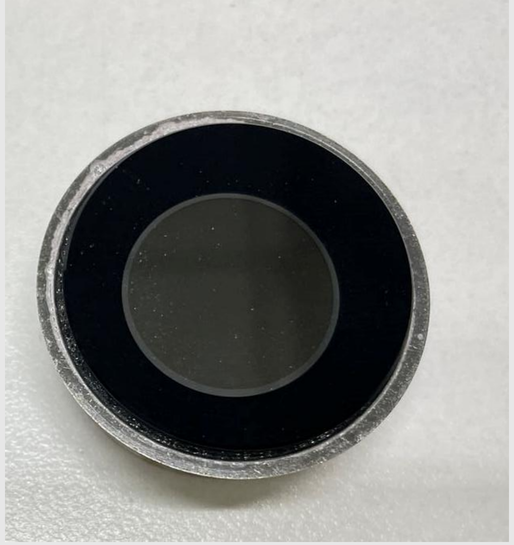
High Gain： $>10^6$

Small Size: Diameter=50mm

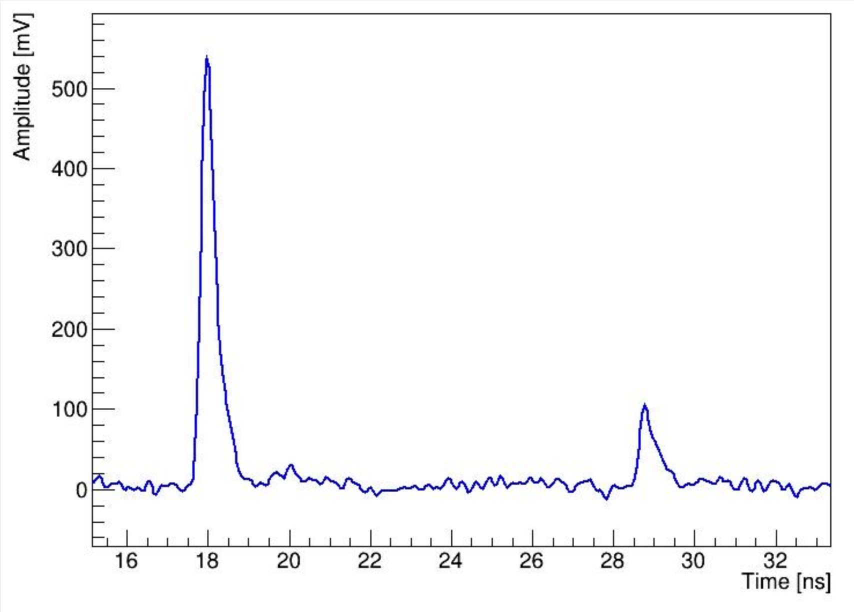
Fast Signal： Rise time < 1ns

TTS@SPE：~30ps

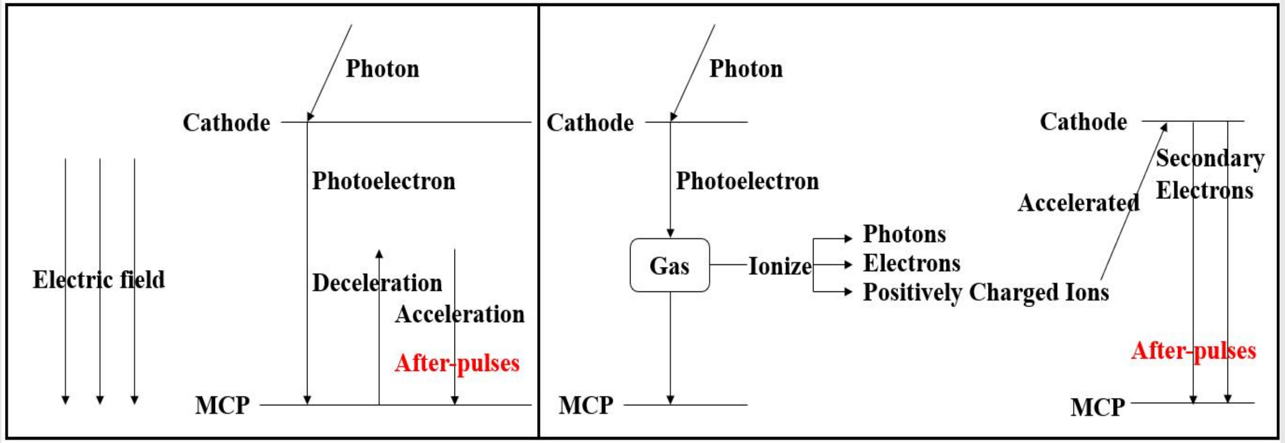




1.0 The PMTs and the Afterpulse----(3) Afterpulse



➢ Typical waveform of afterpulse



➢ Process of electrons back scattering and residual gas ionization

After-pulse: spurious pulses occurring in a PMT after the initial pulse.

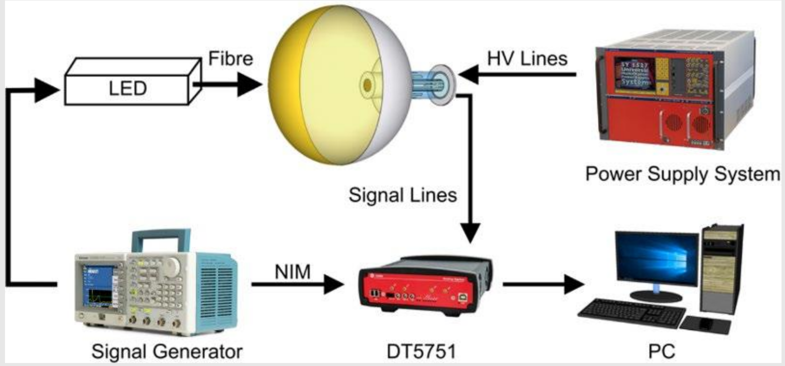
- Similar to actual signals, can contribute to PMT noise and are detrimental to applications requiring low noise levels.
- Caused by ionized residual gases or by back-scattered electrons
- Use After-Pulse Rate (APR) to evaluate the level of after-pulses in a PMT:

$$APR = \frac{N_{After-pulse}}{N_{Main-pulse} \times Q_{Main-pulse}}$$

1.1 After-pulse of 20 inch PMTs

Tested PMTs： 20-inch HQE-MCP-PMT for JUNO, Dynode-PMT R12860

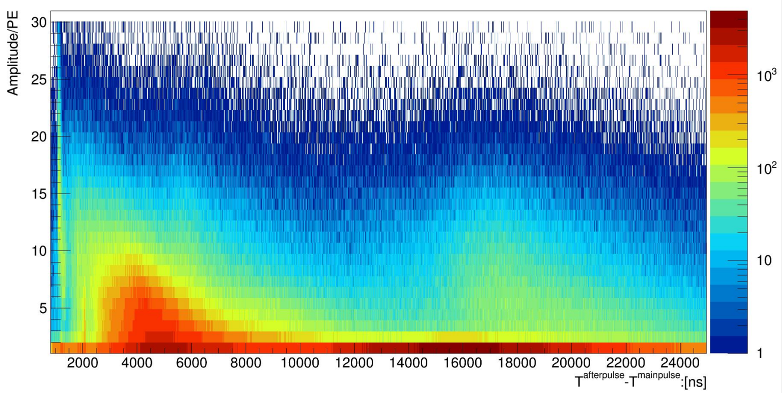
Testing system：



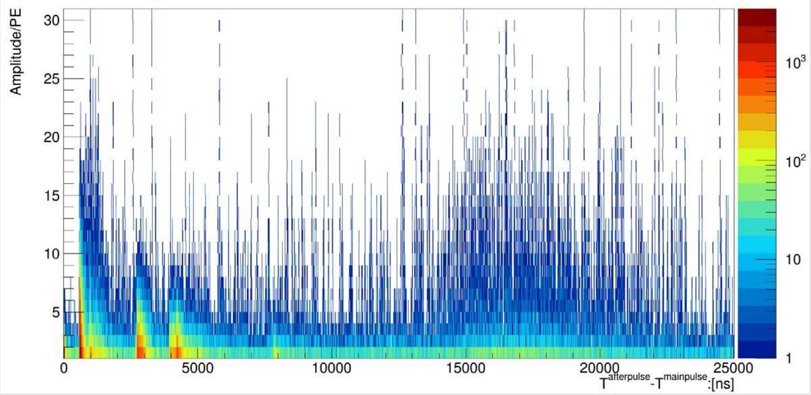
Light source：LED

DAQ：DT5751(1G/Hz sampling rate, 200M Hz bandwidth)

Result：



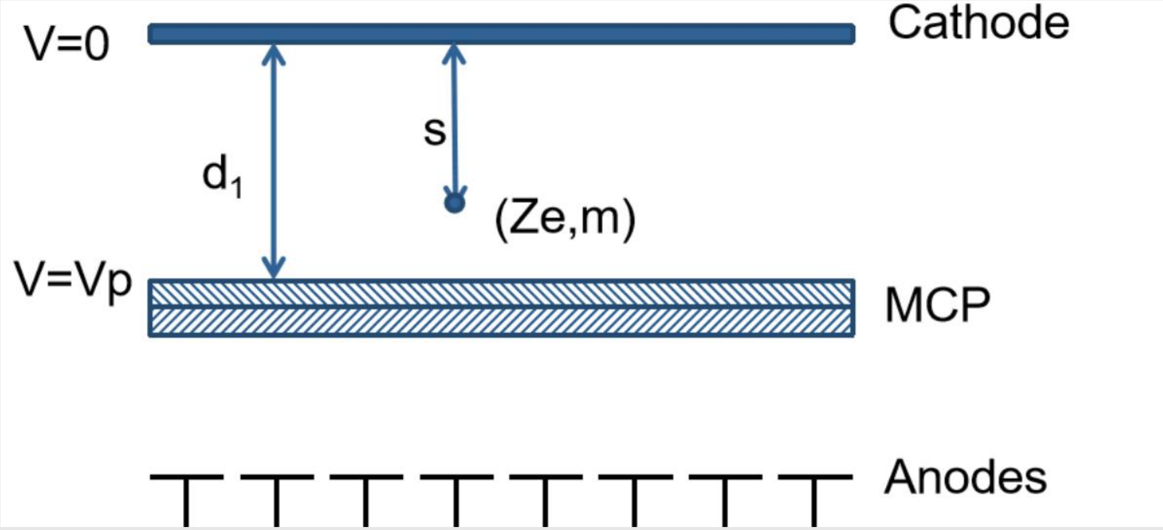
Dynode-PMT
Average afterpulse charge：1.15PE
APR=7.71%



HQE-MCP-PMT
Average afterpulse charge：3.6PE
APR=1.37%

Ref: NIMA 1003 (2021) 165351

1.2 After-pulse of FPMTs



After-pulses caused by back-scattered electrons：

$$T_{delay} = 2 \times \sqrt{2m_e d(d-s)/eV_p}$$

After-pulses caused by ionized residual gases：

$$\begin{cases} V = V_p \dfrac{s}{d} \\ ZeV_s = \dfrac{1}{2} m v^2 \\ T_{delay} = \displaystyle\int_s^0 \dfrac{ds}{v} \end{cases}$$

- The afterpulse of PMT is related to the type of charged particles and the structure of PMT.
- Due to the small size of FPMT, the delay time of after-pulses are very close to the main pulses:
  - The after-pulses caused by back-scattered electrons often mix with the main peak and do not generate additional noise.
  - The after-pulses caused by ionized residual gases reach within 500ns after the main pulses.

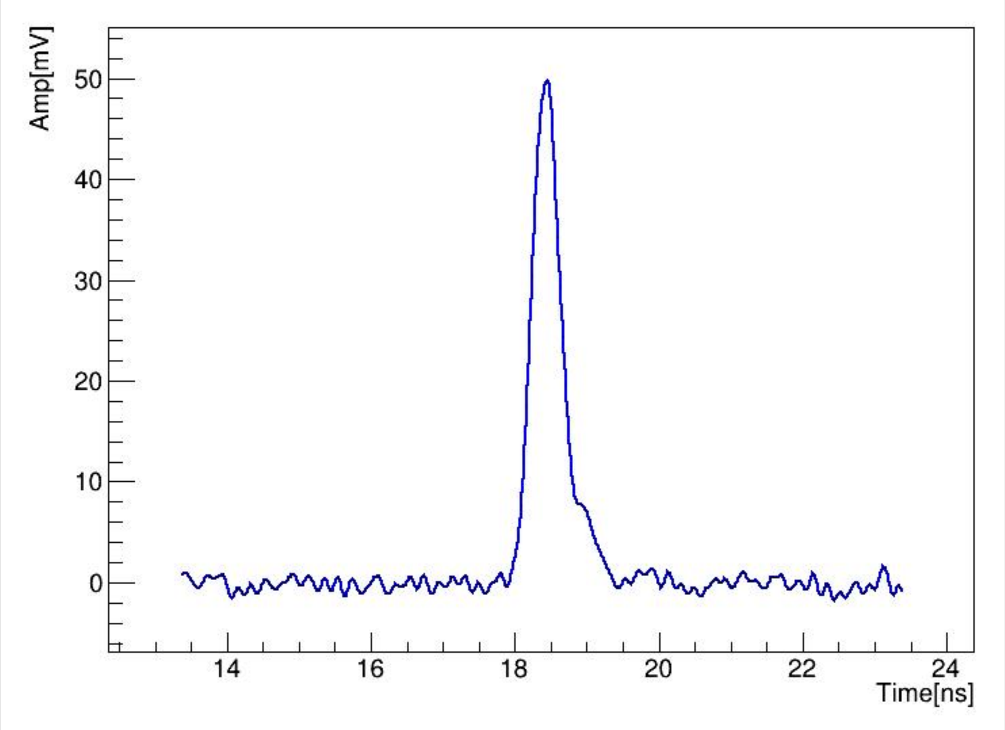
1.2 After-pulse of FPMTs

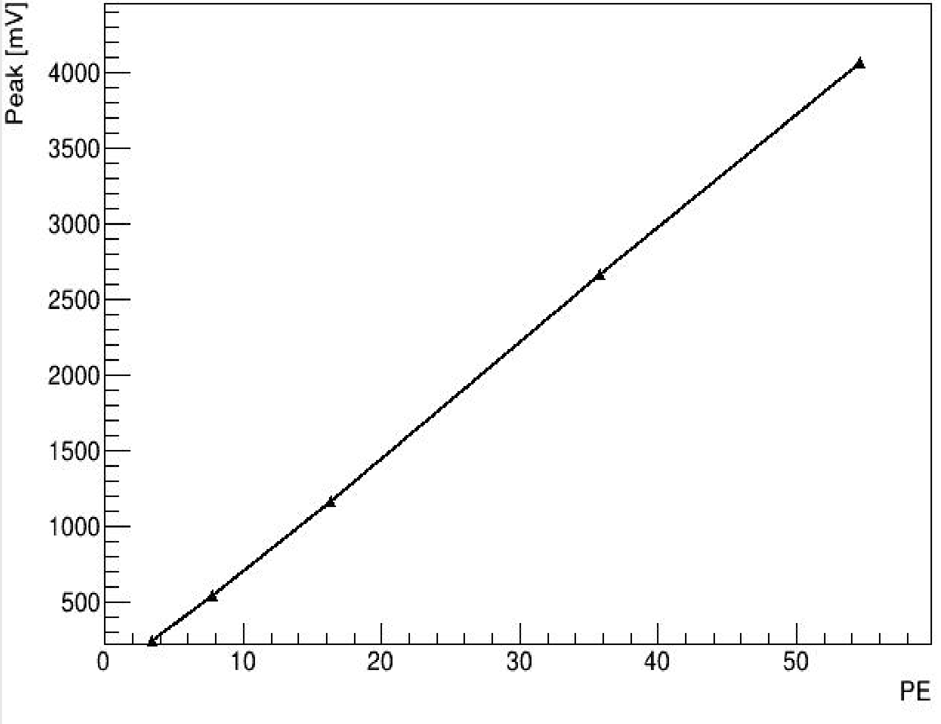
Performance of FPMTs：

- Fast timing performance
- Small size
- High amplitude at SPE
- Good linearity

Testing system：

- High sampling rate DAQ system
- Relatively small time window
- Low light intensity





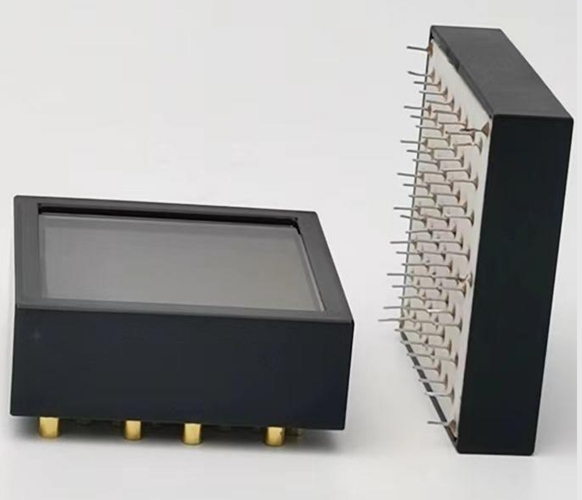
1.2 After-pulse of FPMTs

Tested PMTs：

photek210

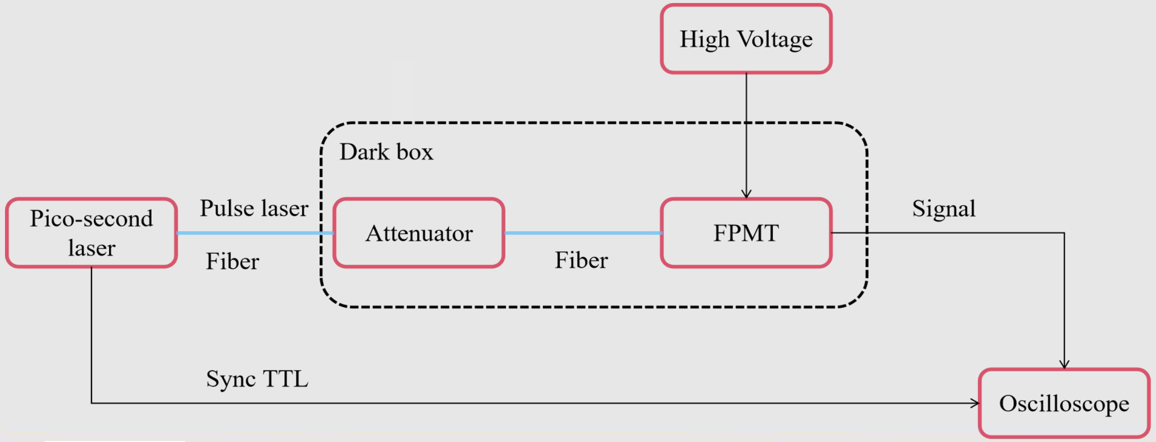
NNVT
SA-FPMT

MA-FPMT
V4.0



MA-FPMT
V6.0

Testing system：



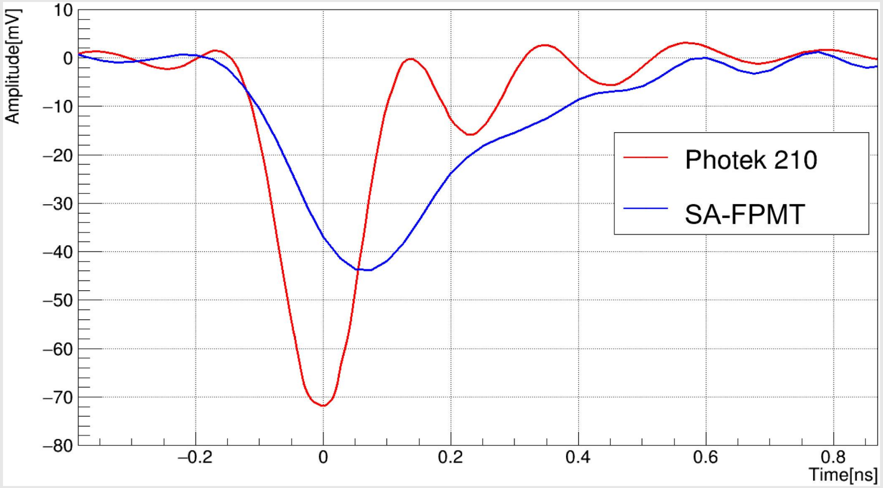
Light source： picosecond laser

DAQ： oscilloscope (10G/Hz sampling rate, 4G Hz bandwidth)

1.2 After-pulse of FPMTs

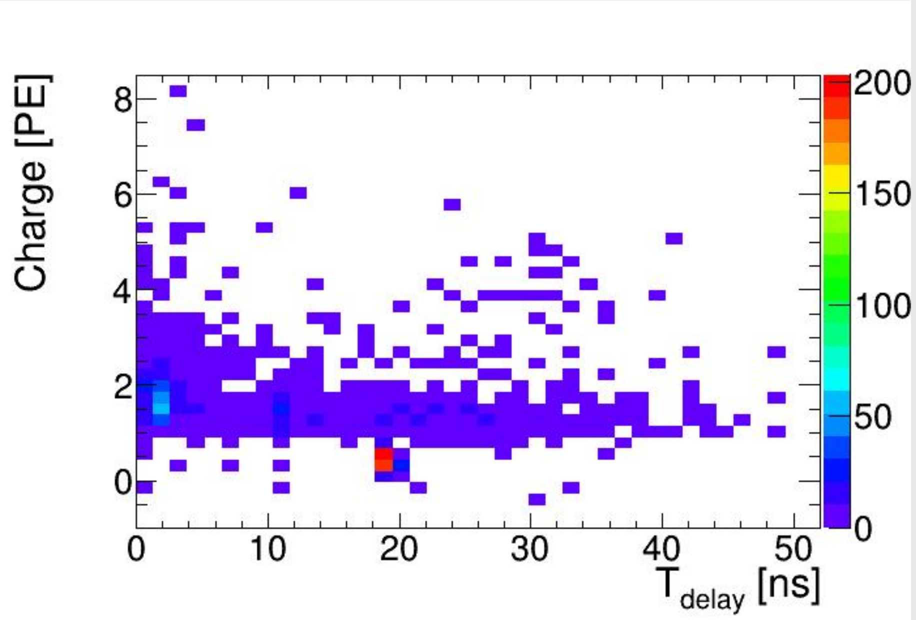
photek210

NNVT
SA-FPMT

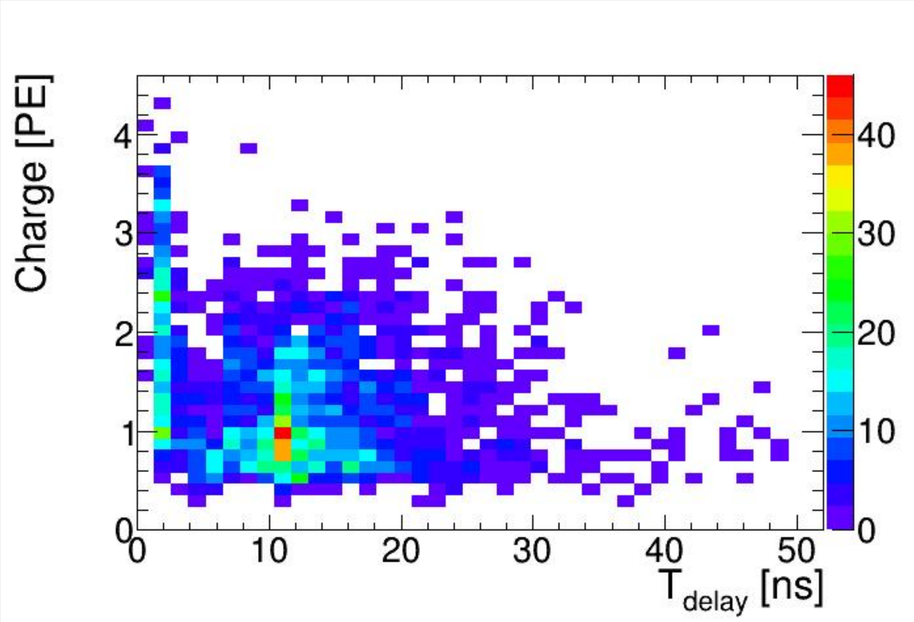


Number	HV/V	Gain	Peak@SPE	RT	FT	FWHM
photek210	-4300V	8.5E5	33.5mV	132.8ps	318.9ps	207.3ps
SA-FPMT	-2300V	7.3E6	115.7mV	228.3ps	564.6ps	330.5ps

1.2 After-pulse of FPMTs



Photek210
Average charge：1.9PE
APR=0.11%



SA-FPMT
Average charge：1.3PE
APR=0.80%

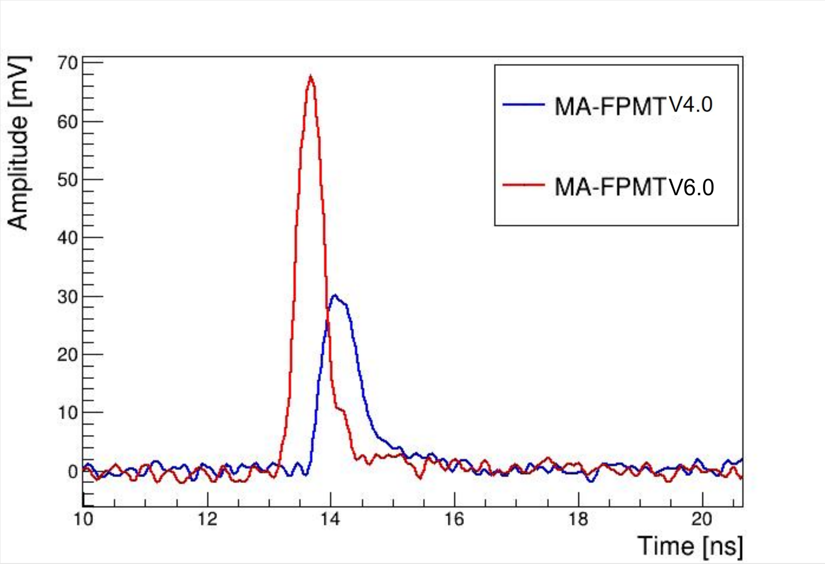
Ref: Lingyue Chen et al 2024 JINST 19 T10004

1.2 After-pulse of FPMTs

The structure of MA-FPMT was adjusted to achieve better timing performance

MA-FPMT V4.0

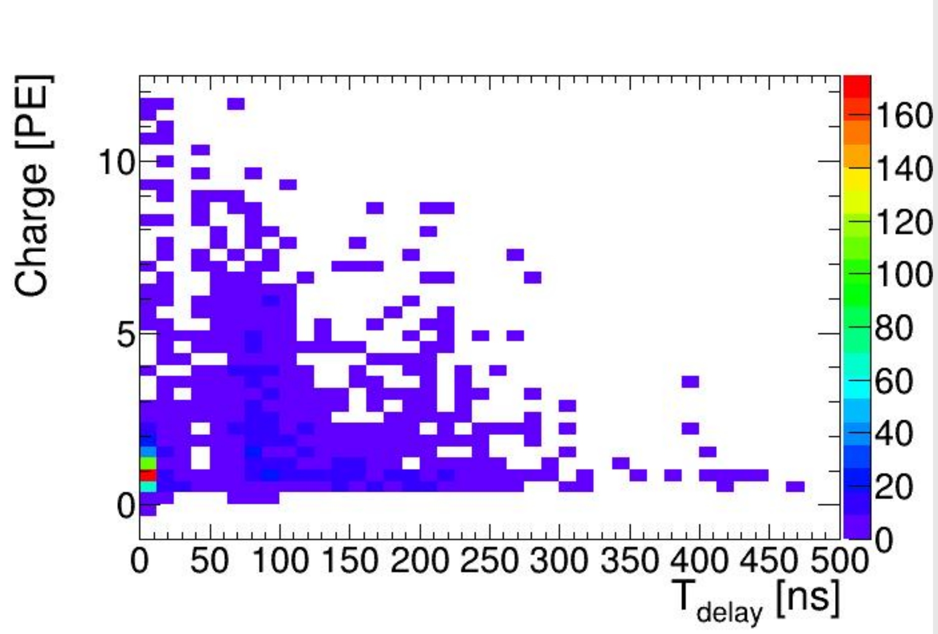
MA-FPMT V6.0



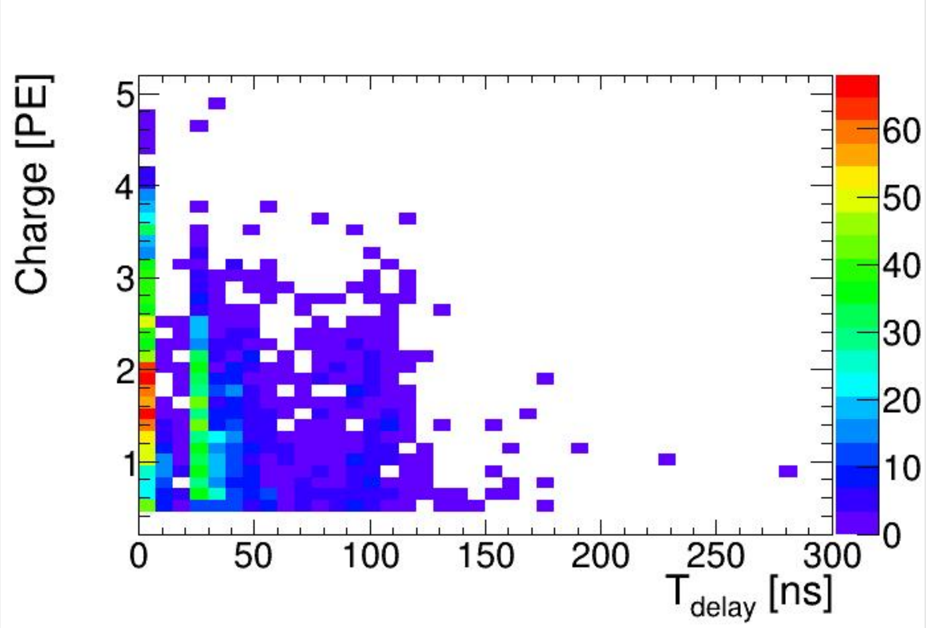
Number	HV/V	Gain	Peak@SPE	RT	FT	FWHM
MA-FPMT V4.0	-1725	3.1E6	39.7mV	383ps	979.9ps	729.2ps
MA-FPMT V6.0	-1370V	5.6E6	73.7mV	303.9ps	473.6ps	518.1ps

1.2 After-pulse of FPMTs

The new version of the MA-FPMT has improved time performance and the afterpulse ratio (APR) is maintained below 1%.



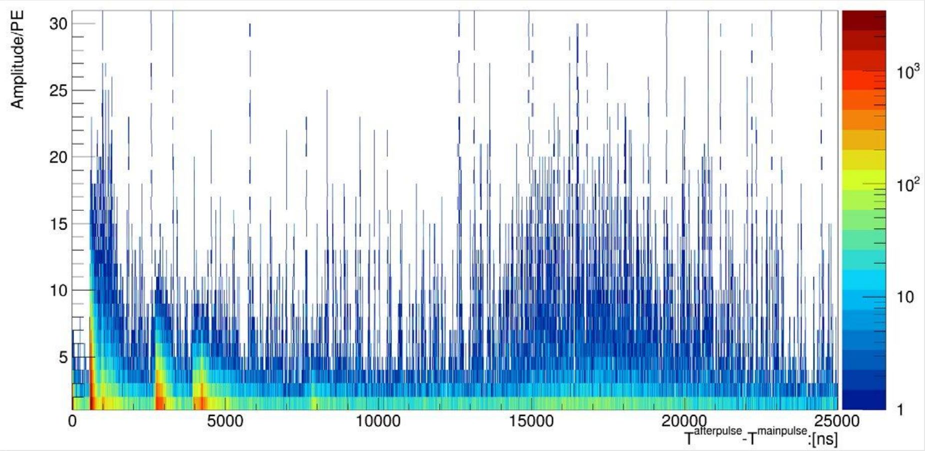
MA-FPMT-V4.0
Average charge：2.2PE
APR=0.39%



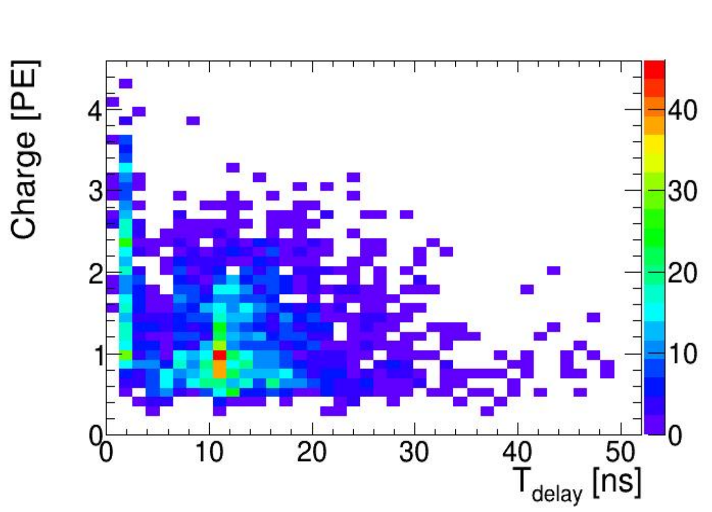
MA-FPMT-V6.0
Average charge：0.9PE
APR=0.83%

Ref: Lingyue Chen et al 2024 JINST 19 T10004

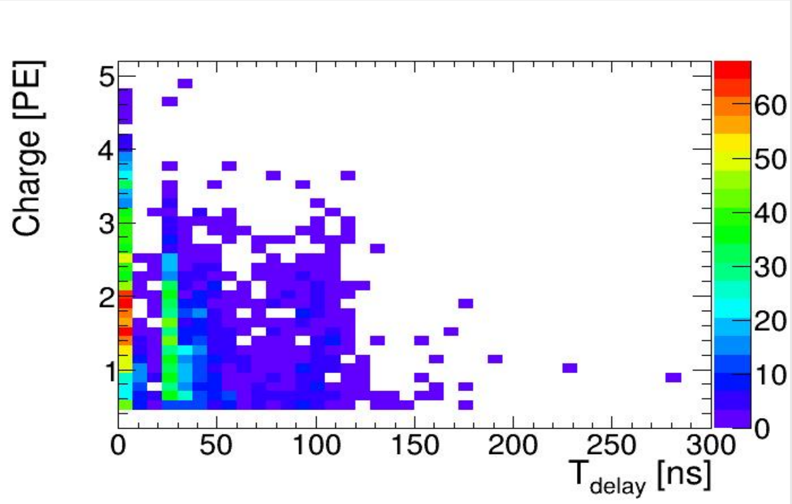
1.3 Summary



HQE-MCP-PMT
Average afterpulse charge：3.6PE
APR=1.37%



SA-FPMT
Average charge：1.3PE
APR=0.80%

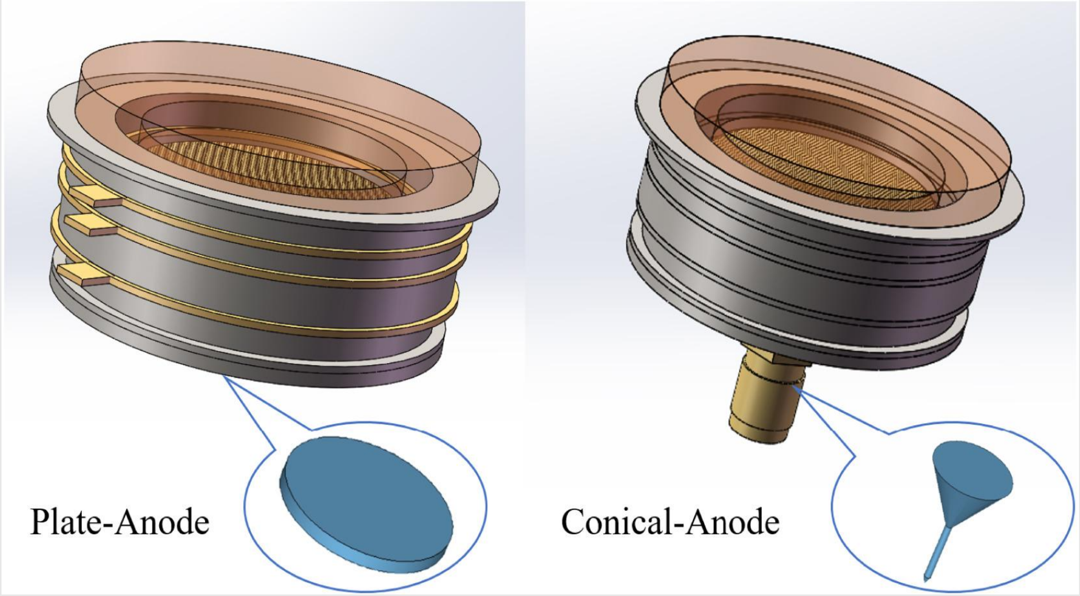


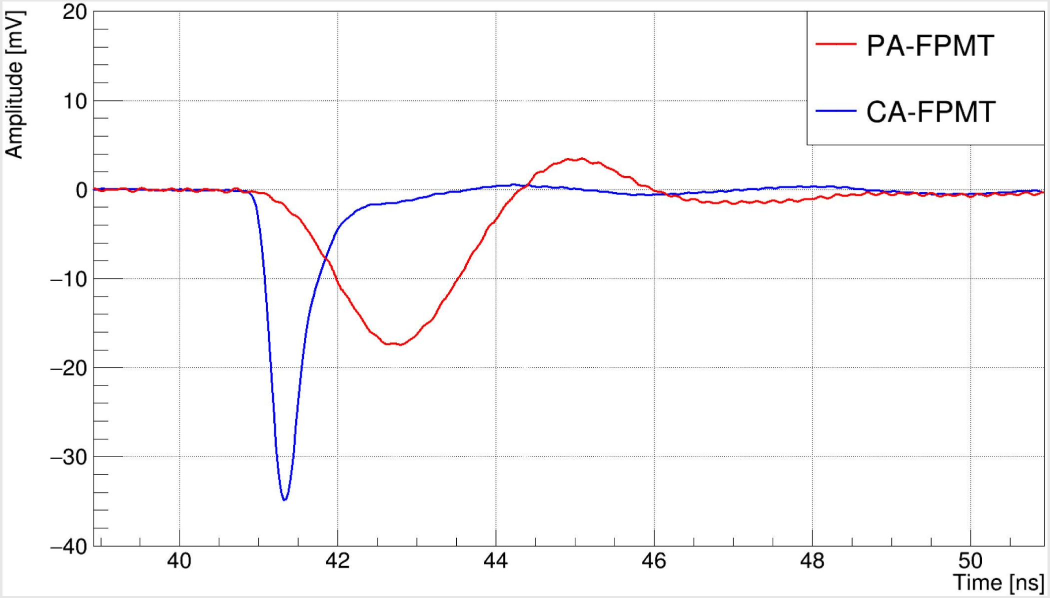
MA-FPMT-V6.0
Average charge：0.9PE
APR=0.83%

- The small size of FPMT reduces the flight time of residual gas particles, thereby shortening the delay time;
- The small size of FPMT results in less residual gas inside the PMT, which can achieve lower afterpulse rates.

2 FPMTs in magnetic field

To achieve better timing performance, the Plate-Anode FPMT (PA-FPMT) was optimized to Conical-Anode FPMT (CA-FPMT)



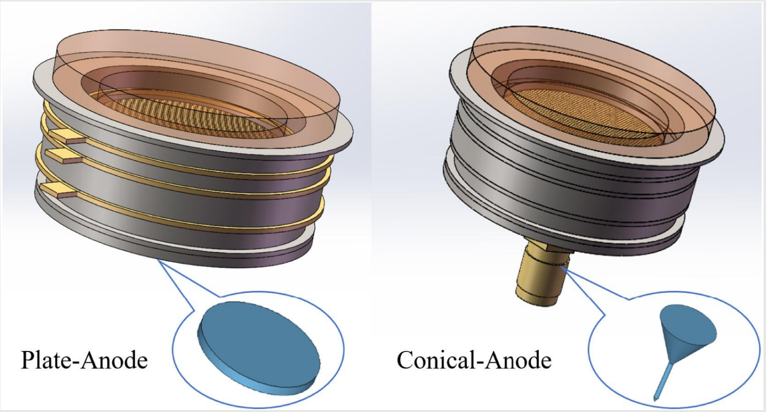


	HV	Gain	Amplitude	RT	FT	Width	TTS@SPE
PA-FPMT	-2000V	1.9×10^6	7.6mV	1.4ns	1.4ns	1.8ns	71.0ps
CA-FPMT	-2300V	7.3E6	115.7mV	228.3ps	564.6ps	330.5ps	27.7ps

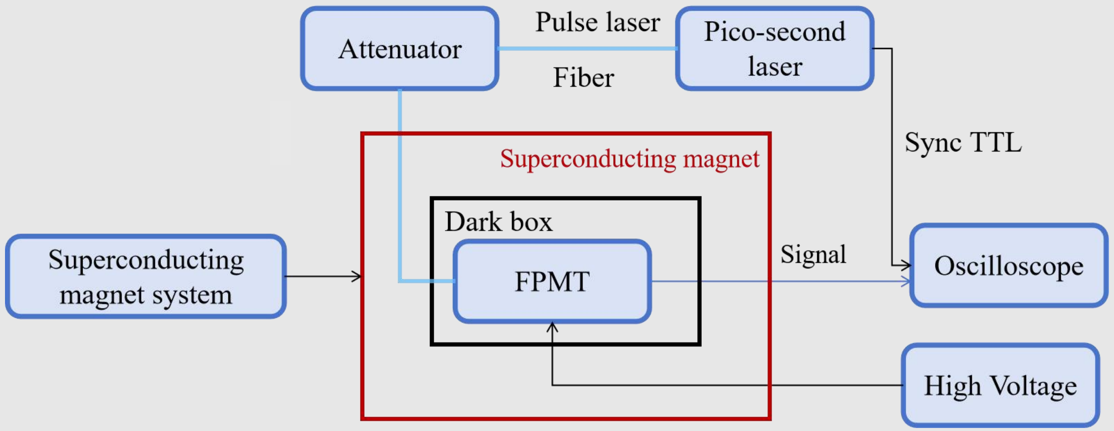
Ref: NIMA 1041 (2022) 167333

2 FPMTs in magnetic field

Tested PMTs：

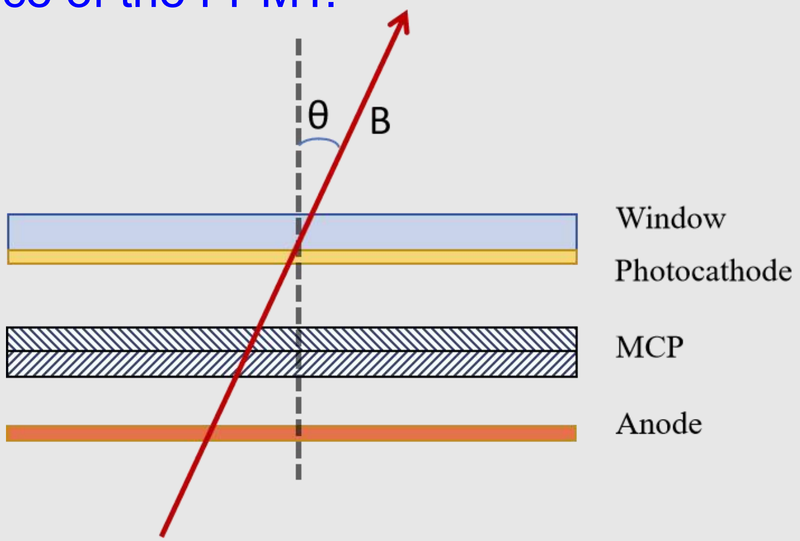


Testing system：

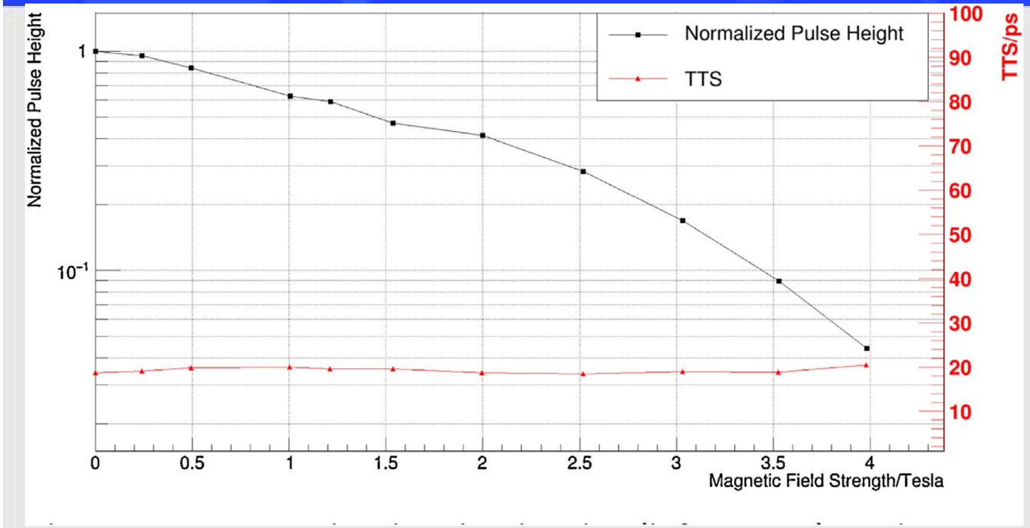


Testing method：

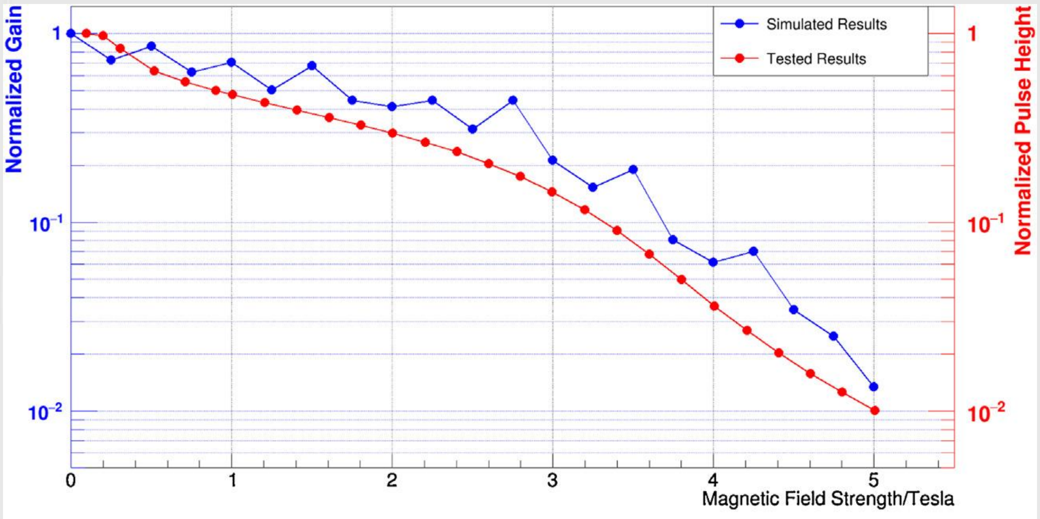
- FPMTs were placed into a superconducting magnet to test the performance changes under different magnetic field strengths.
- Altering the angle between the FPMT and the magnetic field to test the impact of magnetic field angles on the performance of the FPMT.



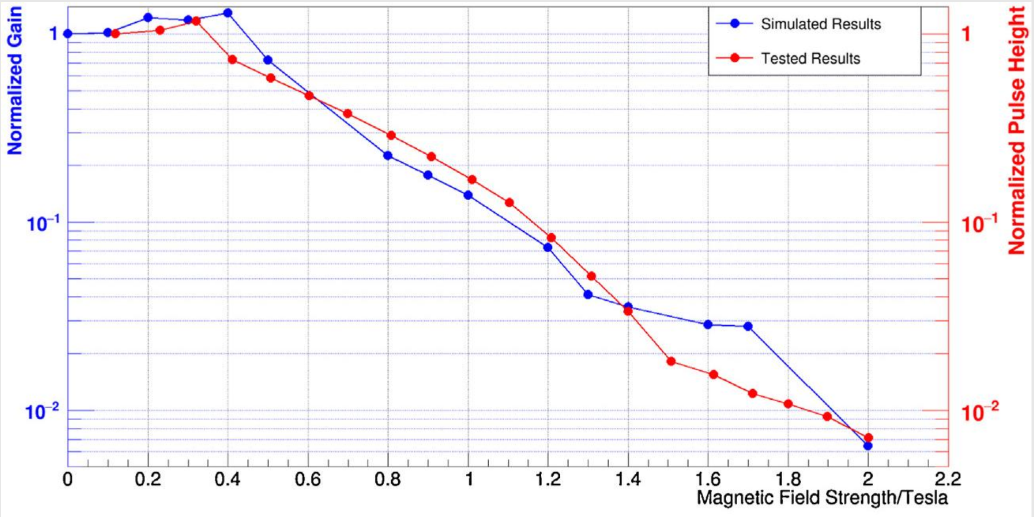
2.1 Plate-anode FPMT in magnetic field



- The experiment was conducted under multi-photon mode
- Great magnetic field tolerance of Plate-anode FPMT: the magnetic field strength where the pulse height decreases to 1/100 of the original large-signal reaches 5T at 0° and 1.85T at 90°
- Time resolution does not depend on magnetic field strength under fixed conditions



0°



90°

Ref: Sensors and Actuators A 318 (2021) 112487

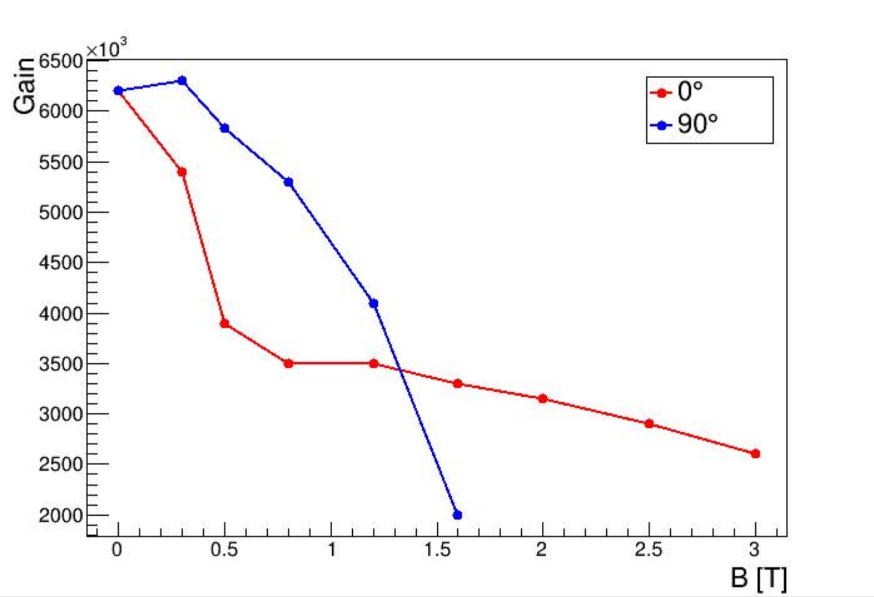
2.2 Conical-anode FPMT in magnetic field

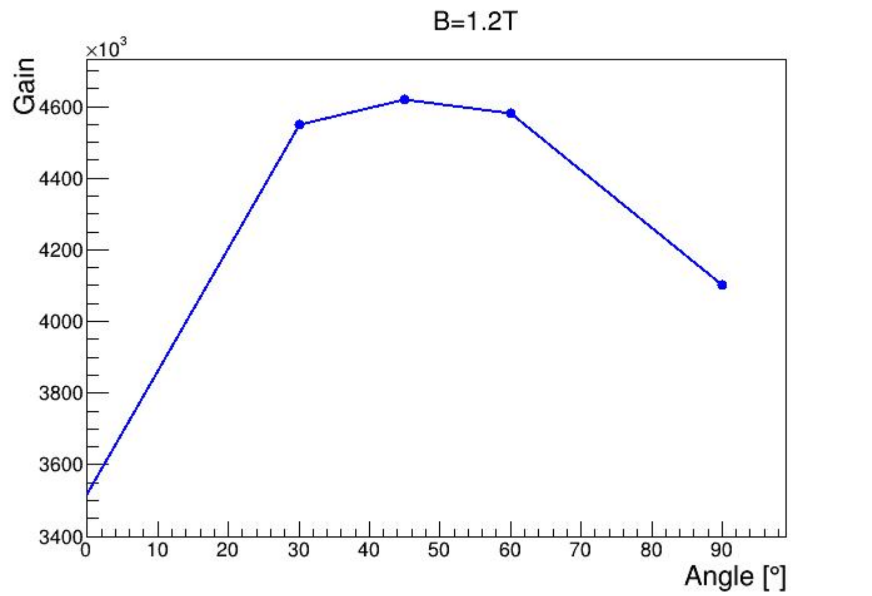
Performance of CA-FPMT：

✓ Fast timing performance: ~200ps RT

✓ High single-photon amplitute: ~70mV

Single-photon detection in magnetic field

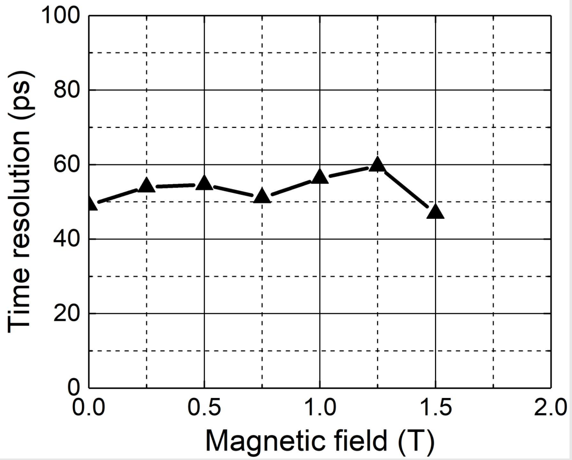


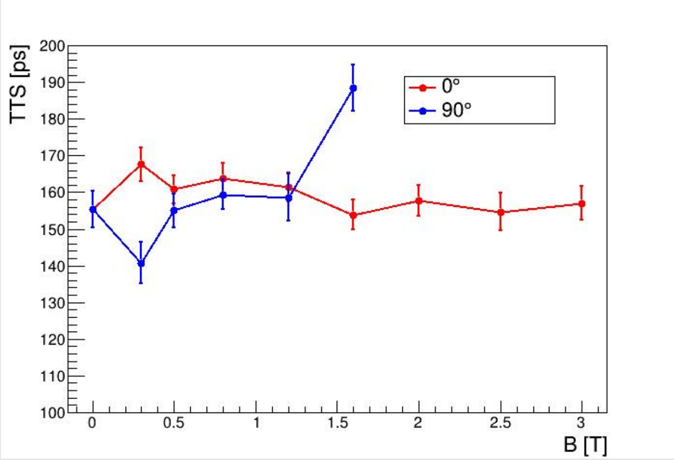


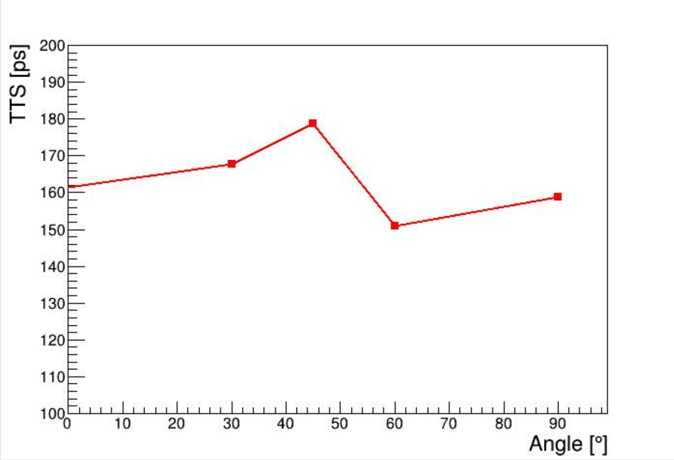
- Strong resistance to magnetic fields: single-photon detection capibility in strong magnetic field
- The effect of the magnetic field depends on the angle.

2.2 Conical-anode FPMT in magnetic field

- Time resolution does not depend on magnetic field strength under fixed conditions: Changing the magnetic field strength and angle does not alter the TTS, which is consistent with simulation results.
- When the magnetic field strength is high, the gain of the FPMT is low, resulting in small signal amplitudes and increased interference from baseline noise on the TTS.





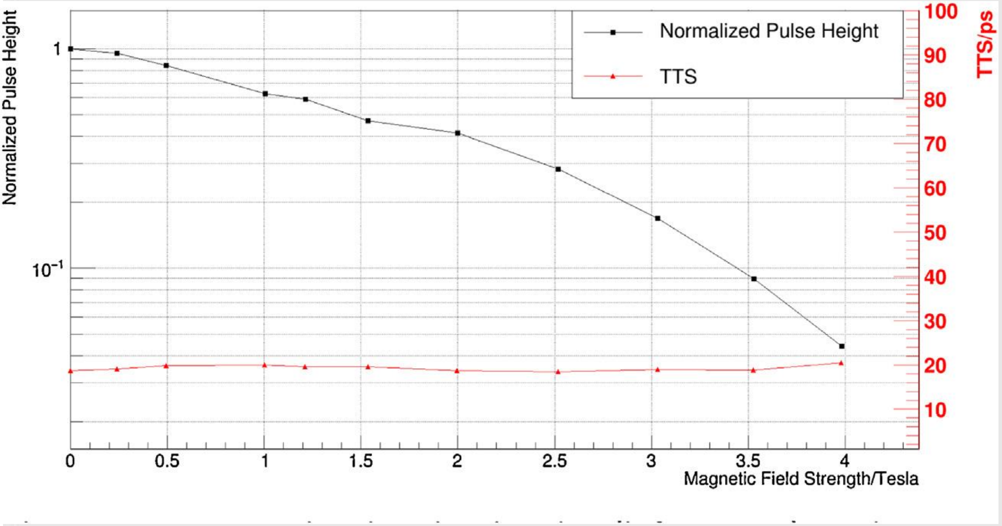


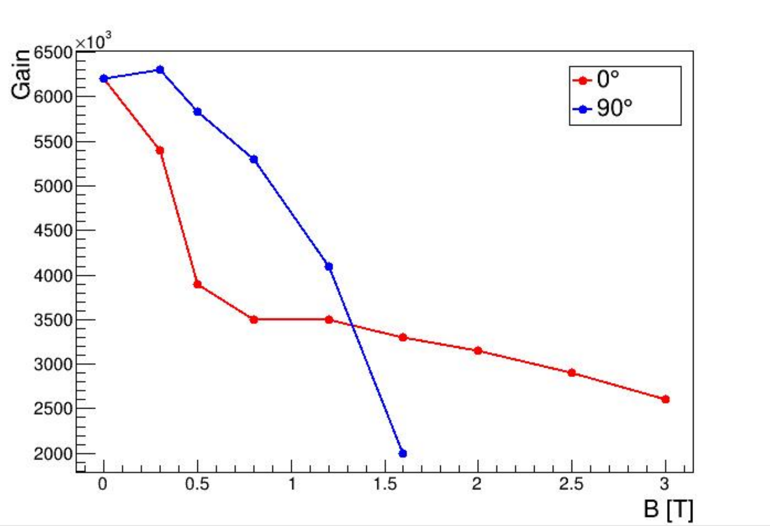
➢ Simulation

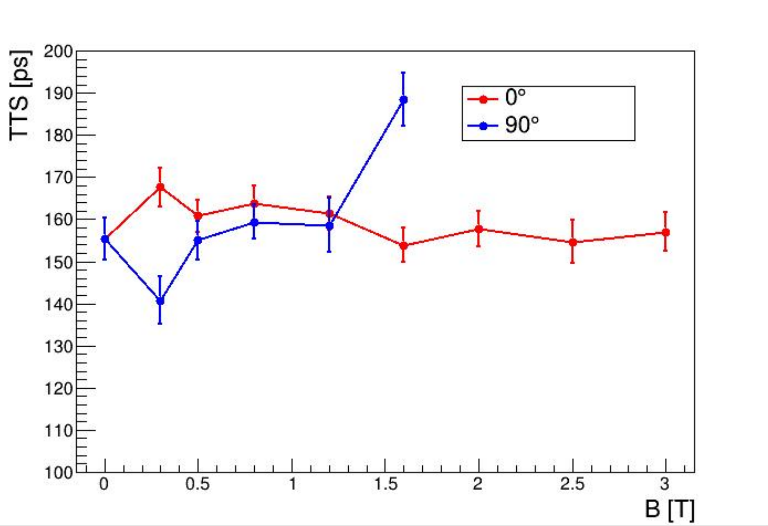
➢ Experiment

Ref： L. Li et al 2020 JINST 15 C03048

2.3 Summary







- PA-FPMT
- CA-FPMT

- The conical anode greatly optimized the timing performance of FPMT and allows FPMT to conduct single photon tests in strong magnetic fields, demonstrating stronger magnetic field resistance than PA-FPMT.
- Time resolution does not depend on magnetic field strength under fixed conditions

Thanks!