Performance evaluation of 20cm MCP-PMTs

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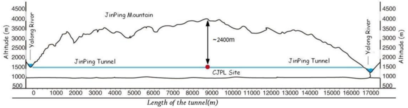
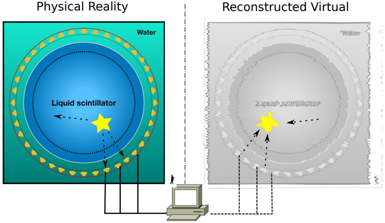
November 10, 2023, Zhuhai

Jinping Neutrino Neutrino Observatory





1. Jinping Mountain Tunnel in Xichang City, Sichuan Province (2400 m of rock);
2. 500-ton liquid scintillator detector in construction;
3. ν deposits energy in LS and emits photons.

How to observe these photons?

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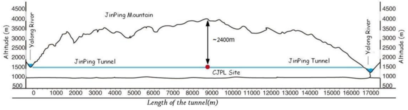

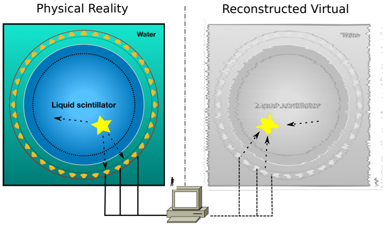

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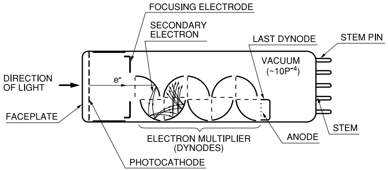
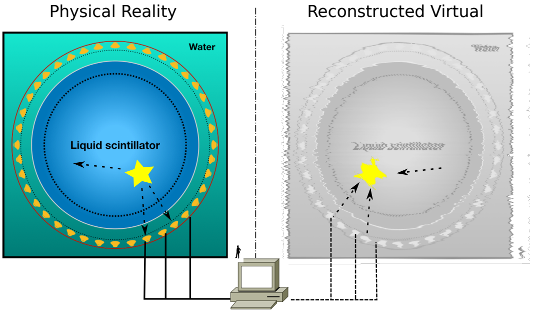
Photomultiplier Tube (PMT)



Photoelectric effect and electron multiplication

The requirement of PMT



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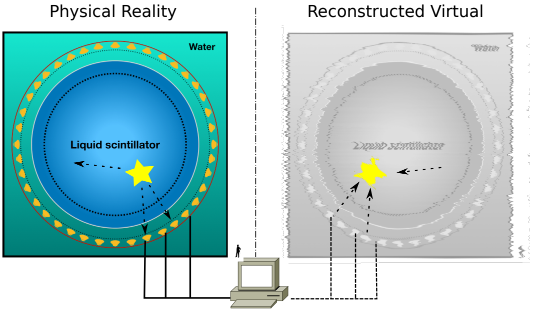

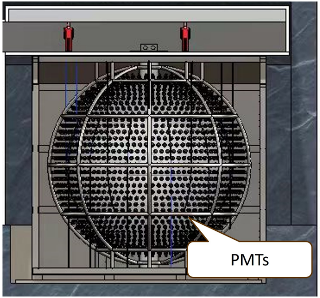

1. nearly 4,000 PMTs: to control the cost of PMTs
2. High Photon detection efficiency(PDE): up to 30 % for **energy measurement**
3. High time resolution: nanosecond **timing resolution**, for **position measurement**
4. Reduce background impacts: low dark noise (fake signals), high signal-to-noise ratio

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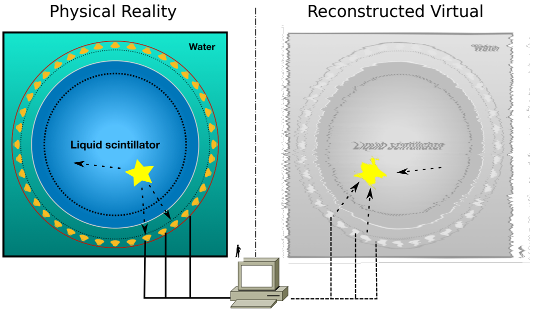

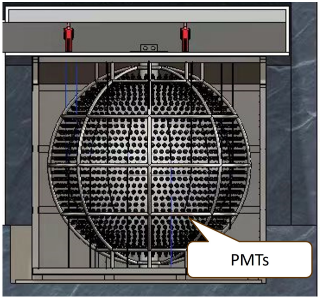

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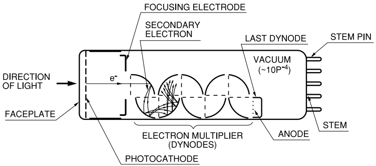
Keys: All parameters mentioned above, particularly PDE and Transit time spread (TTS).

⌀20 cm MCP-PMT



Classical PMT: multi-stage **dynode**

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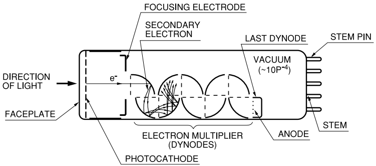

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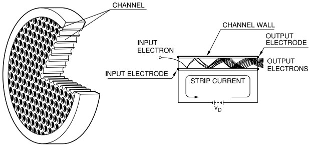

(a) Schematic structure of an MCP (b) Principle of multiplication

MCP: small, fast time response

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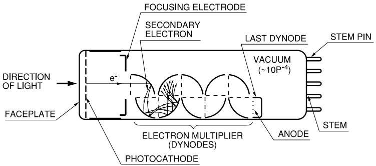

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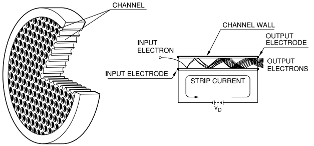

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1. Photons hit the **photocathode** and generate electrons through the photoelectric effect
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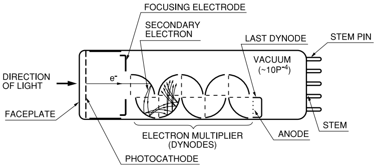

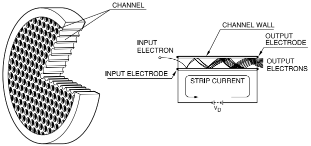

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Classical PMT: multi-stage **dynode**

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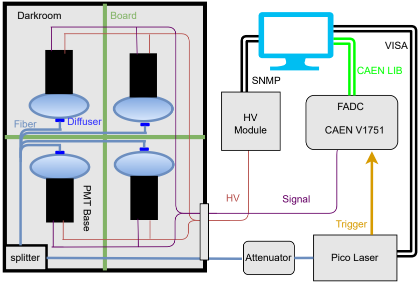
- JNE uses the ⌀20 cm MCP-PMT from NNVT
- To improve PDE, the MCP has an **ALD coating** on upper surface

Experimental Setup



1. Measurements are conducted in a dark box.
2. FADC: 10-bit, 1 GHz sampling rate.
3. PiL040XSM picosecond laser: 405 nm, splited into four channels .
4. Each pulse collects 10 us of data, with approximately 5 % containing photon information.
5. Each testing run lasts for 20 hours, with data acquisition, storage, and analysis managed by self-innovate software for fully automatical execution.

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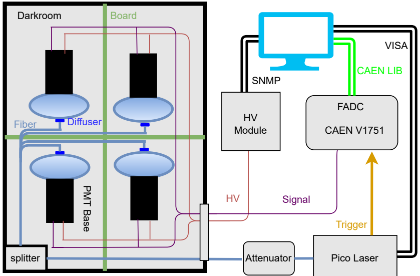

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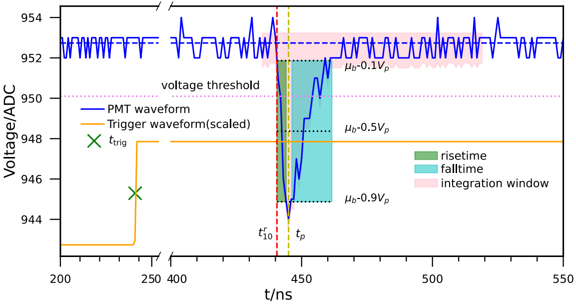
Testing Procedure

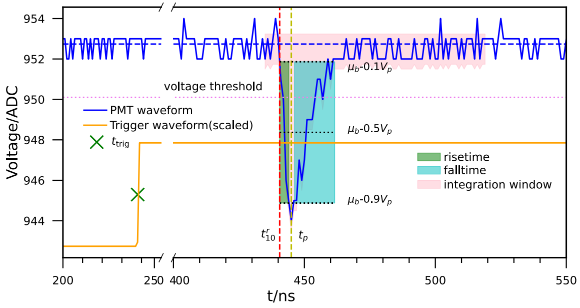
1. Nine MCP-PMTs were tested, with a dynode PMT from Hamamatsu as a reference.
2. The four PMTs were moved in a cycle within the dark box to eliminate the influence of different light intensities in different compartments.

Data Processing



- laser signals at 240 ns
- detected light signals at 440 ns
- negative pulse

Data Processing



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Photon Counting Capability

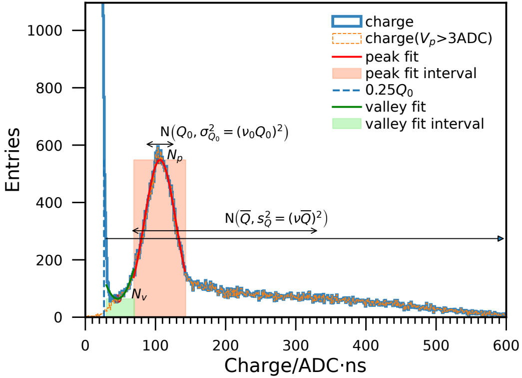
1. Charge distribution
2. Photon detection efficiency(PDE)

Time Resolution Capability

1. Transit time spread(TTS)

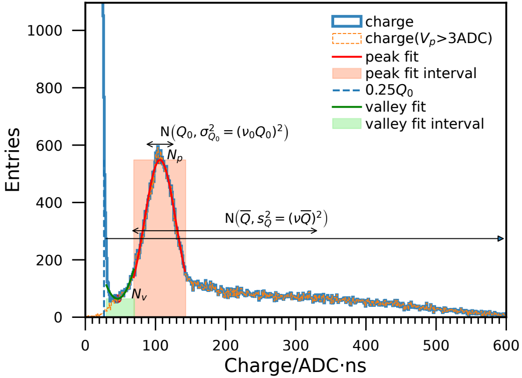
- Calculate the baseline and subtract it.
- Charge: the result of integrating the pulse, which is proportional to the pulse height.
- TT: the difference between the 10% rise time of the pulse and the laser trigger time.

Charge Distribution



- Gaussian fit to the peak (light red)
- quadratic fit to the valley (light green).

Charge Distribution

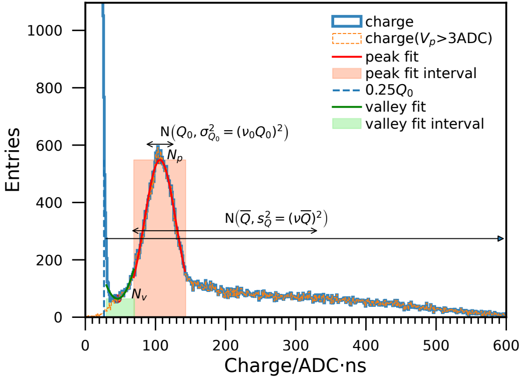


- Gaussian fit to the peak (light red)
- quadratic fit to the valley (light green).
- Peak-to-Valley ratio reaches 6, better than similar products (usually 3-4).
- a long tail on the right-hand side, approximately 40%.
- The relative standard deviation:

$$\nu = \sqrt{\mathrm{Var}[\mathrm{Charge}]}/\mathrm{E}[\mathrm{Charge}]$$

the smaller ν, the better energy resolution

Charge Distribution



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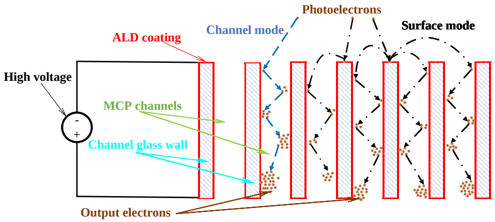
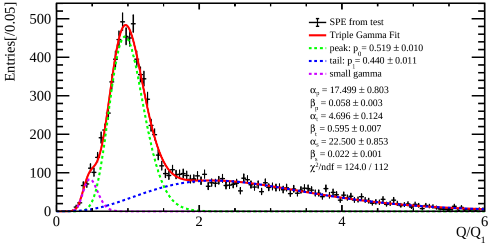
- The long tail structure: significantly different from that of Classical dynode PMTs.
- Two amplification modes:
  1. tail: large and broad
  2. main peak: small and narrow

Two Amplification Modes





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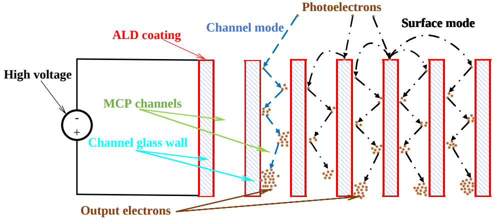

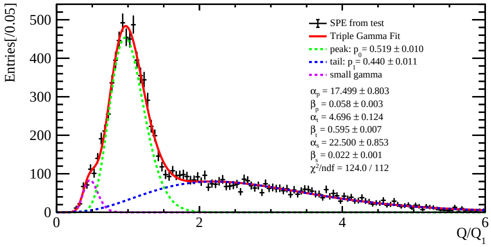

main peak (channel mode)

1. small and narrow
2. electrons enter MCP channels directly
3. **easy to count photons**

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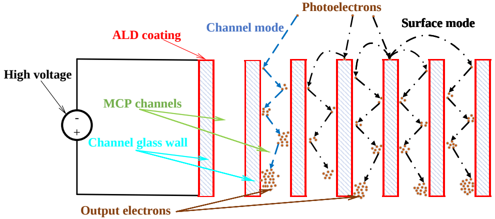

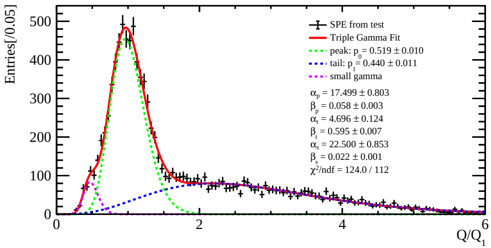

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tail (surface mode)

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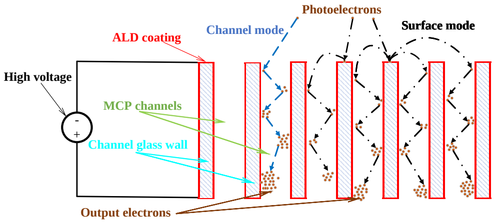

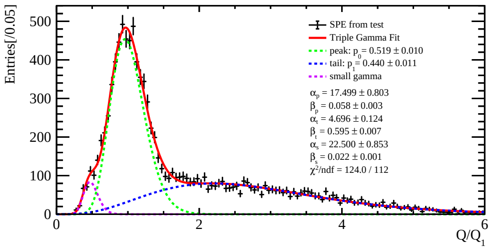

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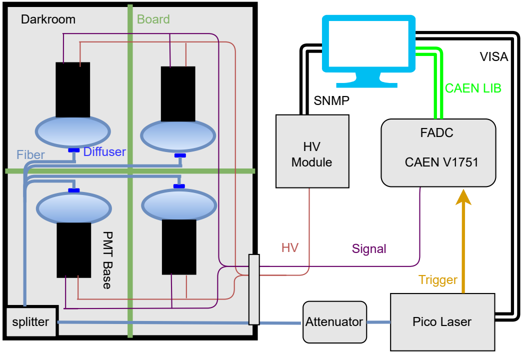
"Tail structure" reduces the energy resolution and needs to be studied!

Relative Photon Detection Efficiency (ϵ^0)



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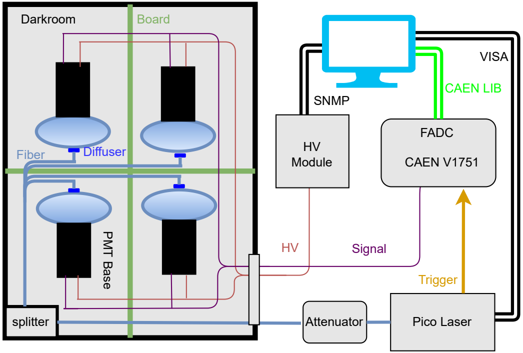

Characterizing the probability of photons converting into observable signals

- The PDE of reference PMT is : ϵ_0
- The PDE of tested PMT is : ϵ_k
- Testing each PMT on each channel
- The relative relationships: $\epsilon_k^0 = \frac{\epsilon_k}{\epsilon_0}$
- General linear model of Binomial exponential family distribution is used for ϵ^0.

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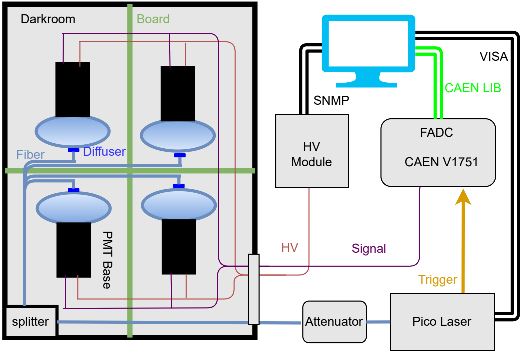

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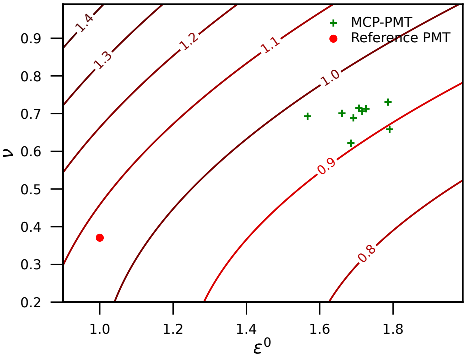
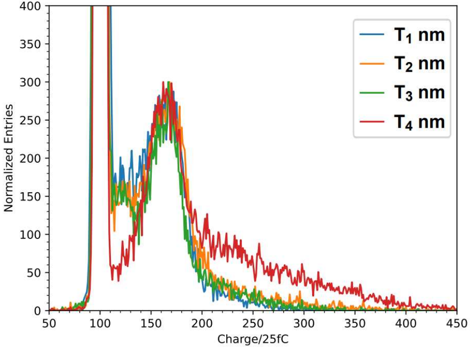
tested $\epsilon^0 = 1.7$, significantly improving photon counting and energy resolution

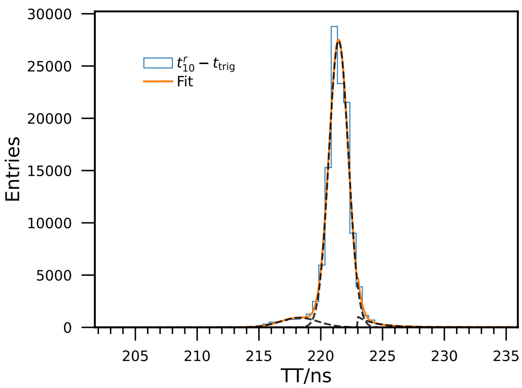
Energy Resolution

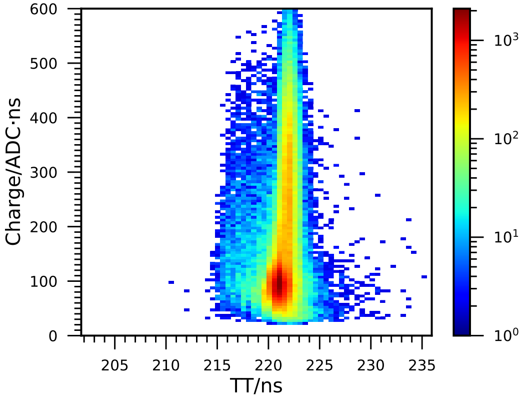




- Energy resolution is determined by $\frac{\sqrt{1+\nu^2}}{\epsilon^0}$ which is the smaller, the better.
- The thicker the ALD coating, the bigger the tail, the larger the ν, the higher ϵ^0
- There is a balance between PDE and energy resolution, and finally T_4 nm is chosen.

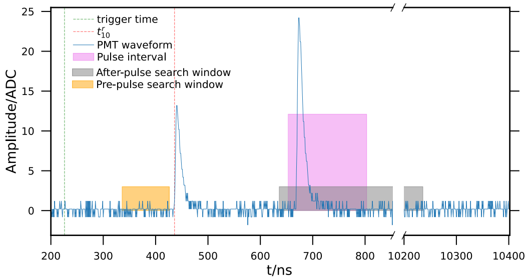
Transit Time Spread(TTS)

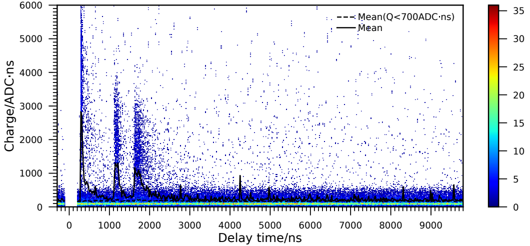




1. Gaussian fitting of the Transit Time (TT) to get TTS of 1.7 ns, a significant improvement compared to the previous generation ⌀50 cm PMT (which is 10 ns).
2. There is a certain correlation between transit time and charge size to be quantified.

Afterpulse





Ionization of gas inside the MCP-PMT generates ions that can strike the photocathode and produce additional electrons, with a delay time on the order of 100 ns.

- The timing of afterpulses is related to the properties of the ions ($^Z_M X$) with a relationship of $\sqrt{\frac{M}{Z}}$
- Afterpulses are concentrated at 300 ns, 550 ns, 1200 ns, and 1700 ns, with a ratio of approximately $1 : \sqrt{3} : \sqrt{16} : \sqrt{32}$
- Possible ion components include H^+, He^+, O^+, or $CH_4{}^+$, $O_2{}^+$.

Summary

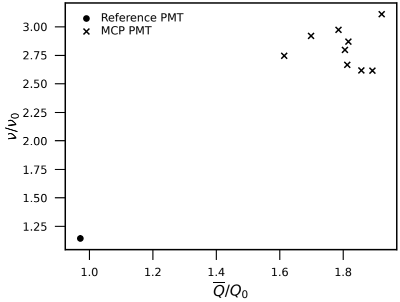
- The new ⌀20 cm MCP-PMT from NNVT used in the Jinping Neutrino Experiment demonstrates superior performance in terms of PDE and Peak-to-Valley ratio, with other terms comparable to similar international products.
- The long tail in the charge distribution is countered by the high PDE, resulting in an overall boost in energy resolution
- The ongoing research on new waveform analysis methods holds promise for mitigating the impact of the tail component in the charge spectrum.

Paper Information

Performance evaluation of the 8-inch MCP-PMT for Jinping Neutrino Experiment.
https://doi.org/10.1016/j.nima.2023.168506

1. Dark count rate
2. Afterpulse

Gain and single PE resolution



- The gain of the main peak G_1: $\frac{C_1}{e \times 50\Omega}$
- The gain of the total charge G: $G\frac{\mu_C}{e \times 50\Omega}$
- The main peak resolution Res_1: $\frac{\sigma_{C_1}}{C_1}$
- The total charge resolutionRes: $G\frac{\mu_C}{e \times 50\Omega}$
- G is about 2 times G_1 for the MCP-PMTs
- Mean of Res_1, Res: about 0.25, 0.69

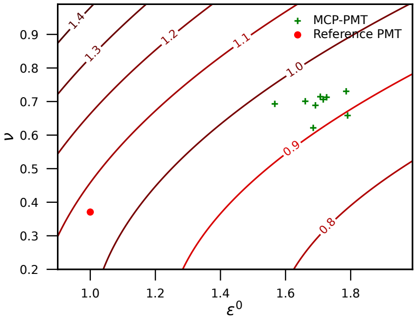
Peak-to-valley ratio and some time characteristics

1. The mean P/V ratio of MCP-PMTs is about 5.8 while the reference PMT is about 2.4.
2. Estimated mean and deviation of rise time, fall time, and FWHM are 3.71 ± 0.15 ns, 15.6 ± 1.8 ns, and 9.07 ± 0.63 ns for 9 MCP-PMTs.

5 Energy resolution boost

- Relative PDE
- TTS

Energy resolution boost



- the number of expected photons N on a PMT: $\pi(\mu_N)$
- Energy E of an event is proportional to $N = k\eta E$
- The output charge distribution C is a hierarchical model

$$E[C] = \mu_N \mu_C \quad (1)$$

$$Var[C] = \mu_C^2 \mu_N + \mu_N \sigma_C^2 \quad (2)$$

N is estimated as $\hat{N} = \frac{C}{\mu_C}$ and E is estimated as $\hat{E} = \frac{\hat{N}}{k}$. The reconstructed energy resolution

$$\frac{\sqrt{Var[\hat{E}]}}{E[\hat{E}]} = \frac{\sqrt{\mu_c^2 \mu_N + \mu_N \sigma_c^2}}{\mu_N \mu_c} = \frac{\sqrt{1 + (\frac{\sigma_c}{\mu_c})^2}}{\sqrt{\mu_N}} = \frac{\sqrt{1 + (\frac{\sigma_c}{\mu_c})^2}}{\sqrt{k\eta E}}$$

Dark count rate

$$\mathrm{DCR}/\mathrm{kHz} = \frac{N_{\mathrm{noise}}}{N_{\mathrm{trig}}} \frac{1}{T_{\mathrm{DCR}}/\mathrm{ns}} \times 10^6 \tag{3}$$

- $[-200, -150]$ ns relative to main pulse
- T_{DCR} is 50 ns

Relative PDE

1. total light intensity I_n for nth run, jth splitter ratio α_j, kth PMT PDE η_k
2. Expected photon number $p_{njk} = I_n \alpha_j \eta_k$
3. Observed trigger rate $R_{njk} = 1 - e^{-p_{njk}}$

0th PMT is the only one reference PMT. $\alpha_j^0 = \frac{\alpha_j}{\alpha_0}$, $\eta_k^0 = \frac{\eta_k}{\eta_0}$, $I_n^0 = I_n \alpha_0 \eta_0$, $i \equiv njk$

$$\log(p_i) = \log(I_0 \alpha_0 \eta_0) + \log(I_n^0) + \log(\alpha_j^0) + \log(\eta_k^0) \tag{4}$$

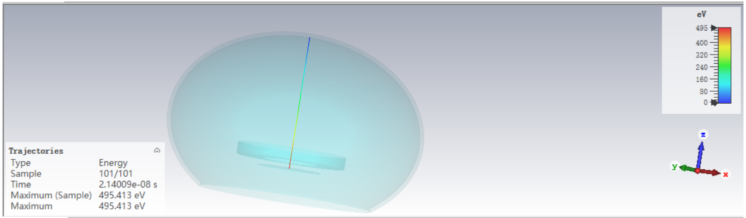
$$R_i = 1 - e^{-e^{\log(I_0\alpha_0\eta_0)+\log(I_n^0)+\log(\alpha_j^0)+\log(\eta_k^0)}} \tag{5}$$

The trigger number N_{trig_i} of kth PMT in nth run with jth splitter obey Binomial distribution $B(R_i, N_{t_i})$, in which N_{t_i} is total number of waveforms.

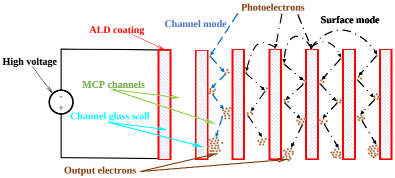
$$\mathcal{L} = \prod_i R_i^{N_{\mathrm{trig}_i}} (1 - R_i)^{N_{t_i} - N_{\mathrm{trig}_i}} \tag{6}$$

General linear model of Binomial exponential family distribution with Cloglog link function

TT

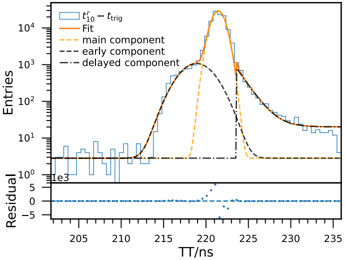


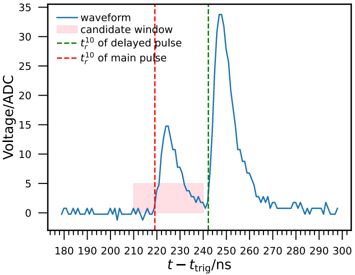
- Cathode, focus dynode, MCP
- CST studio: electric field and trajectory simulation

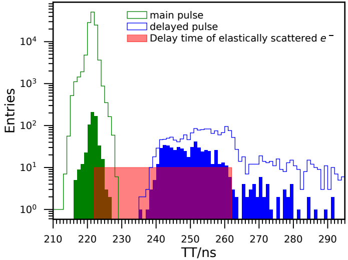


- The drift times of the electrons at the top of PMT with 0 eV and 3 eV are respectively about 21 ns and 18 ns
- The electrons hitting on the surface of MCP generate the secondary electrons (including a single elastic scattering electron)

TTS

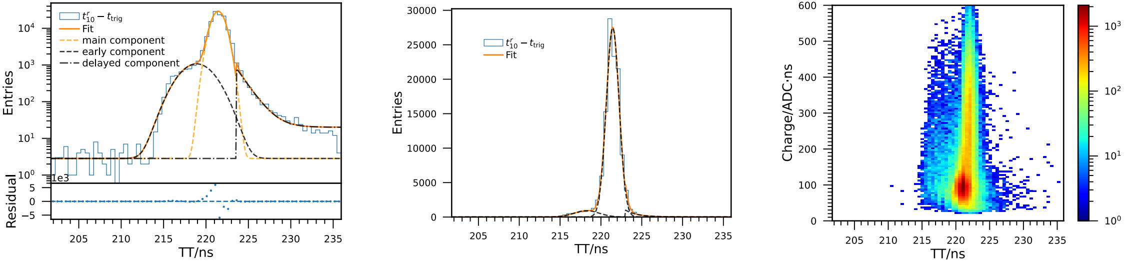






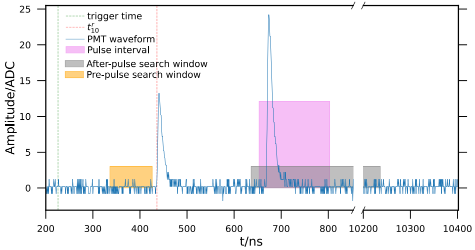
- Multiple secondary electrons with different kinetic energy may cause two or more pulses
- Elastic scattering electrons: The sharp difference between them at about 40 ns after the main peak, twice times drift time of electrons from the cathode to the MCP
- $B + N_t G(\mu_{\mathrm{TT}}, \sigma^2_{\mathrm{TT}}) + N_K G(\mu_K, \sigma_K^2) + H(\mu_{\mathrm{TT}} + 2\sigma_{\mathrm{TT}}) \left(b_S + N_S e^{-\frac{t-(\mu_{\mathrm{TT}}+2\sigma_{\mathrm{TT}})}{\tau_S}} \right)$

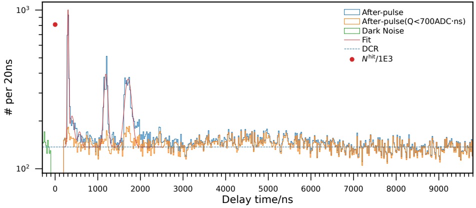
TTS



- TTS is defined as FWHM: $2\sqrt{2\ln(2)}\sigma_{\text{TT}}$
- The long tail in charge distribution

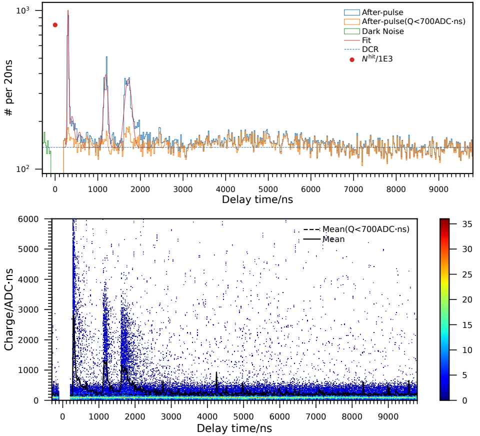
After pulse categories





- Pre-pulses: photons hitting on the MCP or the first dynode directly rather than the photocathode; 10 ns scale
- After-pulses: the ionization of gaseous impurities between the cathode and first dynode or MCP when photoelectrons go through;100 ns scale
- After-pulses: the relation between time and ions $(^{Z}_{M}X)$ is $\sqrt{\frac{M}{Z}}$
- Search window: <-10 ns; >200 ns
- The peak position t_p and equivalent charge C_{equ} of the after-pulse and pre-pulse are calculated

Parameterization



- The relative t: the difference between t_p of pre/after-pulse and t_r^{10} of main pulse
- around 300 ns, 550 ns, 1200 ns and 1700 ns, $1 : \sqrt{3} : \sqrt{16} : \sqrt{32}$
- Assumption: H^+, He^+ or other unknown ions, O^+ or $CH_4{}^+$, and $O_2{}^+$ or other unknown ions
- Substracting dark noise rate $N_{\mathrm{DCR}} = N_{\mathrm{trig}} \cdot \mathrm{DCR} \cdot T_{\mathrm{bin}}$, in which N_{trig} is the number of triggered waveforms
- $\sum_{i=1}^{4} A_i G(t_i, \sigma_i^2)$
- $[-150, -10]$ ns $[200, 9800]$ ns