Study on the limited time performance of FPMT and SiPM under femtosecond laser

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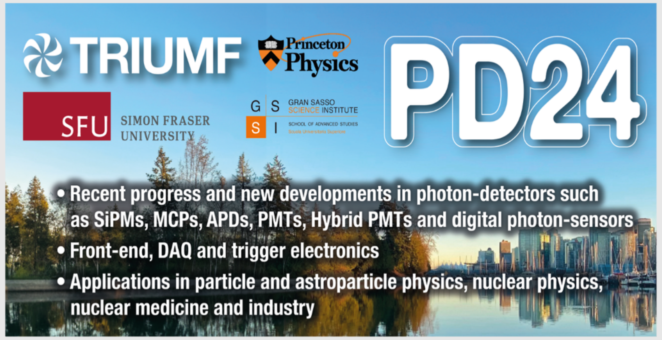
On behalf of the PMT Lab in IHEP



Outline

- 1. Introduction of the PMT Lab in IHEP
- 2. The R&D of 2 inch FPMT
- 3. Limited Time Resolution (LTR) of FPMT
- 4. Limited Time Resolution (LTR) of SiPM

1. Introduction of PMT Lab

PMT Lab

- ① PMT Simulation/Design
- ② Performance Evaluation
- ③ Special Measurement

- The only laboratory in China with national-level PMT testing qualification.

- Anode Pulse Signal NIMA 1041 (2022) 167333
- After Pulse JINST 13 (2018) P05014; NIMA 1003 (2021) 165351
- Dark Count JINST 16 (2021) T06015;

- SPE Spectrum JINST 13 (2018) T01005
- Gain Characteristic IEEE NSS/MIC(2019) 9059610;
- Temperature Dependence IEEE NSS/MIC(2018) 8824420; JINST 15 (2020) T08004

- Quantum Efficiency JINST 15 (2020) T06005; NIMA 971 (2020) 164021;
- Detection Efficiency JINST 16 (2021) T05007; 核技术 2018 41(1) 010401;
- Dark Current JINST 10 (2015) T08001

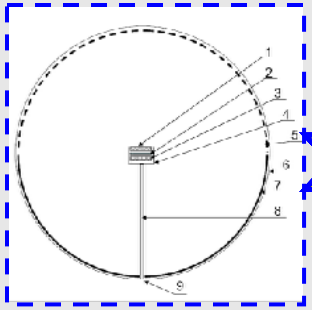
- TTS JINST 17 (2022) T04002; NIMA 977 (2020) 164333;
- LTR NIMA 1055 (2023) 168518;
- CTR NIMA 1049 (2023) 168089; NIMA 1062 (2024) 169173;

- CE Uniformity NIMA 827 (2016) 124-130; NIMA 848 (2017) 1-8;
- Photocathode Uniform NIMA 1027 (2022) 166257;
- Angular Response NIMA 952 (2020) 162002;

- Cathode Linearity JINST 10 (2015) P03023;
- Magnetic Characteristics SENSOR ACTUAT A 318 (2021) 112487;
- Aging Effect JINST 15 (2020) T06008; Nucl.Sci.Tech. 27 (2016) 38

1.1 The R&D of LPMT

Design 2009



2” MCP-PMT (2010)

5” MCP-PMT (2011)

8” MCP-PMT (2012-2013)

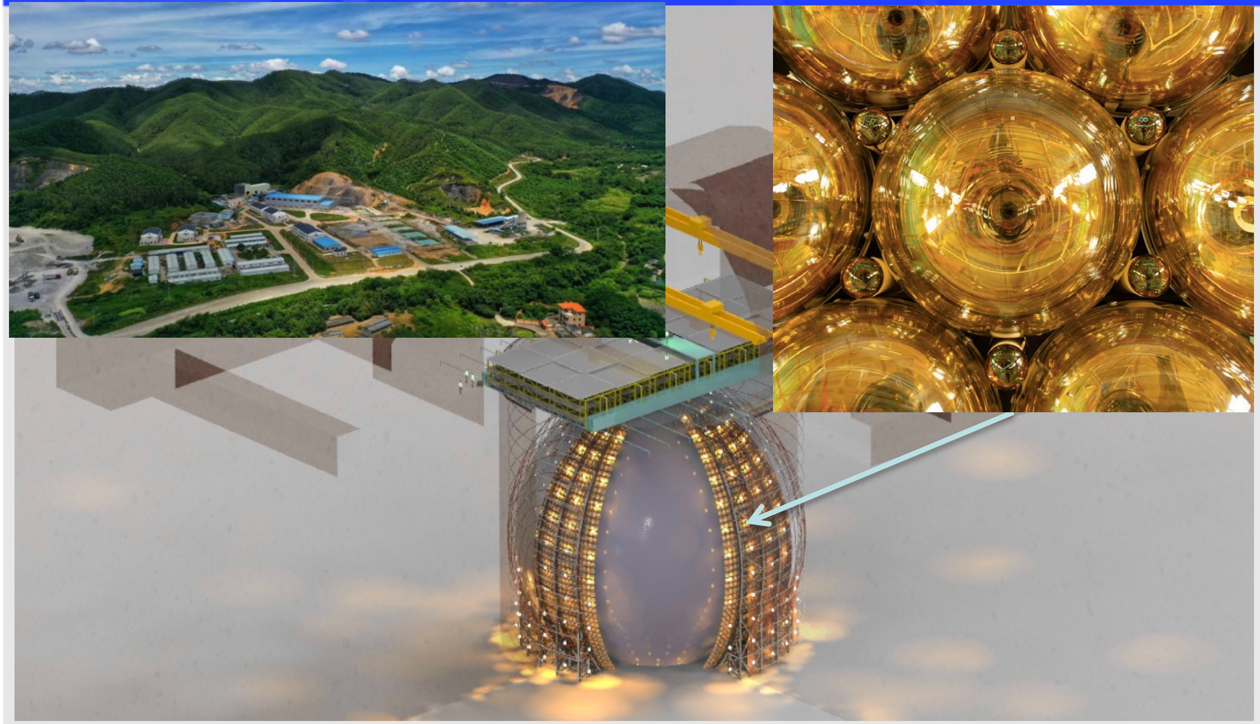
20” MCP-PMT (2015)

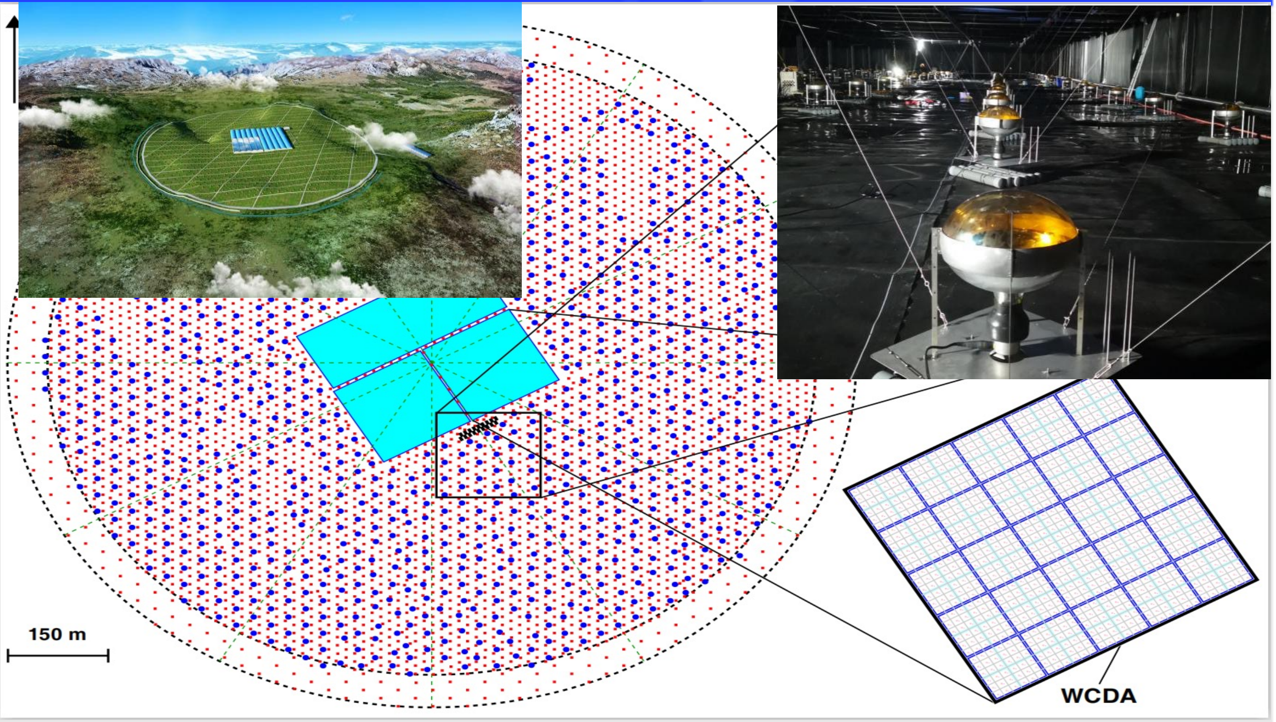
20” MCP-PMT (2017-2020)

- From 2010-2020，the 2”, 5”,8” and 20” MCP-PMT prototypes were successfully produced, and the performance were also improved for the production of High CE MCP modules and high QE photocathode.

Characteristics （20inch）	unit	MCP-PMT Prototype（IHEP）	MCP-PMTs 15K pieces（NNVT）
Electron Multiplier	--	MCP	MCP
Photocathode Mode	--	reflection+ transmission	reflection+ transmission
Quantum Efficiency（400nm）	%	26 (T), 30 (T+R)	32%
Collection Efficiency		~99%	99%
Detection Efficiency（400nm）	**%**	**~ 27%**	**31.5%**
Detection Efficiency（420nm）	**%**	**--**	**28.3%**
P/V of SPE		＞ 5	7.1
TTS on the top point	ns	~15	~ 20
Rise time/ Fall time	ns	R~2 , F~20	R~1.4 , F~24
Anode Dark Rate	Hz	~30K	40K
After Pulse Time distribution	us	0.1, 4.5	0.2 , 0.8 , 3 , 4.5, 17
After Pulse Rate	%	2.5%	5.2%
Glass	--	Low-Potassium Glass	Low-Potassium Glass

1.2 The application of LPMT





Jiangmen Underground Neutrino Observatory (JUNO)

- JUNO has already supported the MCP-PMT collaboration group in the R&D of the 20-inch MCP-PMT from 2009 to 2020.
- Yifang Wang at IHEP is our group leader for this type of MCP-PMT development, and the company NNVT is responsible for the mass production work.

Parameters	JUNO	LHAASO
Total number	15000	2270
DE@400nm	30%	26.8%
Dark Rate	~ 40KHz	~ 20KHz
TTS	~20ns	~5.5ns

Large High Altitude Air Shower Observatory（LHAASO）

- LHAASO has already ordered 2270 pieces of 20" Flower-like MCP-PMTs, which have different performance compared to those used in JUNO.
- The 20 inch Prototype with potting has also post to the HyperK PMT Group in Tokyo University for the testing.

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- 1. Introduction of the PMT Lab in IHEP
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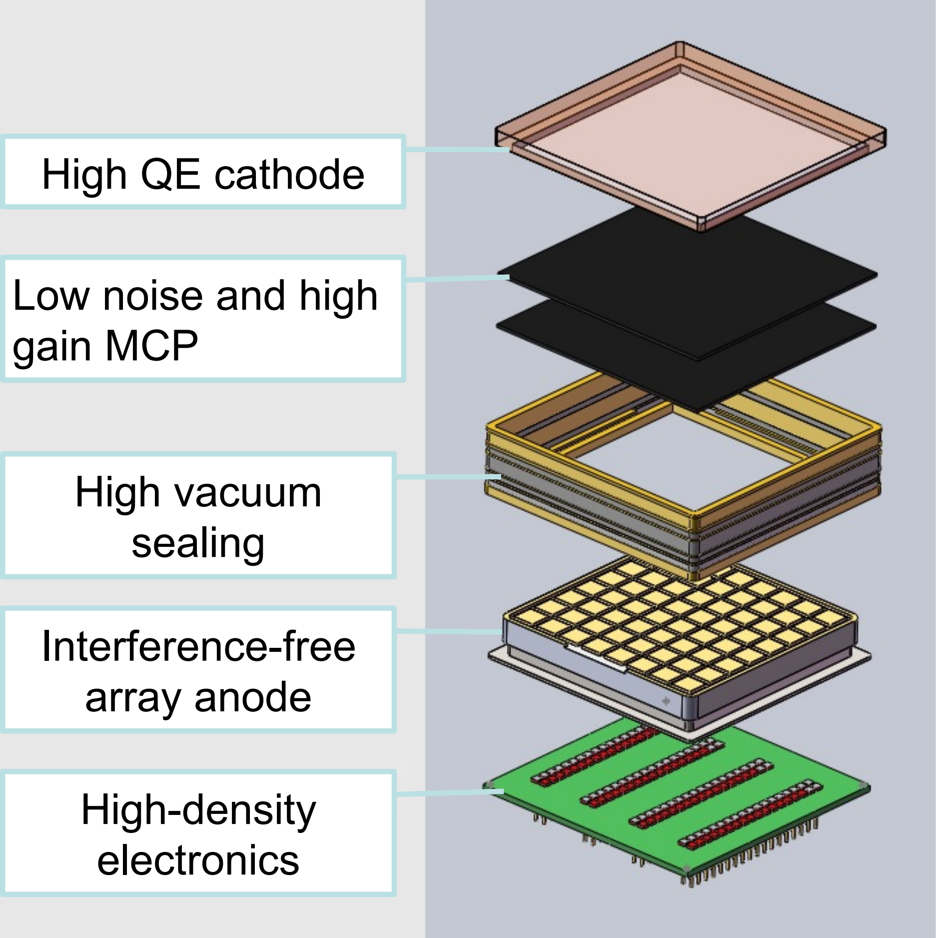
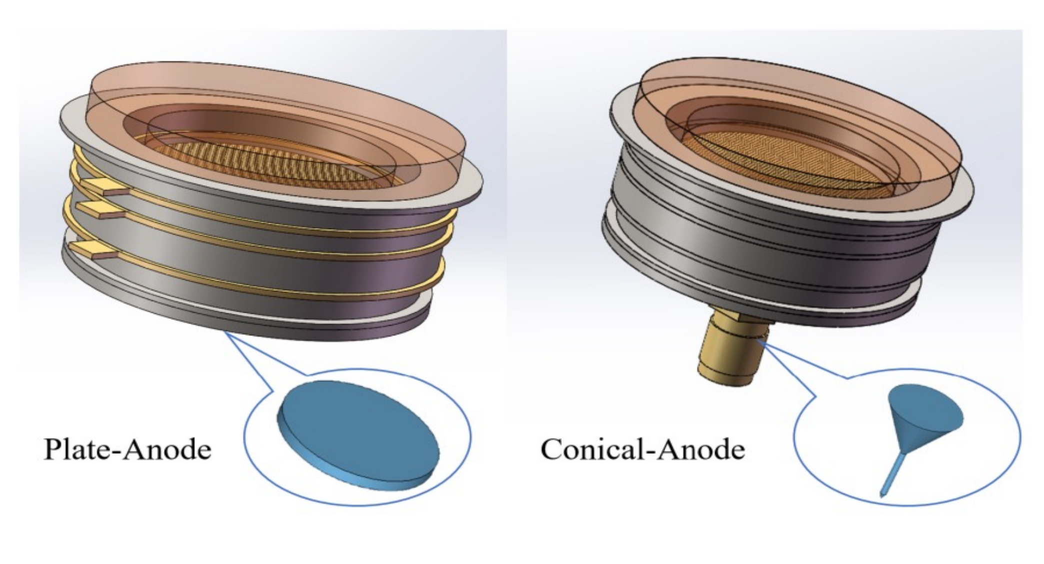
2.1 The R&D of FPMT



Starting from 2020, Our team has overcome the key technologies of FPMT and gradually completed the development of FPMT from single anode to 8*8 anodes.

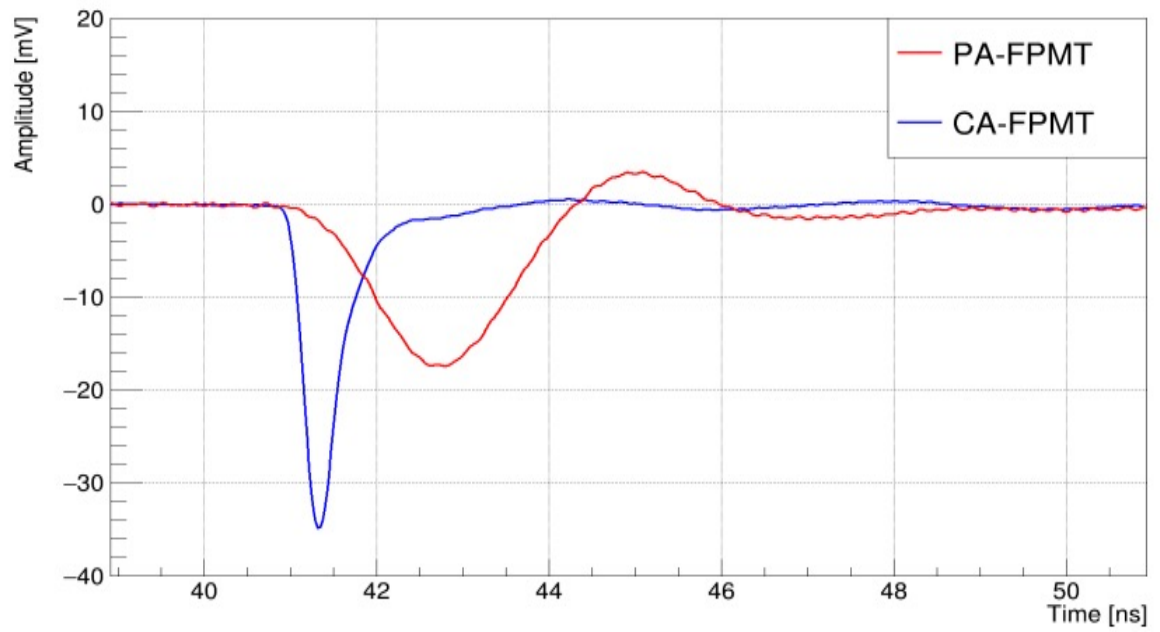
2.2 The performance of 1 inch FPMT

- Anode optimization of Single anode FPMT



2022 NIMA 1041 167333

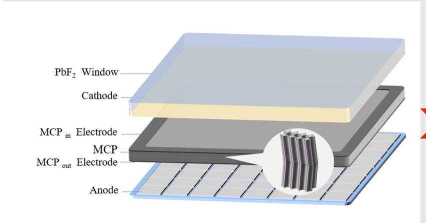
- The waveforms of two kinds of FPMT



	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	96 ps	350 ps	190ps	45 ps	10 ps
Plate-Anode	-2000	1.9E6	28.8	7 mV	1.4 ns	1.4 ns	1.8 ns	70 ps	25 ps
Conical-Anode	-3181	2.6E6	6.3	53 mV	150 ps	420 ps	330 ps	27 ps	5 ps

2.3 The R&D of 2 inch FPMT

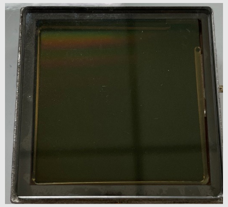
FPMT Structure



1

V1.0 Flat glass window FPMT

TTS (Sigma): **49.9** ps



- 2022 J. Phys.: Conf. Ser. 2374 012131
- PoS(ICHEP2020) 867

2

- JINST 17 (2022) T04002

V2.0 Step glass window FPMT

TTS (Sigma):**38.5** ps

3

V3.0 Flat lead glass window FPMT

TTS (Sigma):**56.0** ps

4

- JINST 18 (2023) C12020

V4.0 Flat lead glass window FPMT

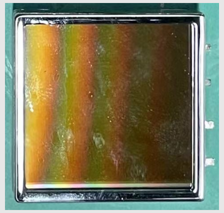
TTS (Sigma):**55.6** ps

5

V5.0 Flat lead glass window FPMT

TTS (Sigma):**36.7** ps

CTR(FWHM):**156** ps



- PoS(ICRC2023) 444 047
- NIMA 1049 (2023) 168089

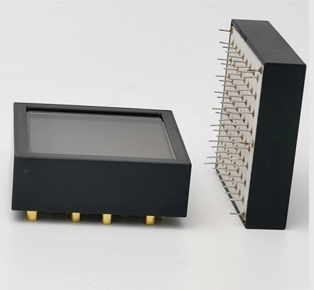
6

- NIMA 1062 (2024) 169173

V6.0 Step lead glass window FPMT

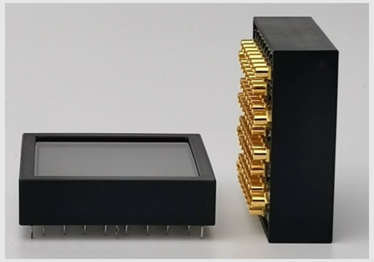
TTS (Sigma):**26** ps

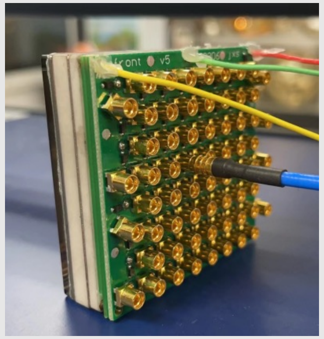
CTR(FWHM):**100** ps



2.4 The performance of 2 inch FPMT

- 8*8 Anodes FPMT

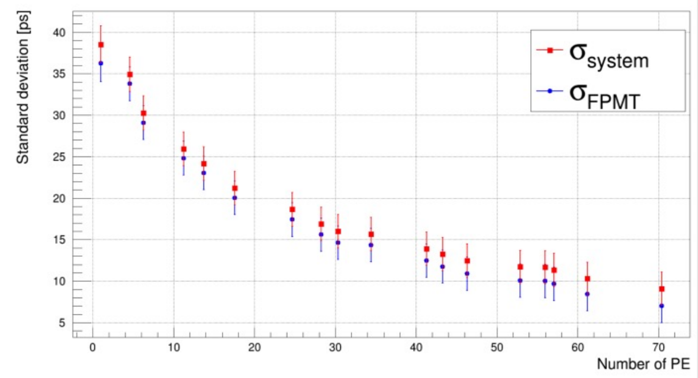




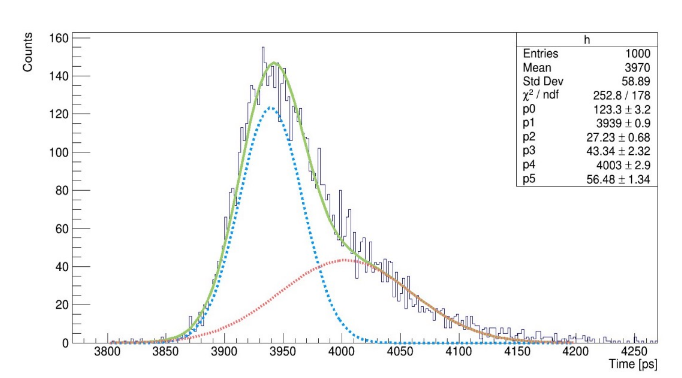
2022 JINST 17 T04002

2023 NIMA 168089

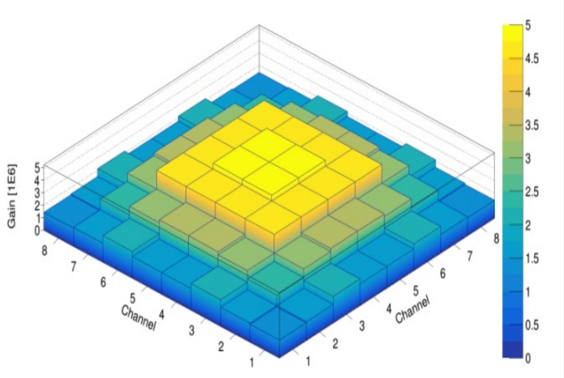
2023 JINST 18 C12020



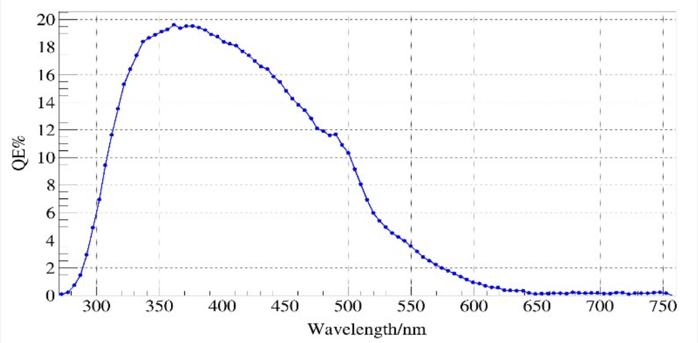
- TTS Variation with light intensity



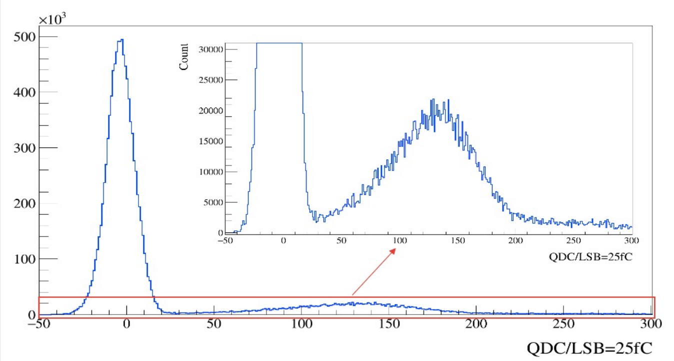
- TTS Spectrum



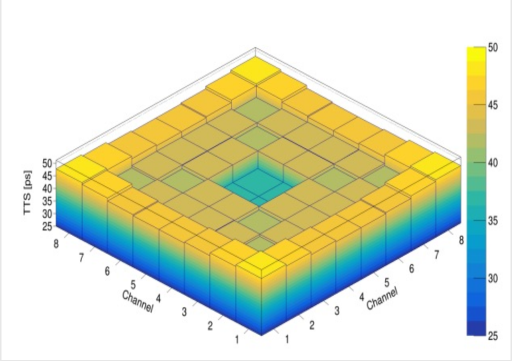
- Uniformity of Gain



- QE @400nm ~20%



- P/V @SPE>4



- Uniformity of TTS

	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek-253	-2600	1.2E7	11.2	113 mV	490 ps	1.1 ns	~1 ns	45 ps	16 ps
8*8 Anodes	-1500	3.9E6	18.6	45 mV	334 ps	660 ps	~900 ps	40 ps	10 ps
CRW-FPMT	-1500	9.6E6	10.9	145 mV	279 ps	355 ps	394 ps	26 ps	10 ps

2.5 The datasheet of FPMT

PMT Type	QE@400nm	gain	P/V	RT	Width	TTS @SPE	TTS @MPE
Photek 210	15.7%	2.6×10^{6}	2.0	96 ps	190ps	45 ps	10 ps
1anode FPMT	22.7%	2.6×10^{6}	6.3	150ps	330 ps	**27 ps**	5 ps
2*2 Anode FPMT	22.5%	1.9×10^{6}	6.5	243ps	378 ps	67 ps	17 ps
4*4 Anode FPMT	21.2%	1.0×10^{7}	1.8	431ps	Not test	107 ps	28 ps
8*8 Anode FPMT	21.6%	4.0×10^{6}	18.6	334ps	900 ps	40 ps	10 ps
8*8 CRW-FPMT	21.6%	9.6×10^{6}	10.9	279ps	394 ps	**26 ps**	10 ps

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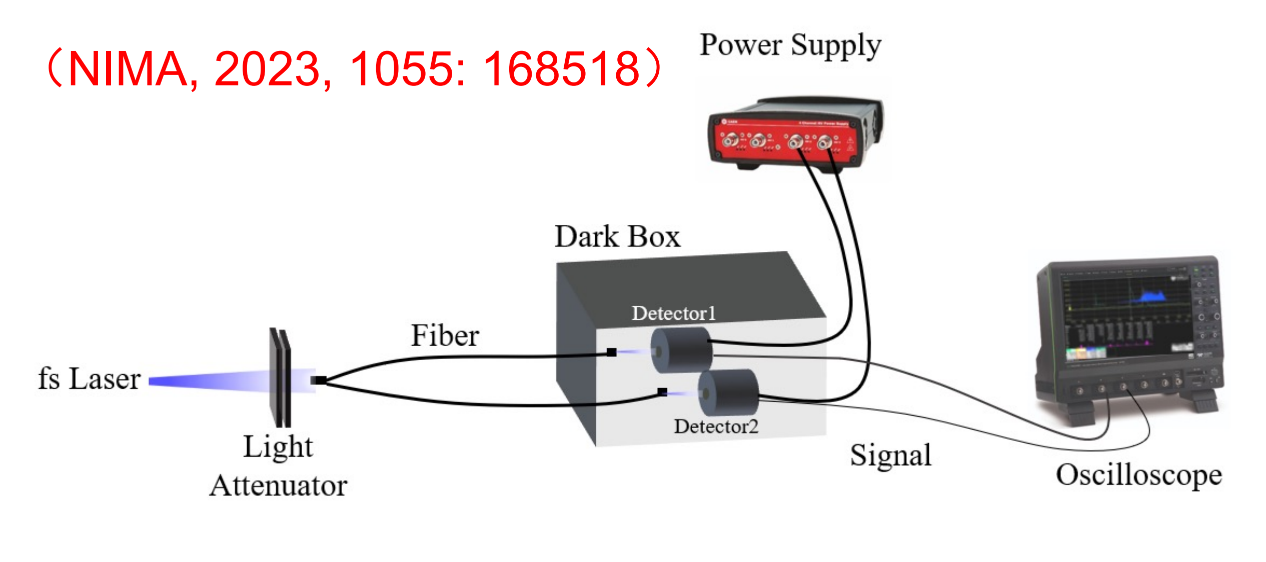
3.1 The LTR of FPMT and SiPM under fs Laser



Experimental Setup

Type of the Fs Laser: Spfire ACE-1001HP

Pulse Width： <120fs

Frequency： 1kHz

Wavelength： 400nm

Detector1： Photek 210

Detector2： Photek210、Single anode-FPMT
8*8 anodes FPMT and SiPMs(SenSL)

DAQ： Oscilloscope Sample rate 40 Gs/s
Band width 4GHz system TR：500 fs

	HV/V	gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek210-1	-4700V	2.9E6	2.0	93.2mV	95.8 ps	348 ps	192.7 ps	43.5 ps	10.3ps
Photek210-2	-4800V	1.9E6	4.5	96.7mV	100 ps	275 ps	150 ps	46 ps	21.4ps
IHEP-FPMT-single	-3181V	2.6E6	6.3	53 mV	150 ps	420 ps	330 ps	27 ps	5 ps
IHEP-FPMT-64 anode	-1500V	9.6E6	10.9	144.9 mV	279 ps	355 ps	394 ps	26 ps	10 ps

All the detectors work in a multi photons mode, and the gain were turned down.

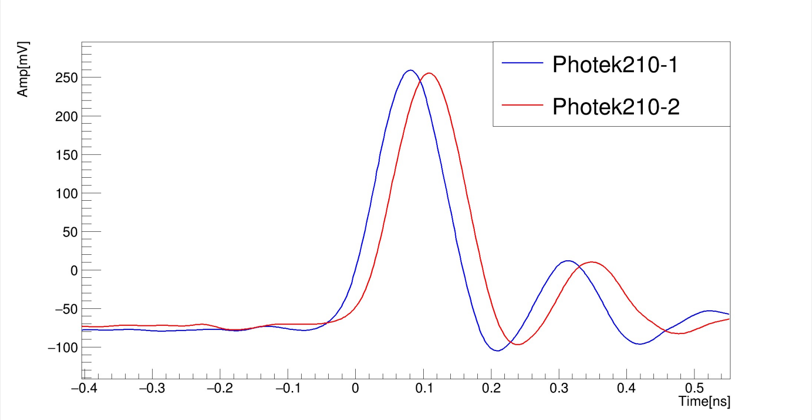
3.2.1 The LTR of Photek-210

LTR（ limited time resolution）： The time resolution of single detectors under multiple photons radiation.

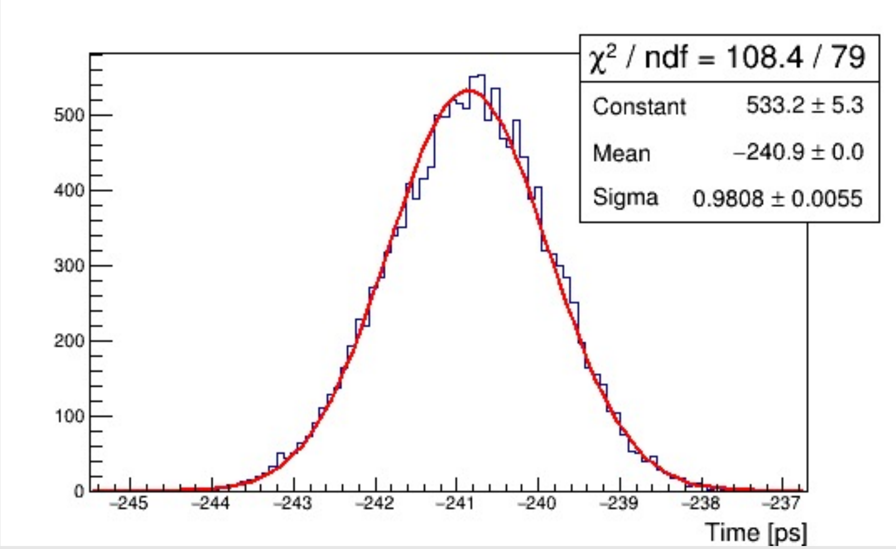
CTR（Coincidence time resolution）： the tested coincidence time resolution between two detector.

$$CTR_{tested}^2 = TR_{sytem}^2 + LTR_{D1}^2 + LTR_{D2}^2$$

- We have conducted the CTR calculation using lead edge discrimination, with a 50% pickup threshold applied.
- Both Photek-210 detectors were treated as the same type and have the same LTR performance.
- The number of photons hitting the PMT should be around 2000.
- One Photek-210 was used as the trigger of the other detectors.



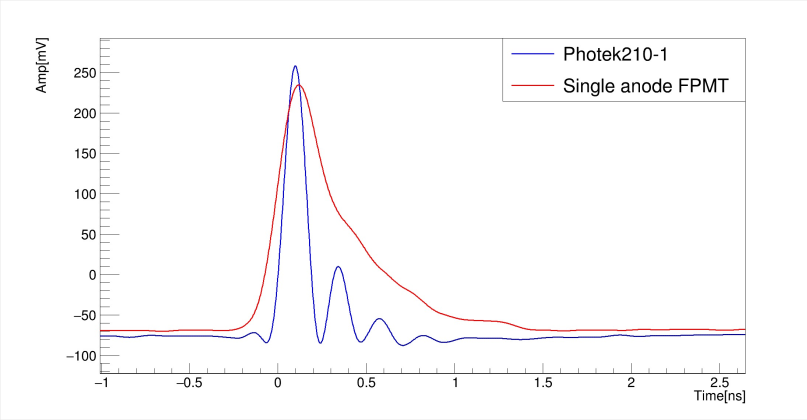
Typical waveform of Photek 210 retest



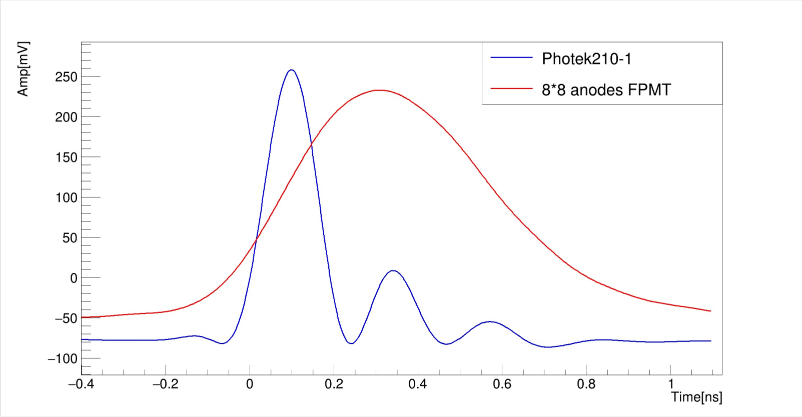
Photek 210

CTR_{tested}: 0.98 ps **LTR: 0.60 ps**

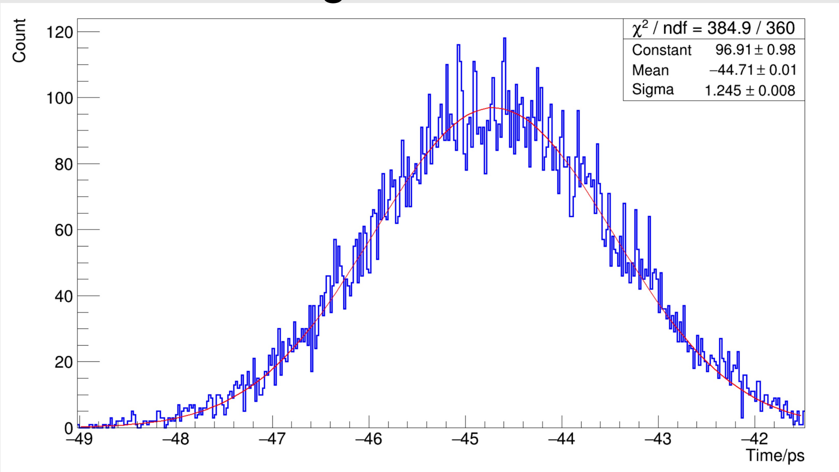
3.2.2 The LTR of FPMT in IHEP



Typical waveforms of Photek 210 and single-anode FPMT

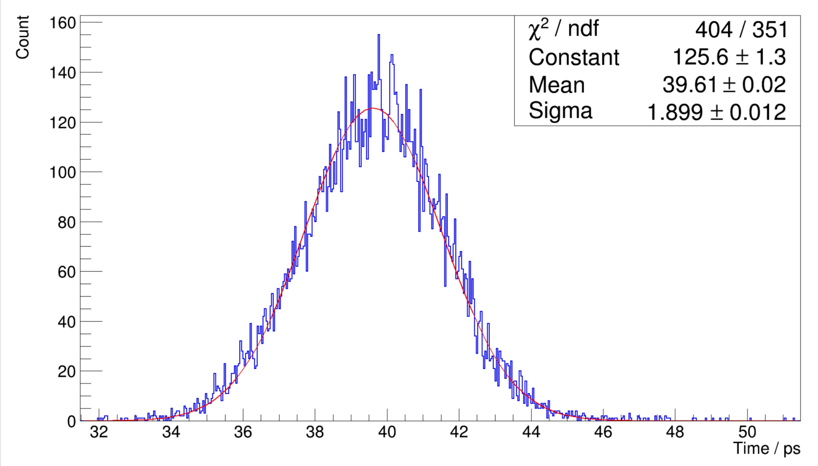


Typical waveforms of Photek 210 and 8*8 anode FPMT



Single-anode FPMT

CTR_{tested}： 1.25 ps **LTR： 0.97 ps**



8*8 anodes FPMT

CTR_{tested}： 1.90 ps **LTR： 1.73 ps**

- The anode structure of the single anode structure FPMT is a conical anode, which has been optimized for waveform time characteristics faster than the 8*8 anode FPMT.
- Factors such as the detection efficiency of the FPMT may also influence the differences in its LTR.
- Further experiments and analysis are needed.

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4.1 The Performance of SiPM

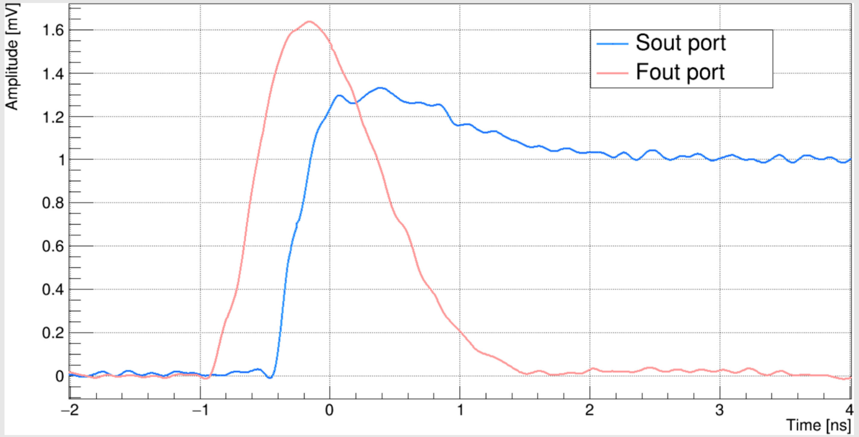
- One Photek-210 was used as the trigger for the SiPM, employing the same method as described in section 3.1 for the LTR test of the SiPM.
- SenSL-J-30035 and NDL-EQR-20 were tested. Its performance at picosecond laser were listed in the table.

SenSL-J-30035

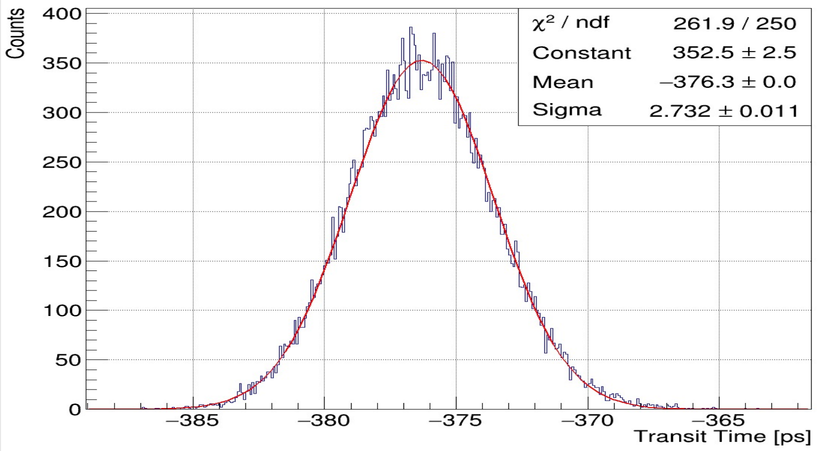
NDL-EQR-20-11-3030

	HV/V	gain	RT	FT	Width	TTS@MPE
SenSL-Fast out	28.5V	1.6E6	558.0 ps	1.1 ns	2.2 ns	7.3 ps
SenSL-Slow out	28.5V	1.6E6	660.3 ps	145.0 ns	147.0 ns	7.3 ps
NDL-1	29 V	8.0E5	1.5 ns	47.4 ns	15.8 ns	10.8 ps
NDL-2	29 V	8.0E5	1.7 ns	44.1 ns	16.1 ns	11.7 ps

4.2 The LTR of SenSL SiPM

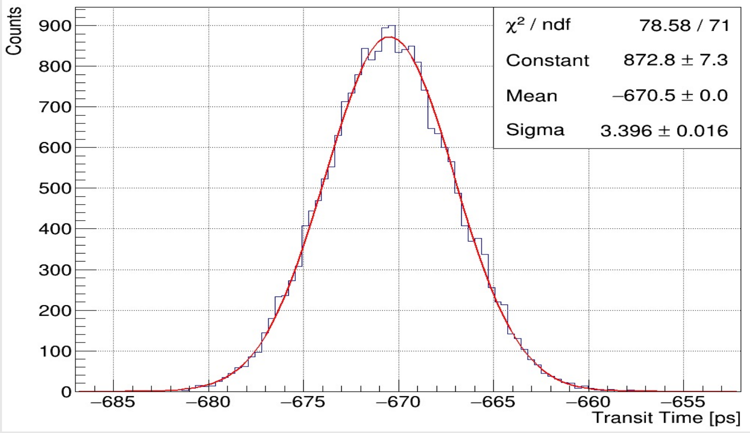


Waveform of SenSL-J-30035 under Femtosecond laser



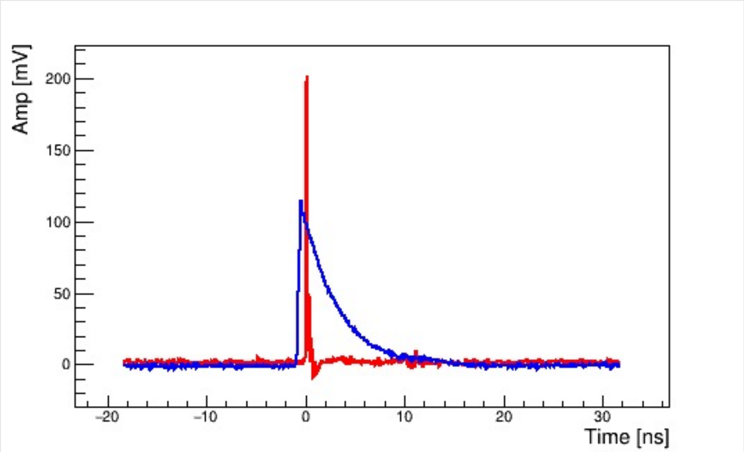
SenSL-J-30035 Fast out

CTR_{tested}: 2.73 ps **LTR: 2.61 ps**

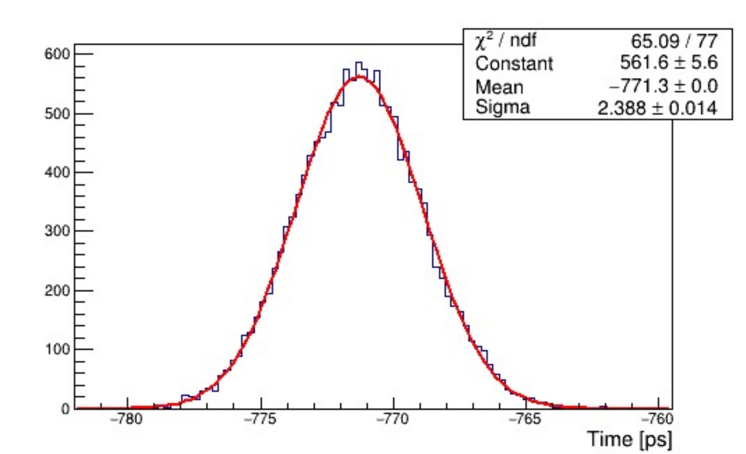


SenSL-J-30035 Slow out

CTR_{tested}: 3.40 ps **LTR: 3.30 ps**

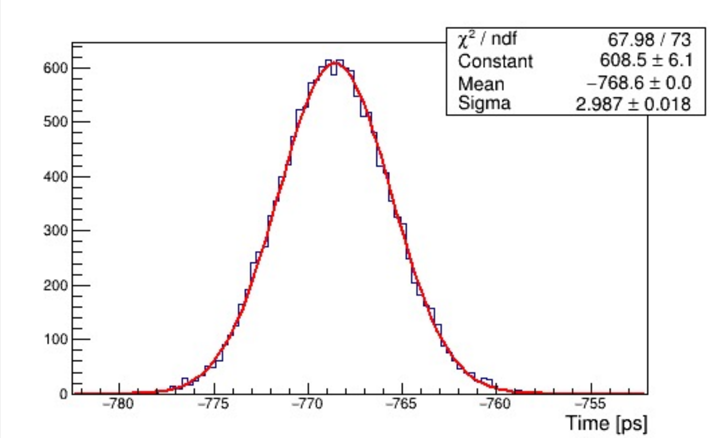


Waveform of NDL-1 under Femtosecond laser



NDL-EQR-1

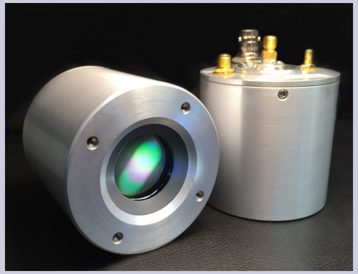
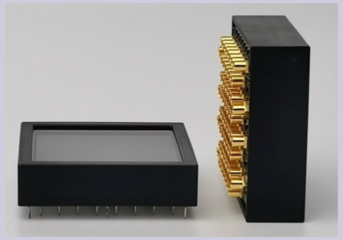
CTR_{tested}: 2.39 ps **LTR: 2.25 ps**



NDL-EQR-2

CTR_{tested}: 2.99 ps **LTR: 2.88 ps**

4.3 LTR Summary of FPMT/SiPM

	Photek-210	Single-anode FPMT	8*8 anodes FPMT	SenSL SiPM	NDL-SiPM
					
Rise Time	95.8ps	150 ps	279 ps	558 ps	1.5 ns
Fall Time	348 ps	330 ps	355 ps	1.1 ns	47.4 ns
TTS@SPE	43.5 ps	27 ps	26 ps	-	-
LTR	**0.60 ps**	**0.97 ps**	**1.73 ps**	**2.61 ps**	**2.25 ps**

Summary

- From the test results, it can be seen that MCP-based PMTs show certain advantages in both single-photon time resolution and ultimate time resolution, which can be attributed to the low noise and fast response time characteristics of MCP itself.
- The differences in the ultimate time performance between FPMT and SiPM are related to the detector's noise level, waveform information, detection efficiency, and other factors. More experiments need to be conducted for further analysis.

Thank you for your attention !