The R&D of the MCP based PMTs for High Energy Physics Detectors

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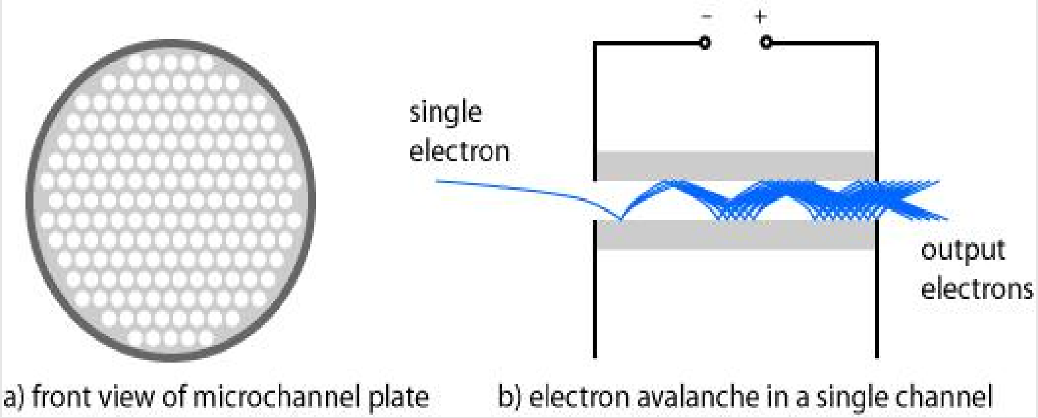
Outline

- 1. The Conventional PMTs
- 2. The 20 inch Large MCP-PMT （LPMT)
  - 2.1 The Design of LPMT;
  - 2.2 The Roadmap for the R&D of LPMT;
  - 2.3 The HPD LPMT for JUNO;
  - 2.4 The Fast LPMT for LHAASO;
- 3. The 2 inch Fast timing MCP-PMT (FPMT)
  - 3.1 The Roadmap for FPMT;
  - 3.2 The Performance of FPMT;
  - 3.3 The CTR of FPMTs;
  - 3.4 The Beam Test Results;
- 4. Summary

1.1 The Conventional -- Small-MCP-PMT

➢ The Microchannel Plate MCP



performance of the MCP:

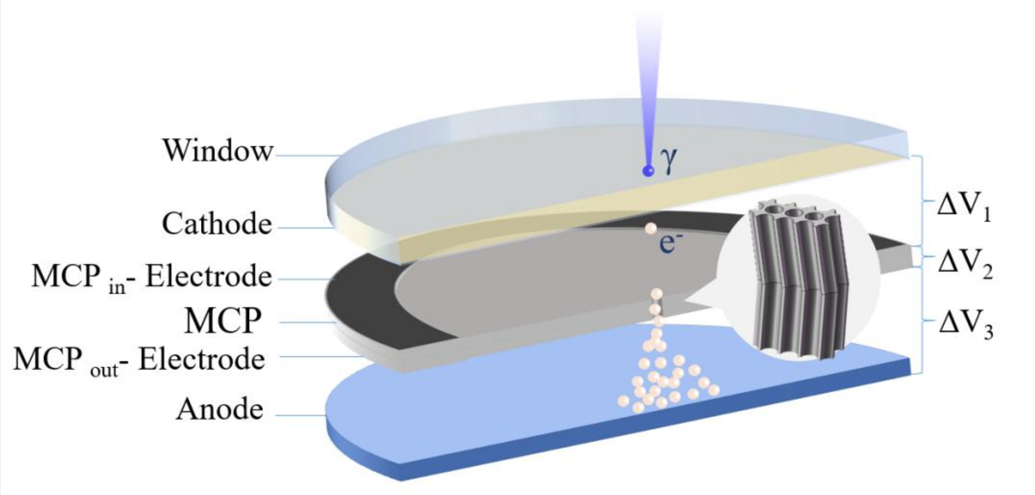
➢ High Gain： 1×10^4 / 1 pic

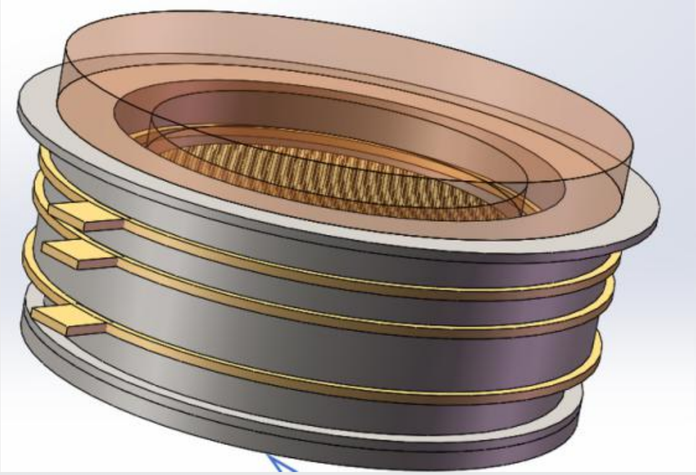
➢ Small Size: Diameter=50mm

➢ Fast Signal：Rise time < 1ns

➢ TTS@SPE：~30ps

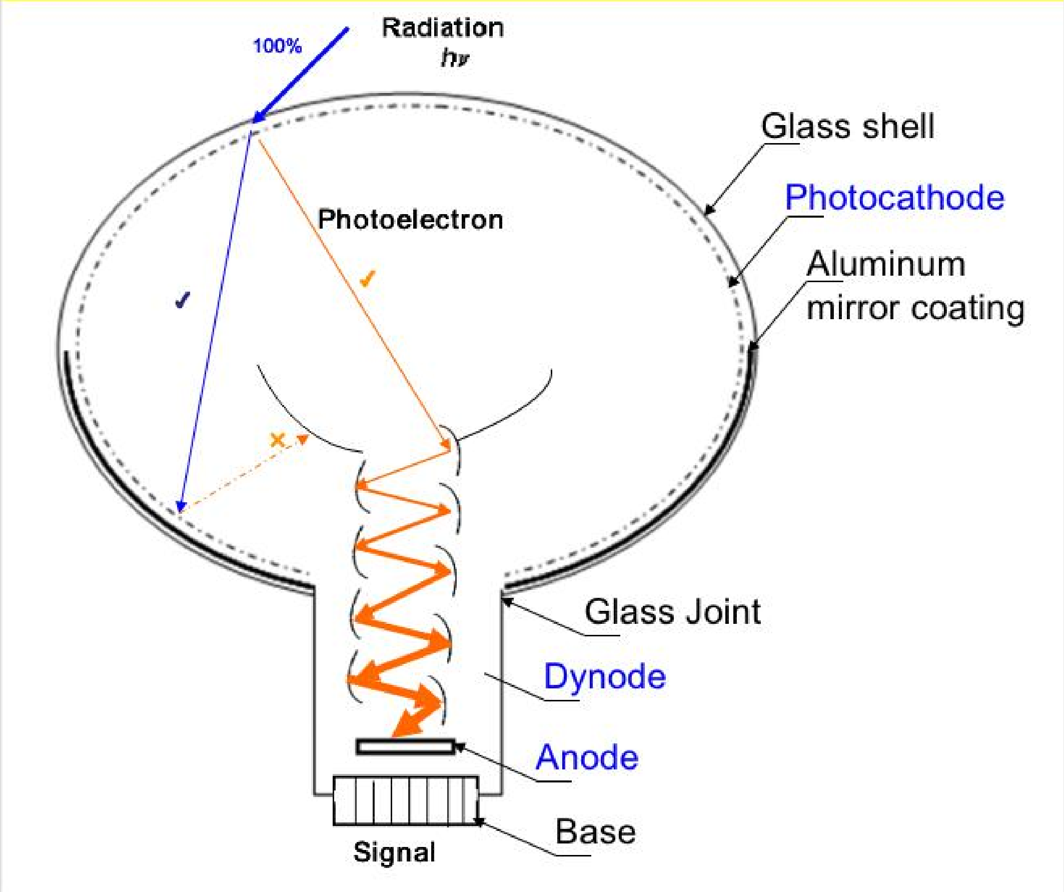
➢ The Conventional small，fast timing MCP-PMT， FPMT





1.2 The Conventional -- Dyonde-PMT

➢ The 20 inch Dynode PMT



The first PMT in the world in 1933
"Kubetsky's tube"

How to improve the PDE of PMT?

Quantum Efficiency (QE) :

20%

Collection Efficiency (CE) of Anode:

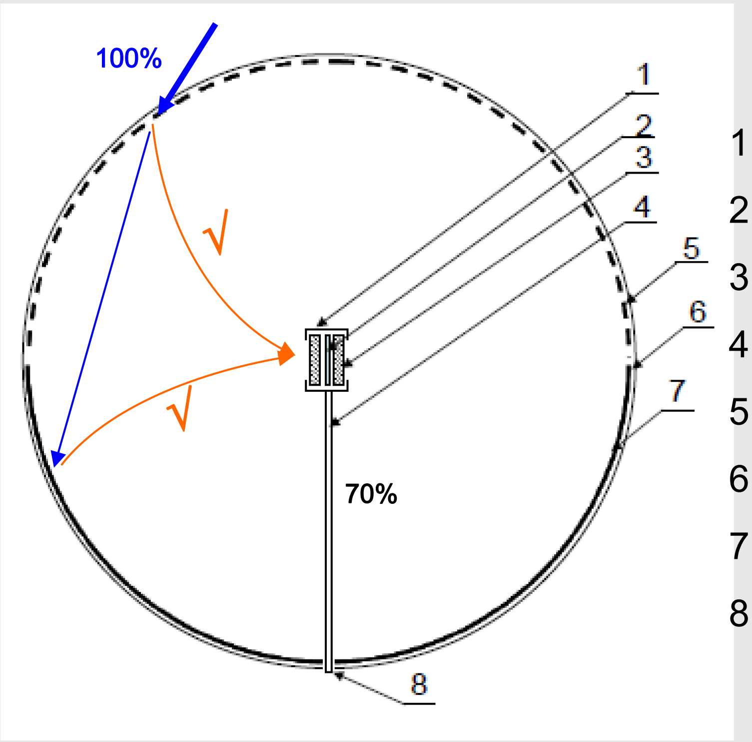
70%

Photon Detection Efficiency (PDE)= QE_{Trans} * CE = 20% * 70% = 14%

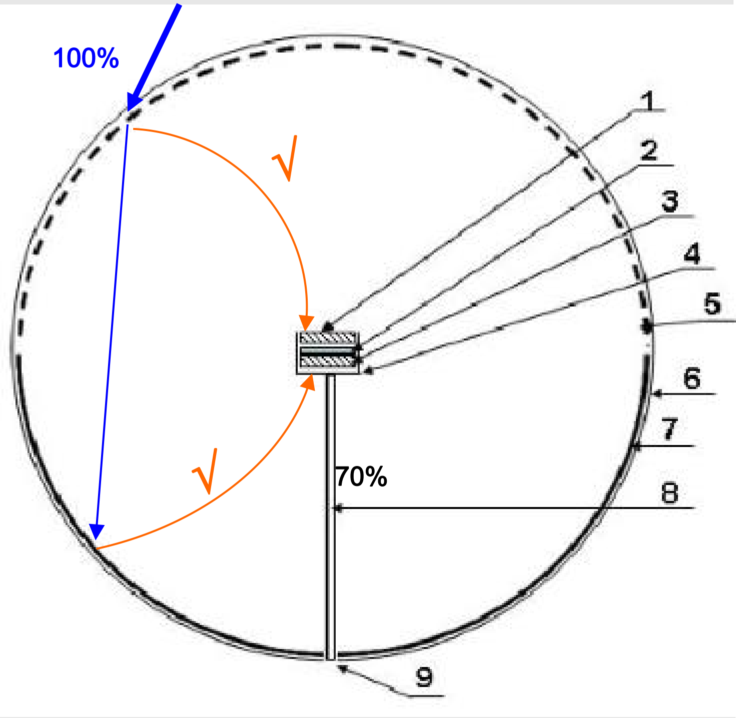
2.1 the design of a Large MCP-PMT (2009)

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } ~ 4π viewing angle!



1.Insulated trestle table
2.Anode
3.MCP dodule
4.Bracket of the cables
5.Transmission Photoca
6.Glass shell
7.Reflection Photocatho
8.Glass joint



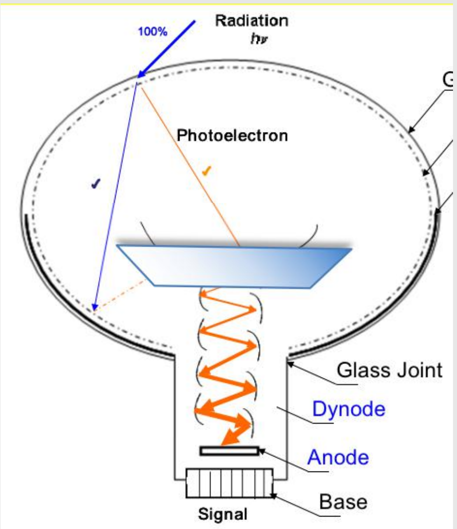
$$PD = QE_{Trans} * CE + TR_{Photo} QE_{Ref} * CE$$

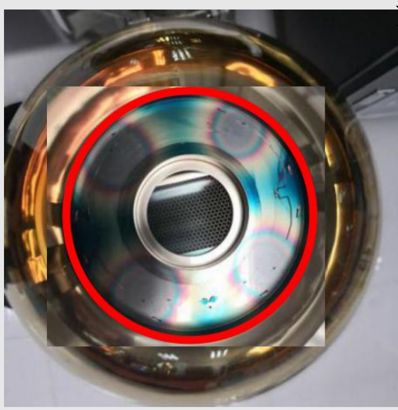
Photon Detection Efficiency: 15% → 30% ; ×~2 at least !

2012 NIMA 695

2.2 The Roadmap -- （1） Technology

➢ Dynode-PMT





① MCPs for the SPE test

2016 NIMA 824

Quantum Eff.=20%

②QE=30%

2020 NIMA 971

- new tech. for the Photochade

Collection Eff.=70%

③CE=100%

2017 NIMA 868

- ALD coatting for the MCP

Detection Eff.=14%

④DE=30%

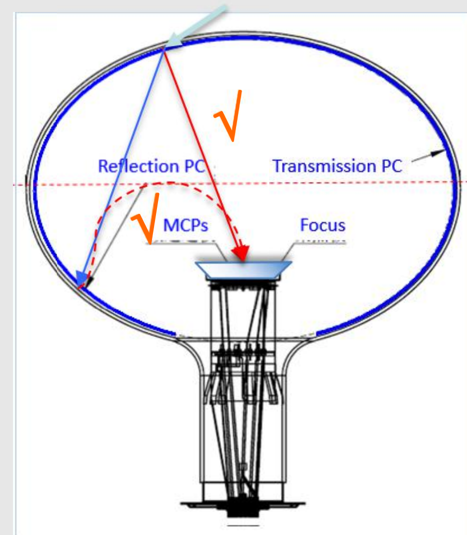
2021 JINST 16 T05007

⑤ Low-Potassium Glass

2018 NIMA 898

⑥ Low cost （3000$, 20KRMB）

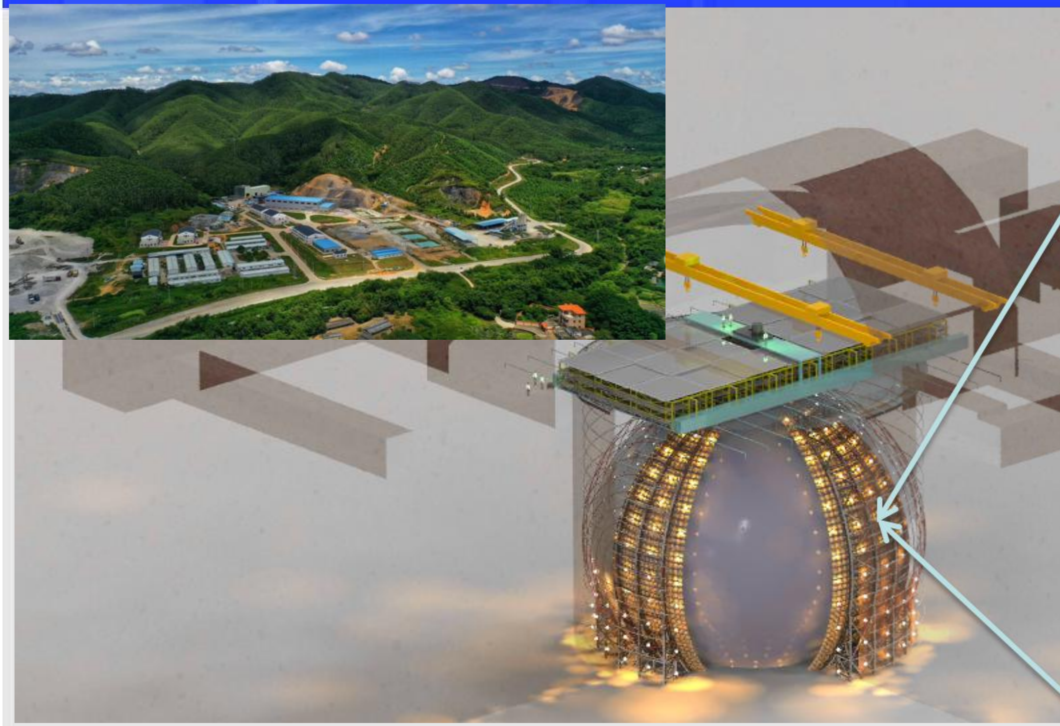
➢ MCP-PMT

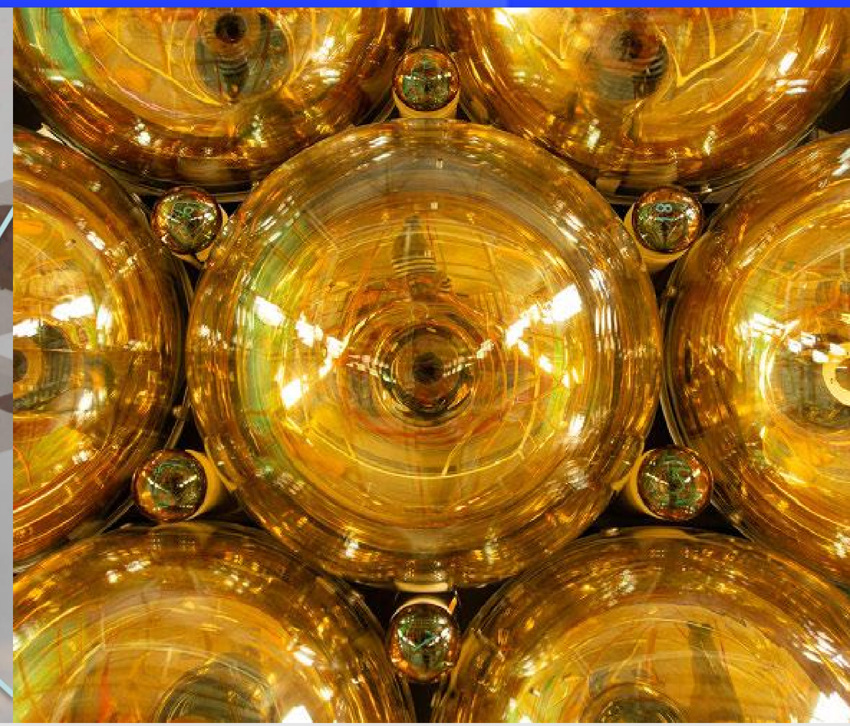


2.2 The Roadmap -- （2） Parameters

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

2.3 The High PDE 20” MCP-PMT for JUNO





—JUNO（**Jiangmen Underground Neutrino Observatory**), has already supported the MCP-PMT collaboration group to R&D the 20 inch MCP-PMT from 2009 to 2020.

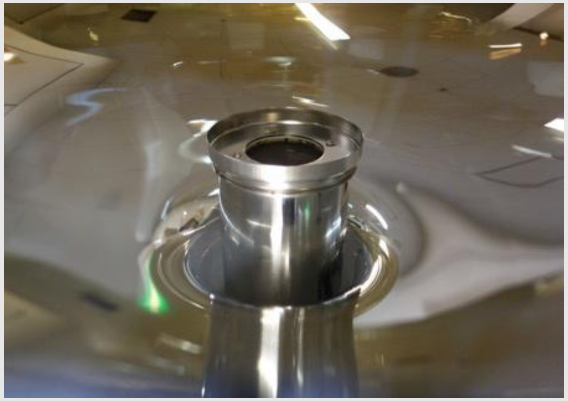
—Yifng Wang in IHEP is our group leader for this type of MCP-PMT development and the the company NNVT is the one to do the mass production work.

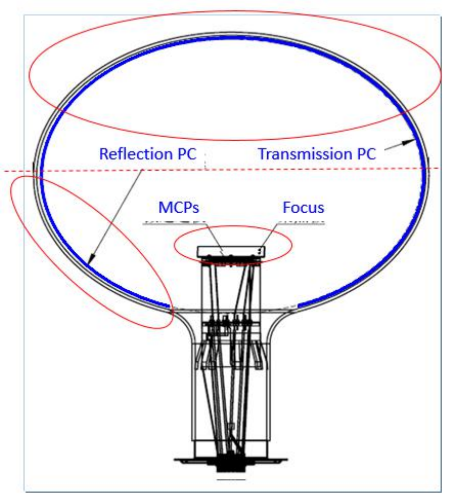
Parameters	MCP-PMT	Dynode-PMT
Total number	15000	5000
DE@420nm	28.3%	27.6%
Dark Rate	~ 40KHz	~ 17KHz
P/V	~7	~3

2020 NIMA 952; 2021 JINST 16 C11003

2.4 The FAST 20” MCP-PMT for LHAASO

- Normal focusing electrode





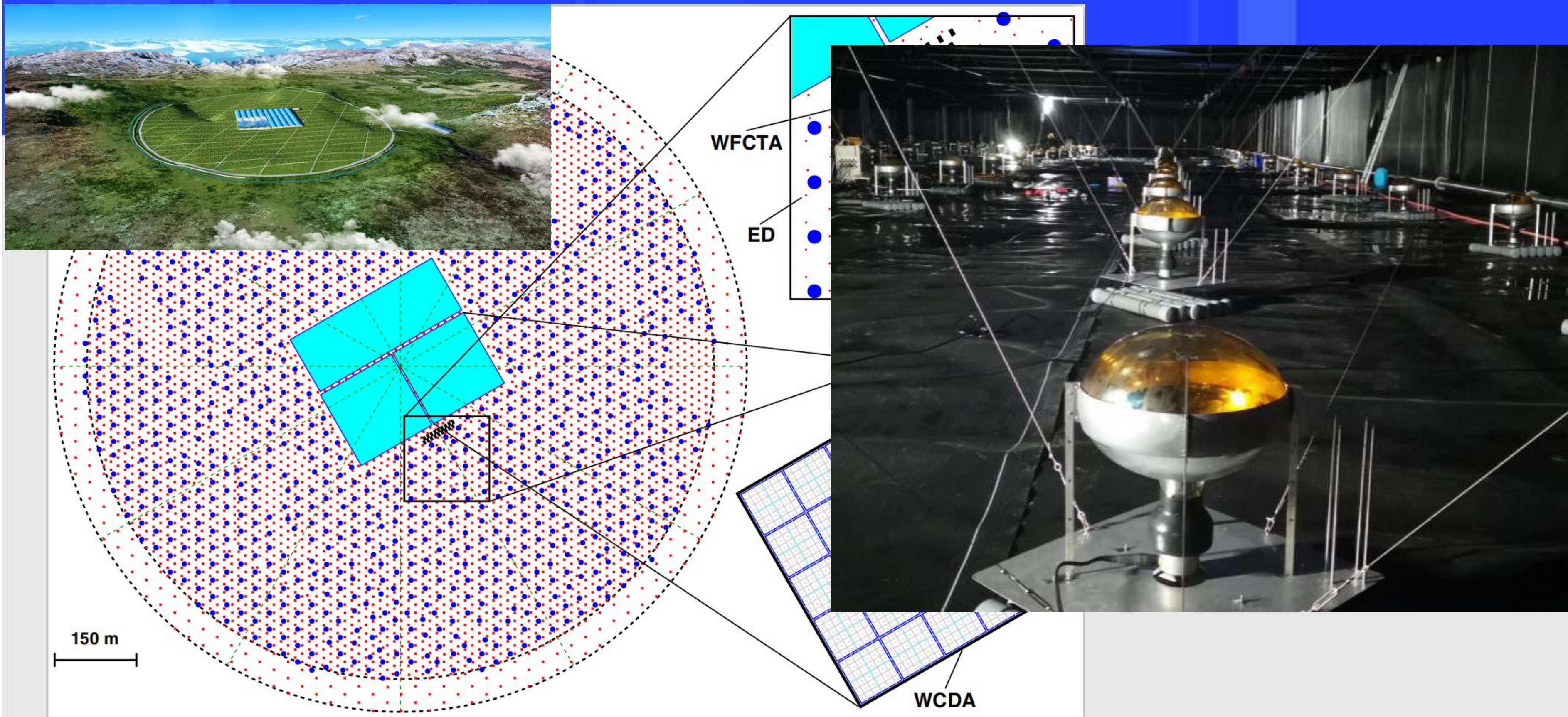
- Flower-like focusing electrode

——By changing the construction of the focusing electrode, using the flower-like one, the TTS of the PMTs is improving from 20ns to 5ns, but the CE of the prototype is decreasing to 85%,

——By decreasing the area of the photocathode for better TTS, the dark rate of the PMT also much better than the normal one, from 40KHz to 20KHz.

Characteristics	Normal focusing electrode		Flower-like focusing electrode
QuantumEfficiency (400nm)	~30%		~30%
Relativity Detection Efficiency	~ 100%	↓	85%
P/V of SPE	**~ 7**	↓	**~ 5**
TTS on the top point	~20ns	↑	4.3 ns
Anode Dark Count	~40KHz	↑	~20KHz

2020 NIMA 977;



—LHAASO（**Large High Altitude Air Shower Observatory**), has already ordered 2270 pics 20” Flower-like-MCP-PMT.

—The 20 inch Prototype with potting has also post to the HyperK PMT Group in Tokyo University for the testing.

—The performance are different from the tubes for JUNO.

Parameters	JUNO	LHAASO
Total number	15000	2270
DE@400nm	30%	26.8%
Dark Rate	~ 40KHz	~ 15KHz
TTS	~20ns	~5.5ns

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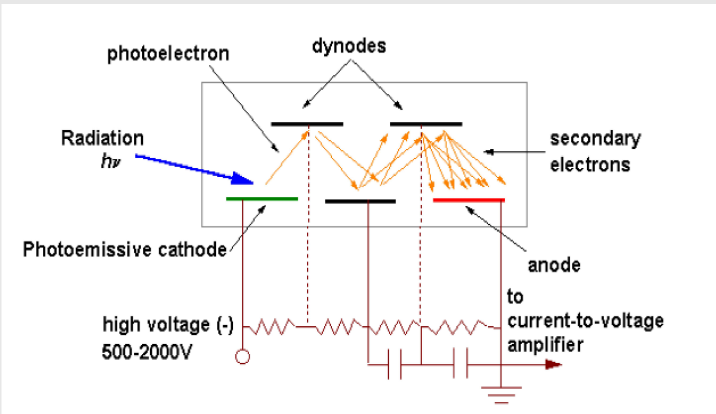
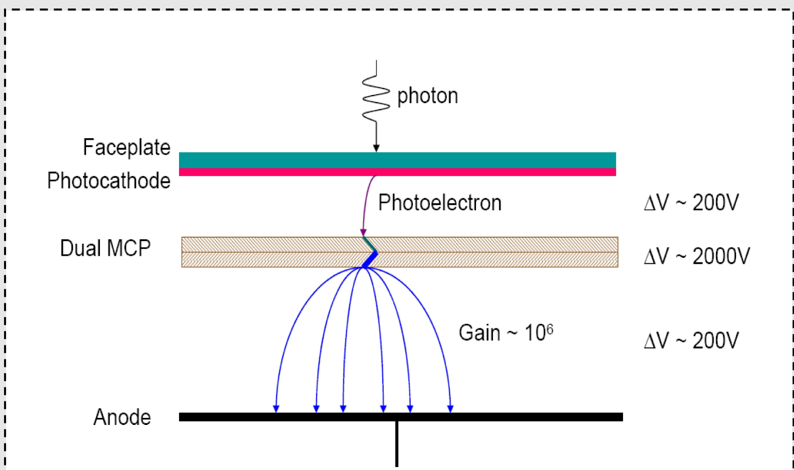
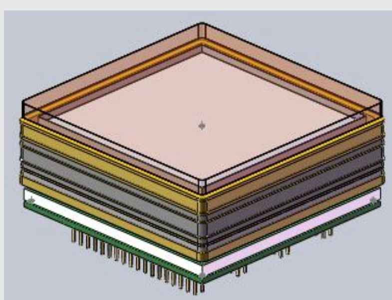
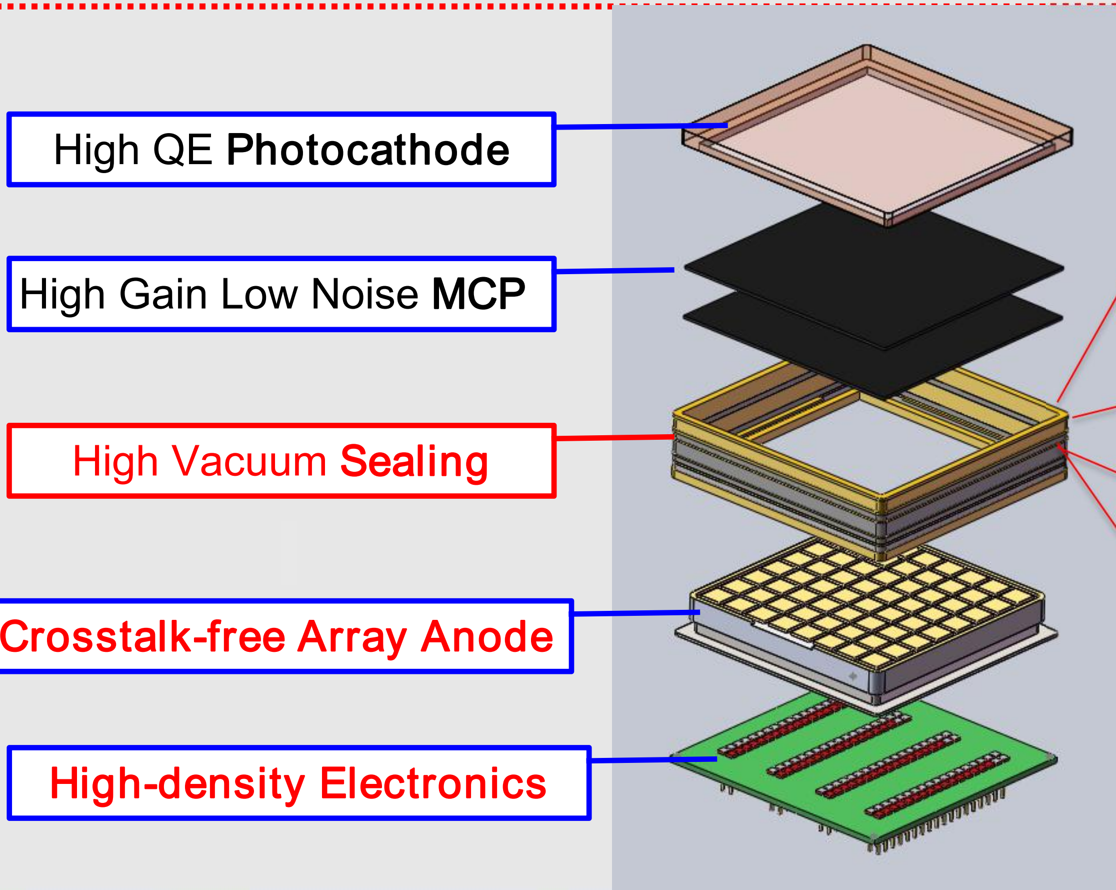
3.1 The Roadmap for FPMT-- （1） Purpose

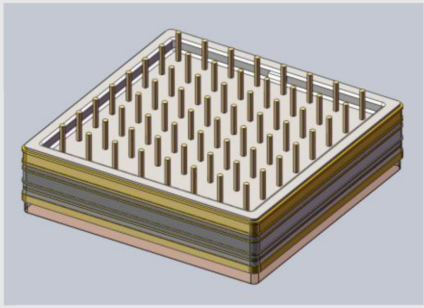
	Operation Principle	Small Size （proximity focusing）	Large Size （electrostatic focusing）
Dynode		2“ Dynode-PMT ✔ 	20“ Dynode-PMT ✔ 
MCP		2“ MCP-PMT ? 	20“ MCP-PMT ✔ 

3.1 The Roadmap for FPMT -- （2）Technology

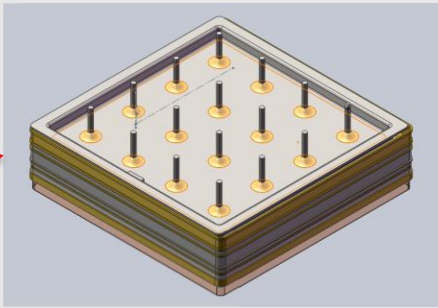
- --Five Core technologies are needed to produce this new type of 2 inch Fast MCP-PMT；
- --We have the experience of the PC, MCP production, but need do more research on the sealing, the anode, and the electronics.



➢ 2 inch - 8X8 ch.



➢ 2 inch - 4X4 ch.



➢ 1inch- 1ch.

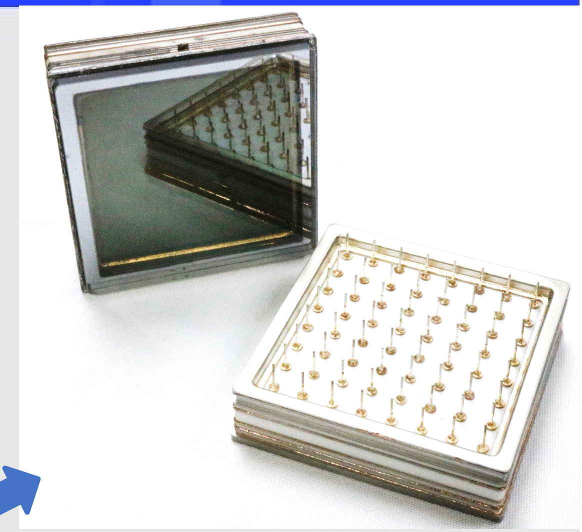
➢ 1 inch- 4ch.

3.1 The Roadmap for FPMT -- （3）Prototypes

- Single Anode FPMT

- 2*2 Anodes FPMT

- 4*4 Anodes FPMT

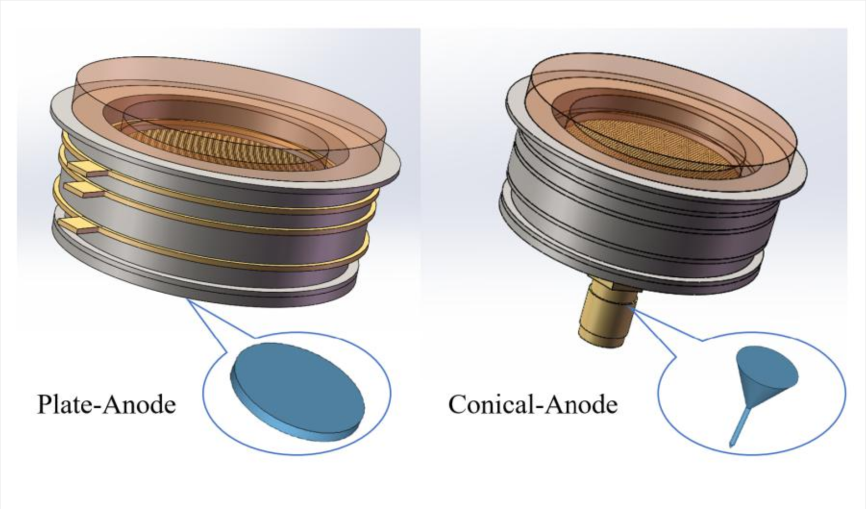


- 8*8 Anodes FPMT

FPMTs developed in IHEP+NNVT

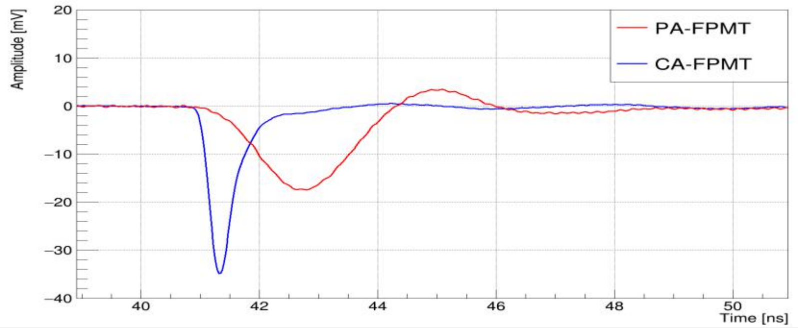
3.2 The Performance -- （1） Single Anode FPMT

➢ Anode Optimization

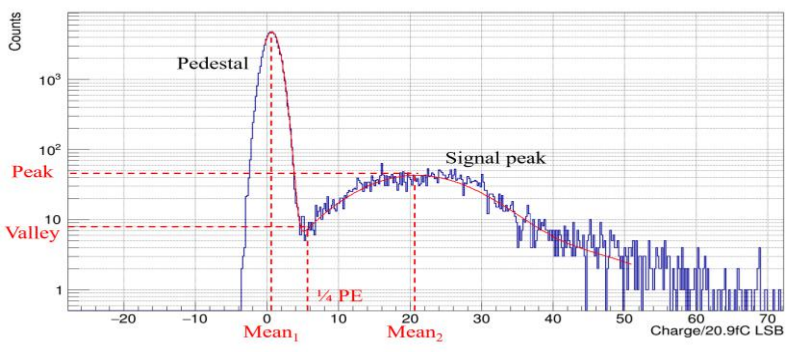


2022 NIMA 1041

➢ Waveform comparison



➢ SPE Spectrum

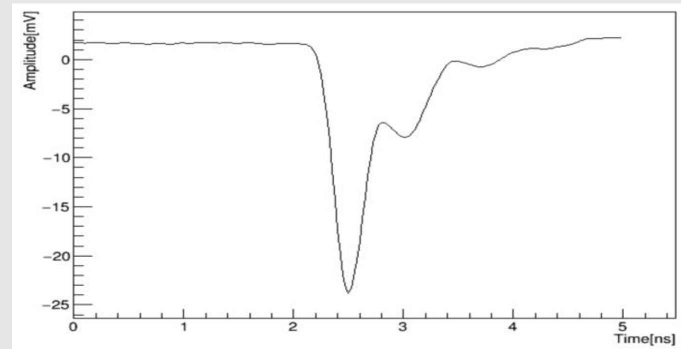


	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	96 ps	350 ps	190ps	45 ps	10 ps
Plate-Anode	-2000	1.9E6	28.8	7 mV	1.4 ns	1.4 ns	1.8 ns	70 ps	25 ps
Conical-Anode	-3181	2.6E6	6.3	53 mV	150 ps	420 ps	330 ps	27 ps	5 ps

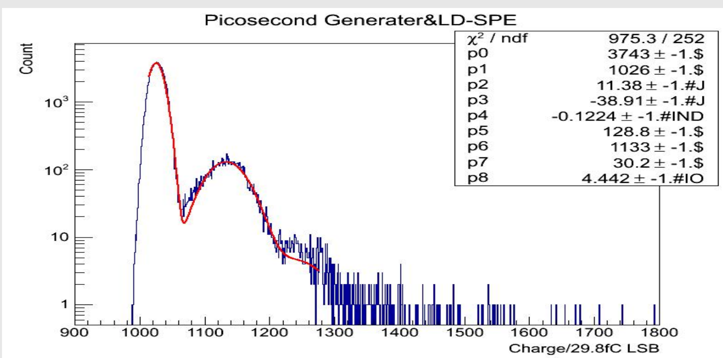
3.2 The Performance -- （2）2X2 Anode FPMT

➢ **2*2 Anodes FPMT**

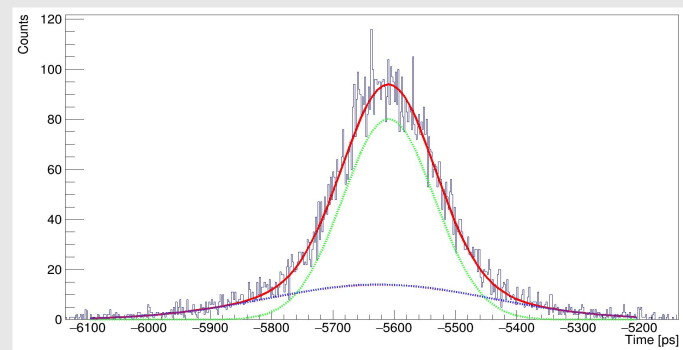
➢ Average waveform of SPE



➢ SPE Spectrum



➢ SPE-TTS Spectrum



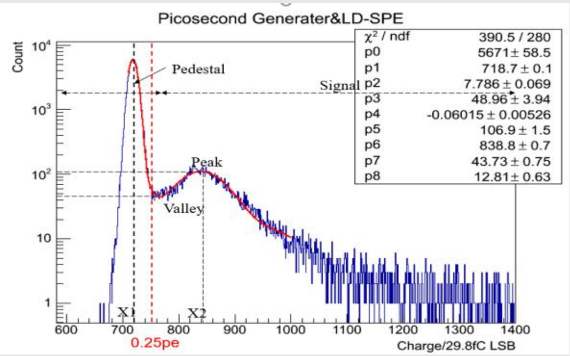
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	**96 ps**	350 ps	190 ps	**45 ps**	10 ps
2X2-Anode	-2500	1.9E6	6.5	34 mV	243 ps	516 ps	378 ps	**67 ps**	17 ps

Ref： Sen Qian， Oral report, The R&D of the Ultra Fast 8X8 Readout MCP-PMTs, ICHEP 2020

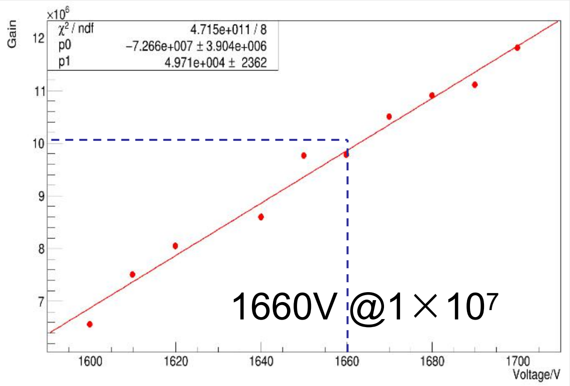
3.2 The Performance -- （3）4X4 Anode FPMT

PoS(ICHEP2020)867

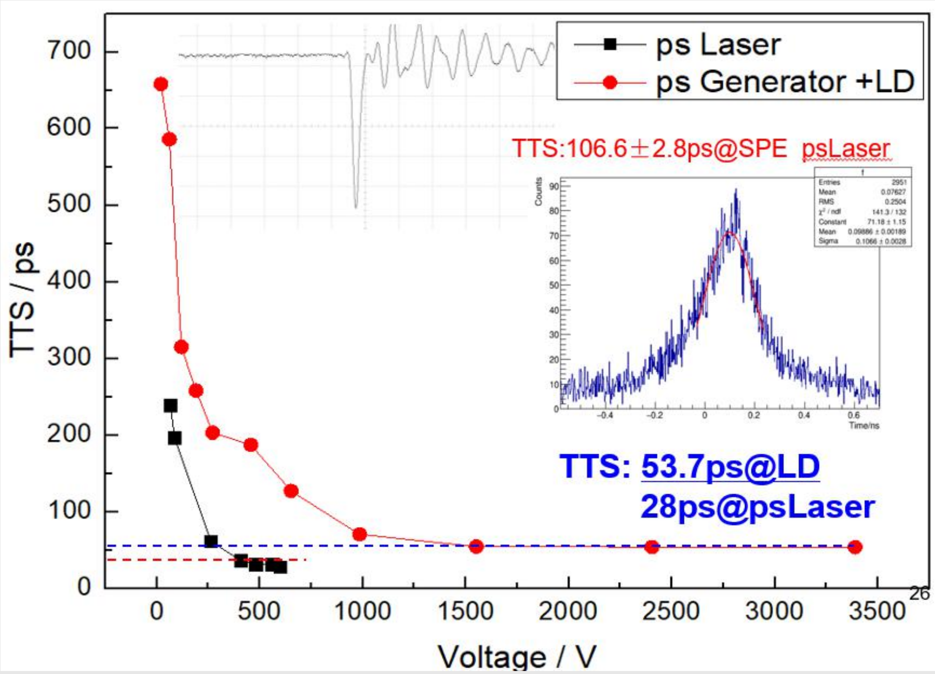
➢ SPE Spectrum



➢ HV-Gain



➢ SPE-TTS Spectrum

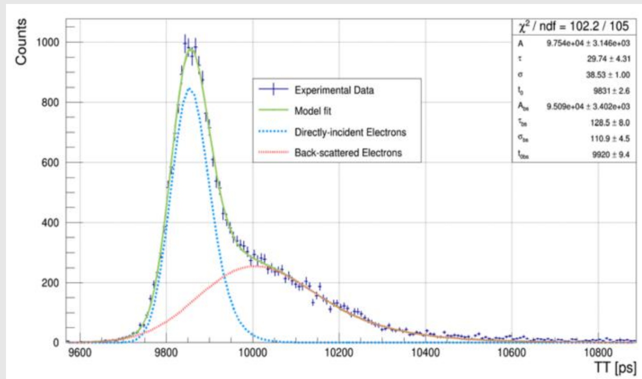


	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek-253	-2600	1.2E7	11.2	113 mV	490ps	1.16ns	-	45 ps	16 ps
4X4 -Anode	-1660	9.6E6	2.0	21 mV	430ps	--	--	107 ps	28 ps

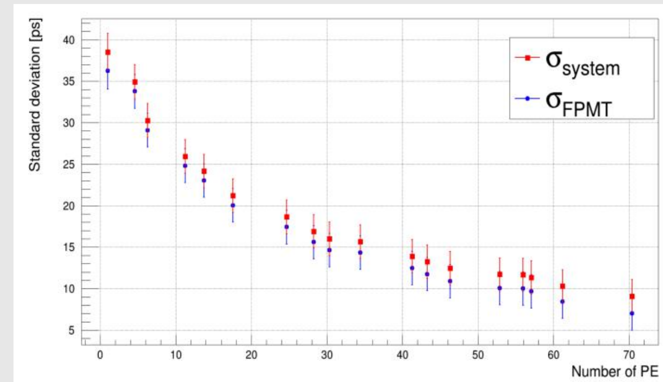
3.2 The Performance -- （4） 8X8 Anode FPMT

2022 JINST 17 T04002

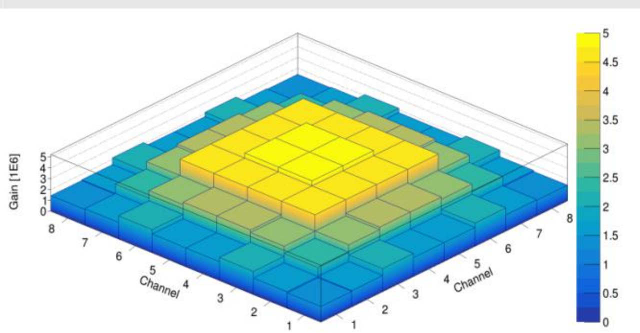
➢ TTS Spectrum



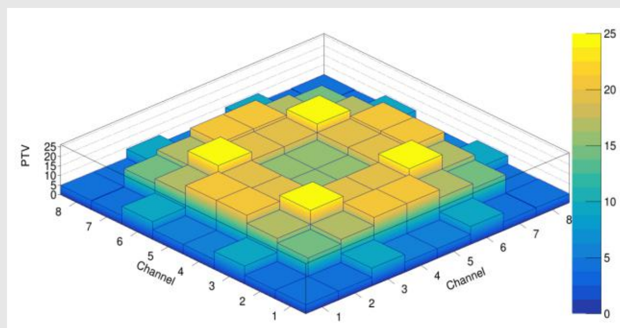
➢ TTS Variation with light intensity



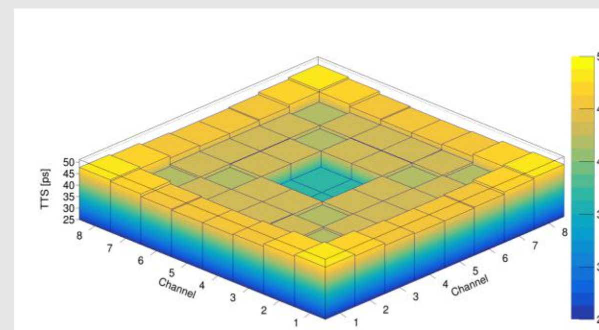
➢ Uniformity of Gain



➢ Uniformity of P/V



➢ Uniformity of TTS



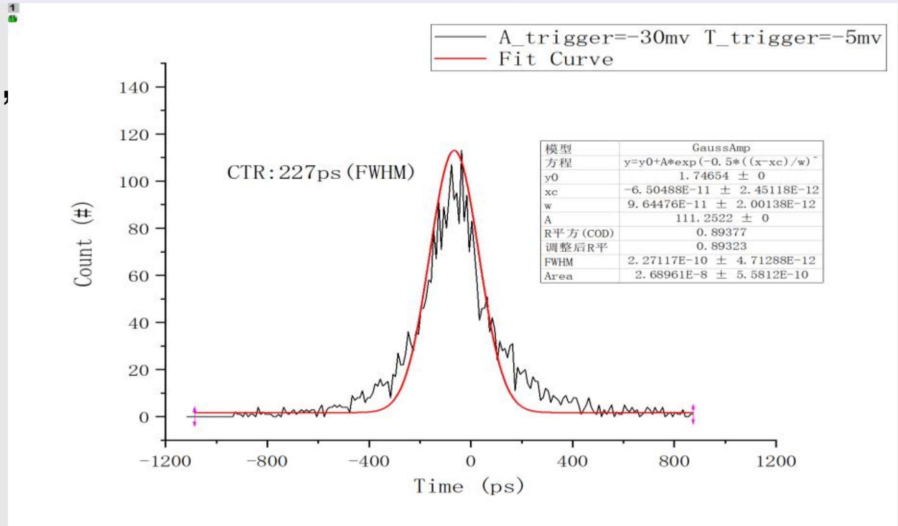
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek-253	-2600	1.2E7	11.2	113 mV	490 ps	1.1 ns	~1ns	45 ps	16 ps
8*8 Anodes	-1500	3.9E6	18.6	45 mV	334 ps	660 ps	~900ps	40 ps	10 ps

3.3 The CTR of FPMTs

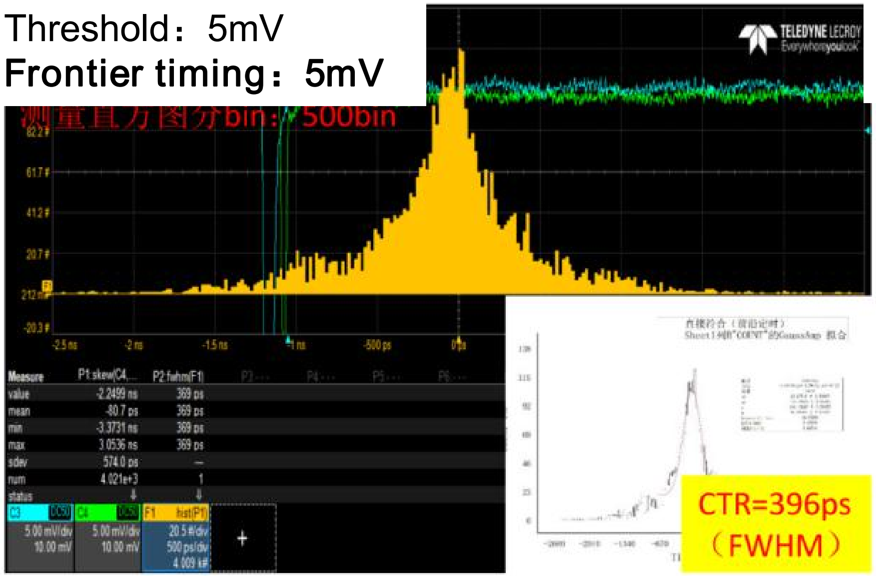
- ✓ **Radioactive sources：** Sodium（^{22}Na），
- ✓ **Crystal：** Lead Fluoride（PbF_2）
- ✓ **DAQ：** Oscilloscope~25ps
- ✓ **FPMT：** 8*8 Anodes FPMT*2

The Best **Coincidence Time Resolution：**

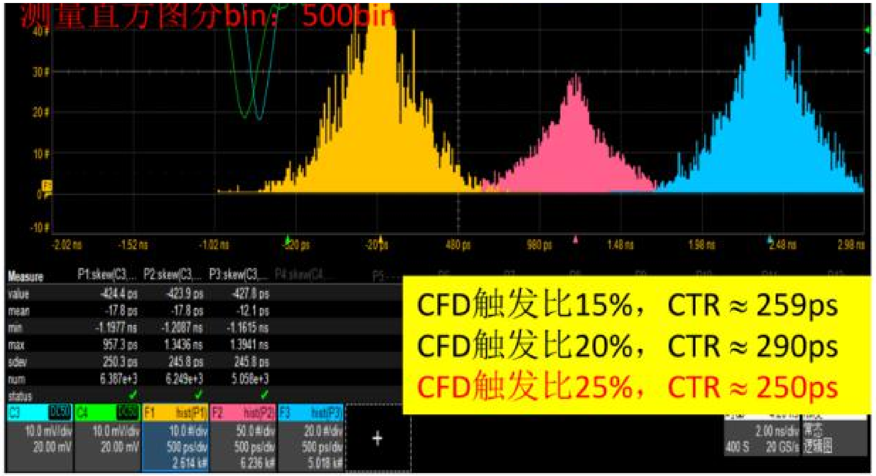
CTR：227ps（FWHM）**96.6ps**（Sigma）



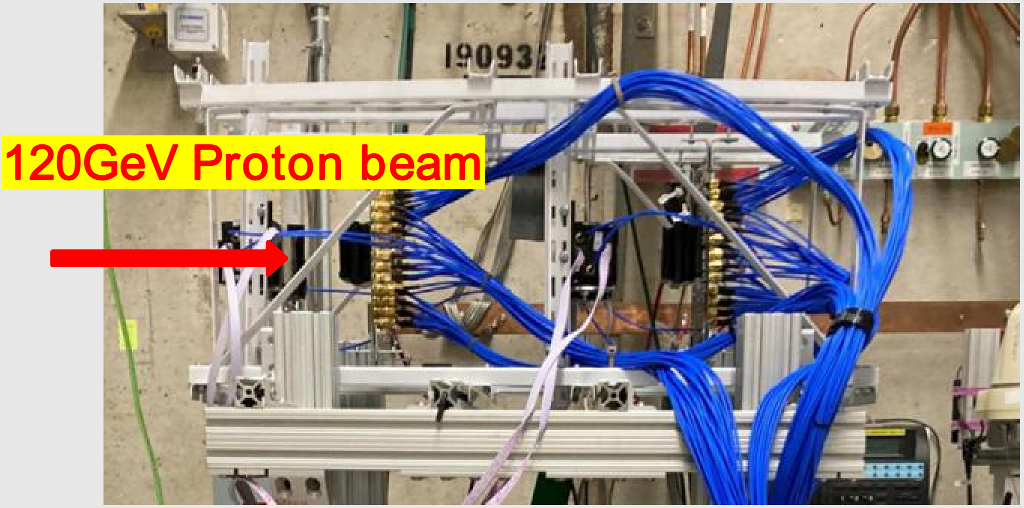
Threshold：5mV
Frontier timing：5mV



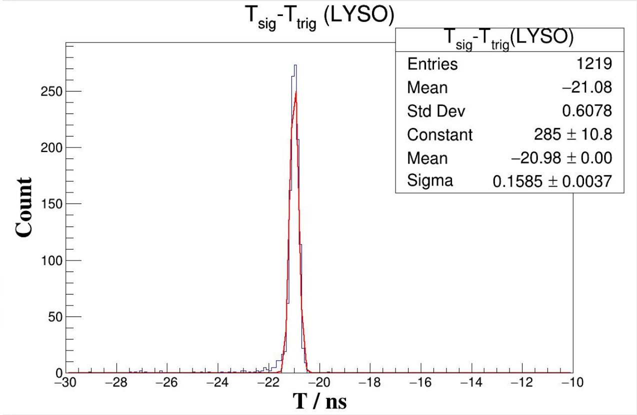
Threshold：5mV
CFD：15%（yellow）、20%（Red）25%（Blue）



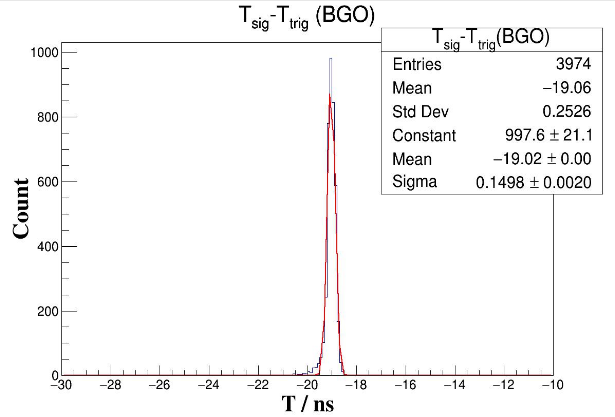
3.4 The Beam Test -- （1）Proton



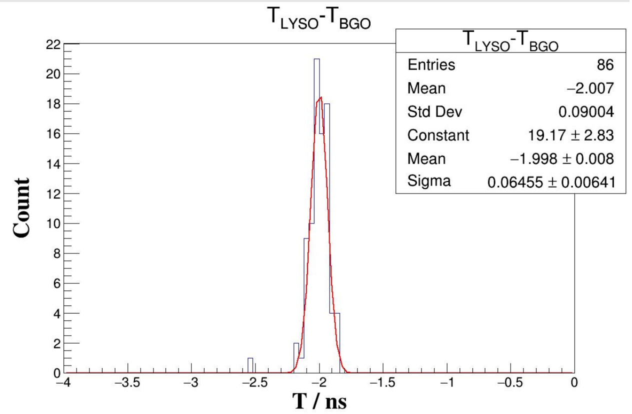
- Beam：120GeV Proton (Fermi)
- Crystal：LYSO & BGO
- PMT： 8*8 FPMT
- DAQ：CAEN V1742~50ps；
- Carried out by Zhenyu Ye (UIC)
  Zhihong Ye (THU)



- LYSO single channel
  Time Resolution
  Sigma：158.5 ps

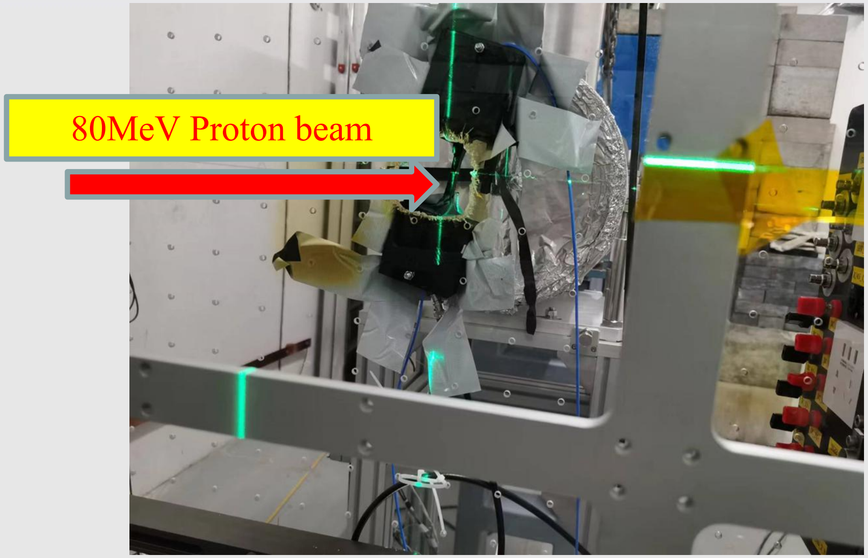


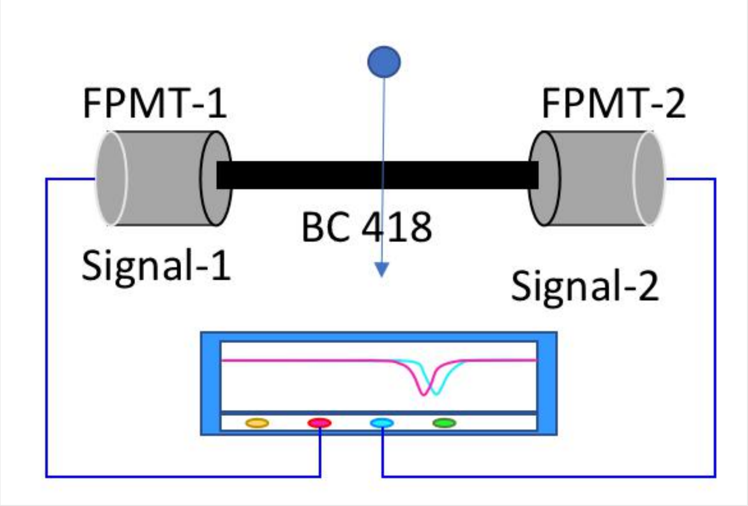
- BGO single channel
  Time Resolution
  Sigma：149.8 ps



- LYSO & BGO
  Coincidence Time jitter~64 ps
  Single tube Time jitter ~45ps

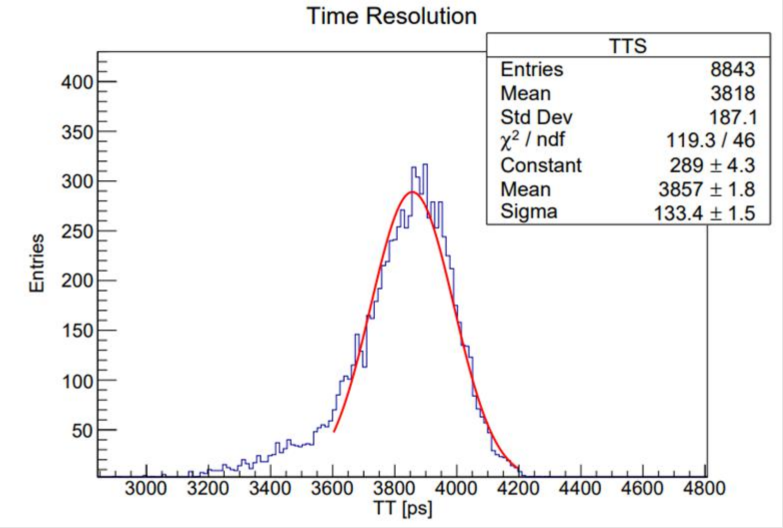
3.4 The Beam Test -- （2）Proton





- Beam：80 MeV Proton (CSNS)
- Plastic Scintillator：BC418
- PMT： Conical-Anode FPMT
- DAQ：1Gs/s ~80ps

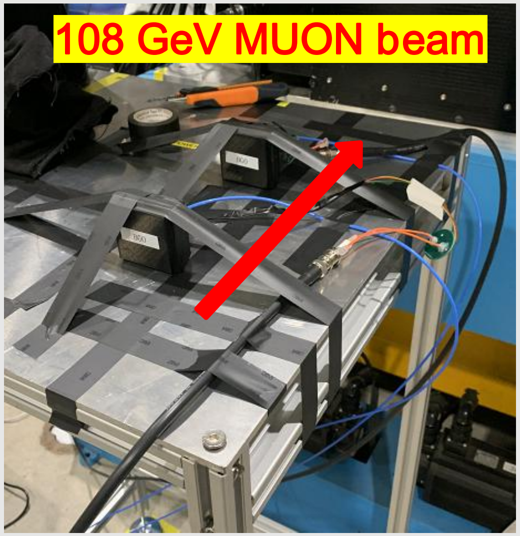
➢ BC418 double channel Time Resolution



Coincidence time jitter~133 ps

Single tube Time jitter ~93 ps

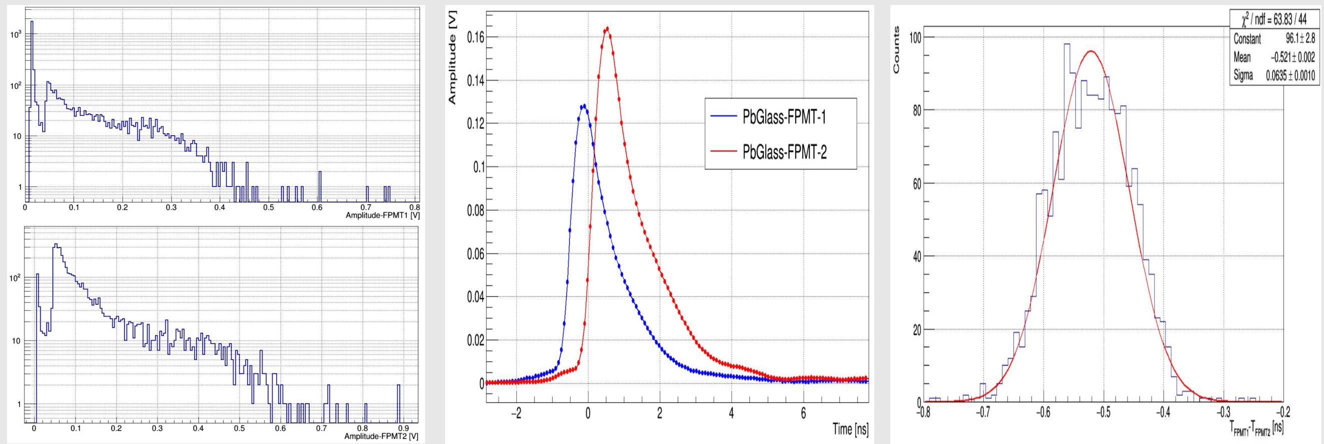
3.4 The Beam Test -- （3）Muon



➤ Lead Glass + FPMT

Coincidence time jitter~63 ps

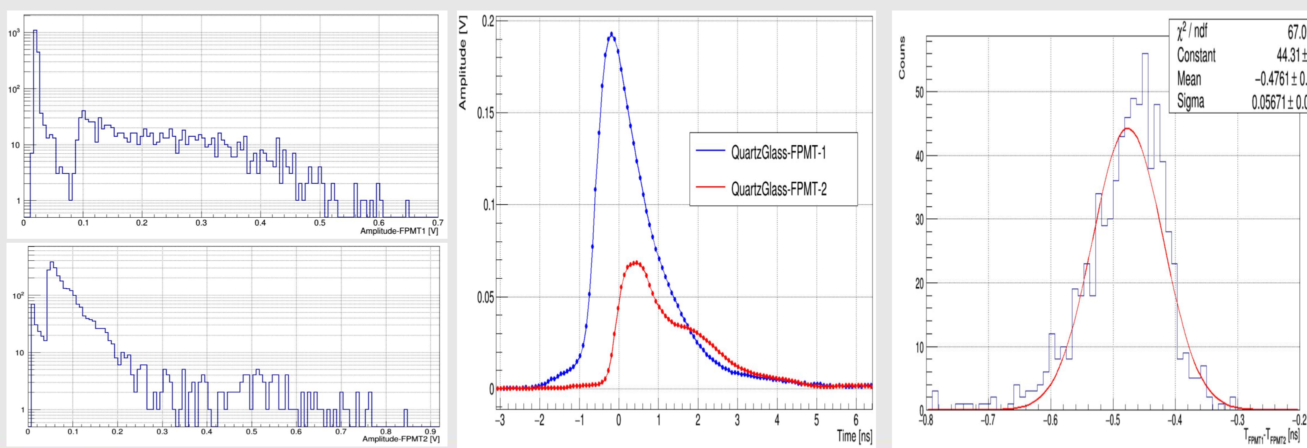
Single tube Time jitter ~**45ps**



➤ Quartz Glass + FPMT

Coincidence time jitter~56 ps

Single tube Time jitter ~**40ps**



- **Beam**：(CERN)

  108GeV Muon
- **Scintillator**：

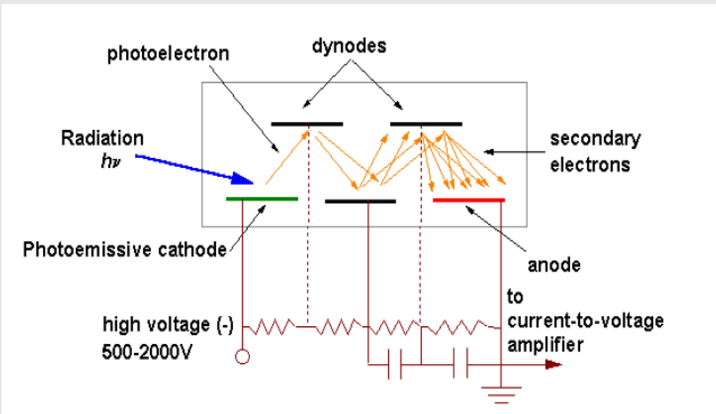
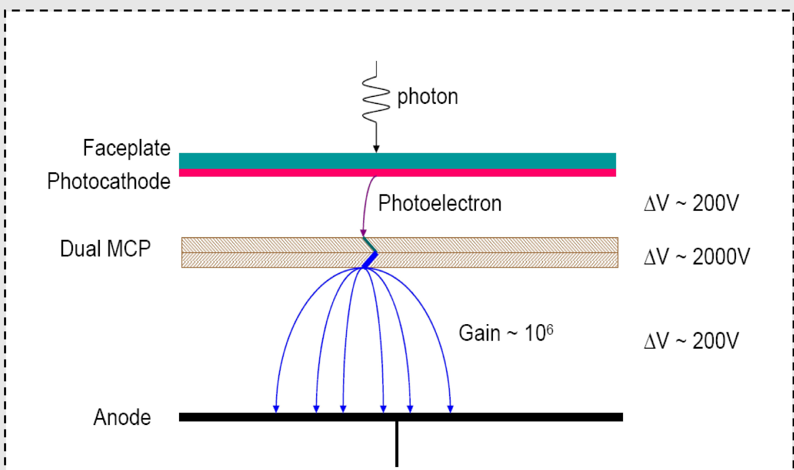
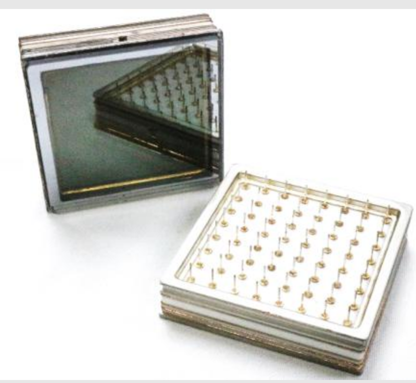
  Pb Glass, Quartz Glass;
- **PMT**： 8*8 FPMT

  TTS = 50ps@SPE;
- **DAQ**：15 GSa/s ~ 25ps

Outline

- 1. The Conventional PMTs
- 2. The 20 inch MCP-PMT （LPMT）
  - 2.1 The Design of LPMT；
  - 2.2 The Roadmap for the R&D of LPMT；
  - 2.3 The HPD LPMT for JUNO；
  - 2.4 The Fast LPMT for LHAASO;
- 3. The Fast timing MCP-PMT (FPMT)
  - 3.1 The Roadmap for FPMT；
  - 3.2 The Performance of FPMT；
  - 3.3 The CTR of FPMTs;
  - 3.4 The Proton Beam Test；
- 4. Summary

4. Summary-- （1） The PMTs

	Operation Principle	Small Size （proximity focusing）	Large Size （electrostatic focusing）
Dynode		2“ Dynode-PMT ✔ 	20“ Dynode-PMT ✔ 
MCP		2“ MCP-PMT ✔ 	20“ MCP-PMT ✔ 

4. Summary-- （2）The Group

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Institute of High Energy Physics, CAS

effort by **Yifang Wang**

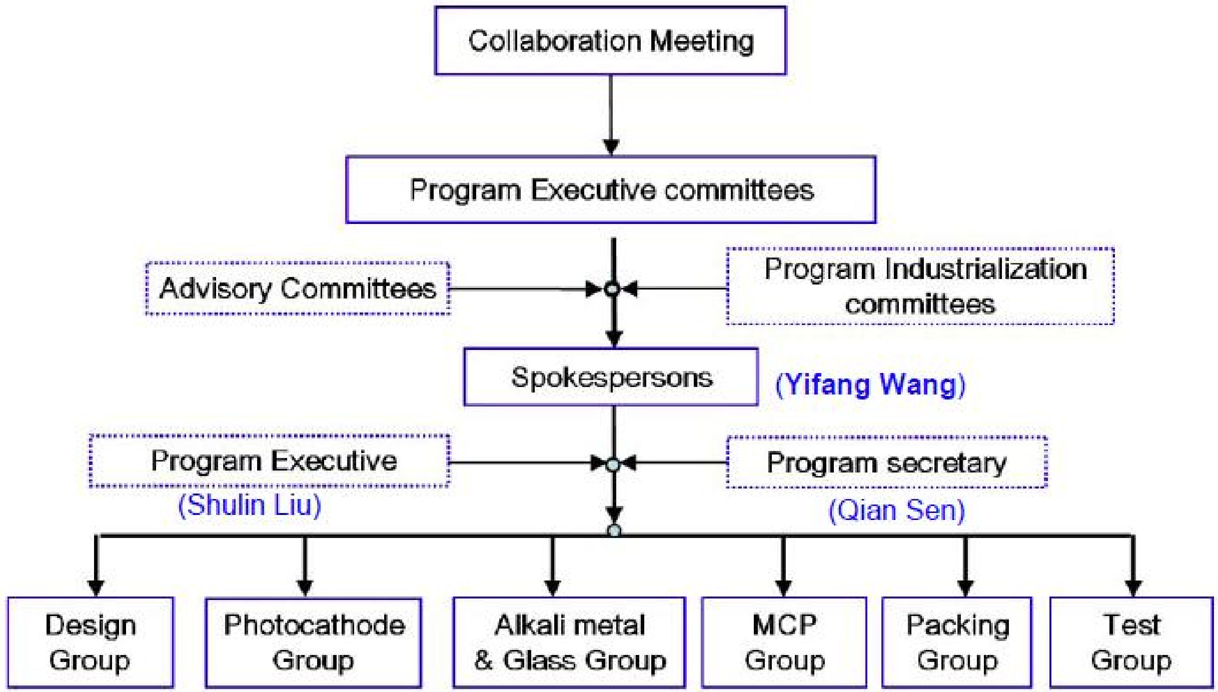
北方夜视技术股份有限公司
NORTH NIGHT VISION TECHNOLOGY CO.,LTD

中国科学院西安光学精密机械研究所
XIAN INSTITUTE OF OPTICS AND PRECISION MECHANICS OF CAS

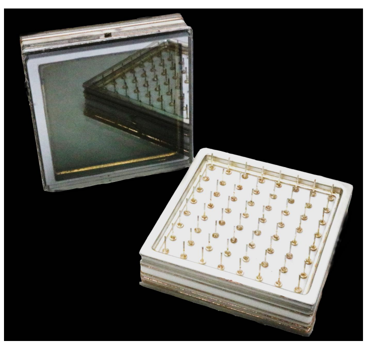
中核（北京）核仪器厂
CNNC Beijing Nuclear Instrument Factory

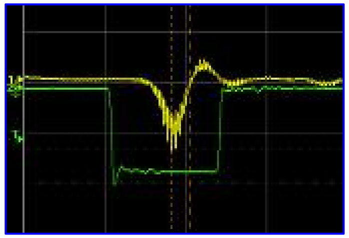
南京大学

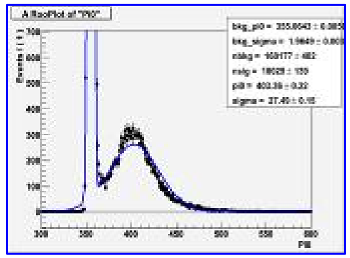
Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)

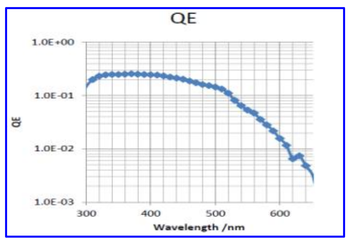


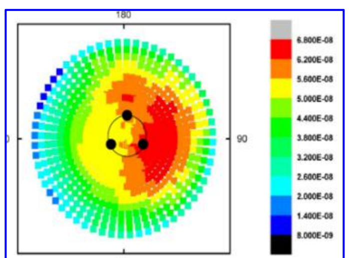
4. Summary-- （3） The PMT Test Facility











Others

……

- ➢ Anode Pulse Rise Time;
- ➢ Pre/Late/After Pulse;
- ➢ Dark Count

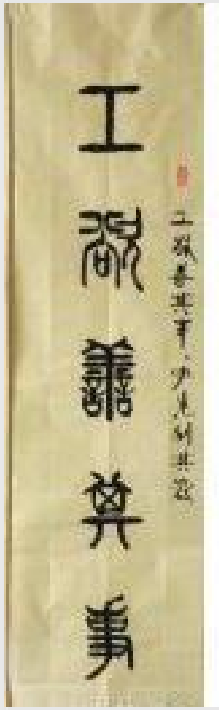
- ➢ The Single Photoelectron Spectrum;
- ➢ The voltage distribution (BASE) ;
- ➢ The Supply voltage;
- ➢ Typical Gain Characteristic;
- ➢ Anode Dark Current

- ➢ Spectral Response；
- ➢ Wavelength of Maximum Response；
- ➢ Cathode Sensitivity: Luminous(2856K);
- ➢ Quantum efficiency with λ

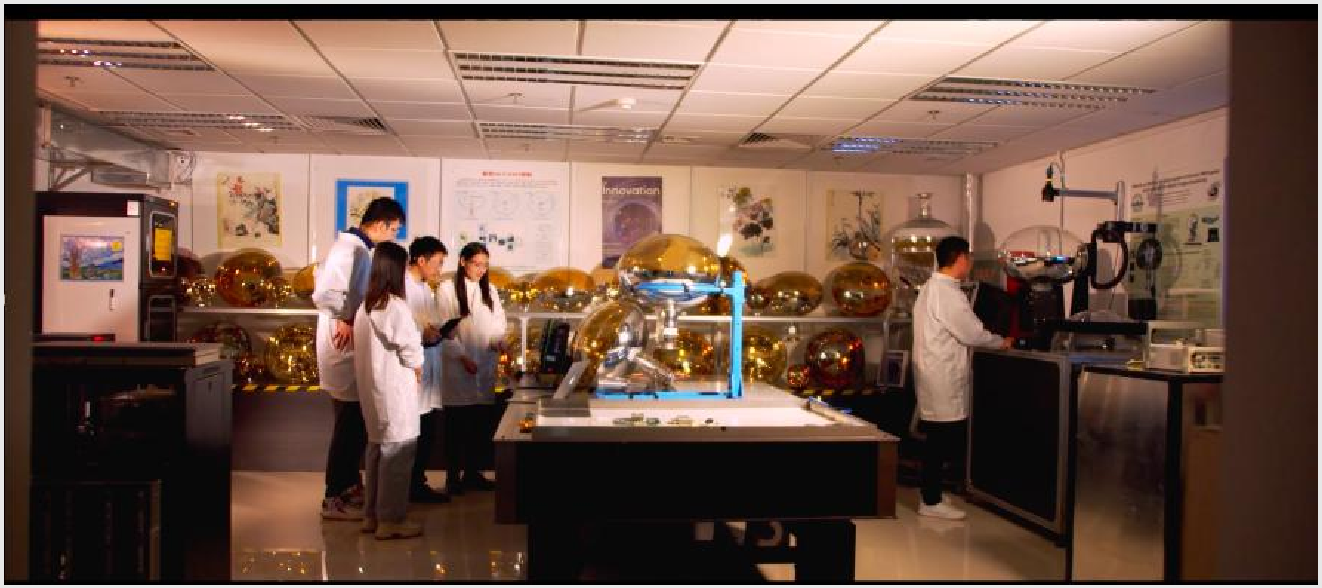
- ➢ Photocathode efficiency Area;
- ➢ Photocathode efficiency Uniform;
- ➢ The position of the Sb, K, Cs;

- ➢ The linearity of the PMT
- ➢ Magnetic characteristics;
- ➢ Transit Time Spread (FWHM)

4. Summary--(4) The Photodetector Lab in IHEP



工欲善其事必先利其器 = Work must first of its profits



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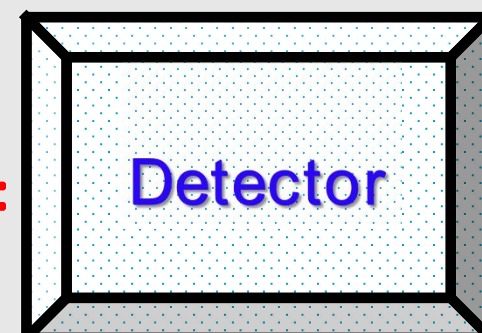
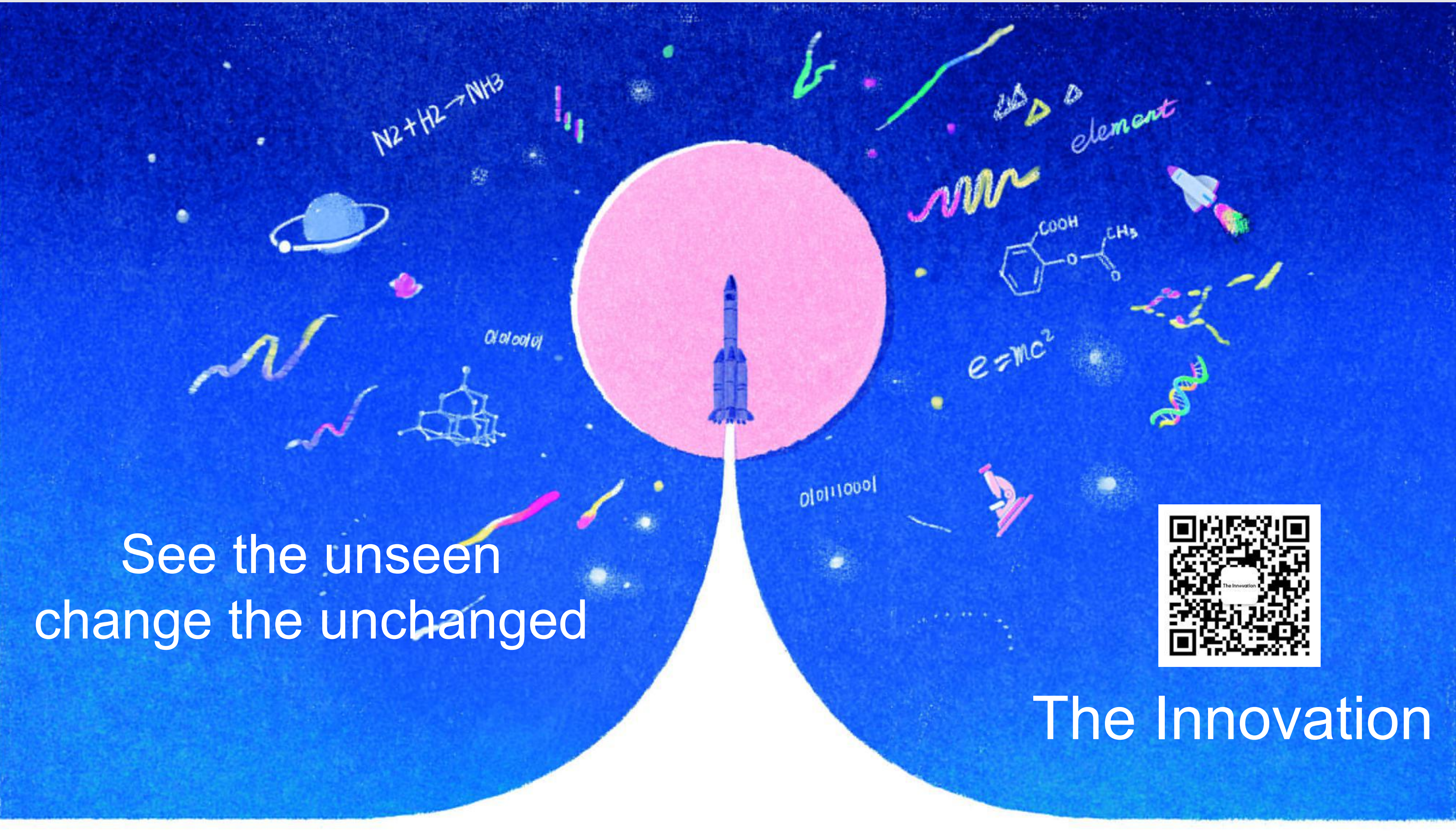


谢谢！

Thanks for your attention!

Any Comment & Suggestion are welcomed!

THANKS



See the unseen
change the unchanged

The Innovation