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The R&D of the FPMTs for High Energy Physics Detectors

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On behalf of the FPMT R&D Group

The CEPC Workshop on Flavor Physics, New Physics and Detector Technologies

Fudan university, ShangHai

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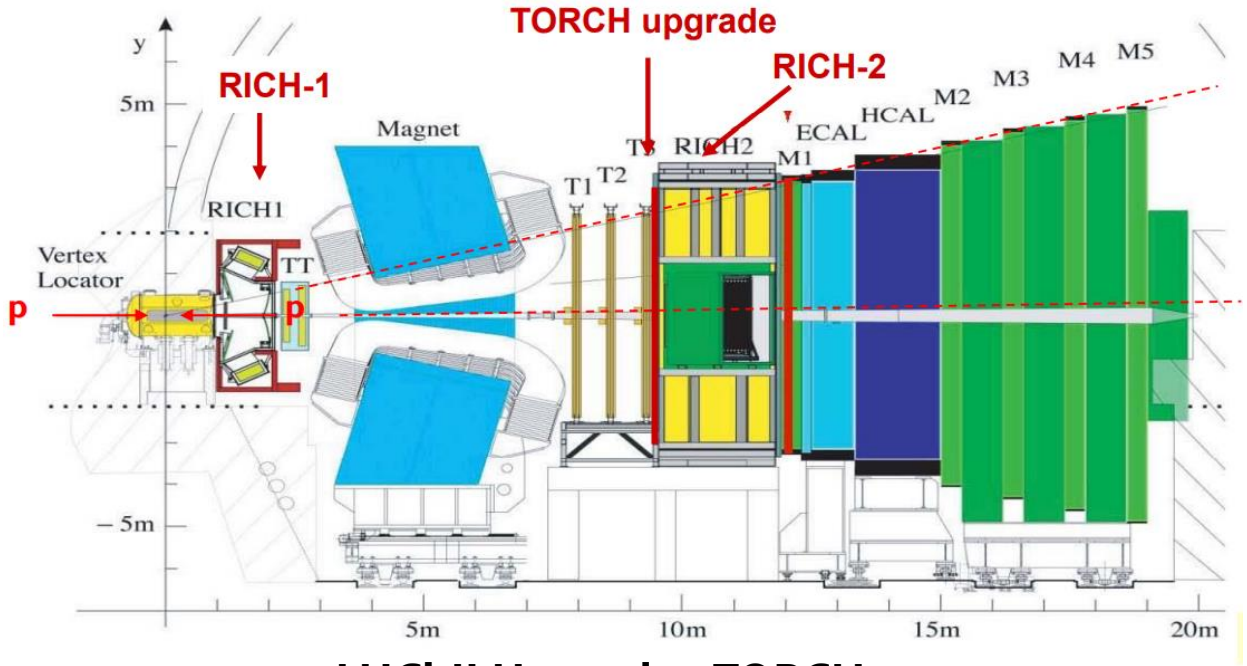
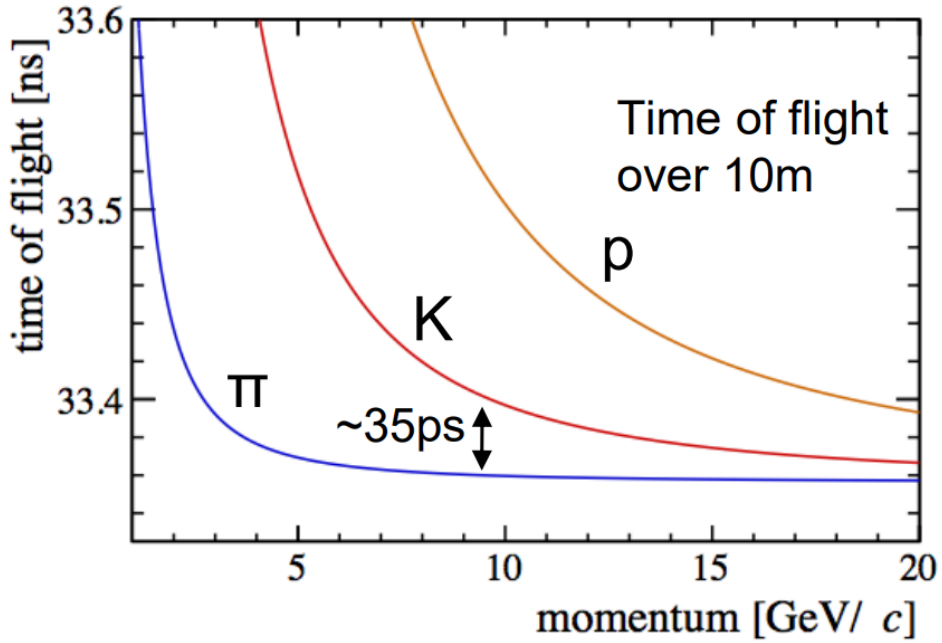
Outline

- 1. Fast Timing Detectors used in HEPs
- 2. R&D of FPMT
- 3. Time resolution of FPMT in Beam test

1.1.1 Potential Applications of Fast timing detector-TORCH



LHCbII Upgrade –TORCH
(**T**ime **O**f internally **R**eflected **CH**erenkov light)



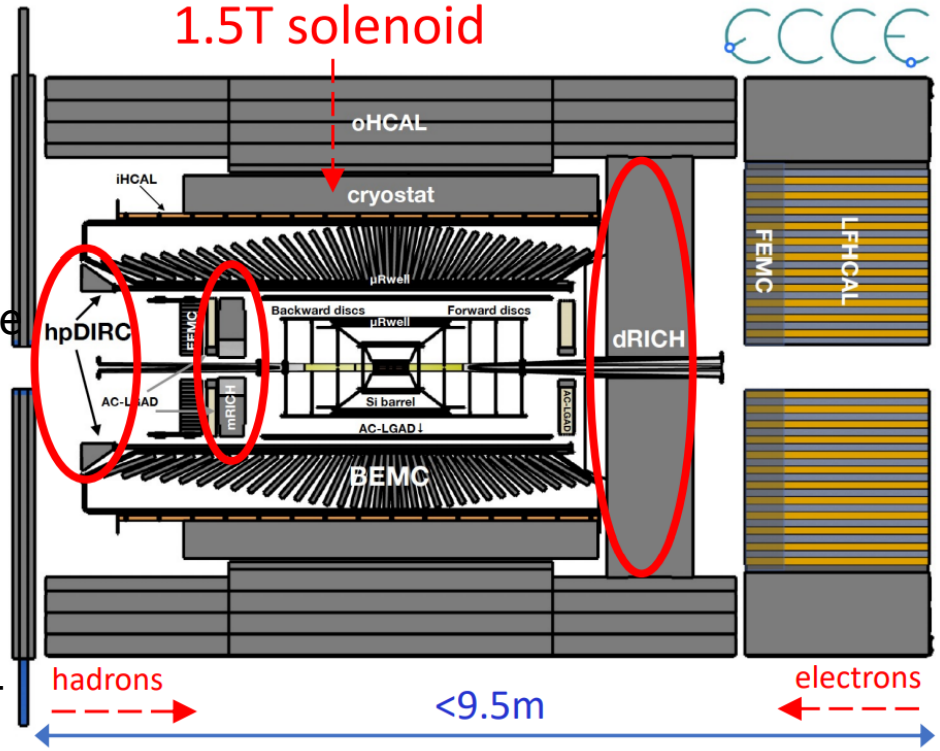
PID of pions, kaons and protons

- The σ_{TOF} requirement dictates timing single photons to a precision of **70 ps** for ~30 detected photons, and ideal time resolution of fast timing detector is ~33 ps from calculation. Multi-anode MCP-PMT is considered as the detector option.

Ref: 1.Neville Harnew, TheTORCH time of flight detector and status of R&D, 31 March 2020 (report of 5th Workshop on LHCb Upgrade II)
2. Ulrik Egede. LHCb PID system & TORCH detectorLHCb PID system & TORCH detector 2023.08.14

1.1.2 Potential Applications of Fast Timing Detector-EIC-RICH

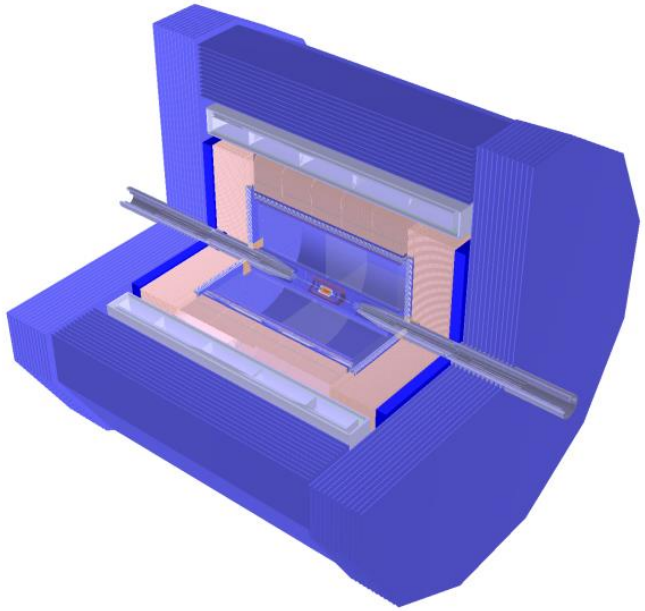
- The U.S. has approved the construction of EIC in BNL
  - 10 GeV/c electrons + 100 GeV/c protons
  - Measure the three-dimensional distribution of gluons inside nucleons and nuclei, the mystery of proton spin, the mystery of mass, the saturation of gluons, etc
- EPIC is one of the detectors on the collision point
- MCP-PMT can be substituted (optimized according to both time-sensitive or position-sensitive):
  - <20ps TOF: LGAD
  - Dual-RICH position-sensitive photon detector: Currently using SiPM/MaPMT, consider LAPPD
  - Calorimeter's antimagnetic photon detector: tentative SiPM/MaPMT



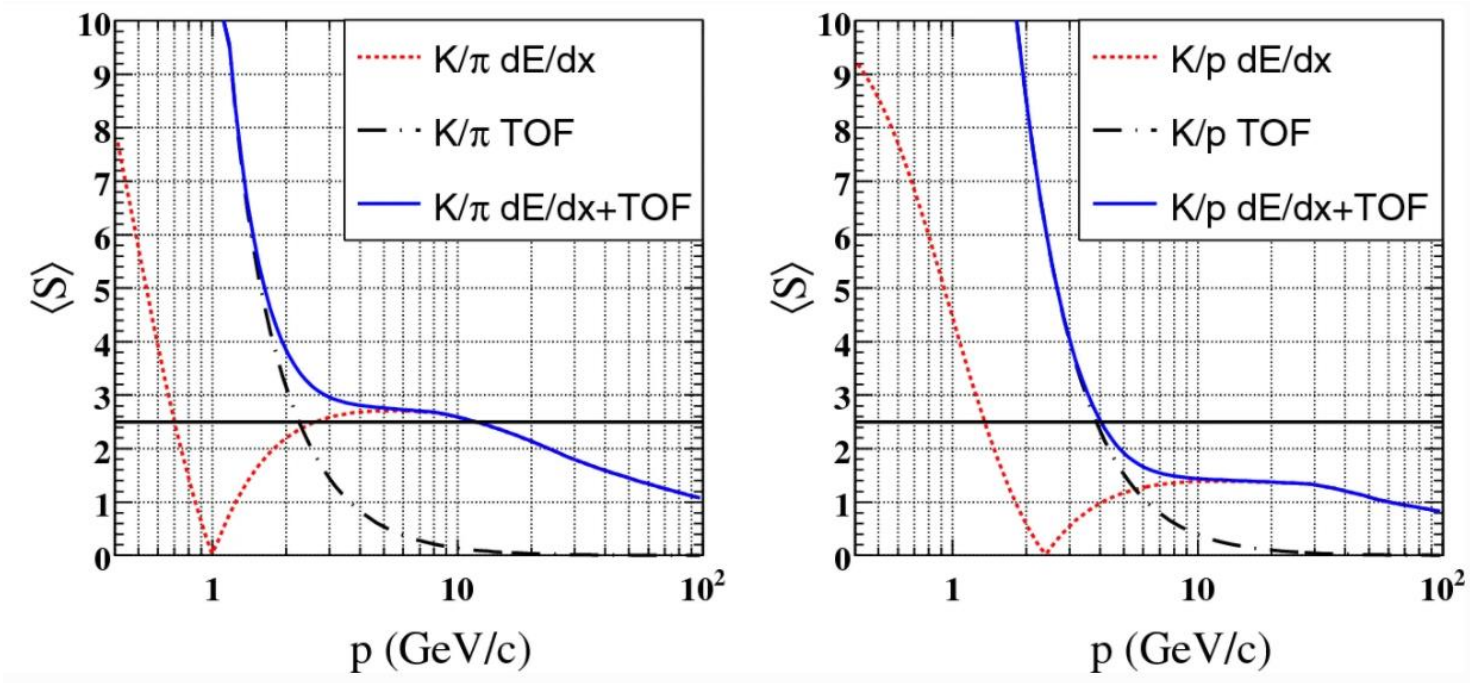
	Default option	Single photon time resolution	Spatial resolution equivalent	Sensor area
E-endcap mRICH	SiPMs	best possible	~3mm pixels	64 ~10x10 cm^2 spots
Barrel DIRC	MCP-PMTs	<100 ps	~3mm pixels	~0.65 m^2 total
H-endcap dRICH	SiPMs	~100 ps	~3mm pixels	~3.10 m^2 total

Ref: Brookhaven Lab R&D on Capacitively Coupled LAPPDs with 2D Pixelated Readout Planes for Ring Imaging Cherenkov Detectors, report in Ad hoc LAPPD workshop

1.1.3 Potential Applications of Fast Timing Detectors-CEPC-PID



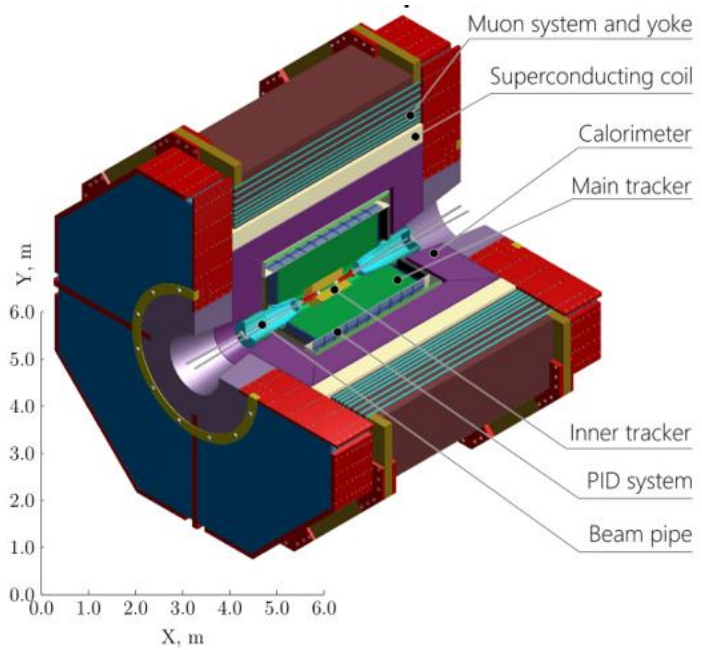
CEPC Detector



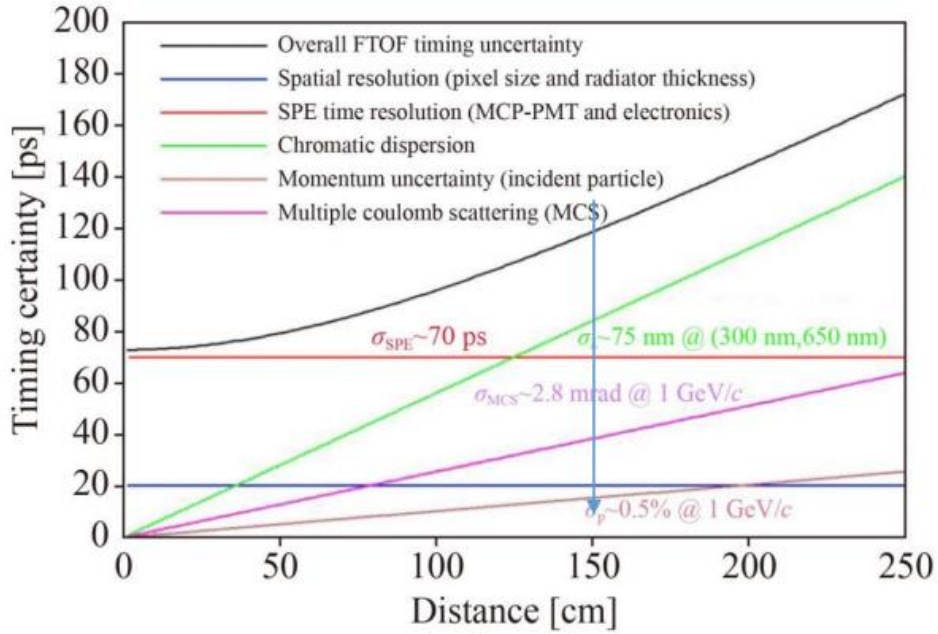
Supposing TOF information with **a 50 ps time resolution**, accounting for the time resolution and the location of the ECAL, the TOF information can provide K/π (K / p) separation **better than 2.5 σ** up to 2.1 (4.0) GeV/c. By combining TOF and dE / dx, more than 2.0 (1.4) σ K/π (K / p) separation can be achieved up to 20 GeV/c.

Ref: F. An, et, al. Monte Carlo study of particle identification at the CEPC using TPC dE / dx information, Eur. Phys. J. C (2018) 78:464

1.1.4 Potential Applications of Fast timing Detector- STCF



The STCF Detector Conceptual Design



The DTOF detector of STCF

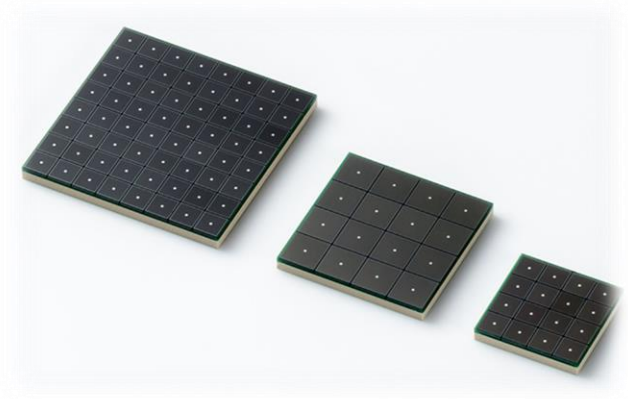
The DIRC-like high-resolution TOF detector is proposed.

For the requirement of 4σ π/K@2 GeV/c, the system time resolution should be **< 50 ps**, the intrinsic time resolution should be **< 30 ps**.

Multi-anode MCP-PMT is considered as the detetcor option.

Ref: Qian Liu, R&D for the STCF PID detector, 2023.08.15

1.2 Fast-timing Detectors



SiPM

Dynode -PMT

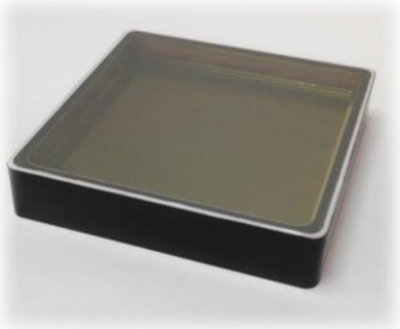
MCP -PMT (FPMT)

	SiPM	Dynode-PMT	MCP-PMT (Fast PMT)
Time resolution	~100 ps	~200 ps	~40 ps
Channels	Extensible array	8×8	64×64 (max)
Gain	10^5~10^6	10^6~10^7	10^6~10^7
Detection Efficiency	30~50%	20~30%	20~30%
Magnetic field resistance	Yes	No	Yes

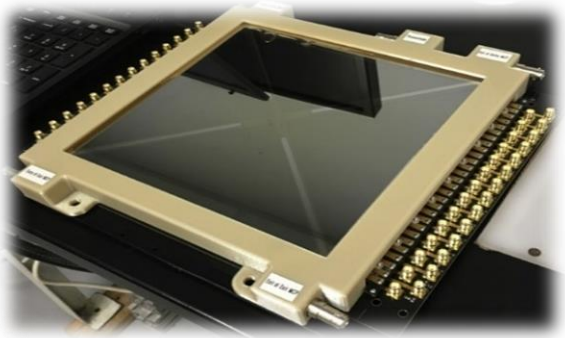
FPMT has ultra-fast time resolution and excellent magnetic field resistance!

1.3 FPMT Products

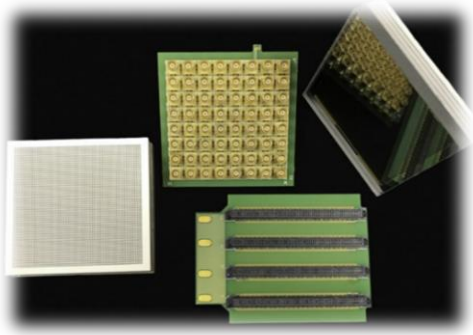
Hamamatsu(Japan)



Photonis (France)



LAPPD(USA)

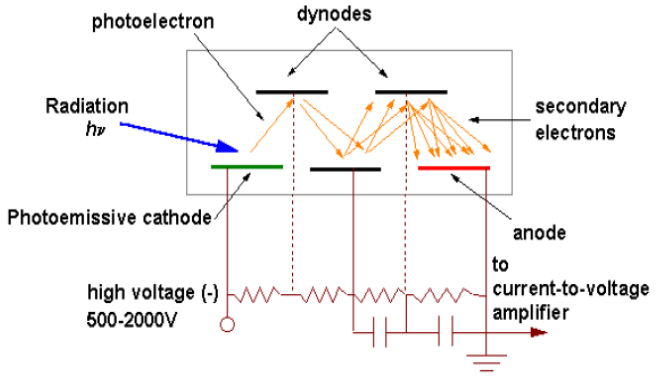
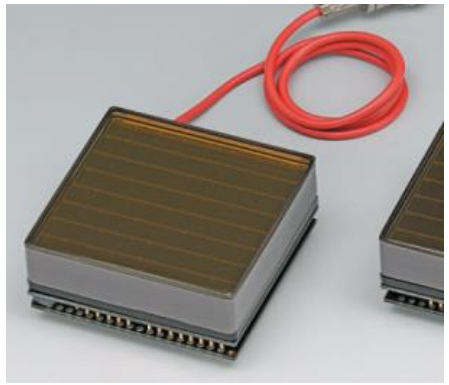
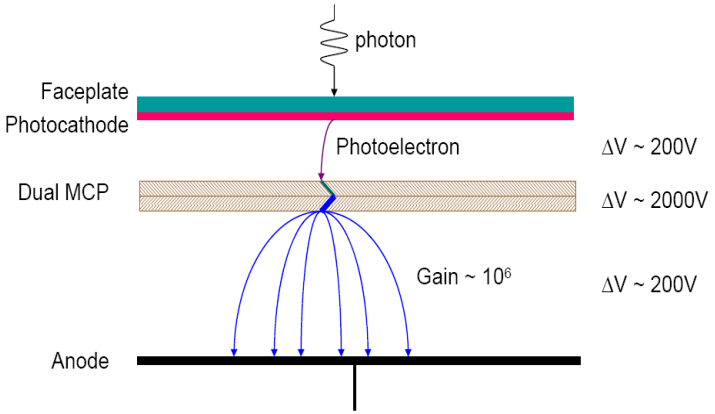
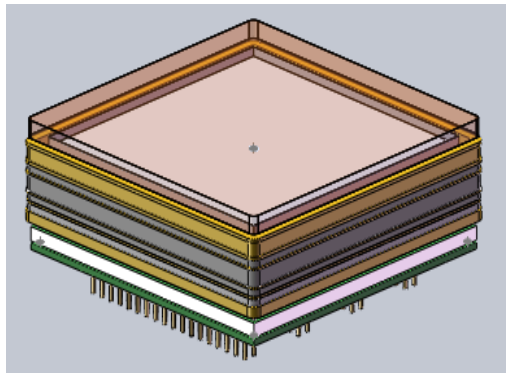


Photek(UK)

Manufacturers	Hamamatsu	Photonis	LAPPD	Photek
Type	R10754-07-M16	XP85012	LAPPD	MAPMT253
Sensitive area/mm	23×23	53×53	20×20	53×53
Gain	1.0 x 10^6	1.0 x 10^5	7.5x 10^6	1.0 x 10^6
QE@Peak	~20%@380nm	22%@380nm	22.3%@365nm	21%@290nm
TTS@SPE/ps	**31(RMS)**	~120(RMS)	64(RMS)	**<40 (RMS)**
Rise time/ps	195	600	850	**<175**
Anodes	4×4	8×8	28 strip lines	**64×64**

Expensive!

2.1 R&D of Fast Timing PMT

	Operation Principle	Small Size (proximity focusing)	Large Size (electrostatic focusing)
Dynode		2 " Dynode-PMT ✓  H8500	20 " Dynode-PMT ✓  R12860
MCP		2 " MCP-PMT ? 	20 " MCP-PMT ✓ 

IHEP Design： After the successfully 20 inch MCP-PMT R&D， the PMT group in IHEP try to design and produce the 2 inch FPMT, with fast time resolution and low cost!

2.2 R&D of Fast Timing PMT

--There are **5** Core technologies need to develop to produce this new type of 2 inch Fast MCP-PMTs;
--We have the experience of the PC, MCP, but need do more research on the Sealing, the Anode, and the Electronics.

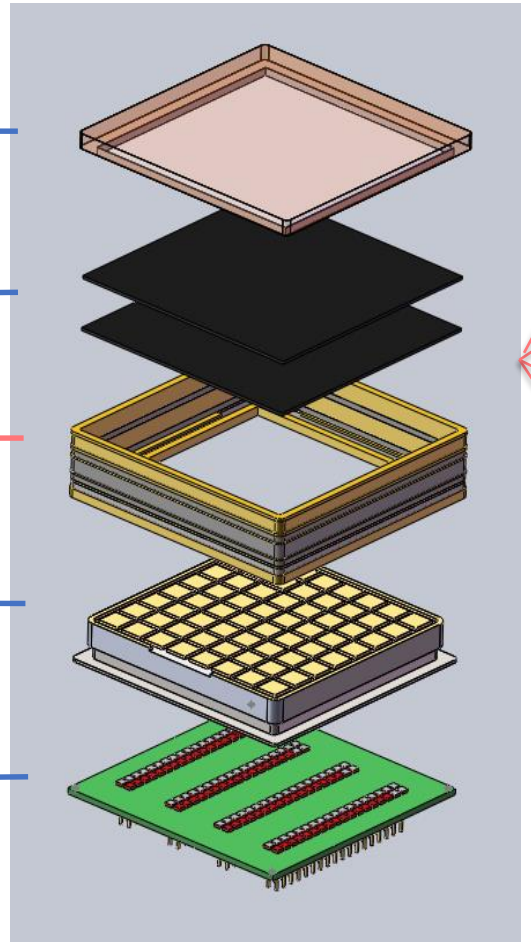
High QE **Photocathode**

High Gain Low Noice **MCP**

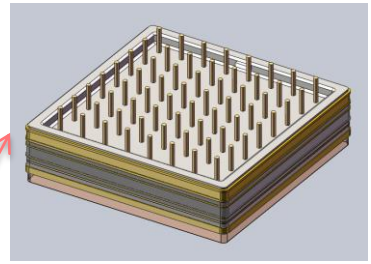
High Vacuum **Sealing**

Crosstalk-free array Anode

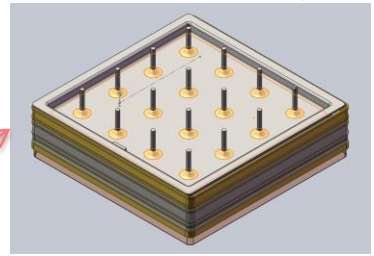
High-density Electronics



8X8 Channles，2 inch

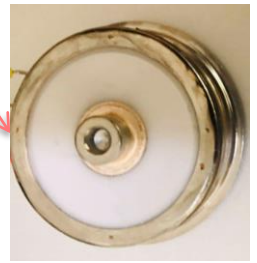


4X4 Channles，2 inch



2X2 Channles，1 inch

1 Channle，1 inch

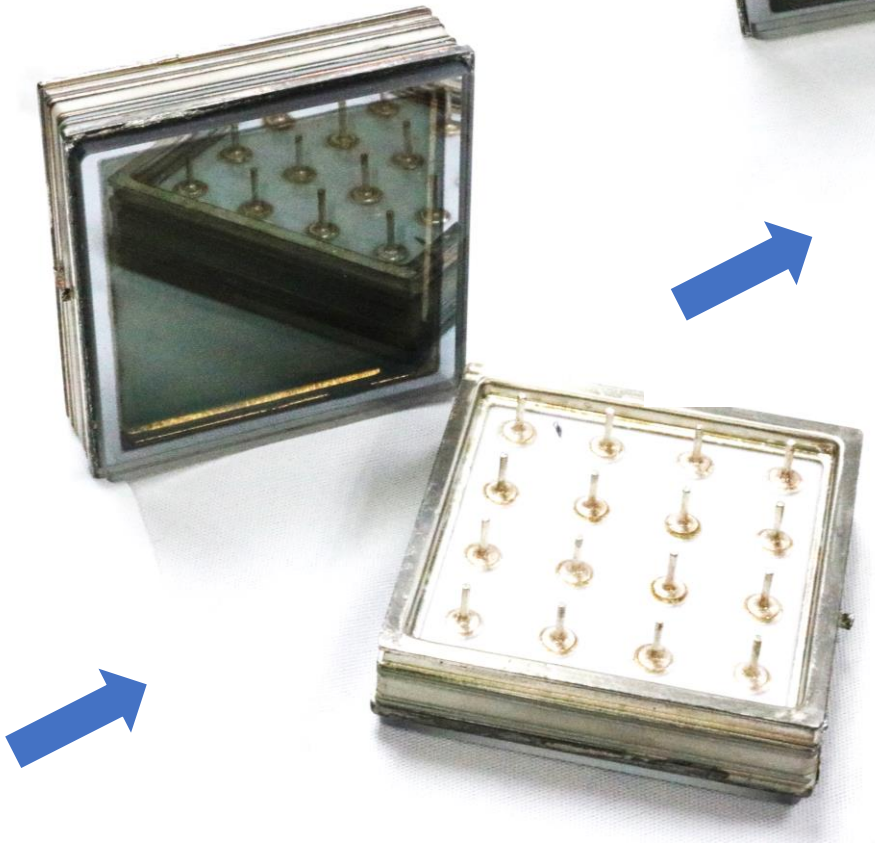


Ref: Qian Sen,The R&D of the Ultra Fast 8X8 Readout MCP-PMTs, reported in ICHEP2020, 30 July,2020

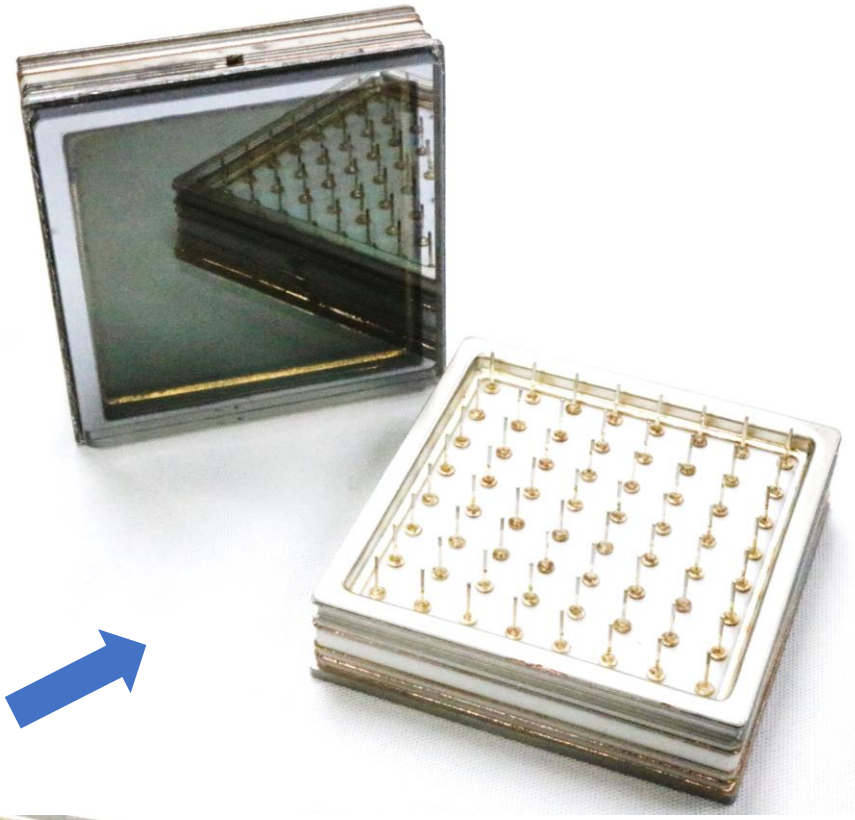
2.3 FPMT from single anode to 8*8 anode

Single Anode FPMT

2*2 Anodes FPMT



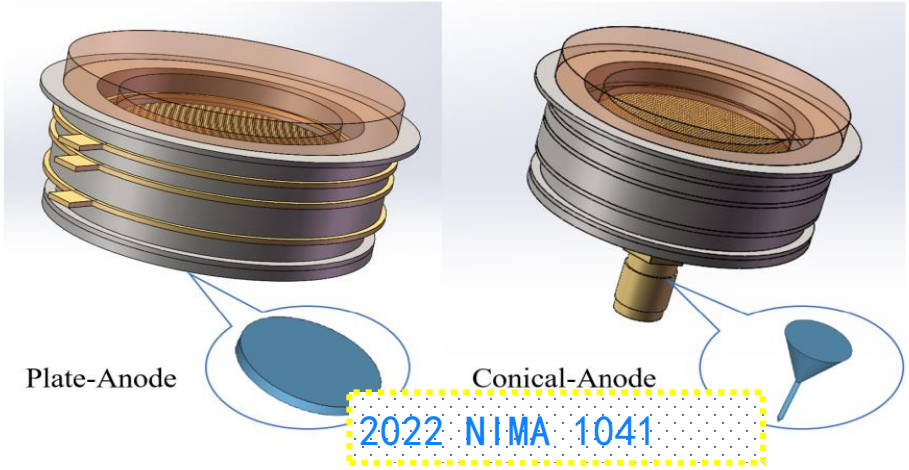
4*4 Anodes FPMT



8*8 Anodes FPMT

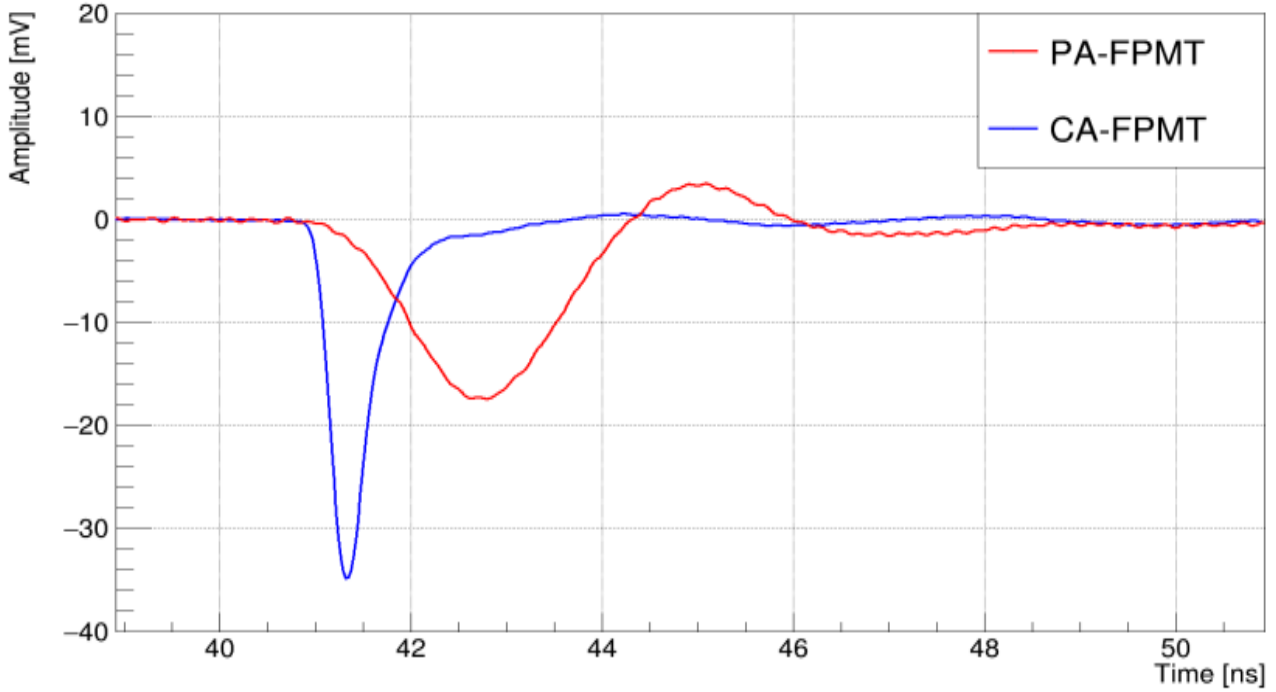
2.4 Performance of single anode FPMT

➢ Anode Optimization



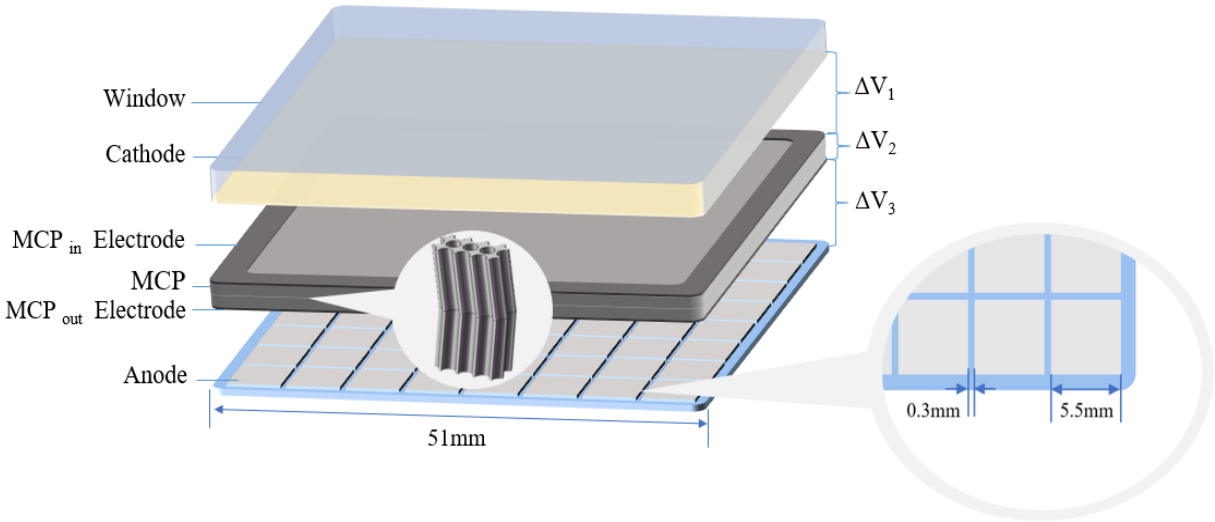
After anode structure optimization, the time performance has been greatly improved!

➢ Waveform comparison



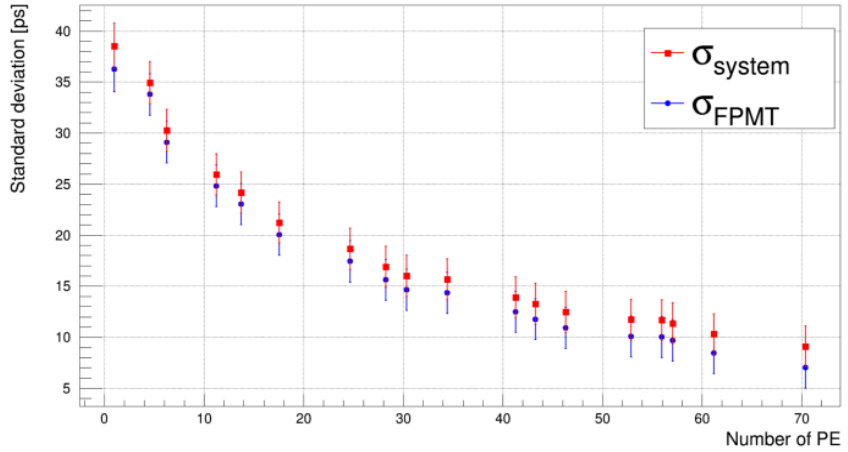
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	**96 ps**	350 ps	190ps	**45 ps**	10 ps
Plate-Anode	-2000	1.9E6	28.8	7 mV	**1.4 ns**	1.4 ns	1.8 ns	70 ps	25 ps
Conical-Anode	-3181	2.6E6	6.3	53 mV	**150 ps**	420 ps	330 ps	**27 ps**	**5 ps**

2.5 Performance of 8*8 anodes FPMT

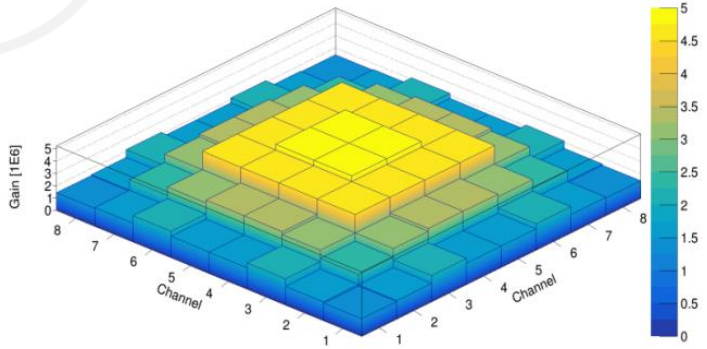


Basic structure of 8*8 anodes FPMT

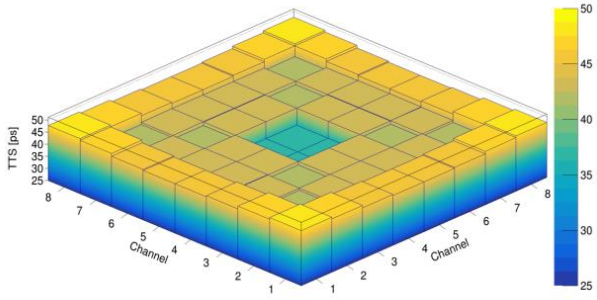
2022 JINST 17 T04002



➢ TTS Variation with light intensity



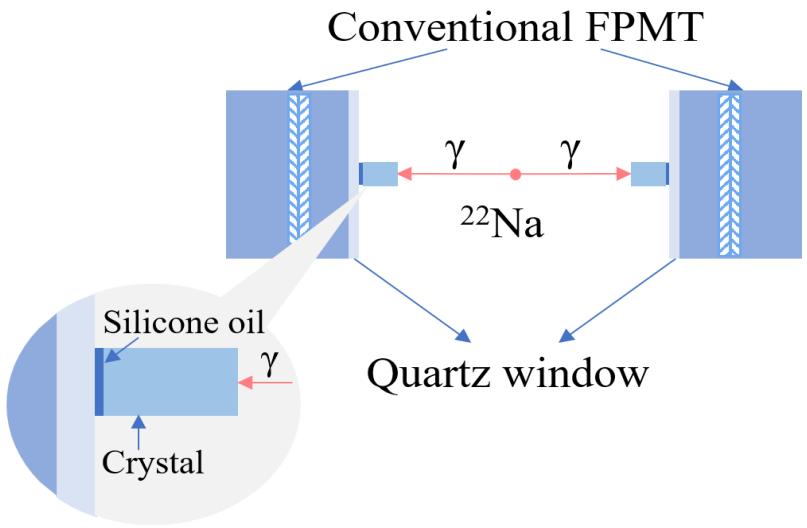
➢ Uniformity of gain

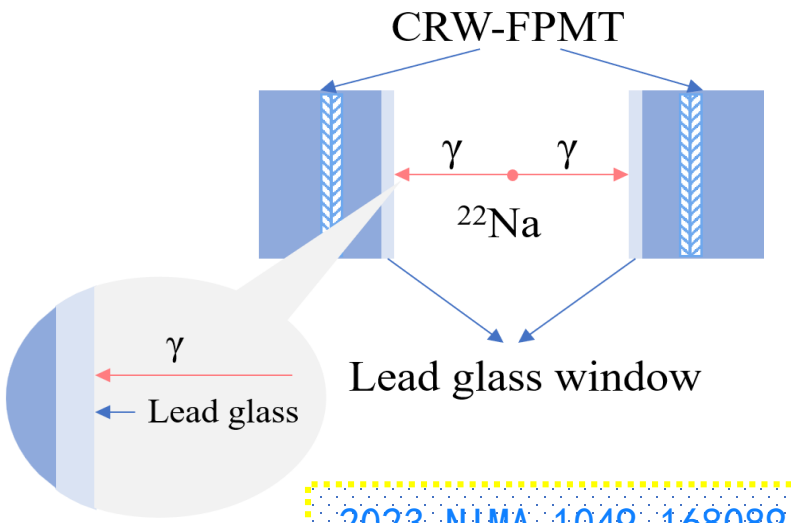


➢ Uniformity of TTS

	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**

2.6 Performance of 8*8 anodes Cherenkov Radiator Window-FPMT





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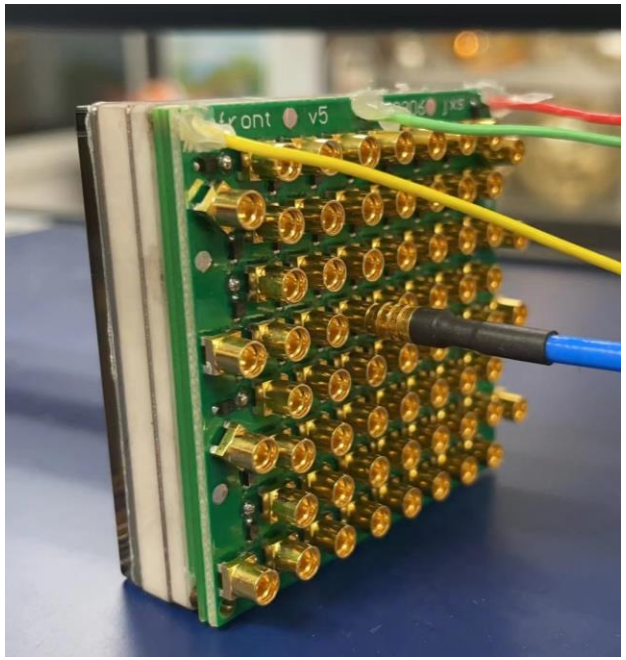
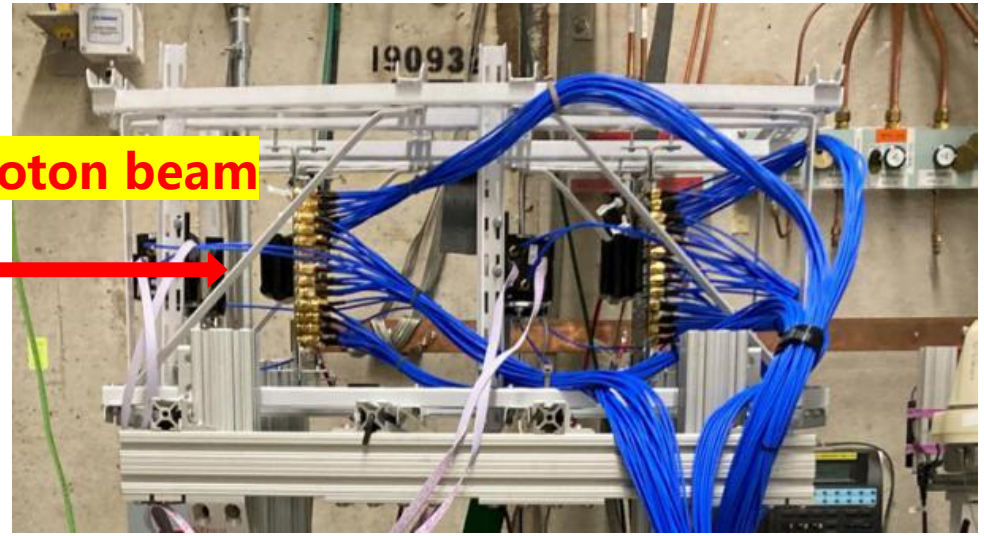


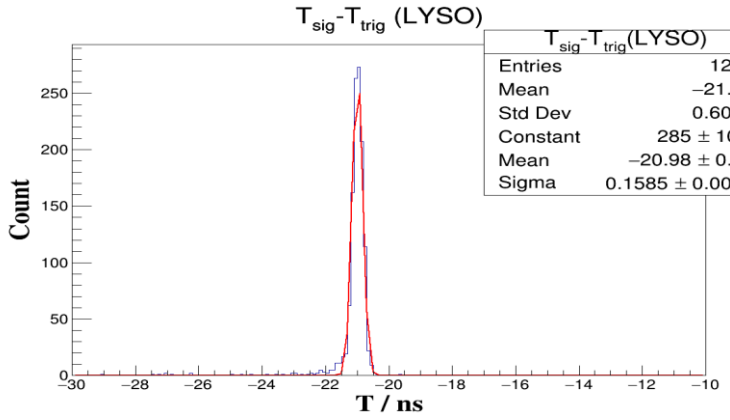
CRW-FPMT can detect particles directly!

	HV/V	Gain	P/V	幅度(SPE)	RT	FT	Pulse Width	TTS @SPE
CRW-FPMT-1	-2004	6.0E6	7.4	99.4 mV	**215.3 ps**	490.0 ps	424.0 ps	**27.2 ps**
CRW-FPMT-2	-1500	8.7E6	5.9	132.7 mV	287.0 ps	347.1 ps	467.1ps	**31.2 ps**

3.1 Beam test of 8*8 FPMT at Fermi Lab

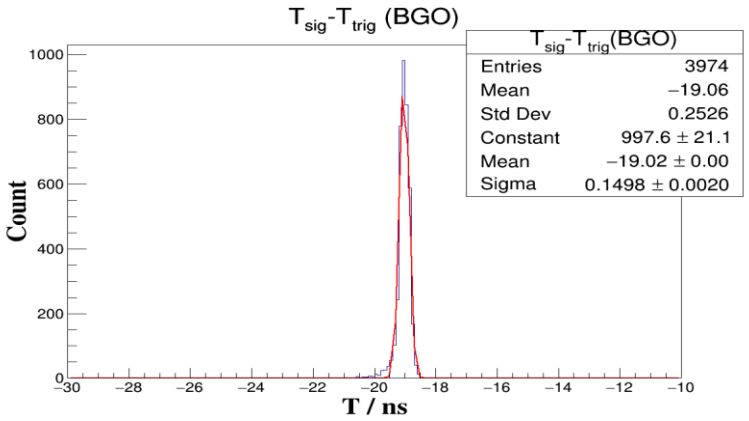


- Beam：120GeV Proton (Fermi)
- Crystal：LYSO & BGO
- PMT： 8*8 FPMT
- DAQ：CAEN V1742~50ps;
- Carried out by Zhenyu Ye (UIC)
  Zhihong Ye (THU)



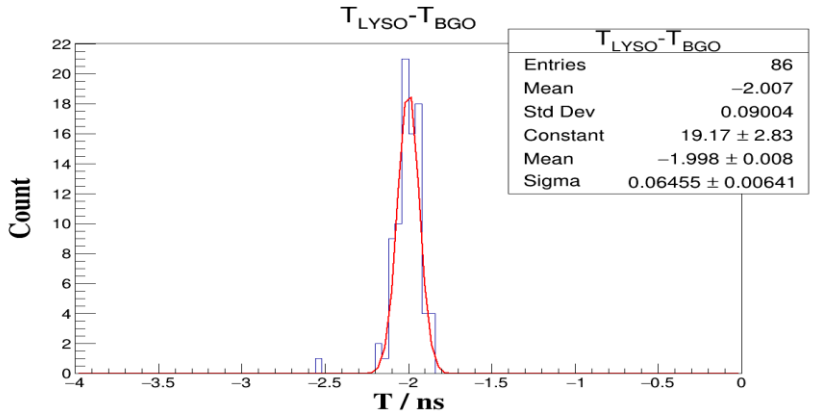
➢ LYSO single channel
Time Resolution

Sigma：158.5 ps



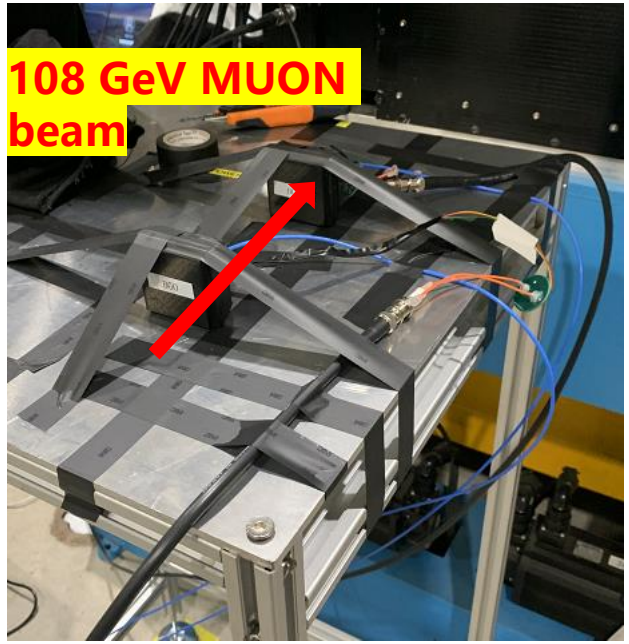
➢ BGO single channel
Time Resolution

Sigma：149.8 ps



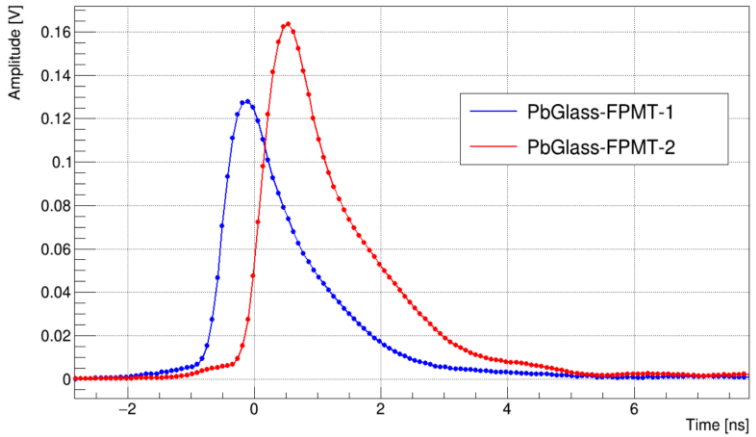
➢ LYSO & BGO
Coincidence Time jitter~64 ps
Single tube Time jitter **~45ps**

3.2 Beam test of 8*8 FPMT at CERN

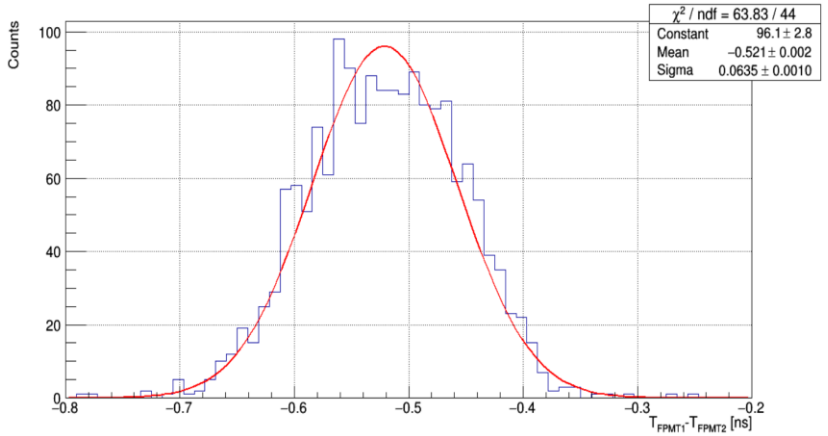


- **Beam:** (CERN)
  108GeV Muon
- **Scintillator:**
  Pb Glass, Quartz Glass;
- **PMT:** 8*8 FPMT
  TTS = 50ps@SPE;
- **DAQ:** 15 GSa/s ~ 25ps

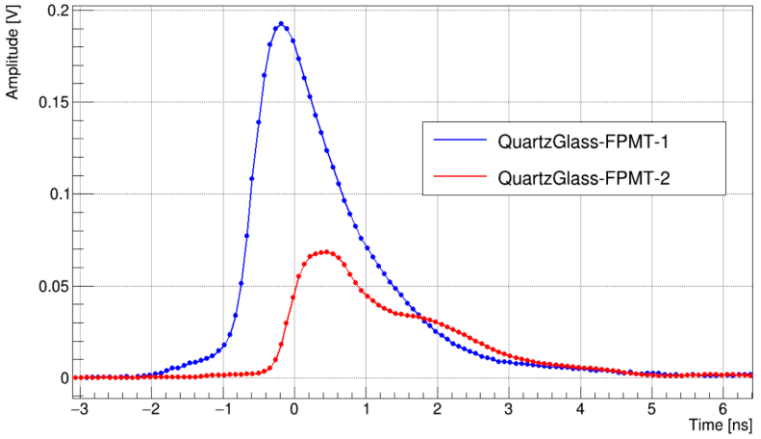
➢ Lead Glass + FPMT



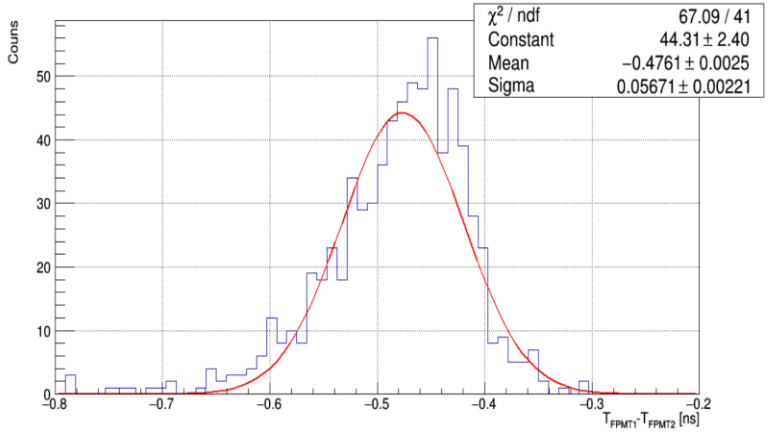
Coincidence time jitter~63 ps
Single tube Time jitter ~**45ps**



➢ Quartz Glass + FPMT



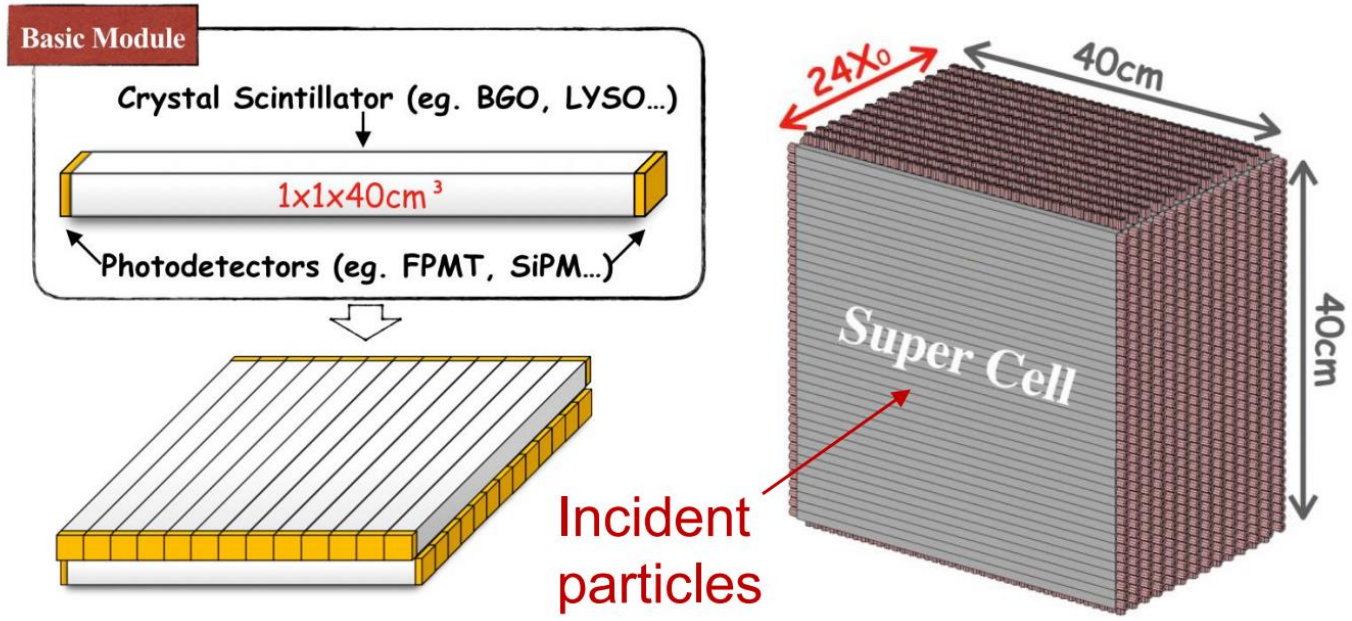
Coincidence time jitter~56 ps
Single tube Time jitter ~**40ps**



Summary

- FPMT tubes from single anode to 8*8 anode have been successfully developed.
- The TTS@SPE of single anode FPMT and 8*8 anode FPMT have both achieved **30 ps.**
- Beam test results are limited by electronics, and more detailed tests will be performed for the new generation of FPMT in the future.
- **Looking forward to the application of FPMT in HEPs.**

Potential Applications of FPMT-CEPC-ECAL

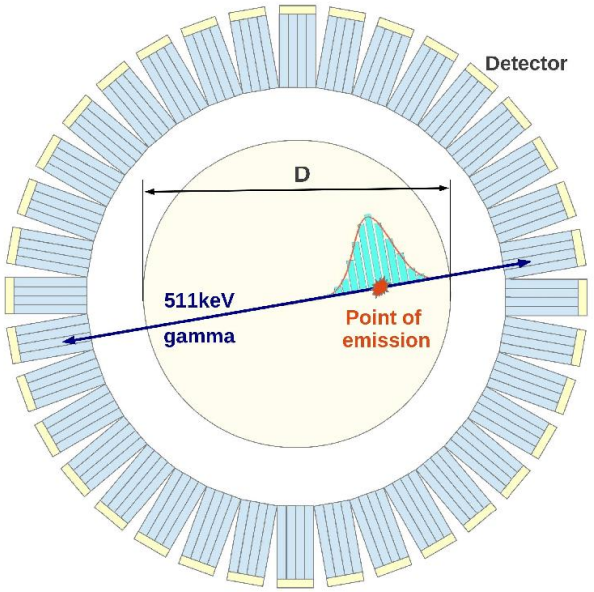


5D crystal ECAL
(3D spatial + energy + time)

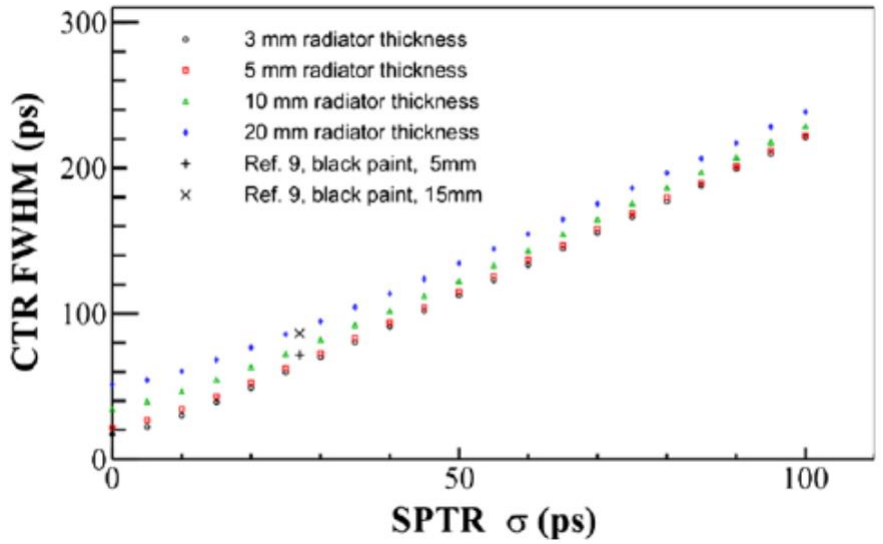
- FPMT has good single-photon detection capability
- FPMT has big sensitive area
- One FPMT can achieve a maximum of 64*64 channels of readout
- FPMT+LYSO ->excellent time resolution
- Low noise

Ref: Yong Liu, 3D Crystal Calorimeter for CEPC: R&D status, The 4th FCC Physics and Experiments Workshop Nov. 10-13, 2020

Potential Applications of FPMT-TOF-PET

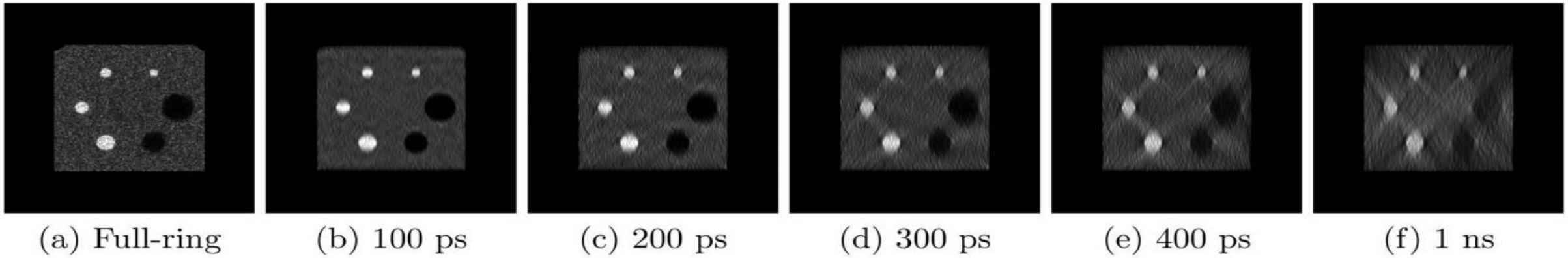


TOF-PET



CTR vs SPTR of FPMT

- If the CTR (FHWM) of TOF-PET is **<100ps**, its imaging quality will be greatly improved[ref1]
- **Demand for FPMT[ref2]: TTS@SPE <30ps**



Ref1:Ota, R. , et al. Medical Physics 45.5(2018).
Ref2: Qingguo Xie, et al. Conceptual Design and Simulation Study of an ROI-Focused Panel-PET Scanner. PLoS ONE 8(8): e72109.

CTR: Coincidence Time resolution
SPTR: Single Photon Time Resolution, characterized by TTS@SPE

Thanks for your attention!