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The Application of the Fast PMT beyond the High Energy Physics

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On behalf of the FPMT R&D Group

The 2023 International Workshop on the High Energy Circular Electron Positron Collider

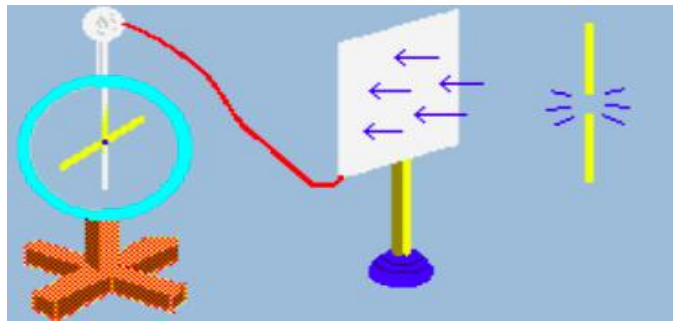
Nanjing

Oct 25，2023

Outline

- 1. Introduction of FPMT
- 2. FPMT application in HEPs
- 3. FPMT application beyond HEPs

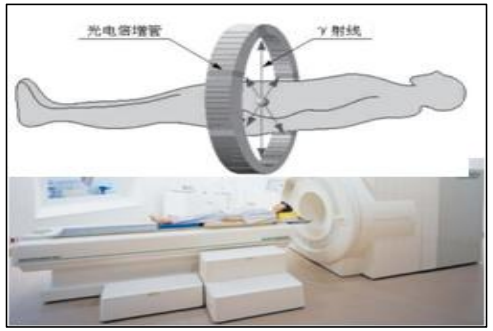
1.0 Introduction of PMT



Photoelectric effect principle

Family photo of domestic PMT

➢ High Energy Physics

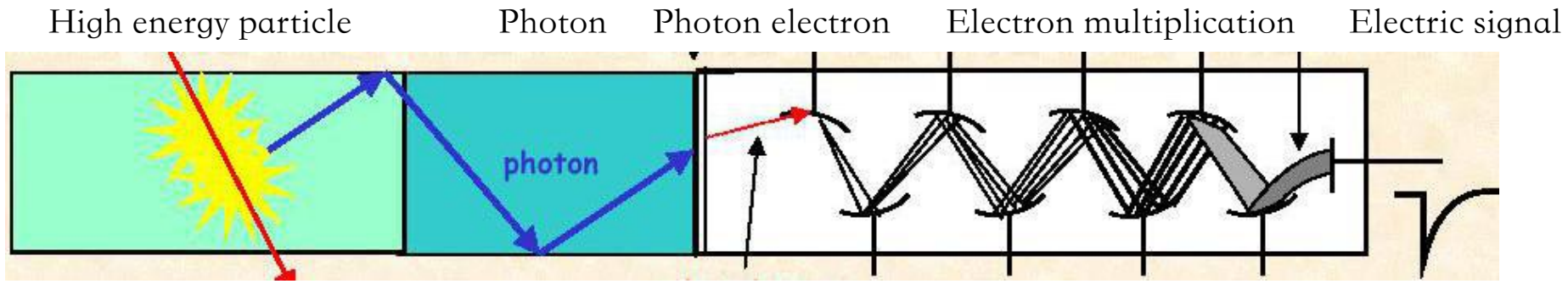


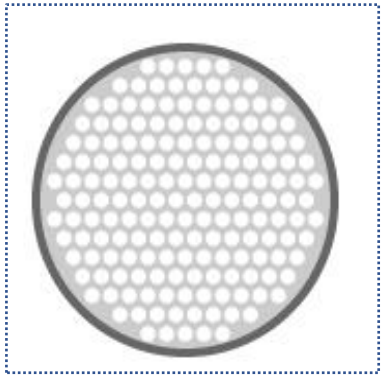
➢ Medical Instrument

➢ Aerospace

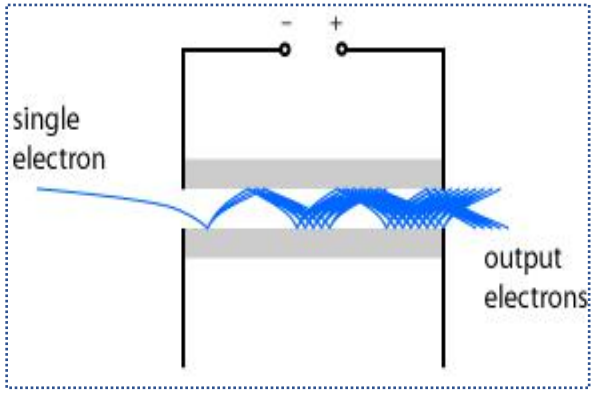
➢ Analytical Instrument

1.1 Nuclear radiation detection principle

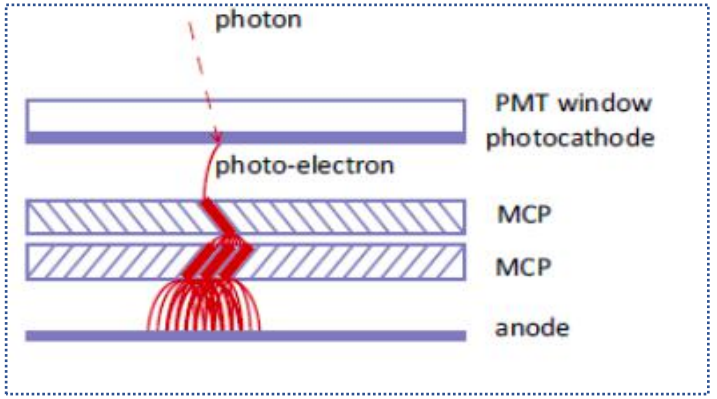




➢ Micro Channel Plate (MCP)



➢ Working principle of MCP



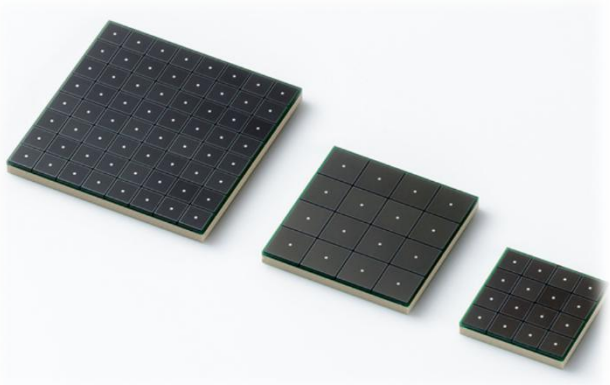
➢ Working principle of MCP-PMT

Fast time resolution position-sensitive photomultiplier (FPMT):

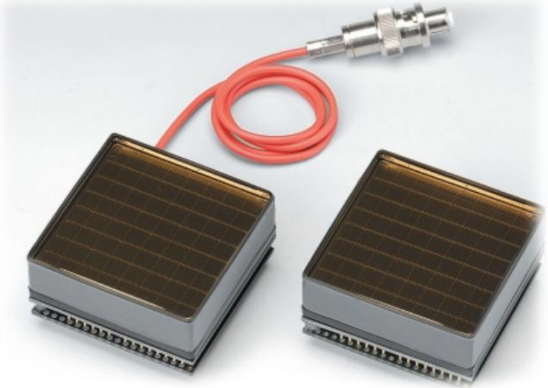
Fast time resolution= 50ps@SPE ; position-sensitive=8X8 anodes;

Magnetic resistance characteristic; Single photon detection;

1.2 Fast-timing Detectors



SiPM



Dynode -PMT

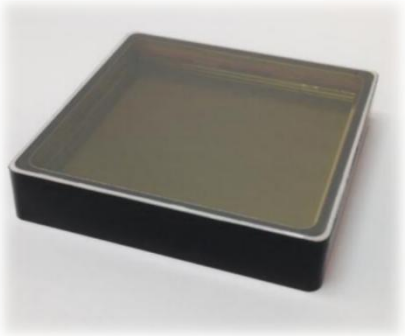
MCP -PMT (FPMT)

	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

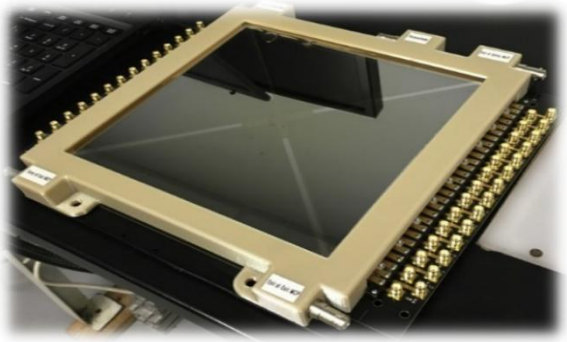
FPMT has ultra-fast time resolution and excellent magnetic field resistance!

1.3 FPMT Products

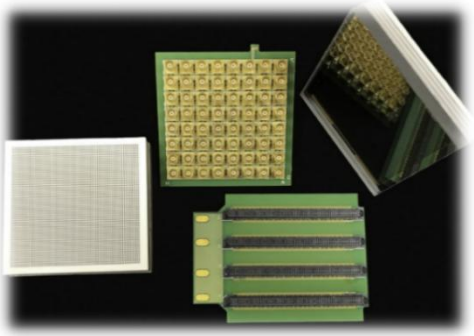
Hamamatsu(Japan)



Photonis (France)



LAPPD(USA)

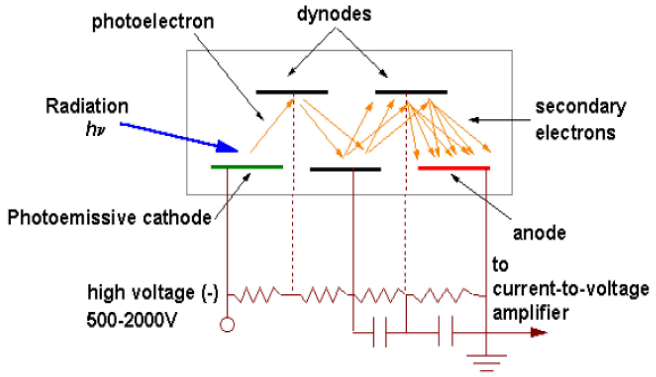
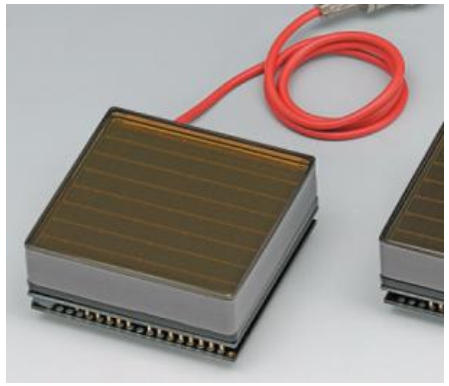
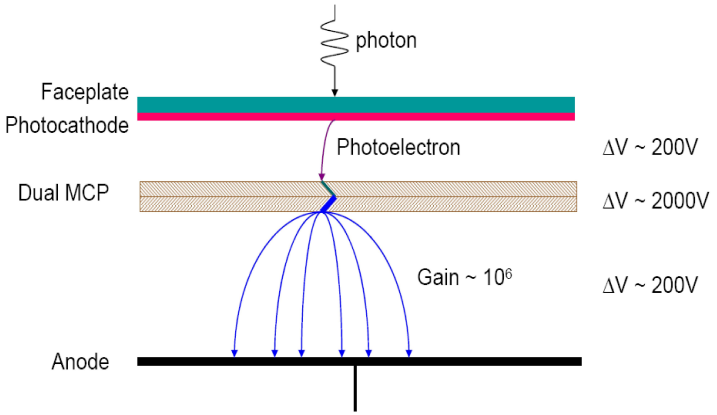
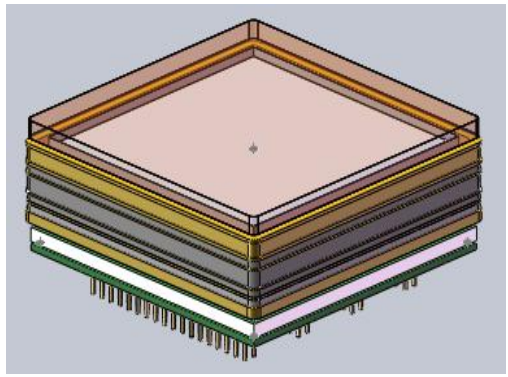


Photek(UK)

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!

1.4 R&D of Fast Timing PMT

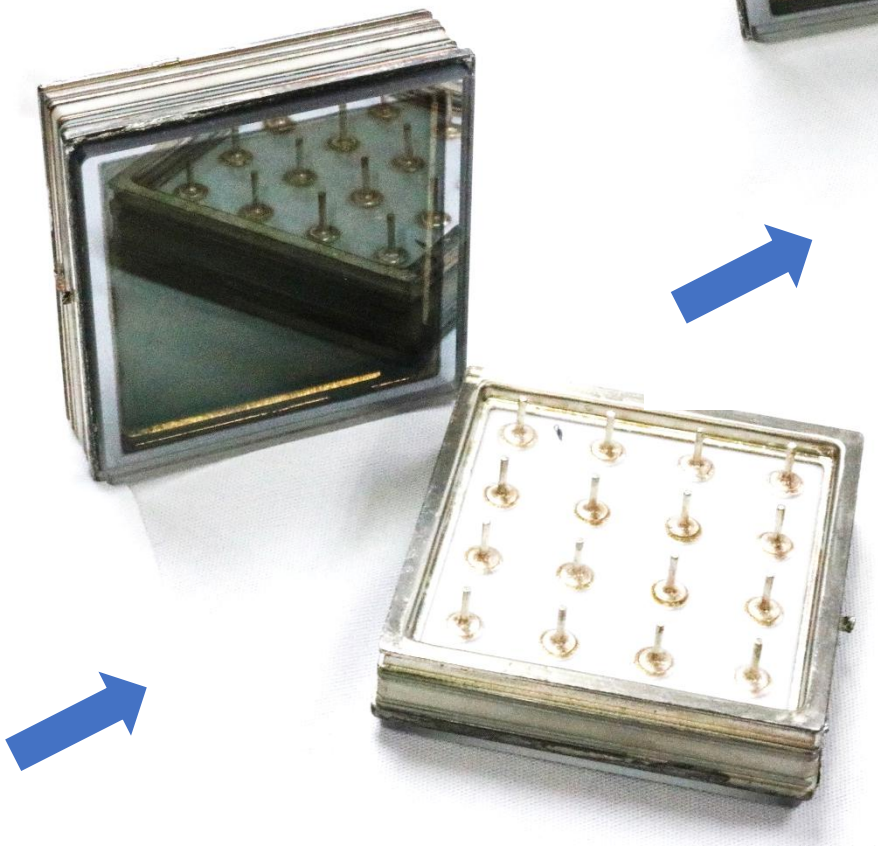
	Operation Principle	Small Size (proximity focusing)	Large Size (electrostatic focusing)
Dynode		2 " Dynode-PMT ✓  H8500	20 " Dynode-PMT ✓  R12860
MCP		2 " MCP-PMT ? 	20 " MCP-PMT ✓ 

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!

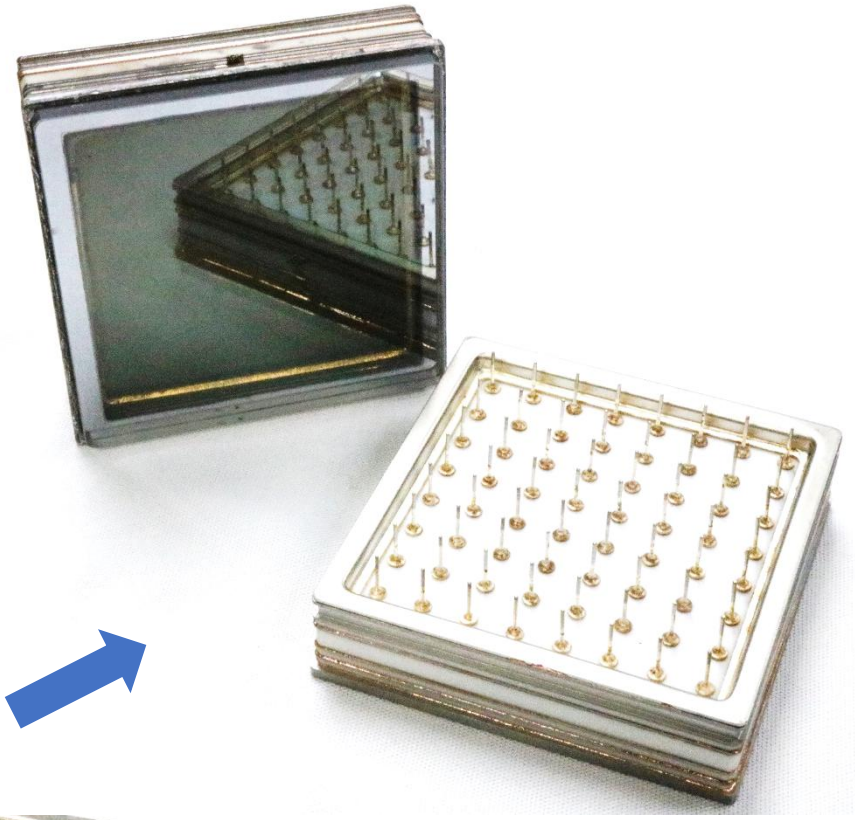
1.5 FPMT from single anode to 8*8 anodes

Single Anode FPMT

2*2 Anodes FPMT

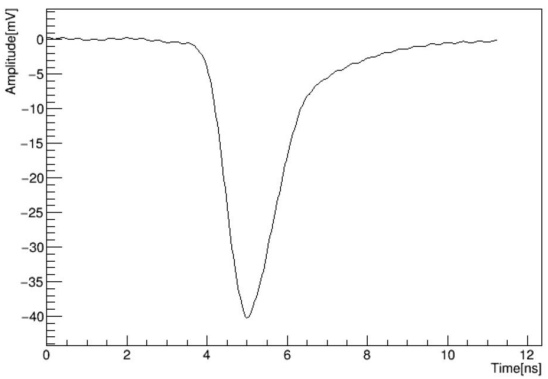


4*4 Anodes FPMT

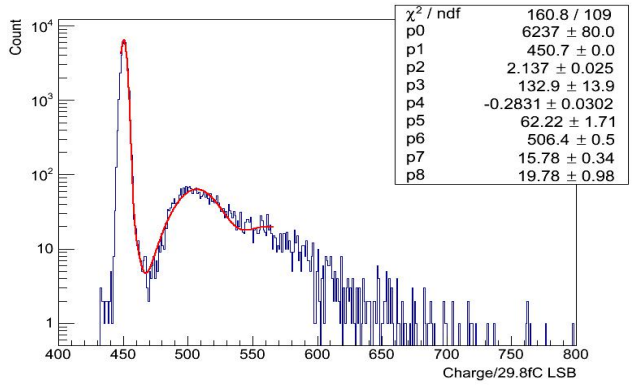


8*8 Anodes FPMT

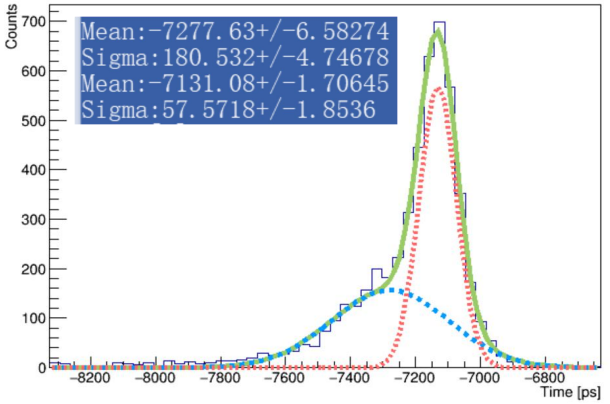
1.6 FPMT Performance Calibration



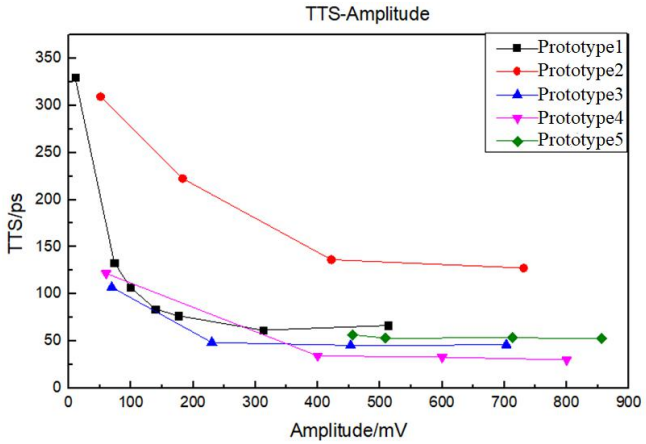
Waveform



SPE



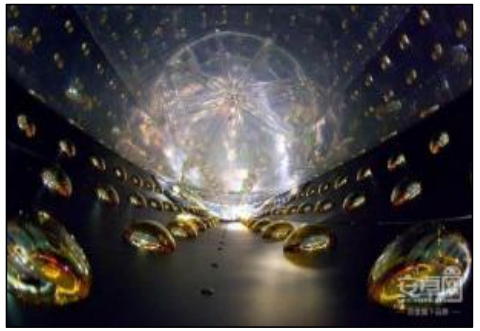
TTS@SPE



TTS@MPE

Anode Structure	FPMT Type	QE@400nm	gain	P/V	RT	Width	TTS@SPE	TTS@MPE
Single Anode	Photek-210	16.4%	1.0×10^6	10.9	111ps	195ps	29ps	Not Given
	IHEP-1- PMT	22.7%	**2.6×10^6**	6.3	150 ps	330 ps	27ps	5ps
Multi Anode	Photek-253	14.1%	1.0×10^6	Not Given	175ps	430ps	40ps	Not Given
	IHEP 2*2 FPMT	22.5%	1.9×10^6	6.5	**243ps**	378ps	66.8ps	16.6ps
	IHEP 4*4 FPMT	21.2%	**1.0×10^7**	1.8	431ps	Not test	106.6ps	28ps
	IHEP 8*8 FPMT	21.6%	4.0×10^6	18.6	334ps	900ps	**40 ps**	**10 ps**

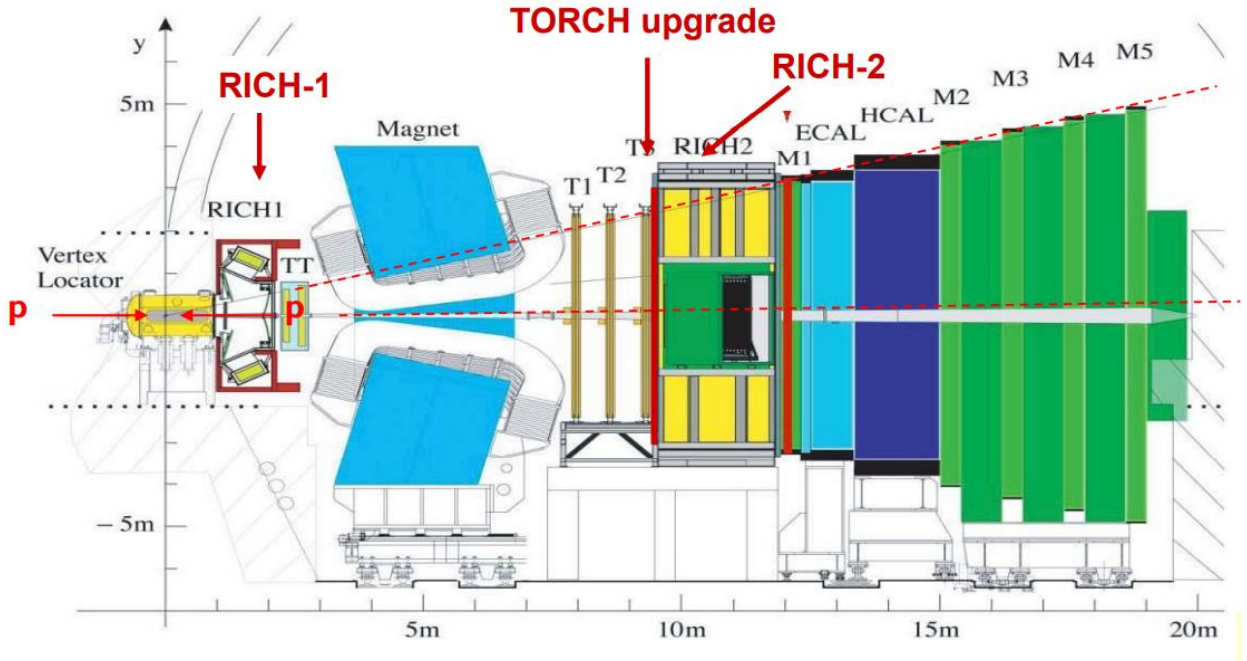
- 1. Introduction of FPMT
- 2. FPMT application in HEPs
- 3. FPMT application beyond HEPs



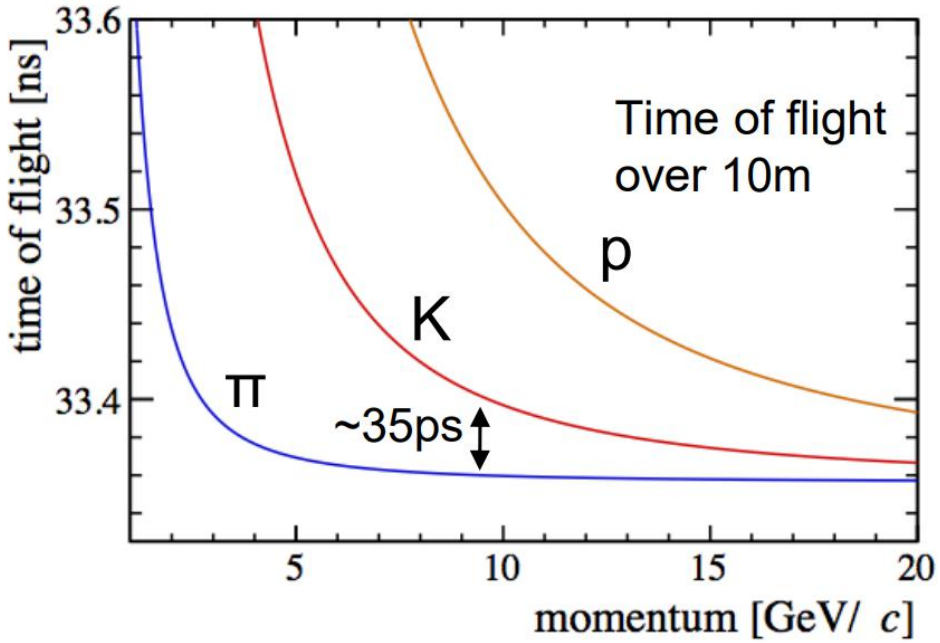
High energy physics

- 2.1 LHCb-TORCH
- 2.2 EIC-RICH
- 2.3 CEPC-PID
- 2.4 STCF-DIRC
- 2.5 TOF-ECAL

2.1 Potential Applications of Fast timing detector-TORCH



LHCbII Upgrade –TORCH
(Time Of internally Reflected CHerenkov light)



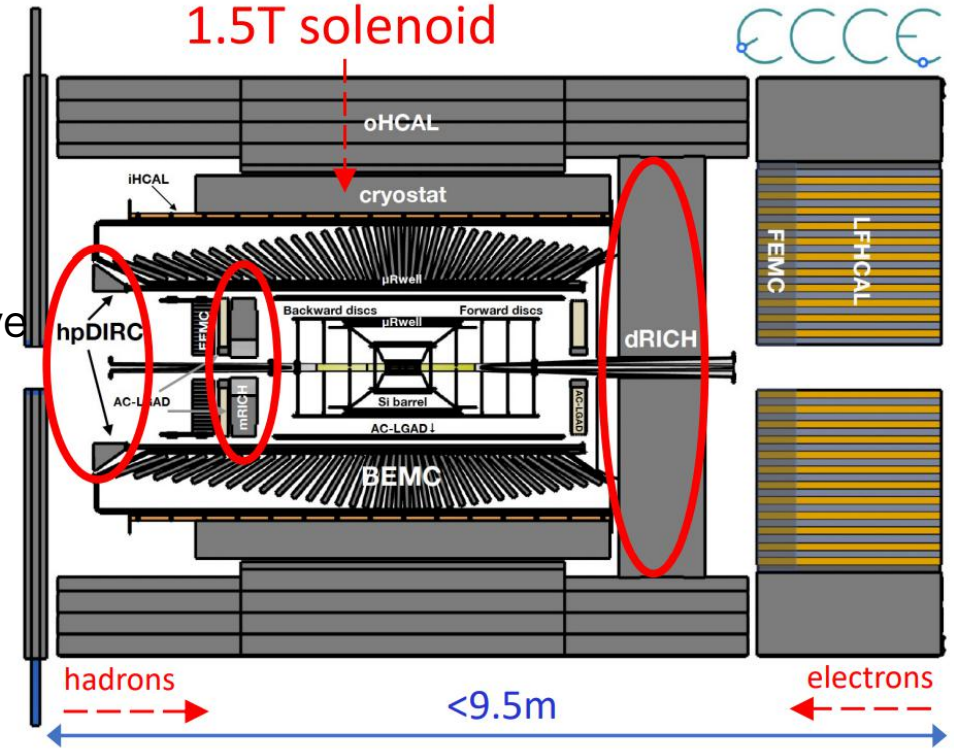
PID of pions, kaons and protons

- 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

2.2 Potential Applications of Fast Timing Detector-EIC-RICH

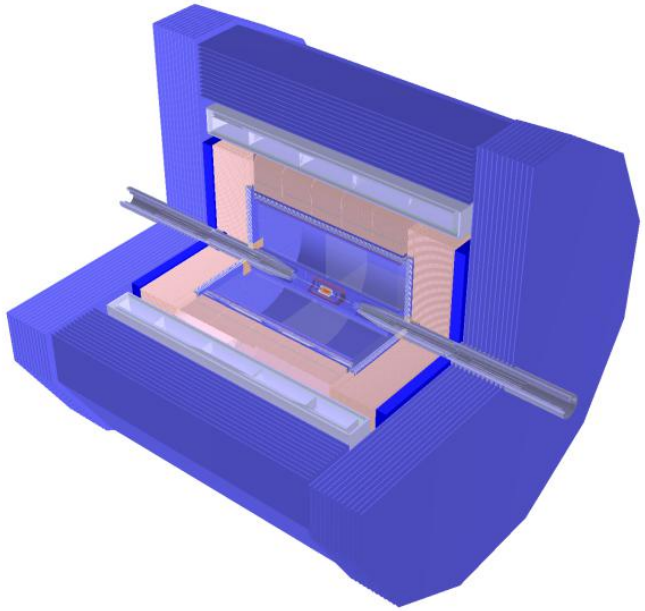
- The U.S. has approved the construction of EIC in BNL
  - 10 GeV/c electrons + 100 GeV/c protons
  - Measure the three-dimensional distribution of gluons inside nucleons and nuclei, the mystery of proton spin, the mystery of mass, the saturation of gluons, etc
- EPIC is one of the detectors on the collision 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



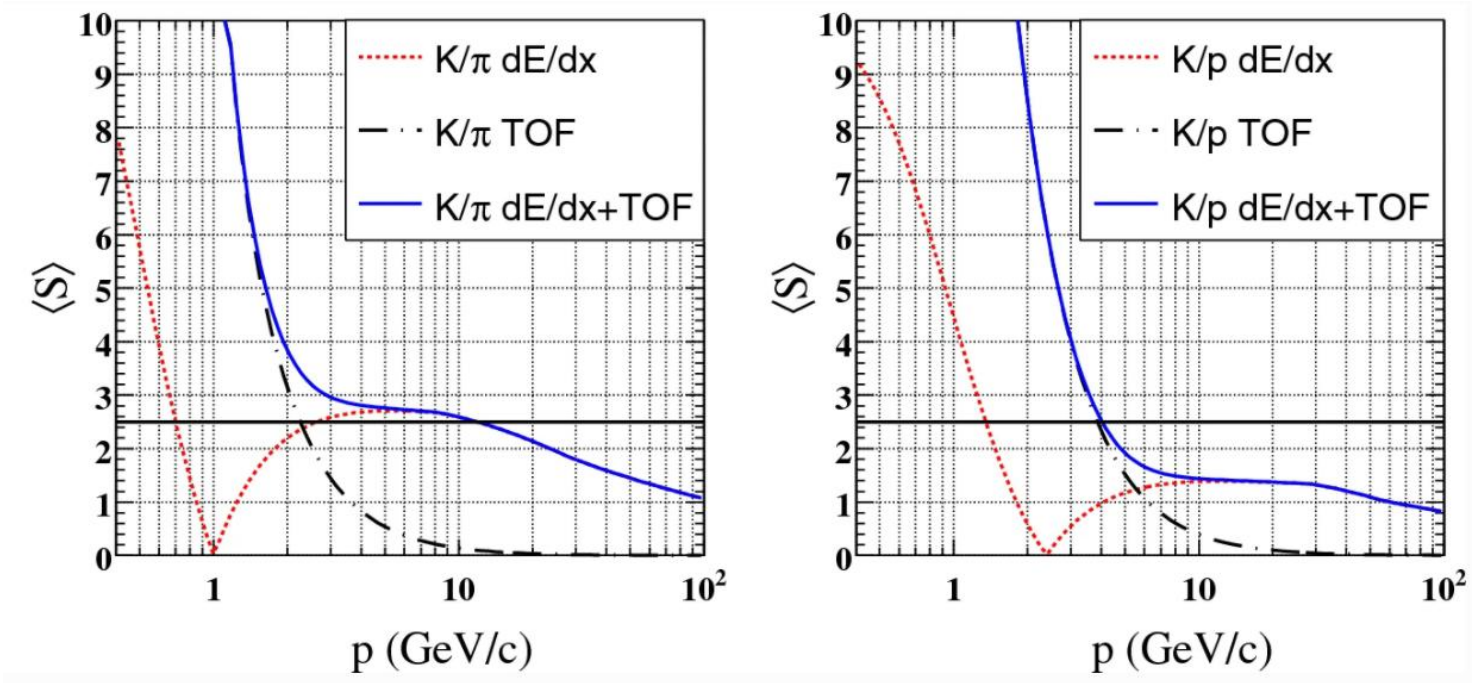
	Default option	Single photon time resolution	Spatial resolution equivalent	Sensor area
E-endcap mRICH	SiPMs	best possible	~3mm pixels	64 ~10x10 cm^2 spots
Barrel DIRC	MCP-PMTs	<100 ps	~3mm pixels	~0.65 m^2 total
H-endcap dRICH	SiPMs	~100 ps	~3mm pixels	~3.10 m^2 total

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

2.3 Potential Applications of Fast Timing Detectors-CEPC-PID



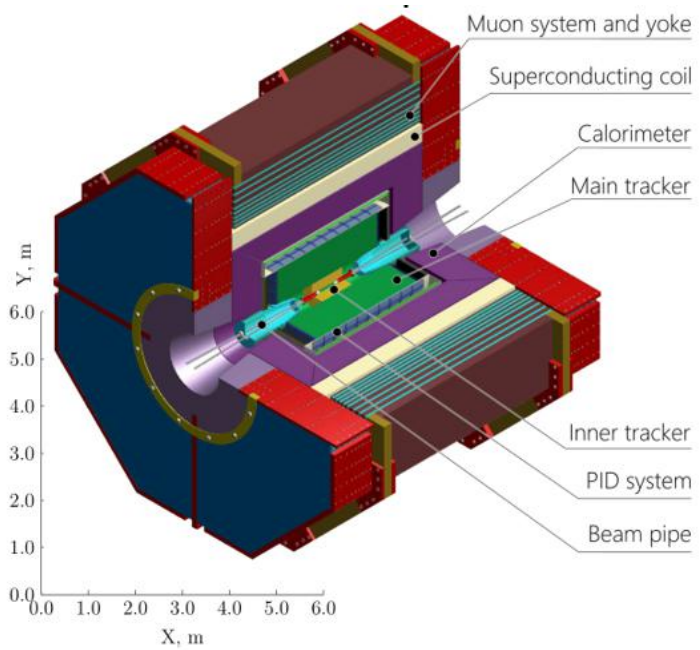
CEPC Detector



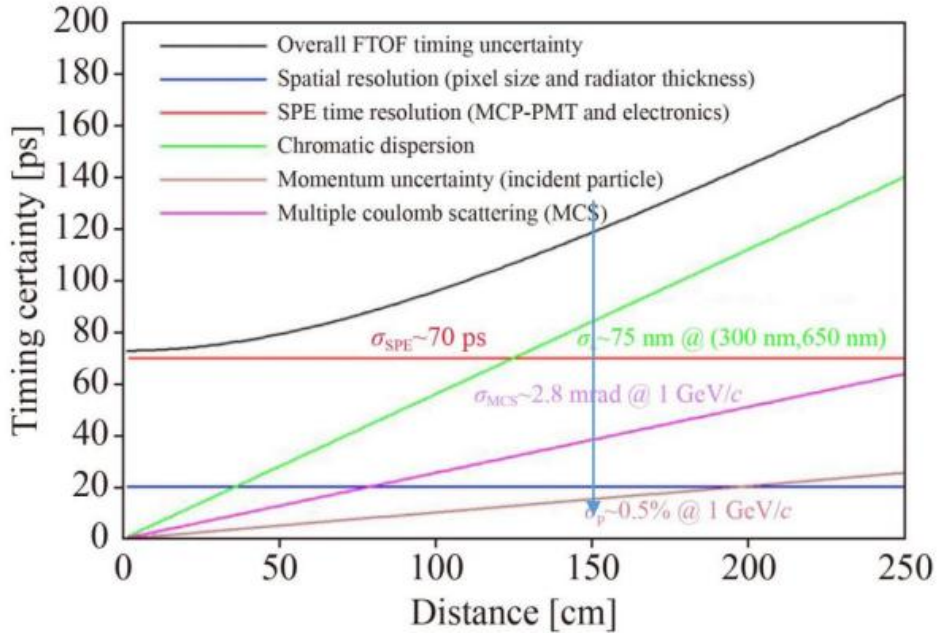
Supposing TOF information with a 50 ps time resolution, accounting for the time resolution and the location of the ECAL, the TOF information can provide K/π (K / p) separation better than 2.5 σ up to 2.1 (4.0) GeV/c. By combining TOF and dE / dx, more than 2.0 (1.4) σ K/π (K / p) separation can be achieved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

2.4 Potential Applications of Fast timing Detector- STCF



The STCF Detector Conceptual Design



The DTOF detector of STCF

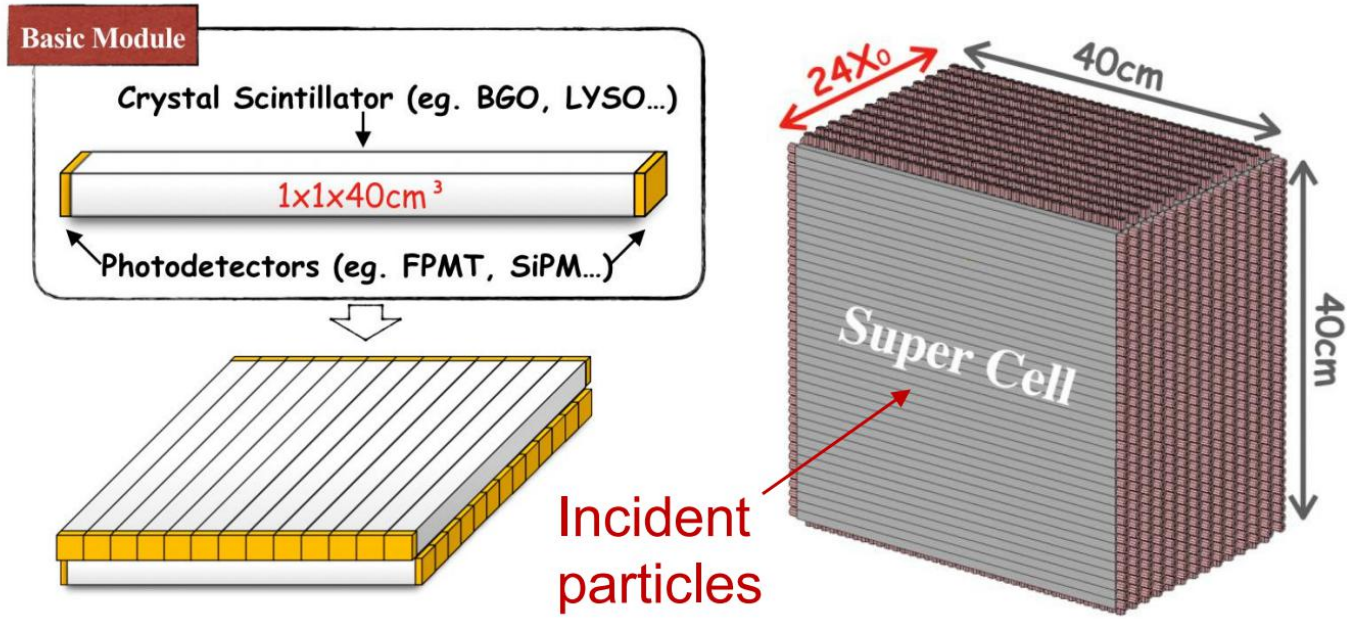
The DIRC-like high-resolution TOF detector is proposed.

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

2.5 Potential Applications of FPMT-CEPC: TOF-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

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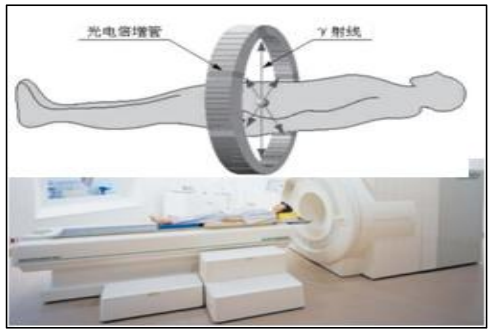


➢ Medical Instrument

- 3.1 TOF-PET

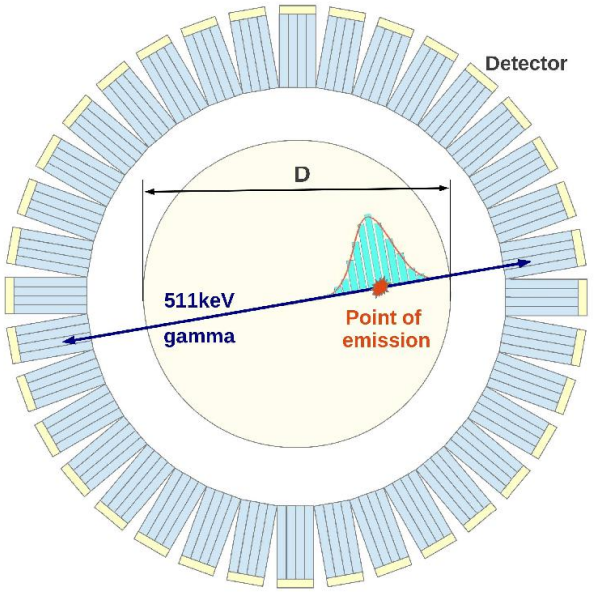
➢ Aerospace

- 3.2 LIDAR

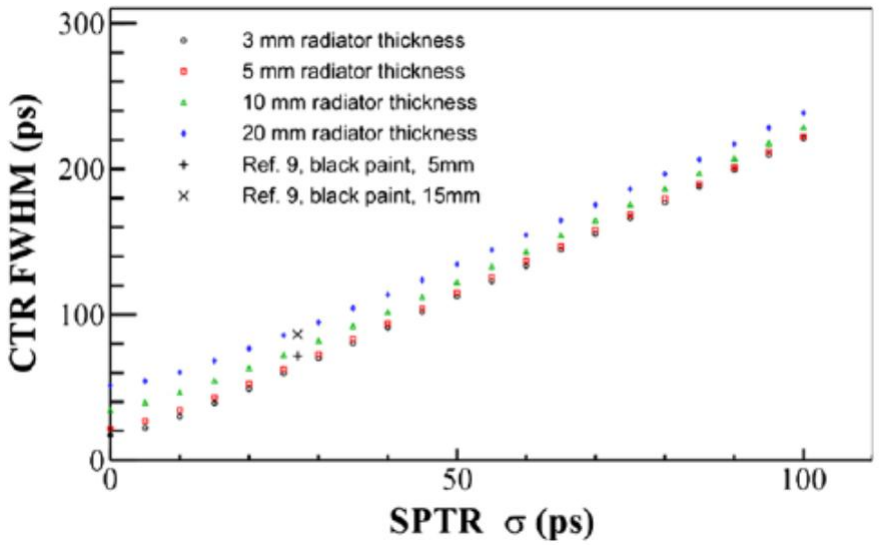
➢ Analytical Instrument

- 3.3 TCSPC
- 3.4 Flow cytometry
- 3.5 Two-photo microscope

3.1 Potential Applications of FPMT-TOF-PET

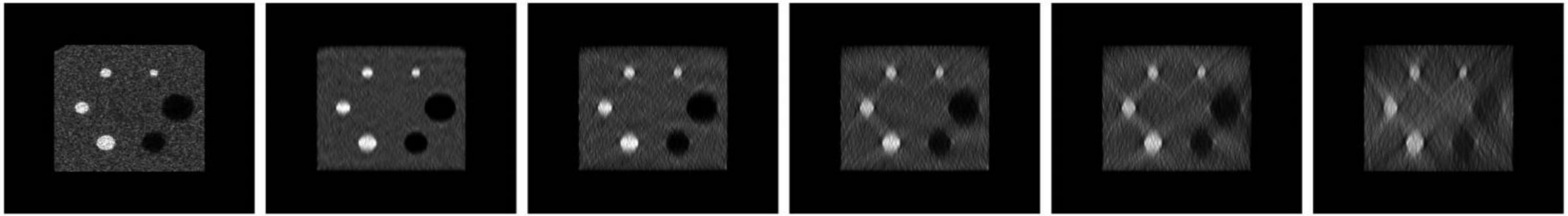


TOF-PET



CTR vs SPTR of FPMT

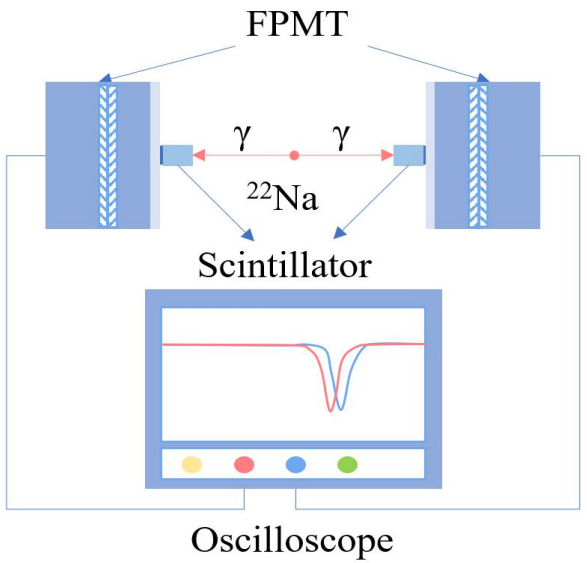
- If the CTR (FHWM) of TOF-PET is <100ps, its imaging quality will be greatly improved[ref1]
- Demand for FPMT[ref2]: TTS@SPE <30ps

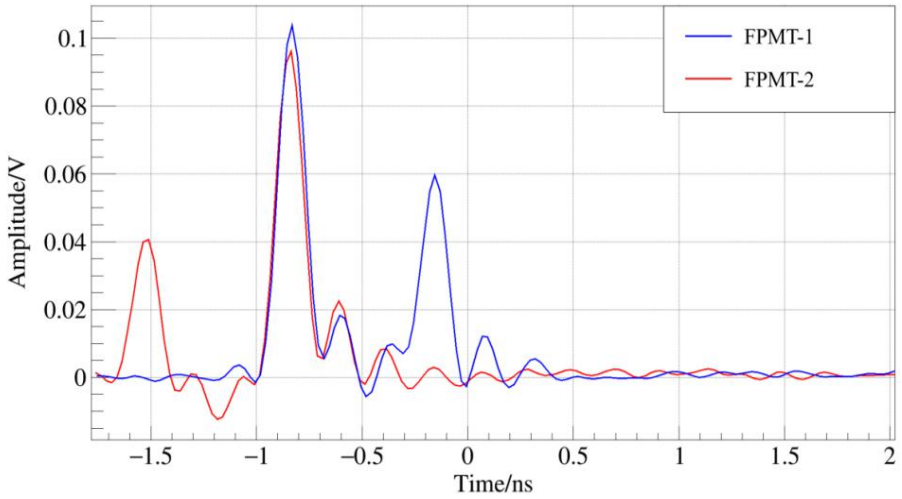


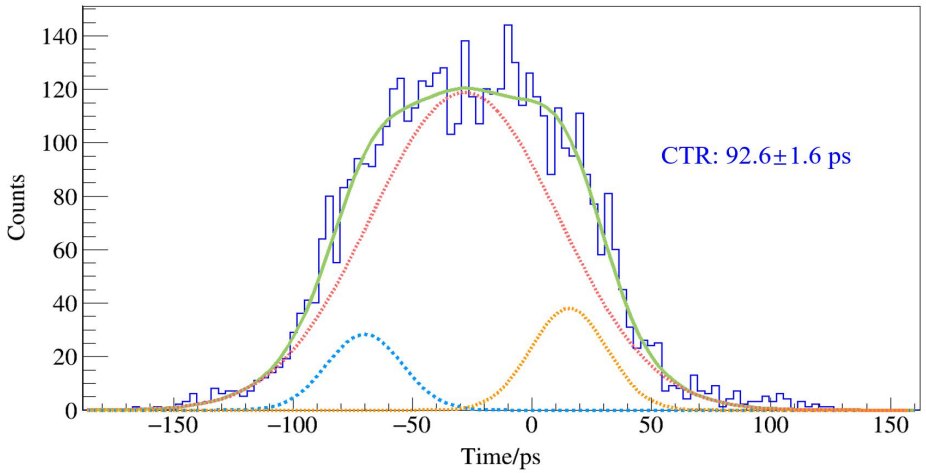
(a) Full-ring (b) 100 ps (c) 200 ps (d) 300 ps (e) 400 ps (f) 1 ns

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







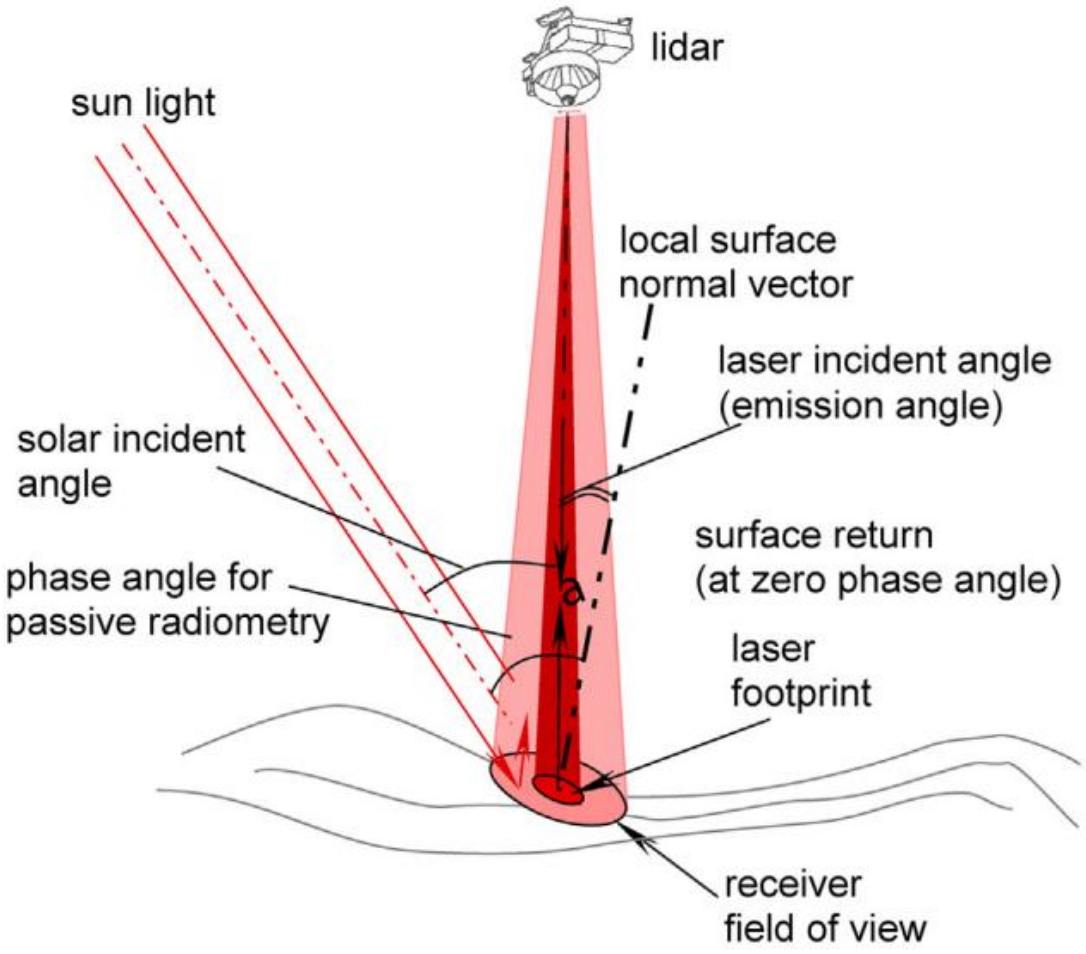
➢ Principle of CTR based on FPMT

➢ Typical coincidence waveform

➢ CTR result of FPMT coped with LYSO

- The FWHM of the main peak is the CTR obtained from the FPMT coupled LYSO crystal test.
- That is, CTR= 92.6±1.6 ps, which is better than the test result of SiPM coupled LYSO.

3.2 Potential Applications of FPMT-In Aerospace



LIDAR for space program [ref1]

Space programs based on LIDAR instrumentations, recording altitude dependent laser scattered signal from the atmosphere, ocean and ground, require state-of-the-art detectors

Requirements for the detector

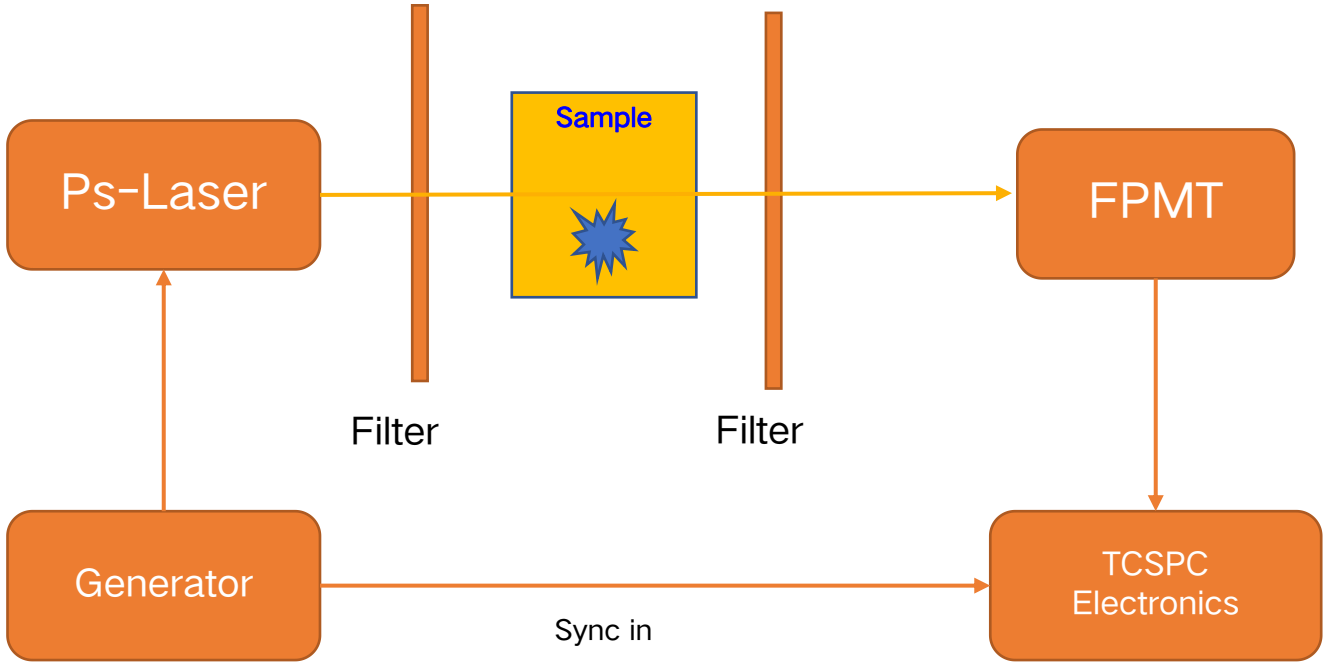
- excellent timing response
- high dynamic range
- best properties for single photon counting detection
- Long life time

Ref1: http://www2.geog.ucl.ac.uk/~mdisney/teaching/GEOGG141/papers/lidar_from_spave.pdf
Ref2: Dmitry A. Orlov, et al. From single photon counting to high rate capability with fast timing MCP-PMTs for LIDAR, https://doi.org/10.1117/12.2519061

3.3 Potential Applications of FPMT- TCSPC-FILM

TCSPC: Time-Correlated Single Photon Counting

FILM: Fluorescence Lifetime IMaging



Schematic diagram of fluorescence lifetime test

IRF: Instrument response function

Can be used to characterize the test accuracy of the system[ref1]

Jitter of optical

Jitter of electronics

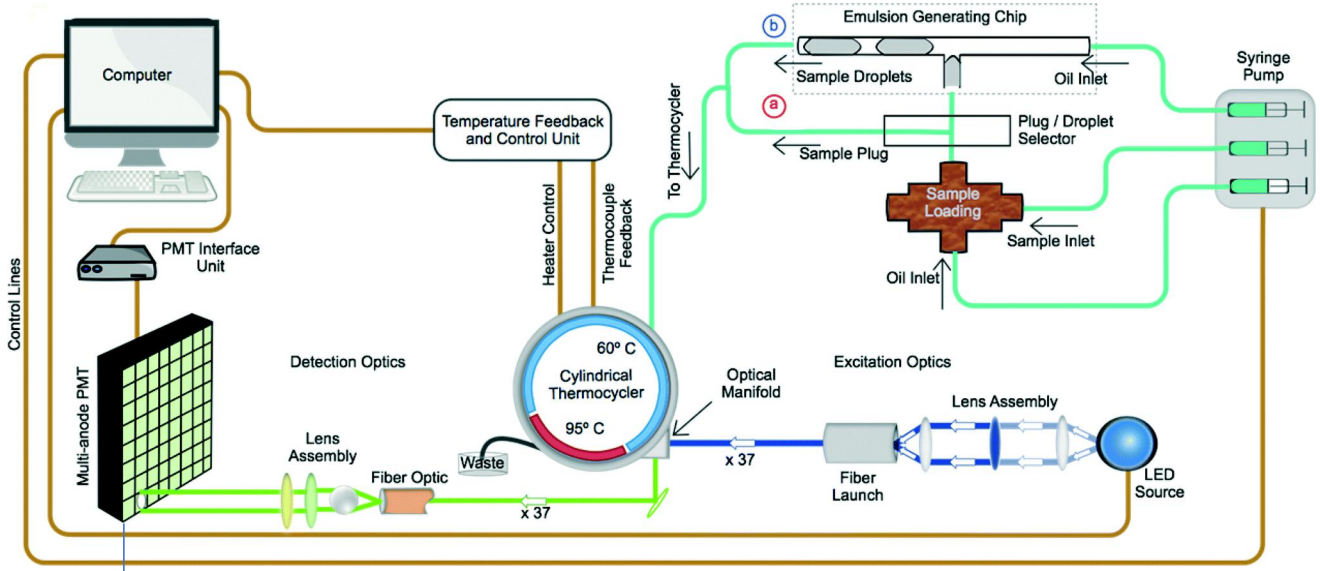
$$\Delta t_{IRF}^2 = \Delta t_{optical}^2 + \Delta t_{tts}^2 + \Delta t_{jitter}^2$$

TTS of FPMT

If IRF of <20ps[ref2], the TTS (Sigma) of FPMT needs to be <10ps

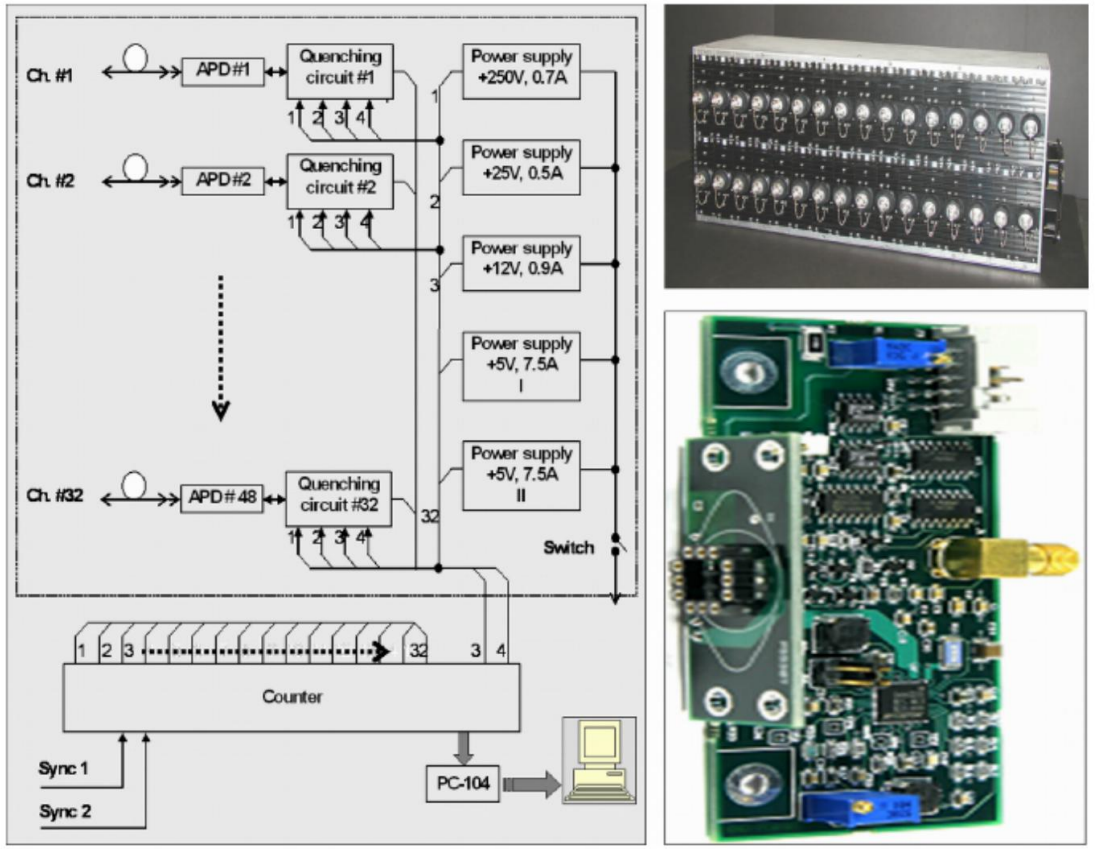
Ref1: Wolfgang Becker et al, Rev. Sci. Instrum. 87, 093710 (2016)
Ref2:https://www.becker-hickl.com/wp-content/uploads/2018/12/sub-20ps-irf-v03.pdf

3.4 Potential Applications of FPMT-Flow cytometry



Working principle of multi-channel PMT-based RT-PCR[Ref1]

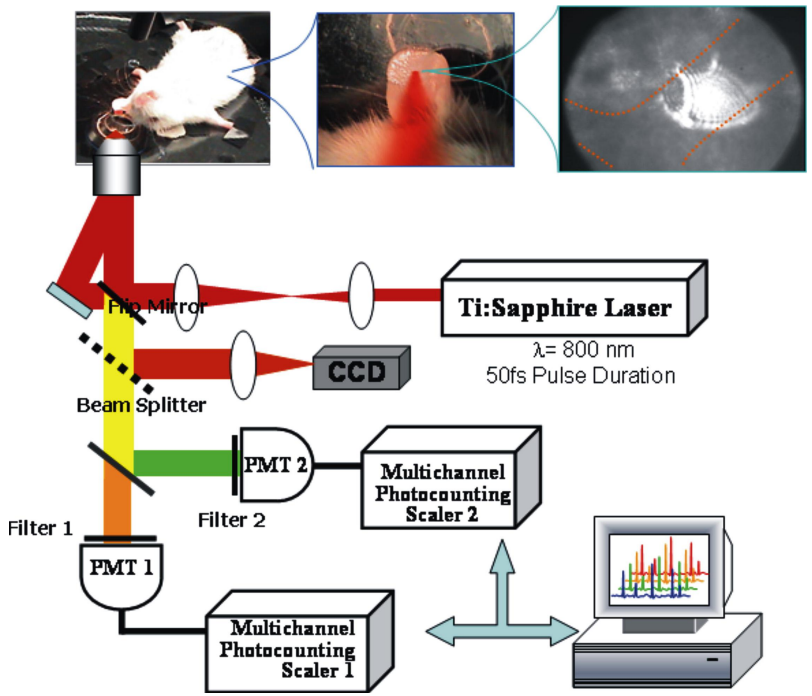
- High gain required
- Good single photon resolution
- High signal-to-noise ratio
- Fast time response capability
- Multi-Channel Readout



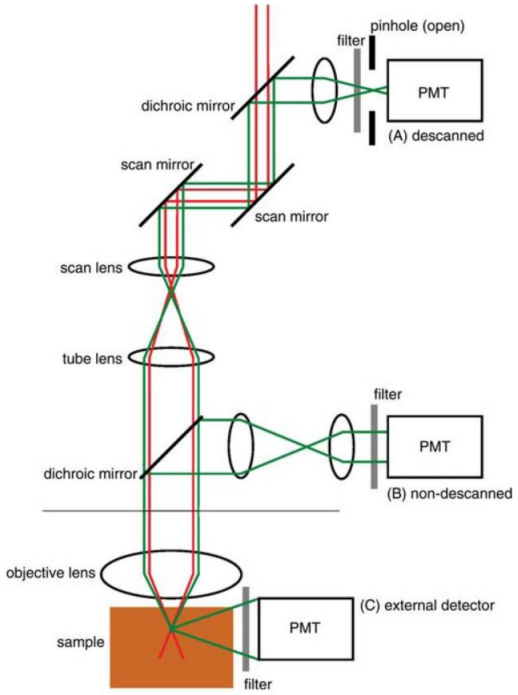
SPAD-based multi-channel DNA sequencing device probe module [Ref2]

Ref1: Andrew C. Hatch, Lab Chip, 2014,14, 562-568
Ref2: Georgiy Gudkov, et al."Proc. SPIE 6372, Advanced Photon Counting Techniques, 63720C (3 November 2006)

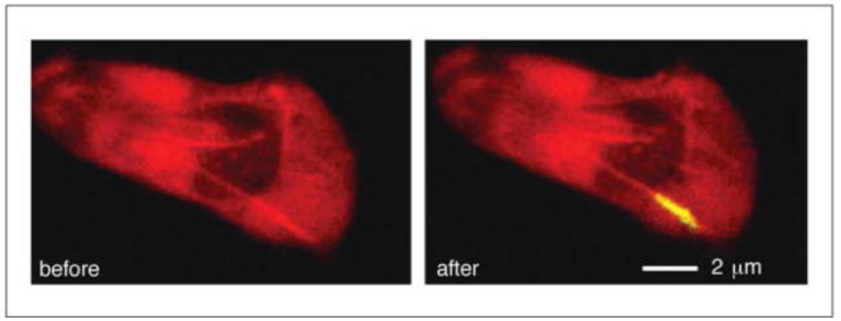
3.5 Potential Applications of FPMT-Two-photon microscope



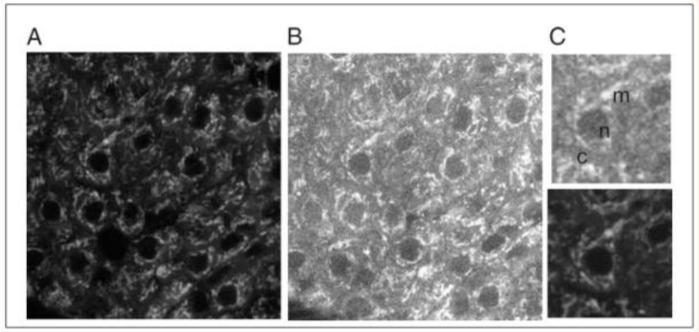
Dual-channel, two-photon flow cytometry for in vivo measurements[ref1]



Principles of two-photon microscopy[ref2]



Well-positioned photoactivation of light-converting fluorescent proteins by two-photon excitation[ref2]

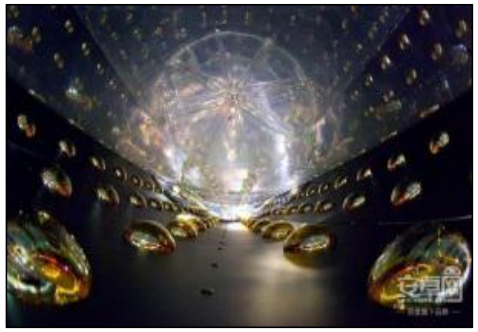


Two-photon imaging in pancreatic islet detection[ref2]

- The in vivo application of multichannel flow cytometry using two-photon excitation will greatly enhance the ability to study circulating cells in cancer and other disease processes.

If the time resolution of the PMT and photon counter is raised to the order of ps, the technology will have revolutionary progress in the field of real-time imaging of circulating cellular gene expression changes and blood vessels in vivo.

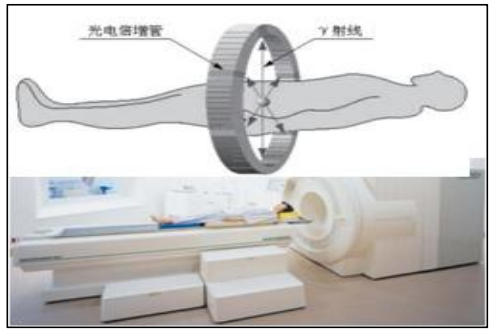
Ref1: Tkaczyk ER, Zhong CF, Ye JY, et al. In Vivo Monitoring of Multiple Circulating Cell Populations Using Two-photon Flow Cytometry. Opt Commun. 2008 Feb 15;281(4):888-894.
Ref2: Benninger RK, Piston DW. Two-photon excitation microscopy for the study of living cells and tissues. Curr Protoc Cell Biol. 2013;Chapter 4:Unit-4.11.24.



High energy physics

- LHCb-TORCH
- EIC-RICH
- CEPC-PID
- STCF

...



Medical Instrument

- TOF-PET

Aerospece

- LIDAR

Analytical Instrument

- TCSPC
- Flow cytometry
- Two-photon microscope

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.**
- FPMT has relevant applications in many fields such as high energy physics, nuclear medicine imaging, lidar, bio-detection, etc.
- **We welcome cooperation based on FPMT applications.**

Thanks for your attention!