INTERNATIONAL WORKSHOP
ON THE HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER
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R&D of MCP-PMT for single photon detection

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10/11/2025

Outline

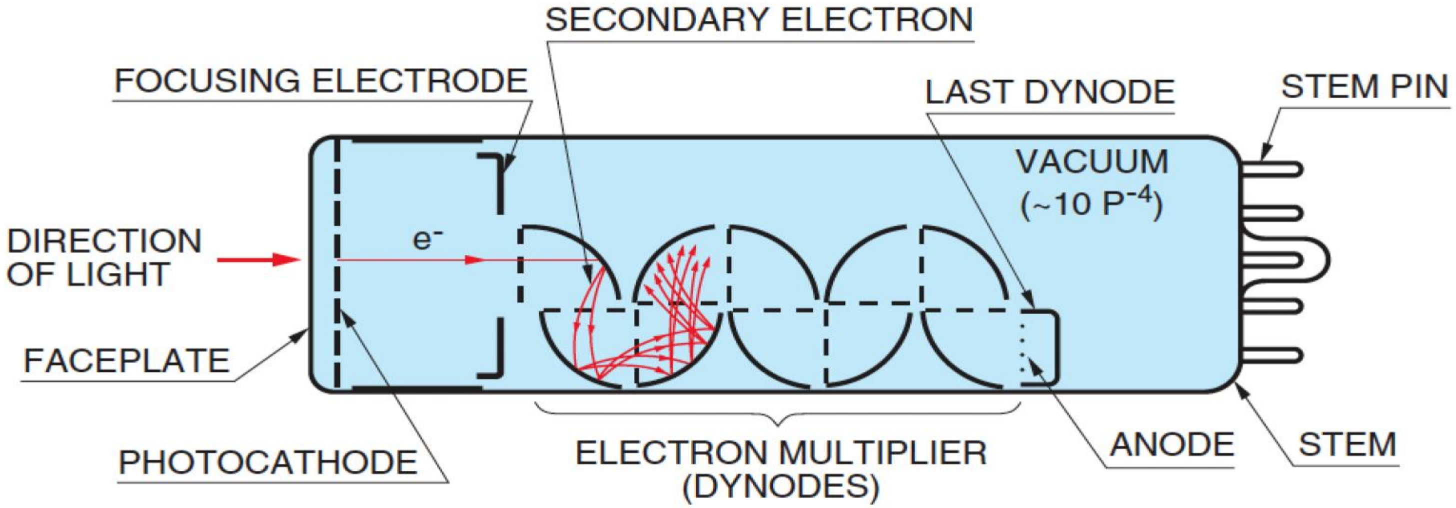
- Overview of MCP-PMTs
- R&D of MCP-PMTs in XIOPM

Outline

- **Overview of MCP-PMTs**
- **R&D of MCP-PMTs in XIOPM**

Photomultiplier tubes (PMTs)

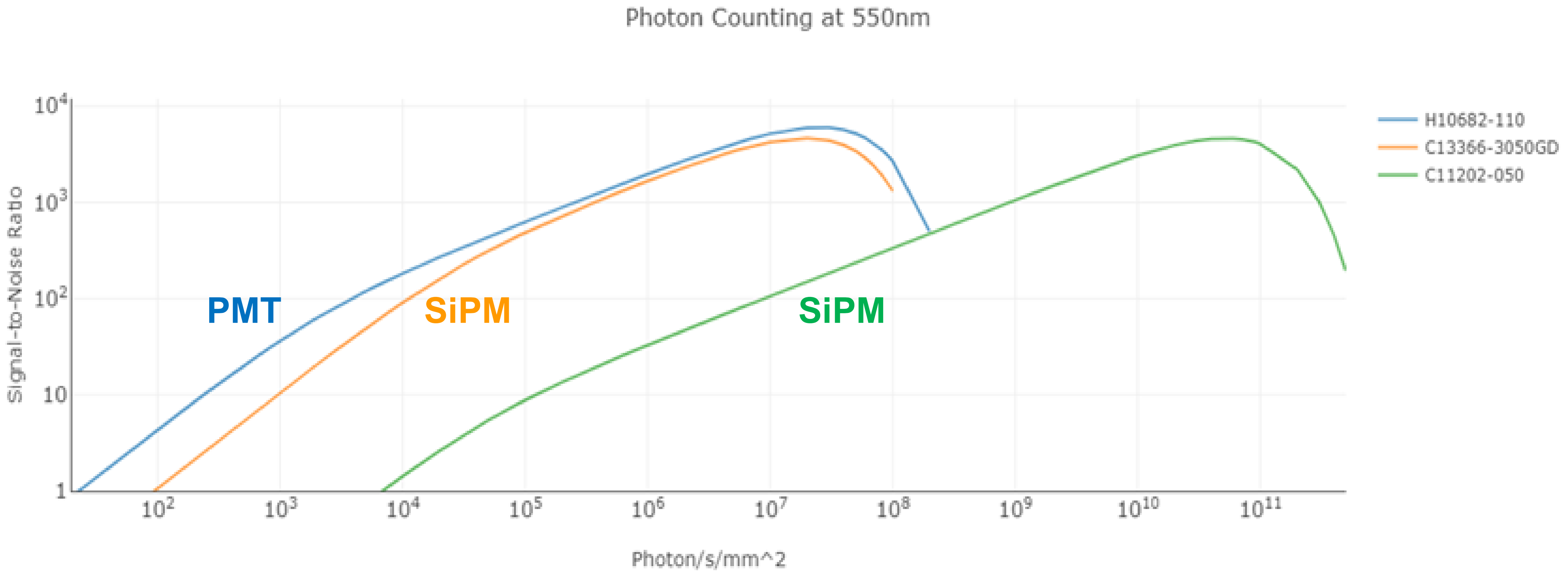
- PMTs are the most common photodetectors in particle and nuclear detection
  - Single photon sensitive
  - High gain and low noise
  - Large sensitive area
  - Sensitive to scintillation light and Cherenkov light



Construction and Operation Principle of dynode PMTs Hamamatsu Handbook

Photomultiplier tubes (PMTs)

- The signal-to-noise ratio of PMT is better than that of SiPM especially for few photon detections.



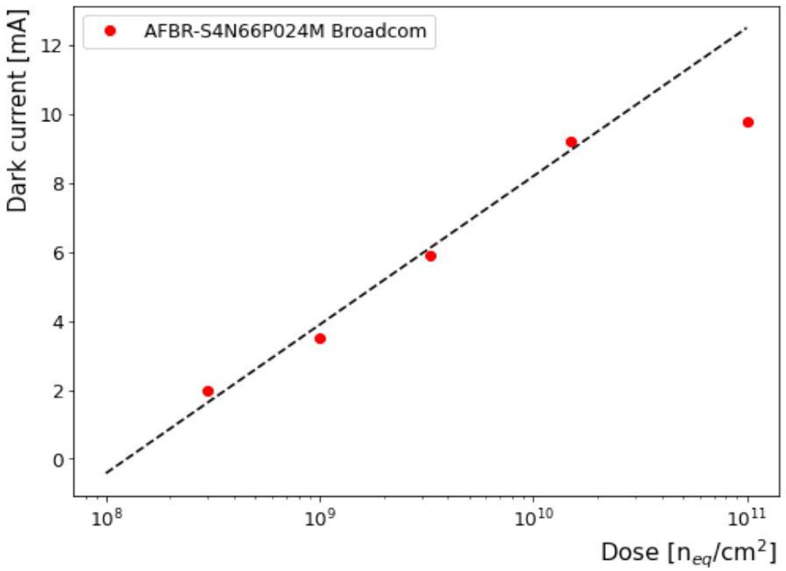
Hamamatsu website

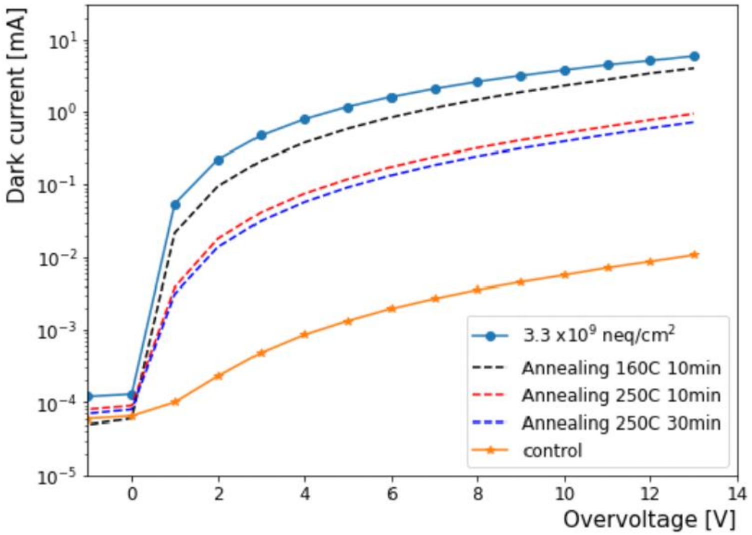
Photomultiplier tubes (PMTs)

XIOPM

■ SiPM radiation resistance

- Assessment of 6 × 6mm² SiPMs (Hamamatsu, Broadcom, OnSemi)
- before/after neutron irradiation at the ˇReˇz Cyclotron (7 samples)
- SiPM dark current increases drastically with the irradiation dose
- Loss of the SiPM photon resolution after irradiation ($\Phi > 3 \times 10^8$ neq/cm²)





J. Pe˜na-RodrÅLıguez. DRD4 meeting 2025 (BUW)

■ MCP-PMT radiation resistance

High radiation resistance

60 MeV protons, 5e11 p/cm2

Hi-QE Blue MCP-PMT	BEFORE	AFTER
QE_max, %	35.9	36.4
QE at 400 nm, %	32.9	33.5
Reference MCP voltage	1500	1500
Gain at reference voltage	2.25E5	2.27E5
P/V	4.9	4.8
DR (counts > 0.3 of mean enrgy), cps	150	480
MCP-DR (counts > 0.3 of mean energy),cps	0.15	1.4
Collection Efficiency	0.928	0.923
0.75 linearity range (full area), μA	3.1	2.9
0.5 linearity range (full area), μA	4.9	4.9
Transit Time Spreads, sigma of Gaussian fit	23	24
Transit Time Spread, RMS <200 ps	36	36
Waveform: Risetime, ps	256	239
Waveform: FWHM, ps	750	732
Afterpulsing (amp=10, threshold=30 mV)	6.1E-4	7.7E-4

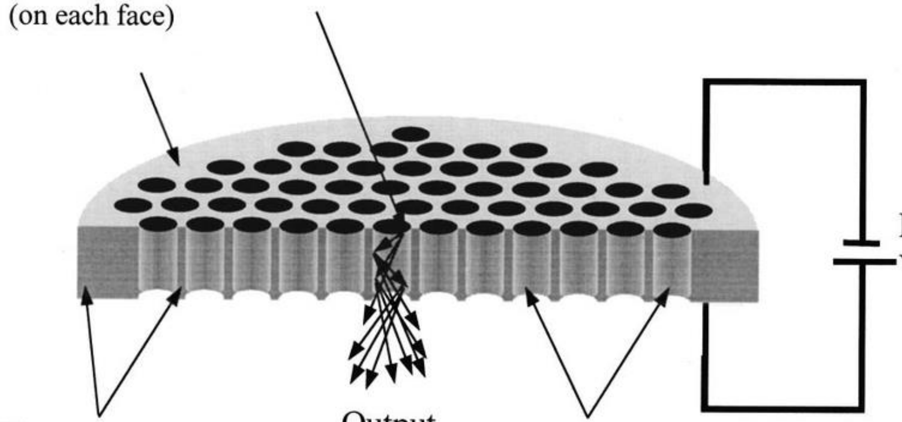
No radiation damage was found
60 MeV protons, 5e11 p/cm2

Microchannel plate (MCP)

XIOPM

■ MCP is an excellent secondary electron emission multiplier

- Two-dimensional array of glass capillaries (channels with ~2-25 μm diameter) bundled in parallel in a MCP plate
- Sensitive to electrons, ions, UV light
- Able to detect soft or hard X-rays, neutrons etc if coated with proper photocathode like CsI, Au, CsTe or doped with proper material like B, Li for neutron detection and Pb for hard X-ray…

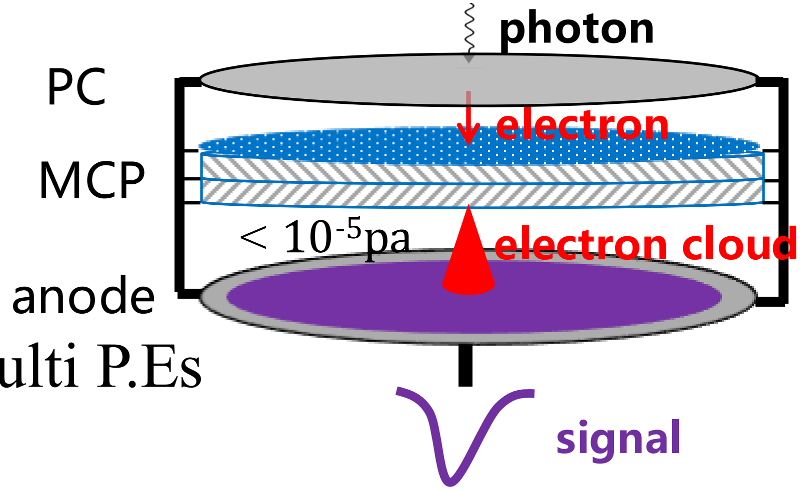


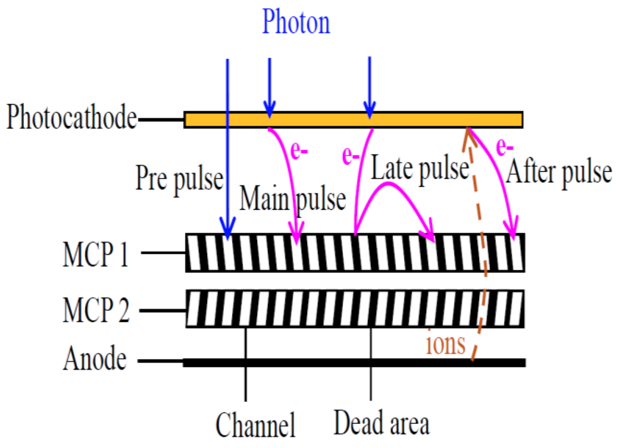
Construction and Operation Principle of MCPs

Microchannel plate (MCP) detectors

■ MCP-PMTs

- 2-stage MCPs
- Single photon sensitive
- Fast timing resolution
  <30 ps for single P.E. , <10 ps for multi P.Es



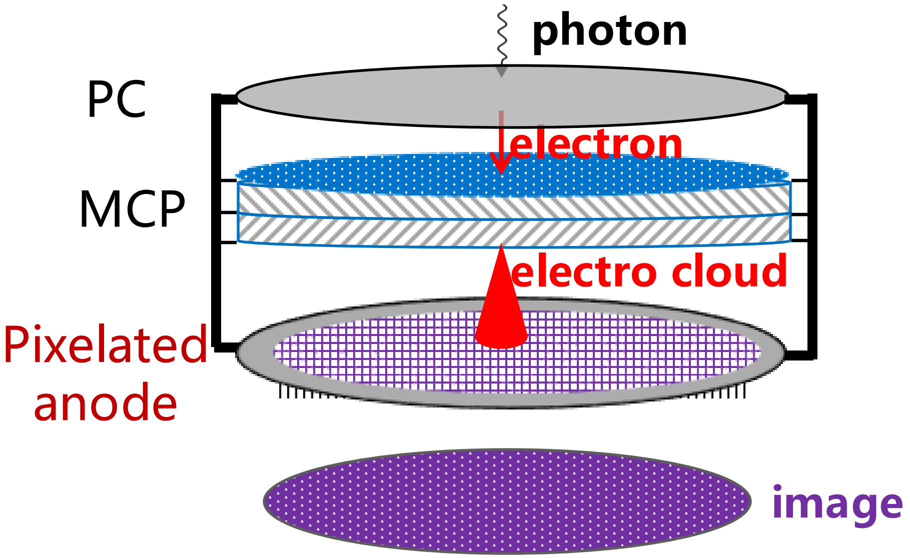


■ Image intensifier

- Usually one-stage MCP for high spatial resolution
- Replace anode with phosphor screen for imaging
- High spatial resolution
  < 8 µm viewed with naked eye, < 20 µm with CMOS

■ Position sensitive MCP detectors

- Replace single anode with position sensitive anodes
- Anodes could be WSZ, resistive strip line, cross strip, pixelated chip…



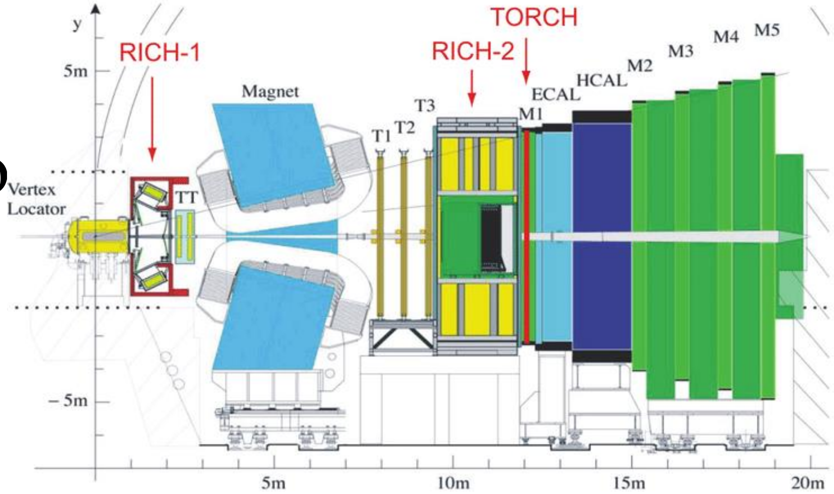
PMT applications

■ Large aperture PMTs

- Large coverage for rare instances
- Neutrino, comic rays, dark matter…

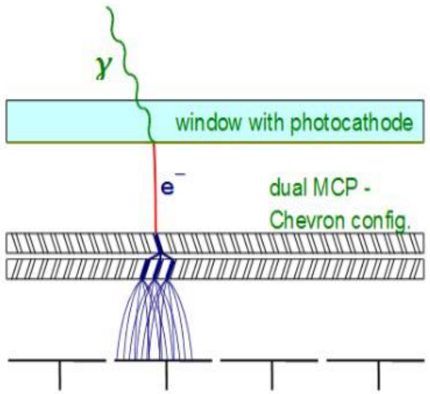
■ Small PMTs and MCP detectors

- PID, TOF
- Space satellites for particle or photon detectio
- Lidar
- Fluorescence lifetime measurements…

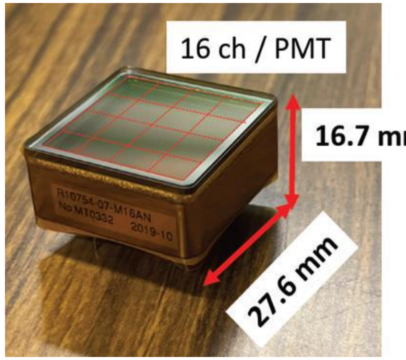


MCP-PMTs for PID

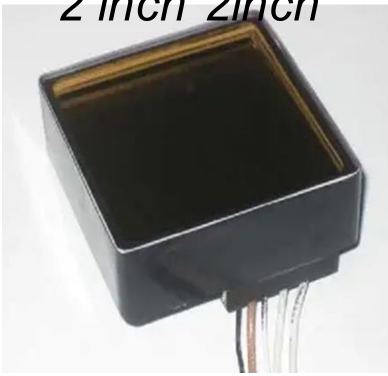
- **DC coupling multi-anode MCP-PMTs** Limited position resolution



Hamamatsu 4*4
*1 inch*1inch*



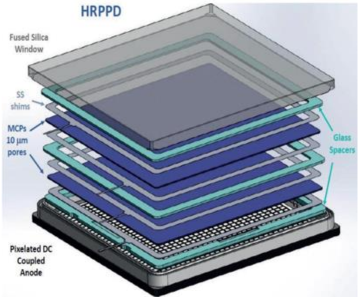
PHOTONIS 8*8
*2 inch*2inch*



XIOPM 4*4
*1 inch*1inch*

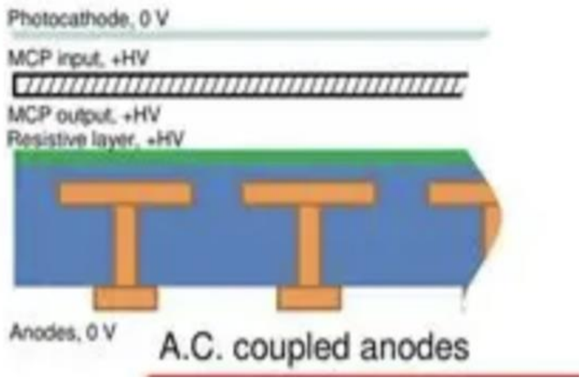
NNVT 8*8
*2 inch*2inch*

Incom HRPPD 32*32
*4 inch*4inch*

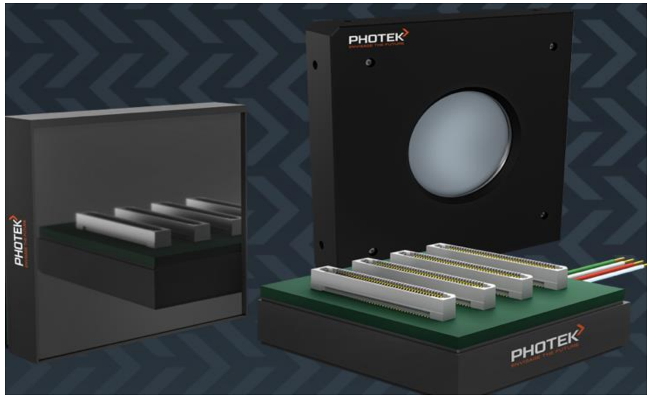


- **AC coupling high granularity MCP-PMTs**

Limited counting rate



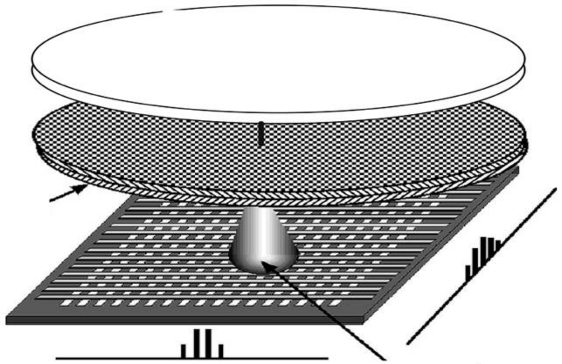
Photek 32*32



- **Cross strip/delay line anode MCP-PMTs**

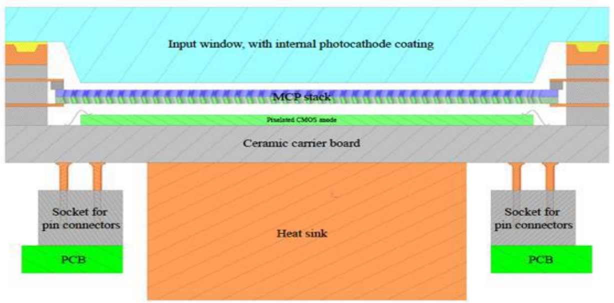
Limited Simultaneous events

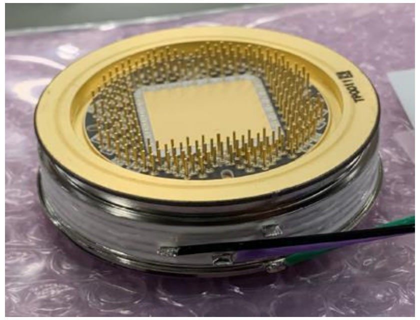
Incom LAPPD



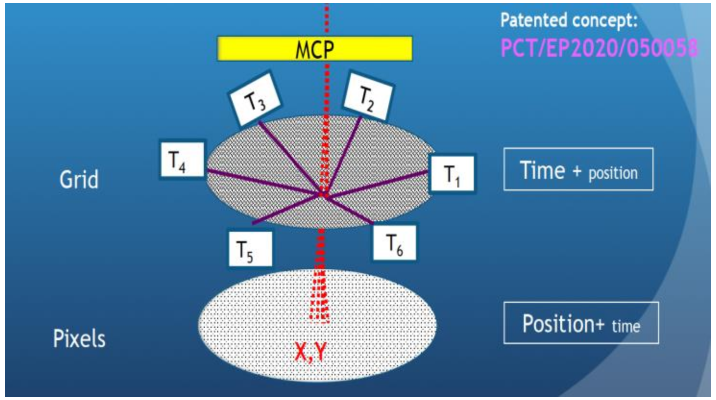
Hybrid MCP-PMTs for PID

- MCP-PMT with embedded Timepix4 ASIC as anode (M. Fiorini)
  - Complete integration of sensor and electronics (55 μmpixel pitch, 195 psTDC bin, data driven read-out up to 160 Gbps)
  - On-detector signal processing, digitization and data transmission with large number of active channels (~230 k pixels)



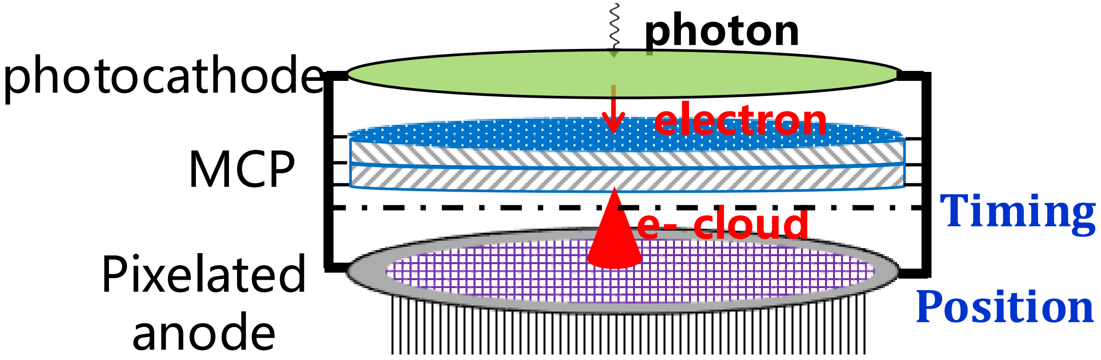


- PICMIC (I. Laktineh)



The first MCP prototype
~ 25 ps temporal resolution

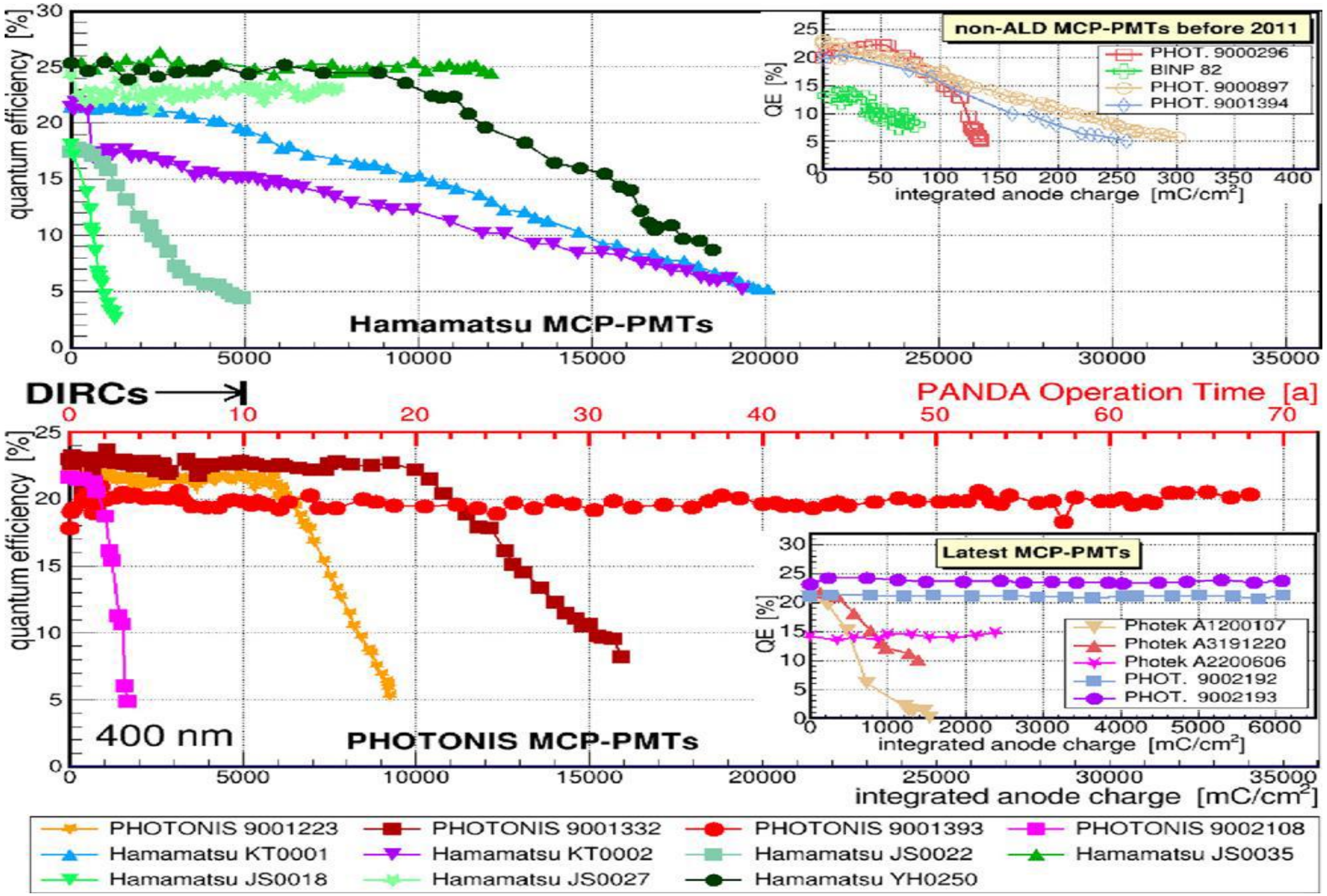
- HSPD (Ping Chen)



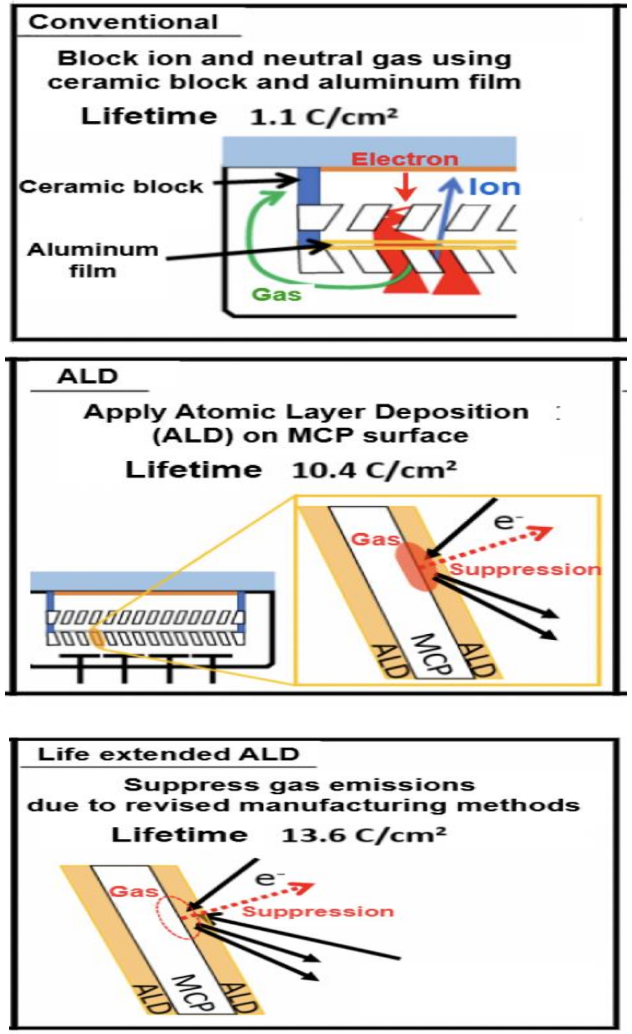
Patent ZL 2023 1 0177552.9

Recent progress on lifetime

From 0.2 C/cm^2 to >35 C/cm^2 in recent years thanks to ALD



Hamamatsu measures

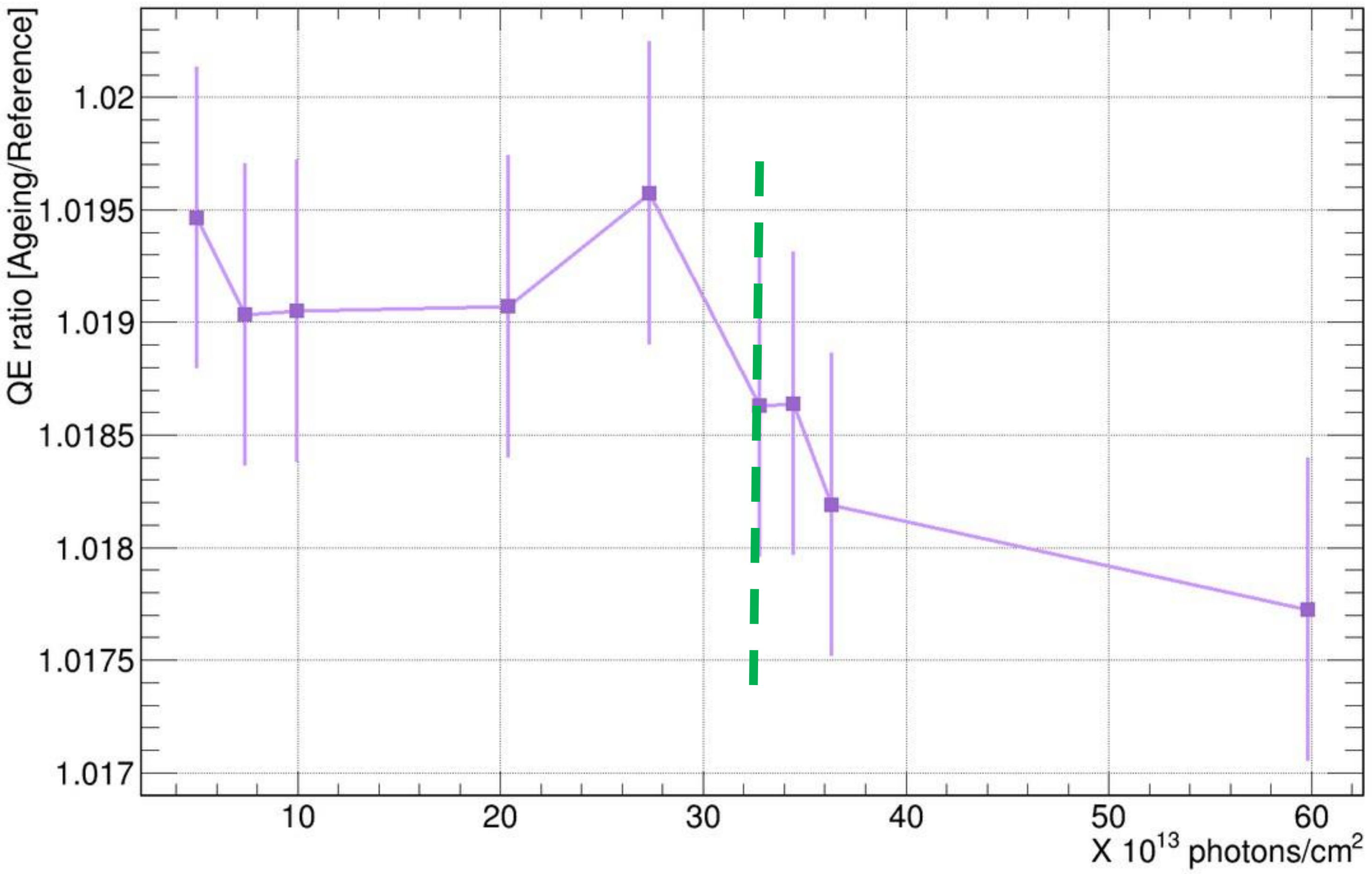


D. Miehling, A. Lehmann et al., NIM A1049 (2023) 168047

Ryotaro Komori et al., RICH 2025

Recent progress on lifetime

Lifetime evaluation for HRPPD

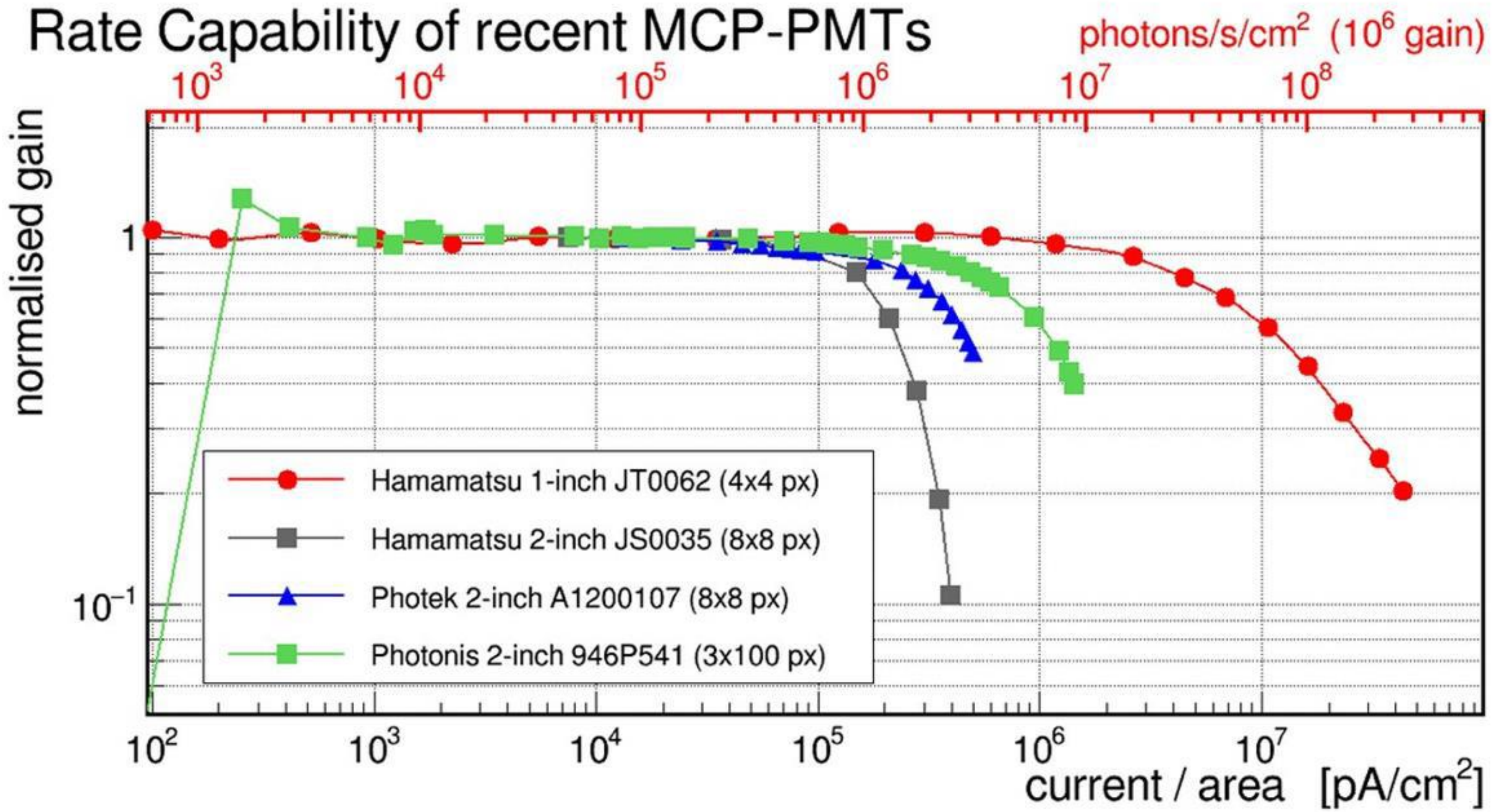


NO evidence of ageing after a photocathode illumination corresponding to 60 years of expected equivalent ePIC run

Jinky Agarwala et.al, RICH 2025

Recent progress on counting rate

Hamamatsu, Photek, Photonis MCP-PMTs Tests for PANDA DIRC detector



Vacuum-based PD: R&D Activities， DRD4 Working Package 4.2
Angela Romano, University of Birmingham

Outline

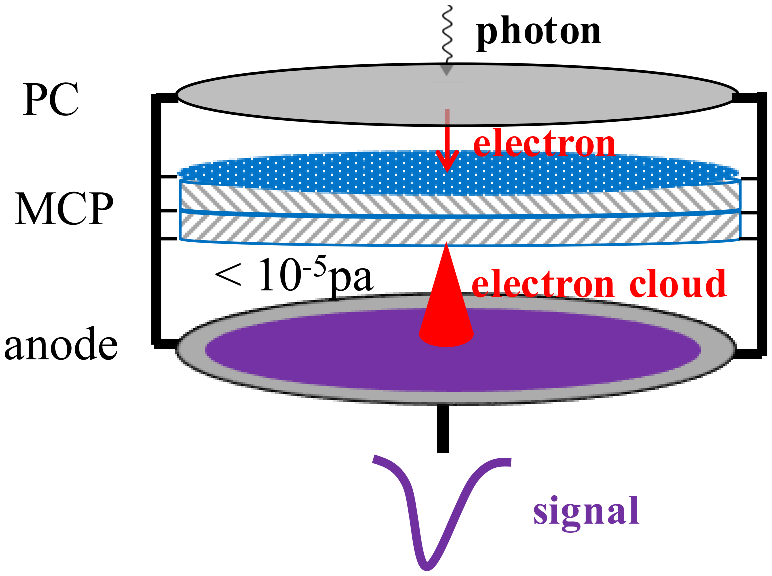
- Overview of MCP-PMTs
- **R&D of MCP-PMTs in XIOPM**

PMT performance specifications

- **Photocathode sensitivity**
- **Response wavelength**
- **Quantum efficiency**
- **Collection efficiency**
- **Detection efficiency**
- **Gain**

  Current gain, pulse gain
- **Dark noise**

  dark current, dark count rate



- **Lifetime**

- **Dynamic range**

  Rate capability

  Maximum output current

  Recovery time
- **Time resolution**

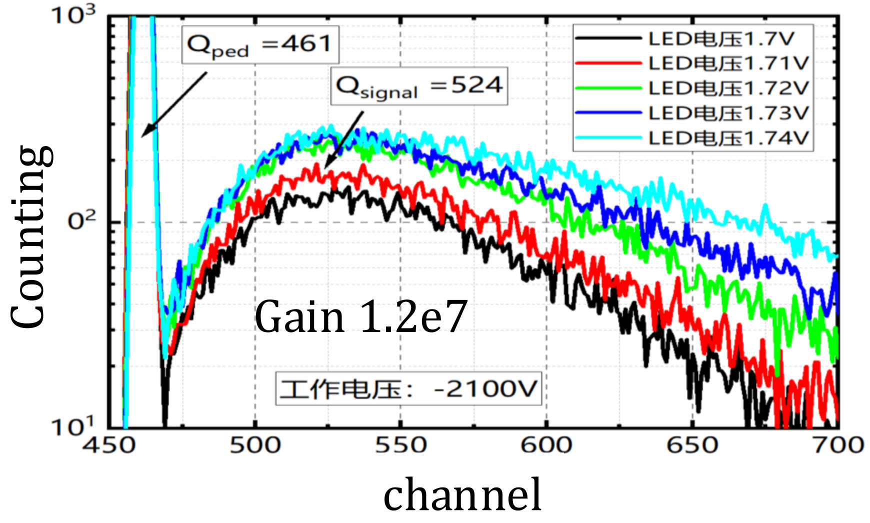
  Rise time, Transit time, TTS

  Pulse width, fall time, after pulse,

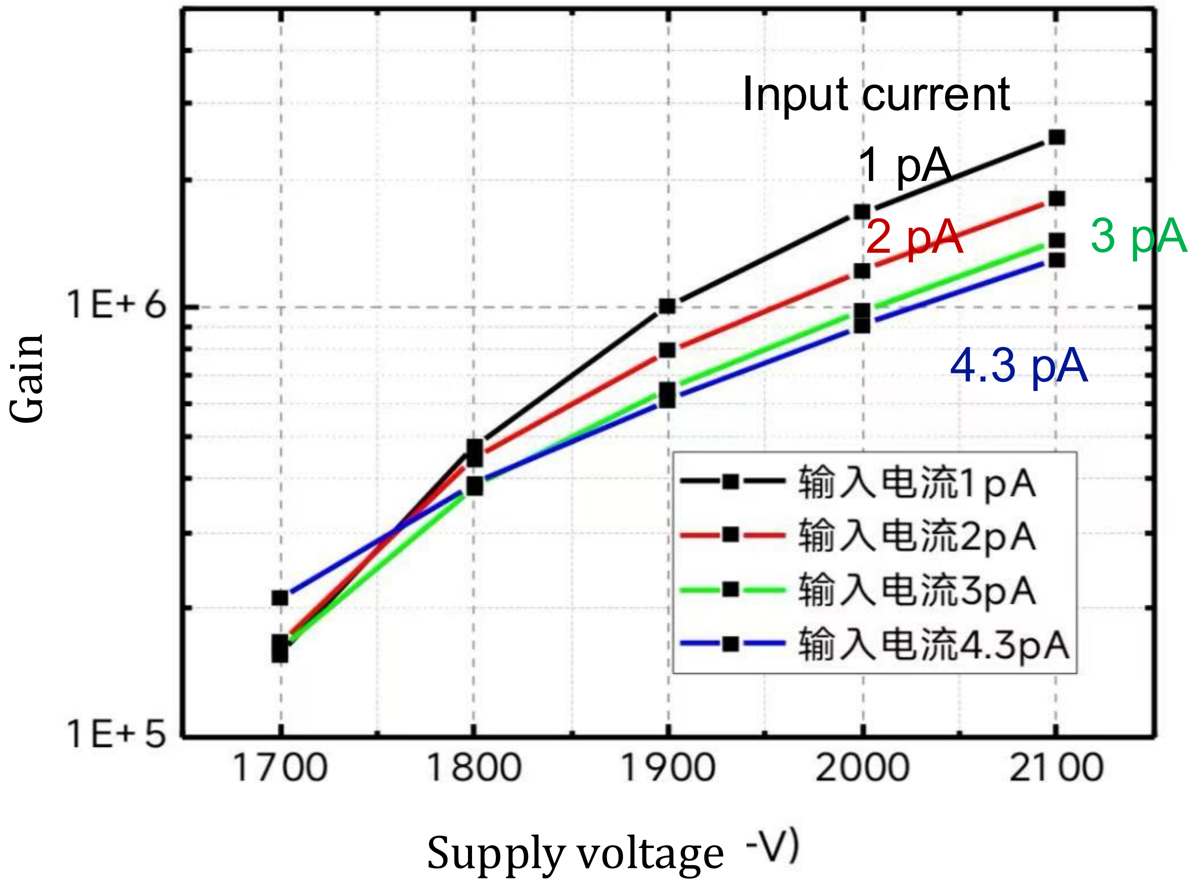
  Late pulse
- **Position resolution**
- **Magnetic field effects**
- **Radiation resistance**

Gain

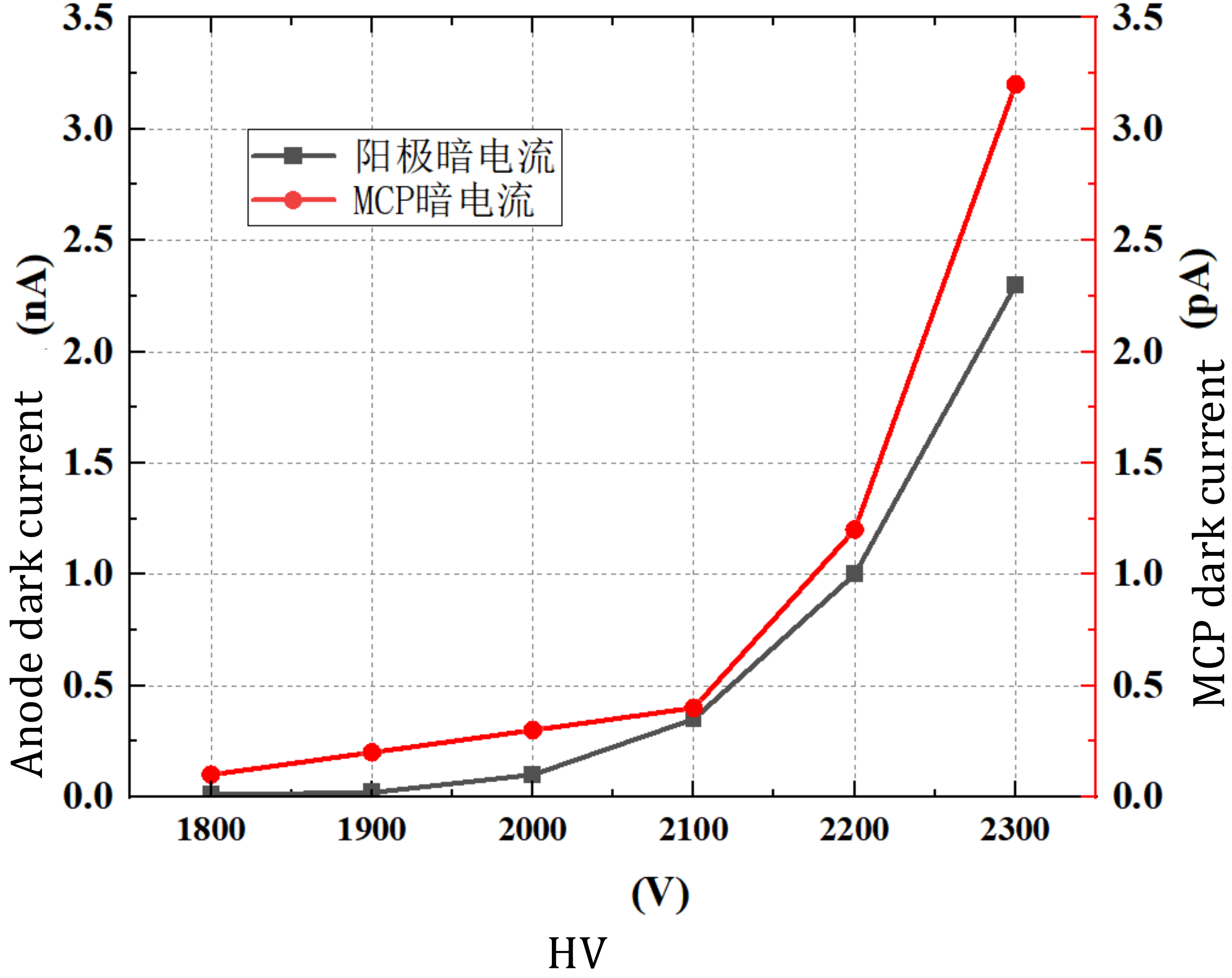
- Determined by the secondary electron emission yield, L/D, basis angle, supply voltage, resistance
- Vary with different input intensities because of limited maximum output charge.
- Single P.E. gain could be one magnitude higher than the current gain



Single photoelectron spectrum



Dark noise

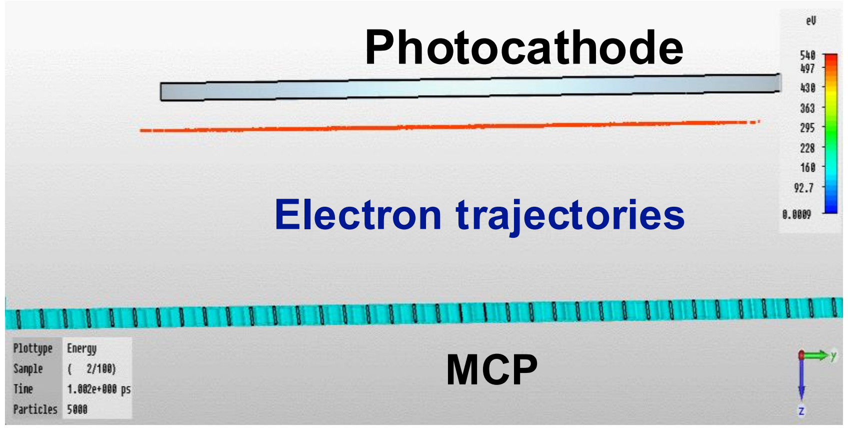


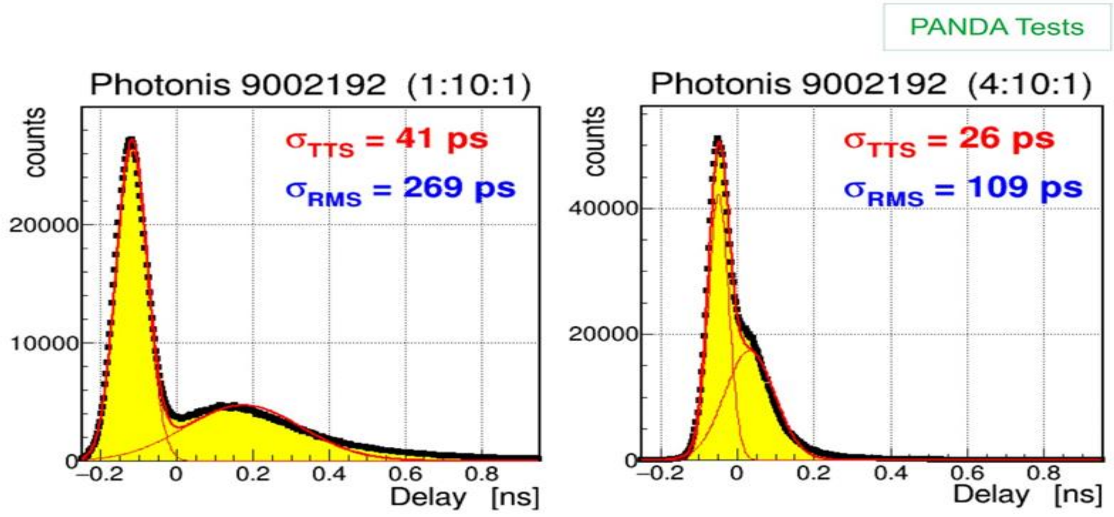
- **Dark noise mainly contributed by photocathode**
- **Dark noise increase sharply at high HV**

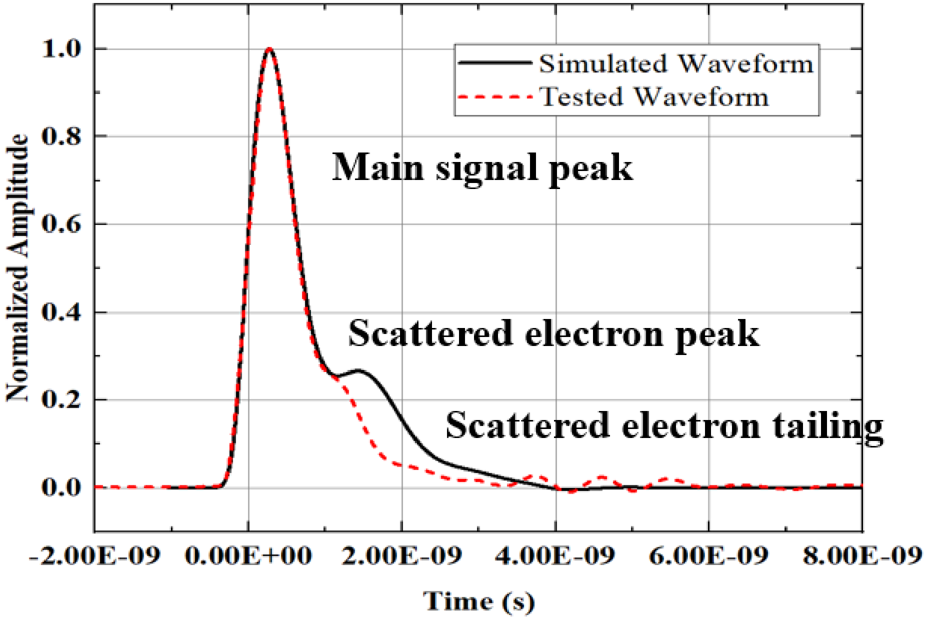
- Gain 1.4*10^6
- Rome temperature
- 0.1 Hz/mm^2 @ 10mV threshold , SPE level
- 0.01 Hz/mm^2 @ 20mV threshold

Time performance

- Delayed pulses worsen time performance, which caused by the electron backscattering on the MCP input surface
- Larger open area ratio could minimize late pulses



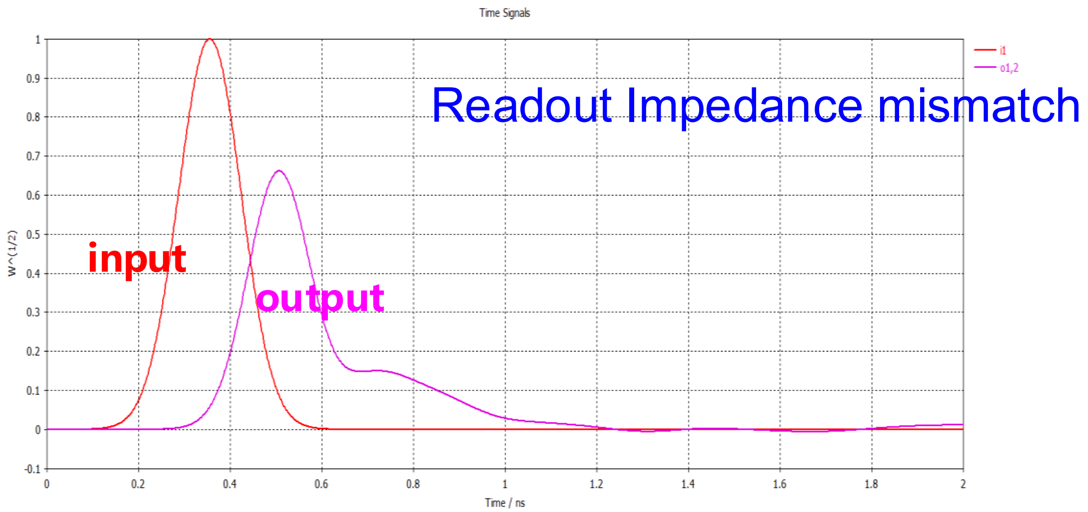


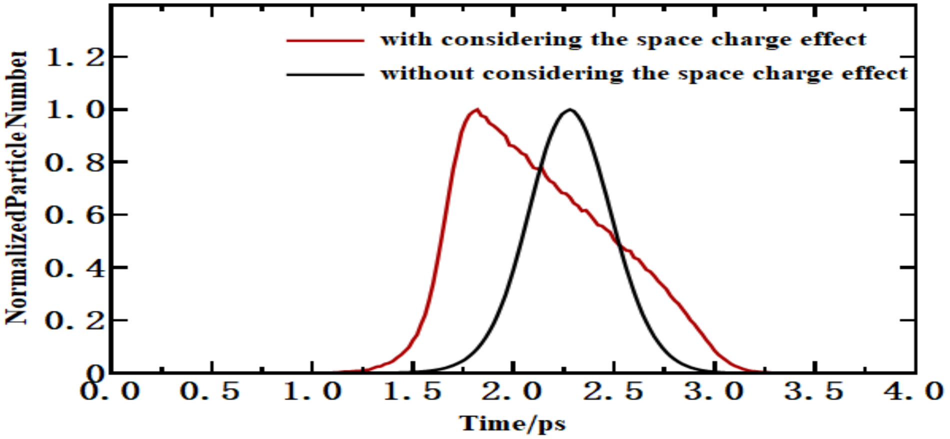


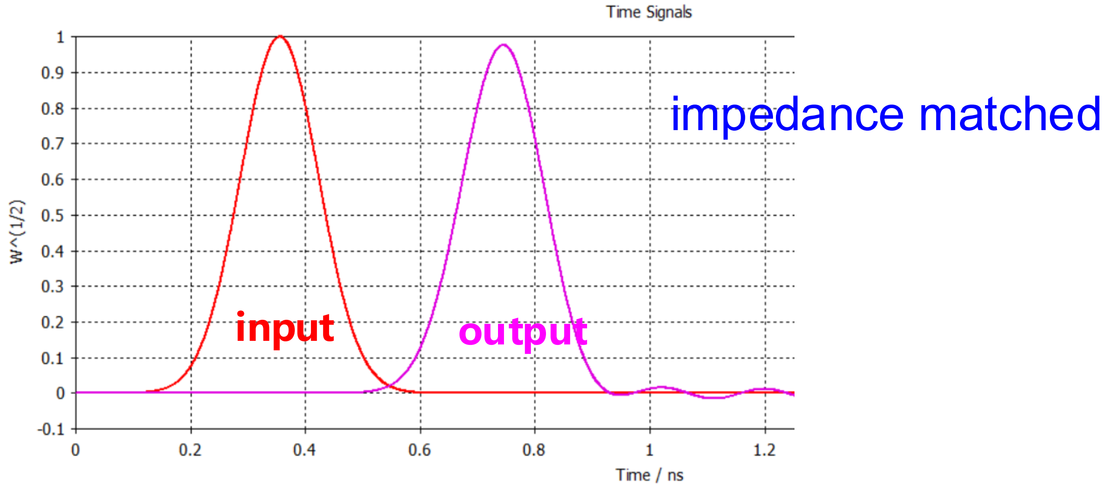
Ref. Albert Lehmann, Status/Limitations of MCP-PMT Performance

Time performance

- TTS could deteriorate as it becomes saturated.
- The waveform is usually not perfect because of impedance mismatch between the metal anode and the coaxial line.

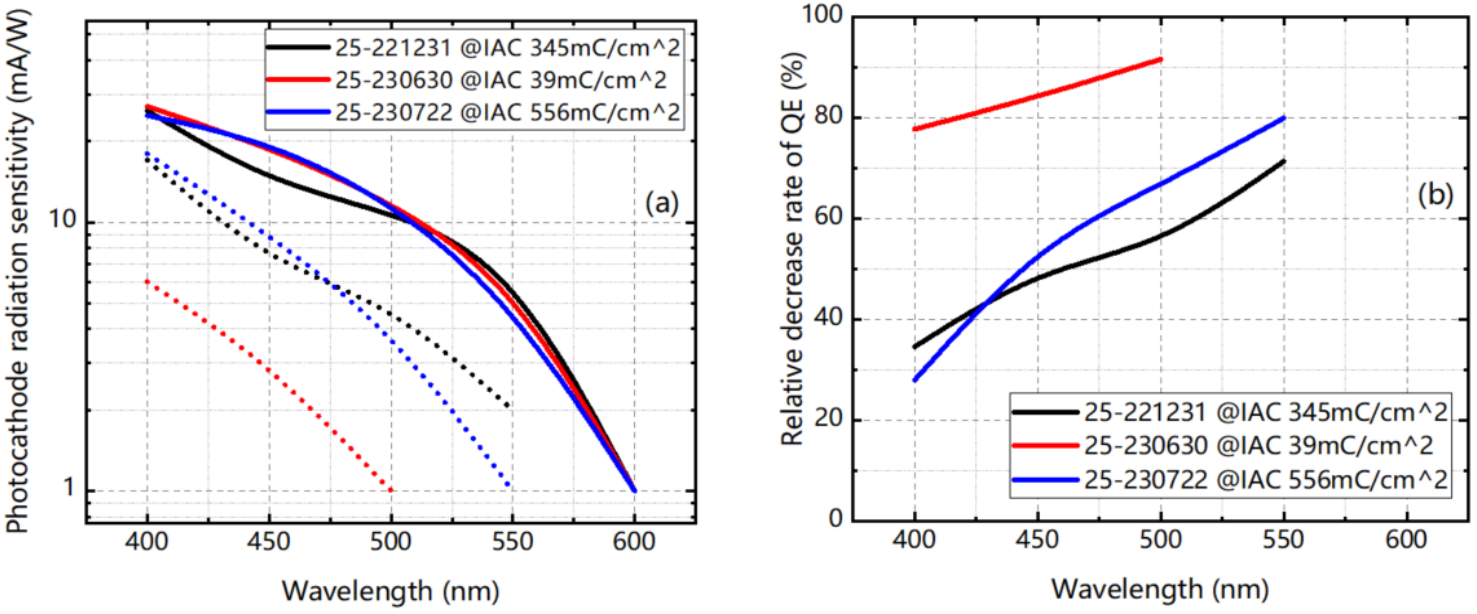


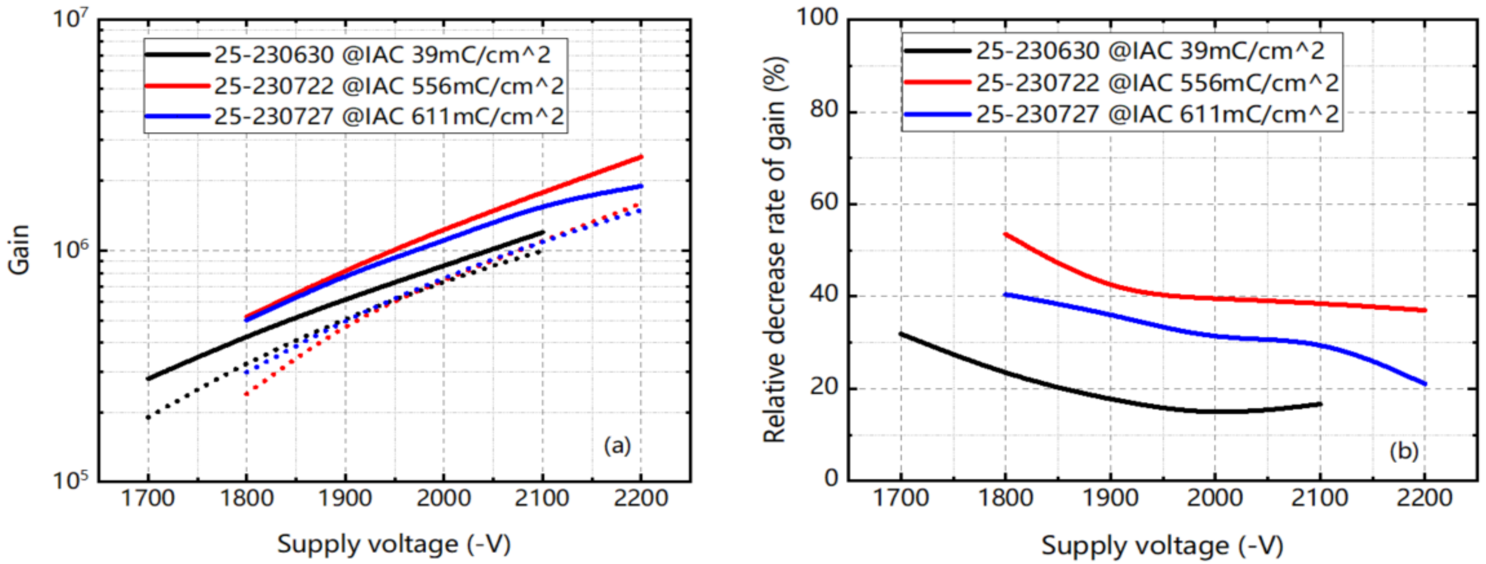




Lifetime

- Both photocathode sensitivity and MCP gain decrease when illuminated for a long time.
- Photocathode QE decreases more significantly at longer wavelengths.
- QE could decrease by 80% while gain decreases by less than 20% for an integrated output current of 39 mC/cm^2 .

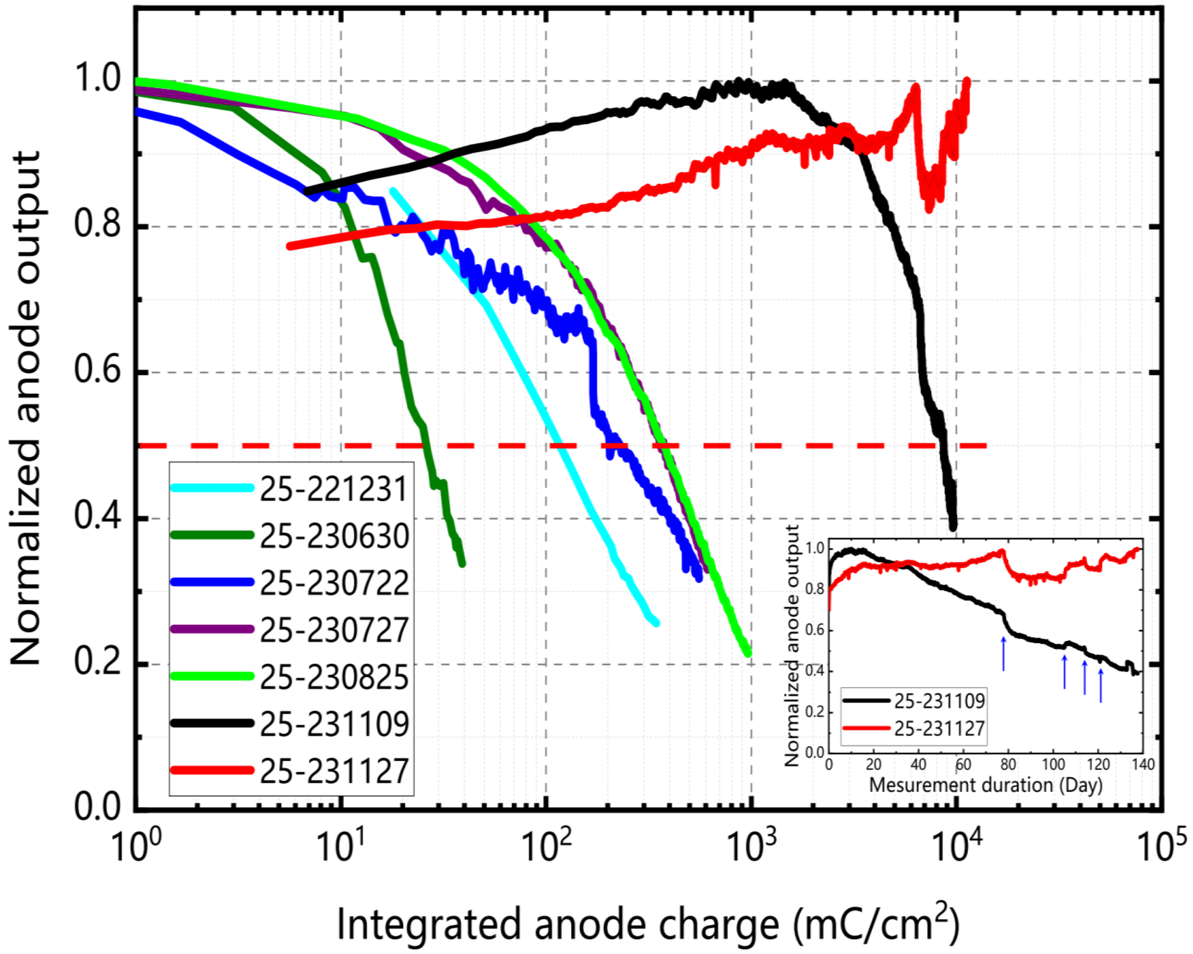




Lifetime

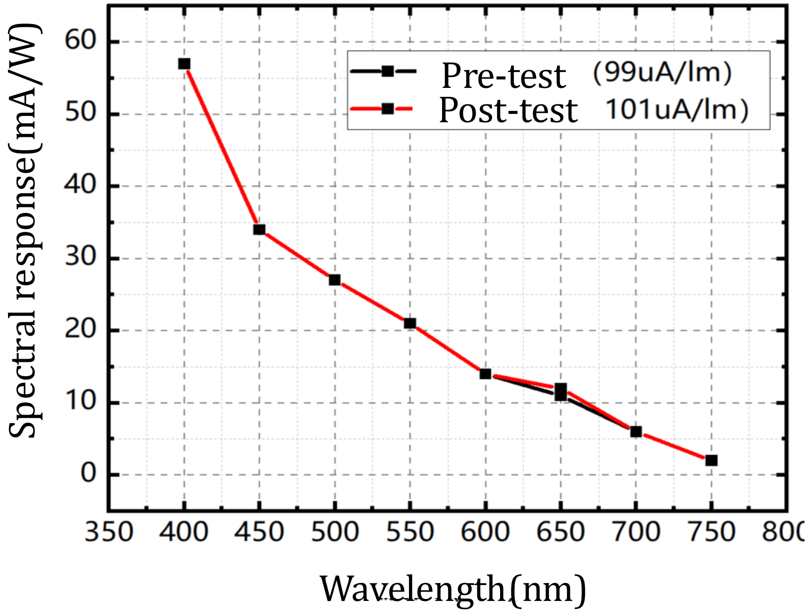
- Coated Al_2O_3 layer by ALD technique and optimized the electron scrubbing volume to improve the lifetime.
- Lifetime increased from 373 mC/cm^2 to 11000 mC/cm^2 as increase the thickness of the ALD-layer.
- Lifetime increased from 117 mC/cm^2 to 373 mC/cm^2 as increase the scrubbing volume from 0.43 μA·h/cm^2 to 0.75 μA·h/cm^2.
- Lifetime increased more than 400 times.

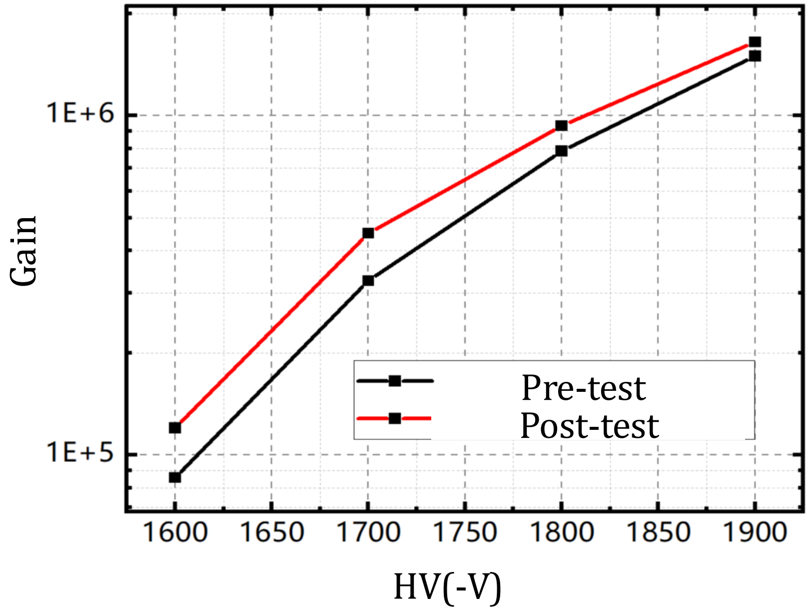
International Journal of Modern Physics A(2024) 2442016

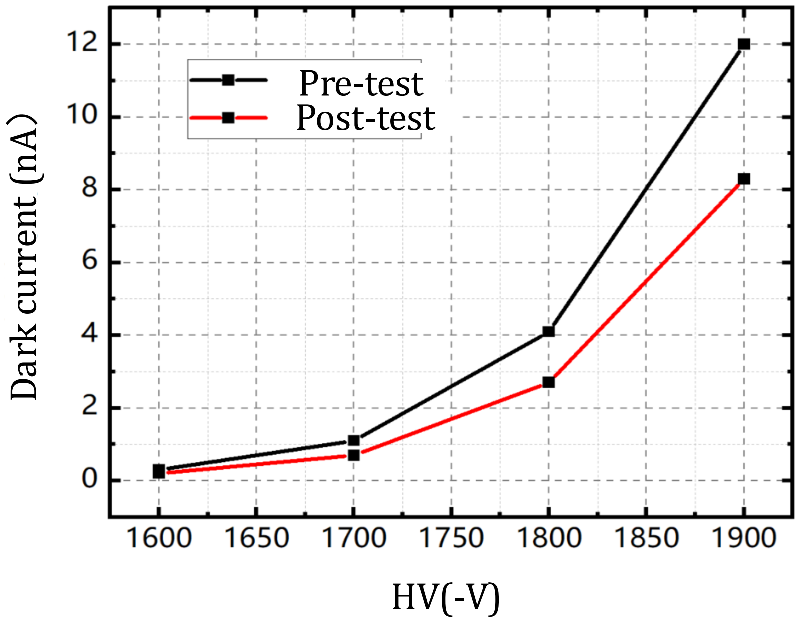


Lifetime

- No degradation in photocathode and MCP, dark current decreased.
- The increase in gain may be due to the multiplication from both the ALD layer and the MCP, which requires further study.
- Continue to optimize the ALD and scrubbing processes.







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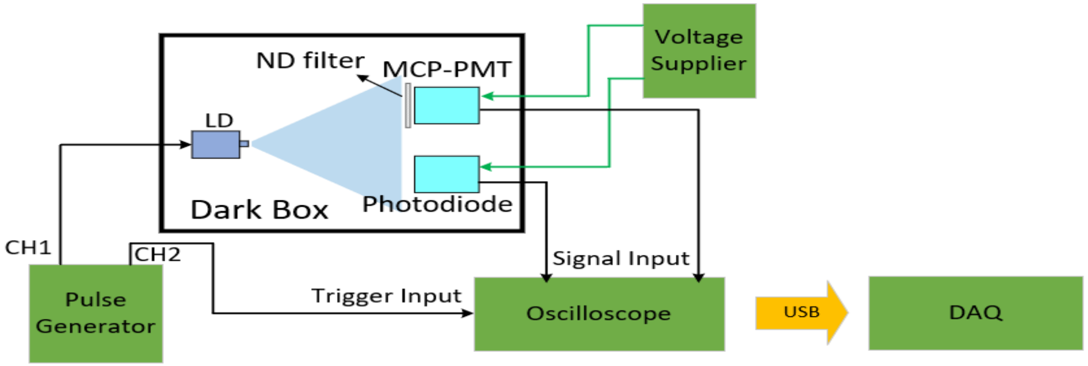
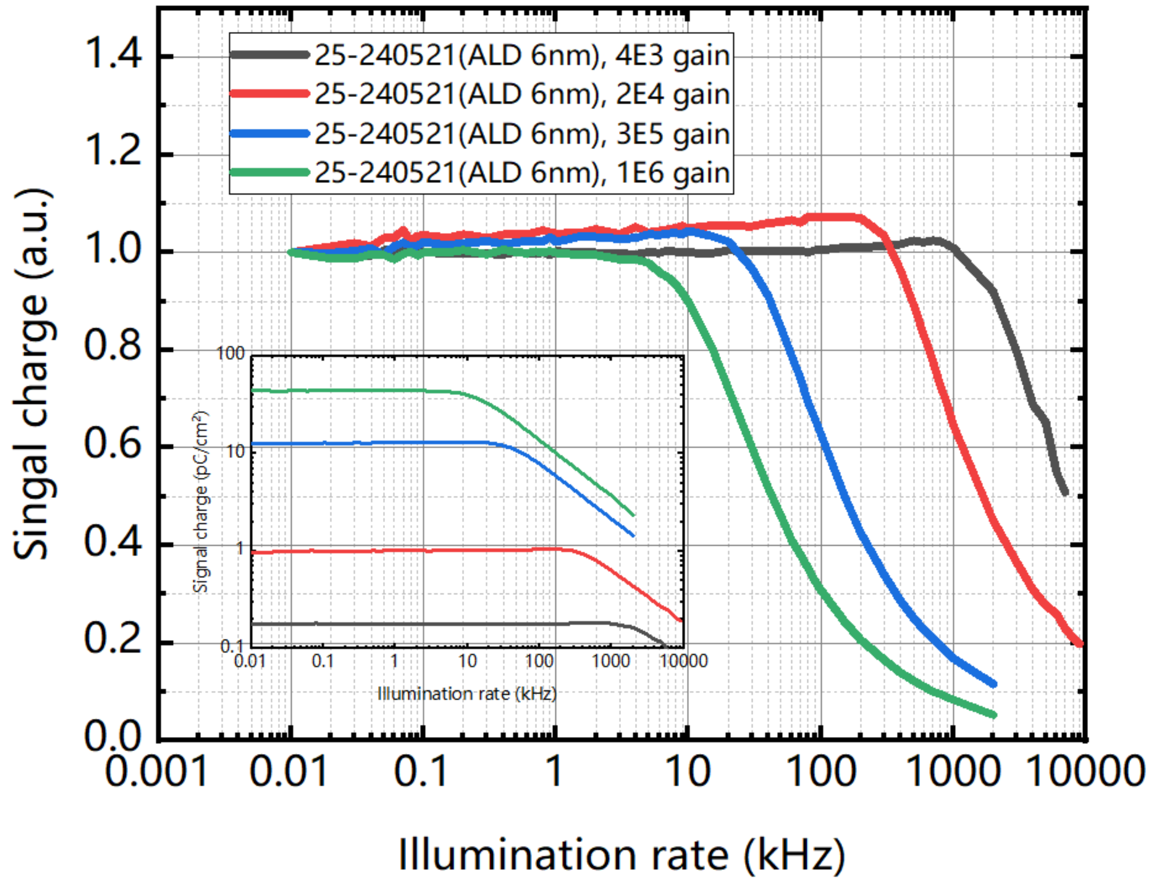
Rate capability

- Measurement setup
  - LD driven by a pulse generator
  - 10 ns pulse width
  - ~3500 photons/cm^2/pulse
- Counting rate of ALD-MCP PMT
  - 3 MHz@4e3 gain
  - 600 kHz@2e4 gain
  - 50 kHz@3e5 gain
  - 15 kHz@1e6 gain

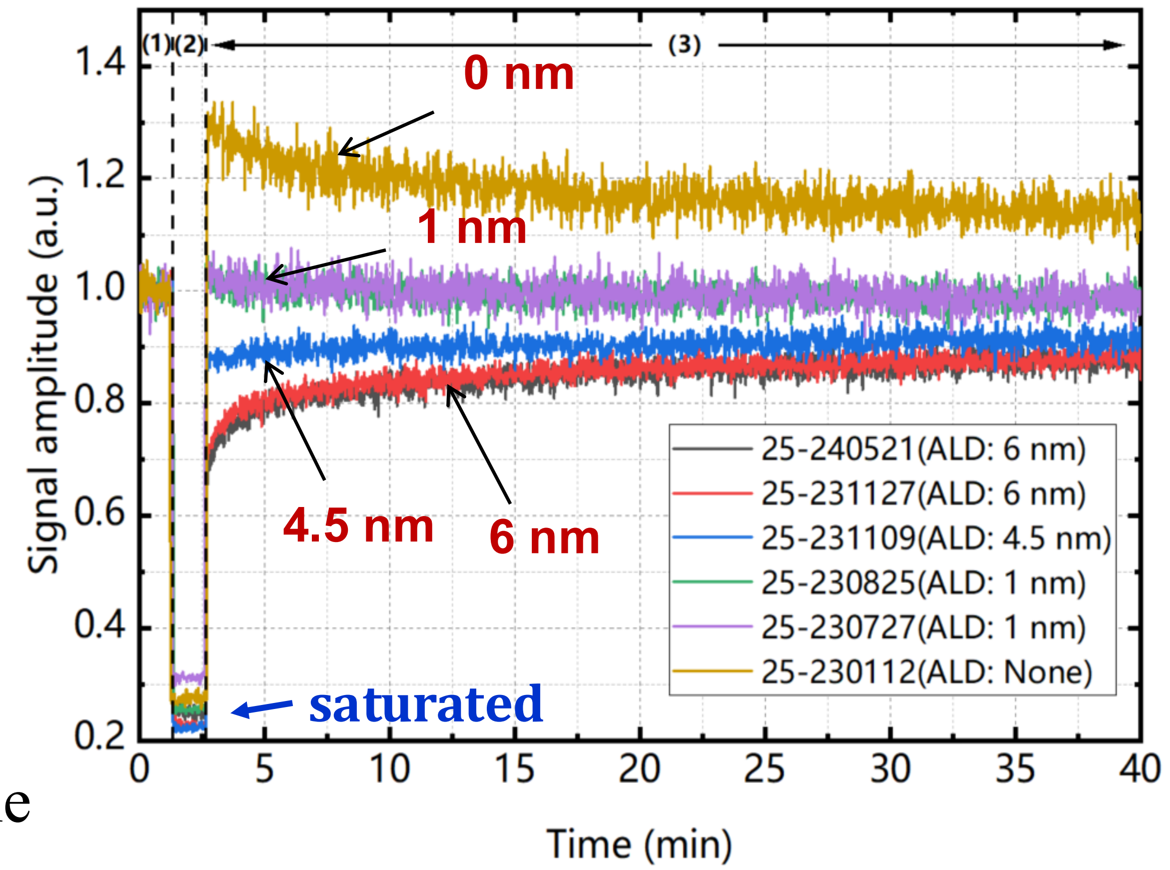




52.5 MHz for single P.E @ 1e6 gain

Saturation recovery behaviors

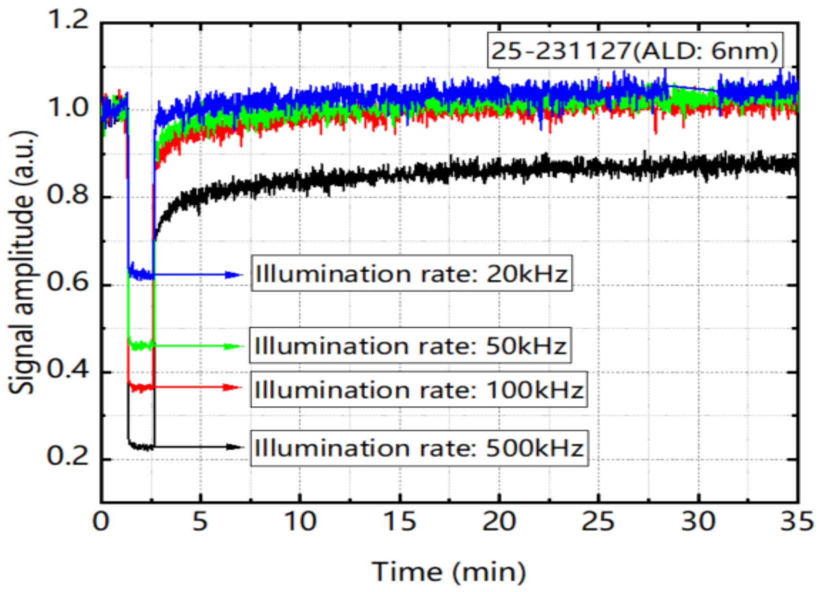
- Measurement setup
  - MCP-PMTs with different thickness of ALD films were operated at 1E5 gain.
  - Illuminated by LD at rates of 10 Hz for phase (1) and (3), 500 kHz for phase (2).
- Longer recovery time for thicker ALD-layer
- The MCP without the ALD layer appears to exhibit superlinearity and a long recovery time.
- Recovery of the MCP with the ALD layer of 1 nm is fast.
- Further research will be conducted to confirm the phenomena and causes.

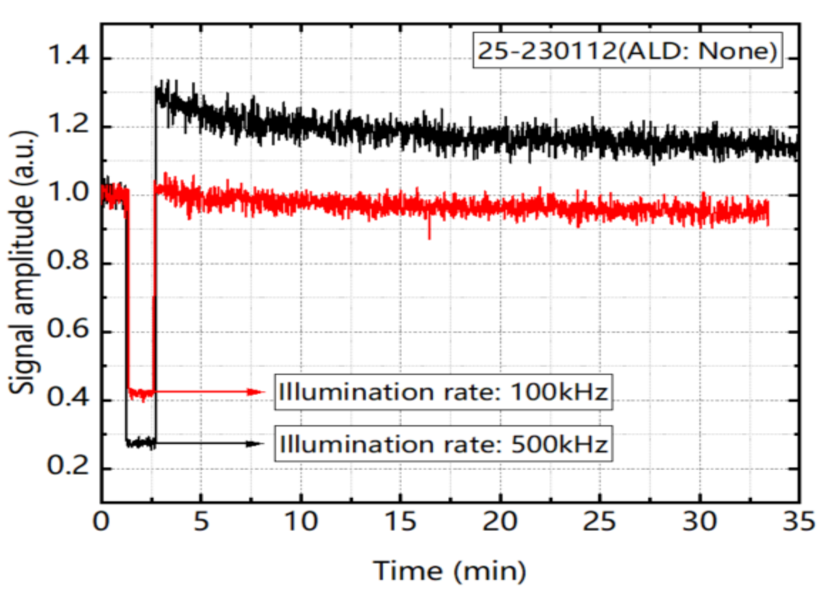


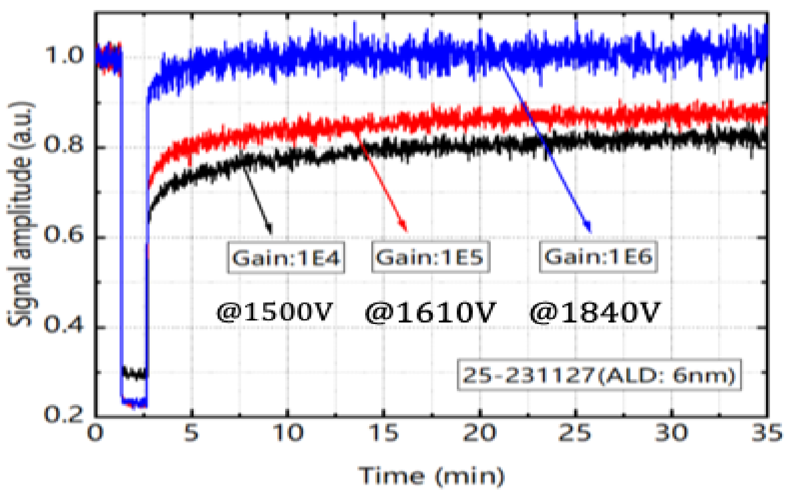
NIM A 1074 (2025) 170323

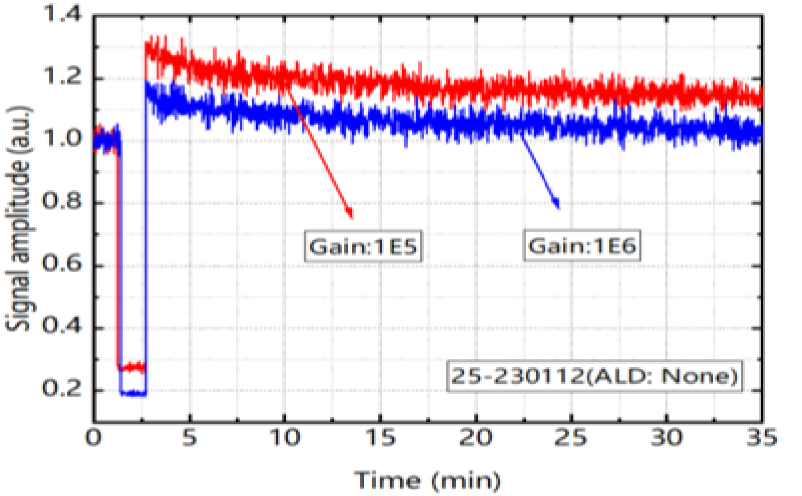
Saturation recovery behaviors

- Heavier saturation, longer recovery time.
- A higher supply voltage appears to be beneficial for recovery of the ALD-MCP.
- The super-linearity can be lower for none ALD-MCP.









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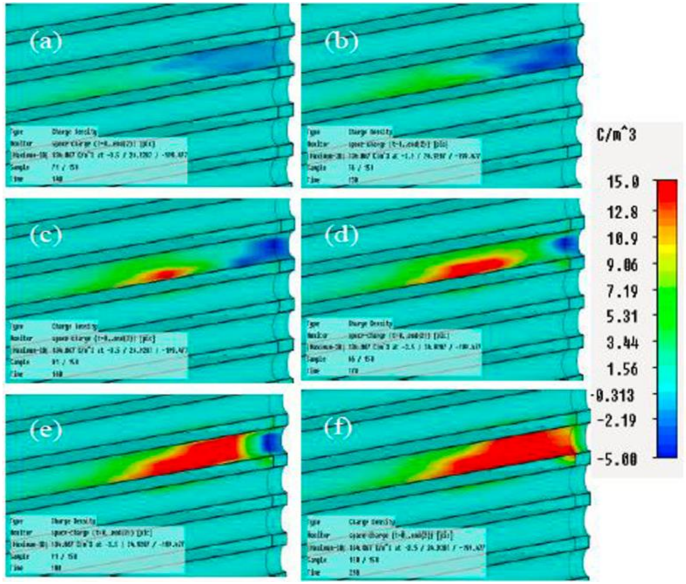
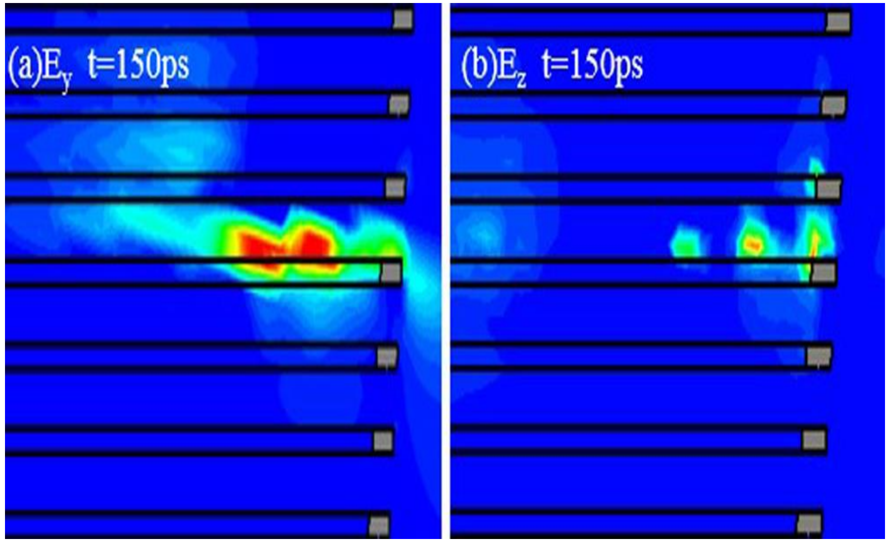
Saturation mechanisms

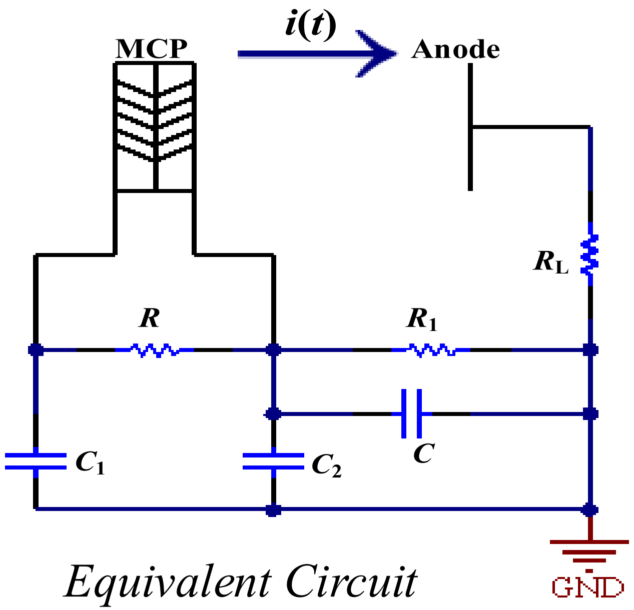
- Electrons loss radial momentum because of strong space charge effect.
- The positive self-consistent electric field inhibits secondary electron generation。
- Electric potential between MCP and anode decreasing diminishes high-density electron collection.
- These three mechanisms predominate in different situations.
- Detailed research into the mechanisms underlying various saturation phenomena is currently underway.



Evolution of three-dimensional charge distribution



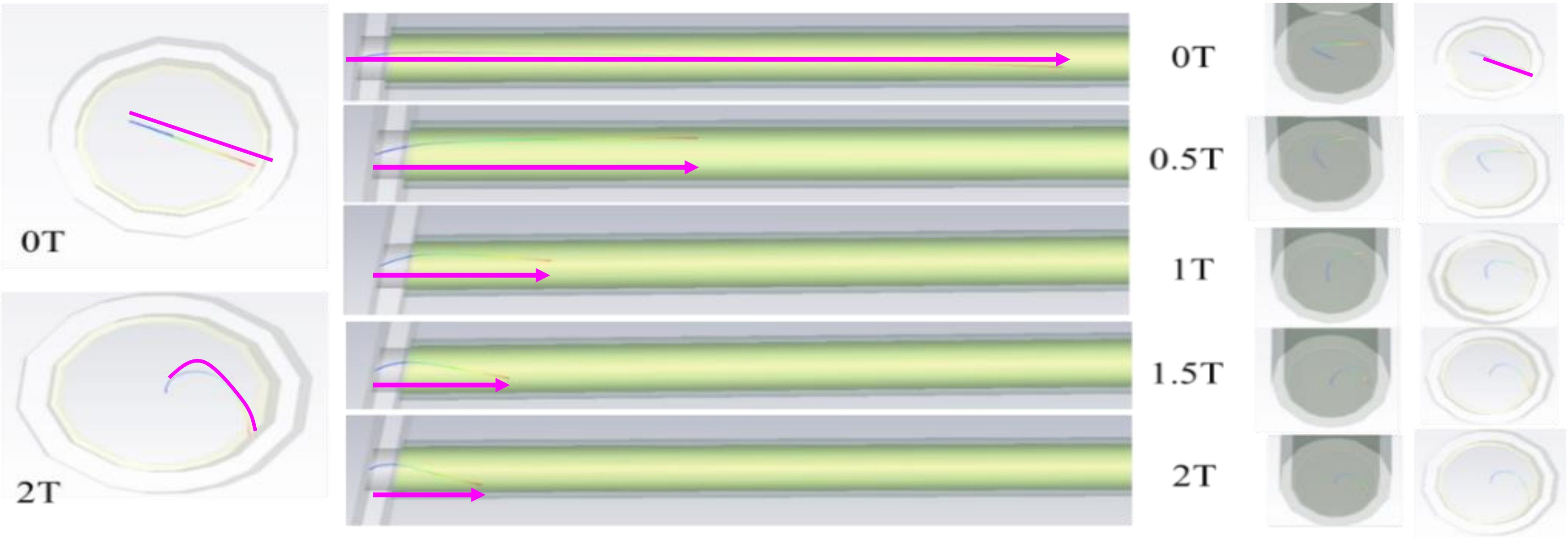
Self-consistent electric field distribution in the channel



Equivalent Circuit

Magnetic field effects

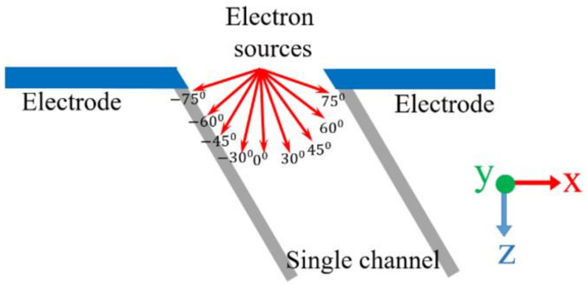
- To figure out how magnetic field decreases gain, electron trajectories in the MCP channel under the magnetic fields are simulated with CST program.
- Electrons move in a spiral under the influence of a magnetic field.
- Shorter accelerating distance, lower striking energy.

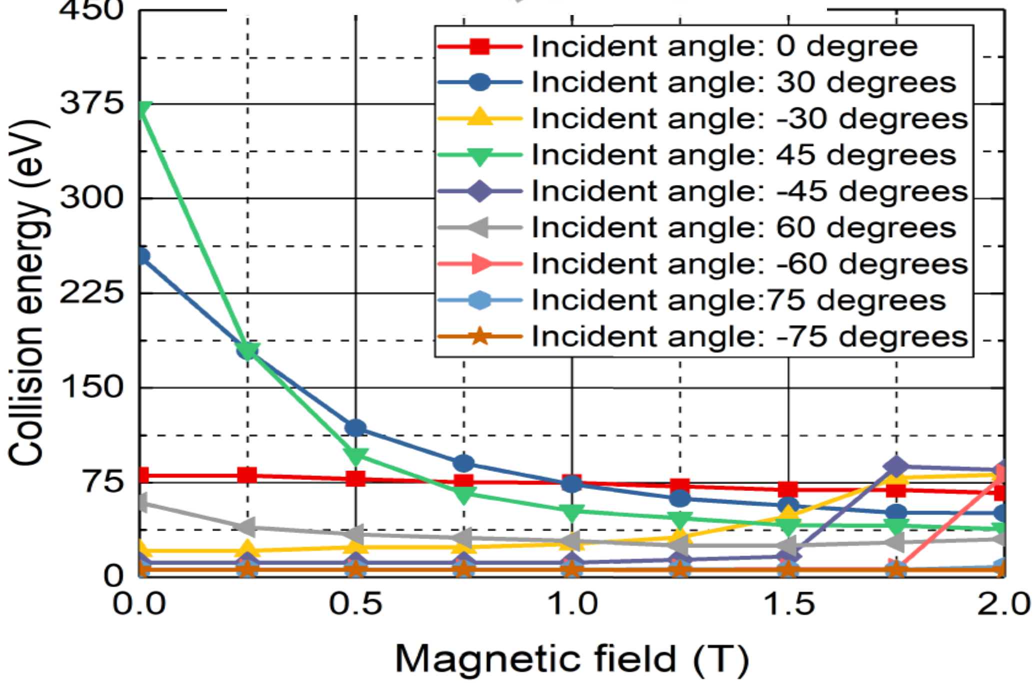


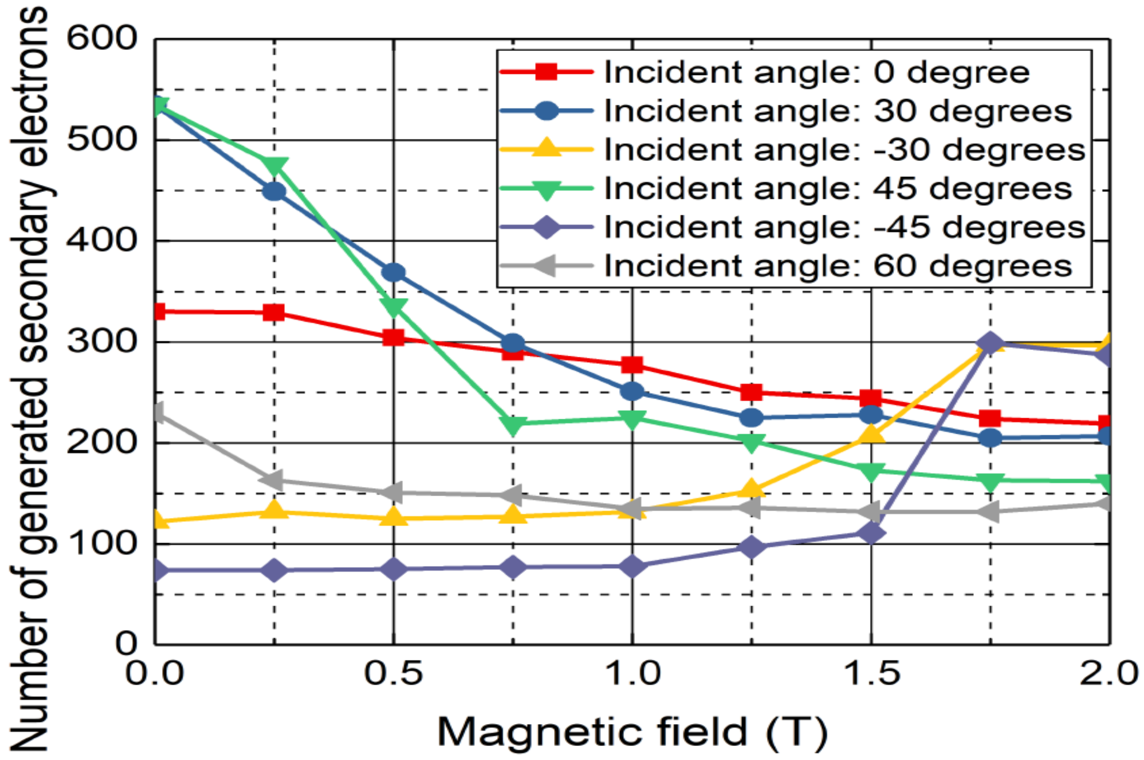
Journal of Instrumentation, 2020,15(C03048): 1-9
IEEE Transactions on Nuclear Science, 2022, 69(4): 850-857

Magnetic field effects

- Fewer secondary electrons are emitted when primary electrons strike the MCP with lower energy.







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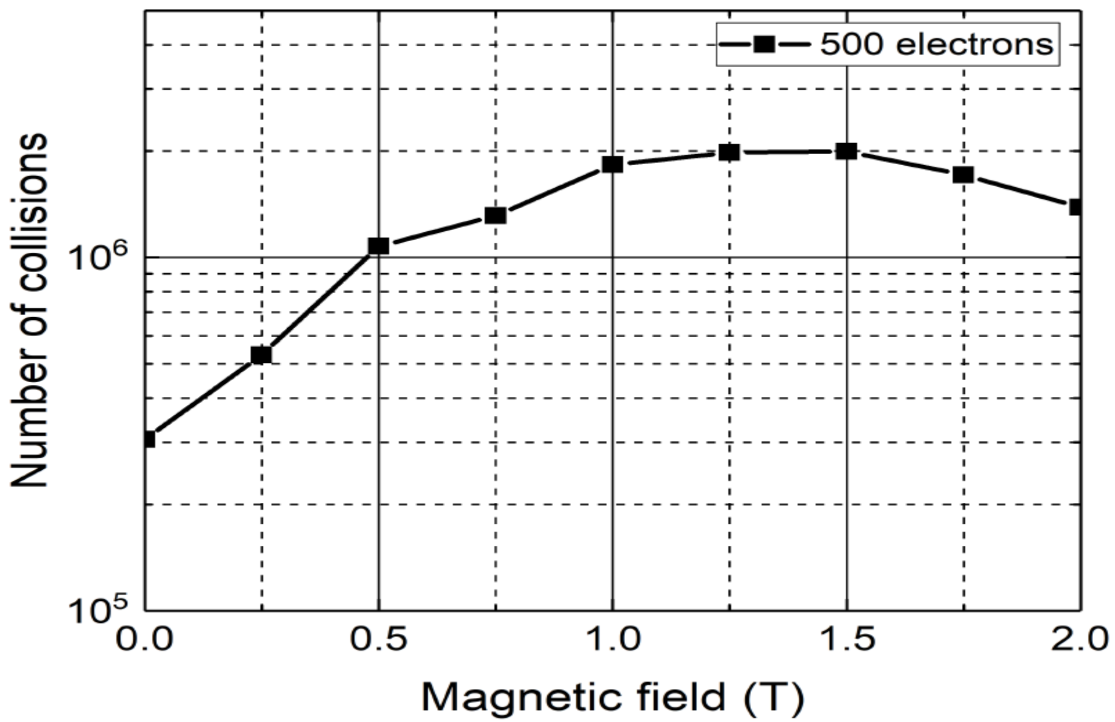
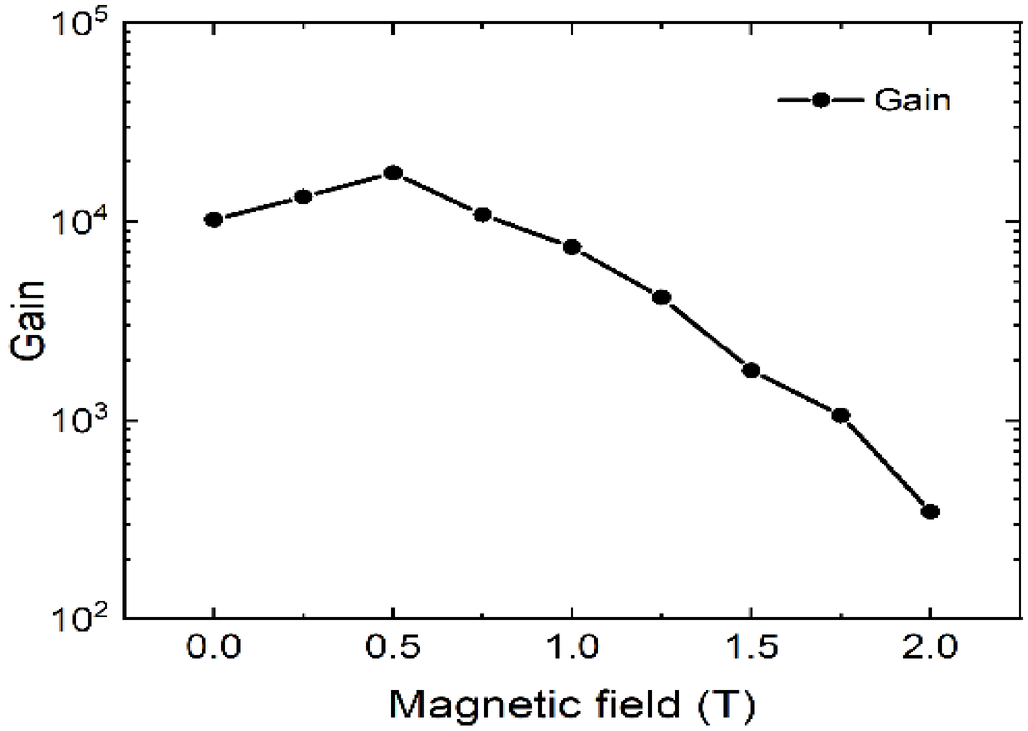
IEEE Transactions on Nuclear Science, 2022, 69(4): 850-857

Magnetic field effects

- The number of electron collisions with the MCP channel increases and then decreases.
- Gain is the result of the combined effect of the number of collisions and the collision energy.





Journal of Instrumentation, 2020,15(C03048): 1-9
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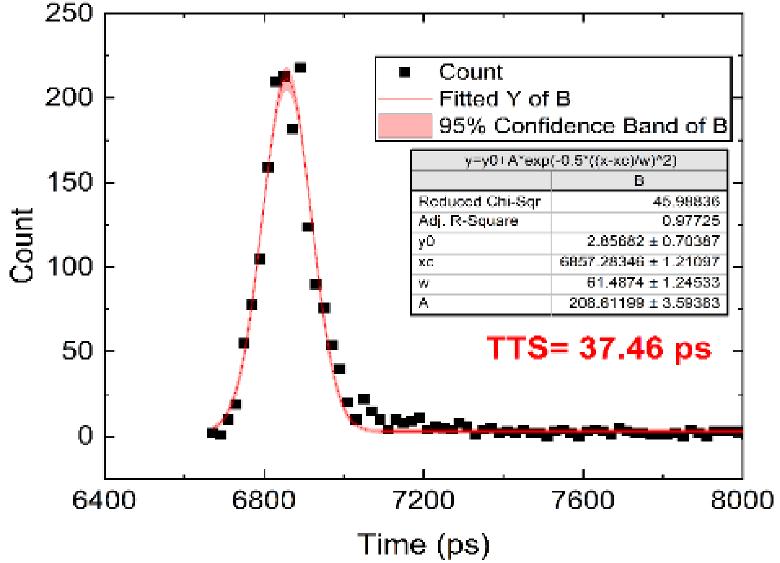
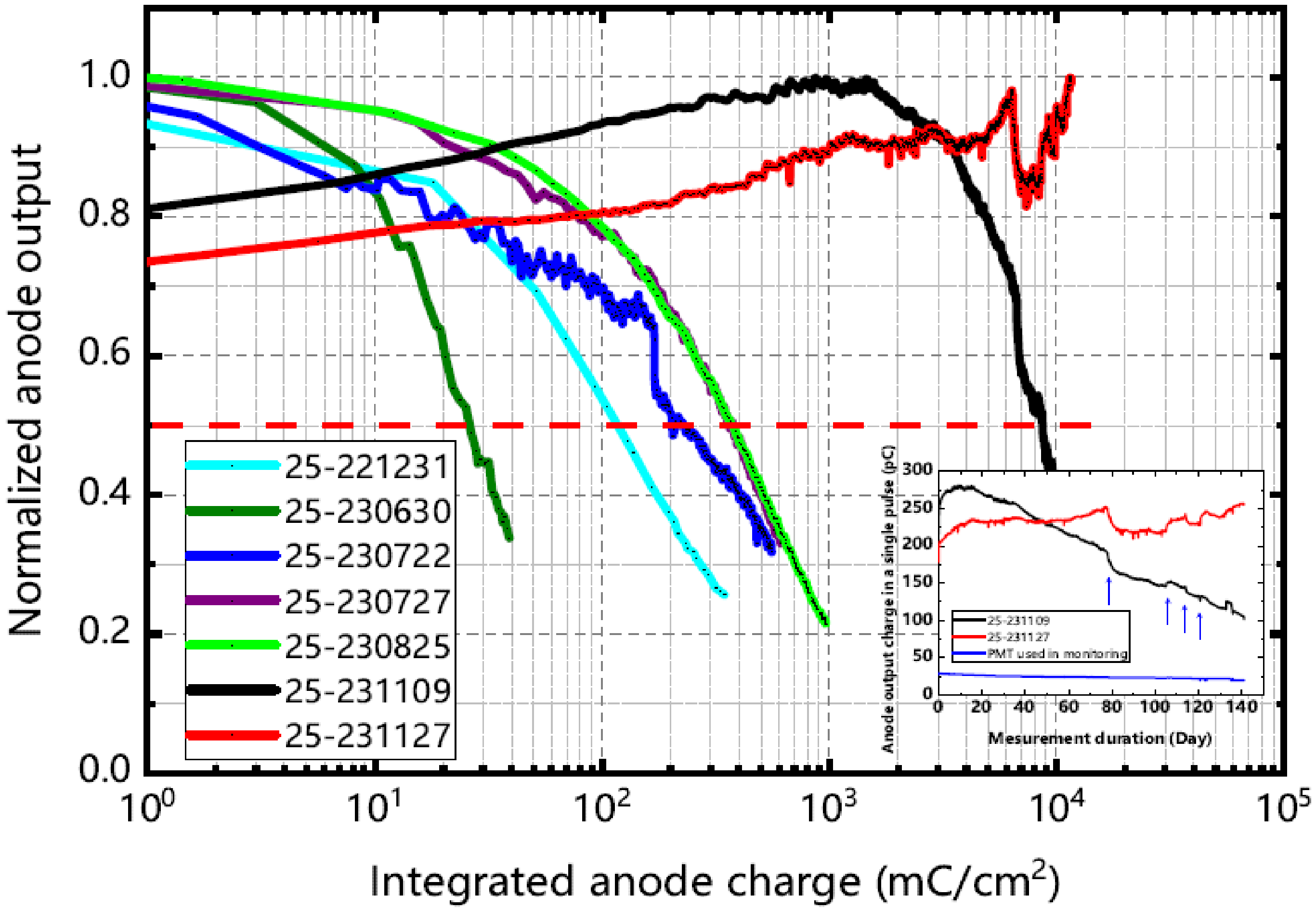
MCP-PMT prototypes and applications

- **Long lifetime multi-anode MCP-PMT for PID**

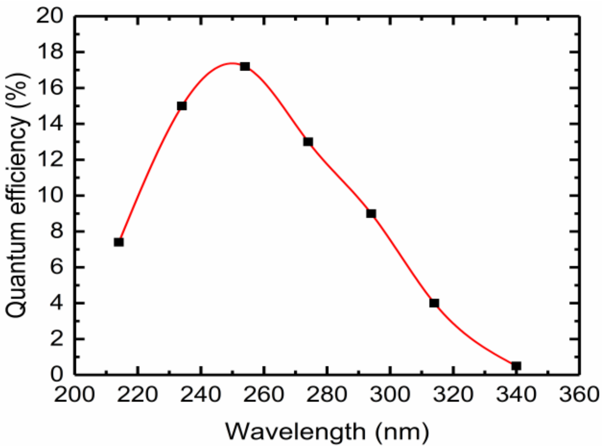




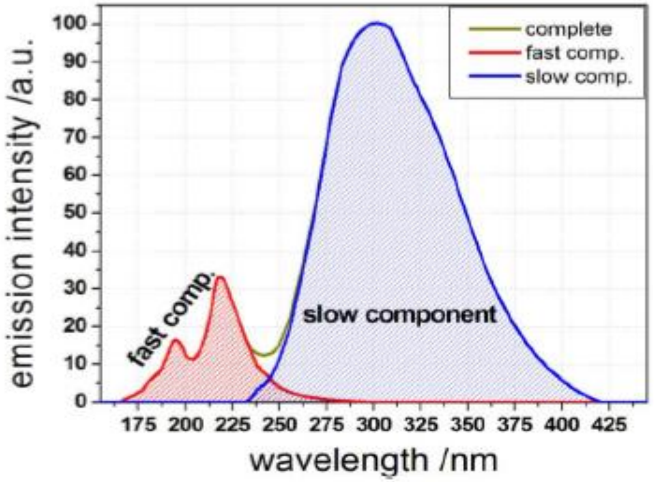
MCP-PMT prototypes and applications

- **Solar-blind MCP-PMT for fast X-ray detections**

- Photocathode : CsTe
- Peak wavelength： 250 nm
- Gain > 1E6
- Rise time: < 350 ps
- TTS @ SPE： < 50 ps

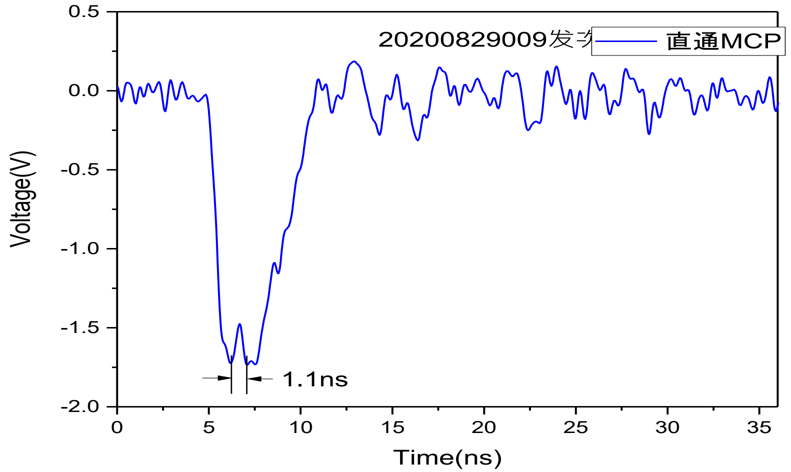


Spectrum response of CsTe MCP-PMT



BaF_2 fluorescence

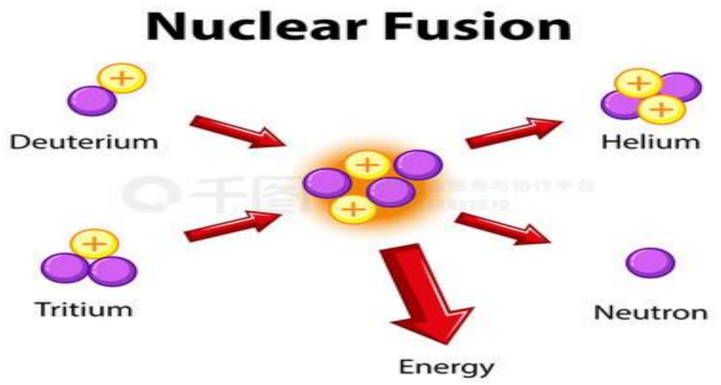
- Solar-blind MCP-PMT+BaF_2
- Better than 1 ns time resolution for X-ray detection.
- The fast and slow components of BaF_2 fluorescence have difference wavelengths.
- The CsTe cathode is mainly sensitive to the fast component of BaF_2.

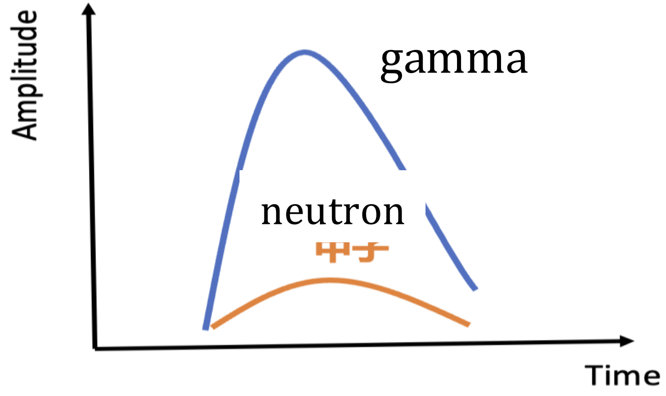


x-ray pulses detection in DCI laser fusion experiment

MCP-PMT prototypes and applications

- **Gated MCP-PMT for neutron detection in strong γ rays**
  - Neutron yield and spectrum detection are key to optimize the nuclear fusion experiment.
  - The intensity of the γ rays produced together with neutron is about 5 orders of magnitude higher than that of neutrons.
  - The MCP-PMT with a gating function is developed.
  - Photoelectron trajectory is controlled by the electric field between the photocathode and the gating electrode.

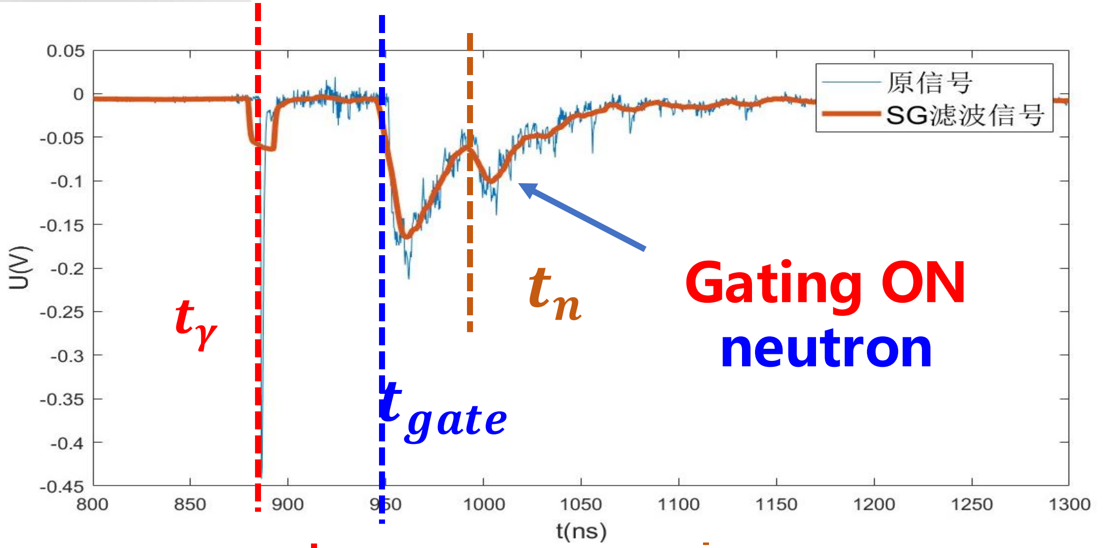


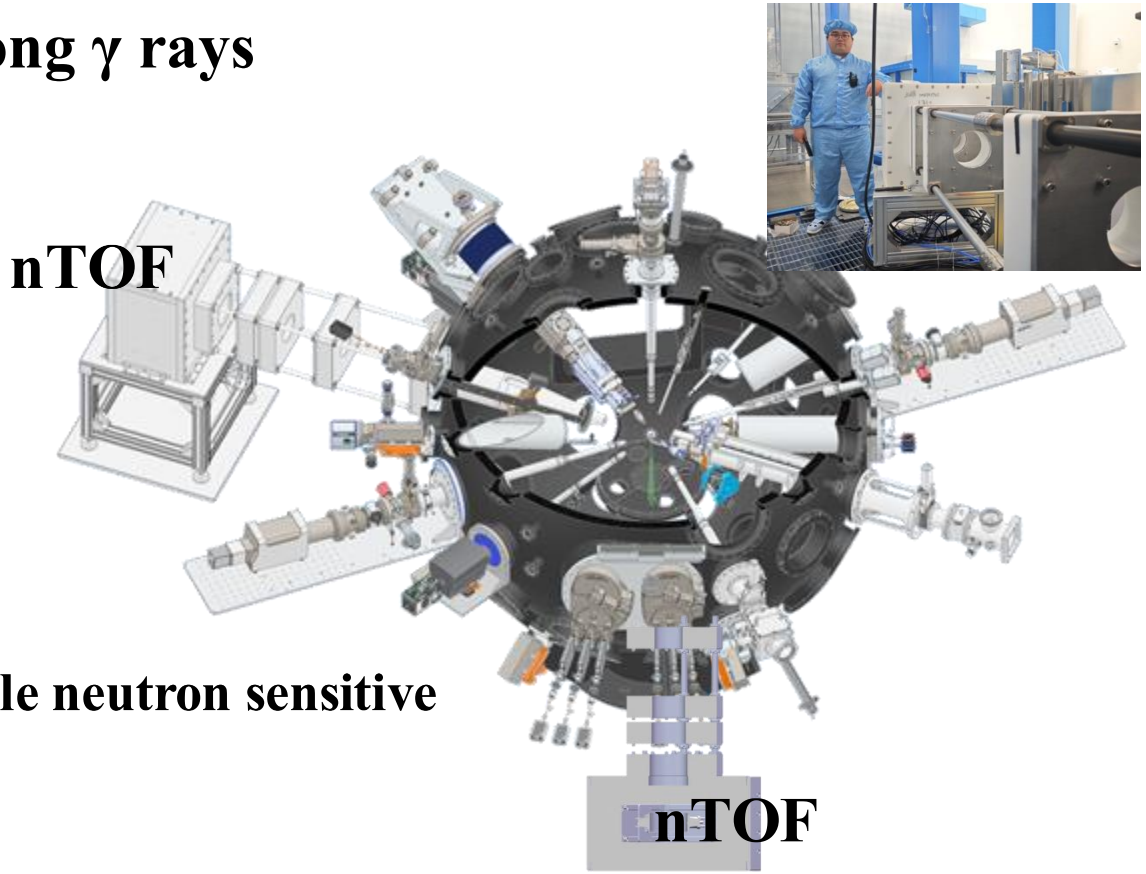


MCP-PMT prototypes and applications

- **Gated MCP-PMT for neutron detection in strong γ rays**

- Photocathode : bialkali
- Gain: > 1E6
- Rise time: < 350 ps
- Gating response time: < 5 ns
- Gating width: 5 ns ~10 ms
- Gating noise: < ±2 mV





Single neutron sensitive

DCI laser fusion facility

NIM A2024,1067(169726): 1-2

Rev. Sci. Instrum. 96, 093502 (2025)

MCP-PMT prototypes and applications

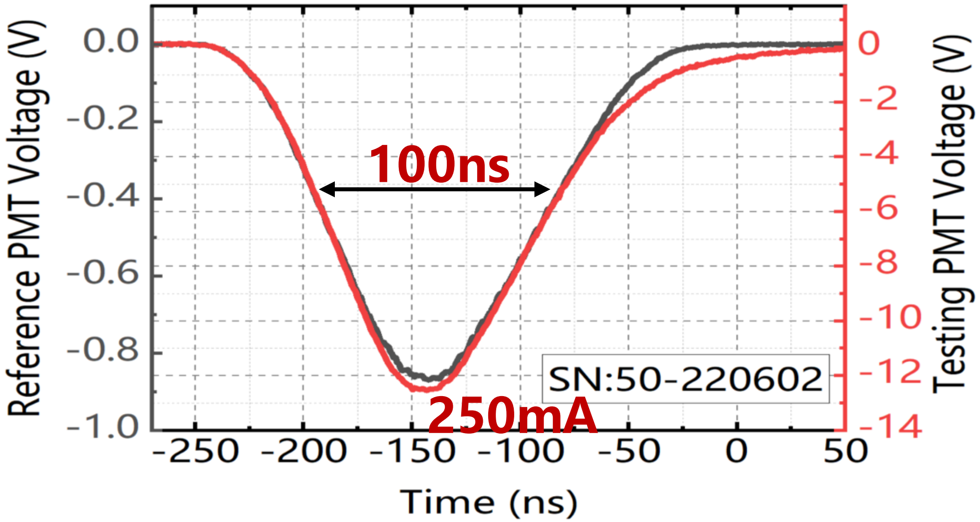
XIOPM

- More than 500 gated MCP-PMTs were delivered to the DCI laser nuclear fusion exp. for neutron yield detection.

MCP-PMT prototypes and applications

- **Large current MCP-PMT for strong radiation detection**

- Photocathode : bialkali
- Gain: > 1E4
- Maximum output current: > 250 nA @100ns
- Nonlinearity ＜ 5%
- Time resolution (FWHM) : ＜ 1ns



Thank you for your attention！

Ping
Xi'an, Shaanxi

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