High-Count-Rate Saturation in MCP-PMT: An Experimental Study

Kuinian Li*, Ping Chen, Yonglin Wei, Hulin Liu, Cong Ma, Jinshou Tian

likuinian@opt.ac.cn

Key Laboratory of Ultra-fast Photoelectric Diagnostics Technology,
Xi'an Institute of Optics and Precision Mechanics,
Chinese Academy of Sciences, Xi'an 710119, China

INTRODUCTION

As the core photoelectric converter in Ring Imaging Cherenkov (RICH) detectors, Microchannel Plate Photomultiplier Tubes (MCP-PMTs) exhibit dynamic responses that govern the spatial resolution of particle trajectory reconstruction. Under high-flux conditions, however, electron cloud saturation in microchannels triggers nonlinear gain attenuation – a critical bottleneck constraining device beam tolerance.

While atomic layer deposition (ALD) technology effectively extends MCP-PMT lifetime, it induces slow saturation recovery. Moreover, how ALD layer thickness influences saturation characteristics remains unclear, necessitating systematic investigation.

To elucidate the factors affecting the MCP-PMT saturation behavior, we developed a test system to probe response characteristics of single-anode MCP-PMTs with varied ALD thickness.

Table.1 ALD layer thicknesses for φ25mm-Cathode MCP-PMTs

ID	#25-240927	#25-241002	#25-230112	#25-230727	#25-230825	#25-231109	#25-240723	#25-240521
Thickness of the ALD layer	0	0	0	1 nm	1 nm	4.5 nm	6 nm	6 nm

METHODS

- The experimental setup incorporated a nanosecond-pulsed laser source.
- MCP-PMTs were characterized under three operational modes using a systematic control-variables method:
  - Constant gain (10⁴ or 10⁶ levels)
  - Constant single-pulse charge (10 pC/cm²)
  - Constant photon flux (1700 ph·cm⁻²·pulse⁻¹)

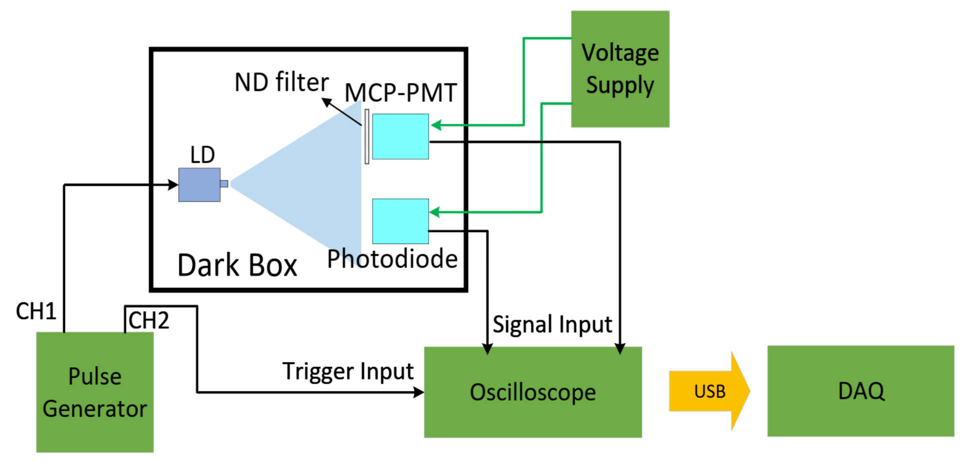

Fig.1 Experimental setup (The pulse frequency is adjusted from 10 Hz to 10 MHz.)

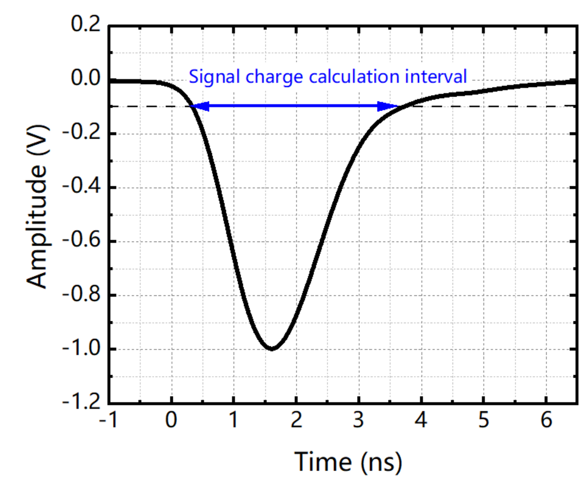

Fig.2 Single-pulse waveform(Average anode current $I_{avg} = Q \times f$, where Q = signal charge, f = pulse frequency)

RESULTS

- Saturation curves and recovery dynamics (methodology detailed in Ref. [Kuinian Li, et al., NIMA 1074(2025)170323])

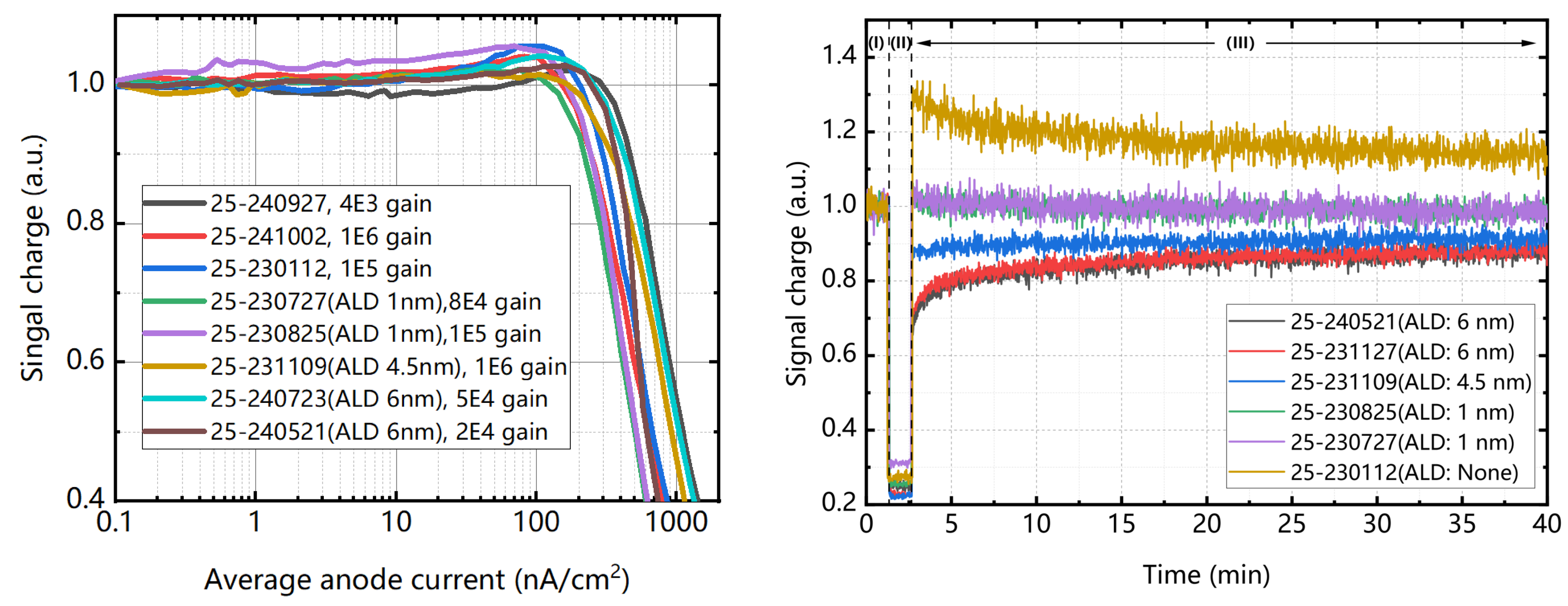

Fig.3 Saturation curves and recovery dynamics demonstrating negligible ALD impact but prolonged recovery with thicker layers.

- Constant gain

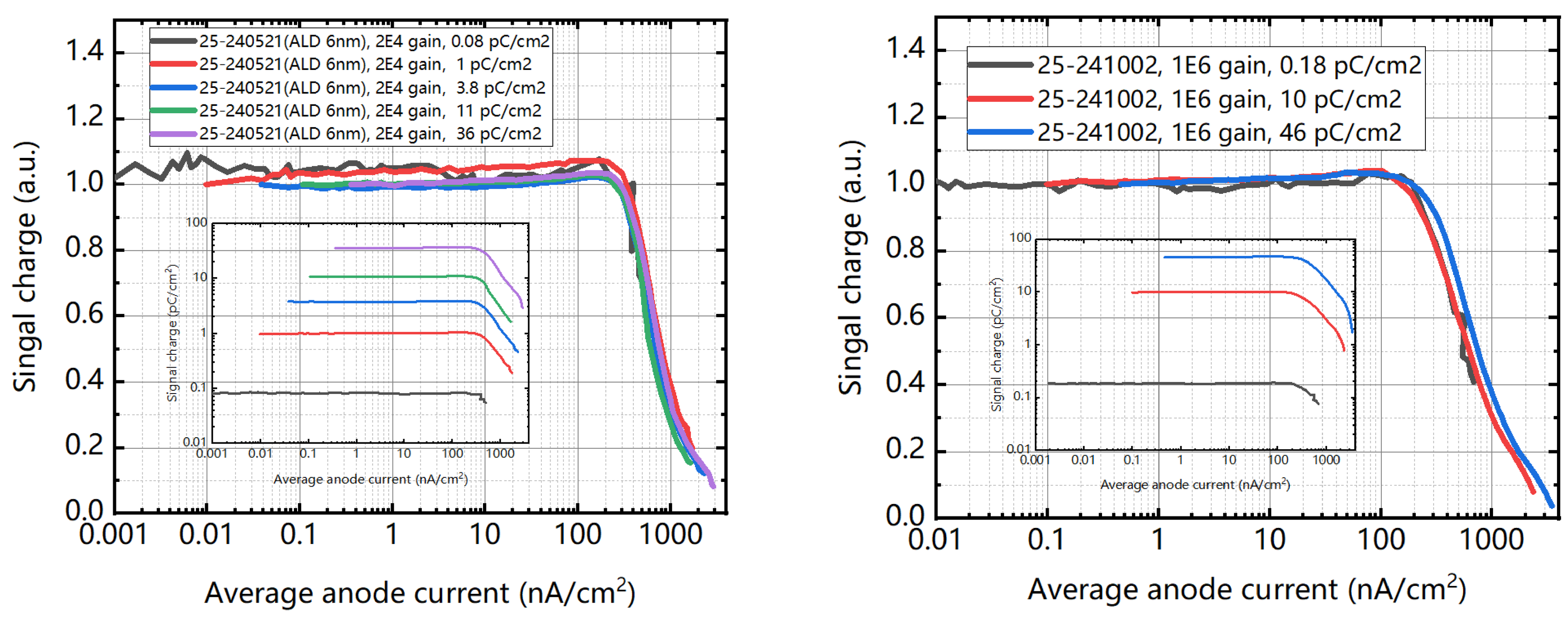

Fig.4 Saturation curves under constant gain (2E4 gain for #25-240521 with 6nm ALD layer and 1E6 gain for #25-241002 without ALD layer)

- Constant single-pulse charge

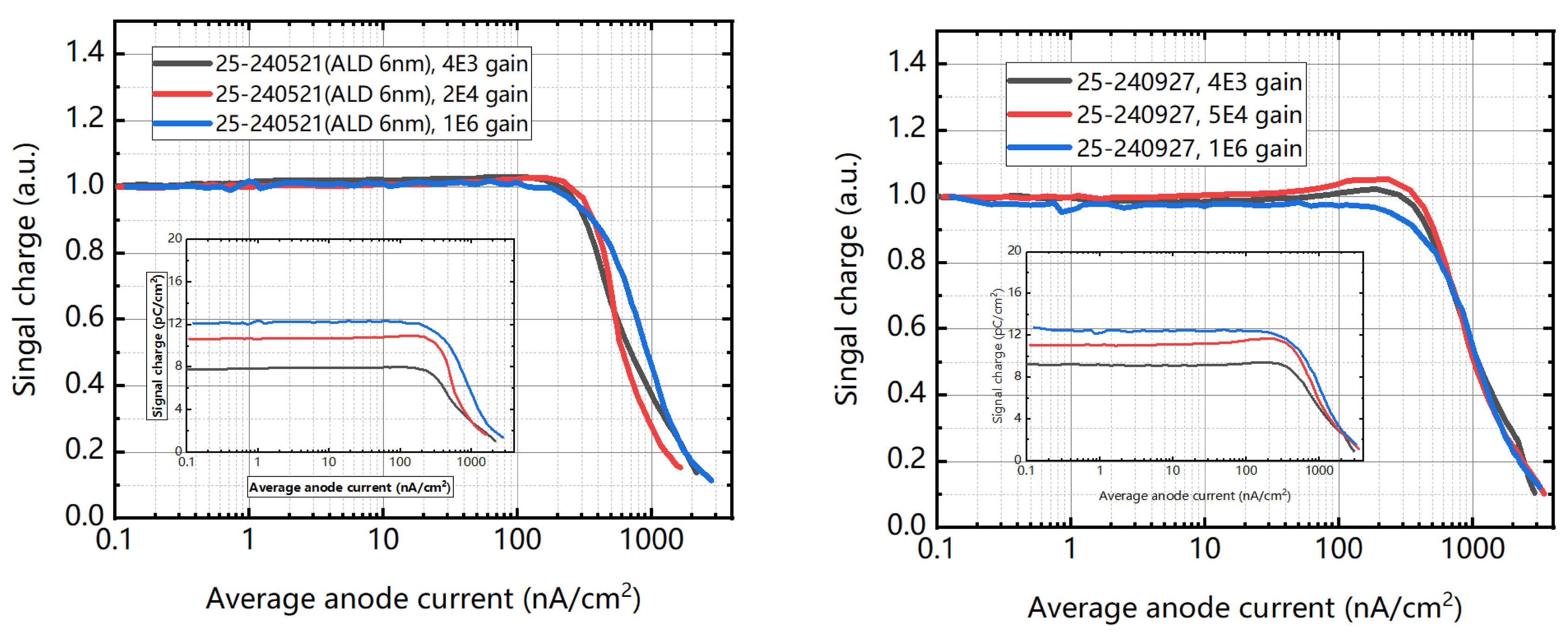

Fig.5 Saturation curves under constant single-pulse charge (Single-pulse output charge is stabilized at ~10 pC/cm² for #25-240521 with 6nm ALD layer and for #25-240927 without ALD layer)

- Constant photon flux

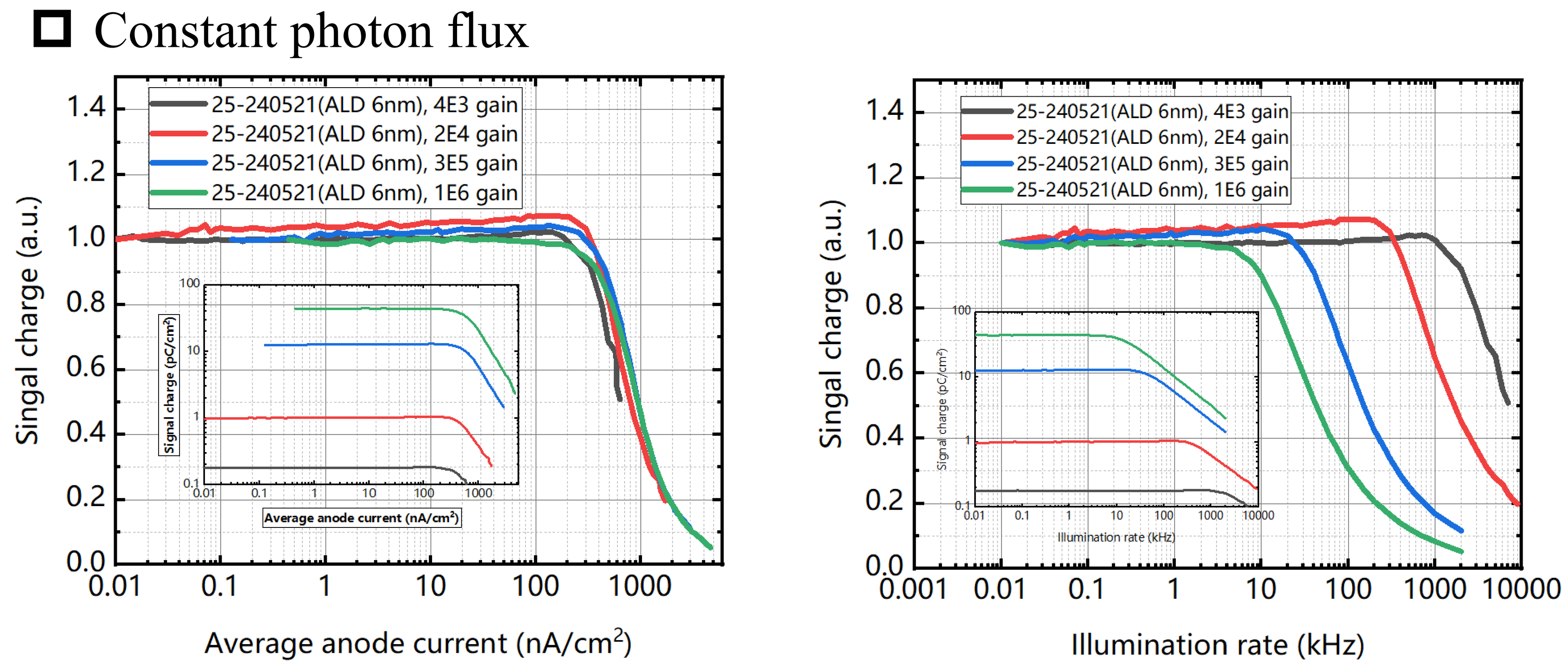

Fig.6 Saturation curves under 1700 ph·cm⁻²·pulse⁻¹ photon flux, with pulse frequency as the abscissa (right).

CONCLUSION

Our experiments reveal that ALD layers ≤6 nm exert negligible effects on saturation behavior. Critically, normalized saturation curves across all three modes consistently validate average anode current as a universal operational-condition-independent metric. Reducing MCP-PMT gain directly enhances the maximum tolerable count rate under constant photon flux. The established evaluation framework provides quantitative criteria for MCP-PMT selection in high-count-rate applications.

ACKNOWLEDGEMENT

This work is supported by National Key Research and Development Program of China (Grant No. 2023YFA1607202) and Strategic Priority Research Program of Chinese Academy of Sciences (Grants No. XDA25031100).