

Characteristics of fast timing MCP-PMTs in magnetic fields

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Abstract

Performance of the microchannel plate photomultiplier tube (MCP-PMT) in magnetic fields is an essential aspect for its application in the proposed electron ion collider. The motivation of this paper is to explore the critical parameters that affect the performance of MCP-PMT in magnetic fields and to guide the design optimization of MCP-PMTs for high magnetic field tolerance. MCP-PMTs with two different designs were examined in magnetic fields, and the results were compared. The magnetic field tolerance of MCP-PMT with new independently biased voltage design shows significant improvement (up to 0.7 T) compared to that of the MCP-PMT with resistor chain design (up to 0.1 T), indicating that optimization of the individual MCP voltage is an essential parameter for magnetic field tolerance improvement. The effects of other parameters such as the rotation angle relative to the magnetic field direction and the bias voltage between the photocathode and entrance MCP were thoroughly studied with the independently biased voltage design. The signal amplitude of the MCP-PMT exhibits enhanced performance at $\pm 8^\circ$ tilt angle due to the original MCP 8° bias angle. Maximum signal amplitude values are observed depending on the optimal bias voltages in different magnetic field strength.

Keywords: Fast timing, Microchannel plate, Photodetector, Electron Ion Collider, Particle identification detector, Rate capability, Magnetic field, Rotation angle.

1. Introduction

The Electron-Ion Collider (EIC) [1], which is recommended in the 2015 Long Range Plan for Nuclear Science [2] as the highest priority for a new facility construction in the US, aims to revolutionize our understanding both of nucleon and nuclear structure and of nuclear dynamics in the many-body regime, where strongly coupled relativistic quantum fluctuations and non-perturbative effects combine to give dynamic origin to nuclear mass and spin. The broad physics program of EIC requires a large multipurpose spectrometer to measure various physics processes over a wide range of rapidity and solid angle. Among these measurements, particle identification, i.e., the separation of electrons, pions, kaons, and protons ($e/\pi/K/p$) in the final state is a fundamental requirement for important physics processes such as semi-inclusive deep inelastic scattering and charm production.

To address the detector requirements for the broad physics program of EIC, several new detector concepts are currently being proposed, including the BeAST detector [3] and sPHENIX detector based on BaBAR solenoid [4] from Brookhaven National Laboratory (BNL), the JLEIC full acceptance detector [5] from Thomas Jefferson National Accelerator Facility (JLab), and the TOPSiDE 5D

particle flow detector [6] from Argonne National Laboratory (ANL). These proposed EIC detector concepts have different layouts of sub-systems, some of which have been worked out in detail, and some of which are still placeholders. Nevertheless, all these detector concepts are based on time-of-flight (TOF) systems and imaging Cherenkov detectors for hadron particle identification. Integration of these sub-systems in the central detector involves placing their photo-sensors in the non-uniform fringe field of a solenoidal magnet, requiring low-cost photon sensors with picosecond timing resolution, millimeter spatial resolution, high rate capability, high radiation and magnetic field tolerance.

The microchannel plate photomultiplier tube (MCP-PMT) [7] is a compact photosensor consisting of a photocathode for photon-electron conversion, two MCPs in a stacked chevron configuration for electron amplification and a readout system for charge collection. The compact design and confined electron amplification by secondary electron emission inside the micron size MCP pores provide the MCP-PMT with picosecond timing resolution and millimeter position resolution, ideal for time-of-flight systems and imaging Cherenkov detectors. The LAPPD collaboration [8] between universities, U.S. national laboratories, and industrial partners have developed the technology to manufacture the worlds largest MCP based photosensor, the Large-Area Picosecond Photon Detector (LAPPDTM). A critical aspect of LAPPDTM technology is its use of low-cost, very large area MCPs [9] at 20 cm \times 20 cm size and all glass vacuum envelope. The MCPs for LAPPDTM are made from bundled and fused capillaries of borosilicate

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glass and then functionalized through atomic-layer depo-
sition [10–12] of conductive and secondary-electron emis-
sive material layers. This revolutionary process eliminates
the chemical etching and hydrogen firing steps, which are
the causes of brittle glass and strong ion feedback in tra-
ditional MCP manufacturing. These features and the in-
herent mechanical stability of borosilicate glass allows the
production of the unprecedented large area MCPs with
long lifetime [13] and low background noise rates [14].

As a collaborator of the LAPPD project, a dedicated
fabrication facility [15] which can produce $6 \times 6 \text{ cm}^2$ MCP-
PMTs with the LAPPD design was built at Argonne Na-
tional Laboratory, serving as a production facility to pro-
vide $6 \times 6 \text{ cm}^2$ MCP-PMTs for early users before LAPPDTM
are mass produced by our industrial partner, Incom, Inc.
[16]. Tens of $6 \times 6 \text{ cm}^2$ MCP-PMTs were produced and
tested at Argonne and delivered to early users for LAPPDTM
feasibility test in their experiments. As Incom, Inc. starts
the mass production of the LAPPDTM, the Argonne fab-
rication facility is converted into an R&D platform for
LAPPDTM design optimization for specific applications.
Small size ($6 \times 6 \text{ cm}^2$) MCP-PMTs with different designs
can be quickly produced in the Argonne fabrication facility
and tested, and the optimal design can be directly trans-
ferred to Incom, Inc. for LAPPDTM mass production.

In this paper, two $6 \times 6 \text{ cm}^2$ MCP-PMTs with differ-
ent designs were produced in Argonne fabrication facility,
and their characteristics in the magnetic field were tested.
We describe the different designs of the two MCP-PMTs
in details in section 2, the magnetic field tolerance mea-
surement setup in section 3. The experimental results are
presented and discussed in section 4, and the conclusions
are drawn at the end of this paper.

2. Design of the MCP photodetector

Two MCP-PMTs with different designs were tested in
this study: the internal resistor chain design and the inde-
pendently biased design. The former relies on ALD coated
MCPs and spacers inside the MCP-PMT for bias voltage
distribution, while the latter relies on external high voltage
divider for bias voltage distribution.

2.1. Internal resistor chain MCP-PMT design

The internal resistor chain MCP-PMT design is adapted
from the original LAPPDTM design [17]. The left panel of
Fig. 1 shows the schematic of the internal resistor chain
MCP-PMT design. The sealed vacuum package consists
of a photocathode, two MCPs, three grid spacers and a
stripline anode. An air-sensitive alkali antimonide photo-
cathode is deposited on the inside surface of the top glass
window, and the electronic connection is led out via a pre-
coated nichrome layer at the edges of the top window to
apply high voltage. Two MCPs with 80 bias angles are
placed in chevron geometry to prevent drift of positive
ions to the photocathode and to ensure a well-defined first

strike of the incoming photoelectrons. The MCPs used
here are sliced from the same ALD coated $20 \text{ cm} \times 20 \text{ cm}$
MCPs for LAPPDTM, featuring a pore size of $20 \mu\text{m}$, a
length to diameter (L/d) ratio of 60:1 and an open area
ratio of 65%. Glass spacers are used between the photo-
cathode and the top MCP, between the MCPs, and be-
tween the bottom MCP and the anode to separate indi-
vidual components and support the stack configuration.
The stripline anode is made by silk-screening of the silver
strips onto glass tile base, and each stripline is grounded
through a resistor. Here it is vital to note that the MCPs
and glass spacers are all coated with resistive materials via
ALD method, making the whole detector stack an inter-
nal resistor chain, expressed by the dashed line circuit in
Fig. 1. When a single high voltage (HV) is applied to the
photocathode, the applied HV is distributed between the
internal components, controlled by the resistances of the
ALD coated MCPs and glass spacers. Signals generated
from incident photons are picked up from the stripline an-
odes and then brought to an oscilloscope or an electronic
waveform digitizer.

The internal resistor chain design only requires one HV
connection from the inside vacuum envelope to outside
through the pre-coated nichrome mask on the top window.
This simple design provides the advantages of ease of im-
plementation and potentially low cost. However, process-
ing and testing of the fabricated MCP-PMTs reveal several
disadvantages: (a) the HV distribution relies on resistance
ratios between the spacers and MCPs, while it is difficult
to find precisely matched resistances for the MCPs and
spacers; (b) the fabrication of MCP-PMT requires thor-
ough baking and scrubbing of the MCPs under vacuum
for outgassing, while experiment processing shows that the
resistances of ALD coated MCPs and spacers reduces ir-
regularly during baking and scrubbing process, making the
resistance match of MCPs and spacers more difficult; (c)
once the detector is sealed, there is no way to individually
optimize the MCPs performance as the bias voltage on
each MCP cannot be adjusted separately; (d) the absolute
quantum efficiency (QE) of the photocathode cannot be
measured using the tradition method as the photocurrent
(nA level) generated from incident photons submerges into
the continuous bias current (μA level) of the resistor chain.

2.2. Independently biased MCP-PMT design

Due to the irregular reduction of ALD coated MCP
and spacer resistances during the photodetector fabrica-
tion process, performance of the two MCPs cannot be op-
timized at the same time. It is necessary to have a new
design such that the bias voltage of each MCP can be ad-
justed independently, referred to as independently biased
MCP-PMT design (IBD), so that the performance of both
MCPs can be optimized. Schematic of the new IBD design
is shown in the right panel of Fig. 1. The major configura-
tion improvement includes: (1) the spacers are bare glass
grids with no ALD coating on the surface, so the spacers
can be treated as insulators; (2) ultra-thin stainless steel

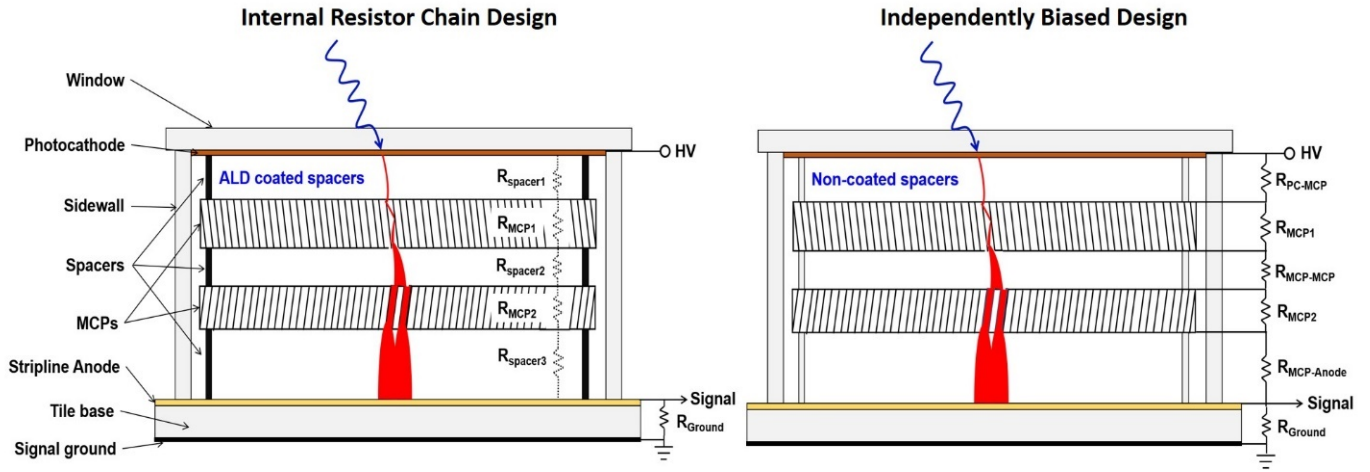


Figure 1: Schematic diagrams of the internal resistor chain design (left) and independently biased design (right). The equivalent electrical circuit in internal resistor chain design is noted as dashed line connections. Notice the major difference of using ALD coated spacers (resistor) in internal resistor chain design and non-coated spacers (insulator) in independently biased design.

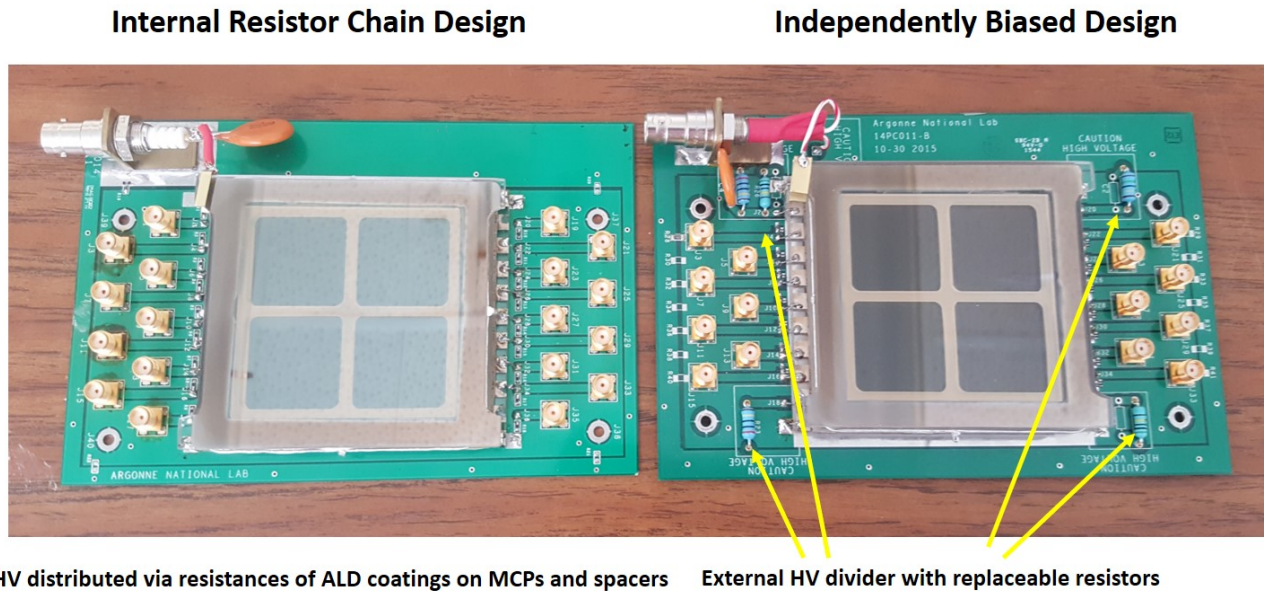


Figure 2: Picture of MCP-PMTs with the internal resistor chain design (left) and independently biased design (right). Simple readout circuit boards were designed to hold the MCP-PMTs. Note that an external HV divider with replaceable resistors was integrated into the readout board of the independently biased MCP-PMT design.

shims with the same pattern as grid spacers are attached between the spacers and the MCP surfaces for HV connections; (3) finger tabs are designed on each shim, leading the shim to the nearest silkscreen printed silver strip contact at the corner, and this leads the MCP surface HV connection to the outside. Four shims are applied for the upper and lower surfaces of the two MCPs. The new IBD design is based on a minimal modification of the internal resistor chain design, using shims and corner strip lines for HV connection, no pins are required to provide high voltage on the MCPs and in the gaps. Fig. 2 shows the picture of a sealed MCP-PMT with the independently biased design (right) in comparison with the internal resistor chain design (left). Simple readout circuit boards were designed to hold the MCP-PMTs. An external resistor chain HV divider is integrated into the readout board of the independently biased MCP-PMT design so that only one HV power supplier is necessary, and the bias voltage of individual MCPs can be independently adjusted by replacing the corresponding resistors.

3. Magnetic field tolerance test facility

At Argonne National Laboratory, a decommissioned superconducting magnet from a magnetic resonance imaging (MRI) scanner was acquired for precise instrument calibration for the g-2 muon experiment [18]. The MRI magnet provides a large bore with a diameter of 68 cm and a very homogeneous field (7 ppb/cm), with a tunable magnetic field strength up to 4 Tesla. This unique facility provides us with a large uniform tunable magnetic field for magnetic field tolerance test of various size detectors. We have built a characterization system compatible with the solenoid magnet to test the performance of the $6 \times 6 \text{ cm}^2$ MCP-PMTs in a strong magnetic field environment. A non-magnetic, light-tight dark box was designed and custom built at the Argonne mechanical shop as a container to constrain the MCP-PMT during the testing within the magnetic field. The dark box was held on a test platform with the detector surface normal to the direction of the magnetic field. The position of the dark box was adjusted so that the center of the MCP photodetector was well-aligned with the center of the solenoid magnet. A rotation mechanism was also integrated with the system, allowing rotation of the MCP-PMTs with an angle θ ($-90^\circ \leq \theta \leq 90^\circ$) during the experiment to study the angle dependence of MCP-PMT performance, as shown in Fig. 3.

Fig. 4 shows a picture of the magnetic field tolerance testing system. A 405 nm light-emitting diode (LED) driven by a pulse generator was used as the light source and was introduced into the dark box through a multimode optical fiber. High voltage was applied to the MCP-PMT from a power supply with continuous voltage control. Signals collected at the striplines were read out through a DT5742 desktop digitizer [19] produced by

CAEN (Costruzioni Apparecchiature Elettroniche Nucleari S.p.A.) with a sampling rate of 5 GS/s. The digitizer is based on a switched capacitor array of DRS4 (Domino Ring Sampler) chips [20], 16 analog input channels, and one additional analog input for the fast trigger.

Another MRI magnet with tunable magnetic field up to 3 Tesla was available at the University of Virginia. A similar magnetic field platform without the rotation mechanism was also set up there for part of the experiment. The following results reported in section 4 was completed with either of the two MRI magnets. Specifically, measurement of MCP-PMT with internal resistor chain design was performed on the University of Virginia MRI magnet, and measurement of MCP-PMT with the independently biased design was performed on the Argonne 4-Tesla magnet facility.

4. Results and discussion

The operational principle of MCP-PMTs relies on an electron multiplication process where the channel wall is bombarded multiple times with secondary electrons. Each channel of the MCP used in this experiment has an internal diameter of $20 \mu\text{m}$ with the inner wall processed with resistive and secondary emissive coating layers, which acts as an independent electron multiplier. When the MCP-PMT is operated in a magnetic field, the trajectories of electrons during electron multiplication process will be affected by the Lorentz force due to the presence of electromagnetic fields. We studied the MCP-PMT performance dependence on magnetic field strength, angle and photocathode to MCP electric field strength as below.

4.1. Magnetic field strength dependence

The performance of MCP-PMTs with the above two designs in the magnetic field was tested at a zero rotation angle θ , i.e., where the direction of the magnetic field is normal to the surface of the MCP photodetector. Since a 405 nm pulsed LED was used here as the light source, the measurements were conducted at a fixed light intensity of 10 photoelectron mode for easy experiment control. The signal amplitude was selected as a relative indicator of the gain and the merit of the MCP-PMT performance in the magnetic field. The results were plotted in terms of the signal amplitude on magnetic field strength as shown in Fig. 5.

The MCP-PMT with internal resistor chain design shows a very poor magnetic field tolerance, the intensity of the peak drops by a factor of 6 with magnetic field increases from 0 to 0.1 Tesla, and another factor of 6 with the magnetic field increases to 0.2 Tesla. This fast drop is mainly because the resistances of the MCPs and spacers were significantly changed during the baking and scrubbing process, resulting in the bias voltage mismatch of the two MCPs. Only one MCP might be biased at the designed optimal HV (typically 1000V per MCP), and the other one

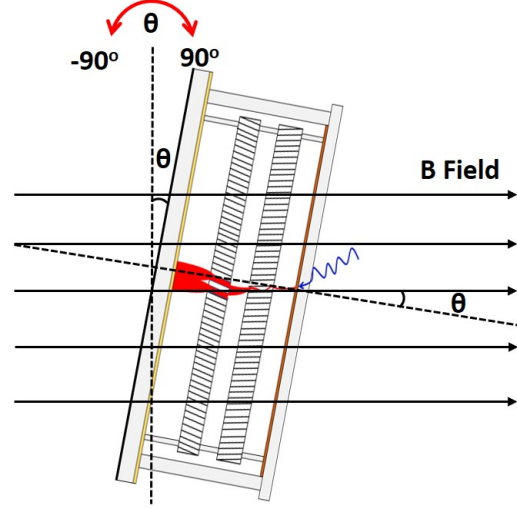
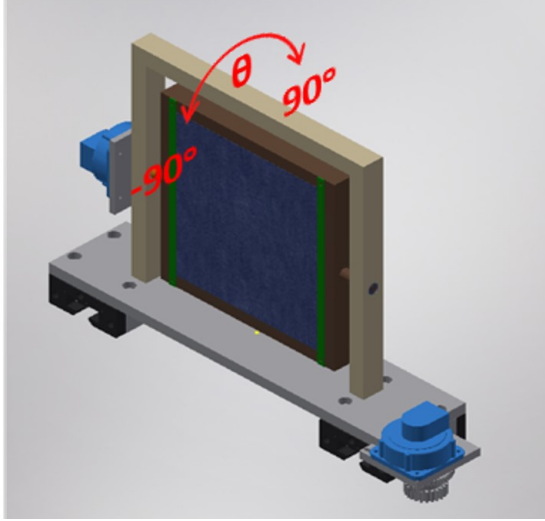


Figure 3: (left) AutoCAD drawing of the custom designed magnetic field tolerance test platform, the center part is rotatable with angle $-90^\circ \leq \theta \leq 90^\circ$. (right) Schematic of the rotation mechanism of the MCP-PMT with the angle θ relative to the magnetic field direction during the measurement.

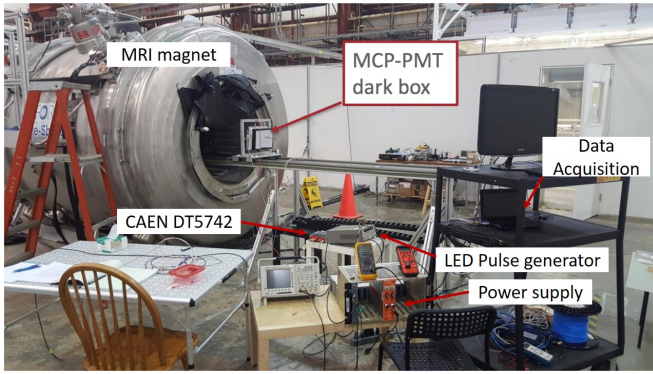


Figure 4: Picture of the magnetic field tolerance testing system.

was biased at HV way off the optimal value. The fast drop of the signal amplitude in the magnetic field indicates that the MCP-PMT with resistor chain design is not suitable for applications in high magnetic field environment over 0.1 T.

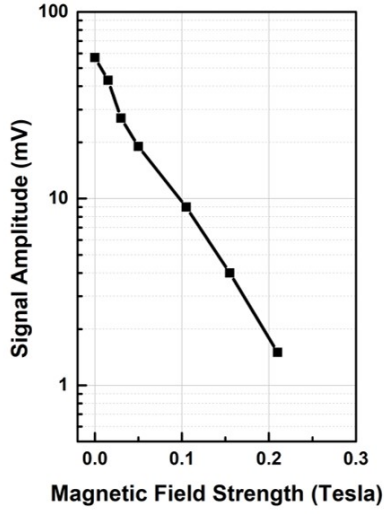
The MCP-PMT with independently biased design shows significantly improved tolerance to magnetic field strength. The performance of the investigated MCP-PMT was measured at various magnetic field strengths and bias high voltages. An external HV divider was used to ensure both MCPs were biased at the same HV for best performance. At a fixed magnetic field strength, the signal amplitude of the MCP photodetector increases as the bias high voltage increases. This behavior is similar to our previous measurements of the MCP-PMT without applying a magnetic field [21]. At a fixed bias voltage of 3100 V, the signal amplitude of the MCP-PMT increases slightly as the magnetic field strength increases to 0.2 T, and then decreases as the magnetic field strength continues to increase, and eventually breaks down with signal amplitude below 5 mV

at magnetic field strength of 0.7 T. With lower biased voltages, the break down magnetic field strengths decrease accordingly. From these results, one may compensate the effect of magnetic field on the MCP-PMT gain by increasing the applied bias voltage, with lower HV at low magnetic field strength while higher HV at high magnetic field strength to maintain the same gain for MCP-PMT operation.

4.2. Tilt angle dependence

With a good performance in the magnetic field, MCP-PMT with the independently biased design was chosen to study its performance dependence on tilt angle between the normal to the MCP-PMT window and the direction of the magnetic field, as shown in Fig. 3. We applied a fixed high voltage of 3000 V on the HV divider and rotated the tilt angles θ from -90° to 90° for a full range angle measurement. Fig. 6 presents the response of the MCP-PMT, in terms of the signal amplitude, as a function of the tilt angle at two magnetic field strengths of 0.25 and 0.5 Tesla, respectively. The signal amplitude shows strong angle dependence at $-30^\circ \leq \theta \leq 30^\circ$ with two local maximums at 8° . The peak angles of 8° are due to the original 8° bias angle of the two MCPs and their chevron configuration. When the direction of one MCP pore is aligned with the direction of the magnetic field, the MCP-PMT shows an enhanced magnetic field tolerance. The signal maximum at 8° corresponds to the position where the direction of top MCP pore is aligned with the direction of the magnetic field, and the signal maximum at -8° corresponds to the position where the direction of bottom MCP pore is aligned with the direction of the magnetic field. The signal amplitude value at 8° is higher than that of -8° , indicating that the effect from the direction of top MCP pores is stronger than that from the bottom MCP pores.

Internal resistor chain design



Independently biased design

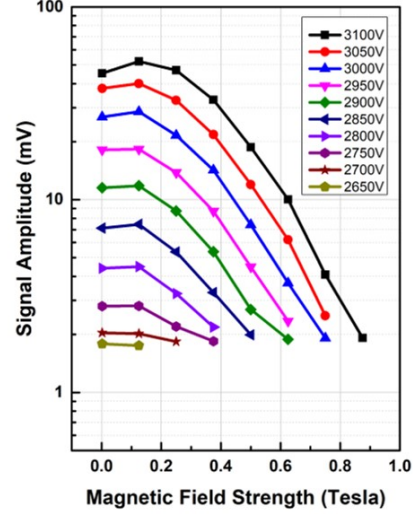


Figure 5: Performance of the MCP-PMTs in terms of signal amplitude in magnetic field: the internal resistor chain design (left) and the independently biased design (right). The magnetic field tolerance of MCP-PMT is significantly improved with bias voltages of both MCPs at optimized values.

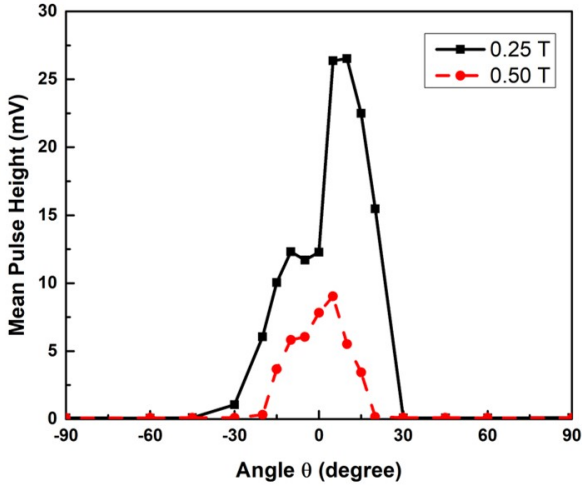


Figure 6: The response of the MCP-PMT as a function of the tilt angles θ between the normal to the MCP-PMT window and the direction of the magnetic field. The two peaks around -8° and 8° indicates the effect due to the 8° bias angle of the MCPs. Note that the intensities of these two peaks are not the same due to the different effect of the top and bottom MCPs.

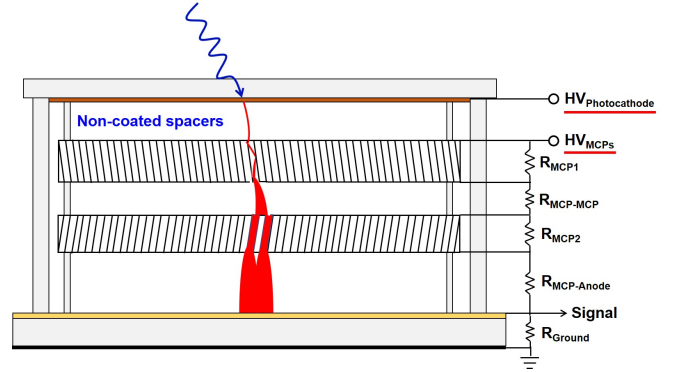


Figure 7: The electrical circuit of HV connections to vary the gap voltage between the photocathode and the top MCP.

4.3. Gap high voltage dependence

The MCP-PMT performance dependence on HV applied to the gap between the photocathode, and top MCP was also studied at different magnetic field strengths. Fig. 7 shows the circuit diagram to vary the applied gap voltage between the photocathode and top MCP during this measurement. The HV of the MCPs was kept at a fixed value, and the HVPhotocathode was varied at different values to adjust the applied gap voltage.

The pulsed signals were recorded, and the signal amplitudes were calculated and plotted as in Fig. 8. At the low magnetic field, the signal amplitude increases as the gap voltage increases and reaches a maximum at gap voltage 500 V, and then the signal amplitude starts to decrease with continuously increased gap voltage. The behavior of MCP-PMT signal amplitude dependence on the gap voltage at the low magnetic field is due to the effect of primary

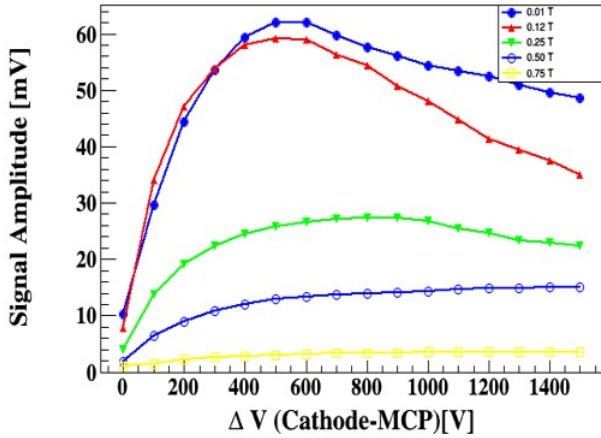


Figure 8: Performance of the MCP-PMTs in terms of signal amplitude as a function of gap voltage applied between the photocathode and top MCP in different magnetic fields.

electron energy on the secondary emission yield of ALD³⁹⁹ coated emissive materials. The MCPs used here were processed with ALD coated emissive materials for secondary emission with their secondary emission yields dependence on surface composition and film thickness studied previously [22]. The measurement data shows that the secondary emission yield of the ALD coated material has the highest value when the primary electron energy is around 300 eV 500 eV, resulting in the maximum signal amplitude for the investigated MCP-PMT with photocathode to MCP gap HV at 500 V. The secondary yield of the ALD coated material starts to decrease with even higher primary electron energy, leading to reduced signal amplitude at over 500 V gap voltage. At high magnetic fields, the magnetic field strength becomes the main parameter affecting the secondary emission process. The secondary yield of the ALD coated material does not decrease anymore with primary electron energy over 500 eV, resulting in a continuously increased signal amplitude even with higher gap voltages.

5. Conclusions

Two 6×6 cm² MCP-PMTs with internal resistor chain design and independently biased design were fabricated at Argonne National Laboratory and characterized with the Argonne magnetic field test facility. The behavior of the MCP-PMT signal amplitude was investigated as a function of the magnetic field strength, the distribution of bias voltage, the tilt angle and the gap voltage. It was found that the MCP-PMT with internal resistor chain design only shows magnetic field tolerance up to 0.1 T. With independently biased voltage design, the magnetic field tolerance of the MCP-PMT is significantly improved up to 0.7 T. It is essential to ensure both MCPs are operated at optimal bias voltage for applications in high magnetic fields. As⁴³⁴

the magnetic field strength increases, the signal amplitude of the MCP-PMT decreases for operation at the same bias voltage, the reduction of signal amplitude can be compensated by increasing the operation voltage, extending the MCP-PMT operation limit in the high magnetic field. Due to the original MCP bias angle of 8° and the chevron configuration, the MCP pores are not aligned with the direction of the magnetic field when the MCP-PMT window surface is normal to the direction of the magnetic field. The MCP-PMT shows higher signal amplitudes when either MCP pores are aligned with the direction of the magnetic field, and the direction alignment of the top MCP pores exhibits a stronger impact on the MCP-PMT performance than that of the bottom MCP pores. Increasing the bias voltage applied on the gap between the photocathode and the top MCP results in a maximum signal amplitude with gap voltage around 500 V at low magnetic fields, while a continuously increased signal amplitude at high magnetic fields.

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