Design and fabrication of prototype 6 cm x 6 cm microchannel plate photodetector with bialkali photocathode for fast timing applications

Junqi Xie¹, Karen Byrum¹, Marcel Demarteau¹, Joseph Gregar¹, Edward May¹, Mathew Virgo¹, Robert Wagner¹, Dean Walters¹, Jingbo Wang¹, Lei Xia¹, Huyue Zhao¹, *the LAPPD collaboration*
¹*High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*

Abstract

Planar microchannel plate-based photodetector with bialkali photocathode is capable of *fast and accurate* time and position resolutions. A new 6 cm x 6 cm photodetector production facility was designed and built at Argonne National Laboratory. Small form-factor MCP-based photodetectors completely *constructed* of glass were designed and *prototypes were successfully fabricated*. Knudsen effusion cells were incorporated in the photocathode growth chamber to achieve uniform and high quantum efficiency photocathodes. The *thin film* uniformity distribution *was simulated and measured for an antimony film deposition, showing uniformity of better than 10%. Several prototype devices have been fabricated with the described system. A typical prototype device with bialkali photocathode exhibits time-of-flight resolution of ~ 27 psec and differential time resolution of ~ 9 psec, corresponding to spatial resolution of ~ 1.3 mm.*

Key words: microchannel plate, photodetector, bialkali photocathode, effusion cells, uniformity, time resolution, differential time resolution, spatial resolution

1. Introduction

Photomultiplier tubes (PMTs) have been widely used in high energy physics particle detection methods, such as time of flight (TOF) measurements, calorimetry and Cherenkov light detection [1-3]. There are several advantages of PMTs to be used for these applications: (1) low photoelectric signals detection, (2) fast time response at psec level, (3) large active area, 20 inches diameter photomultiplier is commercially available. However, the conventional photomultiplier tubes may only detect the intensity of collected photons, but cannot accurately determine the position of the incoming photons. New or upgraded detectors in particle and nuclear physics call for next generation photo detectors [4, 5] with fast time and accurate position resolutions as well as low cost, large area, high quantum efficiency (QE), high gain, low dark current and time of flight response.

Bialkali photocathode (K_2CsSb) is a kind of fast response (pico-second) photocathode with relatively high sensitivity and low dark current widely used in PMT industry. These K_2CsSb photocathodes exhibit ~20% QE [6, 7], which was achieved in 1960s mainly through empirically developed process and by paying considerable attention to production details by commercial manufactures. The improvement of photocathode QE is limited by the poor understanding of the photocathode growth mechanism, the photocathode material properties such as cathode thickness, structural formation, surface roughness and chemical composition, and how these properties influence the overall quantum efficiency. Recently, a series of real time in-situ x-ray studies [8-10] indicate that K-Cs-Sb photocathodes following traditional sequential diffusion methods are mixtures with different stoichiometry and the structures are either amorphous or polycrystalline. The polycrystalline K-Cs-Sb photocathode with stoichiometry near $K:Cs:Sb = 2:1:1$ exhibits much higher QE than others. Since the right stoichiometry improves the photocathode crystallinity, it decreases the defect scattering and increases the electron mean free path, thereby achieving higher QE. A stoichiometric crystalline K_2CsSb photocathode with modified doping profile is expected to achieve much higher QE. Meanwhile, recent advances of functionalized MCP via atomic layer deposition (ALD) technique open great opportunities for revolutionary development of photomultiplier tubes [11, 12]. These MCP channel axes are biased at a small angle ($\sim 8^\circ$) to the surface

normal, when photoelectrons are collected by the MCP channels, each channel can be considered as a continuous dynode structure. MCPs functionalized via newly developed ALD process exhibit significantly improved gain at the same operating voltage cross non-functionalized devices, providing advantages to replace dynode series in a conventional PMT with the MCP stacks.

The large-area picoseconds photodetector (LAPPD) collaboration, a joint effort of Argonne National Laboratory, the University of Chicago, the University of California-Berkeley, the University of Hawaii, and industry partner Incom, Inc., is currently developing large-area, modular photo-detector systems composed of thin, planar, glass-body modules based on newly developed MCP technology [13]. The overall goal of this research project is to develop 20 cm x 20 cm large-area photodetectors capable of mm-scale spatial resolution and pico-second time resolution. A new photodetector production facility capable of producing 6 cm x 6 cm photodetector was designed and constructed at Argonne National Laboratory as a low cost, lower risk path towards commercialization of large area picosecond photodetectors [14]. The new facility consists of load lock, MCP scrubbing chamber, photocathode growth chamber and sealing chamber. Knudsen effusion cells, widely used in molecular beam epitaxy technique, are incorporated into the photocathode growth chamber to achieve molecular beam sources for uniform stoichiometric bialkali K_2CsSb photocathode growth. This paper describes the structure of 6 cm x 6 cm MCP photodetector, the design concept and commissioning of photocathode growth chamber and the fabrication and initial test results of prototype MCP photodetector with bialkali photocathode.

2. 6 cm x 6 cm MCP photodetector assembly

The 6 cm x 6 cm thin planar photodetector based on micro-channel plate (MCP) is designed with glass-body assembly following the 8'' x 8'' LAPPD design [13]. The whole assembly is composed of four components as shown in figure 1: top window, MCP and spacer stack, getters and the base plate. The

photocathode is coated on the inside surface of top window over a metalized pattern that serves to bring the high voltage from outside the vacuum into the interior. Various materials, such as glass, quartz and sapphire, may be used as the top window for different applications and cost consideration. Two MCP capillary plates and three spacers are placed between the top window and base plate. MCPs are coated with secondary emission layer, serving as electron multipliers with exceptional gain and secondary electron emission yield. The spacers are coated with a low resistance layer, serving as a voltage divider to provide current to MCPs. The getters are several thin getter strips besides the sidewall, they are activated inside vacuum via high temperature bake-out. The base plate consists of a glass plate with anode stripes silk-screened onto the upper surface and a square sidewall sealed with glass frit to the anode plate. The anode strips act as transmission lines and provide 2D position information when signals are read out at opposite ends of each strip. All the components are assembled in vacuum chamber via hermetic thermo-compression sealing, producing a functional photodetector.

Micro-channel plate photodetectors combine many of the virtues of photo-multipliers with a relatively simple planar package construction. Compared with the conventional PMTs, the MCP-based photodetector has a much smaller volume, mainly due to the replacement of dynode series with MCP stack. In figure 1, the height of a 6 cm x 6 cm MCP photodetector is only 1.6 cm, while a conventional PMT tube with 5 cm diameter is 13 cm high. In addition, the planar design of the photodetector ensures the position of incoming photons to be imaged on the anode strips. With fast electronic readout, accurate position resolution can be achieved. Use of the alkali photocathode with the compact MCP design ensures efficient and fast time resolution.

Figure 1. Schematics of MCP-based photodetector (left) and conventional photomultiplier (right). note the dimensions are not drawn in scale. The dynode series in conventional PMT are replaced by thin MCP stacks and so the volume of the MCP-based photodetector is significantly reduced. The planar design also provides high position resolution.

3. Photocathode growth chamber design concept

Traditionally and currently used in industry, photocathode deposition is the last step in the photomultiplier tube fabrication process since photocathodes are extremely sensitive to air and water. Other components such as dynodes and anode are pre-assembled in the glass tube together with antimony bead source and alkali dispensers. Antimony bead and alkali dispensers are electrically heated to deposit photocathode on the inside top surface of the glass tube. Since the dynode and anode are both made of metals, the alkali vapor will not affect their performance. However, in the MCP-based photodetector, two MCPs coated with resistive and secondary emission layers are used to multiply the photoelectrons,

replacing the traditional dynode series, the alkali vapor may contaminate the MCPs and so degrade their performance. It is better to deposit photocathode on glass substrate in a vacuum chamber and transfer the substrate to a sealing chamber for photodetector assembly. This provides the opportunity to design and build the photocathode growth chamber based on molecular beam epitaxy (MBE) technique, which has been well developed in the thin film community. The MBE technique has several advantages comparing to the traditional electrical heating method: (a) precise control of the elemental beam flux for the stoichiometric compound; (b) well developed technology for crystalline material deposition; (c) ability to fabricate device structures with designed profiles; (d) easily adopted for use in large-area planar photodetectors.

One of the important evaluation parameters for large area photodetector fabrication is the uniformity of the photocathode. It is critical to obtain uniform source beam fluxes on the substrate surface to ensure uniform photocathode deposition, especially the initial antimony film uniformity, as an optimal Sb film thickness exists for the best final quantum efficiency (QE) of a photocathode [15]. Knudsen effusion cells are incorporated in the photocathode deposition system as source beam generators for this purpose. Inside an effusion cell, source molecules are at equilibrium, the source beam flux comes through a small orifice at the top of the effusion cell. Thus the mass deposition rate per unit area of source surface can be expressed as equation 1, based on the Langmuir-Knudsen relation [16]:

$$R_m = C_m \left(\frac{M}{T} \right)^{\frac{1}{2}} \cos \theta \cos \varphi \frac{1}{r^2} (P_e(T) - P) \quad (1)$$

where R_m is the mass deposition rate, C_m is a constant, M is the source molecular mass, T is the source temperature, r is the distance between deposition point and the orifice, P_e is the source vapor pressure at temperature T , P is the chamber pressure, θ is the molecular beam exit angle and φ is the incident angle of

molecular beam to the substrate. For a square substrate, if the non-uniformity across the substrate is defined as:

$$\delta(\%) = \frac{R_{center} - R_{edge}}{R_{center}} (\%) \quad (2)$$

The uniformity is then expressed as:

$$\sigma = 1 - \delta = (1 + (\frac{W}{2d})^2)^{-2} \quad (3)$$

where W is the side length of the substrate and d is the distance between orifice and the substrate surface. Figure 2 shows the sample uniformity dependence on source-sample distance and sample size. For our photocathode growth chamber, the maximum substrate size is 6cm x 6cm, thus the minimum source-sample distance is about 40 cm to achieve non-uniformity better than 5%.

Figure 2. The thickness uniformity dependence on source-sample distance and sample size. For our system, the photocathode substrate size is 6cm x 6cm, thus the minimum source-sample distance is ~ 40 cm to achieve non-uniformity better than 5%.

For our photodetector production facility, the photocathode growth chamber is a cylinder with a diameter of 6 inches and a height of 18 inches. The top of Knudsen effusion cell orifices are placed at the bottom of the chamber through conflat flanges (CF) and the substrate is held at top portion of the growth chamber through a sample holder. The distance between Knudsen effusion cell and photocathode substrate is set to be ~14 inches (~35 cm), giving good uniformity around 5% at the 6 cm x 6 cm substrate surface.

4. Photocathode growth chamber commissioning

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163 The most commonly used bi-alkali photocathode is a compound coated on the glass substrate through
164 sequential diffusion process [6]. A thin layer of Sb is first deposited on glass, K and Cs vapors are then
165 evaporated and diffused in the Sb lattice to form K-Cs-Sb compound. Its quantum efficiency, response
166 time and dark current are strongly influenced by the growth process, which affects the final compound
167 surface morphology and crystallinity. It is important to control the photocathode growth process by
168 monitoring the photocathode film growth thickness, optical property and its photo response.

169

170 **4.1 Photocathode growth chamber**

171 A dedicated 6 cm x 6 cm photodetector production system consisting of photocathode growth chamber,
172 MCP scrubbing chamber and sealing chamber was designed and built in our lab. These chambers are
173 isolated from each other through gate valves to avoid cross contamination between photocathode
174 deposition, MCP scrubbing and sealing process. Photodetector assembly parts, such as photocathode
175 substrates and MCPs can be freely transferred between chambers via magnetic transfer arms to fabricate
176 the photodetector assembly. The photocathode growth chamber consists of four major parts: the chamber
177 body, the Knudsen effusion cell, the sample holder and diagnostic equipments, including quartz crystal
178 microbalance (QCM), residual gas analyzer (RGA) and optical monitor setup. The Knudsen effusion cells
179 are integrated with proportional-integral-derivative (PID) controllers, providing accurate and reliable
180 operation and achieving excellent flux stability using closed-loop temperature or power feedback. The
181 growth chamber is also equipped with a diode ion pump, after 48 hours of baking at 200 °C under
182 vacuum, the base pressure of the system reaches vacuum level as low as 10^{-10} torr, fulfilling the
183 requirement for bi-alkali photocathode deposition.

184

4.2 Growth and characterization of antimony film

Initial antimony thin films were deposited as the commissioning procedure to test the growth facility and examine the chamber design. Antimony pellets (99.999% purity) purchased from Kurt J. Lesker Company were used as the source material. Antimony pellets were placed in a 40 cc pyrolytic boron nitride (PBN) crucible, with less than 15% volume filled. A 6 cm x 6 cm B33 glass plate was used as substrate for antimony deposition. The glass substrate was sonicated in 2% Citranox solution at 60 °C for 20 minutes followed by 20 minutes deionized (DI) water sonication. It was then rinsed with DI water and blown dry with nitrogen. The chemical cleaned glass substrate was placed in oxygen plasma for 10 minutes for further surface cleaning before it was transferred into the load lock. When the load lock reached 10^{-8} Torr pressure, the glass substrate was moved onto the sample holder in the deposition chamber through a magnetic transfer arm. Both the glass substrate and the crucible assembly filled with antimony pellets were heated over night for outgas purpose. The glass substrate was baked at 200 °C by two halogen lamps and the crucible was heated at 350 °C via Knudsen cell power supply.

The antimony deposition was *in-situ* monitored by quartz crystal microbalance (QCM) and transmission measurement. A QCM monitor sensor was placed near the sample holder and was pre-calibrated with atomic force microscopy (AFM) and profilometer measurement. Transmission of the antimony thin film was also monitored by measuring the transmitted beam intensity of a 543.5 nm laser. The QCM and transmission measurement are cross related to each other, to ensure accurate control of the growth thickness.

Figure 3. (a) AFM image of antimony film grown through MBE technique, the RMS roughness is ~ 1 nm, indicating flat surface. (b) Transmission uniformity of the antimony film on 6 cm X 6 cm glass substrate, the film is uniform in large area (5 cm x 5 cm area). The non-uniform area at the center left is due to a misplaced wire blocking the antimony deposition.

The post-growth antimony thin film on glass substrate was characterized with profilometer and atomic force microscopy to evaluate the thickness and surface morphology. Thicknesses measured via profilometer and AFM were compared to QCM monitor, these values agree with each other. The surface morphology of the antimony film on a glass substrate exhibits a flat surface. Figure 3(a) shows a 10 μm x 10 μm surface image of 8 nm antimony film, the surface root mean square (RMS) roughness is ~ 1 nm, indicating atomic flat film surface.

The transmission map across the whole deposition area was also characterized using a custom designed optical station [17] to evaluate its uniformity distribution. Transmission map across the substrate is shown in figure 3(b), indicating that the antimony film deposited on the 6 cm x 6 cm glass substrate via MBE

technique is uniform at a large area, and the non-uniformity is less than 10% as expected. The successful deposition of an antimony film with the expected thickness uniformity indicates the successful commissioning of the photocathode growth chamber.

4.3 Growth and characterization of bialkali photocathode

With successful commissioning of the photocathode growth chamber, K-Cs-Sb bialkali photocathodes were grown via the traditional diffusion process [6]. Following the deposition of antimony film, potassium and cesium vapors were evaporated from the effusion cell and diffused into the antimony lattice respectively to form K_2CsSb photocathode. Halogen lamps were used to keep the glass substrate at 150 °C. Titanium (99.98% purity) and alkali chromates (K_2CrO_4 and Cs_2CrO_4 99.99% purity) powders purchased from Sigma-Aldrich were used as chemical sources to produce alkali vapors at 650 ~ 750 °C. The alkali vapor growth rate was controlled at 0.2 Å/s via the QCM monitor. The photocurrent was measured *in-situ* to monitor the photocathode growth process. The process was stopped when the photocurrent reached a plateau value.

Figure 4. (a) The dependence of the photocathode QE on the wavelength ranging 250 nm – 600 nm. The photocathode exhibits a peak QE ~ 13% at 350 nm. (b) QE uniformity of the photocathode on 6cm X 6cm glass substrate, the blue cross and edge areas are due to the spacer in contact with the photocathode.

The as-grown photocathode was sealed into an empty glass envelope to perform ex-situ QE measurement on a custom-built optical-electrical station [17]. Figure 4(a) shows the dependence of the photocathode QE on wavelength ranging 250 nm – 600 nm. The peak QE of the photocathode is around 13% at 350 nm. The quick drop of the QE below 350 nm is due to the strong UV absorption of the glass substrate. The photocathode uniformity distribution was also measured and exhibited in figure 4(b). As shown in the figure, the photocathode QE is not uniform across the entire area: the corner and edge areas exhibit higher QE compared to the central area. Comparing to the uniform antimony thickness distribution, most likely, the variation of QE map is due to the non-uniformity of the substrate temperature, caused by the halogen lamp heater design. Two halogen lamps placed at the central area are used to heat the glass substrate, they are ~5 cm above the substrate. Due to the non-uniform radiation, the temperature of the substrate varies from center to corner. Since the thermal couple was attached to a corner of the substrate holder, the corner and edge areas are controlled at the optimal growth temperature (150 °C), while the

temperature of the center area is lower than the optimal temperature. The temperature difference affects the QE, resulting higher QE at the corner and edge areas and lower QE at the central area. The very low QE cross in the center is due to the spacer, which serves as electrical contact to the underneath MCP, is in contact with the photocathode, as shown in figure 5(a).

5. Prototype of 6 cm x 6 cm photodetector

Figure 5. A completed 6 cm x 6 cm photodetector prototype during test, signals from two opposite sides of the anode strip-lines can be observed in 50 Ω loads via the SMA connectors. Spacers and MCPs are visible through the light brown top glass coated with photocathode.

Several prototype 6 cm x 6 cm photodetectors were successfully fabricated after all the processes were commissioned. A glass plate with silk-screened anode stripes was fritted together with glass sidewalls to serve as the base package. Functionized MCPs with secondary emission layer coated via ALD technique were scrubbed following standard process and placed inside the base package together with spacers. A top glass plate coated with K_2CsSb bialkali photocathode was then sealed with the base package, completing the prototype.

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276 Figure 6. Left: An example of a photodetector signal pulse showing the peak signal. Right: The measured transition-
 277 time spread for a photodetector with 2 MCPs. The signal (solid line) was read from one side of a single strip and
 278 fitted with a Gaussian distribution (dotted line).

279

280 Figure 5 shows the image of a prototype device with bialkali photocathode during test. The light brown
 281 photocathode color is observed on the top glass window, and ALD coated MCPs and spacers are clearly
 282 visible through the top window. A typical photocathode QE characteristic is shown in figure 4. The
 283 prototype device was characterized on a custom-built photodetector characterization setup, composed of a
 284 Hamamatsu PLP-10 picosecond light pulser with 405 nm laser and a Tektronix DPO7354 3.5 GHz, 10
 285 GHz/s digital phosphor oscilloscope, to evaluate its time and spatial resolutions. A typical signal pulse
 286 seen at one end of the anode-strip-line is shown in the left hand plot of figure 6. By triggering on the laser
 287 pulse, we measured the time spread in the arrival times of the MCP signals to test its time resolution. A
 288 transition-time distribution obtained with the photodetector prototype is shown in the right hand plot of
 289 figure 6. The distribution is fitted with a Gaussian distribution, and the sigma parameter of the fit is

quoted as a transit-time spread. Here, the photodetector exhibits transit-time spread as low as 27 psec, comparable with that measured from a 33 mm MCP setup [18].

Figure 7. Left: Dependence of difference in the times of signal arrival at the two opposite ends of an anode strip-line as a function of the laser beam position along the strip-line; data (points) compared to the linear fit (solid line). Right: Differential time for pulses at a fixed position on one strip-line; data (solid line) compared to the Gaussian fit (dotted line).

We also evaluated the spatial resolution of the prototype photocathode by determining the differential time resolution and the signal propagation speed along an anode strip-line. The differential time resolution (δT) is defined as the RMS of the difference in the signal arrival at the opposite ends of an anode strip-line. It directly translates into the spatial resolution (δX) in the direction parallel to the anode strip-line following equation 4 [19]:

$$\delta X = \frac{1}{2} V \delta T \quad (4)$$

where V is the signal propagation speed along the anode strip-line, which can be determined by moving the laser beam along the strip-line and measuring the change in the differential timing.

Figure 7 (left) plots the difference in the time of arrival at the two opposite ends of an anode strip-line, measured as a function of the laser beam position along the strip-line. The linear fit slope of 0.1488 mm/ps corresponds to a signal propagation speed of $0.50c$, in agreement with an independent measurement of this parameter applying a network analysis of the anodes [20]. A differential time resolution of ~ 9 psec is observed, translating into a spatial resolution of ~ 1.3 mm (see figure 7, right).

6. Summary

In summary, a 6 cm x 6 cm MCP-photodetector assembly design, capable of both fast time and accurate position resolutions, was described in details. A dedicated photocathode growth chamber was designed and built as part of a new photodetector production system at Argonne National Laboratory. Knudsen effusion cells were incorporated in the photocathode growth chamber for uniform high QE photocathode growth. Antimony films were deposited and characterized to commission the photocathode growth chamber, the non-uniformity of antimony film is less than 10%, within the expectation of calculated non-uniformity distribution. Further work will be done to improve the QE uniformity of bialkali photocathode. Several 6 cm x 6 cm photodetector prototypes were successfully fabricated. A typical prototype device with bialkali photocathode exhibits time-of-flight resolution of ~ 27 psec and differential time resolution of ~ 9 psec, corresponding to spatial resolution of ~ 1.3 mm.

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References

- [1] M. Akatsu *et al.*, “Time-of-propagation Cherenkov counter for particle identification”, *Nucl. Instr. and Meth. A*, **440**, 124 (2000).
- [2] S. Bertolucci *et al.*, “The CDF central and end wall hadron calorimeter”, *Nucl. Instr. and Meth. A*, **267**, 301 (1988).
- [3] S. Kabuki *et al.*, “Development of an atmospheric Cherenkov imaging camera for the CANGAROO-III experiment”, *Nucl. Instr. and Meth. A*, **500**, 318 (2003).
- [4] “Science and Technology of Future Light Sources”, ANL-08/39, BNL-81895-2008, LBNL-1090E-2009, SLAC-R-917, December 2008.
- [5] M. Demarteau *et al.*, “Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 8: Instrumentation Frontier”, *arXiv:1401.6116v1*, (2014).
- [6] A. Sommer, “Photoemissive Materials: Preparation, Properties and Use”, John Wiley & Sons Inc., (1969).
- [7] K. K. Hamamatsu-Photonics, “Hamamatsu Super Bialkali Photocathodes”, (2006).
- [8] S. Schubert, *et al.*, “Bi-alkali antimonide photocathodes for high brightness accelerators”, *APL Mat.* **1**, 032119 (2013).
- [9] J. Smedley, *et al.*, “In situ characterization of alkali antimonide photocathodes”, *Proc. FEL 2013*, (2013).
- [10] J. Xie *et al.*, “Study of bi-alkali photocathode growth on glass by X-ray techniques for fast timing response photomultipliers”, *Proc. SPIE*, **8982**, (2014).
- [11] A. Mane *et al.*, “An atomic layer deposition method to fabricate economical and robust large area microchannel plates for Photodetectors”, *Physics Procedia*, **37**, 722 (2012).

- [12] S. Jokela *et al.*, “Secondary electron yield of emissive materials for large-area micro-channel plate detectors: surface composition and film thickness dependencies”, *Physics Procedia*, **37**, 740 (2012).
- [13] The LAPPD Collaboration, <http://psec.uchicago.edu>
- [14] J. Xie *et al.*, “Development of a small form factor (6 cm x 6 cm) picosecond photodetector as a path towards the commercialization of large area devices”, in proceeding of “The Technology and Instrumentation in Particle Physics 2014”, PoS (2014).
- [15] J. Xie *et al.*, “Large area planar photocathode for MCP-based photodetectors”, to be submitted to *Nucl. Instr. and Meth. A*, (2014).
- [16] I. Langmuir, “The constitution and fundamental properties of solids and liquids”, *J. Am. Chem. Soc.*, **38**, 2221 (1916).
- [17] J. Xie *et al.*, “Instrumentation for Theory-Inspired Photocathode Development within the Large Area Picosecond Photodetector (LAPPD) Project”, *Physics Procedia*, **37**, 811 (2012).
- [18] B. Adams *et al.*, “A test-facility for large-area microchannel plate detector assemblies using a pulsed sub-picosecond laser”, *Rev. Sci. Instrum.*, **84**, 061301 (2013).
- [19] B. Adams *et al.*, “Measurements of the gain, time resolution, and spatial resolution of a 20×20 cm² MCP-based picosecond photo-detector”, *Nucl. Instr. and Meth. A*, **732**, 392 (2013).
- [20] H. Grabas *et al.*, “RF strip-line anodes for large-area MCP-based photodetectors”, *Nucl. Instr. and Meth. A*, **711**, 124 (2013).

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