Preprint typeset in JINST style - HYPER VERSION

A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration

B. W. Adams[a],[*], K. Attenkofer[a,†], M. Bogdan[c],K. Byrum[a], A. Elagin[c], J. W. Elam[a], H. J. Frisch[c], J.F.Genat[c], H. Grabas[c,‡], J. Gregar[a], E. Hahn[d], M. Heintz[c], Z. Insepov[a], V. Ivanov[f], S. Jelinsky[g], S. Jokela[a], S. W. Lee[a], A. U. Mane[a], J. McPhate[g], M. J. Minot[e], P. Murat[d], K. Nishimura[h,§], R. Northrop[c], R. Obaid[c,¶], E. Oberla[c], E. Ramberg[d], A. Ronzhin[d], O. H. Siegmund[h], G. Sellberg[d], N. T. Sullivan[b], A. Tremsin[g], G. Varner[h], I. Veryovkin[a,‖], A. Vostrikov[c], R. G. Wagner[a], D. Walters[a], H.-H. Wang[a], M. Wetstein[c,], J. Xie[a], Z. Yusof[a,††], A. Zinovev[a]**

[a] *Argonne National Laboratory, Argonne IL, 60439*
[b] *Arradiance Inc., Sudbury MA, 01776*
[c] *Enrico Fermi Institute, University of Chicago, Chicago IL 60637*
[d] *Fermi National Accelerator Laboratory, Batavia IL, 60510*
[e] *Incom, Inc, Charlton MA 01507*
[f] *Muons,Inc; Batavia IL 60610*
[g] *Space Sciences Laboratory, University of California, Berkeley CA. 94720*
[h] *University of Hawaii, Honolulu HI, 96822*
E-mail: `frisch@hep.uchicago.edu`

ABSTRACT: The Large-Area Picosecond PhotoDetector (LAPPD) Collaboration was formed in 2009 to develop large-area photodetectors capable of time resolutions measured in pico-seconds (psec, 10^{-12} s), with accompanying sub-millimeter spatial resolution. During the next three and one-half years the Collaboration developed the LAPPD$^{\mathrm{TM}}$ design of 20×20 cm^2 modules with gains greater than 10^7 and non-uniformity less than 15%, time resolution less than 50 psec for single photons and spatial resolution of 700 μm in both lateral dimensions. We describe the R&D performed to develop large-area micro-channel plate glass substrates, resistive and secondary-emitting coatings, large-area bialkali photocathodes, and RF-capable hermetic packaging. In addition, the Collaboration developed the necessary electronics for large systems capable of precise timing, built up from a custom low-power 15-GigaSample/sec waveform sampling 6-channel integrated circuit and supported by a two-level modular data acquisition system based on Field-Programmable Gate Arrays for local control, data-sparcification, and triggering. We discuss the formation, organization, and technical successes and short-comings of the Collaboration. The Collaboration ended in December 2012 with a transition from R&D to commercialization.

KEYWORDS: pico-second time-of-flight; large-area photodetectors; MCP-PMTs; waveform sampling ASICs; photon and charged particle detectors.

Contents

[*]Present Address:Incom, Inc. 294 Southbridge Road, Charlton, MA 01507
[†]Present Address:Brookhaven National Laboratory, Upton NY, 11973
[‡]Present Address: Univ. of California Santa Cruz, Santa Cruz CA 95064
[§]Present Address: Ultralytics LLC, Arlington VA 22203
[¶]Present Address: University of Connecticut, Storrs CT, 06269
[‖]Present Address: University of Illinois, Chicago IL 60607
[**]Present Address: Iowa State University, Ames, IA 50011
[††]Present Address: Illinois Institute of Technology, Chicago, IL 60616

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1. Introduction

The Large-Area Picosecond PhotoDetector Collaboration (LAPPD) was formed in 2009 to develop photodetectors capable of making time measurements measured in pico-seconds (psec, 10^{-12} s) with sub-mm spatial resolution over areas measured in square-meters [1]. Micro-channel plates (MCPs) consist of pores with the small spatial dimensions necessary for psec timing [2, 3, 4]. MCPs also naturally provide homogeneity over large areas, excellent spatial resolution, high gain, and low noise. Here we summarize the R&D undertaken by LAPPD to realize an MCP-based 20 $\times$ 20 cm^2 photodetector module with gain greater than 10^7, dark noise less than 0.1 counts/cm^2-s, time resolution less than 50 psec for single photons, and spatial resolution of 700 μm in each of the two lateral dimensions. In addition, LAPPD developed the necessary electronics for large systems capable of precise timing, built up from a custom low-power 15-GigaSample/sec (GS/sec) waveform sampling 6-channel integrated circuit and supported by a two-level modular data acquisition system based on Field-Programmable Gate Arrays (FPGA) for local control, data-sparcification, and triggering.

The project was made possible by the availability of funding from the American Recovery and Reinvestment Act (ARRA) [5] through the Department of Energy (DOE). The ARRA funding, which came to LAPPD via Argonne National Laboratory (ANL), allowed supporting collaborating institutions with expertise in the needed technologies. Strong support from the DOE based on the possibility of large cost-savings at the proposed Deep Underground Science and Engineering Laboratory (DUSEL) [6, 7] facility was crucial.

The LAPPD Collaboration was formed with participants from each of three complementary kinds of institution, national laboratories, universities, and US companies, each with its own strengths, culture, and limitations. Industry brought specific manufacturing facilities and industrial techniques; the national laboratories brought access to a wide range of facilities and expertise for the synthesis and characterization of materials; the universities brought specific photodetector and electronics expertise. The project gained enormously from having experts in many unanticipated areas of material science and electronics.

The objectives of this paper are: 1) to provide a review of the major technical accomplishments of LAPPD; 2) to provide guidance based on experience for starting and sustaining a major joint Laboratory-Industry-University effort; and 3) to provide the historical context. The organization of the paper is as follows. The science motivation, early technical ideas, and formation of the Collaboration are described in Section 2. Section 3 describes the organization of LAPPD into five major technical areas and the corresponding multi-disciplinary management structure. The Collaboration goals, divided into those corresponding to each of the five technical areas, are presented in Section 4. Section 5 summarizes technical R&D. Section 6 assesses the achievement of the goals, including the failure to make a fully-functional sealed LAPPD$^{\text{TM}}$ module before the transition to commercialization. Section 7 briefly describes the facilities that the individual institutions constructed or otherwise brought to bear on the development of capillary substrates, resistive and emissive coatings, performance characterization, hermetic packaging, and GHz electronics. The motivating role played by the joint proposal from the DOE and the National Science Foundation (NSF) for a large underground neutrino facility, the Deep Underground Science and Engineering Laboratory (DUSEL) [6], is summarized in Section 8. Section 9 presents the infrastructure developed to communicate technical information in many disciplines both within and external to the collaboration. Section 10 describes the end of the project in Dec. 2012 and the subsequent transition to commercialization [8], with continuing R&D under the DOE detector and SBIR/STTR programs [9] and private funding. The author list and executive summary from the 2009 DOE proposal are shown in Appendix A. The unique, but critical, path from initial seed funding to the formation of the Collaboration and writing and subsequent funding of the Proposal is laid out in Appendix B.

2. Motivation and Selection of the Technology for Psec Timing

2.1 Applications

The LAPPD effort to develop very precise timing in particle physics, with a nominal goal of 1 psec, grew out of a recognition of the inability to extract all the measurable information (i.e. 4-vectors) from multi-TeV particle collisions at the Fermilab Tevatron in 2003 [10]. A detector capable of psec-resolution timing must have physical dimensions small enough so that variations in the fastest transit times of the photons or electrons forming the amplified signal correspond to a time jitter smaller than the desired resolution [3]. Figure 1 shows the operating principle of a chevron MCP-PMT, for which the typical physical dimension governing the time resolution is a millimeter or less.

With searches at the Collider Detector at Fermilab for new topological event signatures using particle quark content as the first application, the detection of Cherenkov light generated by charged

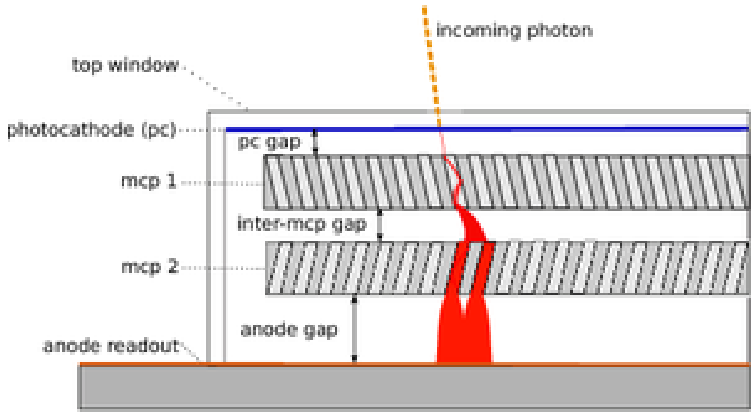


Figure 1. The structure of an $Large-AreaPicosecondPhotoDetector$ photomultiplier tube. The incoming photons are converted in the photocathode to a photo-electron that is accelerated across a vacuum gap. The amplification section consists of a pair of microchannel plates arranged in a chevron configuration. The anode plane responds to the incoming charge and creates a signal that is propagated to the front-end digitizing electronics.

particles traversing a transparent radiator on the front face of a Micro-Channel Plate was selected in 2004 as the most promising method to cover large areas with sub-mm resolution [2]. Prior to this, the ALICE collaboration at CERN had come to the same conclusion [11].

A second technical motivation was the suggestion by H. Nicholson [12] that large-area inexpensive panels of photodetectors could provide substantial cost savings by replacing hundreds of millions of dollars of conventional photomultipliers in the large water Cherenkov neutrino detector proposed for DUSEL [6]. The number of these new photodetectors needed for DUSEL was also financially attractive to companies with existing facilities capable of producing large volumes of the tubes, as described in Section 8.

Commercially available micro-channel plate detectors [13, 14] had not been considered for large-area applications due to their small size, with the largest being 5×5 cm^2 [15]; high-cost per area; long fabrication cycle; and concerns about lifetime due to ion feedback. Any new effort required making detectors with at least an order-of-magnitude larger sensitive area at comparable or lower unit cost, and a new process for fabricating the amplification section that eliminated the source of the ion feedback. In addition, the supporting electronics systems to exploit the fast timing capabilities for large psec-capable systems needed to be defined and developed.

2.2 Intellectual

Early on, in the context of exploiting high energy colliders, we asked the question of what limited time-of-flight resolution in particle detection to the typical 60-100 psec regime. The question proved interesting to a number of us, as it involves fundamental processes such as photo-emission, electron transport and secondary emission, radio-frequency antenna techniques for detecting charge and propagating signals across meter-scale distances, sophistical signal processing to extract a time, and a wide array of challenges in analog and digital electronics. A series of Workshops was devoted to understanding these questions, culminating in one solely devoted to the factors that determine the ultimate limit on timing resolution across these diverse areas [16].

3. Organization of the Collaboration

The formation of a multi-disciplinary collaboration to develop a broad set of new detector technologies crossing many areas of thin-film technology and material science presented an unusual challenge in the context of traditional High Energy Physics (HEP) support. Collaborators in non-traditional HEP areas were often self-selected by their interest in the intellectual and technical problems in their own field; the non-HEP Divisions at ANL in particular proved to be a fertile ground for expertise and facilities. However key expertise and facilities were also provided by the industrial partners and the universities. We describe the project organization below.

3.1 Management

The LAPPD project was managed through the ANL HEP Division, with subcontracts to the industrial partners and universities. H. Frisch was Spokesperson and held a joint appointment at ANL, reporting to H. Weerts as Division Director. K. Byrum and Frisch were Co-PI's on the proposal; R. G. Wagner was the Program Physicist.

The structure of the collaboration is shown graphically in Figure 2. The photodetector development tasks were organized as four parallel structures, with co-leaders from the appropriate areas of expertise. Integration was identified as a separate parallel task, as shown. These five areas are described in more detail below in Section 3.2.

In order to reduce the risk inherent in a project that had so many new technologies, the hermetic packaging design task was split into developing two separate solutions, an evolutionary ceramic package by the Space Sciences Laboratory (SSL) group of O. Siegmund, and a 'frugal' all-glass package by Chicago, ANL, and collaborators, as described in Section 3.3.

Communication of information across the many areas of technical development in the collaboration was provided by bi-annual 'Godparent reviews' and Collaboration Meetings, a web blog and library of figures, technical specifications (prints), and documents, and a weekly meeting using the blog for agenda and talks, as described in Section 9.

3.2 The Organization of Photodetector Module Development

The primary photodetector R&D was divided up into the four areas shown in Figure 2. Hermetic Packaging refers to the development of a thin, robust, economical sealed tube housing that can maintain ultra-high vacuum for decades. The Micro-channel Plate Group was responsible for the development of robust large-area capillary substrates and the resistive and secondary-emitting coatings necessary to convert them into high-gain low-noise MCPs. The Electronics/Integration Group was responsible for developing digitizing electronics capable of psec resolution, scalable multi-channel systems, and the interface to the electrical and mechanical aspects of the package. The Photocathode Group was formed to transfer photocathode fabrication techniques to the large flat-panel format specific to LAPPD. In addition to these four narrowly-focused groups, the Integration Group was responsible for the Collaboration-wide tasks of simulation, testing, system integration, and documentation.

The major necessary R&D developments in each area are listed below in Section 4.

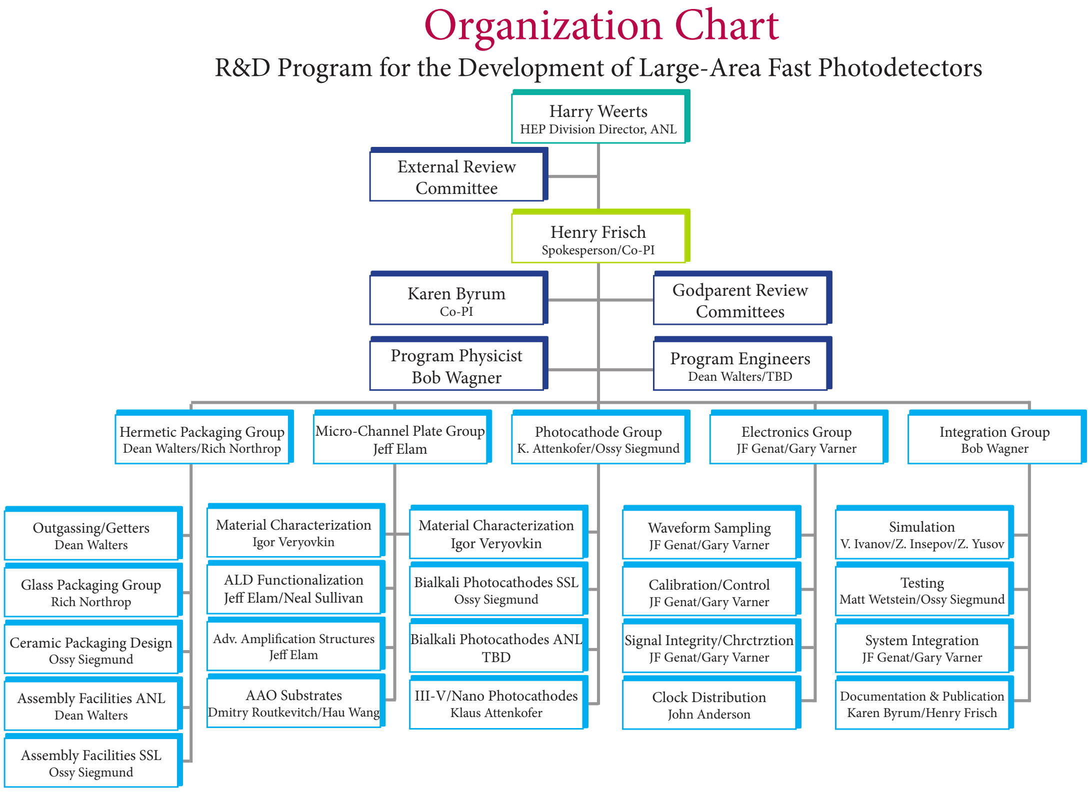


Figure 2. The organization chart for the LAPPD Collaboration as of Feb. 2010. The effort was organized into five areas: Hermetic Packaging, Micro-channel plates, Photocathodes, Electronics, and Integration. Twice-yearly 'Godparent' Review Committee meetings and Collaboration Meetings and a weekly 'All-collaboration' meeting provided the necessary communication between the groups.

3.3 Risk Management and Organization: Parallel Development of Ceramic and Glass Designs

The Collaboration organized itself into a two-pronged approach to the hermetic package: a ceramic package design, inspired by smaller MCP-PMT designs, and a more radical, all-glass design. The original motivation was risk mitigation, with the "conventional" ceramic module perceived as being lower technical risk, but more expensive, and the novel glass module design viewed as higher technical risk, but ultimately with fewer parts and a simpler assembly with a lower cost and a time resolution goal of 1 psec. The parallel efforts inside a single organization allowed a coordinated program to develop resistive and emissive coatings at the ANL facility with continuous access to MCP testing at Space Sciences Laboratory and ANL/Chicago, and a flow of expertise from SSL on the highly specialized handling and treatment of MCP-PMT components and test equipment. As the two paths became better established the complementary performance characteristics in space and time resolution emerged, as shown in Figure 3.

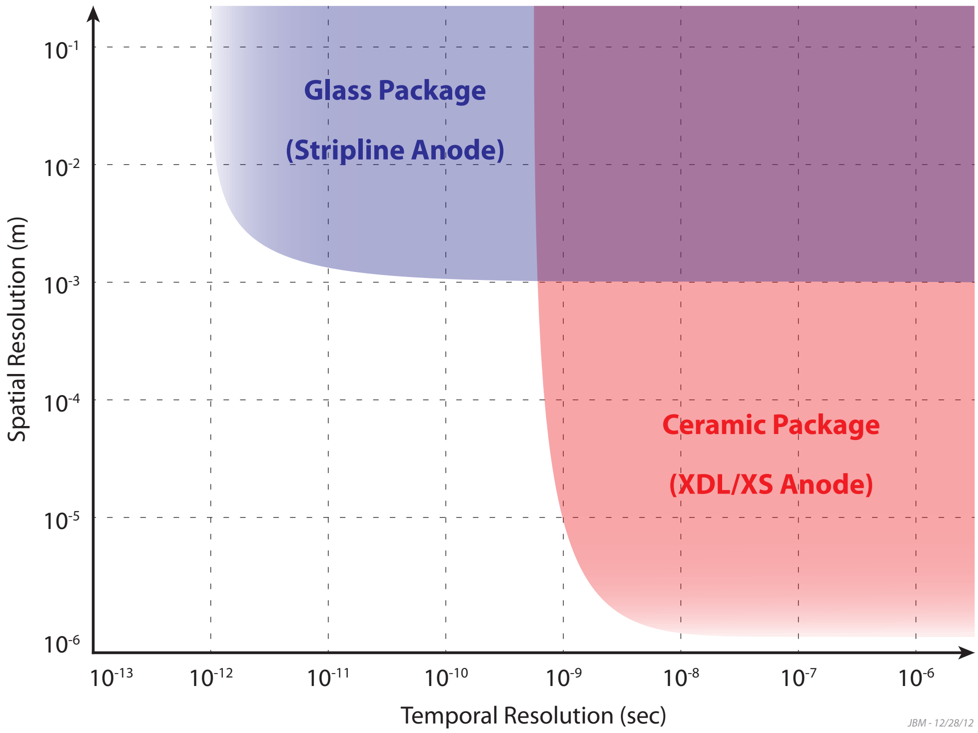


Figure 3. The contrasting performance optimizations in time and space resolution of the ceramic and glass implementations of the LAPPD^{TM} module. The Micro-Channel Plates that form the amplification section of both detectors are identical; the difference comes from choices made for the resolution of the anode that collects the charge. The anode of the glass package consists of high bandwidth micro-strip transmission lines, optimized for time resolution [17]; the finer-detailed anode of the ceramic package has been optimized for spatial resolution [18]. (credit: J. McPhate)

4. Goals

At the time of the proposal the basic issues such as choice of capillary substrate, feasibility of resistive and emissive coatings for capillary plates with surface areas measured in square-meters, feasibility of large systems of psec-resolution electronics, and many others, were wide open. For example, although we knew we needed a small pore size for fast timing, both glass capillary and Anodic Aluminum Oxide substrates seemed viable options. Whether one could uniformly coat large substrates containing large aspect-ratio capillary pores was an open question. The feasibility of building an electronics system capable of maintaining psec resolution over large areas while limiting the power consumption and channel count was a subject of debate.

Basic questions such as these informed the formation of the Collaboration and the organization of the R&D. We list below the initial goals for each of the areas in Tables 1-4. For each goal we have tabulated the LAPPD papers published describing the results of the R&D. A discussion of the successes and failures is given in Section 6.

Goals: Microchannel Plates	
Goal	**References**
Suitability (uniformity, open-area, manufacturability) of drawn glass capillary substrates as MCP's	[19, 20]
Suitability (uniformity, open-area, manufacturability) of AAO etched aluminum substrates as MCPs	[21]
Down-selection decision between glass and AAO substrates	[21]
Development of Atomic Layer Deposition Resistive coatings	[22, 23, 24]
Development of Atomic Layer Deposition secondary-emitting coatings	[25, 26, 26, 27, 28, 29]
Development of high-yield manufacturing techniques for 8" glass substrates	[19, 20]
Implementation of facilities for characterization of the 8" LAPPD^{TM} MCPs for robustness, gain, uniformity, life-time, and time and position resolution	[30], [18]

Table 1. The goals (Column 1) and published references (Column 2) for achievements of the LAPPD Microchannel Plate Group. The reader is encouraged to access the references in the Bibliography for technical details.

Goals: Photocathodes	
Goal	**References**
Transfer of Space Sciences Laboratory techniques for K_2NaSb photocathodes to 8"-square photocathodes on borosilicate glass	[18]
Development/acquisition of equipment and transfer of techniques for K_2CsSb photocathodes to 8"-square photocathodes on borosilicate glass	[31]
Establishing collaborative efforts within and outside of the Collaboration to develop 'theory-based' photocathodes with reproducible quantum efficiency near a predicted limit	[32, 33, 34]

Table 2. The goals (Column 1) and published references (Column 2) for achievements of the LAPPD Photocathode Group.

Goals: Hermetic Packaging	
Goal	**References**
Design of a 'frugal' glass package using widely-available float glass	[35]
Design of a ceramic package evolved from the widely-used Space Sciences Laboratory designs for smaller MCP-PMT packages	[18, 36, 37]
Development and characterization of inexpensive GHz microstrip anodes with good (few psec) time resolution for the glass package	[17]
Development and characterization of high spatial resolution (sub-mm) microstrip anodes for the ceramic package	[18, 36, 37, 38]
Development of the anode seal over the microstrips for the glass package	[19, 20, 35]
Development of electrical contacts and pin structure for the ceramic package	[18, 38]
Development of the window seal for the glass package	[19, 20]
Development of the window seal for the ceramic package	[18]
Production of a hermetic sealed LAPPD^{TM} module with photocathode	See § 6.2.1

Table 3. The goals (Column 1) and published references (Column 2) for achievements of the LAPPD Hermetic Packing Group. We note that the goal of a top seal for the glass package has now been demonstrated.

Goals: Electronics and System Integration	
Goal	**References**
Development and characterization of a multi-channel CMOS Application-Specific Integrated Circuit (ASIC) capable of wave-form sampling at greater than 10 GS/sec	[39]
Development of a corresponding scalable electronics system with multi-mode triggering, FPGA local control and readout, and a simple low-rate generic DAQ interface	[40]
Development of a large-area economical multi-module 'Supermodule' using GHz-bandwidth anodes, fast waveform sampling, robust mechanical packaging, and an optical-fiber readout	[17]
Development of test stands for full system testing and characterization	[30]
Characterization, including gain, uniformity, lifetime, and time and space resolutions, of the performance of the glass and ceramic packages	[36, 18, 3]

Table 4. The goals (Column 1) and published references (Column 2) for achievements of the LAPPD Electronics and Integration Groups.

5. R&D Achievements

The LAPPD goals were set out in annual milestones. All the milestones were achieved, with the (glaring) exception of the production of a self-standing hermetically sealed LAPPD^{TM} module (see Section 6). Here we list some of the essential R&D outcomes.

5.1 Microchannel Plates: Substrates and Coatings

The Collaboration started with two alternatives for the large-area microchannel-plate substrate, anodic aluminum oxide (AAO), and glass. The AAO program was ended in a down- selection to conserve resources, with a patent issued [21]. For the glass substrate, Incom [41] undertook the development, drawing hollow glass tubes down to an inner diameter of 20 microns, assembling and fusing them into a solid block large enough to provide 8"-square plates, and cutting them on an 8^o bias into 1.2 mm-thick wafers to produce a ratio of pore length to diameter of 60:1. The substrates were then manufactured to size and surface finish. The seemingly simple tasks of cleaning adequately for subsequent coating and then characterizing the capillary substrates, each of which has a surface area of 6.5 m^2, required extensive development before being successfully incorporated into the production process. Figure 4 shows an Incom 8” substrate; the transparency is due to an open-area ratio exceeding 65%.

The use of ALD to coat passive substrates was demonstrated by Arradiance before the start of LAPPD [42], and was instrumental in the LAPPD interest in ALD for coating large-area arrays. Figure 5 shows the resistivity of ALD tunable resistance coatings developed in the Energy Systems Division at Argonne. These coatings comprise conducting metallic nano-particles (tungsten (W) or molybdenum (Mo)) in an amorphous dielectric matrix (Al_2O_3). The resistivity drops exponentially with metal content, and the metal content is controlled by adjusting the percentage of ALD metal

Figure 4. Left: An 8” $\times$ 8” glass capillary substrate developed by the Incom corporation. Each substrate contains approximately 80 million 20-micron-diameter capillary pores. The open-area ratio is typically greater than 65%, making the plate appear transparent. Right: A close-up of a similar glass substrate showing the 20-micron capillary structure.

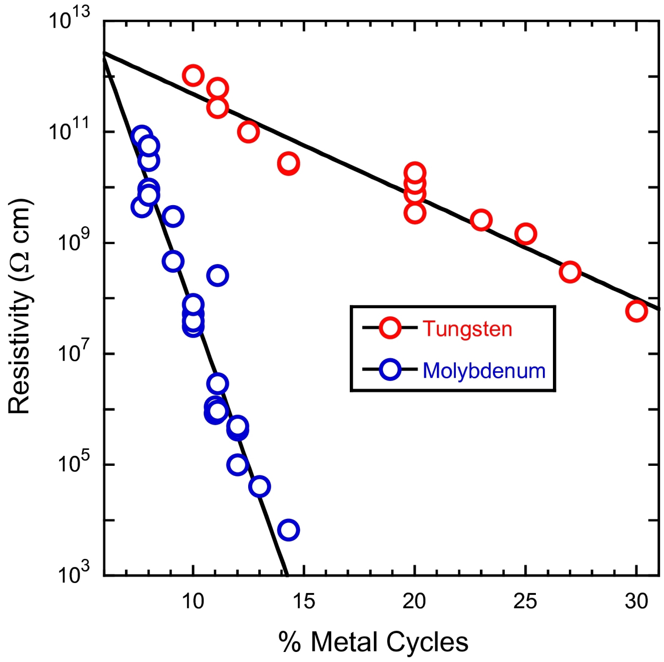


Figure 5. Resistivity of the Argonne ALD tunable resistance coatings used for functionalizing capillary glass arrays to produce MCPs, showing the exponential behavior versus the number of metal cycles. [22, 23].

cycles during the deposition of the coatings. The plot shows the exponential behavior versus the number of metal cycles, a mixed blessing in that the behavior allows covering a large range, but also has a high sensitivity to the metal content. The resistivity of the molybdenum films is more sensitive to the metal cycle percentage than that of the tungsten films because the amount of Mo deposited in a single Mo ALD cycle is approximately twice that of the W ALD [22, 23]

The emission of secondary electrons versus electron energy is an essential input into simulations of the cascade in the capillary pores, used to predict the voltage needed, gain, and pulse behavior [43, 28]. A dedicated facility for the measurement of secondary emission yield (SEY) vs incident electron energy was constructed in the Materials Science Division (MSD) at ANL. Figure 6 shows the measurements of SEY for two standard ALD thin film coatings, MgO and Al_2O_3 [25, 26, 27]. In addition to higher gain, a higher SEY contributes to a narrower transit time distribution due to smaller fluctuations in yield in the first strike (the initiation of the shower by the photoelectron from the cathode).

An image from the SSL test facility that measures gain and uniformity over the full area of a pair of ALD-functionalized LAPPD MCP plates is shown in Figure 7. The gain uniformity is within the $\pm 15\%$ requirement.

Figure 8 shows SSL measurements of the stability of the ALD-coated MCP plates compared to conventional lead glass plates versus the amount of charge extracted. The conventional plates show the loss with ‘scrubbing’, a long (and hence expensive) burn-in process of drawing current from the plates during production to achieve a quasi-stability [36, 18].

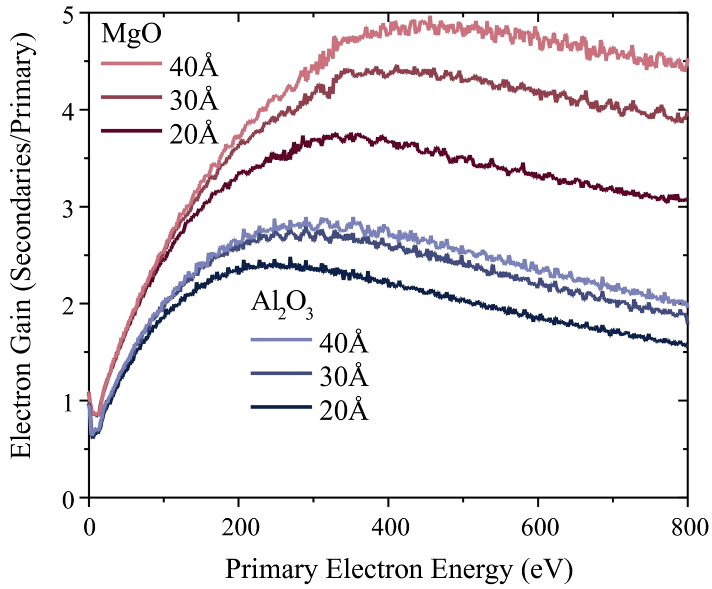


Figure 6. Measurements of the secondary emission of MgO and Al_2O_3 versus incident electron energy [25, 26].

5.2 Hermetic Packaging

The complementary packaging efforts in ceramic and glass are described below in Section 5.2.1 and Section 5.2.2, respectively.

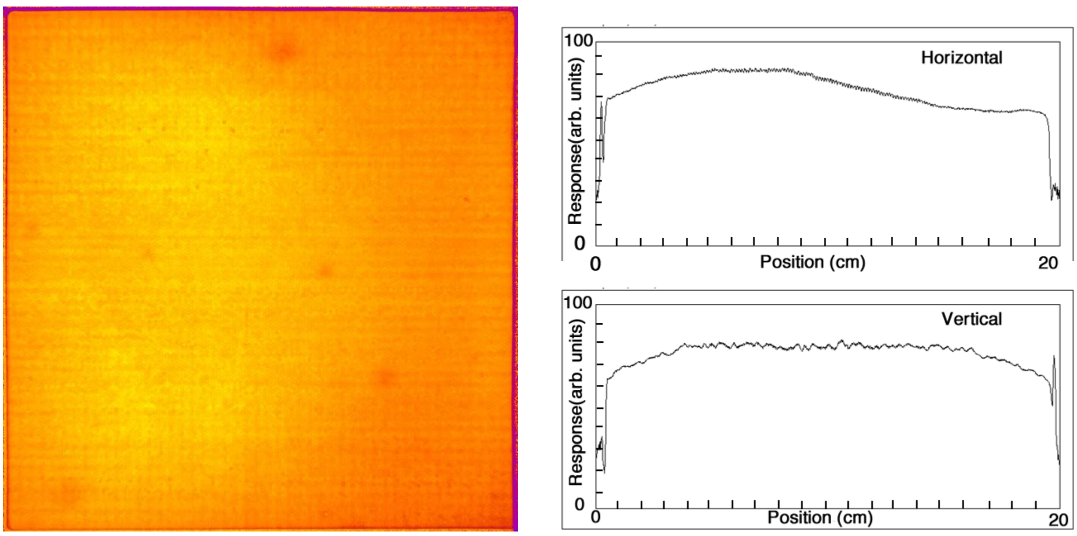


Figure 7. Left: A gain map measured at SSL of a pair of fully functionalized 20-cm-square capillary plates. The mean gain of the pair is 7×10^6. Right: The one-dimensional projections show a gain uniformity within the specification ($\pm 15\%$) adequate for track reconstruction in neutrino events [36, 18].

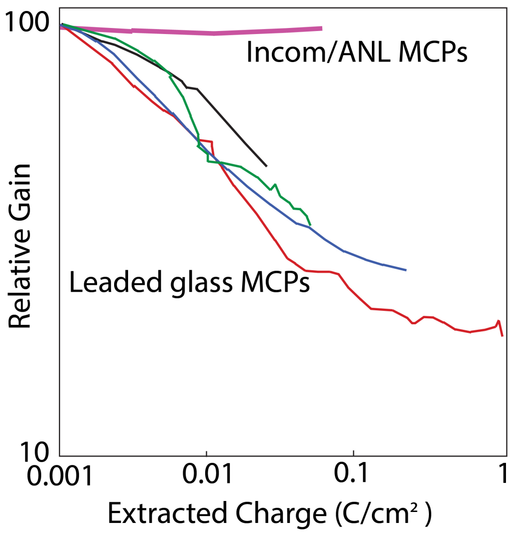


Figure 8. Measurements at the Space Sciences Laboratory of the stability versus charge extracted of an ALD-coated MCP from the ANL ESD group compared to commercial plates [36, 37].

5.2.1 The Brazed Ceramic Package

In order to stay close to their own proven techniques, the SSL group developed a package design that was a direct evolution from their long string of successful designs using well-tried techniques, in particular a brazed high-purity ceramic-metal package, a captured amplification section of MCP plates and spacers that could be electrically tested before the window was sealed, and an indium-bismuth low temperature window seal.

The ceramic anode that forms the bottom surface of the SSL module is shown in the left-hand panel of Figure 9. The right-hand panel shows the lower module assembly, consisting of the anode brazed to a ceramic sidewall with a copper well on top that holds the indium-bismuth eutectic that forms the low temperature seal to the window [18, 36, 37].

Figure 10 shows the mechanical design of the full SSL module [18, 36, 37], including the University of Hawaii electronics package that connects to the anode pins on the back [38].

A test of the fully-assembled SSL LAPPD^{TM} module with photocathode shortly after the Collaboration ended is described in Section 6.2.1.

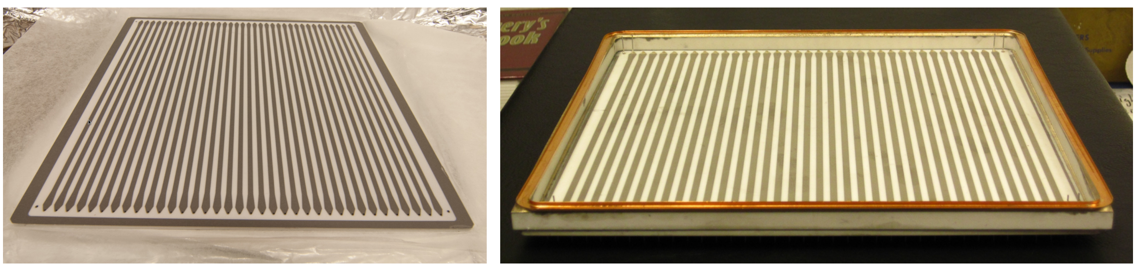


Figure 9. Left: the Space Sciences Lab ceramic anode; Right: a complete SSL module base assembly of anode, sidewall, and copper well for the molten In-Bi solder seal [18, 36, 37].

5.2.2 The Glass Hermetic Package

The glass module design was driven by the goal of achieving time resolutions in the psec range. The mechanical design considerations were consequently inseparable from the high-frequency requirements; extracting the multi-GHz signals from inside the glass vacuum package was identified very early as a challenge. Figure 11 shows the solution, demonstrated at Minotech [44] and at the ANL Glass Shop. The microstrips on the anode are run under the glass sidewall, and the hermetic seal between the sidewall and the anode is made with a glass frit selected for a match in thermal expansion with borosilicate glass.

The left-hand panel of Figure 12 shows a window, in this case with an aluminum cathode, hermetically sealed to the glass sidewall. The right-hand panel shows a closeup of the hermetic seal between the window and the sidewall. This seal is 'flat' (i.e. has no well) and uses pure indium instead of the In-Bi alloy.

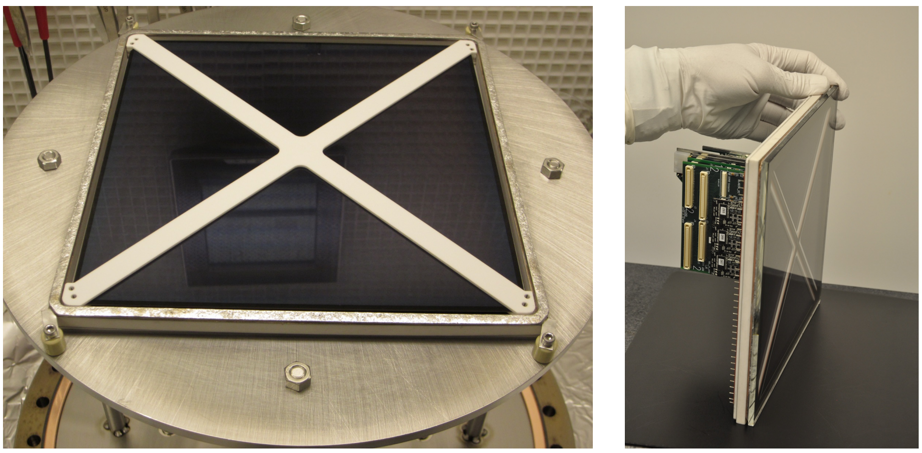


Figure 10. Left: The ceramic module base prior to loading into the large SSL tank for photocathode deposition and sealing of the window. The black surface is the ALD coating on the top MCP. The top 'X' spacer, used to transmit the force of atmospheric pressure between the top window and the bottom anode plate, is also visible [18, 36, 37, 38]. Right: The ceramic module package with the University of Hawaii electronics attached to the anode pins on the back face [38].

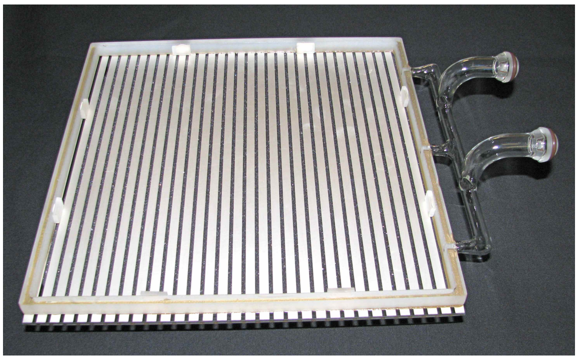


Figure 11. A glass module base assembly showing the microstrip anode [17], and the glass frit joint between the glass sidewall and the anode [35]. The two ports on this assembly are specific to the Demountable test facility at the Argonne Advanced Photon Source, in which the module is sealed with an O-ring and the cathode is a thin aluminum layer [30, 3]. (credit: Joseph Gregar, ANL Glass Shop).

Figure 12. A glass LAPPD^{TM} package with a hermetic indium 'flat' seal between the glass sidewall and the glass top window under test. Right: A close-up of the indium flat seal, taken through a top window with no photocathode. The photo shows the NiCr metalization on the top surface of the sidewall; a Cu layer is visible where the indium has not taken it into solution. The Cu/NiCr "finger" extending towards the bottom of the frame is for distribution of current towards the center of the cathode.

5.3 Photocathodes

Figure 13 shows the first full-size photocathode made in the large-tank facility at the Space Sciences Laboratory. The SSL cathodes are chosen to be K_2NaSb for temperature stability, good conductance, and low background. Figure 14 shows the quantum efficiency versus wavelength of an 8" K_2NaSb photocathode made in the large-tank facility at SSL on a B33 glass substrate [18].

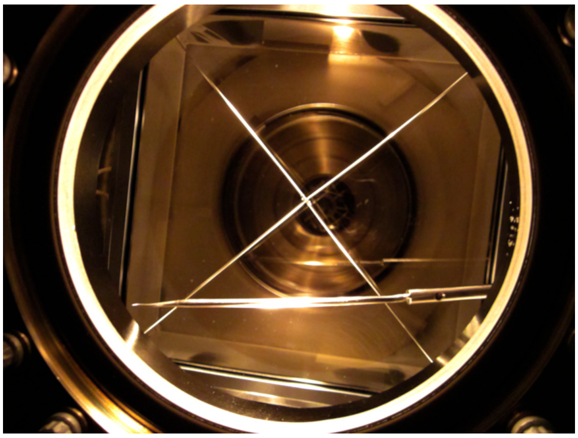


Figure 13. A K_2NaSb photocathode synthesized on a stand-alone LAPPD window in the large fabrication tank at the Space Sciences Laboratory [36, 18].

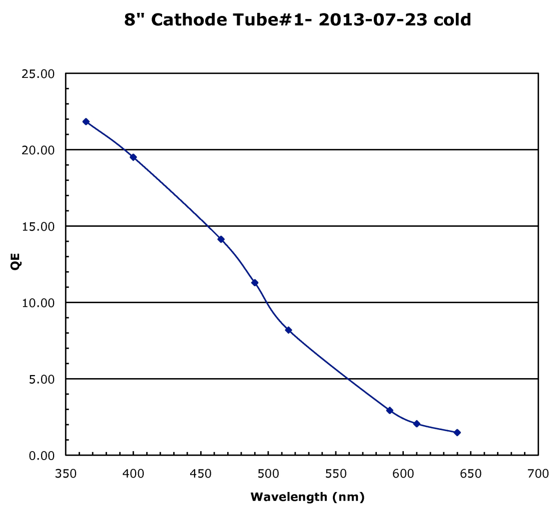


Figure 14. The quantum efficiency versus wavelength of the first 8" K_2NaSb photocathode synthesized in the vacuum facility at the Space Sciences Laboratory [18].

5.4 Electronics

The organization of the electronics effort was determined by the organization of the Collaboration along two parallel development paths, the ceramic package based on the deep SSL expertise and the glass package aimed at psec-level time resolution and lower cost, as described in Section 3.

In keeping with their respective individual emphasis on space and time resolution, the ceramic package uses anode strips with discrete pins through the back anode plate; the glass tile uses 50 Ohm microstrip lines that traverse under the glass sidewall, keeping a uniform impedance up to the input of the waveform sampling chip.

A second difference stems from the Collaboration philosophy of 'Portfolio of Risk'; the front-end electronics for the SSL ceramic package used an existing Hawaii ASIC in 0.25 micron CMOS technology [45]; for the glass package a new mixed analog-digital chip in 0.13 micron CMOS was developed [39]. Figure 10 shows the University of Hawaii electronics package integrated with the anode pins on the back of the ceramic module[38].

A custom integrated circuit, the PSEC4 chip [39], and supporting electronics, capable of time resolution measured in psec and scalable to large systems, were developed in parallel with the photodetector systems. A front-end printed circuit card, the ACDC card, containing five 6-channel PSEC4 chips is shown in the left-hand panel of Figure 15. Up to eight of the 30-channel ACDC cards can be controlled by the Central Card, shown in the right-hand panel. A system of two ACDC cards and one Central Card, i.e. 60 channels, was used in the Demountable test setup, as shown in Figure 17.

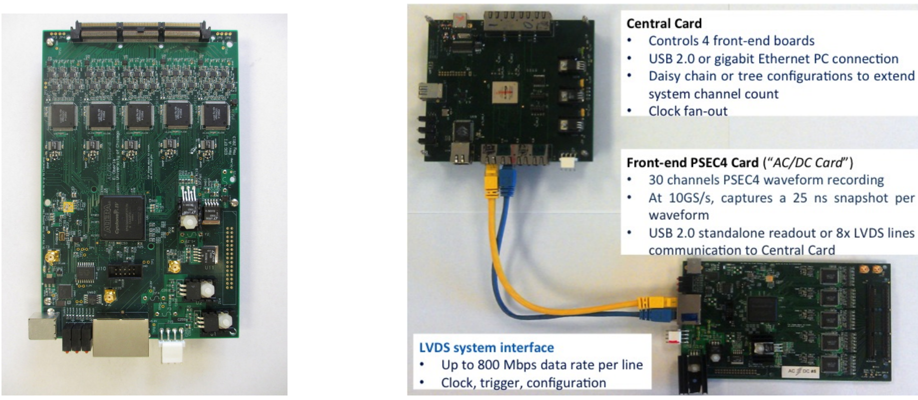


Figure 15. Left: The ACDC front-end card, with five 6-channel 15 GigaSample/sec PSEC4 digitizing chips. Right: A Central Card, used to read out and control up to eight ACDC cards, showing the connection to a single ACDC card. The system is now scalable up to 1920 channels per Central Card in a modular Master/Slave configuration.

For the glass module, the integration of electronics readout with a large-area mechanical design (the 'Supermodule') is illustrated in Figures 15 and 16. GigaHz signals require an integrated treatment of mechanical packaging and signal acquisition. The LAPPD^{TM} glass package design is modular, allowing serial connection of the anode strips from one unit to the next, with readout on the ends of the package. Measurements of bandwidth and crosstalk were made with up to four modules in series, forming a single 90-cm-long microstrip anode [17].

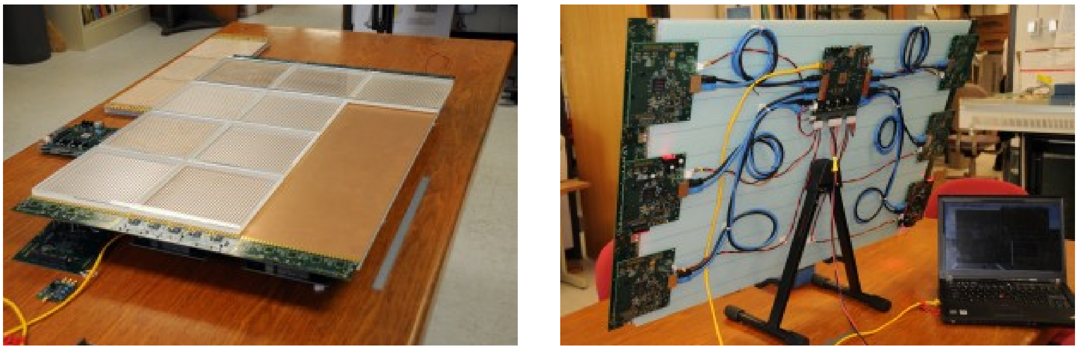


Figure 16. Left: The design of an integrated system of 12 LAPPD$^{\text{TM}}$ modules consisting of three 4-module panels, each read-out on the ends by ACDC cards. Right: A possible integration of the ACDC front-end electronics and Central Card system on the 12-module system. The modularity of the anode-strip readout and electronics allows application-specific variations on this basic structure, with trade-offs in area coverage, bandwidth, and cost.

At the APS lab at Argonne [30], a full detector assembly made from preproduction glass body parts, ALD-functionalized glass capillary MCP's, an internal resistive High Voltage (HV) divider implemented with ALD-coated spacers [35], and a 90-cm-long microstrip anode was operated with the 10-femto-second laser. The test setup (called the 'Demountable') differed from a true LAPPD$^{\text{TM}}$ in that the top-window seal was made with an O-ring rather than an indium solder seal, the photocathode was a thin film of aluminum rather than a bialkali film, and the tube was actively pumped rather than hermetically sealed. Figure 17 shows the Demountable in the APS lab. The blue cables are the readout on the ends of the anode microstrips and go to 60 channels (30 each end) of PSEC4 ASICs which digitize the signals at 10 GS/sec [39]. The data are then read out via the FPGA-based ACDC and Central Card PSEC4 DAQ system [40]. The Demountable test setup, shown in Figure 17, represents one of three sub-assemblies of a Supermodule (Figure 16).

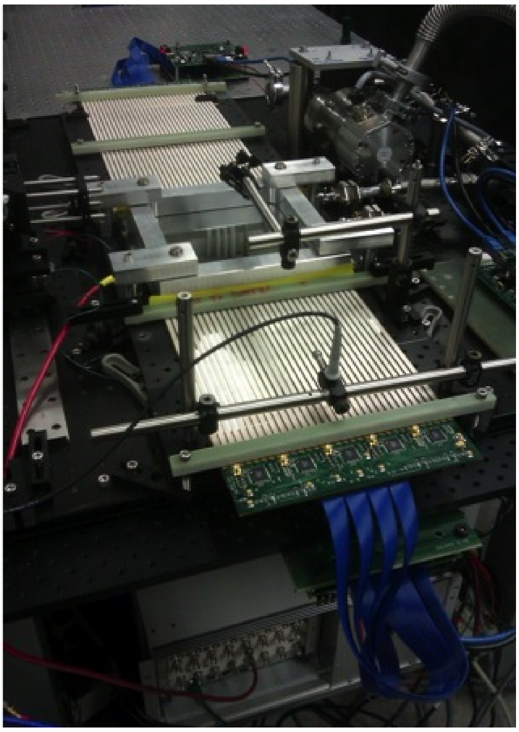


Figure 17. The 'Demountable' LAPPD module, mounted on a 30-strip anode that is 90 cm long to accommodate 4 LAPPD^{TM} modules [17]. The active module is read out on both ends of the 4-module anode using 60-channels of PSEC4 waveform sampling and data acquisition [39]. Three such assemblies would form the Supermodule.

5.5 Performance

We briefly summarize here the detector performance achieved during the Collaboration's existence. We note that this period devoted to R&D ended in Dec. 2012, with the emphasis being on the essential technical developments listed in Section 4. More details can be found in the references listed in the Tables in that section.

Figure 18 shows the response to a single photon from an LAPPD stackup consisting of a window with a metal photocathode, two ALD-coated microchannel plates, three resistive spacers, and an LAPPD module base with microstrip anode, assembled in the Demountable test stand at the ANL Advanced Photon Source femto-second laser lab. Here the electron cascade has formed a pulse that propagates in both directions on the microstrip anode away from the initial charge deposition. Both ends of each of the 30 strips are digitized using 60 channels of the PSEC4 custom waveform sampling ASIC system [39]. The difference in arrival times at the two ends gives the position with sub-mm precision; the average of the times gives the time of arrival.

5.5.1 Gain and Uniformity

Typical measured gains of the chevron pair during MCP development ranged from 5×10^6 to 2×10^7 [18, 37, 36, 3]. Measurements of the secondary emission of MgO and Al_2O_3 versus primary energy (Figure 6) show that further optimization in gain, time resolution, and/or space resolution should be possible by changing the relative high voltages of the MCPs and gaps [3].

A gain non-uniformity of the ALD better than $\pm 15\%$ was achieved, as shown in Fig. 7, and discussed in the references in the right-hand columns of Tables 1 and 3.

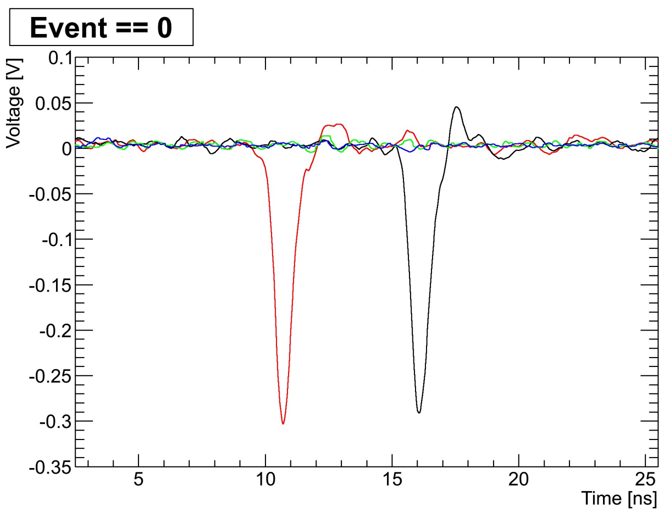


Figure 18. The detector response to a single photon, digitized by the PSEC4 waveform sampling ASIC system, from a complete LAPPD stackup of metal photocathode, ALD-coated microchannel plates, resistive spacers, and LAPPD module base with microstrip anode, assembled in the Demountable test stand at the ANL Advanced Photon Source femto-second laser lab. The red trace is the pulse measured on one end of the microstrip transmission line under the laser spot position; the black trace is the same pulse measured on the other end. The other two traces are neighboring striplines not excited by the laser. [30, 3].

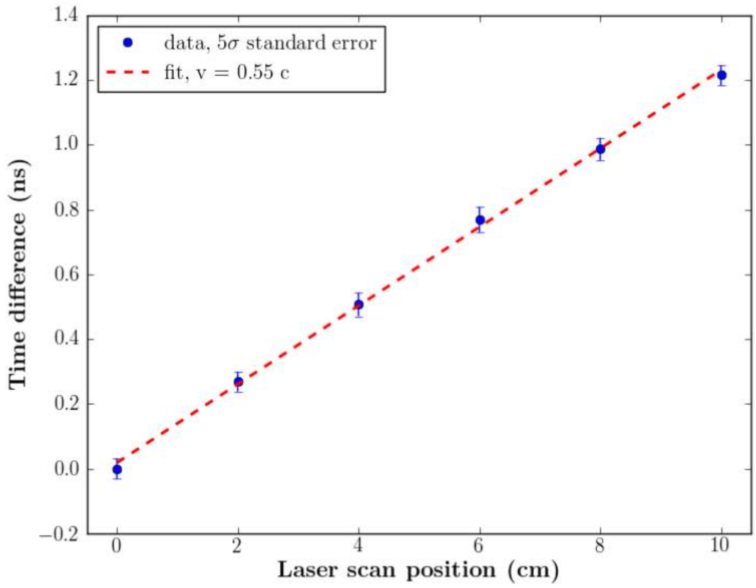


Figure 19. The time difference measured in the APS laser lab between the two ends of the module striplines versus the position of the laser spot projected on the module [3]. Because the position in the strip direction is calculated from the difference in times measured at the strip ends [17], one expects a linear behavior, as observed. The position in the orthogonal direction is measured from the charge sharing on neighboring strips. The measured resolution in each direction is $\sim$ 700 micron [3].

5.5.2 Stability vs Charge Extraction

The ALD-coated plates do not show large loss of gain with charge extracted compared to conventional leaded-glass MCPs, as shown in Fig. 8.

5.5.3 Position Resolution

Figure 19 shows the time difference measured in the APS laser lab between the two ends of the module striplines versus the position of the laser spot projected on the module. The relationship is linear as expected; the measured resolutions in both transverse directions are $\sim$ 700 microns [3].

5.5.4 Differential Timing

Figure 20 shows the time difference measured in the APS laser lab between the two ends of the module striplines versus the inverse of the signal-to-noise ratio. Noise at the APS laser lab was dominated by pickup from the laser pulse generation itself; the typical noise level of PSEC4 is 700 micro-volts, negligible in this environment. Measurements made after the Collaboration period decreased the intercept, which corresponds to large pulses such as would be generated by a particle generating Cherenkov light in the detector window, to $\sim$ 2 psec [3].

5.5.5 Absolute Time Resolution

Absolute time resolution was measured for single photons by attenuating the laser light [3]. A best value for the fitted rms of 47 psec was measured, consistent with estimates of the jitter due to

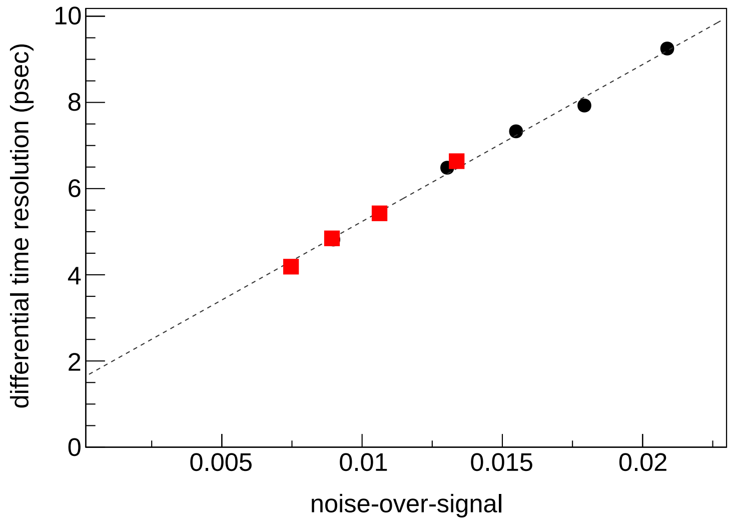


Figure 20. The time difference measured in the APS laser lab between the two ends of the module striplines versus the inverse of Signal-to-Noise in the 8" test chamber in 2012 (black circles) [3]. The error bars are smaller than the symbols. The signals are large due to the high gain; the resolution is dominated by noise from the femto-second laser. The red squares show data taken in 2014 with the Demountable chamber. The intercept of the fitted line intersects at 1.6 psec. With smaller capillary pores [46] and a signal-to-noise ratio dominated by the intrinsic noise of the PSEC4 chip we would expect sub-psec resolution [39, 3, 47].

variations in the geometric path to the first strike for a single photo-electron[3].

6. Goals Achieved and Not Achieved

The LAPPD Collaboration ended in Dec. 2012, and the R&D effort largely moved to technology transfer for commercialization [48], as described in Section 10). Here we briefly summarize the major goals achieved, the opportunities we identified as viable but were unable to explore, and the failure to produce a sealed LAPPD^{TM} module during the R&D.

6.1 Major Goals Achieved

Major goals achieved include:

1. Establishment of the production capability for high-quality 8”-square capillary glass substrates, including fusing into large blocks, slicing and finishing the blocks into uniform smooth wafers, post-manufacturing cleaning, and quality control, documentation, and handling techniques;
2. Development of ALD reactor configurations and processes to produce adequately uniform ALD coatings for both the resistive and SEY layers;
3. Demonstration of deposition of 8”-square photocathodes on B33 glass substrates for both K_2NaSb and K_2CsSb alkali photocathodes.
4. Development of large-area test facilities that have been carried over into commercial production facilities;

5. Extensive measurements of the performance of 8"-square ALD-coated MCP pairs, modules, including uniformity, gain, time and space resolution, and lifetime.
6. Development of the low-cost low-power 6-channel CMOS 15 GS/sec PSEC4 ASIC;
7. Integration and operation with an LAPPD^{TM} detector of the PSEC4-based 60-channel waveform sampling digitizing system with 10 GS/sec at 10.5 bits and 1.6 GHz bandwidth from cathode to DAQ;
8. Development of an FPGA-based scalable front-end and DAQ system of 30-channel (5 PSEC4 ASICs) PC cards and a master control card capable of several psec resolution;
9. Operation of both the pre-production ceramic and glass LAPPD^{TM} module packages; the ceramic with full photocathode- the glass with a metal cathode. The ceramic module was complete but operated in UHV; the glass module was O-ring sealed and externally pumped [1].
10. Demonstration of LAPPD^{TM} performance: gain $> 10^7$, time resolution of < 50 psec for single photons, spatial resolutions of ~ 700 microns.
11. Coordination of and securing funding for the transition to commercial LAPPD^{TM} production.

6.2 Opportunities Missed: What We Did Not Get Done

6.2.1 A Sealed Functioning LAPPD^{TM} Module

LAPPD was not able to successfully fabricate a leak-free sealed LAPPD^{TM} module with a bialkali photocathode in the R&D period, which ended in December 2012. One trial of making a complete tube with photocathode was made shortly after the end of the Collaboration. That first attempt (July 2013) to seal a complete ceramic tile failed when a spot-weld gave way on one corner of the tile, creating a leak. However extensive testing done with the tile still in the UHV tank showed that the tube was fully functional with resolutions in time and space, gain, and noise rates at or beyond specifications.

Figure 21 shows the characterization of the 20 cm (Na_2KSb) photocathode on the first fully-assembled LAPPD^{TM} module while still under vacuum in the SSL tank (see Figure 26). The left-hand panel shows the quantum efficiency as a function of wavelength. The right-hand panel demonstrates the uniformity of the photocathode response over the 20 cm by 20 cm area.

Figure 22 shows the output pulses from the delay-line anode of the fully-assembled tube illuminated by a pulsed laser while under vacuum in the SSL tank. The bandwidth is limited by the UHV-compatible electrical connections to the anode; otherwise the performance of the tube in photocathode response, gain, and spatial mapping was as expected.

We believe that it is important to understand the sealing trial history, as it can easily be misconstrued as a fundamental problem with the design or the sealing technique. Instead, we believe that scaling a highly-tuned commercial recipe such as a low-temperature indium seal of a window with a bialkali photocathode by a factor of four from the Planacon dimensions to the LAPPD^{TM} dimensions will always require many trials. The lessons learned have now been transferred from SSL to the commercialization effort at Incom [20].

Fully integrated trials had been scheduled to be earlier, but were delayed by unforeseen difficulties, overcome, but with a cost in time. Particular problems that were solved by the R&D, but

[1] The ceramic module tests were done not long after the end of the Collaboration.

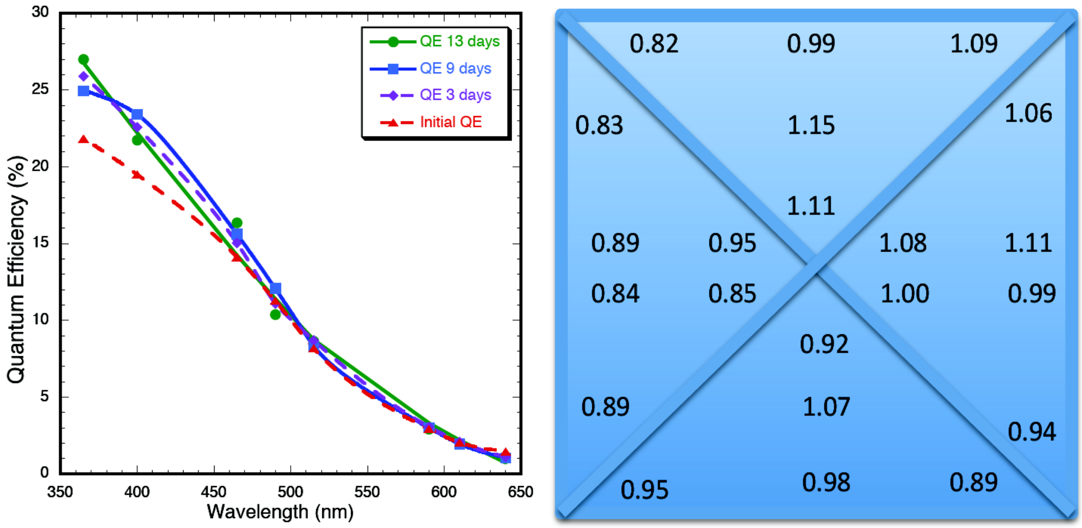


Figure 21. Left: Quantum efficiency as a function of wavelength for the 20 × 20 cm^2 (Na_2KSb) photocathode after transfer and sealing to the first fully-assembled LAPPD^{TM} module while still under vacuum in the SSL tank. The tube was fully functional, with good gain and uniformity. When brought up to air one corner of the seal between the module assembly and the window leaked due to misalignment.

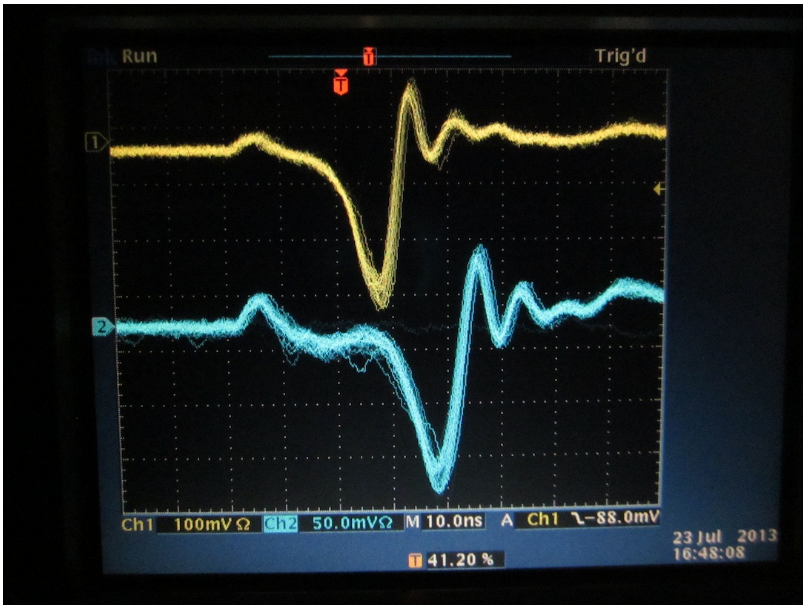


Figure 22. The pulses on the anode delay line from the first trial of a fully-assembled module while still under vacuum in the SSL tank, with the photocathode illuminated by a pulsed 610nm laser.

turned out to be appreciably more difficult than anticipated at the time of the proposal were: a) the cleaning of the 20-micron pore capillary substrates after wafering; b) the consistent synthesis of uniform SEY and resistive layers on the 6.5 m^2 surface-area capillary wafer, particularly in an ALD facility shared with other users using different chemistries; c) subtle packaging problems related to thermal differential expansion over the much larger dimensions during vacuum bakeout;

and d) slowness/inability by the leadership in re-allocating resources for the transition from R&D to production in a wide-spread diverse organization, well-suited for the required individual R&D efforts, but not easily transitioned in budget or expertise onto one primary task.

6.2.2 ALD-enabled High Performance Advanced Designs

The LAPPD R&D effort concentrated on the basic issues of finding at least one solution to each problem. In such a process, if successful, one finds that there are better solutions as well as new opportunities that were not previously realistically within reach. We can imagine a future program dedicated to following up on these, or, perhaps more realistically, a steady chipping away by interested parties (academic, national labs, industry) with funding from a wide variety of sources. In particular, the exploitation of the ALD process to use higher-SEY materials at the pore entrance and discrete dynode structures [49]; and pushing the limit on the measurements of timing resolution below 1 psec [16] remain promising areas in this technology.

6.3 Spin-offs from LAPPD R&D

There were other opportunities that spun off parallel R&D efforts involving individual institutions from the LAPPD Collaboration, supported by the DOE SBIR/STTR program or, in the case of medical imaging, a private foundation:

1. High quantum efficiency theory-based bialkali photocathode synthesis [32, 50];
2. High bandwidth microstrip and pixel anodes [51];
3. Large-area ALD-functionalized MCPs with smaller capillary pores for better time resolution [46];
4. Technology transfer for commercial production [48];
5. Uniform high-gain ALD coatings [52];
6. Use of fast timing for reconstruction of particle tracks using Cherenkov light [53, 40];
7. Use of fast timing for reconstruction of gamma-ray interactions in water-based PET detectors [54].

7. Major Constructed Facilities

The prior existence of major facilities at the collaborating institutions was essential to the project, for reasons of both time, money, and, most importantly, the availability of expert personnel. In addition, major facilities dedicated to LAPPD R&D were constructed at Argonne, the Space Sciences Laboratory at Berkeley, Incom, and Fermilab, and diagnostic equipment and software tools were upgraded at Chicago and Hawaii. Figure 23 shows the facilities at Incom [41] for drawing the glass capillary tubes used in the MCP substrates. After multiple drawings, fusing into a block, slicing into wafers on a bias, and finishing, each 20-cm-square substrate contains $\sim$80-million pores.

The top and bottom surfaces of the wafers were metalized with NiCr at a custom UHV facility constructed at Fermilab to allow uniform evaporation onto 20×20 cm^2 plates while rotating them about an axis parallel to the pores for proper end-spoiling [55]. The left-hand panel of Figure 24 shows the UHV evaporation facility constructed to deposit NiCr electrodes on the top and bottom surfaces of LAPPD^{TM} capillary wafers; In the right-hand panel we reproduce a Fermilab chart of the number of 8”-square micro-channel wafers metalized on both sides versus time.

The coating of the glass capillary substrates with resistive and emissive layers using Atomic Layer Deposition (ALD) was done in the Energy Systems Division (ESD) at ANL. Several existing custom reactors and a large commercial reactor [56], acquired at the start of the project, were shared by LAPPD with other ANL programs for the development of the secondary-emitting and resistive layers. Figure 25 shows the Beneq reactor installed in the ESD labs at ANL.

The large process chamber at the Space Sciences Laboratory, shown in Figure 26, was designed, procured,and commissioned for the LAPPD program. Large-area photocathode development using a K_2NaSb process established by SSL was done in the photocathode sub-assembly. The facility is highly instrumented for process control and subsequent in-situ detector testing. Modifications were made to other existing facilities at SSL, including the processing oven, vacuum baking chamber, the MCP metallizing evaporator, and cleaning equipment.

The development and characterization of high-quality, reproducible, glass substrates with uniform high-gain stable ALD coatings required the building at SSL of extensive testing vacuum facilities to accommodate the large module format. Testing was initially done with a standard 33 mm circular format allowing use of fixturing from prior SSL programs, and quickly evolved to the LAPPD^{TM} 20×20 cm^2 plates. Plates were fabricated at Incom, sent to Argonne where they were checked and further documented, and then transported to Fermilab for metalization, and then

Figure 23. The capillary drawing facilities at Incom. The capillaries are cut, stacked and fused into a solid block, which is then sliced into wafers that are ground, polished, and trimmed to become the MCP substrates.

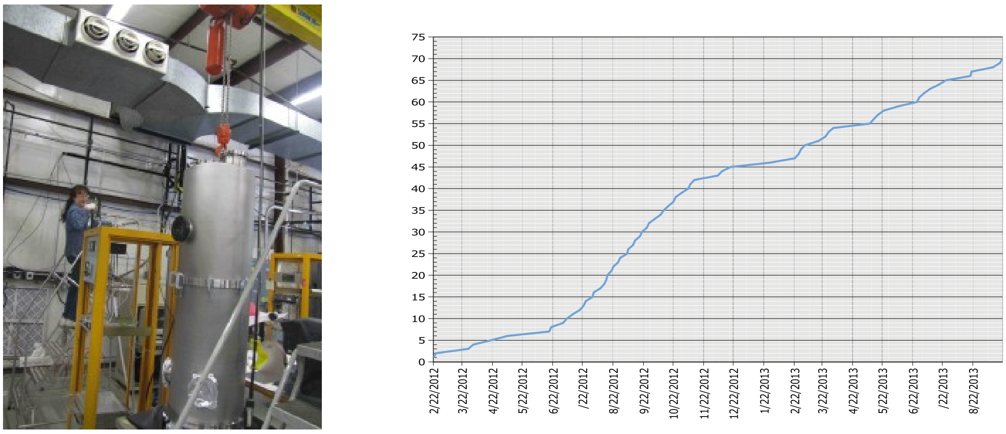


Figure 24. Left: The Fermilab UHV evaporation facility constructed to deposit NiCr electrodes on the top and bottom surfaces of LAPPD™ capillary wafers; Right: A chart of the number of wafers metalized on both sides at the Fermilab evaporation facility versus time.

Figure 25. The Beneq Atomic Layer Deposition facility installed in the Energy Systems Division at ANL, used to functionalize the Incom capillary plates with resistive and secondary-emitting layers. The precursor flow path required extensive modification in order to establish uniformity over the 6.5 m^2 surface area of each capillary plate.

transported back to Argonne, where the ALD resistive and emissive coatings were applied. Plates were then either sent to SSL for tests of gain, uniformity, and lifetime, or to the test facility at the Argonne APS for timing measurements, as well as uniformity and position linearity and resolution with the LAPPD electronics. At each step in the 'pipeline' an effort was made to perform quality control and to enter the details in a database that recorded the history of each microchannel plate.

Figure 27 shows two test facilities constructed at SSL for LAPPD that were essential in the development of uniform high-gain low-noise ALD coatings on glass substrates of high uniformity and very few blemishes. The left-hand panel shows the 'Dual Chamber Vacuum Test Chamber' used for rapid turnaround testing of ALD coatings on the 33 mm circular glass substrates, of which

Figure 26. The UHV photocathode and detector assembly facility constructed for LAPPD at the Space Sciences Laboratory, University of California, Berkeley .

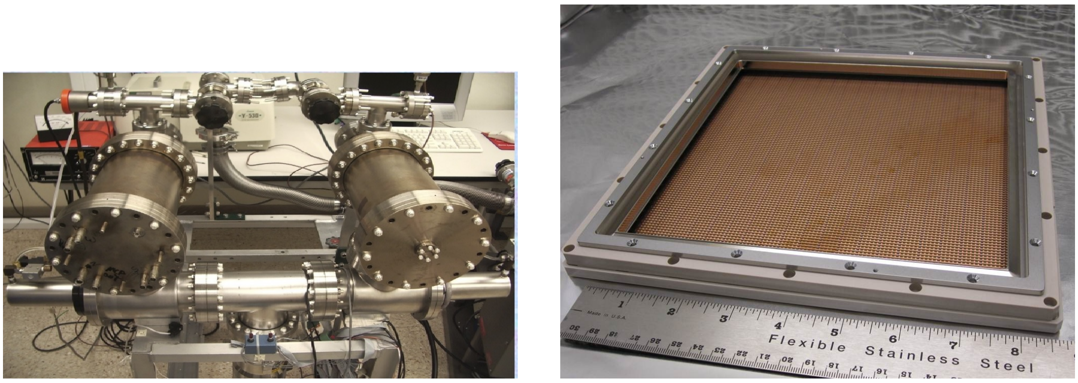


Figure 27. Left:: The Dual Chamber Vacuum Test Chamber at Space Sciences Laboratory, University of California, Berkeley for rapid turnaround testing of ALD coatings on 33 mm circular glass substrates as the processes were being developed at the Argonne Energy Systems Division and Incom, respectively. This 'double barrel test chamber' employs both phosphor screen detectors for single MCP characterization and crossed-delay-line detectors for double MCP stack testing. Right: The SSL '8"-demountable' vacuum facility designed and built for characterizing the performance of 8" ALD-coated MCPs. The detector employs a 200mm cross-delay-line anode for signal readout, achieving sub-100 μm spatial resolution, and is designed for easy MCP replacement to facilitate rapid test cycling.

many could be made from a single 8" wafer. The right-hand panel shows the '8"-demountable' detector, consisting of a high resolution cross-delay-line anode mounted on a large vacuum vessel, designed for rapid test cycling. This instrument was the 'work-horse' facility for the development of the 8" Incom glass substrates and the Argonne ALD coatings, providing measurements of gain uniformity, resolution, and noise.

The Chicago group had been working with commercial Photonis Planacons [57] in the Fermi-

Figure 28. The commercial Photocathode Deposition facility, purchased from Burle/Photonis, installed in the High Energy Physics Division at ANL. The instrumentation used for measuring film thickness and quantum efficiency is in the foreground.

lab beam tests, and so it was natural to work on the extension of the Planacon K_2CsSb cathodes to the 16-times larger area LAPPD^{TM} format. Figure 28 shows the Burle/Photonis photocathode deposition facility purchased by LAPPD and installed in a new lab created in the HEP Division at ANL for photocathode formation and characterization. In order to make 8"-square cathodes, the manifold that held multiple conventional PMT's was replaced by a large glass vessel, created by J. Gregar of the ANL Glass Shop, that contained the Sb beads, alkali sources, and that held the window on which the cathode was deposited. Diagnostic and characterization equipment were added to the installation, as shown in Figure 28.

In addition to the 'pipeline' program of MCP development at Space Sciences Laboratory [36, 18], MCP testing was done at the Advanced Photon Source [30, 3], with the emphasis at SSL being gain, uniformity and lifetime, and with Chicago/ANL concentrating on fast timing. Figure 29 shows the femto-second laser laboratory at the APS that was built up as the test facility for fast timing [30]. A Ti-Sapphire laser capable of 30 fsec pulses and enough intensity to excite a metal cathode was refurbished by LAPPD at a modest cost.

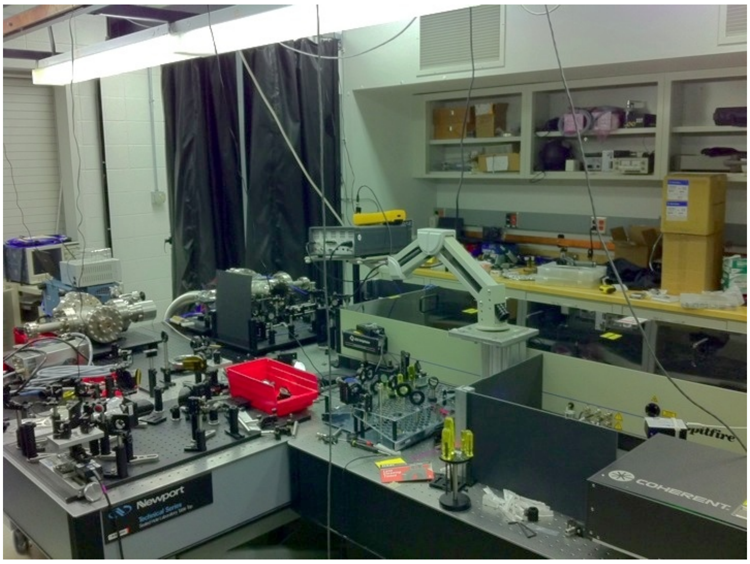


Figure 29. The timing lab constructed at the ANL APS [30] The Ti-Sapphire laser is on the lower right; two vacuum test chambers are visible on the middle left. The laser beam can be transported to several test chambers as well as the 'Demountable' prototype module by components on the optical bench.

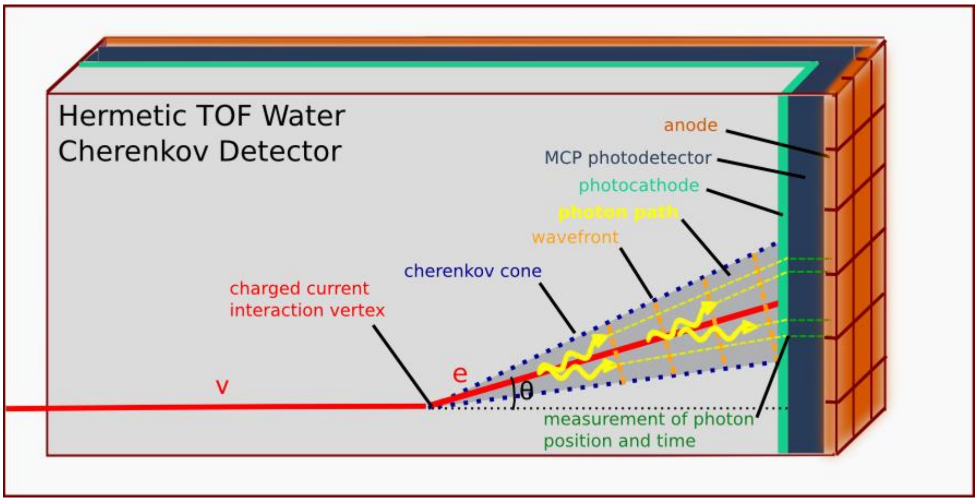


Figure 30. A 2008 conceptual drawing of a large water Cherenkov counter such as was proposed for DUSEL, in this case instrumented with LAPPDs. Note the use of time and position measurements on each Cherenkov photon to locate the track [40]. (credit: Constantinos Melachrinos)

8. The Role of DUSEL in LAPPD

The US joint DOE-NSF proposal for a large underground water Cherenkov neutrino detector to be installed in the Deep Underground Science and Engineering Laboratory (DUSEL) laboratory required a large investment in photodetectors, more than 100M$ [6, 7]. This served as an impetus for developing large-area ‘frugal’ planar detectors made of inexpensive glass components, and given the large payoff for success, was a key motivation for DOE funding of a high-risk endeavor such as LAPPD [12].

Figure 30 shows a 2008 conceptual drawing of a large water Cherenkov counter such as was proposed for DUSEL, in this case instrumented with LAPPDs. Note the use of time and position measurements on each Cherenkov photon that allow using the photon drift times to reconstruct the track [40].

The large water Cherenkov counter for DUSEL was important in another aspect as well: the large amount of money involved for photodetectors attracted the attention of a company that had a facility that could accommodate the size of the LAPPD tubes, and produce them in volume. The resulting proposal from an established photodetector production company provided a strong confirmation of the goals and methods of LAPPD [58]. Figure 31 shows a slide from the proposal. Unfortunately, the large neutrino detector for DUSEL was canceled by the US National Science Board [6] and the commercial interest ended [7].

9. Communicating Technical Information in a Multi-Disciplinary Effort

A non-technical but critical goal of LAPPD was to convince the scientific and commercial communities of the feasibility of large area timing with resolution measured in psec. This was necessary to secure funding, to enable commercialization, and to build a fast-timing community intellectually invested in understanding and developing the detector and supporting technologies such as low-

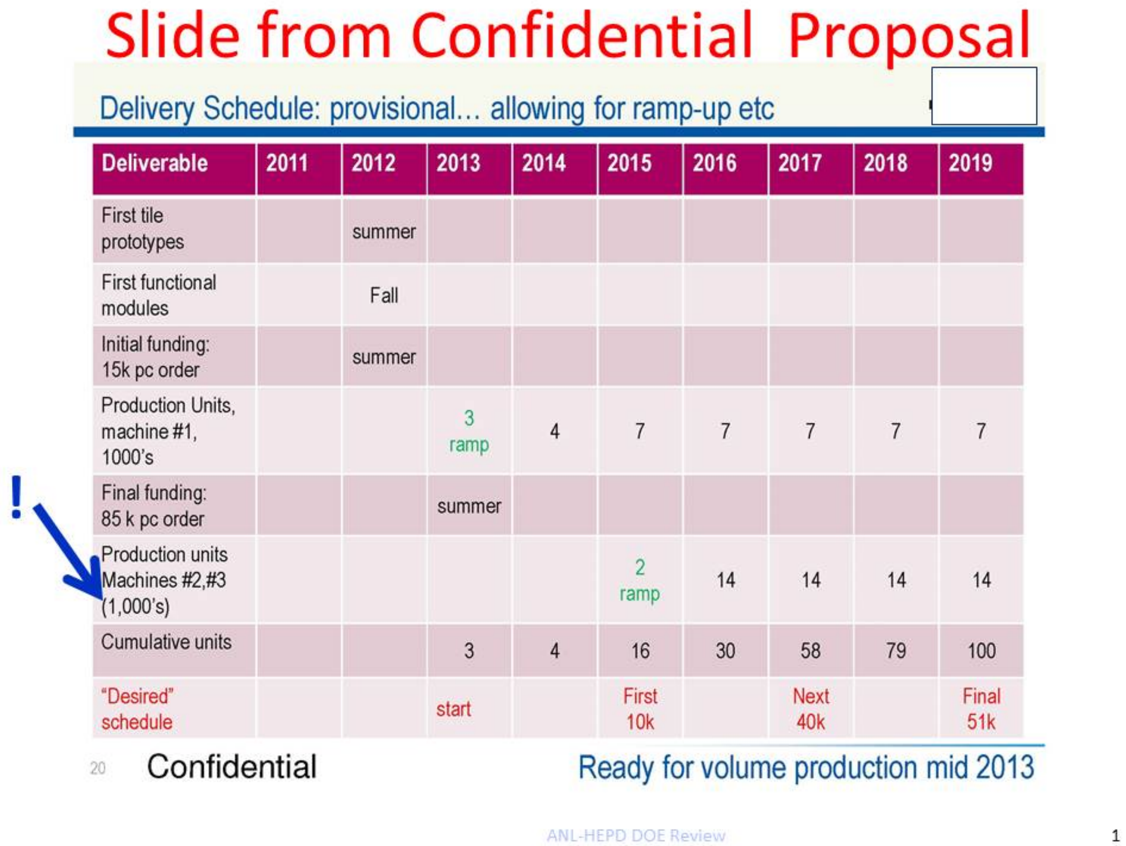


Figure 31. A slide from a proposal for production of LAPPDs for DUSEL [6] by a company experienced in vacuum phototube production. The proposal was to modify an existing production line and then replicate it to produce 20,000 LAPPD modules per year. The commercial interest ended with the cancellation of the DUSEL project. The arrow is to emphasize that the quantities are in units of one thousand modules.

power psec electronics digitization systems, and clock distribution. This communication effort was time-intensive, with multiple weekly meetings, international workshops, interfacing to phototube and other vendors, and extensive web pages, as described below.

9.1 Collaboration Meetings

The LAPPD Collaboration was often described as a 'pick-up ball game', in that the group was self-assembled based on interest, and covered a very wide range in cultures and methods of working. An unusual amount of effort was consequently needed to make efficient progress. LAPPD Collaboration Meetings were held twice-yearly to cover the broad range of material science R&D, proprietary knowledge, and education of those from other fields. The agendas and slides are available on the LAPPD web page [59].

9.2 Designing an Effective Review Process

In addition to the collaboration meetings, each of the four areas of R&D reported to its own review committee, dubbed 'Godparent Review Panels'. The panels met twice per year, out-of-phase with the twice-yearly Collaboration meetings. Each panel was made up of both outside experts and, in an effort to avoid the typical reviewer/reviewee dynamics, LAPPD members who were not participants in the area under review, bringing to the conversation both outside experience and some knowledge of why internal choices that may have been different from conventional wisdom were made. In addition, an effort was made to bring in critics of the overall concept.

The godparent reports and makeup of the initial round of godparent panels are posted on the psec web Library page [60]; the procedure called for a written response by the proponents.

9.3 Collaborative Cross-Community Workshops

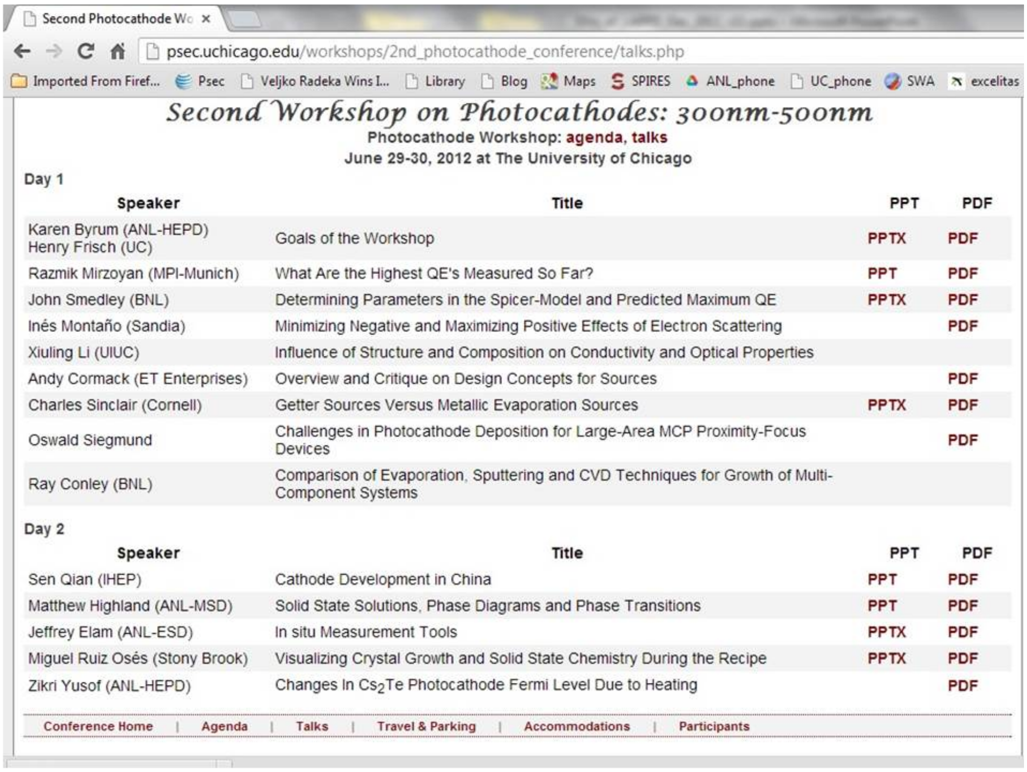
A homogeneous amplification section with a dimension measured in tens of microns should provide fast pulses capable of psec-level time measurements [10, 2, 61, 62]. However there remained many detailed questions. A series of workshops, held alternately in the Chicago area and in France [63], was intended to provide answers to these specific questions one-at-a-time; we first determined the talks needed, and then worked to identify the most expert speakers to that topic, often inviting specialists we did not know. Rather than having speakers report on their own work, the workshop focused on bringing to bear their expertise on the questions and problems. The result was a broadening of the base of both knowledge and community.

The agendas and talks at the Workshops are available on the PSEC Library web page [63]. The workshop on Limitations on Fast Timing and the two workshops on bialkali photocathodes in the 300-500 nm range are particularly good examples of the effectiveness of the top-down assignment of titles and speakers. Figure 32 shows, as an example, the agenda of the second workshop on photocathodes.

9.4 Web-based Documentation for Collaborators, Vendors, and Adopters

In addition to being the repository for proceedings of the Godparent Review Committees, the Collaboration Meetings, and the Workshops, the LAPPD web pages provided the basis of the weekly status reports, papers and conference proceedings, and often-used information on materials and techniques. The Library web pages [64] also serve as a convenient easily-accessed source for external material that is often referred to by detector developers, such as tables of CTE's and moduli of materials, relevant literature on MCP's, photocathodes, and detector performance.

Three custom web-based tools, open to the public, turned out to be heavily used for documentation and communication. The Collaboration Blog provided a forum and archive for test results, schedules, and presentations viewed during the weekly phone meetings [65]. In addition, three 'libraries' were linked to the web page: the Document Library for the Collaboration papers, talks, and internal notes [66]; the Image Library for discussing technical specifications with vendors and archiving prints for reference [67]; and the Figures Library for use in talks and papers [68]. Figure 33 shows a sample page from the Document Library. The Electronics Group, consisting of members from the University of Chicago and University of Hawaii, met separately weekly (the meeting was open to all members, however) and also maintained dedicated web documentation and a separate blog [69].



Second Photocathode Wo ×

psec.uchicago.edu/workshops/2nd_photocathode_conference/talks.php

Imported From Firef... Psec Veljko Radeka Wins I... Library Blog Maps SPIRES ANL_phone UC_phone SWA excelitas

Second Workshop on Photocathodes: 300nm-500nm

Photocathode Workshop: agenda, talks

June 29-30, 2012 at The University of Chicago

Day 1

Speaker	Title	PPT	PDF
Karen Byrum (ANL-HEPD) Henry Frisch (UC)	Goals of the Workshop	PPTX	PDF
Razmik Mirzoyan (MPI-Munich)	What Are the Highest QE's Measured So Far?	PPT	PDF
John Smedley (BNL)	Determining Parameters in the Spicer-Model and Predicted Maximum QE	PPTX	PDF
Inés Montaño (Sandia)	Minimizing Negative and Maximizing Positive Effects of Electron Scattering		PDF
Xiuling Li (UIUC)	Influence of Structure and Composition on Conductivity and Optical Properties		
Andy Cormack (ET Enterprises)	Overview and Critique on Design Concepts for Sources		PDF
Charles Sinclair (Cornell)	Getter Sources Versus Metallic Evaporation Sources	PPTX	PDF
Oswald Siegmund	Challenges in Photocathode Deposition for Large-Area MCP Proximity-Focus Devices		PDF
Ray Conley (BNL)	Comparison of Evaporation, Sputtering and CVD Techniques for Growth of Multi-Component Systems		

Day 2

Speaker	Title	PPT	PDF
Sen Qian (IHEP)	Cathode Development in China	PPT	PDF
Matthew Highland (ANL-MSD)	Solid State Solutions, Phase Diagrams and Phase Transitions	PPT	PDF
Jeffrey Elam (ANL-ESD)	In situ Measurement Tools	PPTX	PDF
Miguel Ruiz Osés (Stony Brook)	Visualizing Crystal Growth and Solid State Chemistry During the Recipe	PPTX	PDF
Zikri Yusof (ANL-HEPD)	Changes In Cs_2Te Photocathode Fermi Level Due to Heating		PDF

Conference Home | Agenda | Talks | Travel & Parking | Accommodations | Participants

Figure 32. The web page for the *Second Workshop on Photocathodes: 300-500nm*, held at UC in June 2012, one of a bi-annual series held in collaboration with P. LeDu and other French colleagues. Note the participation from many communities who normally have little interaction. The two cathode workshops have been followed up by several collaborative efforts [32, 50].

9.5 Areas of Application and Early Adopters: the LAPPD Strategy

The model for LAPPD involvement in applications was to let individual members follow their interests, often in collaboration with prior external associations. Figure 34 shows a pictorial representation from 2010 of this strategy for feedback from, and information flow to, areas of possible application of LAPPD photodetectors. In 2013, after the Collaboration had concluded, Incom organized a meeting of 'Early Adopters' from these areas to better understand specifications and uses [70] as part of their commercialization plan. Specific areas that followed this pattern are the Optical Time Projection Chamber [40], ANNIE [71], Positron-Emission Tomography [72, 73, 74], and non-proliferation monitoring detectors [75].

9.6 Publishing

While the development of large-area psec photodetectors and electronics has been the subject of a large program, there are many areas that are fertile for further development. We encountered many industrial 'recipes' ripe for a deeper understanding of the underlying material science, chemistry, and physics. LAPPD has consequently put a high premium on publishing technical details of the development, including papers on the glass/ALD MCPs [21, 22, 23, 24, 43, 28, 29, 25, 76], fast

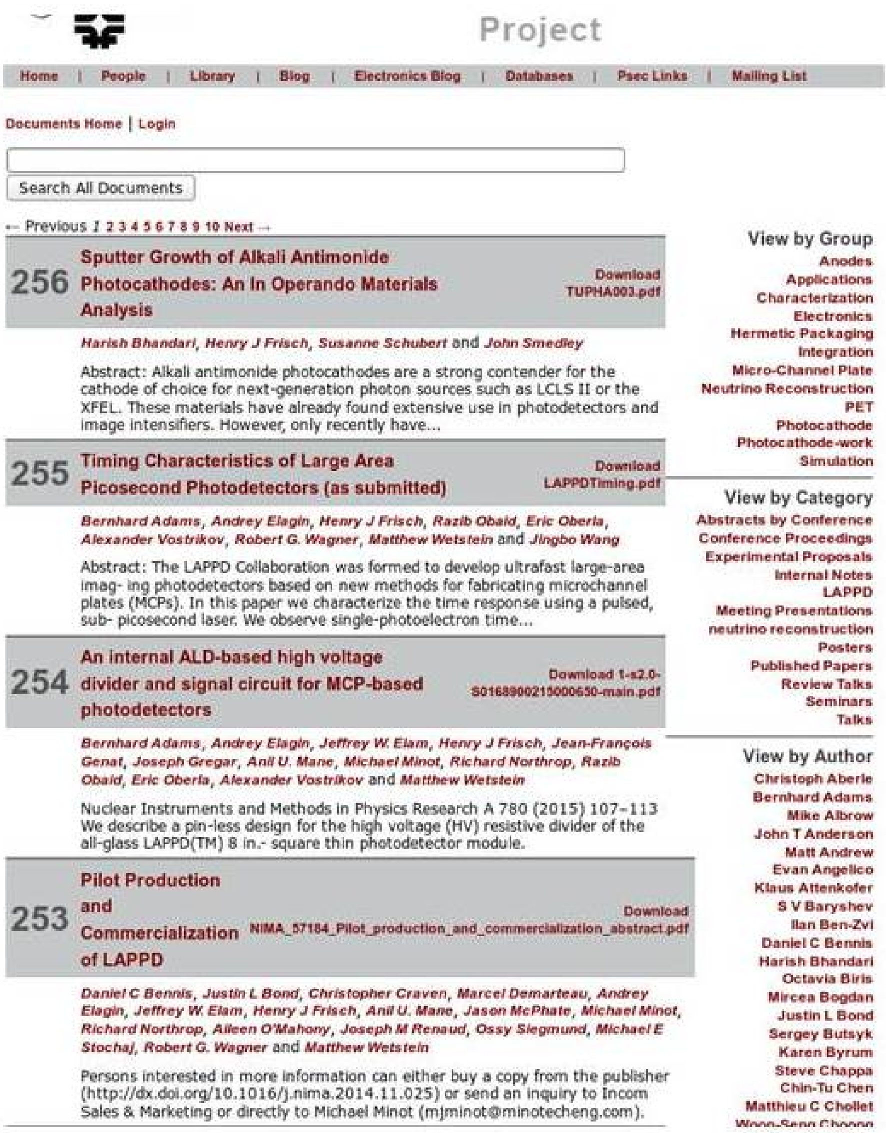


Figure 33. A sample page from the Document Library. The data base is searchable by author, topic, and document type. The Document Library serves both as an archive of results, and has proved useful in interactions with potential adopters, other groups working on fast timing or photodetectors, and prospective students, postdocs, and employees.

timing and electronics [30, 39, 77, 17, 38], and packaging [18, 35, 17, 19, 20]. Conference reports from throughout the R&D can also be found in the Document Library.

In addition to published papers, patents were filed on the technical developments in the MCP and packaging areas, and in uses for HEP/Nuclear Physics and medical imaging [78, 21, 24, 79, 80].

9.7 Mentoring, Awards, Careers

Detector development is both critical to the future of hard sciences and medical care, and yet is

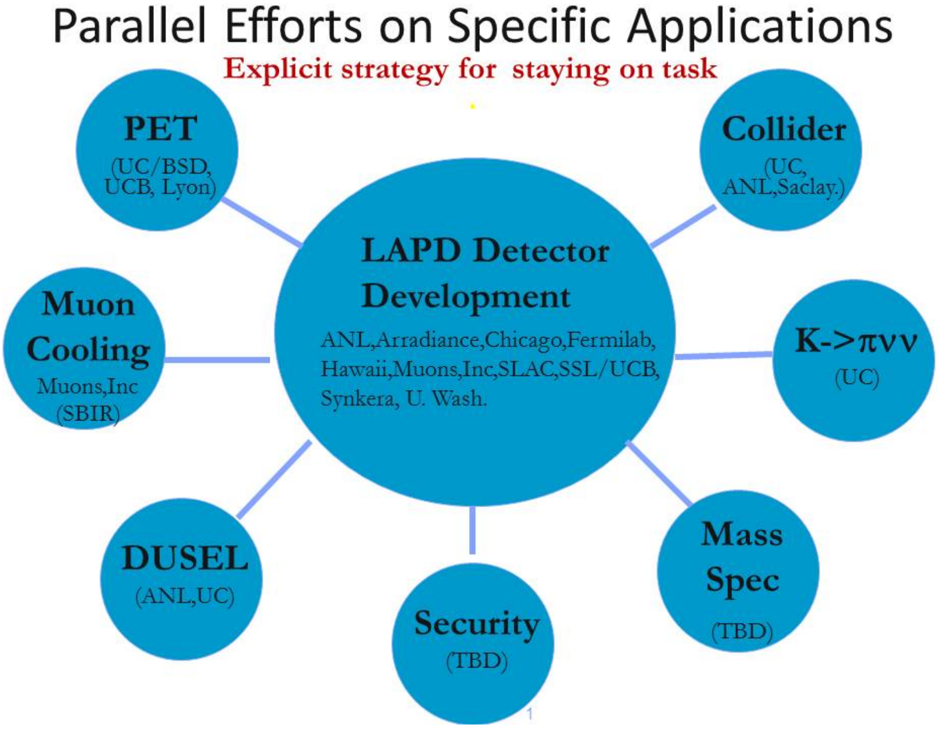


Figure 34. A pictorial representation made in 2010, shortly after the start of the Collaboration, of the strategy for matching user requirements with projected detector capabilities in areas of possible application of LAPPD photodetectors. The LAPPD core effort was focused on the photodetector R&D; specific applications were pursued by individual collaborators working with outside interested groups. In 2013, after the Collaboration had ended, a meeting of 'Early Adopters' from these areas was organized by Incom [70].

widely considered a second-tier and hence dangerous career path for young scientists. This paradox is often discussed, but funding pressures, particularly on universities from which the young scientists come, severely constrain any change. One of the products of the LAPPD project was the recognition of several young scientists: LAPPD postdoctoral fellows were awarded the Lee Grodzins Award (Wetstein), the Charles Townes Fellowship (Ertley), and the Grainger Postdoctoral Fellowship (Wetstein); an LAPPD graduate student (Oberla) won the Grainger Graduate Fellowship; and a high school student working with LAPPD took second place in the national Intel Science Competition (Credo). Senior members were awarded an R&D 100 award. In addition, a large number of REU [81] and SULI [82] students took part in hands-on research in the summer, with several returning as graduate students or postdocs working on LAPPD.

10. End of Collaboration: Path to Commercialization and Adoption

The conclusion of the ARRA funding in 2012 ended the Collaboration structure of university support through subcontracts from ANL and the organization structure shown in Figure 2. Figure 35, from the final review of the Collaboration in Dec. 2012, shows the transition to four parallel, separately funded, and individually managed paths. The purpose of two of the paths was the transition to commercialization: Incom [41], under a DOE Technology Transfer Opportunity award [48], has

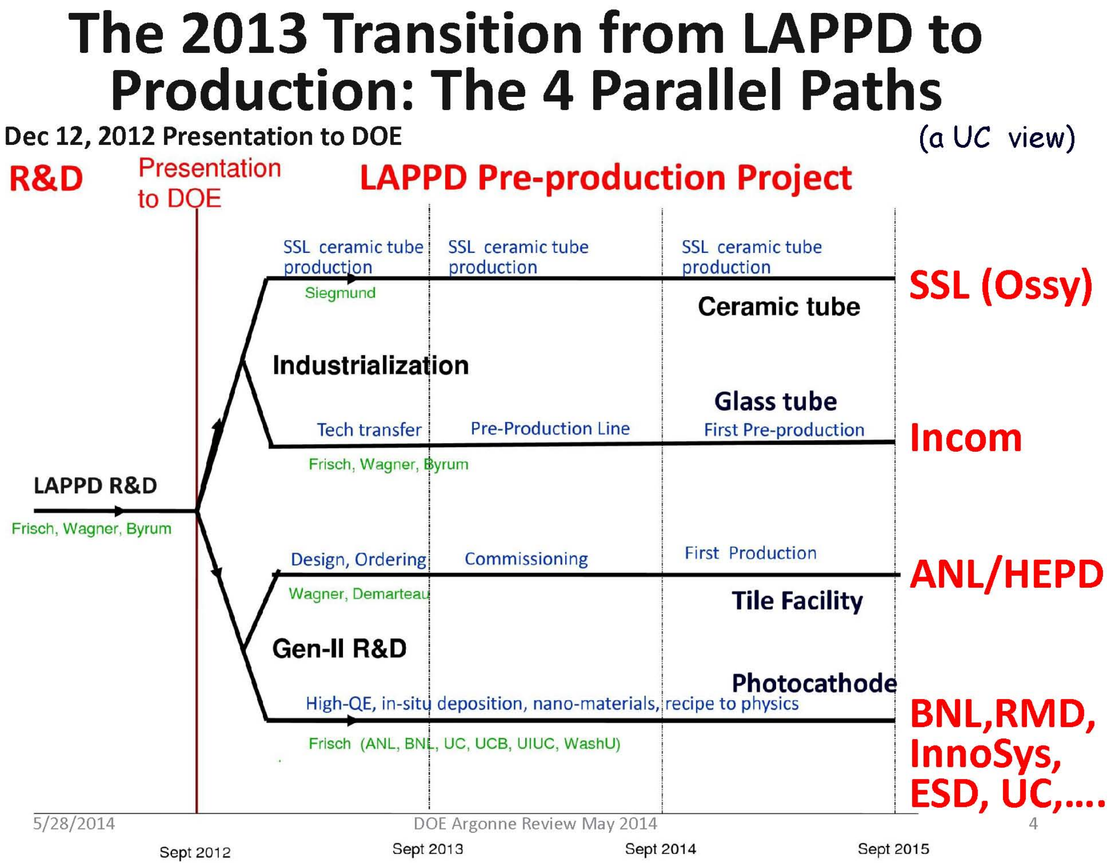


Figure 35. Slide from the DOE review at ANL on Dec. 12, 2012, showing the end of the collaborative R&D and the transition to four parallel, separately funded, and individually managed efforts.

moved forward on commercial production of both the MCP's and also the LAPPD^{TM} detectors [8], and the SSL group continued on the ceramic package program under separate funding. The goals of the other two paths, the subject of collaborative efforts with industry, were to continue R&D on technical avenues that had been identified in the LAPPD project: the bulk synthesis of pure bialkali photocathode material for sputtering onto substrates [32], higher bandwidth glass capillary substrates [46], higher-bandwidth anodes [51], and developing techniques for bringing the yield up and the price down through adopting techniques for conventional PMT production [79].

Lastly, the applications of psec timing have become much better understood, with growing interest in many scientific and commercial applications. The use of the measurement of the coordinates of arrival of photons or charged particles in both time and space has been explored in water Cherenkov counters [40], medical imaging [72, 73, 74, 80], searches for neutrino-less double-beta decay [53], and non-proliferation reactor monitoring [75]. At Fermilab the ANNIE experiment [71] is being constructed to make first tests of the use of LAPPD^{TM} modules, much as was envisaged for DUSEL.

Acknowledgments

We thank Glen Crawford, Division Director of the Office of High Energy Physics of the DOE for his essential support, Howard Nicholson and Peter Kim for their contributions as involved and knowledgeable DOE program officers. The University of Chicago group is grateful for funding from the Driskill and Grainger Foundations and support for University of Chicago personnel by the National Science Foundation. Robert Fefferman, Dean of the University of Chicago Physical Sciences Division, provided the critical seed money at the start of the project. We are also deeply grateful to Michael Detarando, President of Incom, who provided crucial support and resources.

We thank Alfred Sattelberger (Associate Laboratory Director, Physical Sciences and Engineering Directorate) for a crucial rescue of the ANL Glass Shop, and to Harry Weerts (Director, High Energy Physics Division) and Marcel Demarteau (Detector Group Leader, High Energy Physics Division) for their support during this phase of the project. We thank J. V'avra for his many intellectual contributions to the project in the early stages. We are also grateful to Michael Pellin, who provided essential wisdom and knowledge on material science throughout the project, and Eric Delanges and Stefan Ritt who volunteered their expertise on fast sampling electronics. We thank Dmitri Routkevich for his contributions to the AAO substrate effort at the start of the project. We are grateful to Jeffrey Defazio and Emil Schyns of Photonis for their interest and help, and to our excellent vendors who supported the ceramic and glass packaging efforts. Lastly, we deeply thank the many staff members at our home institutions who made the overall effort possible.

11. Appendix A: The LAPPD Proposal Author List

Figure 36 is the page from the 2009 proposal submission to the DOE Office of High Energy Physics listing authors and institutions. The LAPPD Collaboration was unusual in that it was formed with participants from three complementary kinds of institution, national laboratories, universities, and US companies as equal partners. In addition, the self-generated inception and the strong support from the Office of High Energy Physics of the DOE attracted expertise in many unanticipated scientific or technological areas, talent that might not have become involved in a more conventional collaboration.

Figure 37 is the project summary page from the proposal submission. The three areas singled out for emphasis are: 1) high quantum efficiency photocathode development; 2) coating of the plates by Atomic Layer Deposition to produce high-gain low-noise micro-channel plates; and 3) the development of custom fast low-power waveform sampling integrated circuits coupled to transmission lines for readout of micro-channel-based photomultipliers.

The project summary page from the proposal submission to the DOE in 2009 is also reproduced in Appendix A. The three areas singled out for development are: 1) high quantum efficiency photocathode development; 2) use of Atomic Layer Deposition to apply resistive and emissive surface coatings to the walls of the pores of the large area capillary plates to produce high-gain low-noise electron amplification; and 3) the development of custom fast low-power waveform sampling integrated circuits coupled to transmission lines for readout of micro-channel-based photomultipliers. The technical developments and associated published papers and patents in each of these areas and others addressed during LAPPD are discussed below in Section 5.

12. Appendix B: Development of the LAPPD Proposal

Given the seeming importance of developing large-area fast timing for science and the possible large commercial markets, one can ask why developments in time resolution have lagged the remarkable development of space resolution by silicon detectors. No single technical development has been a major technological break-through; the barrier has been, we believe, funding and the organizational constraints of technological development in the US. We describe below the process by which the LAPPD development occurred; some aspects may prove helpful to future similar large technical developmental projects.

12.1 The Critical Roles of Seed Funding and Fermilab Test Beam Results

Seed funding was essential. The experimental program was started in 2005 with a modest grant from the Physical Science Division at the University of Chicago, followed by a three-year Laboratory Directed Research and Development (LDRD) program at ANL [83], a two-year grant from the joint ANL-Fermilab-Chicago program [84], and two years of travel support from the Chicago-France Center of the University of Chicago for US-France collaboration on the electronics [85]. The seed funding allowed a group from ANL, Chicago, Fermilab, Hawaii, Saclay/IRFU, and the Stanford Linear Accelerator Laboratory (SLAC) to test proof-of-principle in 2008 in a small experiment [86] at the Fermilab MTEST facility [87] using commercial Planacon MCP-PMTs [15] and custom RF anodes [88]. The test confirmed the earlier work of Inami et al [61] that Cherenkov light generated in the front window of an MCP-PMT easily gave time resolutions below 10 psec [61, 86, 89, 90]. The measured timing resolution supported the case that precision time-of-flight measurements could be made over large areas using micro-channel-plate photodetectors with transmission-line readouts and custom psec-resolution digitizing electronics, but would require significant R&D. This conclusion led to the formation of the Collaboration and the development of a proposal to the DOE for a 3-year development program.

12.2 Proposal to the Office of High Energy Physics, Department of Energy

The summer and fall of 2008 were devoted to defining the goals, identifying the tasks and desired groups and individuals to address them, and then on defining and writing a proposal to the Office of High Energy Physics of the Department of Energy.

The Collaboration was self-assembled from three kinds of institutions: National Laboratories, US-based industry, and universities. The list of authors and institutions from the 2009 DOE proposal is given in Appendix A. Because the proposal for large-area fast-timing development was self-generated by the group rather than being a response to a request for proposals from any funding agency, it was based on a ‘bottom-up’ intellectual interest by individual participants in their own areas of expertise.

The effort at the Argonne National Laboratory (ANL) involved six Divisions each with its own expertise and facilities: High Energy Physics, X-ray Sciences, Chemistry, Mathematics and Computer Science, Energy Systems, and Material Science. In addition, the Physical Sciences and Engineering Directorate crucially supported the ANL Glass Shop. Fermilab provided expertise in photomultipliers, bialkali photocathodes, micro-assembly of detectors and test facilities, and a facility for the evaporation of large-area precision metal coatings, as well as test-beam facilities;

SLAC (Stanford Linear Accelerator Center) provided deep expertise in photodetectors, test beam measurements, and timing measurements at the outset.

US industry also played an essential role.

Expertise in ALD-functionalized MCPs was provided by Arradiance [91]. Muons, Inc [92], working closely with the Mathematics and Computer Science Division at ANL, supplied code and expertise in simulation of shower development in MCPs. Synkera Technologies [93] applied their expertise in Anodic Aluminum Oxide (AAO) capillary substrates, working closely with the Material Science Division of ANL.

Researchers from four university groups were authors of the initial proposal. The Space Science Laboratory at UC, Berkeley brought extensive experience in the manufacture of MCP-based detectors, a large UHV-capable facility for tube manufacture and characterization, and expertise in electronics, testing, and end-use. The Enrico Fermi Institute at the University of Chicago provided expertise in front-end electronics and large electronics systems, mechanical design and engineering, detector testing and characterization, computer support for integration and documentation, and, working closely with personnel at the Advanced Photon Source, the capability of testing LAPPD^{TM} photodetectors with psec-time resolution. The University of Hawaii brought extensive experience with Application Specific Integrated Circuit (ASIC), front-end electronics, and large systems design. The group from the University of Washington brought expertise in photodetectors and applications.

The Development of Large-Area Fast Photo-detectors

April 16, 2009

John Anderson, Karen Byrum, Gary Drake, Edward May, Alexander Paramonov, Mayly Sanchez, Robert Stanek, Hendrik Weerts, Matthew Wetstein[1], Zikri Yusof
High Energy Physics Division
Argonne National Laboratory, Argonne, Illinois 60439

Bernhard Adams, Klaus Attenkofer
Advanced Photon Source Division
Argonne National Laboratory, Argonne, Illinois 60439

Zeke Insepov
Mathematics and Computer Sciences Division
Argonne National Laboratory, Argonne, Illinois 60439

Jeffrey Elam, Joseph Libera
Energy Systems Division
Argonne National Laboratory, Argonne, Illinois 60439

Michael Pellin, Igor Veryovkin, Hau Wang, Alexander Zinovev
Materials Science Division
Argonne National Laboratory, Argonne, Illinois 60439

David Beaulieu, Neal Sullivan, Ken Stenton
Arradiance Inc., Sudbury, MA 01776

Mircea Bogdan, Henry Frisch[1], Jean-Francois Genat, Mary Heintz, Richard Northrop, Fukun Tang
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

Erik Ramberg, Anatoly Ronzhin, Greg Sellberg
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

James Kennedy, Kurtis Nishimura, Marc Rosen, Larry Ruckman, Gary Varner
University of Hawaii, 2505 Correa Road, Honolulu, HI, 96822

Robert Abrams, Valentin Ivanov, Thomas Roberts
Muons,Inc 552 N. Batavia Avenue, Batavia, IL 60510

Jerry Va'vra
SLAC National Accelerator Laboratory, Menlo Park, CA 94025

Oswald Siegmund, Anton Tremsin
Space Sciences Laboratory, University of California, Berkeley,CA 94720

Dmitri Routkevitch
Synkera Technologies Inc., Longmont, CO 80501

David Forbush, Tianchi Zhao
Department of Physics, University of Washington, Seattle, WA 98195

[1] Joint appointment Argonne National Laboratory and Enrico Fermi Institute, University of Chicago

1

Figure 36. The original set of LAPPD institutions and authors on the 2009 Proposal to the DOE. The Collaboration was self-assembled from three kinds of institutions: National Laboratories, US-based industry, and universities. Because the proposal was self-generated by the group rather a response to a request for proposals by a funding agency, it was based on the intellectual interest of volunteers across many fields in specific aspects in their own areas of expertise.

The Development of Large-area, Fast, Time-of-Flight Detectors

PROJECT SUMMARY

We propose a program to develop a basic family of economical robust large-area photo-detectors that can be tailored for a wide variety of applications that now use photomultipliers. Advances in materials science and nano-technology, complemented by recent innovations in microelectronics and data processing, give us an opportunity to apply the basic concept of micro-channel plate detectors to the development of large-area economical photo-detectors with quantum efficiencies and gains similar to those of photo-tubes, and with inherent good space and time resolution. The new devices are designed to cover large areas economically, being a sandwich of simple layers rather than an assembly of discrete parts. The plan of R&D that follows is intended to solve the critical technical issues and to deliver proto-types that are ready to be commercialized within 3 years.

The initial use of glass capillary MCP substrates and conventional photo-cathode technology provides a proven solution for each of these components on the critical path. Mechanical assembly and the extension of existing photo-cathode technology to large area planar applications, while formidable tasks, are within the scope of current industrial practice. We have the capabilities and facilities at Argonne, the Space Sciences Laboratory (SSL), and our industrial partners to extend the known technologies.

We have also identified three areas in which new technologies have the potential for transformational developments. First, the development of higher quantum efficiency photo-cathodes based on nano-science morphology with customized work-functions and the adaptation of techniques from the solar-energy sector would allow large area detectors and possibly cheaper assembly techniques. Second, Atomic Layer Deposition (ALD) provides a powerful technique for control of the chemistry and surface characteristics of new photo-cathodes. ALD also can be used to form the secondary emission surfaces of the channels one molecular layer at a time, including controlling the geometry of the electron cascade itself, to enable functionalization of channel-plate substrates with high gain and low noise. This capability allows the separation of the properties of the substrate material from the amplification functionality. We have experience in self-organized nanoporous ceramic (Anodic Aluminum Oxide, AAO) that would provide low-cost batch-produced substrates, and also are investigating substrates made from glass capillaries. Lastly, we have already demonstrated that fast waveform sampling using CMOS ASICs at both ends of transmission line anodes allows the coverage of large areas with small numbers of channels, permitting excellent time and space resolution and a built-in noise identification and reduction mechanism. Design work has started on an ASIC with 2-4 times the number of channels per chip than present chips.

Large-area, robust, and affordable photo-detectors would be transformational in a wide variety of areas. Possible applications include cheaper and more precise Positron Emission Tomography (PET) cameras in medical imaging, scanners for transportation security, and particle detectors in high-energy neutrino and collider physics, astrophysics, and nuclear physics. There would also be many possibilities for new products and spin-off technologies. Because the new devices are planar, relatively thin, and physically robust, they will require less volume and infrastructure in large-area applications for which photomultipliers are presently the current solution, providing additional economies and offering new measurement opportunities.

To meet the challenges we have assembled an experienced cross-disciplinary team that integrates expertise and facilities of national laboratories, universities, and industry, and that includes expertise in both the basic and the applied sciences.

Figure 37. The Project Summary page of the 2009 Proposal to the DOE.

References

[1] The original LAPPD institutions include Argonne National Laboratory (ANL), Arradiance Inc., the University of Chicago, Fermilab, the University of Hawaii, Muons,Inc, Stanford Linear Accelerator Laboratory , Space Sciences Laboratory, University of California, Berkeley , and Synkera Corporation. More detail can be found at http://psec.uchicago.edu/.

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[3] B. Adams, A. Elagin, H. J Frisch, R. Obaid, E. Oberla, A. Vostrikov, R. G. Wagner, M. Wetstein and J. Wang *Timing Characteristics of Large Area Picosecond Photodetectors*; Nucl. Inst. Meth. Phys. Res. A. , Vol. 795, pp 1-11 (Sept. 2015); published online June 5, 2015. Note that for high-gain detectors such as the LAPPD$^{\mathrm{TM}}$, with signals consisting of multiple photons, such as from Cherenkov light, the determining factor is the length of time before the first photoelectron strikes the emissive surface. The photon statistics are consequently binomial and not Gaussian, providing a much faster improvement of time resolution than $1/\sqrt{N}$.

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[6] The LAPPD project received a proposal from a large company with detector experience to commercialize the LAPPD design for the Deep Underground Science and Engineering Laboratory (DUSEL) neutrino detector (See, for example, A. Lankford, *S*tatus of the NRC DUSEL Study, http://science.energy.gov/hep/hepap/meetings/previous-meetings/hepap-agenda-june-2011/. . The proposal was to produce 7000 units per year, upgrading after several years to 21,000 per year. The proposal included a detailed schedule and costing. It was abandoned when DUSEL was canceled.

[7] The Deep Underground Neutrino Experiment (DUNE), based on liquid argon, is the successor to the DUSEL water-Cherenkov proposal. See http://www.dunescience.org/.

[8] The University of Chicago has trademarked the LAPPD 8"-square module, with licensing to Incom Inc., to distinguish it from small-format MCP-PMTs or fundamentally different designs.

[9] The Small Business Innovation Research (SBIR) and Small Business Technology Transfer programs are US government programs to foster the development and transfer of technology. See https://www.sbir.gov/about/about-sttr.

[10] H. J. Frisch, Aspen Winter Conference, Jan. 2003

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[12] H. Nicholson, private communication

[13] Photonis/Burle Industries, 1000 New Holland Ave., Lancaster PA, 17601.

[14] Hamamatsu Photonics K.K. See www.hamamatsu.com/us/en/3008.html.

[15] Photonis, Planacon^{TM}; see the Planacon link at http://www.photonis.com/en/product/.

[16] See the Table on factors that determine timing in *The Role of Analog Bandwidth and S/N in Timing* by S. Ritt in *The Factors that Limit Time Resolution in Photodetectors*; Workshop, University of Chicago, Chicago, IL; 28-29 April 2011; http://psec.uchicago.edu/workshops/. We note that with the resolution-determining factors of signal/noise having values of 1V, a sampling rate of 10 GS/sec, and an analog bandwidth of 3 GHz, the simple parametrization gives a resolution of 100 fsec. Of these, only the bandwidth has not been substantially exceeded, being 1.5 GHz.

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US Patent Number 9,139,905. Issued September 22, 2015. Inventors: Jeffrey W. Elam, Hsien-Hau Wang, Michael J. Pellin, Karen Byrum, Henry J. Frisch

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