Development of large-area Micro-channel Plate Photodetectors

Eric Oberla, for the LAPPD collaboration
10-May 2013
Outline

• Large Area Picosecond Photo-Detector (LAPPD): development of low-cost, large-area micro-channel plate photo-detectors (MCP-PMTs) for fast timing + imaging.

• Glass capillary MCPs: design and functionalization

• The glass package: detector stack-up and anode

• Detector testing: Imaging, gain mapping, and timing

• Integrated electronics: DAQ system and fast waveform recording

The 400 sq. cm `Demountable’ LAPPD MCP detector
Large-Area Picosecond Photo-Detector Collaboration (LAPPD)

• **Goals:** Large-area, relatively low-cost, \(~\)picosecond timing

• **Span of R&D efforts:** photocathode, MCP, integrated electronics, hermetic packaging

• **Baseline glass package design:**
  - 20 x 20 cm\(^2\) area = ‘tile’
  - Gain > 10\(^7\) with two MCP plates
  - RF Transmission line anode
  - Internal HV distribution

Limited sensitivity to magnetic field (..?)
Large-Area Picosecond Photo-Detector Collaboration (LAPPD)
The Super Module

- **0.5m² of photo-sensitive area:** 3x4 array of 20cm LAPPD MCP tiles
- **Thin profile glass packaging**
- **Highly integrated electronics:** 180 channels of fast waveform digitization
  → **input:** high voltage + system clk, etc.; **output:** gigabit Ethernet

System bandwidth
~400 MHz
Physics Motivation:

Rare Kaon Decays- backgd rejection by reconstructing $\pi^0$ vertex space point:

E.g. for KOTO (Yau Wah, JPARC)-beat down combinatoric $\pi^0$ bkgds

Vertex (e.g. $\pi^0 \rightarrow \gamma \gamma$)
$T_v, X_v, Y_v, Z_v$

Detectore Plane
$(T_1, X_1, Y_1)$
$(T_2, X_2, Y_2)$

Reconstruct the vertex from the times and positions: 3D reconstruction

Photon 1
$(t1-tv)c$

Photon 2
$(t2-tv)c$

Applications:
- Picoseconds on large area
- Neutrinos
  - Kaons
- Collider
- Muon cooling
- PET scan
- X-ray
- Neutrons

Goals:
- Large area
- Picosecond timing
- Cheap

10 May 2013 [H Frisch slide]
Physics Motivation:

PET need:
1) much lower dose rate
2) faster through-put
3) real-time feedback. 3D localization TOF

Goals:
- Large area
- Picosecond timing
- Cheap

Applications:
- Picoseconds on large area
- Neutrinos
- Kaons
- Collider
- Muon cooling
- **PET scan**
- X-ray
- Neutrons

10 May 2013
Physics Motivation:

Photon tagging:
- ~mm resolution
- ~100 ps TOF time resolution

Can we build a water Cherenkov **optical TPC**?

Goals:
- Large area
- Picosecond timing
- Cheap

Applications:
- Picoseconds on large area
- **Neutrinos**
  - Kaons
  - Collider
  - Muon cooling
  - PET scan
  - X-ray
  - Neutrons
Physics Motivation:

Goals:
- Large area
- Picosecond timing
- Cheap

Applications:
- Picoseconds on large area
- Neutrinos
- Kaons
- Collider
- Muon cooling
- PET scan
- X-ray
- Neutrons

+ Cosmic/gamma-ray instruments?
MCP fundamentals
MCPs from Glass Micro-Capillary Arrays

Chemically produced and treated Pb-glass does 3-functions:
• Provide pores
• Resistive layer supplies electric field in the pore
• Pb-oxide layer provides secondary electron emission

Separate the three functions:
1. Hard glass substrate provides pores;
2. Tuned Resistive Layer (ALD) provides current for electric field
3. Specific Emitting layer provides SEE (ALD)
4. Scalable and cheap(er)
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MCPs from Glass Micro-Capillary Arrays

~80 million pores

10 May 2013
MCP functionalization by Atomic Layer Deposition (ALD)

Beneq reactor for ALD
@Argonne National Laboratory
A. Mane, J. Elam

A)

B)

Porous glass

Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

Conductive coating (thermal evaporation or sputtering)
MCP functionalization by Atomic Layer Deposition (ALD)

40μm pore borosilicate micro-capillary MCP with 83% open area.

Photo of a 20 μm pore, 65% open area borosilicate micro-capillary ALD MCP (20cm).

Photo of a 10 μm pore, 60% open area borosilicate micro-capillary ALD MCP.

Pore distortions at multifiber boundaries, otherwise very uniform.
The 8” glass package

Top Window

MCPs

Grid spacers

Anode microstrips

The Frugal Tile

Ground Plane

Readout Electronics

The Frugal Tile - Detector Assembly
After final amplification, the electron cloud is accelerated towards the anode, inducing EM waves that propagate in both directions along transmission line.
The 8” glass package: Microstrip Anode

Location of event \((x,y)\) determined by the time difference of signal on two ends \((x)\) and the charge-centroid of adjacent strips \((y)\). Efficient use of electronics channels.

- Position resolution \(\leftrightarrow\) differential time resolution \([\sigma_x = \sigma_t \cdot v_{\text{prop}}]\)
  - \(100\) ps \(\approx 1.5\) cm
  - \(10\) ps \(\approx 1.5\) mm
  ...etc.

33mm MCP position scan: \(V_{\text{prop}} \sim 2/3c\) along stripline \((\sigma_t \sim 15\) ps\).
The 8” glass package: **Microstrip Anode**

Silver strips silk-screened on bottom plate. Constructed by Joe Gregar (ANL)

~2 GHz -3dB analog bandwidth for single 8” tile anode == preserve fast rise time inherent to MCPs!
The 8” glass package: Photocathode

Have made >20% 8” PC at SSL; 25% small PC’s at ANL, 18% 4” (larger underway)

NaKsb

[O. Siegmund, et al]

--- Fundamental photocathode a parallel R&D effort ---
The 8” glass package: HV distribution

High Voltage distribution is embedded in the internal stack-up using ALD grid spacers
Imaging: Background counts

Background, 20cm, 20μm pore ALD-MCP Pairs

- 20μm pore, 60:1 L/d ALD-MCP pair, 0.7mm gap/200v.
- Background very low !! 0.068 cnts sec⁻¹ cm⁻² is a factor of 4 lower than normal glass MCPs.
- This is a consistent observation for all MCPs with this substrate material and relates to the low intrinsic radioactivity of the glass.
- Without lead content the cross section for high energy events is also lower than standard glasses.
- There are issues with hotspots on some substrates, however this can be addressed

20cm MCP pair background, 2000 sec, 0.068 cnts sec⁻¹ cm⁻². 2k x 2k pixel imaging. [O. Siegmund, et al]
Imaging: Gain mapping

Mean gain $\sim 7 \times 10^6$

20 $\mu$m pore, 60:1 L/D ALD MCP pair

XY gain slices:

8" MCP pair average gain map image

[O. Siegmund, et al]
Gain and lifetests

Gain curves of 164-163 ALD MCP (33mm diameter, 20 micron) pair during conditioning

[O. Siegmund, et al]

PHD for 20 micron pore MCP pair. 3000 sec. bkgrnd.

UV ‘burn-in’ of ALD MCP pair 164-163 compared with conventional MCPs
Detector Timing: Advanced Photon Source laser lab @ ANL

Andrey Elagin slide


33mm Testing
- Operational experience
- Testing fundamental properties of MCPs
- Study wide variety of sample prototypes

8” Testing
- Demonstrate working 8” MCPs
- Test near complete detector systems with realistic anode
- Optimize and measure key resolutions

Complete detector systems
- Demonstrate complete sealed-tube detector
- Study characteristics of 80cm anode
- Test integrated front-end electronics in fully operational conditions
MCP pulses and timing extraction

Timing analysis approach:
1) Record full waveform (scope/ASIC)
2) Waveform feature extraction
   • Minimal extraction in firmware (ASIC)
   • Full waveform fits/ noise filtering in software (ASIC/commercial scope)

Differential timing vs. (SNR)^{-1}:

Time resolution determinants:
1) Signal to noise
2) Analog Bandwidth
3) Sampling rate
4) Signal statistics

6 ps <--> 0.6mm
Time-of-flight resolution

8” detector + 10 Gsa/s commercial oscilloscope
~few p.e.’s
Full waveform time extraction (filter+fit) [S. Vostrikov, et al]

ΔT = 27.04 psec
Time-of-flight resolution

Single PE time resolutions at many positions on the 8” MCPs
Consistently better than 80 picoseconds
Full Detector System

- So far, waveforms digitized with 4-channel commercial oscilloscope (10 Gsa/s per channel, 15 GHz analog bandwidth)
- For a full LAPPD MCP tile readout, 60 channels of waveform recording is needed. Some tough specs:
  - Keep up 10 Gsa/s sampling rate
  - Preserve as much bandwidth as possible (matched to microstrip anode and MCP risetime)

The custom PSEC4 waveform digitizer
### The PSEC4 ASIC [0.13 μm CMOS]

<table>
<thead>
<tr>
<th></th>
<th>ACTUAL PERFORMANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling Rate</strong></td>
<td>2.5-15 GSa/s</td>
</tr>
<tr>
<td><strong># Channels</strong></td>
<td>6</td>
</tr>
<tr>
<td><strong>Sampling Depth</strong></td>
<td>256 points (17-100 ns) per channel</td>
</tr>
<tr>
<td><strong>Input Noise</strong></td>
<td>&lt;1 mV RMS</td>
</tr>
<tr>
<td><strong>Analog Bandwidth</strong></td>
<td>1.5 GHz (f_3dB)</td>
</tr>
<tr>
<td><strong>ADC conversion</strong></td>
<td>Up to 12 bit (10.5 ENOB)</td>
</tr>
<tr>
<td></td>
<td>clocked @ 1.6 GHz</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>0.1-1.1 V</td>
</tr>
<tr>
<td><strong>Readout Latency</strong></td>
<td>2 μs (min) – 16 μs (max)</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>20mW/channel</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>~20$/channel in quantity</td>
</tr>
</tbody>
</table>

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![PSEC4 ASIC Image](image)

**Graphs:**
- **Graph 1:** Sampling Rate vs. Voltage Control [V] (Measured vs. Fit to Data Simulated)
- **Graph 2:** Amplitude vs. Frequency [GHz] (500mV pp, 50mV pp)

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**Notes:**
- **Ext. Trig.**
- **USB2.0**
- **Signal Inputs** +5V
The PSEC4 ASIC

10-15 Gsa/s Switched capacitor array sampling: ‘analog down-conversion’

[GHz sampling → 10-100 MHz readout: useful in most ‘triggered event’ applications]
PSEC4 detector-integrated DAQ

Analog Card – 5 PSEC-4 ASICs (30 channels)
-6 Analog Cards per SuMo
-system flexibility allows for integration of alternative front-end ASICs
PSEC4 detector-integrated DAQ

Digital Card
-6 per module
-PSEC-4 control, trigger handling, local data reduction & calibration

Central Card
-System control
-Feature extraction
-CPU/GPU interface (Triple Speed Ethernet & USB 2.0)
Full System Testing: the “Demountable”

Demountable 1.0 (May 2012)  Demountable 3.0 (Sep-Dec 2012)

The Demountable:
A full 90 cm anode with a single 8”x8” active MCP tile. The tile is hermetically sealed with a repeatable compression o-ring. The photocathode is Al.
BeCu RF fingerstock used to make anode-anode/anode-electronics electrical connection
Full System Testing: the “Demountable”

Andrey Elagin slide
Full System Testing: the “Demountable”

Single ~1mm diameter laser spot
Full System Testing: the “Demountable”
Full System Testing: the “Demountable”

Charge centroiding for transverse resolution

Sub-mm transverse resolution

Pulse Height dist. (ADC counts)
Summary and plans

- Complete, (compression) sealed Glass packaged 8” MCP tile:
  - ~50 ps single photoelectron TOF
  - ~5-10 ps differential timing resolution (= 0.5-1mm parallel resolution)
  - ~1 mm transverse resolution
  - Gain and resolutions are uniform across entire 64 sq. inch (400 sq. cm) MCP area

- A full DAQ system with the PSEC4 ASIC is functional and performing well. Such a system will be available to ‘first adopters’.
  - It’s expected that any dedicated users will develop their own electronics for a specific experiment
  - PSEC5 design (10 Gsa/s & ~2+ microsecond buffer depth) in planning stages

- The immediate goal of the LAPPD group is producing a standalone sealed tube (~6 months) – not there yet.
Summary and plans

- LAPPDs and cosmic frontier?
The LAPPD ISS*

* ‘international spacer station’

[Bob Metz, Rich Northrup, et al]

10 May 2013
8” 20µm MCP Pair High Resolution Gain Map

MCP 13600 – 016, 102 MΩ – Top
MCP 13600 - 016, 109 MΩ - Bottom

Image with 12µm pixels
Gain map with 12µm pixels

The repeating four large pore pattern is resolved and shows they have higher gain and higher Brightness, effectively 40µm pores with 30:1 L/D.
What we’ve built

- A fast (sub-ps) pulsed laser with precision UV optics, capable of
  - Precision timing measurements using the laser as an external trigger
  - Finding single-PE mode by attenuating laser to the point where only a small fraction of pulses produce any signal
  - capable of illuminating small spots on the MCP (potentially single pores)

- multi-GHz RF electronics
  - several oscilloscopes with 3–10 Gz analog bandwidth
  - high gain, low noise RF amplifiers
  - high-frequency splitters, filters, etc

- Vacuum systems for testing various detector components

- Capability for testing sealed tubes

- Manpower, expertise, and software
Super Module: features

- Fast (800Mbps per line) SerDes interface
- Ethernet & USB2.0
- 5V system power (13A max)
- Analog->Digital Card connection with 240 pin SAMTEC
- Cyclone IV GX
- Stratix III
Waveform Sampling ASICs

- Already in use in many experiments...

LABRADOR3, ANITA Experiment

SAM, H.E.S.S.-II

DRS4, MEG Experiment

TIPP - 10 June 2011
Waveform samplers ‘on the market’:

<table>
<thead>
<tr>
<th>ASIC</th>
<th>Amplification?</th>
<th># chan</th>
<th>Depth/chan</th>
<th>Sampling [GSa/s]</th>
<th>Vendor</th>
<th>Size [nm]</th>
<th>Ext ADC?</th>
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<td>1-5</td>
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<td>no.</td>
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<tr>
<td>PSEC4</td>
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<td>256</td>
<td>1-16</td>
<td>IBM</td>
<td>130</td>
<td>no.</td>
</tr>
</tbody>
</table>
2) Performance: calibrations

*Oscilloscope on a chip?* Not quite... a modified approximation:

For example, a raw **PSEC-3** readout (10 GS/s) of 120 MHz, 150 mV$_{rms}$ sine wave:
2) Performance: calibrations

Voltage pedestals

ADC non-linearity

Time-base non-linearity

DNL

INL

DLL wrap-around offset
2) Performance: calibrations

Want to minimize number of calibration steps!
Power and timing

![Graph showing PSEC4 Power vs. ADC Clock Freq. (MHz)]

- **0.14 mW/MHz**

![Histogram showing Time Difference (ps)]

- **Fit Parameters:**
  - mean: 200.0 ps
  - sigma: 2.55 ps

<table>
<thead>
<tr>
<th>t_diff</th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
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<tr>
<td>RMS</td>
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</table>
240 MHz sine. Some AC non-linearity observed at peaks