Measurements of the Gain, Time Resolution and Spatial Resolution of a 20x20cm MCP-based Picosecond Photo-Detector

Andrey Elagin
University of Chicago

for the LAPPD Collaboration

Vienna 02/12/2013
Outline

• Motivation
• LAPPD design concept
• LAPPD components
  - Micro-channel plates (MCPs)
  - Electronics
• System integration and testing
• Summary and plans
"A jet is a narrow cone of hadrons and other particles…"

Can we be more specific about jets?
- quark content of charged particles
- 4-vectors

Need: ~1ps

*Photons arrive first, followed by pions, kaons, etc.*
Can we do better vertexing?

- Tie the photons to the correct vertex for precise $H \rightarrow \gamma\gamma$ mass reconstruction
- Associate (often forward) jets with VBF Higgs or WW scattering
Neutrinos

Can we build an optical TPC?

H. Nicholson

Reconstruct tracks from measurement of position and arrival time of the photons
Neutrinos

Toy MC

\[ \pi^0 \rightarrow \gamma \gamma \]

Reconstructed 1.5 GeV Pi0 (geant)

Need: \(~100\) ps
Rare Kaon Decays

for KOTO at JPARC

Vertex (e.g. $\pi^0 \rightarrow \gamma\gamma$)

$T_v, X_v, Y_v, Z_v$

One can reconstruct the vertex from the times and positions-3D reconstruction

Need: ~1ps
Medical Imaging

4-Layer Sampling Calorimeter

Legend
- Red: Photocathode
- Light gray: MCP Channel plates
- Orange: Transmission Lines

Need: ~50ps
Large Area Picosecond Photo Detectors

- Large area
- Fast timing
- Inexpensive
Super Module

- **Thin planar glass body detector**
- **Tiles share single delay line anode**
- **Fully integrated electronics**
Glass Package (20x20cm²)

- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object - designed for fast timing

Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL
LAPPD Components

MicroChannel Plates

Hermetic Packaging

Electronics/Integration

Photocathodes
MCP Fundamentals

Conventional Pb-glass MCP
expensive glass processing

Incom glass substrate
cheap glass
MCP by Atomic Layer Deposition (ALD)

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

Porous glass
Resistive coating ~100nm (ALD)
Emissive coating ~ 20nm (ALD)
Conductive coating (thermal evaporation or sputtering)

8x8'' plate
33mm plate
33mm ALD-MCP Performance

J. McPhate, O. Seigmund
8x8" ALD-MCP Gain Uniformity

Mean gain ~7 x 10^6

8" MCP pair average gain map image

J. McPhate, O. Seigmund
RF Strip Line Anode


A. Axtell, P. Jaynes

- Silk-screened silver on inexpensive glass
- 50 Ω impedance
- 1.6-0.4GHz bandwidth
Scope-on-a-chip

E.Oberla, K.Nishimura, G.Varner

Designed by Eric Oberla (UC grad student)

Real digitized traces from anode

20 GS/scope 4-channels (142K$)

17 GS/PSEC-4 chip 6-channels ($130 ?!)
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
Slope $\sim 10\text{ps/mm}$ corresponds to $\sim 2/3 \text{ c}$ signal propagation speed along the anode stripline

$\Delta T = 15\text{ps}$ \quad $\Delta X = 1/2 \quad \Delta T 2/3c = 1.5\text{mm}$
Differential Time Resolution

\[ \Delta T \rightarrow \Delta X \]

\(~ 6 \text{ ps} \rightarrow ~ 0.6 \text{ mm}\)
Time-of-Flight Resolution

$\sigma = 50.61\ \text{psec}$

8" setup

33mm setup

Al$_2$O$_3$ single plate with amp. 33mm MCP #150. One end readout. Feb 3, 2011

Entries 9945
Mean 5.743e-09
RMS 2.303e-11
Constant 1021
Mean 5.74e-09
Sigma 1.73e-11

17ps
System Integration: "Demountable"

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

First results with 90cm-long anode

38 picosecond differential time resolution

46 picosecond Transit Time Spread

<table>
<thead>
<tr>
<th>htemp</th>
<th>Entries</th>
<th>19998</th>
</tr>
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<tbody>
<tr>
<td>Mean</td>
<td>6.755e-09 ± 2.780e-13</td>
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<tr>
<td>RMS</td>
<td>4.015e-11</td>
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<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>436.1 / 63</td>
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<tr>
<td>Constant</td>
<td>1150 ± 10.6</td>
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<td>Mean</td>
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<td>RMS</td>
<td>4.616e-11</td>
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<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>185 / 29</td>
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<tr>
<td>Constant</td>
<td>1807 ± 15.6</td>
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<tr>
<td>Mean</td>
<td>4.550-11 ± 2.270e-13</td>
<td></td>
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</tbody>
</table>
"Demountable" – Full PSEC4 readout

**TTS, near side**
- 82 psec

**TTS, far side side**
- 73 psec
Position Reconstruction

![Diagram showing position reconstruction results with coordinates and statistical metrics]

- **True position, mm**
- **Reconstructed position, au**
- **RMS at reconstructed position, mm**
- **χ²/ndf**
  - p0: 0.1804 ± 0.0033
  - p1: 0.9996 ± 0.00935

PRELIMINARY
Summary and Plans

- Many applications can benefit from precise timing and large area coverage
- Picosecond timing on large area seems to be within the reach of LAPPD (working in a large parameter space of cost and performance)
- 1 year goal: produce first sealed tube
- 3 years goal: deliver first tile systems to early adopters
- More info on the web:
  - http://psec.uchicago.edu/
  - http://psec.uchicago.edu/blogs/lappd/
Back Up
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.
Can we achieve sub-picoseconds?

### How is timing resolution affected?

\[ \Delta t = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3f_s \cdot f_{3dB}}} \]

<table>
<thead>
<tr>
<th></th>
<th>(U)</th>
<th>(\Delta u)</th>
<th>(f_s)</th>
<th>(f_{3dB})</th>
<th>(\Delta t)</th>
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<tr>
<td><strong>today:</strong></td>
<td>100 mV</td>
<td>1 mV</td>
<td>2 GSPS</td>
<td>300 MHz</td>
<td>~10 ps</td>
</tr>
<tr>
<td><strong>optimized SNR:</strong></td>
<td>1 V</td>
<td>1 mV</td>
<td>2 GSPS</td>
<td>300 MHz</td>
<td>1 ps</td>
</tr>
<tr>
<td><strong>next generation:</strong></td>
<td>100 mV</td>
<td>1 mV</td>
<td>20 GSPS</td>
<td>3 GHz</td>
<td>0.7 ps</td>
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<tr>
<td><strong>next generation</strong></td>
<td>1V</td>
<td>1 mV</td>
<td>10 GSPS</td>
<td>3 GHz</td>
<td>0.1 ps</td>
</tr>
</tbody>
</table>

**How to achieve this?**

- includes detector noise in the frequency region of the rise time
- and aperture jitter

Stefan Ritt slide

UC workshop 4/11
Pulse shape fitting

Figure: Noise filter is OFF.

Pulse shape is fitted with Gaussian between two black lines.
Time resolution: Noise filter effect

Figure: Noise filter is OFF.

Figure: Noise filter is ON.

- Pulses with amplitude between 110 and 130 mV selected.
- Time difference distribution is fitted with Gaussian.
- Time resolution is $\sigma$-parameter of the fit.
Figure: Differential time resolution as a function of pulse amplitude.

Figure: Differential time resolution as a function of inverse pulse amplitude.
MCP pulses and timing

Timing analysis approach
- Fit rising edge
- Use constant fraction discriminant

Questions
- Time resolution
- Position resolution

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

Rise time ~0.5 ns
FWHM ~1 ns
10 mV

NIM A607 (2009) 387
Hermetic Packaging
1) Attach pump out tube to 8.66x8.66" frame

2) Apply schott #G018-223 K3 frit paste to frame

3) Fire the frit (many trials to optimize parameters)

4) Prepare for anode plate frit sealing

5) Position anode on top of the frame

6) Add weight

- Tile bases are reliably reproducible
- Mechanical and vacuum properties have been tested
Top Seal

How to close frit sealed tile base at the top and stay at moderate temperatures? Top Seal problem

Use indium or indium alloys

- soft metal
- low melting point (157°C for pure In)
- essentially zero vapor pressure
- indium-glass seals are successfully used by industry
"Cold Seal"

Hydraulic system

Spring compression

Vacuum Control

Heating Control

Hydraulic Cylinder

Chamber

M.Kupfer, D.Walters,
J.E.Indacochea
"Hot Seal"

Phase I (in air)

Phase IIa (in inert atmosphere)
Nitrogen filled glove box

...indium oxidizes quickly...

Phase IIb (add NiCr-Cu layer)

...indium doesn't stick to glass if no O$_2$...

A.E., R.Obaid, R.Northrop, R.Metz

There is also „Groove Seal“ effort at SSL
Photocathodes

Summary of cathodes grown by Burle Equip

- PMT13, 18: Dosing without O₂
- PMT12: Dosing with O₂
- PMT19: Dosing with O₂ and Thicker Sb layer
Photocathodes at ANL

$K_2CsSb$

R. Wagner, J. Xie, et al. with K. Attenkofer @BNL
Photocathodes at SSL

Na$_2$KSB

J. McPhate, O. Seigmund
Commissioning of Optical Station

- Movable optical station can be shared with different growth facilities in the lab.
- QE measurement by Hamamatsu and ANL optical station agree well with each other indicating the home-built optical station is accurate.
Cathodes exhibit characteristic I-V behavior, with QE as high as 24% at 370 nm.
The quick drop at short wavelength is due to glass absorption.
The Chalice Design

- Design is based on the small PMT tube, the chalice can be seen as a LARGE PMT tube.
- Top glass plate is replaceable for reuse.
- Chalice structure is supported by external legs.
- An X-Y scanner was designed and built for QE scan.
Sb Beads Arrangements for the Chalice (4”X4”)

- Numerical simulation of Sb thickness as a function of Sb beads arrangements and distance from window;
- 4 Sb beads arrangement
- 2.5” distance from the window;

Simulation of relative Sb thickness
Center nail (“lightning rod”) for plasma generation

Center X: Lightning rod, which affect the Sb film deposition
Film transmission with known QE were measured and plotted.
Film transmission increases as wavelength increases without regarding the QE value.
The film transmission values at 400 nm were chosen to plot the relation between KCs-Sb cathode QE and film transmission.
The highest QE is around 78% Sb transmission (400nm beam).
Chalice Photocathode Characterization (7’’)

- Flat cathode with average QE (~16%), the highest QE spot reaches over 22%, and the higher QE is at the corner area, which is the thinner Sb area.
- Sb thickness needs to be further reduced to improve QE.
Imaging 20cm, 20µm pore ALD-MCP Pairs

A number (>25) of 20cm MCP substrates have been functionalized by ALD at ANL, re-electroded at UCB-SSL and put through detailed tests.

Image striping is due to the anode period modulation as the charge cloud sizes are too small for the anode. 20cm, 20µm pore, Al₂O₃ SEY, MCP pair image with 185nm non uniform UV illumination.

Expanded area view showing the multifiber edge effects.

Pulse height distributions for UV and background.
Indium Seal Reliability Tests

Seal strength by shear testing
• Limit for the indium bulk strength is 600-760psi
  - tested on 1x1” parts made of copper
  - indium bonds with copper very well
  - the failure is always in the indium bulk and not in the interface
• Measured strength for the glass parts is up to 400psi
• Measured strength for the Cu coated parts is 500-600psi
• The failure is in the interface in the most cases

Aging tests:
• Sealed parts are heated to 80C and 130C for extended period of time
• Most samples remain leak tight
• Some develop O(10^{-10}) cc/s leaks
# Shear Test Results

credit to Marc and Dean

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<thead>
<tr>
<th></th>
<th>Coating</th>
<th>80 °C 68 Hours</th>
<th>80 °C 172 Hours</th>
<th>130 °C 42 hours</th>
<th>130 °C 213 Hours</th>
<th>Shearing Force (lbs)</th>
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<td><strong>Hot seal</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Leak tight samples:</td>
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<td></td>
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<tr>
<td>Bare glass #1</td>
<td>190 lbs</td>
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<tr>
<td>Bare glass #2</td>
<td>278 lbs</td>
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<tr>
<td>Bare glass with groove</td>
<td>268 lbs</td>
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<td>Cu coated glass #3</td>
<td>390 lbs</td>
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<td>Cu coated glass #4</td>
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<tr>
<td></td>
<td>Silver (52In/48Sn Solder)</td>
<td>Leak (10^{-10})</td>
<td>Leak (10^{-10})</td>
<td>Leak (10^{-10})</td>
<td>Leak Tight</td>
<td>N/A</td>
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<td></td>
<td>Titanium</td>
<td>Leak Tight</td>
<td>Leak Tight</td>
<td>Leak Tight</td>
<td>Leak (10^{-10})</td>
<td>138.24</td>
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<tr>
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<td>Chromium</td>
<td>Leak Tight</td>
<td>Leak Tight</td>
<td>Leak Tight</td>
<td>Leak (10^{-10})</td>
<td>173.73</td>
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<td><strong>Cold seal</strong></td>
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<tr>
<td>Bare Glass</td>
<td>190 lbs</td>
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<td>Cu coated glass #3</td>
<td>213 lbs</td>
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<tr>
<td>Cu coated glass #2</td>
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<td>Nichrome</td>
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<td>Leak Tight</td>
<td>191.76</td>
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<td><strong>Aging Matrix</strong></td>
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</table>

- The strength limit determined from 1x1" all copper parts was 600-700 psi
- When divided by area of ~0.66 inch^2, Cu coated parts fall into 500-600 psi

*The area of the interface is quite different between cold and hot seals*
Parallel Efforts on Specific Applications

Explicit strategy for staying on task-Multiple parallel cooperative efforts

LAPD Detector Development
ANL, Arradiance, Chicago, Fermilab, Hawaii, Muons, Inc, SLAC, SSL/UCB, UIUC, Wash. U
Drawing Not To Scale (!)

PET
(UC/BSD, UCB, Lyon)

Collider
(UC, ANL, Saclay)

Muon Cooling
Muons, Inc
(SBIR)

K-\(\pi\nu\)
JPARC

Neutrinos
(Matt, Mayly, Bob, John, ..; Zelimir)

Mass Spec
Andy Davis, Mike Pellin, Eric Oberla

Non-proliferation
LLNL, ANL, UC

All these need work- naturally tend to lag the reality of the detector development

12/19/2012
LAPPD Pre-production Project

R&D End of LAPPD R&D

SSL process development SSL tube production SSL tube customization

Early Adopters/Field Use

Ceramic tube

Glass tube

First Pre-production

Tech transfer Pre-Production Line

ANL Single Tile Facility

First Production

Design, Ordering Commissioning

Improved MCP’s, Cathodes

Collaborative R&D (SSL, ANL, BNL, UCB, UC, Wash U, Industry)

Organization of Pre-production Project


12/11/2012
## Tasks and Responsibilities:

8” Tile/Tube Fabrication: SSL/ANL/Industry Facility Roles

<table>
<thead>
<tr>
<th>Institution</th>
<th>Mission</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
<td>SSL/UC Berkeley</td>
<td>Process Development</td>
<td>1 Tube/Cycle 4-6 Weeks/Cycle</td>
<td>1 Tube/Cycle 2-4 Weeks/Cycle</td>
<td>Customization</td>
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<tr>
<td>ANL</td>
<td>R&amp;D, Application-Specific Development</td>
<td>1 Tile/Cycle 4 Weeks/Cycle</td>
<td>1 Tile/Cycle 2 Weeks/Cycle</td>
<td>1 Tile/Cycle 2 Weeks/Cycle</td>
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<tr>
<td>Industrial Partner†‡</td>
<td>Pilot Production, Full-Scale Production Commercialization</td>
<td>1 Tile/Cycle 1 Week/Cycle</td>
<td>3 Tiles/Cycle 3-4 day turnaround</td>
<td></td>
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<tr>
<td><strong>Total Available Tiles</strong></td>
<td></td>
<td>1-4</td>
<td>10-20</td>
<td>50</td>
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</table>

Table 1: The roles of the collaborating partners in bringing the glass tile to commercial production.

Notes:
†Assuming the hiring of an experienced sealed-tube facility manager in 2013.
‡Assuming the industrial partner has access to an existing vacuum-transfer system that can be adapted to the LAPPD process.
1. **TOF in the LArIAT Beam**
   a) Why: Simplest set-up that has a large impact on HEP programs
   b) Straight-forward interface to experiment
   c) Local, have collaborators in place;
   d) Drop in for scintillators and PMTs at higher cost and better performance
   e) Spec: 4 stand-alone single tile stations, 10 psec time resolution, 50KHz (needs checking)

2. **Small (1-4 m³) water neutrino detector prototype**
   a) Why: Comparison to simulation; test of the optical TPC concept with track reconstruction
   b) If successful, no competition
   c) From 1 to 6 SuperModules;
   d) Spec: Single pe resolution ~ 100psec, low rate

3. **Pre-converter in KOTO**
   a) Why: Archetype for 3D localization and precise timing of high energy photons
   b) Good access to management and technical expertise in the experiment
   c) If successful, no competition
   d) 1-4 SuperModules
   e) Spec: Timing = 1 psec; Rate = 200 kHz; Position = several mm; Trigger latency = 5 µsec
   f) HEP benefit: Increased physics reach
COST COMPARISONS DEPEND ON CAPABILITY
Correlated time-space points can lower overall cost for applications that don’t need time-space resolution it’s very unlikely MCP-PMTs will ever be as cheap as PMT’s. However:

The dt/A Arisaka plot
Does it breaks when pumped?
No, we have grid spacers
The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.

\[ \Delta t \approx \frac{s_1}{c} + \frac{s_2}{n/c} \]

Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns: \( s_1 \) and \( \alpha \). But there are two constraints:

\[ s_1 + s_2 = d \] and \( \Delta t_{\text{measured}} = \frac{s_1}{c} + \frac{s_2}{n/c} \]
Track Reconstruction Using an “Isochron Transform”

Of course, there is a rotational ambiguity in the position of possible tracks.

But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy.

When integrated over all hits, these regions of dense intersection points form clusters around those tracks that share a common vertex. Here we demonstrate closure on a simple two-track toy with light no scattering or dispersion.
The limits of thinking bigger

The development of new technology could push this frontier forward. New capabilities to drive physics. A compromise between LAr and WC?

It’s not only a matter of the size of the target mass! It’s also a matter of what you use for your target mass.

Water:
- lots of free protons
- sensitivity to low energy $\overline{v}_e$

Liquid Argon

Water Cherenkov

new technology