Large Area Picosecond Photo-Detectors

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University of Birmingham Particle Physics Seminar
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Introduction

Photodetectors have been a staple of particle physics for decades, with the conventional PMT a stalwart ‘workhorse’ of the field.

Photodetection will continue to play a critical role in particle detectors but…

Next-generation experiments have challenges of size & cost.

Advancing photosensor technology is a high-impact means of expanding our physics reach; many efforts on this front (e.g., high-QE PMTs, hybrid photosensors). This talk focuses on one particular effort – LAPPDs.
LAPPD Overview

- Overview of Large Area Picosecond Photo-Detectors:

LAPPDs are:
- 400 cm² sensors (20cm x 20 cm)
- Based on microchannel plate technology (MCPs) [see next slide]
- Excellent resolutions:
  - Spatial: < 1 cm
  - Timing: < 100 ps (TTS)
- Capable of imaging single photons
Microchannel Plate PMTs

Microchannel plates themselves are not new technology
- Example: Used in night vision goggles since 1970s

MCP PMTs are also not new
- Photonis Planacon has been in production for many years
- Limitations:
  - Small (~5cm x 5cm)
  - Expensive (~$10k)

The LAPPD project was formed in 2009 to make this technology practical for particle physics experiments!
MCP-PMT Imaging

For more information, please see:

LAPPDs Development

Areas targeted for improvement included:
• Microchannel plates:
  – Selection of substrates:
    Drawn glass capillaries, etched aluminium considered
  – Development of atomic layer deposition:
    Resistive coatings and secondary-emitting coatings

• Photocathodes:
  – Transfer of techniques for $K_2NaSb$ photocathodes to 20cm square photocathodes on borosilicate glass

• Hermetic packaging:
  – Sealing of large tile not trivial! (see upcoming slide)

• Electronics readout:
  – Development of “PSEC” series of ASIC chips
LAPPDs Milestones

Initial work focussed on advancing separate work packages

• Example: First “working” LAPPD had functional MCP… but needed to be continuously pumped and had a poor photocathode (aluminium)

• Small-scale (6cm x 6cm) prototype tiles were produced at Argonne National Lab to develop photocathode, electronics, etc.

For UK-based tests with the Argonne MCP-PMT, see:

Characterisation and testing of a prototype 6 x 6 cm² Argonne MCP-PMT (G. A. Cowan et al 2016)
Following R&D at US universities and national labs, commercialisation was transferred to a US-based company (Incom) and the design was refined.
LAPPD Commercialisation

Incom production facilities in place by 2015:

1) Wafer Slice GCA
2) Apply Electrode
3) ALD Coat MCP
4) Measure & Test
5) LAPPDtm
6) Tile Integration & Seal
# LAPPD Early Production

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>LAPPD#1</th>
<th>LAPPD#2</th>
<th>LAPPD#3</th>
<th>LAPPD#4</th>
<th>LAPPD#5</th>
<th>LAPPD#6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal date</td>
<td>02/05/2016</td>
<td>02/22/2016</td>
<td>03/10/2015</td>
<td>04/28/2015</td>
<td>05/20/2016</td>
<td>06/08/2016</td>
</tr>
<tr>
<td>Indium Seal</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Failed seal</td>
<td>Failed seal</td>
<td>Excellent</td>
</tr>
<tr>
<td>Vacuum Integrity</td>
<td>Cracked window</td>
<td>Cracked window</td>
<td>Low SH</td>
<td>Low SH</td>
<td>High SH</td>
<td>High SH</td>
</tr>
<tr>
<td>PC QE @190°C, @365 nm</td>
<td>1%</td>
<td>4%</td>
<td>1%</td>
<td>6%</td>
<td>9.4%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Performance under Vacuum</td>
<td>Lost electrical connection to the top of entry MCP</td>
<td>Signal lost upon venting</td>
<td>Signal lost upon venting</td>
<td>Dark pulses detected</td>
<td>Dark pulses detected</td>
<td>Dark pulses detected</td>
</tr>
</tbody>
</table>

Tiles #2-6 (Feb – Aug) lost vacuum

Tiles #2-6 (Feb – Aug) lost vacuum → hermetic sealing!

Tile #1 (Feb) had faulty electrical connection
LAPPD Redesign (2016)

- New, streamlined design has fewer spacer layers:

<table>
<thead>
<tr>
<th>Stack Height - High</th>
<th>Stack Height - Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failed Seal</td>
<td>Cracked Window</td>
</tr>
</tbody>
</table>

LAPPD #2 - 6 multiple layers with bow

LAPPD #7 fewer layers, minimal bow
More LAPPD production

Tile #7 (July 2016): Failed seal (window contamination?)
Tile #8 (Aug 2016): Electrical problems

Tile #9 (Sep 2016): First success!

On 14th September 2016, Incom achieved the first successful fabrication of a functioning LAPPD!

Caveat: Photocathode is aluminium (extremely low QE: $10^{-9}$)

Usual bialkali photocathode (Na K Sb) had been replaced to check whether cathode deposits on the indium were contributing to poor seals.

Tile #10 produced in October 2016 with usual bialkali photocathode; → Second success!

Since then, production has been ongoing; tile count now in triple digits!
(Some) LAPPD properties:
- Transit time spread (TTS) better than 60 picosec for single PE resolutions
- Gain > $10^7$
- Readout via 28 striplines (Gen1) or 64 capacitively coupled “pixels” (Gen2)
Testing at Incom

Tile #15

Quantum Efficiency:

LAPPD15 QE map 04/26/17

LAPPD15 Dark Count Rate vs Time @ 1000V

~1 cts/cm²
QE vs. Wavelength & Time

 QE

300 350 400 450 500 550 600 650
Wavelength [nm]

QE MAX 04/04
QE MIN 04/04
QE AVG 04/04

Average QE [%]

4/2/17 4/8/17 4/14/17 4/20/17 4/26/17 5/2/17
Date [m/d/y]
Tile #15 Performance

Operating voltage:
  • 1000 – 1100 V
  • Positive or negative (usually run with negative HV)

Quantum efficiency:
  • Max = 35% ; Ave = 30% ; Min = 21%

Dark noise:
  • 258 Hz (at 1000 V)

Gain:
  • $2.8 \times 10^6$

Readout speed:
  • 1.8 ns (along the strip)

Saturation:
  • None measured
  • Tested w/ O(10k) photons

Dead space:
  • Along cross spacers
As ‘early adopters’, a number of University groups are working with Incom to assist tasks like tile testing:

These tests performed on Tile #12 at Iowa State University; similar test setups now in place at UK Universities (Sheffield, Edinburgh) → See upcoming slides
LAPPDs in UK

First three LAPPDs arrived in the UK in Autumn 2021:

- **Sheffield:**
  - 2x Gen1 LAPPDs
  - Stripline anode readout
  - LAPPDs #96 & #104
  - Ordered for WATCHMAN

- **Edinburgh:**
  - 1x Gen2 LAPPD
  - Pixel anode readout
  - Ordered for LHCb

Upcoming LAPPDs in the UK include:

- **Glasgow:**
  - 1x Gen2 LAPPD ordered
  - Expected in Spring 2022

Initial testing will involve basic characterisation (similar to tests at US universities), and developing UK expertise.

These include:
- Timing resolution
- Position resolution
- Basic QE
- QE vs. wavelength
- Dark count

More advanced follow-on tests in Sheffield test tank (2000 litres)
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LAPPD 96 housed in custom dark box

- 5 HV connections used
  - Each MCP needs for entry + exit
  - Reminder: 2 MCPs per LAPPD
  - Also apply HV to photocathode
  - Resistor chain added
    (see next slide)

- Readout:
  - Initially used commercial scope
    (Tektronix 6)
  - Now using 32-channel VME
digitiser (5 GS/s) from CAEN
  - Will transition later to PSEC
  - Signals via Incom SMA pickup
Initial Setup

LAPPD Connections in a Dark Box: Ground-Referenced HV Supplies

Resistors value chosen:
- \( R1 = 1 \text{ M}\Omega \)
- \( R3 = 0.5 \text{ M}\Omega \)

09 Mar 2022  Matthew Malek
**Initial Measurements**

**Muon coincidence**

- **Motivation:** dark noise measurements distorted by large signals
  - Set up scintillator paddles to tag coincidences
  - Steady rate of muon events seen, with ~70 ns timing offset between the paddle and LAPPD #104
Initial Measurements

Dark noise rate measurement

- **Motivation:** Understanding dark noise rate critical for incorporating LAPPDs into event reconstruction
  - Tile left in the dark to “cool down” for one hour before testing
  - Photocathode voltage varied to gain broader understanding

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Typical dark pulse

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Dark rate with MCP @ 825 V

- **X:** Sample no.
- **Y:** ADC counts
- Purple: -5 mV

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**Graph:**

- **Dark rate (Hz/cm²)**
- **Photocathode voltage (V)**
- **0 V**
- **250 V**
LED measurements

- **Motivation**: Study timing and position resolution via dual-ended readout of anode striplines
  - Fibre held over centre of channel 1
  - Centre of tile (numbering goes from -14 to +14, w/o a “0”)
  - Coincidence can also be seen with pulser driving light source
Measurements made by stepping LED along the strip (parallel) in 25mm increments:

- -75 mm
- -50 mm
- -25 mm
- 0 mm
- +25 mm
- +50 mm
- +75 mm

Strong position tracking is clearly visible (see next slide)
Initial Measurements

Time Difference vs Position - L104 - V_MCP=825V - V_PC=50V

- Strip 13 (0.5 Ohm)
  - Gradient: 0.0107 ± 0.0011
  - Offset: -0.064 ± 0.060
  - Propagation speed: 0.623 ± 0.064 c

- Strip 8 (60.2 Ohm)
  - Gradient: 0.0111 ± 0.0012
  - Offset: 0.363 ± 0.058
  - Propagation speed: 0.601 ± 0.063 c
“PocketWATCH” is a 2000 litre (2 tonne) test tank facility at Sheffield

Construction from 316 SS is compatible with a variety of materials, including:
- Ultra-pure water,
- Gadolinium-loaded water,
- Liquid scintillator
- Gd-loaded liquid scintillator

25 cm dry region allows for deployment of calibration systems via 5-dimensional gantry system

Water is purified and temperature controlled, settings from 5 – 35 C.
Next Steps

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PocketWATCH Facility

Currently operational for PMT testing; easy to add LAPPDs as well!

This facility allows cross-testings of multiple photosensors, including:

• Using PMTs & LAPPDs in water-based liquid scintillator to do Cherenkov / scintillation measurements with fast timing!
Further Tests

Other, more advanced UK tests being considered include:

• Measuring / comparing magnetic susceptibility (alongside PMTs) by using Helmholtz coils to induce a tunable \( B \) field.

• Joint characterisation with other novel photosensor ideas, such as wavelength shifting plates read out by SiPM strips along the edges:

• R&D to adapt LAPPDs for use with other detectors

  *Example:* Replace glass window with MgF crystal and a CsI photocathode for use in VUV expts, such as LAr or LXe.
Introducing BOLEYN

BOLEYN is a ~25 tonne testbed being built at Boulby Underground Lab

- When construction is completed in 2023, it will allow LAPPD tests in a quiet (low background) environment

- Initial instrumentation includes:
  - 90x 10” PMTs (Hamamatsu R7081)
  - 03x LAPPD (2x Gen1 + 1x Gen2)
  - 01x WLS plate w/ SiPM strip readout
First Use in Expts: ANNIE

ANNIE: Accelerator Neutrino-Nucleus Interaction Experiment

Gd-loaded water

Upstream $\mu$ veto

MRD

PMTs

LAPPDs
The ANNIE Experiment

**Primary physics objective:**
A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.

**Current status:**
- All PMTs installed
- 26 tonne water volume is fully loaded with Gadolinium
- MRD completed
- LAPPDs being prepared
- Commissioning w/ beam data NOW
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Motivation for LAPPDs

ANNIE is a small (3m φ, 4m h) water Cherenkov detector at Fermilab, requiring excellent $V_{\text{res}}$ (~10cm).

First deployment of LAPPDs in ANNIE coming up this year!

V$_{\text{res (PMT only)}}$ = 38 cm  
V$_{\text{res (+5 LAPPD)}}$ = 12 cm
LAPPD Deployment

Initial ANNIE running planned for 5 downstream LAPPDs

As more LAPPDs (and $£) becomes available, can actively deploy elsewhere in detector **without** major interruption in running...
Conclusions

- Improved photodetectors can optimise physics reach
  - e.g., convert water Cherenkov to ‘optical TPC’
- LAPPDs are one such type of new photosensor
  - Superior timing and position resolution
  - Imaging sensors
- **After many years, LAPPDs now exist!**
- In US, first deployment in ANNIE @ Fermilab imminent
- In UK, first LAPPDs have arrived, with more on the way
  - Above ground tests taking place at universities now
  - Underground tests @ BOLEYN planned for next year
- Exciting times ahead!
Thank you for listening!