Development of Gen II LAPPD™ (Large Area Picosecond Photo Detector) Systems for Nuclear Physics

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University of Chicago, Chicago IL, USA
Incom Inc. Corporate Overview
  - LAPPD Pilot Production Update

Motivation for Nuclear Physics Program

Phase II Project Objectives

Gen I All-Glass LAPPD™ Design
  - LAPPD™ Performance

Gen II LAPPD™ Year 1 Summary
  - Close Collaboration w/UChicago
  - New Innovations
  - Challenges

Early Adopters/Programs
  - LAPPD Measurement & Test Workshops
    • Device awareness/Commercialization

Year 2 Plans

Outline

Pair of LAPPDs at Massachusetts General Hospital for Proton Beam Testing
Incom Inc. Corporate Overview
Celebrating 47 Years of New Technology Commercialization

- 1st fiber optic faceplate
- Fiber optic CRT product for photo type setting
- Large area fiber optic tapers for medical & scientific digital imaging
- Glass capillary arrays (GCAs)
- Microchannel Plates (MCPs)
- LAPPDs
- 1970s & 1980s
- 1990s
- 2000s
- 2014-2015
- 2016 – 2017

- Pilot Production
  - Glass tile components (INCOM)
  - Develop pilot process for medium scale LAPPD production

- 1985 - Distortion-free fiber optic night vision using INCOM’s MEGAdraw
- Genomic analysis

2018-08-07
SBIR/STTR DOE NP Exchange Meeting
Diverse Technology Development at Incom

**Technologies**
- Glass - including drawing, fusing, heat treatment & finishing
- Optics
- Polymer - including drawing, fusing, and finishing
- Coatings - Atomic Layer Deposition

**Products**
- Fused Fiber Optic Glass Products
- Polymer Fiber Optic Products
- Hollow Core Glass Capillary Array Products
  - Glass Capillary Arrays (GCAs) for Analytical & biological applications
  - X-Ray Optics
  - Microchannel Plates (MCPs)
- Large Area Photodetectors (LAPPDs)

**Markets**
- Nuclear Physics (Do; (Neutrinoless Double Beta decay, TOF at Colliders)
- High Energy Physics
- Medical Diagnostic / Life Sciences (PET, Proton Therapy, ...)
- Material Science, Light Sources
- Defense & Homeland Security: (Reactor Monitoring, Watchman,...)
- Display, Scientific

**LAPPD Production Overview**
- GCAs - Establish reliable GCA production at INCOM using Gen II Finishing
- MCPs - Resistive & Emissive ALD Coat,
- Tile Detector Kits - Manufacture component parts in the form of a “kit” ready for final integration and sealing step,
- Integration & Sealing - Establish UHV integration and sealing of component parts into a final detector tile,
- Demonstrate - Demonstrate multiple-per-month detector tile fabrication
Motivation

- The world’s first Electron Ion Collider (EIC) has been recommended in the 2015 Long Range Plan for Nuclear Science as the highest priority for a new facility construction in US.

- Precise particle identification (PID) \((e/\pi/K/p)\) over a wide range of momentum is essential for the proposed measurements, low cost large area Multi-Channel Plate (MCP) type detector with fast time (< 10psec) and spatial resolution, high rate capability, radiation tolerance and magnetic field tolerance.

- Incom, Inc., the industrial partner of LAPPD collaboration, has successfully commercialized the PILOT production of LAPPD\(^{TM}\). Optimization of current LAPPD\(^{TM}\) design, extensive characterization to address issues, and industrial mass production are critical to the success of EIC PID.

**Ultimate GOAL:** Achieve mass produced low-cost LAPPD\(^{TM}\) with specifications to fulfill EIC requirements.
Large Area Picosecond Photo Detectors - LAPPDs

- **Fast timing, high gain, single photon imaging**
- **Large Area:** 200 x 200 mm\(^2\)
- **Collider TOF - single digit psec**
- **Timing Resolution measured -**
  - <64\(\mu\)S for Single Photo Electron (SPE)
- **QE:** ~20% w/bi-alkali photocathode
- **Low Cost per Unit Area** (in high volume prod)
- **Sub-mm spatial resolution**

**Applications:** NP, HEP and others
- Nuclear physics applications such as Electron Ion Collider (EIC), Neutrinoless double-beta decay (NuDoT)
- DOE-supported R&D
  - Accelerator Neutrino Neutron Interaction Experiment (ANNIE) and WATCHMAN
  - Deep Underground Neutrino Experiment (DUNE),
- homeland security sensors
- medical imaging: PET scanning, proton therapy beam targeting

References from:
- UChicago (A. Elagin)
- ANNIE (M. Wetstein), WATCHMAN (M. Malek), NuDot (J. Gruszko, L. Winslow)

JINST 9 (2014) P06012
What are the major goals for the Phase II Gen II LAPPD™

• Simplifying the robust ceramic lower tile assembly, including the thin film metallization processes to optimize electrical properties of the inside-out anode design.
  • Capacitive signal coupling to an external PCB anode below the tile
  • High fluence applications enabled by use of pixelated anodes
• Further optimizing window-to-ceramic sealing process for borofloat, fused silica, and other top window materials for detection of light in the visible and UV spectrum.
• Analyzing LAPPD™ pilot production processes to identify and implement measures for reducing cost and maximizing yield and throughput for scale-up to high-volume production.
• Incorporate the designs of the anode, lower tile assembly and top window sealing process, fabricate working Gen-II LAPPD™s for both pad and microstrip applications.
• Designing and fabricating test and measurement stations for the Gen-II LAPPD™ inside-out detector for use in the sealing tank and in the final inspection facility.
• Fabrication of a Gen-II LAPPD™ test station for long duration life testing.

• Subcontract collaboration contributions at the University of Chicago
  • Weekly/daily communication with Professor Henry Frisch’s team (Parallel efforts)
  • Monolithic piece lower tile with wall penetrations
    – for HV contact and In-situ photocathode deposition (air transfer process)
• Ceramic Metallization
• Chemical/Physical Characterization Tools
• External Signal PC-Board Pickup for Pad/Strip/Patterned Readout
• Front-End Electronics and DAQ Systems
Advantages of LAPPD™

Completely different MCP manufacture technology, eliminated the etching and firing processes in old technology, using robust borofloat glass making low-cost, large area MCPs possible.

Glass capillary array (GCA)

Functionalized MCP

Illustration from Ertley, 2016

World largest MCP-PMT: Large Area Picosecond PhotoDetector (LAPPD™)

- **Large-area** (20 cm x 20 cm): world’s only method for such large area MCPs, cheap B33 glass
- **Low-cost (in volume)**: labor cost is the same as making one small MCP-PMT, but area is 16 times larger
- **Comparable performance** compared to commercially available MCP-PMTs
LAPPD<sup>TM</sup> Key performances

Large Area Photocathode production process is established QE > 20% demonstrated in sealed LAPPDs

<table>
<thead>
<tr>
<th>LAPPD S/N</th>
<th>Maximum %</th>
<th>Average %</th>
<th>Minimum %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAPPD #13:</td>
<td>23.5</td>
<td>18.6±3.3</td>
<td>13.5</td>
</tr>
<tr>
<td>LAPPD #15:</td>
<td>25.8</td>
<td>22.3±3.0</td>
<td>15.7</td>
</tr>
<tr>
<td>LAPPD #22:</td>
<td>14.7</td>
<td>10.6</td>
<td>7.0</td>
</tr>
<tr>
<td>LAPPD #25:</td>
<td>10</td>
<td>7.1</td>
<td>5.0</td>
</tr>
<tr>
<td>LAPPD #29:</td>
<td>19.6</td>
<td>13.0±6.0</td>
<td>3</td>
</tr>
<tr>
<td>LAPPD #30:</td>
<td>22.9</td>
<td>17.2±2.5</td>
<td>13</td>
</tr>
<tr>
<td>LAPPD #31:</td>
<td>19.6</td>
<td>16.0±1.9</td>
<td>12.1</td>
</tr>
<tr>
<td>LAPPD #32:</td>
<td>22.7</td>
<td>20.8±1.0</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Uniform QE at 20% average was achieved, but varies from run to run, addressing it now at INCOM

Gain & Timing

Note: Position measurement along and across anode strips show 2.2 mm and 0.95mm spatial uncertainty
Innovation (Incom)in the LAPPD design (Gen II)

• Inside out anode
  – Capacitively coupled signals
  – Both striplines or user defined pixelated pattern
  – Outside of the package - easily changed

• Ruggedized Design Optimized for Capacitive Coupling
  – Rugged materials (toughness, strength)
    • Alumina ≥ fused silica/quartz ≥ Borofloat
    • Eliminate tile failures due to cracked LTA
    • Improved performance in portable field applications
  – Capacitive coupling is improved over B33
    • due to dielectric constant and low loss tangent
    • for temporal and spatial resolution
(UC) The Monolithic Ceramic Tile Base w. Capacitively-Coupled Anode/External Pickup

Sidewall and anode plane are green-trimmed and then ground to spec after full fire- no fritted or brazed large (long) joint

Ceramic tile bases from 4 vendors

10 nm-thick NiCr anode plane (DC ground)
Summary of Gen II Sealing commissioning trials from both Incom and UChicago.

<table>
<thead>
<tr>
<th>Seal Trial date</th>
<th>Side Wall Seal Surface</th>
<th>Window Transfer</th>
<th>PC QE @125-150°C, @365 nm</th>
<th>Anode</th>
<th>MCP Function</th>
<th>Stack Height</th>
<th>Window deflection</th>
<th>Window Seal (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Phase I Incom Nov 2016</td>
<td>Flat</td>
<td>Air</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Low</td>
<td>Yes</td>
<td>Yes, but due to low internal stack height window cracked and vacuum was lost</td>
</tr>
<tr>
<td>2) Incom CLTA #1 Oct 2017</td>
<td>Flat</td>
<td>UHV</td>
<td>6%</td>
<td></td>
<td>N/A</td>
<td>low</td>
<td>Yes</td>
<td>Yes, but due to low internal stack height window cracked and vacuum seal maintained</td>
</tr>
<tr>
<td>3) Incom Tile #24 Nov 2017</td>
<td>Grooved</td>
<td>UHV</td>
<td>20%</td>
<td>Ag strips</td>
<td></td>
<td></td>
<td>No</td>
<td>No, separated</td>
</tr>
<tr>
<td>4) Incom Tile #27 Jan 2018</td>
<td>Grooved</td>
<td>UHV</td>
<td>7%</td>
<td>Ag strips</td>
<td></td>
<td></td>
<td>No</td>
<td>No, separated</td>
</tr>
<tr>
<td>5) UC Tile #17 July 2017</td>
<td>Flat</td>
<td>Air</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Slow leak Unknown</td>
</tr>
<tr>
<td>6) UC Tile #21 Dec 2017</td>
<td>Flat</td>
<td>Air</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Slow leak Unknown</td>
</tr>
<tr>
<td>7) Incom CLTA #2 Mar 2018 8) Incom CLTA #3 Apr 2018</td>
<td>Flat</td>
<td>UHV</td>
<td>6%</td>
<td>metallized inside out ground plane</td>
<td>N/A</td>
<td>low</td>
<td>Yes</td>
<td>Slow leak in one corner</td>
</tr>
<tr>
<td>9) UC Tile #23 Mar 2018</td>
<td>Flat</td>
<td>Air</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Slow leak Unknown</td>
</tr>
<tr>
<td>10-13) UC Tiles 24-27 through July 2018</td>
<td>Flat</td>
<td>Air</td>
<td>N/A</td>
<td>metallized inside out ground plane</td>
<td>Yes</td>
<td>Excellent</td>
<td>Yes</td>
<td>Slow leak Unknown</td>
</tr>
</tbody>
</table>

NOTE: Tile numbering includes all previous glass LAPPD Tiles

- GEN I LAPPD (All Glass Design) window to LTA sealing is well established with routine success > 65%
- Equivalent sealing to a ceramic body has proven to be very challenging. (1/6 Incom, 0/7 UC)
- The underlying cause is not fully established, but results to date point to surface finish of the ceramic, effective thickness, coverage and bonding of thin films. Mechanical tolerances and stack height are key as well.
A thin metal layer anode serves as a DC ground on the inside of the detector. 88% of an MCP fast signal pulse was capacitively coupled through the ceramic, to strips or pads on the outside.


Incom UHV Transfer Process Ceramic LTA w/ Photocathode
DOE-NP Phase II SBIR, Oct 2017

Mean QE=11.6%
$Q_{E_{\text{max}}}$: 16.0%
$Q_{E_{\text{min}}}$: 7.0%

(L) PCB with the pixelated pads
(R) LAPPD with signal-pickup pads facing the tile
UC Air-Transfer Process

1. Window with pre-deposited Sb layer transferred in air
2. Dual vacuum bake-out & seal
3. Alkali vapors to form PC
4. Seal copper tubes

Pulses and photo-response map after complete processing in one of the first system commissioning trials

HV distribution is being upgraded to allow for absolute QE measurements
Surface Finish of Ceramic Sealing Edge (Incom & UC)

<table>
<thead>
<tr>
<th>As rec’d (200 grit diamond tool)</th>
<th>after Incom CNC (600 grit diamond tool)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rp</td>
</tr>
<tr>
<td>Rp</td>
<td>μm</td>
</tr>
<tr>
<td>1.683</td>
<td>66.3</td>
</tr>
<tr>
<td>1.220</td>
<td>48.4</td>
</tr>
<tr>
<td>1.625</td>
<td>54.0</td>
</tr>
<tr>
<td>1.599</td>
<td>63.0</td>
</tr>
</tbody>
</table>

Surface viewed/measured using an Olympus Scope (A. Elagin - UC)

50 μm
Near Term Trials to Address Sealing Issues @ Incom

- Bond alloy to sidewall
  - CTE matched alloy
    - CNC’d to size
  - Adhere to ceramic sealing edge using frit or metallization scheme
  - CNC top surface features analogous to the Gen I geometry for window sealing
- Use fused silica or Quartz LTAs
UC Metallization of Ceramic Sealing Surface

1. Ion-assisted Evaporation (2 vendors) - NiCr, Cu; SSL Gen-I inspired

2. Fired Moly-Manganese (W) – Ni-Au (2 vendors) - 1450°C

ASTM Standards on flatness, coverage, adhesion
## LAPPD™ Early Adopter/Current Programs

<table>
<thead>
<tr>
<th>PRINCIPAL INVESTIGATOR &amp; SPONSOR</th>
<th>PROGRAM TITLE</th>
</tr>
</thead>
</table>
| **Bill Worstell, Incom Inc. Phase II** | TOF Proton Radiography for Proton Therapy  
Fermilab / U Chicago  
Dmitri Denisov/Henry Frisch |  
- Two LAPPD for Fermilab beamline testing by January 2019 |
| **Mayly Sanchez and Matthew Wetstein, Iowa State** | ANNIE - Atmospheric Neutrino Neutron Interaction Experiment  
- ANNIE funding has now been committed  
- LAPPD #25 Delivered February 2018  
- LAPPD #31 - September 2018  
- Three more before November |
| **Andrey Elagin (U of Chicago)** | Neutrino-less Double-Beta Decay |
| **Mickey Chiu (BNL)** | Phenix Project - “eIC Fast TOF” |
| **Erik Brubaker, Sandia National Lab/CA** | Neutron Imaging Camera  
LAPPD #22 Delivered February 2018 |
| **John Learned, U. of Hawaii, and Virginia Tech** | Short Baseline Neutrino (NuLat) |
| **Lindley Winslow (MIT)** | Search for Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors |
| **Bill Worstell, Incom Inc, Bob Wagner & Junqi Xie. ANL, Jefferson Laboratory** | Magnetic Field Tolerant Large Area Picosecond Photon Detectors for Particle Identification |
| **Andrew Brandt, University of Texas, Arlington** | Life Testing of LAPPD |
| **Dr Matthew Malek, The University of Sheffield** | ~10,000 LAPPDs for Hyper-Kamiokande (10 years) |
LAPPD Measurement & Test Workshop

- Familiarize early adopters with the LAPPD, and provide early access.
- Provide researchers with raw data for their own evaluation and use, which might include using the data to evaluate LAPPD readiness for their program applications.
- Workshop Schedule / Dates:

<table>
<thead>
<tr>
<th>Workshop #</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Oct 9-11, 2018</td>
</tr>
<tr>
<td>5</td>
<td>Feb 12-14, 2019</td>
</tr>
<tr>
<td>6</td>
<td>May 14-16, 2019</td>
</tr>
<tr>
<td>7</td>
<td>Sep 10-12, 2019</td>
</tr>
<tr>
<td>8</td>
<td>Feb 11-13, 2020</td>
</tr>
<tr>
<td>9</td>
<td>May 12-14, 2020</td>
</tr>
</tbody>
</table>
Ph II Gen II Summary

- The Gen I LAPPD is proven for:
  - Full size, fully integrated LAPPD are routinely sealing in pilot production with high yield
  - LARGE area MCP with high sustained gain and well-formed Pulse Height Distributions
  - Photocathode process with spatially uniform QE, moderately high QE and time stability
  - Positional accuracy shown to be < 3 x 1mm (0.7 x 0.7 mm with RF strips)

- Capacitive signal coupling to an external PCB anode below the tile is proven
  - Both pixelated and stripline PCBs designed, fabricated and in use
  - Low-Power Multichannel 10-15 GHz Waveform Sampling Electronics Systems designed, fabricated and in use
  - Stations for performance testing inside sealing tank and in the Dark Box Room are working well for both Gen I and Gen II style LAPPDs

- Early Adopters have attended our on-going LAPPD Measurement & Test workshops.

- As Pilot Production processes are optimized the documented SOPs are updated.

- GEN II Sealing of Glass to Ceramic has proven to be more challenging than initially expected, but a focus on the fundamentals provides encouragement that this will be resolved shortly.
Year 2 Challenges and Plans

• **#1 FOCUS:** Continue to optimize the sealing process on the Gen II ceramic LTA to top window

• **Fabricate working detector tiles** while auditing tolerances on starting components and procedures to fine-tune the entire LAPPD fabrication process including photocathode synthesis. Equipment upgrades will be investigated as needed.

• Continuously **update document control** for bill of materials, standard operating procedures and developmental processes. This is a dynamic task and these are living documents that we will be updated constantly through Year 2.

• Finalize development of the testing electronics and measurement protocols for working Gen II LAPPDs

• Continue working with UTexas on **lifetime testing** while setting up Incom’s own life test station

• **Supply Gen-II LAPPD™s** to specific NP, HEP or commercial applications that can be enabled by this technology. Customers may include TJNAL, BNL, Iowa State University (ANNIE), MIT (NuDot) and the beamline at Fermilab.
Current Funding & Personnel Acknowledgements for Incom Funding

• **DOE (NP, HEP, NNSA) Personnel:** Dr. Michelle Shinn, Dr. Manouchehr Farkhondeh, Dr. Elizabeth Bartosz, Dr. Alan L. Stone, Dr. Helmut Marsiske, Carl C. Hebron, Dr. Kenneth R. Marken Jr, Dr. Manny Oliver, Dr. Donald Hornback

• DOE, DE-SC0015267, NP Phase II - “Development of Gen-II LAPPD™ Systems For Nuclear Physics Experiments”

• DOE DE-SC0018445 NP Phase I “Magnetic Field Tolerant Large Area Picosecond Photon Detectors for Particle Identification”

• DOE, DE-SC0011262 Phase IIA - “Further Development of Large-Area Micro-channel Plates for a Broad Range of Commercial Applications”

• DOE DE-SC0017929, Phase II- “High Gain MCP ALD Film” (Alternative SEE Materials)

• NIH 1R43CA213581-01A Phase I - “Time-of-Flight Proton Radiography for Proton Therapy”

• DOE DE-SC0018778 Phase I “ALD-GCA-MCPs with Low Thermal Coefficient of Resistance”

• NASA 2018-I SBIR Proposal: S1.06-1093 Phase 1 “Curved Microchannel Plates and Collimators for Spaceflight Mass Spectrometers”

• **Contact Information:** Michael R. Foley: mrf@incomusa.com
Back up slides
LAPPDTM installed at magnetic field test facility

<table>
<thead>
<tr>
<th>Feature</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodetector Material</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>Window Material</td>
<td>Fused Silica Glass</td>
</tr>
<tr>
<td>Photocathode Material</td>
<td>Multi-Alkali (K2NaSb)</td>
</tr>
<tr>
<td>Spectral Response (nm)</td>
<td>160-850</td>
</tr>
<tr>
<td>Wavelength – Maximum Sensitivity (nm)</td>
<td>≤ 365 nm</td>
</tr>
<tr>
<td>Photodetector Active Area Dimensions</td>
<td>195mm X 195mm</td>
</tr>
<tr>
<td>• Minimum Effective Area</td>
<td>34,989 mm^2</td>
</tr>
<tr>
<td>• Active fraction with Edge Frame X-Spacers</td>
<td>92%</td>
</tr>
<tr>
<td>Anode Data Strip Configuration</td>
<td>28 silver strips, Width = 5.2 mm, gap 1.7 mm, nominal 50 Ω impedance</td>
</tr>
<tr>
<td>Voltage Distribution</td>
<td>5 taps for independent control of voltage to the photocathode and entry and exit of MCP</td>
</tr>
</tbody>
</table>

20 cm LAPPD in dark box
LAPPD Design

Fused silica window with photocathode on inside surface

20 cm x 20 cm MCPs, spacers

Strip line anode and sidewall

Voltage tab at each corner to independently power MCPs

• Signal and high voltage delivered on strips passing under a frit bond.
• No wall or anode penetrations.
• Active area: 195 x 195mm less the x-spacers
  o 34,989 mm², 350 cm²
  o 92% active area

Signal readout, both ends of 28 strip lines

Illustration provided by Univ. of Chicago
Low-Power Multichannel 10-15 GHz Waveform Sampling Electronics Systems

Eric Oberla’s Ph.D thesis; Mircea Bogdan, John Podczerwinski, Horatio Li, Evan Angelico; John Porter of Sandia funded PSEC4A Mosis run; Jonathan Eisch, Miles Lucas,, .. (ANNIE)

We (Porter, Sandia) have the new PSEC4A ASIC

We have a new Central Card- Mircea Bogdan
Now 64 bds (1920 channels)
Now +SFP and VME

Central Card
- Controls 4 front-end boards
- USB 2.0 or gigabit Ethernet PC connection
- Daisy chain or tree configurations to extend system channel count
- Clock fan-out

Front-end PSEC4 Card (“AC/DC Card”)
- 30 channels PSEC4 waveform recording
- At 10GS/s, captures a 25 ns snapshot per waveform
- USB 2.0 standalone readout or 8x LVDS lines communication to Central Card

LVDS system interface
- Up to 800 Mbps data rate per line
- Clock, trigger, configuration
Gain: LAPPD 25

- Pulse height distributions and average gain are shown vs. MCP voltage for single photo electrons
- Gain is as high as $6 \times 10^6$ at 900 V/MCP.

Light source: laser or LED