LAPPD™
Large-Area Picosecond Photo-Detectors

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University of Chicago

Research Techniques Seminar, Fermilab, November 28, 2017
Outline

• Introduction to LAPPD™ and potential applications
• LAPPD™ commercialization status
• R&D towards a batch production process
Large-Area Picosecond Photo-Detector

**Atomic Layer Deposition (ALD)**
- J. Elam and A. Mane at Argonne
  (process is now licensed to Incom Inc.)
- Arradiance Inc. (independently)

**LAPPD™**
- Material: borofloat glass
- Area: 8x8"
- Thickness: 1.2mm
- Pore size: 20 μm
- Open area: 60-74%

**Single PE time resolution <50ps**

Micro-Capillary Arrays by Incom Inc.

Micro-Channel Plates (MCPs)
LAPPD Prototype Testing Results

Single PE resolution

Reconstruction of the laser beam footprint

Demonstrated characteristics:
- single PE timing ~50 ps
- multi PE timing ~35 ps
- differential timing ~5 ps
- position resolution < 1 mm
- gain > 10^7

NIMA 795, (2015) 1
arXiv:1603.01843
See our doc library at:
http://lappddocs.uchicago.edu/
Colliders

• Identify the quark content of charged particles
• Assign tracks and photons to vertices

CDF top quark event

Need 1ps
Vertexing Using Arrival 4D-points

E.g. rare Kaon decays (KOTO at JPARC): background rejection by reconstructing $\pi^0$ vertex space point (beat combinatorics background)

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

Photon 1

$$(t_1-t_v)c$$

Detector Plane

$$(T_1, X_1, Y_1, Z)$$

Need 1ps

Photon 2

$$(t_2-t_v)c$$

$$(T_2, X_2, Y_2, Z)$$
Large Directional Liquid Scintillator

Simulation of a $0\nu\beta\beta$ event
(selected event with large angle between electrons)

- Distinct two-track topology with preference to be "back-to-back"
- Most of electrons are above Cherenkov threshold

PE arrival times, TTS=100 ps

- Fast (arrives early) and directional
  - directionality reconstruction
  - event topology reconstruction (e.g., 2-track vs 1-track)
Optical Time Projection Chamber

- Like a TPC but drifts photons instead of electrons
- Exploits precise location and time for each detected photon
- Would allow track /vertex reconstruction in large liquid counters

Suggestion to use LAPPD’s for DUSEL and the name (OTPC) due to Howard Nicholson

- It doesn’t have to be water (use prompt Cherenkov light that arrives early)
- In fact, for long tracks optical tracking should also work using just scintillation
Eric Oberla’s Optical TPC

- Water
- Flat mirrors
- Direct Cherenkov light (yellow)
- Reflected Cherenkov light (green)
- 1 foot/1000 psec muon
- 780 psec later

Photonis MCPs and Chicago striplines/PSEC4
Beam’s Eye View of the OTPC

Water

Flat mirrors

24 cm

Stereo view mirror mount

5 cm

Beam-tagging MCP-PMT

Normal view mirror mount

5 cm

Stereo view

Normal view

Photonis MCPs and Chicago striplines/PSEC4

Reflected Cherenkov light arrives 780 psec later depending on position and angle

Eric Oberla’s Ph.D thesis
OTPC at Fermilab Test Beam

Eric Oberla's Ph.D thesis

Five Photonis Planacons
LAPPD Electronics at Chicago

Delay-line anode
- 1.6 GHz bandwidth
- number of channels scales linearly with area

PSEC-4 ASIC chip
- 6-channel, 1.5 GHz, 10-15 GS/s

NIM 711 (2013) 124

NIM 735 (2014) 452

30-Channel ACDC Card (5 PSEC-4)

Central Card (4-ACDC;120ch)
Multichannel Systems

- 60-channel LAPPD prototype at the ANL Laser Lab
- 180-channel self-triggered Optical TPC at Fermilab
- Central card controls several front end boards
- New central cards by Mircea Bogdan handles 1920 channels
- PSEC4A is back from Mosis (funded by Sandia, work by E.Oberla)
What is ANNIE?
The Accelerator Neutrino Neutron Interaction Experiment

- A measurement of the abundance of final state neutrons from neutrino interactions to aid in understanding neutrino-nucleus interactions.

- An R&D effort to further water-based neutrino detection technology.

Slide courtesy of M. Wetstein
ANNIE R&D

- Demonstration of LAPPDs in a neutrino experiment
- Application of fast, waveform sampling (PSEC) electronics
- First use of Gd on a neutrino beam

- A test bed for other novel photosensors
- Possible later addition of water-based liquid scintillator
ANNIE Completed Phase I

Slide courtesy of M.Wetstein
Incom LAPPD “Preliminary” Results & Timeline

• DOE Pilot Production Facility Funding - April 2014
• Incom Pilot Production Facility - November 2015
• LAPPD Commissioning Trials Initiated - December 2015

#1 -> #8 - Dec. 2015 to Aug. 2016, Seal & Connectivity Trials
#9 - 9/14/2016, First Sealed Tile - Aluminum Photocathode
#12 - 12/21/2016, QE (365nm Max/Avg/Min) = 16.5% /11.1% /6.7%
#15 - 03/31/2017, QE 365nm (Max/Avg/Min) = 35.1% /30.3% /21.6%
#22 - 10/10/2017, QE 365nm (Max/Avg) = 14.7% / 12.6%, High Gain MCPs, Peaked SPE PHD

• Exploitation Phase Begins - QI 2018
  Operate Pilot Production on a routine basis
  Produce prototypes for early adopters

Slide courtesy of M. Minot at Incom Inc.
With X-Spacers Excluded:
Mean QE=12.58, $\text{QE}_{\text{max}}$: 14.74%
Standard Deviation ($\sigma$): 1.18 or 9.4% of mean

Slide courtesy of M. Minot at Incom Inc.
LAPPD #22 Dark Count Rate - PC On (-50V)

Dark Count Rate [Hz/cm²]

@70mV threshold

MCP Voltage [V]

Preliminary

Slide courtesy of M. Minot at Incom Inc.
LAPPD #22 - PHDs for Single Photoelectrons

Data collected with 3dB attenuation at the Amptek amplifier input
Insert: Single photoelectron at 950 V/MCP, 0dB

Slide courtesy of M. Minot at Incom Inc.
See file “Onlinemetadata_20171110_Spellman with plots.xlsx”

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<th>Filename</th>
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Slide courtesy of M. Minot at Incom Inc.
A ~1mm diameter 405 nm 60 pS laser spot was moved laterally along an anode strip:

- Laser spot position is derived by measuring the time of arrival of the MCP pulse at each end of the strip and knowing the time a pulse takes to propagate across the entire strip.
- Linearity deviations occur at the ends, and at the transit across the X-spacer, where dark pulses are included in the measurement.

See “OnlineMetadata_2017_1114_Spellman v1.xlsx”
Innovators & Early Adopters

- Collaborators with an expressed willingness to evaluate early LAPPD prototypes, sharing round-robin test results and technical performance feedback.
  - Opinion leaders able to influence the adoption of LAPPD for established or future technical programs.
  - Ability to evaluate prototype performance under practical conditions or facilities not available to Incom Inc. Examples: magnetic fields, neutron beam, Cherenkov light, Fermi Lab Particle Beams, Neutrino-less Double-Beta Decay, life testing, etc.

- Incom is committed to working with early adopters to insure that LAPPD are available to be evaluated for appropriate applications.
  - Measurement & Test Workshop to facilitate hands on experience with LAPPD, and establish standardized M&T procedures.
  - Short term loan & leasing agreements
  - Purchase with discounts to Early Adopters with DOE funded programs.

Slide courtesy of M. Minot at Incom Inc.
<table>
<thead>
<tr>
<th>Principal Investigator &amp; Sponsor</th>
<th>Program Title</th>
</tr>
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<tr>
<td>Bill Worstell, Incom Inc.</td>
<td>TOF Proton Radiography for Proton Therapy</td>
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<tr>
<td>Henry Frisch (U of Chicago)</td>
<td>LaRiaT (Liquid Argon Beam-line Experiment, Fermi Lab)</td>
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<td>Sub-psec TOF for collider vertex and particle ID</td>
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<td>Track reconstruction in a small water Cherenkov counter</td>
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<td>Double-beta decay development</td>
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<td>Mayly Sanchez, Matthew Wetstein, Iowa State</td>
<td>ANNIE - Atmospheric Neutrino Neutron Interaction Experiment</td>
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<tr>
<td>Mickey Chiu (BNL)</td>
<td>Phenix Project - “eIC Fast TOF”</td>
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<td>Erik Brubaker, Sandia National Lab/CA</td>
<td>Neutron Imaging Camera</td>
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<tr>
<td>John Learned, U. of Hawaii, and Virginia Tech</td>
<td>Short Baseline Neutrino (NuLat)</td>
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<tr>
<td>Lindley Winslow (MIT)</td>
<td>Search for Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors</td>
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<tr>
<td>Andrey Elagin (U of Chicago)</td>
<td>Neutrino-less Double-Beta Decay</td>
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<td>Bill Worstell, Incom Inc, Bob Wagner &amp; Junqi Xie. ANL, Jefferson Laboratory</td>
<td>Magnetic Field Tolerant Large Area Picosecond Photon Detectors for Particle Identification</td>
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<td>Andrew Brandt, University of Texas, Arlington</td>
<td>Life Testing of LAPPD</td>
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<tr>
<td>Dr Matthew Malek, The University of Sheffield</td>
<td>Hyper-Kamiokande Upgrade (~10,000 LAPPD in 10 years)</td>
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Slide courtesy of M. Minot at Incom Inc.
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.

• Establish standardized measurement protocols.

• Evaluate alternative electronic readout options; examples include PSI DRS4 Evaluation Boards, Ultralytics LAPPD Readout Card, PSEC4 Eval boards, CAEN DRS4 Readout, other.

• First Ever Workshop - November 13-16, 2017
  – Kurtis Nishimura (U of Hawaii, working with John Learned, and Erik Brubaker, Sandia)
  – Josh Brown (Berkeley, working with Erik Brubaker, Sandia)
  – Julieta Gruszko (MIT, working with Lindley Winslow)

• Data Collected - Analysis underway, results expected in early December
  – Pulse height vs. laser trigger rate at fixed MCP voltages
  – Scans along and across strips for position and crosstalk assessment
  – Photocathode scans with 42 volts and 10 volts between the photocathode and MCP
  – 160,000 single photoelectron waveforms using DRS4 evaluation boards

• Next Workshop – January 22 – 26, 2018 Spaces Available

Slide courtesy of M. Minot at Incom Inc.
For more information

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Slide courtesy of M. Minot at Incom Inc.
Goal of the R&D Effort at UChicago

Affordable large-area many-pixel photo-detector systems with picosecond time resolution

LAPPD module 20x20 cm²

Example of a Super Module

We are exploring if an In-Situ process (without vacuum transfer) can be inexpensive and easier to scale for a very high volume production.

Production rate of 50 LAPPDs/week would cover 100m² in one year.

UChicago goal is to develop alternative high volume, scalable, low cost processing options (in close collaboration with Incom Inc.)
Can We Make LAPPDs in Batches Like PMTs?
In-Situ Assembly Strategy

Make photo-cathode after the top seal
(PMT-like batch production)

Step 1: pre-deposit Sb on the top window prior to assembly
Step 2: pre-assemble MCP stack in the tile-base
Step 3: do top seal and bake in the same heat cycle
    using dual vacuum system
    can vent the outer vacuum and access the detector
    prior to PC synthesis
Step 4: bring alkali vapors inside the tile to make photo-cathode
Step 5: flame seal the glass tube or pinch the copper tube
Indium Solder Flat Seal Recipe

Input:
- Two glass parts with flat contact surfaces (also trying to seal ceramic + fused silica)

Process:
- Coat 200 nm of NiCr and 200 nm of Cu on each contact surface (no vacuum break in between NiCr and Cu depositions)
- Make a sandwich with 99.995% pure indium wire (etch the In wire 5% HCl just before assembly)
- Bake in vacuum at 250-300°C for 24hrs (go significantly above melting – known as “superheat” in soldering industry)
- A good compression over the entire perimeter is needed to compensate for non-flatness and to ensure a good contact (no seal without a press on the edges!)

Metallization pattern is based on SSL seal by O. Siegmund et. al.
Here is what we know about the seal:

(XPS with depth profile was used to characterize the seal)

- NiCr layer will provide tie layer
- Cu provides protection against oxide on NiCr
- Indium wire gets squished—oxide broken (this principle is also used in cold seal by D. Walters at ANL)
- Cu diffuses into bulk Indium
- Ni and Cr diffuse into bulk Indium
- Indium bonds to the glass (presumably through a very thin layer of Cr—this is on the edge of sensitivity)

Many thanks to R. Jarrett at Indium Corp. for expert advice on indium metallurgy
Heat Cycle
In-Situ LAPPD Fabrication

Heat only the tile not the vacuum vessel

Intended for parallelization
In-Situ Assembly Facility UChicago

The idea is to achieve volume production by operating many small-size vacuum processing chambers at the same time or/and make several tiles in bigger chambers.

Looking forward towards transferring the in-situ process to industry.
First Sealed In-Situ Glass LAPPD

August 18, 2016

(Cs-Sb photo-cathode)

Flame seal by J.Gregar, Argonne
Ceramic Gen-II LAPPD

January, 2017

Tab for single HV connection

Indium seal perimeter

Resistive buttons (internal resistors)
Internal HV Divider

Diagram showing the internal high voltage (HV) divider setup with components such as Top Window Photocathode, MCP 1, MCP 2, Microstrip Anode, signal ground plane, and readout connections for far and near ends.
Gen-II LAPPD

- Robust ceramic body
- Anode is not a part of the sealed detector package
- Enables fabrication of a generic tile for different applications
- Compatible with in-situ and vacuum transfer assembly processes

Monolithic ceramic body

10 nm NiCr ground layer inside is capacitively coupled to an outside 50 Ohm RF anode

NiCr-Cu electroding for the top seal

Ground pins

Two tubulation ports for the in-situ PC synthesis (improved gas flow)

Joint effort with Incom Inc. via DOE SBIR
Gen-II LAPPD: “inside-out” anode

- Custom anode is outside
- Capacitively coupled
- Compatible with high rate applications

For details see NIMA 846 (2016) 75
In-Situ LAPPD: work in progress

LAPPD batch production milestones:

• Developed a robust metallurgy scheme for hermetic packaging
• Demonstrated Cs transport from a source outside of the detector package to the entire 20x20 cm² window surface in the presence of full size MCPs (we did make Cs-Sb photo-cathode)
• Showed that MCP initial resistance can be recovered after Cs-ation (MCPs are NOT permanently damaged or changed)
• Confirmed that capacitively coupled readout works well
List of problems discovered so far:

• MCP plates go to lower resistance (recoverable in air)
• We had exposed Cu on the window- Indium wets it. Cs interacts with Indium to forms a flakes/powder inside the entire volume.
• Resistive buttons interact with Cs (now use new buttons)
• Measuring QE is made more difficult by our internal HV divider (can’t get current across the PC-MCP gap directly).
Cs-In-(X?) Flakes/Powder Story

Ongoing investigation

Figure 4: A spectrum from a dust fleck shown in the SEM picture above. The peaks indicate the existence of indium and Cs, and not their quantitative relative composition.

Figure 5: This spectrum is taken from the layer on the window that had turned black and flaky. The spectrum looks almost identical to that of the dust flecks.

We are getting new windows with improved metallization to avoid/limit In “seen” by Cs
Sb Story

We start with 10nm of Sb on the window - this layer could be sitting in air for months before assembly.

Photo-cathode experts were/are worried...
Sb oxidation is the main concern.

Things to consider:
• We bake the whole detector including window at 300C for 16hrs and we do see reduction in the original Sb layer thickness (are we getting rid of oxide by long heating?)
• Eventually we have to characterize the Sb layer after the bake (may have to adjust original thickness or heat cycle)
• We have done XPS studies of the Sb layer as received from vendor (air exposed for 3 months)
Can we make PC after Sb was exposed to air?
Sb XPS Studies

Sb test coupon: fused silica microscope sliced with 200nm of NiCr + 200nm of Cu + 10nm of Sb

UChicago XPS details
(XPS expert support by Alexander Filatov at UChicago)

X-ray gun:
- 10 mA at 15 kV
- high resolution mode step size 0.1 eV
- area of the analyzed spot 300x700 mum

Ar ion beam (for depth profiling):
- beam size 6x6 mm
- beam energy 2 kV
- beam density 7.78 A/cm²

Depth profiling was performed using 5 sec etches by the Ar ion beam. We estimated that a 5 sec etch removes on average 0.25 nm of the surface material.

Side note on thin film coatings
- Good quality films are expert’s territory
- Sb deposition in particular:
  - H.L. Clausing Inc.,
  - Bing Shi at the Argonne Thin Film Deposition Lab
- NiCr-Cu isn’t easy, but we have one more commercial vendor for that
Sb XPS Studies

XPS scan before any ion etching

Oxidized Sb

Sb metal

Intensity(cps)

Binding Energy (eV)

Sb 3d no etch: 2(ETCH_6mm_2)
XPS Spectrum Lens Mode: FOV 1: Survey Res: 5 Iris (Aper): slot (SPECTRUM SLIT)
Sb XPS Studies

Intermediate scans within first 35 seconds of etching

Signal of oxidized Sb going down
Sb metal is growing
Sb XPS Studies

After 40 seconds we see pure Sb metal (preferential sputtering of oxygen is not completely excluded, but it would have to be very strong).

No Sb metal is seen after 200s
Assuming initial 10nm Sb thickness the average etch rate is 0.5A/sec
Therefore Sb-oxide thickness is \(\sim 40 \text{sec} \times 0.5\text{A/sec} = 2\text{nm}\)
What’s Next?

We've just got a new lab

We've got 2nd processing chamber (parallelization!)

We are getting lots of components
In-Situ Tile #21

Assembled, sealed, and baked. Now preparing for the “In-Situ” photocathode shot.
Summary

• Lots of fast timing applications including Fermilab experiments
• Large-Area Picosecond Photo-Detectors are being commercialized by Incom Inc.
  • Incom is transitioning from commissioning to exploitation
  • Let them know about your application and become an early adopter of LAPPD
• Chicago group is exploring if an In-Situ, PMT-like, process can be used to manufacture LAPPDs without vacuum transfer of the window
  • We consider this as a high risk R&D where success is not guaranteed but the pay-off is attractive enough to try
  • So far we don’t see obvious show-stoppers
  • Lots of technical challenges
• We would like to build a stronger Fermilab-Chicago connection
Acknowledgements

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plus Eric Oberla and Mircea Bogdan on electronics
plus 12 high school and undergrad students last summer

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• DOE, DE-SC0011262 Phase IIA - "Further Development of Large-Area Micro-channel Plates for a Broad Range of Commercial Applications"
• DOE, DE-SC0015267, Development of Gen-II LAPPDTM Systems For Nuclear Physics Experiments
• DOE DE-SC0017929, Phase I - "High Gain MCP ALD Film" (Alternative SEE Materials)
• NIH 1R43CA213581-01A Phase I - Time-of-Flight Proton Radiography for Proton Therapy
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Back-up
ABSTRACT

A first experimental test of tracking relativistic charged particles by ‘drifting’ Cherenkov photons in a water-based optical time-projection chamber (OTPC) has been performed at the Fermilab Test Beam Facility. The prototype OTPC detector consists of a 77 cm long, 28 cm diameter, 40 kg cylindrical water mass instrumented with a combination of commercial $5.1 \times 5.1 \text{ cm}^2$ micro-channel plate photomultipliers (MCP-PMT) and $6.7 \times 6.7 \text{ cm}^2$ mirrors. Five MCP-PMTs are installed in two columns along the OTPC cylinder in a small-angle stereo configuration. A mirror is mounted opposite each MCP-PMT on the inner surface of the detector cylinder, effectively increasing the photo-detection efficiency and providing a time-resolved image of the Cherenkov light on the opposing wall. Each MCP-PMT is coupled to an anode readout consisting of thirty 50 $\Omega$ microstrips. A 180-channel data acquisition system digitizes the MCP-PMT signals on one end of the microstrips using the PSEC4 waveform sampling-and-digitizing chip operating at a sampling rate of 10.24 Gigasamples-per-second. The single-ended microstrip readout determines the time and position of a photon arrival at the face of the MCP-PMT by recording both the direct signal and the pulse reflected from the unterminated far end of the strip. The detector was installed on the Fermilab MCenter secondary beam-line behind a steel absorber where the primary flux is multi-GeV muons. Approximately 80 Cherenkov photons are detected for a through-going muon track in a total event duration of $\sim 2 \text{ ns}$. By measuring the time-of-arrival and the position of individual photons at the surface of the detector to $\leq 100 \text{ ps}$ and a few mm, respectively, we have measured a spatial resolution of $\sim 15 \text{ mm}$ for each MCP-PMT track segment, and, from linear fits over the entire track length of $\sim 40 \text{ cm}$, an angular resolution on the track direction of $\sim 60 \text{ mrad}$. 
Fast Timing Pre-requisites

1) Fast source (e.g. prompt Cherenkov light)
2) Psec-level pixel size (e.g. MCP pores)
3) High gain (e.g. MgO ALD MCPs give >10^7)
4) Low noise

Schematic of an MCP-based Photo-Detector
Getting to 100 fs won’t be that easy but it’s a nice goal to have.
PHDs measurement scheme

Setup

- Laser 405nm 55pS
- Neutral Density Filter
- Anode Strips
- Laser trigger
- Gate generator
- MCA
- PC

Raw Pulse
Gate Pulse
Amplified Pulse

Femilab Detector Seminar - Andrey Elagin for Incom Inc.
Slide courtesy of M. Minot at Incom Inc.
Sb XPS Studies

Between 45 seconds and 80 seconds we see pure Sb metal (preferential sputtering of oxygen is not completely excluded, but it has to be very strong)

black - 45 sec
blue - 70 sec
red - 80 sec

Peak at 530.4 eV belongs to Auger signals of a Cu metal underlayer
Sb XPS Studies

Continue ion etch: Sb metal goes down, Auger Cu goes up

No Sb metal is seen after 200s
Assuming initial 10nm Sb thickness the average etch rate is 0.5Å/sec
Sb XPS Studies

Assigning the ~530eV and 540eV peaks to Auger Cu
Sb XPS Studies

Assigning the \(~530\text{eV}\) and \(540\text{eV}\) peaks to Auger Cu

![Graph showing the binding energy spectrum with peaks at ~530eV and 540eV.](graph.png)
PSEC4 ASIC

NIMA 735, (2014) 452-461

- Fabricated using IBM-8RF 130nm CMOS process
- Each of 6 channels is a switch capacitor array
  - 256 samples deep
  - on-chip ADC
  - sampled of 10's MHz clock using VCDL
- 10Gs/s, 1.5GHz
- Controlled by FPGA

Evaluation board

PSEC4 die
Present (now old) Time Resolution

Single Photo-electron
PSEC4 Waveform sampling
Sigma=44 psec

Differential Time Resolution
Large signal Limit
Oscilloscope Readout
Black line is $y=3.1x+0.5$ (ps)
Red line is $y=2.8x +1.5$ (ps)
Where the constant term represents the large S/N limit (0.5-1.5 ps)

Highly non-optimized system (!)- could do much better
Timing res. agrees with MC

< 6 psec

Time resolution on 2 ends of 8\textquotedbl–anode strip vs. (S/N)^{-1} in psec (pair of 8\textquotedbl MCP’s)

M. Wetstein, B. Adams, A. Elagin, R. Obaid, A. Vostrikov, ...
The PSEC4 custom integrated circuit was designed for the recording of fast waveforms for use in large-area time-of-flight detector systems. The ASIC has been fabricated using the IBM-8RF 0.13 μm CMOS process. On each of the six analog channels, PSEC4 employs a switched capacitor array (SCA) of 256 samples deep, a ramp-compare ADC with 10.5 bits of DC dynamic range, and a serial data readout with the capability of region-of-interest windowing to reduce dead time. The sampling rate can be adjusted between 4 and 15 Gigasamples/second (GSa/s) on all channels and is servo-controlled on-chip with a low-jitter delay-locked loop (DLL). The input signals are passively coupled on-chip with a −3 dB analog bandwidth of 1.5 GHz. The power consumption in quiescent sampling mode is less than 50 mW/chip; at a sustained trigger and a readout rate of 50 kHz the chip draws 100 mW. After fixed-pattern pedestal subtraction, the uncorrected integral non-linearity is 0.15% over a 750 mV dynamic range. With a linearity correction, a full 1 V signal voltage range is available. The sampling timebase has a fixed-pattern non-linearity with an RMS of 13%, which can be corrected for precision waveform feature extraction and timing.
First Signals from an In-Situ LAPPD

(Sb cathode)

Near side: reflection from unterminated far end

Far side: reflection is superimposed on prompt source

Readout (50-Ohm transmission line)

The tile is accessible for QC before photo-cathode shot

This is helpful for the production yield

April, 2016
Metallurgy of the Seal

Moderate temperatures and short exposure time:
- A thin layer of copper quickly dissolves in molten indium
- Indium diffuses into the NiCr layer

Depth profile XPS

Low melting InBi alloy allows to explore temperatures below melting of pure In (157°C)

Glass with NiCr-Cu metallization exposed to InBi at ~100°C for <1hrs (it seals at these conditions)

InBi was scraped when still above melting (72°C)

The ion etch number is a measure for the depth of each XPS run

Layer depth (uncalibrated)

XPS access courtesy of J. Kurley and A. Filatov at UChicago
Metallurgy of a Good Seal

Higher temperatures and longer exposure time
• Indium penetrates through entire NiCr layer

XPS of the glass side of the interface

Glass with NiCr-Cu metallization bonded by **pure In** at ~350°C for 24hrs (it seals at these conditions)

Cut and scrape at the metal-glass interface

We now reliably seal at 250-300°C for 12-24hrs

XPS data courtesy of A. Filatov at UChicago
Indium seal recipes exist for a long time

Why do we need another indium seal recipe?

PLANACON™
(MCP-PMT by Photonis)

Make larger photo-detectors
Our recipe scales well to large perimeter

Simplify the assembly process
Our recipe is compatible with PMT-like batch production
Does the time resolution go as $1/N$ or $1/\sqrt{N}$ photo-electrons?

**Hypothesis:**

- In an MCP-PMT the time jitter is dominated by the 1\textsuperscript{st} strike: path length to the 1\textsuperscript{st} strike varies
- Smaller pores, increased bias angle are better
- “IF gain is such that a single photon shower makes the pulse (e.g. $10^7$), time jitter is set by the probability that NO photon has arrived in interval $\delta t$” - H. Frisch

This assumes that one fits the waveform to determine pulse $T_0$

E.g. if 50 photoelectrons (from Cherenkov light in a window) arrive within 50 psec, the probability that one goes for $T$ psec with NO photon making a first strike goes as $e^{-T}$

$\Rightarrow$ a $1/N$ dependence
Low-Dose Whole-Body PET Camera

Chin-Tu Chen, Henry Frisch, Chien-Min Kao, and Heejong Kim

4-Layer Sampling Calorimeter

Transmission Line  Anode  MPC

Legend

- Red: Photocathode
- Light Gray: MCP Channel plates
- Brown: Transmission Lines

Need: ~50ps
Low-Dose Whole-Body PET Camera

Simulation and reconstruction work by Carla Grosso-Pilcher

Event 2, $E_{\text{dep}1}=359.511$, $E_{\text{dep}2}=352.787$ (eV)

Photo-detector planes

Water-based liquid scintillator