Large-area MCP-based Photo-detectors, Ultra-fast timing, and sub-mm Spatial Resolution (LAPPD)

Henry Frisch
Enrico Fermi Institute, Univ. of Chicago
and HEPD, Argonne National Laboratory
The 4 `Divisions’ of LAPPD

**Hermetic Packaging**
See Bob Wagner’s talk

**Electronics/Integration**
This talk

**MicroChannel Plates**
See Ossy’s talk

**Photocathodes**
See (hear) Klaus Attenkofer’s talk
Outline

1. The Power of Correlated Time/Space Points
2. MCP’s, Transmission Lines, and Waveform Sampling
3. The 4 Determinants of Time Resolution
   a) Signal/Noise (S/N)
   b) Analog Band-width (ABW)
   c) Sampling Rate
   d) Signal statistics
4. What is the ultimate resolution at decent area & cost?
5. Water Cherenkov Counters; PET Cameras; TOF at Colliders; TOF for Fixed Target; Security; and New Ideas
MCP+Transmission Lines Sampled at Both Ends Provide Time and 2D Space

Field Programable Gate Arrays (not as shown - PC cards will be folded behind the panel - not this ugly…)

8” Tiles

10-15 GS/sec Waveform Sampling ASICS

Single serial Gbit connection will come out of panel with time and positions from center of back of panel
Time and Space Points

Pulses from the 2 ends of an 8” silk-screened cheap-glass anode strip

5 nsec/div
50 psec/pt
Reconstructing the vertex space point:
Simplest case- 2 hits (x,y) at wall

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

Detector Plane
$T_1$, $X_1$, $Y_1$

$T_2$, $X_2$, $Y_2$
Good timing alone doesn’t do it-

The ALICE TPC: Drift electrons onto wires that measure where and when for each electron.

Good time resolution would buy nothing if one integrated over a whole (blue) TPC sector - ie didn’t correlate when and where

Correlated time and space points allow 3D reconstructions
DAQ system

- Targeted to Super Module readout

Analog Card – 5 PSEC-4 ASICs (30 channels)
- system ABW = 1.5 GHz
- flexibility allows for integration of alternative front-end ASICs

Eric Oberla slide from ANT11
DAQ system

- Backside of Super Module:

**Digital Card** – 4 per module
- PSEC-4 control, trigger handling, & calibration

Eric Oberla slide from ANT11
Extract time, position of pulse using time from both ends

**DAQ system**

- Backside of Super Module:

![Diagram of DAQ system](image)

**Eric Oberla slide from ANT11**
The 4 Determinants of Time Resolution

a) Signal/Noise (S/N)
b) Analog Band-width (ABW)
c) Sampling Rate
d) Signal statistics

Simulation of Resolution vs abw

Jean-Francois Genat

Brown line: 10 Gs/sec (we’ve done >15); 1.5 GHz abw (we’ve done 1.6); S/N 120 (N=0.75mv, S is app specific)
Anode Testing for ABW, Crosstalk,..

Herve’ Grabas, Razib Obaid, Dave McGinnis
Anode Testing for ABW, Crosstalk,

Herve’ Grabas, Razib Obaid, Dave McGinnis

Tile row assembly of 3 tile anodes – abw >500 MHz
Anode Testing for ABW, Crosstalk,..
The PSEC4 Waveform Sampling ASIC

PSEC4: Eric Oberla and Herve Grabas; and friends...

PSEC-4 ASIC

- Sampling rate capability > 10GSa/s
- Analog bandwidth > 1 GHz (challenge!)
- Relatively short buffer size
- Medium event-rate capability (up to 100 KHz)

→ 130 nm CMOS

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
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<tbody>
<tr>
<td>Sampling Rate</td>
<td>2.5-15 GSa/s</td>
</tr>
<tr>
<td># Channels</td>
<td>6 (or 2)</td>
</tr>
<tr>
<td>Sampling Depth</td>
<td>256 (or 768) points</td>
</tr>
<tr>
<td>Sampling Window</td>
<td>Depth*(Sampling Rate)^1</td>
</tr>
<tr>
<td>Input Noise</td>
<td>&lt;1 mV RMS</td>
</tr>
<tr>
<td>Analog Bandwidth</td>
<td>1.5 GHz</td>
</tr>
<tr>
<td>ADC conversion</td>
<td>Up to 12 bit @ 2GHz</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>0.1-1.1 V</td>
</tr>
<tr>
<td>Latency</td>
<td>2 µs (min) – 16 µs (max)</td>
</tr>
<tr>
<td>Internal Trigger</td>
<td>yes</td>
</tr>
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</table>

Eric Oberla, ANT11
PSEC-4 ASIC

• 6-channel “oscilloscope on a chip” (1.6 GHz, 10-15 GS/s)
• Evaluation board uses USB 2.0 interface + PC data acquisition software
6-channel ‘Scope-on-a-chip’

Real digitized traces from anode

Eric Oberla (grad student)

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

17 GS/PSEC-4 chip 6-channels ($130 ?!)
PSEC-4 Performance

Digitized Waveforms

Input: 800MHz, 300 mV_{pp} sine

- Sampling rate: 10 GSa/s
- Sampling rate: 13.3 GSa/s

- Only simple pedestal correction to data
- As the sampling rate-to-input frequency ratio decreases, the need for time-base calibration becomes more apparent (depending on necessary timing resolution)

Eric Oberla, ANT11
Digitization Analog Bandwidth

3 dB loss

ABW ~ 1.6 GHz

PSEC4: Eric Oberla and Herve Grabas+ friends...
Noise (unshielded)

PSEC4: Eric Oberla and Herve Grabas+ friends...

Channel 3

Entries: 51200
Mean: 0.2038
RMS: 0.7781
Integral: 5.12e+04
$\chi^2$/ndf: 276.5/29
Constant: 8445 ± 47.7
Mean: 0.06695 ± 0.00335
Sigma: 0.7547 ± 0.0026

RMS = 755 microvolts

Full-Scale ~1.2 volts (expect S/N>=100, conservatively)

Eric Oberla, ANT11
Signal- want large for S/N

We see gains $>10^7$ in a chevron-pair

Ossy Siegmund, Jason McPhate, Sharon Jelinsky, SSL/UCB

ALD by Anil Mane and Jeff Elam, ANL
Can we go deep sub-picosec?:
the Ritt Parameterization (agrees with JF MC)

### How is timing resolution affected?

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

- **Assumes zero aperture jitter**

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

Includes detector noise in the frequency region of the rise time and aperture jitter.

**Stefan Ritt slide, doctored**

S/N, \(f_z\): DONE

abw: NOT YET

100 femtosec

10/31/2011 Light11 Ringberg Castle
Parallel Efforts on Specific Applications

- **PET**
  (UC/BSD, UCB, Lyon)

- **LAPD Detector Development**
  ANL, Arradiance, Chicago, Fermilab, Hawaii, Muons, Inc, SLAC, SSL/UCB, UIUC, Wash. U

  *Drawing Not To Scale (!)*

- **Collider**
  UC, ANL, Saclay

- **Muon Cooling**
  Muons, Inc (SBIR)

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

- **K- > πνν**
  JPARC

- **Mass Spec**
  Andy Davis, Mike Pellin, Eric Oberla

- **Non-proliferation**
  LLNL, ANL, UC

Explicit strategy for staying on task-
Multiple parallel cooperative efforts

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

Spec: signal single photon, 100 ps time, 1 cm space, low cost/m2 (5-10K$/m2)*

(Howard Nicholson)
Proposal (LDRD) to build a little proto-type to test photon-TPC ideas and as a simulation testbed

`Book-on-end’ geometry-long, higher than wide

Close to 100% coverage so bigger Fid/Tot volume

$\Delta x, \Delta y << 1 \text{ cm}$

$\Delta t < 100 \text{ psec}$

Magnetic field in volume

Idea: to reconstruct vertices, tracks, events as in a TPC (or, as in LiA).
Can we build a photon TPC?

Work of Matt Wetstein (Argonne, & Chicago) in his spare time (sic)
Works on GEANT events too

Reconstructed 750 MeV Muon (geant)

x position (mm)
0 500 1000 1500 2000

z position (mm)
-1500 -1000 -500 0 500 1000 1500

Matt Wetstein; ANL&UC
Application to Colliders

At colliders we measure the 3-momenta of hadrons, but can’t follow the flavor-flow of quarks, the primary objects that are colliding. 2-orders-of-magnitude in time resolution would all us to measure ALL the information=>greatly enhanced discovery potential.

A top candidate event from CDF- has top, antitop, each decaying into a W-boson and a b or antib. Goal- identify the quarks that make the jets.

Specs:
Signal: 50-10,000 photons
Space resolution: 1 mm
Time resolution 1 psec
Cost: <100K$/m2:

t-tbar -> W^+bW^-bbar->
e+ nu+c+sbar+b+bbar
Detectors Continued
My choice for development is time-of-flight (!?). Precise measurement of the 3-vector, the point of origin, and the particle type gives all the information possible about each particle.
If we could measure with $\sigma = 1$ psec (yes) in a path length of 1.5m (e.g. CDF), get $1 \sigma \pi - K$ separation at $p_T = 25$ GeV.

Is this crazy?

- There exist GaAs Schottky photodiodes with $\sigma \sim 1$ psec, so no law of nature precludes it.
- Need a fast source of light - e.g. Cherenkov radiation.
- Light cannot bounce - has to go straight in.
- Need spatial resolution $< 300 \mu$m for $\delta t = 1$ psec.
- Find the collision ‘start’ time by measuring the time of tracks relative to each other.
- Have to calibrate entire volume in situ - need lots of $\pi$, $K$, $p$, ...

So, could we build an outer layer for a central (solenoidal) detector with good spatial resolution and segmentation such that for every track with $p_T < 25$ GeV we measure not only $p_x$, $p_y$, $p_z$, but also its flavor content?

Invitation from Joe Lykken and Maria Spiropulu- led to psec TOF
Rather than use the Start time of the collision, measure the difference in arrival times at the beta=\(c\) particles (photons, electrons and identified muons) and the hadrons, which arrive a few psec later.
Can we solve the depth-of-interaction problem and also use cheaper faster radiators?

Simulations by Heejong Kim (Chicago)

Alternating radiator and cheap 30-50 psec planar mcp-pmt's on each side
Proposal: Alternating radiator and cheap 30-50 psec thin planar mcp-pmt's on each side (needs simulation work)
Cherenkov-sensitive Sampling Quasi-Digital Calorimeters

A picture of an em shower in a cloud-chamber with ½” Pb plates (Rossi, p215- from CY Chao)

A ‘cartoon’ of a fixed target geometry such as for JPARC’s KL-> pizero nunubar (at UC, Yao Wah) or LHCb
A `Quasi-digital’ MCP-based Calorimeter

Idea: can one saturate pores in the the MCP plate s.t. output is proportional to number of pores. Transmission line readout gives a cheap way to sample the whole lane with pulse height and time- get energy flow.

Electron pattern (not a picture of the plate!) - SSL test, Incom substrate, Arradiance ALD. Note you can see the multi’s in both plates => ~50 micron resolution

Oswald Siegmund, Jason McPhate, Sharon Jelinsky, SSL (UCB)
More Information:

- **Main Page:** http://psec.uchicago.edu
- **Library:** Workshops, Godparent Reviews, Image Library, Document Library, Links to MCP, Photocathode, Materials Literature, etc.;
- **Blog:** Our log-book - open to all (say yes to certificate Cerberus, etc.) - can keep track of us (at least several companies do);

The End
BACKUP SLIDES
The 4 `Divisions’ of LAPPD

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**Electronics/Integration**

This talk

**Photocathodes**

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The Large-Area Psec Photo-Detector Collaboration

Organization Chart

R&D Program for the Development of Large-Area Fast Photodetectors

Harry Weerts
HELPHML, ANL

External Review Committee

Henry Frisch
Spokesperson Co-PI

Karen Byrum
Co-PI

Gooparent Review Committees

Program Physicist
Bob Wagner

Program Engineers
Dean Walters/BNL

Hermetic Packaging
Group
Dean Walters/BNL/NTNO

Material Characterization
Igor Vedyovkin

Micro-Channel Plate
Group
Jeff Eam

Photocathode
Group
K. Attencio/Co-PI

Electronics Group
JF Gerat/Gary Yamer

Integration Group
Bob Wagner

Outgassing/Getters
Dean Walters

Glass Packaging Design
Rick Northrop

Ceramic Packaging Design
Ossy Segmound

Assembly Facilities ANL
Dean Walters

Assembly Facilities SSL
Ossy Segmound

Material Characterization
Igor Vedyovkin

ALD Functionalization
Jeff Eam/Neal Sullivan

Cold Amplification Structures
Jeff Eam

AAO Substrate
Dmitry Putilrivod/P. Wang

Bialkali Photocathodes
SSL/Ossy Segmound

Bialkali Photocathodes
AN/Co-PI

III/V/Nano Photocathodes
Klaus Attencio

Waveform Sampling
JF Gerat/Gary Yamer

Calibration/Control
JF Gerat/Gary Yamer

Signal Integrity/Characterization
JF Gerat/Gary Yamer

Clock Distribution
JF Gerat/Gary Yamer

Simulation
V. Kravzov/Z. Insepov

Testing
A. Adams/M. Wernick/Z.
O. Segmound

System Integration
JF Gerat/Gary Yamer

Documentation & Publication
Karen Byrum/Henry Frisch
Microchannel Plates-2

- Argonne ALD and test Facilities
  - In situ measurements of R (Anil)
  - Femto-second laser time/position measurements (Matt, Bernhard, Razib, Sasha)
  - 33 mm development program
  - 8” anode injection measurements

The Test Stand
- Ultra-fast (femto-second pulses, few thousand Hz) Ti-Sapphire laser, 800 nm, frequency triple to 266 nm
- Small UV LED
- Modular breadboards with laser/LED optics

Anil Mani and Bob Wagner

Razib Obaid and Matt Wetstein
Microchannel Plates-3

• SSL (Berkeley) Test/Fab Facilities

Ossy Siegmund, Jason McPhate, Sharon Jelenski, and Anton Tremsin-
Decades of experience
(some of us have decades of inexperience?)
Microchannel Plates-4b

Performance:

Noise (bkgd rate). <=0.1 counts/cm²/sec; factors of few > cosmics (!)

Post-bake ~2000 sec
~0.1 events cm² sec⁻¹

Ossy Siegmund, Jason McPhate, Sharon Jelinsky, SSL/UCB
Microchannel Plates-4d

Performance: burn-in (aka `scrub’)

Gain drop <5% over 16 hours at 0.01 C cm⁻², quite stable since then.

Measurements by Ossy Siegmund, Jason McPhate, Sharon Jelinsky, SSL/UCB

Typical MCP behavior—long scrub times

Measured ANL ALD-MCP behavior (ALD by Anil Mane, Jeff Elam, ANL)
First Pulses From an 8" MCP
Matt Wetstein, Bernhard Adams, Razib Obaid, Sasha Vostrikov (ANL and UC)

average arrival time (picoseconds) versus position (mm)

From the time difference of the 2 ends of the strip one gets the longitudinal position, from the average of the 2 ends the time (and of course from which strip(s) one gets the transverse position) => so have 2D at wall plus Time-of-Arrival

TrueError bar prob. like this (ask Matt)

Note
c= 0.3mm/ps
1/c=3.3 psec/mm
Photocathodes

Subject of next talk by Klaus- touch on here only briefly

LAPPD goal- 20-25% QE, 8”-square

2 parallel efforts: SSL (knows how), and ANL (learning)

ANL Optical stand

First cathodes made at ANL

Burle commercial equipment
SSL has years of experience making bialkali photocathodes-
They are our treasury bonds (Swiss francs?) in the LAPPD `portfolio of risk’
Hermetic Packaging

• Top Seal and Photocathode - this year’s priority

3 parallel paths

Tile Development Facility at ANL

Production Facility at SSL/UCB

Commercial RFI for 100 tiles
(Have had one proposal for 7K-21K tiles/yr)
The End