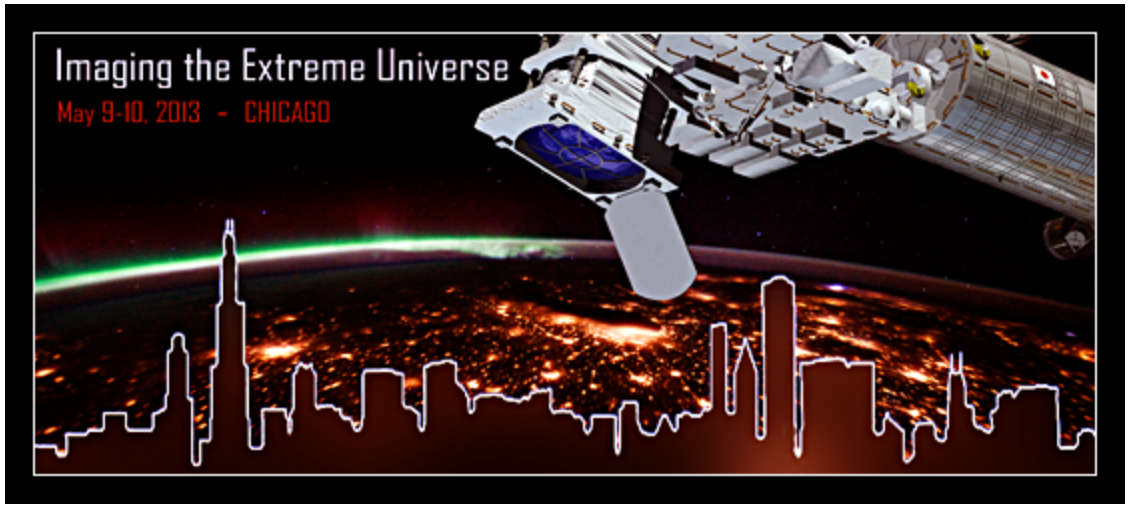
Development of large-area Micro-channel Plate Photodetectors



Eric Oberla, for the LAPPD collaboration

10-May 2013

Argonne NATIONAL LABORATORY

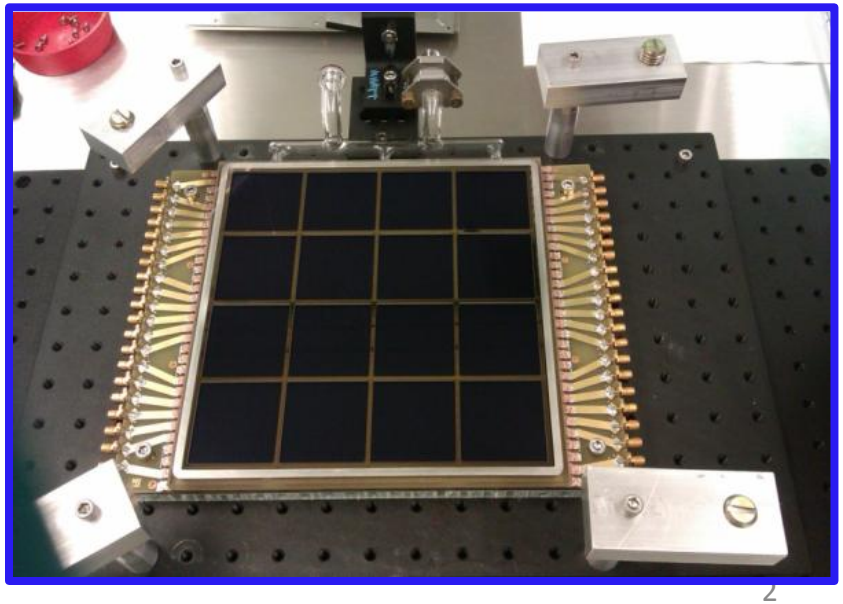
HIGH ENERGY PHYSICS
THE UNIVERSITY OF CHICAGO

Outline

- **Large Area Picosecond Photo-Detector (LAPPD) :** development of low-cost, large-area micro-channel plate photo-detectors (MCP-PMTs) for fast timing + imaging.
- **Glass capillary MCPs:** design and functionalization
- **The glass package:** detector stack-up and anode
- **Detector testing**: Imaging, gain mapping, and timing
- **Integrated electronics:**

  DAQ system and

  fast waveform recording

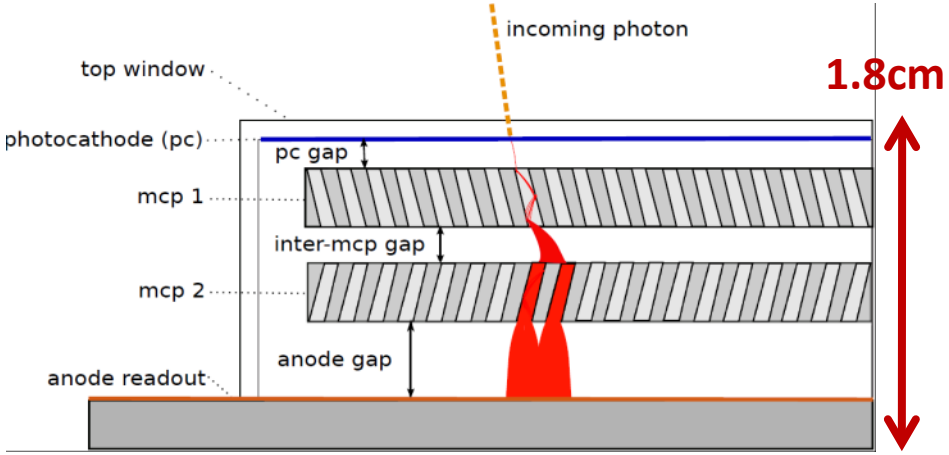


The 400 sq. cm `Demountable' LAPPD MCP detector

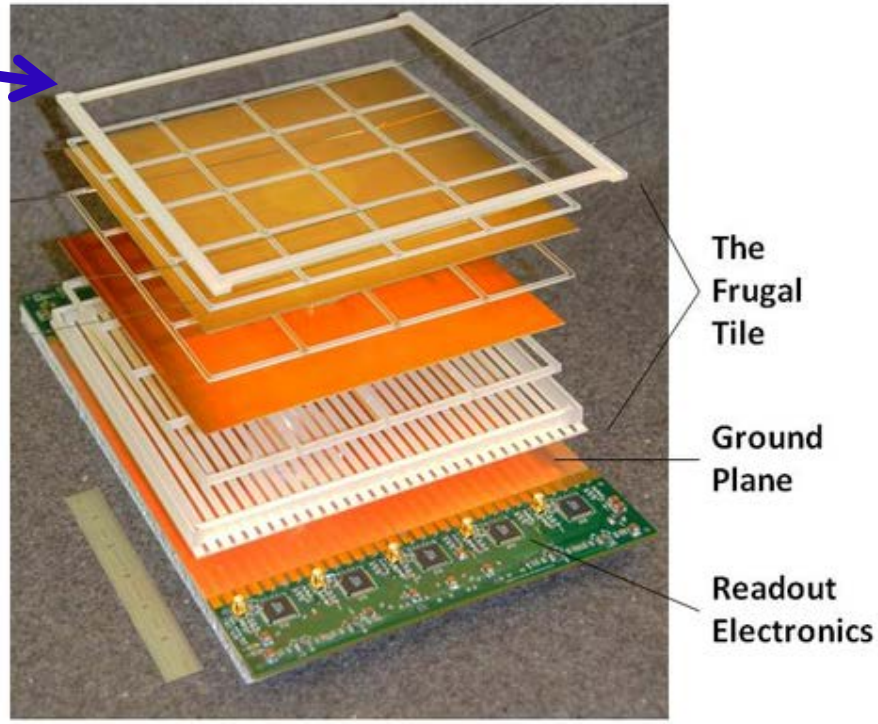
Large-Area Picosecond Photo-Detector Collaboration (LAPPD)

LAPPD Collaboration

- **Goals:** Large-area, relatively low-cost, ~picosecond timing
- **Span of R&D efforts:** photocathode, MCP, integrated electronics, hermetic packaging
- **Baseline glass package design:**
  - 20 x 20 cm^2 area = **'tile'**
  - Gain > 10^7 with two MCP plates
  - RF Transmission line anode
  - Internal HV distribution

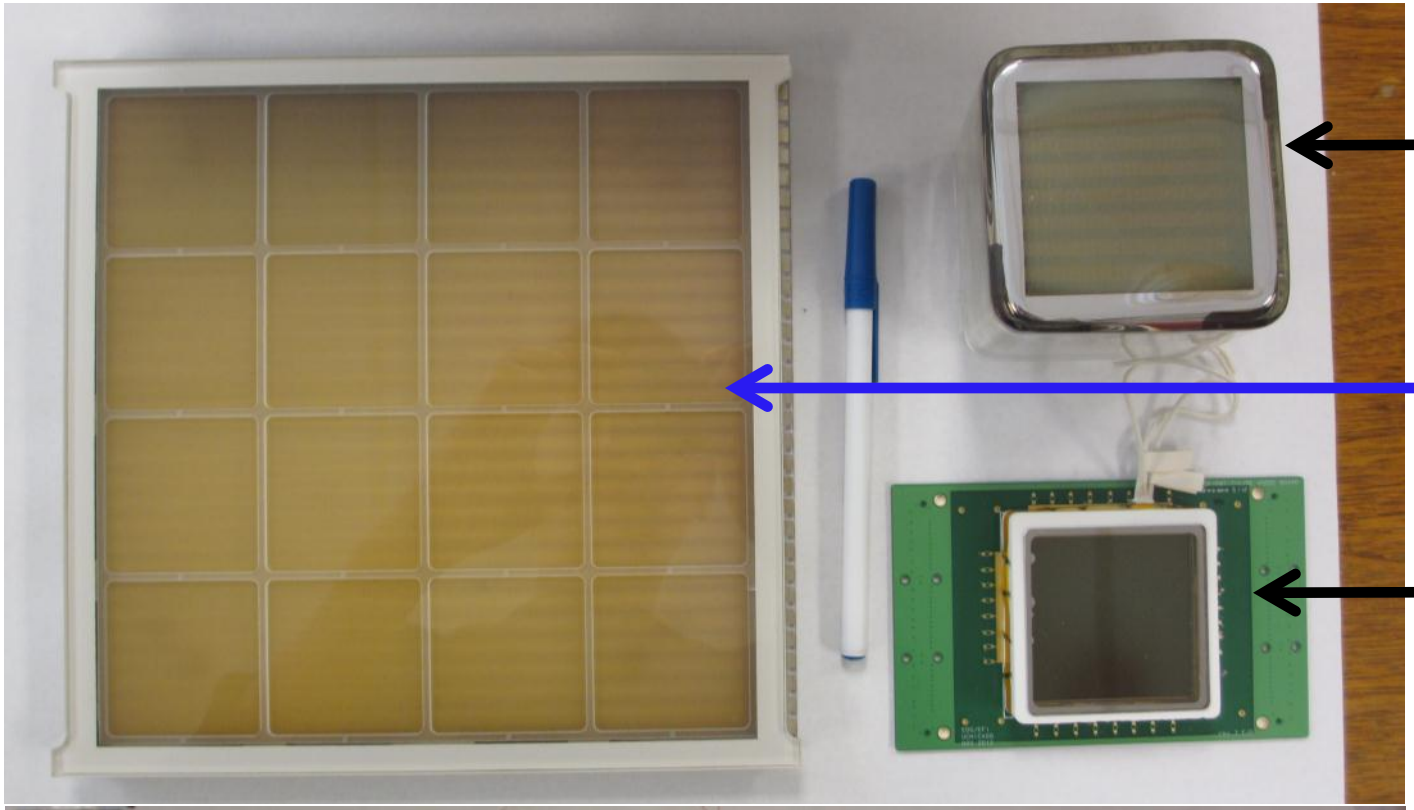


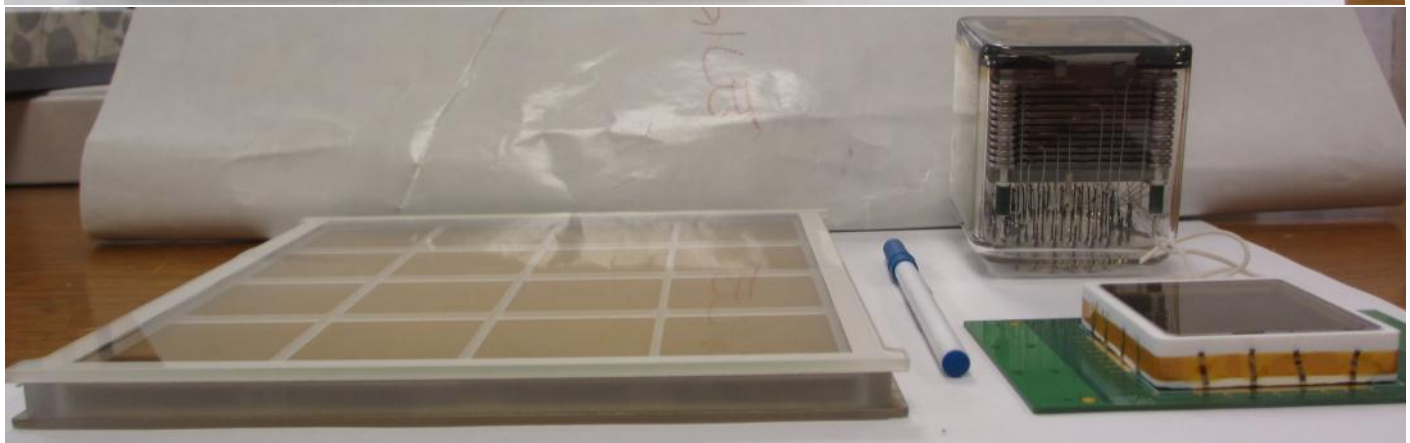
Limited sensitivity to magnetic field (..?)



The Frugal Tile - Detector Assembly

Large-Area Picosecond Photo-Detector Collaboration (LAPPD)



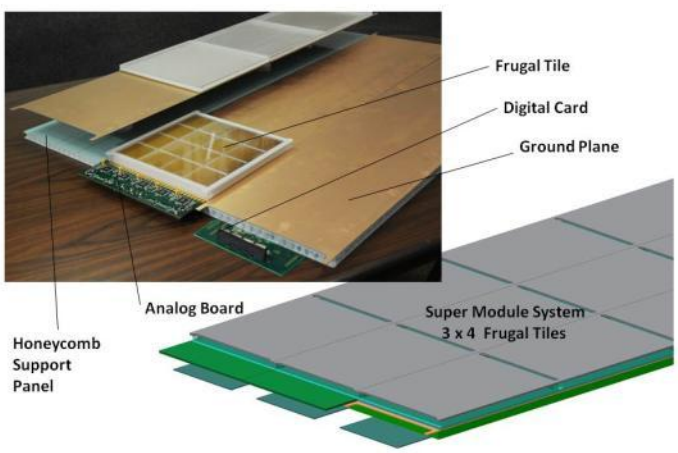


The Super Module

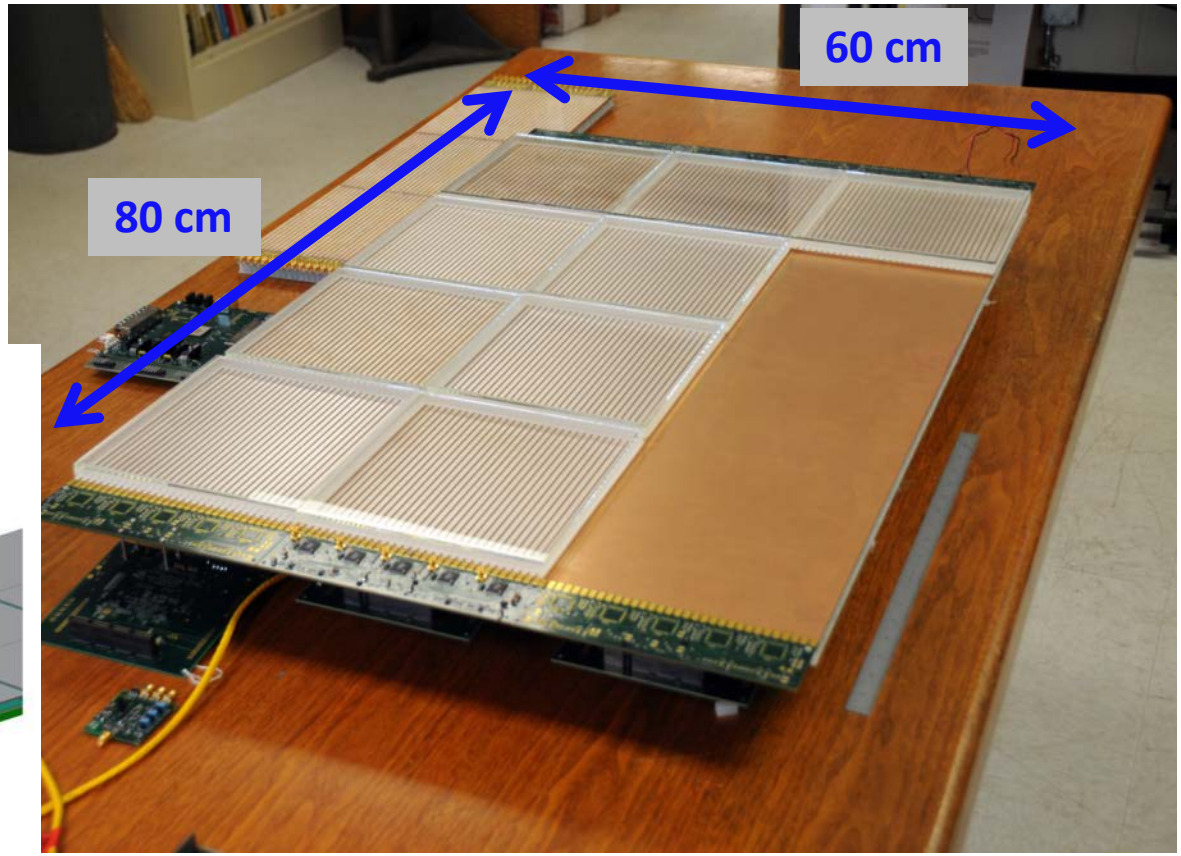
- **<u>0.5m^2</u> of photo-sensitive area:** 3x4 array of 20cm LAPPD MCP tiles
- **Thin profile glass packaging**
- **Highly integrated electronics:** 180 channels of fast waveform digitization

→ <u>input</u>: *high voltage + system clk, etc.*; <u>output</u>: *gigabit Ethernet*

System bandwidth ~400 MHz



Tray and Tiles - The Super Module System

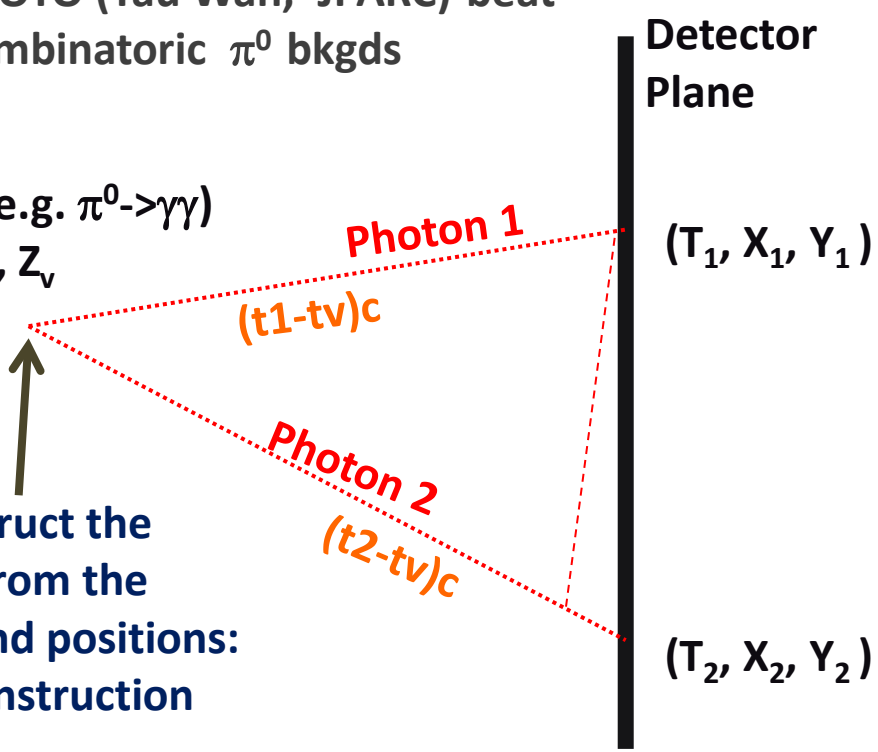


Physics Motivation:

LAPPD Collaboration

Rare Kaon Decays- backgd rejection by reconstructing π^0 vertex space point:

E.g. for KOTO (Yau Wah, JPARC)-beat down combinatoric π^0 bkgds



Reconstruct the vertex from the times and positions: 3D reconstruction

[H Frisch slide]

Goals:

- *Large area*
- *Picosecond timing*
- *Cheap*

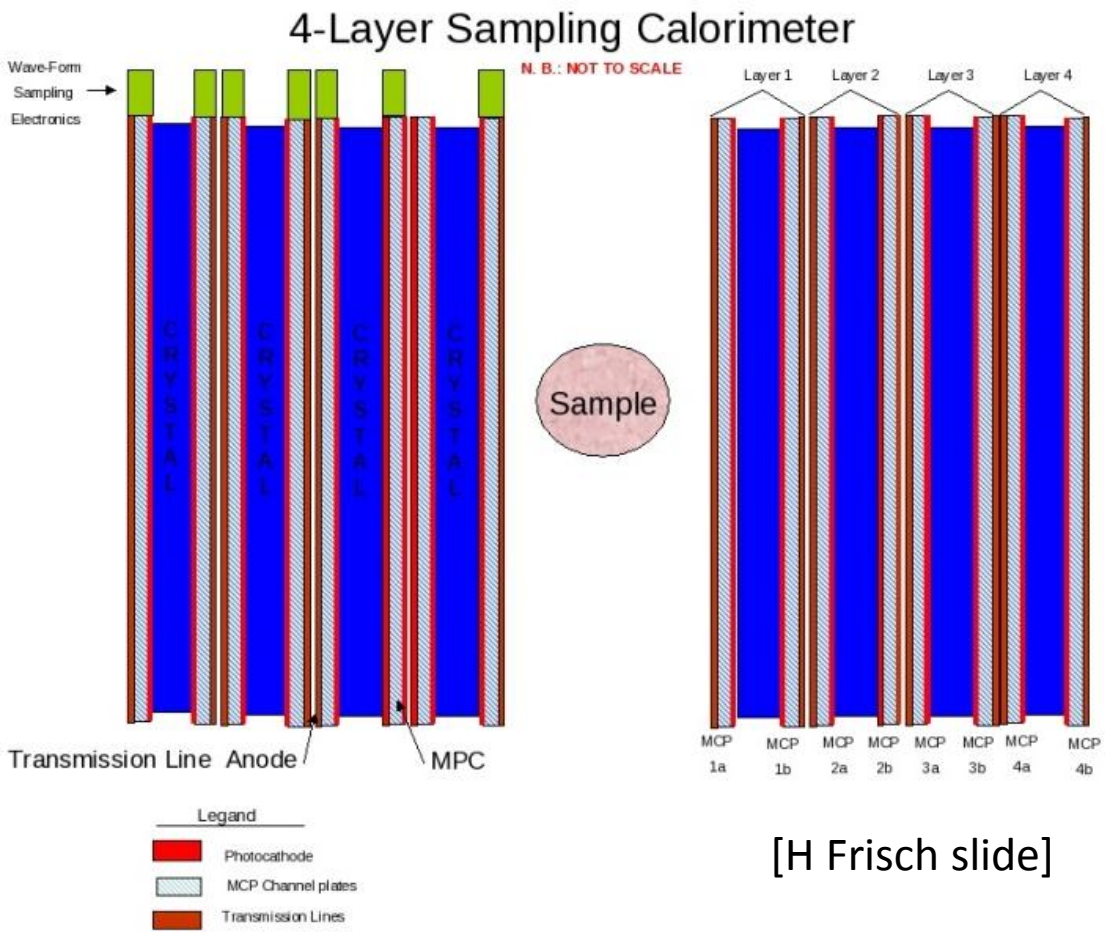
Applications:

- **Picoseconds on large area**
- *Neutrinos*
- *Kaons*
- *Collider*
- *Muon cooling*
- *PET scan*
- *X-ray*
- *Neutrons*

Physics Motivation:

LAPPD Collaboration

PET need: 1) much lower dose rate
2) faster through-put
3) real-time feedback. 3D localization TOF



[H Frisch slide]

Goals:

- *Large area*
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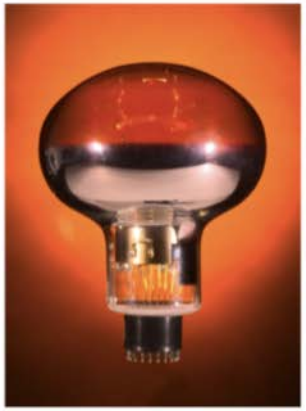
- *X-ray*
- *Neutrons*

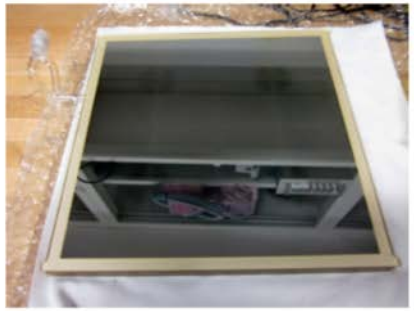
Physics Motivation:

LAPPD Collaboration

Reinventing the unit-cell of light-based neutrino detectors

[M. Wetstein slide]





- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

Photon tagging:

- ~mm resolution
- ~100 ps TOF time resolution

Can we build a water Cherenkov **optical TPC?**

Goals:

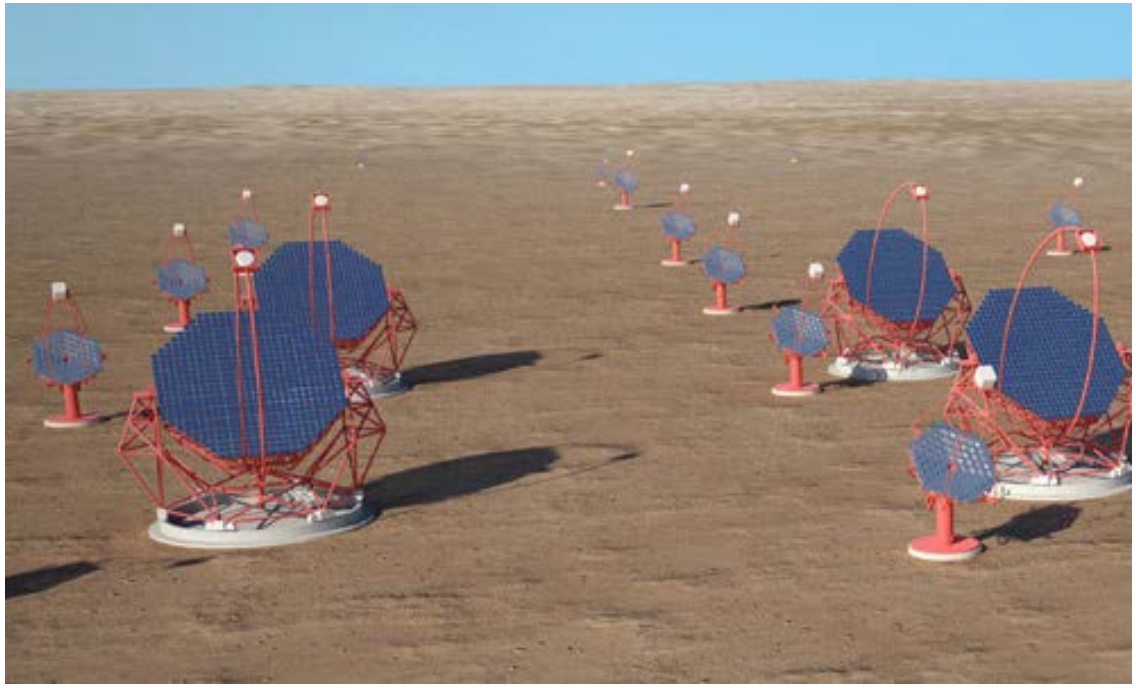
- *Large area*
- *Picosecond timing*
- *Cheap*

Applications:

- **Picoseconds on large area**
- *Neutrinos*
- *Kaons*
- *Collider*
- *Muon cooling*
- *PET scan*
- *X-ray*
- *Neutrons*

Physics Motivation:

LAPPD Collaboration



Goals:

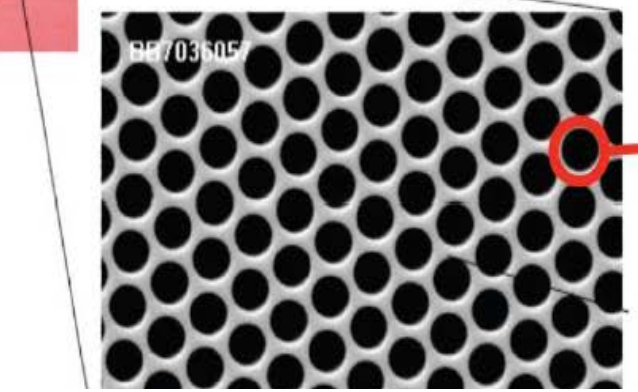
- *Large area*
- *Picosecond timing*
- *Cheap*

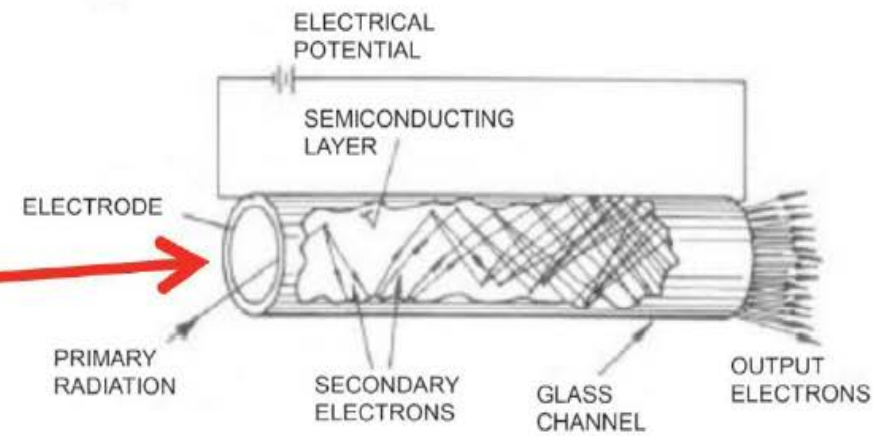
Applications:

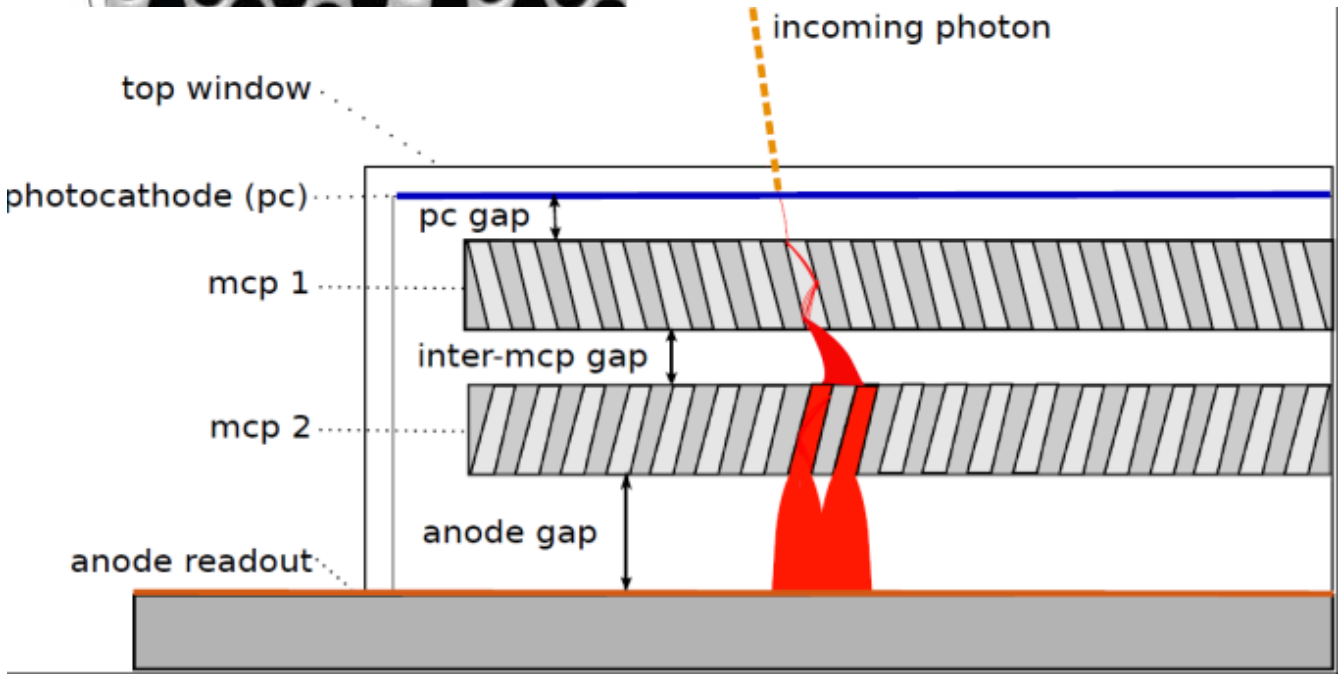
- **Picoseconds on large area**
- *Neutrinos*
- *Kaons*
- *Collider*
- *Muon cooling*
- *PET scan*
- *X-ray*
- *Neutrons*

+ Cosmic/gamma-ray instruments?

MCP fundamentals

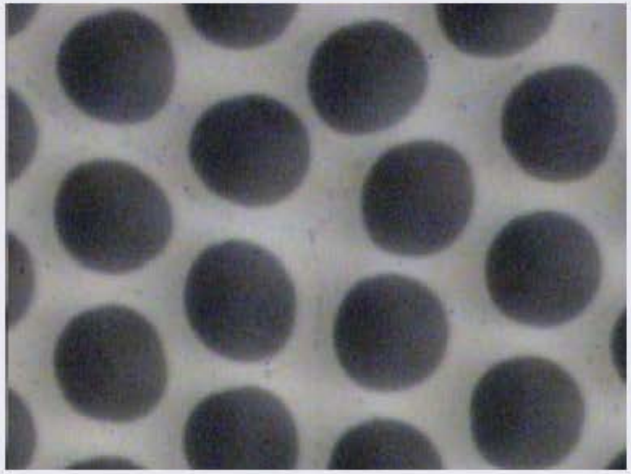






MCPs from Glass Micro-Capillary Arrays

Commercial MCP



Incom glass substrate MCP

Chemically produced and treated Pb-glass does 3-functions:

- Provide pores
- Resistive layer supplies electric field in the pore
- Pb-oxide layer provides secondary electron emission

Separate the three functions:

1. Hard glass substrate provides pores;
2. Tuned Resistive Layer (ALD) provides current for electric field
3. Specific Emitting layer provides SEE (ALD)
4. Scalable and cheap(er)

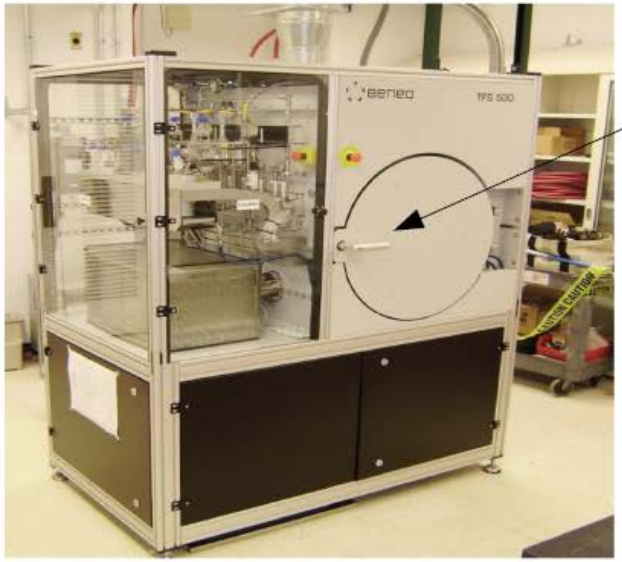
MCPs from Glass Micro-Capillary Arrays

~80 million pores

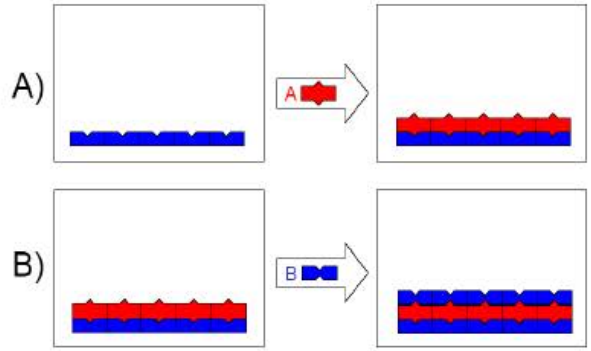
e the three functions:
glass substrate provides
;;
d Resistive Layer (ALD)
des current for electric field
fic Emitting layer provides
ALD)

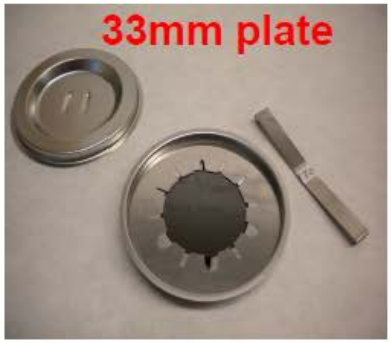
MCP functionalization by Atomic Layer Deposition (ALD)

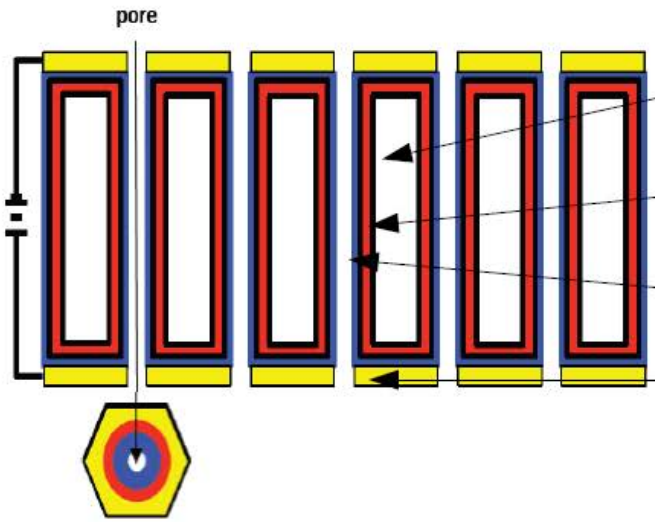
LAPPD Collaboration



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





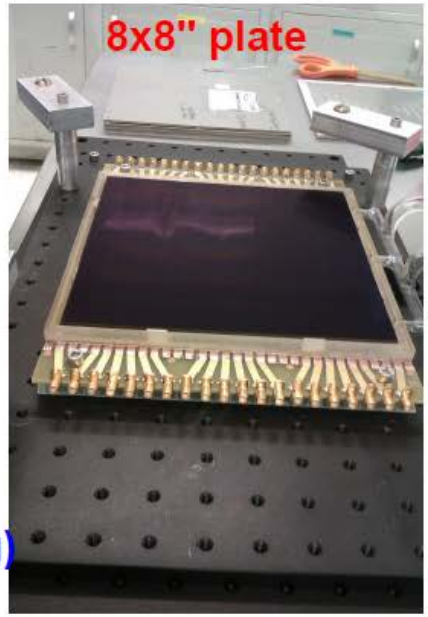


Porous glass

Resistive coating ~100nm (ALD)

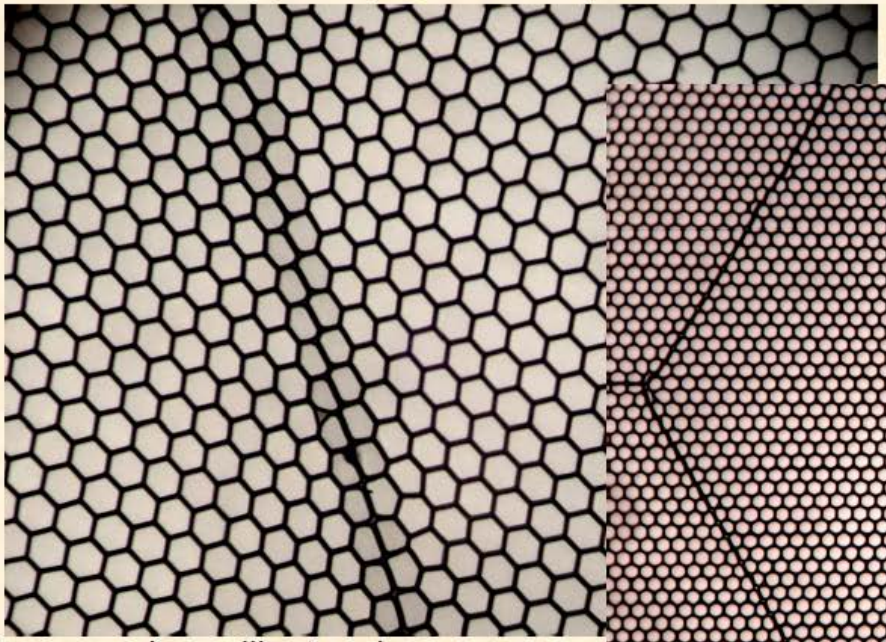
Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)



MCP functionalization by Atomic Layer Deposition (ALD)

LAPPD Collaboration



40μm pore borosilicate micro-capillary MCP with 83% open area.

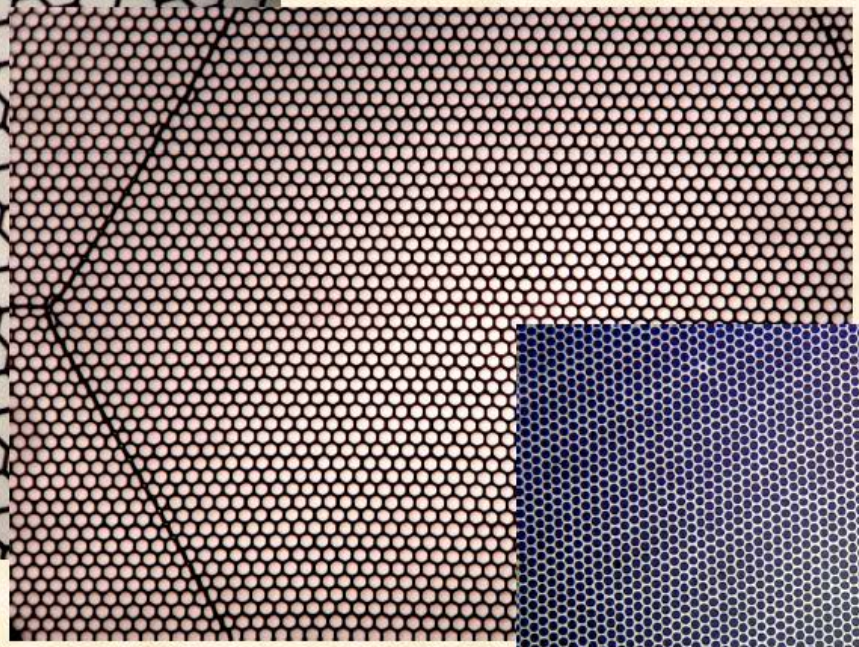


Photo of a 20 μm pore, 65% open area borosilicate micro-capillary ALD MCP (20cm).

Pore distortions at multifiber boundaries, otherwise very uniform.

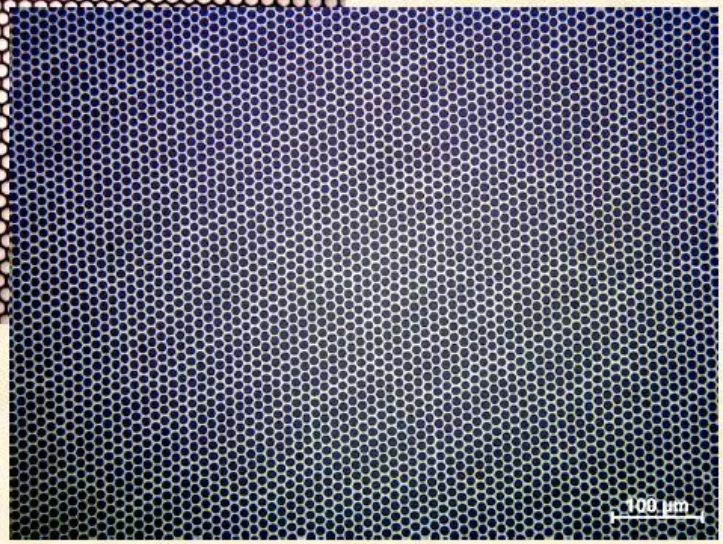
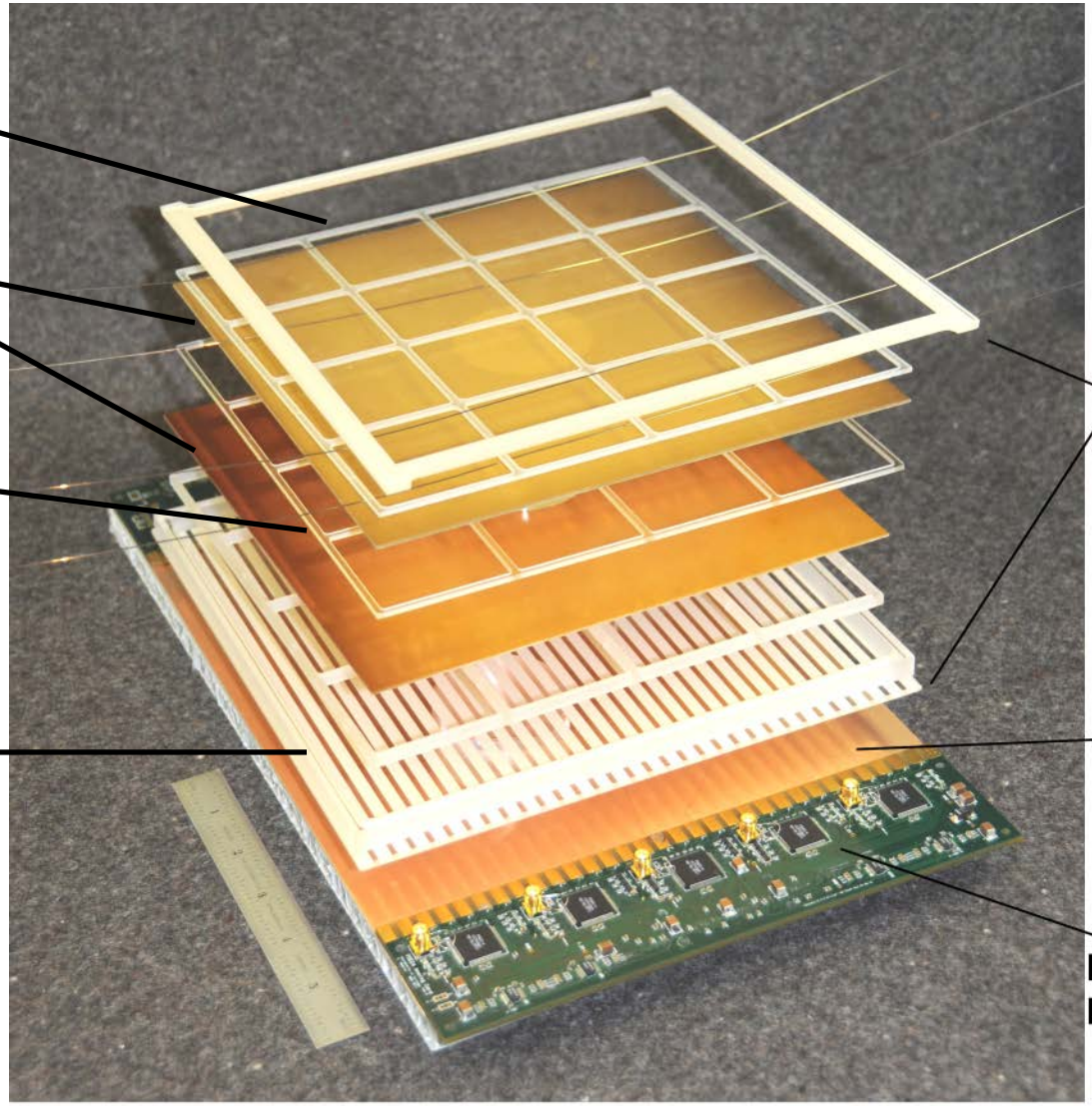


Photo of a 10 μm pore, 60% open area borosilicate micro-capillary ALD MCP.

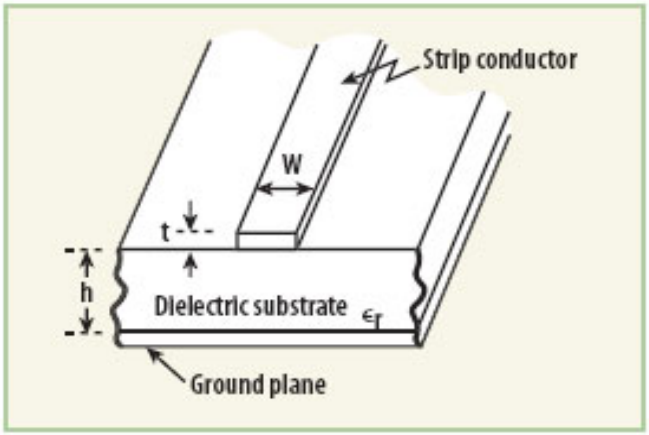
The 8” glass package



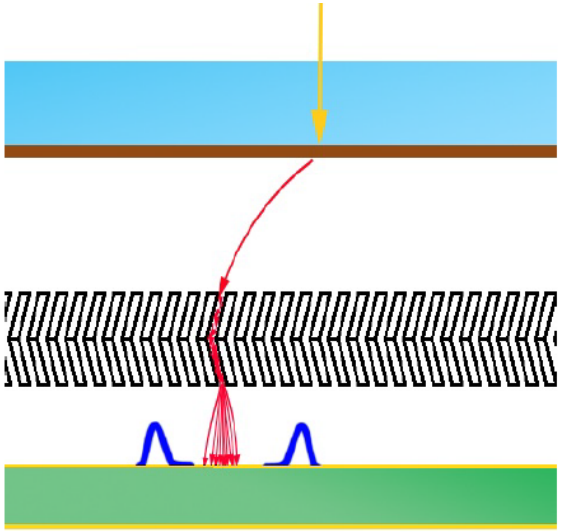
The Frugal Tile - Detector Assembly

The 8” glass package: **Microstrip Anode**

LAPPD Collaboration

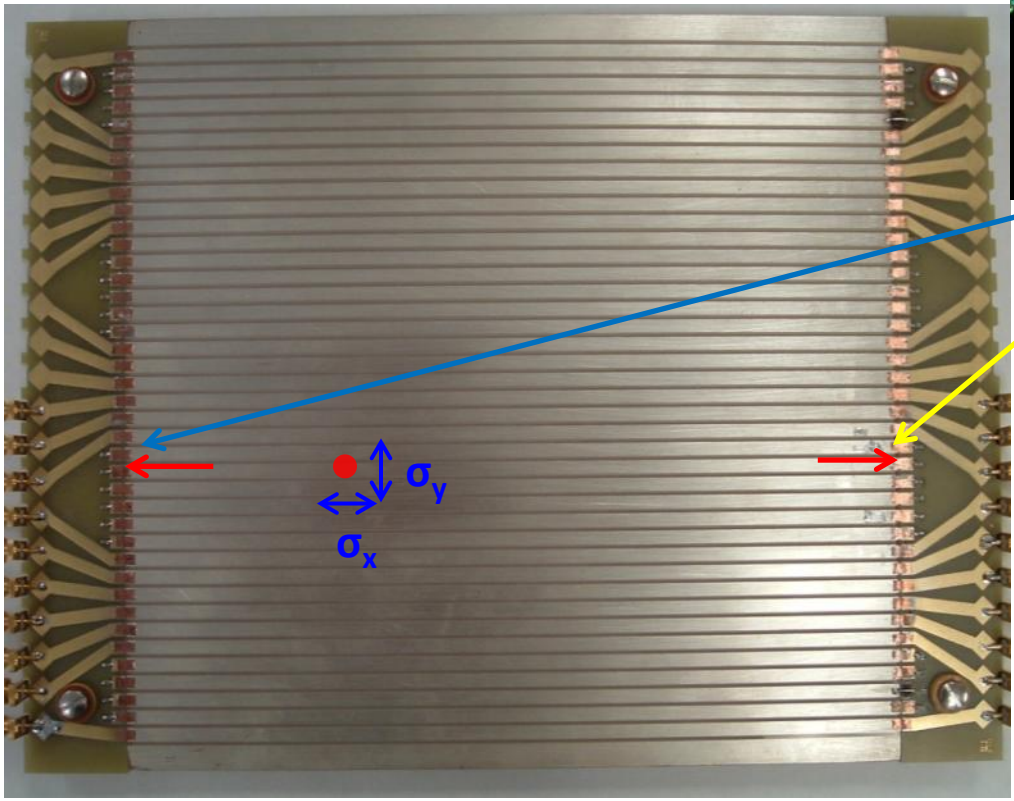


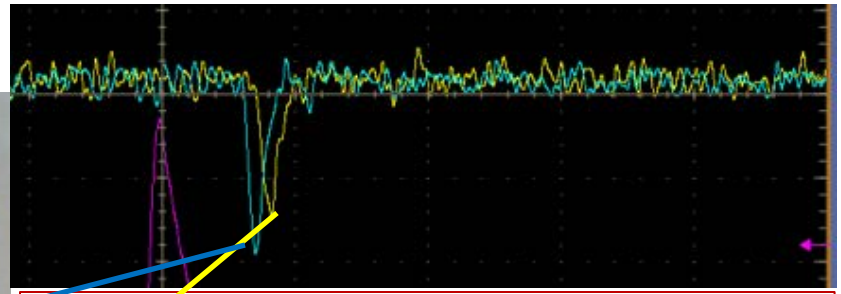
1. Microstrip transmission lines consist of a strip conductor and a ground metal plane separated by a dielectric medium.

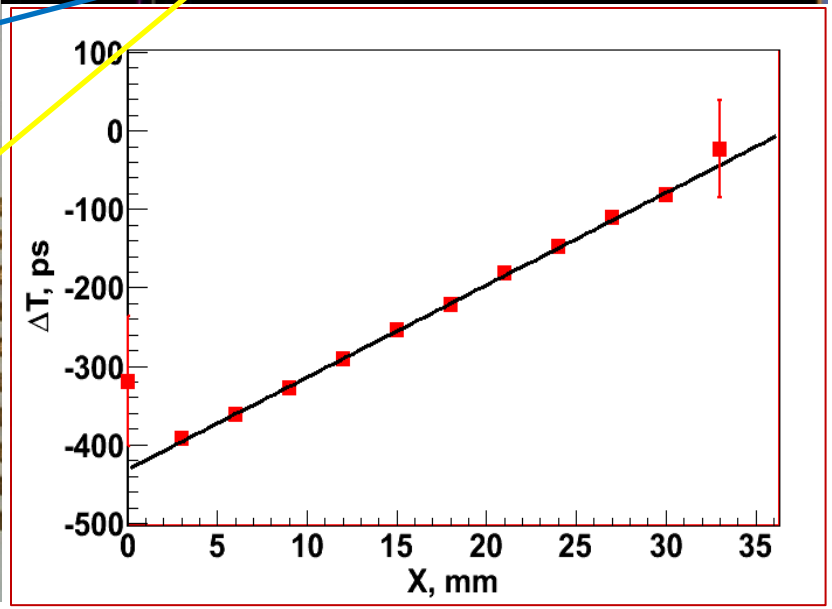


After final amplification, the electron cloud is accelerated towards the anode, inducing EM waves that propagate in both directions along transmission line.

The 8” glass package: **Microstrip Anode**







Location of event (x,y) determined by the time difference of signal on two ends (x) and the charge-centroid of adjacent strips (y). Efficient use of electronics channels.

- Position resolution <--> differential time resolution **[$\sigma_x = \sigma_t * v_{prop}$]**

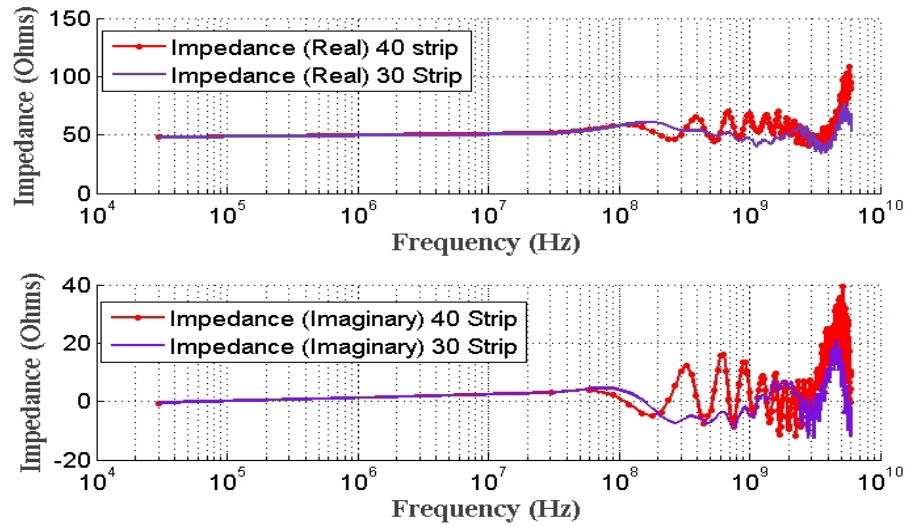
  100 ps ~ 1.5 cm

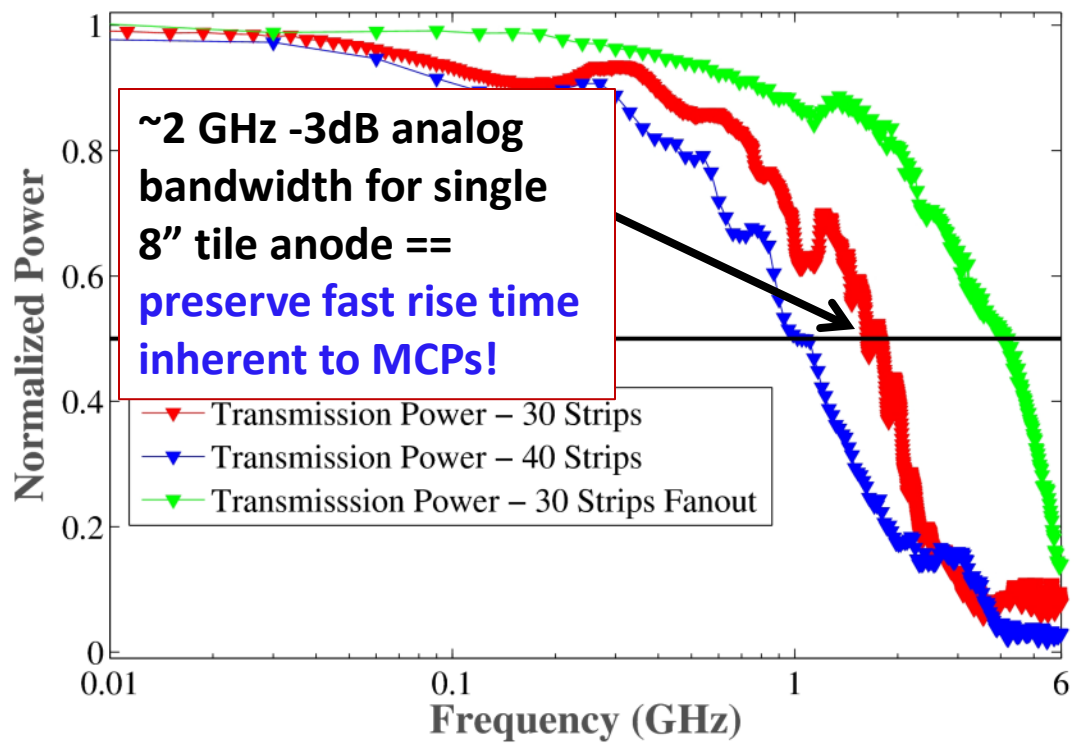
  10 ps ~1.5 mm …etc.

33mm MCP position scan: **V_{prop} ~ 2/3c** along stripline (**σ_t ~15 ps**).

The 8” glass package: **Microstrip Anode**

Silver strips silk-screened on bottom plate. Constructed by Joe Gregar (ANL)





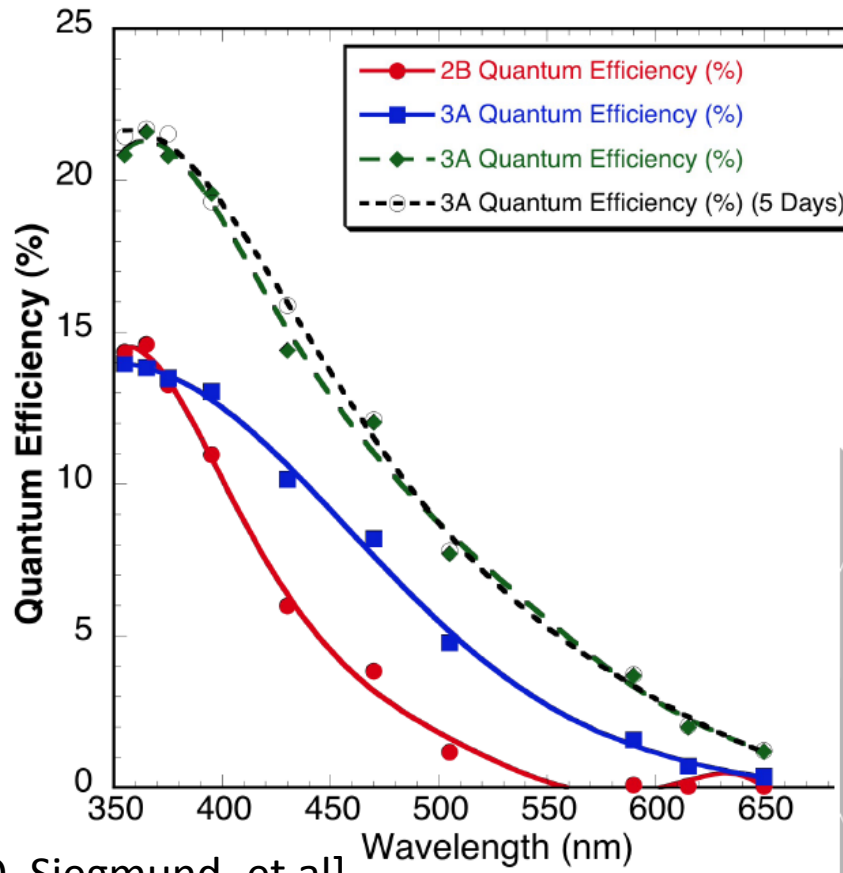
The 8” glass package: **Photocathode**

LAPPD Collaboration

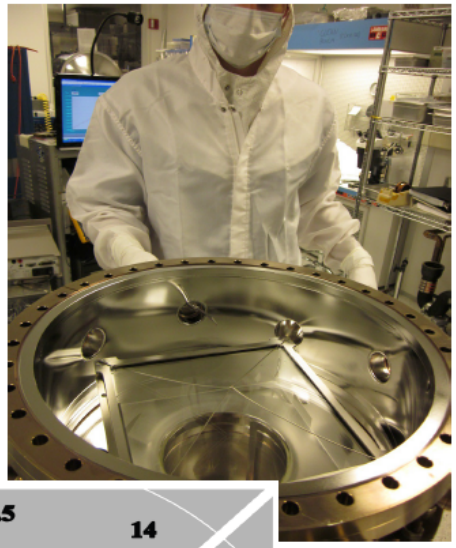
Have made >20% 8” PC at SSL; 25% small PC’s at ANL, 18% 4” (larger underway)

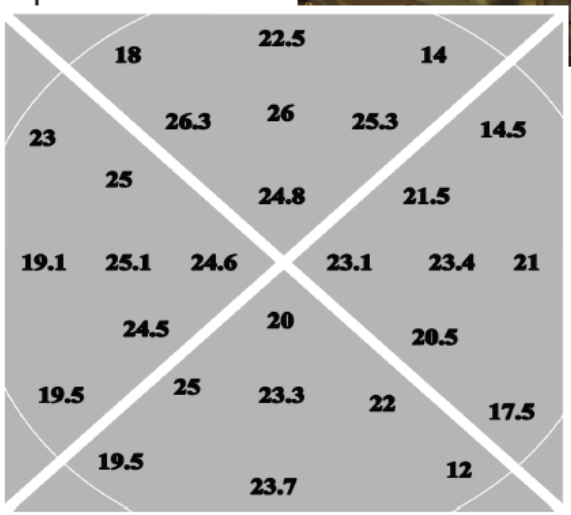
J.McPhate, O.Seigmund

NaKSb



[O. Siegmund, et al]



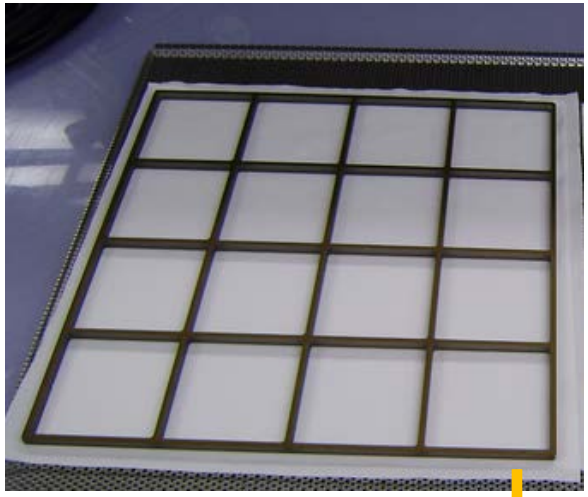


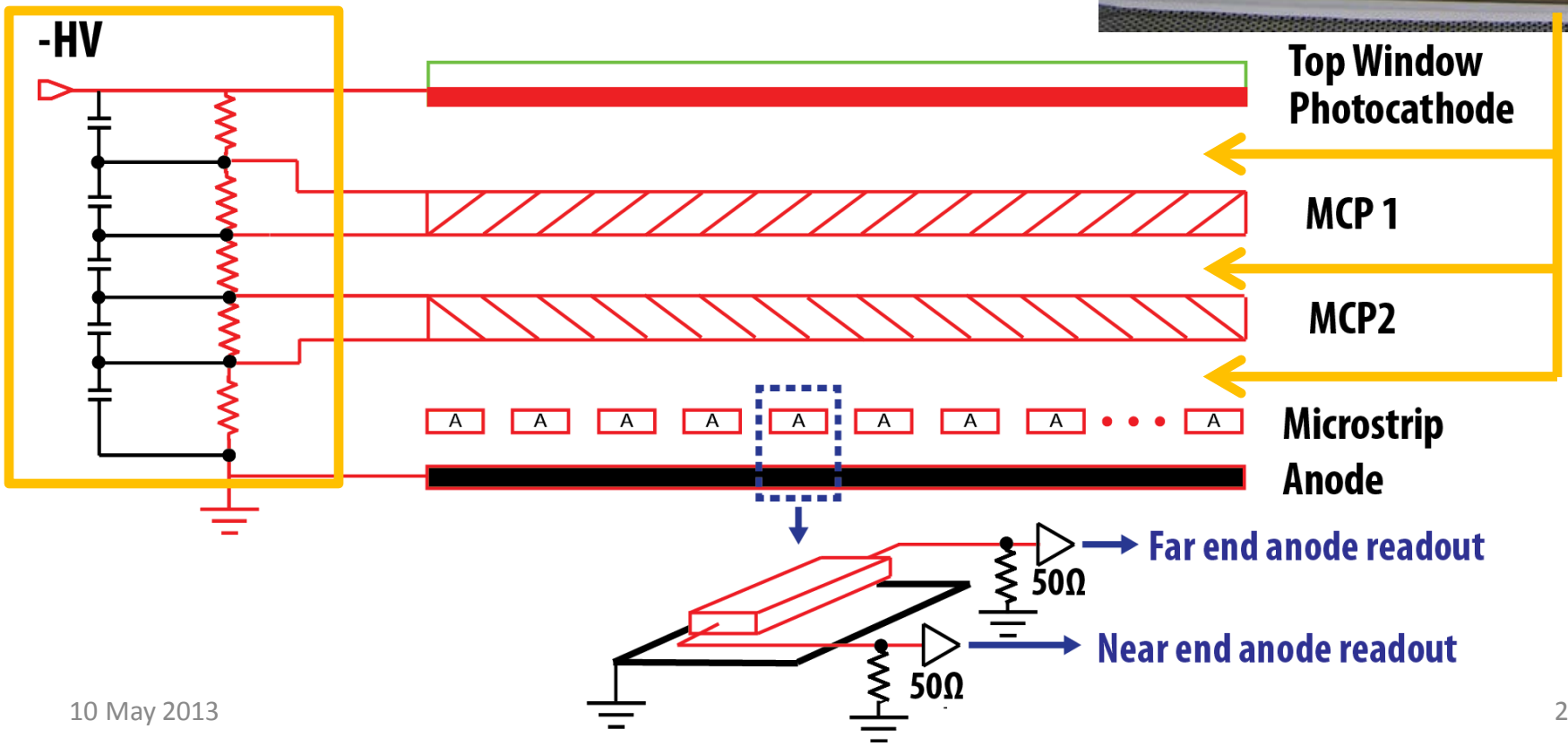
44

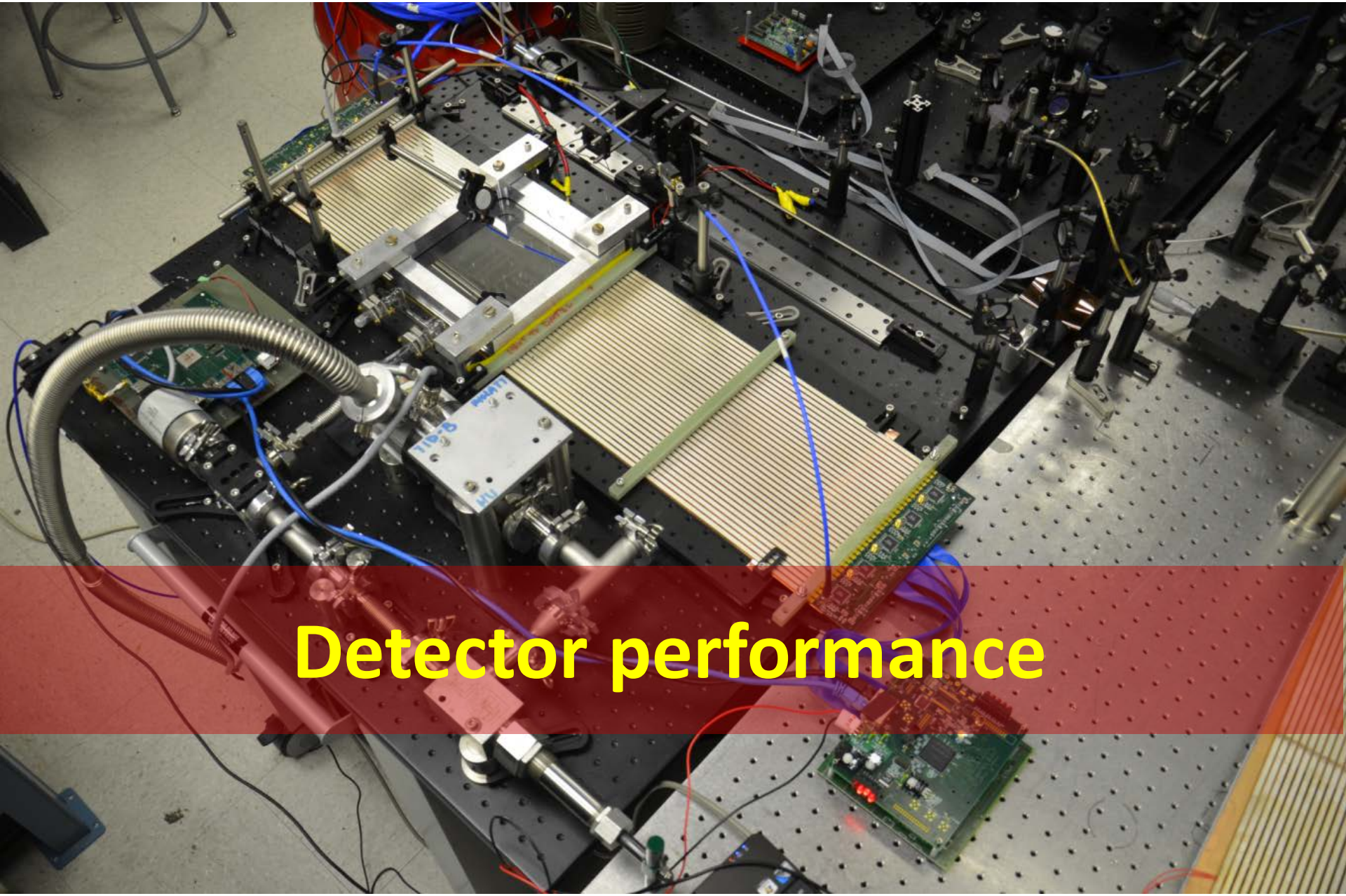
-- Fundamental photocathode a parallel R&D effort --

The 8” glass package: **HV distribution**

High Voltage distribution is embedded in the internal stack-up using ALD grid spacers



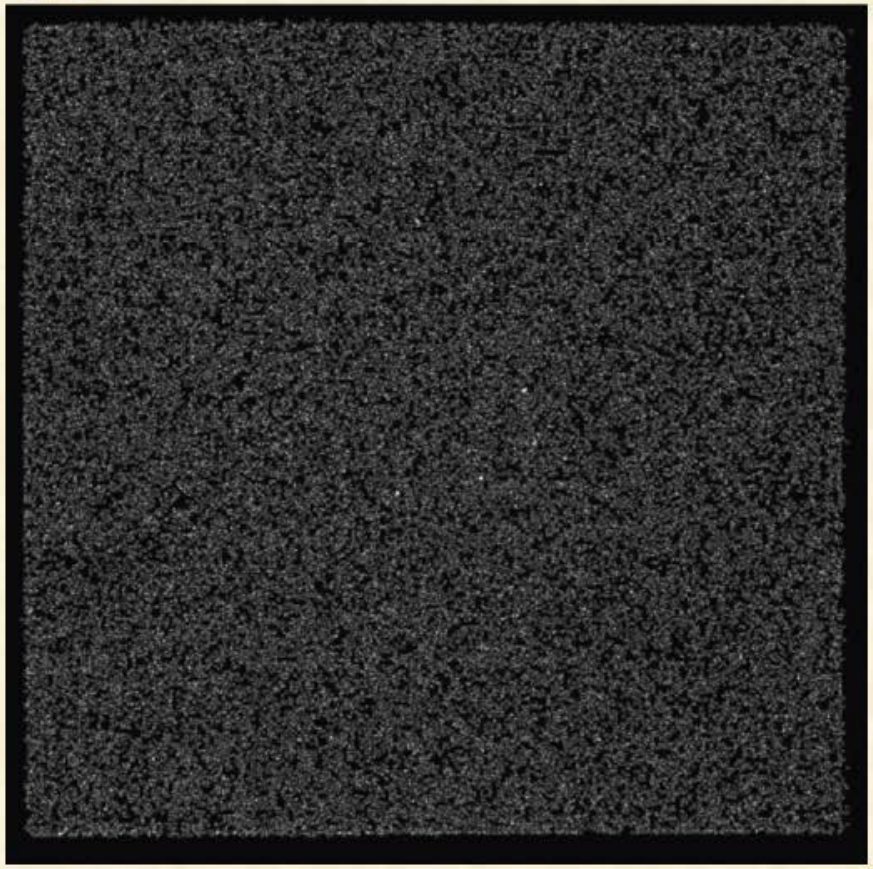




Detector performance

Imaging: Background counts

Background, 20cm, 20μm pore ALD-MCP Pairs



20cm MCP pair background, 2000 sec, 0.068 cnts sec^{-1} cm^{-2}. 2k x 2k pixel imaging.

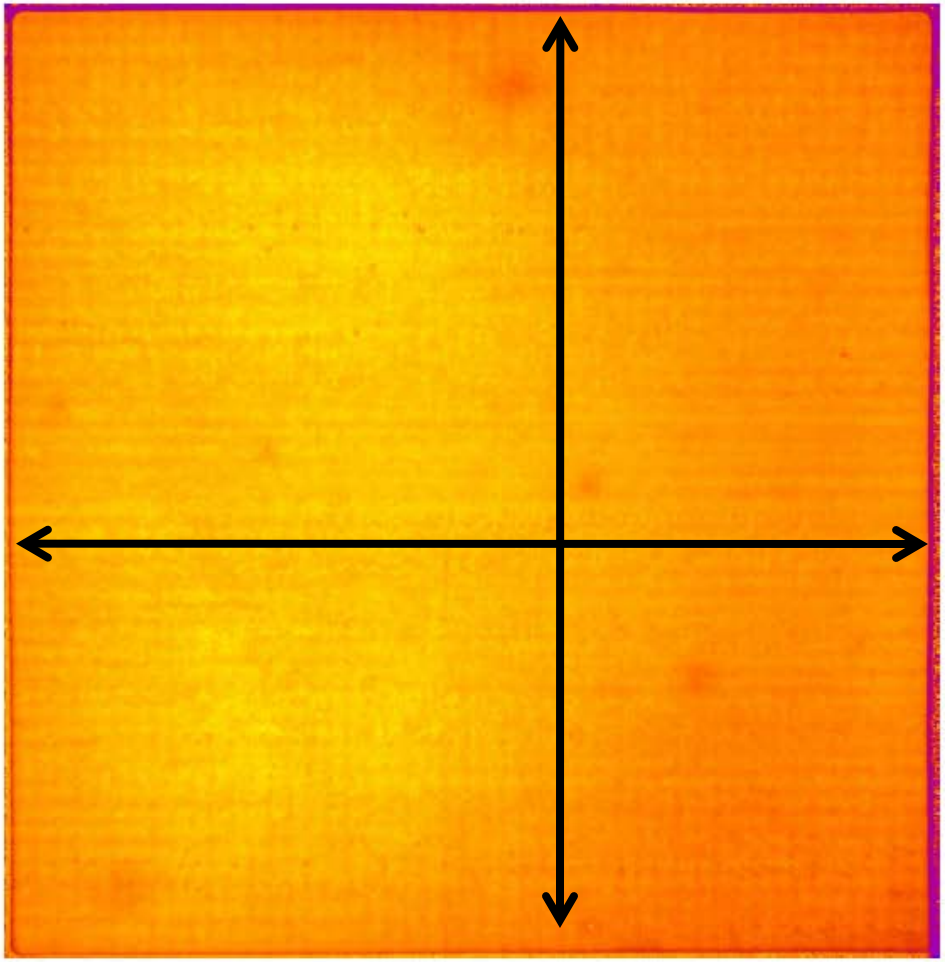
- 20µm pore, 60:1 L/d ALD-MCP pair, 0.7mm gap/200v.
- Background very low !! 0.068 cnts sec^{-1} cm^{-2} is a factor of 4 lower than normal glass MCPs.
- This is a consistent observation for all MCPs with this substrate material and relates to the low intrinsic radioactivity of the glass.
- Without lead 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

[O. Siegmund, et al]

Imaging: Gain mapping

LAPPD Collaboration

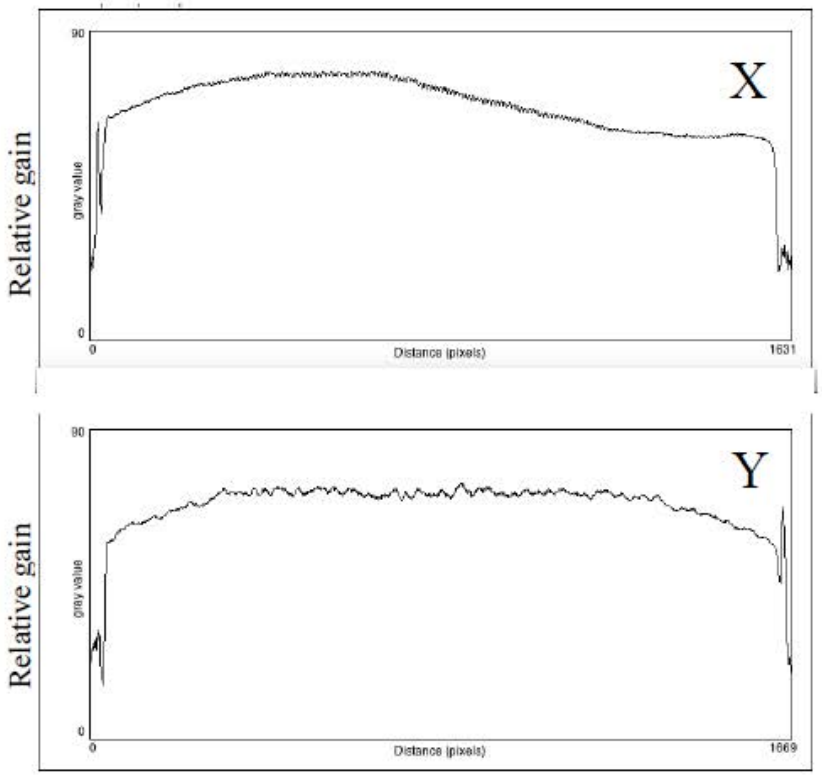
Mean gain ~7 x 10^6



8” MCP pair average gain map image

20 µm pore, 60:1 L/D ALD MCP pair

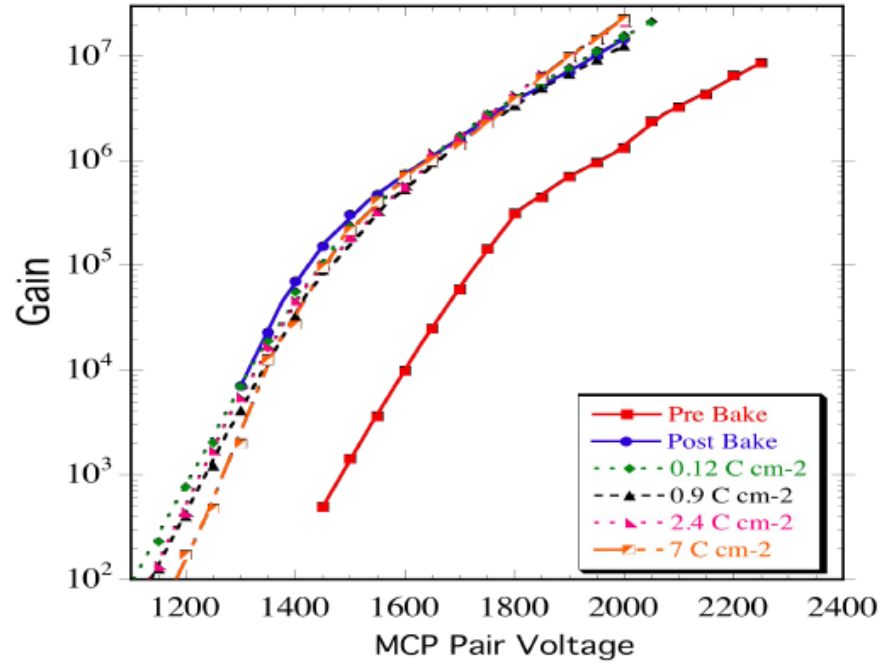
XY gain slices:



[O. Siegmund, et al]

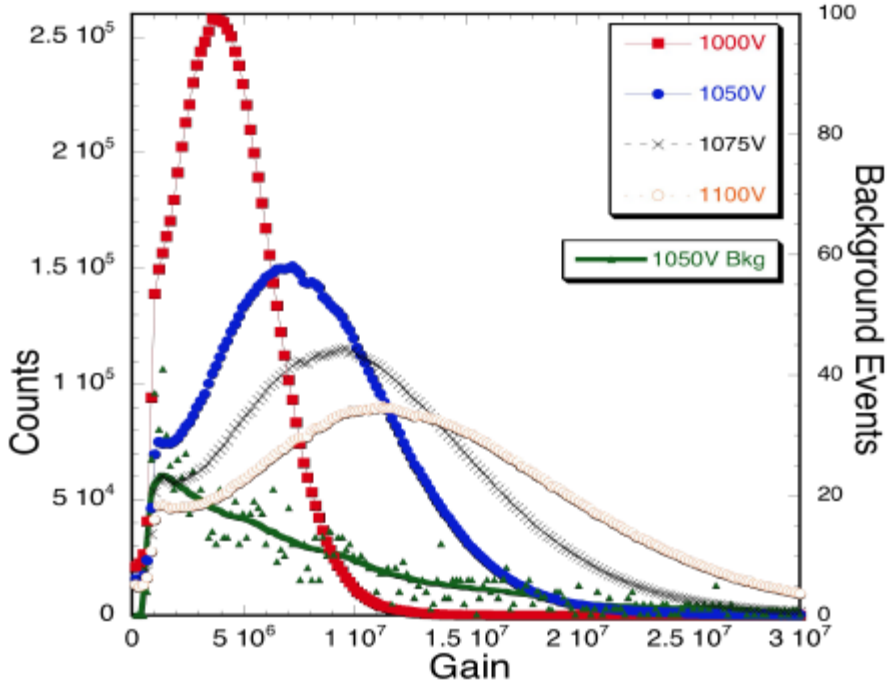
Gain and lifetests

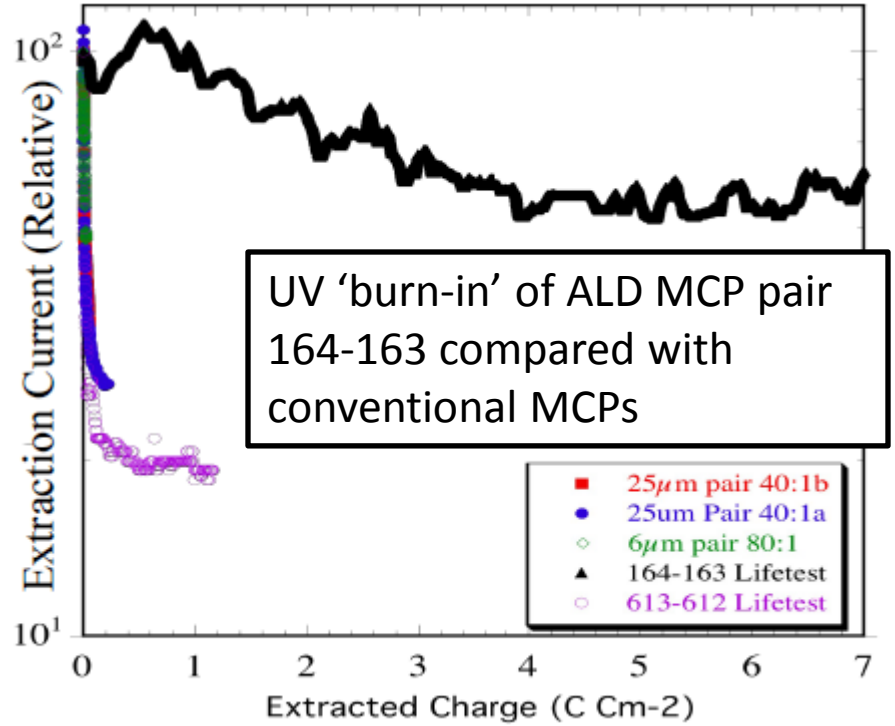
Gain curves of 164-163 ALD MCP (33mm diameter, 20 micron) pair during conditioning



[O. Siegmund, et al]

PHD for 20 micron pore MCP pair. 3000 sec. bkgnd.



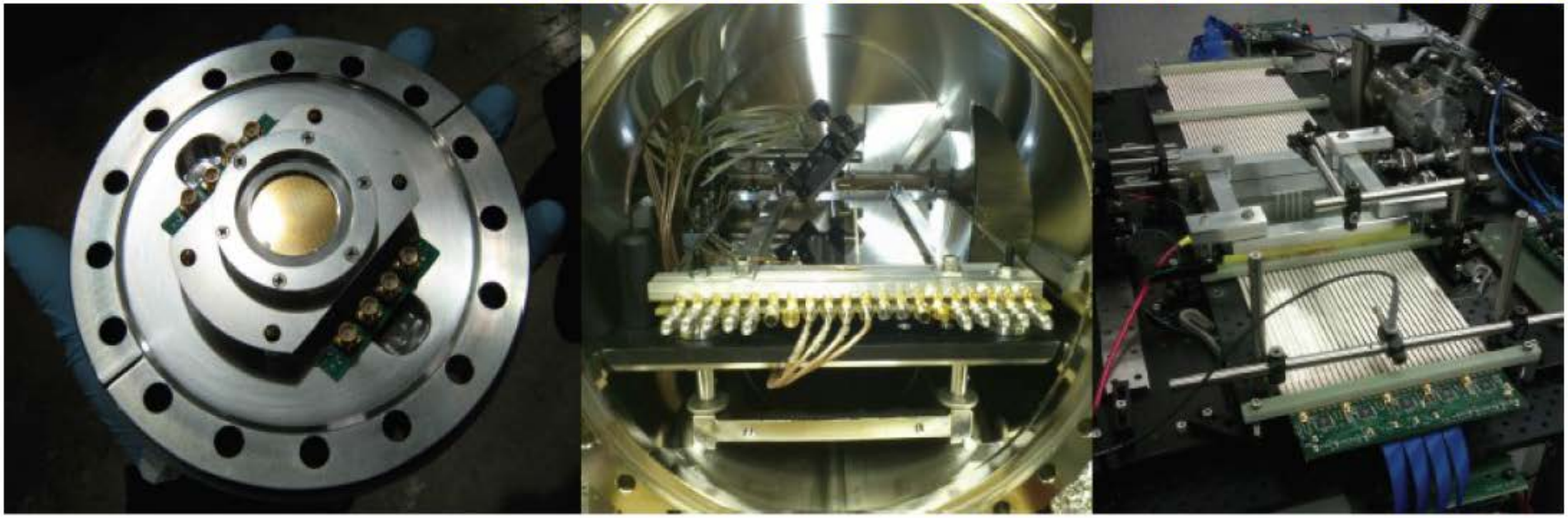


UV 'burn-in' of ALD MCP pair 164-163 compared with conventional MCPs

Detector Timing: Advanced Photon Source laser lab @ ANL

Andrey Elagin slide

B.Adams, A.E., E.Oberla, R.Obaid, A.Vostrikov, M.Wetstein



33mm Testing

- Operational experience
- Testing fundamental properties of MCPs
- Study wide variety of sample prototypes

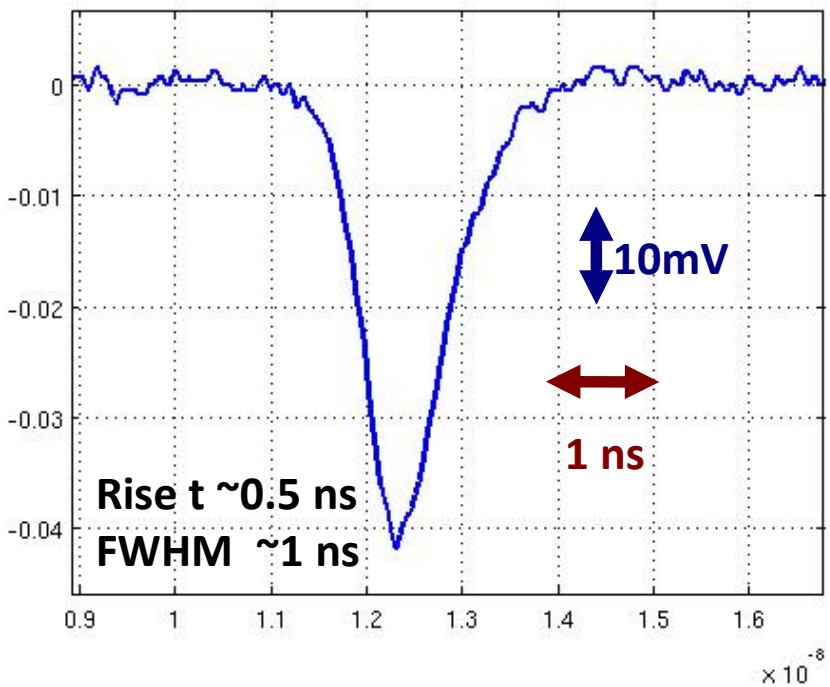
8" Testing

- 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

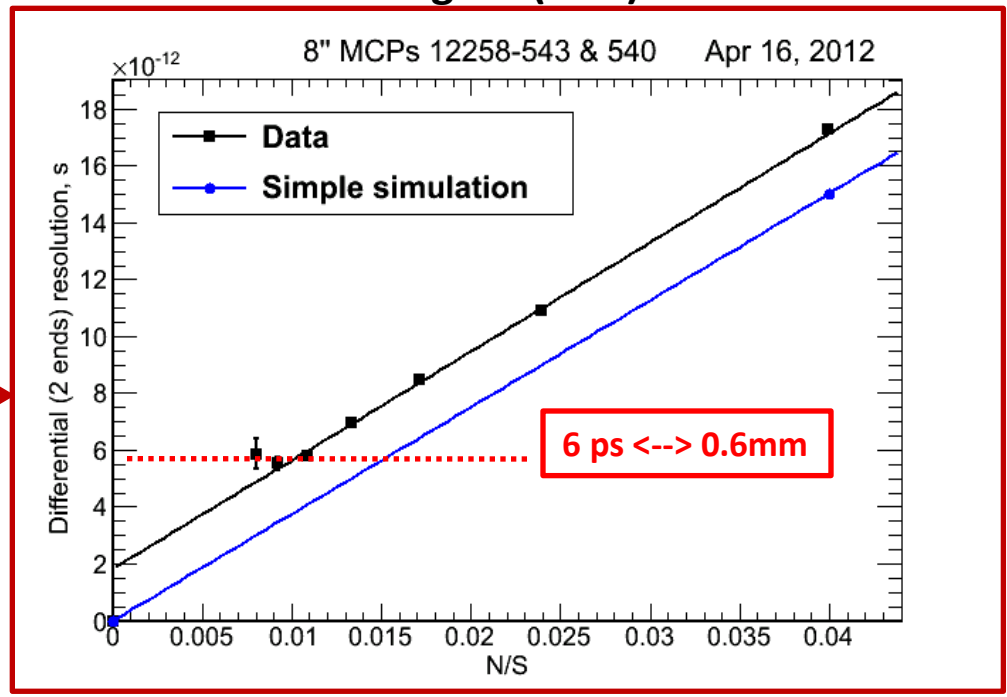
MCP pulses and timing extraction



Timing analysis approach:

1) **Record full waveform (scope/ASIC)**
2) **Waveform feature extraction**
   - Minimal extraction in firmware (ASIC)
   - Full waveform fits/ noise filtering in software (ASIC/commercial scope)

Differential timing vs. $(SNR)^{-1}$:



Time resolution determinants:

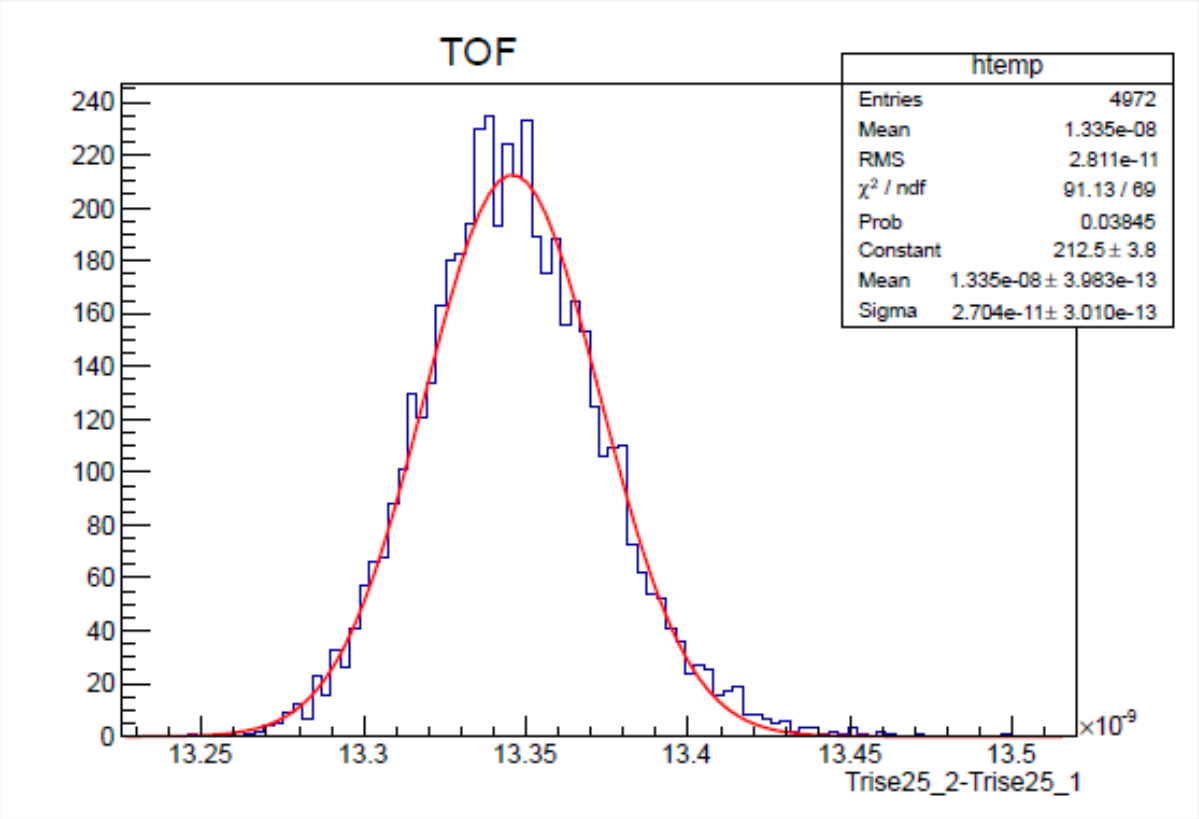
1) Signal to noise
2) Analog Bandwidth
3) Sampling rate
4) Signal statistics

Time-of-flight resolution

LAPPD Collaboration

8” detector + 10 Gsa/s commercial oscilloscope
~few p.e.’s
Full waveform time extraction (filter+fit) [S. Vostrikov, et al]

$$\Delta T = 27.04 \text{ psec}$$

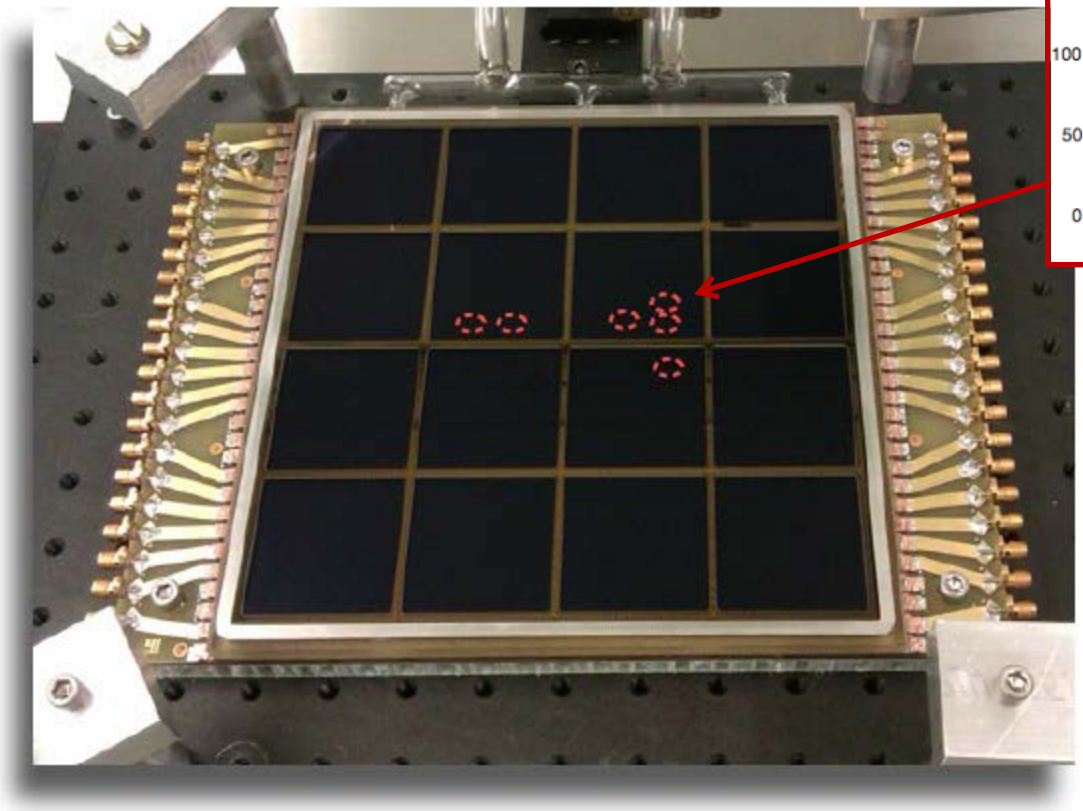


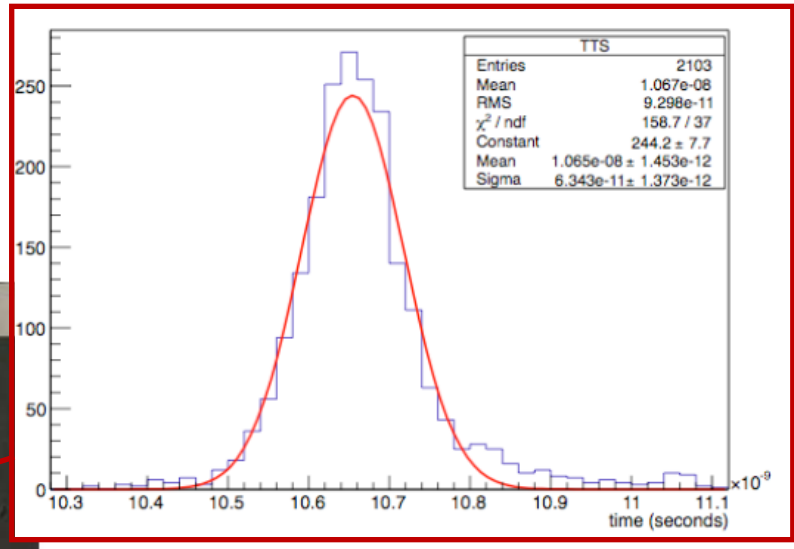
Time-of-flight resolution

LAPPD Collaboration

Single PE time resolutions at many positions on the 8” MCPs

Consistently better than 80 picoseconds



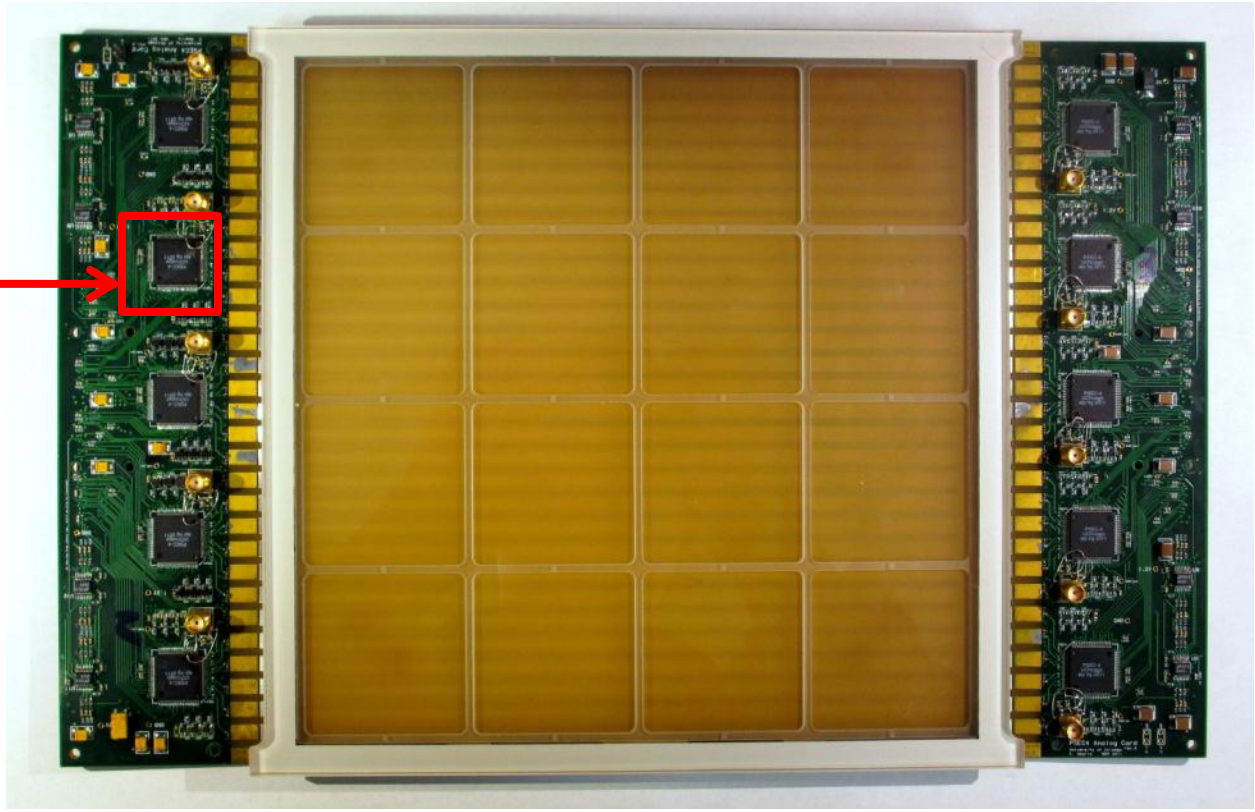


Full Detector System

LAPPD Collaboration

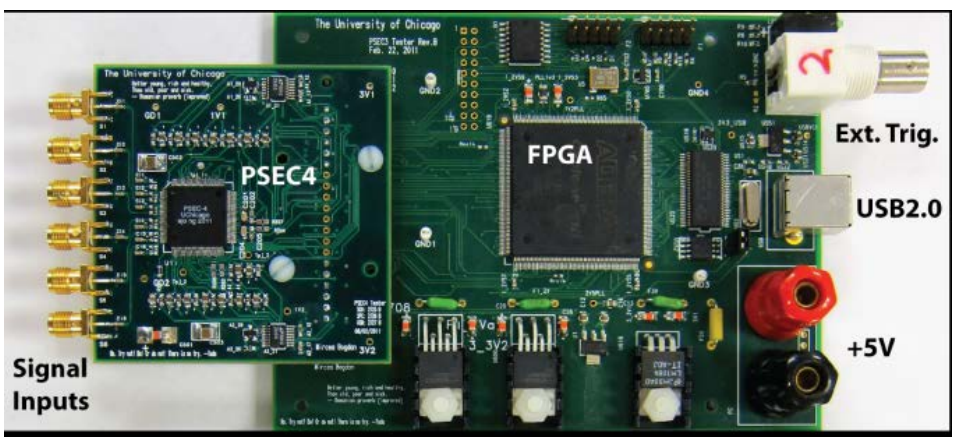
- So far, waveforms digitized with 4-channel commercial oscilloscope **(10 Gsa/s per channel, 15 GHz analog bandwidth)**
- For a full LAPPD MCP tile readout, 60 channels of waveform recording is needed. Some tough specs:
  - **Keep up 10 Gsa/s sampling rate**
  - **Preserve as much bandwidth as possible** (matched to microstrip anode and MCP risetime)

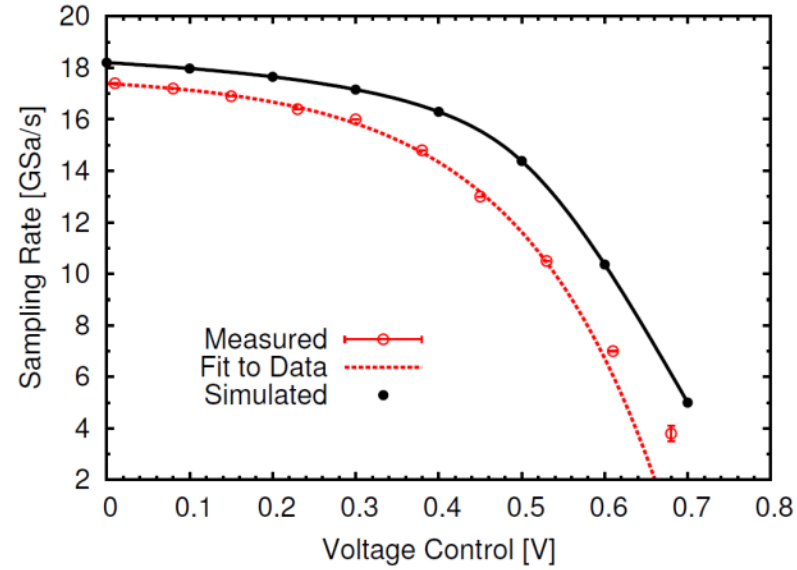
The custom PSEC4 waveform digitizer

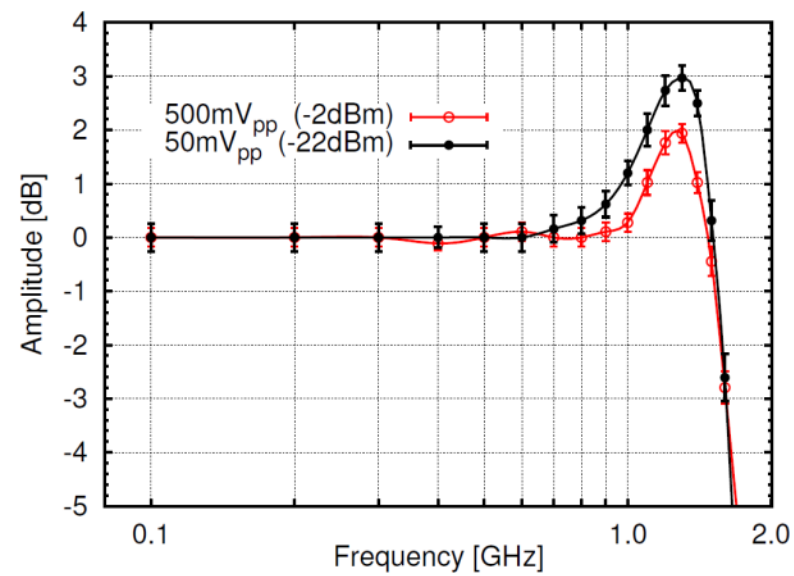


The PSEC4 ASIC [0.13 µm CMOS]

	ACTUAL PERFORMANCE
Sampling Rate	2.5-15 GSa/s
# Channels	6
Sampling Depth	256 points (17-100 ns) per channel
Input Noise	<1 mV RMS
Analog Bandwidth	1.5 GHz (f_{3dB})
ADC conversion (ramp-compare)	Up to 12 bit (10.5 ENOB) clocked @ 1.6 GHz
Dynamic Range	0.1-1.1 V
Readout Latency	2 µs (min) – 16 µs (max)
Power	20mW/channel
Cost	~20$/channel in quantity



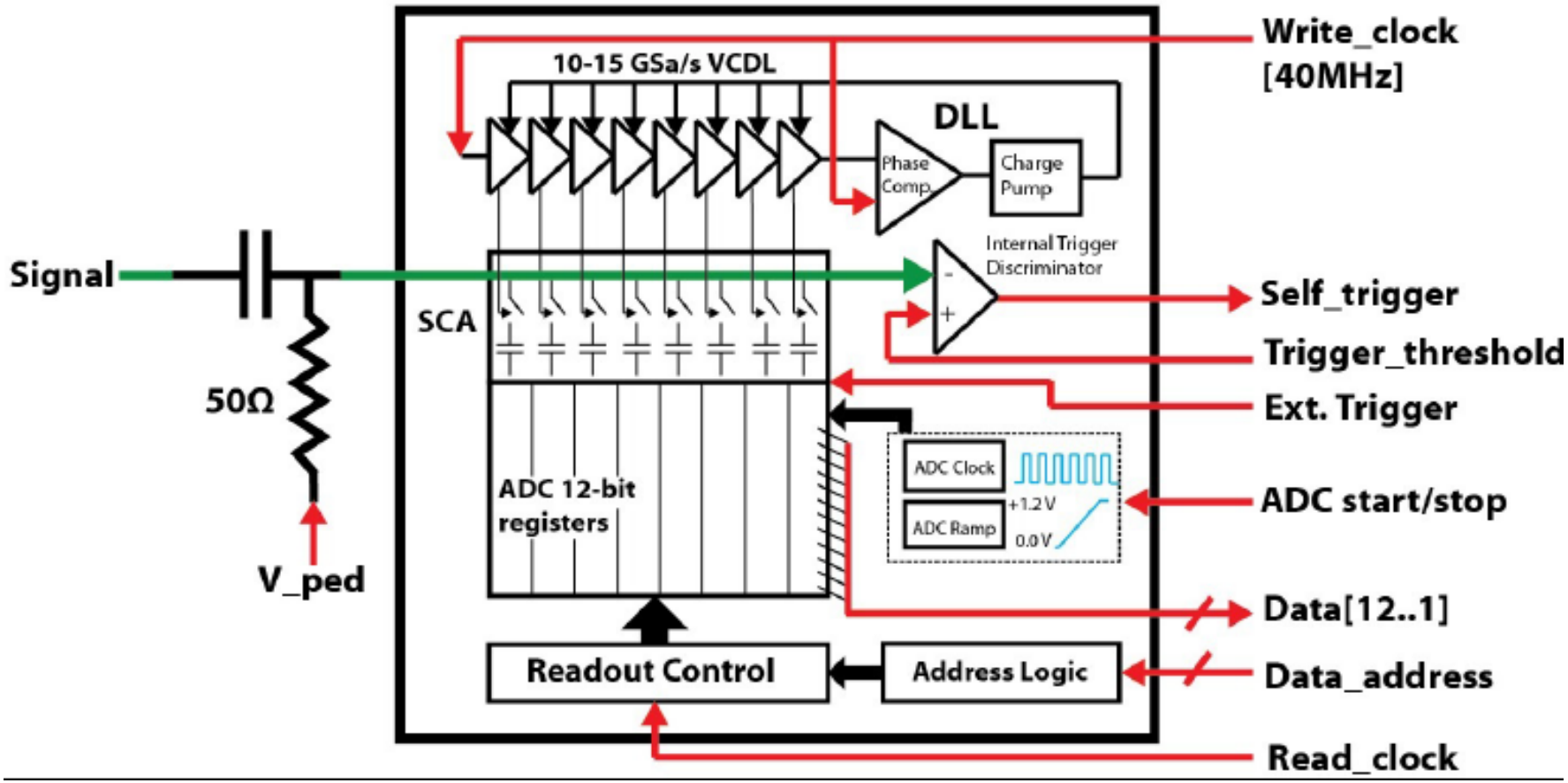




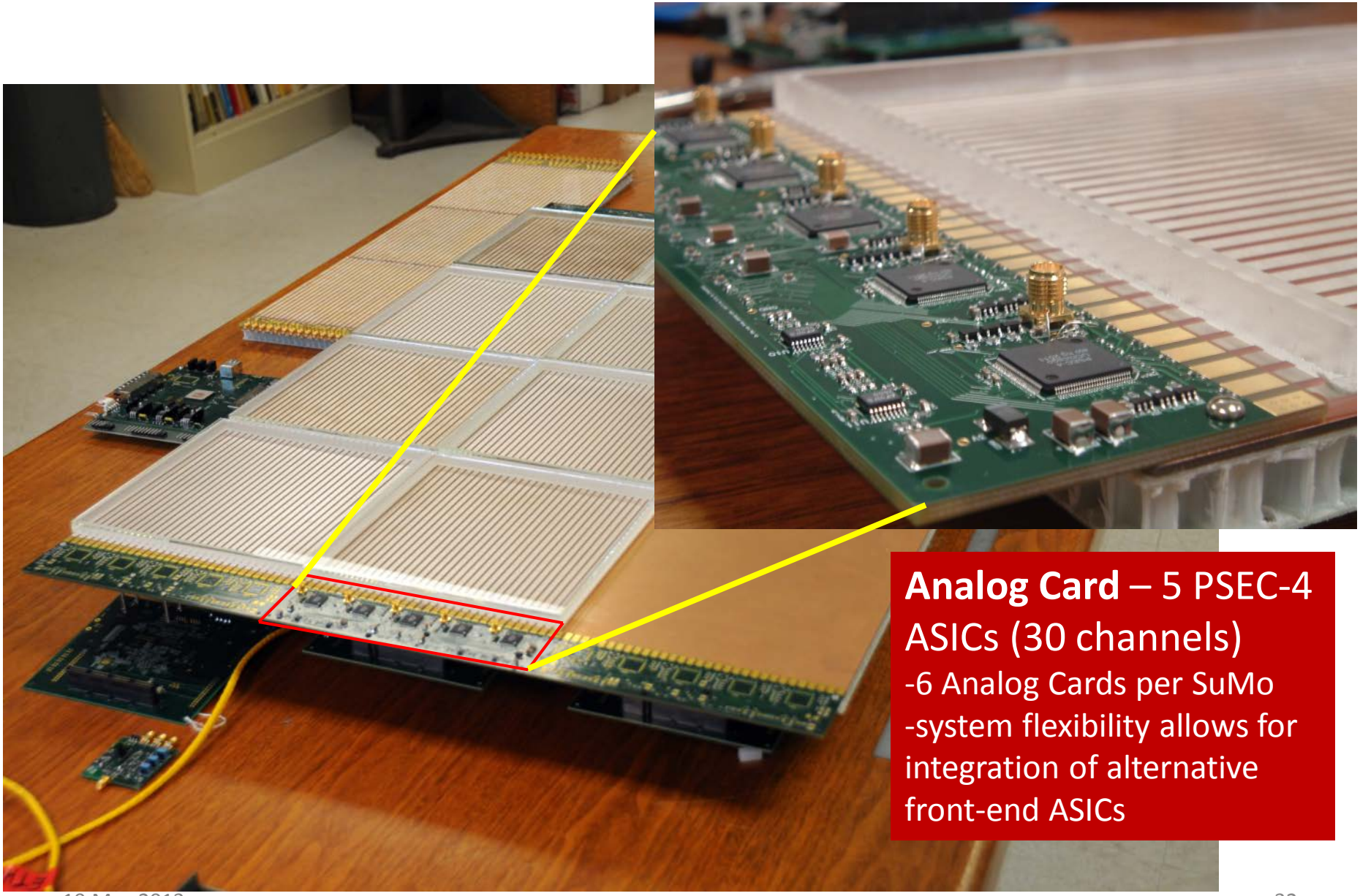
The PSEC4 ASIC

10-15 Gsa/s Switched capacitor array sampling: ***'analog down-conversion'***

[GHz sampling→ 10-100 MHz readout: useful in most 'triggered event' applications]



PSEC4 detector-integrated DAQ

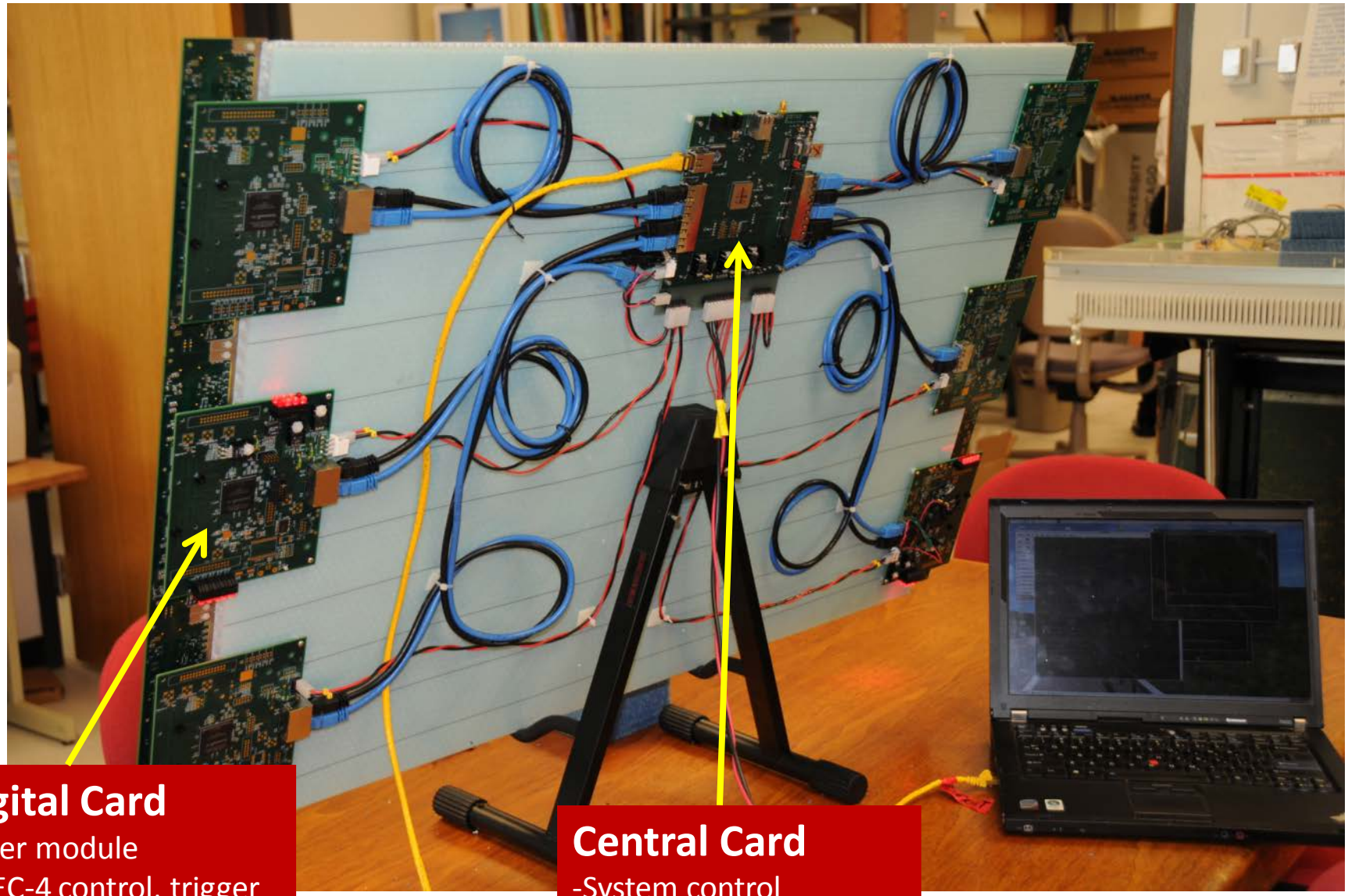


Analog Card – 5 PSEC-4 ASICs (30 channels)

-6 Analog Cards per SuMo

-system flexibility allows for integration of alternative front-end ASICs

PSEC4 detector-integrated DAQ

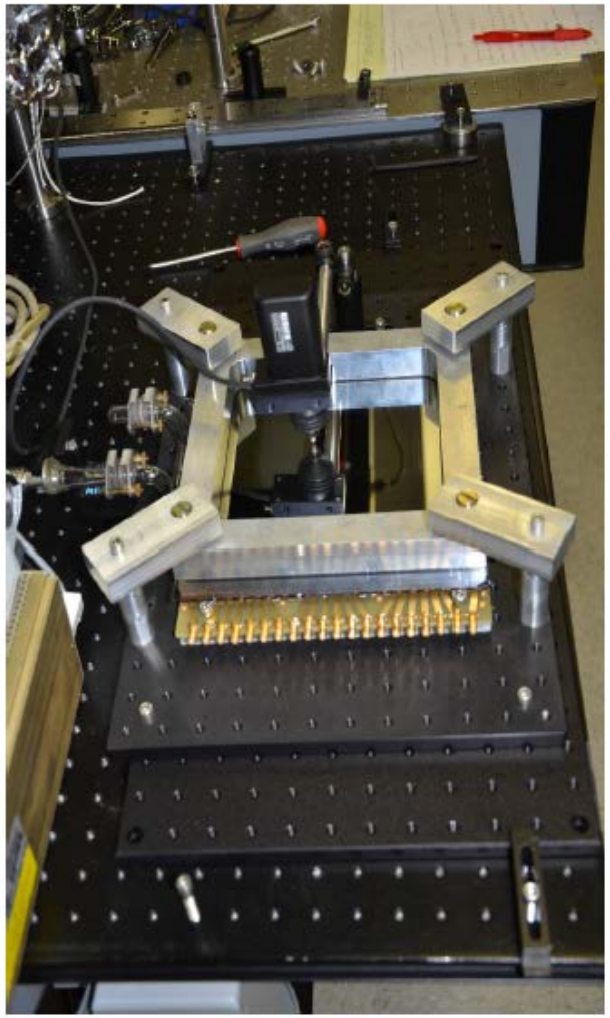


Digital Card
-6 per module
-PSEC-4 control, trigger handling, local data reduction & calibration

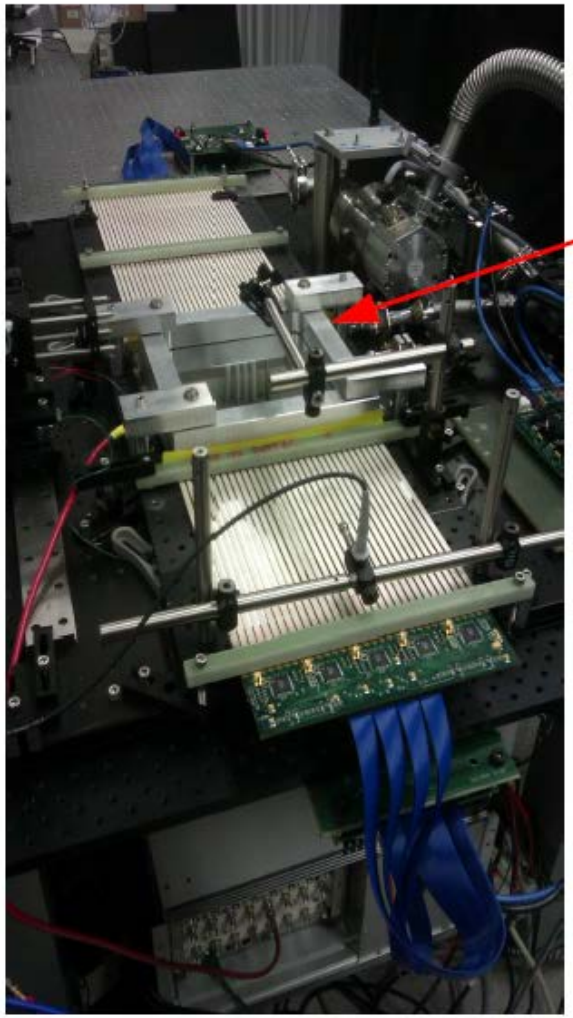
Central Card
-System control
-Feature extraction
-CPU/GPU interface (Triple Speed Ethernet & USB 2.0)

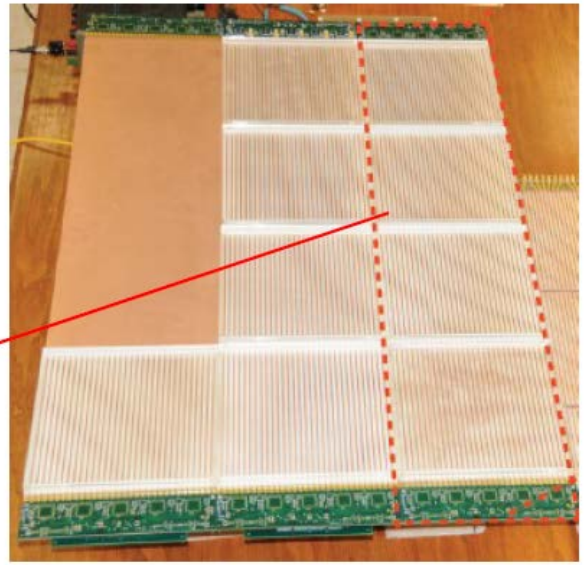
Full System Testing: the "Demountable"

Demountable 1.0 (May 2012)



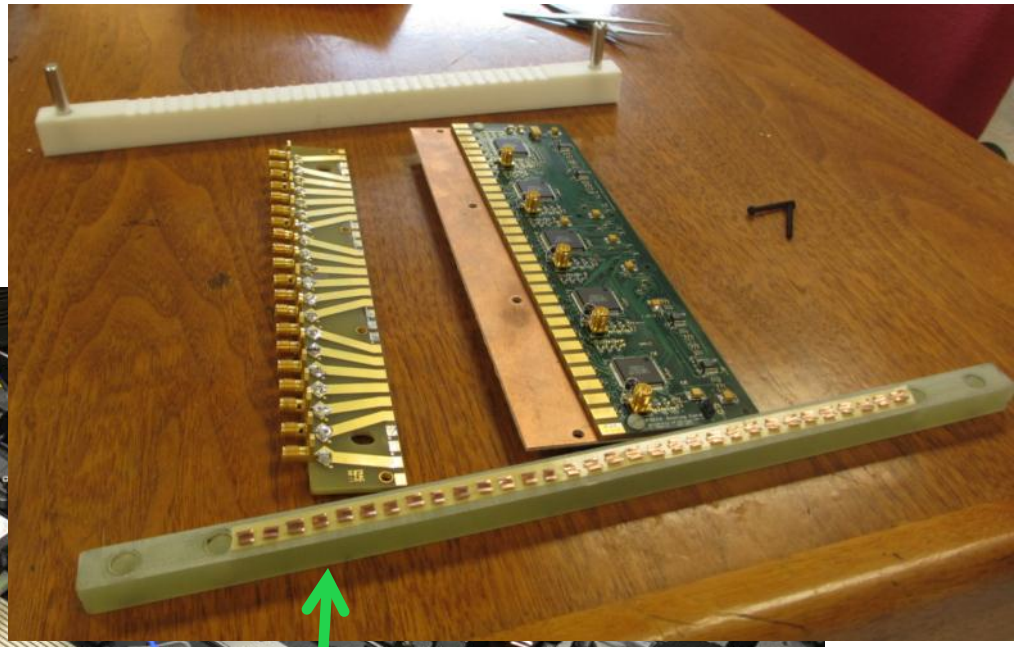
Demountable 3.0 (Sep-Dec 2012)

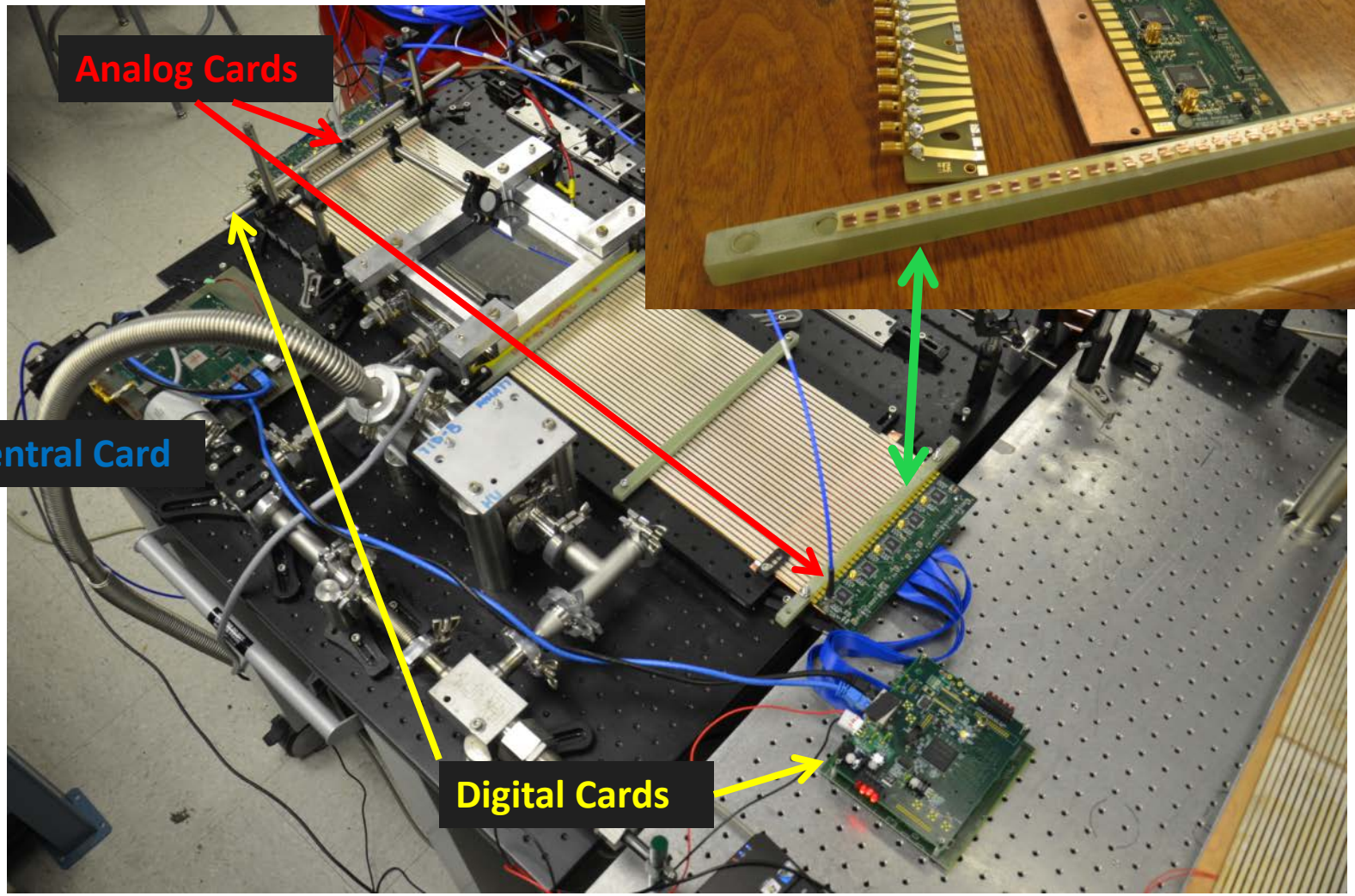




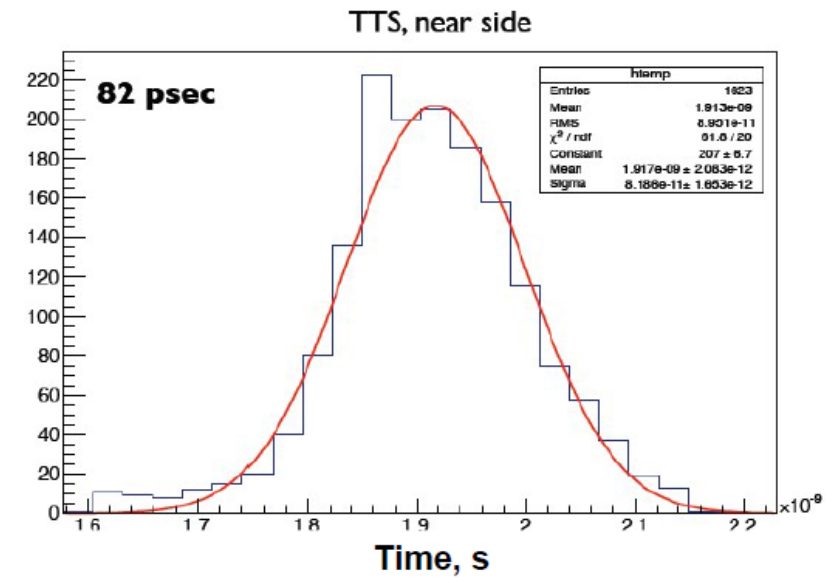
The Demountable:
A full 90 cm anode with a single 8"x8" active MCP tile. The tile is hermitically sealed with a repeatable compression o-ring. The photocathode is Al.

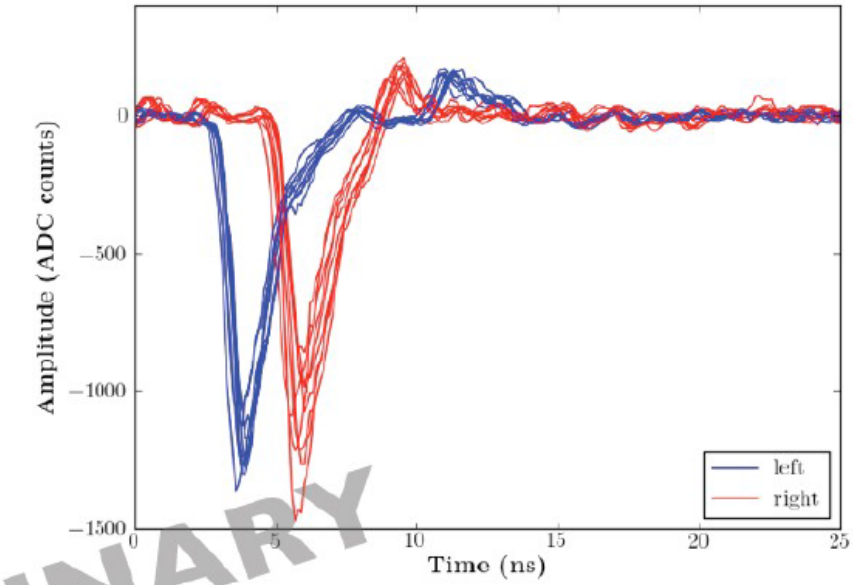
BeCu RF fingerstock used to make anode-anode/anode-electronics electrical connection

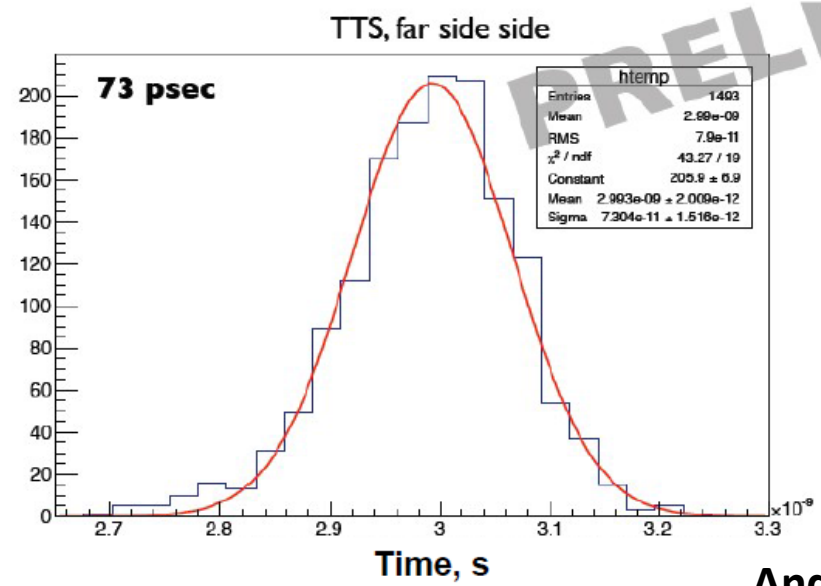


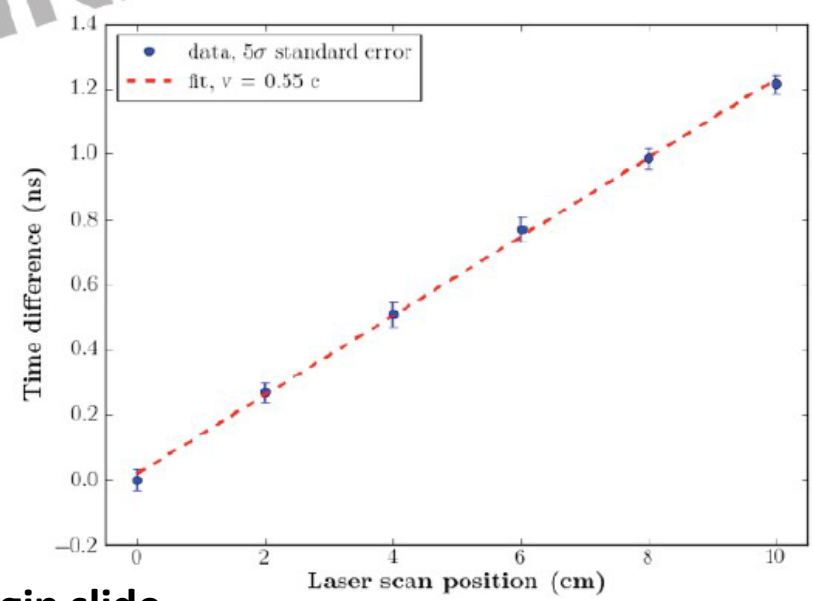


Full System Testing: the "Demountable"



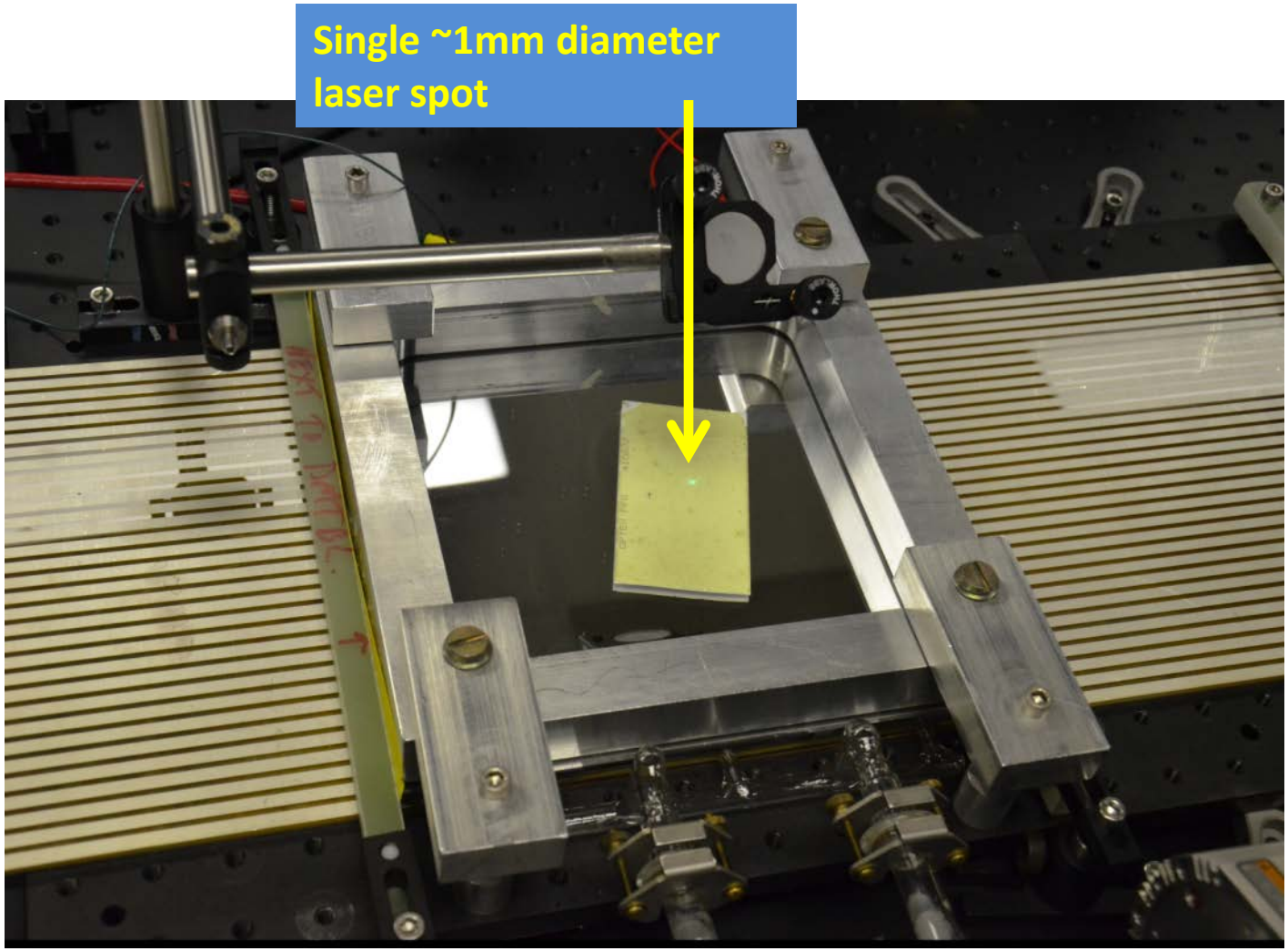




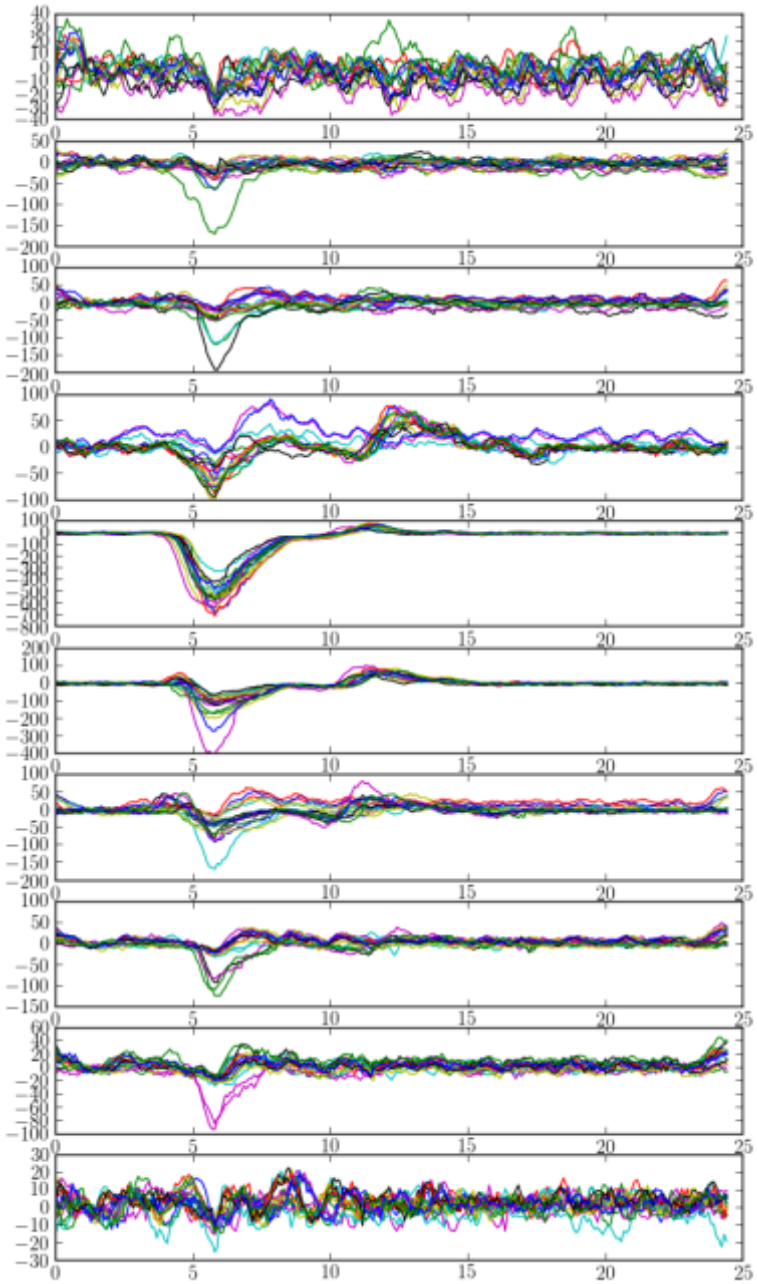


Andrey Elagin slide

Full System Testing: the "Demountable"

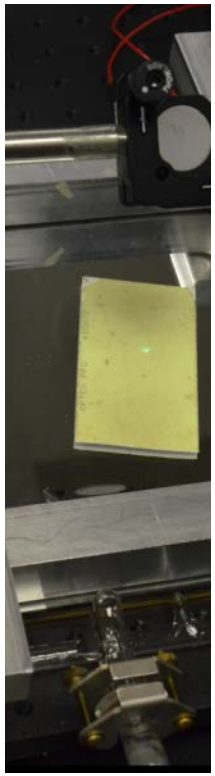


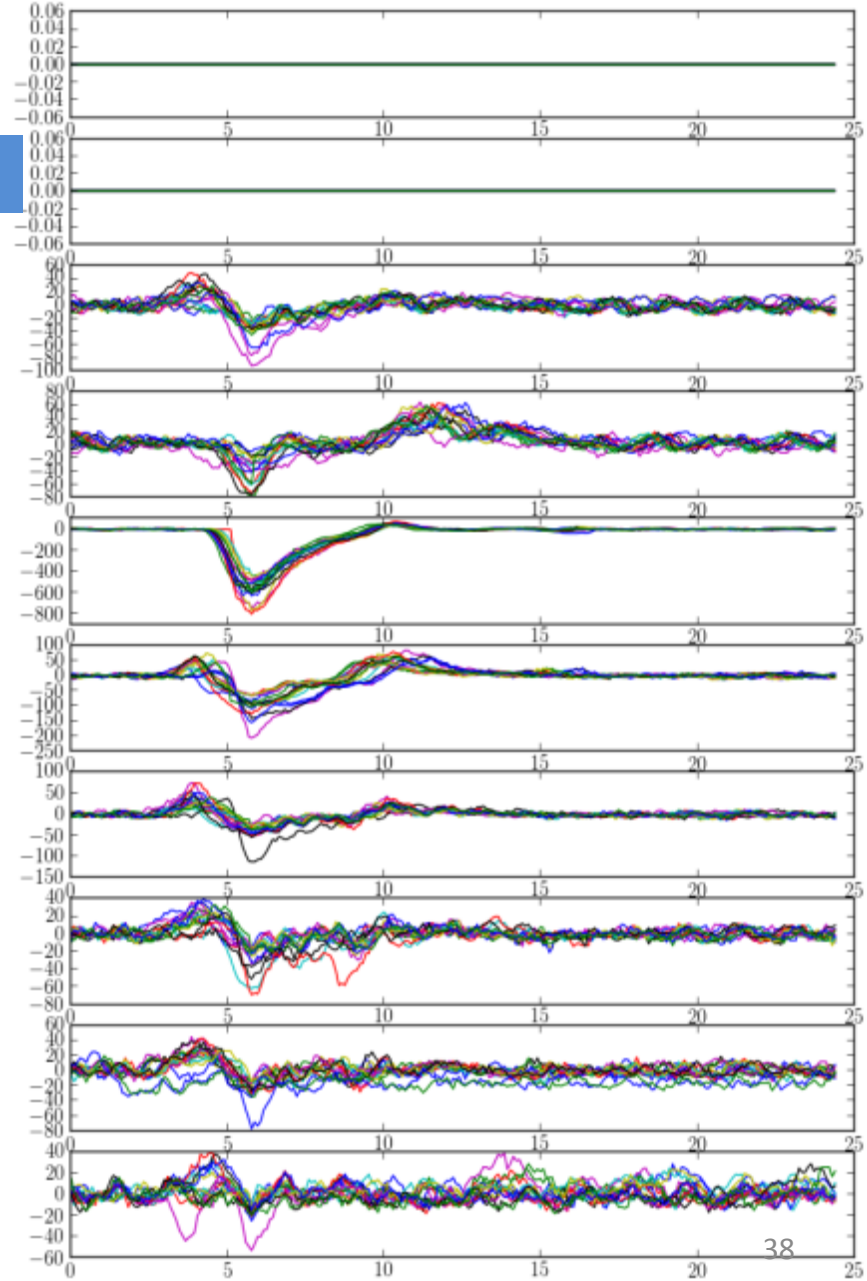
Full System Testing: the “Demountable”



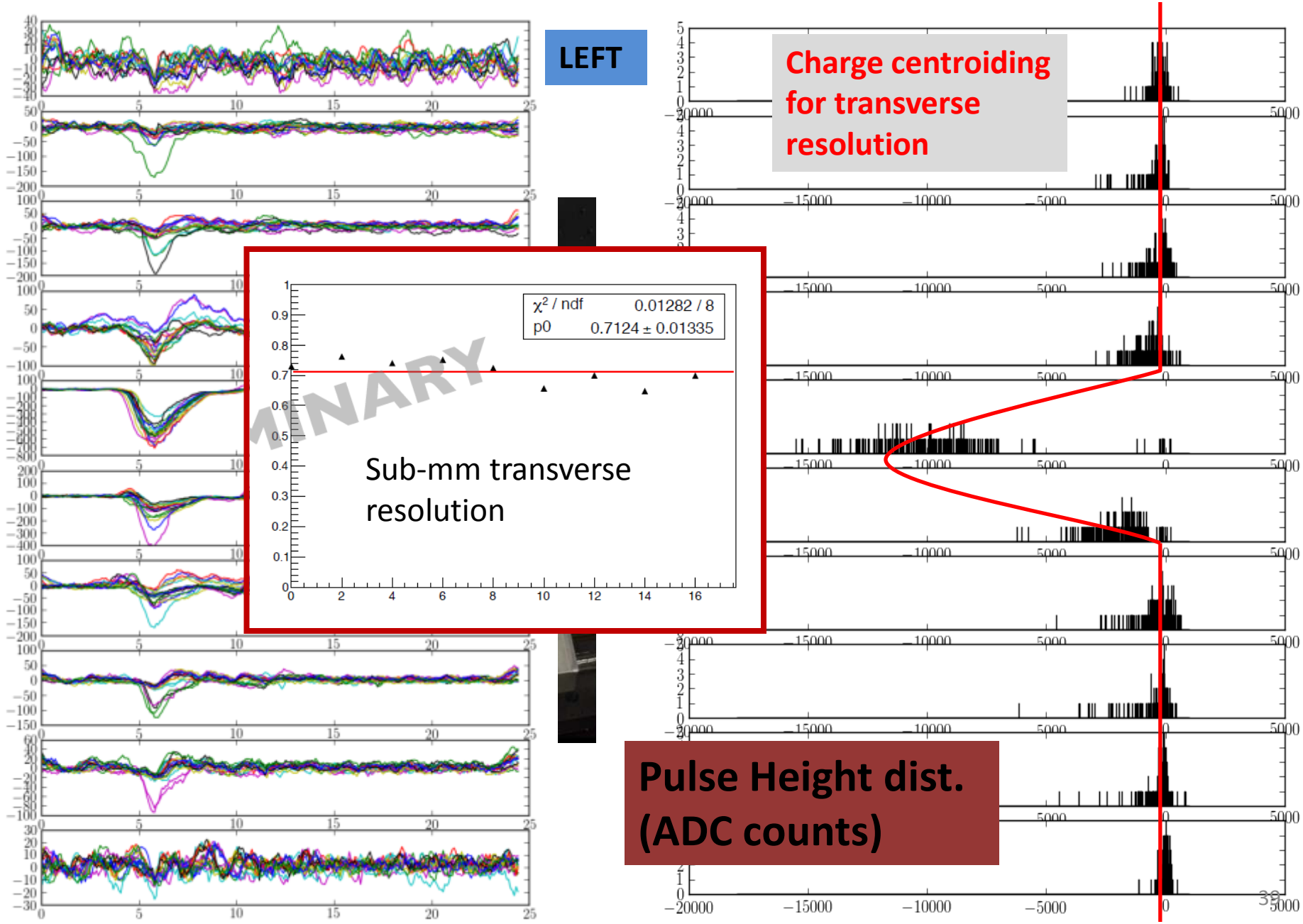
LEFT

RIGHT





Full System Testing: the "Demountable"



Summary and plans

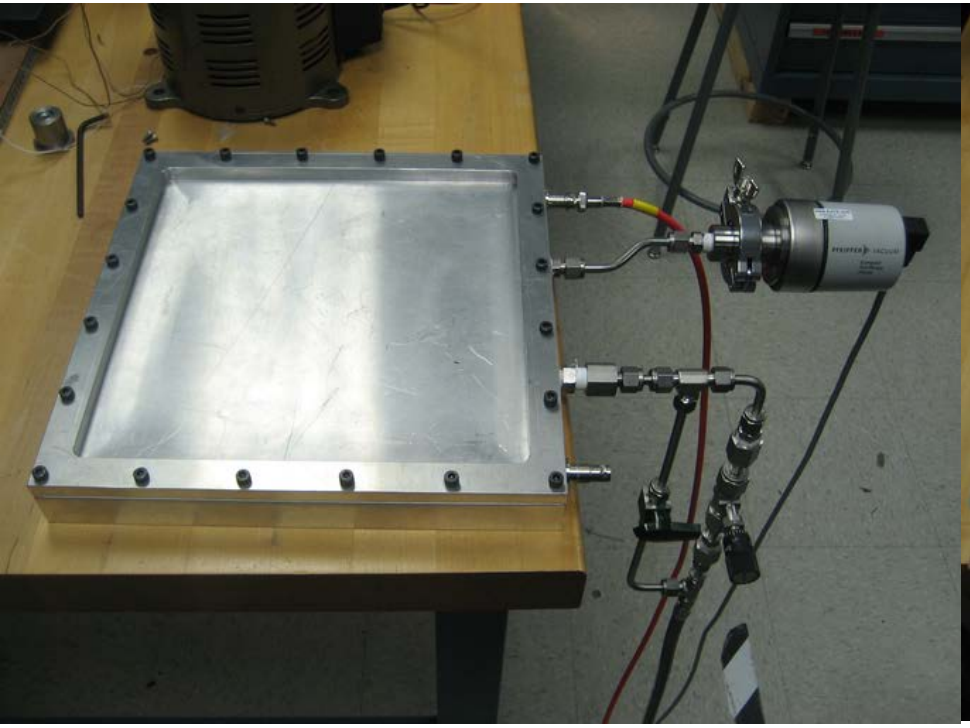
LAPPD Collaboration

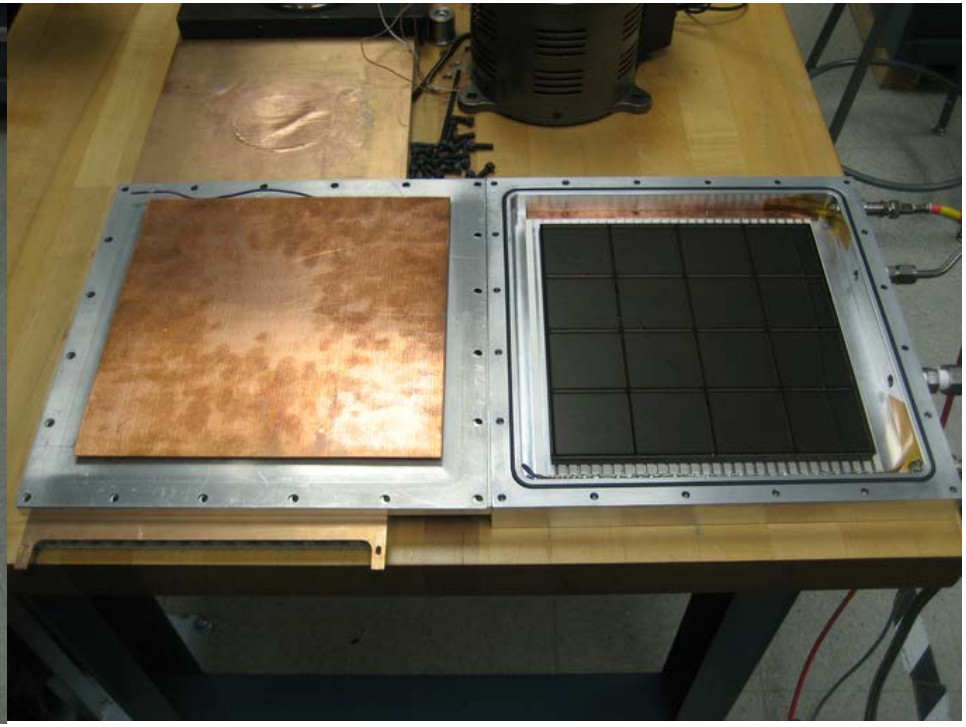
- Complete, (compression) sealed Glass packaged 8” MCP tile:
  - ~50 ps single photoelectron TOF
  - ~5-10 ps differential timing resolution (= 0.5-1mm parallel resolution)
  - ~1 mm transverse resolution
  - Gain and resolutions are uniform across entire 64 sq. inch (400 sq. cm) MCP area
- A full DAQ system with the PSEC4 ASIC is functional and performing well. Such a system will be available to ‘first adopters’.
  - It’s expected that any dedicated users will develop their own electronics for a specific experiment
  - PSEC5 design (10 Gsa/s & ~2+ microsecond buffer depth) in planning stages
- **The immediate goal of the LAPPD group is producing a standalone sealed tube (~6 months) – not there yet.**

Summary and plans

- LAPPDs and cosmic frontier?

The LAPPD **ISS***





[Bob Metz, Rich Northrup, et al]

* ‘international spacer station’

8” 20µm MCP Pair High Resolution Gain Map

Bottom MCP Bias direction

Top MCP Bias direction

MCP 13600 – 016, 102 MΩ – Top

MCP 13600 - 016, 109 MΩ - Bottom

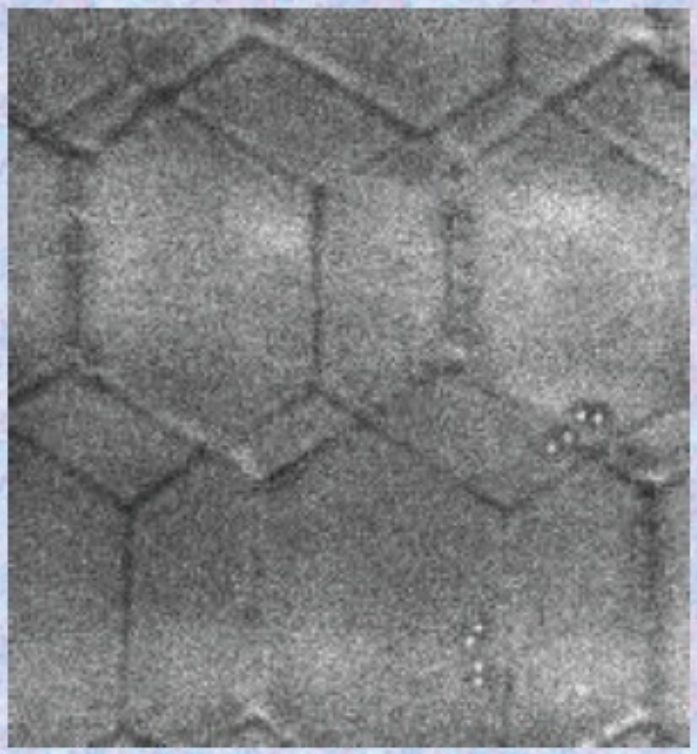
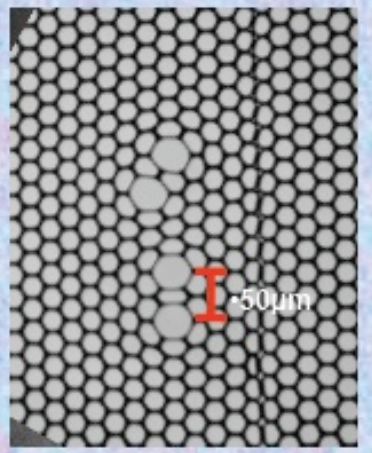
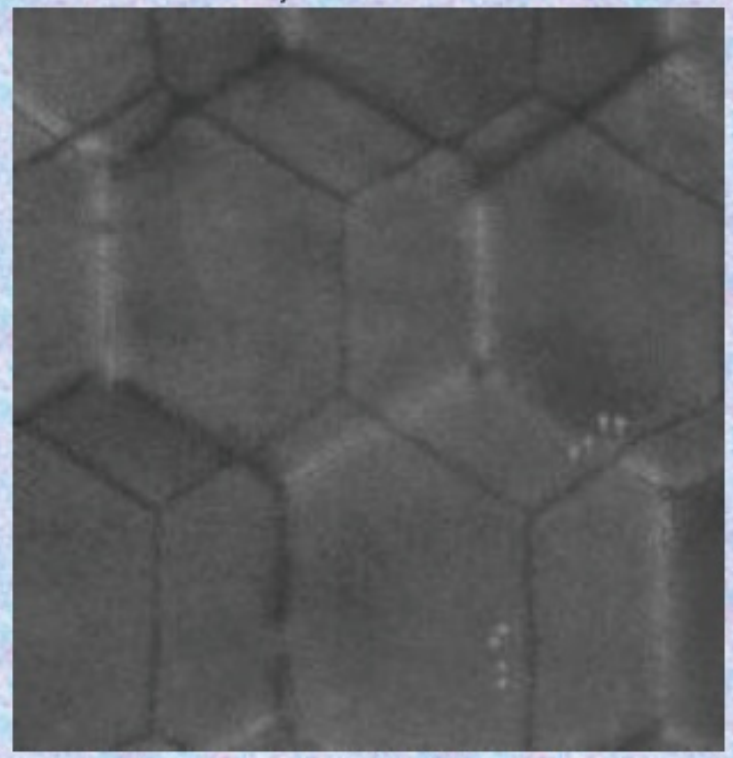


Image with 12µm pixels





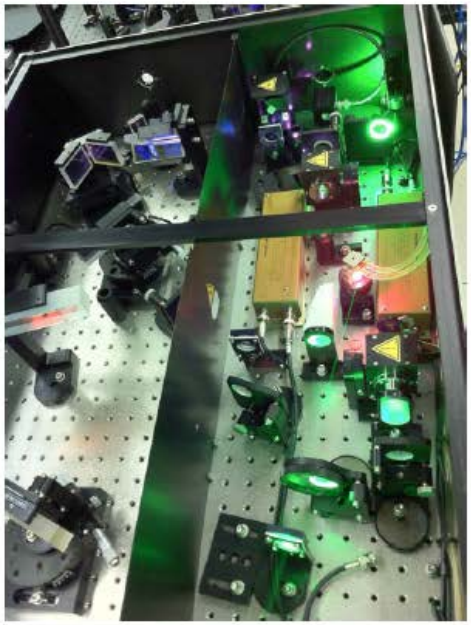
Gain map with 12µm pixels

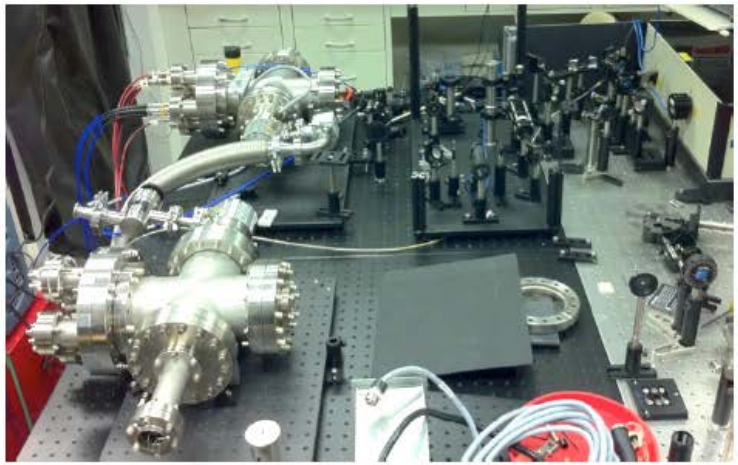
The repeating four large pore pattern is resolved and shows they have higher gain and higher Brightness, effectively 40µm pores with 30:1 L/D.

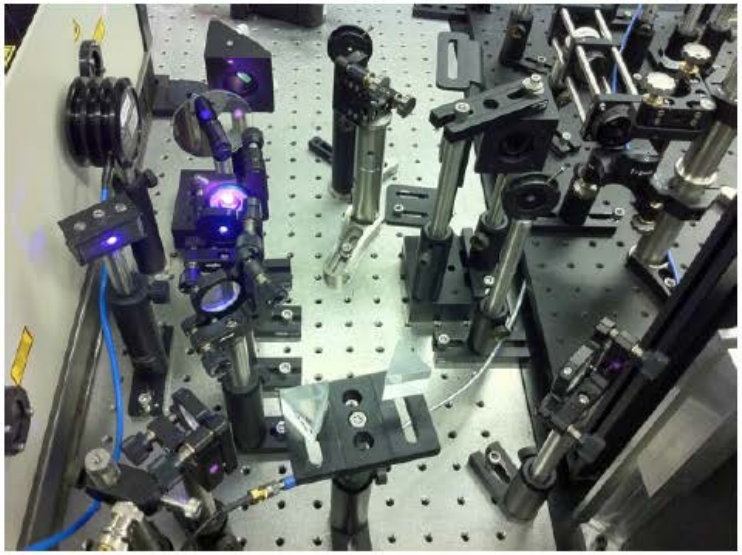
[O. Siegmund, et al]

What we've built

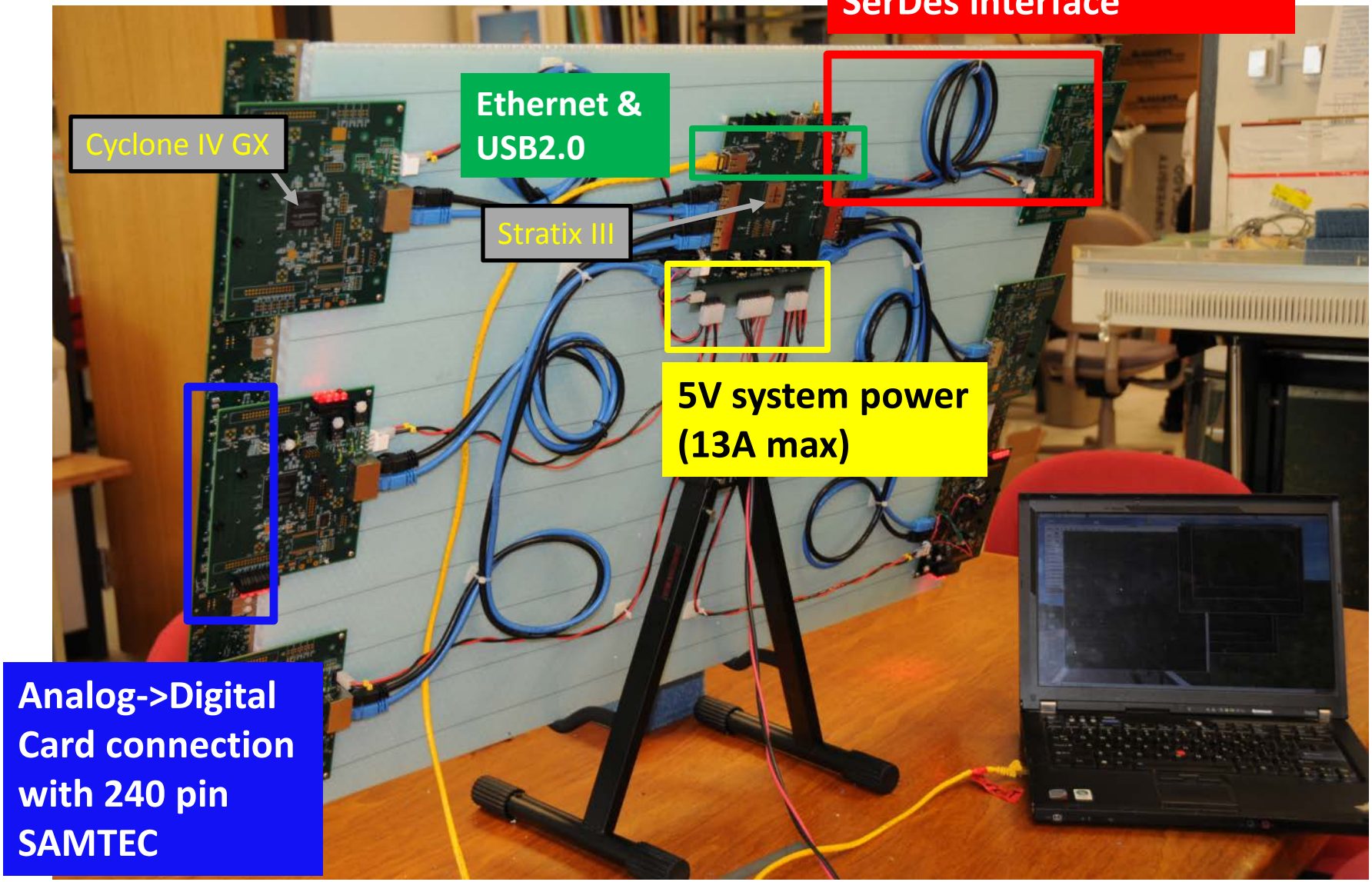
- A fast (sub-psec), pulsed laser with precision UV optics, capable of
  - Precision timing measurements using the laser as an external trigger
  - Finding single-PE mode by attenuating laser to the point where only a small fraction of pulses produce any signal
  - capable of illuminating small spots on the MCP (potentially single pores)
- multi-GHz RF electronics
  - several oscilloscopes with 3-10 Gz analog bandwidth
  - high gain, low noise RF amplifiers
  - high-frequency splitters, filters, etc
- Vacuum systems for testing various detector components
- Capability for testing sealed tubes
- Manpower, expertise, and software





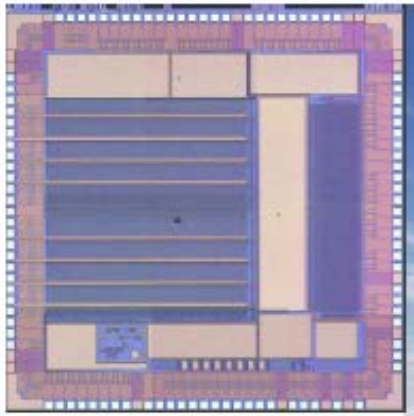


Super Module: features

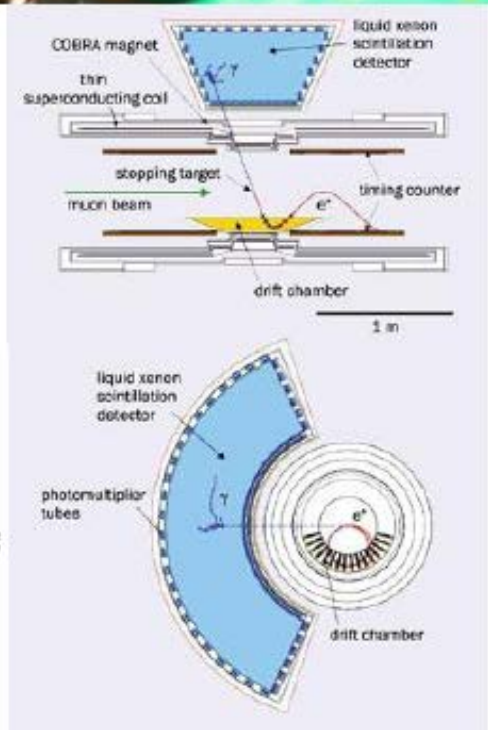


Waveform Sampling ASICs

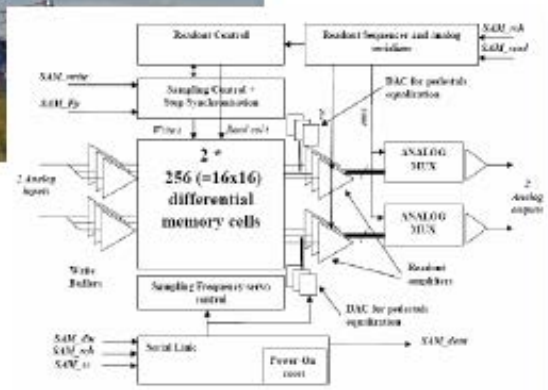
- Already in use in many experiments…



LABRADOR3,
ANITA Experiment



DRS4,
MEG Experiment



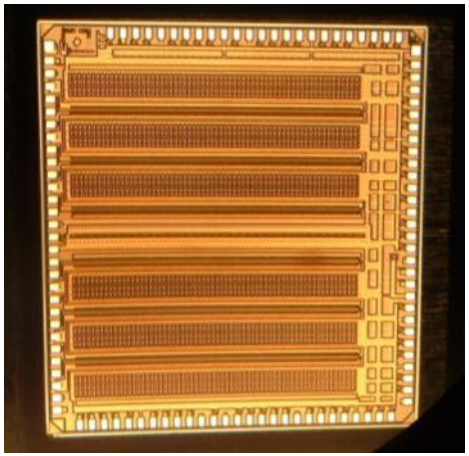
SAM,
H.E.S.S.-II

Waveform samplers 'on the market':

ASIC	Amplification?	# chan	Depth/chan	Sampling [GSa/s]	Vendor	Size [nm]	Ext ADC?
DRS4	no.	8	1024	1-5	IBM	250	yes.
SAM	no.	2	1024	1-3	AMS	350	yes.
IRS2	no.	8	32536	1-4	TSMC	250	no.
BLAB3A	yes.	8	32536	1-4	TSMC	250	no.
TARGET	no.	16	4192	1-2.5	TSMC	250	no.
TARGET2	yes.	16	16384	1-2.5	TSMC	250	no.
TARGET3	no.	16	16384	1-2.5	TSMC	250	no.
PSEC3	no.	4	256	1-16	IBM	130	no.
PSEC4	no.	6	256	1-16	IBM	130	no.

2) **Performance:** calibrations

Oscilloscope on a chip? Not quite…a modified approximation:



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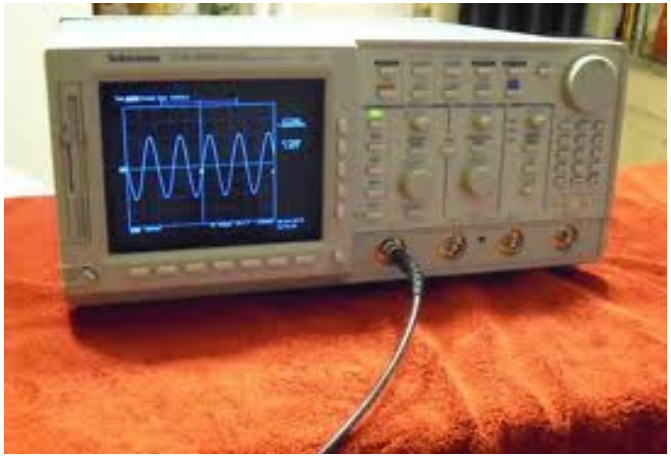
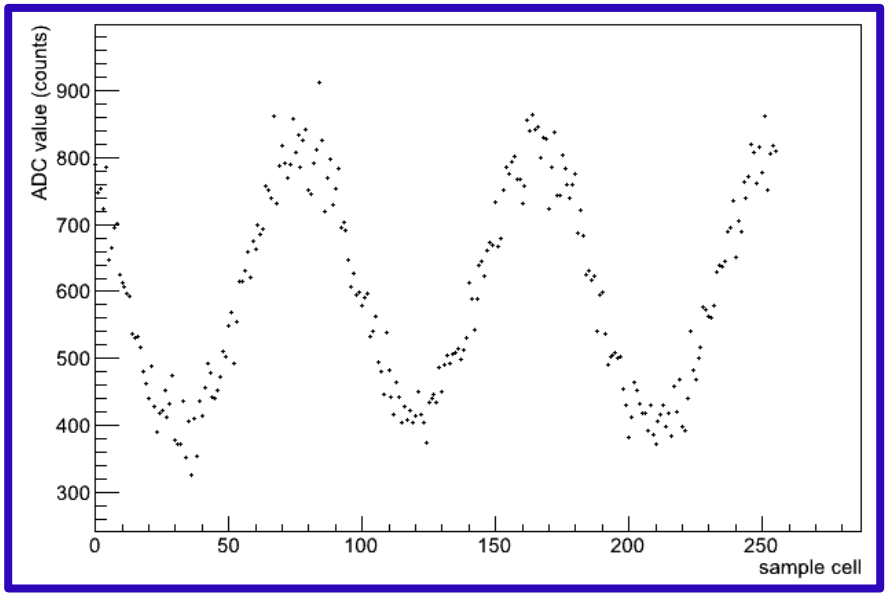
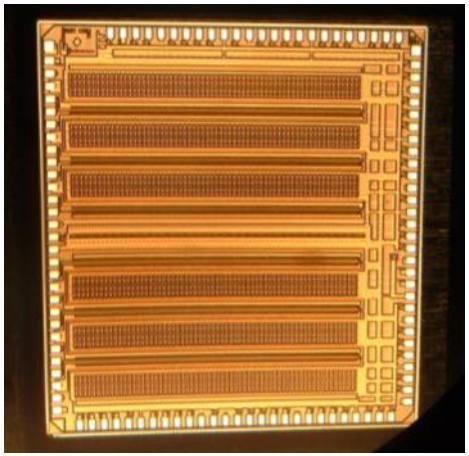


For example, a raw **PSEC-3** readout (10 GS/s) of 120 MHz, 150 mV_{rms} sine wave:



2) **Performance:** calibrations



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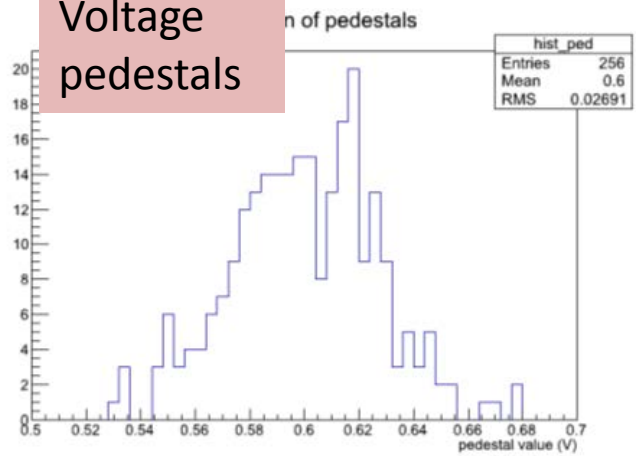
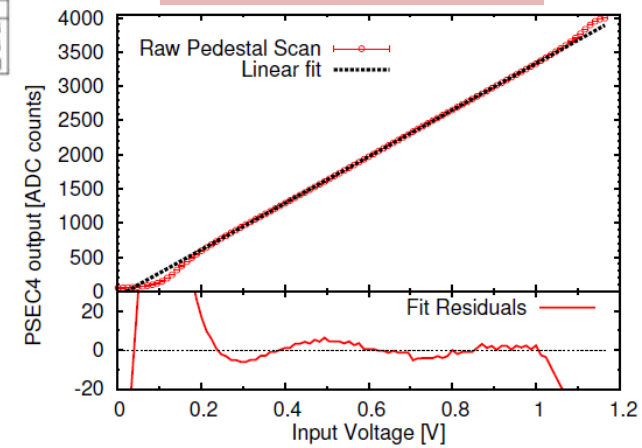
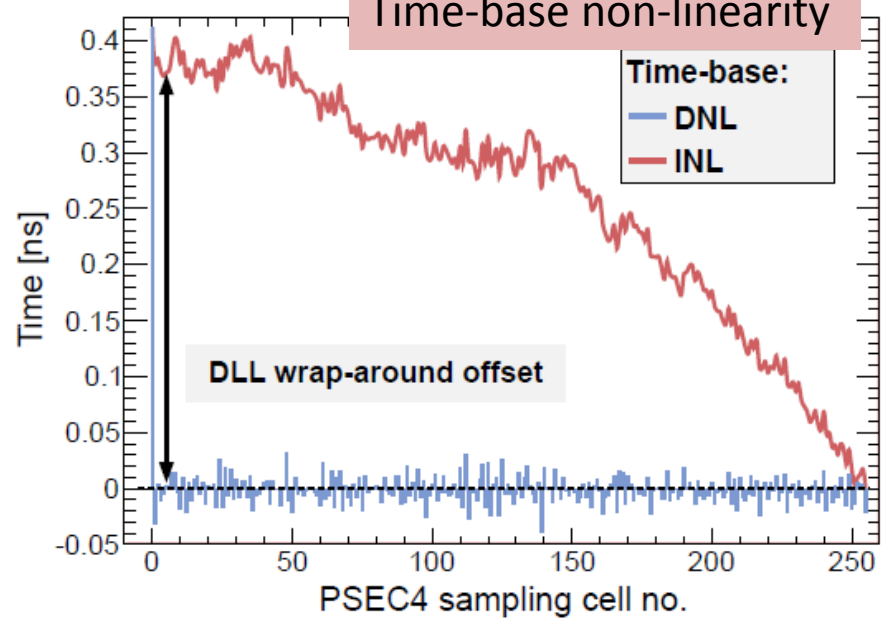
Voltage pedestals



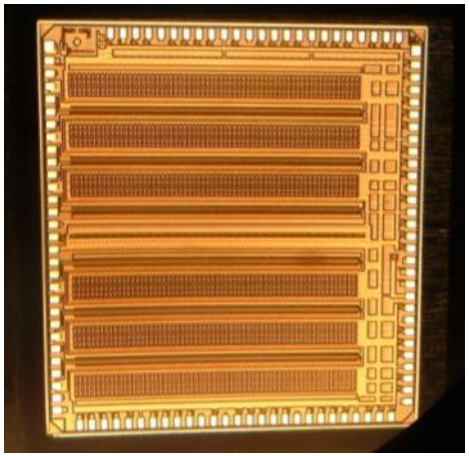
ADC non-linearity



Time-base non-linearity



2) **Performance:** calibrations



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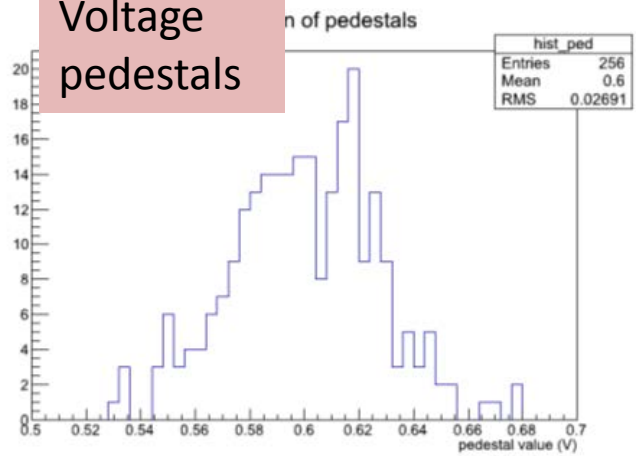
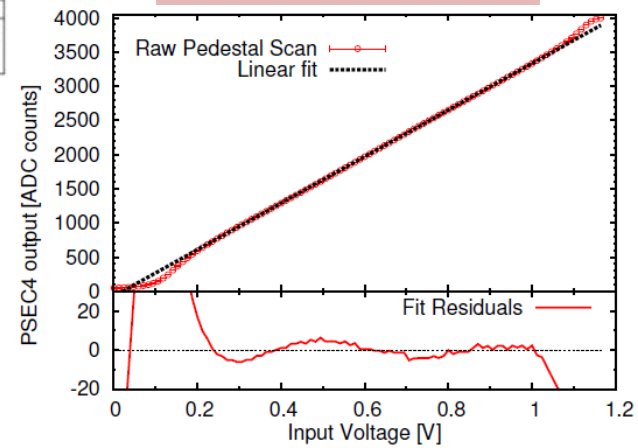
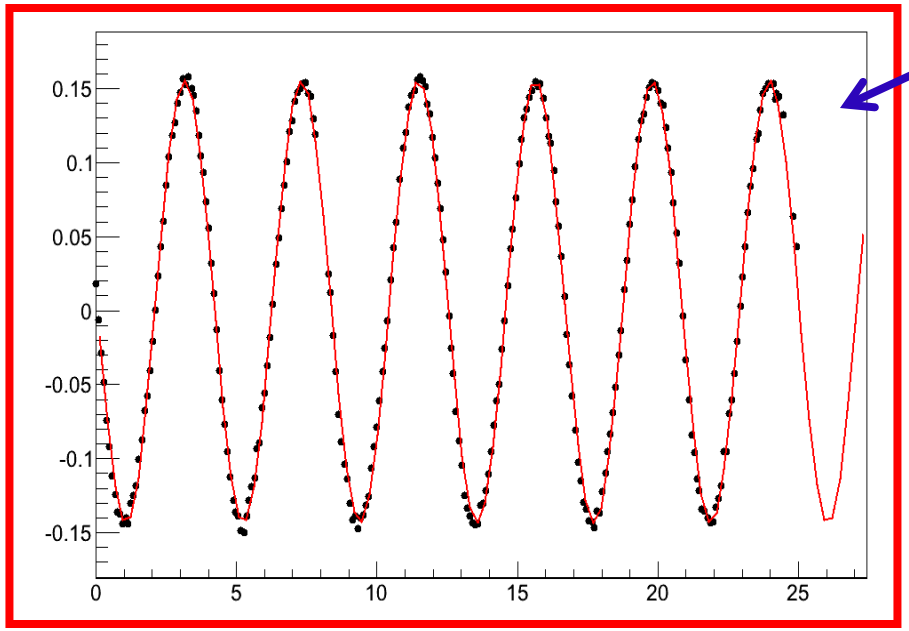
Voltage pedestals

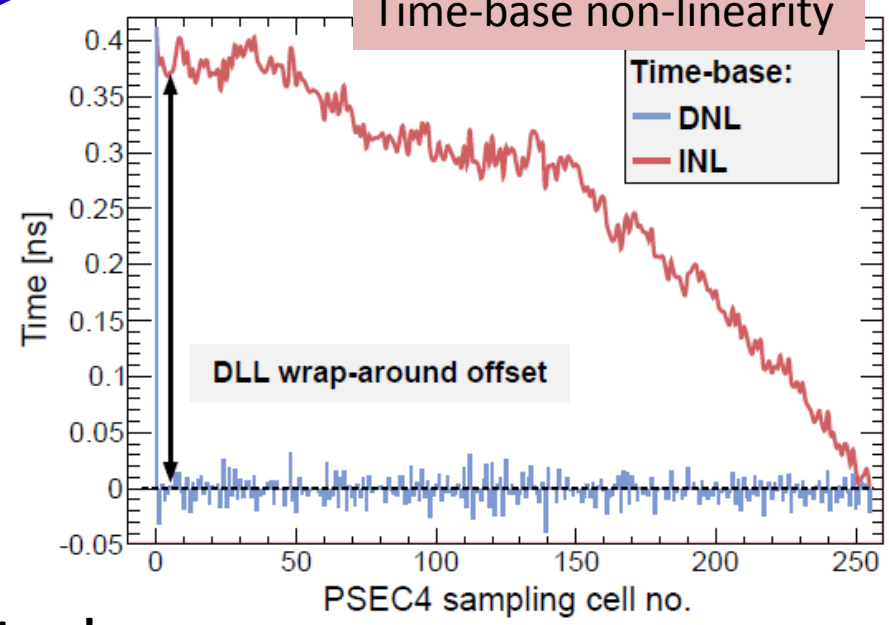


ADC non-linearity



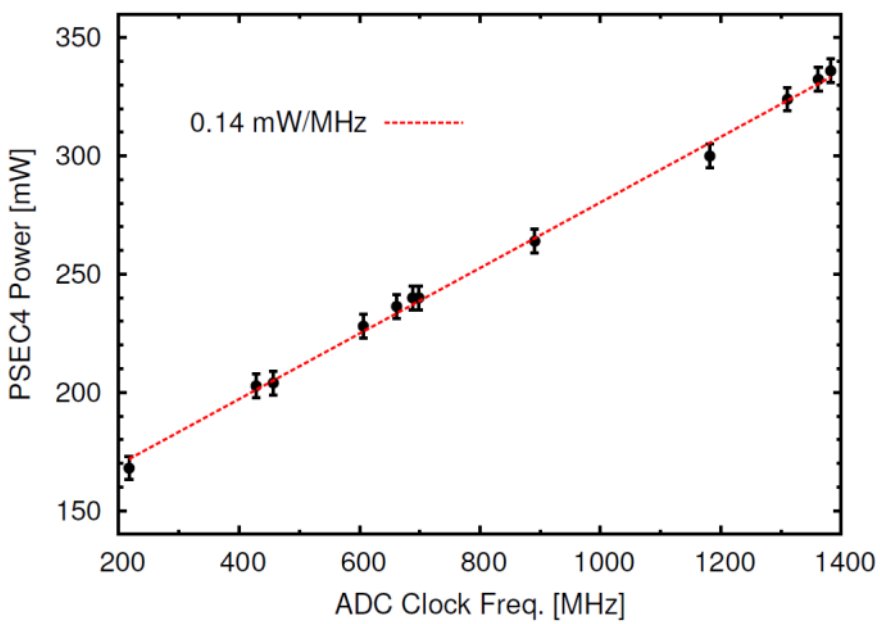


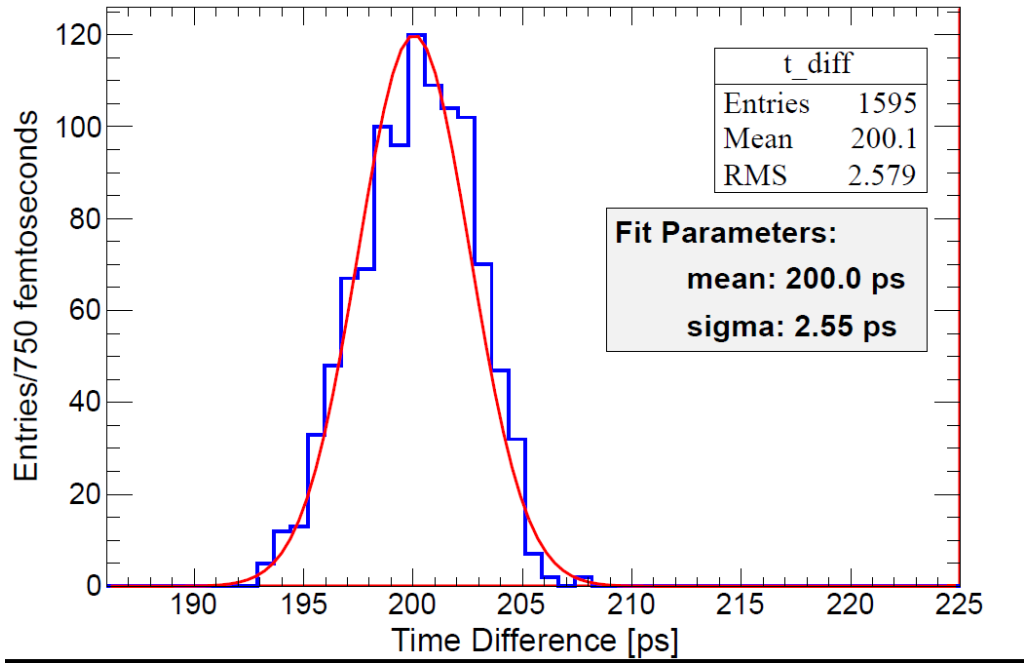
Time-base non-linearity



Want to minimize number of calibration steps!

Power and timing





240 MHz sine. Some AC non-linearity observed at peaks