Measurements of the Gain, Time Resolution and Spatial Resolution of a 20x20cm MCP-based Picosecond Photo-Detector

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University of Chicago

for the LAPPD Collaboration

Vienna 02/12/2013

Outline

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- Motivation
- LAPPD design concept
- LAPPD components

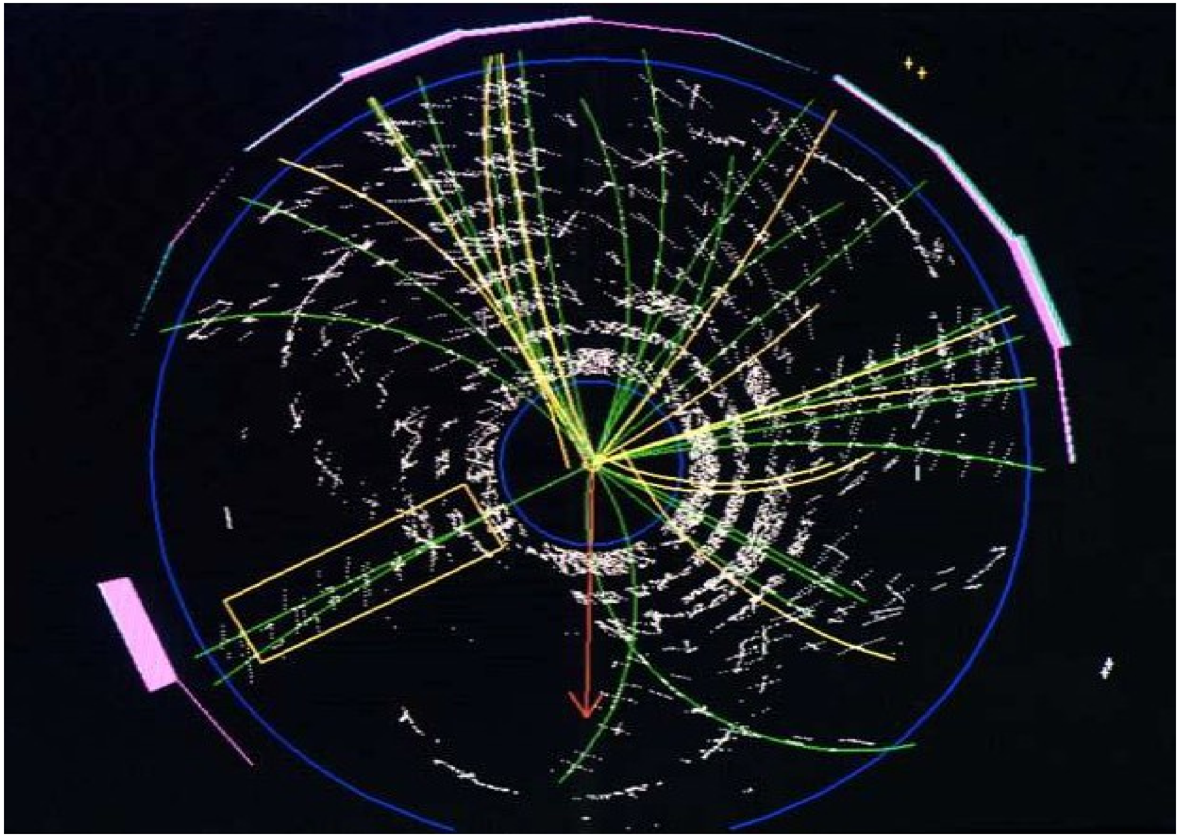
  - Micro-channel plates (MCPs)

  - Electronics
- System integration and testing
- Summary and plans

Colliders

„A jet is a narrow cone of hadrons and other particles..."

Can we be more specific about jets?
- quark content of charged particles
- 4-vectors



Need: ~1ps

Photons arrive first, followed by pions, kaons, etc.

Colliders

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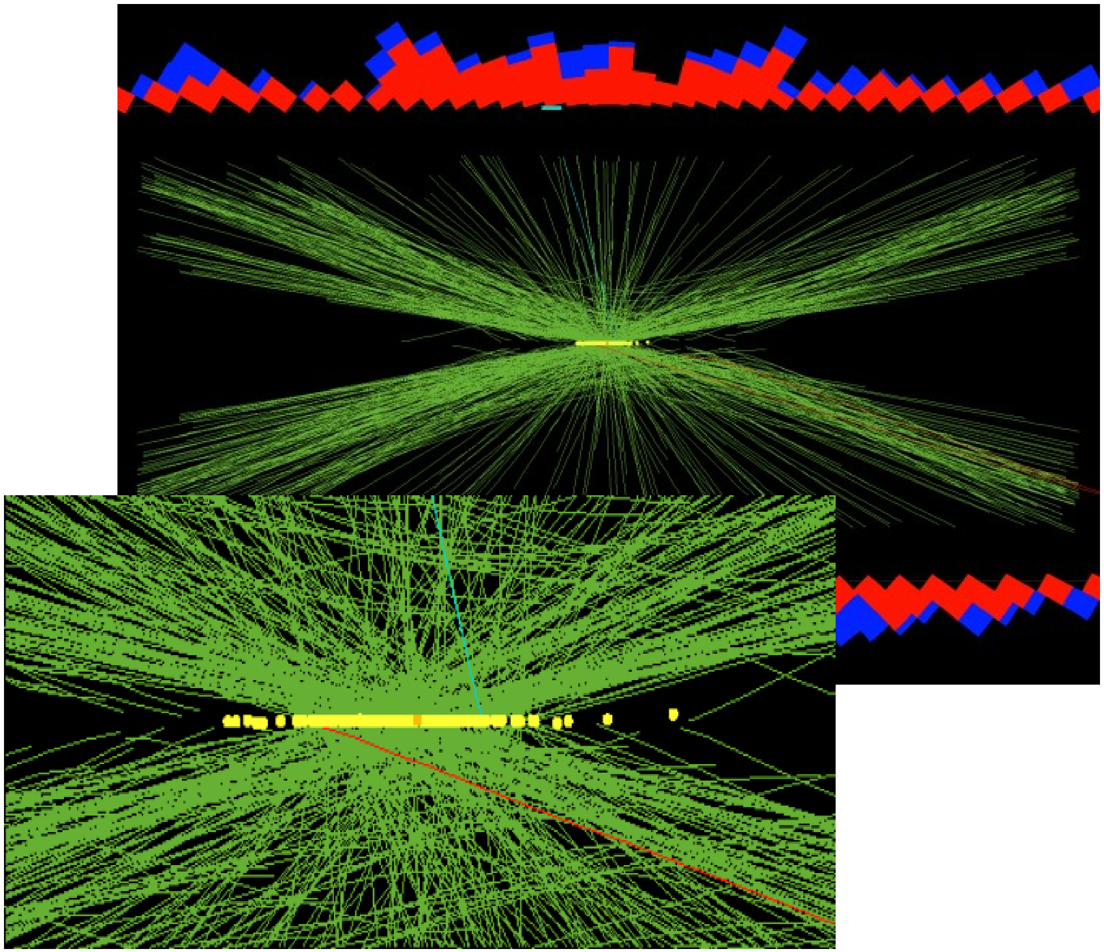
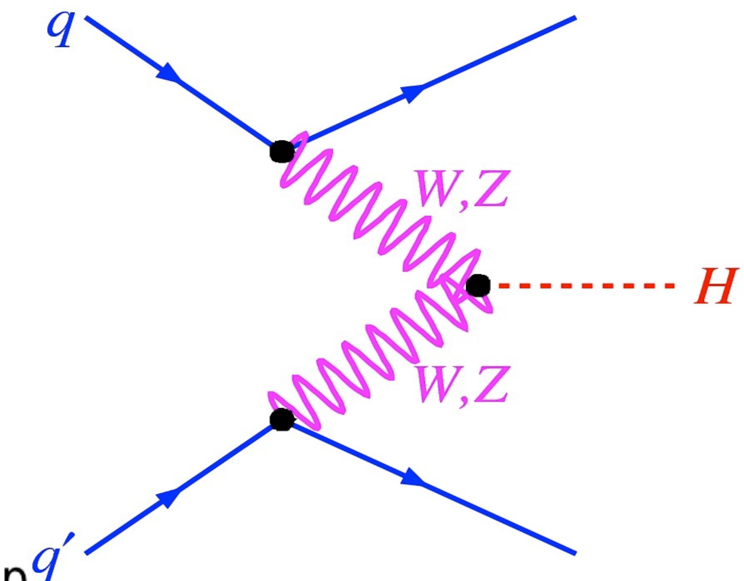
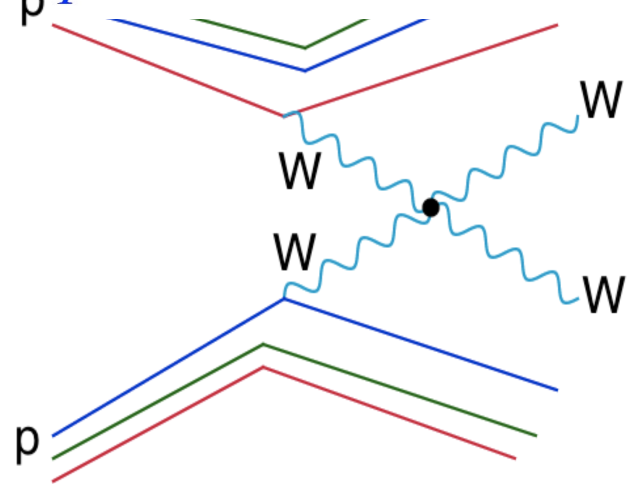
Can we do better vertexing?







- Tie the photons to the correct vertex for precise H→γγ mass reconstruction
- Associate (often forwad) jets with VBF Higgs or WW scattering

Neutrinos

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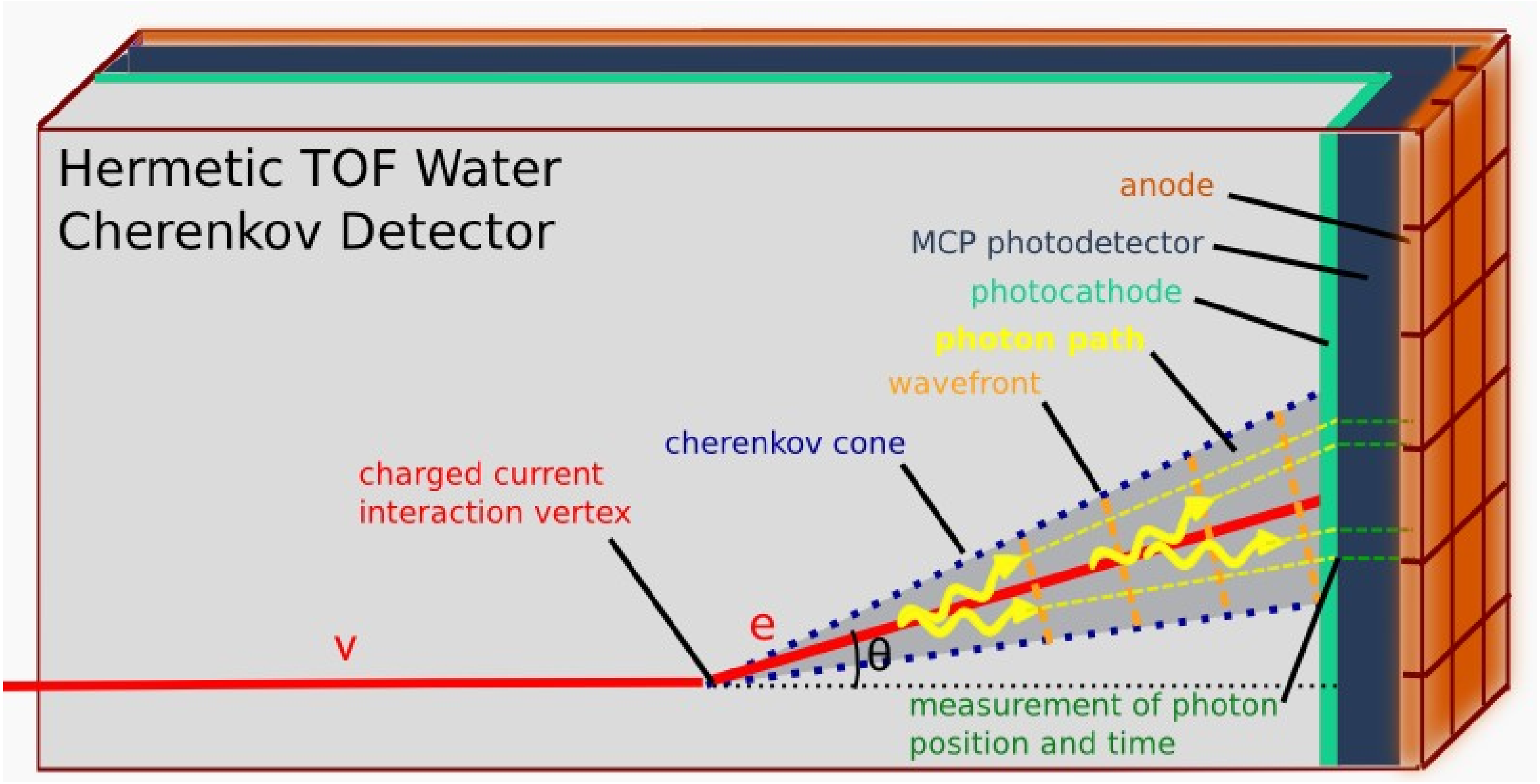
Can we build an optical TPC?

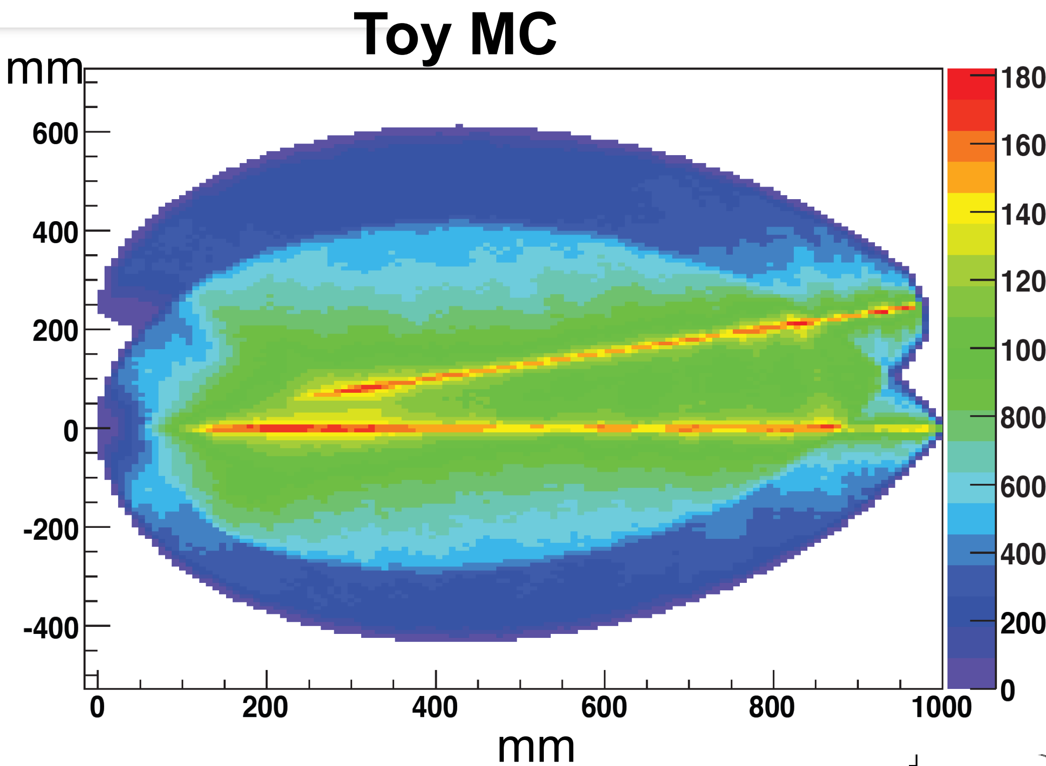
H. Nicholson



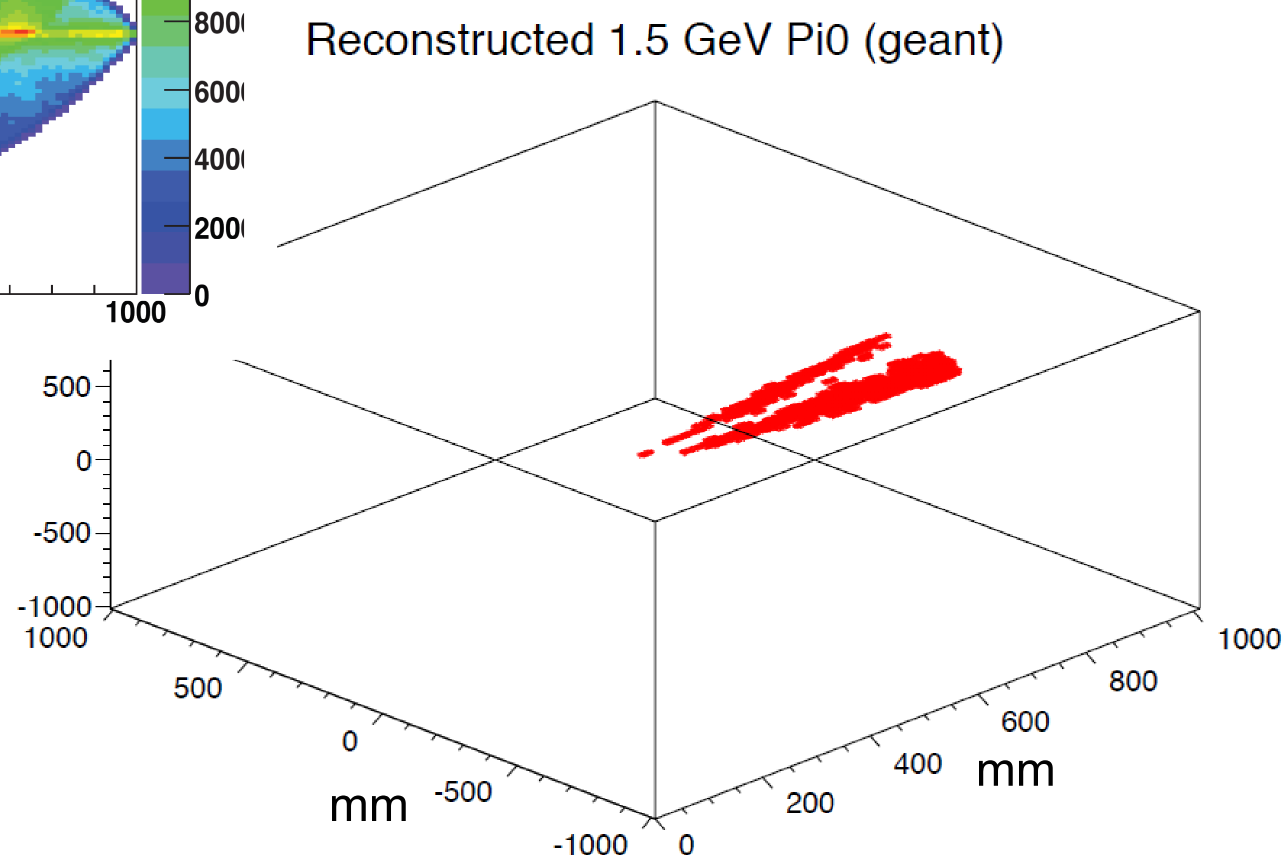
Reconstruct tracks from measurement of position and arrival time of the photons

Neutrinos

M. Wetstein



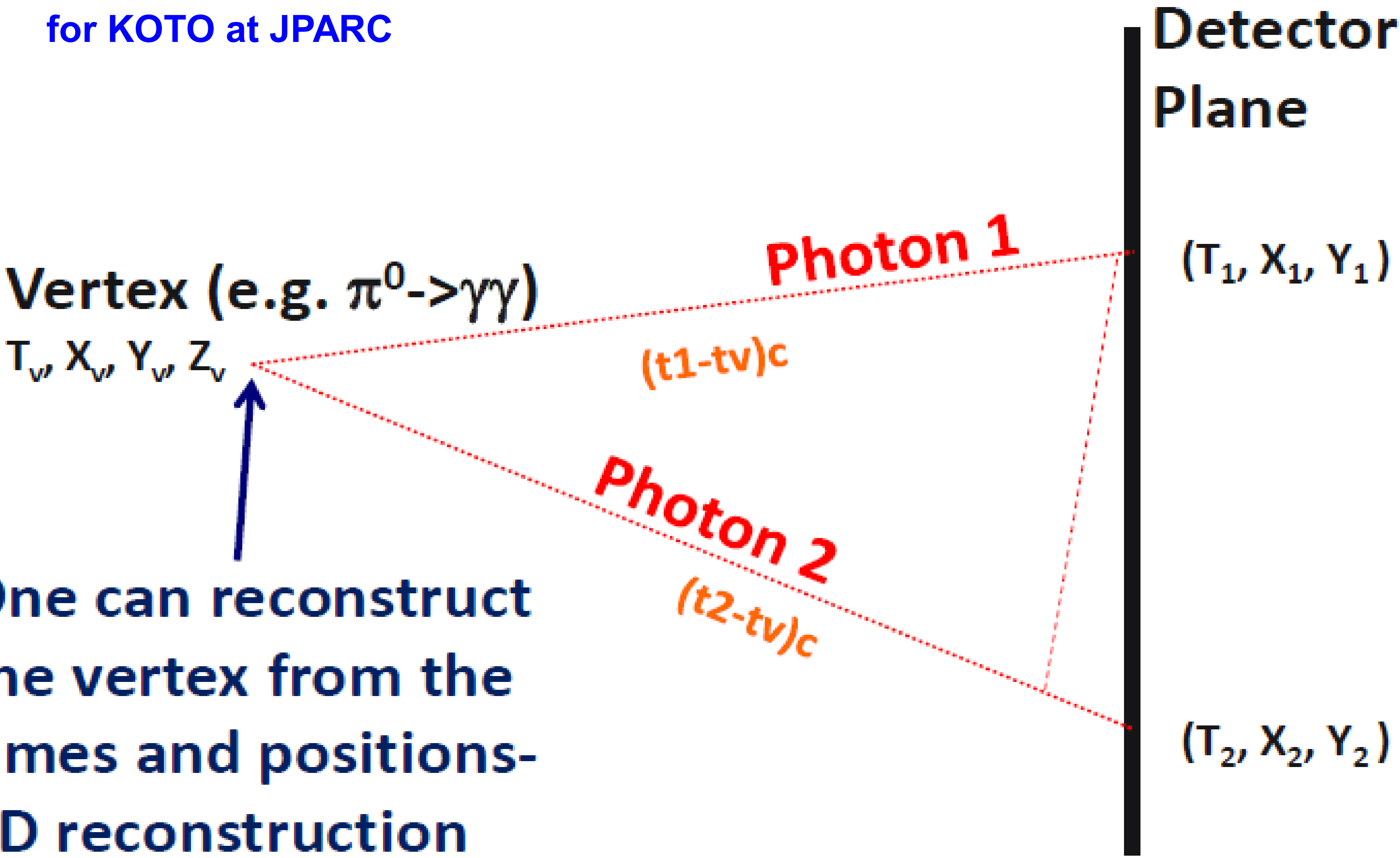
$\pi^0 \rightarrow \gamma\gamma$



Need: ~100ps

Rare Kaon Decays

for KOTO at JPARC



One can reconstruct the vertex from the times and positions- 3D reconstruction

Need: ~1ps

Medical Imaging

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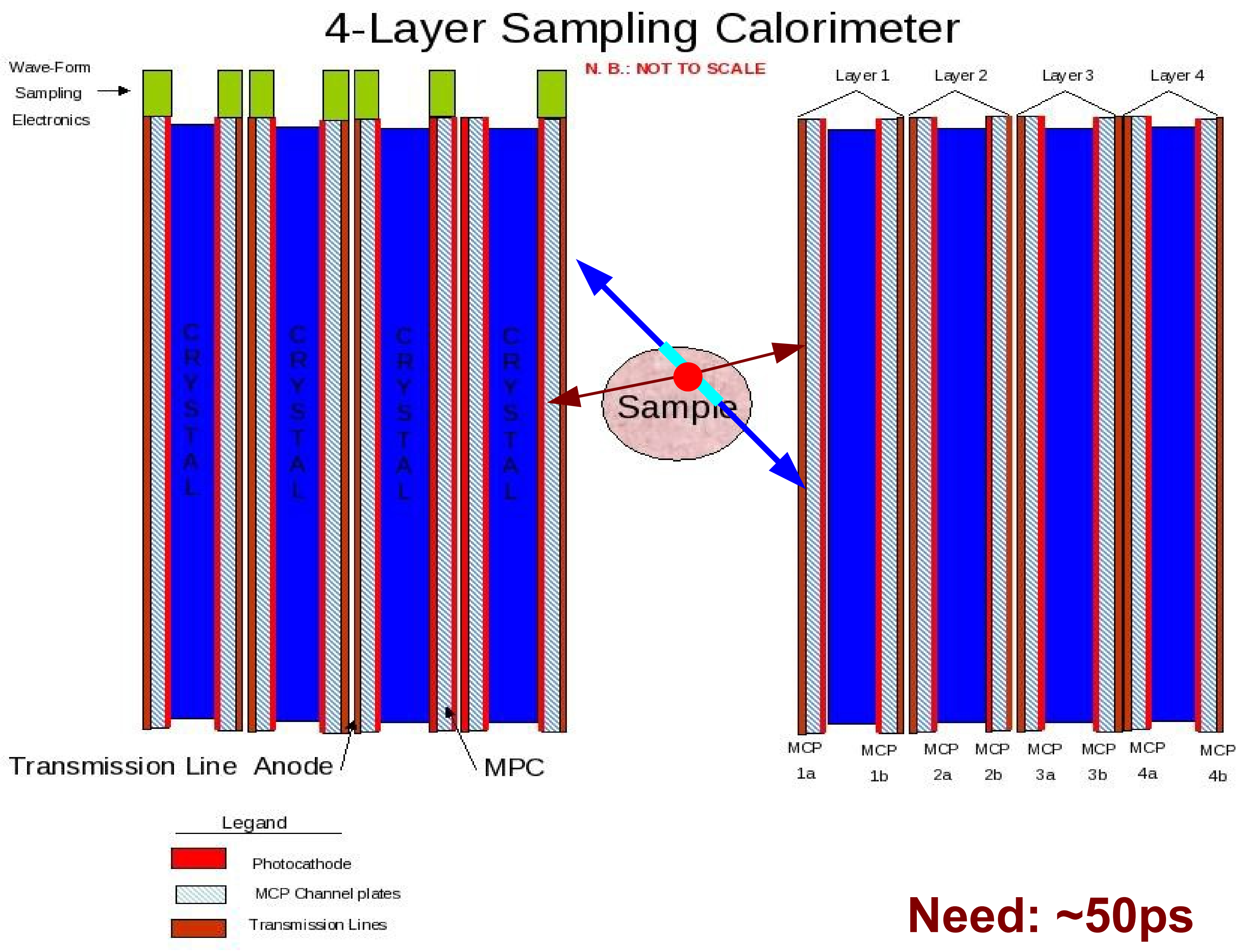

Need: ~50ps

Large Area Picosecond Photo Detectors

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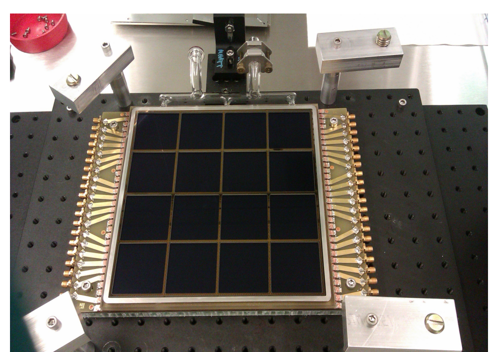
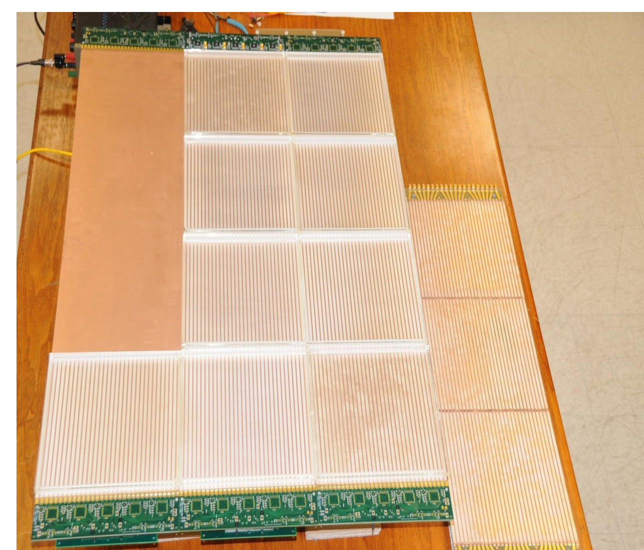
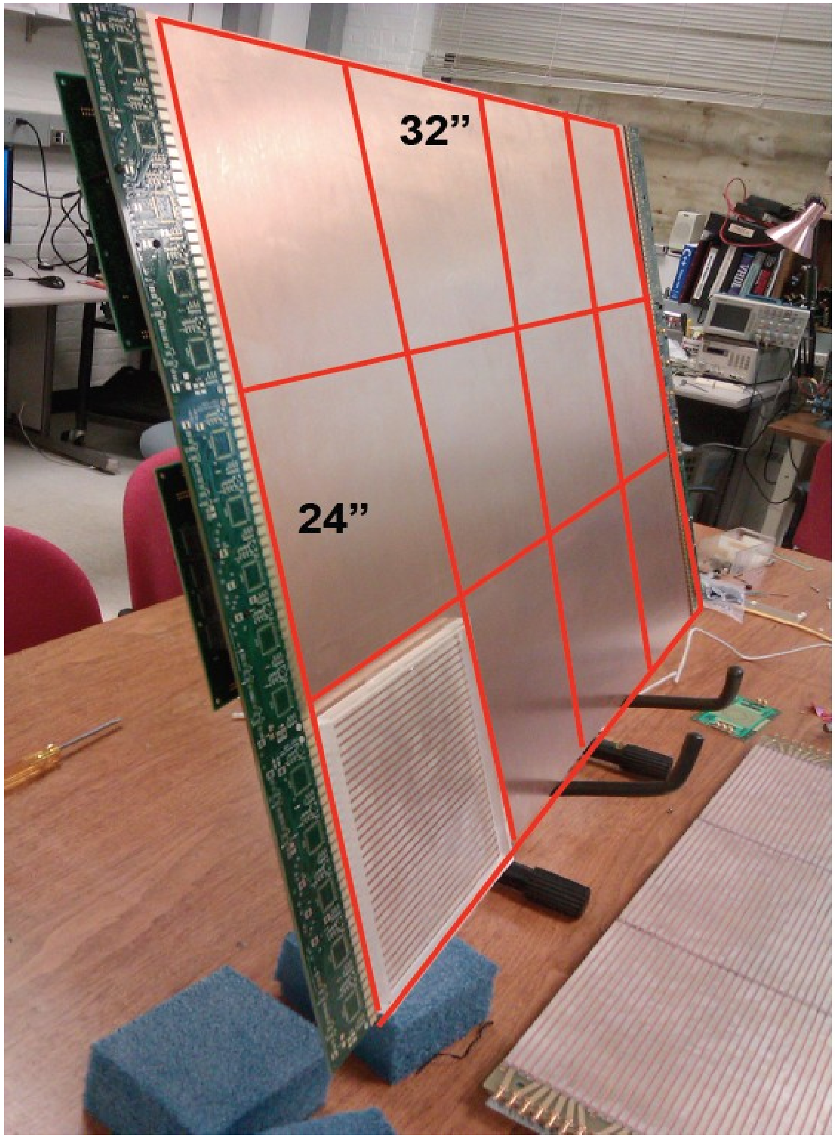
- *Large area*
- *Fast timing*
- *Inexpensive*

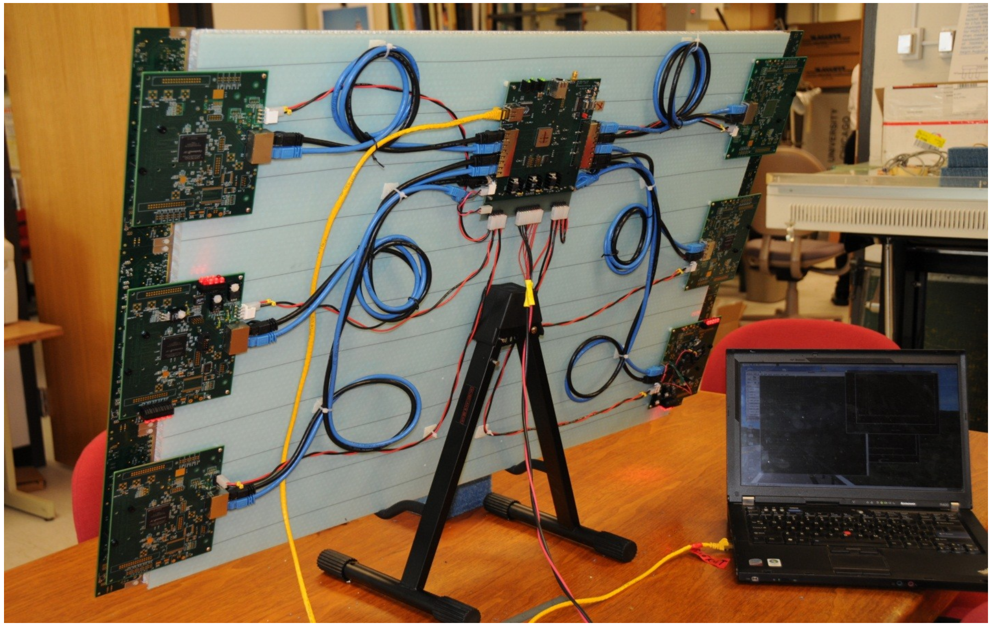




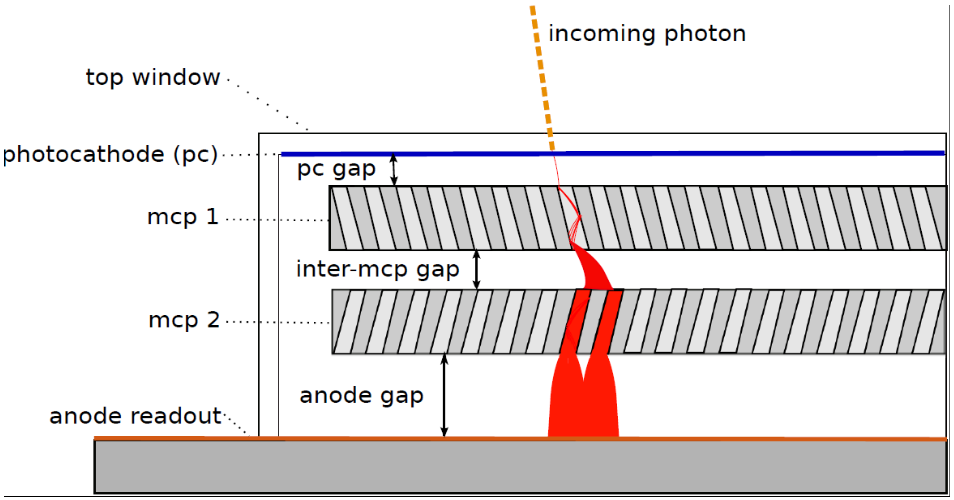
Super Module

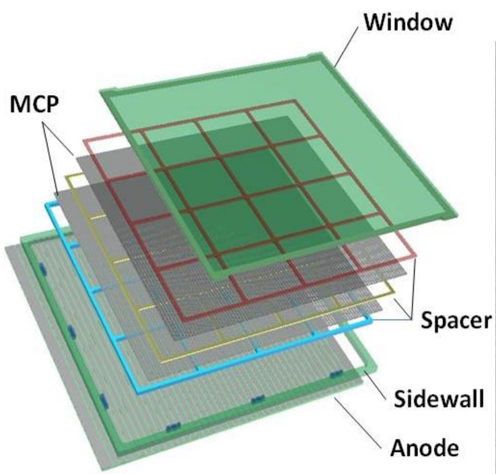


- ***Thin*** ***planar glass body detector***
- ***Tiles share single delay line anode***
- ***Fully integrated electronics***

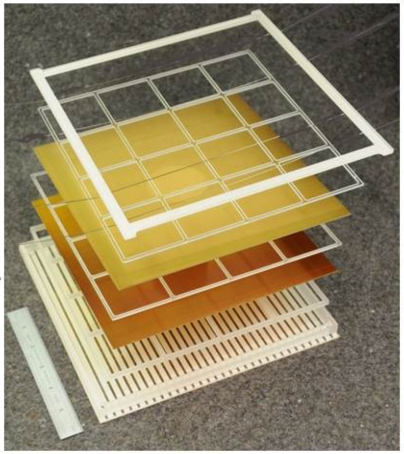


Glass Package (20x20cm^2)





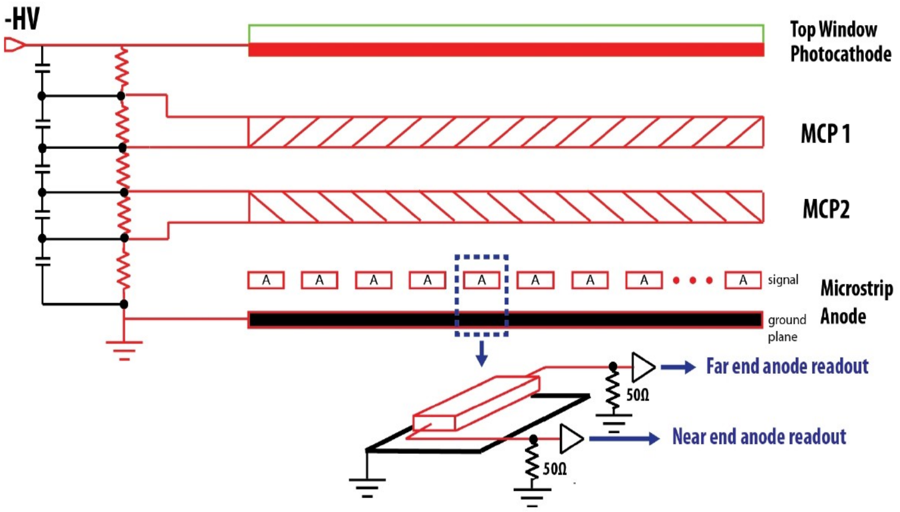
Design Drawing - September 2010



Actual Glass Parts - April 2012

The Frugal Tile

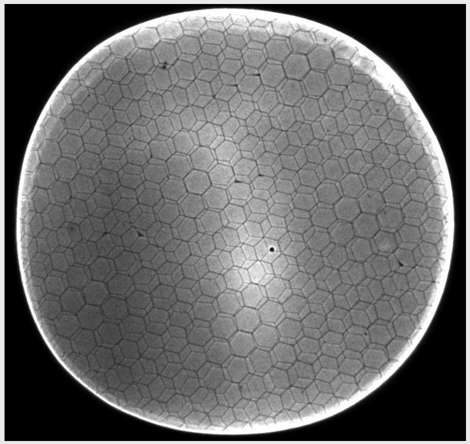
- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object
  - designed for fast timing



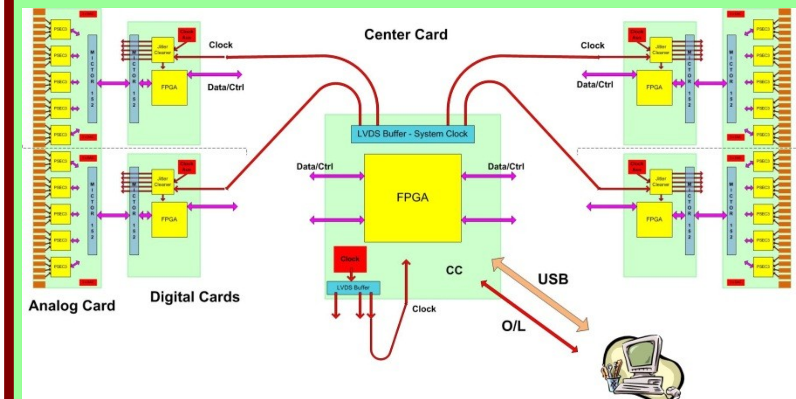
Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL

LAPPD Components

MicroChannel Plates

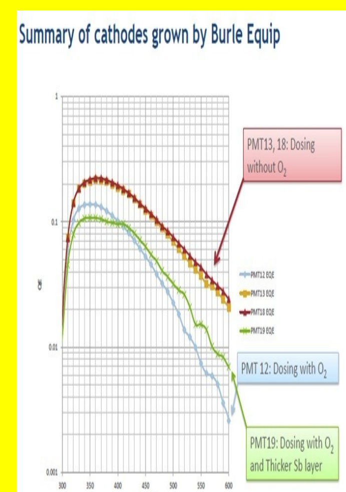


Electronics/Integration



Hermetic Packaging

Photocathodes



MCP Fundamentals

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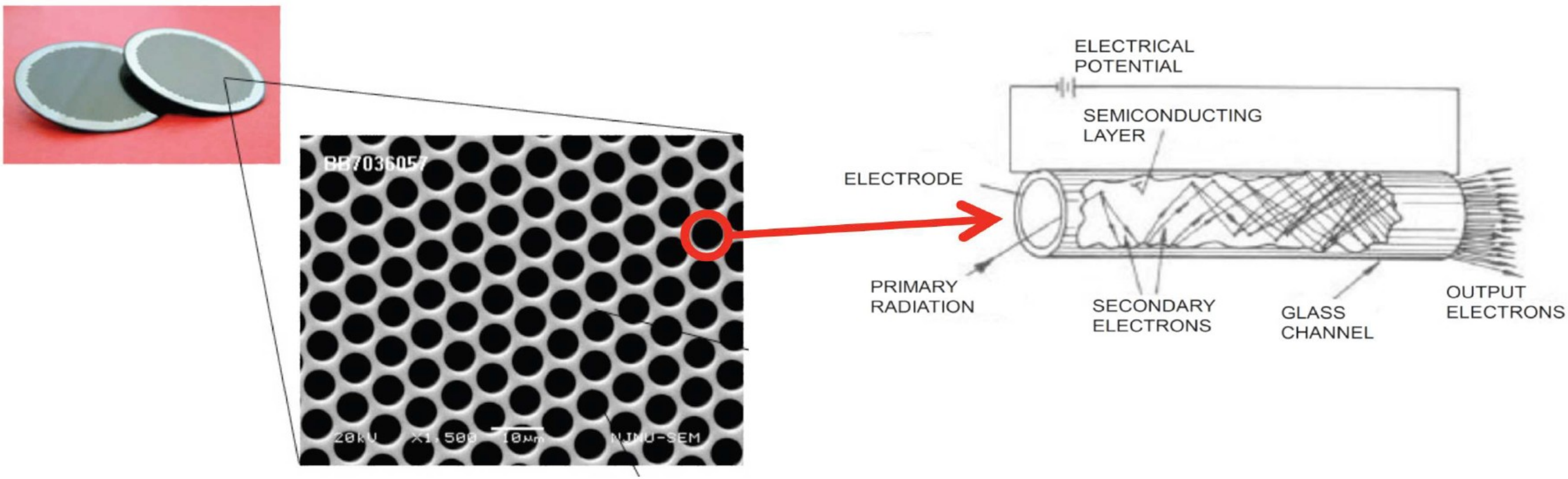
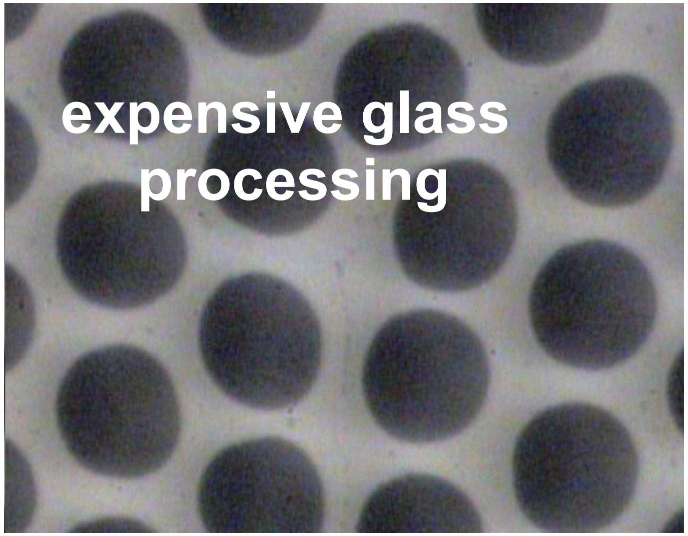


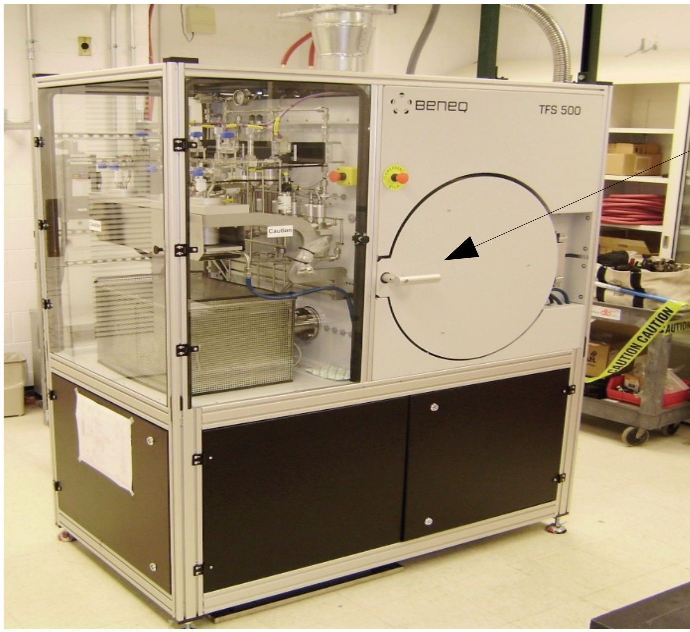
Conventional Pb-glass MCP



Incom glass substrate

MCP by Atomic Layer Deposition (ALD)

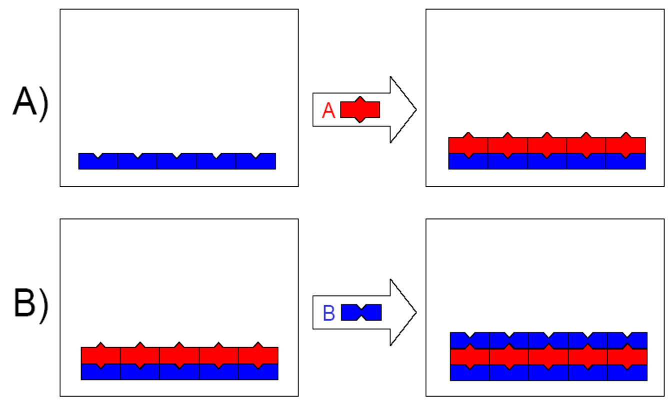
University of Chicago

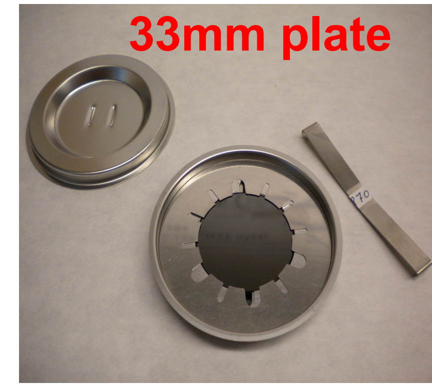


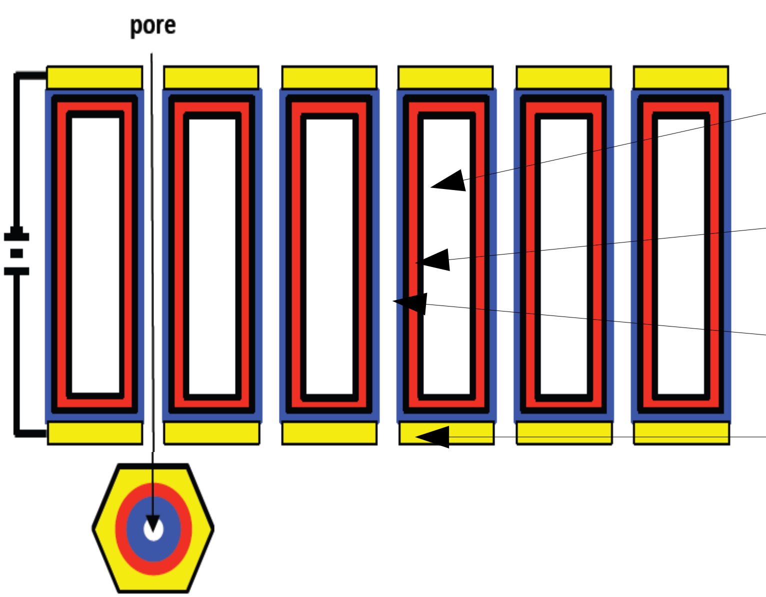
Beneq reactor for ALD

@Argonne National Laboratory

A.Mane, J.Elam





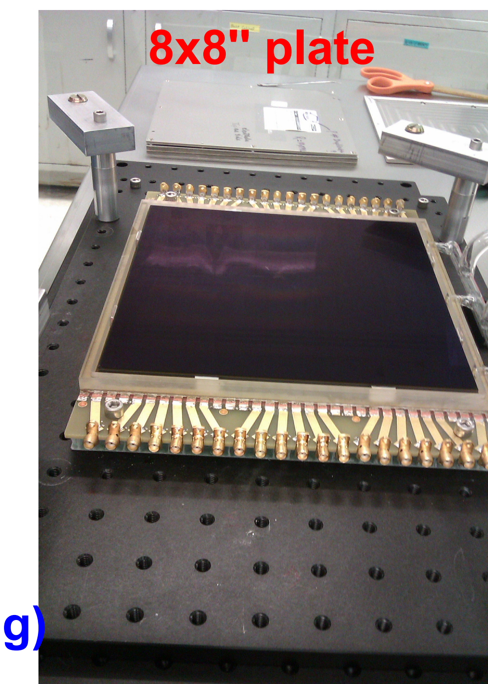


Porous glass

Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

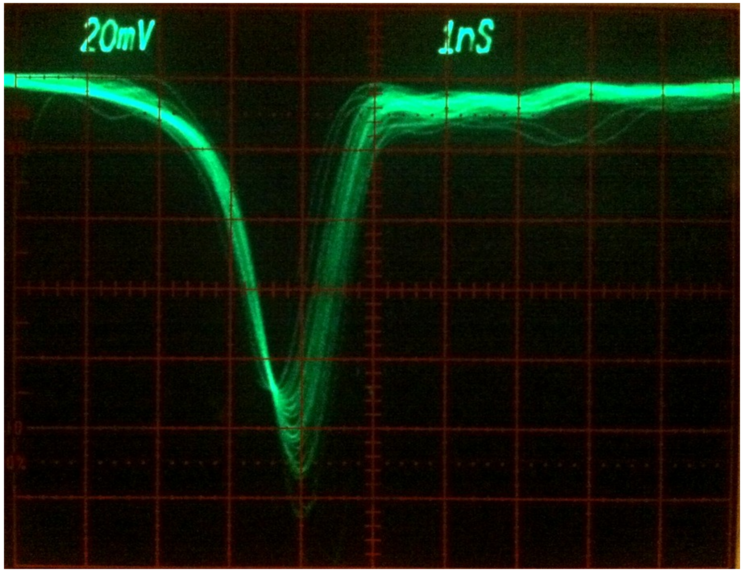
Conductive coating
(thermal evaporation or sputtering)

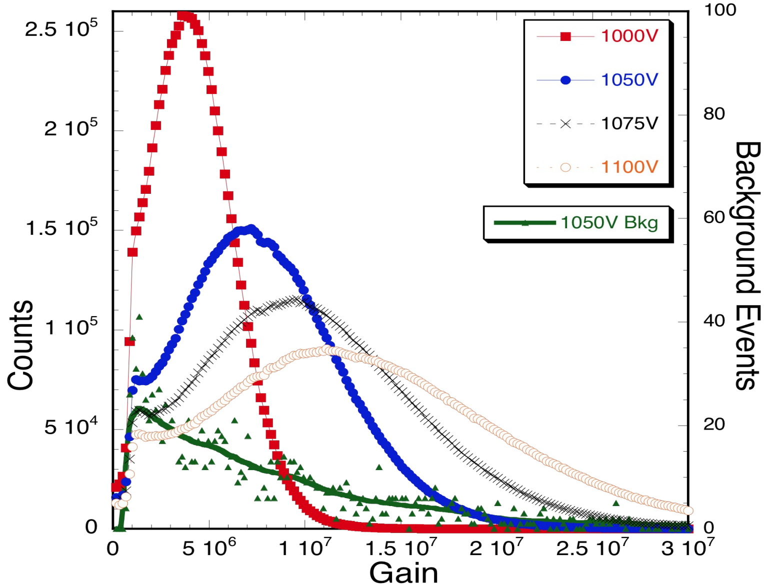


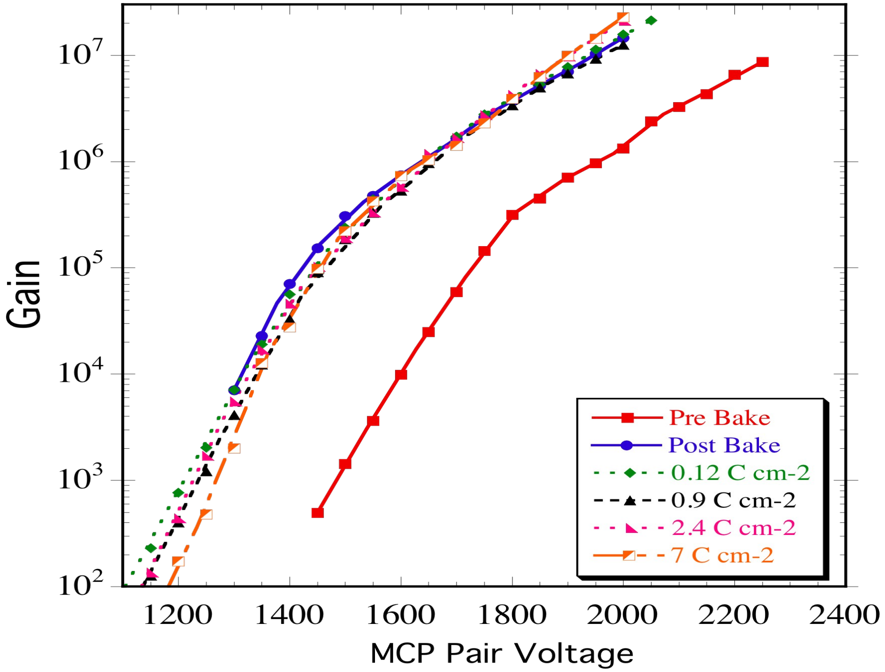
33mm ALD-MCP Performance

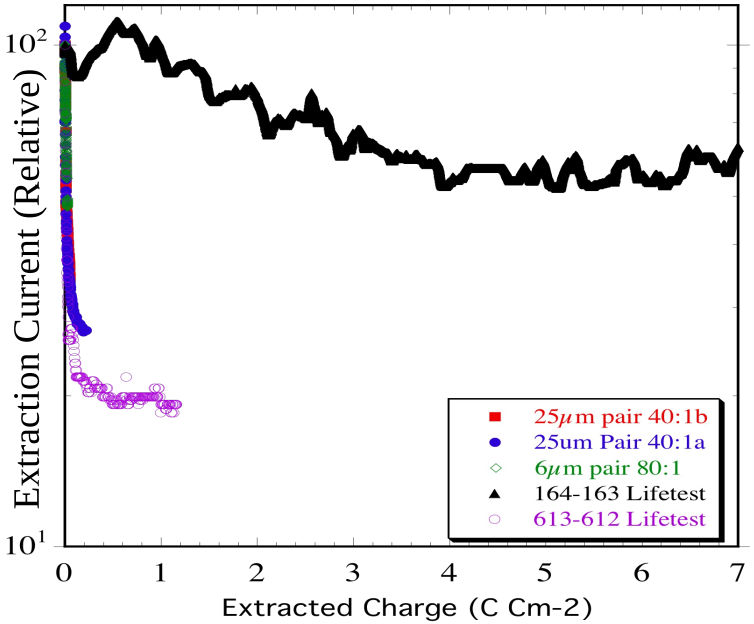
University of Chicago

J.McPhate, O.Seigmund







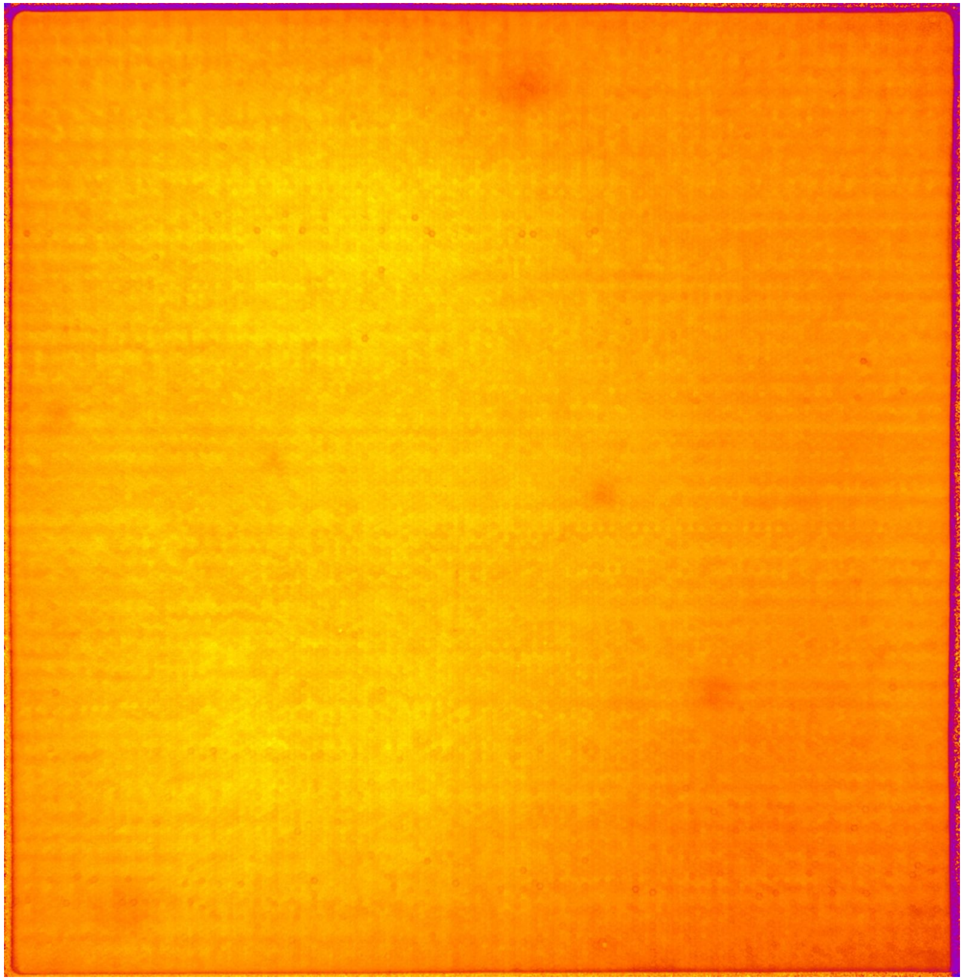


8x8" ALD-MCP Gain Uniformity

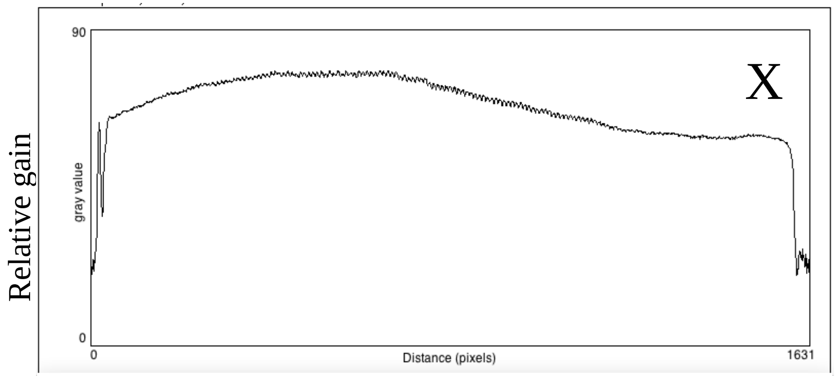
University of Chicago

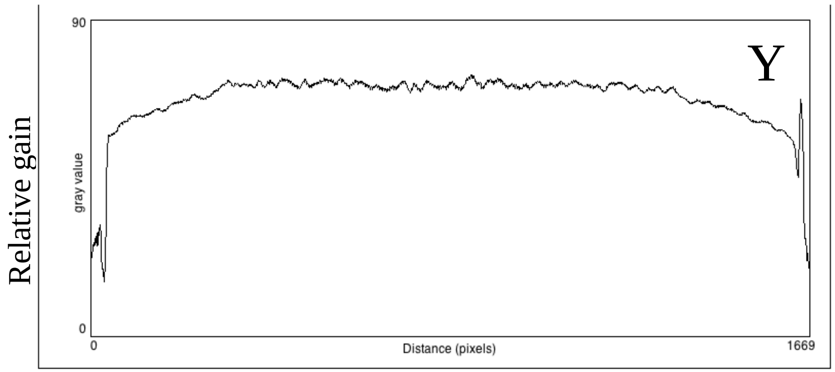
J.McPhate, O.Seigmund

Mean gain ~7 x 10^6



8” MCP pair average gain map image



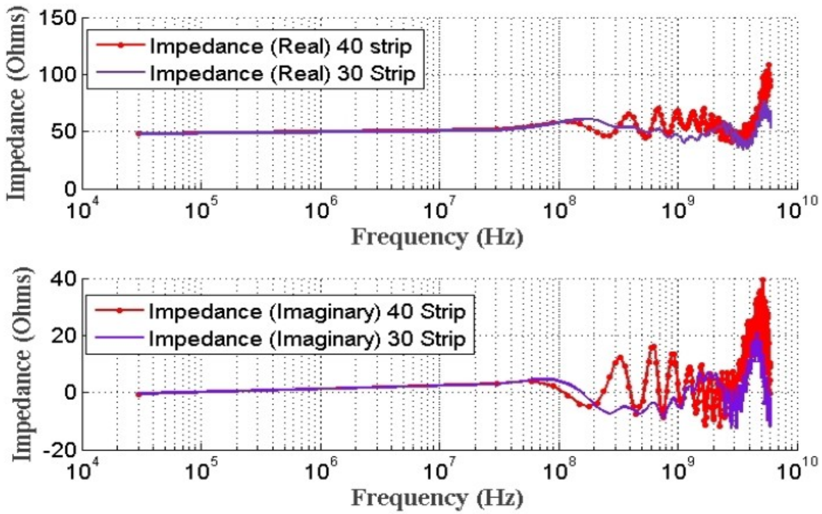


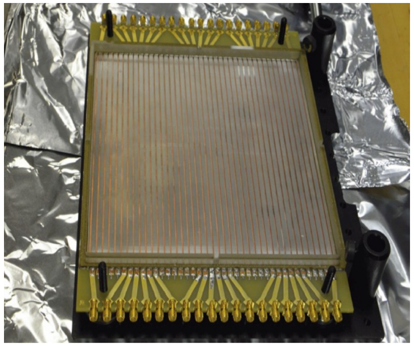
RF Strip Line Anode

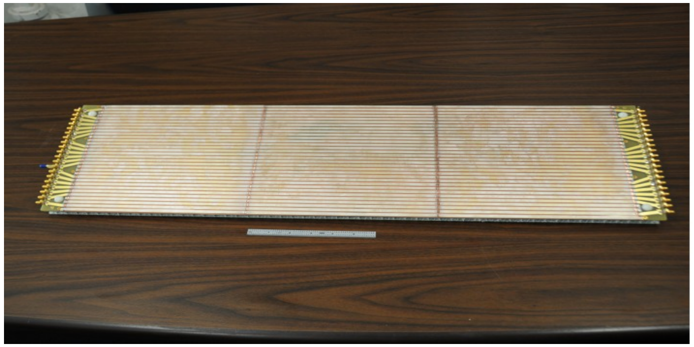
H.Grabas, R.Obaid,
E.Oberla, H.Frisch
J.F.Genat

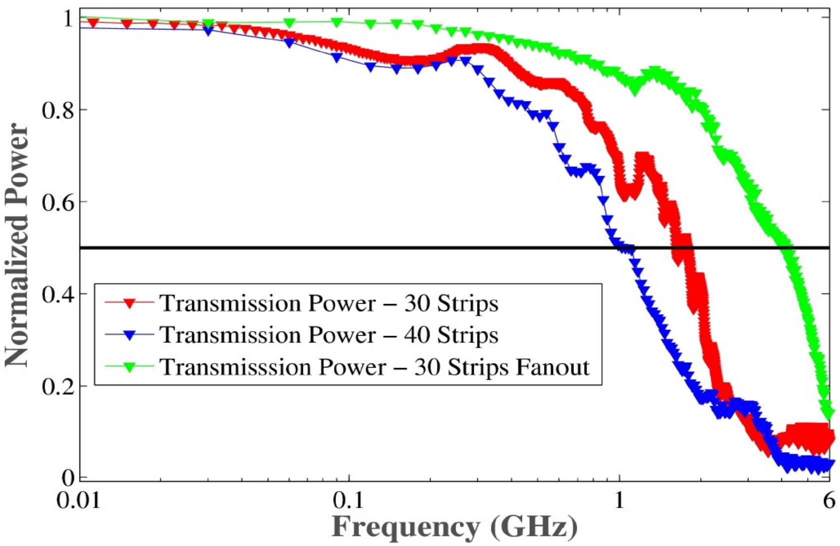
A.Axtell, P.Jaynes

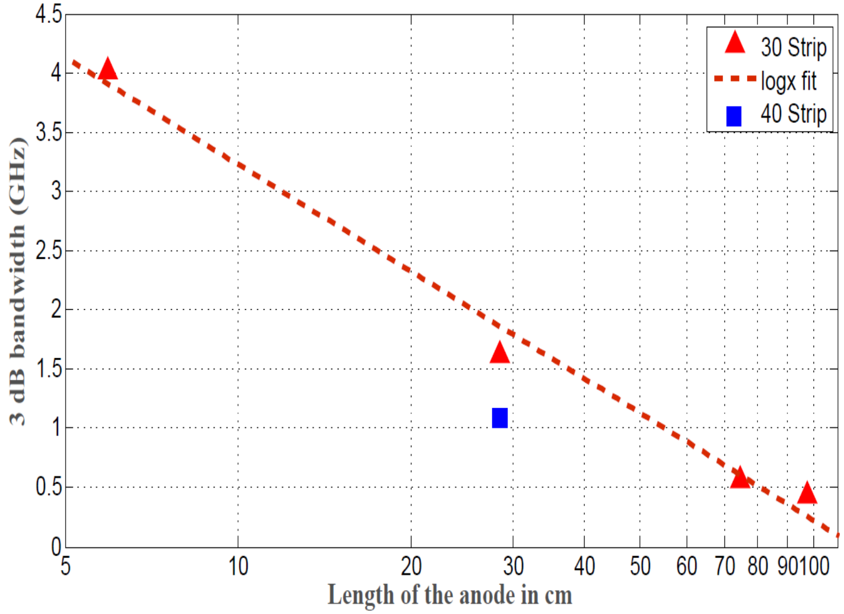
- Silk-screened silver on inexpensive glass
- 50 Ω impedance
- 1.6-0.4GHz bandwidth







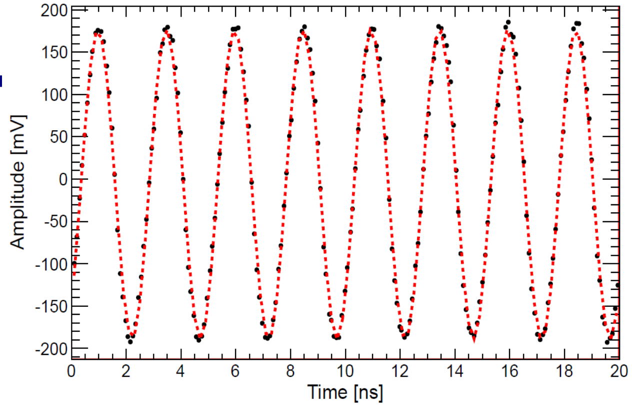




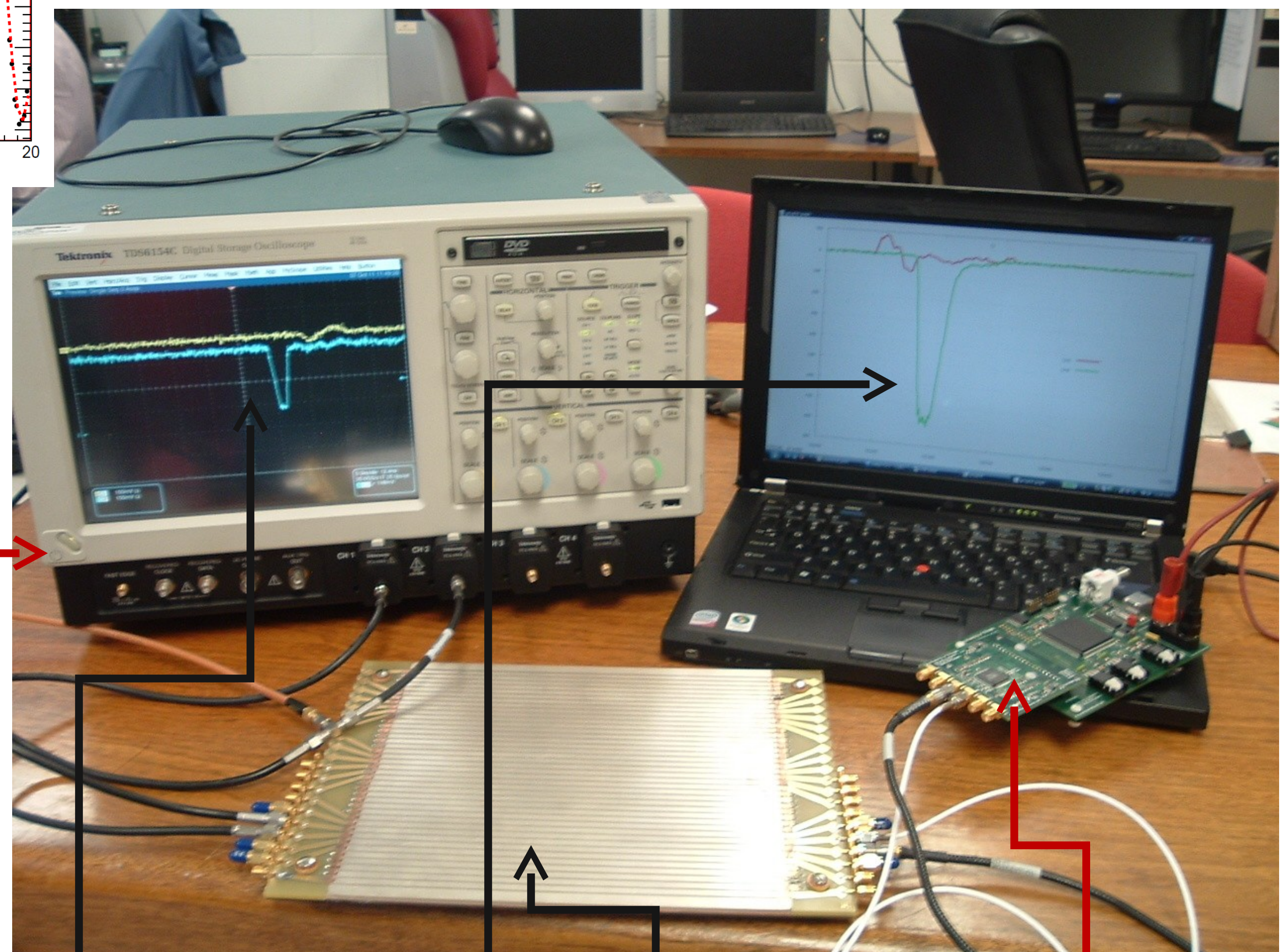
Scope-on-a-chip

University of Chicago

E.Oberla, K.Nishimura, G.Varner



Designed by Eric Oberla (UC grad student)



Real digitized traces from anode

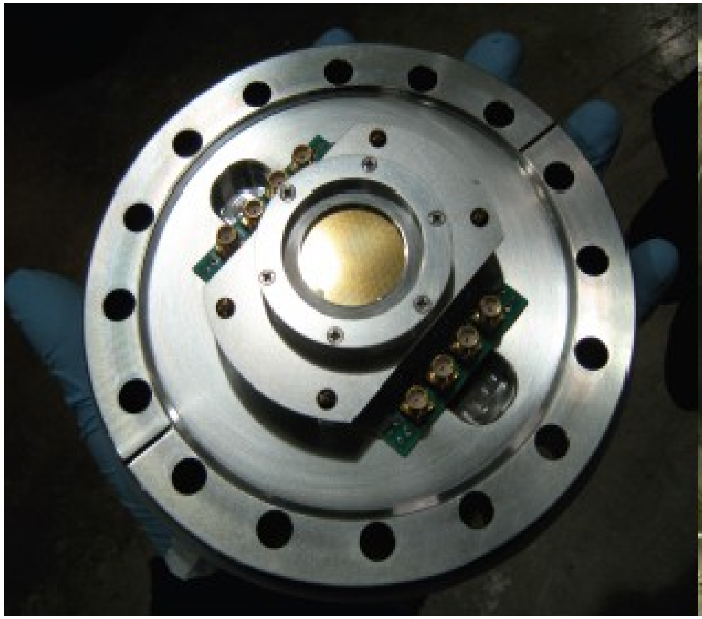
20 GS/scope
4-channels (142K$)

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

18

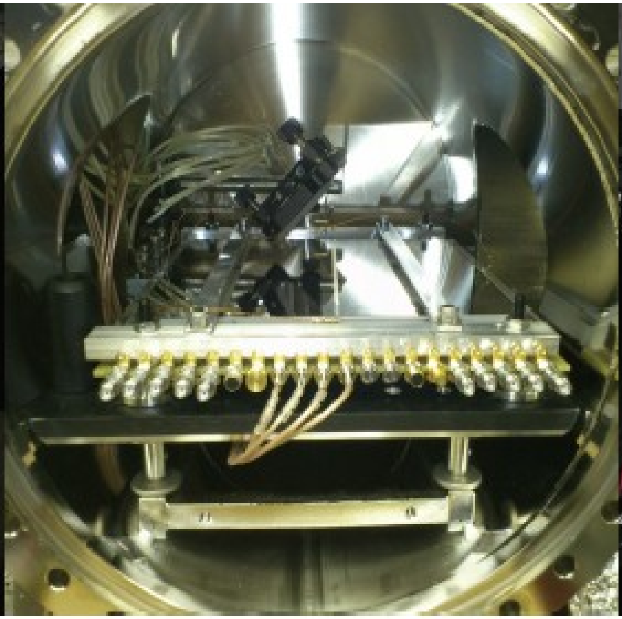
System Integration and Testing

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



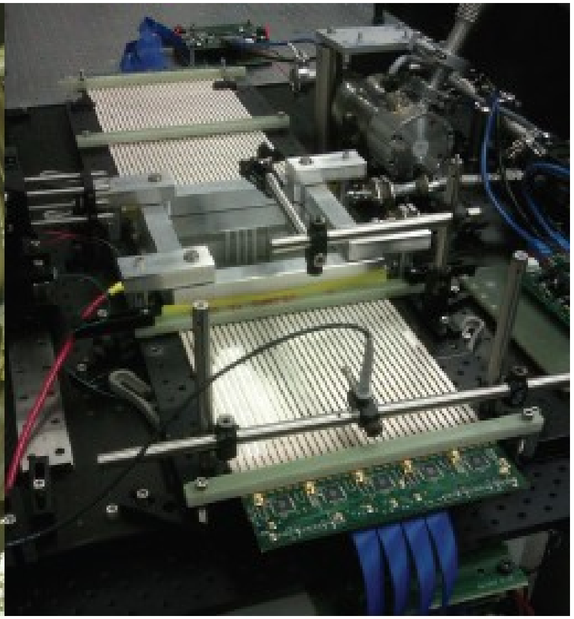
33mm Testing

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



8" Testing

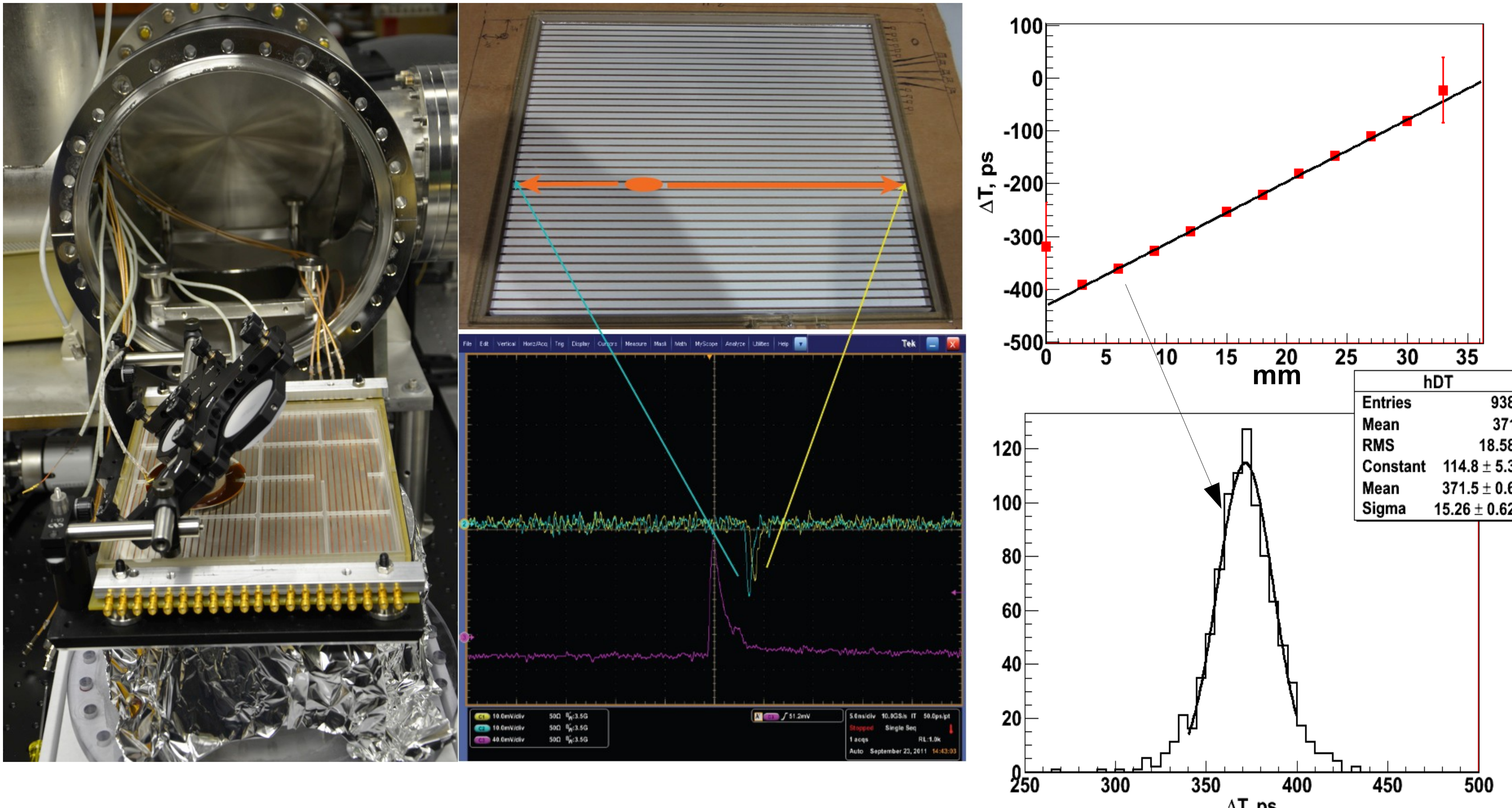
- Demonstrate working 8" MCPs
- Test near complete detector systems with realistic anode
- Optimize and measure key resolutions



Complete detector systems

- Demonstrate complete sealed-tube detector
- Study characteristics of 80cm anode
- Test integrated front-end electronics in fully operational conditions

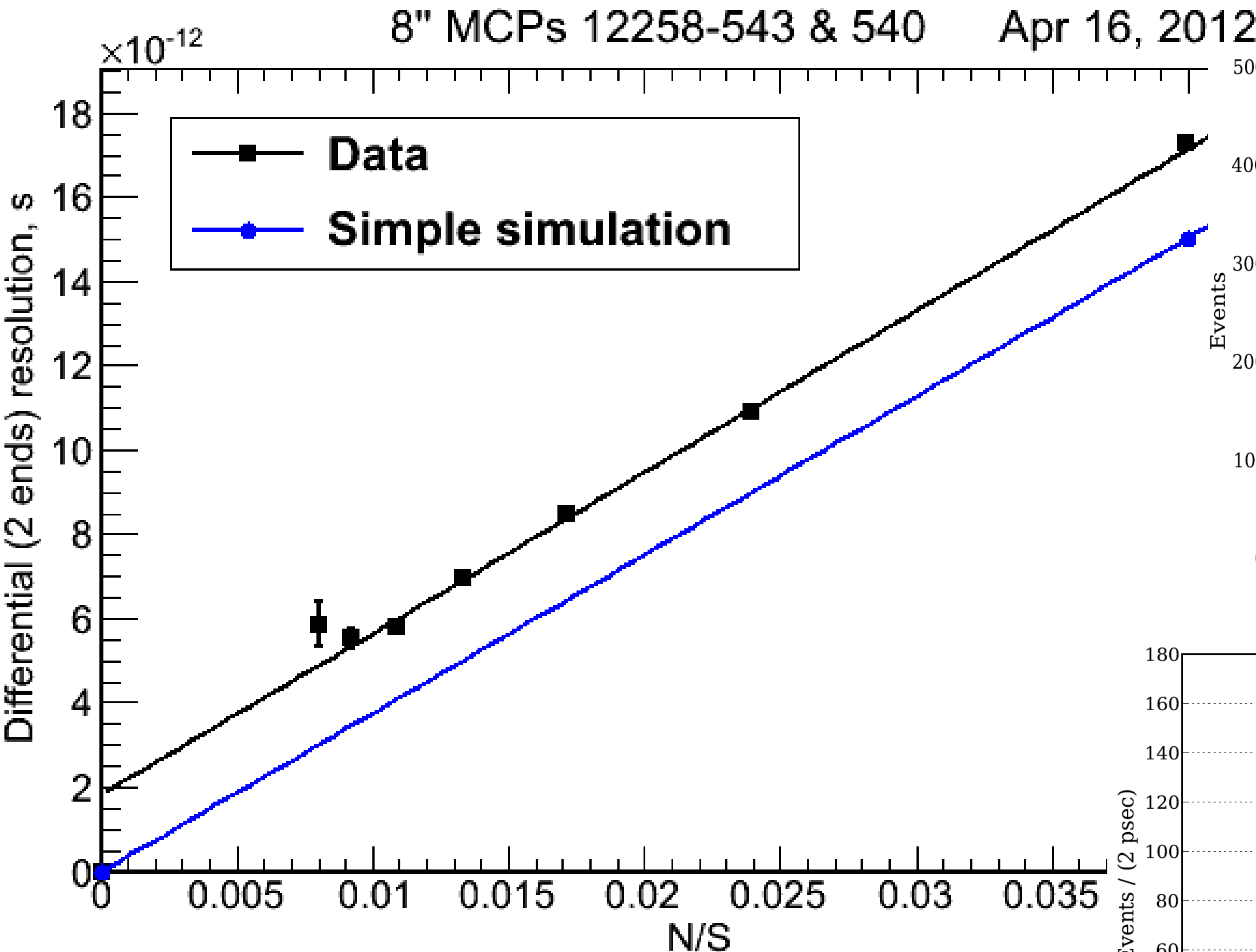
8" MCP in Action

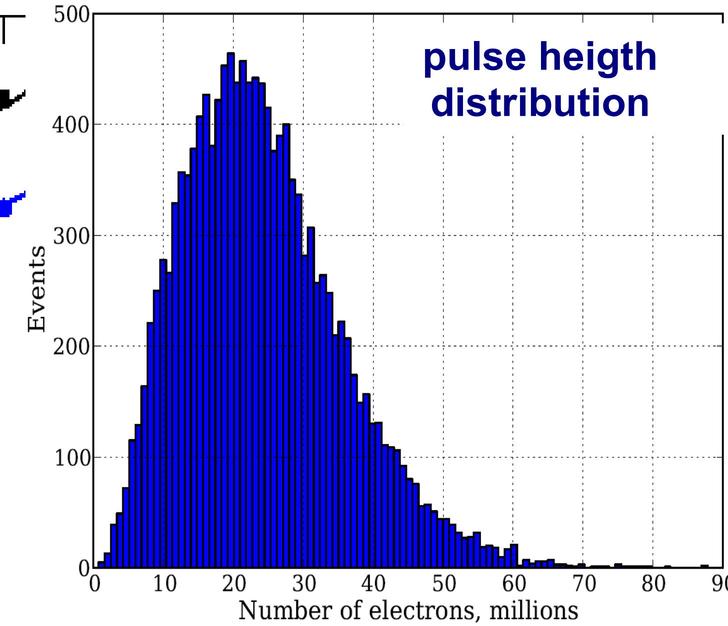


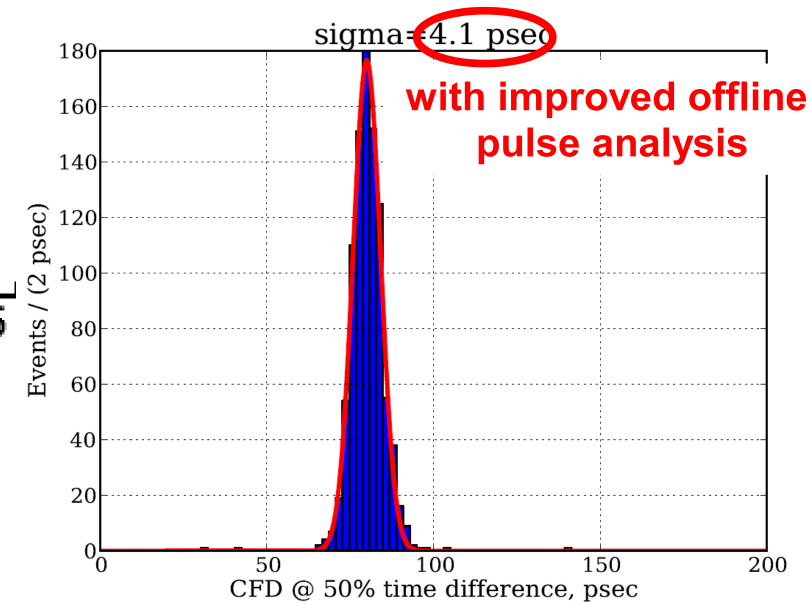
Slope ~10ps/mm corresponds to ~2/3 c signal propagation speed along the anode stripline

ΔT = 15ps → ΔX = 1/2 ΔT 2/3c = 1.5mm

Differential Time Resolution

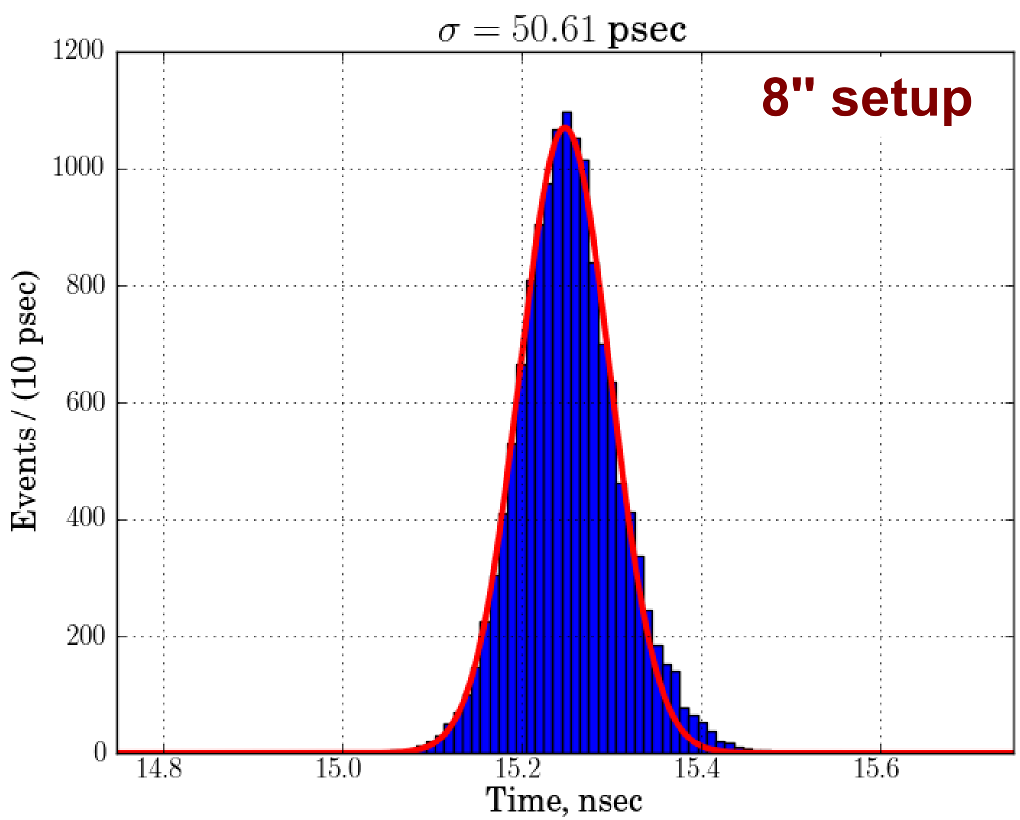


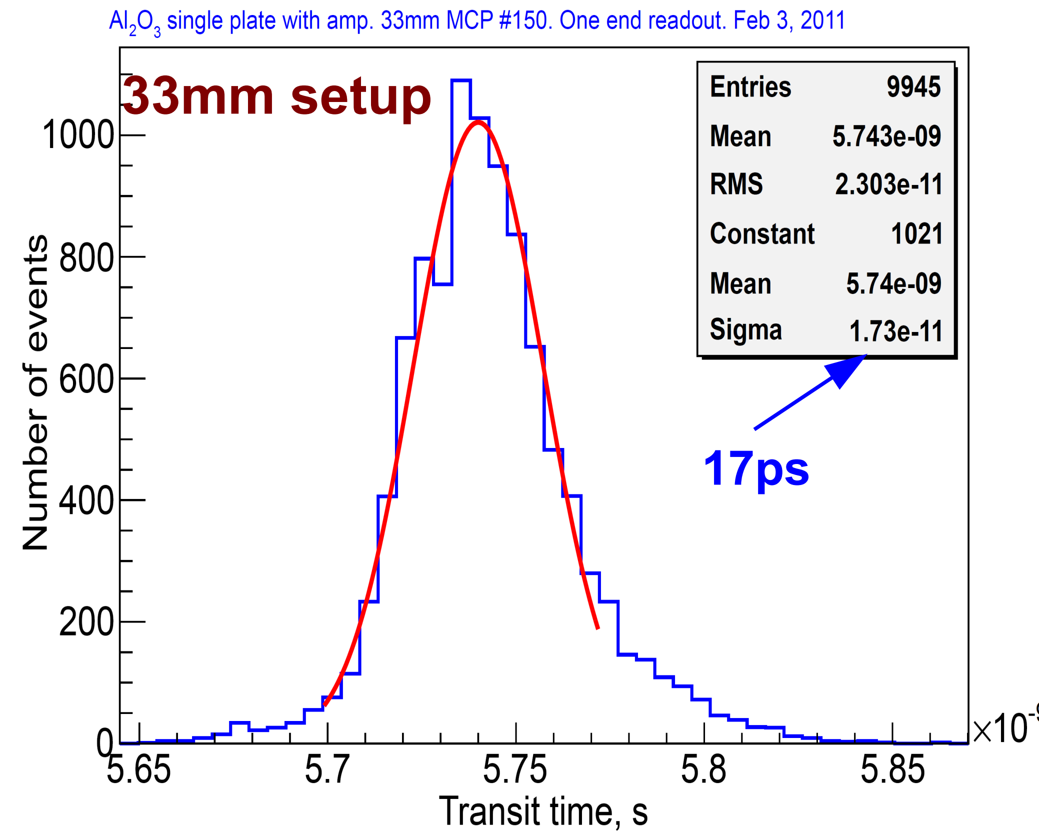




~6 ps in ΔT → ~0.6 mm in ΔX

Time-of-Flight Resolution





System Integration: "Demountable"

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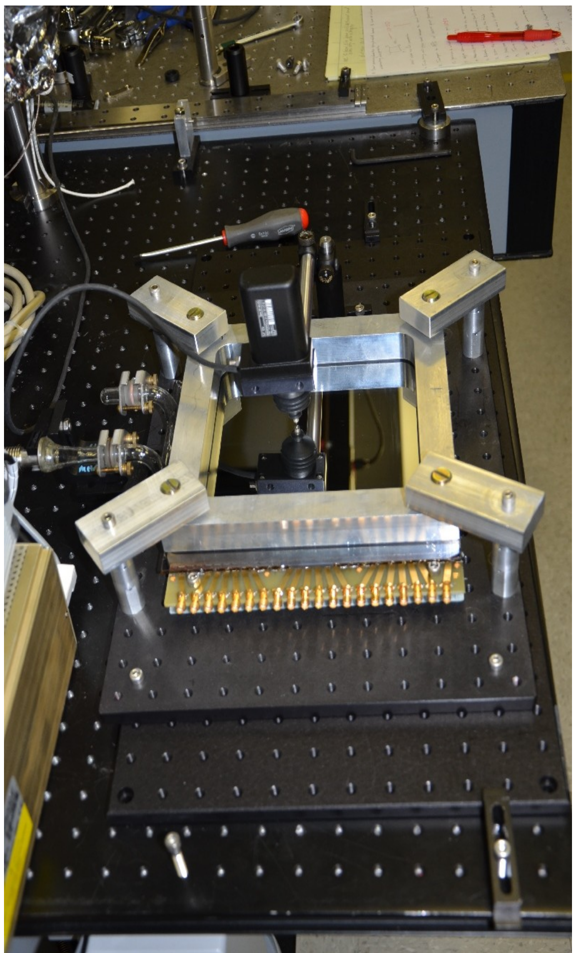
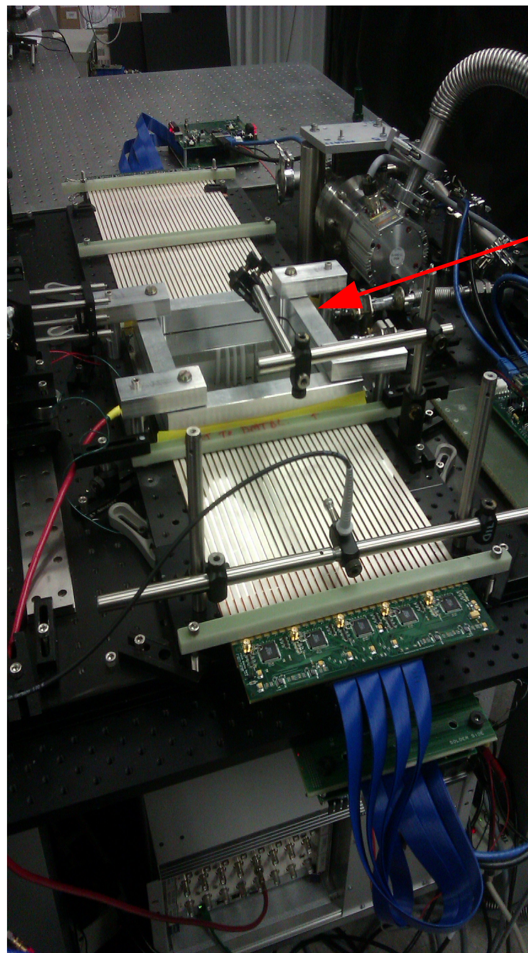
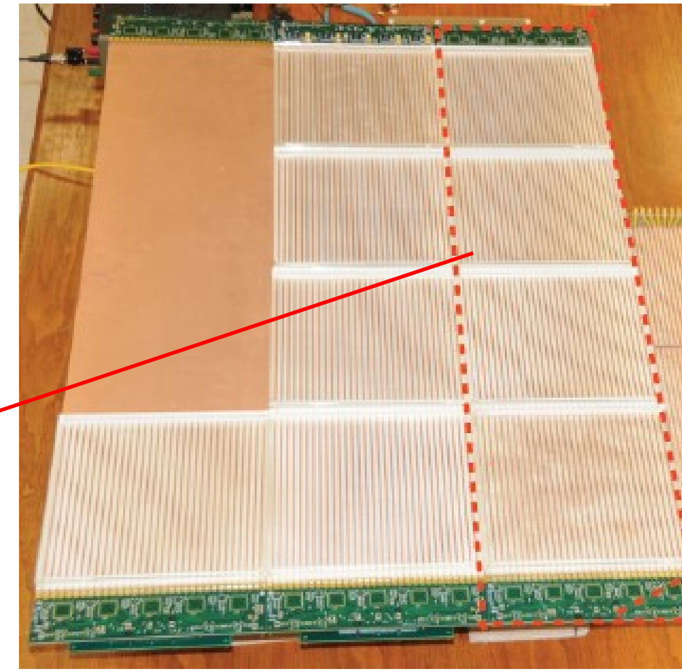
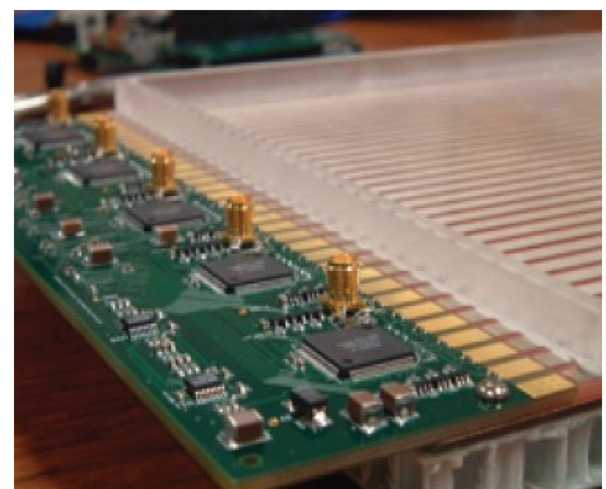
Demountable 1.0 (May 2012)

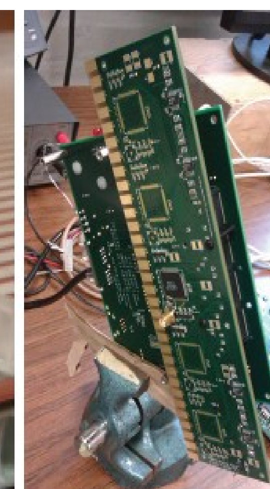


Demountable 3.0 (Sep-Dec 2012)







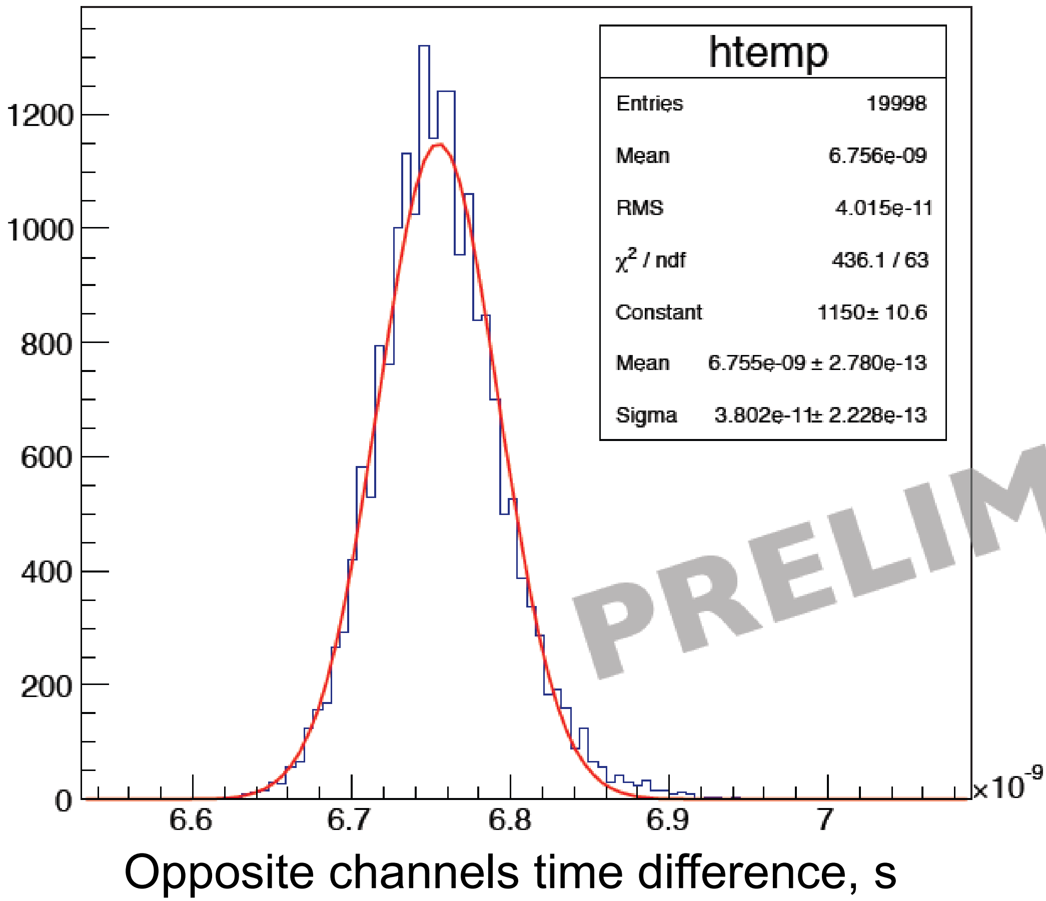


"Demountable" - Oscilloscope

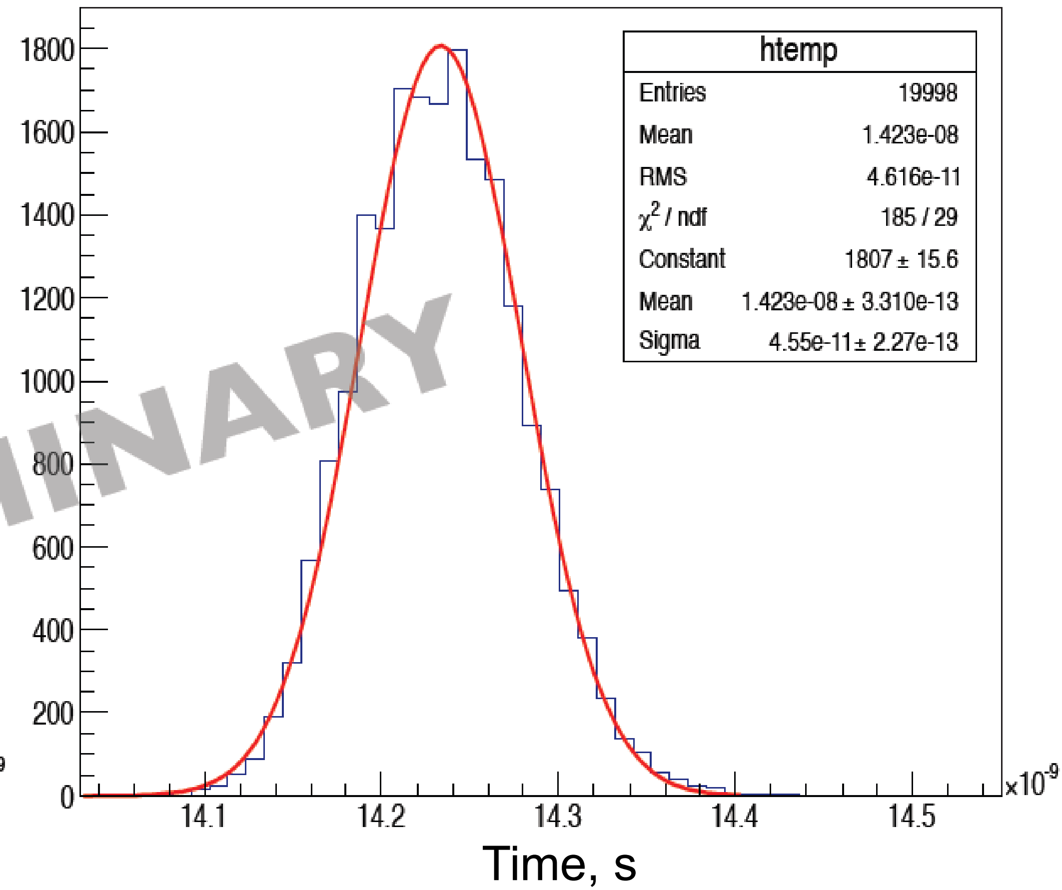
University of Chicago

First results with 90cm-long anode

38 picosecond differential time resolution

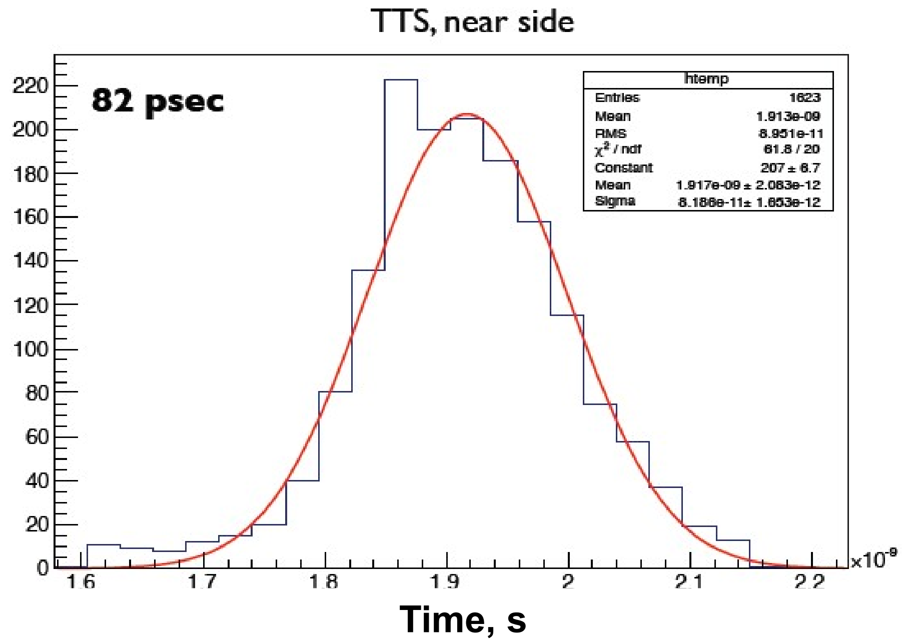


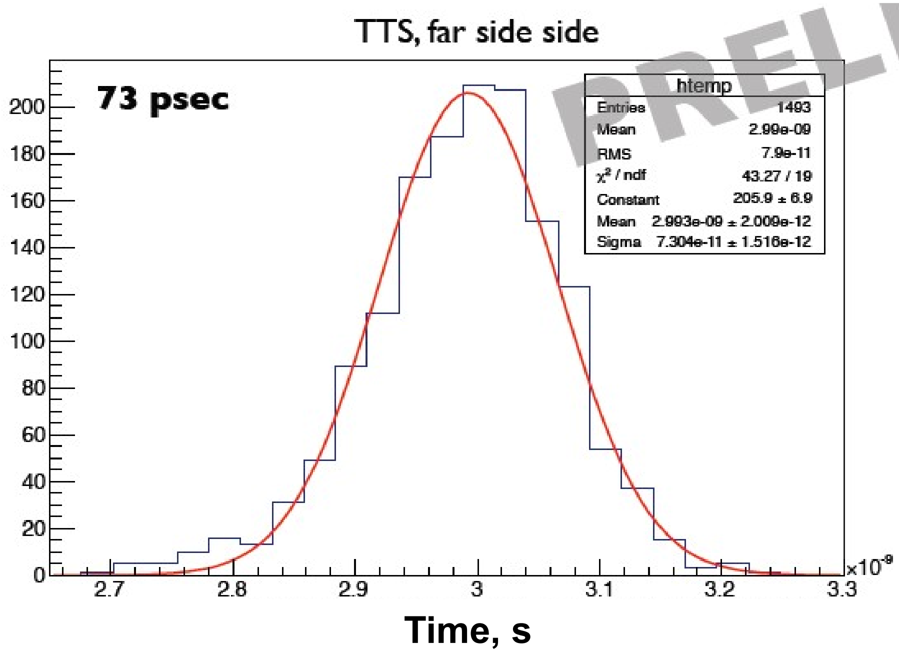
46 picosecond Transit Time Spread

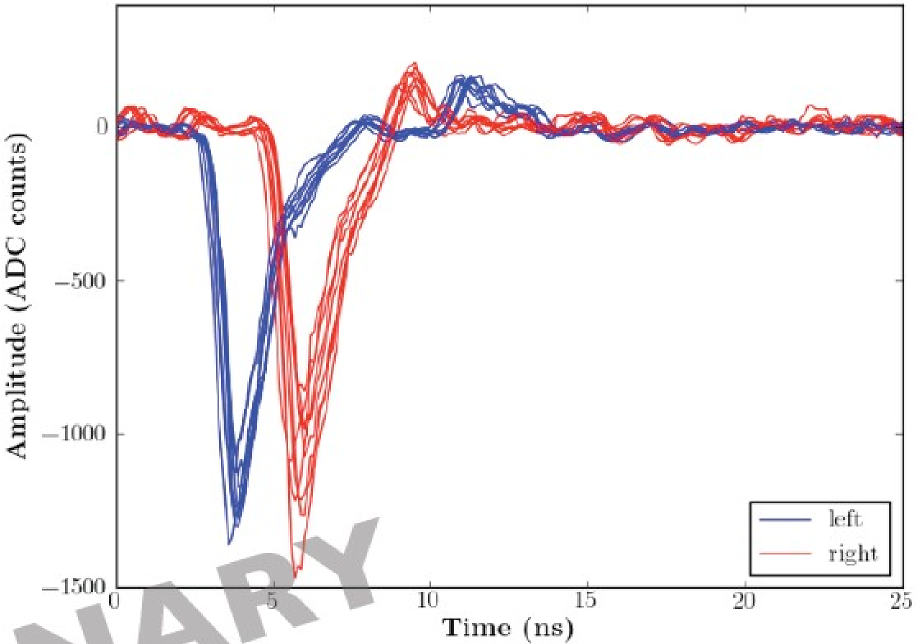


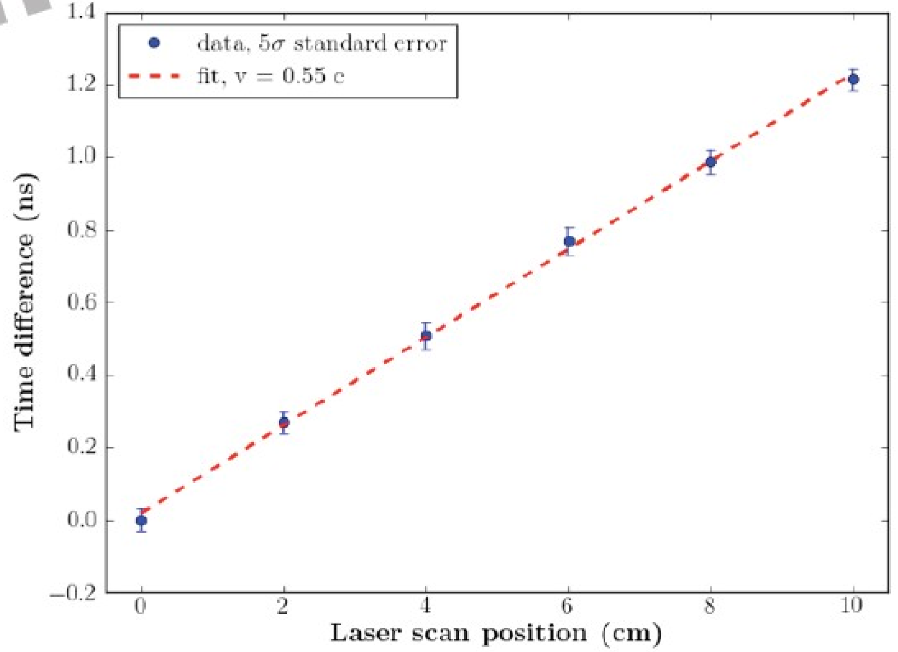
"Demountable" – Full PSEC4 readout

University of Chicago



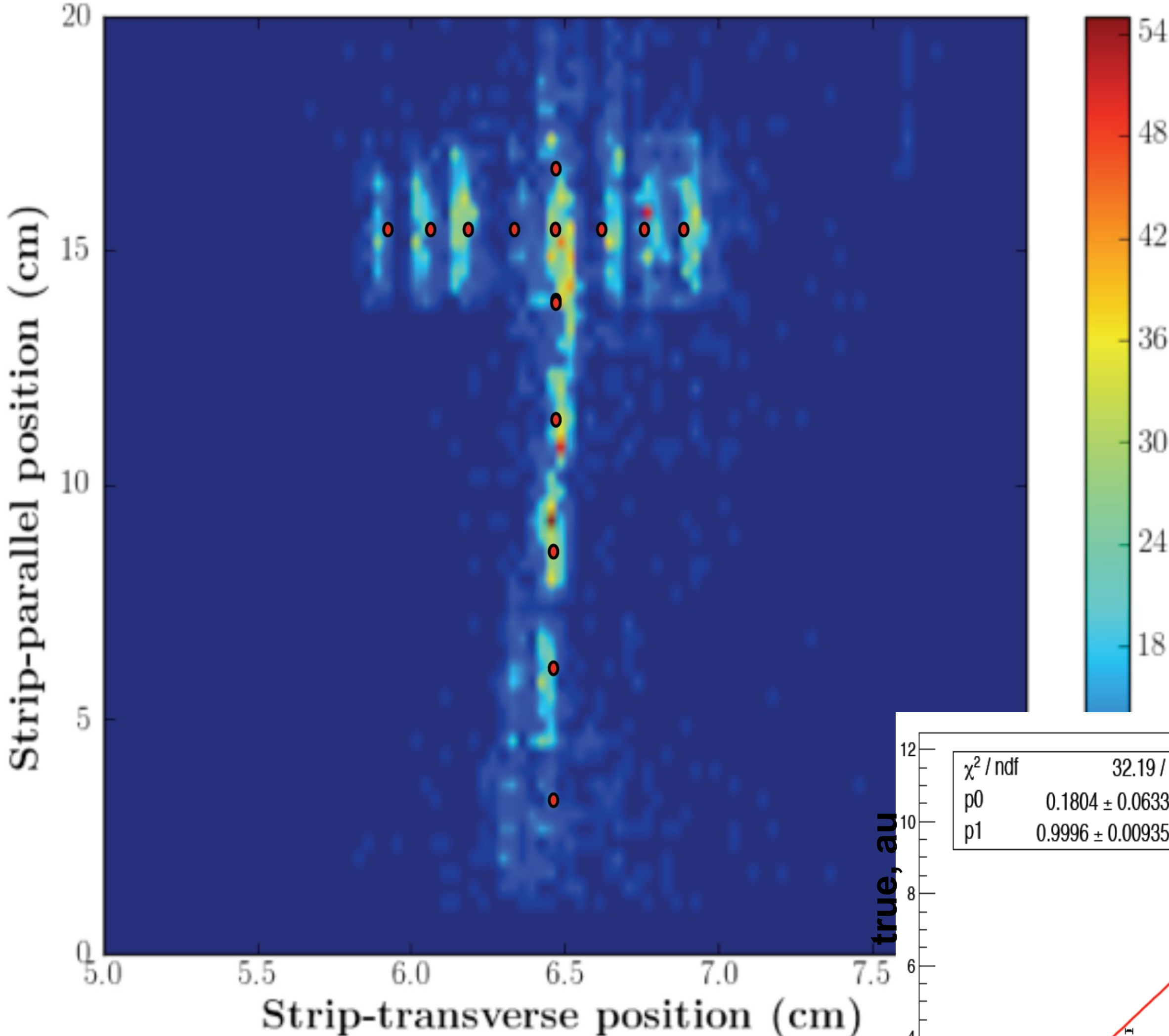


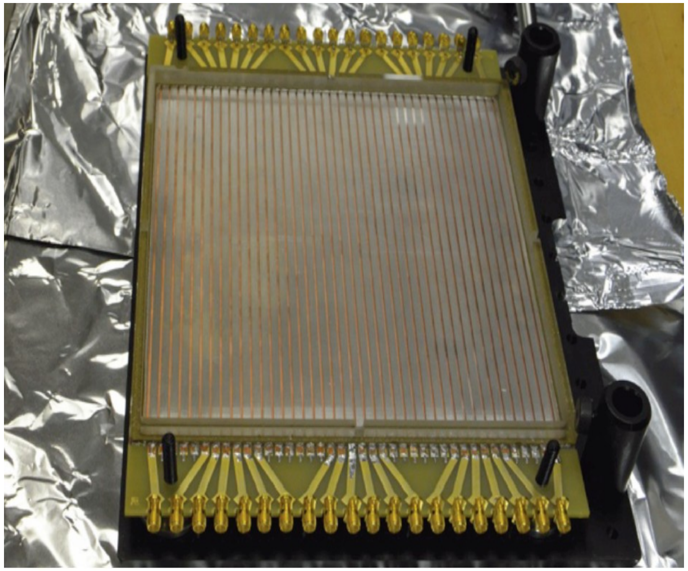


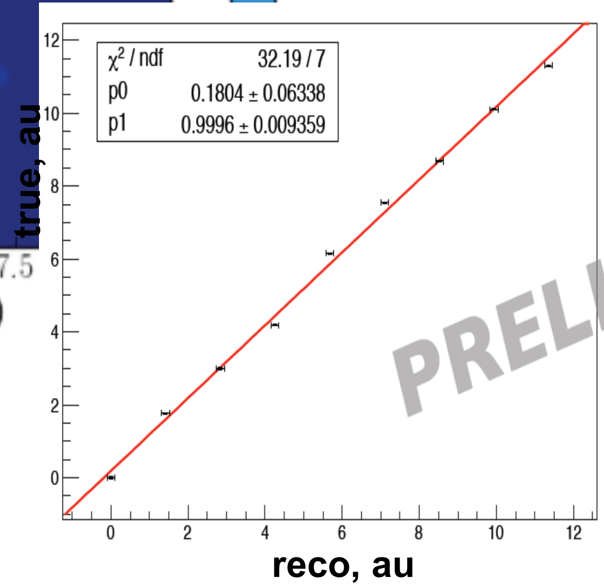


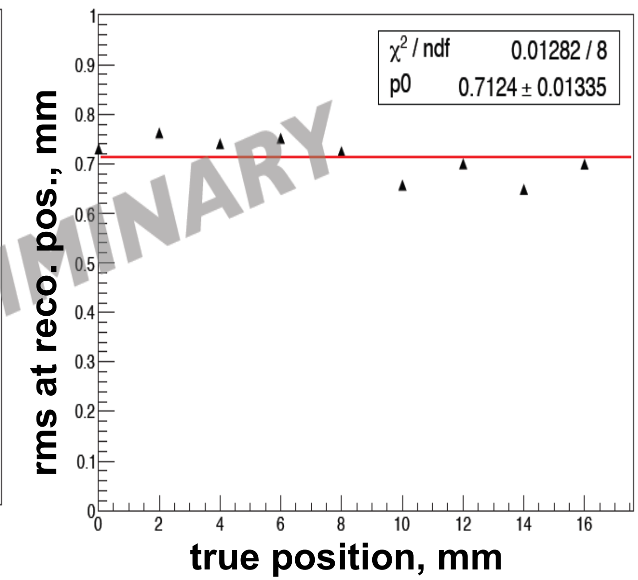
PRELIMINARY

Position Reconstruction









Summary and Plans

University of Chicago

- Many applications can benefit from precise timing and large area coverage
- Picosecond timing on large area seems to be within the reach of LAPPD (working in a large parameter space of cost and performance)
- 1 year goal: produce first sealed tube
- 3 years goal: deliver first tile systems to early adopters
- More info on the web:

  http://psec.uchicago.edu/

  http://psec.uchicago.edu/blogs/lappd/

APS Testing Team

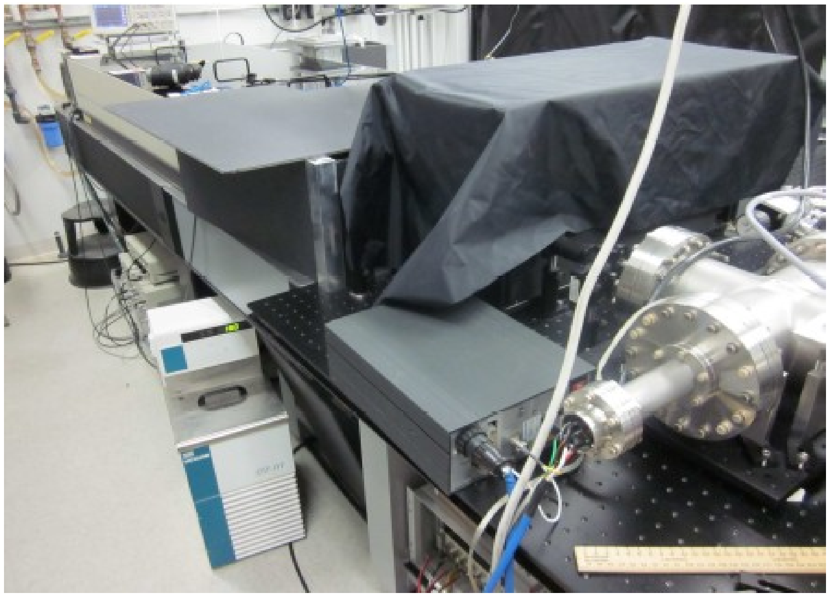
University of Chicago

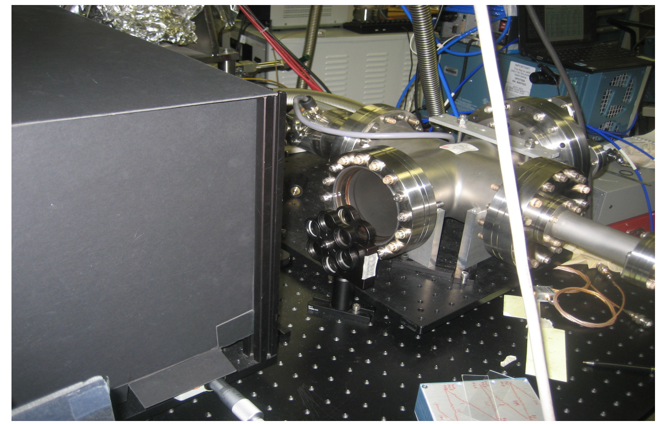
Back Up

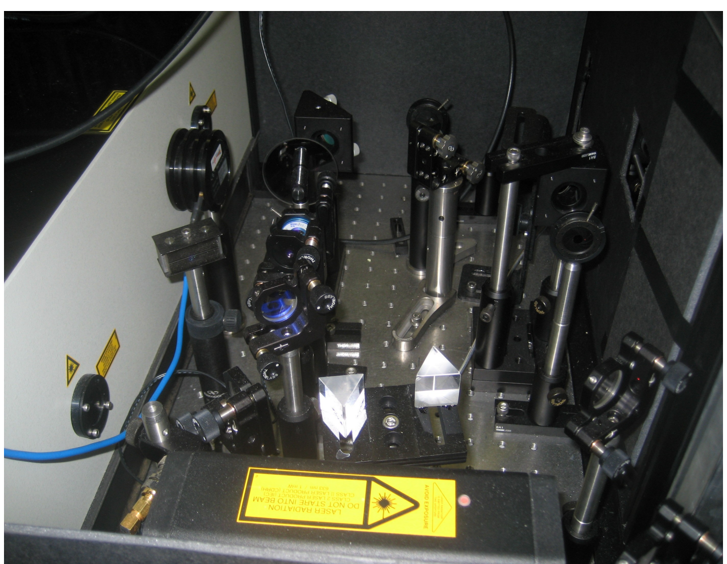
University of Chicago

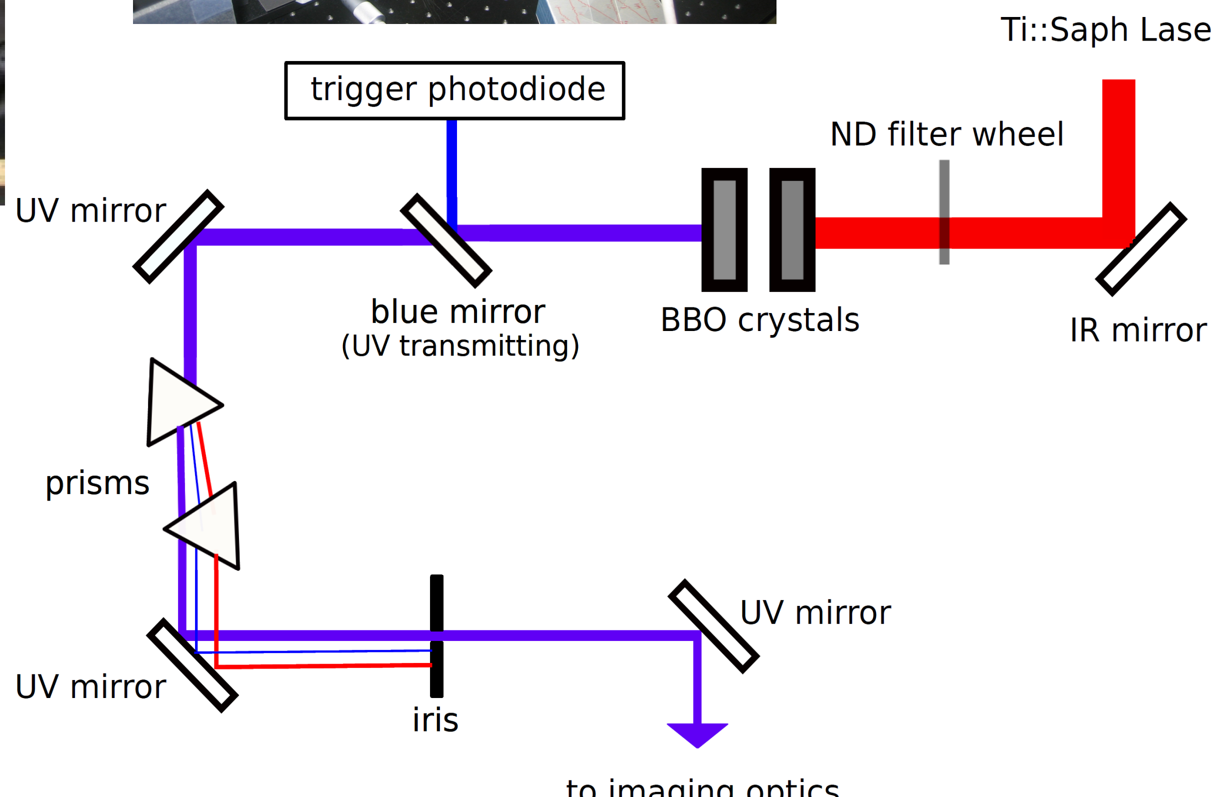
Sub-picosecond Pulsed Laser @APS ANL

University of Chicago



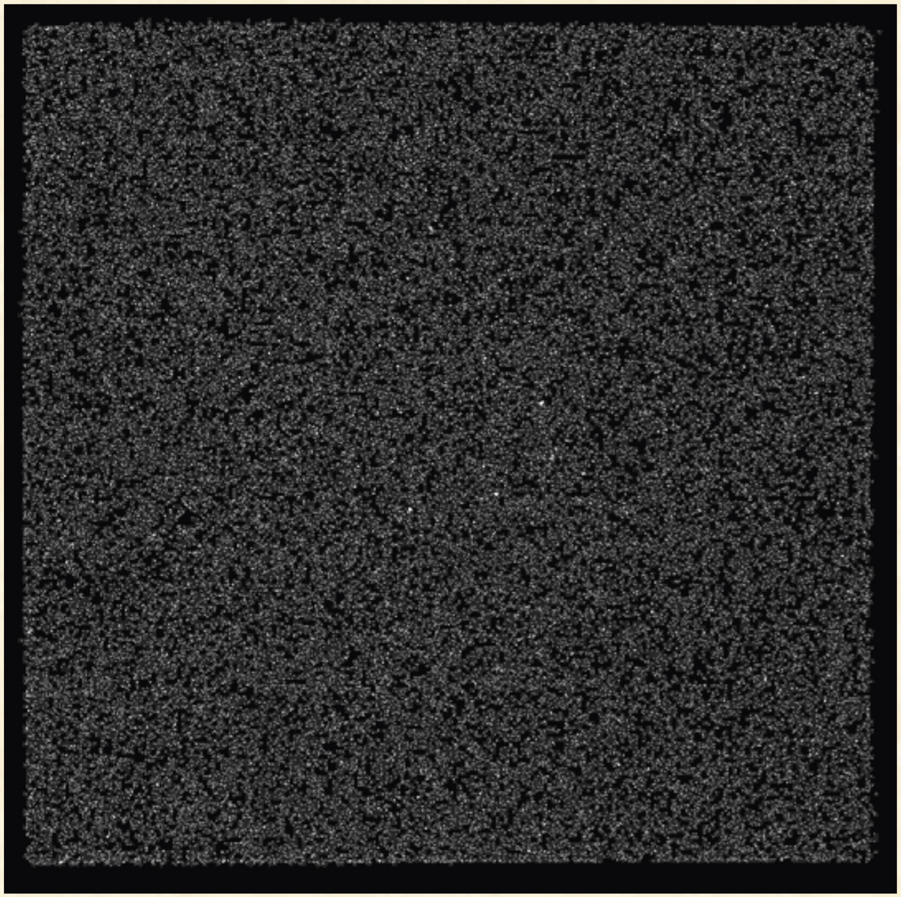






Background

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.

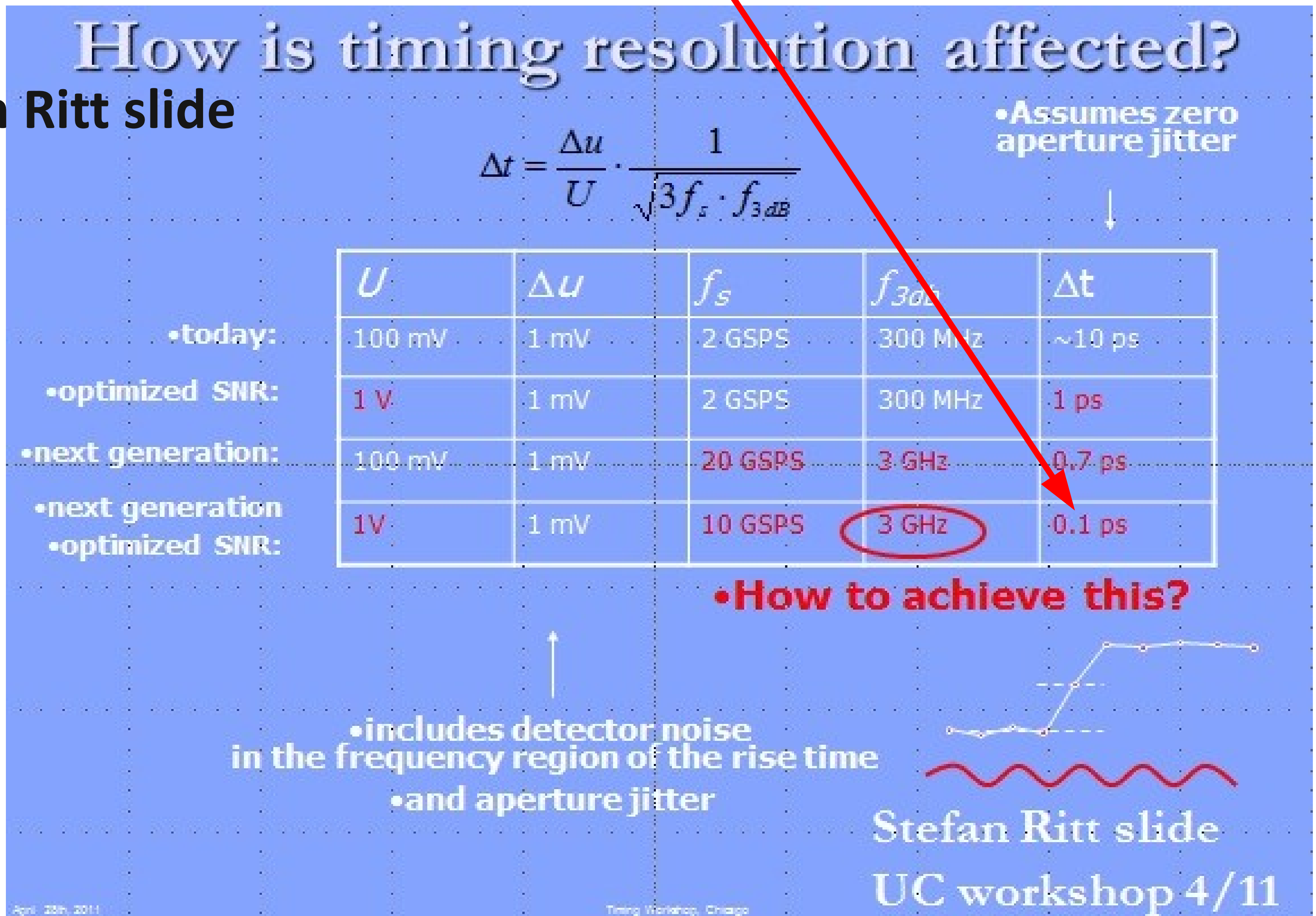
- 20µm pore, 60:1 L/d ALD-MCP pair, 0.7mm gap/200v.
- Background very low !! 0.068 cnts sec^{-1} cm^{-2} is a factor of 4 lower than normal glass MCPs.
- This is a consistent observation for all MCPs with this substrate material and relates to the low intrinsic radioactivity of the glass.
- Without lead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

Timing Limits

University of Chicago

Can we achieve sub-picoseconds?

Stefan Ritt slide



How is timing resolution affected?

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

•Assumes zero aperture jitter

	U	Δu	f_s	f_{3dB}	Δt
•today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
•optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
•next generation:	100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
•next generation •optimized SNR:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

•How to achieve this?

•includes detector noise in the frequency region of the rise time

•and aperture jitter

Stefan Ritt slide

UC workshop 4/11

April 28th, 2011 Timing Workshop, Chicago

Pulse shape fitting

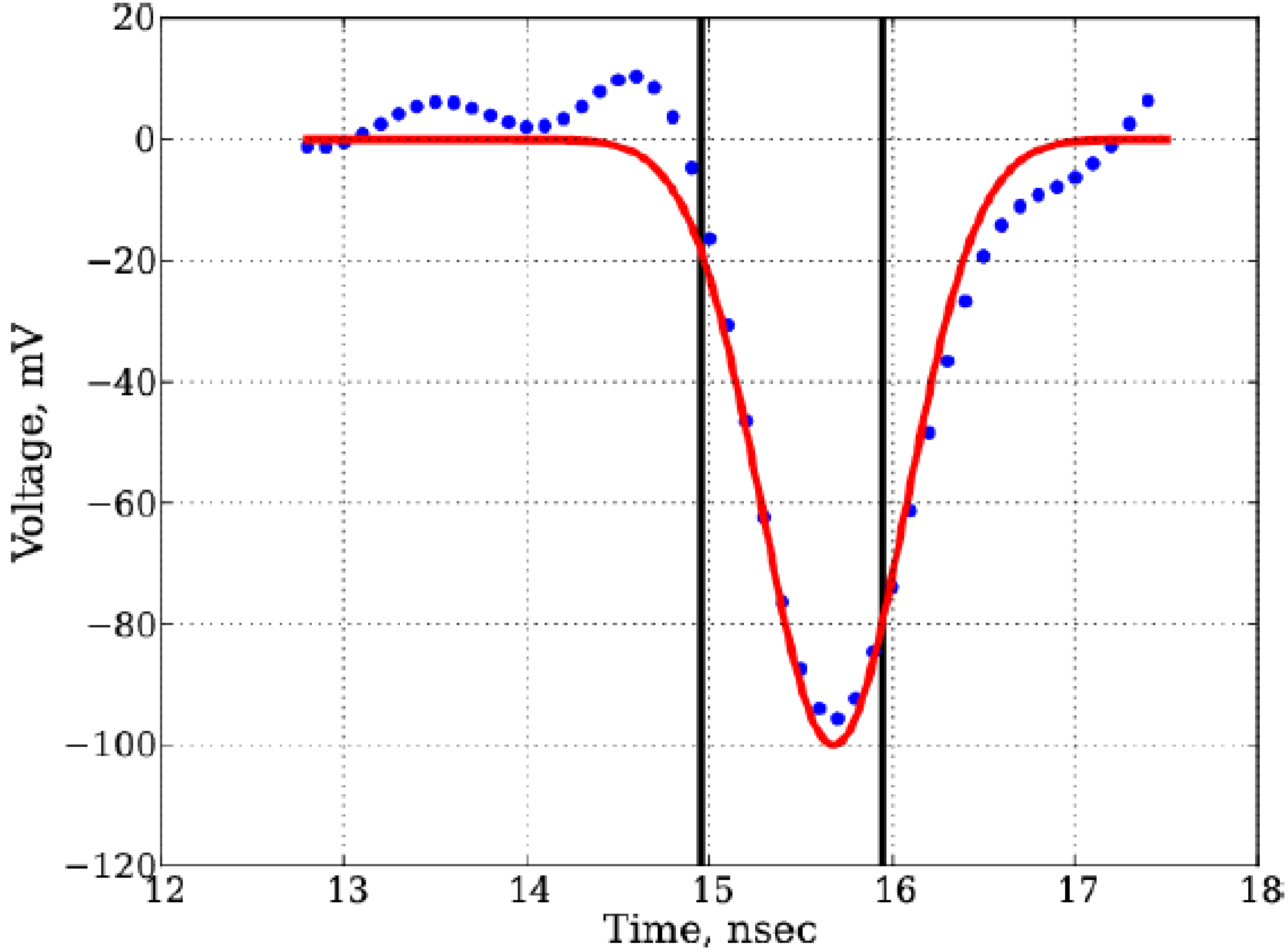


Figure: Noise filter is OFF.

Pulse shape is fitted with Gaussian between two black lines.

Time resolution: Noise filter effect

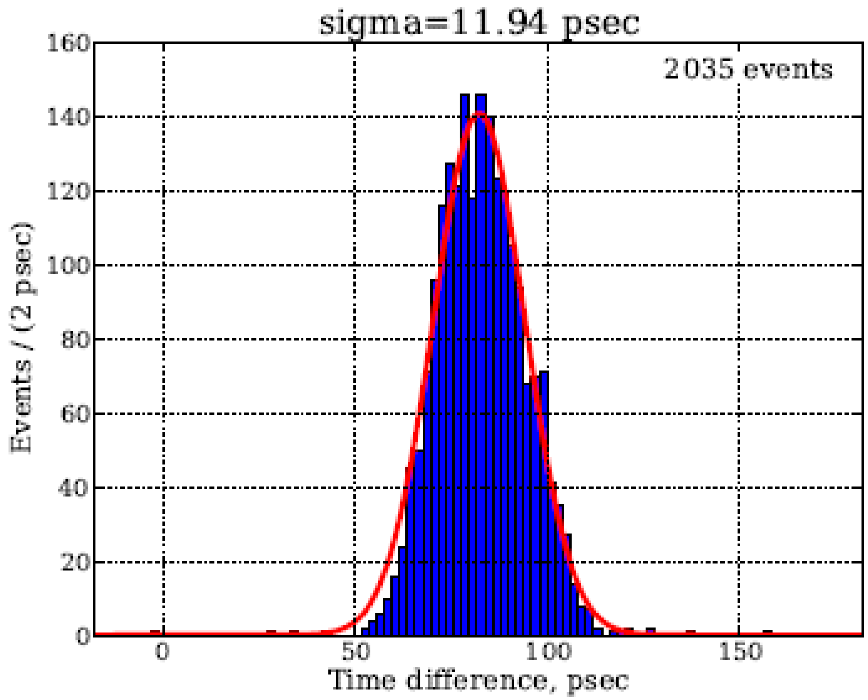


Figure: Noise filter is OFF.

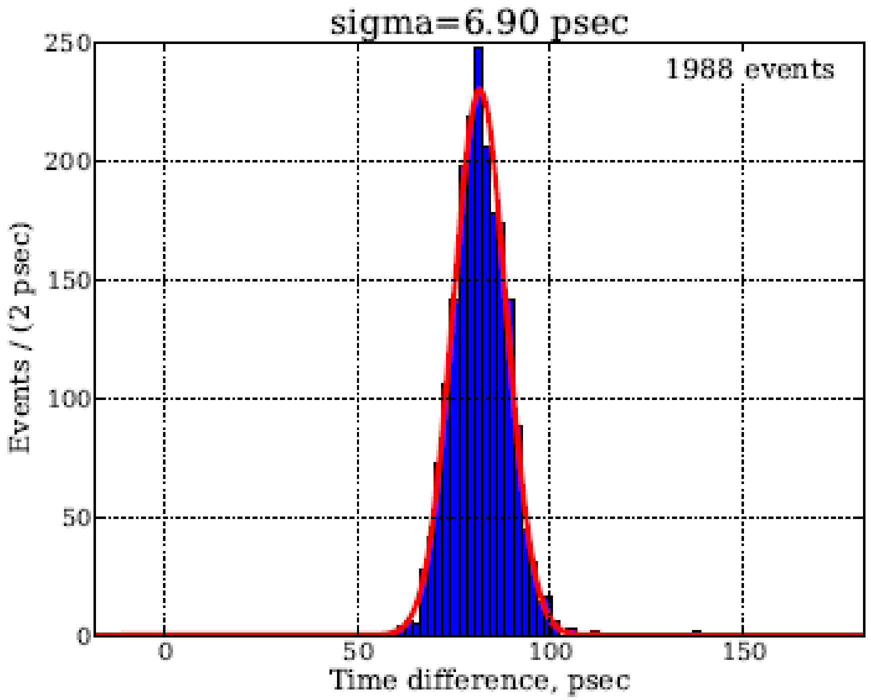


Figure: Noise filter is ON.

- Pulses with amplitude between 110 and 130 mV selected.
- Time difference distribution is fitted with Gaussian.
- Time resolution is σ-parameter of the fit.

Differential time resolution vs. Pulse amplitude

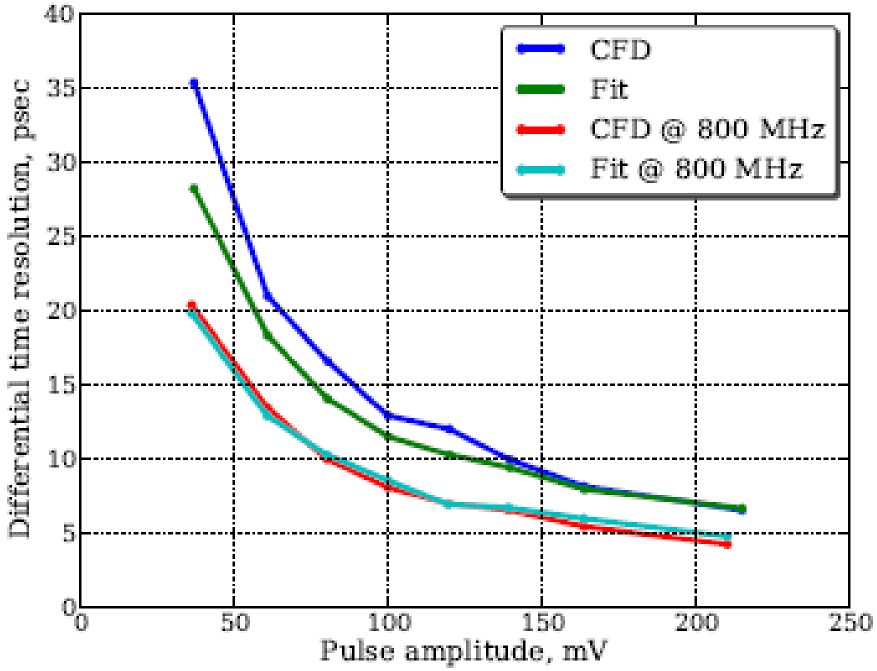


Figure: Differential time resolution as a function of pulse amplitude.

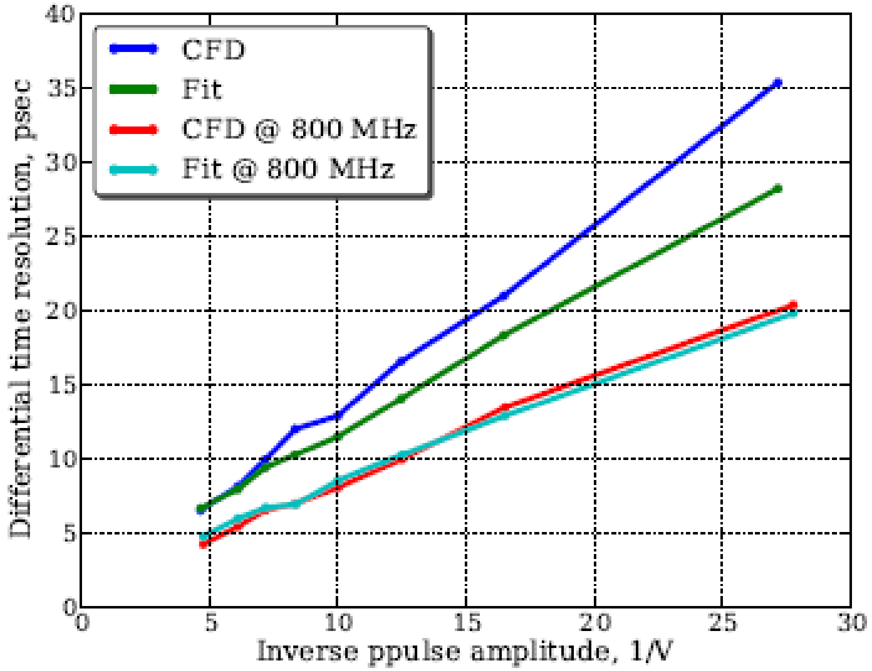
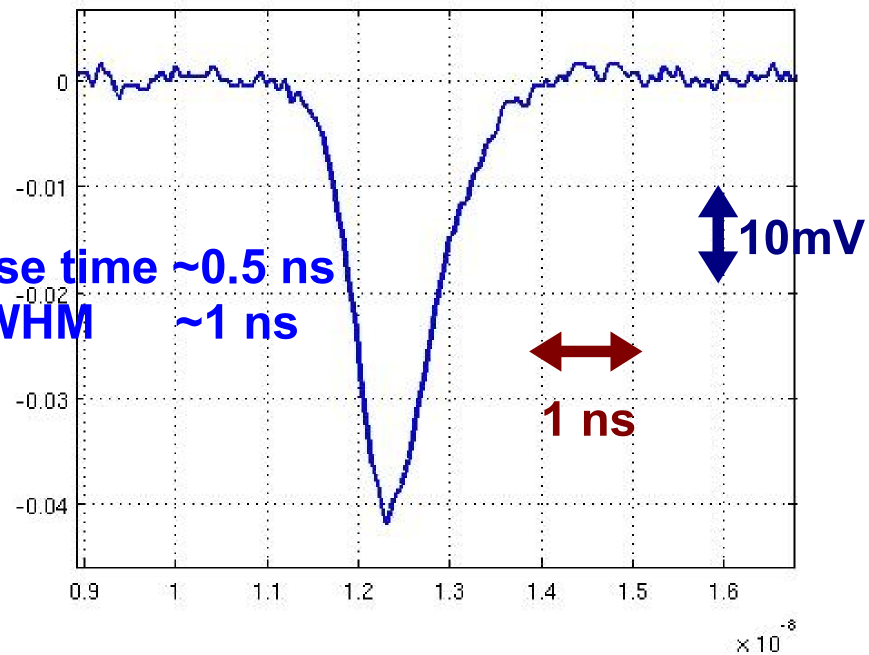


Figure: Differential time resolution as a function of inverse pulse amplitude.

MCP pulses and timing



Rise time ~0.5 ns
FWHM ~1 ns

Timing analysis approach

- Fit rising edge
- Use constant fraction descriminant

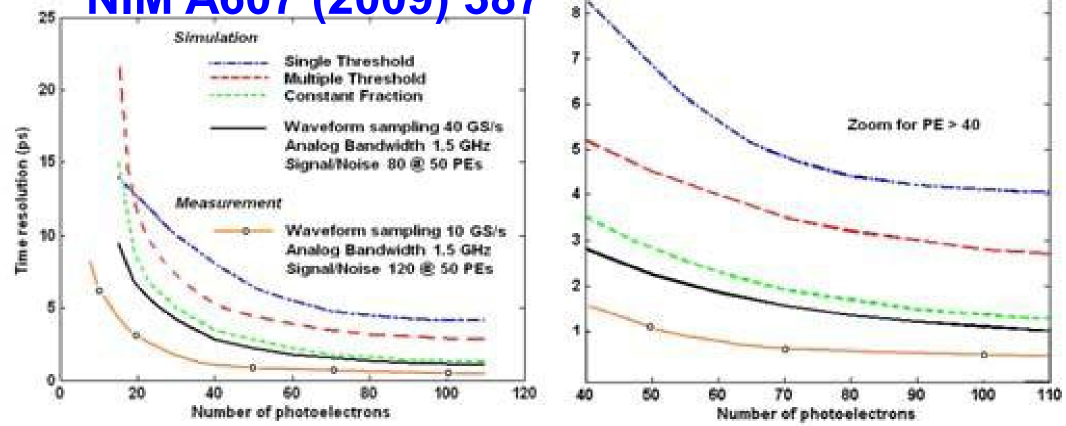
Questions

- Time resolution
- Position resolution

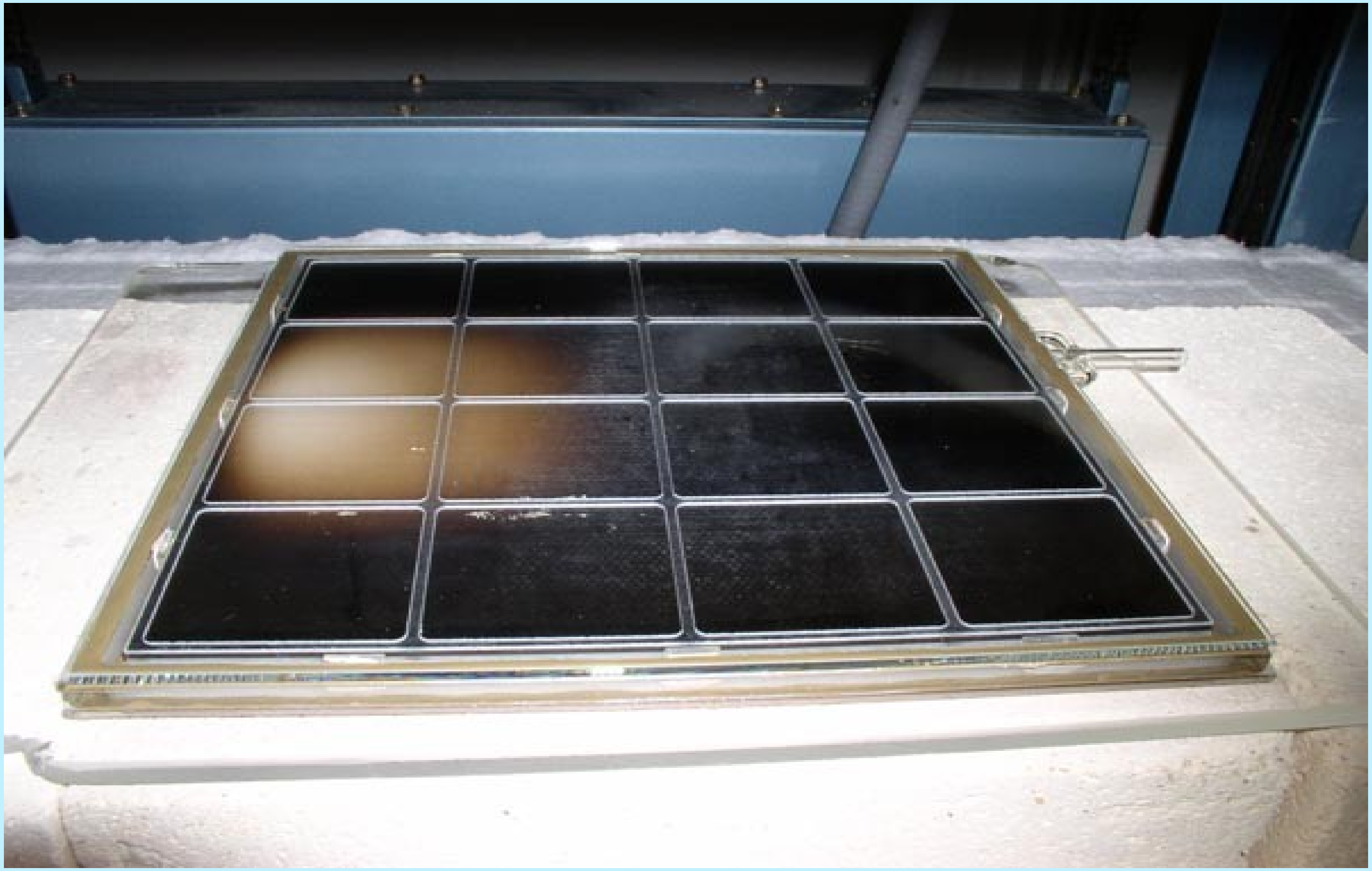
Time resolution determinants:

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

NIM A607 (2009) 387



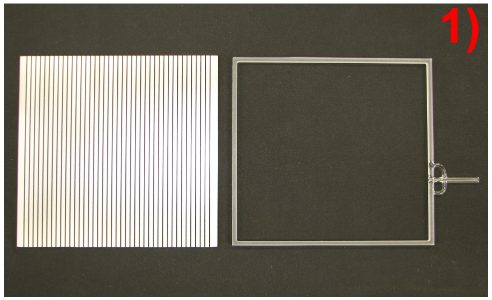
Hermetic Packaging

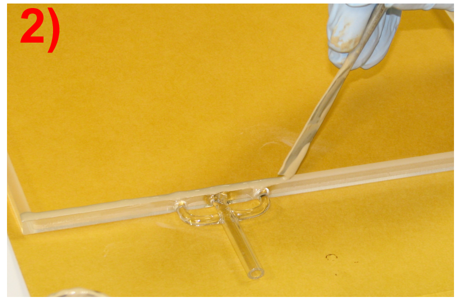


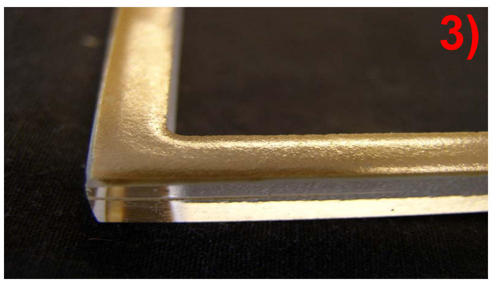
Frit Seal

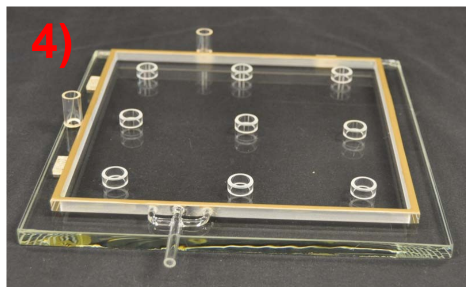
University of Chicago

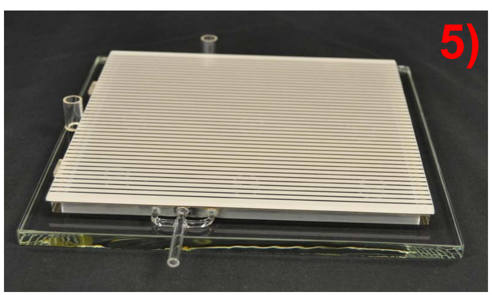
J.Gregar, M.Minot

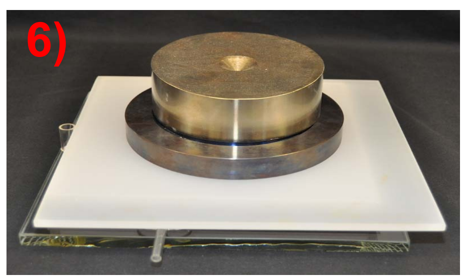












1) Attach pump out tube to 8.66x8.66" frame

2) Apply schott #G018-223 K3 frit paste to frame

3) Fire the frit (many trials to optimize parameters)

4) Prepare for anode plate frit sealing

5) Position anode on top of the frame

6) Add weight

- **Tile bases are reliably reproducible**
- **Mechanical and vacuum properties have been tested**

Top Seal

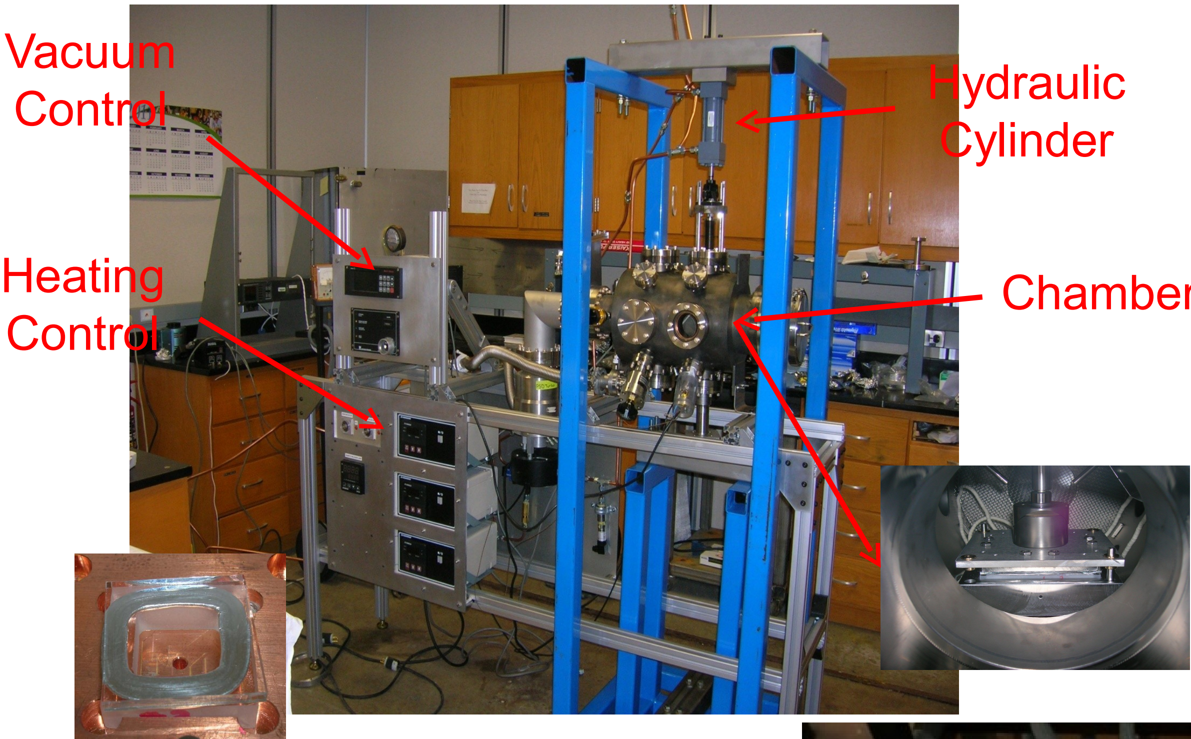
How to close frit sealed tile base at the top and stay at moderate temperatures? Top Seal problem

Use indium or indium alloys

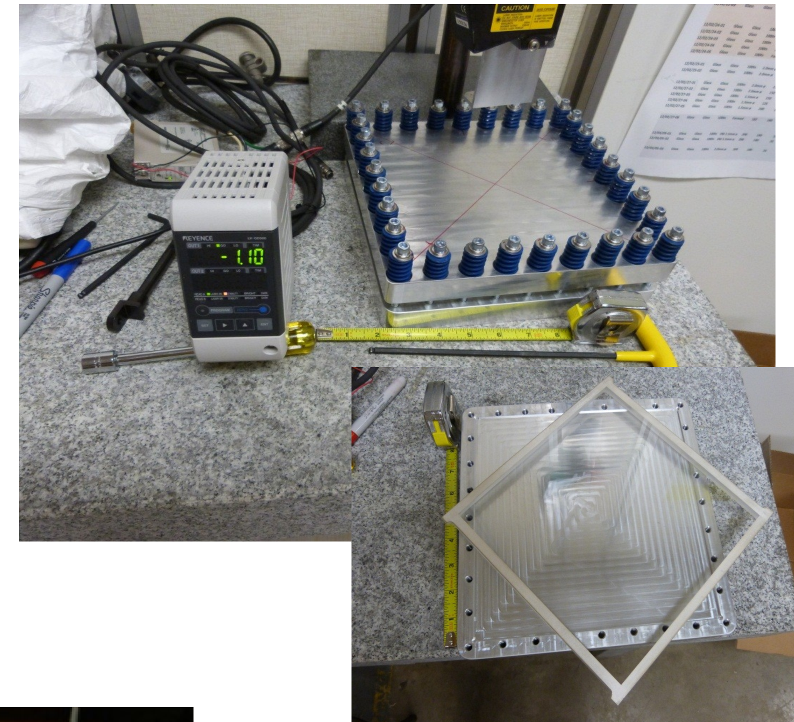
- soft metal
- low melting point (157C for pure In)
- essentially zero vapor pressure
- indium-glass seals are successfully used by industry

"Cold Seal"

Hydraulic system



Spring compression



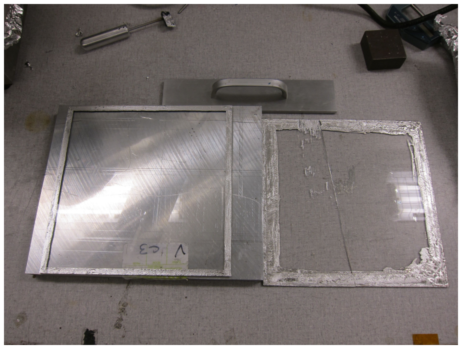
M.Kupfer, D.Walters,

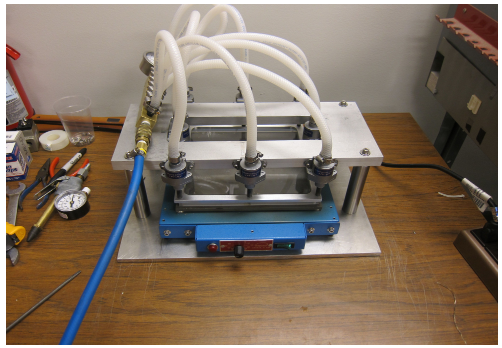
J.E.Indacochea

"Hot Seal"

A.E., R.Obaid, R.Northrop, R.Metz

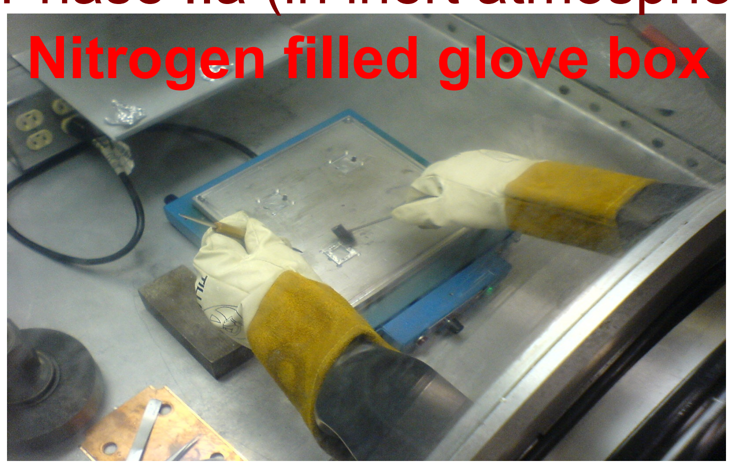
Phase I (in air)





...indium oxidizes quickly...

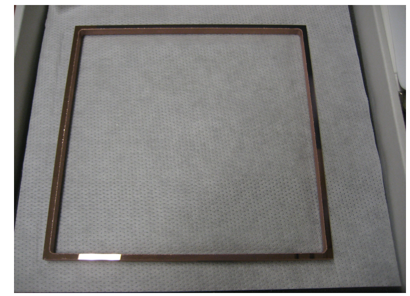
Phase IIa (in inert atmosphere)

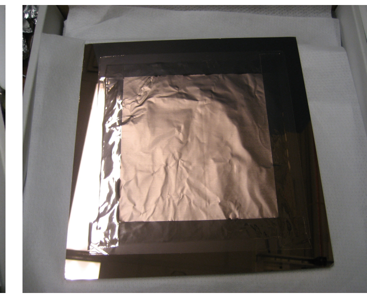


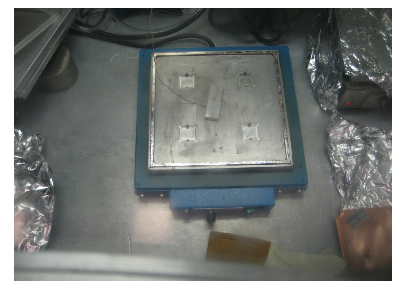
...indium doesn't stick to glass if no O_2...

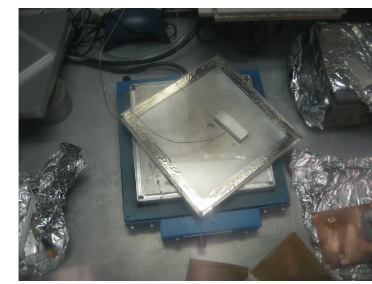
There is also „Groove Seal“ effort at SSL

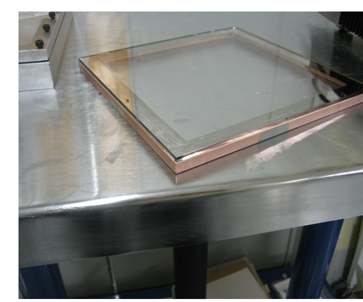
Phase IIb (add NiCr-Cu layer)



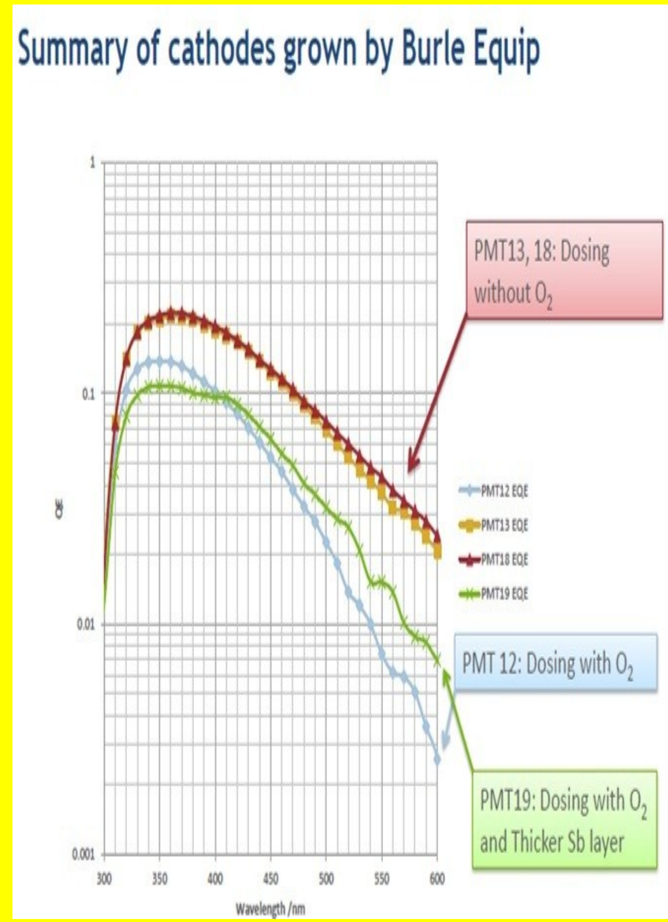








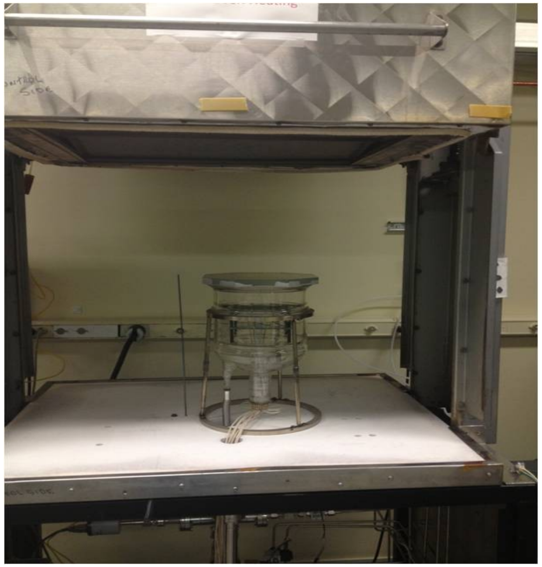
Photocathodes

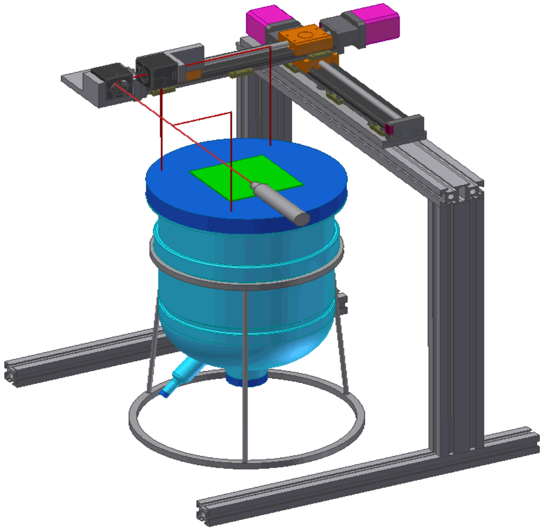


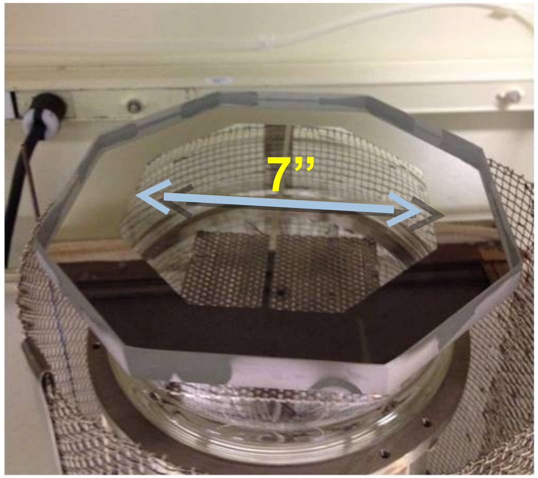
Photocathodes at ANL

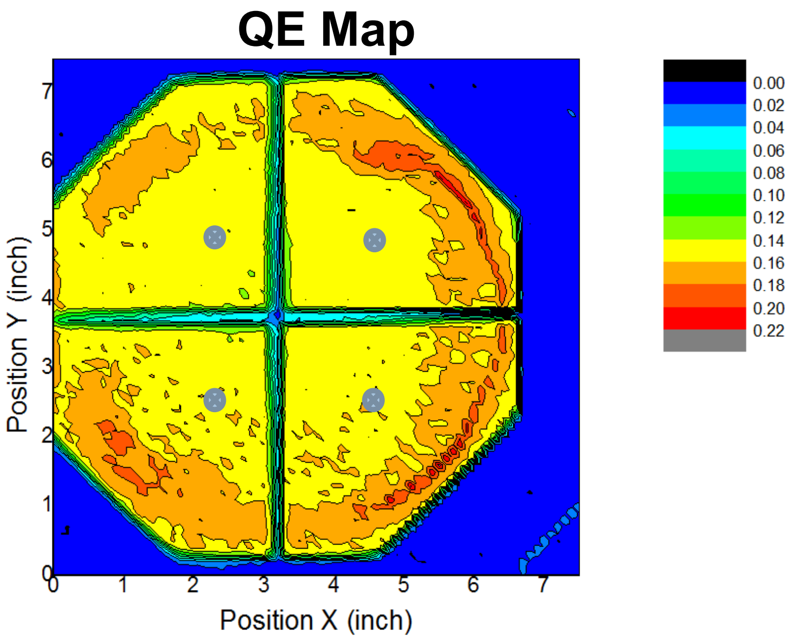
K_2CsSb

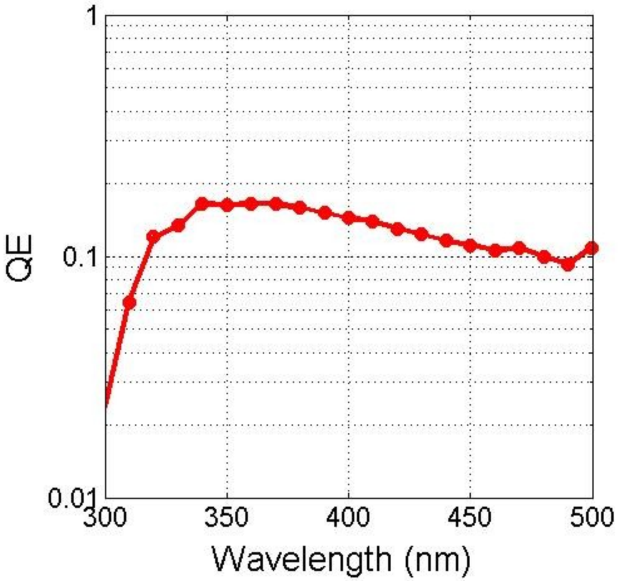
R.Wagner, J.Xie, et.al
with K.Attenkofer @BNL







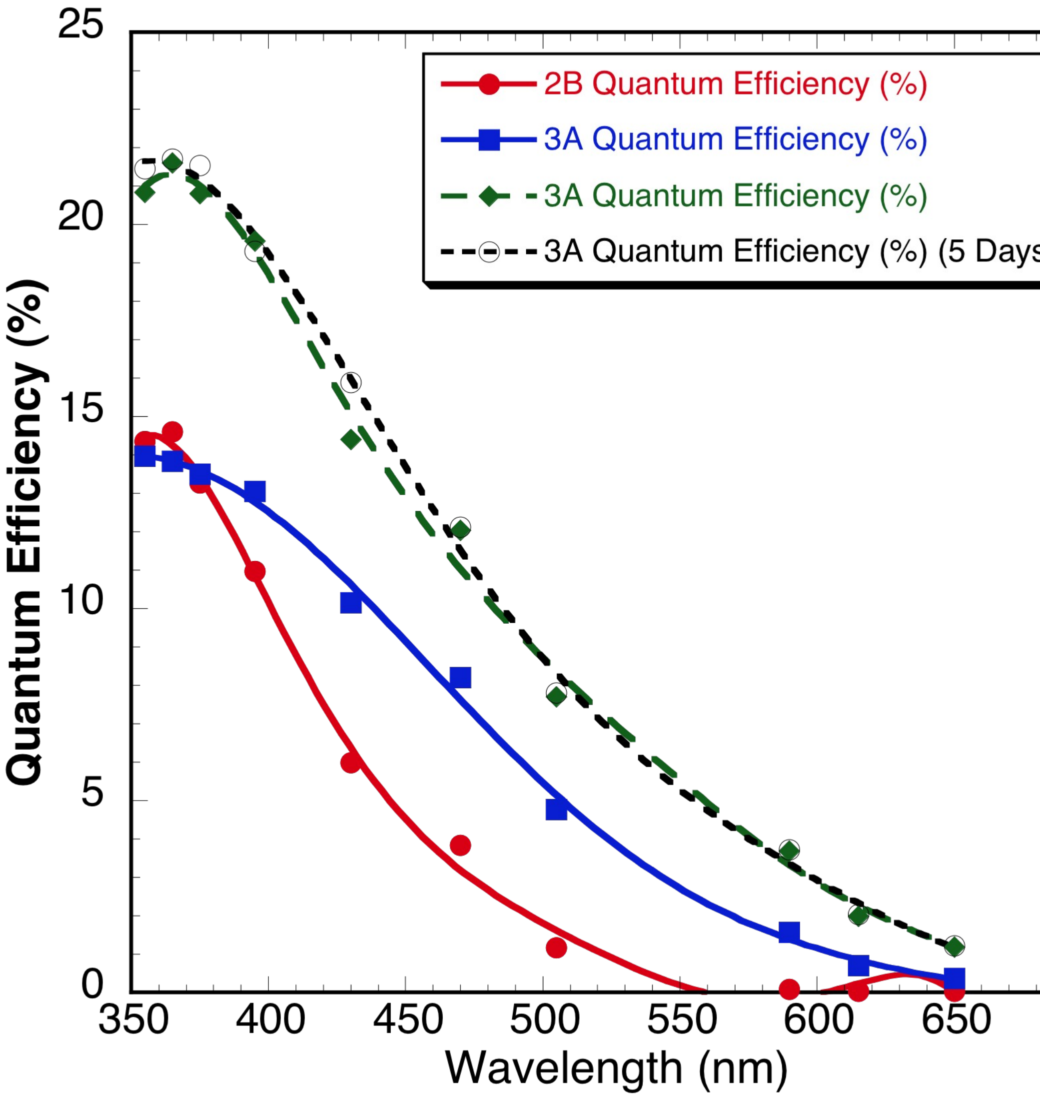


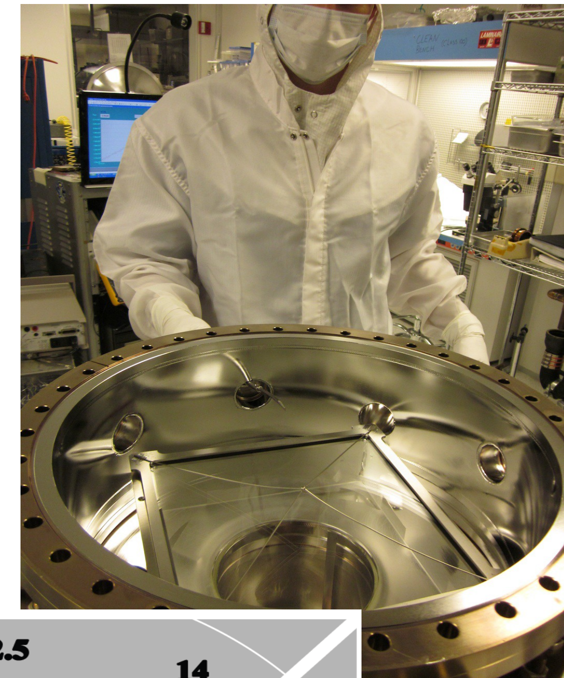


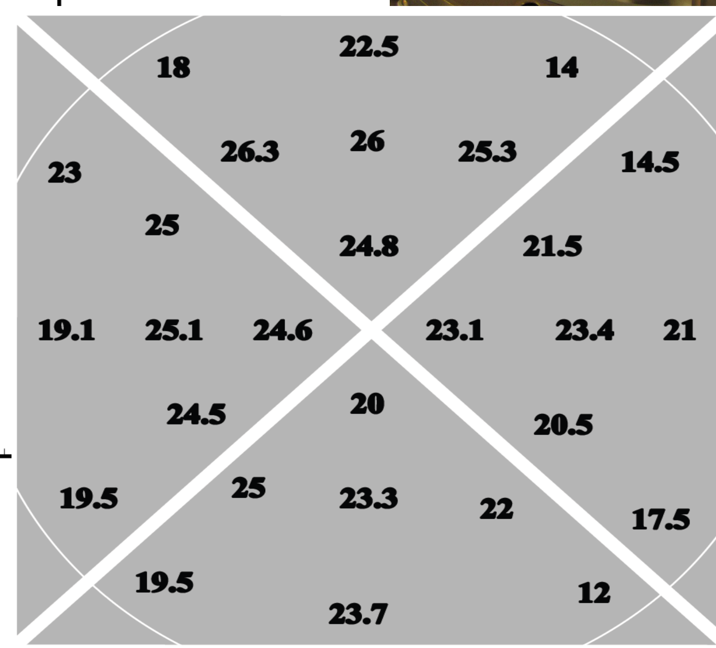
Photocathodes at SSL

Na_2KSb

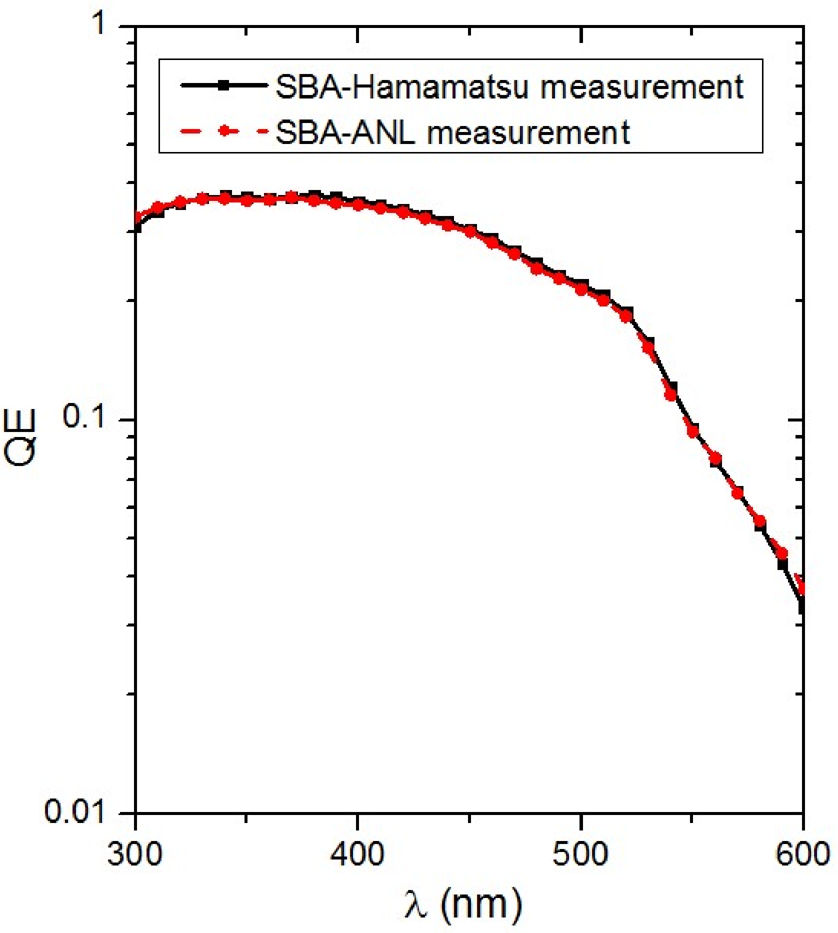
J.McPhate, O.Seigmund







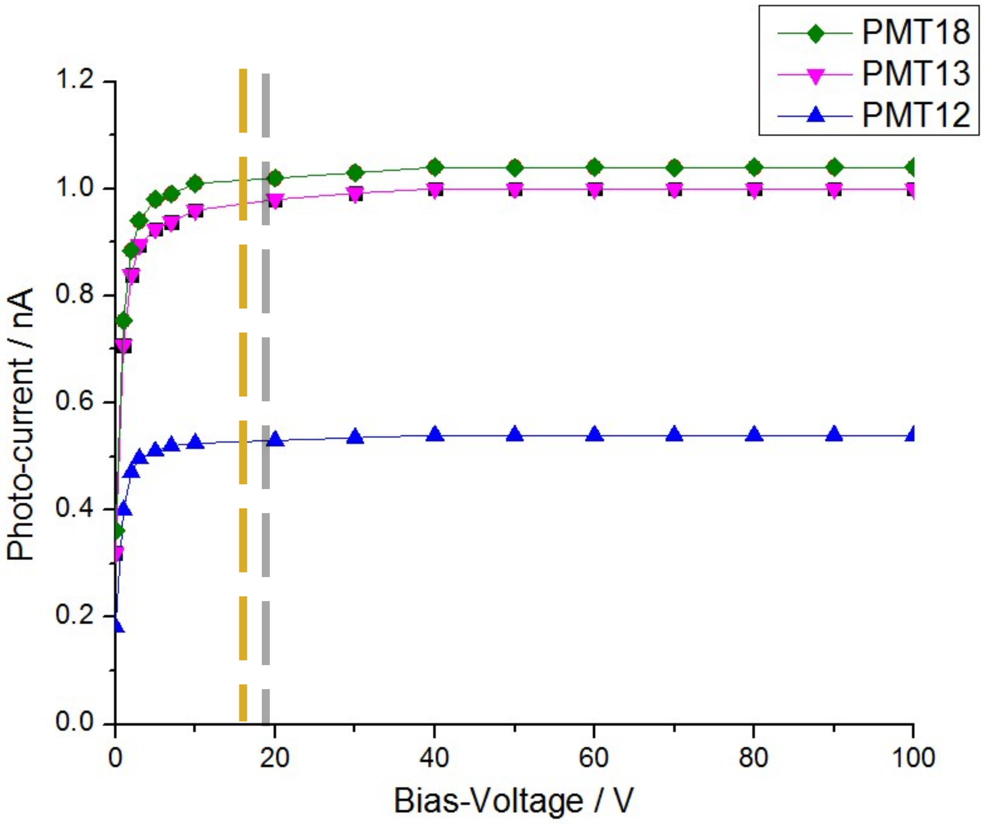
Commissioning of Optical Station



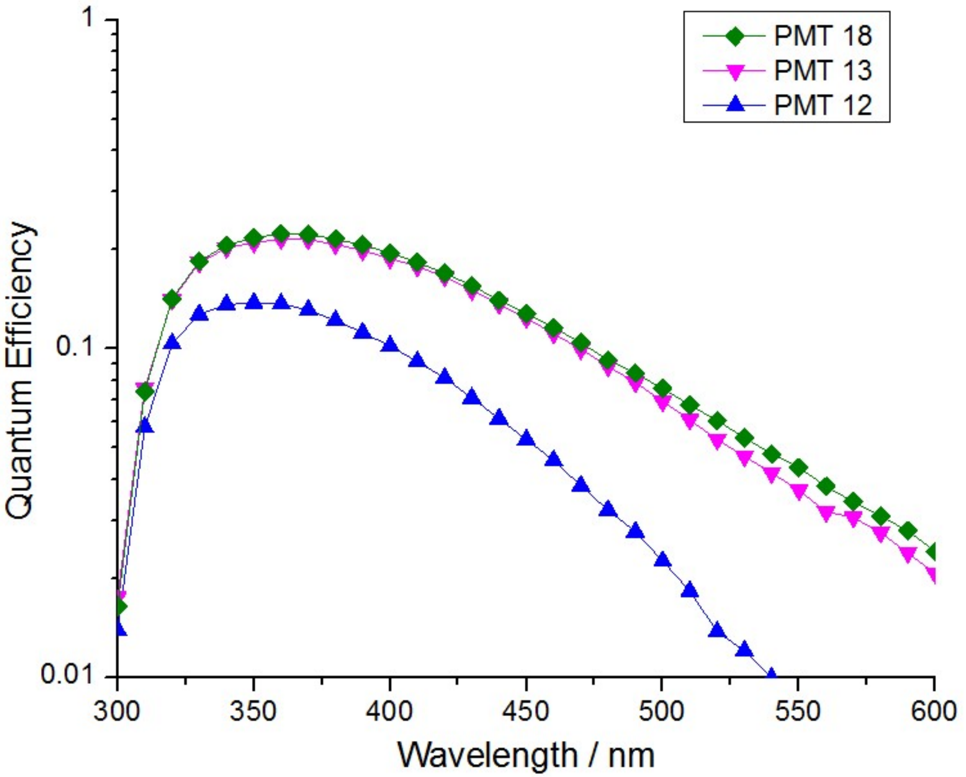
- Movable optical station can be shared with different growth facilities in the lab.
- QE measurement by Hamamatsu and ANL optical station agree well with each other indicating the home-built optical station is accurate.

Small PMT Photocathode Characterization

I-V Characteristic

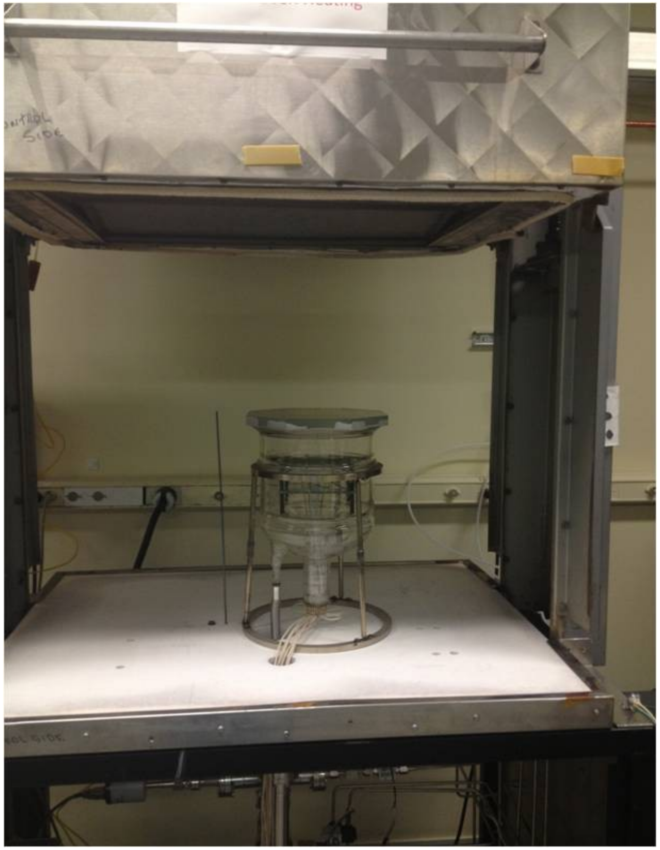


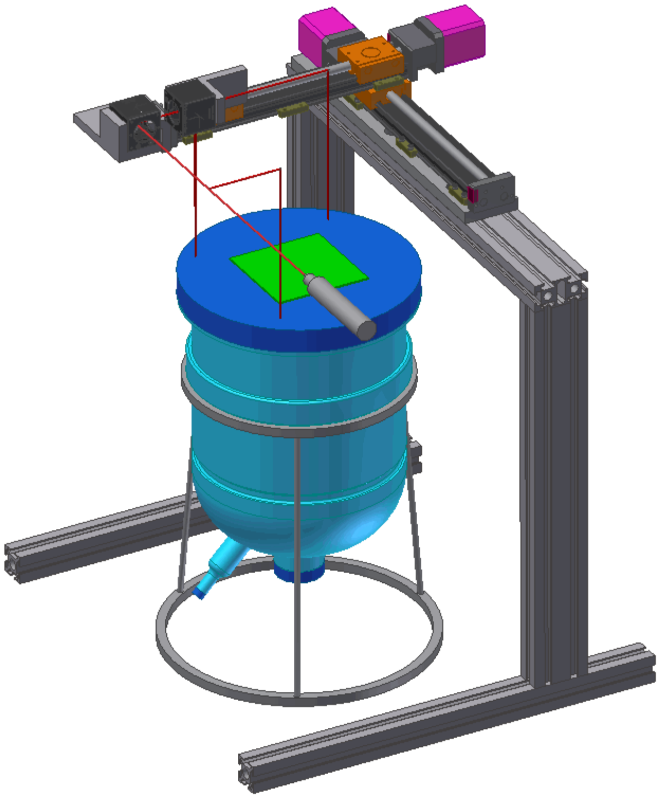
QE Measurement



- Cathodes exhibit characteristic I-V behavior, with QE as high as 24% at 370 nm.
- The quick drop at short wavelength is due to glass absorption.

The Chalice Design



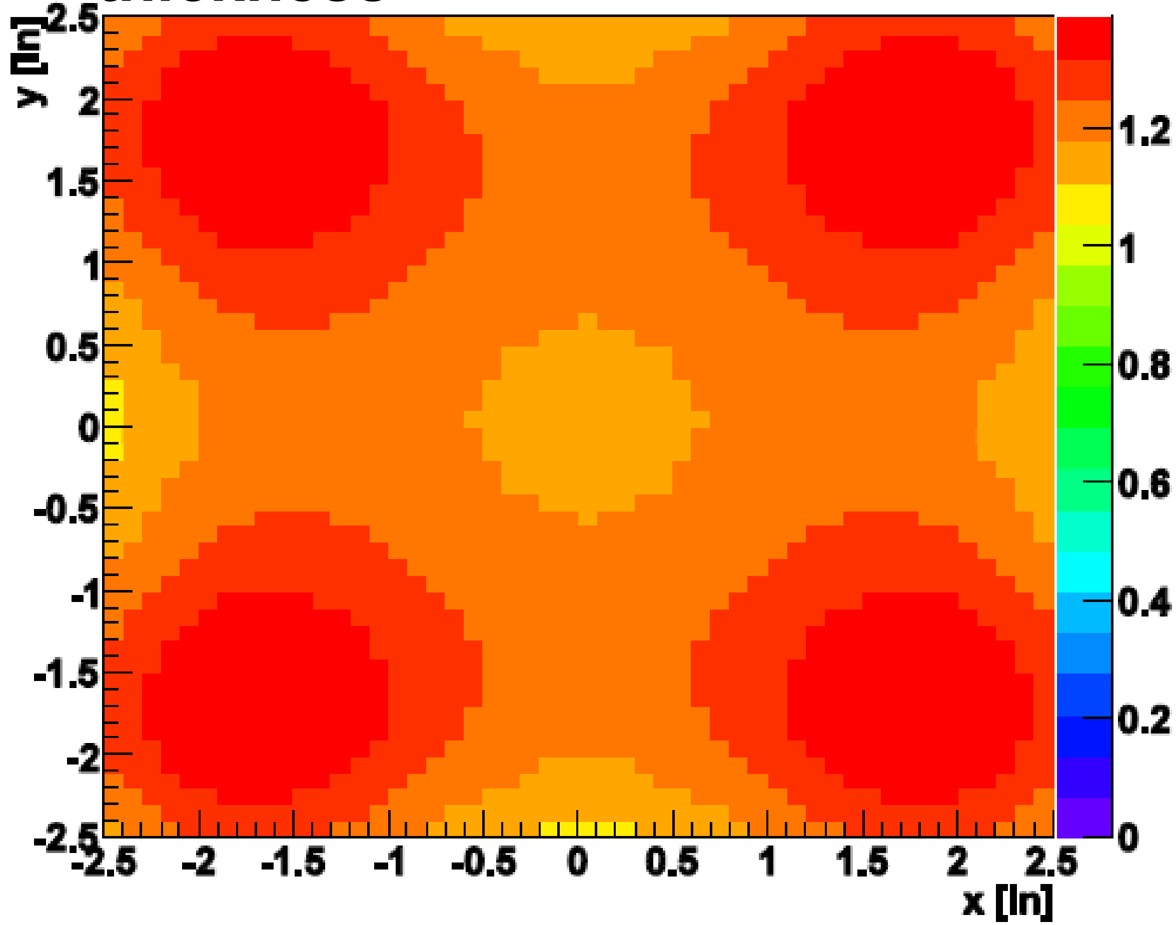


- Design is based on the small PMT tube, the chalice can be seen as a LARGE PMT tube.
- Top glass plate is replaceable for reuse.
- Chalice structure is supported by external legs.
- An X-Y scanner was designed and built for QE scan.

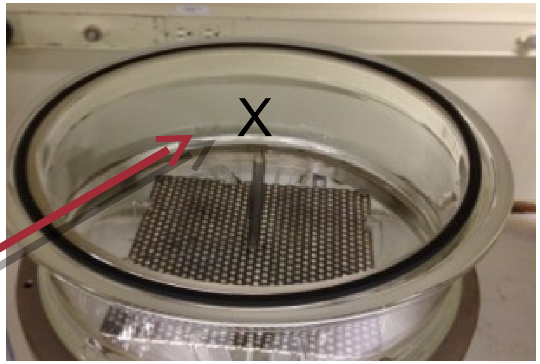
Sb Beads Arrangements for the Chalice (4''X4'')

- Numerical simulation of Sb thickness as a function of Sb beads arrangements and distance from window;
- 4 Sb beads arrangement
- 2.5" distance

Simulation of relative Sb thickness

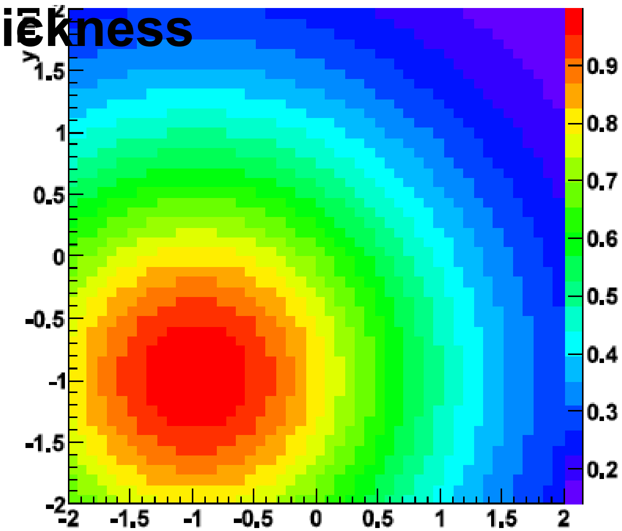


Comparison of QE Map and Sb Transmission Map

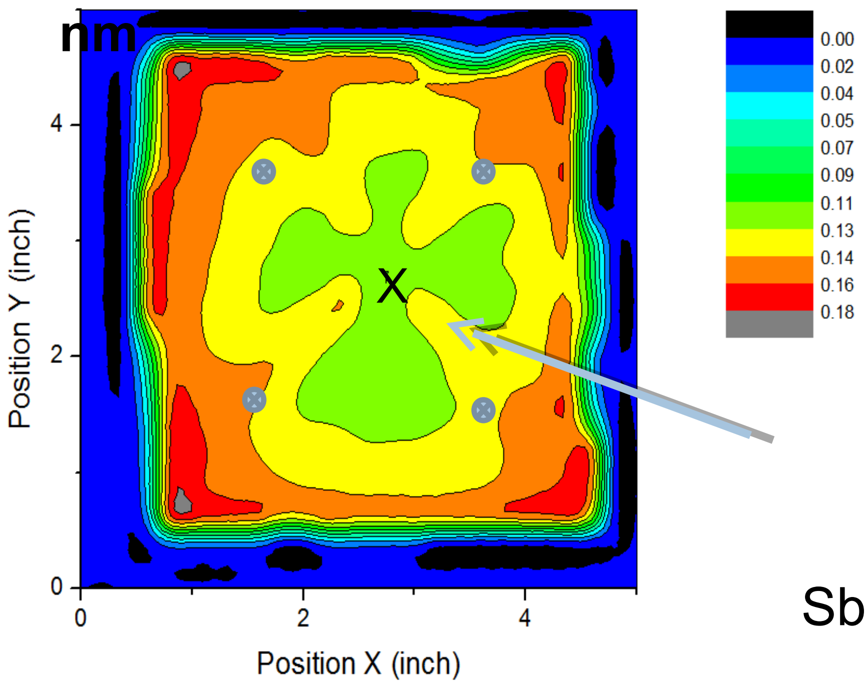


Center nail ("lightning rod") for plasma generation

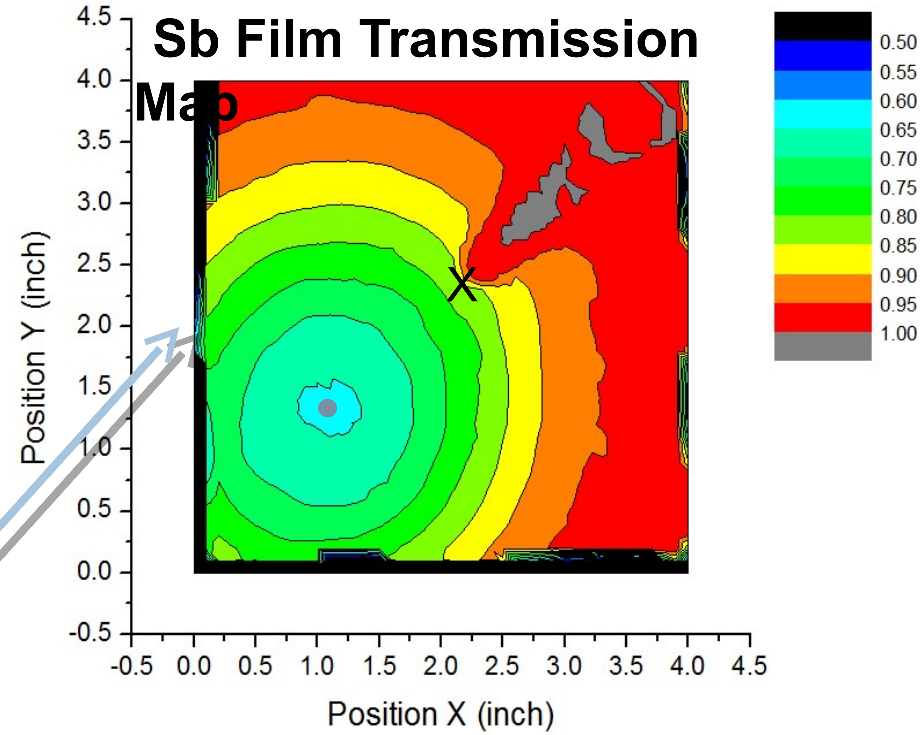
Simulation of relative Sb thickness



4"X4" QE Map at 370 nm



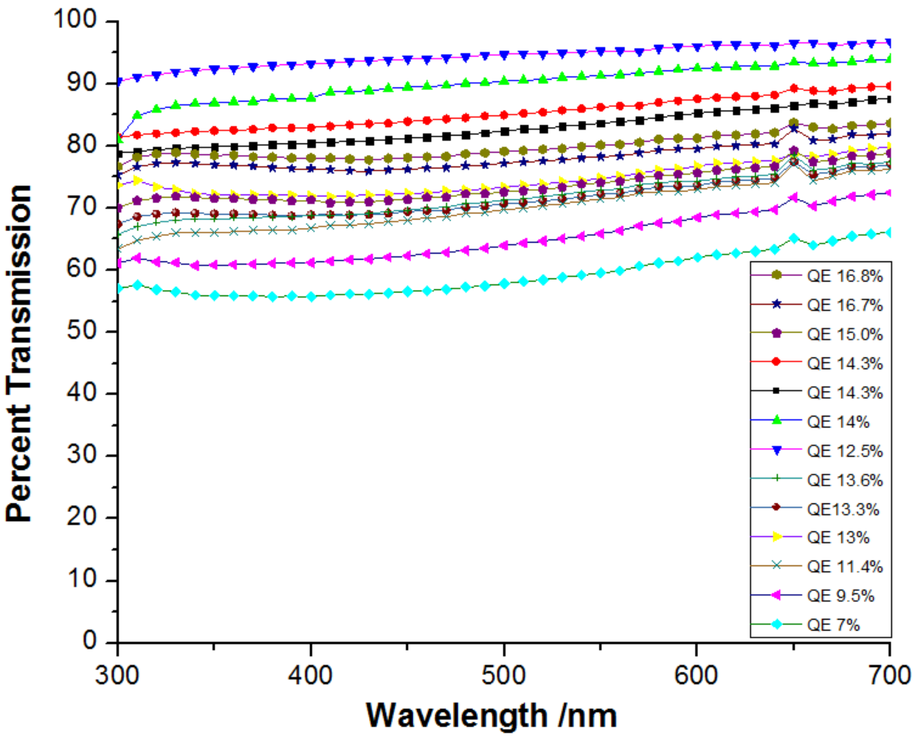
Sb Film Transmission Map

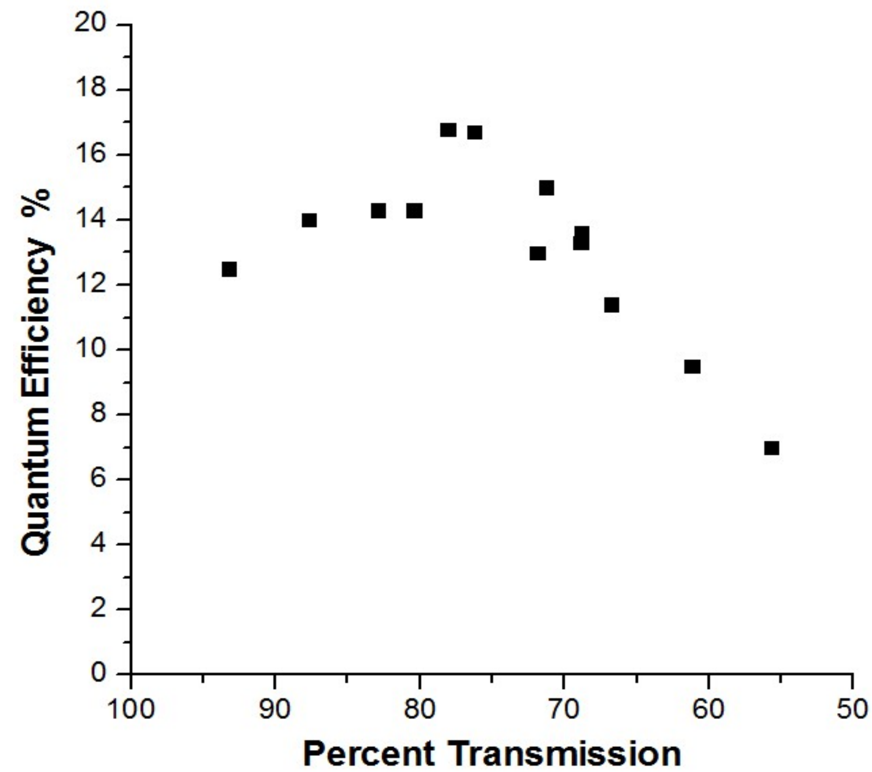


Sb bead

Center X: Lightning rod, which affect the Sb film deposition

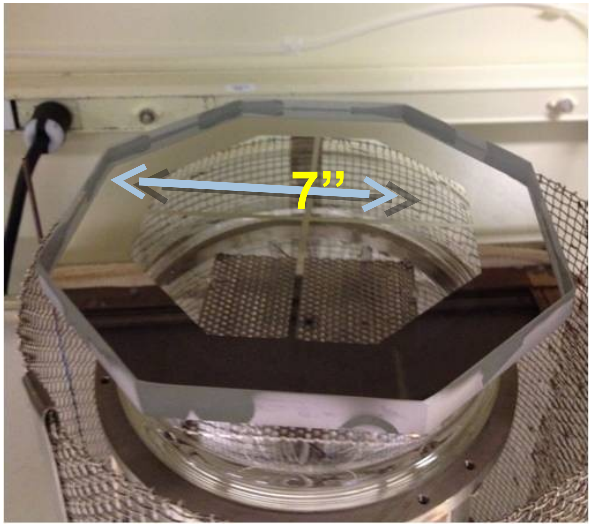
Sb Film Transmission Curve with Different Photocathode QE

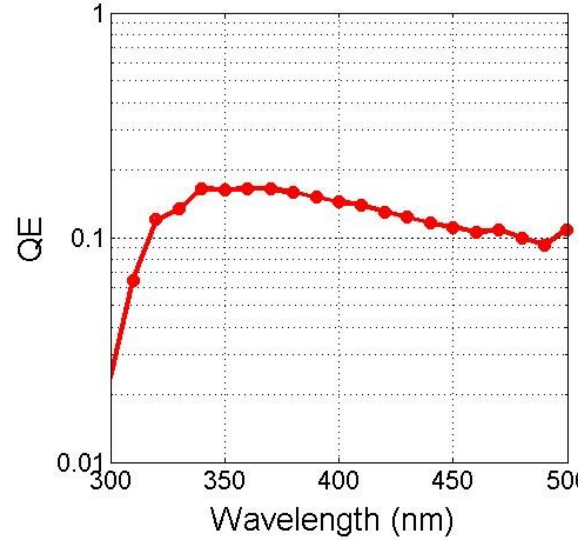




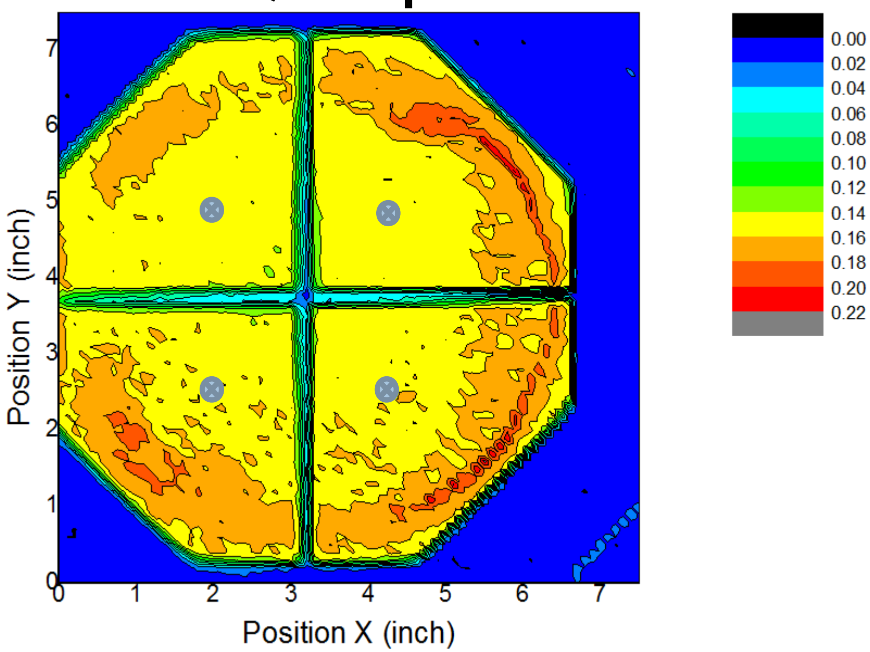
- Film transmission with known QE were measured and plotted.
- Film transmission increases as wavelength increases without regarding the QE value
- The film transmission values at 400 nm were chosen to plot the relation between KCs-Sb cathode QE and film transmission.
- The highest QE is around 78% Sb transmission (400nm beam).

Chalice Photocathode Characterization (7'')

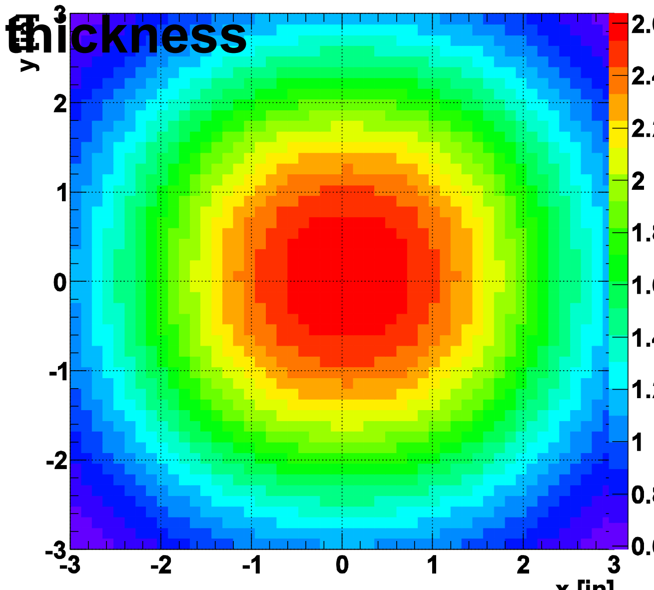




QE Map



Simulation of Sb layer thickness

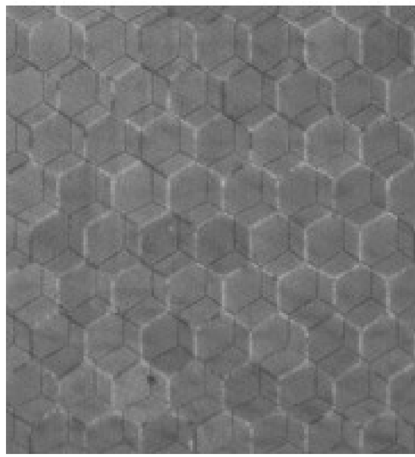


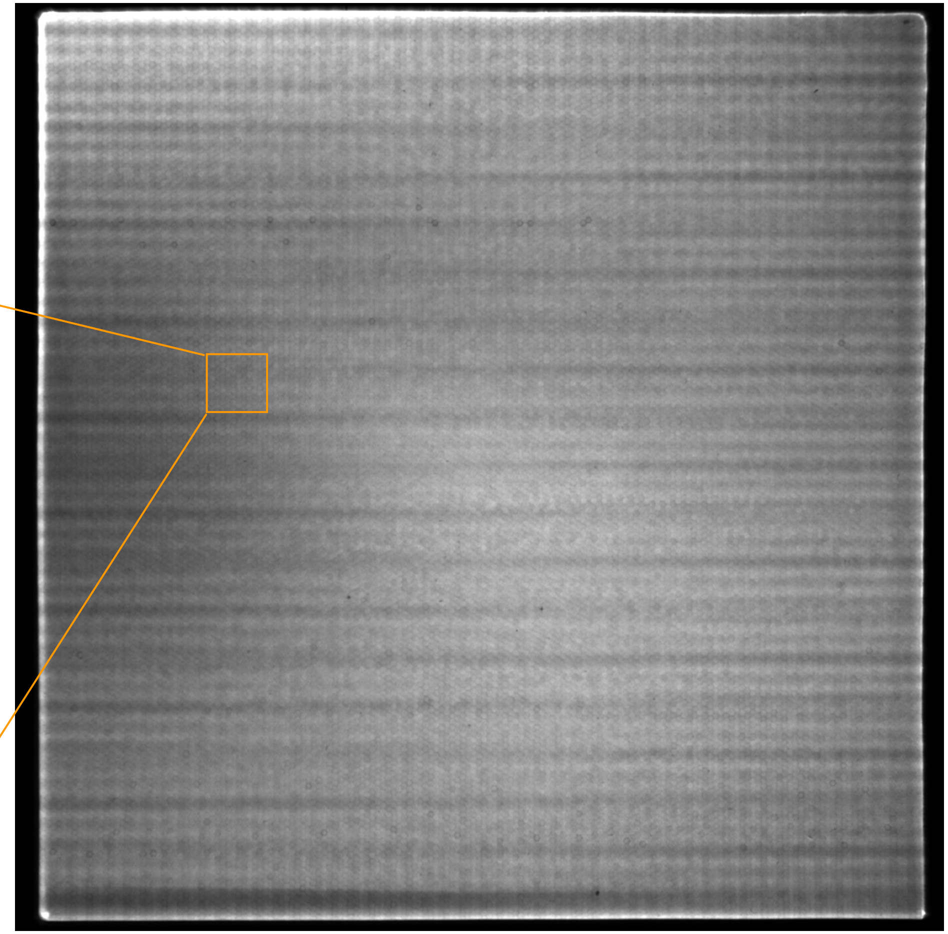
- Flat cathode with average QE (~16%), the highest QE spot reaches over 22%, and the higher QE is at the corner area, which is the thinner Sb area.
- Sb thickness needs to be further reduced to improve QE.

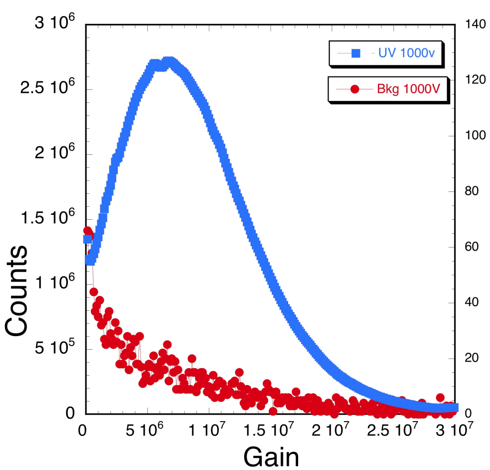
Imaging 20cm, 20µm pore ALD-MCP Pairs

A number (>25) of 20cm MCP substrates have been functionalized by ALD at ANL, re-electroded at UCB-SSL and put through detailed tests.

Expanded area view showing the mutifiber edge effects.







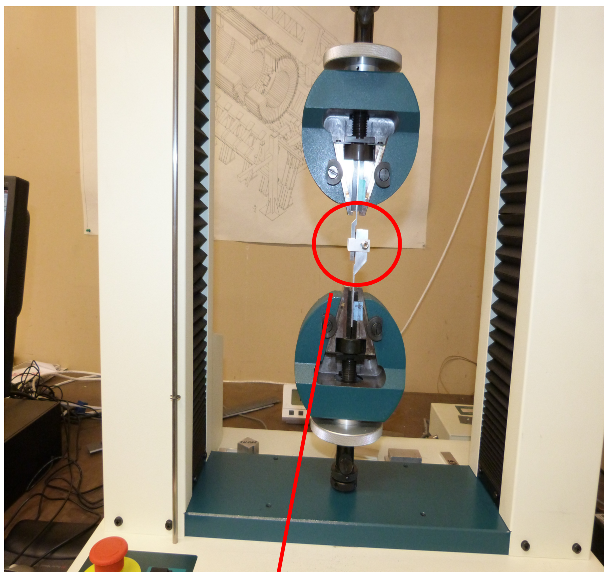
Pulse height distributions for UV and background.

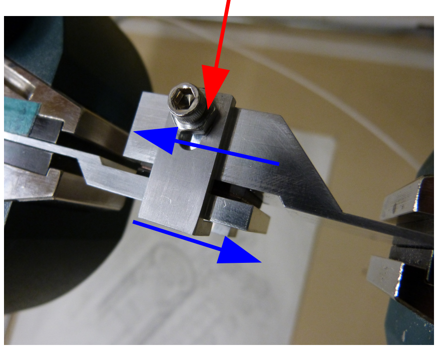
Image striping is due to the anode period modulation as the charge cloud sizes are too small for the anode. 20cm, 20µm pore, Al_2O_3 SEY, MCP pair image with 185nm non uniform UV illumination.

Indium Seal Reliability Tests

Shear testing setup

M.Kupfer, D.Walters





Seal strength by shear testing

- Limit for the indium bulk strength is 600-760psi
  - tested on 1x1" parts made of copper
  - indium bonds with copper very well
  - the failure is always in the indium bulk and not in the interface
- Measured strength for the glass parts is up to 400psi
- Measured strength for the Cu coated parts is 500-600psi
- The failure is in the interface in the most cases

Aging tests:

- Sealed parts are heated to 80C and 130C for extended period of time
- Most samples remain leak tight
- Some develop O(10^{-10}) cc/s leaks

Shear Test Results

credit to Marc and Dean

Hot seal

Leak tight samples:

Bare glass #1	190 lbs
Bare glass #2	278 lbs
Bare glass with groove	268 lbs
Cu coated glass #3	390 lbs
Cu coated glass #4	345 lbs

Samples with a leak:

Bare glass #4	47 lbs
Cu coated glass #1	213 lbs
Cu coated glass #2	221 lbs

Cold seal

Aging Matrix

Coating	80 °C 68 Hours	80 °C 172 Hours	130 °C 42 hours	130 °C 213 Hours	Shearing Force (lbs)
Silver (52In/48Sn Solder)	Leak (10^{-10})	Leak (10^{-10})	Leak (10^{-10})	Leak Tight	N/A
Titanium	Leak Tight	Leak Tight	Leak Tight	Leak (10^{-10})	138.24
Chromium	Leak Tight	Leak Tight	Leak Tight	Leak (10^{-10})	173.73
Bare Glass	Leak Tight	Leak Tight	Leak Tight	Leak (10^{-10})	186.21
Nichrome	Leak Tight	Leak Tight	Leak Tight	Leak Tight	218.32
ITO	Leak Tight	Leak Tight	Leak Tight	Leak Tight	191.76

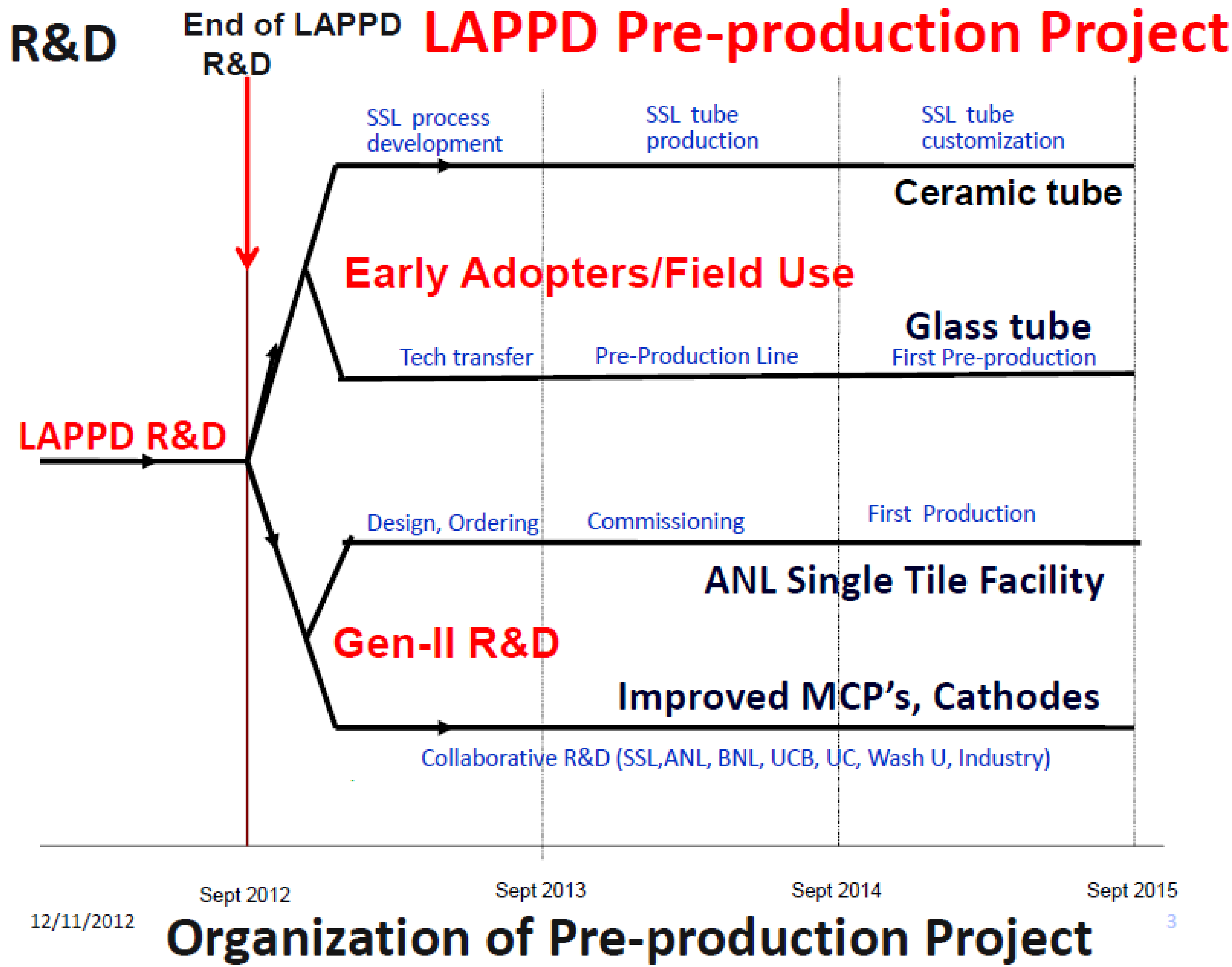
JSAMRL Joining Science and Advanced Materials Research Laboratory

The University of Illinois at Chicago

The strength limit determined from 1x1" all copper parts was 600-700 psi
When divided by area of ~0.66 inch^2, Cu coated parts fall into 500-600 psi

The area of the interface is quite different between cold and hot seals

Parallel Efforts on Specific Applications


R&D
End of LAPPD R&D
LAPPD Pre-production Project
SSL process development
SSL tube production
SSL tube customization
Ceramic tube
Early Adopters/Field Use
Glass tube
Tech transfer
Pre-Production Line
First Pre-production
LAPPD R&D
Design, Ordering
Commissioning
First Production
ANL Single Tile Facility
Gen-II R&D
Improved MCP's, Cathodes
Collaborative R&D (SSL,ANL, BNL, UCB, UC, Wash U, Industry)
Sept 2012
Sept 2013
Sept 2014
Sept 2015
12/11/2012
Organization of Pre-production Project
3

TASKS AND RESPONSIBILITIES:

8" Tile/Tube Fabrication: SSL/ANL/Industry Facility Roles

Institution	Mission	Year 1	Year 2	Year 3
SSL/UC Berkeley	Process Development	1 Tube/Cycle 4-6 Weeks/Cycle	1 Tube/Cycle 2-4 Weeks/Cycle	Customization
ANL	R&D, Application-Specific Development		1 Tile/Cycle† 4 Weeks/Cycle	1 Tile/Cycle† 2 Weeks/Cycle
Industrial Partner‡	Pilot Production, Full-Scale Production Commercialization		1 Tile/Cycle 1 Week/Cycle	3 Tiles/Cycle 3-4 day turnaround
Total Available Tiles		1-4	10-20	50

Table 1: The roles of the collaborating partners in bringing the glass tile to commercial production.
Notes:
†Assuming the hiring of an experienced sealed-tube facility manager in 2013.
‡Assuming the industrial partner has access to an existing vacuum-transfer system that can be adapted to the LAPPD process.

1. TOF in the LArIAT Beam
   a) Why: Simplest set-up that has a large impact on HEP programs
   b) Straight-forward interface to experiment
   c) Local, have collaborators in place;
   d) Drop in for scintillators and PMTs at higher cost and better performance
   e) Spec: 4 stand-alone single tile stations, 10 psec time resolution, 50KHz (needs checking)

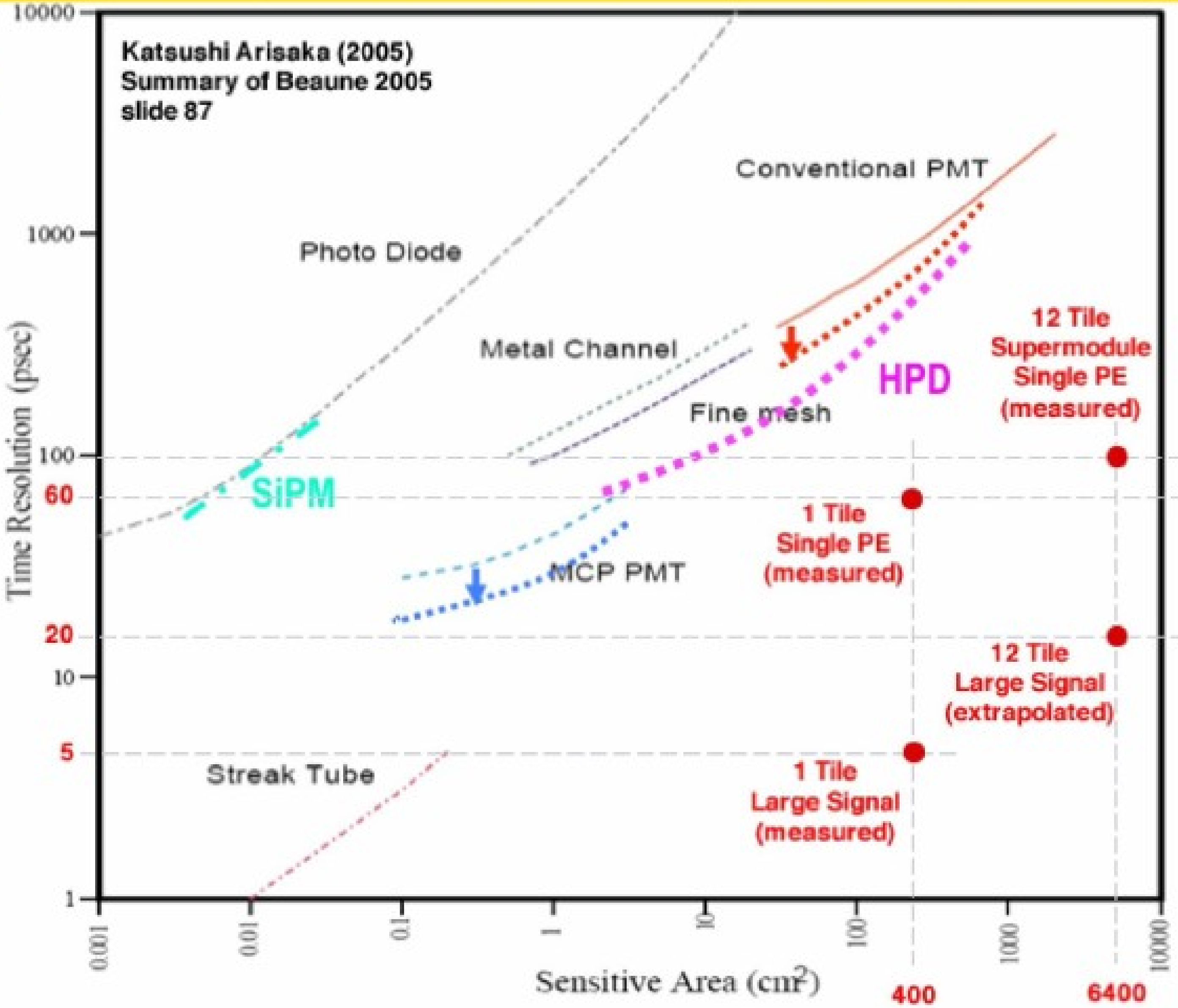
2. Small (1-4 m^3) water neutrino detector prototype
   a) Why: Comparison to simulation; test of the optical TPC concept with track reconstruction
   b) If successful, no competition
   c) From 1 to 6 SuperModules;
   d) Spec: Single pe resolution ~ 100psec, low rate

3. Pre-converter in KOTO
   a) Why: Archetype for 3D localization and precise timing of high energy photons
   b) Good access to management and technical expertise in the experiment
   c) If successful, no competition
   d) 1-4 SuperModules
   e) Spec: Timing = 1 psec; Rate = 200 kHz; Position = several mm; Trigger latency = 5 μsec
   f) HEP benefit: Increased physics reach

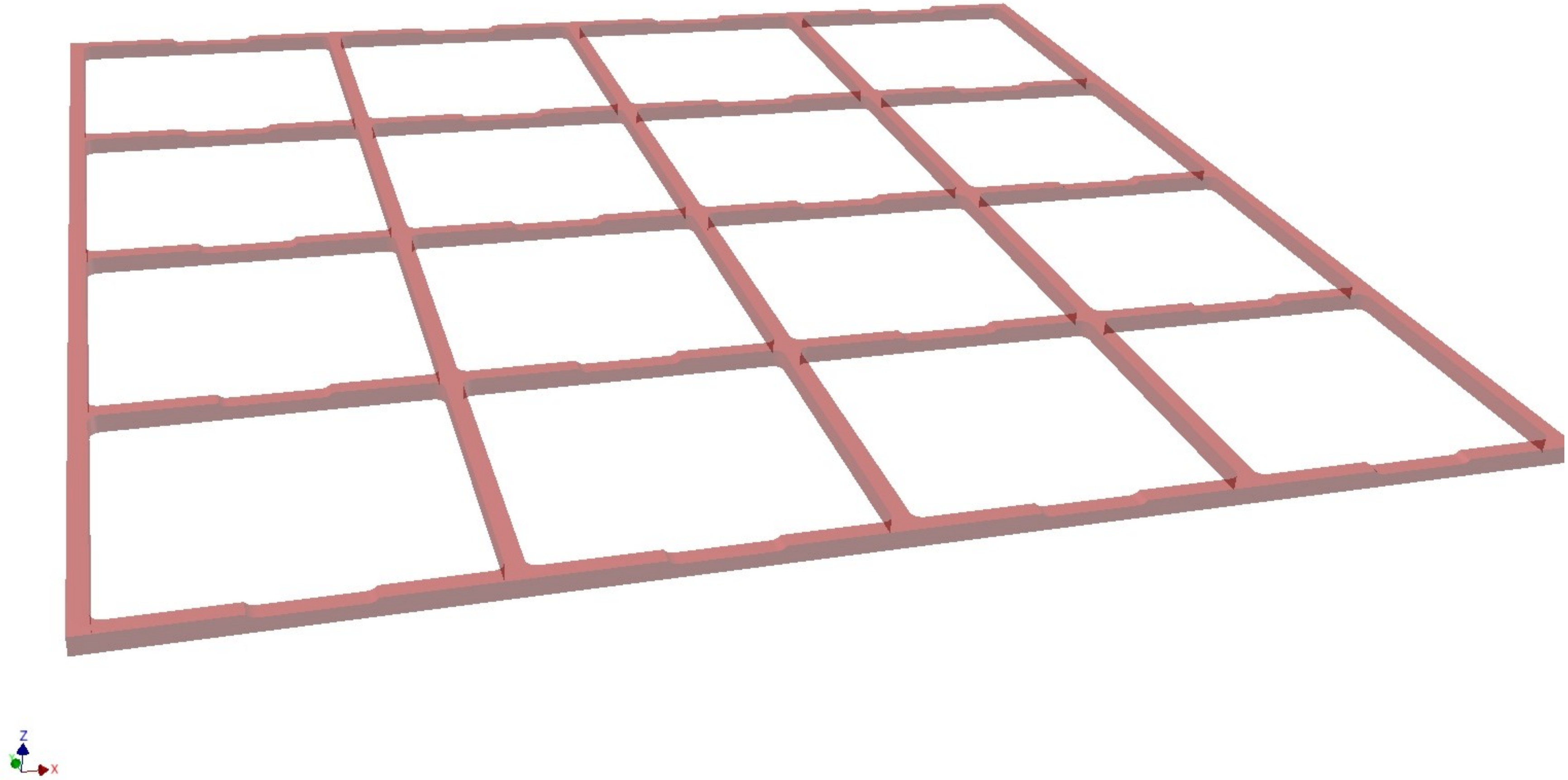
COST COMPARISONS DEPEND ON CAPABILITY

Correlated time-space points can lower overall cost- for applications that don't need time-space resolution it's very unlikely MCP-PMTs will ever be as cheap as PMT's. However:

The dt/A Arisaka plot

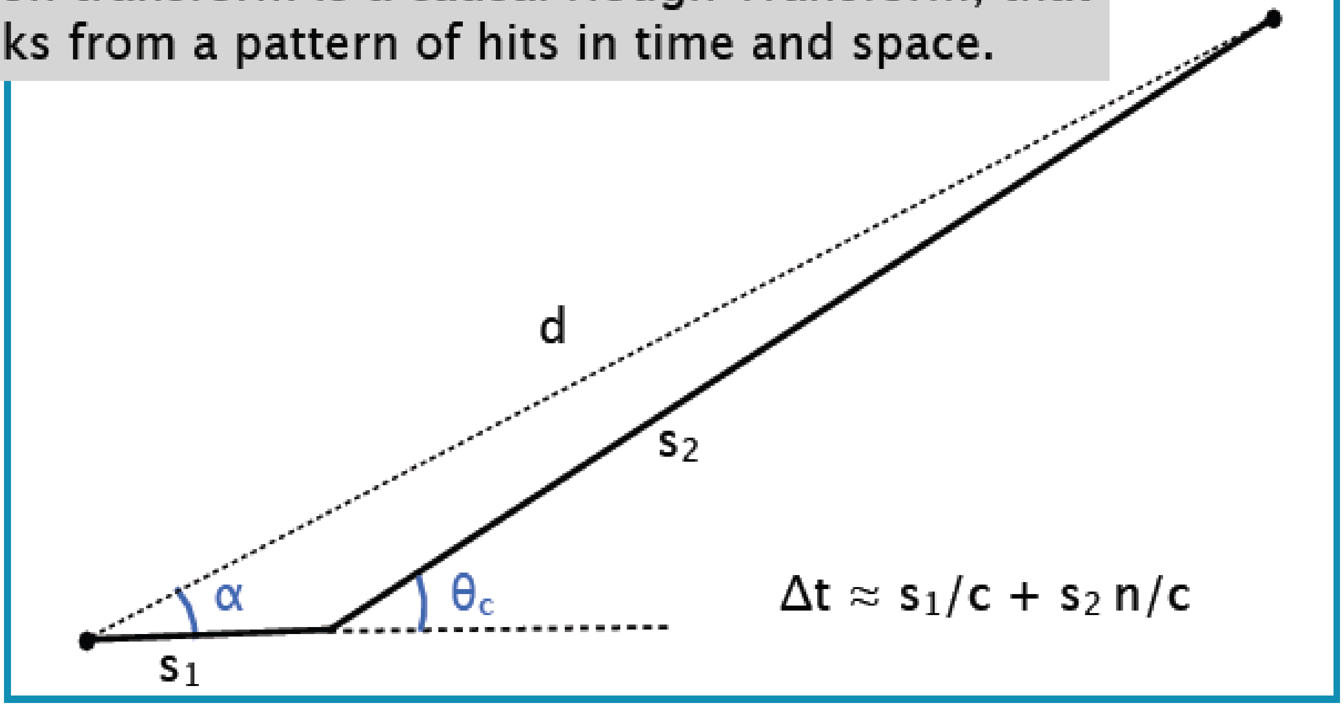


Does it breaks when pumped?
No, we have grid spacers



Track Reconstruction Using an "Isochron Transform"

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

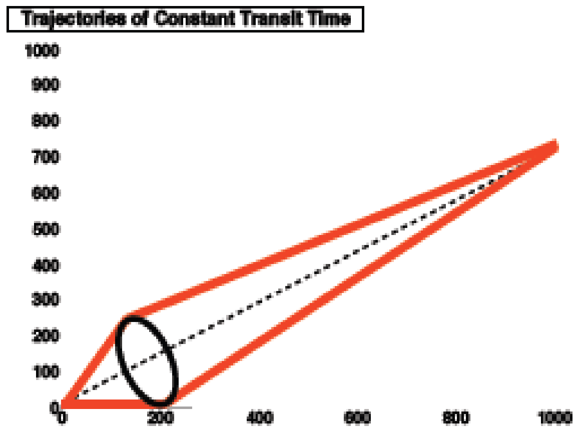
s_1 and α

but there are two constraints:

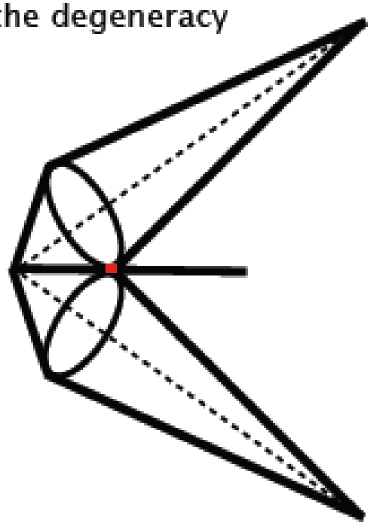
$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

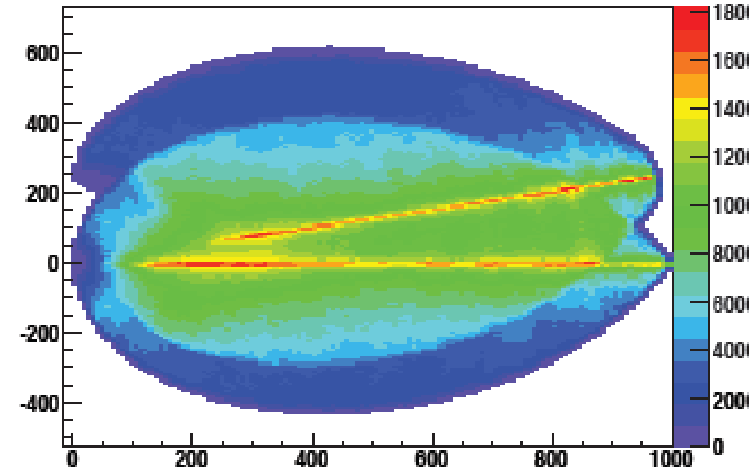
Track Reconstruction Using an "Isochron Transform"

Of course, there is a rotational ambiguity in the position of possible tracks.

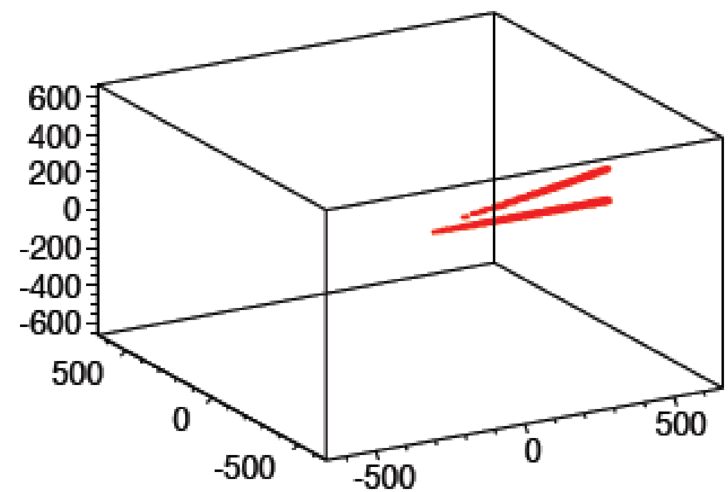


But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy

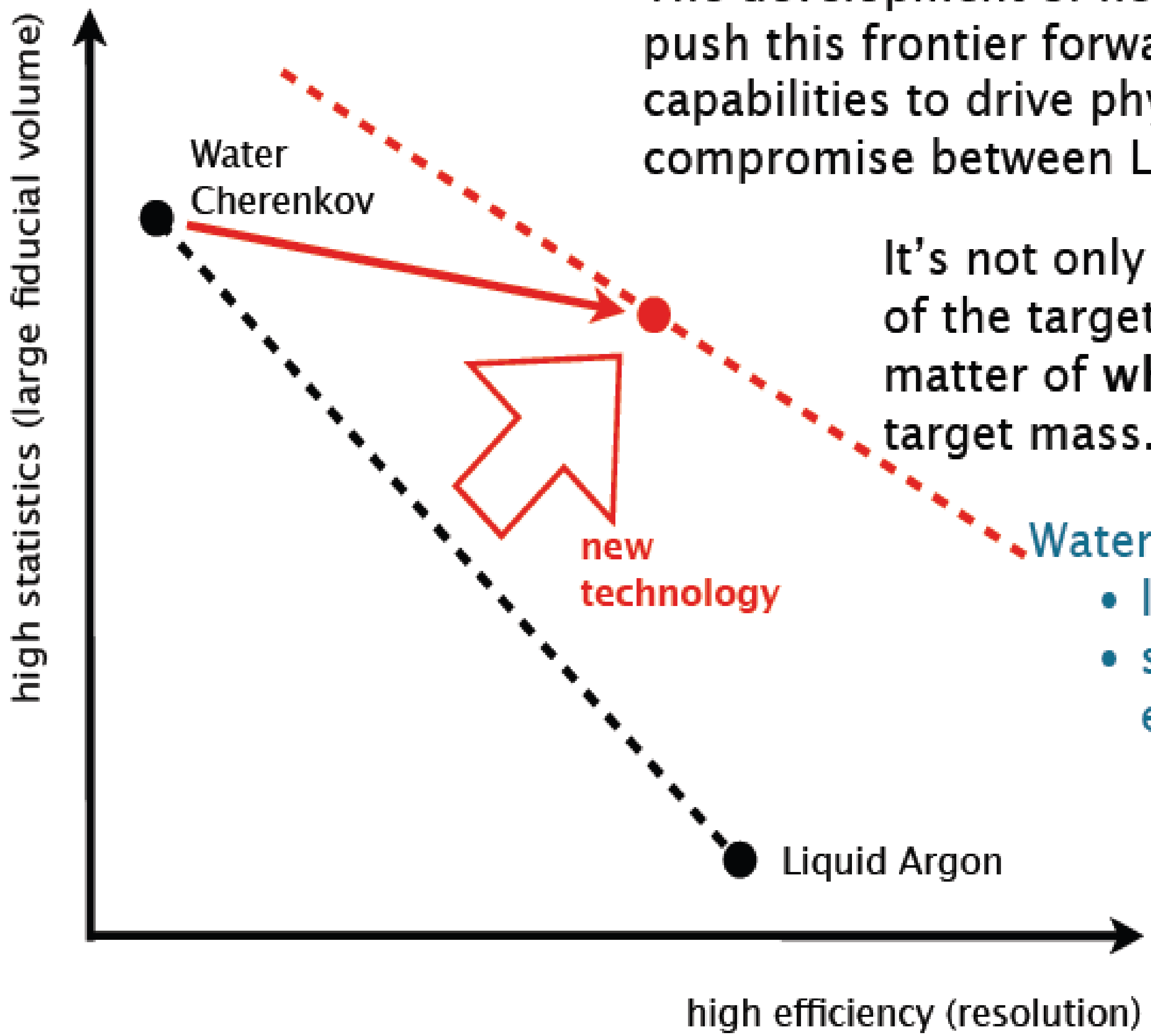




When integrated over all hits, these regions of dense intersection points form clusters around those tracks that share a common vertex. Here we demonstrate closure on a simple two-track toy with light no scattering or dispersion



The limits of thinking bigger



The development of new technology could push this frontier forward. New capabilities to drive physics. A compromise between LAr and WC?

It's not only a matter of the size of the target mass! It's also a matter of **what** you use for your target mass.

Water:

- lots of free protons
- sensitivity to low energy $\overline{\nu}_e$