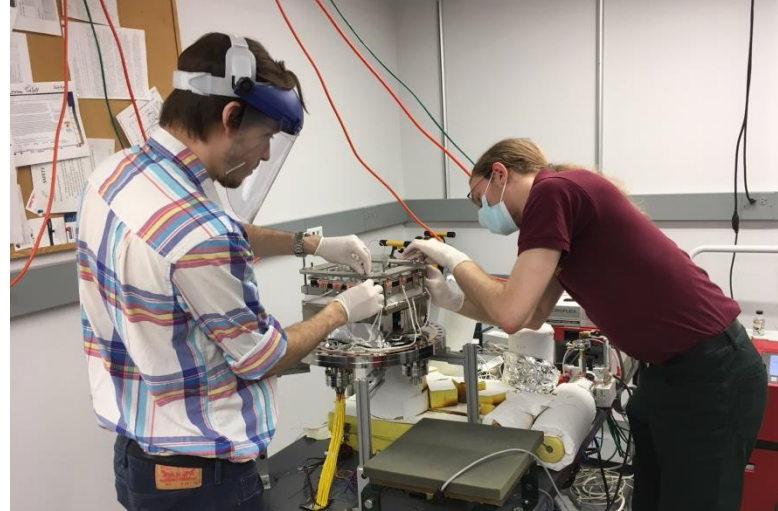
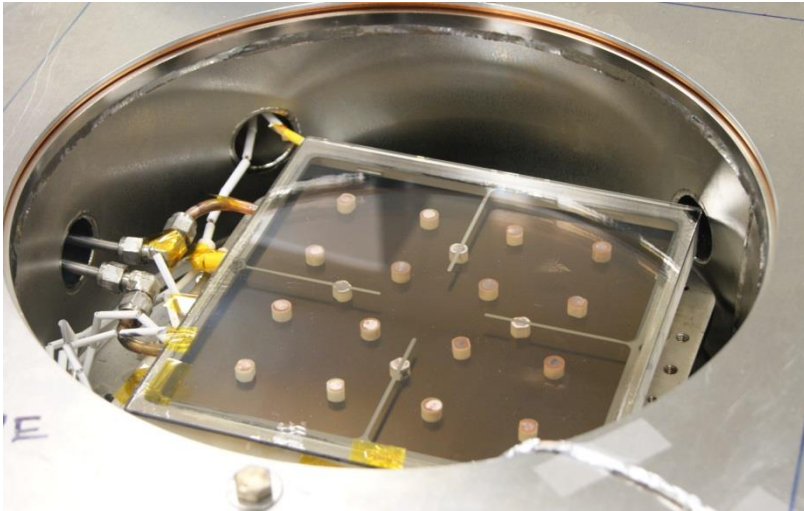
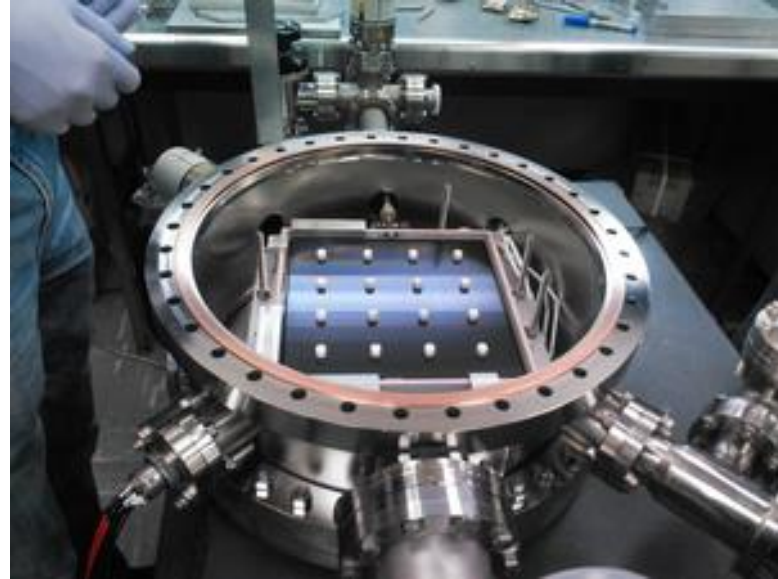


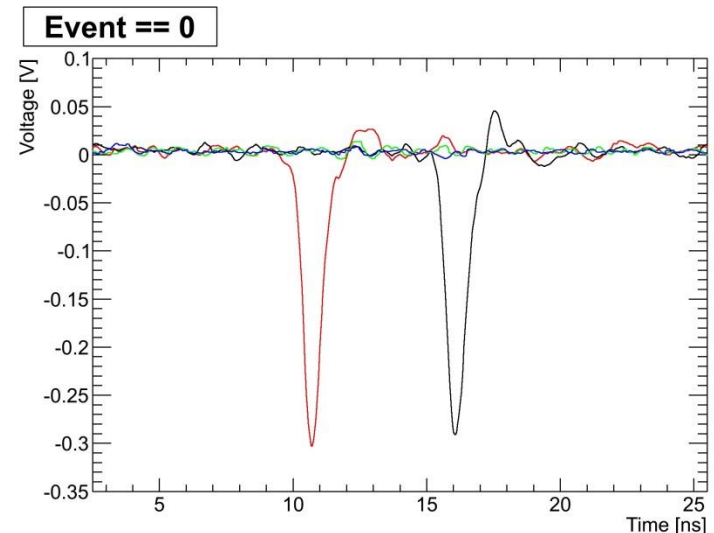
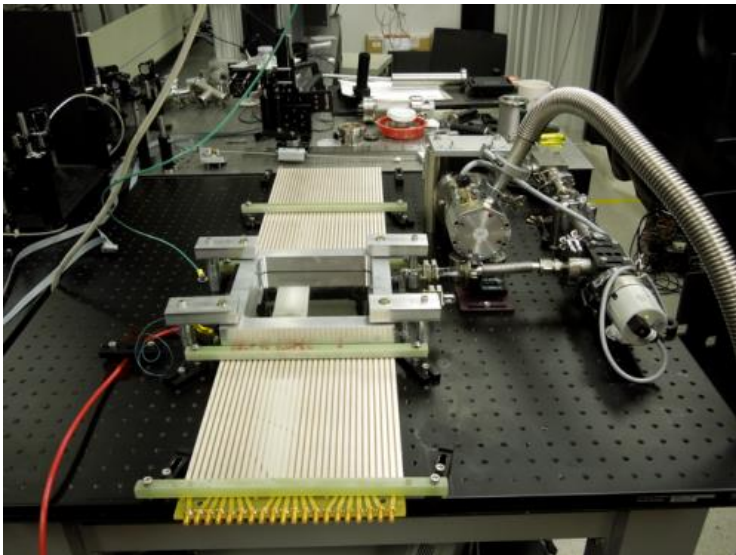
Psec timing/LAPPD program at Chicago

Evan Angelico, Andrey Elagin, HJF, Rich Northrop, Carla Pilcher, Eric Spieglan plus Eric Oberla (emeritus) and Mircea Bogdan on electronics plus 12 (!) HS and undergrad students last summer



Our (UC) LAPPD™ 'Tile'

1. 8" x 8" active area (MCP size)
2. Amplification: a pair of MgO MCPs in a chevron config.
3. Measured gain typically $\geq 10^7$
4. Space resolution 700 microns in 2D (strips); 300 microns with $\frac{1}{2}$ " pads if signals are shared
5. Time resolution: < 50 psec single photon measured, goal of a < a few (or one) for charged particles traversing window (50 PE) or high energy photons (i.e. large pulses)



Topics

- 1. Photodetector development (R&D with Incom Inc)**
 - a) Indium window-to-tilebase seal
 - b) Application-independent anode (pads or strips)– metal resistive capacitive coupling
 - c) Ceramic robust high-bandwidth 1-piece body
 - d) PMT-process batch production: facilities, process
 - e) Theory-based photocathodes (with RMD, Smedley, Attenkofer)
- 2. Electronics (Eric Oberla, Mircea Bogdan, ANNIE)**
 - a) Multibuffer 130nm CMOS 10 GS/sec ASIC development
 - b) Scalable FPGA-based DAQ readout/control for ANNIE
- 3. Goals- expand physics reach via psec timing frontier: testbeam and simulation studies (PhD students, Elagin):**
 - a) Optical Time Project Chamber for double-beta decay
 - b) Collider photon/ch vertexing and track quark content

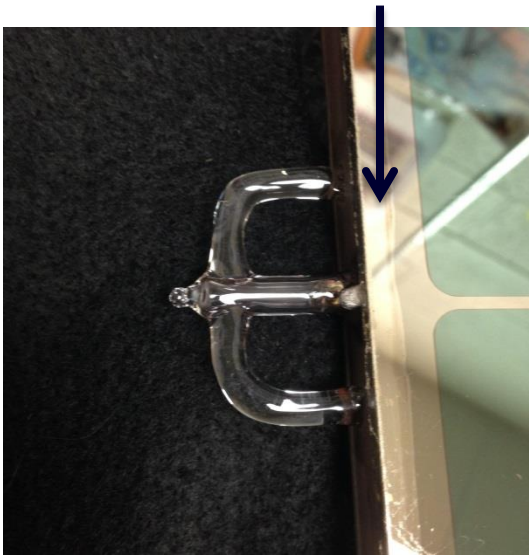
Recent papers (see lappdocs.uchicago.edu)

- E. Angelico, T. Seiss, B. W, Adams, A. Elagin, H. J. Frisch, E. Spiegler; **Capacitively coupled pickup in MCP-based photo-detectors using a conductive, metallic anode**; Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)
- A. Elagin, H. J. Frisch, B. Naranjo, J. Ouellet, L. Winslow, T. Wongjirad; **Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing**; Nucl. Inst. Meth. Phys. Res. A. (Sept. 2016)
- E. Oberla and H.J. Frisch; **Charged particle tracking in a water Cherenkov optical time-projection chamber**; Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016) ISSN 0168-9002. arXiv:1510.00947

Andrey and Evan will give talks at Light 2017 next week on tile production and OTPC.

Photodetector Development

1: **TOP SEAL:** glass sidewall to window- **consider proven**



Recipe (lots of characterization, vendor/Ossy input)

1. Very clean glass surfaces
2. 200 nm of Nichrome
3. 200 nm of Cu **w no vacuum break**
4. .9999 Indium wire sized for volume
5. Etch Indium wire in 5% HCl
6. Thermal cycle 100C above melting
7. Press down on window edges w DOF

What happens: (Andrey Elagin FIB/SEM/ studies) (ITT story)

1. Nichrome layer will provide tie layer
2. Cu provides protection against oxide on NiCr
3. Indium wire gets squished--oxide broken (Walters)
4. Cu diffuses into bulk Indium (Ossy said so)
5. Nickel and Chrome diffuse into bulk Indium (!)
6. A very thin layer containing chrome on the glass forms the bond to the indium.

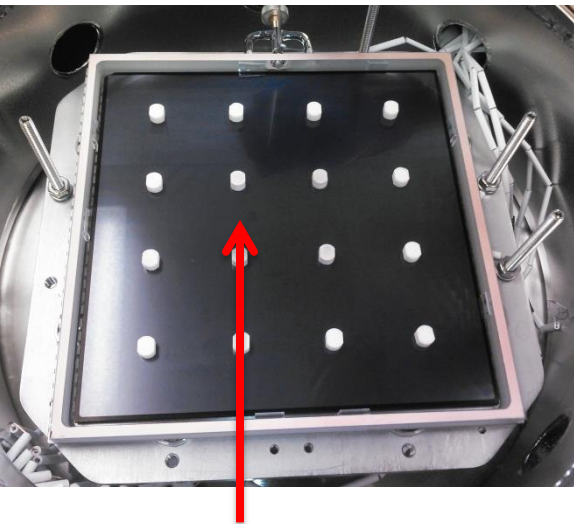
Photodetector Development

TOP SEAL- continued

The LAPPD size introduces 3 serious problems not experienced in making smaller tubes:

1. Uniform metalization, indium distribution, and cleanliness over a much longer length (~36")
2. Uniform pressure and heating over that length
3. In a transfer process base sealing surface level to a mil or less (?-number I don't know, as we use wire captured in place between the window and sidewall)

And, a precise STACK HEIGHT over entire tile.

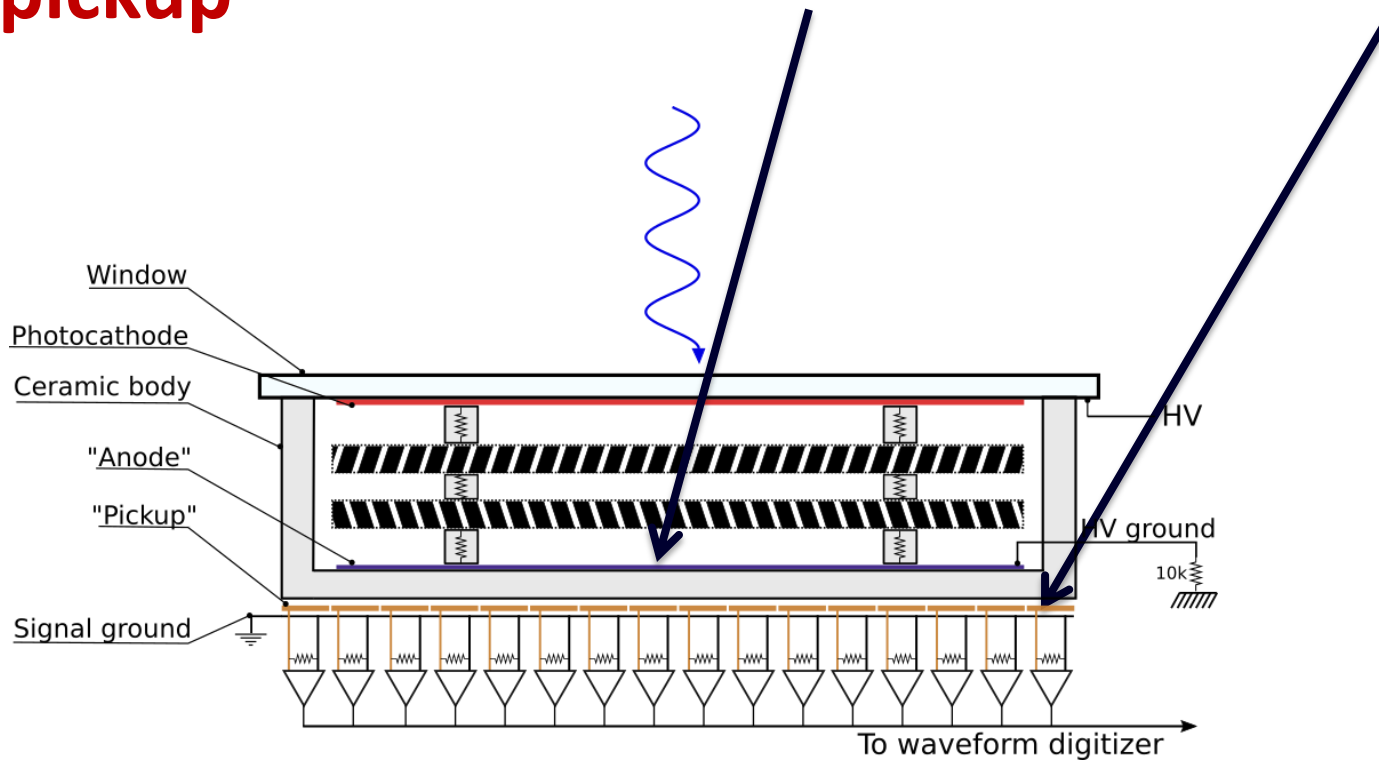


1. FEA and many trials dictate a stack height **low** by 0.002 ± 0.0005 " over the tile interior
2. Each button spacer has to be custom shimmed to meet the above
3. Pressing uniformly on the edges over the seal area on all 4 sides is essential

Note buttons make stack height a discrete problem

Photodetector Development

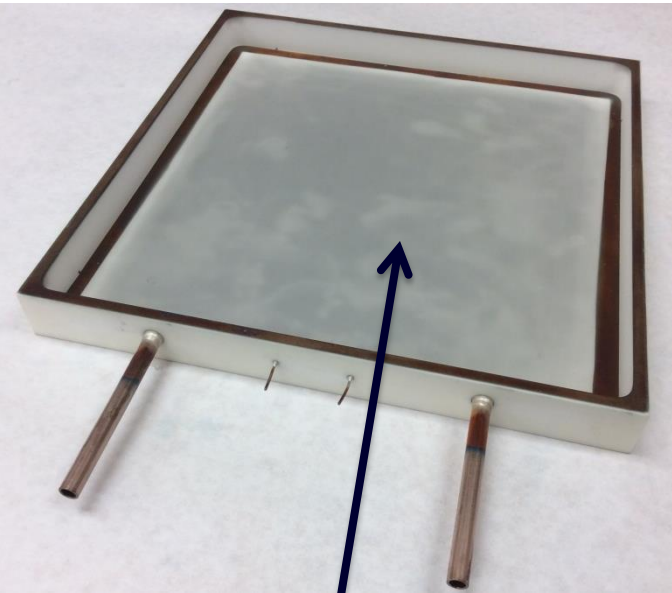
2: Capacitively coupled anode w. external signal pickup



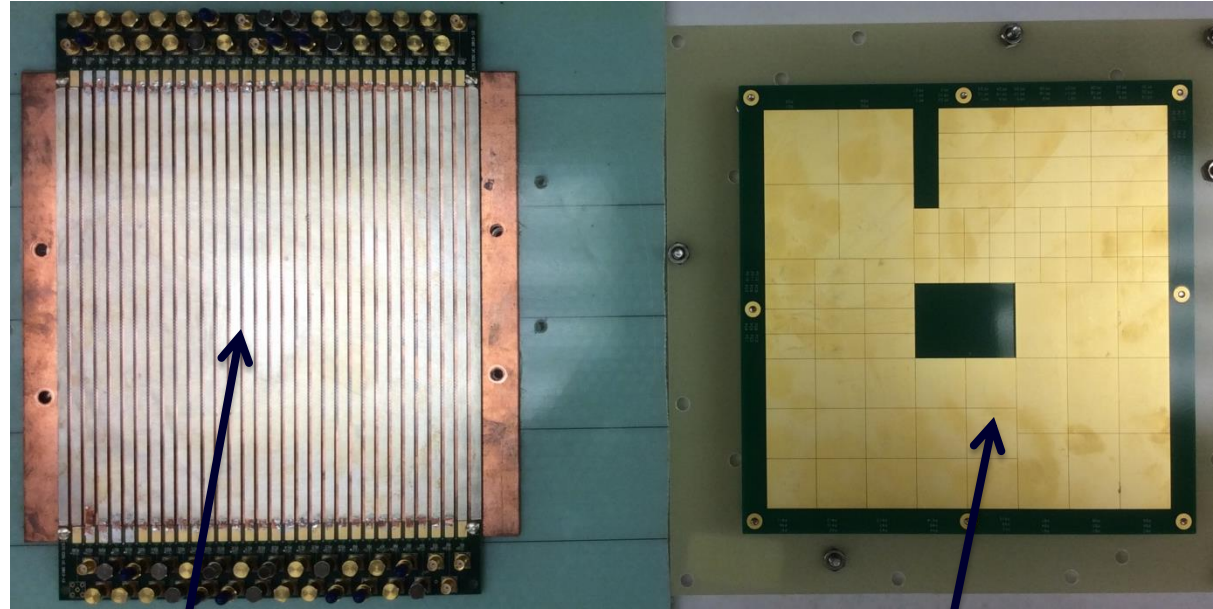
1. Metal layer rather than thick-film for production during seal layer coating (also realities of thick-film)
2. 10nm of NiCr is resistive enough for RC (capacitive) coupling

Photodetector Development

2: Capacitively coupled anode w. extrnl signal pickup



**10 nm-thick NiCr
anode plane
(DC ground)**

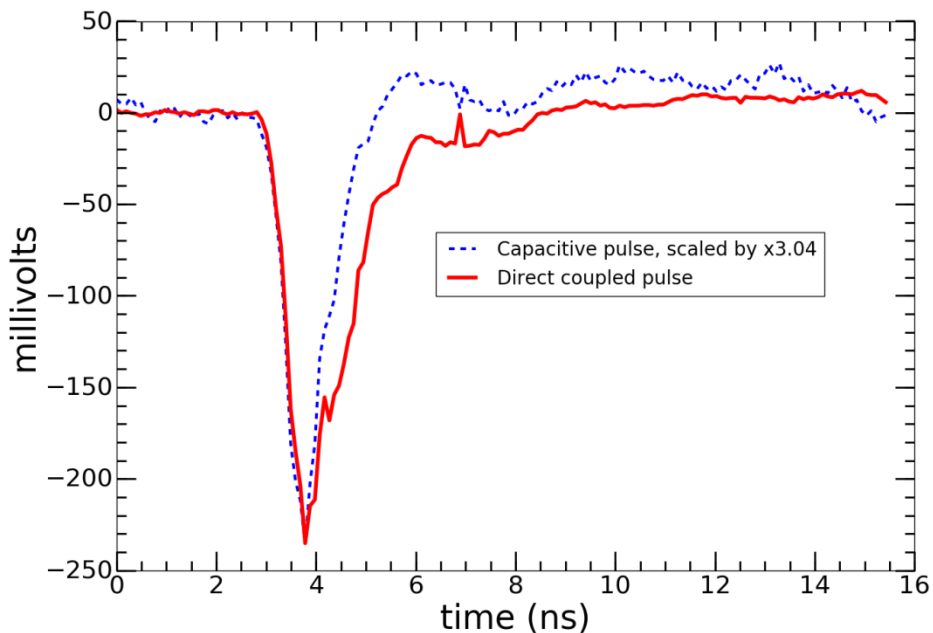


**50-ohm
stripline
readout
(E. Angelico)**

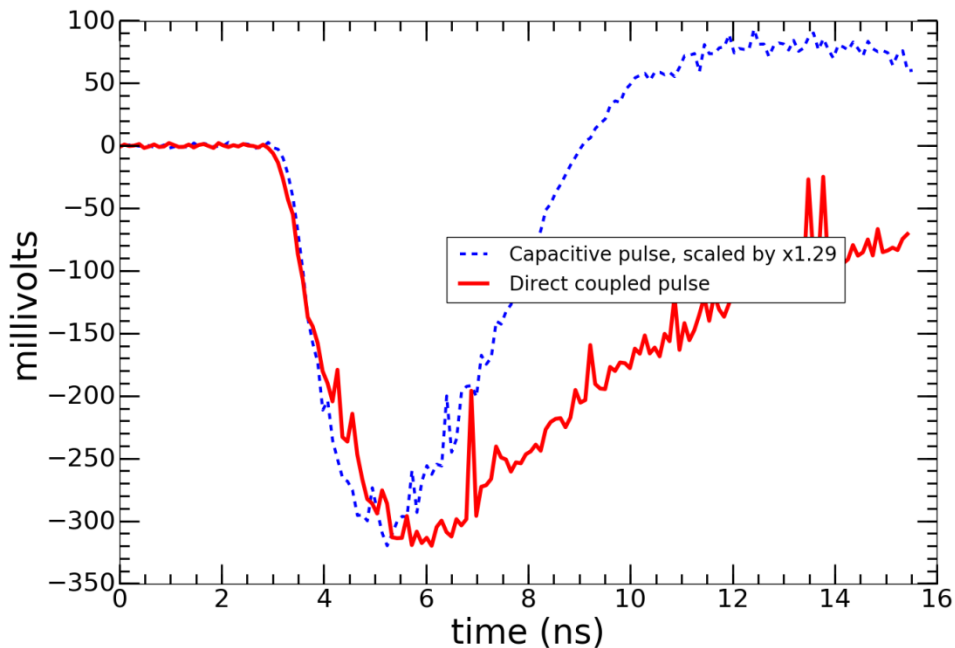
**LHC Pad test
pattern
readout
(T. Seiss)**

Photodetector Development

Capacitively coupled anode w. extrnl signal pickup



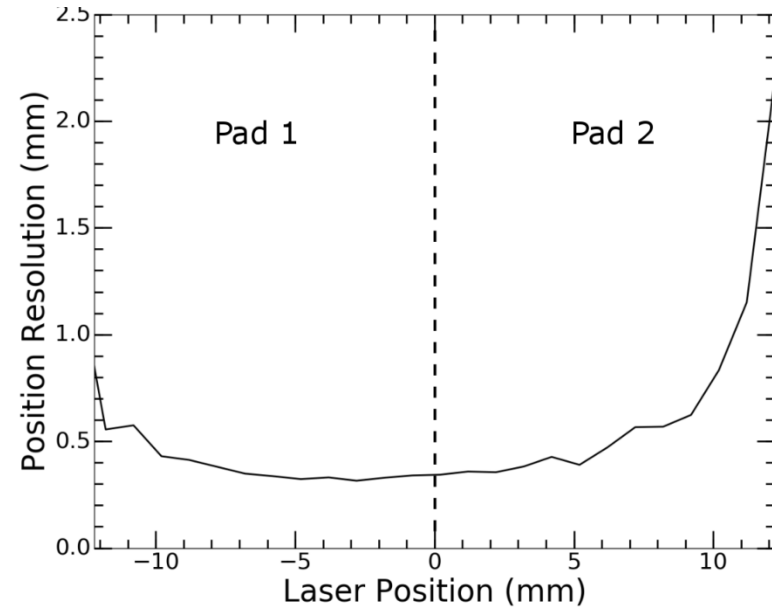
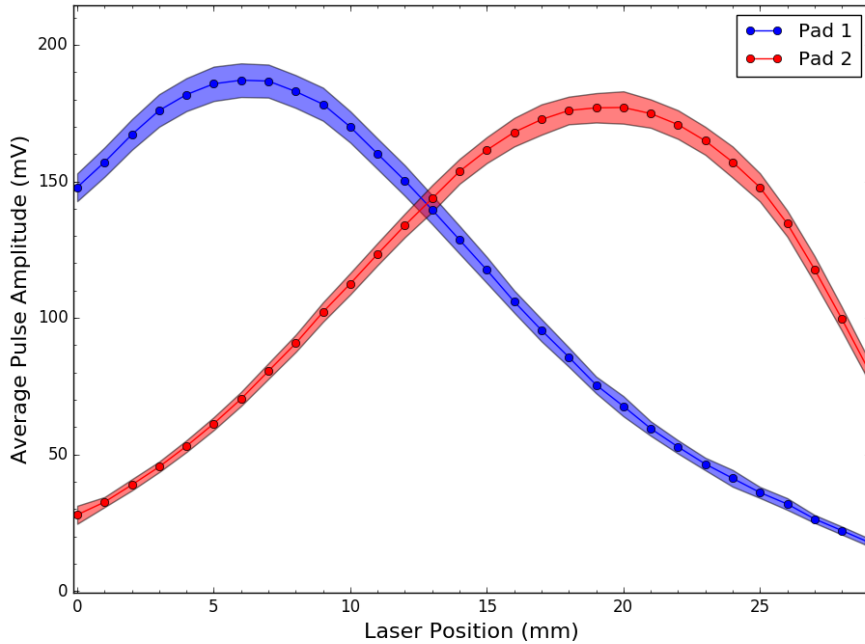
**Comparison of risetimes
direct vs capacitively coupled
on strip readout PC-card**



**Comparison of risetimes
direct vs capacitively coupled
on pad readout PC-card**

Photodetector Development

Capacitively coupled anode w. extrnl signal pickup



Sharing of the signal across two adjacent $\frac{1}{2}$ " pads

Position resolution with $\frac{1}{2}$ " pads and large signals (256 pads per LAPPD).

Advantage for Incom in they make 1-design tube; user defines readout pattern, resolution, band-width on card

3: Ceramic robust high-bandwidth 1-piece tile base

1. Our university group complement s Incom's commercial focus on production of their glass tile design in 2 ways:
 1. Develop physics applications (e.g. OTPC; later in talk)
 2. Evolutionary design options- (but don't get in their way on the Gen-I glass tile while working on Gen-II!)
2. Have developed a 'Green-trimmed' ceramic tile base with the following **advantages**:
 1. One piece- no assembly of sidewall and base w. frit
 2. Hotter bake-out possible as no frit or silver ink anode
 3. Higher bandwidth than glass (also no ion migration)
 4. More robust than glass
 5. Working closely with Mike Foley of Incom under a DOE Nuclear Physics SBIR

Disadvantages: long lead-times, no experience (vs glass)

Photodetector Development

3: Ceramic robust high-bandwidth 1-piece tile base



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

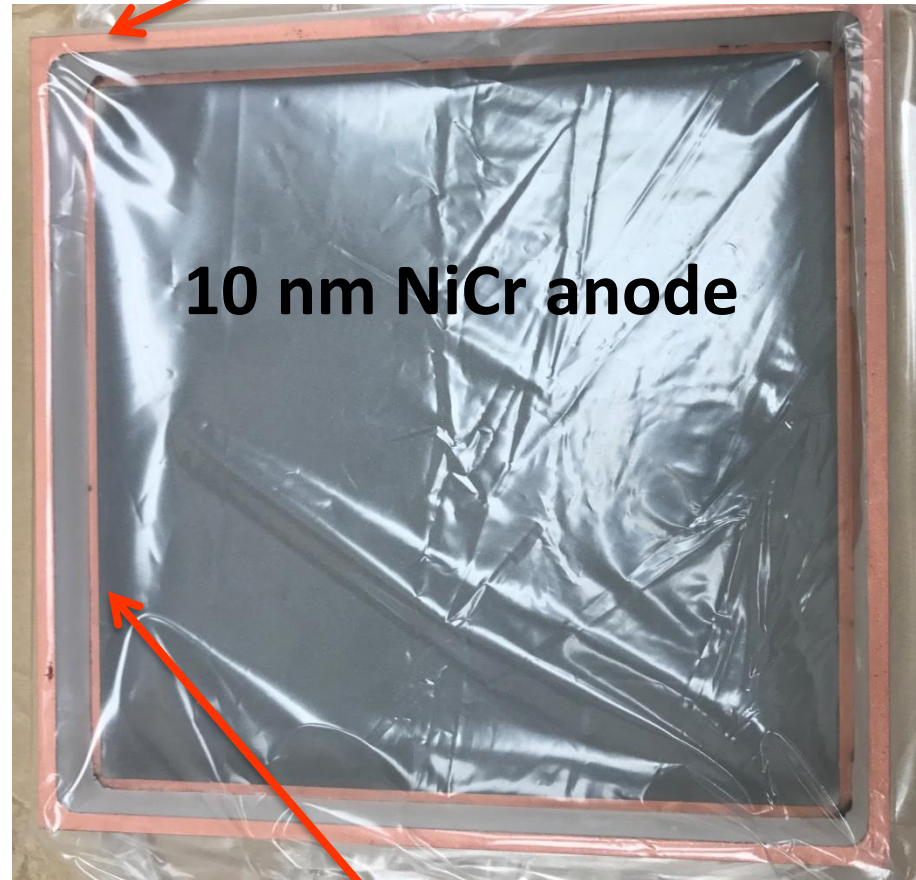


Ceramic tile bases from 4 vendors- have 5 from each

Photodetector Development

3: Ceramic robust high-bandwidth 1-piece tile base Multipurpose metallizing ('coating') glass or ceramic

200/200 nm NiCr/Cu seal surface



10 nm NiCr anode

NiCr/Cu anode border

1. Major roadblock for both glass and ceramic (surprise!)- source of a lot of delay working out
2. Expert territory only: Eileen Hahn (Fermilab), Sharon Jelinsky (SSL), Bing Xu (ANL), commercial precision optical coaters (2 vendors)
3. Here we use coating for sealing surfaces, capacitively-coupled anode, and connection to pins to interior- single process (no vacuum break between sealing layers)
4. Now have 2 good vendors+

Photodetector Development

4: Batch production process/facility development (w. Incom)

Conventional PMTs are (usually) made in batches, using the hermetic package as the UHV environment

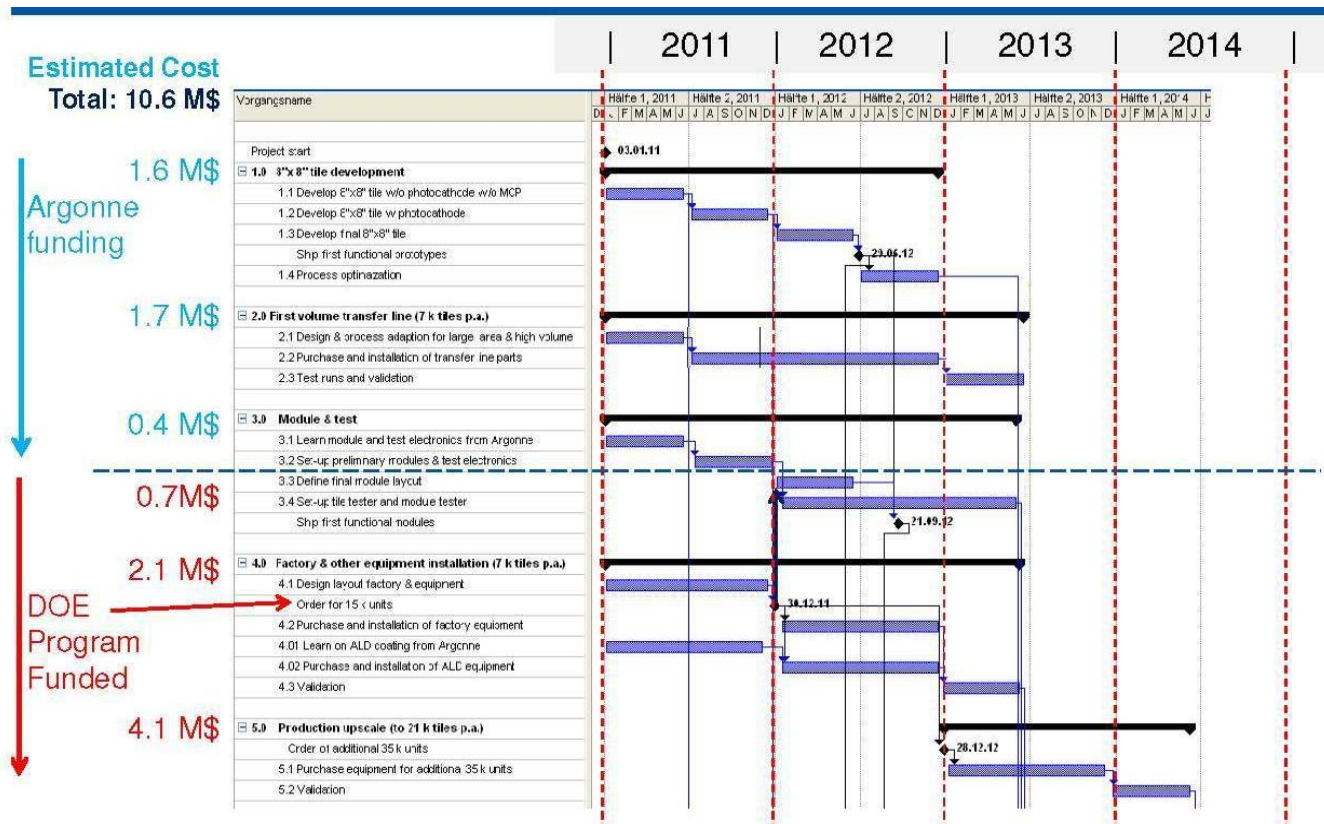


PMT Process Characteristics

1. Many tubes on one pump
2. Very poor external vacuum- Oring seal on tubulation, small long path to small pump. Internal getter+alkali provide the UHV pumping
3. External oven heating only tube (not vessel)
4. Alkali source internal or external (Brits)
5. Tubes are accessible during photocathod synthesis

Photodetector Development

Batch production process/facility development (w. Incom)



Schedule from a serious proposal by industry at the time of DUSEL

For HEP use we estimate industry needs to make 50/week (2000/yr; 6000/postdoc). Not nuts- had a serious proposal for DUSEL-from a large company making a similar photodevice . However went down with DUSEL as well. Necessary to get price down, adequate availability.

Photodetector Development

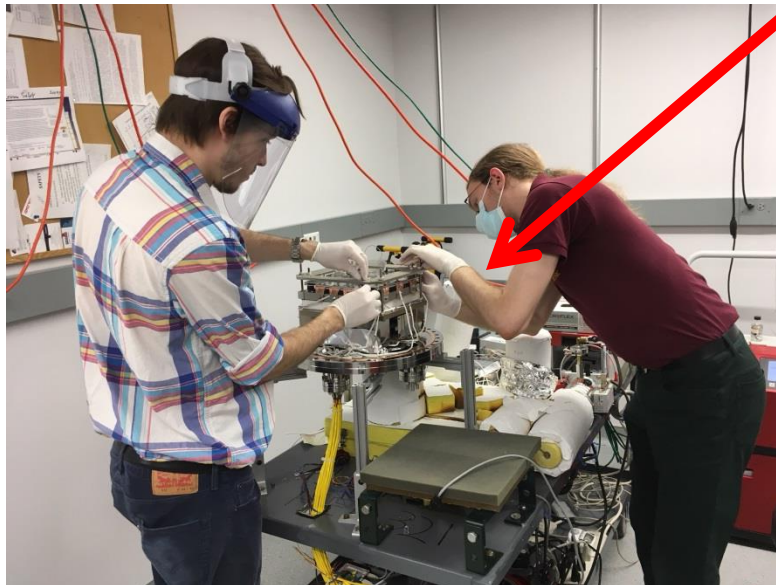
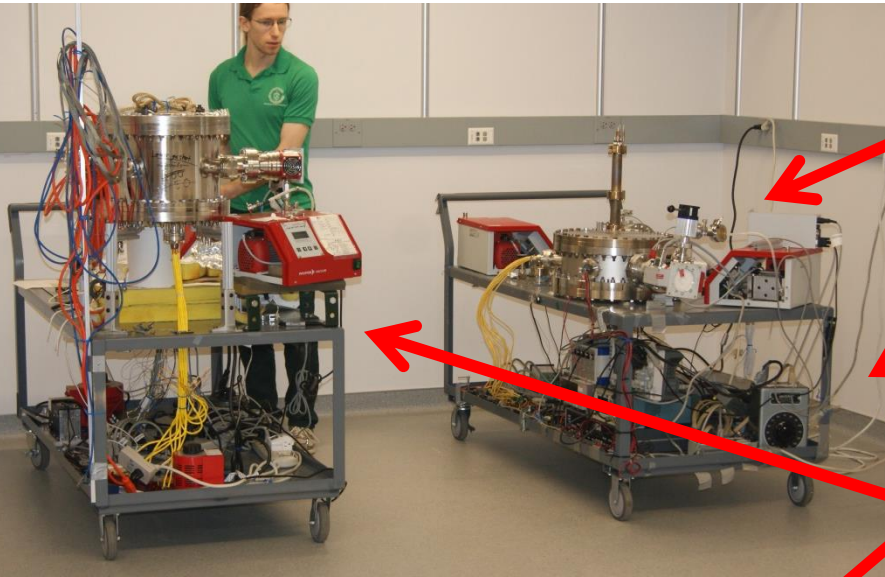
Batch production process/scaleable facility development (w. Incom NP SBIR)- replicable

Margherita I

New lab (!)

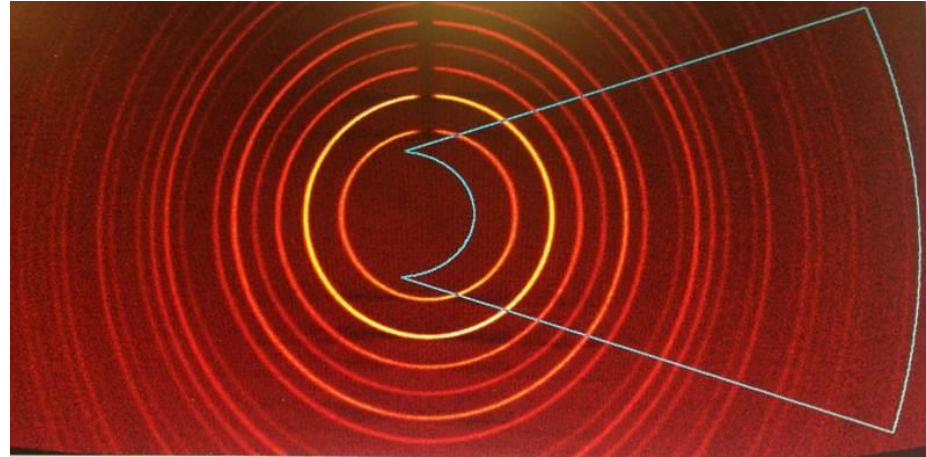
Wet lab (!!)

Margherita II (improved)



Photodetector Development

5: Theory-based photocathodes (w. RMD, Smedley, Attenkofer ; Luca Cultrera)



K2CsSb powder diffraction of RMD cathode material taken at UC

A screenshot of a web browser displaying the agenda for the "Second Workshop on Photocathodes: 300nm-500nm". The browser address bar shows the URL "psec.uchicago.edu/workshops/2nd_photocathode_conference/talks.php". The page title is "Second Workshop on Photocathodes: 300nm-500nm" and the subtitle is "Photocathode Workshop: agenda, talks". The dates are "June 29-30, 2012 at The University of Chicago". The agenda is organized into two days, Day 1 and Day 2, each with a table of speakers and titles. The speakers listed include Karen Byrum (ANL-HEPD), Henry Frisch (UC), Razmik Mirzoyan (MPI-Munich), John Smedley (BNL), Inés Montaño (Sandia), Xiuling Li (UIUC), Andy Cormack (ET Enterprises), Charles Sinclair (Cornell), Oswald Siegmund, Ray Conley (BNL), Sen Qian (IHEP), Matthew Highland (ANL-MSD), Jeffrey Elam (ANL-ESD), Miguel Ruiz Osés (Stony Brook), and Zikri Yusof (ANL-HEPD). The titles range from "Goals of the Workshop" to "Changes In Cs2Te Photocathode Fermi Level Due to Heating". The page also includes navigation links for "Conference Home", "Agenda", "Talks", "Travel & Parking", "Accommodations", and "Participants". The browser's taskbar at the bottom shows various application icons.

Agenda of 2nd cathode workshop at UC

Collaboration with BNL and RMD, and also Cornell, on 'theory-based' cathodes and workshops led to: a) ties to the cathode community , and the in-situ initiative

Photodetector Development

In-situ photocathode synthesis (Springer, Sinclair)

Idea is to emulate RCA/Burle PMT production

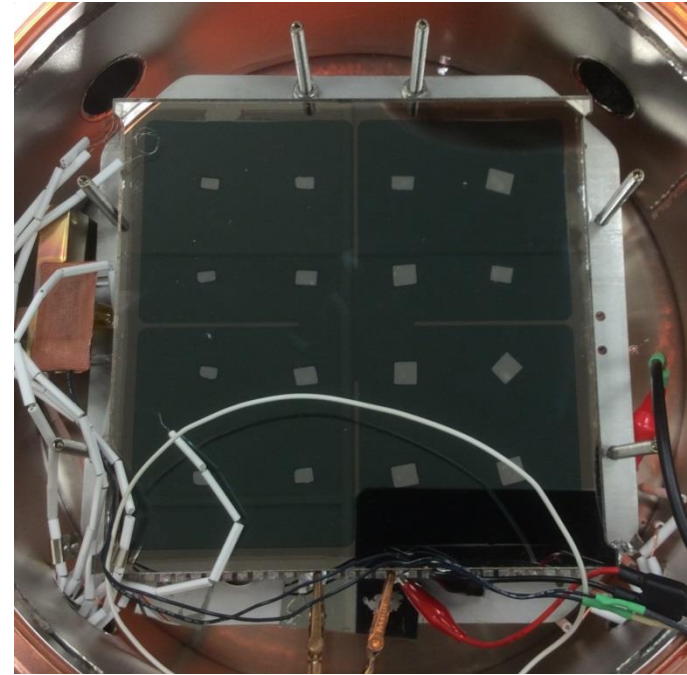
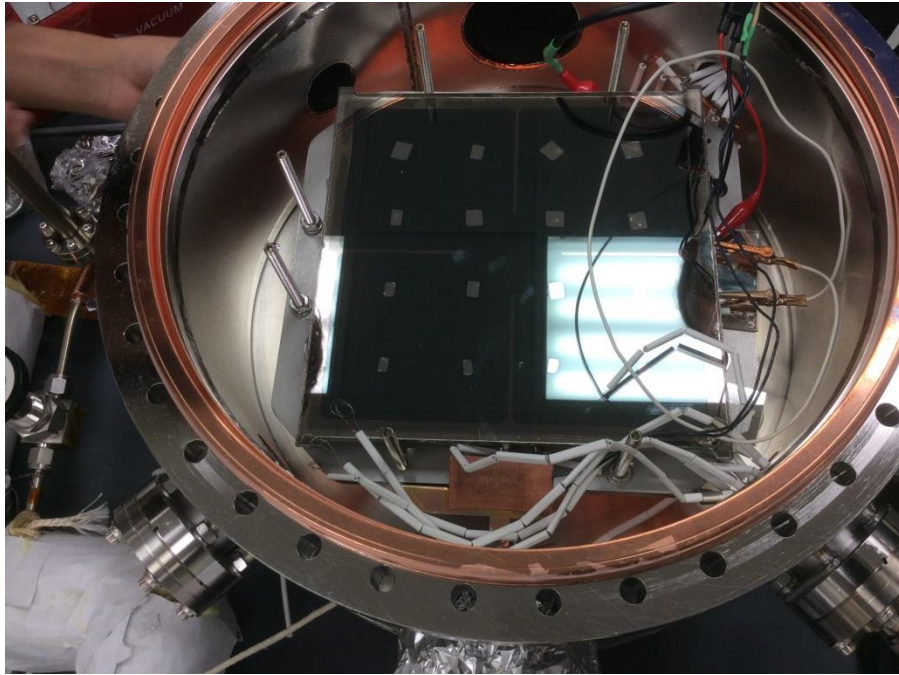
Steps:

1. Coat (NiCr/Cu) border and electrode fingers on window
2. Pre-deposit a 10nm Antimony (Sb) layer overlapping border and fingers
3. Seal window to tile base with a bake-out/sealing thermal cycle: dual vacuum- 1) tile and 2) vessel
4. Bring vessel to air, leaving sealed tile on its pump
5. Introduce alkali vapor through tubulation while measuring QE of (exposed) window and resistance of MCP plates and stack
6. Pinch off tubulation when photocathode is done

We have used a `GodParent Committee' (CDF) to guide us: Klaus Attenkofer (BNL), Luca Cultrera (Cornell), Jeff Elam (ANL), Mike Pellin (ANL), Matt Poelker (JLAB), Charlie Sinclair (Cornell, SLAC), John Smedley (BNL), Gary Varner (Hawaii, Chair)

Photodetector Development

In-situ photocathode synthesis (Springer, Sinclair)



- **GPs recommended doing only Cs first**
- **Expect uniformity to be determined by thickness of Sb layer- should very uniform**

Photodetector Development

In-situ photocathode synthesis (Springer, Sinclair)

Successes

- We have learned how to manipulate the movement of Cs around inside the system (remember we're beginners)
- Vapor reached everywhere on the window- uniform
- Chemical reaction between Cs and Sb seems to be 'self-limiting' as expected- reaches a defined end-point
- QE seems to be consistent with reasonable Cs₃Sb cathode, but we cannot measure it precisely yet (subtlety I missed completely- can explain if asked in questions)
- MCP plates are not permanently damaged/changed

Problems discovered:

- MCP plates go to lower resistance (recoverable in air)
- We had exposed Cu on the window- Indium wet it. Cs interacts with Indium to form a black powder.
- Resistive buttons interact with Cs (new buttons yesterday)
- Measuring QE is made more difficult by our internal HV divider (can't get current across first gap directly).

In-Situ Cathode Synthesis Trials in Progress

E.g. The black powder from cesiating excess indium

Sealing surface on top of sidewall

Black powder NiCr anode

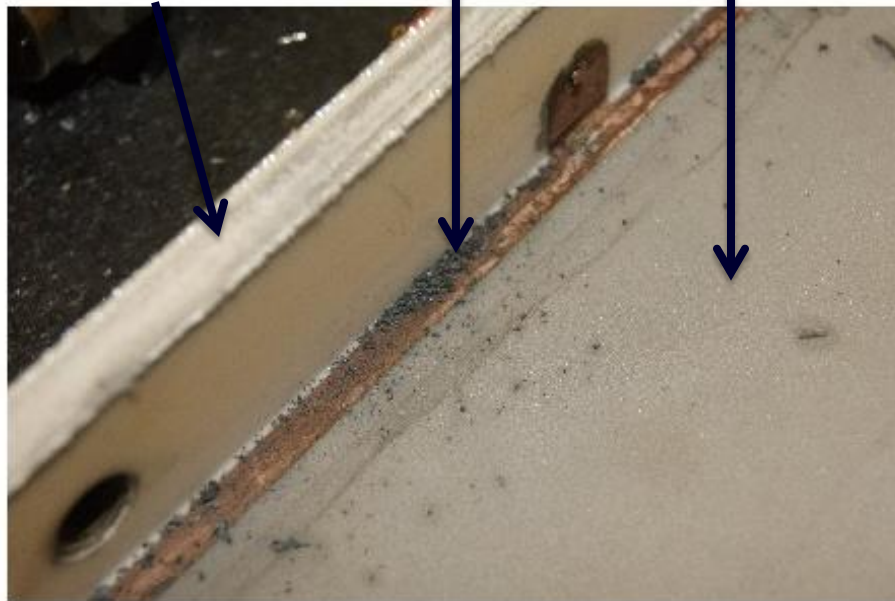
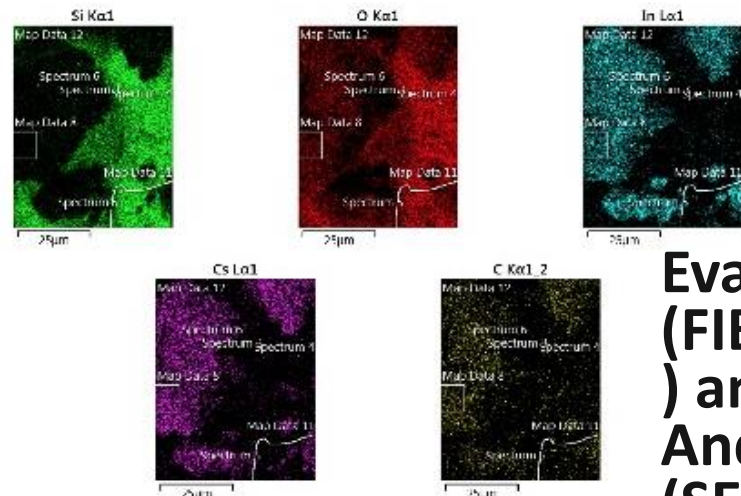


Figure 1: This black dust was found thrown throughout the tile, in crevices and on MCPs and on glass beads. We presume that it came from the window. It was collected from multiple locations and analyzed. This dust is from the window, and flaked everywhere.

(New windows will have no exposed Cu-few weeks away)



Evan (FIB/SEM) and Andrey (SEM)

Figure 3: The individual chemical maps from the Figure 2. Notice that the dust specs are mostly Cs and Indium, and the empty space is Si and O. This only confirms that the black dust is some mixture of Cs and Indium, and not its relative composition or homogeneity.

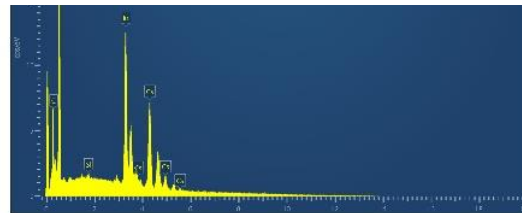


Figure 4: A spectrum from a dust fleck shown in the SEM picture above. The peaks indicate the existence of indium and Cs, and not their quantitative relative composition.

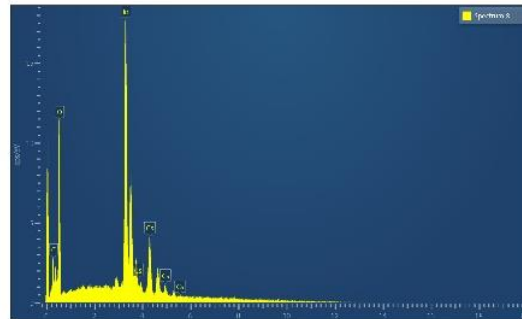


Figure 5: This spectrum is taken from the layer on the window that had turned black and flaky. The spectrum looks almost identical to that of the dust fleck.

Analysis showing it's a CsIn compound

Electronics

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

We have a new Central Card- Mircea Bogdan

Central Card

- Controls 4 front-end boards **Now 64 bds (1920 channels)**
- USB 2.0 or gigabit Ethernet PC connection **Now +SFP and VME**
- Daisy chain or tree configurations to extend system channel count
- Clock fan-out

We (Porter, Sandia) have the new PSEC4A ASIC

Front-end PSEC4 Card ("AC/DC Card")

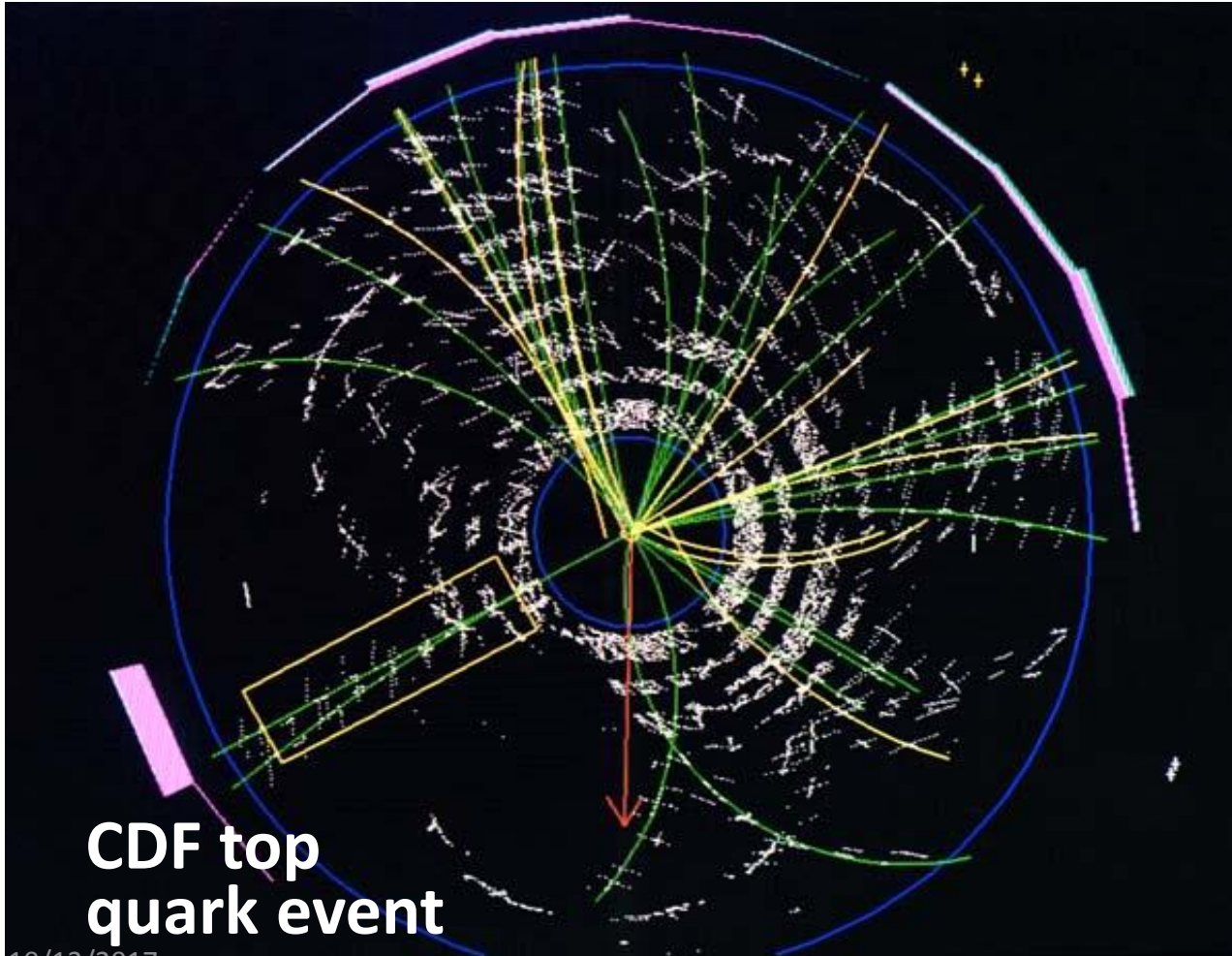
- 30 channels PSEC4 waveform recording
- At 10GS/s, captures a 25 ns snapshot per waveform
- USB 2.0 standalone readout or 8x LVDS lines communication to Central Card **Now +SFP and VME**

LVDS system interface

- Up to 800 Mbps data rate per line
- Clock, trigger, configuration

The Original Motivation: I Got Tired of @\$! Jets

- Goals: 1) Measure all 4-vectors– can reconstruct masses
2) assign tracks to vertices (e.g. CMS forward Ecal.)
3) vertex photons at colliders (4-vectors!);



Aside: Use photons (and electrons) as reference time- i.e. do differential timing of tracks from the same vertex to eliminate external clock jitter

Three Timing Cases to Distinguish

The factors limiting the ultimate timing resolution are different in each of the following cases:

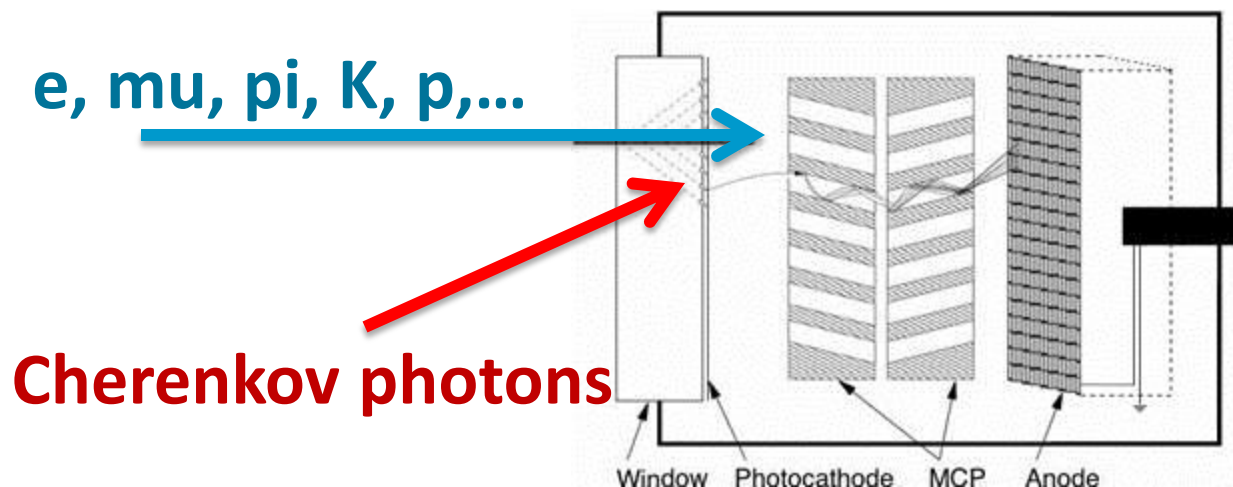
1. Single optical photons (Scintillation or Cherenkov)
2. Charged Particles above Cherenkov Threshold(H₂O,glass)
3. Electromagnetic showers from High Energy photons

I will focus on #2 and #3, relativistic charged particles and high energy photons, for which psec or sub-psec time resolutions I believe are plausible given certain detection criteria are met.

Note: In what follows I treat time and space distances in the same units, i.e. $c=1$, and 1 psec = 300 microns; 1 nsec = 1000 psec; 1 nsec = 1 foot

Criteria for Sub-Psec Timing-1

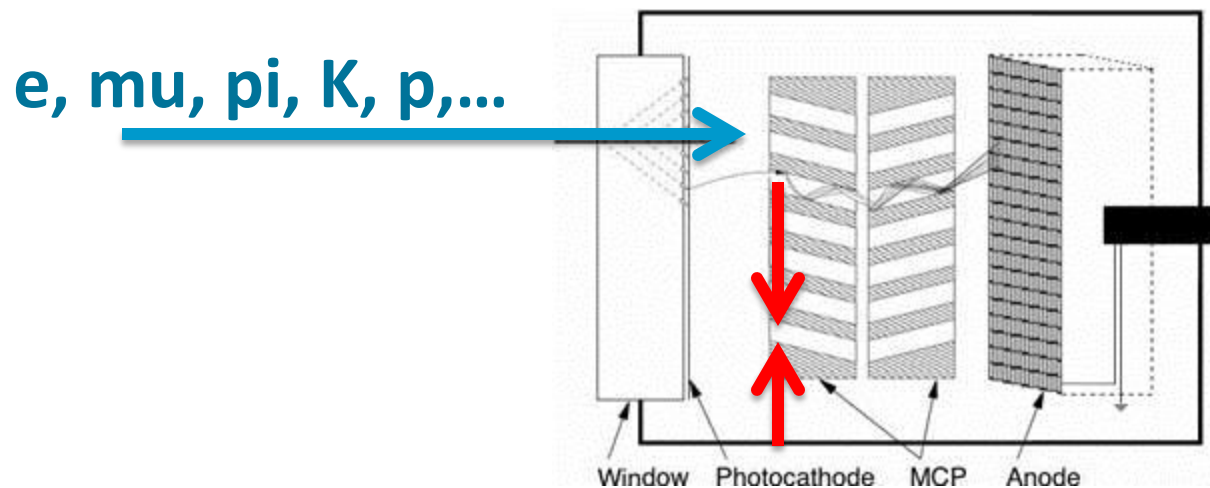
Fast Source: A psec source in time-space of many photons in a time-space interval (example: Cherenkov light from a charged particle traversing a radiator or the entrance window of a photodetector);



(Or early in an electromagnetic shower such as in a pre-radiator or EM calorimeter (separate discussion));

Criteria for Sub-Psec Timing-2

Psec-level pixel size (example: 10-20 micron pores in an MCP plate)

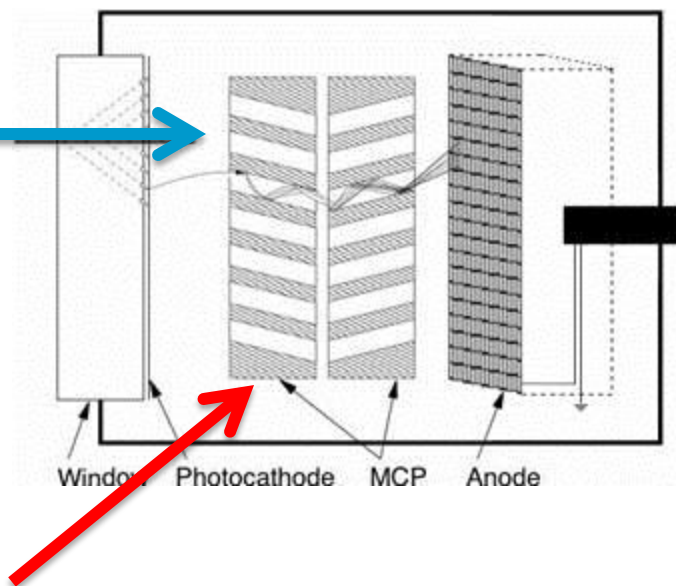


10-20 micron pore

Criteria for Sub-Psec Timing-3

High gain: The gain has to be high enough that **a single photon triggers, i.e. the first photon 'in' determines the leading edge of the pulse** and consequently the timing.

e, mu, pi, K, p,...



N.B. NOT
 $1/\sqrt{N}$

Amplification section: Gain-bandwidth, Signal-to-Noise, Power, Cost (eg: two-stages of MgO MCPs give gain $>10^7$)

Signal-to-Noise, Rise-time Dependences

Long discussions at UC/ANL /France workshops of dependence on analog bandwidth, gain, noise, digitization methods, etc. ;

Answer (S. Ritt) is that **at the level of present performance, using waveform sampling, the achievable time resolution is well-described by three parameters: 1) analog band-width (aka rise-time); 2) signal-to-noise; and 3) the sampling rate (assuming sufficient number of bits not to limit).**

- **Show Stefan Ritt's Rule-of-Thumb. For a sampling rate proportional to analog bandwidth it's only 2 parameters.**

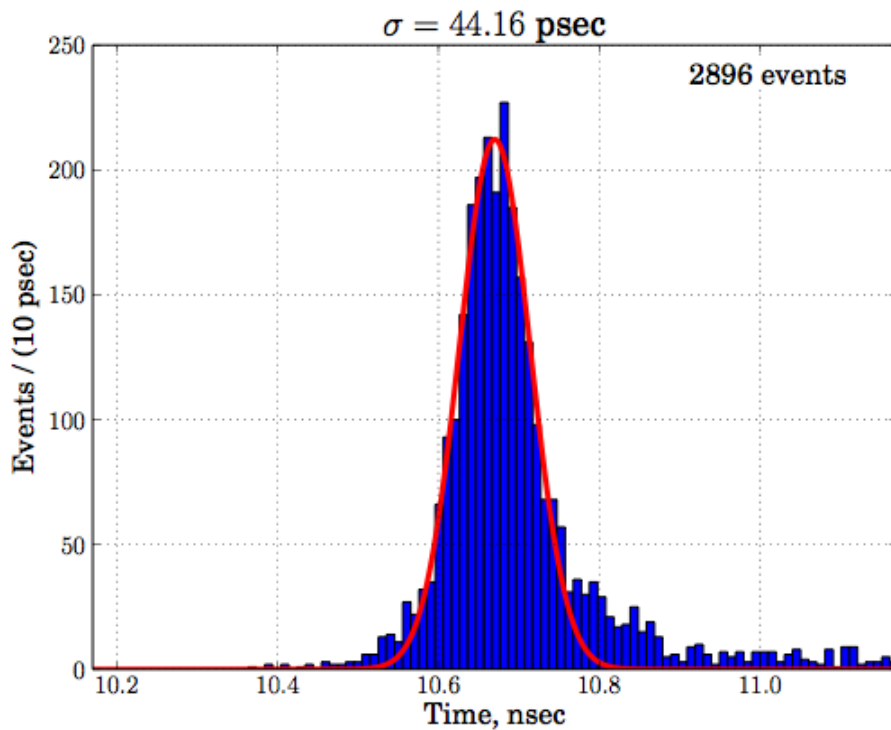
Breaking the 1-Psec Barrier?

Stefan Ritt (PSI) table from 2nd Chicago Photocathode Workshop (annotated) (see psec.uchicago.edu/library)

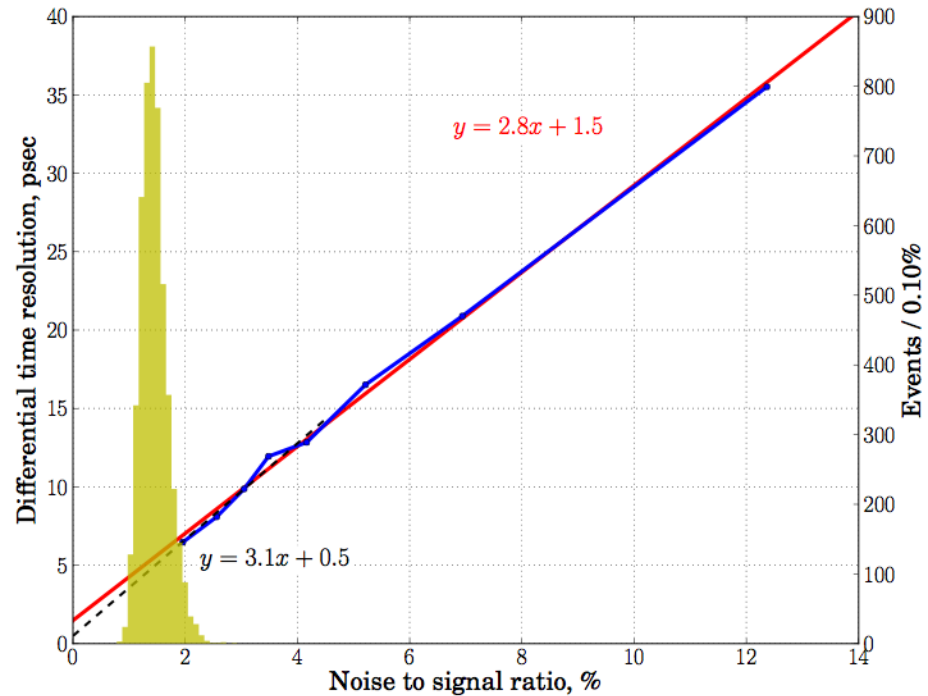
Signal	Noise	Sampling	Bandwidth	Resolution
U	ΔU	f_s	f_{3db}	Δt
100 mV	1 mV	2 GSPS	300 MHz	~10 ps
1 V	1 mV	2 GSPS	300 MHz	1 ps
100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
1 V	1 mV	10 GSPS	3 GHz	0.1 ps
LAPPD: 1V	0.7 mv	15 GS/sec	1.5 GHz	??

Before 100 fsec something else will surely bite us, but still...

Present (now old) Time Resolution



Single Photo-electron
PSEC4 Waveform sampling
Sigma=44 psec



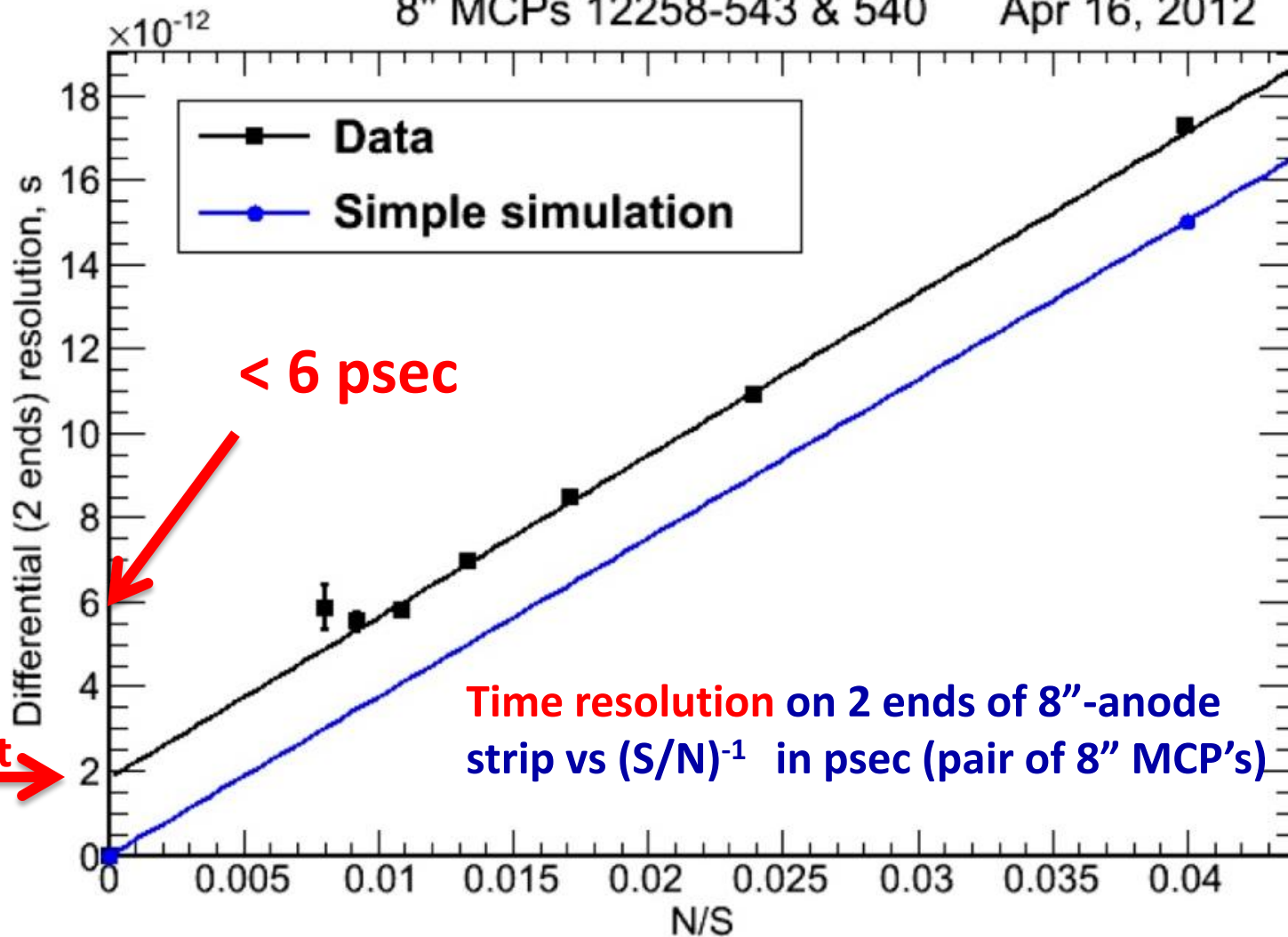
Differential Time Resolution
Large signal Limit
Oscilloscope Readout
Black line is $y = 3.1x + 0.5$ (ps)
Red line is $y = 2.8x + 1.5$ (ps)
Where the constant term represents the
large S/N limit (0.5-1.5 ps)

Highly non-optimized system (!)- could do much better

Timing res. agrees with MC

8" MCPs 12258-543 & 540

Apr 16, 2012



N = RMS of the noise; S = signal amplitude

M. Wetstein, B. Adams, A. Elagin, R. Obaid, A. Vostrikov, ...

Opinion, pure and simple (why not)

Next round of big collider detectors

- **Should measure 4-vectors of all tracks up to (say) $P_T = 25$ GeV using ultra-fast TOF**
- **Should vertex all particles using ultra-fast TOF, including photons**
- **For ultra-fast TOF need small pixels, high gain, and lots of photons in a coherent localized pulse.**



John Lindsley (air-shower array pioneer, with Bruno Rossi at MIT). Volcanos in background. Very primitive and wonderful- amazing summer for a 15-yr old



Volcano ranch group car: predecessor of the WWII Navy Weapons carrier we drove out in the morning (summer, 1960)

The End

Acknowledgements

- **H. Marsiske, H. Nicholson and the US DOE Office of Science**
- **Staff and management at Incom and Arradiance**
- **Colleagues and collaborators at ANL , SSL, and Hawaii**
- **Others in the field of fast-timing , with special thanks to T. Ohshima and J. Vavra; and waveform sampling, with special thanks to E. Delagnes, J.F.-Genat, S. Ritt, and G. Varner**

This work supported by U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences and Offices of High Energy Physics and Nuclear Physics under contracts DE-SC0008172 and DE-SC0015367; the National Science Foundation under grant PHY-1066014; and the Physical Sciences Division of the University of Chicago.

Backup Slides

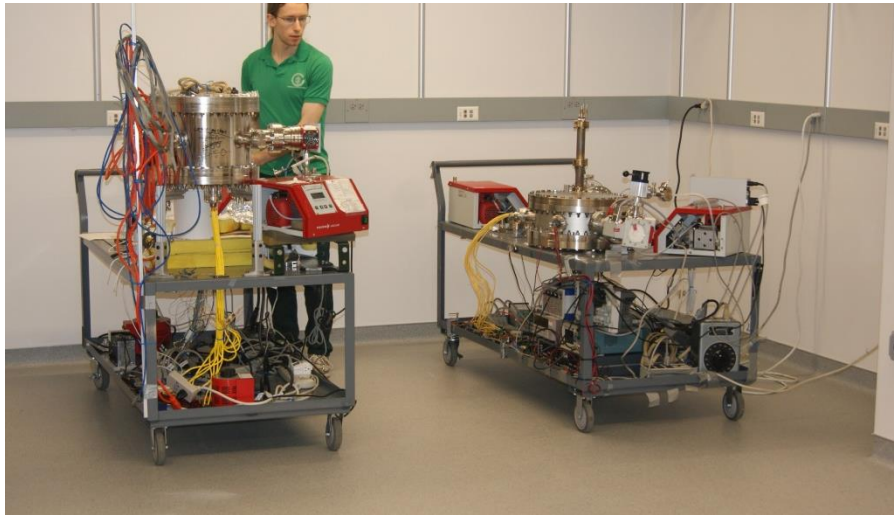
Photodetector Development



Joe Gregar (master glassblower Argonne) and Andrey



Ceramic tile bases from 4 vendors



Second Margherita for ceramic in our brand-new lab; new wet lab₇(!)



A Plea

As money gets tight we naturally pull back from risk and disruptive technologies. However the big gains in our exploratory capabilities have come from new things- often not easy- e.g. the TPC and silicon vertex detectors (I was on a godparent committee that approved Aldo Menzione's for CDF). We should aim for 'a portfolio' of risk'— judiciously and thoughtfully chosen; but we should fight the shutting down either new initiatives or career paths for young physicists interested in new ideas.

(N.B. not a plea for my program per se- much broader and more important to the future of US basic science)