A Summary of Timing Measurements at Fermilab for PET-TOF

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TIPP
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Time-of-flight measurements can be used to significantly improve PET reconstruction resolution.

Fermilab has been studying timing resolution of photodetectors for generic high energy physics studies. (Note: resolutions are Gaussian sigma unless otherwise noted.)

These timing results can be applicable to PET imaging

The results shown here are a survey of some of the timing issues results that Fermilab has obtained.

I'll talk about:

- The experimental method for timing resolution:
  - CFD analog timing
  - High speed digitization
- Measurements using Photek microchannel plate PMT
- Lab measurements of Hamamatsu and IRST SiPM's
- Timing in LYSO Crystals
- SiPM Electronics Development

A history of timing measurements at Fermilab

The Fermilab Crew

- Mike Albrow
- Sergey Los
- Mike Martens
- Erik Ramberg
- Anatoly Ronzhin
- Jinyuan Wu
- Andriy Zatskerliany

The Chicago Crew

- Chin-Tu Chen
- Chien-Min Kao
- Heejong Kim

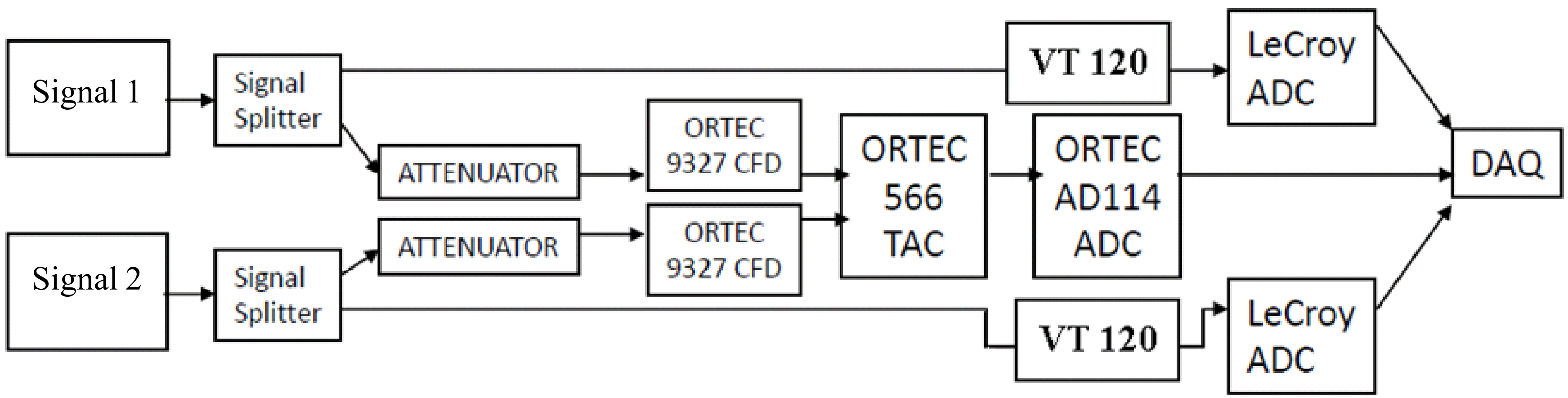
Detectors Studied

- Photonis Planacon
- Photek 210
- Photek 240
- Hamamatsu SiPM
- IRST SiPM
- STM SiPM

Papers

- Nucl.Instrum.Meth.A606:404-410,2009
- FERMILAB-CONF-09-573-PPD, 2009
- Nucl.Instrum.Meth.A616:38-44,2010
- FERMILAB-TM-2456-E, Jan 2010
- Nucl.Instrum.Meth.A623:316-317,Nov 2010
- Nucl.Instrum.Meth.A623:931-941,Nov 2010
- FERMILAB -TM-2487-PPD, February 2011

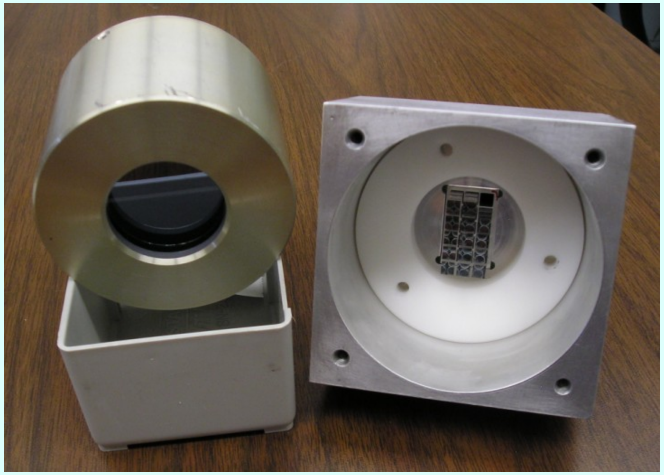
We have typically used Ortec electronics for splitting/amplification/discrimination:

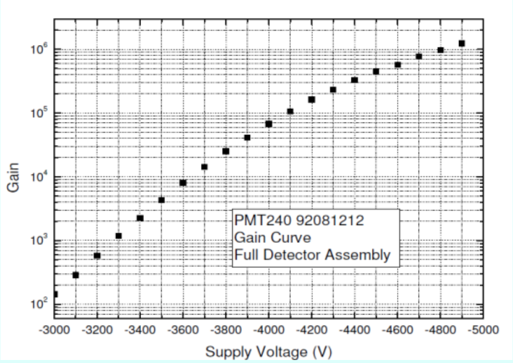


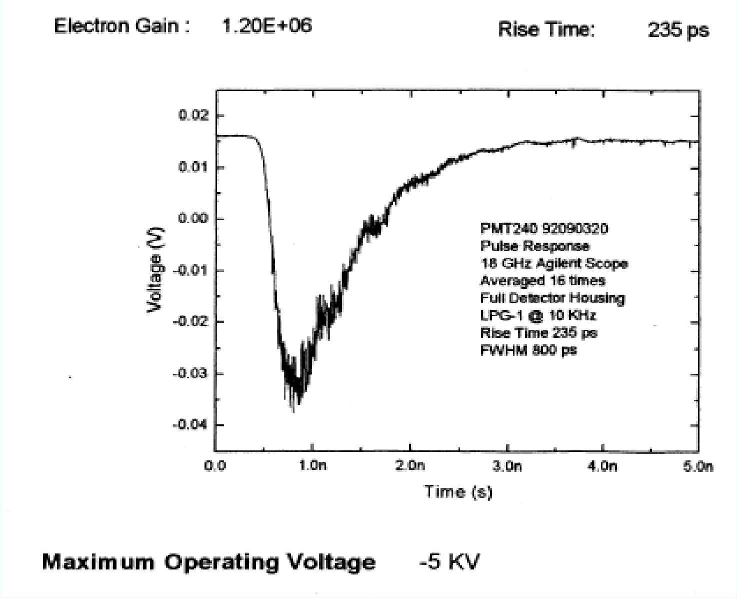
CFD = 'Constant Fraction Discriminator'
TAC = 'Time to Amplitude Converter'
ADC = 'Analog to Digital Converter'

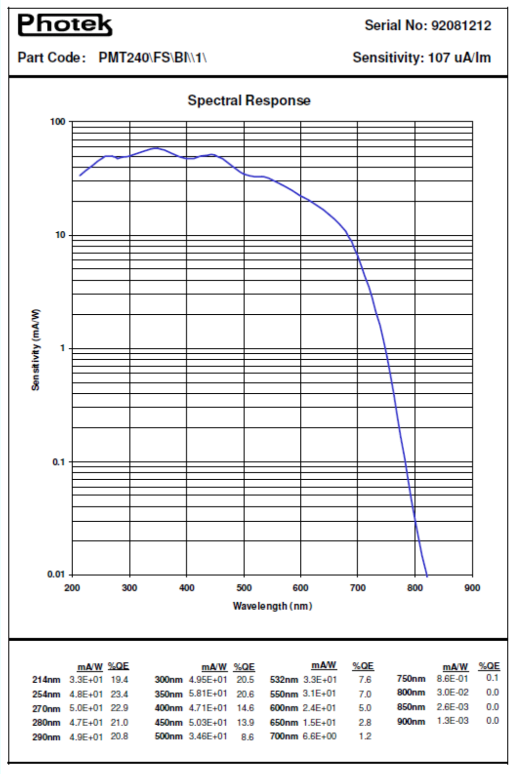
For benchtop measurements, we often use NIM trigger pulse from PLas laser or LED, and skip the CFD and ADC measurement of that signal. For test beam measurements, we put 3 devices in line and form 3 separate timing difference measurements so we can disentangle contributions from each device. Electronic resolution is consistently 2-3 psec.

The Photek 240 MicroChannel Plate Phototube



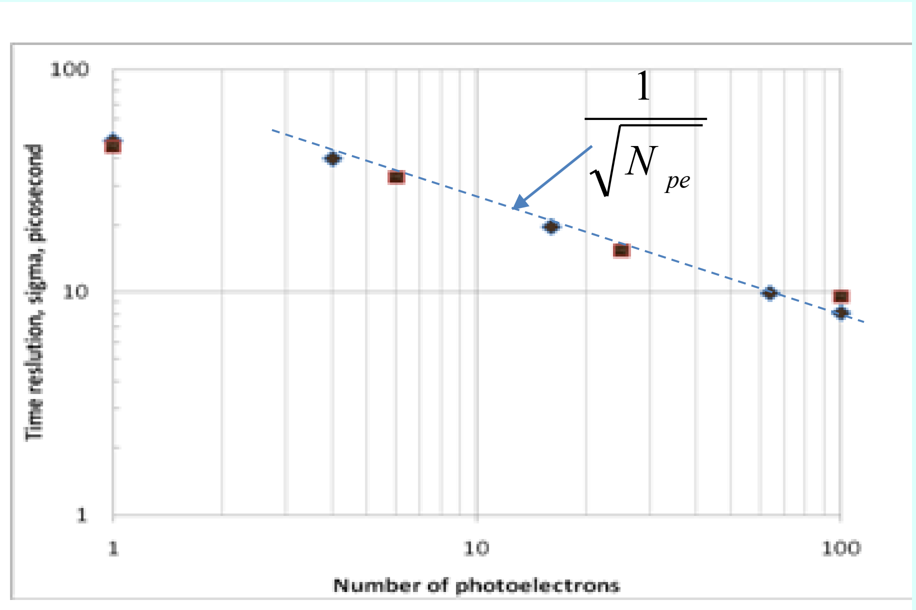




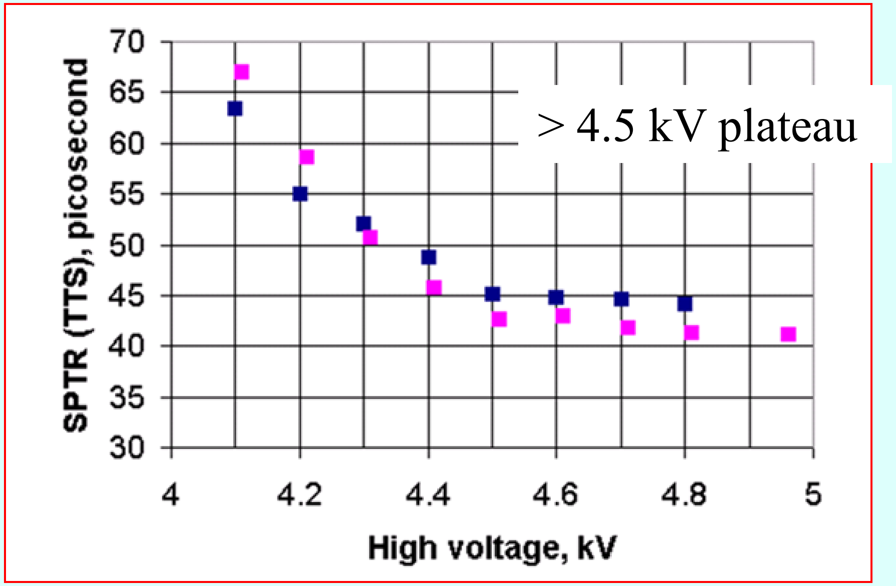


	mA/W	%QE		mA/W	%QE		mA/W	%QE		mA/W	%QE
214nm	3.3E+01	19.4	300nm	4.95E+01	20.5	532nm	3.3E+01	7.6	750nm	8.6E-01	0.1
254nm	4.8E+01	23.4	350nm	5.81E+01	20.6	550nm	3.1E+01	7.0	800nm	3.0E-02	0.0
270nm	5.0E+01	22.9	400nm	4.71E+01	14.6	600nm	2.4E+01	5.0	850nm	2.6E-03	0.0
280nm	4.7E+01	21.0	450nm	5.03E+01	13.9	650nm	1.5E+01	2.8	900nm	1.3E-03	0.0
290nm	4.9E+01	20.8	500nm	3.46E+01	8.6	700nm	6.6E+00	1.2			

Some bench-test results on Photek 240



Time resolution vs # photoelectrons



Transit Time Spread (TTS) vs HV;
1 mm laser spot at centre and edge (18mm)

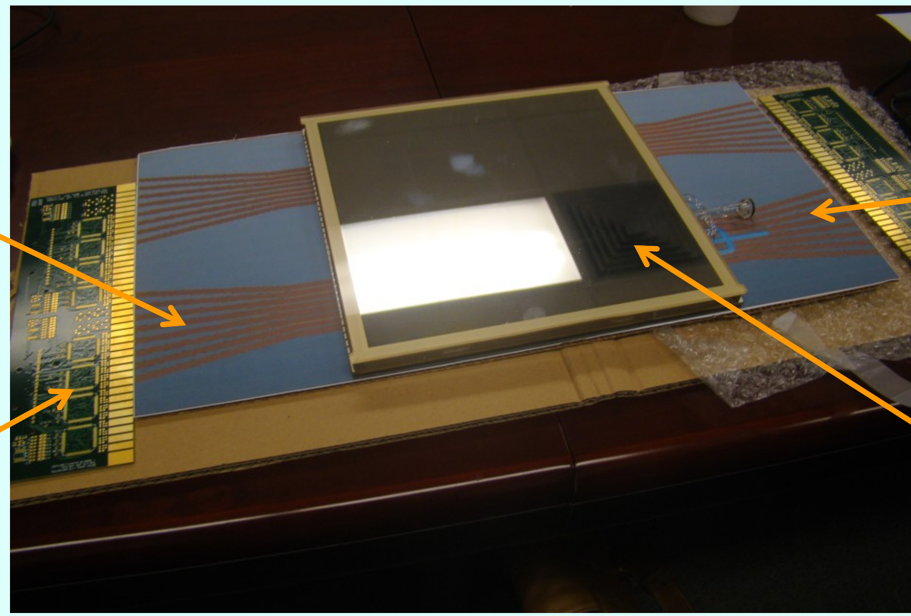
Laser spot to centre, intermediate and outer positions on photocathode shows no significant shift (< 3 ps).

Single Photon Timing Resolution has better performance than multi-photon extrapolation would indicate.

Fermilab is supporting the U.Chicago/ANL development of high speed, high resolution, large area, thin MCP phototubes, by providing technicians and creating a new 8" evaporative coating facility.

A mockup of the 8" MCP/PMT

Transmission line readout retains superb timing resolution



Readout on both ends gives 1 mm positional resolution

U.C. is developing high speed digitizers (10-20 GHz)

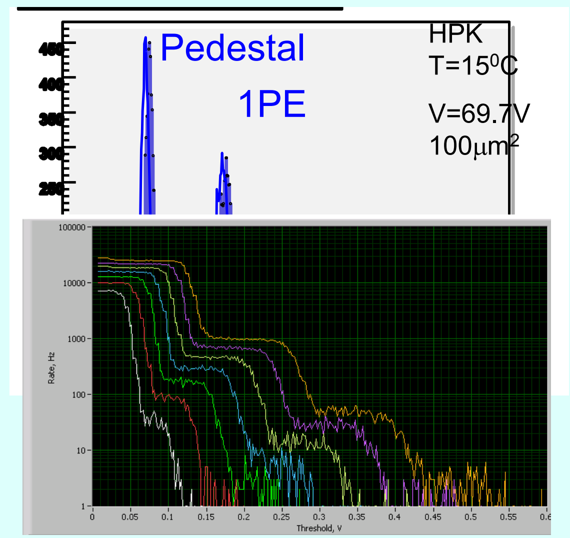
Micro Channel Plate has been developed with new process (ALD coating of drawn glass channels)

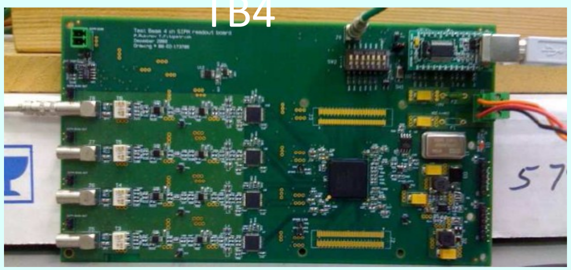
See other talk on this project (abstract #300):

Heejong Kim: "An Application of Micro-channel plate photomultiplier tube to Positron Emission Tomography"

SiPM Characterization and Readout

- SiPMs are arrays of tiny APDs which count Geiger mode avalanches
- Fermilab has developed a general facility for characterization of SiPMs
  - Dark current and photo response
  - Cross talk
  - Temperature dependence
  - Four channel readout board with waveform digitization
    - 12 bit, 250MSPS ADC
    - Large FPGA
    - USB interface
    - On-board bias control





Studies of SiPM Intrinsic Timing

- Photoelectron N_{pe} peaks all resolved.
- Feature size of <100 μ should give excellent timing resolution
- We use a high-pass circuit to concentrate on early (fast) part of pulse and keep pulse width small to meet input specs of Ortec 9327 CFD

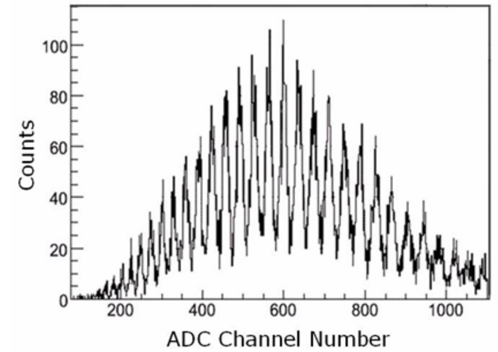
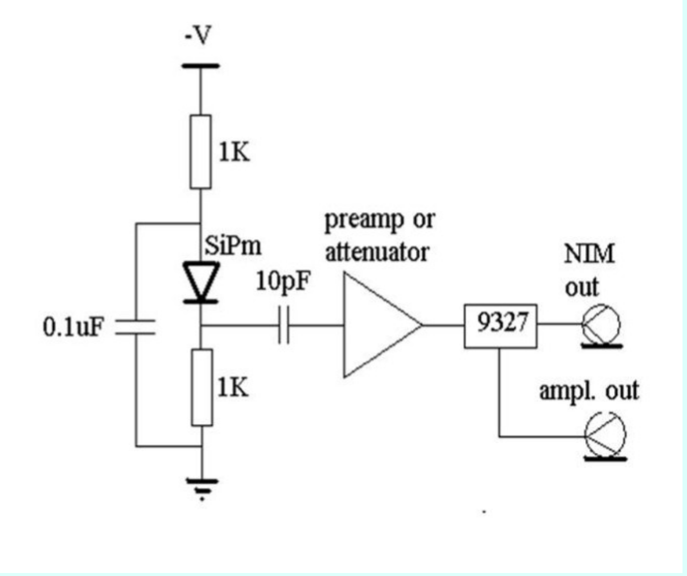


Fig. 13. Single photoelectron spectrum from a 3.5x3.5 mm² STM biased at 3.5 V OV and illuminated by laser light at 405 nm. The charge was integrated for a fixed gate time of 50 ns (250 fC per ADC channel). About 30 photoelectrons peaks can be clearly separated in the spectrum. ADC channel number 600 corresponds to 17 photoelectrons peaks.



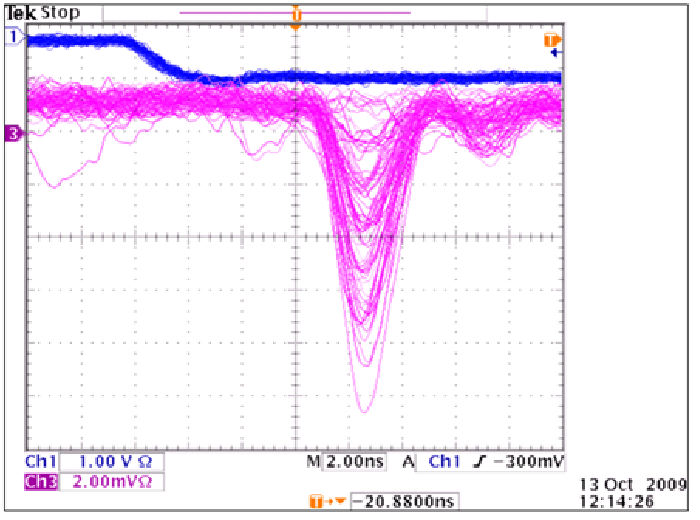
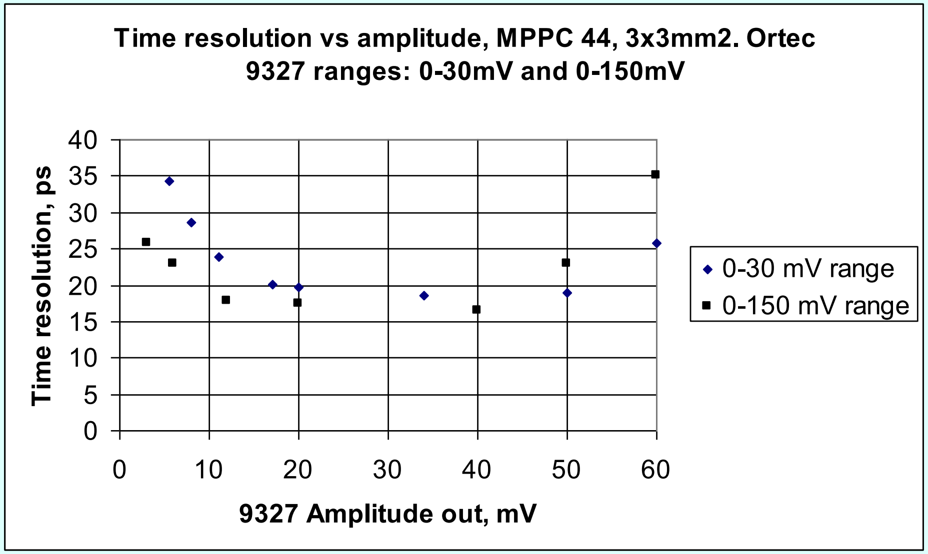


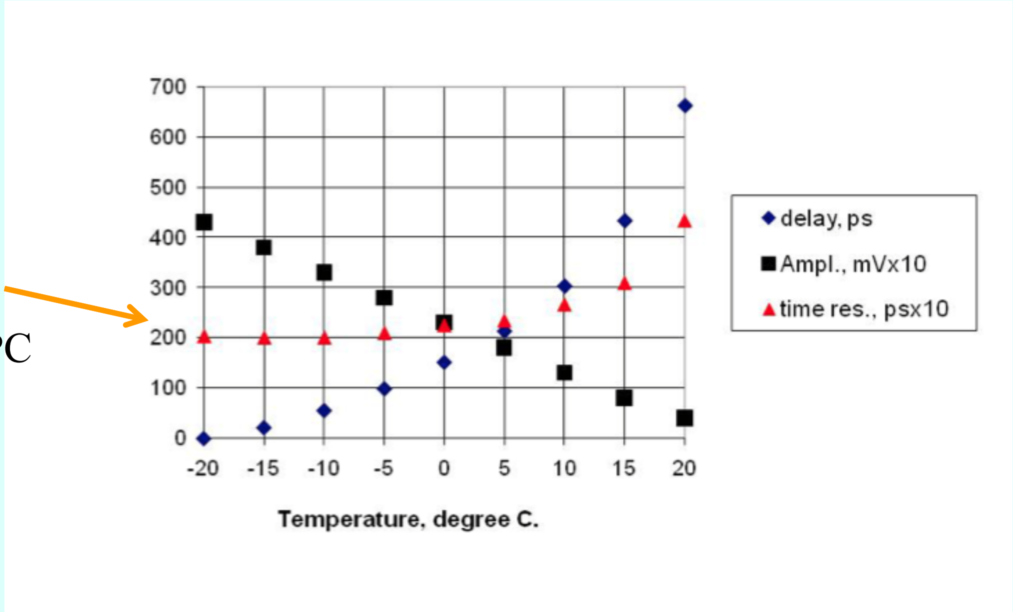
Fig. 12. Snapshot of STM output signal with a few photons illumination. Signal is
9327 requierements to input signal.

Hamamatsu MPPC Results on the bench



Time resolution vs 9327 input amplitude (large light input gives better than 20 psec resolution)

Temperature Dependence for Hamamatsu MPPC



SiPM Timing Dependence on Wavelength

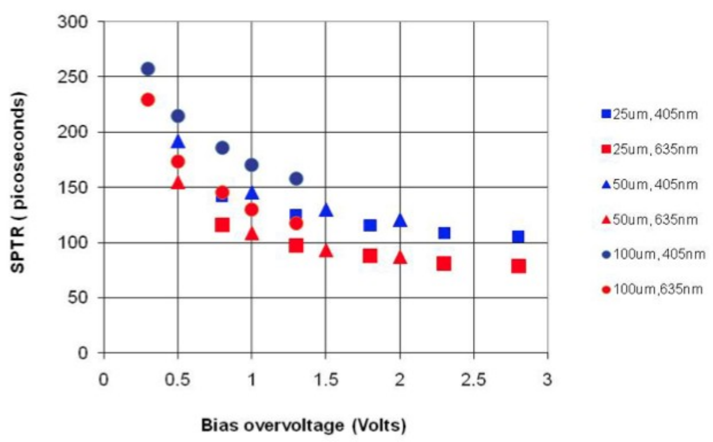
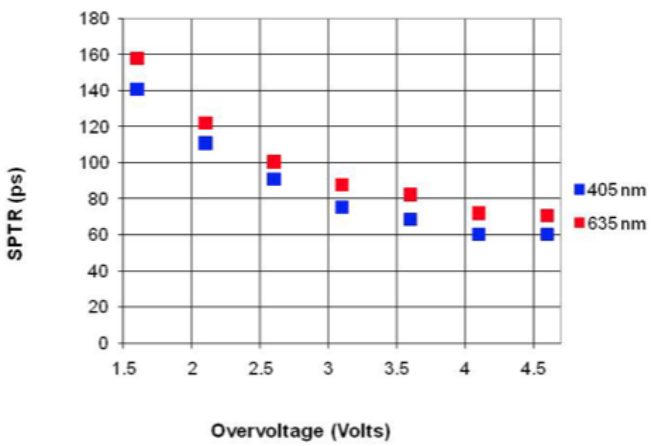


Figure 7. SPTR of various MPPC's (1x1 mm^2 sensitive area) illuminated by blue (405 nm) and red (635 nm) PiLas light vs. overvoltage.

Hamamatsu – red light gives better timing resolution



IRST – blue light gives better timing resolution

Figure 8. SPTR of the IRST SiPM (1x1 mm^2 sensitive area) illuminated by blue and red laser light vs. overvoltage.

Wavelength Dependent Carriers in SiPM

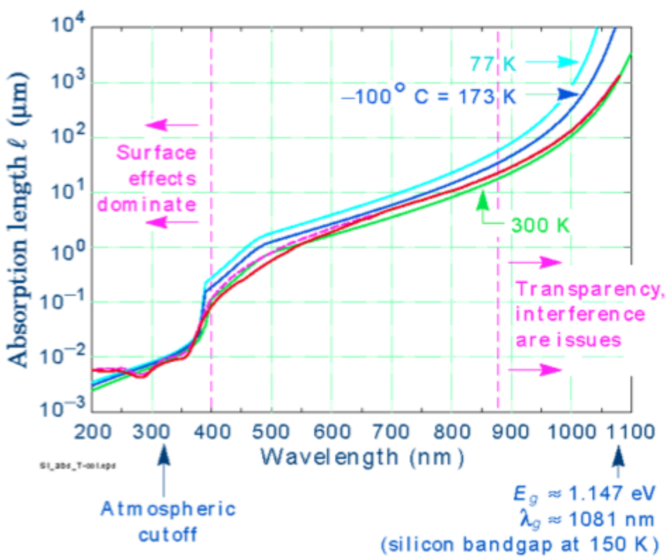


Figure 12. Absorption length in silicon as a function of photon wavelength colored curves correspond to different temperature. [2]

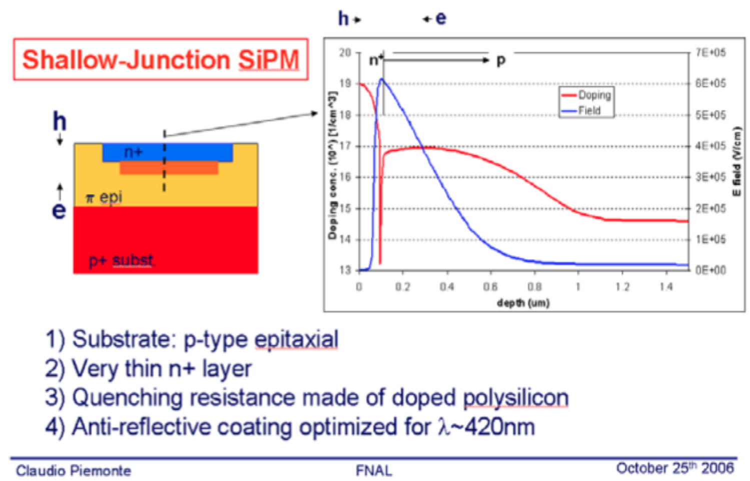
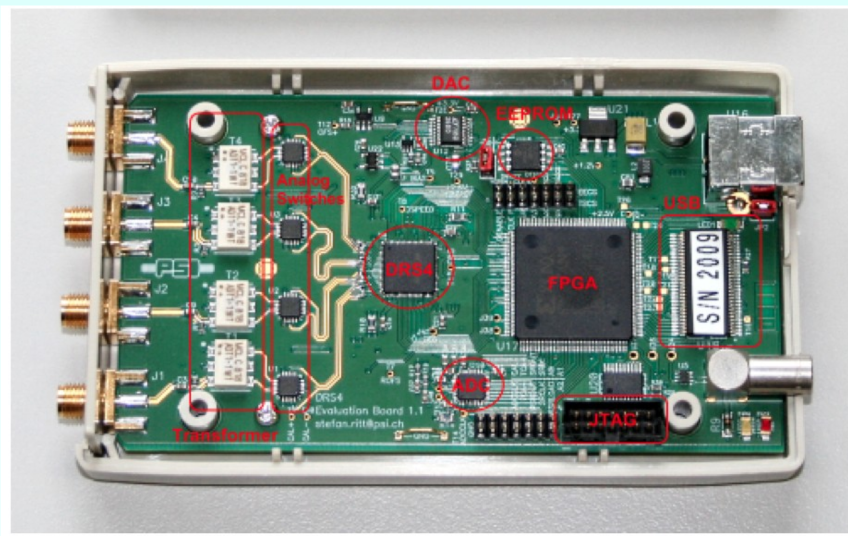


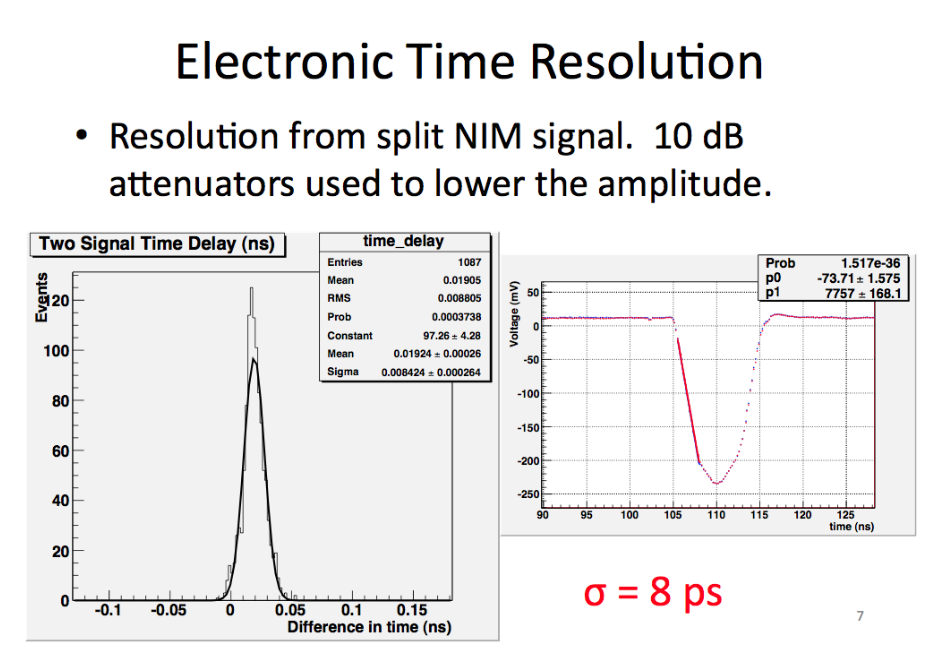
Figure 13. Distribution of the electric field and doping inside of IRST SiPM (top right) and the shallow-junction SiPM structure (left side of the drawing). Data presented by Claudio Piemonte at Fermilab. [3]

The type of carrier (holes, electrons) and their diffusion into the high field region in SiPM's will differ depending on wavelength and type and depth of doping

Tests with the DRS4 Digitizer

We've begun using the PSI 5 GS/sec digitizer DRS4 evaluation board to look at timing characteristics of SiPM's





Simple linear slope fit in the 10-90% range gives 8 ps resolution

Waveform analysis of Scintillator using MPPC photodetector with DRS4

DRS4: 5 GS/s, four input channels, PC readout thru USB port

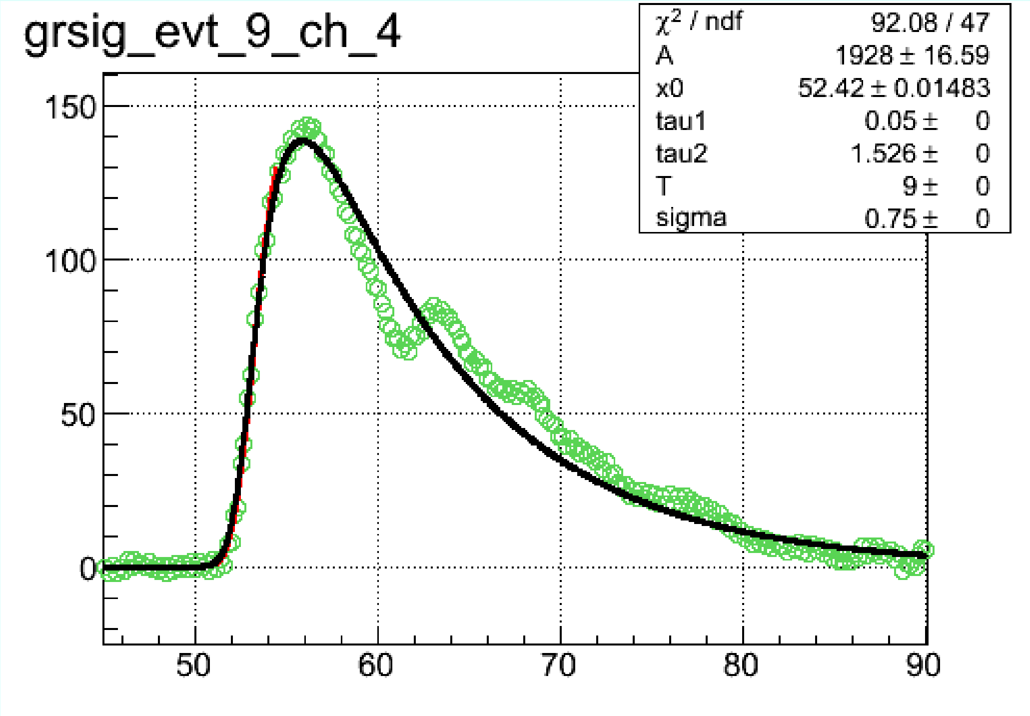
Model: charging and discharging of a capacitor:

p(x) = (1 - exp(-x/tau1))*exp(-x/tau2)

We then convolute this with scintillator decay function and resolution function

1. Fit the leading edge with T, tau2 and resolution fixed
2. Use tangent to the middle of the fit to the leading edge to obtain time stamp
3. Fit the whole pulse to obtain scint decay time T and discharge time tau2
4. Resolution of this method is about 4 psec

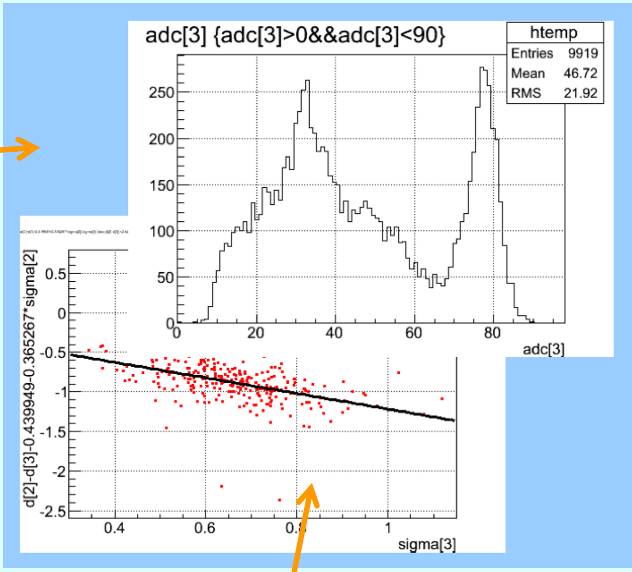
(See poster – abstract 195:
Andriy Zatserklyaniy: "Waveform analysis of SiPM signals with DRS4 board")



Time resolution with LYSO crystals

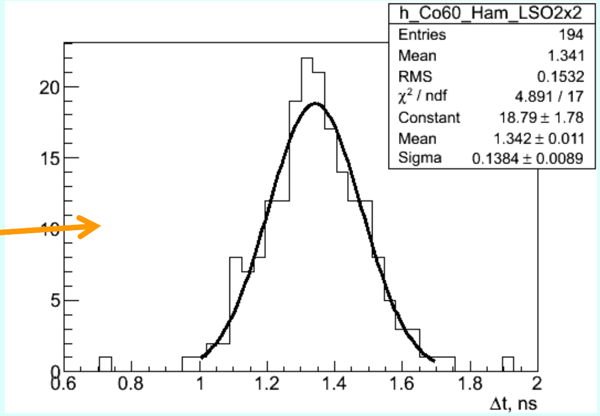
- LYSO crystals 2x2x7 mm^3.
- Source: ^{60}Co and ^{22}Na
- Hamamatsu MPPC 3.5x3.5 mm^2
- Clipping capacitor 10 pF on output of the MPPC
- ORTEC preamplifier 120C

Use pulse height analysis to select events from photoelectric peak (~15% FWHM energy resolution)



Time resolution for ^{60}Co: 138 ps

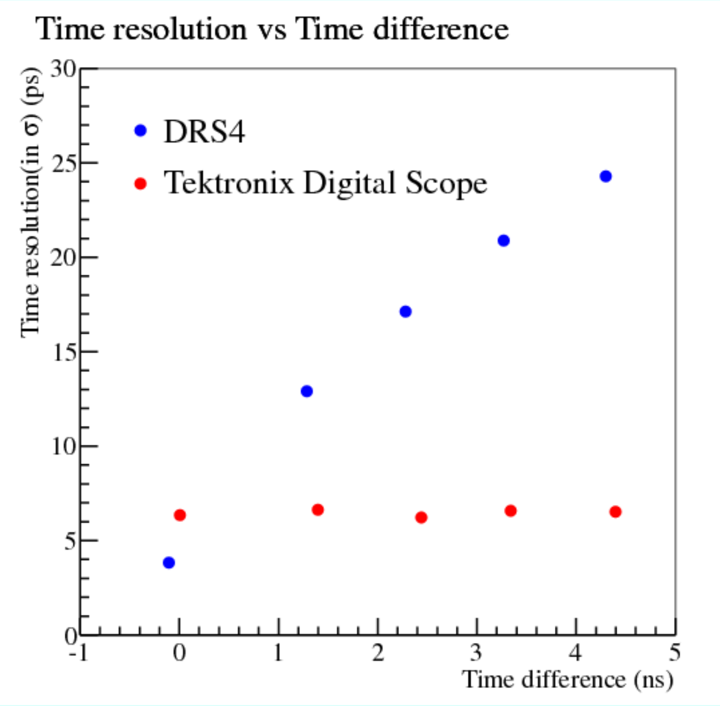
Time resolution for ^{22}Na: 152 ps)



Systematic dependence of resolution on noise level

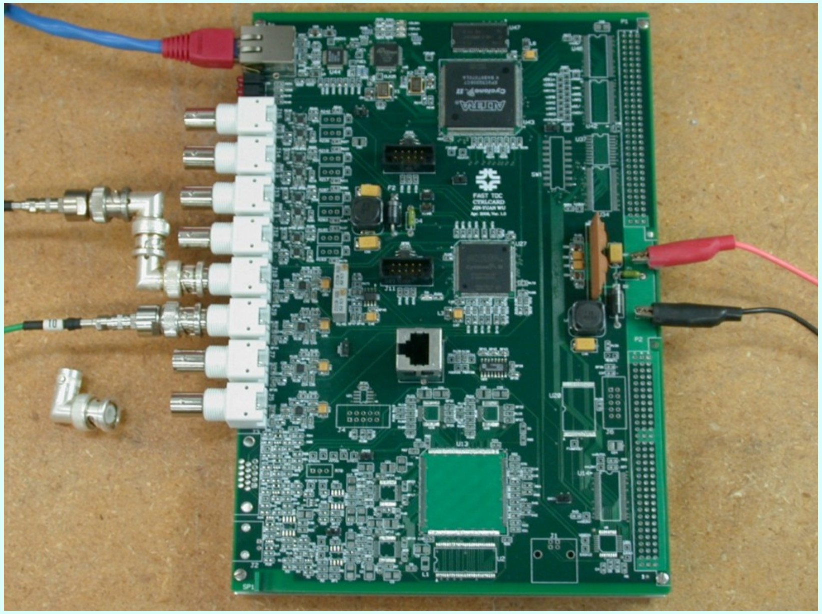
Still learning details about calibrating digitizer

- Have found that the DRS4 timing resolution, in comparing two separate channels, depends on the delay between the channels.
- This calibration issue may affect our results



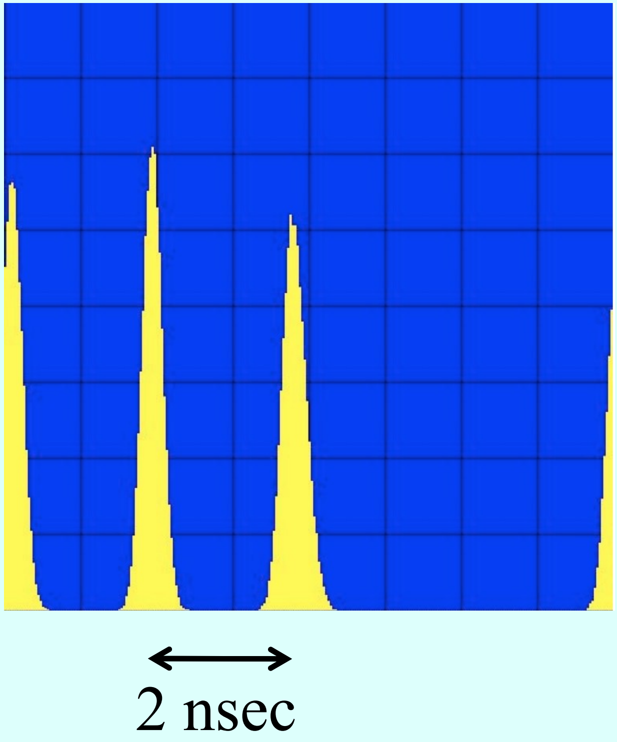
We've developed a cheap FPGA based 'Wave Union' TDC with 15 psec resolution:

8 channel, 6U VME board



(See other talk, abstract 429: Arden Warner "Cryogenic Loss Monitors with FPGA TDC Signal Processing"

Effect of adding BNC adapters



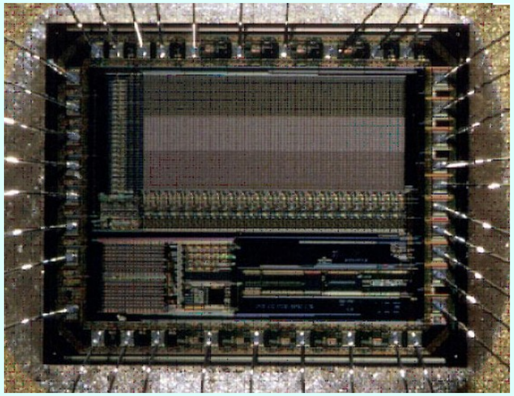
This promising type of TDC can be expanded to large channel count and could be highly effective for PET-TOF. Needs to be combined with a CFD circuit to compensate for pulse height.

3-Dimensional ASIC program

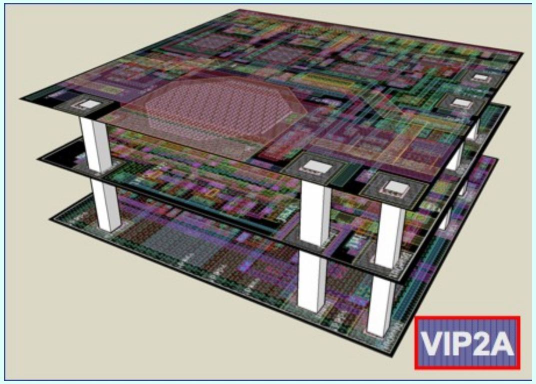
Fermilab began exploring 3D technology for HEP several years ago and its ASIC development group submitted the first 3D IC (VIP1) for high energy physics to MIT Lincoln Labs in October 2006.

We led the formation of a large international consortium (http://3dic.fnal.gov) addressing this new technology. This group of 17 members from 6 countries shared a multi-project run in 2009 and are still testing structures coming from that run.

A very important development has occurred in that the tools and techniques learned from this process have been adopted by the major silicon fabrication brokers: MOSIS, CMP and CMC.



Conventional Monolithic Active Pixel Sensor



'VIP2A' test structure for 3D pixelated detectors

3D Techniques for SiPM

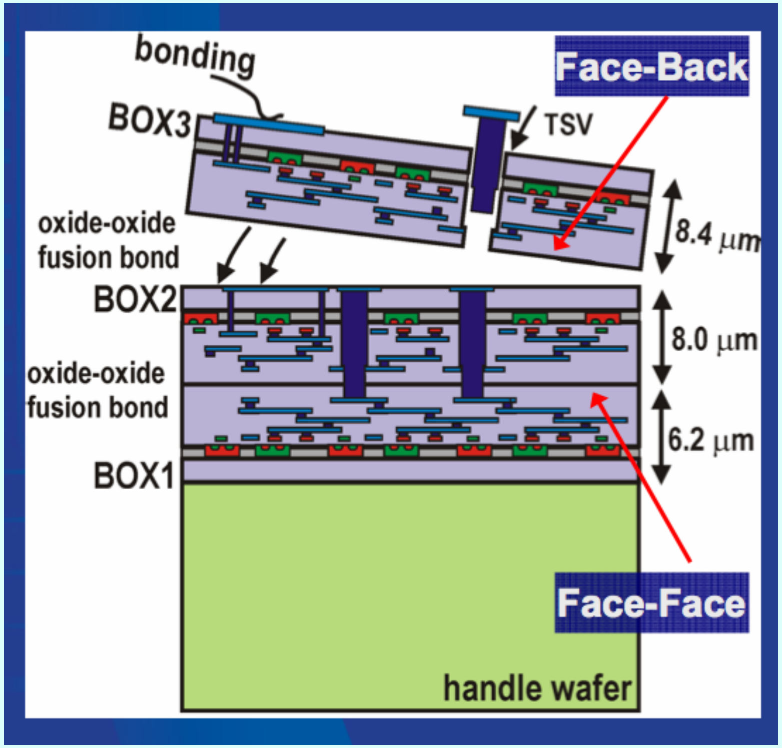
A 3D SiPM would be a powerful photodetector since each diode could conceivably be addressed separately and the timing for each hit known precisely. The full surface could then be active.

Currently the techniques developed by Fermilab for 3D ASICs involve 'Face to Face' bonding of shallow depth circuits, with a 'handle wafer' used for applying pressure in bonding.

'Face to Back' technique then adds a 3rd layer, with through-silicon-vias ('TSV') giving access to the already bonded circuits.

Neither technique will work for a 3D SiPM, since the avalanche layer is at a shallow depth and has to be exposed to the light.

Fermilab is developing the techniques now for 'Back to Face' bonding – a tricky business.



Summary

• Fermilab has been involved in a long series of timing measurements of various photodetectors and our initial method, using conventional Ortec electronics, consistently gives <3 psec electronic resolution.

•Lab measurements of microchannel plate phototubes give superb performance (~45 ps single photon timing resolution) with no positional dependence for the most advanced Ortec tube. This superb resolution will be inherent in ANL large area photodetector project)

• SiPM studies on the bench (Hamamatsu and IRST) show interesting differences in wavelength dependence of timing resolution, probably related to doping profiles. Typical single photon timing resolutions are 60-100 psec.

• DRS4 5 Gs/sec digitizer gives very good (~4 ps) electronic time resolution in our lab measurements.

• Fitting of entire LYSO pulses with a Co-60 source gives 140 ps and with a Na-22 source gives 160 ps

• Fermilab is developing several types of SiPM timing readout, including a cheap FPGA based TDC and pioneering techniques for 3D SiPM fabrication