Development of Small-Pixel CZT and CdTe Detectors with Hybrid Pixel-Waveform Readout System

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- Previous efforts on the ERPC detectors.
- Development of small pixel CdTe and CZT detectors for nuclear medicine applications.
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- Preliminary Results I: waveform-based timing estimation.
- Future outlook.

Motivation of Our Detector Development Effort

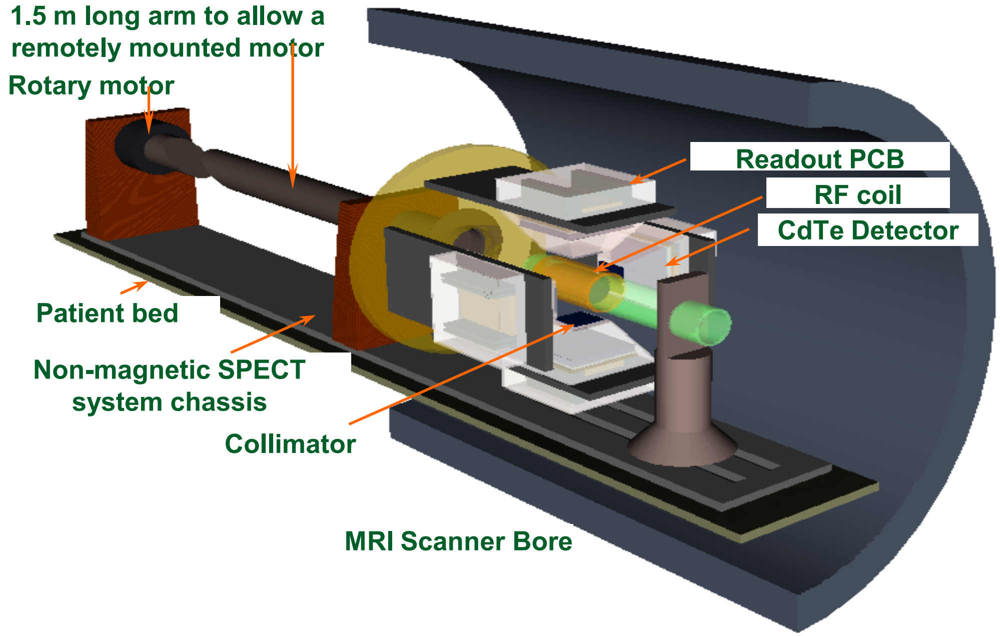
One CZT/CdTe detector architecture that fits many gamma ray applications – such as SPECT and PET for medical imaging, Coded aperture and Compton cameras for security and astrophysics applications?

We would like to have a detector that has

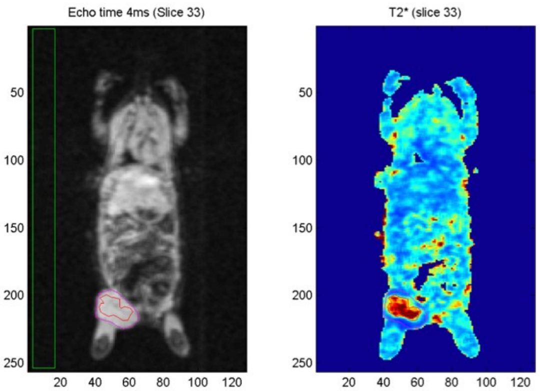
- Excellent spatial resolution in 3-D (a 100-250μm),
- Excellent timing resolution (a few ns),
- Excellent energy resolution (a few percent),
- Adequate count rate capability (250k per cm^2),
- Being able to deal with multiple interaction events.

All across a wide energy range 30 keV - several MeV

A High-Resolution MRI-Compatible SPECT System



The Siemens Allegra 3 T MRI scanner at BIC that will be used in the combined SPECT/MRI System.



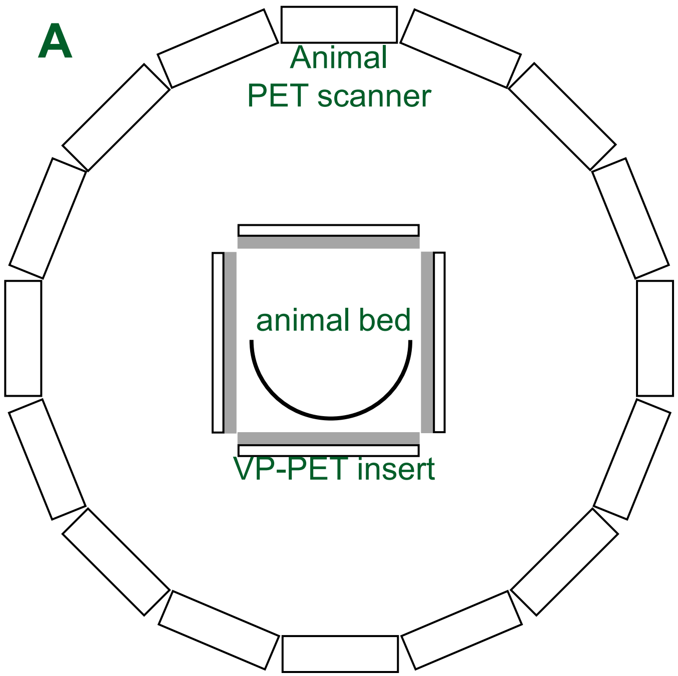
Left: A 3-D whole-body image of a rat acquired with the 3 T Allegra scanner. Right: T2* relaxation of the tissues. The images were obtained with a multiecho fast low angle shot (FLASH) sequence written by Professor Brad Sutton of UIUC. It resulted in 0.5 mm isotropic resolution from an 8 minutes whole body scan.

- We are developing a MRI-compatible SPECT system with four heads installed on a rotational gantry.
- Two key objectives: (a) demonstrate the capability of achieving an sub-500 μm SPECT resolution inside MRI scanner (b) provide a flexible platform for testing different detector and system designs

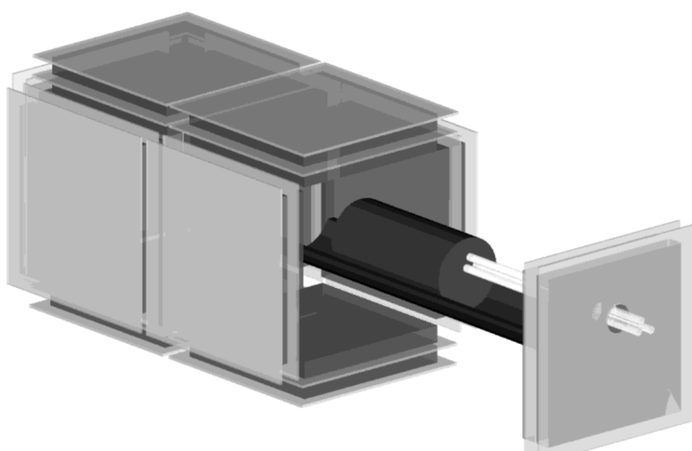
NCI, R21/R33CA004940, R21CA135736-01A1.

A Sub-500 μm Resolution PET Insert

A



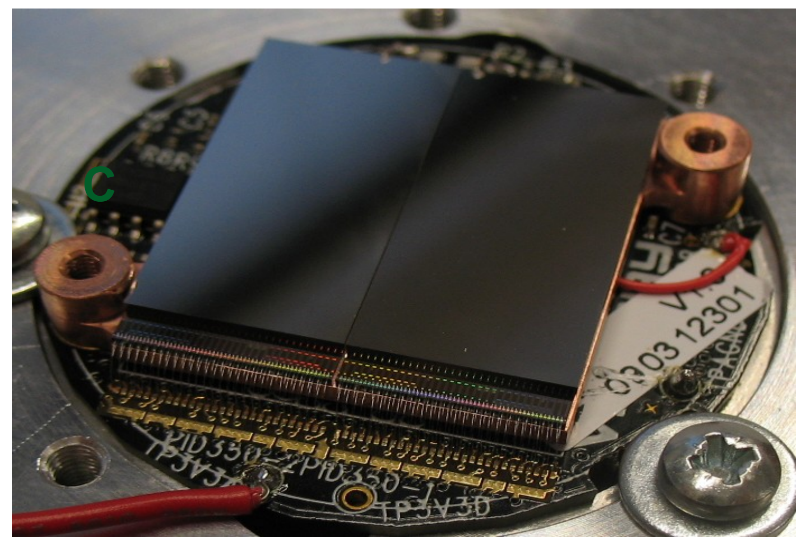
B



(A) Geometry of a potential 4-panel VP-PET insert device inside an animal PET scanner.

(B) A potential implementation of the detector technology proposed in this work.

(C) A prototype PET detector developed for the PET application.

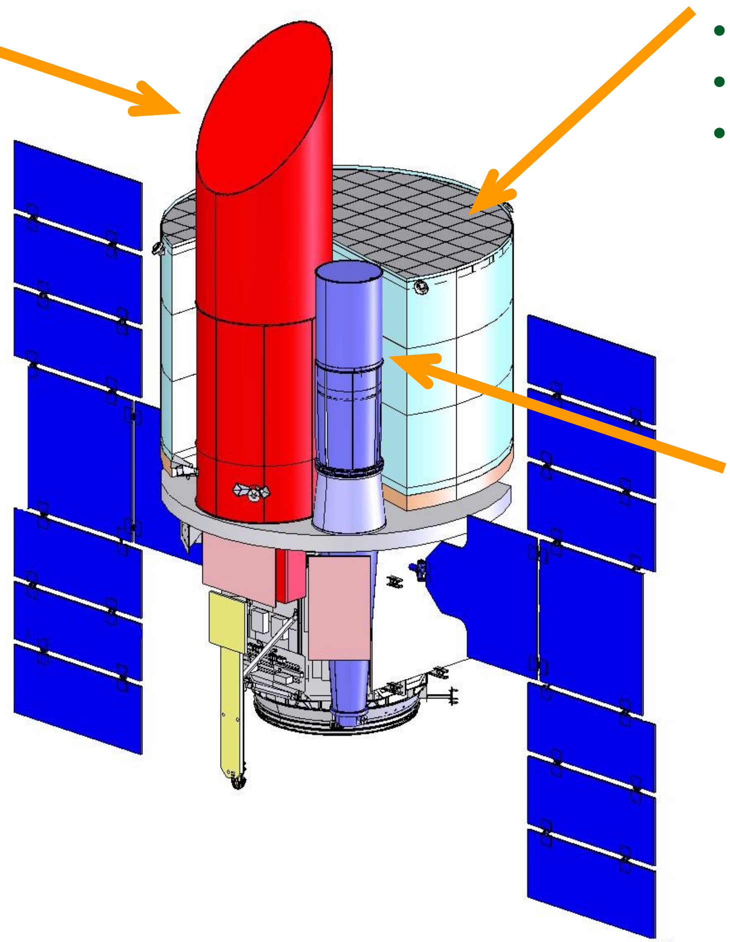


DOE, Office of Biological and Environmental Research (DE-FG2-08ER6481). PI Y. C. Tai, WashU

Focal Plane Detector for the EXIST Mission

IRT (1.1m, -30˚C),
- 0.3-1 μm (CCD),
- 0.9-2.2 μm (NIRSPEC).

HET (5-600 keV):
- Tungsten mask (7.7 m^2),
- CZT detectors (4.5 m^2),
- BGO rear shield (4.5 m^2).



SXI (0.1-10 keV):
- 950 cm^2 @ 1.5 keV.

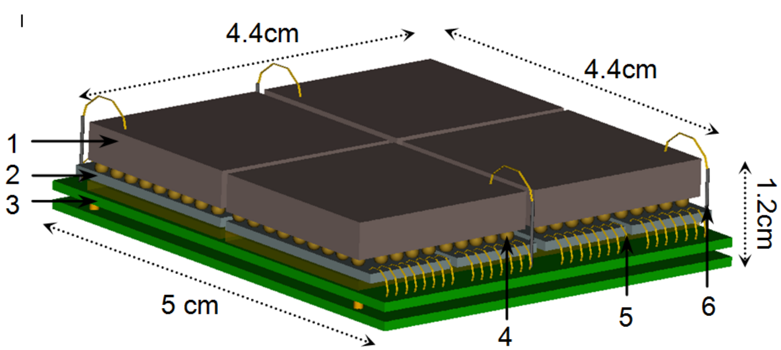
Supported by NASA, Grant # 08-APRA08-0122

Launch: Altas V-401 into LEO.

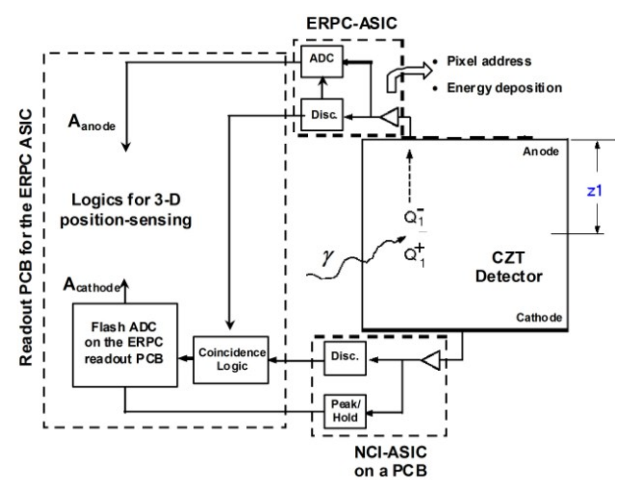
Energy-Resolved Photon Counting Detector – Design Concept and Considerations

Basic design target: generic, high performance and flexible.

- Hybrid photon detector concept with highly pixelated (pixel size: 350 μm) CdTe or CZT bump-bonded to 2-D readout ASIC – compact, high resolution.
- ADC on each channel – all digital output, amplitude, time stamp, pixel address for each hit.
- Flexible sparse logic – allowing signals from adjacent pixels to be summed together.

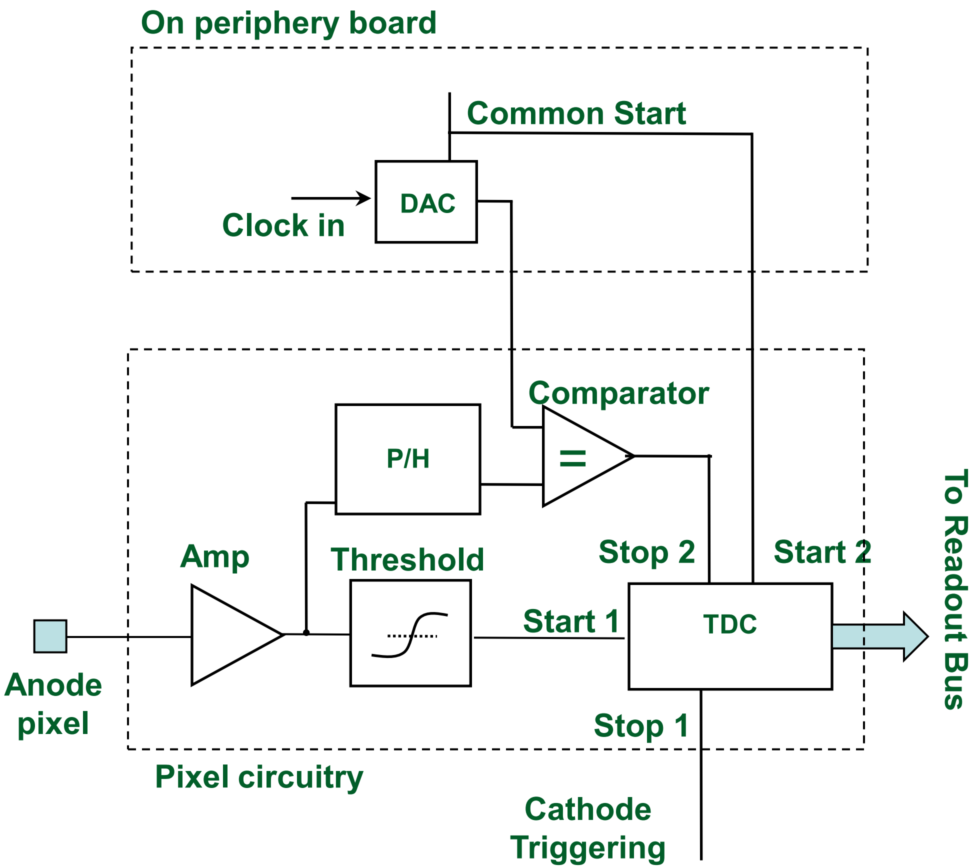


The proposed ERPC detector. (1) CZT crystals of 4.4cm × 4.5 cm × 2-4 mm in size, (2) ERPC ASICs, (3) Readout PCBs, (4) indium bump-bonding between CZT detector to the ASIC, (5) wire-bonds between the ASIC and the PCBs and (6) Cathode signal out.

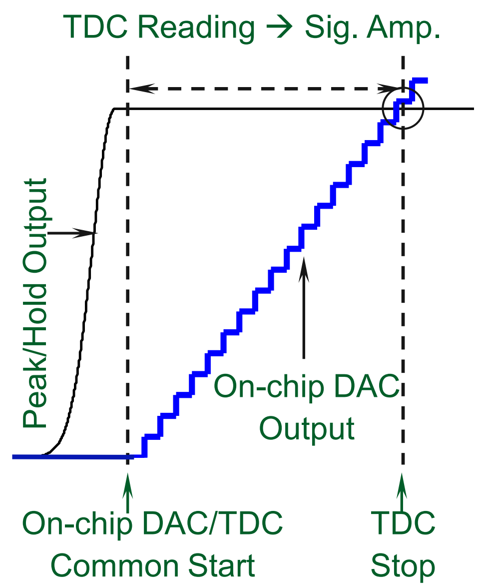


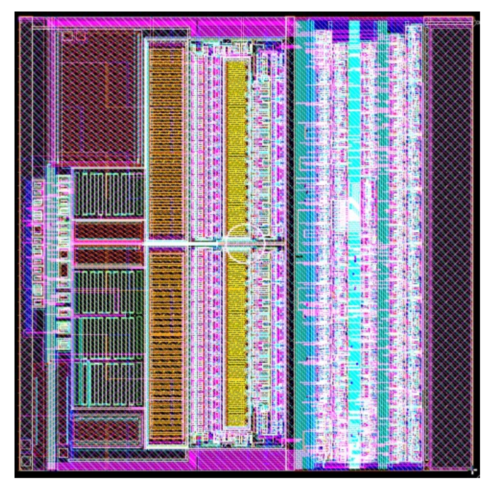
Z. He et al, NIM A380 (1996) 228, NIM A388 (1997) 180.

Pixel Circuitry



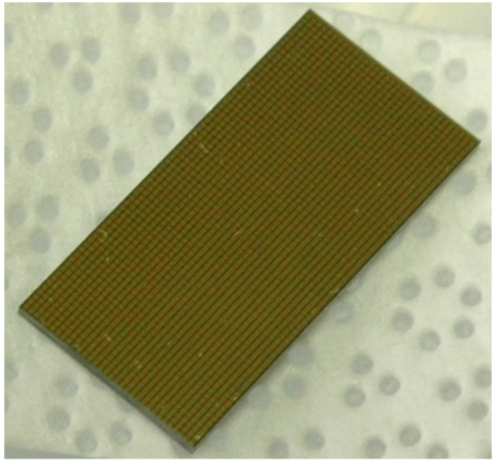
Pixel circuitry

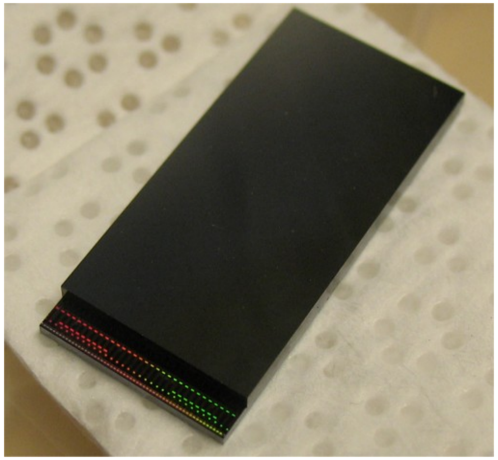


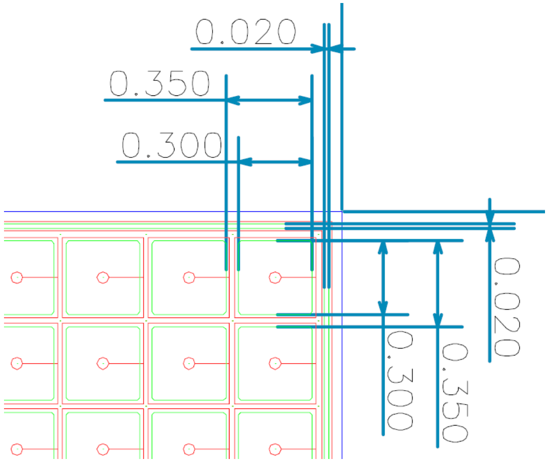


Pixel layout: 350 μm x 350 μm, containing 2682 electrical components

Pixelated CdTe Detectors



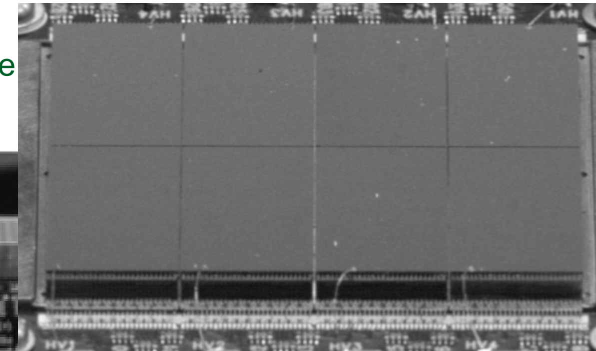




- A pixelated CdTe detector of 11mm × 22mm × 1 or 2 mm in size and having 32×64 350 μm × 350 μm pixels.
- ERPC detectors with 2 mm thick CdTe detectors will be used in the prototype system.
- Other pixel sizes – 515 um, 700 um read out with the same ASIC?

The Prototype ERPC Detectors

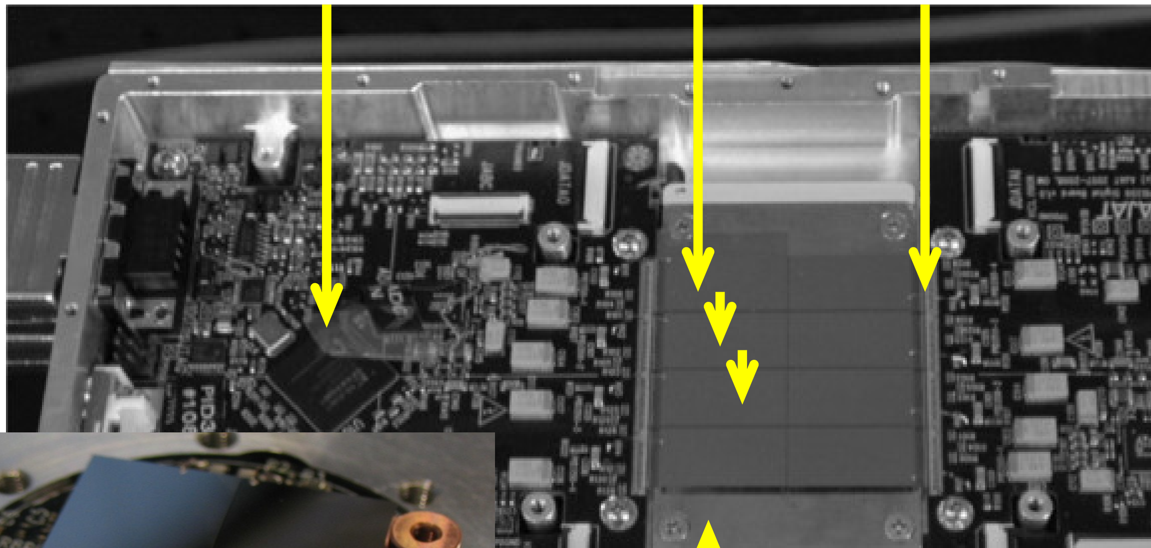
2 mm CdTe detector



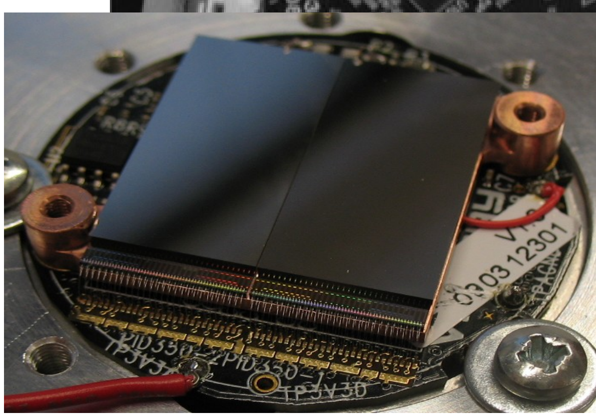
FPGA for controlling the readout sequence

Detector hybrids 1.1 cm × 2.2 cm

Wire-bonding to the readout PCB

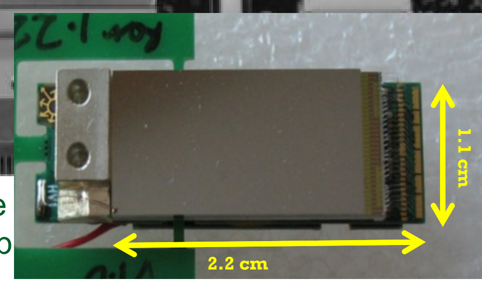


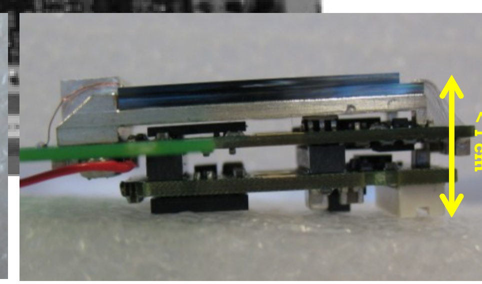
Copper substrate supporting the hyb



A Compact CdTe Detector

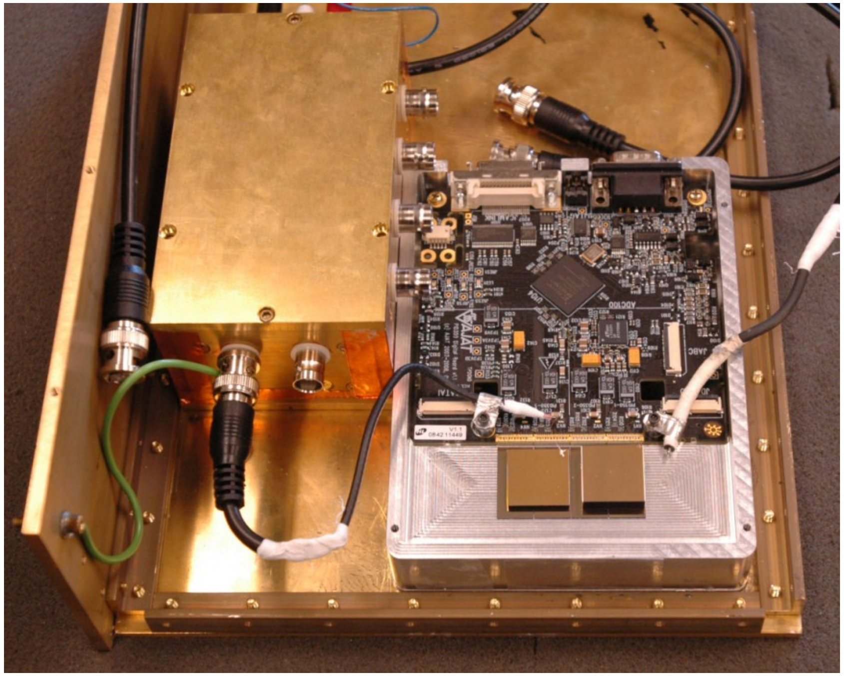
(Picture courtesy, Dr. K. Spartiotis, Oy Ajat)





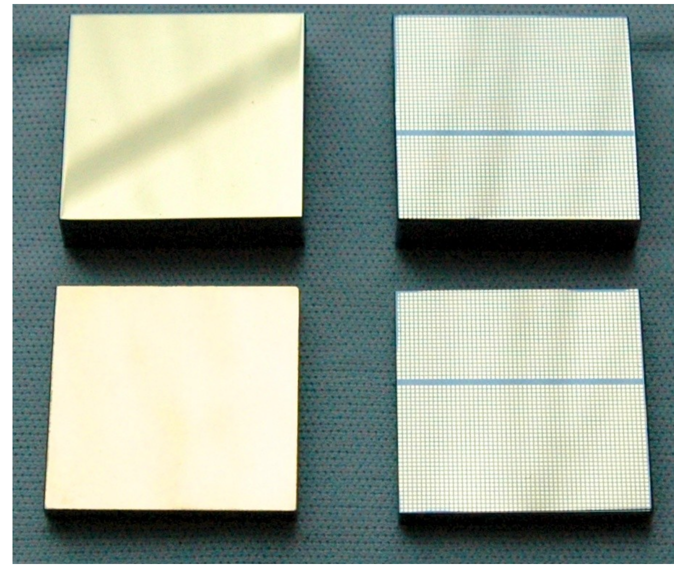
(Picture courtesy, Dr. K. Spartiotis)

CdZnTe Detectors



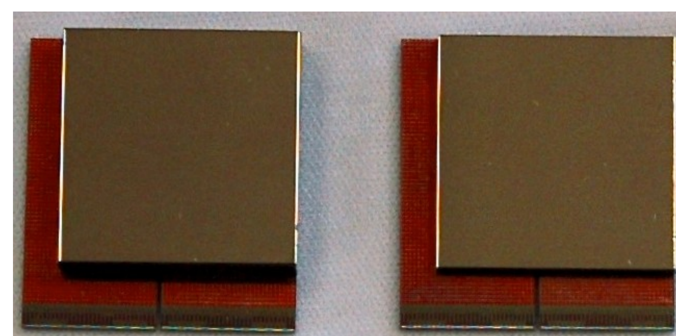
1.9cm×1.9cm×5mm CZT detector, cathode side

Anode side



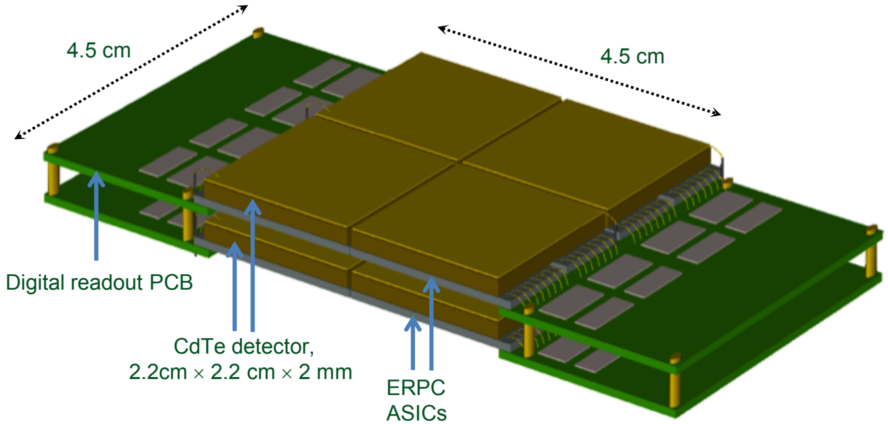
2mm thick CZT detector, cathode side

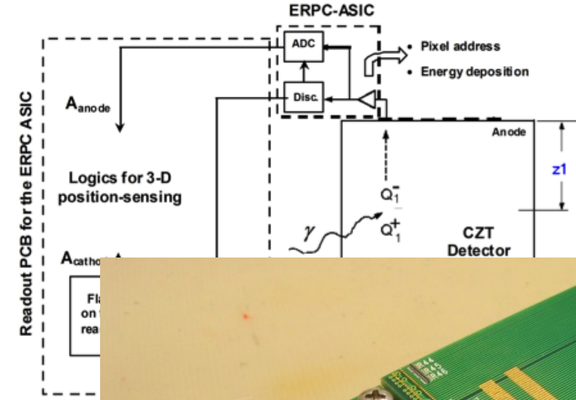
Anode side

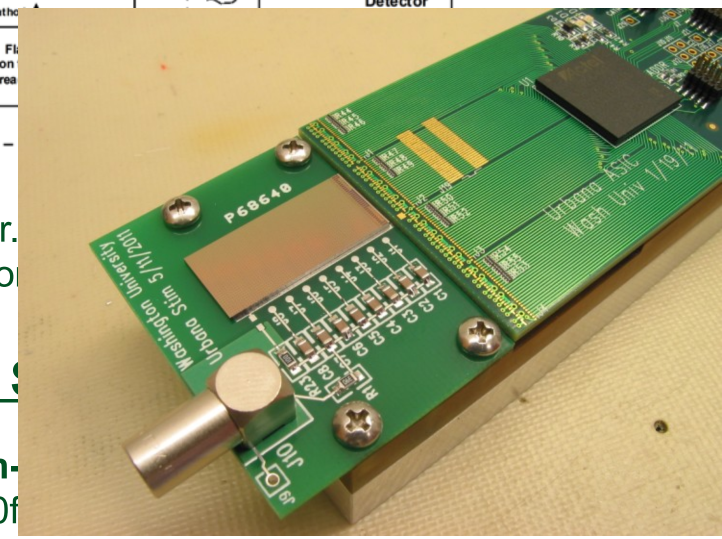


- We are exploring the use of CZT detectors of 2 mm and 5 mm thicknesses with the ERPC ASIC (fabricated by Creative Electron Ltd.).
- Two different CZT-ASIC bonding techniques (SnBI bump-bonding and Ag/Cu conductive epoxy bonding) are under evaluation.

Next Generation Ultrahigh Resolution CZT/CdTe Detectors

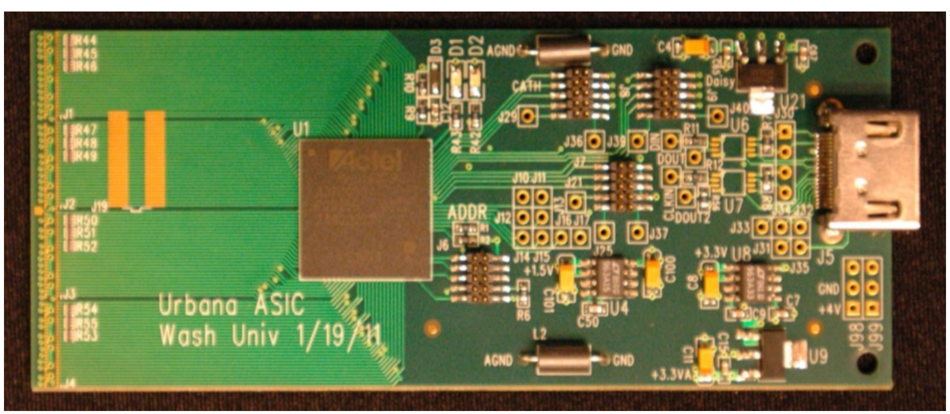






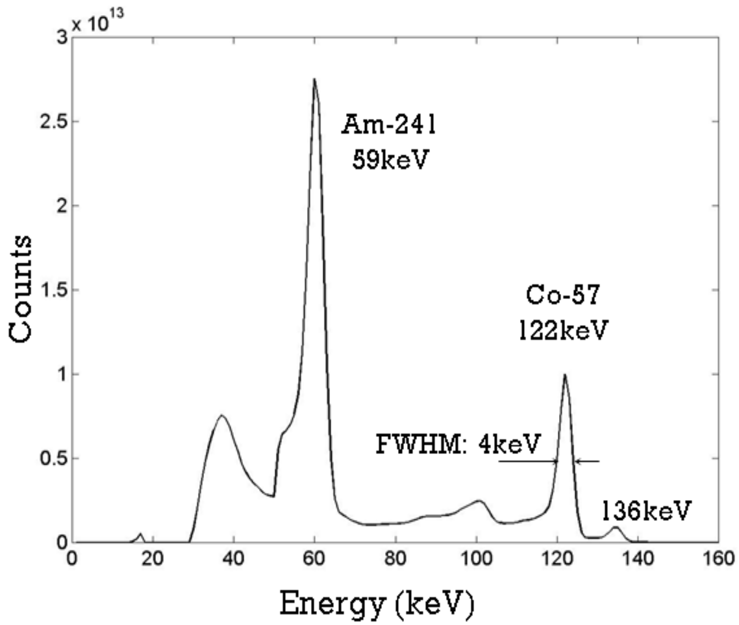
Left: The proposed MRI-compatible ERPC CdTe detector.
the cathode-to-anode ratio to derive the depth-of-interactio

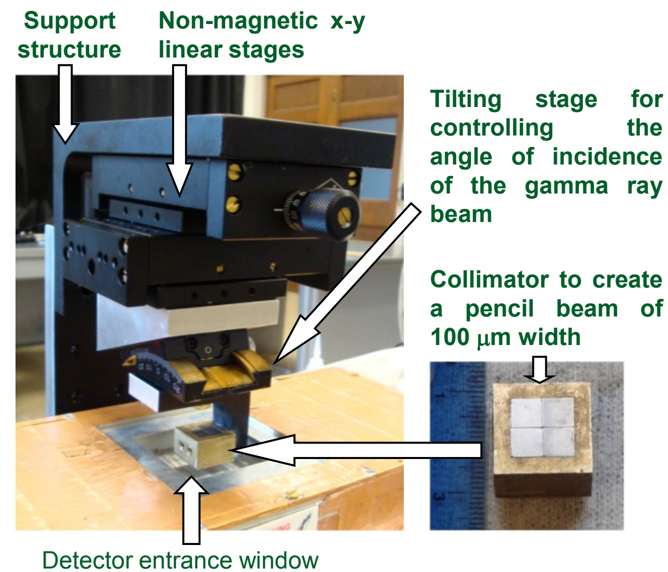
A New Digital Readout System for the S



- ❑ **High-**
  1000f
- ❑ **Anode and cathode readout** (ERPC ASIC for anode and NCI ASIC for cathode),
- ❑ **Relatively compact**, width of the readout PCB is equal to the width of the CZT/CdTe detectors (4.5 cm), allowing a compact ring geometry.

Energy Resolution

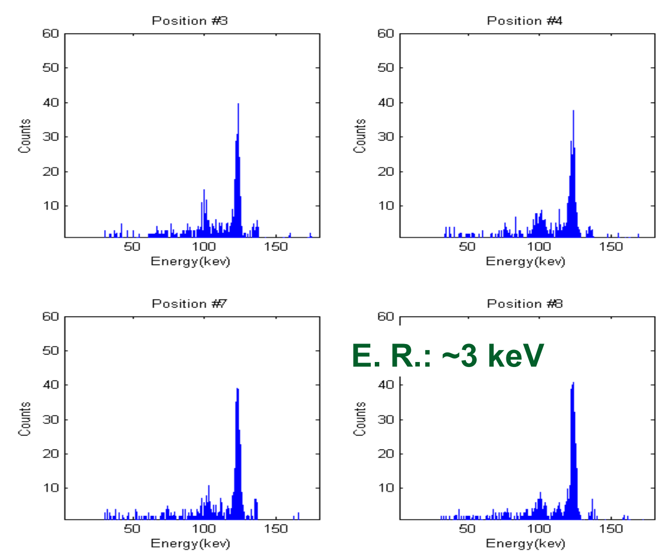




(Upper left) Energy spectrum with events acquired on all 16384 pixels after correcting the channel-by-channel variation of gain and offset.

(Upper right) Experimental setup for illuminating the detector with a fine pencil-beam.

Lower right: energy spectra measured on a single pixel with events at different depths-of-interaction.



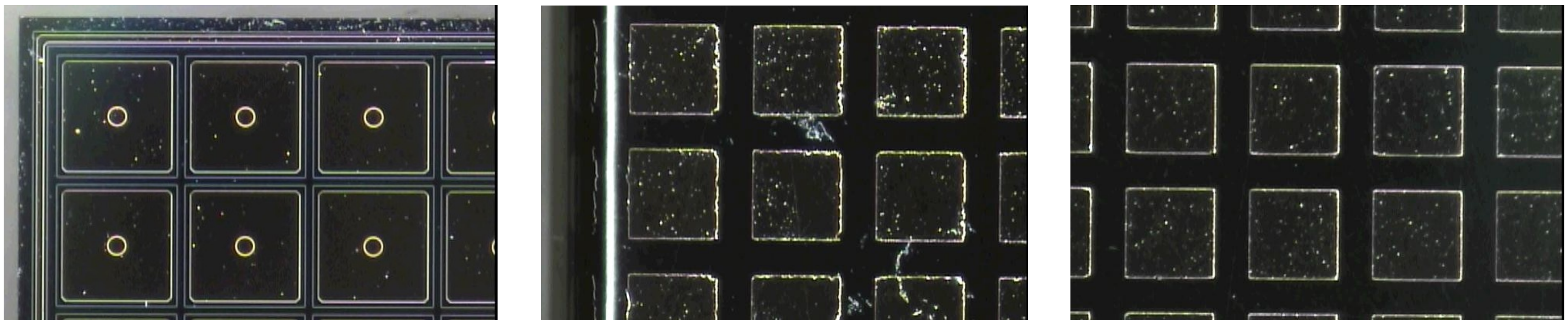
Problems of Current Small Pixel CZT Detectors

The key problem for further improvement is the degraded charge collection efficiency associated with CZT or CdTe detectors relying on small-pixel effect for single polarity charge sensing.

- Energy information collected on the anode pixels is not reliable.
- DOI information acquired with C/A Ratio will not be accurate.
- Timing resolution obtained at anode pixels will be subject to systematic error – therefore limited to several tens of ns – questionable for PET applications.
- DOI information measured by electron drifting time (as currently used in the Michigan system) will be limited by the poorer timing resolution.
- Increased system complexity in readout electronics.

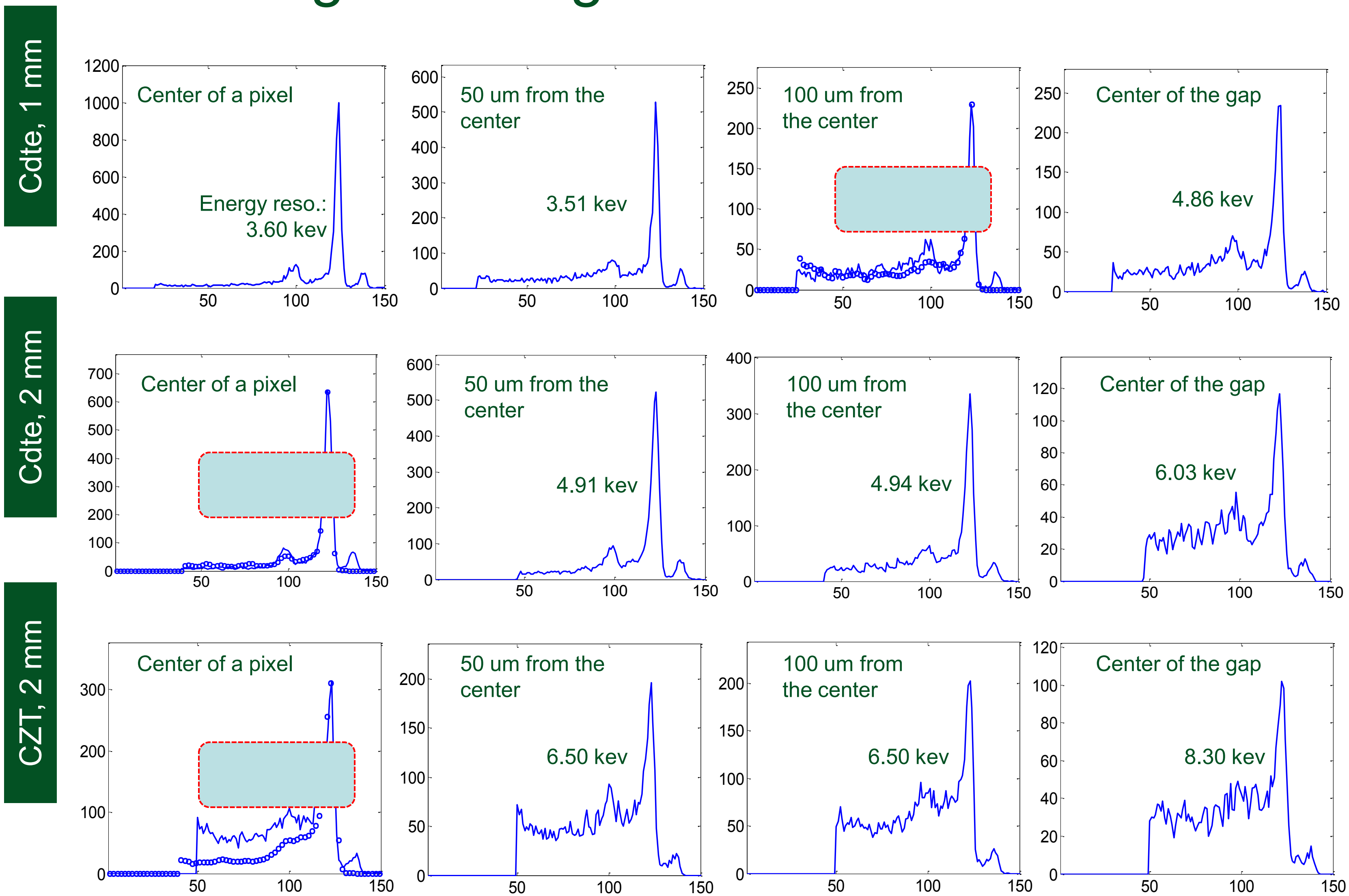
Limitation on CdZnTe Detector Fabrication

Photos of the pixels on the 2 mm, 5 mm CZT detectors and the 1mm CdTe detectors

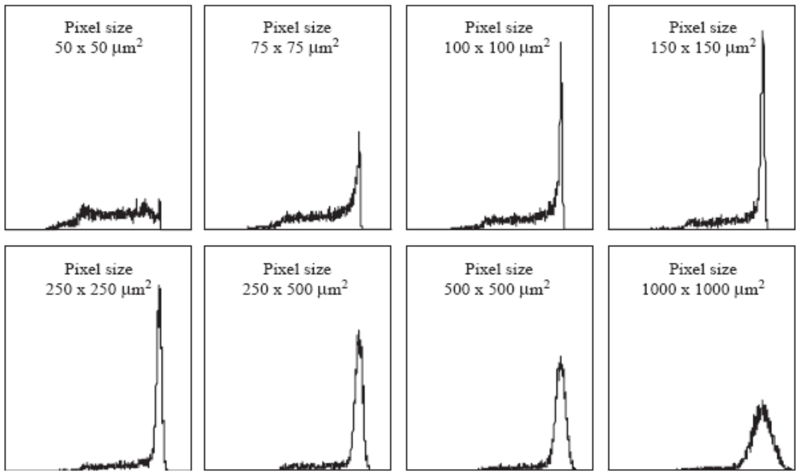


- The anode side of the detectors has square pixels of 350 um pitch and the actual pixel contacts are 250 um × 250 um in size (fabricated by Creative Electron Ltd.)..
- Each anode pixel has a thin layer of gold (50 nm thickness) in direct contact with the CZT crystal and a second layer of nickel of 100 nm on top of the gold layer.

Problem I: Poor Energy Resolution due to Charge Sharing Between Small Pixels



Problem I: Poor Energy Resolution due to Charge Sharing Between Small Pixels



A simulated pulse-height spectra with different pixel size. The detector is 0.75mm CdTe irradiated by 60keV gamma rays. (Konstantinos Spartiotis et al, NIM A550, 2005)

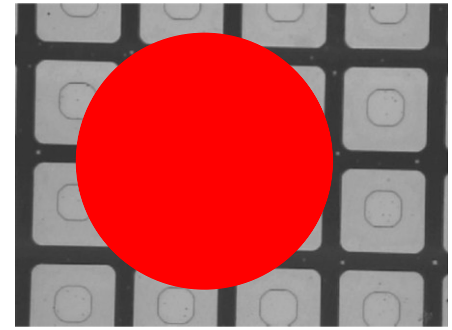
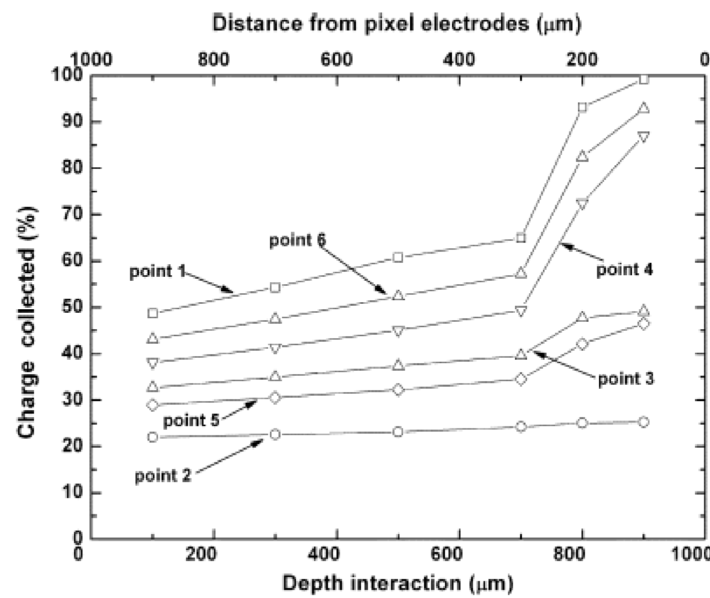


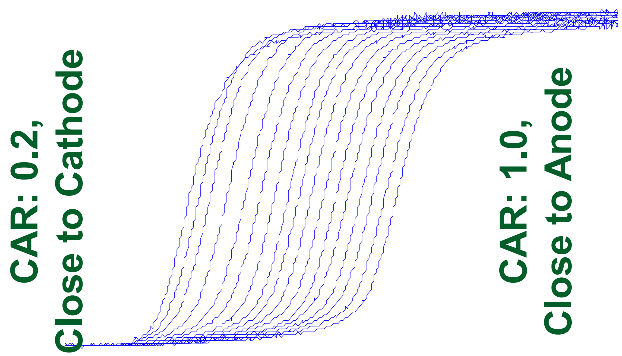
Photo of a CdTe detector used with Medipix2 readout chip. Pixel size: 45μm. (Pellegrini at al, NIM A53, pp361, 2005).

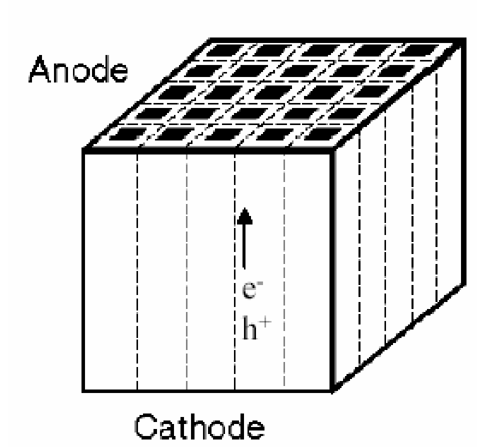


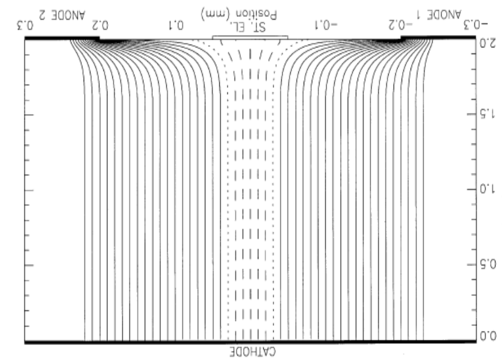
Right: Measured charge-collection efficiency on a given pixel.

Problem II: Poor Timing Resolution

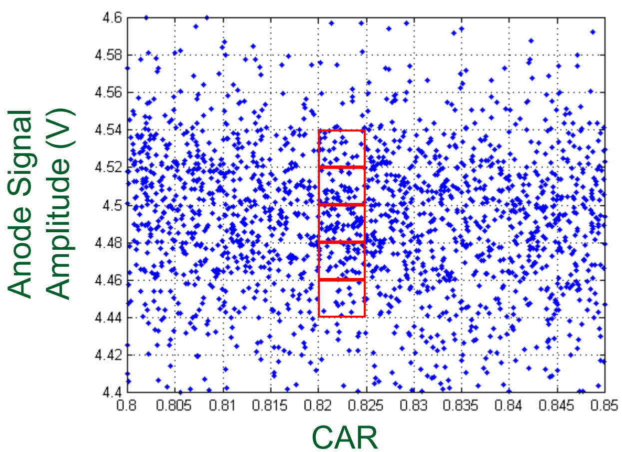
Analogue Triggering on Anode Signals



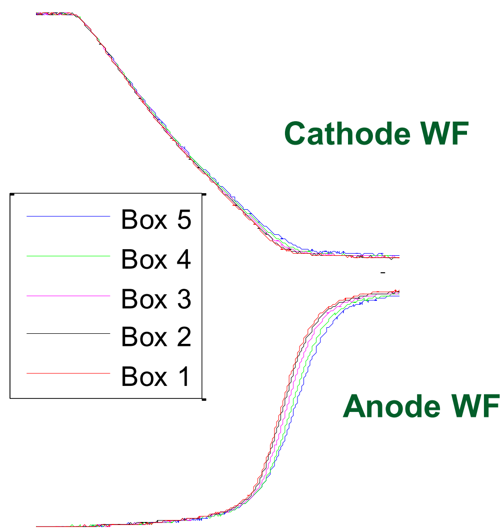




Measured mean waveform from an anode pixel – charge collection time depends on DOI

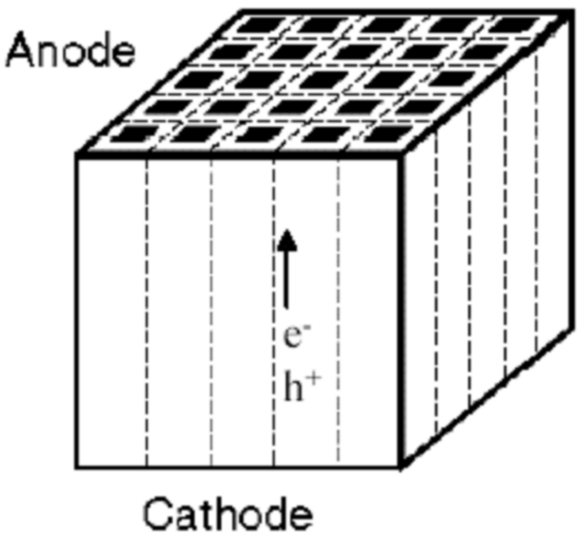


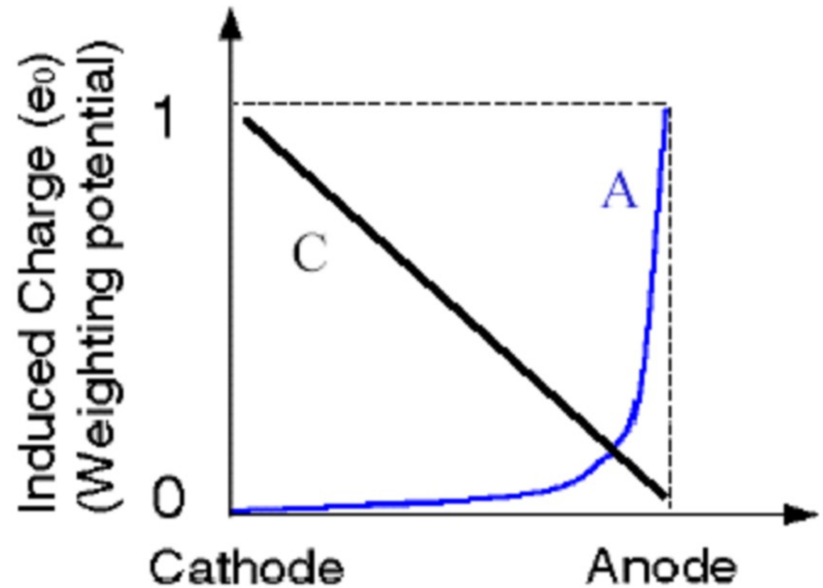
Comparing events from the same depth and having the same energy deposition



A closer look reveals that even for events with the same DOI, charge collection times could vary …

Problem III: Difficulties in Getting DOI





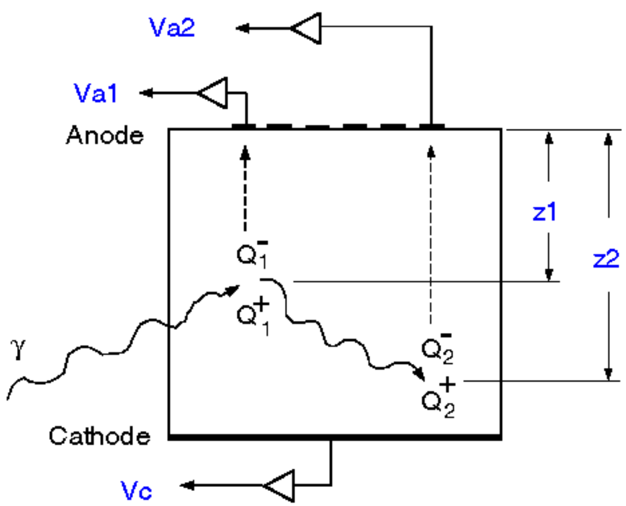
Z. He et al, NIM A380 (1996) 228, NIM A388 (1997) 180.

Signal from anode pixel ⇒ No. of electrons collected by the pixel (N) and its lateral position (x, y).

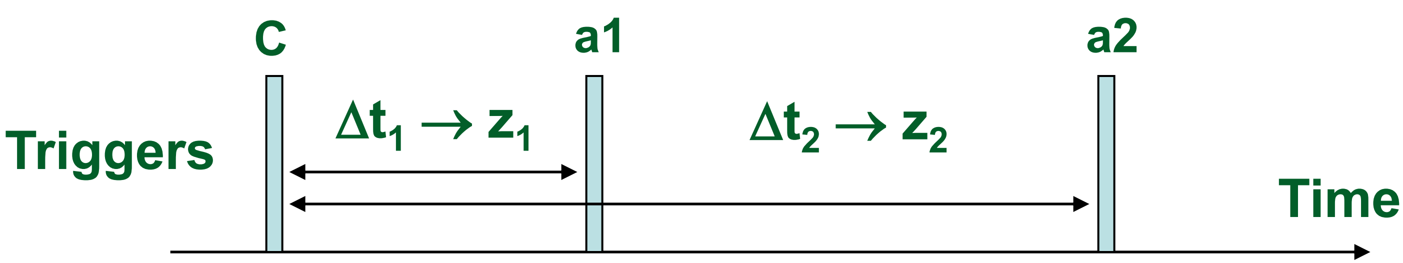
C/A ⇒ Interaction depth (z).

N, x, y, z ⇒ Energy deposition E_0 and interaction location.

Problem III: Difficulties in Getting DOI

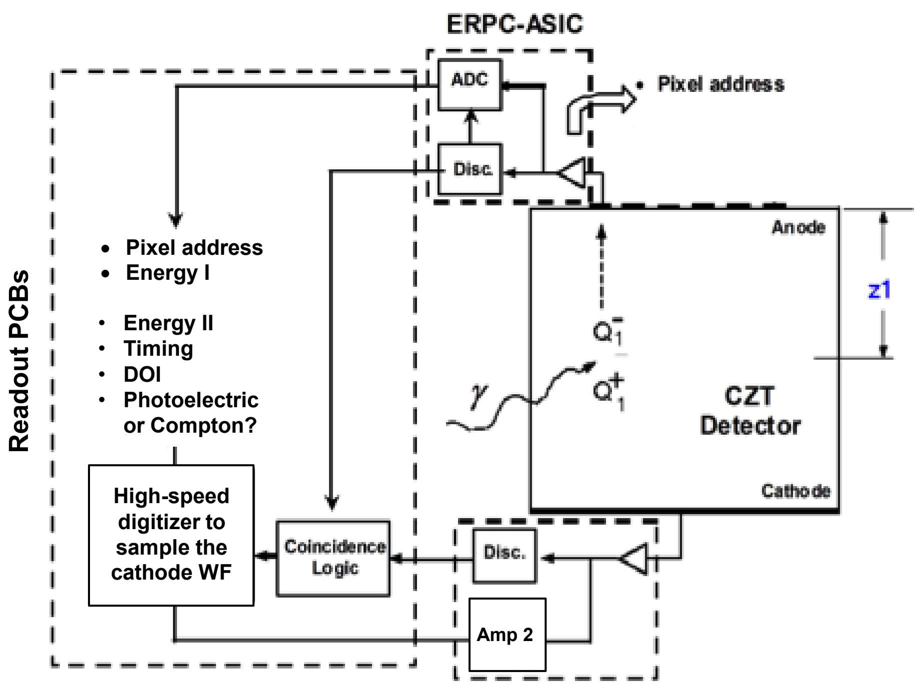


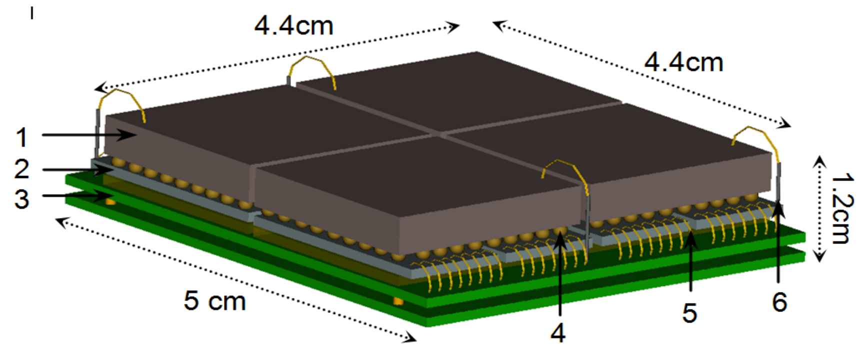
- For multiple interactions, C/A ratio is no longer sufficient for determining interaction sites.
- Extra information is provided by drifting times for each electron cloud.
- The accuracy of determining interaction depth is <0.5mm



3-D Position Sensitive Detectors Developed by Prof. Zhong He

Small Pixel CZT Detectors with a Hybrid Pixel-Waveform Readout System

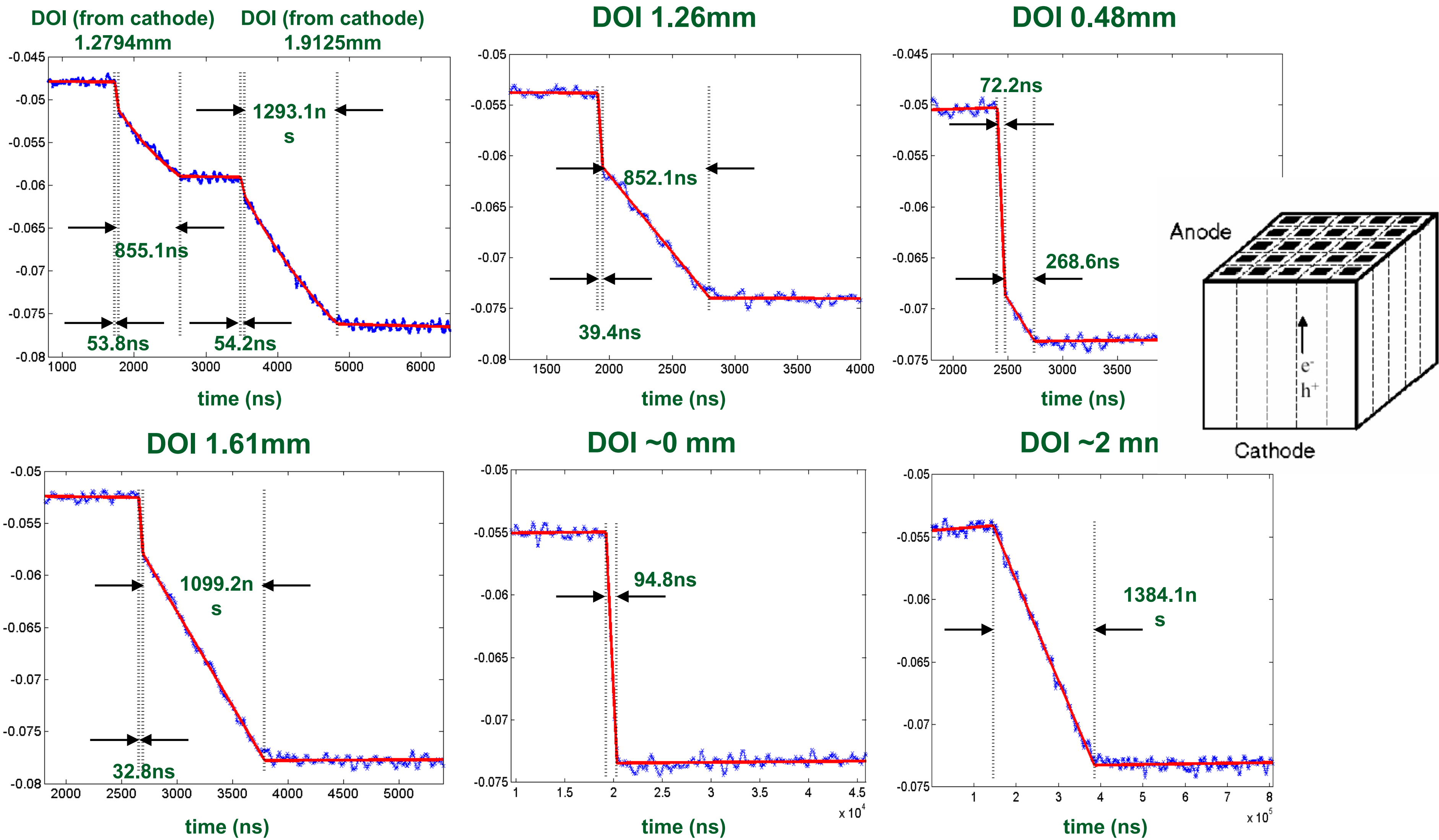




(1) CZT or CdTe crystals of 4.4cm × 4.5 cm × 1-5 mm in size, (2) ERPC ASICs, (3) Readout PCBs for both reading out ERPC ASICs and digitizing cathode waveforms, (4) indium bump-bonding between CZT detector to the ASIC, (5) wire-bonds between the ASIC and the PCBs and (6) Cathode signal out.

Fig. 1: Gen-II ERPC detectors with HPWF readout system. **Left**: Design schematic; **Right**: 3D rendering of the HPWF-ERPC detector design.

DOI Measurements with 2 mm Thickness CZT Detectors



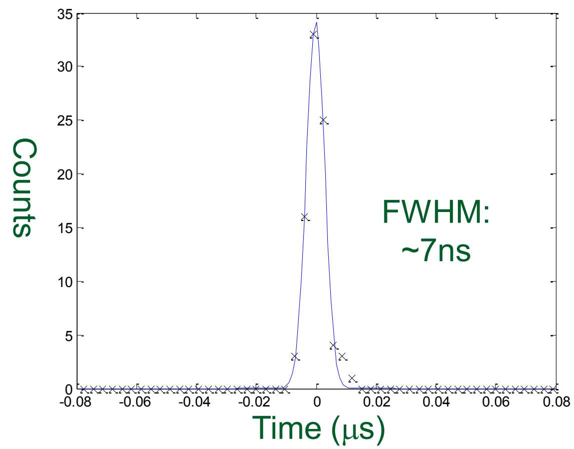
Theoretical Waveform Models

Waveform Models for Use in Timing Estimation

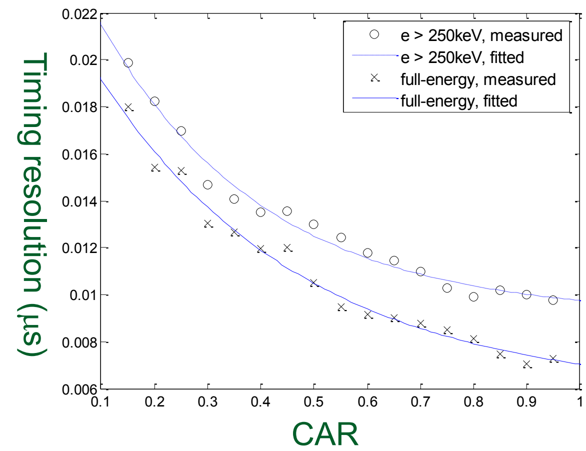
Waveform Models	Definition	No. of Model Parameters
Double Exponential	$\overline{w}(t)=\begin{cases}\lambda_1\cdot t+\lambda_2, & t<t_0\\ (\lambda_1\cdot t+\lambda_2)+\lambda_3\cdot\lambda_4\cdot\left[1-\exp(-\frac{t-t_0}{\lambda_4})\right] & t\geq t_0\\ +\lambda_5\cdot\lambda_6\cdot\left[1-\exp(-\frac{t-t_0}{\lambda_6})\right] & \end{cases}$	7 (λ_1, λ_2, t_0, λ_3, λ_4, λ_5 and λ_6)
Single Exponential	$\overline{w}(t)=\begin{cases}\lambda_1\cdot t+\lambda_2, & t<t_0\\ (\lambda_1\cdot t+\lambda_2)+\lambda_3\cdot\lambda_4\cdot\left[1-\exp(-\frac{t-t_0}{\lambda_4})\right] & t\geq t_0\end{cases}$	5 (λ_1, λ_2, t_0, λ_3 and λ_4)
Linear	$\overline{w}(t)=\begin{cases}\lambda_1\cdot t+\lambda_2, & t<t_0\\ \lambda_3\cdot t+[(\lambda_1-\lambda_3)\cdot t_0+\lambda_2] & t\geq t_0\end{cases}$	4 (λ_1, λ_2, t_0 and λ_3)
"Optimal"	Derived by averaging multiple observed waveforms. Needed for all potential interaction sites.	—

(Meng, NIM, 2005).

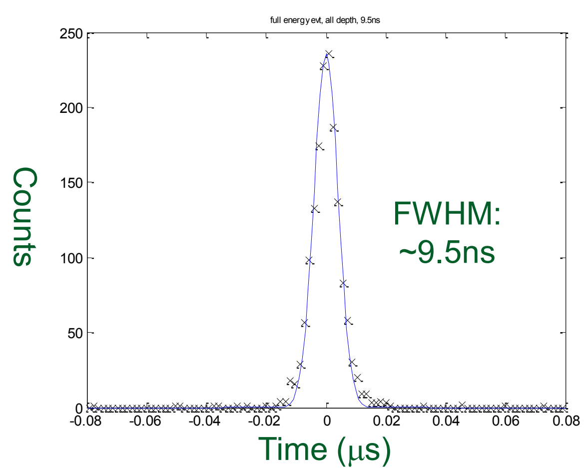
Results II: Measured Timing Resolution



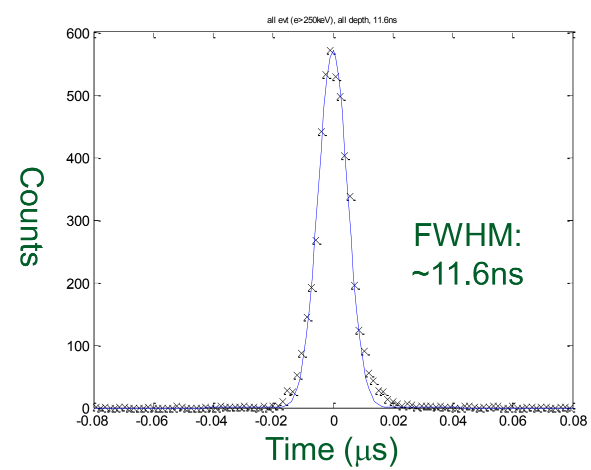
Measured timing resolution with full energy events close to the cathode (CAR of ~0.9).



Timing resolution as a function of CAR with full energy events and events having energy deposition >250keV (circles).



Measured timing resolution, full energy events and CAR ∈ [0.1, 1.0].



Timing resolution, energy deposition greater than 250keV and CAR ∈ [0.1, 1.0].

Results IV: Predicted Timing Resolution

Measured and estimated timing resolution

Timing Resolution	CZT, 10 mm thickness	CZT, 5 mm	CZT, 2 mm
Trig. on cathode ($2.25cm^2$, V_{Bias}: 140V/mm)	30 ns [1]	~20 ns [2]	8-10 ns
Trig. on anode ($1\times1mm^2$, V_{Bias}: 140V/mm)	40 ns	—	—
WF fitting (V_{Bias}: 140V/mm)	10 ns	—	—
WF fitting, (V_{Bias} : 500V/mm)	~ 7 ns [3]	~ 3 ns	~ 2 ns
WF fitting, (V_{Bias} : 500V/mm)	~ 4 ns	~ 2 ns	Sub-ns (?)

1. Experimentally measured.
2. Simply scaled with increasing electric field strength.
3. Simulated using the analytical waveform model.

Summary

- We have developed a relatively generic detector architecture for small pixel CZT or CdTe detectors.
- We have produced and experimentally evaluated CdTe and CZT detectors of 1 mm to 5 mm thicknesses readout with the ERPC readout system. Both 1 mm and 2 mm thickness detectors have offered reasonable imaging performance for SPECT applications.
- An improved detector pixelation process is needed for CZT detectors to improve the charge-collection process and therefore their spectroscopy performance.

To further improve the performance for future small-pixel CZT or CdTe detectors, we are currently developing a readout circuitry that utilizes both the anode signals and cathode signal waveforms.

Many thanks and questions?