Front-end electronics for medical and security applications

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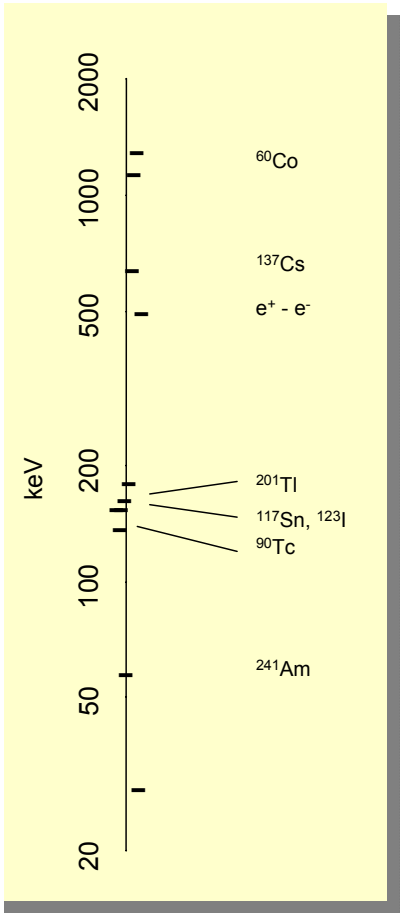
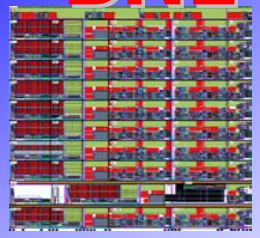
Motivation

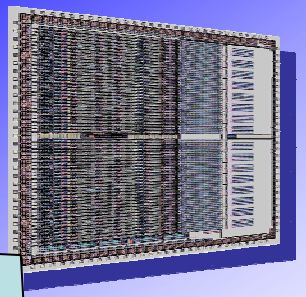
- Widespread adoption of radiation detectors in industrial/commercial sectors
- Detection requirements overlap with research needs in accelerator-based science:
  - single-photon detection capability
  - energy range 30 – 1000 keV
  - energy discrimination ~ 1%
- Increasing need for ASIC readout:
  - multi-element solid-state sensors
  - mobile operation
  - cost- and complexity-sensitive applications
- Encouragement of technology transfer:
  - 1980 Bayh-Dole legislation permits research institutions in the U.S. to take title to inventions arising out of federally-funded research



BNL ASICs for medical/security applications



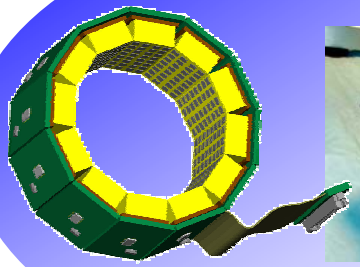
Dual-energy x-ray absorptiometry for bone mineral density determination



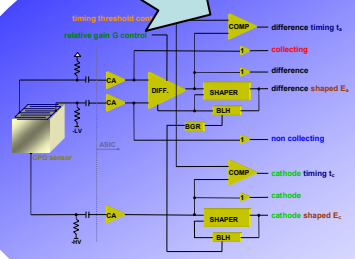
High-rate, multi-energy line scanner for explosives detection system

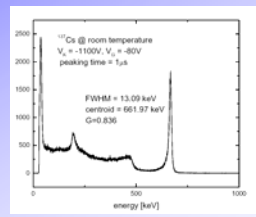
- low noise & power front end circuits
- submicron CMOS technology
- design for harsh environments
- data concentration techniques

Gamma camera for nuclear medicine



Miniature tomograph for awake-animal PET studies

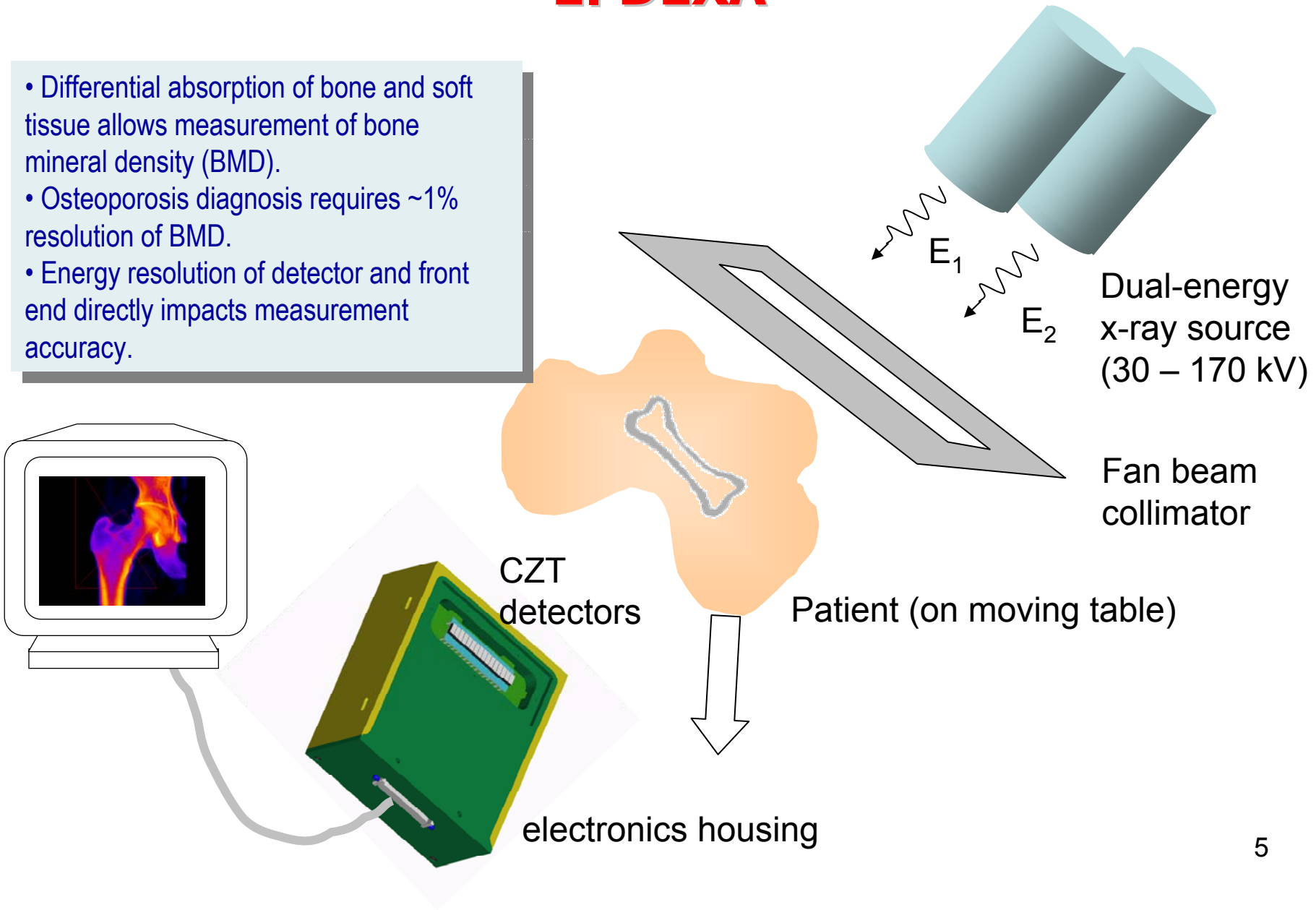




Coplanar grid detector for isotopic identification of nuclear materials

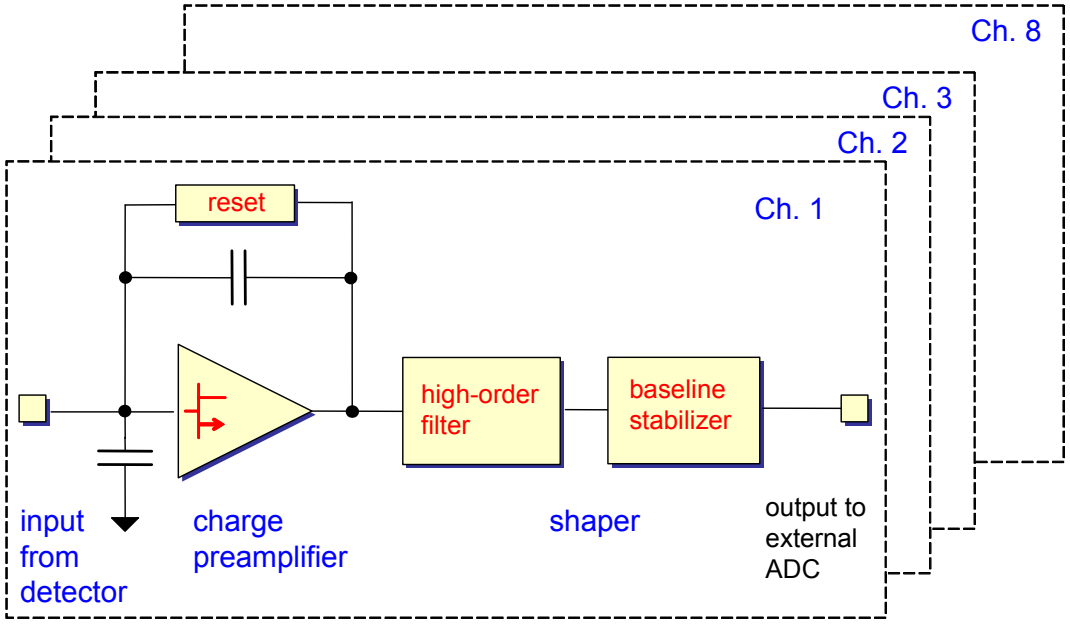
1. DEXA

- Differential absorption of bone and soft tissue allows measurement of bone mineral density (BMD).
- Osteoporosis diagnosis requires ~1% resolution of BMD.
- Energy resolution of detector and front end directly impacts measurement accuracy.



ASIC replacement of discrete front-end electronic boards

- Two 8-channel ASICs replaced 17 circuit boards, ~ 500 components.
- ~ 18 mW/channel, 6.5X lower power than discrete solution.
- 14% improvement in noise ➔ energy resolution.
- Additional applications to industrial radiography.



Design for Performance

- Optimization of the front-end MOSFET based on
  - measured 1/f and white noise
  - accurate modeling of g_m, C_{gs} in moderate inversion
- Continuous preamp reset self-adaptive to detector leakage current
- High-order filter and baseline stabilzer for rate capability

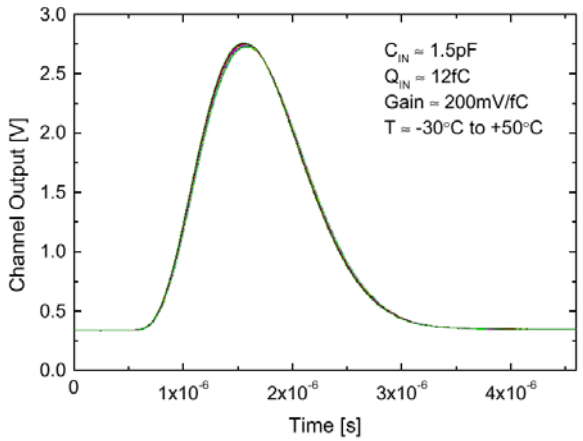
Design for reliability and ease of use

- Self-biased, BGR-derived currents
- Programmable gain and shaping time
- Test capacitor per channel
- High output drive capability
- Circuits tolerant to variations in
  - temperature
  - process
  - power supply
  - detector DC leakage current
  - loading

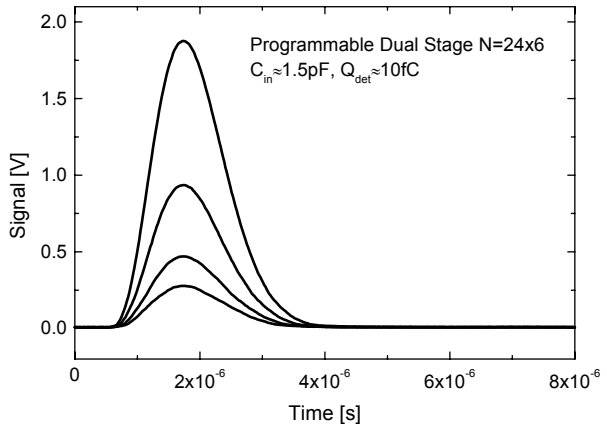
G. De Geronimo et.al., "A generation of CMOS readout ASICs for CZT detectors", IEEE Trans. Nucl. Sci. 47, Dec. 2000, 1857 - 1867

Practical amplifier considerations

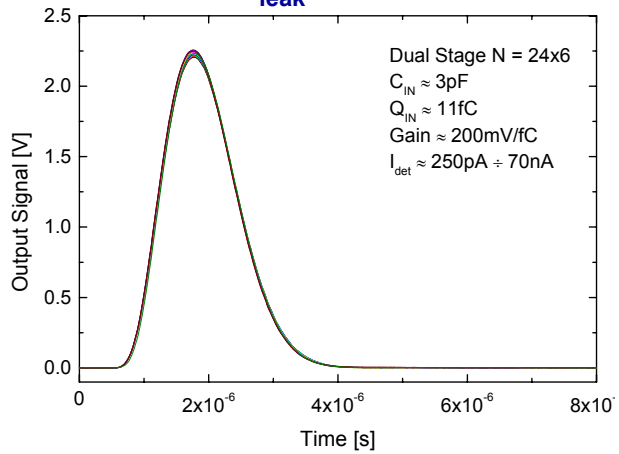
Pulse vs. temperature



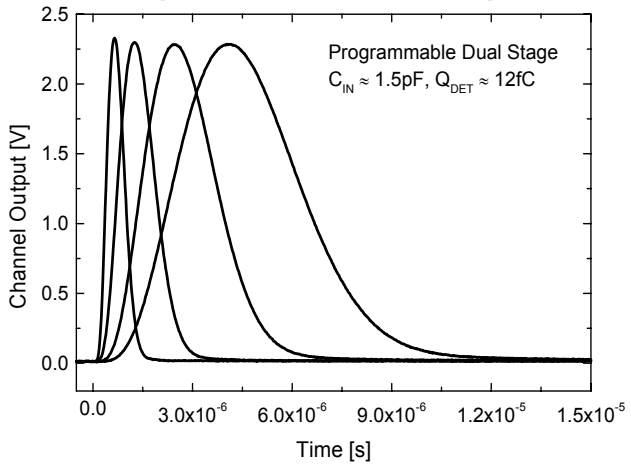
Programmable gain



Pulse vs. I_{leak}



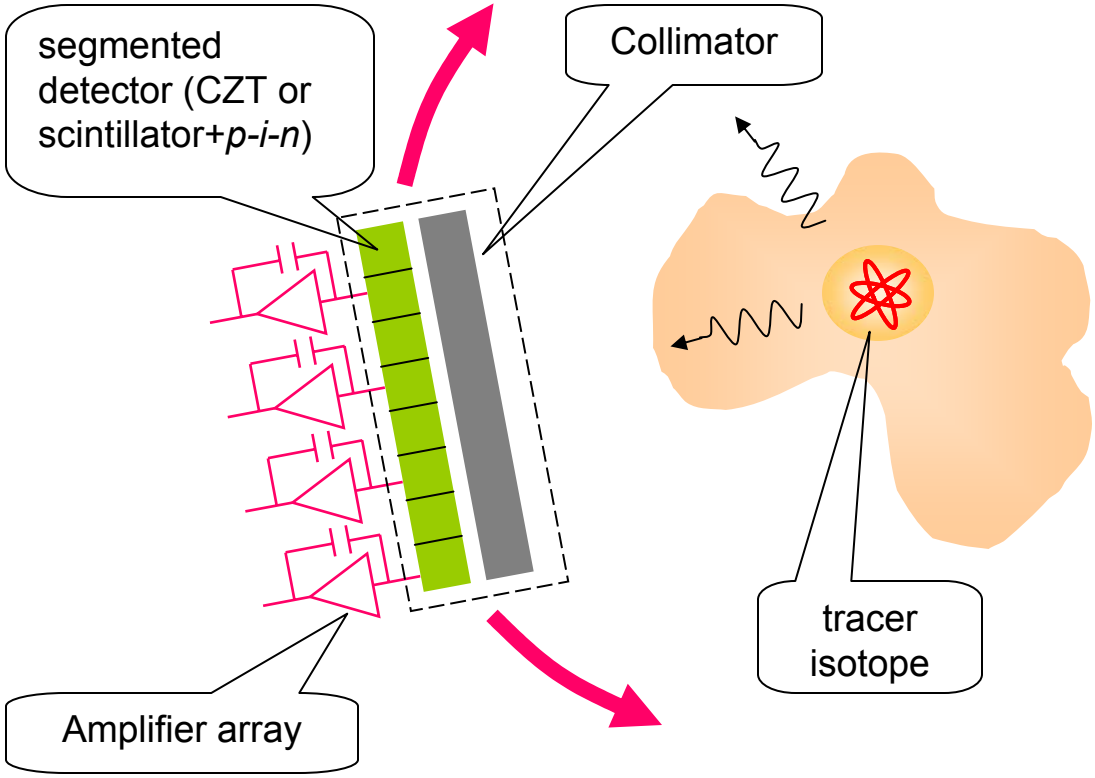
Programmable peaking time

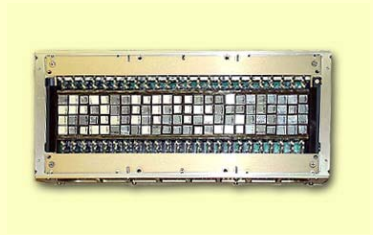


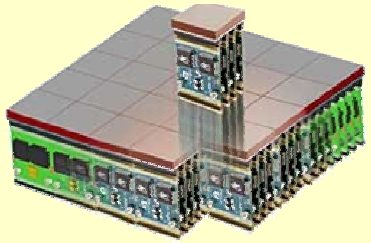
	I_{leak}	Supply	Temperature	Rate (to 5/tp)	Cin	Zload
Gain	< 0.1%/nA	<.001%/V	-0.04%/°C	< 0.1%	<0.1%/pF	No slew-rate limit
Baseline	< 0.3mV/nA	<30 µV/V	75 µV/°C	< 8 mV	-	Zout ~ 150 Ω

2. Gamma Camera

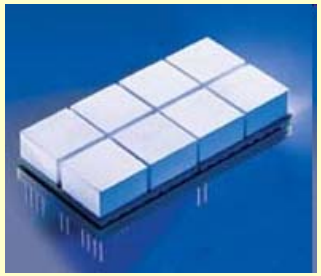
- Pixelated detector, 1 – 2 mm pitch, 0.3 – 4*10^3 elements in camera head.
- Tomographic reconstruction (SPECT) or handheld intraoperative probe.
- Energy resolution and good calibration needed for scatter rejection.





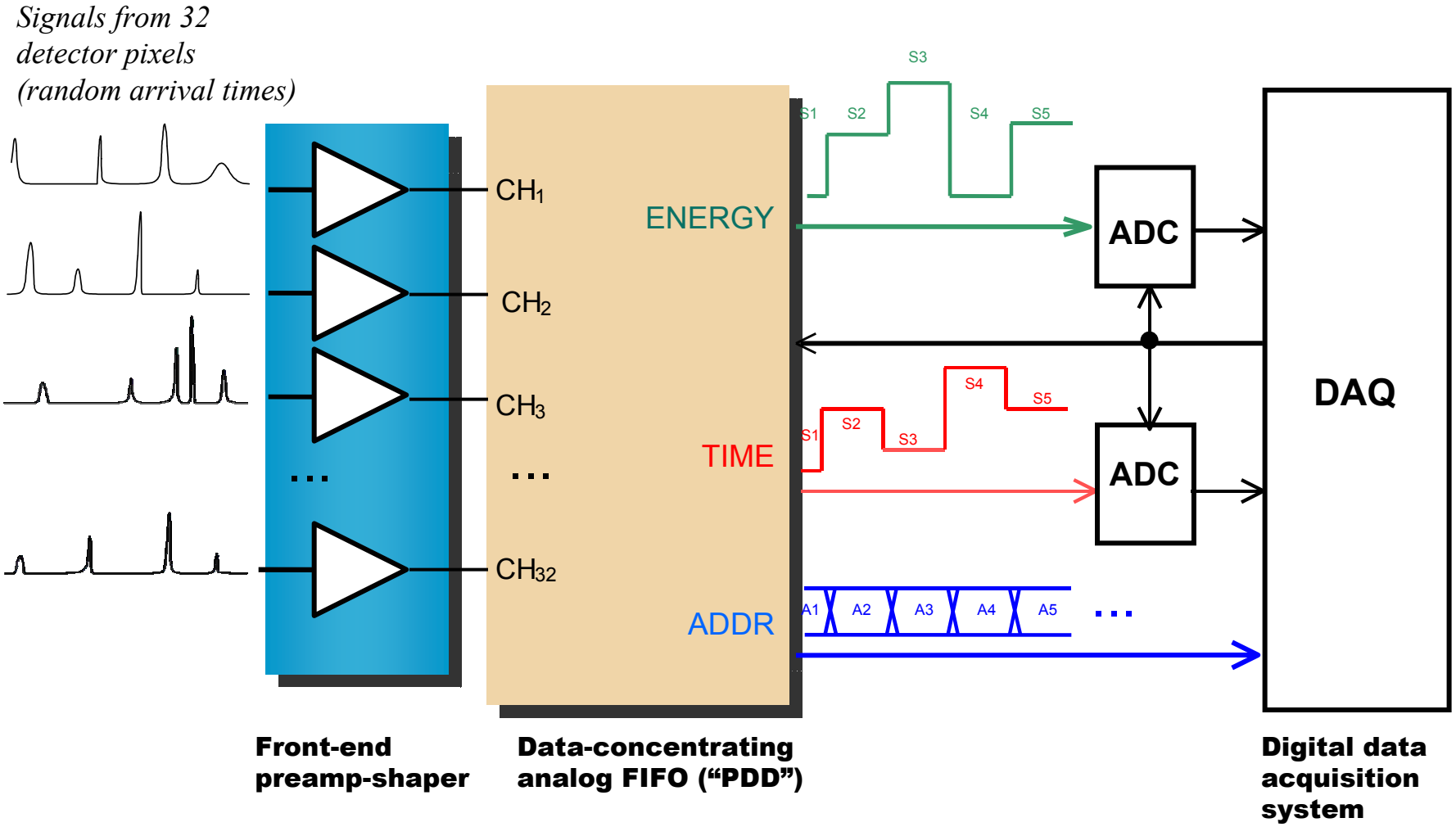


CZT pixels

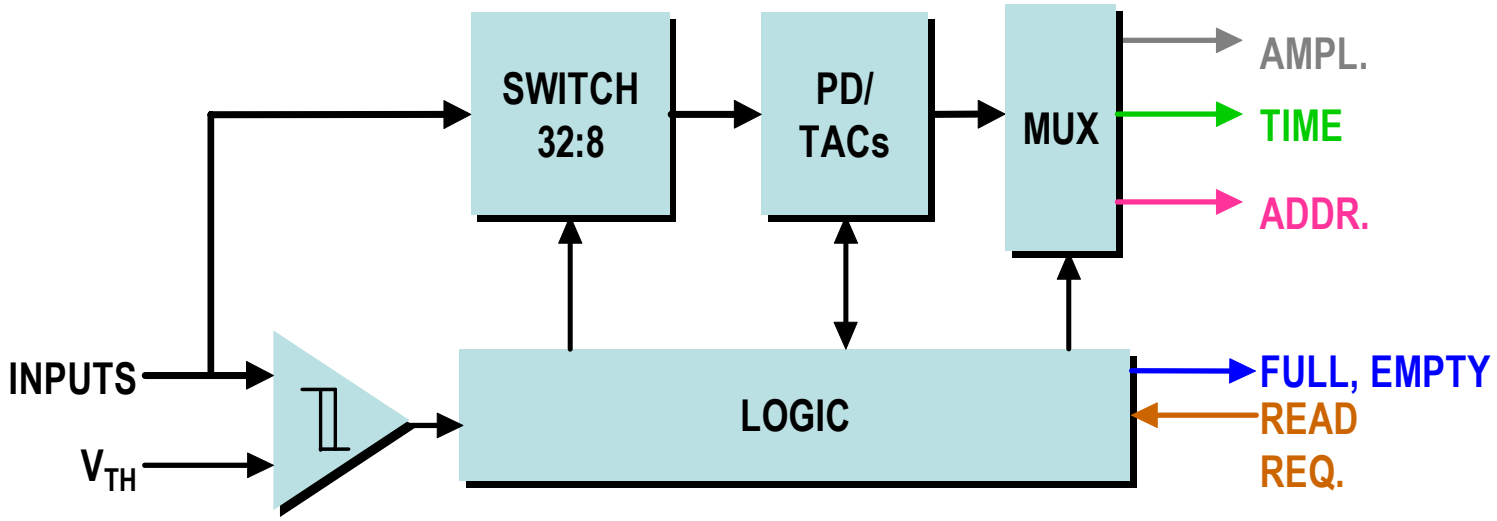


CsI + Si *p-i-n*

Two-chip solution with analog data concentration



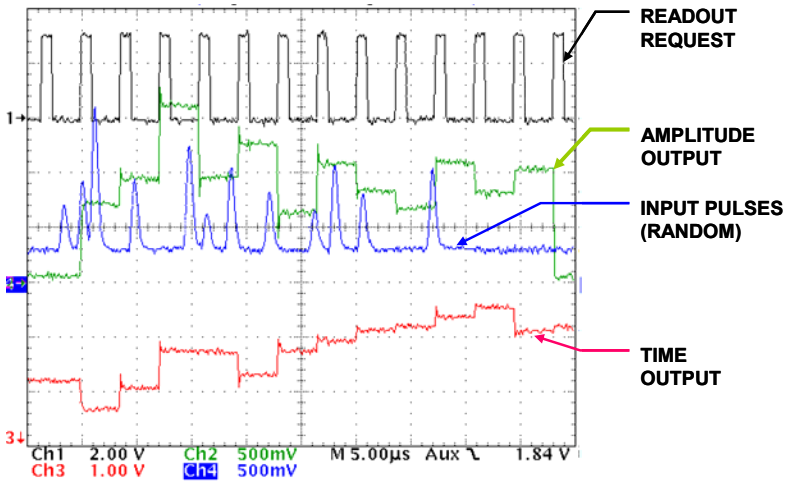
PDD ASIC Block Diagram



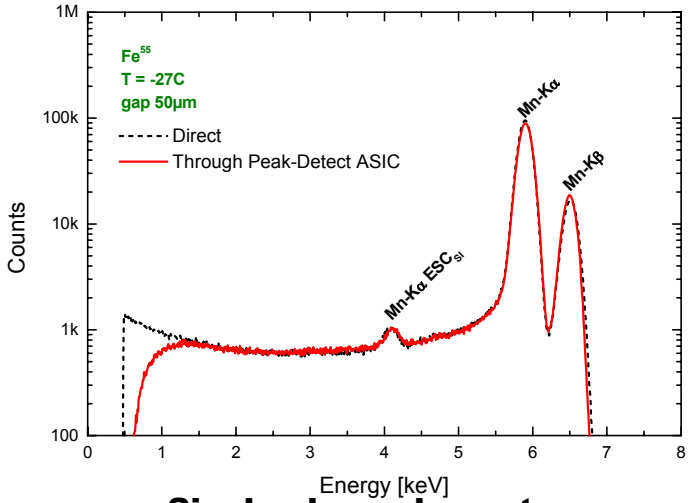
- New architecture for efficient readout of multichannel detectors
  - *Self-triggered and self-sparsifying*
  - *Simultaneous amplitude, time, and address measurement for 32 input channels*
  - *Set of 8 peak detectors act as derandomizing analog memory*
  - *Rate capability improvement over present architectures*
- Based on new 2-phase peak detector combined with dual-mode TAC
  - *High absolute accuracy (0.2%) and linearity (0.05%), timing accuracy (5 ns)*
  - *Accepts pulses down to 30 ns peaking time, 1.6 MHz rate per channel*
  - *Low power (2 mW per channel)*

P. O'Connor, G. De Geronimo, A. Kandasamy, *Amplitude and time measurement ASIC with analog derandomization: first results*, IEEE Trans. Nucl. Sci. 50(4), pp. 892-897 (Aug. 2003).

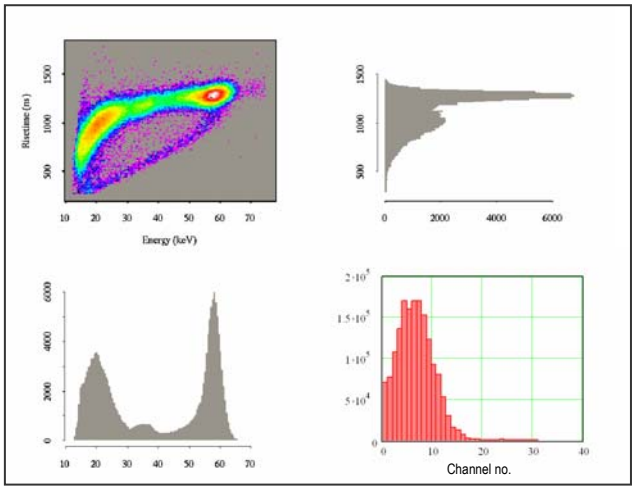
PDD results



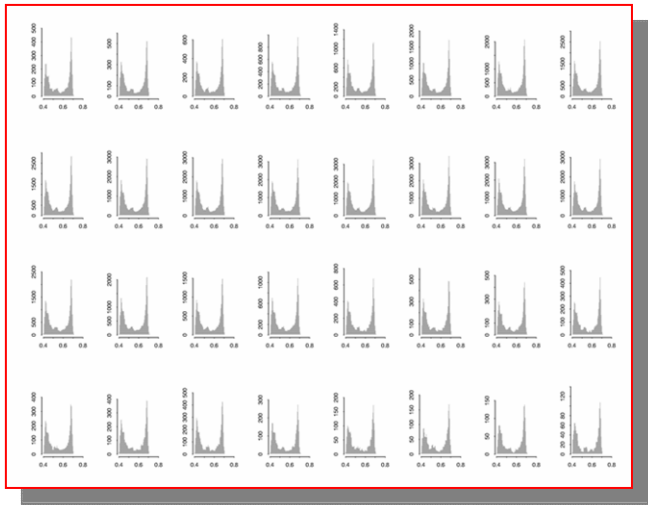
Waveforms



Single-channel spectrum (with/without PDD)

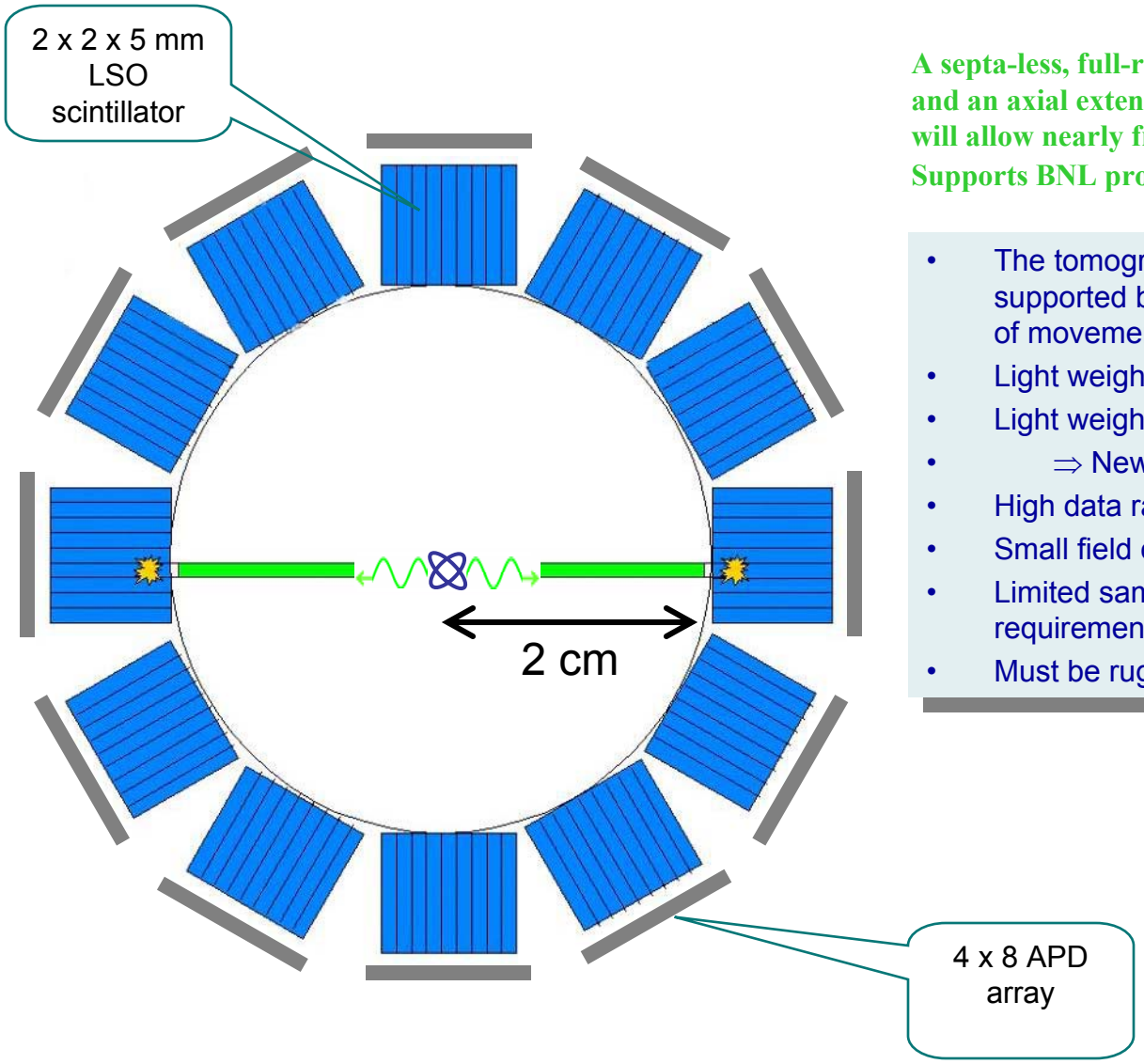


Multiparametric spectra



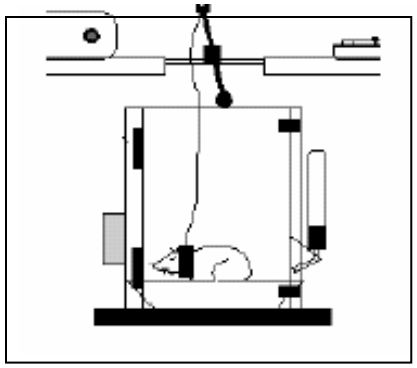
Multichannel spectra

3. RatCAP: Rat Conscious Animal PET

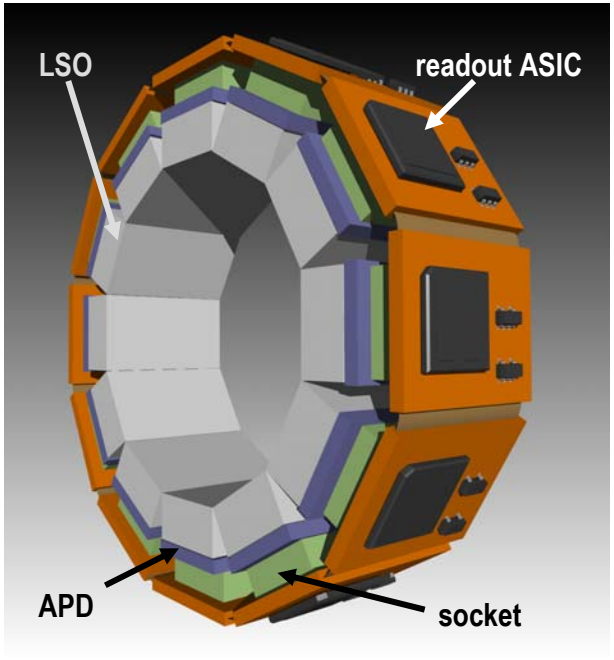


A septa-less, full-ring tomograph with a diameter of 4 cm and an axial extent of 2 cm, suspended by a tether, which will allow nearly free movement of the awake animal. Supports BNL program in addiction research.

- The tomograph ring must be light enough to be supported by the rat and allow reasonable freedom of movement
- Light weight detectors (~ 150 g total weight)
- Light weight electronics with low power dissipation
- ⇒ New custom ASIC
- High data rates and large singles background
- Small field of view and large parallax effects
- Limited sampling due to space and weight requirements
- Must be rugged enough withstand activity of the rat

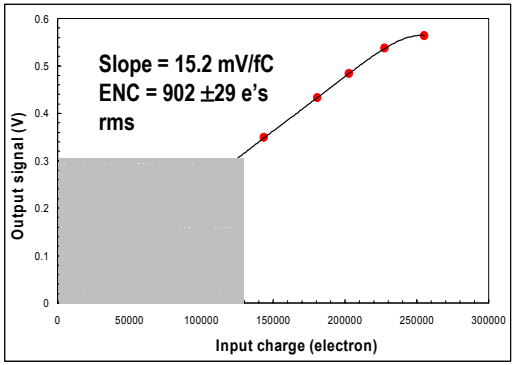


Electronics for a mobile, miniature animal PET tomograph

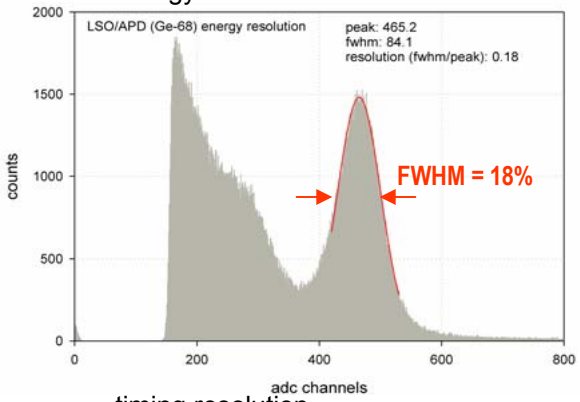


- 0.18 μm CMOS
- 1.5 mW/channel
- 32 channel ASIC
- Preamplifier + shaper + timing discriminator
- address encoding
- serialized output

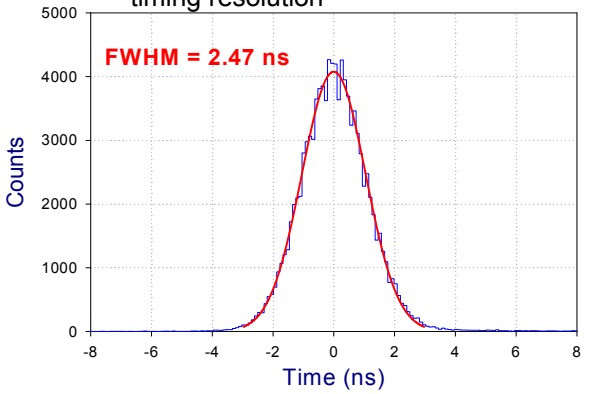
linearity



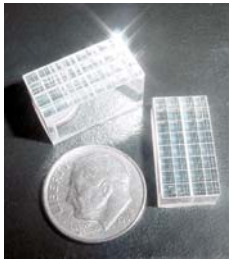
energy resolution



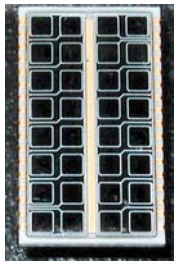
timing resolution



Mockup of the portable ring on the head of a rat



LSO scintillator

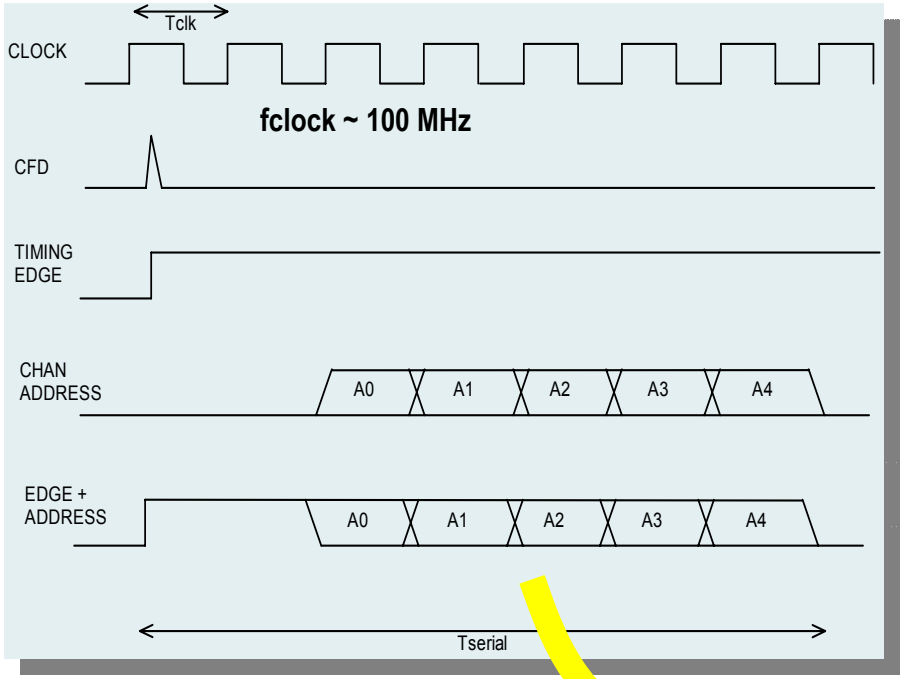


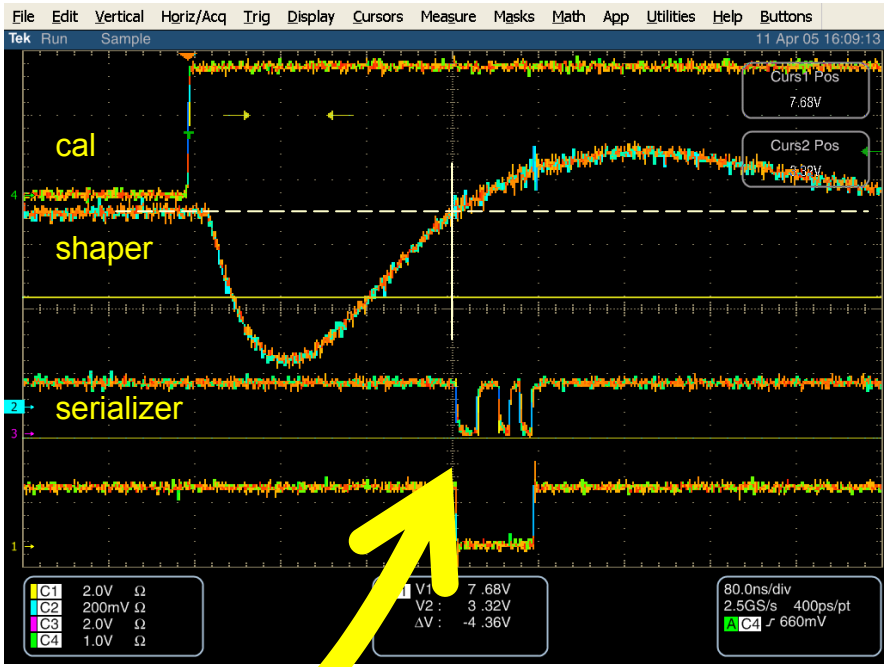
APD array

ASIC preamplifier with CFD vs. BaF_2/PMT

RatCAP ASIC address serializer

- 384 channels on ring make it impossible to bring all signals off detector.
- Analog pulse height information is not saved, lower level discriminator only.
- Discriminator pulse is encoded to give 5 bit address
- Leading edge of encoded serial pulse train gives time information





J.-F. Pratte et al., *Front End Electronics for the RatCAP mobile animal PET scanner*, IEEE Trans. Nucl. Sci. 51(4), pp. 1318-1323 (Aug. 2004).

4. Coplanar Grid CZT detector

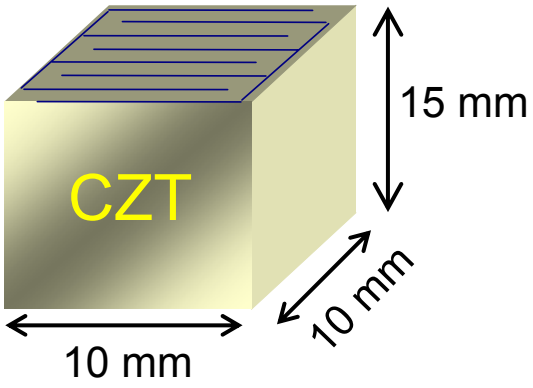
Charge induction by coplanar grid electrodes

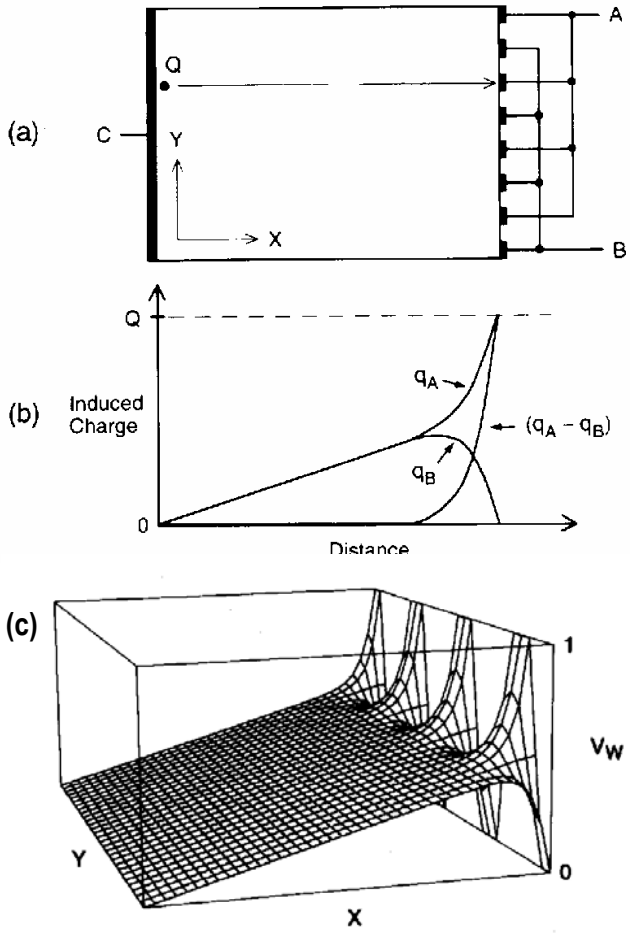
Since hole mobility and lifetime in CZT are low, charge induction in conventional detector depends on depth of photon conversion

Coplanar grid electrode principle:

Top electrode is segmented into two grids A and B (a). Electrons are collected at grid A. Induced charge from electron collected at A is shown in (b) as a function of distance from the top electrode. The difference in charge induction on the two top electrodes, $q_A - q_B$, is negligible for charges moving deep in the bulk. Only charges moving within a short distance of the top electrode are sensed.

Weighting potential for charge induction on A is shown in (c).

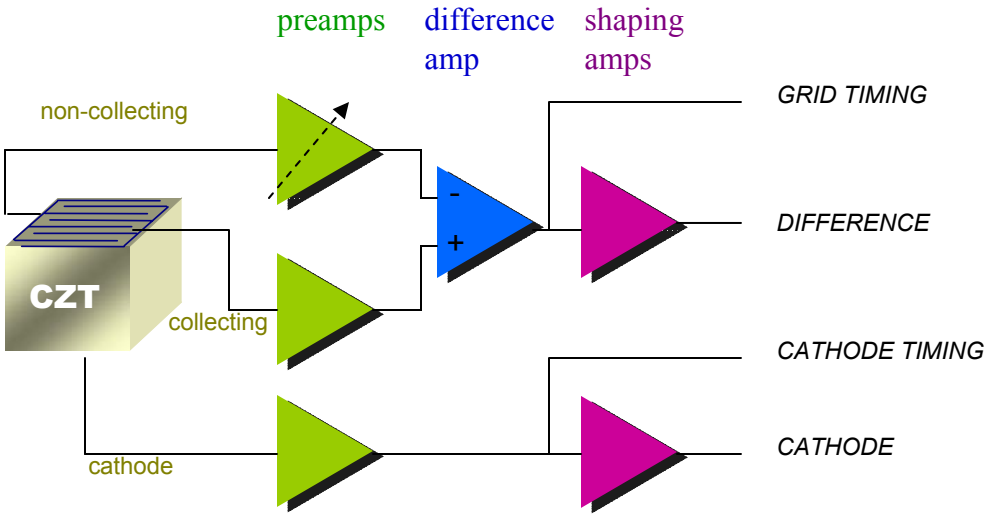




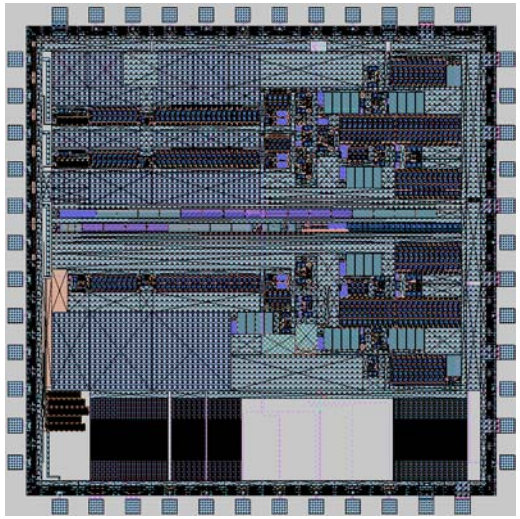
Luke, P., "Unipolar charge sensing with coplanar electrodes – application to semiconductor detectors", *IEEE Trans. Nuclear Science* vol. 42, no. 4, pp. 207-213, Aug. 1995.

0.25 μm Front End ASIC for CPG Detector

ASIC block diagram

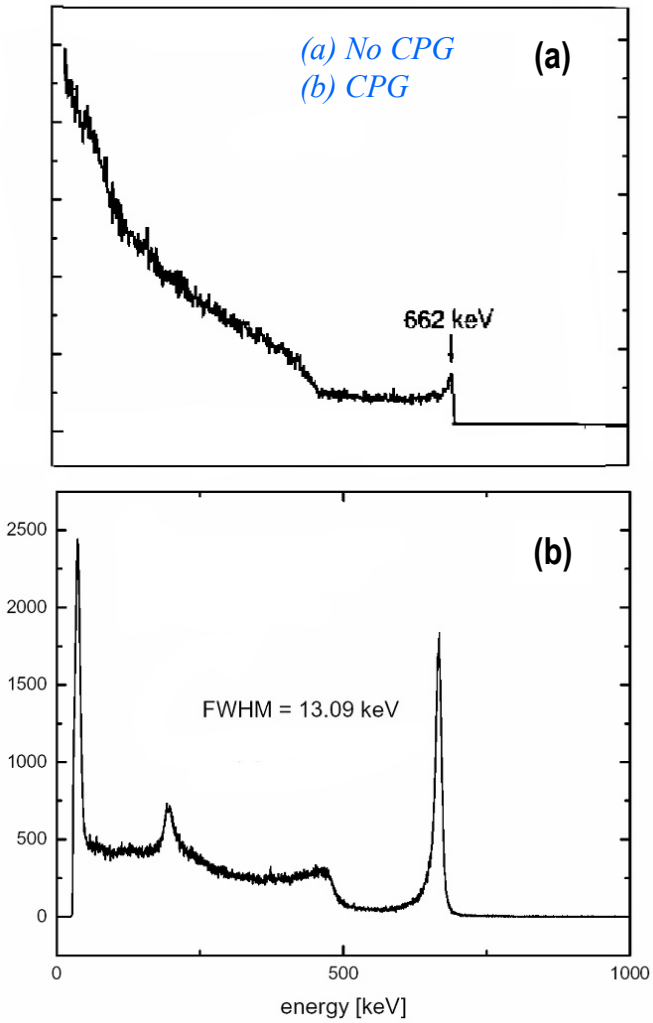


- Grids charge amplifiers
- Cathode charge amplifier
- High order shapers
- Timing circuits
- Integrated test capacitors
- Power: 25 mW
- New method of electron trapping compensation using collecting grid timing



Layout size: ≈ 3.1×3.1 mm²

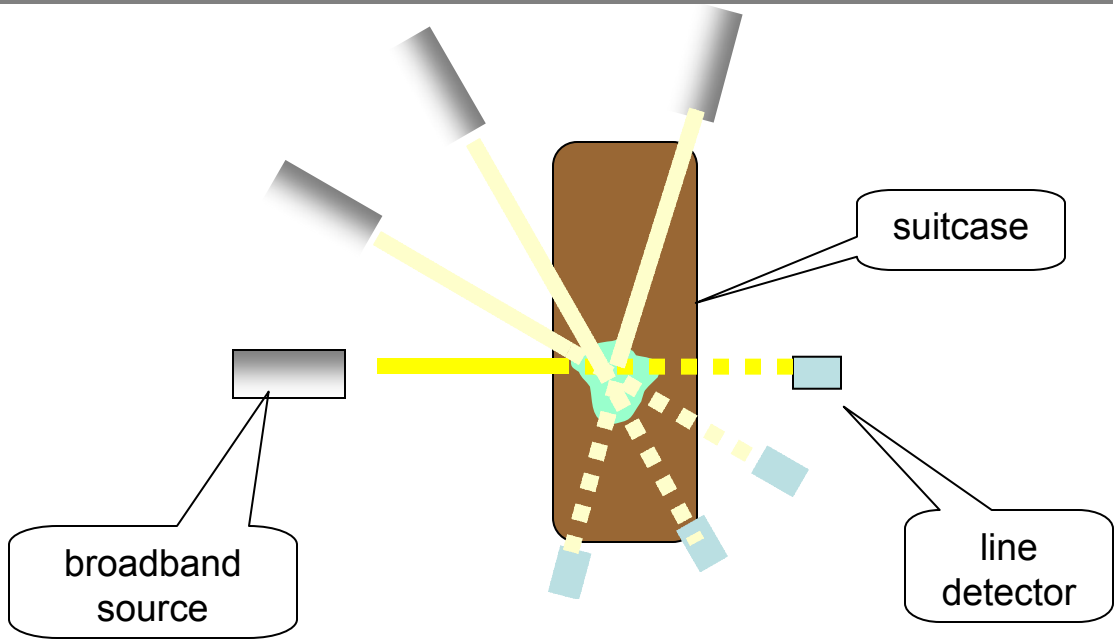
^{137}Cs spectrum



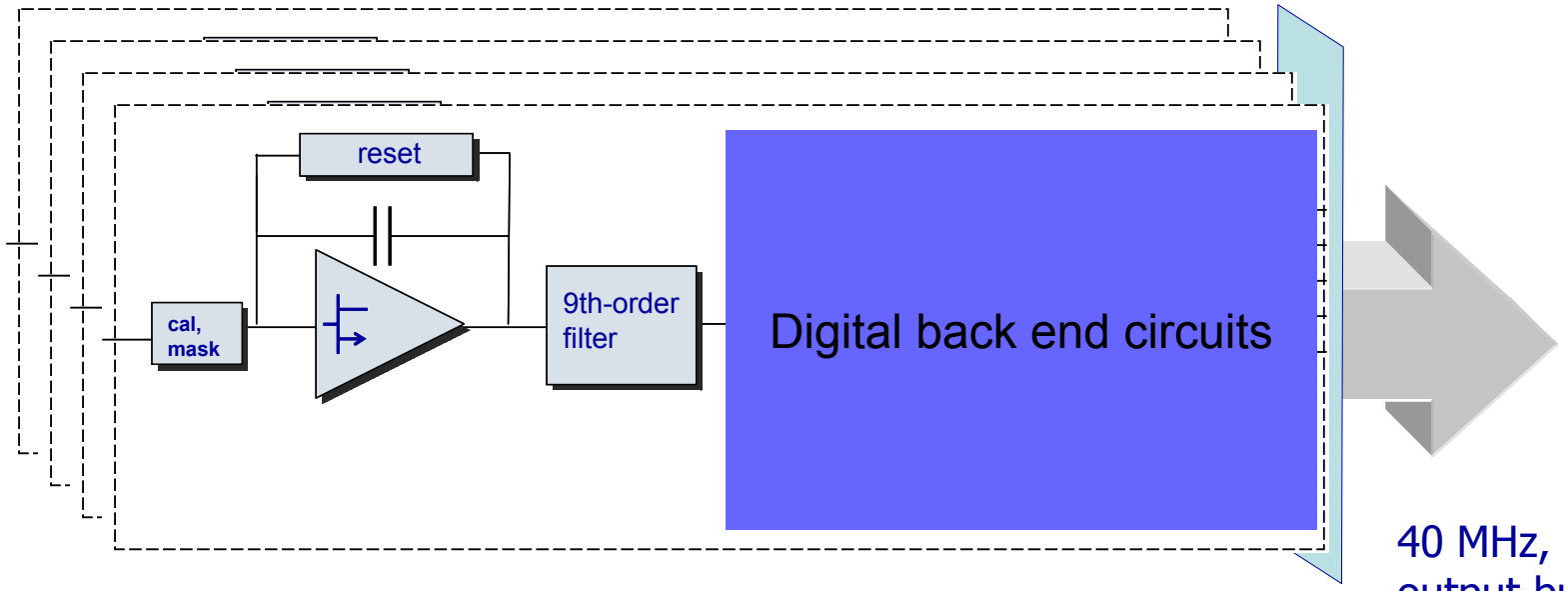
G. De Geronimo et al., *Front End ASIC for Co-planar grid sensors*, IEEE Trans. Nucl. Sci. (accepted for publication).

5. Explosives Detection System

Transmission image acquired from several angles as object moves through scanner → gives crude tomography of object.
Several energy windows are acquired at each position.
Differential absorption + tomography give Zeff and density in each volume element of object.
Match to template with explosives signature (N-rich, high density compared to organics).



Multi-window photon-counting ASIC



40 MHz, 16bit output bus

- 64 channels, each with:
  - preamp, shaper
  - 5 x (discriminator, 16-b counter)
  - gain and offset trim
  - MHz count rate capability
- zero deadtime
- 0.25μm CMOS, 5 mW/channel
- 600,000 MOSFETs