Ongoing projects in preclinical imaging at the TU München:

The MADPET-II project
&
Investigation of novel photodetectors for multimodal imaging

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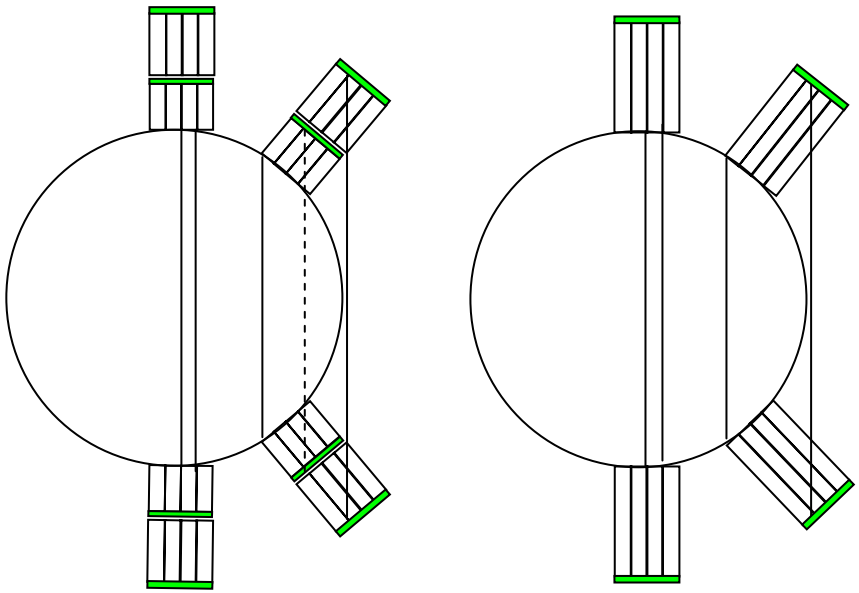
THE MADPET-II PROJECT

1. Motivation
2. MADPET-II Front-ends
3. Signal processing chain
4. DAQ Features
5. Energy and time resolution
6. Temperature effects
7. Depth Of Interaction information
8. Sensitivity

Motivation

Dual radial crystal layer:

DOI ⇒ **Improved resolution** near edges of FOV



Granulated crystals:

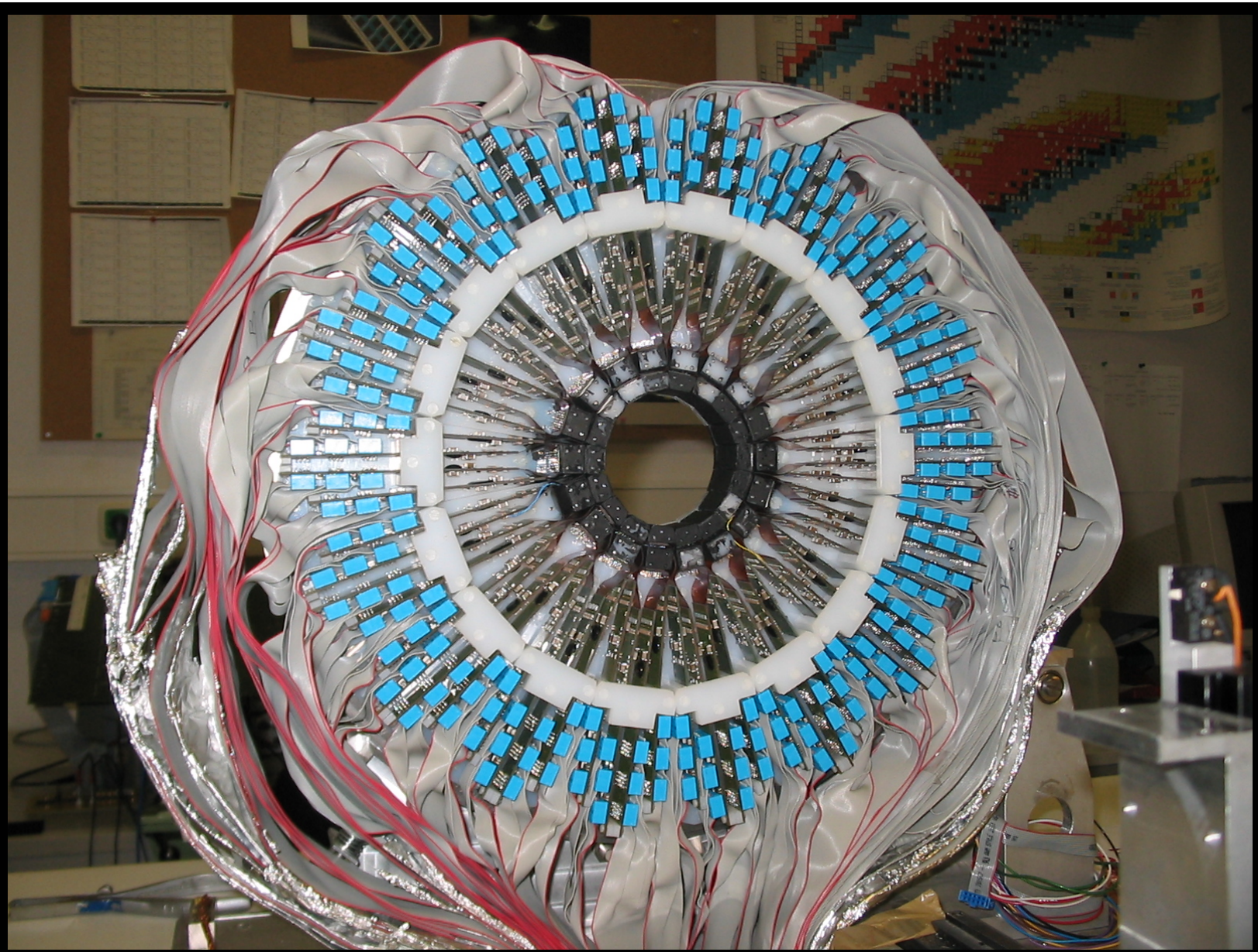
Identify Compton scatter within a detector block ⇒

Improved sensitivity without loss of resolution

Individual crystal readout:

No signal multiplexing ⇒ parallel signal processing for every detector channel ⇒ minimization of dead time

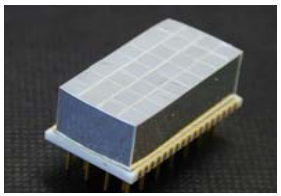
MADPET-II Front-Ends



Signal processing chain

Front-End

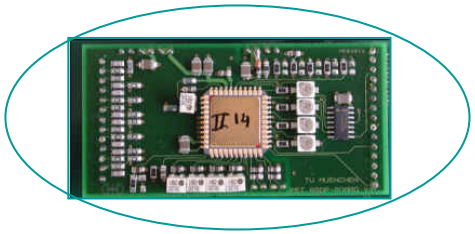
4x8 channels



2 x Charge Sensitive Preamplifier (16 channels)

Analog processing

4 channels



Differential Receiver

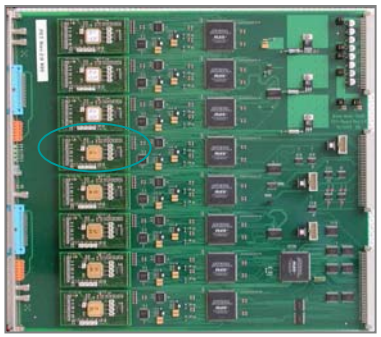
Shaping Amplifier

Constant Fraction Discriminator → TDC → **Time Stamp**

Peak Detector → ADC → **Pulse Height**

Digital processing

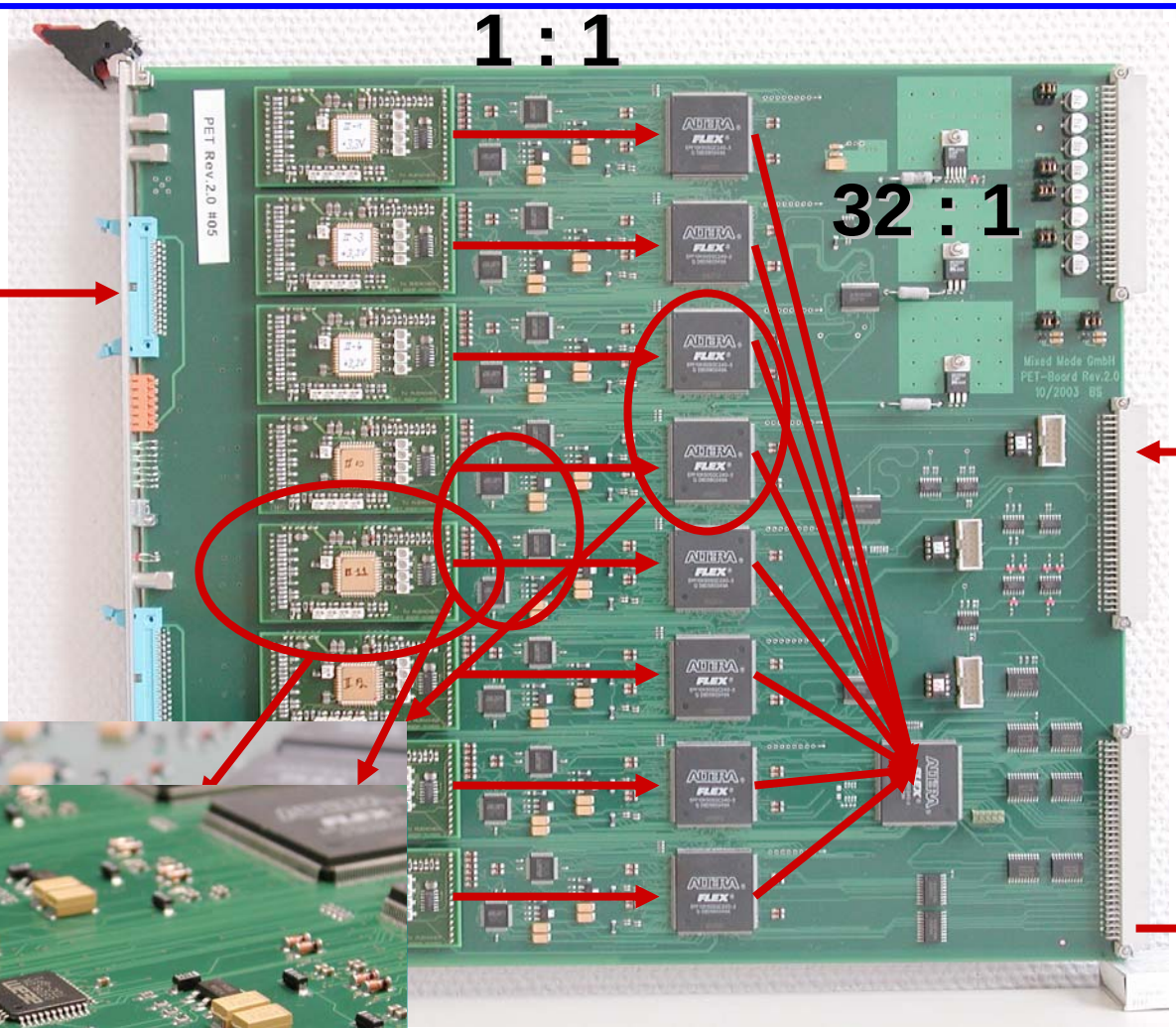
32 channels



Global clock

Readout electronics

From front end:
- Differential signals via 4.75 m cables
- 32 channels

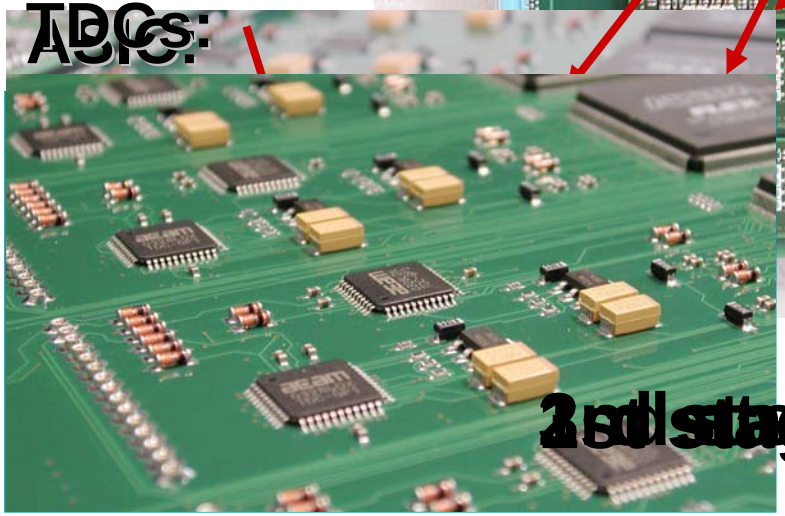


From CCI board:
- System clock 40 MHz
- Global sync 3.2 µs

To CCI:
- 2 x 32 bit data words

FIFO / ADCs and TDCs:

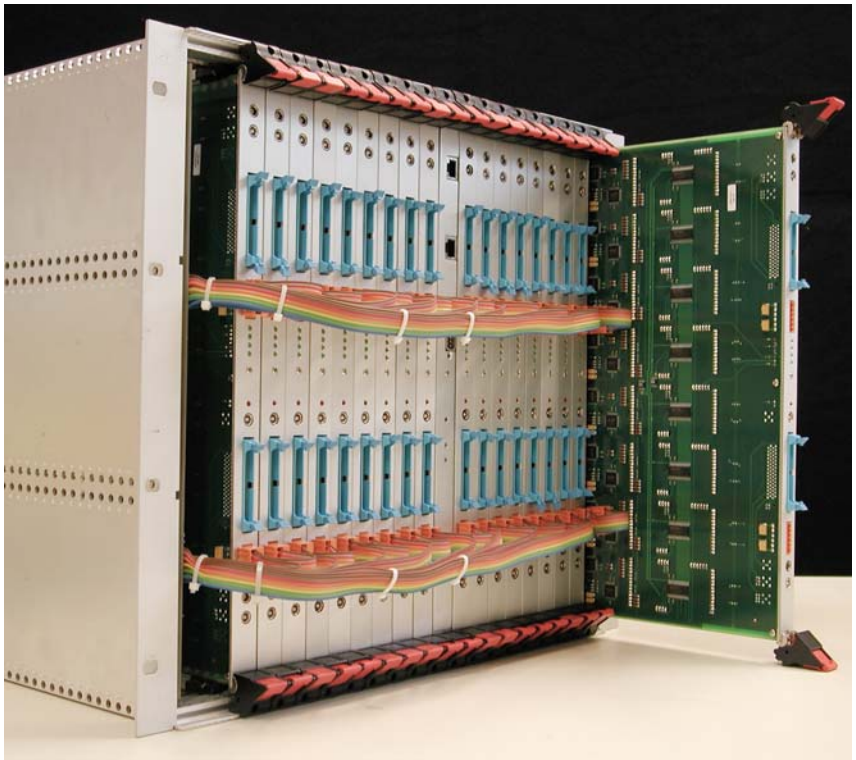
4 channel ASIC:



- Differential signal, shaping amplifier, 3 bit peak detector, 2 stage FIFO, 256 x 64 bit
- 1st stage FIFO: 256 x 64 bit
- 2nd stage FIFO: 256 x 64 bit
- Trigger, reset, clock system clock

Data transfer

2 x



Gigabit Ethernet (128 MB/s)

18 PET boards + CCI board

- Micro-controller module (Motorola)
- Gigabit Ethernet controller (Intel)

Linux server

- 1.4 GHz
- 64 bit PCI bus
- 480 GB RAID

DAQ Features

DAQ Features	PROs	CONs
List mode data format Recorded time stamp and pulse height for every detected event	Maximum flexibility in data processing	disc space requirements
Post-acquisition coincidence sorting	application of variable energy & time coincidence windows	Processing time
Software-based tomograph tuning: –Pulse height calibration –Timing calibration –Randoms subtraction	Evaluation of different methods	timing walk effects
3D list mode MLEM reconstruction with a **Monte Carlo-based** System Matrix	Detection process taken into account	• Duration of reconstruction • noise

System stability

- Uncertainty in the extraction of energy information
  - ➢ Drift of the photopeak position due to temperature fluctuations in the front-end detector area

→

- Not reliable energy calibration among detectors
- Possible effect on system-wide energy resolution

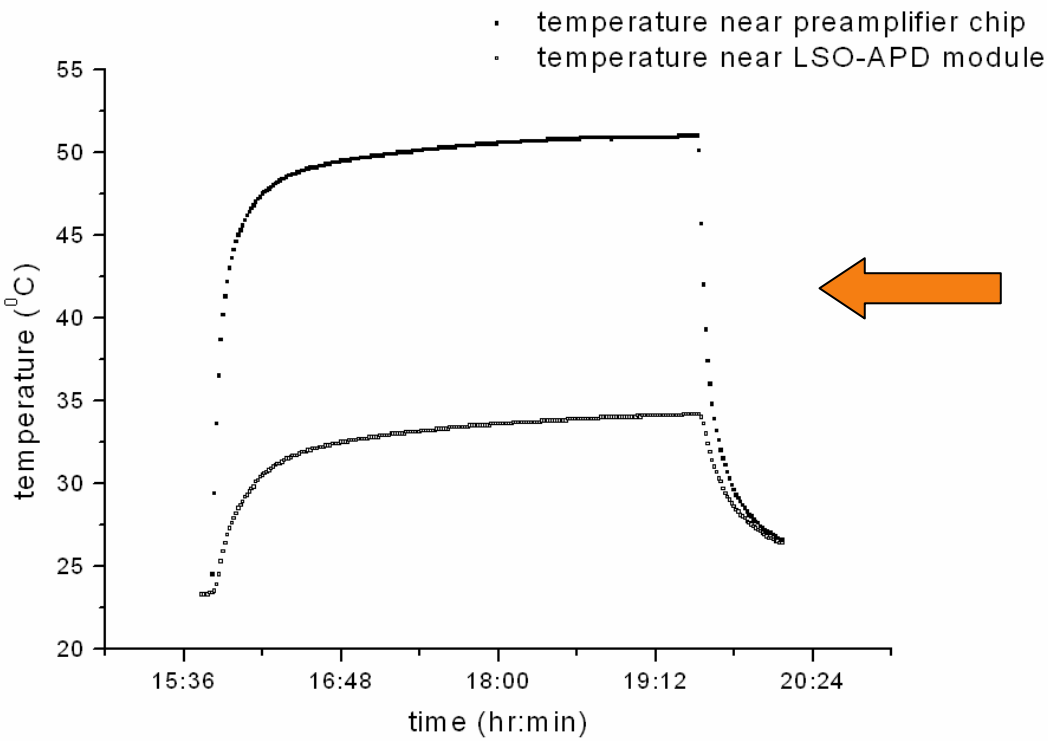
↓

- Uncertainty in the extraction of time information
  - ➢ Energy (amplitude) dependent walk and jitter of the constant fraction time pick-off circuit

→

- Delays among electronic channels
- Broadening of system-wide time resolution

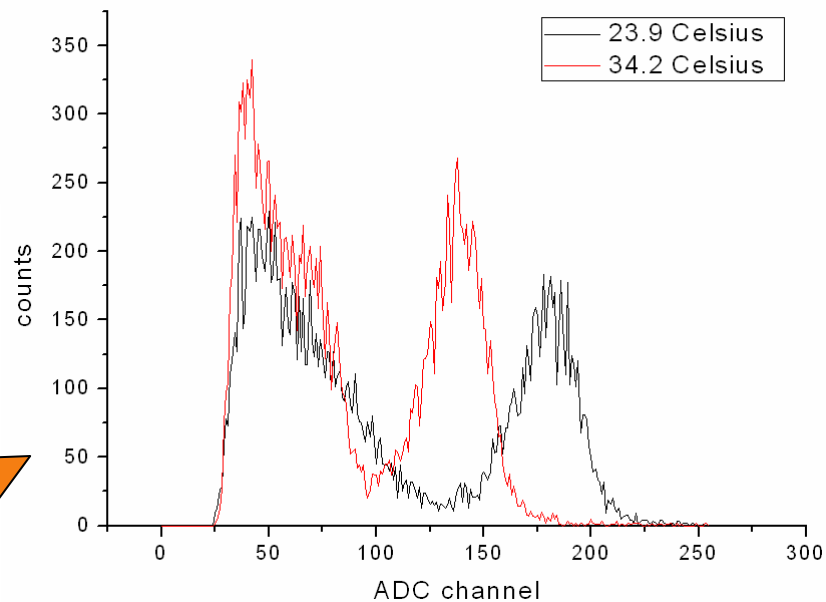
Temperature fluctuations



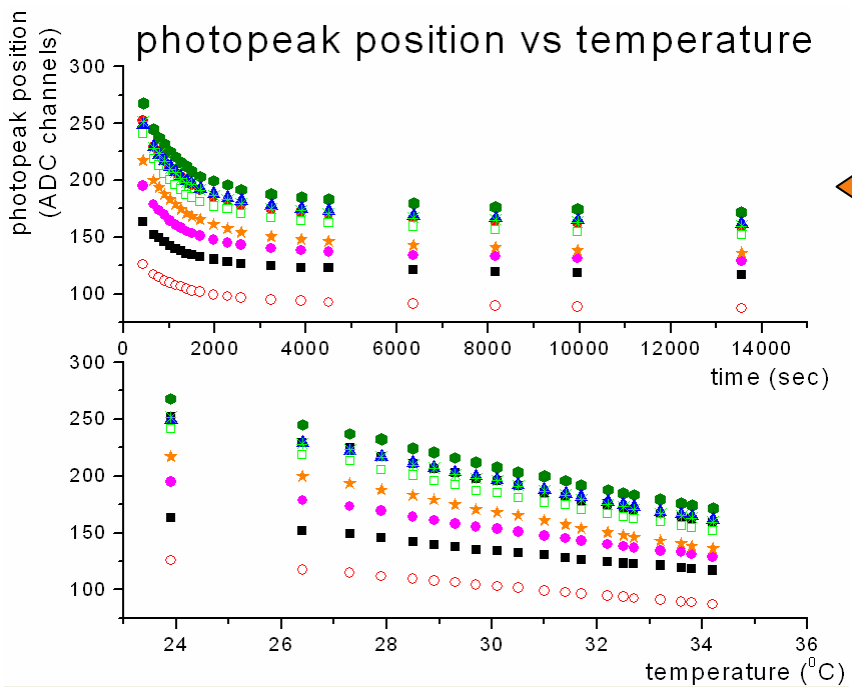
The charge sensitive preamplifier power consumption (30 mW / channel) increases the temperature of the front-end by ~10 °C

Temperature sensitivity of LSO light output & APD gain

Drift of the photopeak position in the acquired energy spectra



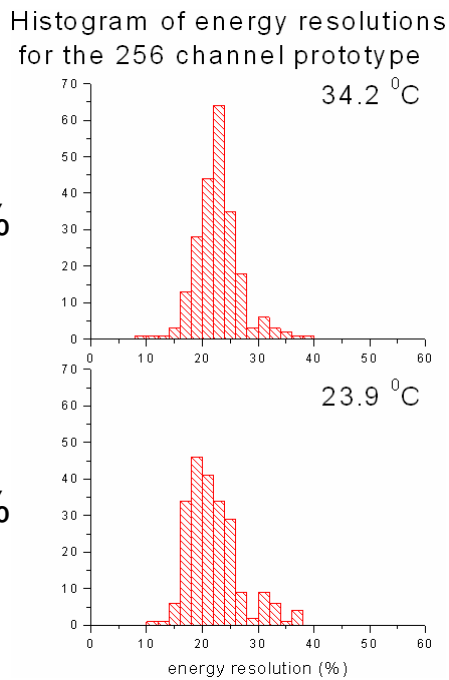
Energy uncertainty



- Linear relationship between photopeak position and temperature:

$$R^2_{mean} = 0.99624 \pm 0.00135$$

- Mean observed shift of the photopeak position : ~ **(3.407 ± 0.066) %/^{0}C**



mean=(22.8±0.3)%

mean=(22.1±0.4)%

- Small increase in mean energy resolution with increasing temperature : **~ 3% increase for 10.3 °C** temperature increase

V. Ch. Spanoudaki et al. *„Effect of Temperature on the Performance of Proportional APD-Based Modules for gamma ray detection in Positron Emission Tomography "* to appear in IEEE Trans. Nucl. Sci.

Time uncertainty

- **Front-end electronics**

✓ Variations on the rise time of APD & preamplifier output signals

- **Non-Delay line Constant Fraction timing**

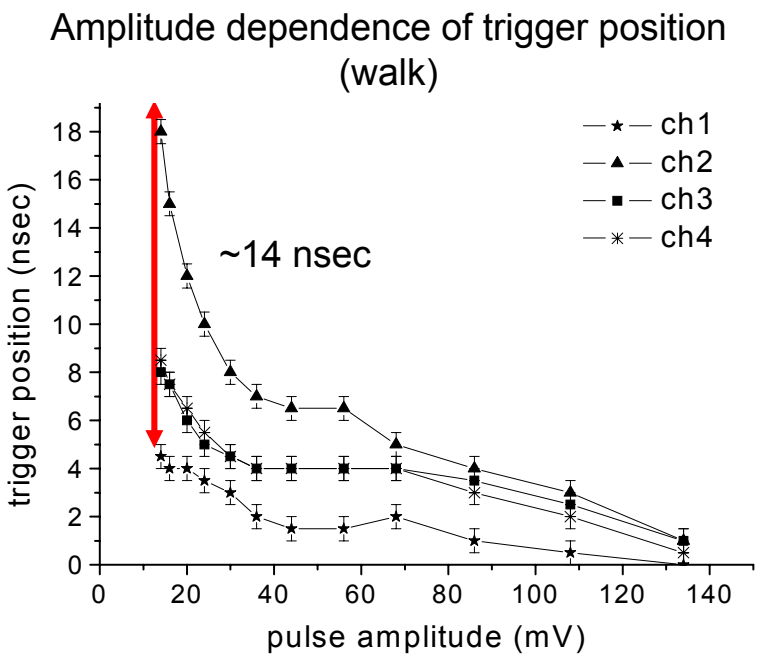
✓ Time walk : Dependence of trigger position on pulse amplitude

⇓

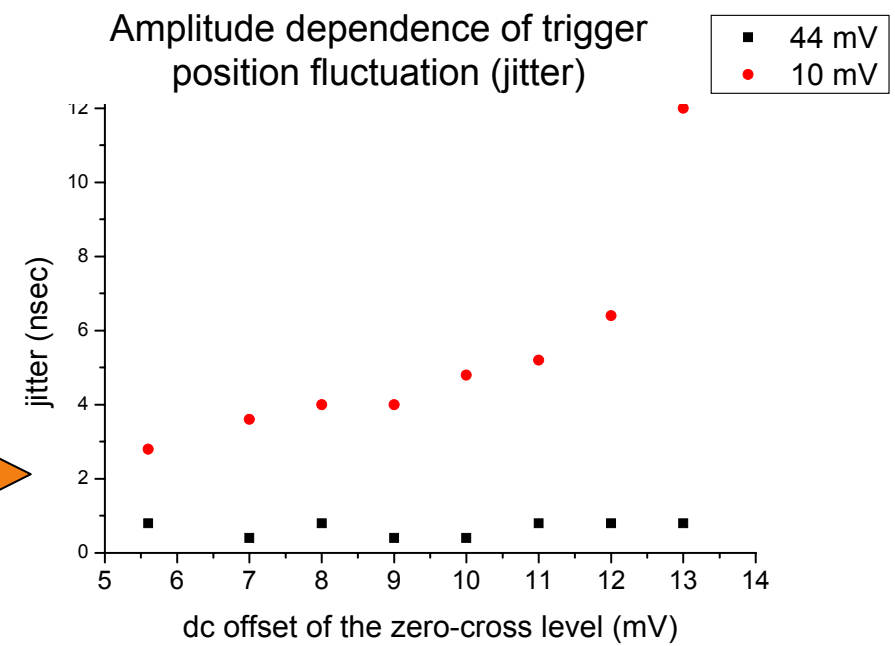
Time delays between channels : ~ nsec differences in trigger position for same pulse amplitude

✓ Time jitter : Random fluctuation of the trigger position around a mean value

Effect on time



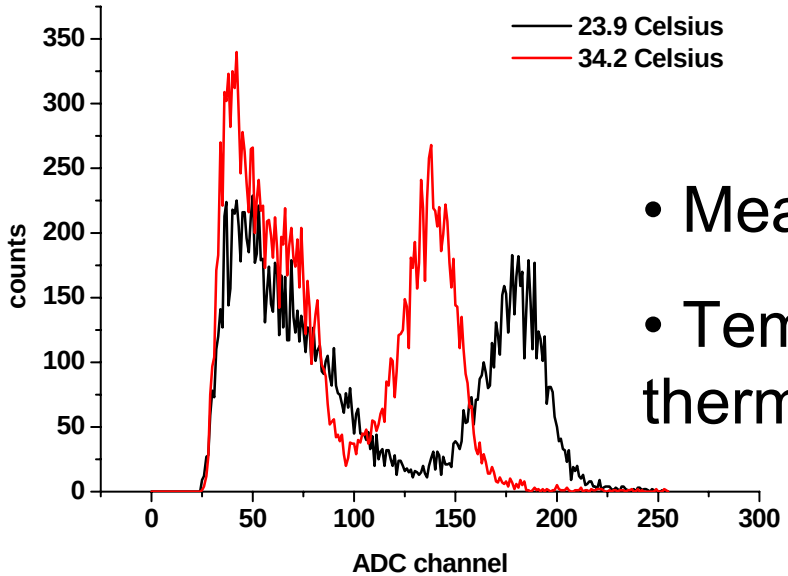
- Delays among electronic channels for the same input amplitude
- Increasing delays with decreasing input amplitude



- Increasing jitter with increasing zero-cross level
- Increasing jitter with decreasing input amplitude

V. Ch. Spanoudaki et al. *„An Analog Signal Processing ASIC for a Small Animal LSO-APD PET Tomograph “* NIMA(2006) 564, 451-462

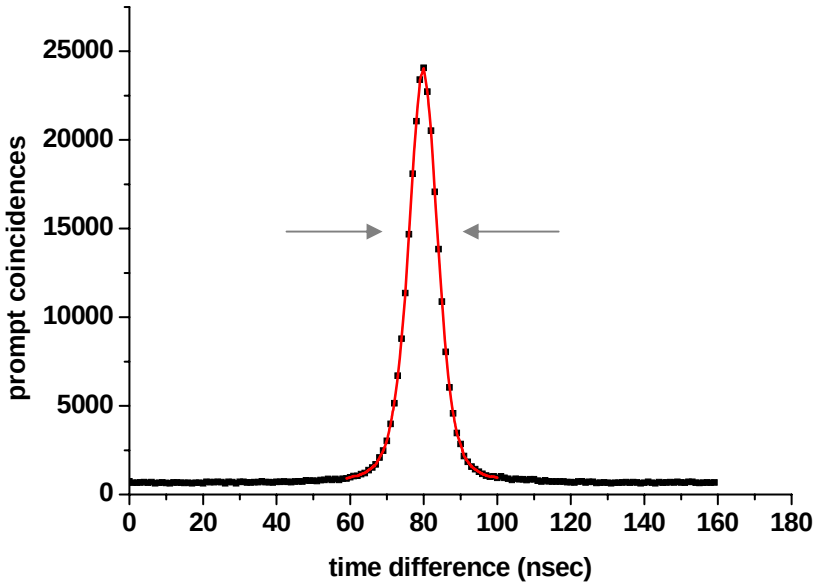
Energy & Time Resolution



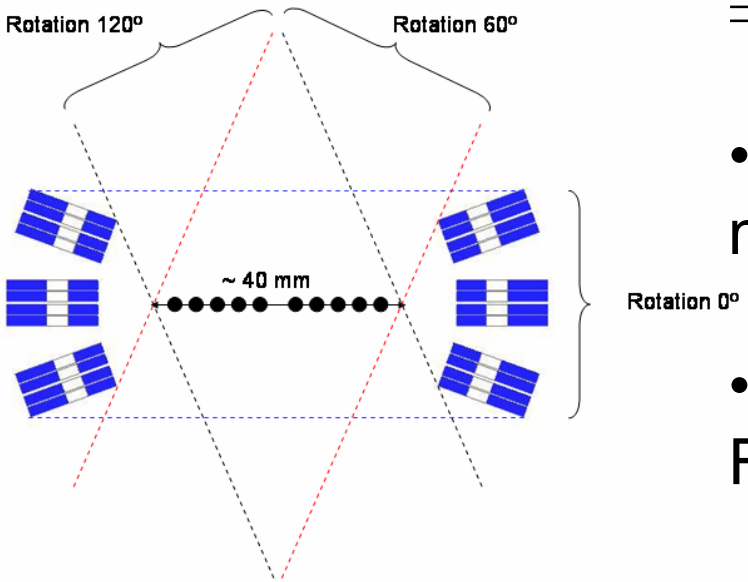
- Mean energy resolution ~ 23 % @ 35 ^{0}C
- Temperature stabilization using thermoelectric (Peltier) cooling

- correction for interchannel delays:
  - ➢ use of an external reference
  - ➢ iterative method
- 3.8 ns FWHM for two detector channels

System-wide FWHM~ 9 ns



First DOI Results (Setup)



- Acquisition with 384-channels

⇒ Rotation of the phantom in 3 steps, 60° each

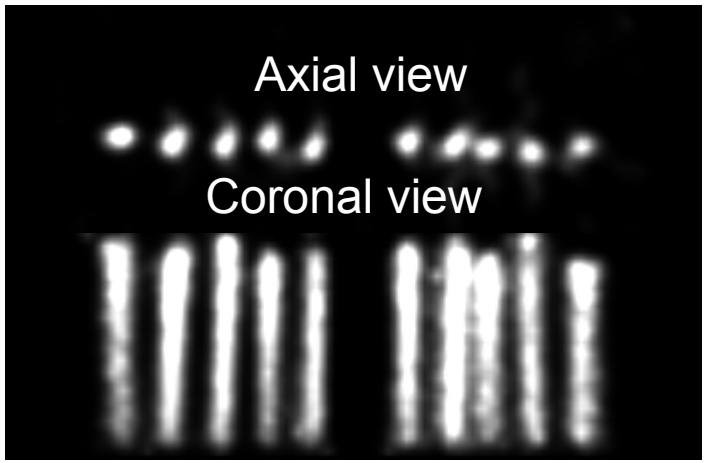
- 10 capillaries, 0.25 mm Ø each, 4.25 mm distance between capillaries

- Phantom distributed along the radial FOV (~ 40 mm for the 384-ch prototype)

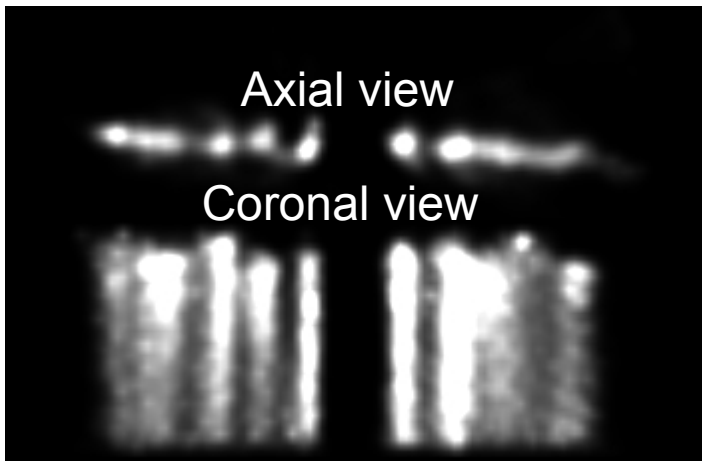
- MLEM reconstruction algorithm, 30 iterations, 400 keV lower energy threshold, 20 ns time coincidence window
- Acquired image reconstructed in two ways:
  1. Considering two radial crystal layers of 6 mm & 8 mm length
  2. Considering one crystal layer of 14 mm length

First DOI Results

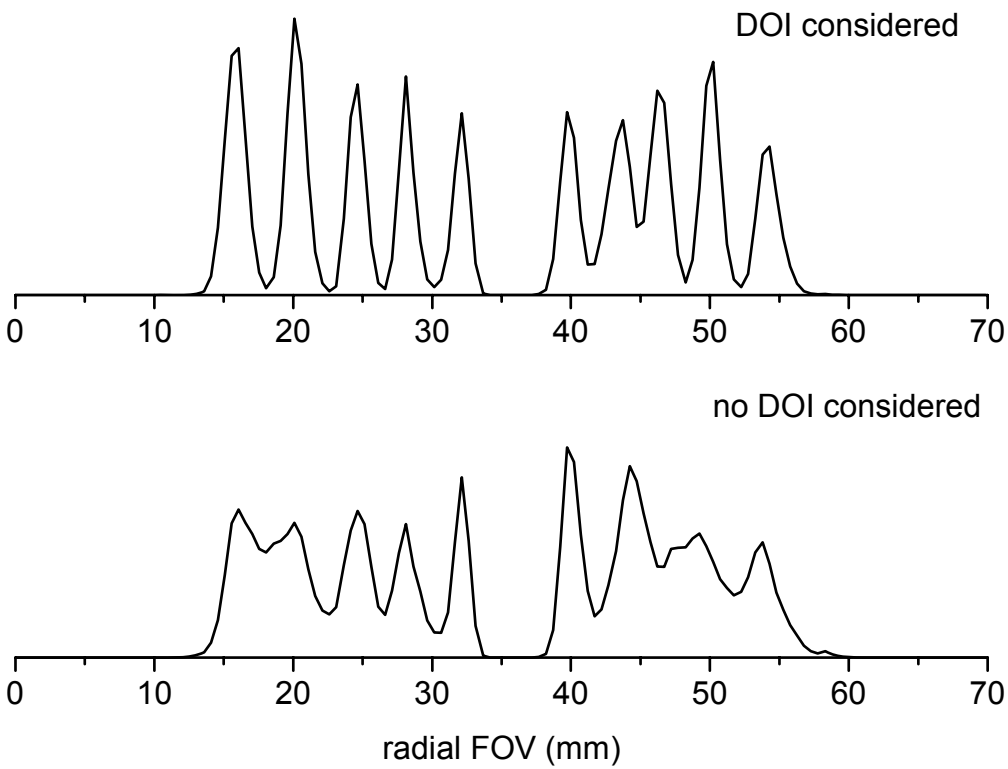
With DOI



Without DOI

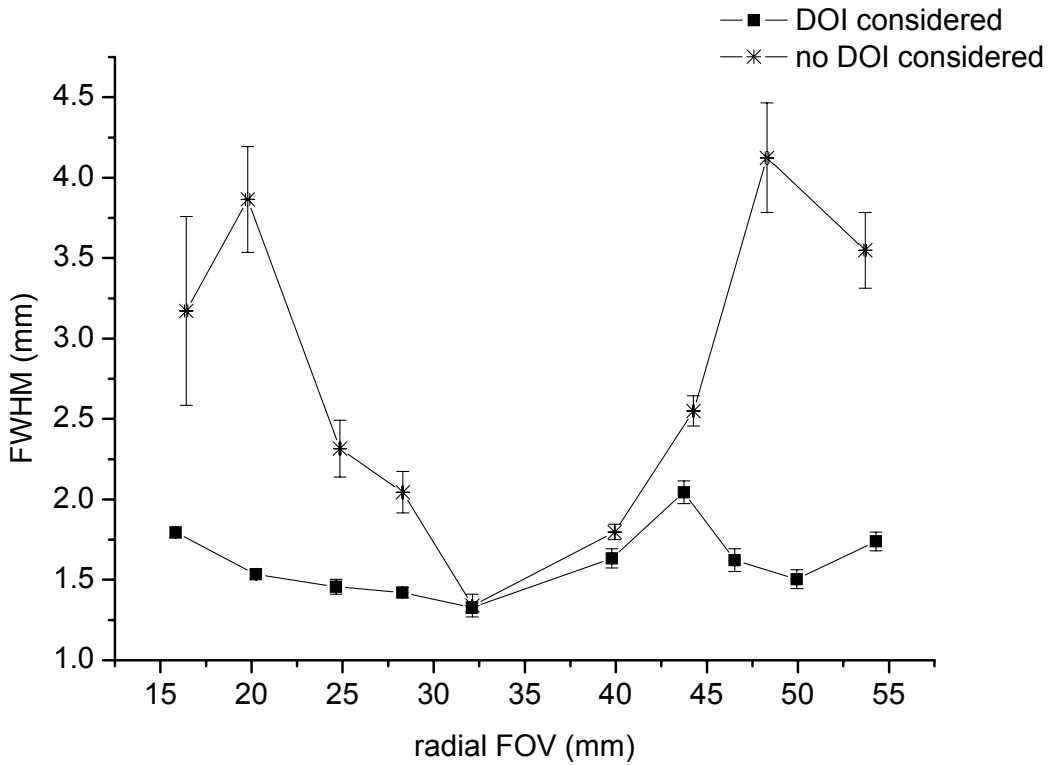


Line profiles along a central slice



First DOI Results

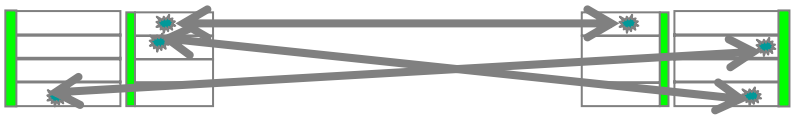
- No correction for variations on detector efficiencies (normalization)
- 1 mm FWHM gaussian filter used

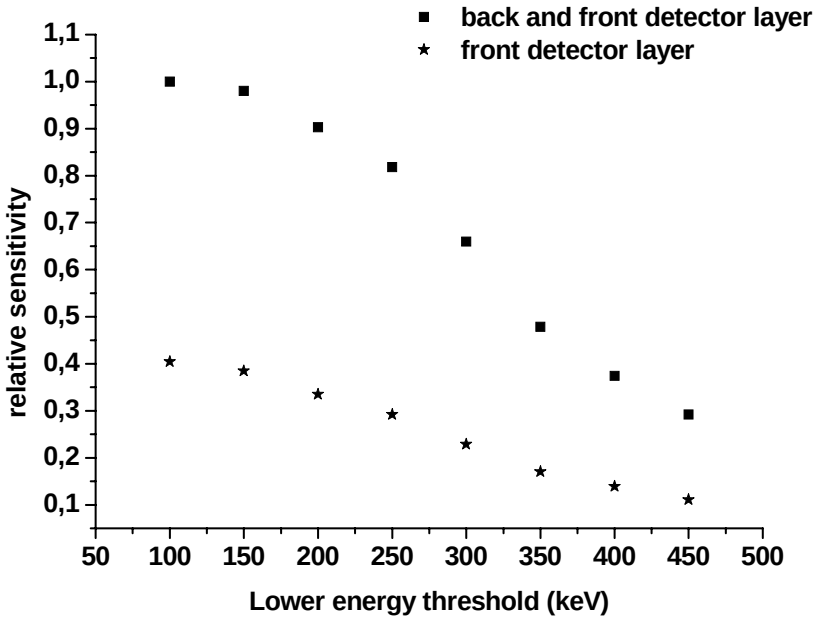


- Gaussian fits applied to line profiles
- mean FWHM for the central slice (1.25 ± 0.08) mm after correcting for gaussian smoothing

Sensitivity

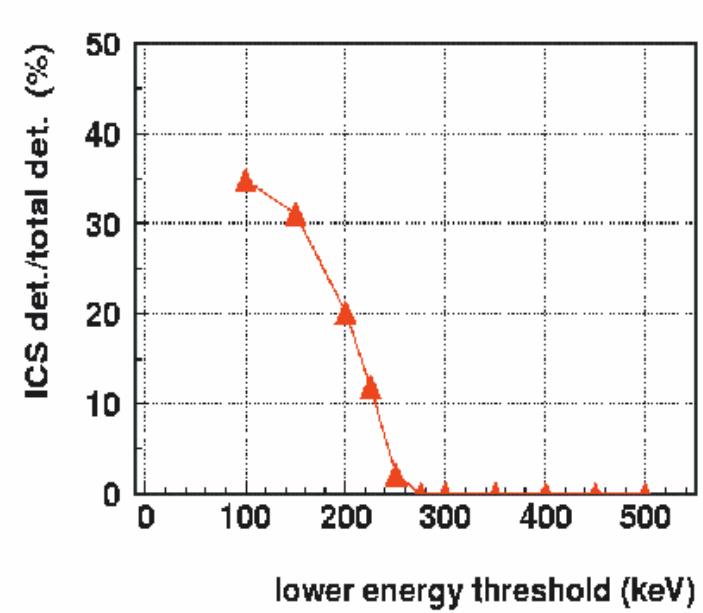
Coincidences between every possible detector pair





Improve spatial resolution while maintaining sensitivity

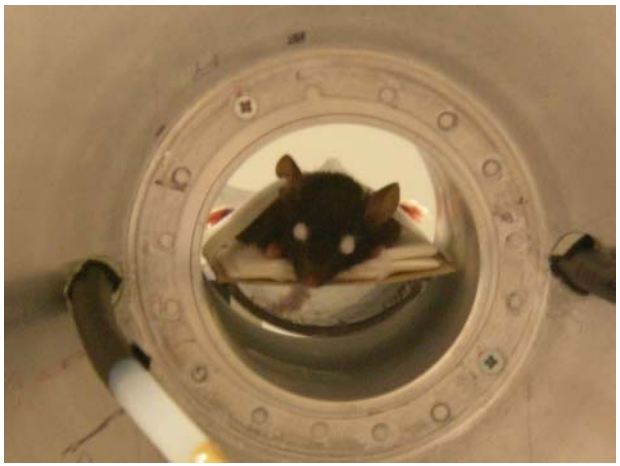
Detection of intercrystal scatter



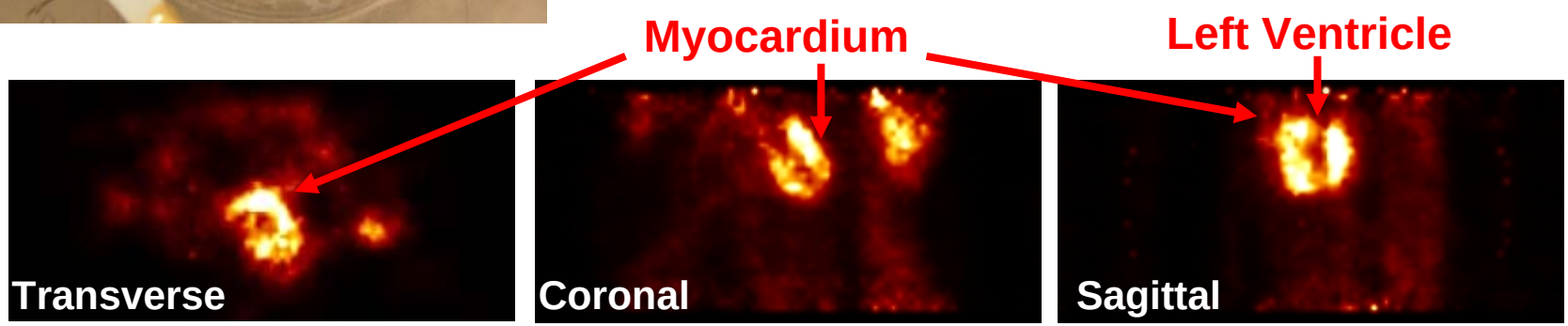
M. Rafecas et al. „Intercrystal scatter in a dual layer, high resolution LSO-APD positron emission tomograph“ Phys. Med. Biol. , 48(2003), pp. 821-848

Improve sensitivity while maintaining spatial resolution

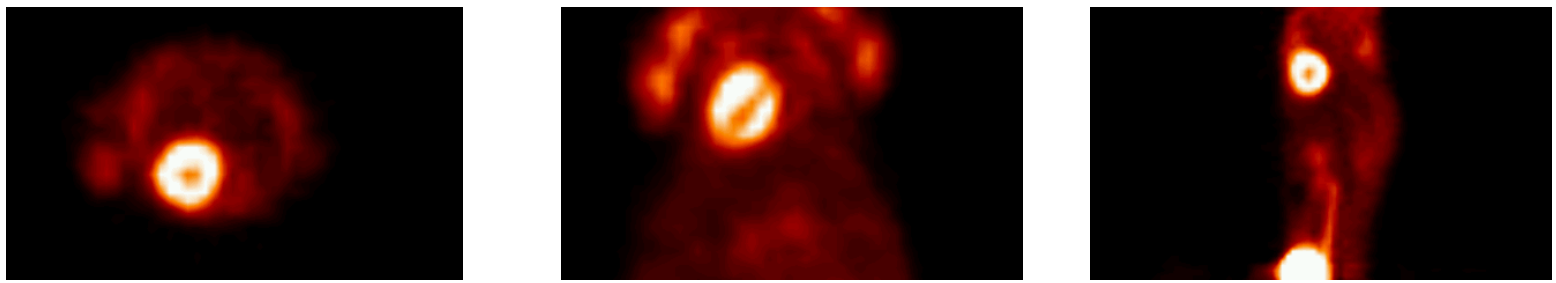
Mouse heart imaging



- MLEM, 20 iterations, 400-700 keV
- No correction for variations on detector efficiencies (normalization), no time calibration, no randoms subtraction



Focus Micropet



Conclusion

- ✓ List mode DAQ ⇒ Maximum flexibility on data processing
- ✓ Good scanner performance in terms of energy (~23 %), time (~9 ns) resolution
- ✓ First images from MADPET-II : DOI Information ⇒ maintenance of spatial resolution along the FOV (~1.3 mm)
- ✓ Dual radial crystal layer and detection of intercrystal scatter ⇒ good compromise between sensitivity and spatial resolution

SiPMs for PET/MR

1. Motivation
2. SiPM features
3. Non-linear response
4. Intrinsic resolution
5. 2x2 SiPM prototype array
6. Gamma spectroscopy
7. LYSO-SiPM timing
8. Readout design
9. MR compatibility
10. Planar imaging with SiPMs

Motivation

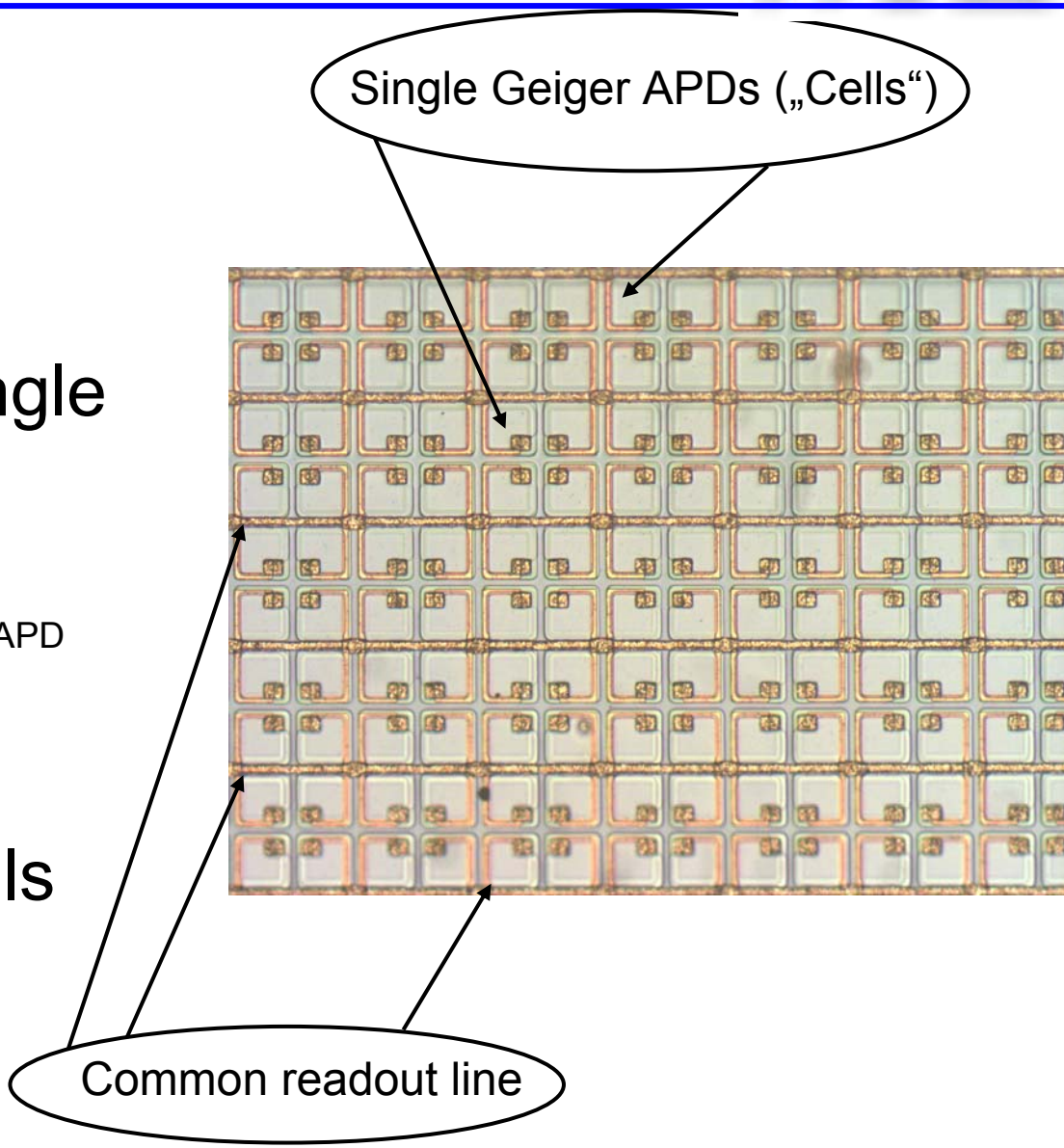
Use of SiPMs as scintillation crystal readout for Positron Emission Tomography

Advantages:

- High gain ⇒ well defined pulse shape
  ⇒ elimination of charge sensitive preamplifier
- Triggering on single electron pulses
  ⇒ improved time resolution
- Insensitivity to magnetic fields
  ⇒ appropriate for simultaneous PET/MR imaging

SiPM Features

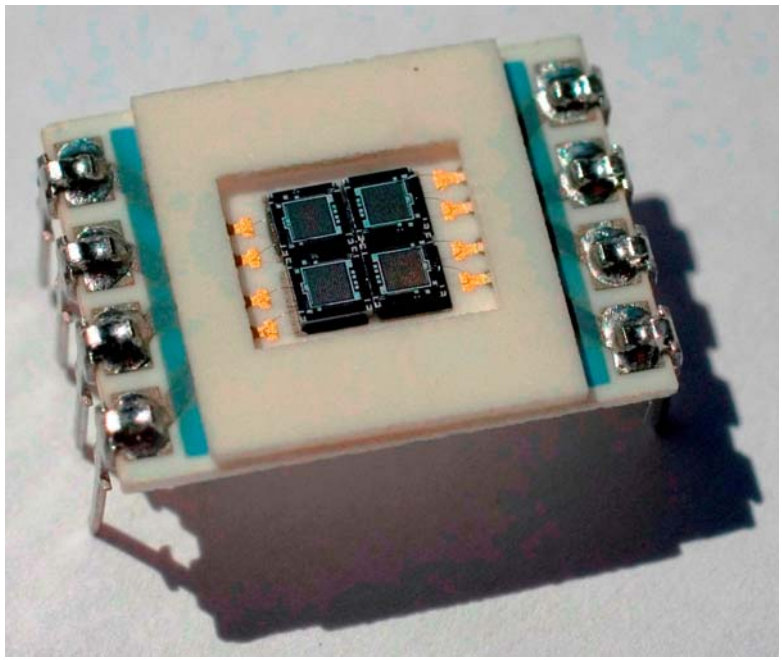
- Array of Geiger mode APDs → Gain ~ 10^6
- ~ 1 ns rise time for single electron pulses
- $\text{Output}_{\text{SiPM}} = \sum_{\#\text{cells}} \text{Output}_{\text{APD}}$
- # incident optical photons ~ # "fired" cells



Single-channel SiPMs

- Hamamatsu 1x1 mm^2 MPPCs
- a) 1600 cells, PDE 25%, gain ~10^5
- b) 400 cells, PDE 50%, gain ~10^6
- QE > 70 % @ 420 nm

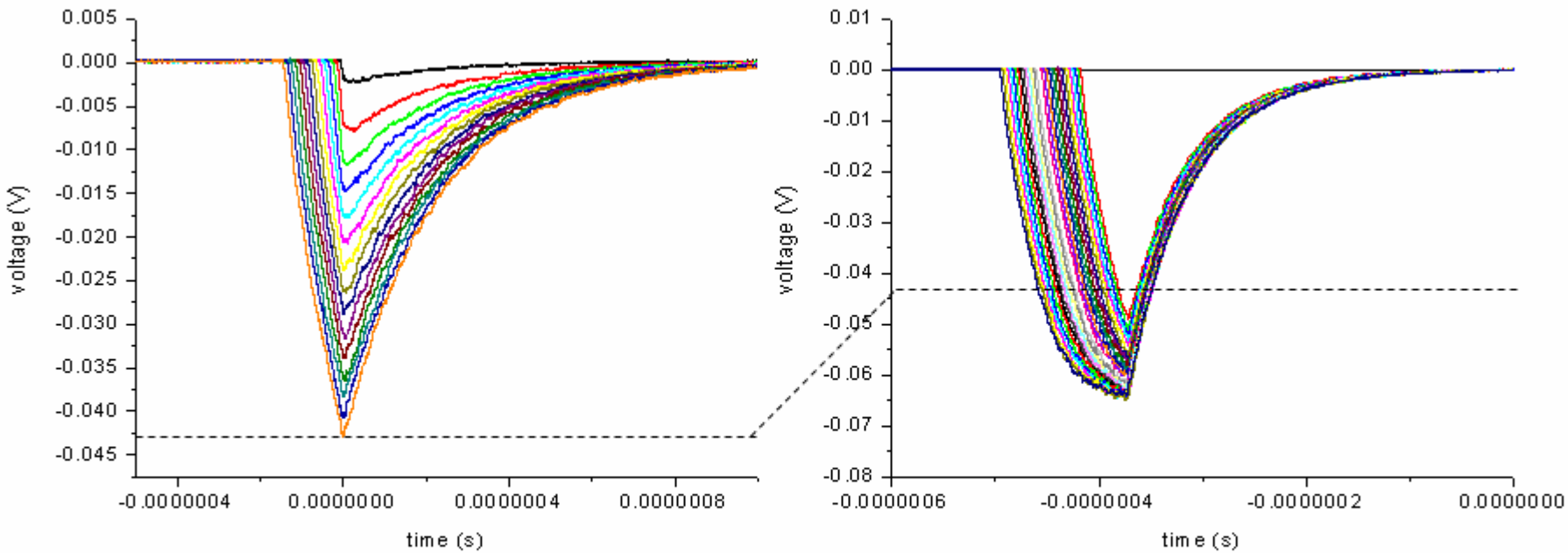
- Pulsar & MePhI 1x1 mm^2 SiPMs
- 1024 cells, PDE 50 %
- QE < 10 % @ 420 nm
- QE > 70 % @ 565 nm
- 4 SiPMs arranged in a 2x2 array
- 0.3 mm distance between detectors
- Mounted on a ceramic carrier
- Ceramic frame for epoxy coating



Non-linear response

✓ Light pulses from a LED (emission @ 650 nm) of 10 – 200 nsec duration (10 nsec step)

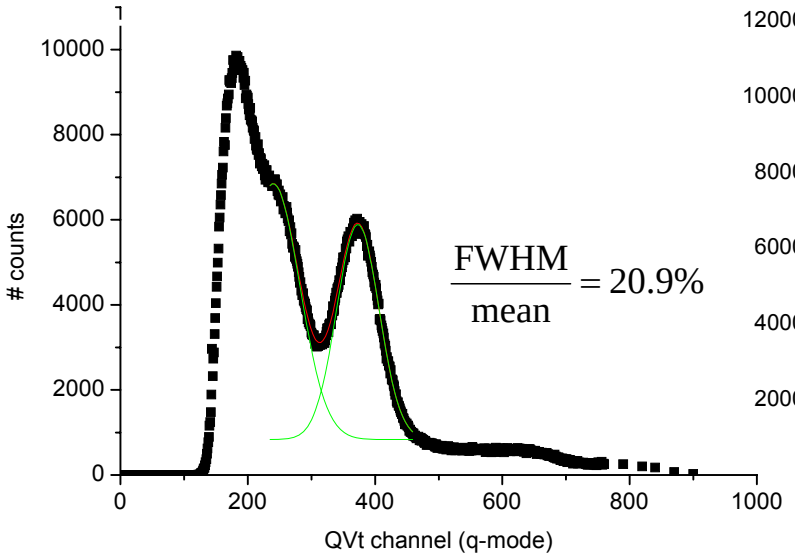
✓ Pulse height & rise time (Δt) of the SiPM signal recorded as a function of light pulse width

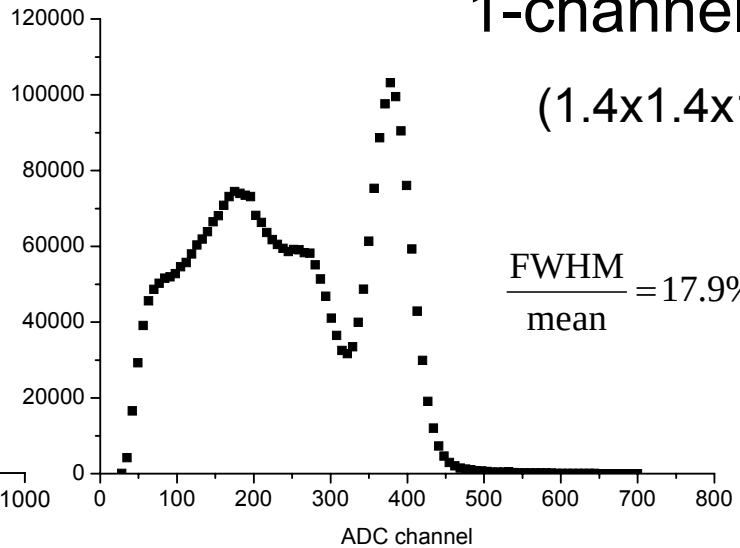


γ-spectroscopy

1-channel LSO-SiPM

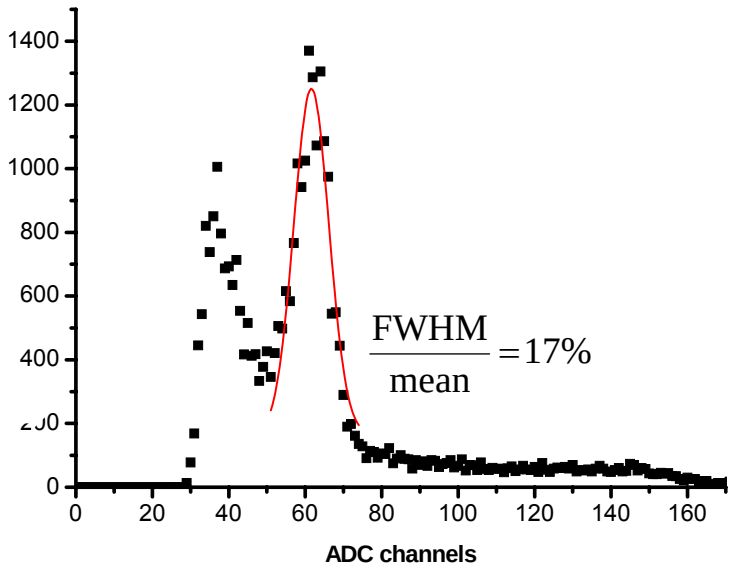
(1.4x1.4x12 mm^3 LYSO)





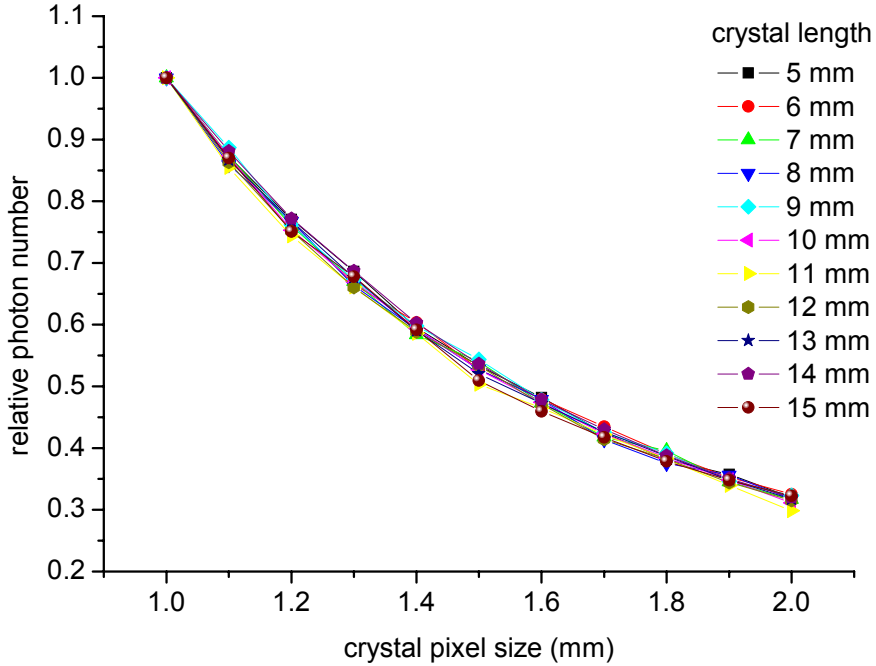
1-channel LSO-APD from MADPET-II

(S8550 Hamamatsu, 2x2x6 mm LSO)



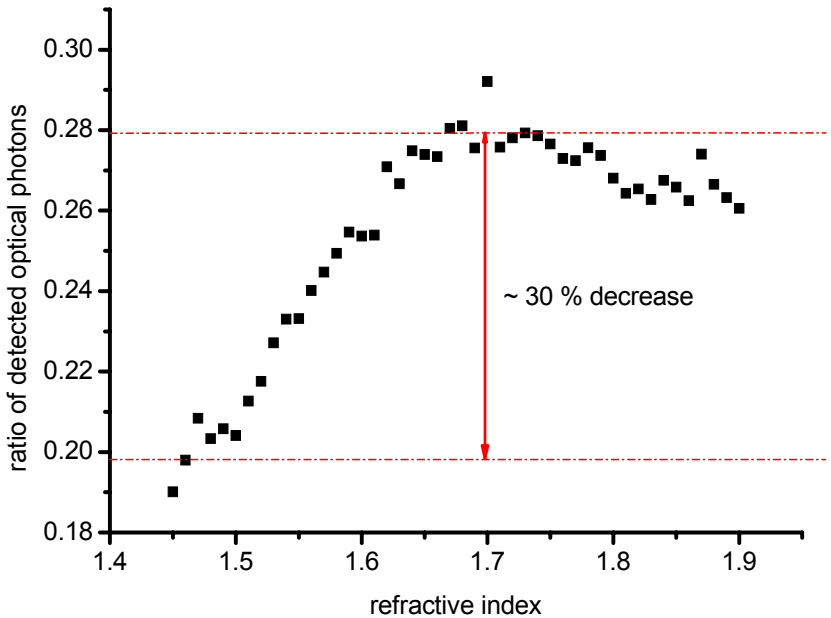
Energy resolution degradation

optical photon tracking simulations (DETECT2000)



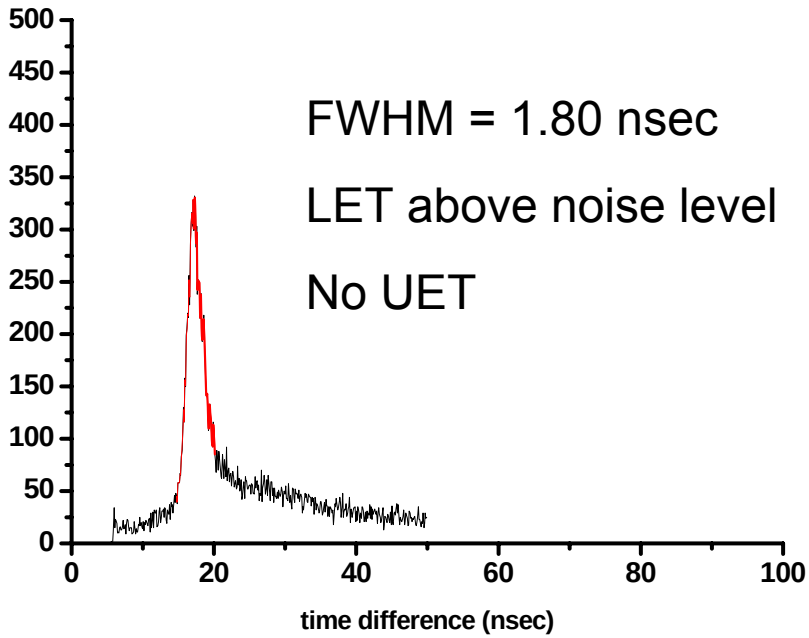
1:4 LSO-SiPM area mismatch

Non-optimum choice
of the optical coupling

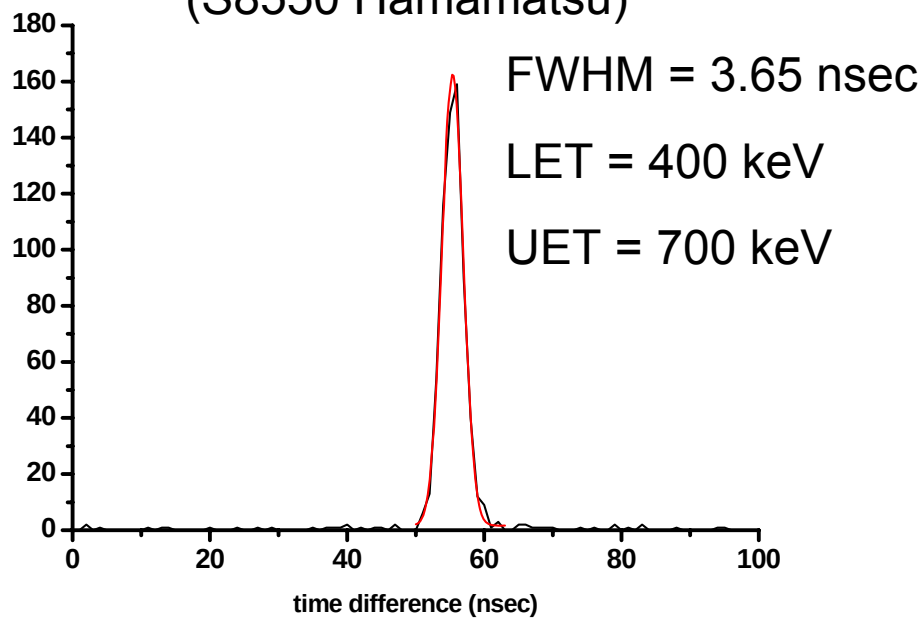


LSO-SiPM Timing

1-channel LSO-SiPM



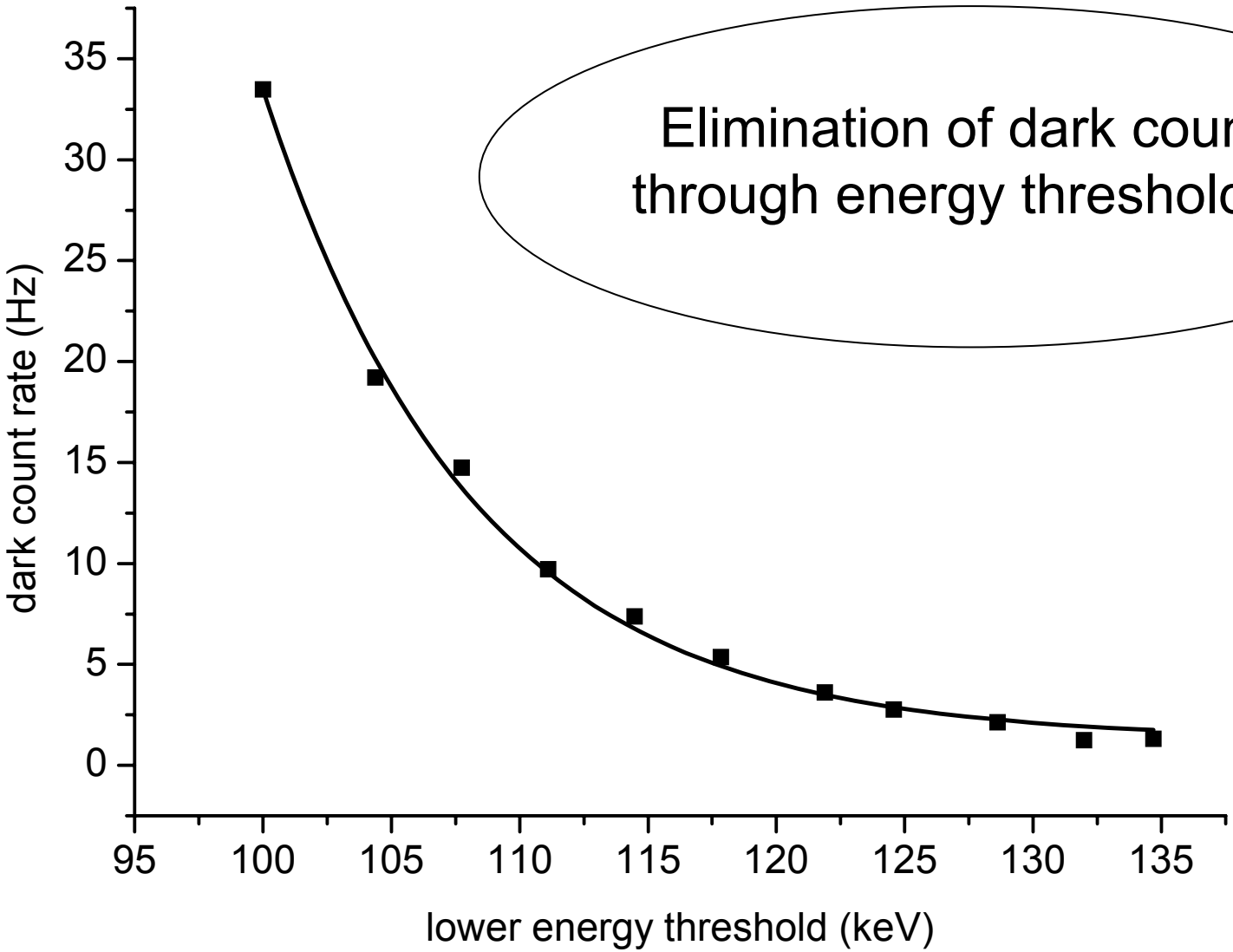
1-channel LSO-APD from MADPET-II (S8550 Hamamatsu)



✓ Single LSO-SiPM (LSO-APD) detector in coincidence with a Plastic Scintillator-PMT

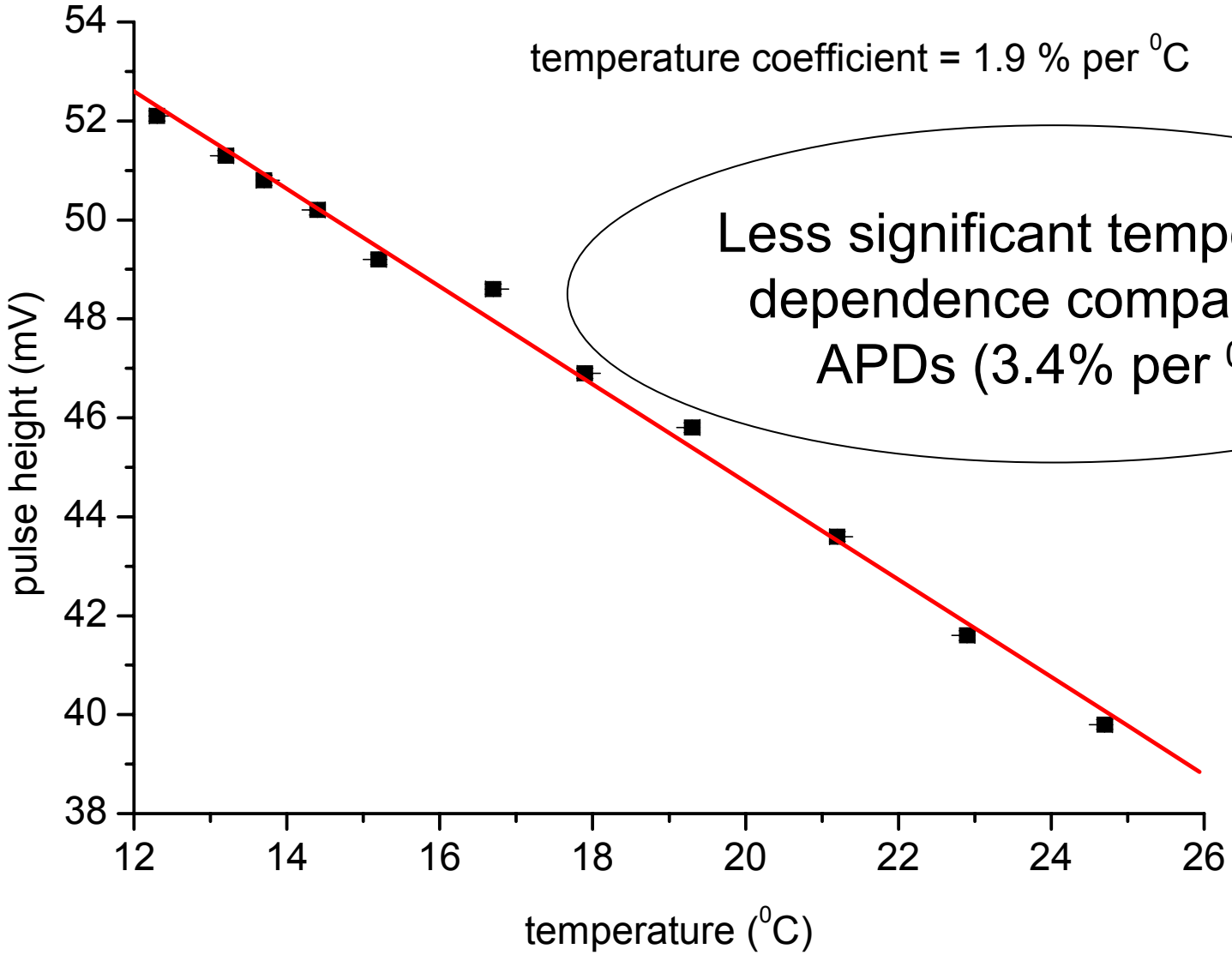
✓ Constant Fraction time pick-off (7 ns delay, no shaping)

Dark counts



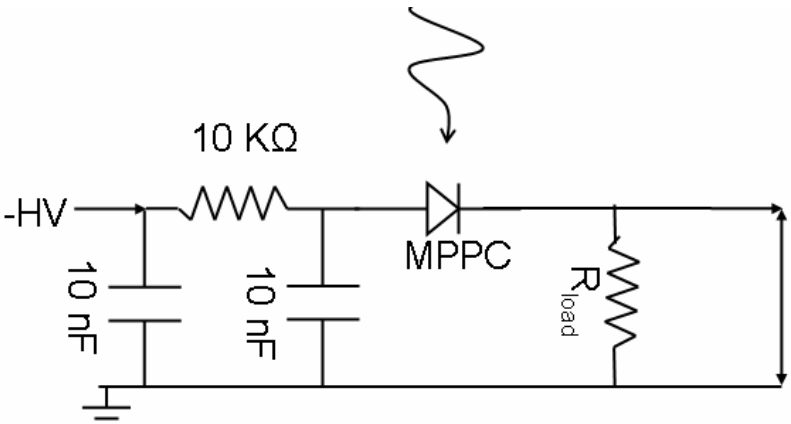
Elimination of dark counts through energy thresholding

Temperature dependence

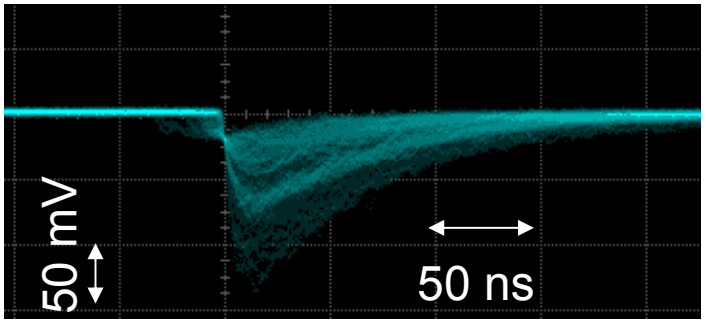


Less significant temperature dependence compared to APDs (3.4% per ^{0}C)

Simplified detector model for PET



Signal output



- Elimination of the charge sensitive preamplifier
- Possibility for passive shaping

Readout design

Possible changes in pulse shape due to recovery time effects

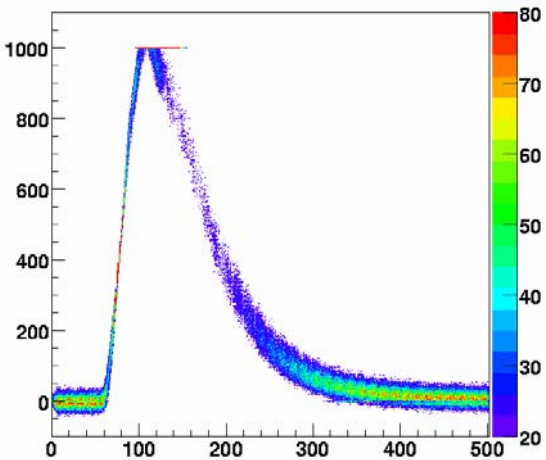
⬇

Constant Fraction time pick-off inefficient

<u>Alternative</u> : a) Triggering on the first photoelectron

b) Time pick-off based on the sampled signal

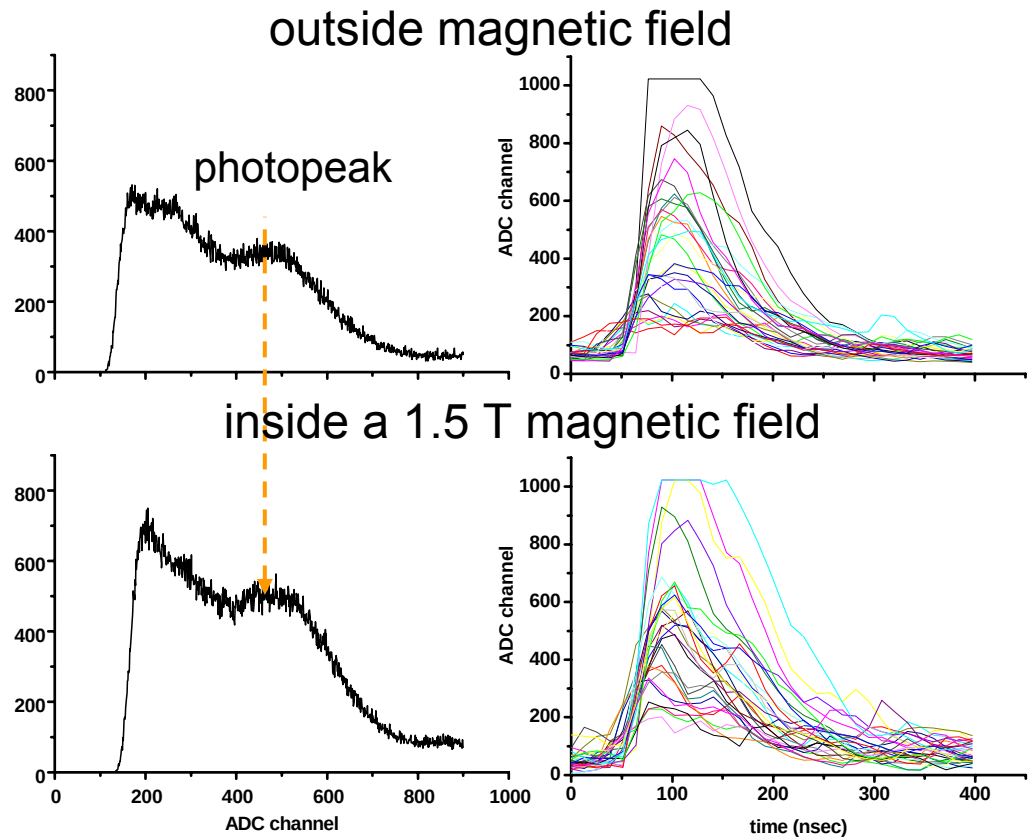
- ✓ Currently 80 MHz sampling ADC system
- ✓ Post-acquisition definition of the event time stamp using software based CFD logic
- ✓ Higher sampling rate design in progress



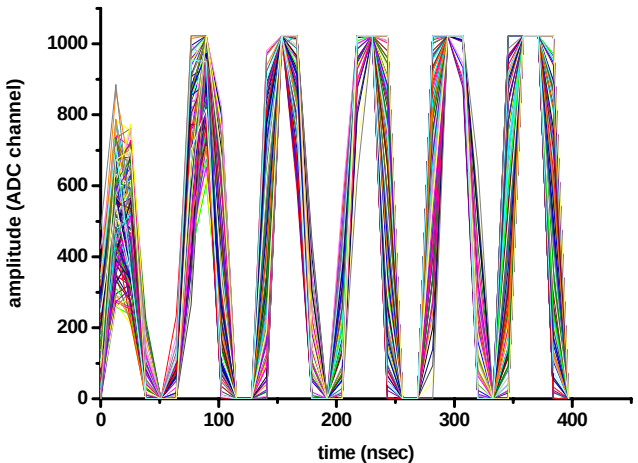
A. Mann et al. *„A Sampling ADC Data Acquisition System for Positron Emission Tomography“*
IEEE Trans. Nucl. Sci. 53(2006), pp. 297-303

MR compatibitlity

Philips Achieva, 1.5 T



RF – SiPM signal interference

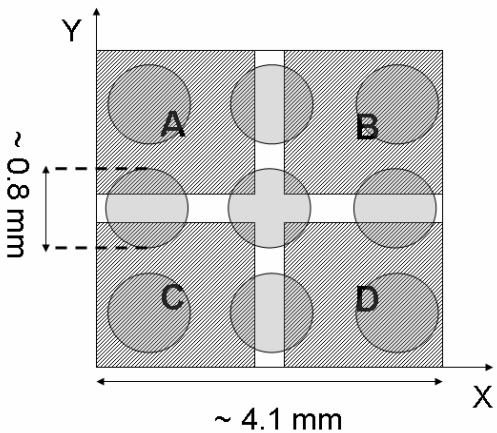


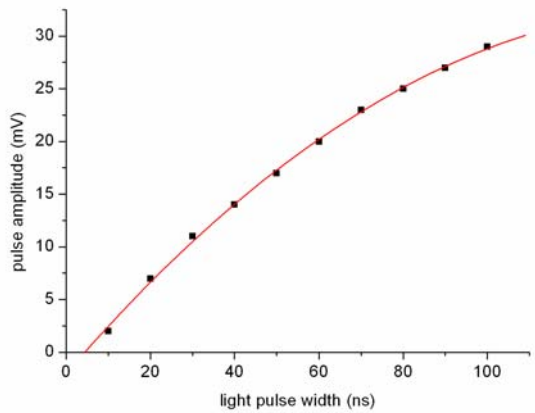
- No EMI shielding of detector module
- ~ 10 % data loss during RF signal due to ADC saturation

Planar Imaging with SiPMs

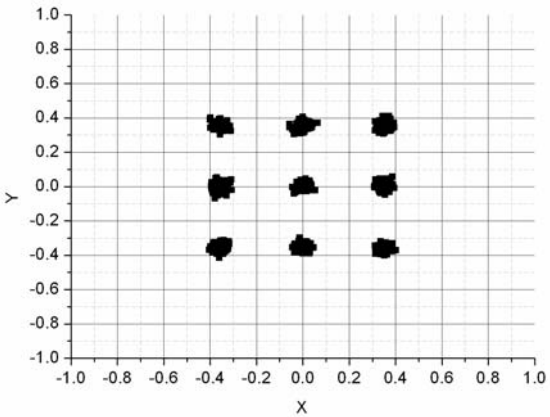
Illumination with a collimated light source at various positions and for different light-pulse widths

Setup



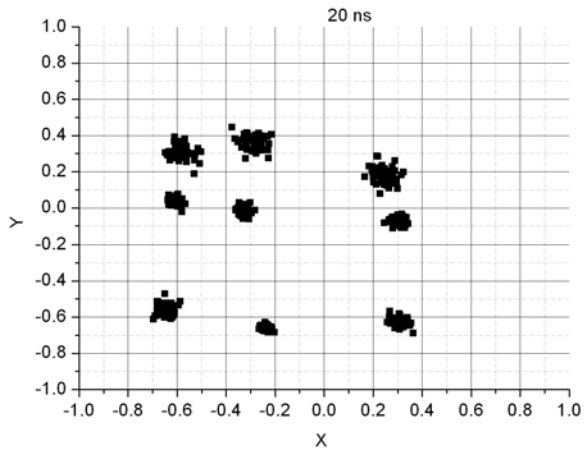


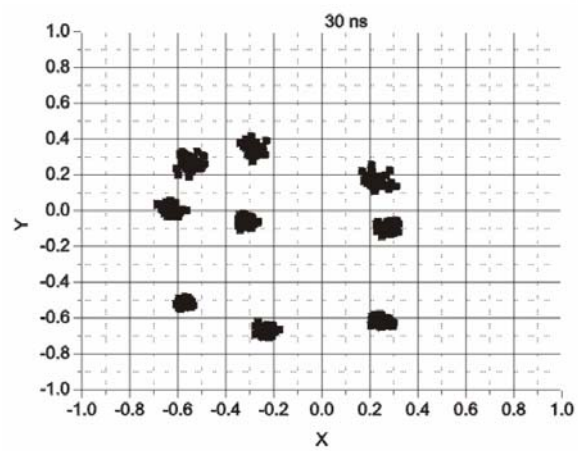
Simulation (DETECT2000)

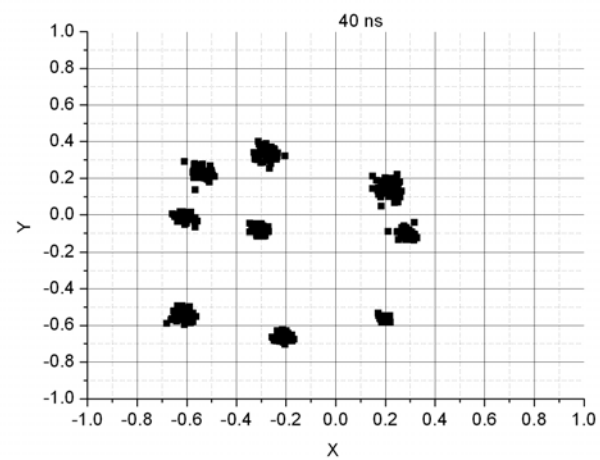


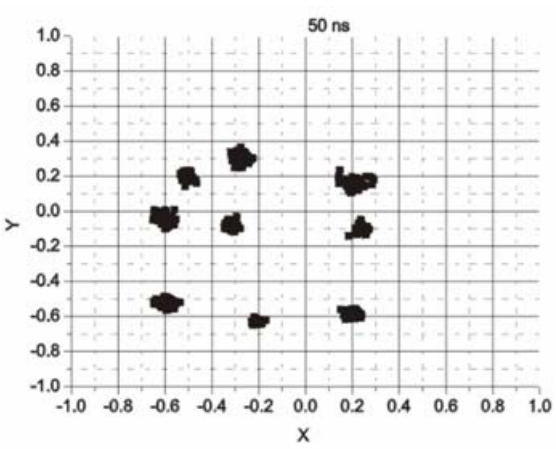
$$X = \frac{(B+D)-(A+C)}{A+B+C+D} \qquad Y = \frac{(A+B)-(C+D)}{A+B+C+D}$$

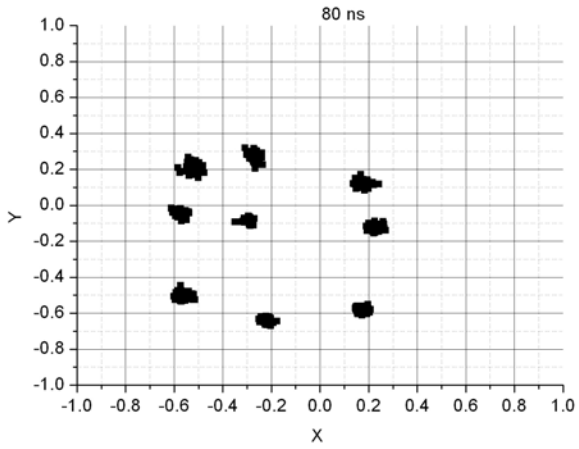
Planar Imaging with SiPMs

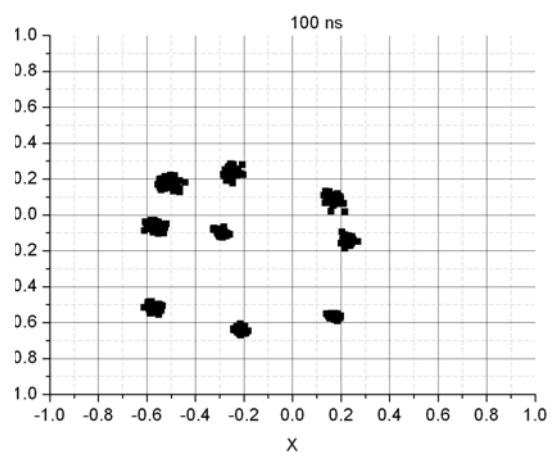












Conclusions & Future Work

- SiPMs can be an **alternative to PMTs and APDs for scintillator readout in PET and PET/MR**
- Achieved **energy resolution** of a LSO-SiPM detector (**20 %**) is degraded by current SiPM designs
(low sensitivity to blue light, small sensitive area)
- **Time resolution** against a fast scintillator/PMT is superior to LSO/APD (**1.8 nsec** for CFD time pick-off)
- **Full functionality of SiPMs inside a 1.5 T MR scanner**
- **A sampling ADC based DAQ** is under development to compensate for pulse shape variations

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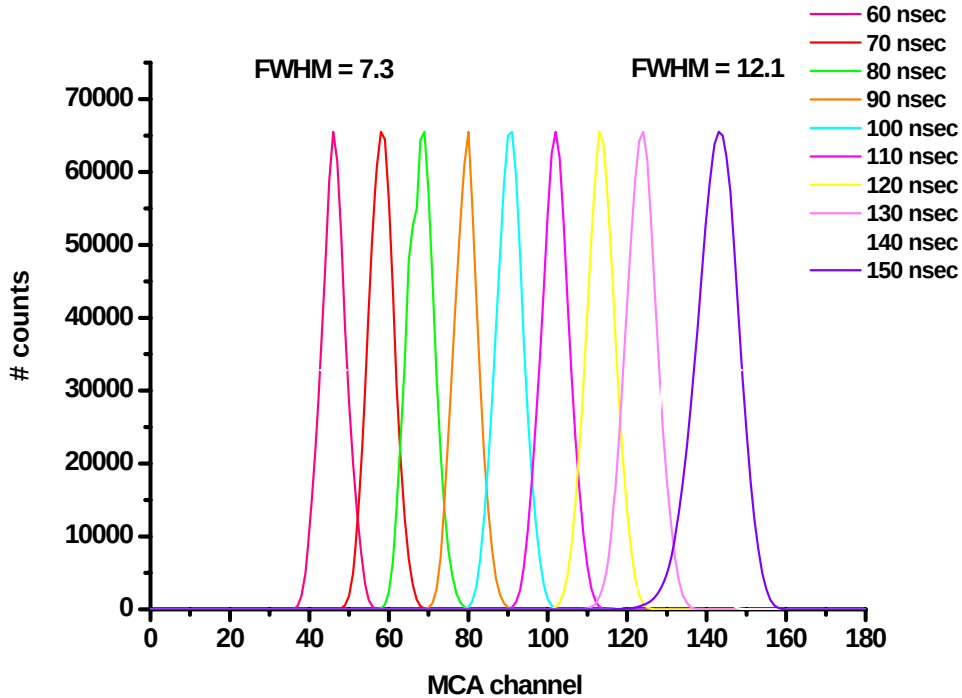
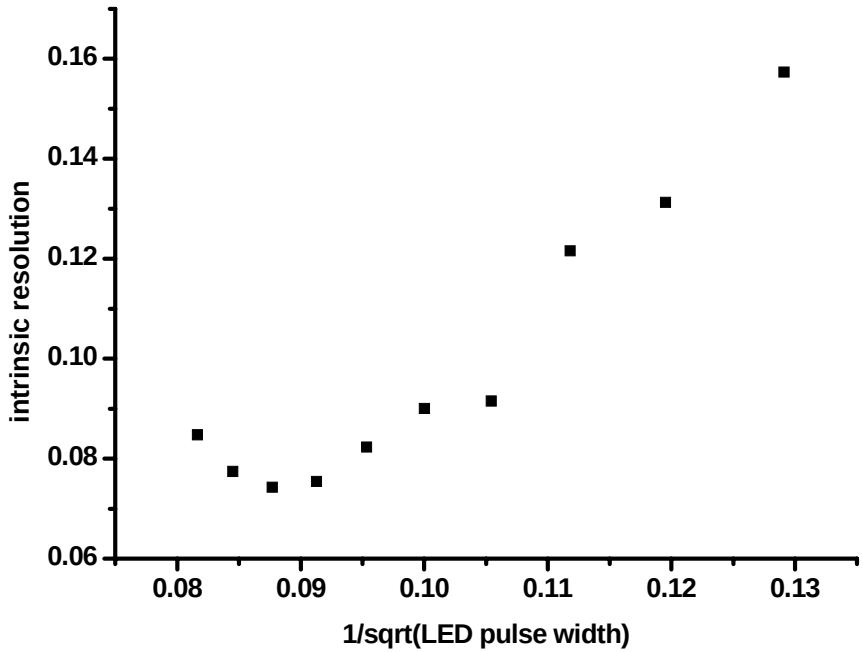
- Bavarian Research Foundation

Intrinsic Resolution



✓ Broader distribution of the delta function with increasing light pulse width

✓ Non-Poissonian behaviour of the SiPM intrinsic resolution (=FWHM/peak) @ large number of optical photons