An innovative detection module concept for PET

4D-MPET project

(**4 D**imensions **M**agnetic compatible module for **P**ositron **E**mission **T**omography)

INFN Pisa; INFN Torino; Polytechnic of Bari; University of Pisa; INFN Perugia.

Speaker:

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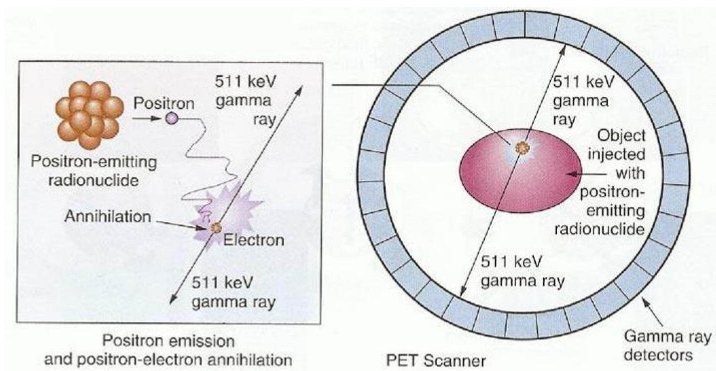
Outline

- 4DMPET Project at INFN
- Readout architecture
- Clustering and additional features
- Conclusions

Project goal

A positron emission tomography (PET) scanner detects pairs of γ-rays emitted by a positron-emitting radionuclide inside the body. 3D images of radionuclide concentration are reconstructed by computer.



Positron emission and positron-electron annihilation

PET Scanner

4DMPET goal:

The design of a PET detection module capable of working inside a magnetic resonant imaging (MRI) system.

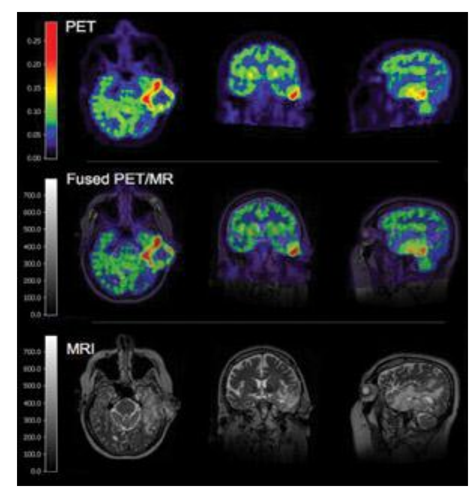
Project goal

Why PET/MRI?

Nowadays PET and MRI are performed separately in time with distinct machines:

- Two images to be merged together
- Movements of the patient on the couch
- Data corruption from image fusion techniques

Philips Ingenuity TF PET/MR Combo



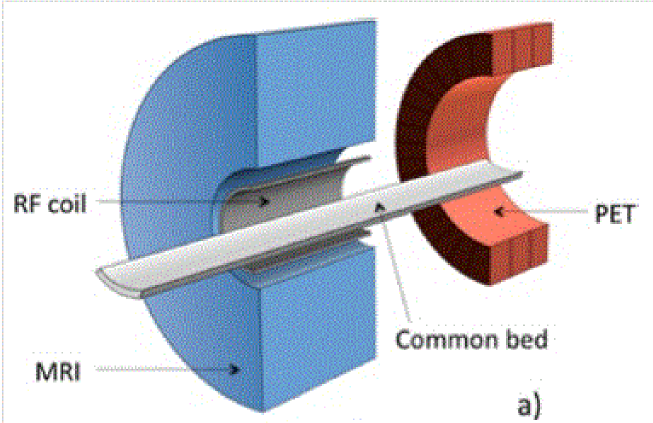
PET and MRI image fusion

Project goal

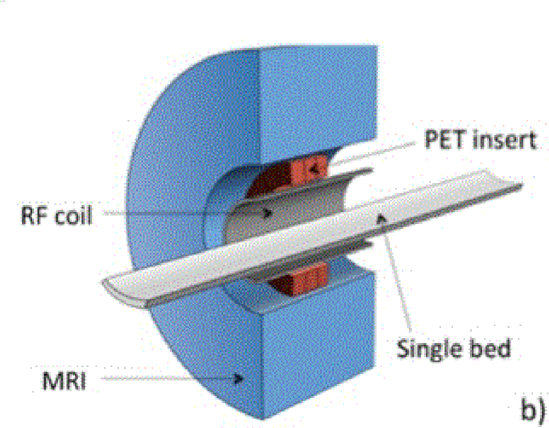
Why PET/MRI?

Hybrid PET/MRI systems provide functional and morphological information *at the same time*:

- No image fusion required
- Space and costs saving
- Better soft tissue contrast
- Lower radiation doses



Separated PET and MRI rings



Hybrid PET/MRI scanner

Main features

- Silicon Photomultipliers (SiPM) coupled to a single LYSO scintillator crystal:
  - MRI compatible detectors
  - x and y coordinates determined with high precision [1]
- Time of Flight (TOF):
  - Reduces image background noise [2]

$$\frac{S/N_{tof}}{S/N_{non-tof}} = \sqrt{\frac{2D}{c\Delta t}}$$

D = object size

Δt = time resolution

- Depth of Interaction (DOI):
  - Decreases the uncertainty of the z coordinate [3]
- Integrated readout electronics for compact time and energy measurement

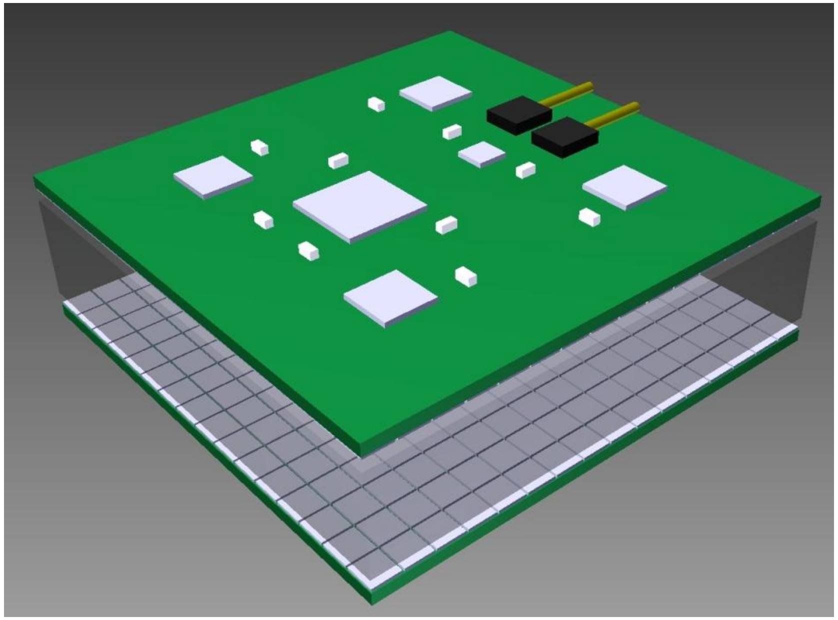
Detection module layout

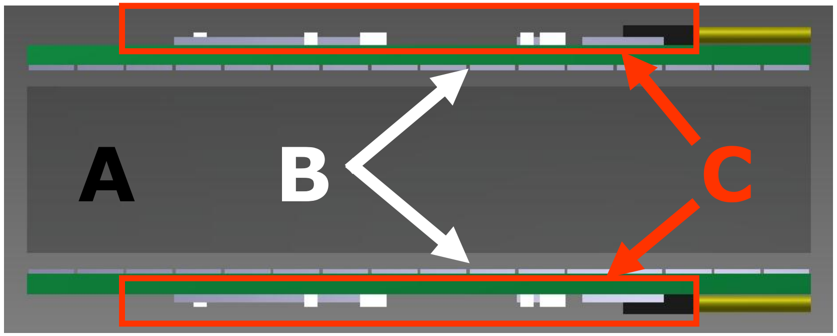
A. LYSO scintillator slab of 48 mm × 48 mm × 10 mm (τ_{decay} = 40 ns)

B. Top and bottom SiPM layers:

- 16 x 16 square pixels
- 3 mm pixel pitch
- microcell size of 50 μm

C. Independent and identical readout boards





side view

Detection module layout

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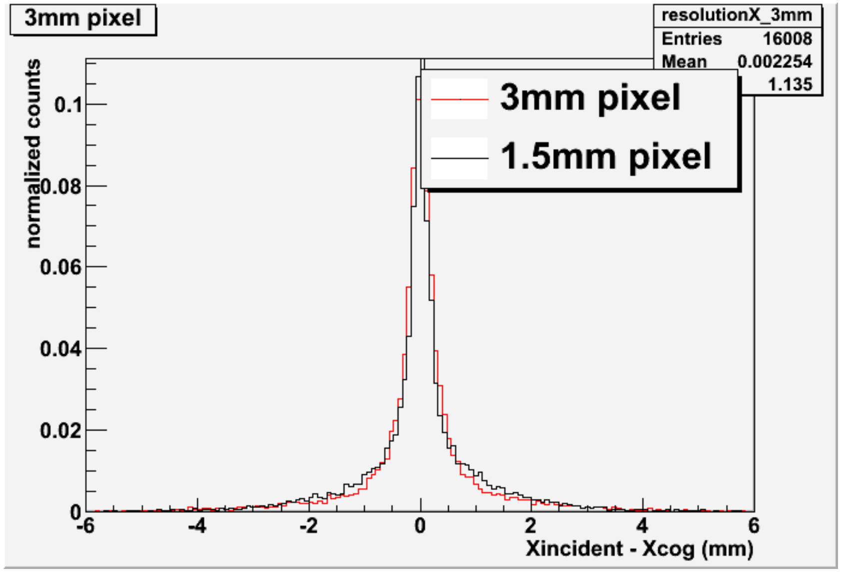
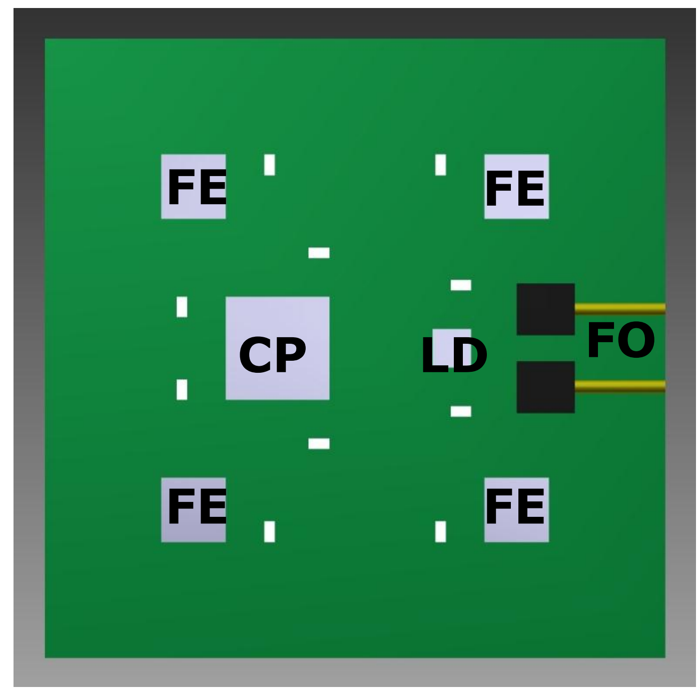
Pixel size	1.5 mm	3 mm
σ (mm)	1.14	1.13
FWHM (mm)	0.32	0.48
FWTM (mm)	1.61	1.44



F. Pennazio *et al.*, "Simulations of the 4DMPET SiPM Based PET Module", 2011 IEEE Nuc. Sci. Symp./Med. Imag. Conf.

Detection module layout

- 4 front-end (FE) mixed-mode ASIC's (64 channels each)
- Cluster processor (CP) ASIC
- Laser driver/photodiode receiver/clock reconstruction (LD) ASIC
- Fibre-optics (FO)

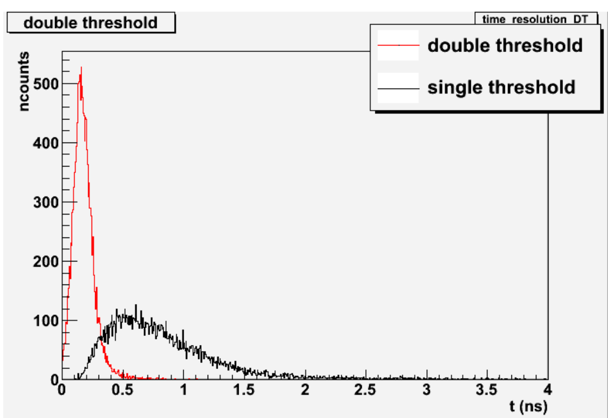


top view

- Communication through LVDS pads
- Wire-bonded without package

Front-end mixed-mode ASIC

- Double threshold technique for very high resolution TOF (σ_{LSB}=100ps):
  - Low threshold on single *ph-e* for an efficient measure of the interaction time
  - High threshold to discriminate events from noise (SiPM dark count ~ 2 MHz/mm^2 @ 27°C)



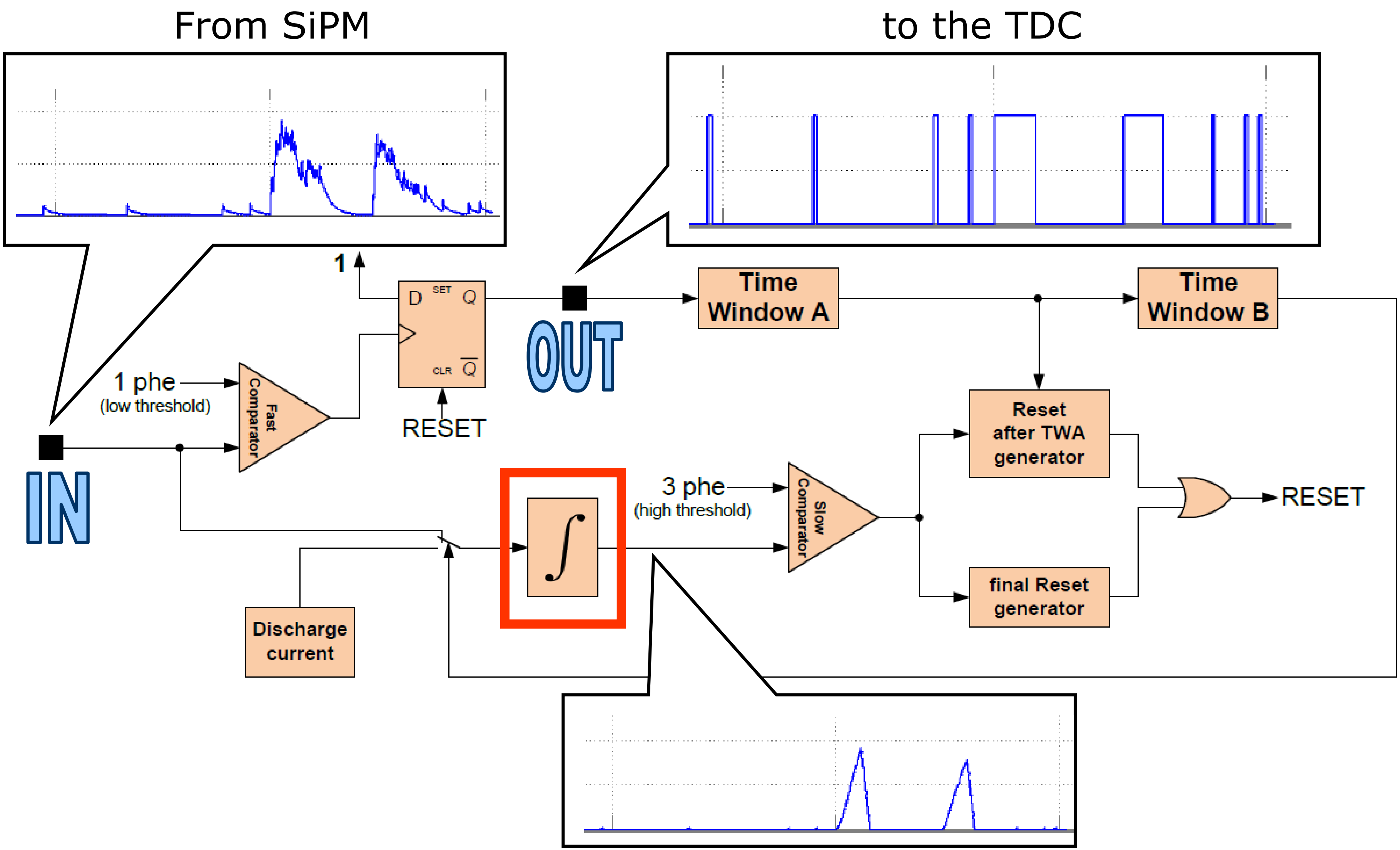
Double threshold	
σ (ns)	0.102
FWHM (ns)	0.160
FWTM (ns)	0.326

F. Pennazio *et al*., "Simulations of the 4DMPET SiPM Based PET Module", 2011 IEEE Nuc. Sci. Symp./Med. Imag. Conf.

Front-end mixed-mode ASIC

- Multiple channels (256 total)
- Energy evaluation based on Time Over Threshold (TOT) technique
- Two conversion levels:
  - From SiPM outputs to digital pulses (front-end, AMS 0.35μm SiGe-BiCMOS)
  - From digital pulses to TOF+TOT information (Time to Digital Converter, UMC 65nm)

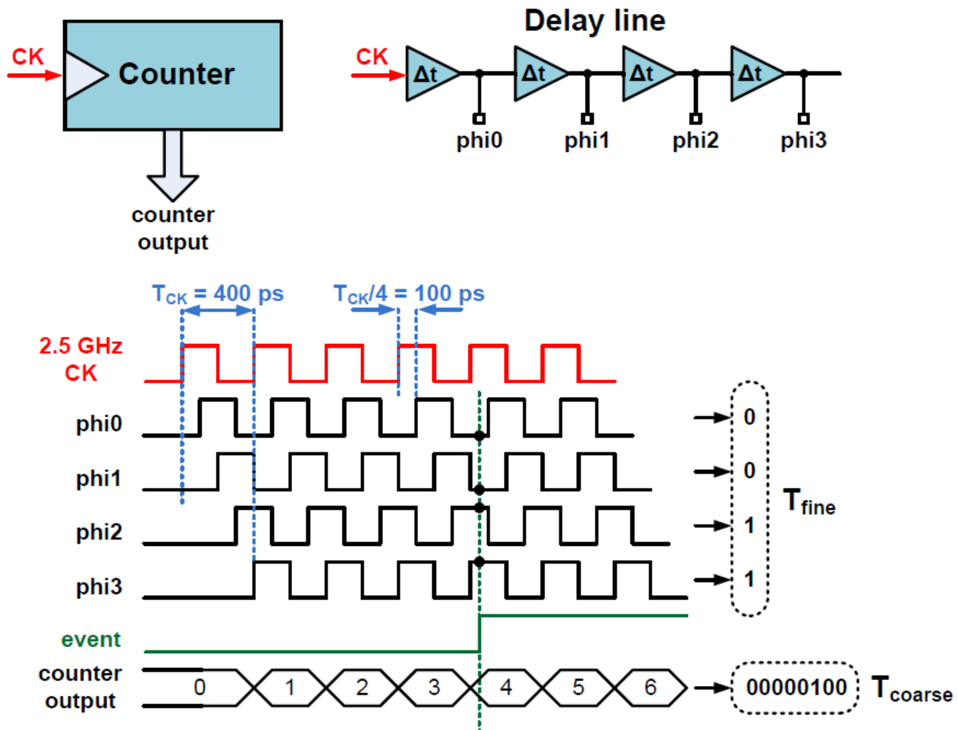
Front-end mixed-mode ASIC



Front-end mixed-mode ASIC

- Current mode approach for high resolution TOF:
  - Compatible with CMOS (current mirrors)
  - Very low R_{in} for fast response
  - Wide bandwidth
- Programmability for calibration via on-chip DACs:
  - Time windows (A,B)
  - High threshold
  - Discharge current
- Signal shaping:
  - No constraints on the stability and uniformity of the signal
  - Lower precision required for the TOT measurement

Time to Digital Converter (TDC)



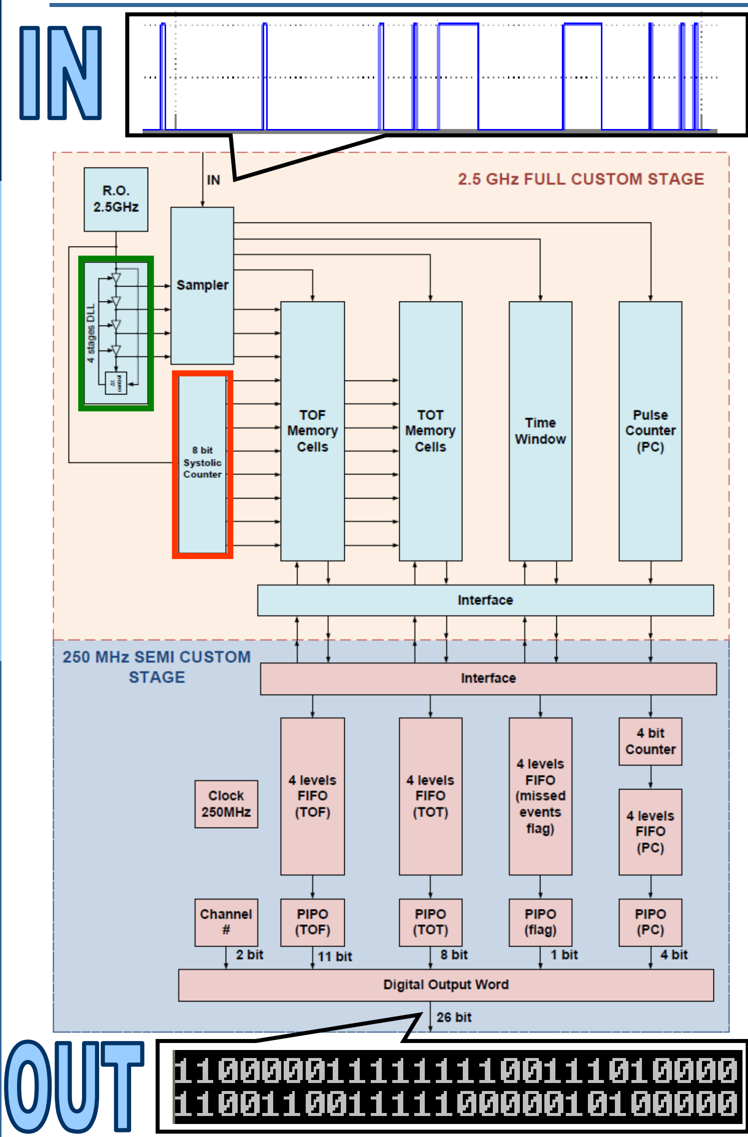
Rising and falling edge of events are measured by sampling:

- 8 bit systolic counter:
  - Coarse time T^c
  - T^c_{LSB} = 400 ps
- 4 stages delay-locked-loop:
  - Fine time T^f
  - T^f_{LSB} = 100 ps

TOF = T^c + T^f (rising edge)

TOT = T^c (falling edge)

Time to Digital Converter (TDC)

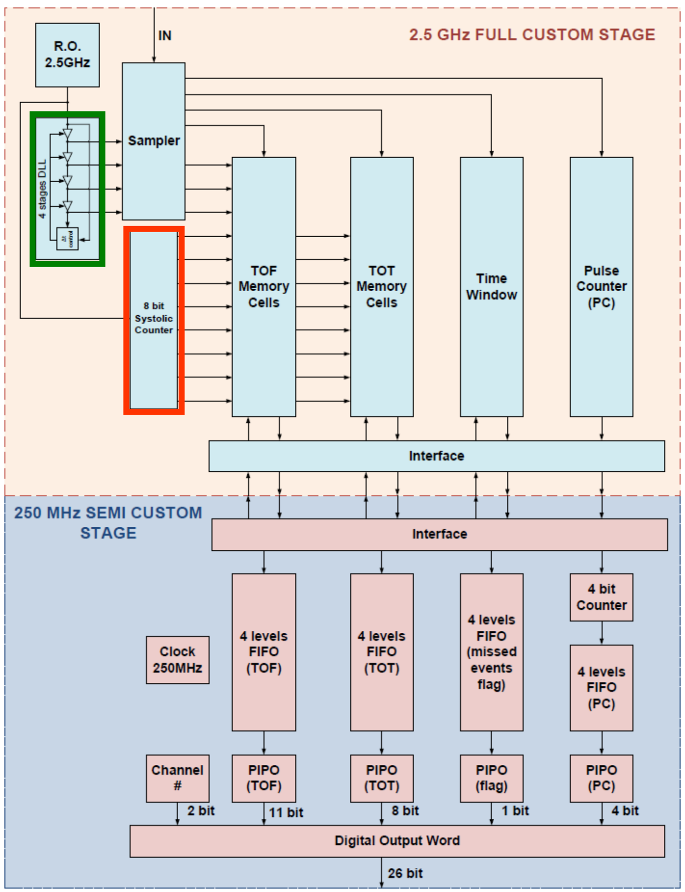


from the front-end

- TOF timestamp: 100 ps
- TOT timestamp: 400 ps
- Nominal σ_{LSB} (TOF): 29 ps
- Dynamic range: 102.4 ns
- Double hit res.: 70 ns
- 26 bit digital output word
- Other features:
  - Total pulses count
  - Missed event flag

to the cluster processor

Time to Digital Converter (TDC)



- TOF timestamp: 100 ps
- TOT timestamp: 400 ps
- Nominal σ_{LSB} (TOF): 29 ps
- Dynamic range: 102.4 ns
- Double hit res.: 70 ns
- 26 bit digital output word
- Other features:
  - Total pulses count
  - Missed event flag

output: 11001100111110000010100000

Ch# | flag | TOF | TOT | pulses cnt

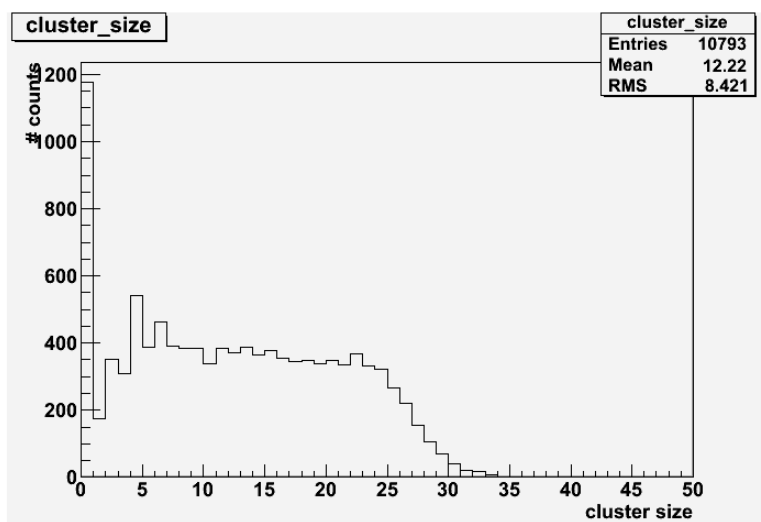
missed event 11100000000000000000000000

Cluster processor ASIC

It reduces the amount of data to be sent to the external acquisition system.

Three *cluster finding* algorithms investigated:

- Timestamp clustering
- Timestamp and spatial clustering
- Timestamp and spatial clustering with centroid



Cluster processor ASIC

Asymmetry in the cluster size on the two crystal faces can be exploited for DOI evaluation:

$$z_{est} = D + \frac{D}{2}\left(\frac{n_{down} - n_{up}}{n_{down} + n_{up}}\right)$$

D=detector depth; n_{up}=top face cluster size; n_{down}=bottom face cluster size.

Estimation of the DOI based on the resulting fitted calibration curve has shown a z resolution of 1.3 mm FWHM [4].

Additional features (ongoing…)

- LD ASIC to minimize the number of communication devices to one optical input and one optical output
- Active temperature control:
  - To reduce the SiPM dark count
  - To avoid degradations in the electronics performance
- Shielding to relax MRI compatibility requirements
- Two modes of operation:
  - Clinical (TOF [coarse + fine], TOT)
  - Pre-clinical (coarse timestamp only, TOT)

Conclusions

An innovative PET detection module MRI compatible is under development featuring:

- LYSO coupled to 3 mm pitch SiPM on both faces
- Large detection area (48 mm x 48 mm)
- 8(coarse) + 4(fine) bits for TOF with σ_{LSB} of 29 ps
- 8 bits energy information based on TOT
- DOI with a resolution of 1.3 mm FWHM
- Clustering algorithms for smart data reduction

Conclusions

- 4-channels prototypes of the front-end and TDC ASICs will be submitted during 2012
- Software algorithms for the cluster processor are being studied

	Our solution	Philips Gemini TF PET/CT	Siemens Biograph mMR MR/PET
Hybrid PET/MRI	**Yes**	**No**	**Yes**
Scintillator crystal	**LYSO**	**LYSO**	**LSO**
Crystal size (mm)	**48 x 48 x 10**	**32 x 32 x 22**	**32 x 32 x 22**
Detectors	**SiPM**	**PMT**	**APD**
#channel ASIC	**256**	**N.A.**	**9**
TOF	**Yes (100 ps)**	**Yes (650 ps)**	**No**

References

[1] C. Piemonte *et al.*, "Characterization of the First Prototypes of Silicon Photomultiplier Fabricated at ITC-irst", *IEEE Trans. on Nucl. Science*, Vol. 54, N. 1 February 2007, pp. 236-244. MIC Conf. Record CD-ROM (N41-2),2007.

[2] W. Moses, "Recent Advances and Future Advances in Time-of-Flight PET", *Nucl Instrum Methods Phys Res* A. 2007 October 1; 580(2): 919–924.

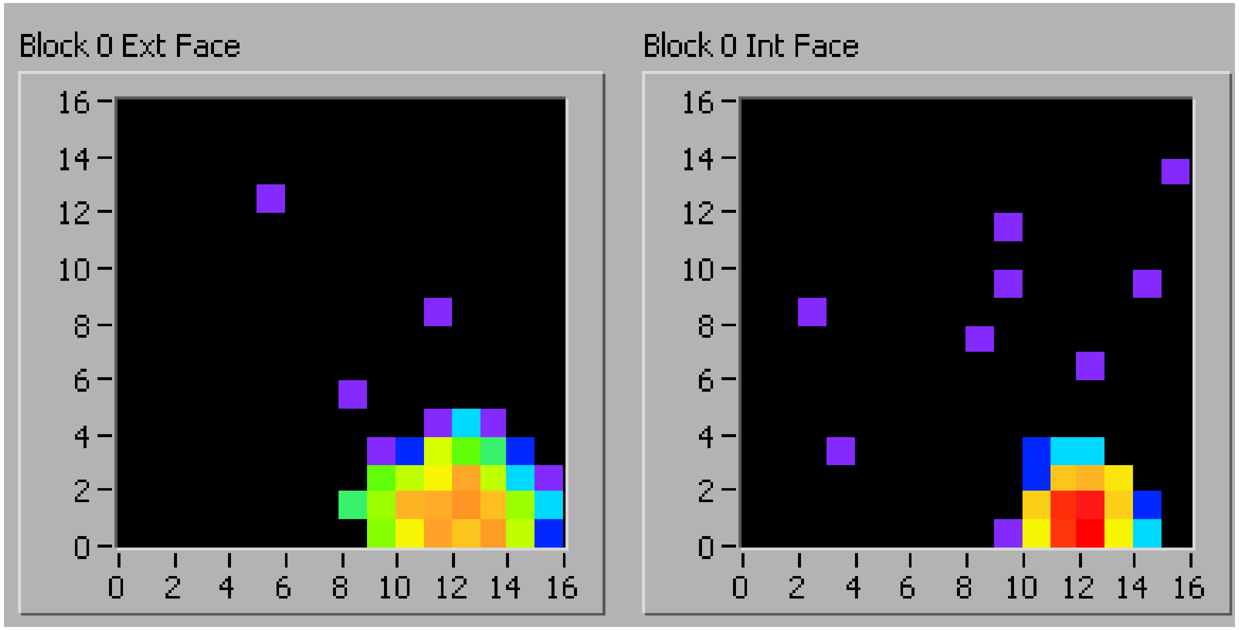
[3] S. E. Derenzo, W. W. Moses, R. H. Huesman and T. F. Budinger, "Critical instrumentation issues for 2 mm resolution, high sensitivity brain PET", in *Quantification of Brain Function*, K. Uemura, N.A. Lassen, T. Jones, *et al.*, Amsterdam: Elsevier Science Publishers, 1993 pp. 25-37.

[4] F. Pennazio *et al.*, "Simulations of the 4DMPET SiPM Based PET Module", *IEEE Nuclear Science Symposium / Medical Imaging Conference,*M6-5, 2316-2320, Valencia, Spain, 2011.

FE specifics

- R_{in} = 17 Ω
- BW = 250 MHz
- C_{out} = 28 pF (FBK IRST, 625 cells)
- C_{out} = 300 pF (Hamamatsu, 3600 cells)

Timestamp and spatial clustering with centroid



Event not contained within the readout face