DEVELOPMENT AND CHARACTERIZATION OF A SCALABLE TOF-PET DETECTOR FOR TOTAL-BODY APPLICATIONS

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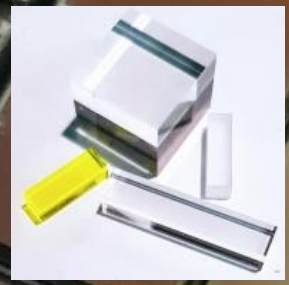
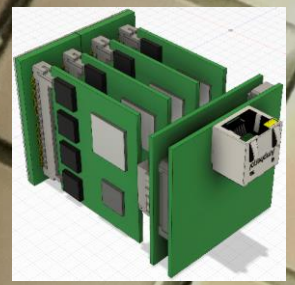
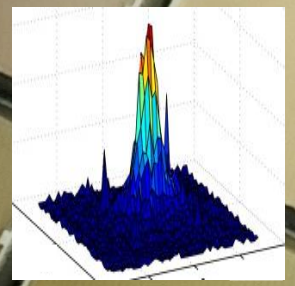
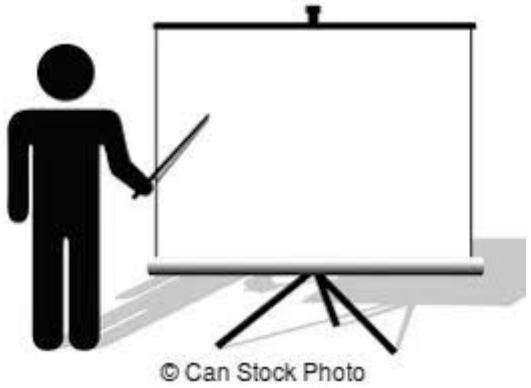






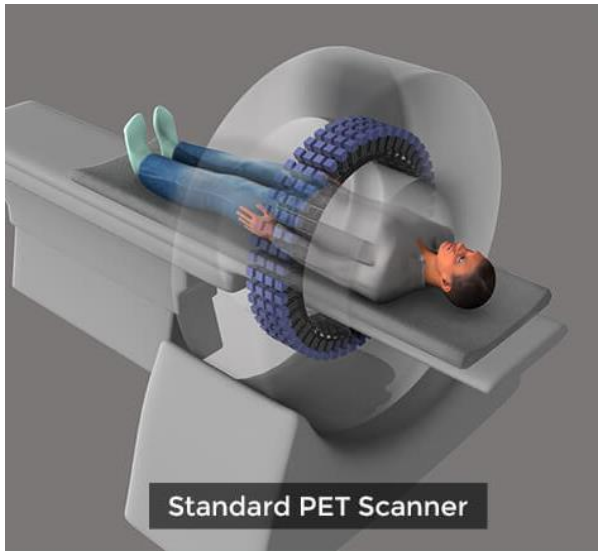
Presentation outline

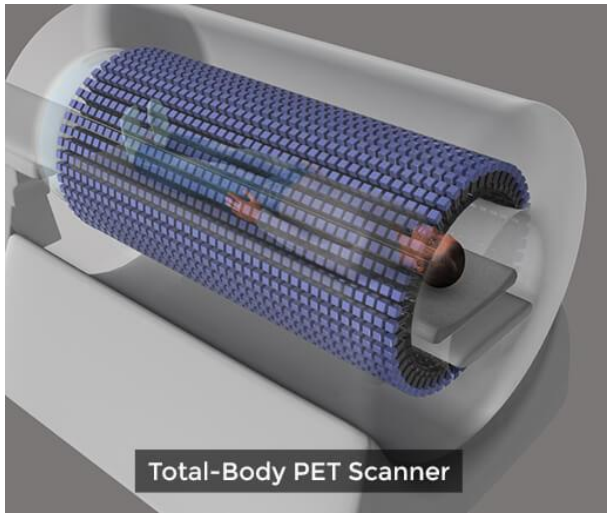
- Total body PET and Time-of-Flight PET
- The UTOFPET project
- Detector design: scintillator, photosensor and front-end electronics
- Data acquisition system
- Experimental results: event positioning and time resolution
- Conclusions



Total-body PET

- Total body PET consists in realizing scanners with very long axial coverage
- This can bring a 40-fold increase in sensitivity
- Challenges
  - High number of detectors
  - Huge amount of data generated



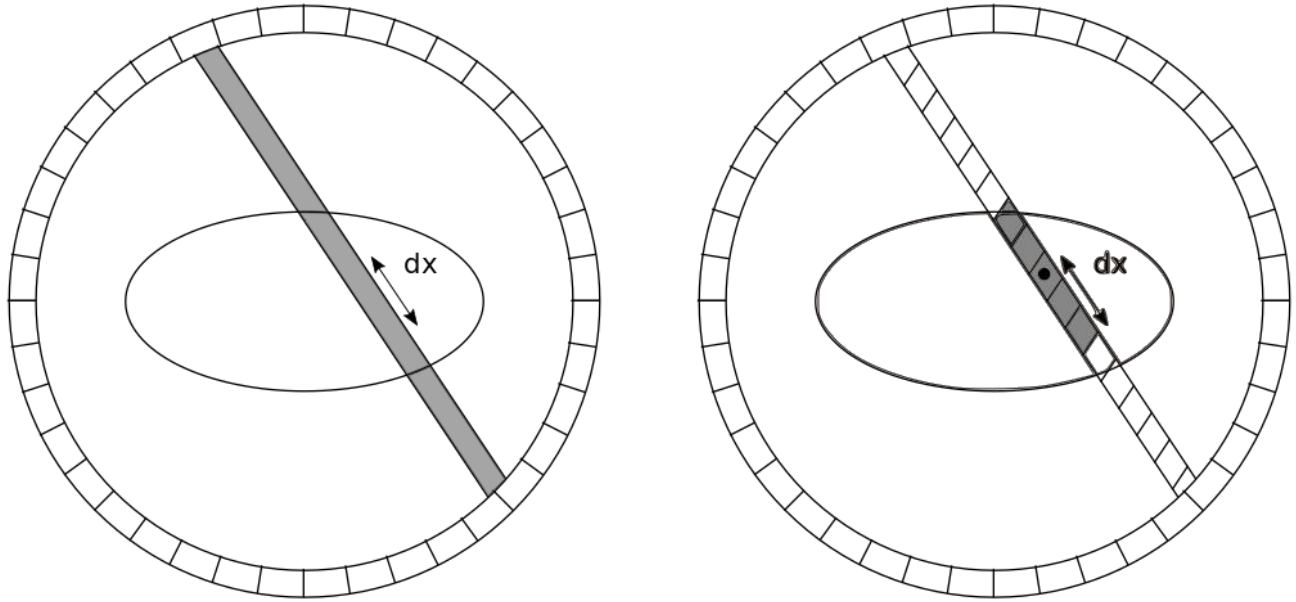


Time-of-flight PET

- Time of flight improves SNR by better localizing the photon emission position
- The improvement factor is

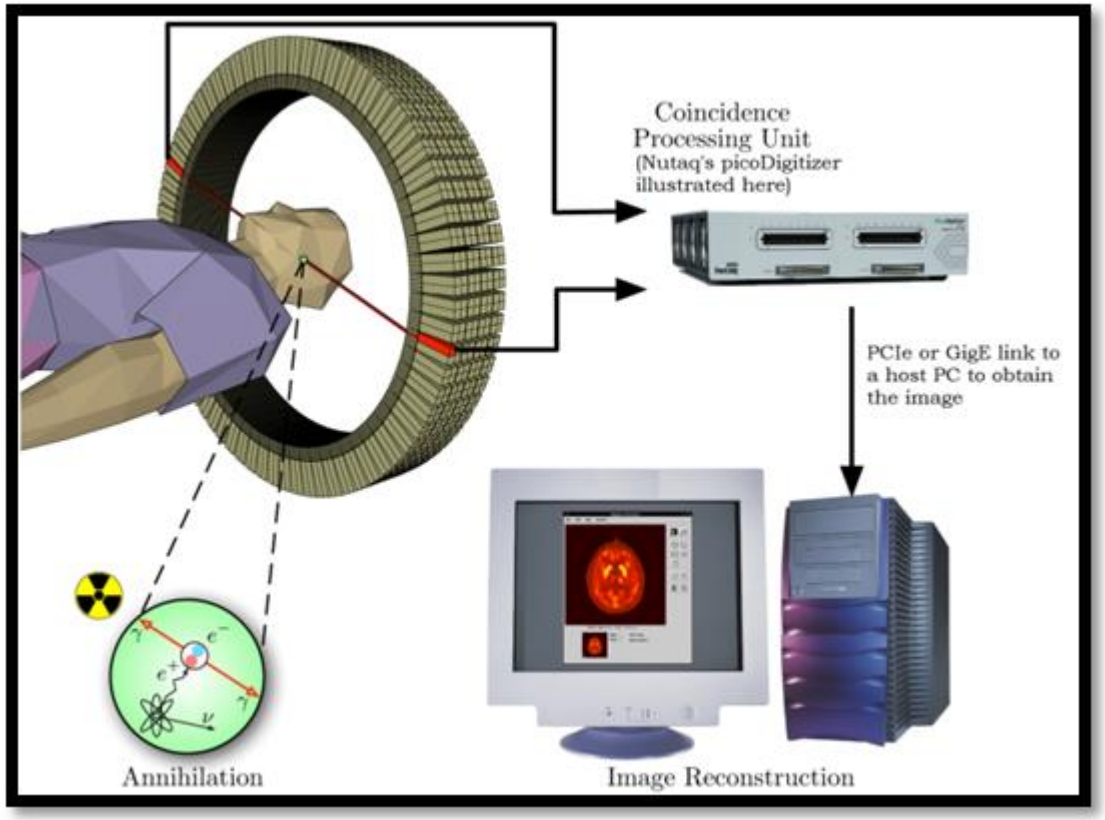
$$SNR_{gain} = \sqrt{\frac{1}{\alpha^2} \cdot \frac{D}{c\,\Delta t/2}}$$

- $\alpha \approx 1.5$ is an empirical factor



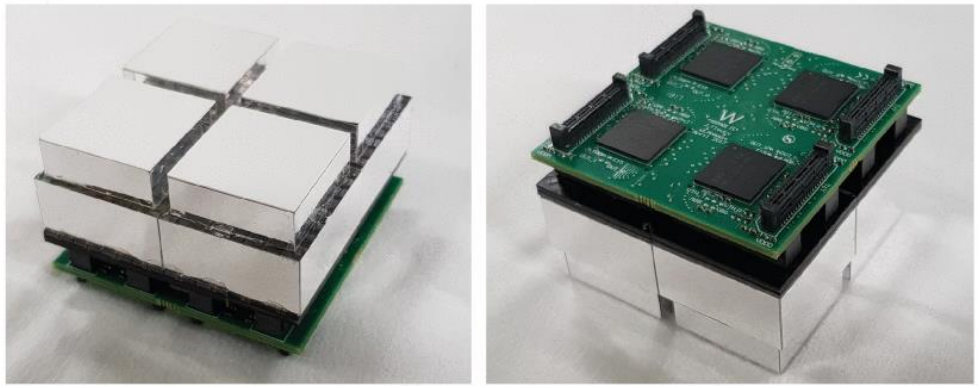
The UTOFPET project

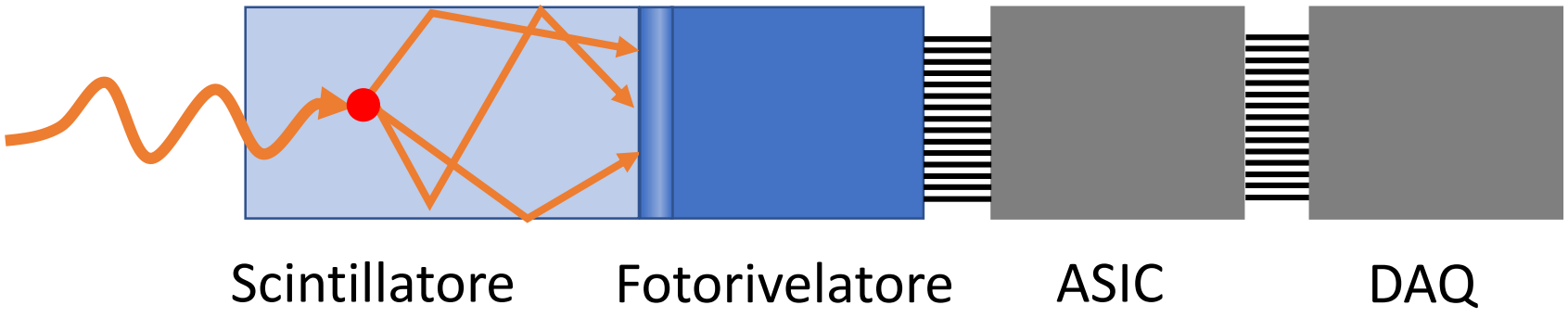
- PET detector prototype
  - Very good time resolution (CTR < 200 ps)
  - Intrinsic spatial resolution below < 1 mm
  - High count rate (1 MHz on a 25 cm^2 area)
  - Fully autonomous and modular, thus infinitely scalable



Components of a PET detector

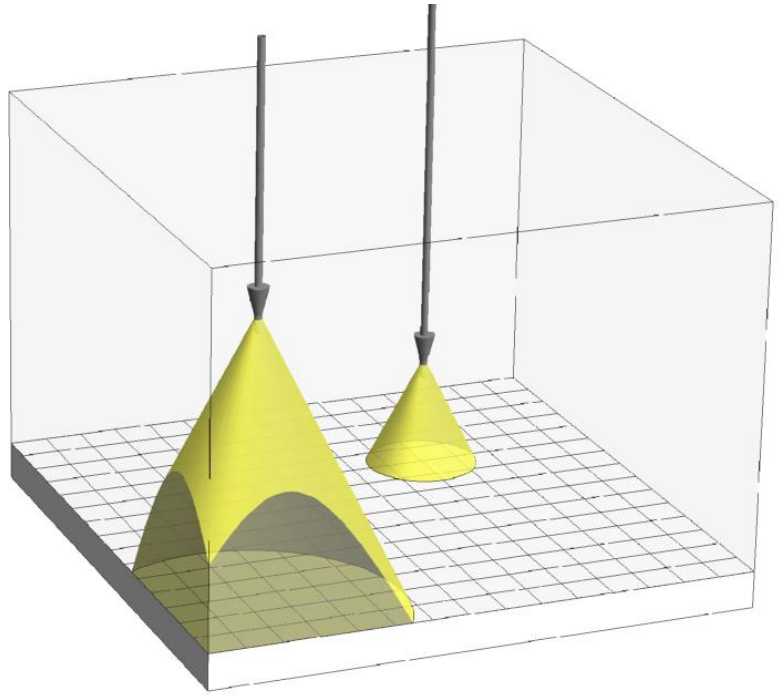
- Scintillating crystal
- Photodetector
- Read-out electronics (ASIC)
- Acquisition system (DAQ)

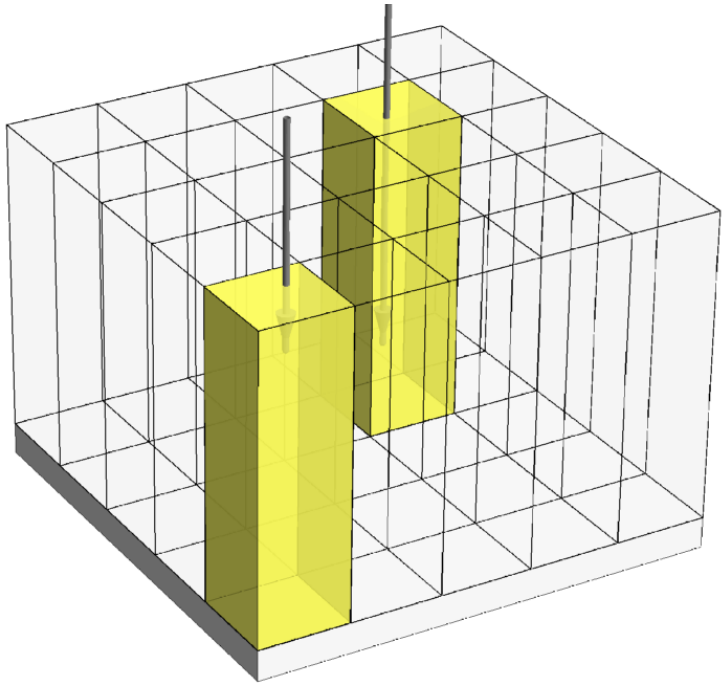


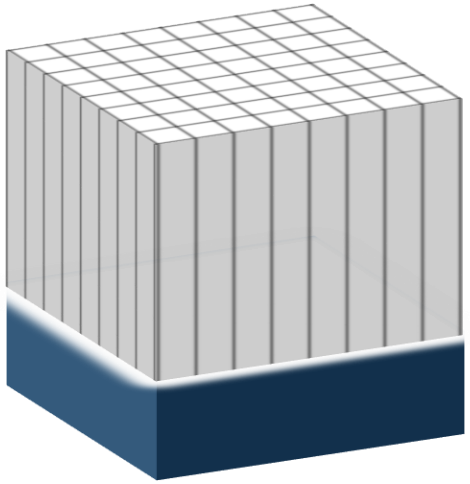


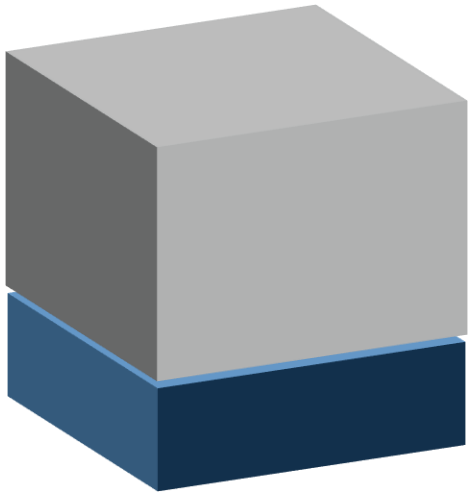
Scintillating crystal

- Pixellated crystals make it easier to reach very good timing
- However time resolution degrades rapidly with the increase of crystal length
- Monolithic crystals offer DOI correction



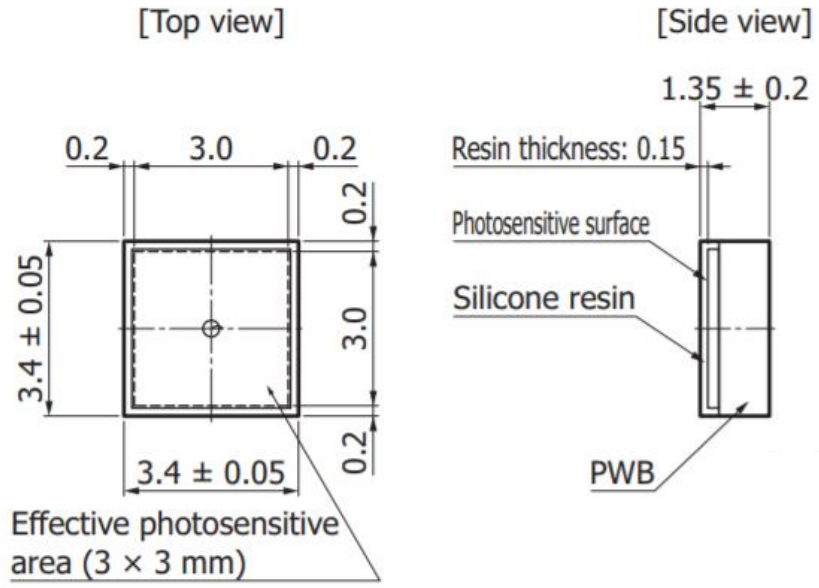


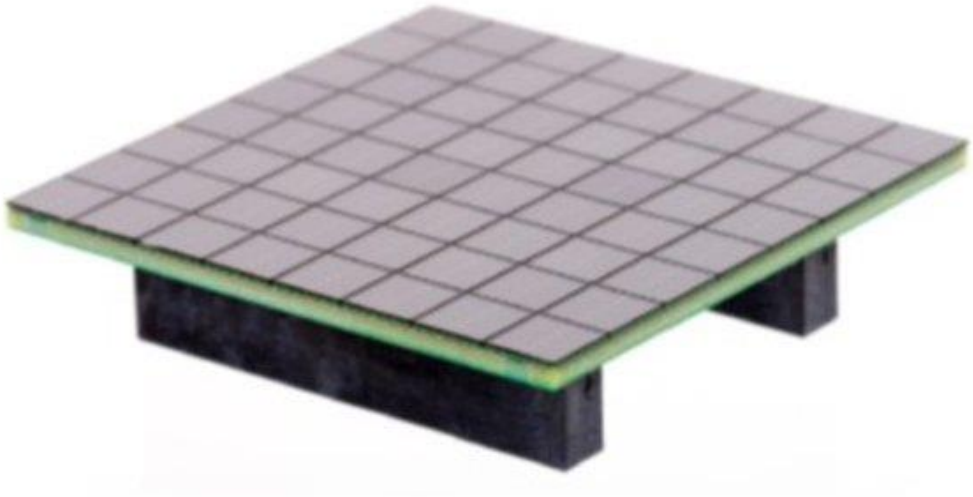




Photodetector

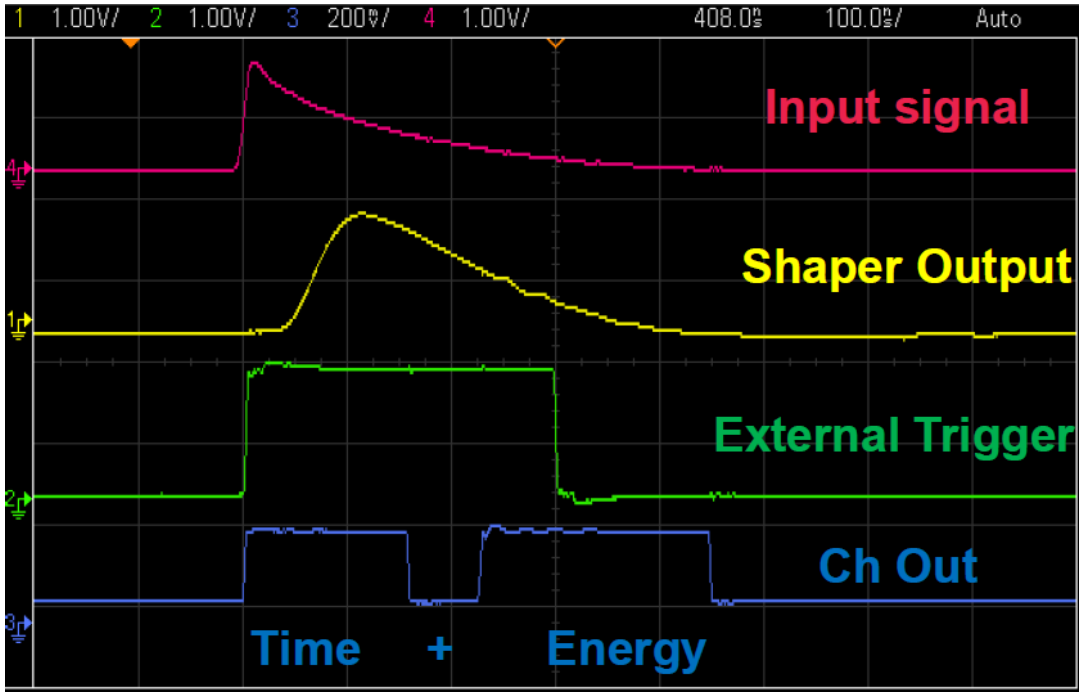
- 256 silicon photomultipliers arranged in a 16 x 16 matrix
- Two possible sizes:
  - 16 x 3.4 mm x 3.4 mm -> 54.5 mm
  - 16 x 4.4 mm x 4.4 mm -> 70.4 mm
- Broadcom, Hamamatsu and ONSemi SiPMs have all been evaluated, obtaining time resolutions below 200 ps with all of them.

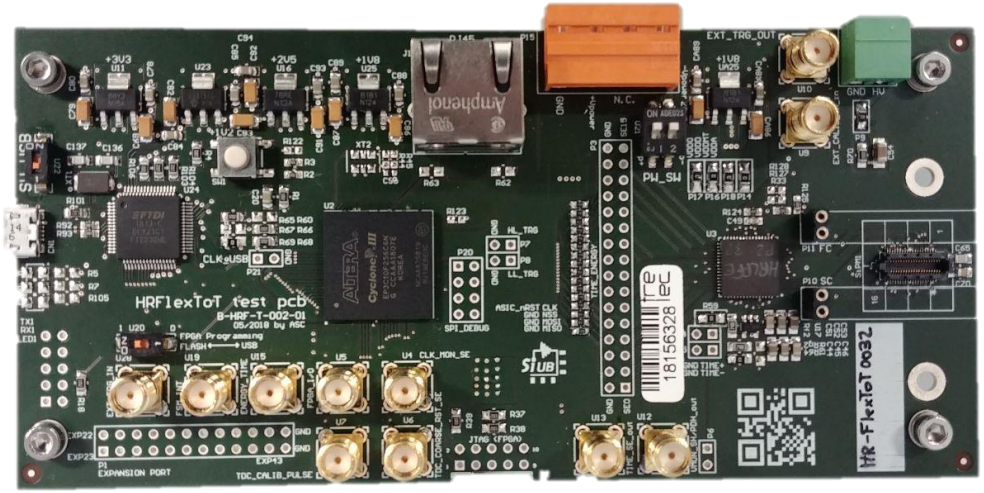




Electronics: ASIC

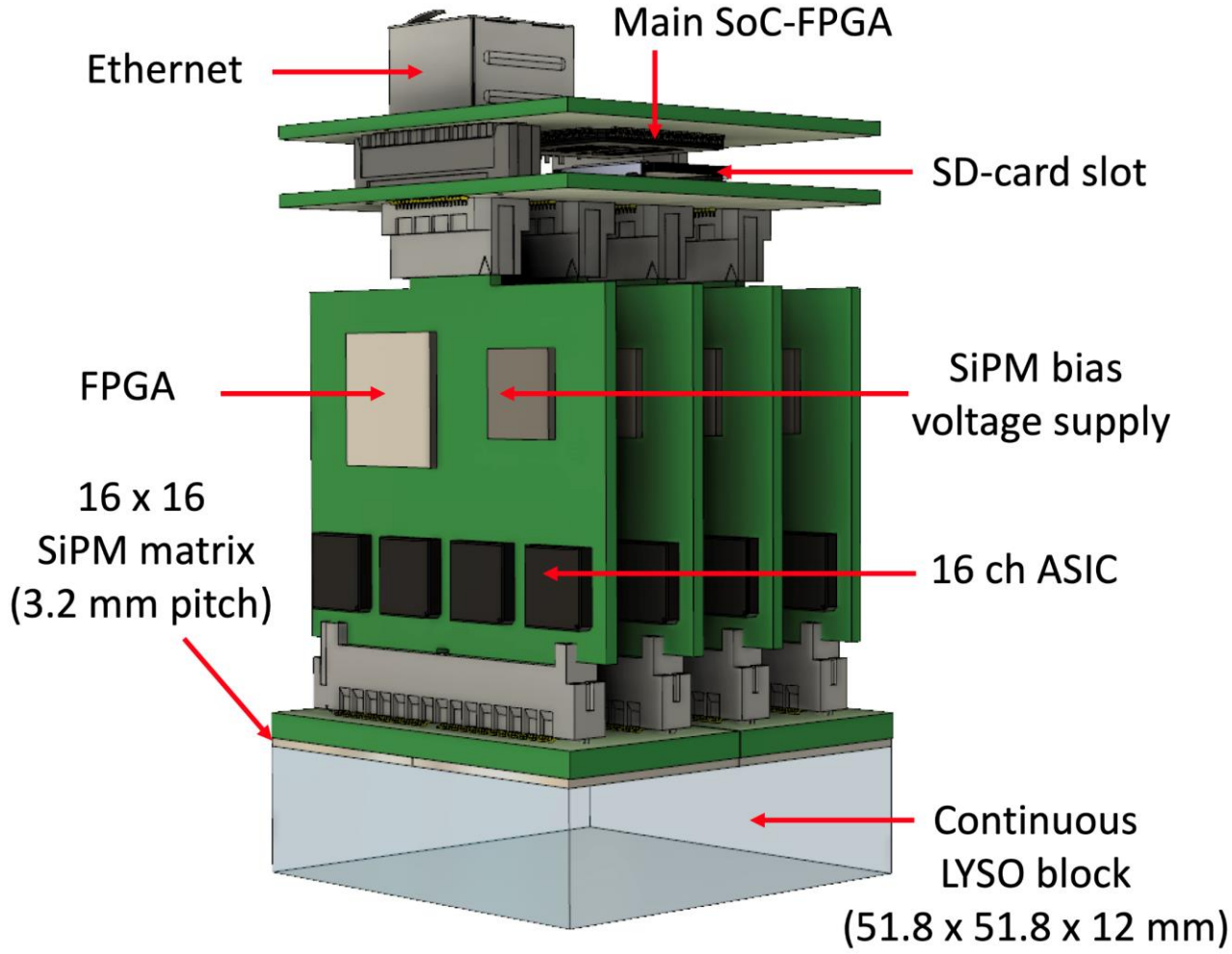
- The HRFlexTOT is a 16-channel ASIC.
- 16 ASICs will be needed to read 256 canali
- **Very low power consumption: 3.5 mW per channel**
- Linear energy measurement
- The ASIC output must be measured inside the DAQ system
- 1 pin for each output channel: 256 pins





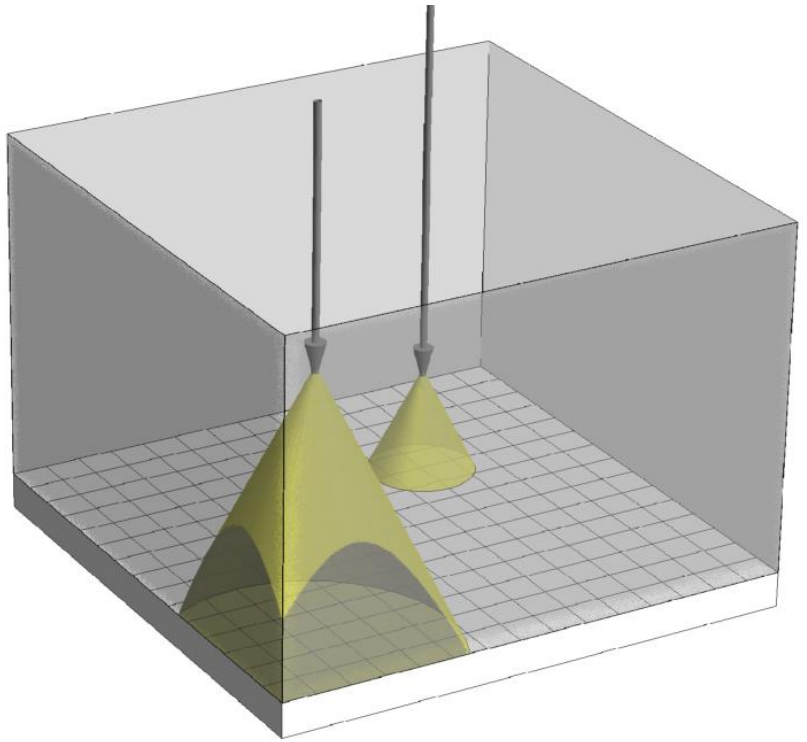
Elettronics: data acquisition system

- The DAQ is fully autonomous
- 4 low-cost FPGAs for ASIC read-out
- 1 main SoC-FPGA for module configuration, interfacing and data storage
- SD card, ethernet and USB connection
- Power over ethernet



Event positioning

- The use of a monolithic crystal makes it harder to place the event in the matrix
- We used simulated data generated by Ghent University with Geant 8.0
- The lateral crystal sides are modelled as rough surfaces painted with black paint, while the top is polished and covered with a specular reflector.



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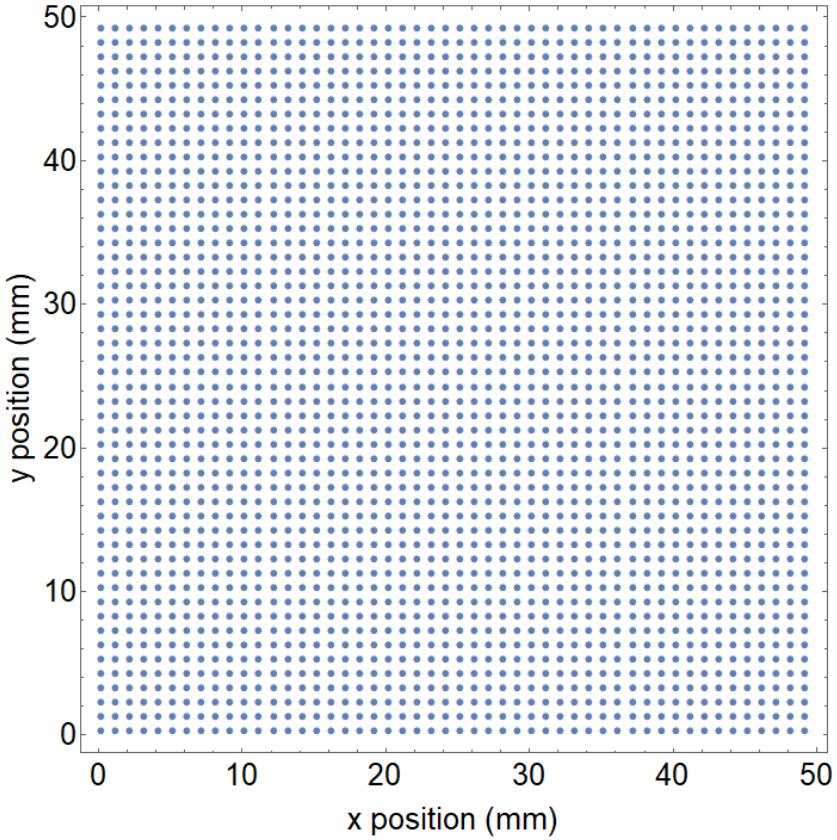
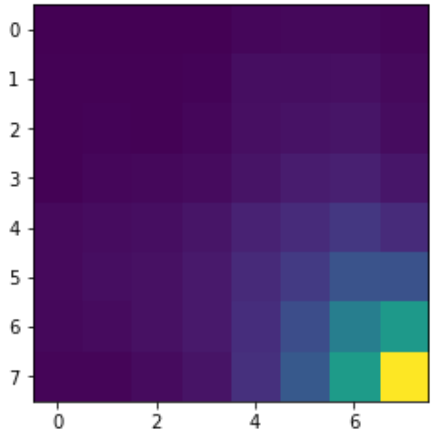
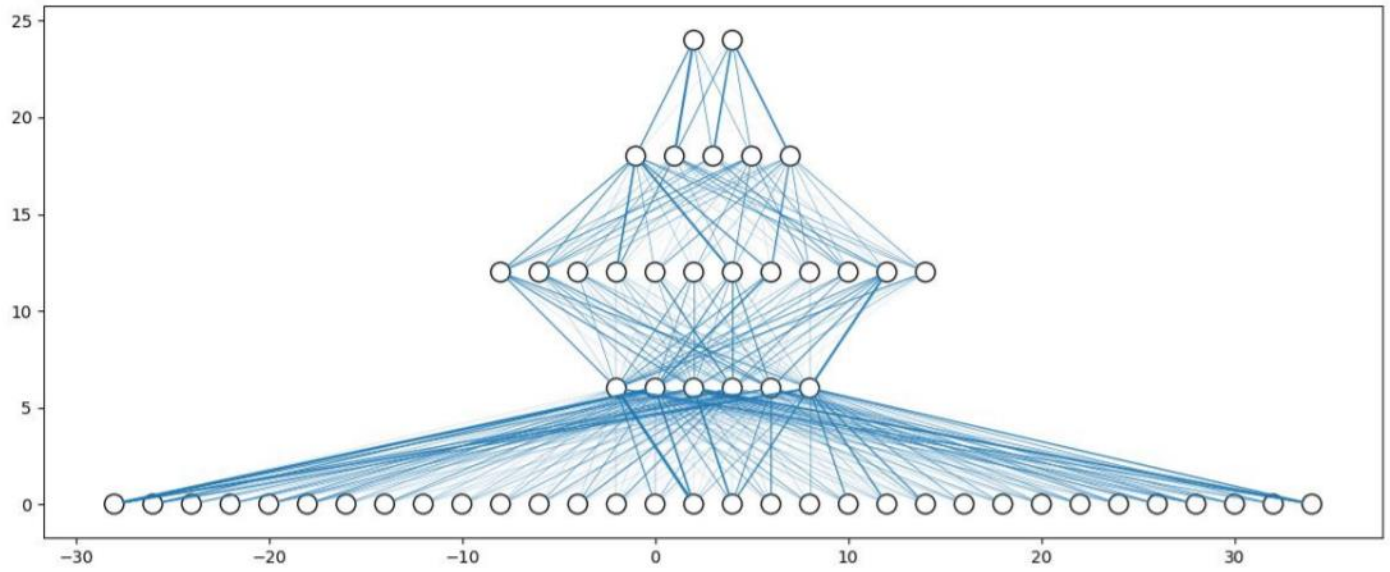




Event positioning

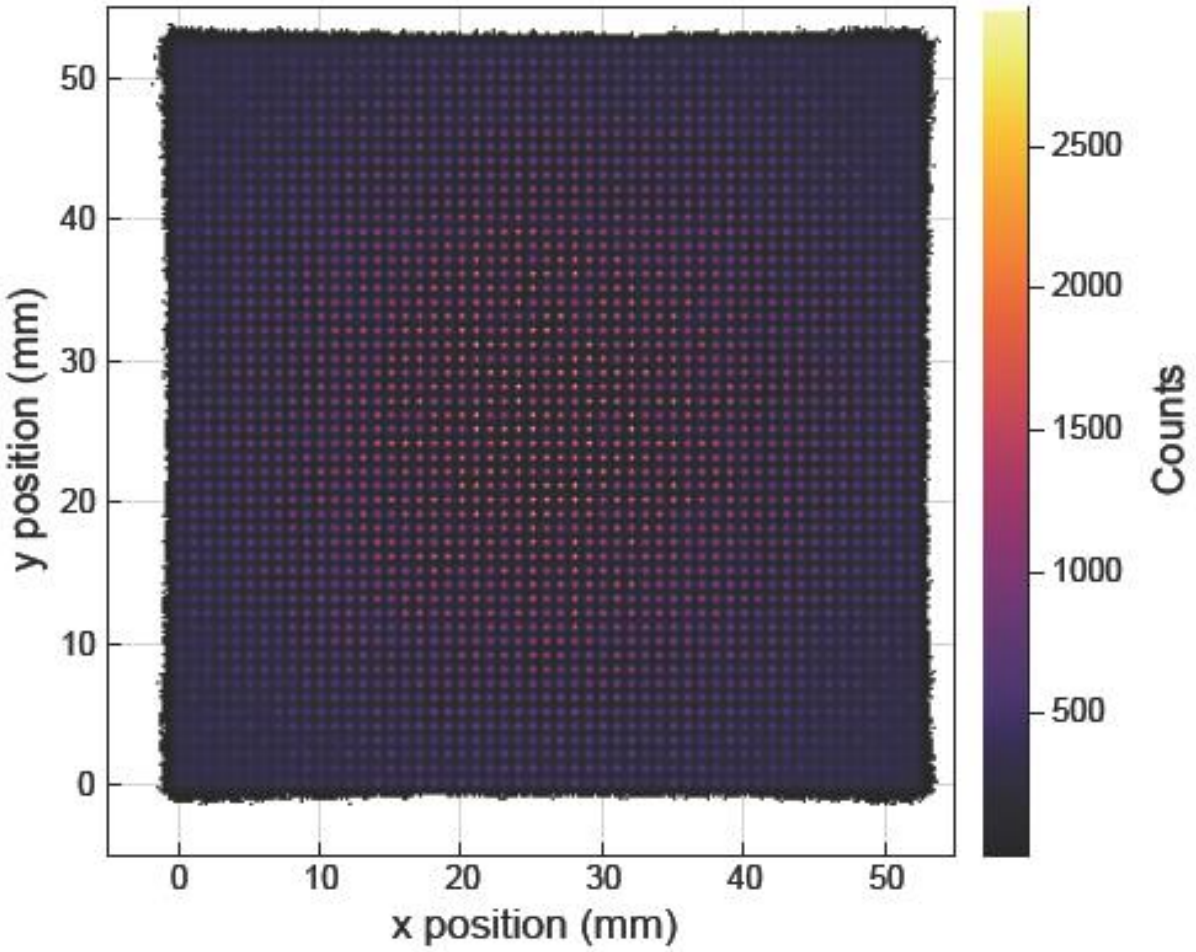
- Standard algorithms based on likelihood estimation or nearest neighbors are too slow or imprecise
- Neural networks are very fast in FPGA and can be trained to reliably identify interaction position

- Network complexity is determined by number of layers and parameters
- Less parameters means the network can run faster and process more events



Event positioning

- The average reconstruction error in the corners across the diagonal is below 0.4 mm
- The width of the reconstructed spot is below 0.5 mm (average of (x,y) widths)
- Each irradiated pixel position can be easily distinguished



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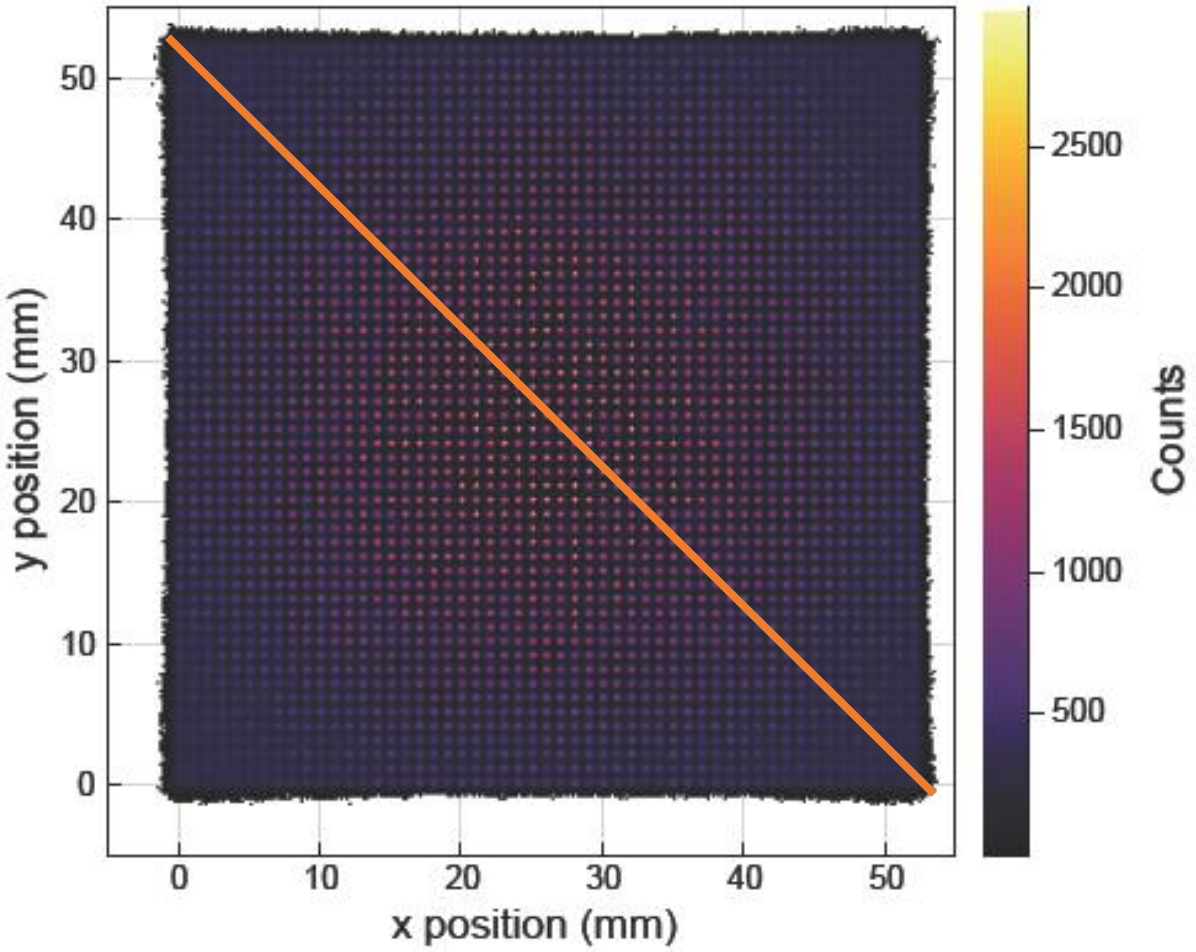

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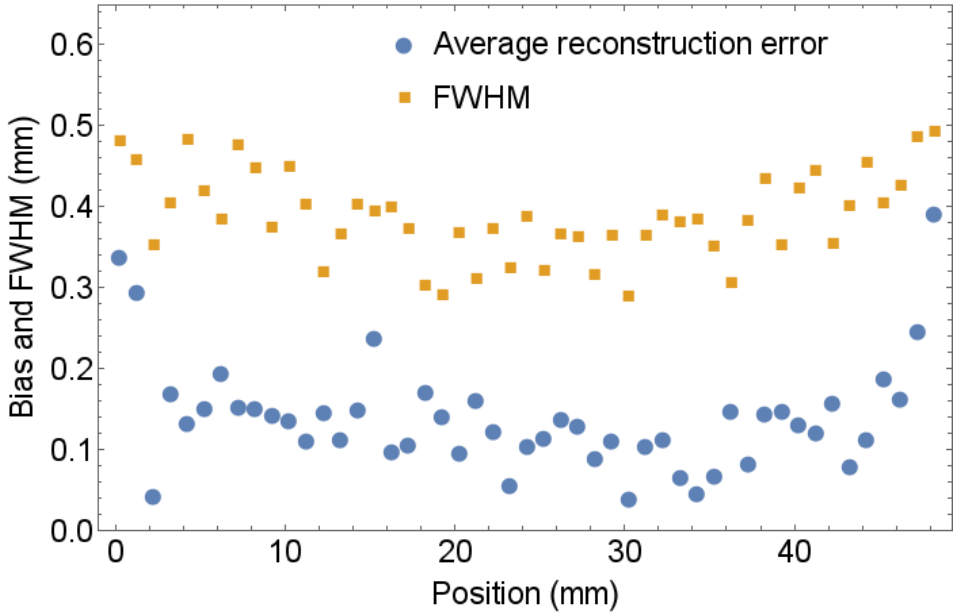
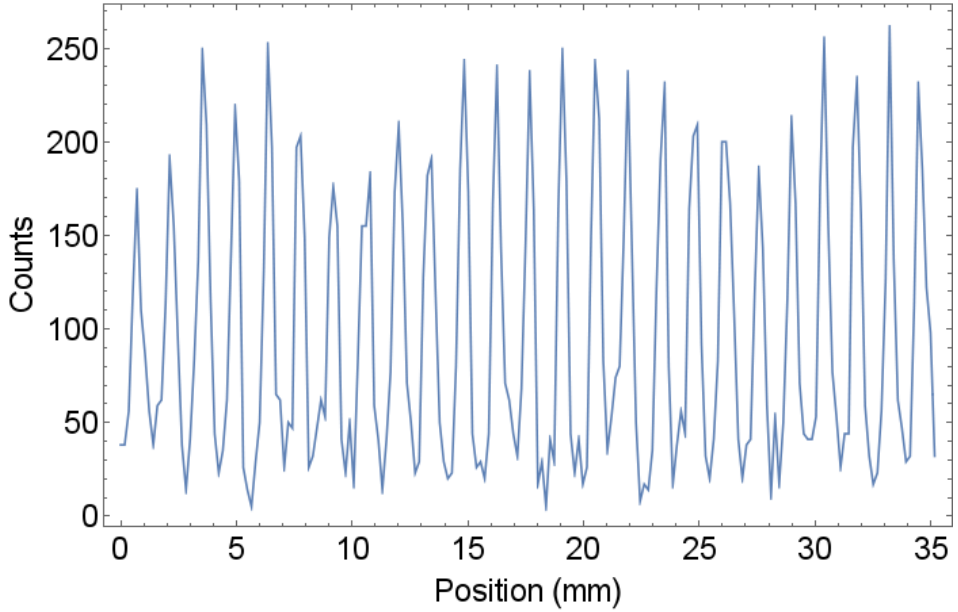




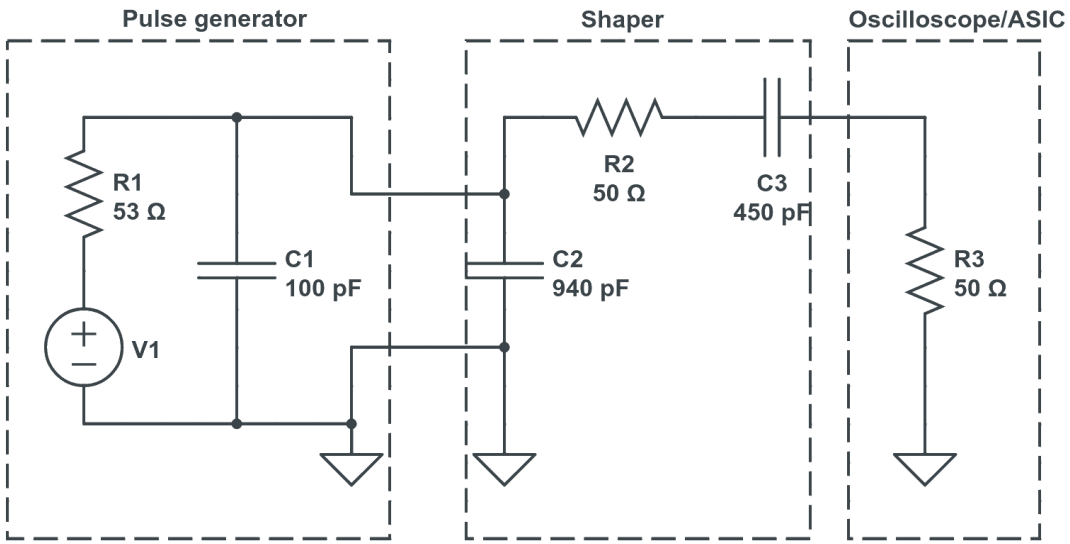
ASIC characterization

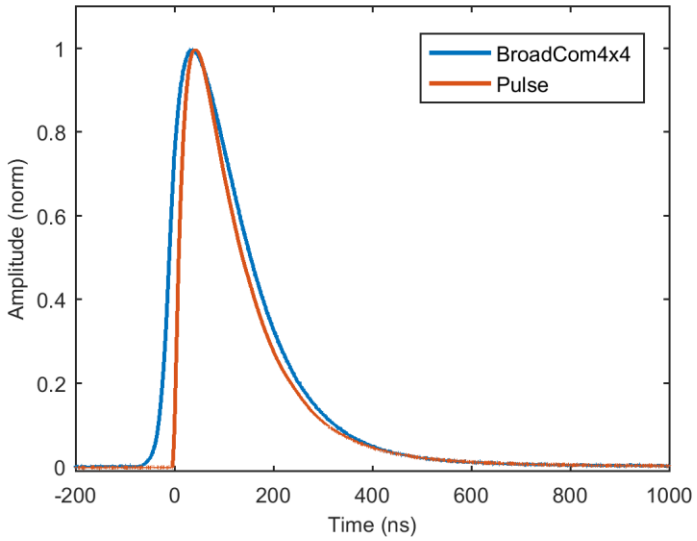
Performance metrics

- Linearity of the ASIC energy measurement
- Maximum count-rate

Measurement setup

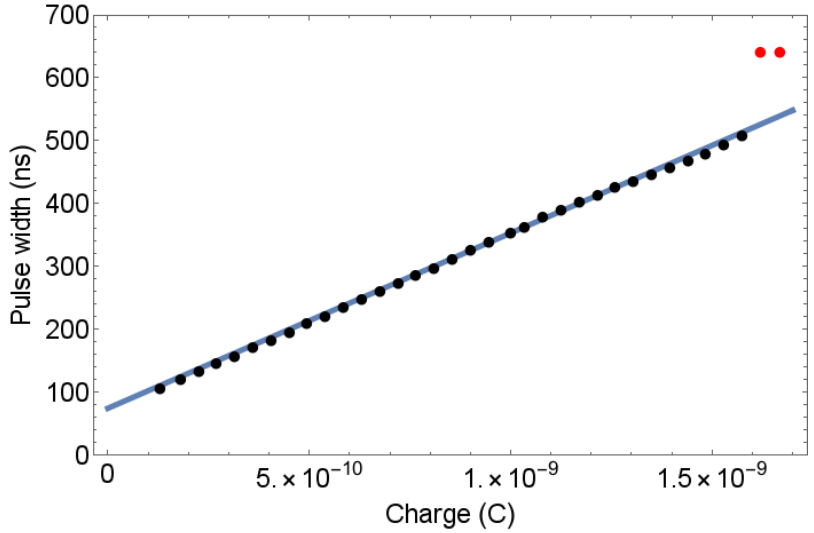
- Simulated SiPM with a pulse generator and a charge injector
- Oscilloscope read-out

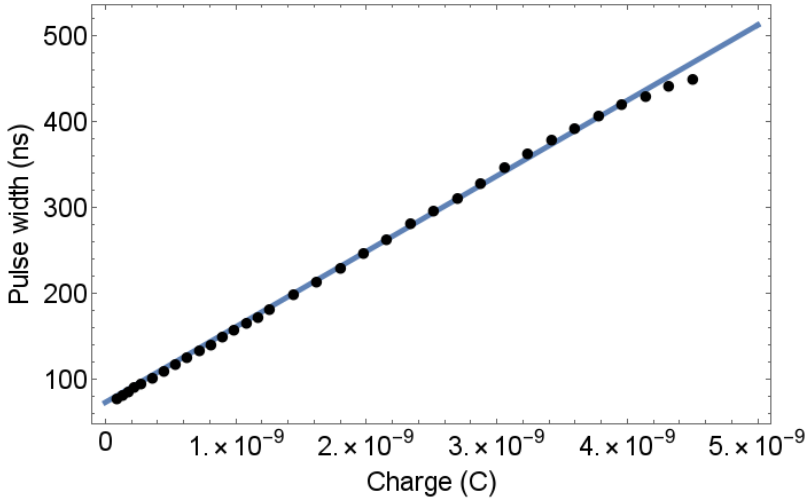


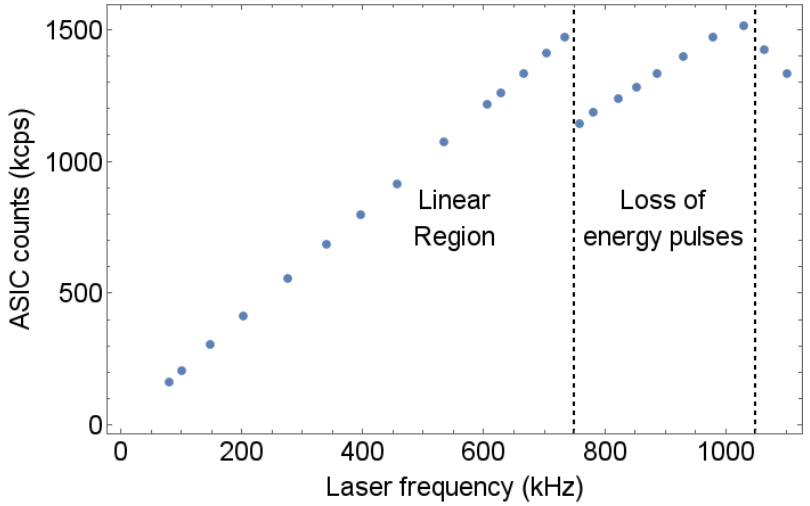


ASIC characterization

- Linear response up to 5 nC of injected charge
- Baseline is independent of gain
- Maximum count-rate of about 730 kHz

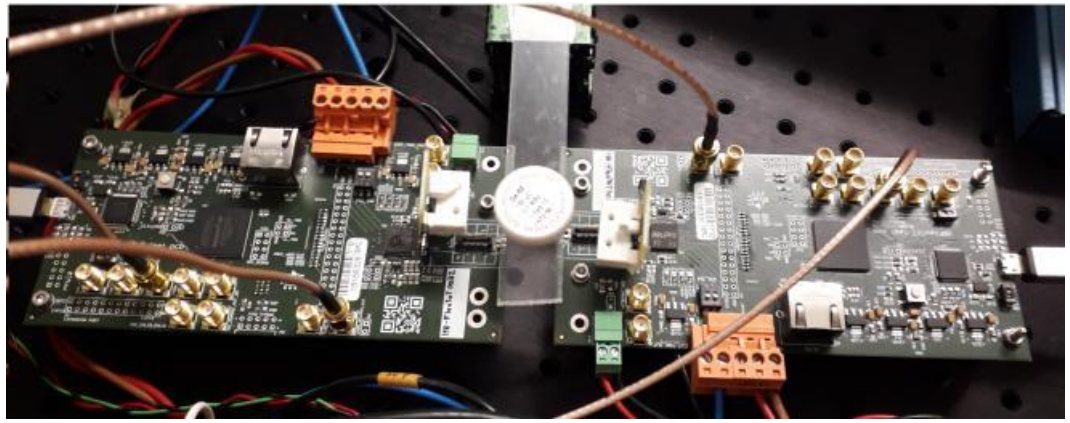






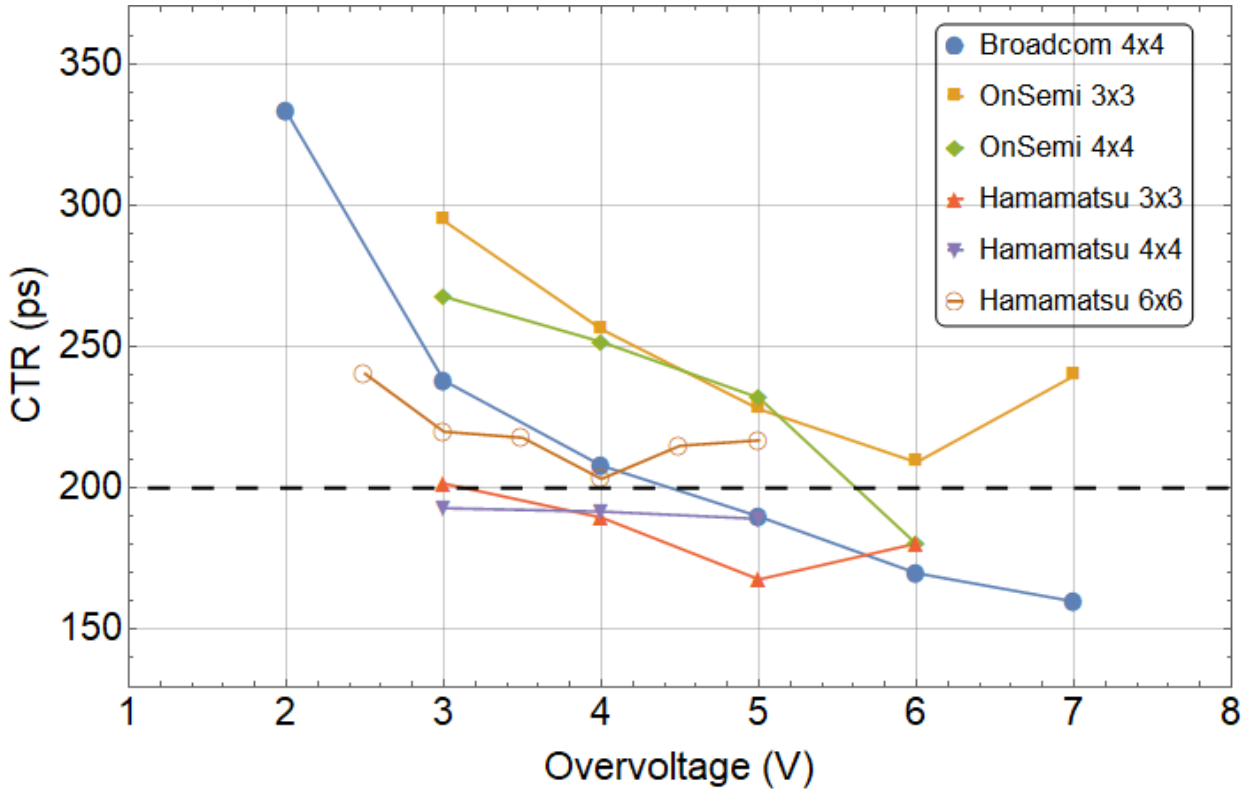
Detector performance

- First results have been obtained with single SiPMs and 3 mm x 3 mm x 5 mm pixellated crystals
- The ASIC was read-out at the oscilloscope but the main results have been verified with an early version of the data acquisition system



Timing resolution

- BroadCom and Hamamatsu SiPMs with 3 mm x 3 mm and 4 mm x 4 mm active area reached a CTR below the 200 ps target.
- Bigger area SiPMs get worse results due to the higher dark noise of large area devices
- Results on Hamamatsu and Broadcom SiPMs have been replicated FPGA-embedded TDCs as read-out electronics.



Conclusions

- Preliminary measurements based on pixelated crystals show that our specifications can be met using the HRFlexToT and our DAQ system
- CTR below 200 ps, 730 kHz maximum event rate
- Simulated data show that using a neural network to estimate the event position in a monolithic crystal is effective and feasible

Future developments

- The ASIC boards are being designed and produced
- We have signed an agreement with the HRFlexToT producers
- Measurements will have to be repeated on monolithic crystals
- Event positioning will include DOI information and possibly contribute to timing information