Development of the thin TOF-PET scanner based on fast monolithic silicon pixel sensors

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on behalf of the TT-PET collaboration
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PET/MRI Imaging

- Positron Emission Tomography (PET)
  - Positrons from a radionuclide introduced in a body annihilate with the nearby tissue, emitting two back-to-back photons
  - The photons are detected in coincidence, tracking a line of response (LOR)

- Hybrid PET-MRI Imaging
  - Combining functional Image by PET and morphological image by MRI
Time-of-Flight (TOF)

- TOF information improves the signal-to-noise ratio (SNR) of reconstructed images

\[
\frac{\text{SNR}_{\text{TOF}}}{\text{SNR}_{\text{CONVENTIONAL}}} \sim \sqrt{\frac{D}{\Delta x}}
\]
Depth-of-Interaction (DOI)

- Sensitivity for photon depth of interaction improves the spatial resolution across the whole view of the scanner.
- It also reduces the uncertainty of TOF measurements.
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The TT-PET Scanner

- We are developing silicon monolithic pixel sensors with 30 ps time resolution for electrons
  - corresponding to 100 ps time resolution for MIPs

- A wedge is composed of 60 layers (12 supermodules)

- 16 wedges in a ring structure with cooling blocks

- The scanner is meant to be inserted in small animal commercial MRI
Detector simulation performed with Geant4 simulation shows excellent performance of the TT-PET scanner

Reconstruction without TOF

Reconstruction with TOF

- The very good spatial resolution (< 750 mm FWHM) does not degrade on the border of the scanner thanks to the depth of interaction measurement

- The SNR of the reconstructed image is improved thanks to the TOF measurement

arXiv: 1811.12381
Target for the TT-PET

\[ \text{NECR} = \frac{T^2}{T + S + R} \]

- **Requirements**
  - Coincidence window: 500 ps
  - The LOR intercepts the phantom
  - The energy deposits in the both pixels are larger than 20 keV
- High NECR (~ 900 kcps) for a 50 MBq source
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ASIC Demonstrator

- ASIC demonstrator in 130 nm IHP SiGe-HBT technology ($\beta = 900$, $f_T = 250$ GHz)
  - 30 pixels, size: $500 \times 500$ $\mu$m$^2$
  - Amplifier, discriminator, 50 ps binning TDC, logic and serializers
    - The output of the discriminator is sent to a fast-OR chain, which preserves TOT and TOA
  - Thinned to 100 $\mu$m, backplane metallized
  - 1500 $\Omega$*cm resistivity (full depletion voltage: ~ 45 V)
    - Confirmed by laser TCT measurement

arXiv: 1811.10246
The time of arrival and the time over threshold of the fast-OR output signal are digitized using a CMOS-based hybrid TDC made of a free-running ring oscillator with a binning of 50 ps and a 700 ps counter, developed on purpose for this project. Both the counter and the 14 states of the ring oscillator are read for the measurement of the time of arrival and the time over threshold of the signal.

A 10 MHz clock is distributed to the different chips to offer a common time reference for the TDCs and run the chip logic.

2 Experimental setup and methods

2.1 The experimental setup at the SPS beam test facility at CERN

In order to study the efficiency, timing performance, front-end noise and uniformity of response, the demonstrator chip was tested at the SPS beam test facility at CERN with MIPs. The experimental setup (Figure 2) consisted of a tracking telescope that provided the trigger and the particle track parameters to three demonstrator chips. The three chips were read out using a readout system developed at the DPNC, with a custom firmware designed to operate the demonstrator with an external trigger.

Figure 2. The experimental setup at the SPS beam test facility. The red line represents the particle beam. Four of the tracking telescope planes are visible on the left. The three boards with the demonstrator were downstream with respect to the telescope. The board containing chip 0 was rotated by 180 degrees along the vertical axis with respect to the other two boards.

The chips were operated at two working points: a low-power working point, with a preamplifier power consumption of 160 µW/channel, compliant with the TT-PET power requirements, and, for comparison, a working point with power consumption of 375 µW/channel, as was used for the –3–
Greater than **99.9% efficiency** was observed for the 26 pixels that were readout

- 4 pixels were masked on hardware due to noise induced from signal-ended clock line
- The region defined by the continuous lines shows the area used for efficiency calculation
4 Conclusions

- **110 ps RMS** was measured at 375 $\mu$W/channel power consumption

- **130 ps RMS** was measured at 160 $\mu$W/channel power consumption

- Pixel area: $500 \times 500 \ \mu m^2$, 750 fF capacitance

**Best time resolution ever for silicon monolithic pixel sensor!**
22Na Measurement

Lead box for radiation protection

- 30 ps time resolution with electrons from 511 keV photons can be achieved thanks to the larger signal w.r.t. MIPs

- Measurement with 22Na source
  - Two boards, one with lead on one side and one with lead on both sides
  - Larger signal is expected by electrons bouncing back from lead

\[
\sigma_t \sim \frac{\text{rise time}}{S/N}
\]
Larger TOT (Time over threshold) values are observed with lead on both sides

Measurement for time resolution and efficiency is being done
Conclusions

- **The TT-PET scanner**, which aims at the construction of a small animal TOF-PET scanner, was designed to exploit **Time-of-Flight (TOF)** and **Depth-of-Interaction (DOI)** of a multi-layer silicon structure.

- Excellent performance of the TT-PET scanner was expected by Geant4 simulation and image reconstruction.

- ASIC demonstrator with silicon monolithic pixels was fabricated in **IHP SiGe-HBT technology**.

- **More than 99.9% efficiency** and **110 ps at 375 μW/channel power consumption** were measured at CERN SPS testbeam facility.

- Measurement with $^{22}$Na source is on-going to prove the ~30 ps time resolution with 511 keV electrons.
Laser Edge-TCT Measurement

- Laser edge-TCT measurement at DPNC
  - Depletion lengths correspond to 1500 Ω*cm resistivity