A Miniaturised Calorimeter for Endoscopic Positron Emission Tomography.

Milan Zvolský on behalf of the EndoTOFPET-US Collaboration

CHEF 2013, Paris

25.04.2013
Objectives of the EndoTOFPET-US Project

Positron Emission Tomography (PET)

- Radiotracer ($\beta^+$ emitter) concentrates in the metabolic active areas
- $e^+e^- \rightarrow 2\gamma$ (back-to-back, 511 keV each)
- Detect the two $\gamma$s in *coincidence*
Objectives of the EndoTOFPET-US Project

- Development of new biomarkers
- Intra-operative Time-of-Flight (TOF) PET Detector
- Prototype for prostate & pancreas cancer
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Challenges

- Extreme miniaturisation
- Fast crystals & ultra-fast photodetection
- Aim for our project: Coincidence time resolution 200 ps FWHM (3 cm)
- This reduces background noise from other organs → better image quality
- Image reconstruction for free-hand imaging, image resolution of 1 mm
Outline

1. Detector Design
2. Scintillation Crystals
3. SiPMs
4. DAQ & System Integration
5. Image Reconstruction
6. System Simulation
7. Conclusion
Endoscopic PET Head (Prostate Prototype)

- PET head volume: $23 \times 23 \times 40 \text{ mm}^3$
- 324 detector channels
- 2 matrices of $9 \times 18$ crystals
  $0.71 \times 0.71 \times 15 \text{ mm}^3$
- Coupled to multi-digital SiPMs

Commercial Ultrasound (US) Endoscope
Hitachi EUP-U533

US Transducer

PET Head Extension

EM Tracking Sensor
Water Cooling
2 Matrices of 9x18 Crystals
md-SiPM Array
md-SiPM PCB
External PET Plate

- Plate area: $23 \times 23 \text{ cm}^2$
- 4096 crystals $\times 3.5 \times 3.5 \times 15 \text{ mm}^3$
- Coupled to discrete MPPCs with through-silicon via (TSV) technology
- Dedicated fast 64 channel ASIC & cooling embedded in detector housing
- Mounted on robotic arm

Through-Silicon Via (TSV)

- Discrete TSV Multi Pixel Photon Counter (MPPC)
- Less deadspace
- Minimum connection length
- Collaboration with Hamamatsu for the photosensor prototype

- Operation voltage spread $\approx 200 \text{ mV}$
- Gain spread $\approx 15\%$
Optimising the Detector Design

Sensitivity

- Full system simulation
- Plate in coincidence with head
- Sensitivity = \( \frac{\text{# true coincidences}}{\text{# decays}} \)
- Detector sensitivity increases with longer crystals

Coincidence Time Resolution (CTR)

- Single channel simulation
- Single channel time resolution (STR) = Spread of the time-of-arrival of the first photon from each event
- \( CTR = \sqrt{2} \cdot (STR) \)
- Time resolution deteriorates with longer crystals
Crystal Energy Resolution & Light Yield

**Internal Probe**
- 2 Matrices of $9 \times 18$ crystals (LYSO)
- $0.71 \times 0.71 \times 15$ mm$^3$ (delivered)

**External plate**
- 256 Matrices of $4 \times 4$ crystals (LYSO)
- $3.5 \times 3.5 \times 15$ mm$^3$ (ordered)

- Energy resolution $\approx 13\%$, similar for internal probe
- Matrix Light yield (LY): 10200 ph/MeV (dry contact). With glue: LY doubles
- Narrow photopeak for the entire matrix (on both prototype matrices), similar for a single pixel $\rightarrow$ Uniform LY among pixels (spread ca. 10%)
SiPM: Analog (a) vs. Multi-Digital (md)

a-SiPM for External Plate

- Analog charge output ($\Sigma Q_i$)
- Signal digitisation: integral output charge in $\Delta t$
- $E \propto Q$
- $t$ via time of threshold crossing

md-SiPM for Endoscope

- Each cell digitised locally (# pixel fired)
- Photon arrival time recording
- Fast time pick-up
- $E = N_{\text{pixel fired}}$
- High Dark count rate (DCR), but able to turn off hot pixels & cooling
md-SiPM for the Endoscope

- Challenge: 324 detector channels + crystals + r/o electronics on $23 \times 23 \times 40 \text{ mm}^3$
- High granularity for excellent timing

Energy measurement: 416 SPAD pixels
(Single photon avalanche diode)

Time measurement: 48 column-wise shared Time-to-digital converters (TDCs)
→ precise time of first 48 photons

- Fill factor $\approx 57\%$
- Photon detection efficiency (PDE) $\approx 17\%$
Hot Pixel Masking

Suppress DCR by masking hot pixels:

- 41 MHz DCR w/o masking ($T = 20^\circ C$, 3 V excess bias)
- 23 MHz with $\approx 10\%$ masking

Dark count rate for different temperatures

Single pixel time resolution

120 ± 13 ps FWHM (excl. laser & clock jitter)
Coincidence Time Resolution of Crystals

- Crystals coupled to MPPCs
- Time-over-threshold measurement with ultra-fast amplifier-discriminator chip (NINO) in combination with TDC

Left: Coincidence between 1 endoscopic crystal ($0.71 \times 0.71 \times 10 \text{mm}^3$) and 1 plate crystal ($3.1 \times 3.1 \times 15 \text{mm}^3$) (single MPPC)
Right: Coincidence between 1 endoscopic crystal and $4 \times 4$ plate crystal matrix (monolithic MPPC array)

$\text{CTR} = 249 \pm 20 \text{ps}$
a-SiPM ASIC (Outer Plate)

Requirements:
- Time binning of 50 ps
- SiPM bias tunable within 0.5 V
- Low power consumption to minimise cooling
- Cope with high channel density of 4096 ch on $23 \times 23\,\text{cm}^2$

2 dedicated fast 64 ch ASICs:
- StiC ASIC (Uni Heidelberg)
- TOFPET-ASIC (LIP Lisbon)

E measurement:
- Time-over-threshold method
- Time measurement: Set threshold to 1st pixel fired

<table>
<thead>
<tr>
<th></th>
<th>StiC</th>
<th>TOFPET-ASIC</th>
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<tbody>
<tr>
<td>Jitter (at &gt;5pC)</td>
<td>&lt; 30 ps</td>
<td>&lt; 25 ps</td>
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<tr>
<td>Input bias lin. range</td>
<td>0.7 V, 50 ps</td>
<td>0.5 V, 50 ps</td>
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<tr>
<td>TDC time bin width</td>
<td>19 mW/ch, 64</td>
<td>7 mW/ch, 128</td>
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<tr>
<td># channels</td>
<td>160 MBit/s</td>
<td>160 MBit/s</td>
</tr>
<tr>
<td>Output rate</td>
<td></td>
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Tracking of the Detector Movement

**Goal:** Image resolution better than 1 mm

**Tracking Precision**
- Electromagnetic: $\approx 2 - 3$ mm
- Optical: $\approx 0.1 - 0.4$ mm
- Mechanic: $\approx 50 \mu m - 0.1$ mm

**External Plate**
- Optical tracking: accurate. Problem: Line of sight
- $\rightarrow$ Mechanic tracking via robotic arm

**Endoscope (Prostate)**
- High tracking accuracy needed $\rightarrow$ Robotics
- Pancreas: No mechanical tracking
- Track device optically & mechanically
Data Acquisition & System Integration

- **Analog SiPMs**
  - **ASiCs**
  - **Merge data**
  - Front-End board FPGAs

- **Digital SiPMs**

- **200 kHz**

- **40 MHz**

- **Merge data**
  - Preselect coincidence candidates

- **Extract Time & Energy**
  - Reconstruct in-detector Compton scattering
  - Energy filter
  - Coincidence Selection

- **ListMode for reconstruction**

- **350 kHz**

- **<50 kHz**

- **Tracking Info from Plate**
- **Tracking Info from Endoscope**

- **Ultrasound**

- **Monitor (US)**
- **Monitor (Video)**
- **Monitor (Vital Signals)**

- **Endoscope**
- **Pedal**
- **M.D.**
- **Assistant**

- **Basins**

- **DAQ**
- **Reco**
- **US**
- **Tracking**

Milan Zvolský (DESY)
PET Image Reconstruction

Challenges

- Time of flight (TOF)
- Limited angle problem
- Freehand → undefined volume of interest
- Low sensitivity, high noise
- Reconstruct the image on-line to provide guidance for the physician

Solution

- ML-EM iterative reconstruction: Good performance in case of Poissonian noise
- GPU Computation: Solving a massively parallel problem

- GPU speedup by factor $O(10)$
- Image reconstruction in $O(\text{min.})$
System Simulation

- Simulation of whole detector system → optimise design, test reconstruction
- GATE (Geant4 Application for Emission Tomography) with custom extensions
- Simulate movement of detectors
- Test sensitivity, image resolution etc. on simple source distributions

1.04 mm FWHM
## Conclusion & Outlook

### Very challenging system
- Extreme miniaturisation
- Fast scintillating crystals
- Ultra-fast photodetection
- Image reconstruction for free-hand imaging

- Coincidence time resolution close to design goal of 200 ps
- Using state-of-the-art discrete through-silicon via MPPCs
- md-SiPM prototype tested
- 2 dedicated ASICs developed, performing up to specs
- Image resolution of 1 mm within reach

### Schedule: Start pre-clinical tests in summer 2014
THANK YOU FOR YOUR ATTENTION

Many thanks to the endoTOFPET-US collaborators for their contribution and the honor of speaking on their behalf!

This research project has received funding from the European Union 7th Framework Program (FP7/ 2007-2013) under Grant Agreement No. 256984 (EndoTOFPETUS)