A Miniaturised Calorimeter for Endoscopic Positron Emission Tomography.

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on behalf of the EndoTOFPET-US Collaboration

CHEF 2013, Paris

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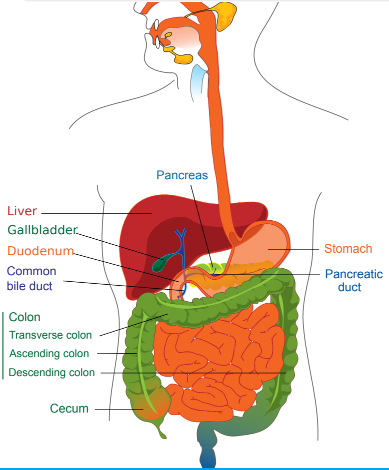
Objectives of the EndoTOFPET-US Project

Positron Emission Tomography (PET)

- Radiotracer (β^+ emitter) concentrates in the metabolical active areas
- $e^+e^- \to 2\gamma$ (back-to-back, 511 keV each)
- Detect the two γs in *coincidence*



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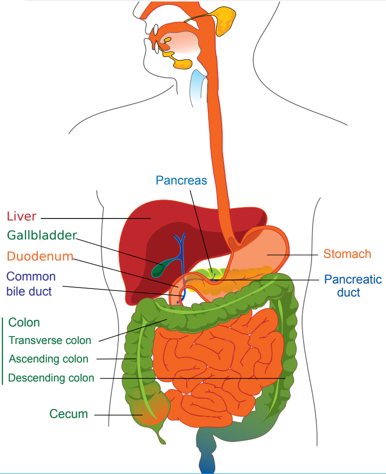
- Development of new biomarkers
- Intra-operative Time-of-Flight (TOF) PET Detector
- Prototype for prostate & pancreas cancer



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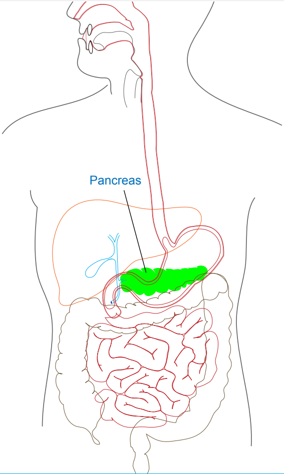

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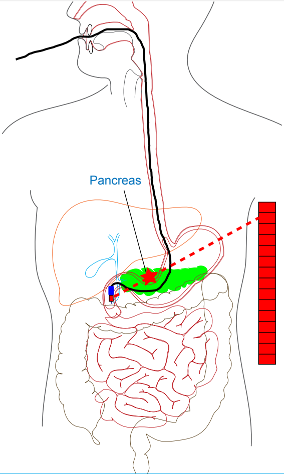

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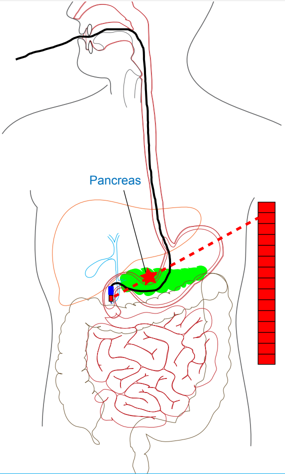
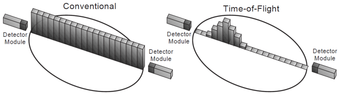


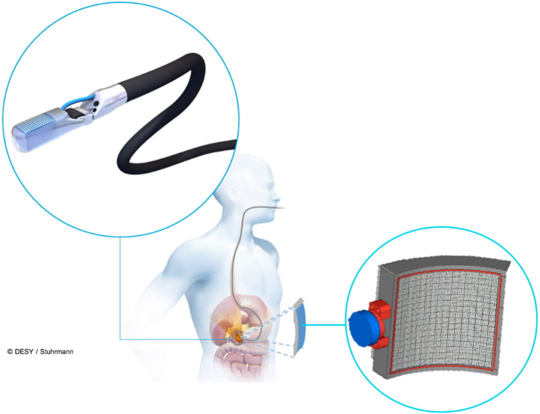


Challenges

- 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

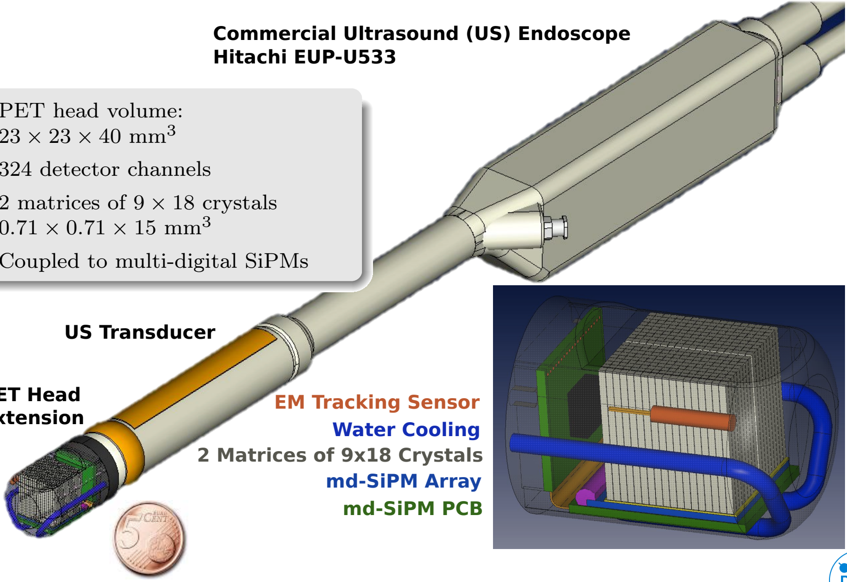
Outline.

1. Detector Design
2. Scintillation Crystals
3. SiPMs
4. DAQ & System Integration
5. Image Reconstruction
6. System Simulation
7. Conclusion

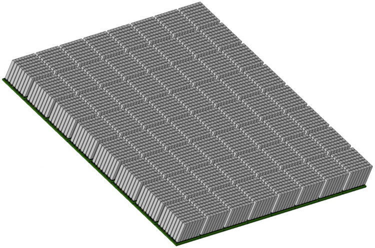


Endoscopic PET Head (Prostate Prototype)

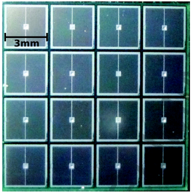
- PET head volume:
  $23 \times 23 \times 40\ \mathrm{mm}^3$
- 324 detector channels
- 2 matrices of 9×18 crystals
  $0.71 \times 0.71 \times 15\ \mathrm{mm}^3$
- Coupled to multi-digital SiPMs

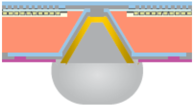


External PET Plate



- Plate area: 23×23 cm^2
- 4096 crystals à $3.5 \times 3.5 \times 15$ 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 ≈ 200 mV
- Gain spread $\approx 15\%$

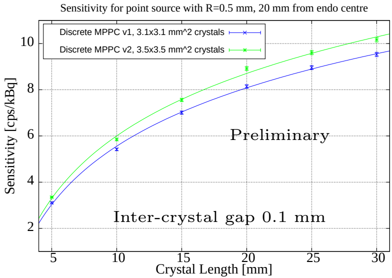
Optimising the Detector Design

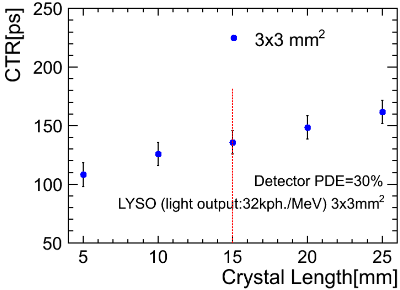
Sensitivity

- 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
- $\text{CTR} = \sqrt{2} \cdot (\text{STR})$
- Time resolution deteriorates with longer crystals



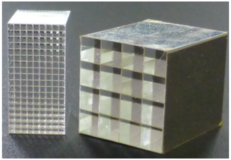


Crystal Energy Resolution & Light Yield

Internal Probe

2 Matrices of 9 × 18 crystals (LYSO)

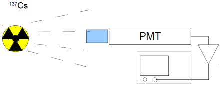
$0.71 \times 0.71 \times 15\ \mathrm{mm}^3$ (delivered)

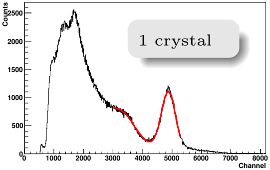


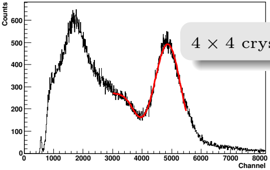
External plate

256 Matrices of 4 × 4 crystals (LYSO)

$3.5 \times 3.5 \times 15\ \mathrm{mm}^3$ (ordered)





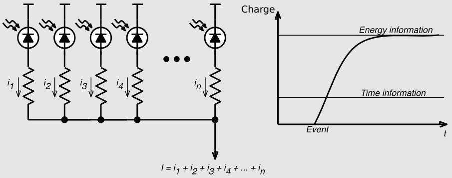


- Energy resolution ≈ 13%, similar for internal probe
- Matrix Light yield (LY): 10200 ph/MeV (dry contact). With glue: LY doubles
- Narrow photopeak for the entire matrix (on both prototype matrices), similar for a single pixel → Uniform LY among pixels (spread ca. 10%)

SiPM: Analog (a) vs. Multi-Digital (md)

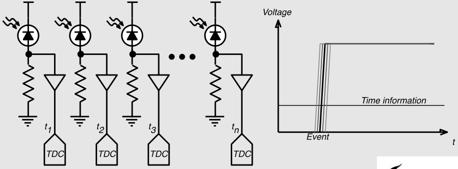
a-SiPM for External Plate

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



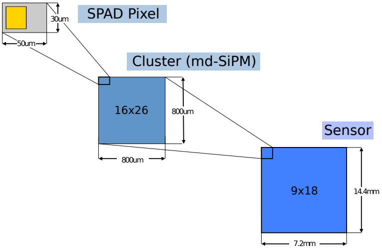
md-SiPM for Endoscope

- 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

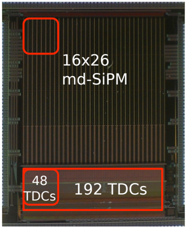


md-SiPM for the Endoscope

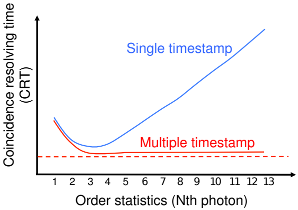
- Challenge: 324 detector channels + crystals + r/o electronics on $23 \times 23 \times 40$ mm^3
- High granularity for excellent timing



Sketch of md-SiPM sensor for endoscope



Sensor prototype



Lower bound on timing resolution

- Energy measurement: 416 SPAD pixels (Single photon avalance diode)
- Time measurement: 48 column-wise shared Time-to-digital converters (TDCs) $\rightarrow$ precise time of first 48 photons

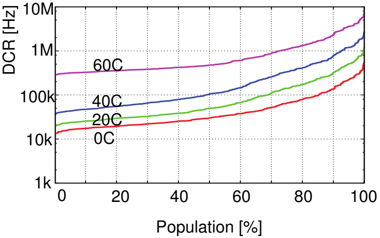
- Fill factor $\approx 57\%$
- Photon detection efficiency (PDE) $\approx 17\%$

md-SiPM Prototype Characterisation

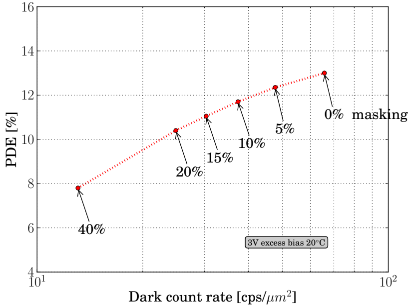
Hot Pixel Masking

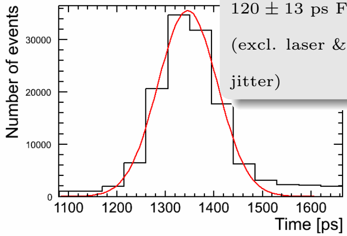
Suppress DCR by masking hot pixels:

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



Dark count rate for different temperatures



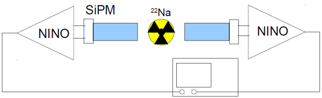


120 ± 13 ps FWHM (excl. laser & clock jitter)

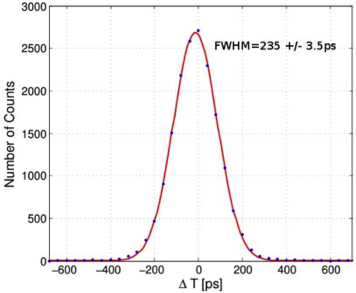
Single pixel time resolution

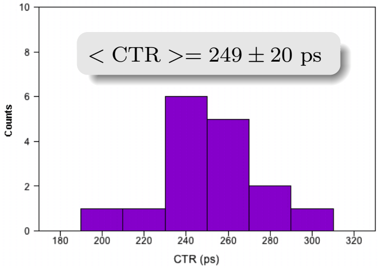
Coincidence Time Resolution of Crystals

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





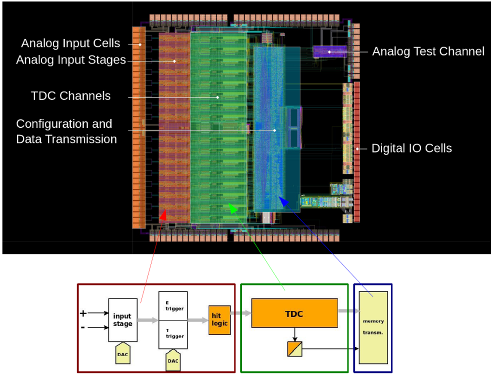
a-SiPM ASIC (Outer Plate)

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 23×23 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

	StiC	TOFPET-ASIC
Jitter (at >5pC)	< 30 ps	< 25 ps
Input bias lin. range	0.7 V	0.5 V
TDC time bin width	50 ps	50 ps
Power consumption	19 mW/ch.	7 mW/ch
# channels	64	128
Output rate	160 MBit/s	160 MBit/s

Universität Heidelberg
Zukunft. Seit 1386.

Tracking of the Detector Movement

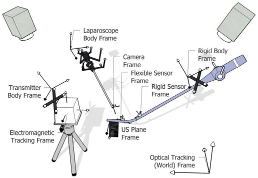
Goal: Image resolution better than 1 mm

Tracking Precision

- Electromagnetic: $\approx 2 - 3$ mm
- Optical: $\approx 0.1 - 0.4$ mm
- Mechanic: $\approx 50\,\mu\text{m} - 0.1\,\text{mm}$

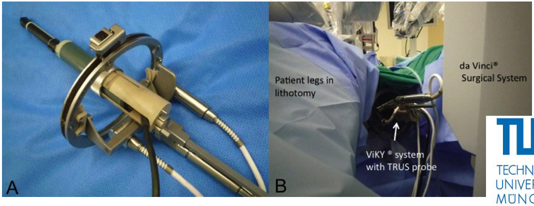
External Plate

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

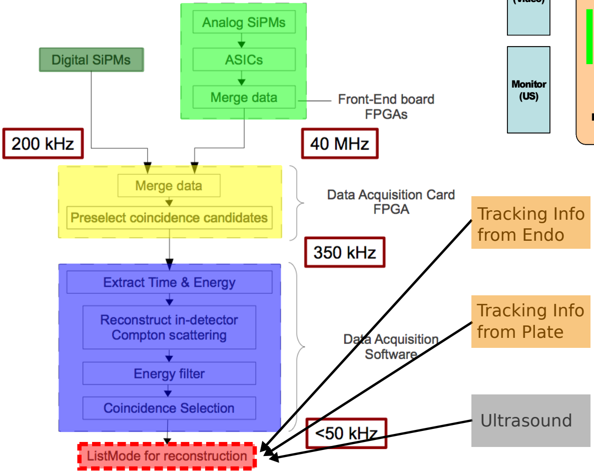


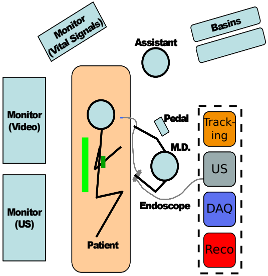
Endoscope (Prostate)

- High tracking accuracy needed $\rightarrow$ Robotics
- Pancreas: No mechanical tracking
- Track device optically & mechanically



Data Acquisition & System Integration

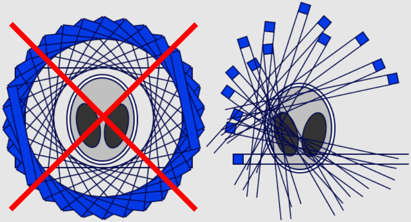




PET Image Reconstruction

Challenges

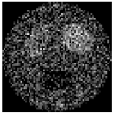
- Time of flight (TOF)
- Limited angle problem
- Freehand
  → undefined volume of interest
- Low sensitivity, high noise
- Reconstruct the image on-line to provide guidance for the physician



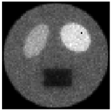
Solution

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

Original Image



Filtered Backprojection (ramp filter)

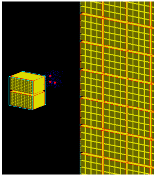


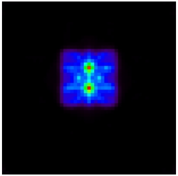
Maximum-Likelihood (ML-EM)

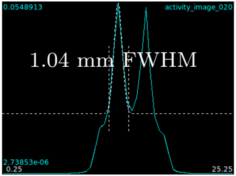
- GPU speedup by factor $\mathcal{O}(10)$
- Image reconstruction in $\mathcal{O}(\text{min.})$

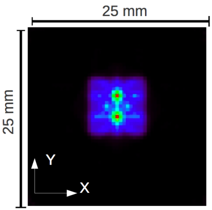
System Simulation

- 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

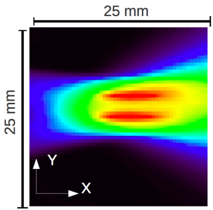






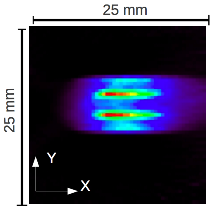


Full Rotation



Limited Rot

0th iteration



Limited Rot

20th iteration

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

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

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