TOFPET ASIC - status and perspectives

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1. Context
   - EndoTOFPET-US FP7
   - Requirements and specifications

2. Design of the TOFPET chip
   - Chip and channel Architecture
   - Front-end
   - Time-to-Digital Converter
   - Chip integration

3. TOFPET characterization
   - Test setup
   - Electrical Characterization Results
   - Tests with MPPCs
   - System-ready hardware

4. Outlook
Outline

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4. Outlook
Combined TOF-PET (200 ps time resolution), ultrasound imaging and endoscopic biopsy

PET components:
- dSiPM/crystal endoscopic probe
- aSiPM/crystal external plate
Design of a low power SiPM readout ASIC for Time of Flight applications

- integrates signal conditioning and discrimination circuitry and high-performance TDCs for each of 64 independent channels
- targets 25 ps r.m.s. intrinsic resolution and features fully digital output

TOFPET ASIC developed in the framework of the FP7 project EndoTOFPET-US

- PET time-of-flight detector plate (4000 channels)
- MPPC (16-channel arrays, 3x3 mm²) and LYSO crystals
- Coincidence time resolution (CTR) 200 ps (FWHM)
### Features of an ASIC for SiPM readout in PET applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels</td>
<td>64</td>
</tr>
<tr>
<td>Clock frequency</td>
<td>80 – 160 MHz</td>
</tr>
<tr>
<td><strong>Dynamic range of input charge</strong></td>
<td><strong>300 pC</strong></td>
</tr>
<tr>
<td>SNR ($Q_{in} = 100$ fC)</td>
<td>&gt; 20-25 dB</td>
</tr>
<tr>
<td>Amplifier noise (in total jitter)</td>
<td>&lt; 25 ps (FWHM)</td>
</tr>
<tr>
<td><strong>TDC time binning</strong></td>
<td><strong>50 ps</strong></td>
</tr>
<tr>
<td>Coarse gain</td>
<td>$G_0$, $G_0/2$, $G_0/4$</td>
</tr>
<tr>
<td>Max. channel hit rate</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Max. output data rate</td>
<td>320 Mb/s (640 w/ DDR)</td>
</tr>
<tr>
<td>Channel masking</td>
<td>programmable</td>
</tr>
<tr>
<td><strong>SiPM fine gain adjustment</strong></td>
<td><strong>500 mV (5 bits)</strong></td>
</tr>
<tr>
<td>SiPM</td>
<td>up to 320pF term. cap., 2MHz DCR</td>
</tr>
<tr>
<td>Calibration BIST</td>
<td>internal gen. pulse, 6-bit prog. amplitude</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td><strong>&lt; 10 mW per channel</strong></td>
</tr>
</tbody>
</table>
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4 Outlook
Overview of the channel architecture

- **Time** and **charge** measurements with independent TDCs
- Trigger level **0.5 p.e.** with SNR = 25 dB
- Target intrinsic resolution **25 ps r.m.s.**
- Charge measured with Time-over-threshold
- Low-power **8-11 mW p/channel**
- **Single-Ended Input**
Overview of the chip architecture

The TOFPET ASIC consists of a 64-channel analogue block, calibration circuitry, Golden-references and Bias generators and a global controller.

- LVDS 10 MHz SPI configuration link and dark count measure
- LVDS up to 640 Mbps data output interface; 8B/10B encoding
- On-chip DACs and reference generators
Front-end for SiPM readout

- Low-Zin pre-amplifier, 2 independent TIA branches for **Timing** and **Energy** triggers
- coarse gain adjustment, optional shaping function for **Vout_E**
- Selectable delay line for dark count filtering
- Representation for cathode readout, extra circuit for anode type SiPM
Inputs for TDC

- **t0**: 50 ps time stamp from rising edge of DOT
- **t2**: 50 ps time stamp from falling edge of DOE

$\text{ToT (energy meas)} = t_2 - t_0$
Time-to-Digital Converter

**Analogue TDC with 25ps/50ps time binning** - based on Analogue Interpolators

- TDC Control: switching, hit validation, buffer allocation, data reg.
- Time stamp: 10-bit master clock count + Fine time measurement
Channel Layout

- 64 channels, form factor **0.1 x 2.5 mm**
- Each channel comprises:
  - front end 2-polarities
  - local calibration circuitry
  - discriminators for timing, energy
  - DACs for input DC setting, thresholds
  - delay line for DCR filtering
  - TDC-analogue: current sources, TACs, wilkinson ADC and latched comparator
  - TDC-digital: sequence control, buffer assignment, 50-bit register, interface with back-end
128-channel System-in-a-Package
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25 $mm^2$ IBM 0.13$\mu m$ CMOS/RF

- submitted June 2012 within a CERN dedicated run
- 112 chips per wafer
- available as naked dice
- available as 128-channel SiP BGA-packaged
TOFPET ASIC test setup

- Two mezzanines and power adapter board
- Mezzanines with crystal matrices are face-to-face
Front-end noise estimation

- number of events as function of threshold
  (both thresholds set to the same value)
- fit to a cumulative probability distribution function
- 2.5 mV r.m.s. (agrees to simulation results)
**Step 1**: TDC calibrated with a test pulse sweep across 50 ns (500 ps step, 10000 pulses p/ step)

**Step 2**: Correct for TDC non-linearity

**Step 3**: Trigger simultaneously two channels and measure time difference (removes common mode test pulse jitter)

- **Distribution with 29 ps r.m.s.,**
  corresponds to a **per channel error of 21 ps r.m.s.**
Multi-Photon Time Resolution

- Laser: no optical attenuator \( (N_{ph} > 1000) \)
- \( 32 \) ps r.m.s., includes jitter from the laser and the test pulse

\[
\begin{align*}
\chi^2 / \text{ndf} & \quad 22.12 / 6 \\
\text{Constant} & \quad 1171 \pm 23.1 \\
\text{Mean} & \quad 5.748e-06 \pm 5.296e-13 \\
\text{Sigma} & \quad 3.154e-11 \pm 3.679e-13 \\
\text{Base} & \quad -0.3459 \pm 0.8862
\end{align*}
\]
Single-Photon Time Resolution

- Laser: w/ optical attenuator \((N_{ph} = 1)\)
- both thresholds set to 0.5 p.e. level
- laser triggered at 80 kHz rate, known time in respect to the start-of-frame
- ToT distribution of events within 1 ns of the expected laser pulse time show the 1 photon and 2 photon peaks
  - 110 ps r.m.s., after optimization of the HV
Coincidence Time Resolution - preliminary

- **MPPC discrete TSV 4x4 arrays** (3 x 3 mm$^2$ pixels)
- **Single Crystal on each array** (3 x 3 x 15 mm$^3$)
- **CTR = 270 ps FWHM**
- Result does not depend on the threshold setting other channels

![Graph showing CTR results](image)

- $\chi^2 / \text{ndf} = 32.53 / 47$
- Constant: $81.84 \pm 3.52$
- Mean: $-2.161e-12 \pm 2.786e-12$
- Sigma: $1.156e-10 \pm 3.608e-12$
- Base: $1.235 \pm 0.232$
Energy Calibration - preliminary

- ToT vs. Qin characteristic is non-linear
- Data acquired with $^{22}\text{Na}$, $^{176}\text{Lu}$, $^{137}\text{Cs}$
- Fit to an exponential function to correct energy spectrum
- **Preliminary** energy resolution 17%
New hardware development: FEB/A for 2 ASICs
First tests with FEB/A - occupation map

Flood histogram:
- 128 channels
- number of counts in the photopeak

Source placed 37 mm above crystals

Photopeak position ToT (ns)

White spots: automatic calibration failed in 4 channels
First tests with FEB/A - CTR

- MPPC discrete TSV 4x4 arrays (3 x 3 mm² pixels)
- Crystal 4x4 matrix on each array (3.5 x 3.5 x 15 mm³)
- Crystal-SiPM matching 73 %

![Coincidence Time Resolution](chart.png)

<table>
<thead>
<tr>
<th>hDelta</th>
<th>1742</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>1742</td>
</tr>
<tr>
<td>Mean</td>
<td>1.236e-09 ±3.347e-12</td>
</tr>
<tr>
<td>Sigma</td>
<td>1.316e-10 ±2.665e-12</td>
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</tbody>
</table>

FWHM = 309 ps
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4. **Outlook**
ASIC distributed to several groups for Medical Imaging and HEP
Integration of EndoTOFPET-US external plate - FEB/A characterization ongoing
TOFPET offspring under way
  TOFPETv2 - design ongoing at PETsys
    Targets time resolution better than 20 ps r.m.s.
    high-rate applications
    Linear ToT
    improved energy resolution
Combined TOF-PET (200 ps time resolution), ultrasound imaging and endoscopic biopsy

PET components:
- dSiPM/crystal endoscopic probe
- aSiPM/crystal external plate

Thank you!
Test setup for SPTR and MPTR tests

- Tests with Bare Die
  - MPPC: TSV arrays (3x3 mm$^2$)
  - (for CTR only): 15 mm$^2$ long LYSO
  - nominal: 160 MHz, DVDD=1v5

- PicoQuant Laser
  - MPTR: LI=1.5, no optical attenuator ($N_{ph} >> 1000$)
  - SPTR: LI=7.5, WITH optical attenuator ($N_{ph} = 1$)

- Nominal test conditions:
  - $T = 18-20$ C
  - TP rate = 80 KHz
  - $V_{thE}$ approx 500mV above $V_{th,noise}$
  - $V_{thT}$ approx 10mV$^1$ above $V_{th,noise}$

$^1$for CRT with LYSO, nominal $V_{thT}$ setting is to 100 mV above noise (corresponds to a threshold of 2-3 equivalent photoelectron charge)
Laser CTR

- free-running laser
  \( CTR_{\text{laser}} = 100 \text{ ps FWHM} \)
- \( mptr_{\text{sigma}} = \frac{CTR_{\text{laser}}}{(2.35 \times \sqrt{2})} = 30 \text{ ps r.m.s.} \)
First tests with FEB/A - ToT

ToT spectrum
Operation with SiPMs - Rejection of dark pulses

Filtering of spurious pulses: TDC is not triggered

- Quiet operation mode: limited TDC CTRL switching, TAC re-assignment,…
- Critically dependent on the quality of the power supply (main contributor for the delay line jitter)
- Synchronous validation schemes are implemented as backup.
Concept of the front-end

- Low-Zin pre-amplifier, 2 independent TIA branches for **Timing** and **Energy** triggers
- **Fine adjustment of the HV bias** (6-bit over 500mV range) of the SiPM
- Selectable shaping function for **Vout_E**
- Selectable delay line for dark count filtering
- Usable for p-type or n-type (hole, electron collection) devices
Floorplan of the 64-channel IC

- 64 channels side-by-side, 102 $\mu m$ pitch
- calibration circuits, reference and bias generators