Timing performance of the silicon PET insert probe

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The MADEIRA collaboration

- Acronym stands for Minimizing Activity and Dose with Enhanced Image quality with Radiopharmaceutical Administration.
- Specific objectives:
  - Increased image quality with physics based image reconstruction methods
  - Novel instrumentation techniques
  - New time schemes for the application of the radiopharmaceuticals
  - Model bio-distribution for enhanced dosimetry
**PET probe insert**

- Improve image quality by recording events with good spatial information (proximity focus).
- Work in coherence with conventional external ring to minimize artifacts due to limited angle tomography.
- Also known as Virtual Pinhole PET (Tai et al., JNM 49(3) 2008)
PET Probe

We chose high resistivity silicon in form of segmented pin diodes as the probe sensor. Properties:

- Supreme spatial resolution (1 μm achieved)
- Compactness, robustness; ideal for probes (“monolithic” sensor, no amplification required)
- Mature development and processing.
- Excellent energy resolution.
- Works in magnetic fields.

However:

- Low efficiency (2 % per 1 mm thick sensor for PET photons, all Comptons)
- Timing.
PET probe model

A test sensor used for material test:

- 256 pads, 1.4 x 1.4 mm² square pads
- 1 mm thick, same wafer/material as the probe sensor
- Coupled to same electronics as the final probe.
- First stage electronics done on application specific integrated circuit (ASIC) in a form of a silicon chip. ASIC is called VATAGP7, made by Gamma Medica – IDEAS, Norway.
- Self-triggering circuit: the input is split into slow & fast channel; fast channel is fed to a leading edge discriminator for the trigger signal.
- Fast shaper: 50 ns nominally (more later)
- Slow shaper: 500 ns
- Sample and hold circuit to fix analog value at max.
- Sparse readout:
  - Only hit channel read
  - Address and (buffered) analog value
Timing setup

- Test the module with 22-Na annihilation photons
- Timing reference: LYSO/PMT setup coupled to constant fraction discriminator (CFD).
- Time to analog converter (Ortec TAC 566) and peak sensing ADC (CAEN V785) digitize the trigger delay.
- Record energy of interaction in Silicon and delay between LYSO and Si trigger.
Results

There are 3 contributions to timing uncertainty:
- Time-walk (blue)
- Jitter
- Broadening related to position of interaction

For time-walk corrected events, position related broadening dominates:
- Do we understand it?
- Can we compensate?
- Can we live with it?
Time resolution and position of interaction

Point-like photon interactions

1 mm³ cube; 511 keV incident photon

GEANT 4

Induction; Ramo theorem $I = e_0 v E$

Pad side

Ionization transport; $v = \mu E$; $E$ not homogeneous

Pad side

Simulation:

- GEANT 4 for particle tracks
- TCAD for 3D weighting field
- Some heavy C++
Signal formation in silicon (animation)

- Animation of 100 electron-hole pairs created at 250 um (left) and 750 um (right) depth in sensor
- Electrons are dyed red, holes black
- Raw signal (per pair) on electrode (current in pA, time in ns) shown.
Comparison to simulation

- Simulation is a good description of the data (!)
- Good agreement even without jitter!
- Shaping time discrepancy (50 ns expected, excellent fit for 150 ns found) → talk to chip designer :-(
- Position related broadening is understood.
Voltage scan

- Increasing bias voltage is a simple remedy (\( U \rightarrow E \rightarrow v \)).
- Well matched to simulation up to 430 V.
Efficiency performance

- Timing extremely important for proper event matching
- Typical time-windows between 6 ns (LYSO) to 12 ns (BGO) [Saha, 2005]
- Compromise between efficiency and rejection of randoms

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Time window</th>
<th>10 ns</th>
<th>20 ns</th>
<th>20 ns 200 V</th>
<th>30 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-340 keV</td>
<td>51 %</td>
<td>75 %</td>
<td>61 %</td>
<td>86 %</td>
<td></td>
</tr>
<tr>
<td>80-340 keV</td>
<td>56 %</td>
<td>81 %</td>
<td>67 %</td>
<td>93 %</td>
<td></td>
</tr>
</tbody>
</table>
**Predictions of probe performance**

- The only significant change is reduction in pad size (1.4 → 1 mm)
- This influences only the weighting field.
- Rely on simulation to anticipate probe performance

<table>
<thead>
<tr>
<th>Eff [%]</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4 mm</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>30 ns</td>
<td>86</td>
<td>95</td>
</tr>
<tr>
<td>20 ns</td>
<td>74</td>
<td>82</td>
</tr>
<tr>
<td>10 ns</td>
<td>51</td>
<td>58</td>
</tr>
</tbody>
</table>
Summary & Conclusions

- We measured timing properties of silicon sensors which will be used for MADEIRA PET probe.
- Good agreement to theory/simulations was found.
- Timing resolution is significantly deteriorated due to position of interaction related broadening.
- Broadening can be reduced by over-biasing the sensors.
- Timing window will be a compromise between random event rejection and efficiency.
- The performance of the actual probe will not differ significantly from the tested model.