AX-PET: Demonstrator for an axial Positron Emission Tomography

Chiara Casella, ETH Zurich
AX-PET: Demonstrator for an axial Positron Emission Tomography

- **Axial concept**
  What is it? Why?

- **AX-PET detector**
  “Demonstrator” for a PET scanner

- **AX-PET detector performance**
  from characterization measurements with 22-Na sources

- **Tomographic image reconstruction, few examples**

- **Preliminary results with Digital Si-PM from Philips**
  as alternative photodetectors for the AX-PET
PET: “in-vivo” functional imaging technique in nuclear medicine

Positron Emission: \[ p \rightarrow n + e^+ + \nu_e \]
Positron Annihilation: \[ e^+ e^- \rightarrow \gamma \gamma \]
\( (E_\gamma = 511 \text{ keV}) \)

How does a PET work?

1. **Inject the radiotracer into the body**
   - Radiotracer: biologically active compound mixed to the positron emitter.

2. **Wait for uptaking period**

3. **Start the acquisition (i.e. detection of coinc. events)**
   - Clear event signature: coincidence of 2 photons of known energy (511 keV) emitted co-linearly

4. **Feed the data into the reconstruction algorithms**

5. **Obtain the image of the activity concentration**
Axial concept

from radial ... ... to axial!

- long crystals
- oriented along the axial direction
- several layers arrangement

always a compromise between
good spatial resolution (small L, small $\delta p$)
or good sensitivity (long L)

$$\delta p = L \cdot \sin \theta$$

max interaction efficiency, long L
$$\epsilon = 1 - e^{-\mu L}$$

min parallax error => short L
- deterioration of the spatial resolution
- non-uniformity in the field of view

the axial geometry allows for a parallax free system, in which spatial resolution and sensitivity are completely decoupled:

- improve spatial resolution $\iff$ reduce $d$
- improve sensitivity $\iff$ increase $Nr$ layers

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AX-PET detector concept

- 3D localization of the photon interaction point + energy measurement
- high granularity => possibility to identify Compton scattering events in the detector

**Crystals:**
- trans-axial coordinate \((x,y)\)
  - digital resolution from crystal size \((d/\sqrt{12} \times 2.35\) FWHM\)
- energy

**Wave length shifter strips:**
- axial coordinate \((z)\)
  - center of gravity => resolution better than digital \((<w)\)
**AX-PET module**

- **SCINTILLATOR CRYSTALS**:  
  - Inorganic LYSO (Lu$_{1.8}$Y$_{0.2}$SiO$_5$: Ce, Prelude 420 Saint Gobain) crystals  
    - high atomic number  
    - high density ($\rho = 7.1$ g/cm$^3$)  
    - $\lambda$ @511 keV ~ 1.2 cm  
    - quick decay time ($\tau = 41$ ns)  
    - high light yield (~32000 $\gamma$/ MeV)  
    - $3 \times 3 \times 100$ mm$^3$

- **WAVE LENGTH SHIFTING STRIPS (WLS)**:  
  - ELJEN EJ-280-10x  
  - highly doped (x10 compared to standard) to optimize absorption  
  - $0.9 \times 3 \times 40$ mm$^3$

- Each crystal and WLS strip is readout individually by its own photodetector

**Photodetectors**

- **MPPC (Multi Pixel Photon Counter) from Hamamatsu**  
  - also known as SiPM / G-APD  
    - high PDE (~50%) ✓  
    - high gain ($10^5$ to $10^6$) at low bias voltage ✓  
    - insensitive to magnetic field ✓  
    - compact size ✓  
    - temperature dependent ✓  
    - dark rate ✓

- MPPC S10362-33-050C:  
  - $3\times3$ mm$^2$ active area  
  - $50 \mu$m x $50 \mu$m pixel  
  - 3600 pixels  
  - Gain ~ $5.7 \times 10^5$

- MPPC 3.22×1.19 Octagon-SMD:  
  - $1.2 \times 3.2$ mm$^2$ active area  
  - $70 \mu$m x $70 \mu$m pixel  
  - 1200 pixels  
  - Gain ~ $4 \times 10^5$  
  - custom made units

~ 1000 pe  
~ 10 - 50 pe

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AX-PET demonstrator

**Goal of the collaboration:**
Build and fully characterize a "demonstrator" for a PET scanner based on the axial concept. Assess its performances.

**Demonstrator:** Two identical AX-PET modules, used in coincidence

- two modules built - at CERN
- module performance assessed (22-Na source)   
  - individually - at CERN
  - in coincidence
- tomographic image reconstruction  
  (with a dedicated gantry setup)
- all stages fully supported by simulations

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AX-PET detector performance

• Characterization measurements with 22-Na source + tagger
• Methods and results in: \textit{NIM A 654 (2011) 546-559}

• LYSO energy response

**typical LYSO energy spectrum (in ADC counts)**

\[
\frac{\Delta E}{E} \sim 11.8 \% \text{ FWHM @} 511 \text{ keV}
\]

(averaged over 96 crystals)

\[
\frac{\Delta E}{E} \sim 12.8 \% \text{ FWHM @} 511 \text{ keV}
\]

(on the module sum)

**Multiplicities**: when 2 modules coincidence: \((0.66)^2 \sim 0.43 \text{ photoelectric interactions}

\begin{itemize}
\item \textbf{LYSO energy response}
\item \textbf{2-D moving station}
\item \textbf{PMT}
\item \textbf{LYSO energy response}
\item \textbf{Module}
\item \textbf{22Na source}
\item \textbf{NIM A 654 (2011) 546-559}
\item \textbf{Characterization measurements with 22-Na source + tagger}
\item \textbf{Methods}
\end{itemize}
**AX-PET detector performance**

**Spatial resolution:**

1. **axial direction** (two detector coincidences):
   - axial coordinate: from center of gravity method (continuous distribution)

   \[
   R_{intr} = \sqrt{R_{meas}^2 - R_\rho^2 - R_{180}^2} \approx 1.35 \text{ mm, FWHM}
   \]
   - Intersection of the LOR with the central plane.
   - Includes contribution from:
     - intrinsic resolution
     - physics of positron emission

2. **trans-axial direction**: digital, from crystal size

   \[
   R_{x,y} = (3\text{mm}/\sqrt{12}) \times 2.35 \sim 2 \text{ mm FWHM}
   \]
**Parallax free demonstration**

Parallax error is more and more important outside the center of the FOV.

Intersection of LORs with the plane containing the source

F2F

OBL

Parallax free demonstration

Intrinsic resolution is **not degraded by parallax effects**, even in very oblique configuration!

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Simple image reconstruction

**capillaries:**
- L = 3 cm
- $\varnothing = 1.4$ mm
- pitch = 5 mm

- central FOV
- measurements performed at ETH Zurich, Radiopharmaceutical Institute
- capillaries filled with 18-F in water solution

**Profiling** of the reconstructed capillaries (3 different measurements) and resolutions (FWHM) of reconstructed sources. The resolution still includes the capillary finite size (1.4 mm inner diameter).

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NEMA phantom

NEMA-NU4 IQ (mouse) phantom:

Three regions in the same phantom to address three different aspects:
- Hot & Cold rods for contrast
- Homogeneous cylinder for assessing the ability to reconstruct homogeneous distributions
- Series of small rods for resolution

- Extended FOV
- Measurements performed at AAA (Advanced Accelerator Applications), St Genis, France
- July 2011
- Phantom filled with 18-F in water solution

NEMA phantom hot / cold / warm - July 2011, AAA

Reconstructed 1 mm rod => FWHM ~ 1.6 mm

Different color scale!
Resolution phantom

Mini Deluxe phantom

- extended FOV
- measurements performed at AAA
- phantom filled with 18-F in water solution

July 2011, AAA

Rods oriented parallel to Z axis

- Fixed time acquisition: 120 s /step
- 60 iterations + post-reconstruction smoothing
- No corrections
- Artefacts due to data truncation (FOV too small...)

Chiara Casella, 22/5/2012
Rods oriented parallel to Z axis

**Mini Deluxe phantom**

- Rods oriented parallel to Z axis
- Extended FOV
- Measurements performed at AAA
- Phantom filled with 18-F in water solution

July 2011, AAA

**Parallel to Z axis**

- Rods oriented parallel to Z axis
- Fixed time acquisition: 120 s /step
- 60 iterations + post-reconstruction smoothing
- No corrections
- Artefacts due to data truncation (FOV too small...)

**Perpendicular to Z axis**

Results presented in Valencia, IEEE 2011
Inter-Crystal Scattering (ICS)

Images shown before used only photoelectric absorption events!

But ignoring ICS events is underutilization of the acquired data

=> Attempts to include ICS events in the reconstruction i.e. improve sensitivity

“triple” ICS events => 2 possible LOR:

- include both LOR, equal weight ("Prob50")
- include both LOR, weight from \((d\sigma/d\Omega)_{\text{Klein-Nishina}}\) ("Prob")
- include only one LOR, the one with max Prob. \((d\sigma/d\Omega)_{\text{Klein-Nishina}}\) ("MaxProb")

NEMA Phantom:

- triple ICS (correctly reconstructed) / photoelectric ~ 20%
- photoelectric events largely dominate the reconstruction

Works in progress!!! Preponderance of standard (photoelectric) coincidences => ICS inclusion provides only a small advantage. Improvement expected to increase for smaller data sets.
Digital SiPM from Philips

Digital SiPM: currently under test as possible alternative photodetector for AX-PET

- fully digital implementation of SiPM / G-APD
- CMOS electronics integrated in the same substrate of each photodiode
- all photodiodes + their electronics connected to:
  - Photon counter
  - TDC => time information

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Interest of dSiPM for PET applications:

- **Timing information; intrinsically very good time resolution (~ 50 ps)**
  
  => **Great potential for TOF-PET**

- Small; high level of integration; e.g. bias supply included => Compactness
- Digital => Low noise.
- Digital => Temperature and gain stability less crucial than in analogue devices.
- Possibility to disable individual cells => Significant reduction in the dark count rate (but lower PDE)
- MRI compatible

**Two different implementations**
- **DPC6400-22-44**: 6400 cells/pixel
  - better filling factor, higher PDE
  - larger dark count rate
  - higher saturation
- **DPC3200-22-44**: 3200 cells/pixel

**MPPC**: 3600 cells
3x3 mm²

**Full tile**: 64 (8x8) sensors

**Sensor (“pixel”)**: 3.3x3.8 mm²

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Goal: test the potentiality of a TOF-PET combined with the axial concept

reduced size AX-PET like module
• 4 LYSO (2x2) and 16 WLS strips (2x8)
• dSiPM coupled to LYSO and WLS strips
• axial coordinate measurement, axial resolution
• timing of the photons vs axial position

dual side readout of the LYSO
• timing (mean time measurement)
• (modest) axial coordinate measurement (both from time and from light yield sharing)

coincidences setup

Setups currently being built!

Tile need to be cooled to reduce the dark count rate!

<table>
<thead>
<tr>
<th>Condition</th>
<th>Dark Count PER CELL</th>
<th>Dark Count PER PIXEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>room T</td>
<td>~ 2.5 kHz</td>
<td>8 MHz</td>
</tr>
<tr>
<td>10 °C</td>
<td>~ 1 kHz</td>
<td>3.2 MHz</td>
</tr>
<tr>
<td>10 °C, 10% worst cells disabled</td>
<td>~ 350 Hz</td>
<td>~ 1 MHz</td>
</tr>
</tbody>
</table>

measured on DPC3200-22-44
Minimal AX-PET like setup

- basic setup, poor mechanical precision and reproducibility - no cooling

**AX-PET components:**
- one LYSO crystal
- one WLS strip
- 22-Na source

- \((\text{LightYield})_{\text{lyso}} \sim 800-1500 \text{ pe} \, @511 \text{ keV}\) (strongly dependent on optical coupling)

- after correcting for dSiPM saturation
  \[ \Rightarrow R_{\text{FWHM}} \sim 12.3\% \, @511 \text{ keV} \]

- \((\text{LightYield})_{\text{wls}} \sim 50 \text{ pe} \) (@511 keV energy deposition in the LYSO)

- clear correlation in the LYSO/WLS responses

- large spread in the WLS response due to non collimated beam

- no axial coordinate measurement, this would need more WLS strips!

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Timing perfs, first results

- basic setup, poor mechanical precision and reproducibility

- **two small LYSO scintillator crystals**
  - **non AX-PET standard**
  - (2x2x12)mm³ ; (2x2x15)mm³
  - teflon wrapped, optical coupling with grease

- **two DLS_3200 tiles**

- 22-Na source

- measure the time difference ($\Delta t$) between the arrival of the first photons in the tiles

- **$\Delta t = 200 \text{ ps, FWHM}$** (cutting on events with 511 keV energy deposition)

- Tile cooling with a Peltier unit ($T_{\text{Peltier}} = 5^\circ \text{C}$)

- Need to repeat the measurement with the long AX-PET crystals

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Conclusions

Axial concept for a PET scanner:
- i.e. long and axially oriented scintillation crystals, intrinsically parallax free system
  Spatial resolution and sensitivity could both be optimized

AX-PET implementation:
- 3D spatial information of the photon interaction point with:
  - matrix of LYSO crystals and WLS strips
  - individual readout of each channel (Si-PM)

Two modules built (i.e. AX-PET demonstrator)
- Energy resolution ~ 12% FWHM, @ 511 keV
- Spatial resolution ~ 1.35 mm FWHM
  (competitive with state of the art PET)

AX-PET demonstrator:
Extensively tested with sources and successfully used for phantoms image reconstruction!

Digital SiPM as promising alternative for photodetector for AX-PET
- excellent time resolution => great potentiality for TOF-PET
- currently being tested for the possibility of TOF-PET combined with the axial concept
- final setup being built
- preliminary promising results (from rudimentary setups):
  - $\Delta t \sim 200$ ps FWHM (with short crystals!!!)
  - $L_Y \sim 1500$ pe for AX-PET LYSO scintillators
  - $\Delta E/E \sim 12\%$ FWHM @511 keV
  - axial resolution ...... (results still to come....)

- calorimeter with tracking capabilities (granularity)
- novelty as a PET detector:
  - geometry
  - materials and technology “stolen” from high energy physics
  - WLS implementation
  - Compton scattering reconstruction

So... Stay tuned :-) !!!

Chiara Casella, 22/5/2012
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typical energy spectrum of one LYSO inside the module:

- photopeak (511 keV)
- Compton continuum (0 - 340 keV)
- Lu X-ray peak (~ 55 keV)

Light yield at 511 keV ~ 1000 pe
(from independent calibration measurements)

Energy resolution

- from gaussian fit of the photopeak
- AFTER ENERGY CALIBRATION

< R_FWHM > ~ 11.8% @511 keV
(averaged on 96 LYSO crystals)
**LYSO energy calibration**

**Photopeak + Intrinsic Lu radioactivity:** very good tool for the energy calibration

- LYSO No. 21 - 22Na coinc. trigger

  - with source, coincidence
  - no source, internal trg.

- LYSO No. 21 - 22Na coinc. trigger
  - 511 keV
  - 202 keV
  - 55 keV
  - 303 keV

- LYSO contains Lu-176
  - A ~ 39 cps/g
  - => ~ 250 Bq / bar
  - => ~ 12 kHz / module

**Deviation from linearity (~ 5% effect)**

- MPPC saturation. Due to:
  - limited nr of cells in the MPPC (3200)
  - important light yield in the scintillator (~1000)
typical integrated raw spectra of few WLS strips

- beam spot collimated at the center of the module (WLS 13)
- 511 keV energy deposition in the LYSO

• more than 1 WLS participate to the event (typically 2-4)
• noise should not be included

Light yield in WLS cluster ~ 100 pe
@511 keV LYSO energy deposition
(from independent calibration measurements: 1 pe ~ 4 ADC)

axial coordinate:
derived from center of gravity method
from all the WLS participating to the cluster
Readout & DAQ

**Individual analogue readout of MPPC output**

Custom designed DAQ system

- **fully analogue** readout chain
- **not optimized** at all for this specific application

- **Amplifiers**: OPA486 (Lyso) / OPA487 (WLS)
- Fast **energy sum** for all the crystals in the module
- **VATA GP5 chip**
  - 128 ch charge sensitive integrating
  - fast (~ 50ns shaper + discriminator) / slow (~ 250ns shaper) branches
  - **sparse readout** mode: only the channels above thr are multiplexed into the output
- analogue info processed by custom made VME ADC
Individual analogue readout of MPPC output
Custom designed DAQ system

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Fast energy sum & Trigger

- analogue sum of the whole module (i.e. total energy over 48 crystals)
- with a proper threshold choice (LL x HL x notHHL)
  => select only events with 511 keV total energy deposition

TRIGGER

\[ \Sigma E_{\text{Mod1}} \]
\[ \Sigma E_{\text{Mod2}} \]

TRIGGER = 2 modules
- each one discriminated @ 511 keV energy sum
- used in coincidence

=> Selection of the good events
• measure delay of coincidence wrt Mod2
• measurement from the scope [Lecroy Waverunner LT584 L 1GHz]
  (no time information in the AX-PET readout)

Measured time resolution : \textbf{FWHM} \sim 1.9 \text{ ns}
**Count rate curves (example: NEMA phantom)**

**NEMA, Module1 rate vs. activity**

\[ \text{Module Rate [kHz]} \]

**NEMA, trigger vs. single rate**

\[ R_{\text{Trigger}} = k \cdot R_{\text{Single}} \]

**NEMA, DAQ vs. trigger rate**

\[ \text{DAQ rate vs Activity (convolution of all contributions)} \]

**NEMA, DAQ rate vs. activity**

\[ R_{\text{DAQ}} = \frac{R_{\text{Trigger}} \cdot e^{-R_{\text{trigger}} \cdot \tau_p}}{1 + \tau_{NP} \cdot R_{\text{trigger}} \cdot e^{-R_{\text{trigger}} \cdot \tau_p}} \]
Towards a tomographic reconstruction...

How to mimic a full scanner with 2 modules only available?

Central FOV:
rotating the phantom...

θ = 0°, 20°, 40°... 180° (9 steps)
φ = 0°

Extended FOV:
...and rotating also the module

θ = 0°, 20°, 40°... 360° (18 steps)
φ = 20°

1 tomographic acquisition = 27 steps acquisition
mimics a 18-modules ring, with coincidences between face-to-face ± one adjacent modules

Chiara Casella, CERN Detector Seminar, 2/3/2012
Setup for tomographic reconstruction

The two modules are mounted on top of a portable platform, which houses also the electronics, power supply, etc...

- One rotating motor for the source / phantom
- One module fixed (Mod1); the other rotating (Mod2)

setup @ CERN, Big 304
Spatial resolution: small animal PET comparison

N. Auricchio - VCI 2010, Febr 2010

Small animal PET comparison
from N. Auricchio, VCI 2010 (Feb 2010)
AXPET result ($R_{FWHM} \sim 1.35 \text{ mm}$) is competitive with (commercial) state of the art PET scanner

- Sensitivity parameter is not meaningful in the demonstrator setup (2 mods only, limited solid angle coverage)
- AXPET not really tuned to be a small animal PET!
D-SiPM: first preliminary results

LYSO light yield

Raw spectrum

511 keV

1.27 MeV

LYSO energy spectrum, Na-22 source

Energy spectrum
(calibrated, corrected for saturation)

R_FWHM ~ 12.3%

PRELIMINARY !!!

Chiara Casella, CERN Detector Seminar, 2/3/2012
Digital Silicon Photomultiplier (D-SiPM)

**pixel (i.e. diode) state machine:**

1. **ready**
2. **valid?** (yes/trigger)
3. **integration**
4. **readout**
5. **recharge**

**READY:**
- All diodes charged above breakdown
- Recharge transistors open

**valid?:**
- Trigger (1st, 2nd, 3rd, 4th photon)
- **yes** integration
- **no** recharge

**Integration Time:**
- (5-40) ns
- (0-20) μs
- 680 ns

**Readout:**
- Proceeds line by line
- The number of photons detected in a line is added to the photons accumulator
- While reading out one line, the preceding one is recharged
- Sensor is still sensitive during readout ⇒ ~1/2 readout time still contributes to the integration time

**Recharge / Reset:**
- Global pixel recharge
- TDC reset

See: Thomas Frach, CERN Detector seminar, Oct 2011
Digital Silicon Photomultiplier (D-SiPM)

Digital SiPM – Trigger Logic

- Each sub-pixel triggers at first photon
- Sub-pixel trigger can be OR-ed or AND-ed to generate probabilistic trigger thresholds
- Higher trigger threshold decreases system dead-time at high dark count rates at the cost of time resolution

Digital SiPM – Validation Logic

- Similar to the trigger logic
- Logic combination of sensor lines
- Sets higher photon threshold → energy threshold

Validation check: at the subpixel level

See: Thomas Frach, CERN Detector seminar, Oct 2011
Validation check: **at the subpixel level**

Each subpixel is divided into rows regions.

Regions ORed / ANDed depending on the exact validation pattern.

Management of the subpixels validation:

- **DLS_6400**: All subpixels are ANDed $\iff$ Validations patterns: $[4, 8, 16, 32]$
- **DLS_3200**: All subpixels are ORed $\iff$ Validations patterns: $[1, 2, 4, 8]$
D-SiPM: Dark counts

PHILIPS
DLD8K – Dark Counts

Control over individual SPADs enables detailed device characterization

- Over 90% good diodes (dark count rate close to average)
- Typical dark count rate at 20°C and 3.3V excess voltage: ~150cps / diode
- Low dark counts (~1-2cps) per diode at -40°C

Fig. 6. Total dark count rate of the sensor at different temperatures.

switching off diodes is equivalent to loss of sensitive area => PDE reduction

see: Thomas Frach, CERN Detector seminar, Oct 2011

Thomas Frach,
NSS-MIC_Conference_Record_2009_N28-005.pdf
D-SiPM: Timing properties

PHILIPS

DLD8K – Photon And Time Resolution

**Photon Resolution**

- Sensor triggered by attenuated laser pulses at first photon level
- Laser pulse width: 36ps FWHM, $\lambda = 410\text{nm}$
- Contribution to time resolution (FWHM):
  - **SPAD**: 54ps
  - **Trigger network**: 110ps
  - **TDC**: 20ps

**Time Resolution**

- $T_{\text{res}}(N) = 27.8 + 354.9/N$

TDC:

1 tick = 19.5 ps
24 bits $\Rightarrow$ 1 frame $\sim$ 330 $\mu$s
($2^{24} \times 19.5\text{ps}$)

Intrinsic
(avalanche spreading uncertainty)

Works in progress to reduce it

see : Thomas Frach, CERN Detector seminar, Oct 2011
DLD8K – Scintillator Measurements (I)

- 3 x 3 x 5 mm$^3$ LYSO in coincidence, Na-22 source
- Time resolution in coincidence: **153ps FWHM**
- Energy resolution (excluding escape peak): 10.7%
- Excess voltage 3.3V, 98.5% active cells
- Room temperature (31°C board temperature, not stabilized)
Digital Light Sensor Array DLS 6400-22-44 V2.0

Key Features
- 8 x 8 pixel array
- Single photon counting capability
- Integrated Time-to-Digital converter
- First photon trigger
- Excellent timing resolution
- Fully digital interface
- Four side tileable

Specifications

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
<th>DLS 6400-22-44 V2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Dimensions</td>
<td>32.6 x 32.6 mm²</td>
</tr>
<tr>
<td>Pixel Pitch (H x V)</td>
<td>4.0 mm x 4.0 mm</td>
</tr>
<tr>
<td>Pixel Active Area</td>
<td>3.8 x 3.3 mm²</td>
</tr>
<tr>
<td>Number of Cells Per Pixel</td>
<td>6396</td>
</tr>
<tr>
<td>Cell Size</td>
<td>30 x 50 μm²</td>
</tr>
<tr>
<td>Spectral Response Range</td>
<td>380 nm – 700 nm</td>
</tr>
<tr>
<td>Peak Sensitivity Wavelength (λ_p)</td>
<td>420 nm</td>
</tr>
<tr>
<td>Quantum Efficiency (PDE) @ λ_p</td>
<td>30 %</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>54 %</td>
</tr>
<tr>
<td>Dark Count Rate</td>
<td>&lt; 5 MHz / pixel at room temperature</td>
</tr>
<tr>
<td>Operational Bias Voltage</td>
<td>&lt; 35 V</td>
</tr>
<tr>
<td>Temperature Dependence of PDE</td>
<td>-0.33%/°C in the range of 15°C - 25°C</td>
</tr>
<tr>
<td>Intrinsic Timing Resolution</td>
<td>approx. 40 ps</td>
</tr>
</tbody>
</table>
**Time of Flight PET:**

Constraint the location of the emission point in a LOR measuring the arrival time of the two 511 keV photons

Not tight enough to avoid image reconstruction

Significantly improves S/N

\[ \Delta x = \frac{c}{2} \Delta t \]

Position of the annihilation wrt the center of the FOV

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<table>
<thead>
<tr>
<th>(\Delta t)</th>
<th>(\Delta x)</th>
</tr>
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<tbody>
<tr>
<td>800 ps</td>
<td>12 cm</td>
</tr>
<tr>
<td>500 ps</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>100 ps</td>
<td>1.5 cm</td>
</tr>
</tbody>
</table>
AX-PET inspired other developments

**COMPET**: University of Oslo, Norway - E. Bolle et al.

research project for a pre-clinical PET scanner with high sensitivity, high resolution. MRI compatible

- no axial geometry
- 3D reco of photon interaction point with LYSO + WLS + G-APD

E. Bolle et al, NIM A 648(2011) S93-S95

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**Tampere University** (Finland): build a small specific scanner based on AX-PET (toward possible commercialization...)

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**Low cost planar detector for PET**

Triumph, Canada - F. Retiere et al.