Usage of long axially oriented crystals in PET developments: timing and axial resolutions

II Symposium on Positron Emission Tomography
September 21st - 24th 2014, Jagiellonian University, Kraków, Poland

Chiara Casella - ETH Zurich
Usage of long axially oriented crystals

Question 1: is there a TOF potential in an AX-PET like device?
Chiara Casella (ETHZ), Matthieu Heller (CERN), Christian Joram (CERN), Thomas Schneider (CERN),

Question 2: are there possible alternatives to the WLS strips for the definition of the axial coordinate?
Chiara Casella (ETHZ), Matthieu Heller (CERN), Oliver Holme (ETHZ), Christian Joram (CERN)
no timing information available in the AX-PET readout (fully analogue readout chain)

measurement from the scope [Lecroy Waverunner LT584 L 1GHz]

delay of coincidence wrt Mod2

MODULE1 LYSO SUM
MODULE2 LYSO SUM

\[ \Delta t \]

modest TOF potential in the original AX-PET layout (but anyhow not foreseen in the electronics)

for a TOF extension of the AX-PET:

timing information is needed with high timing resolution (~ few 100s ps)

state of the art full-systems TOF-PET (clinical):
e.g. Philips Vereos PET/CT => CRT (coincidence time resolution) ~ 350 ps FWHM
dSiPM : Digital SiPM (Philips)

- fully digital implementation of SiPM
- electronics on the same Si substrate as for the sensor
- on-board TDC (19.5 ps resolution)

Interest of dSiPM for PET applications:

- **High resolution timing information** => TOF-PET
- **Integration** (bias supply included, amplifier, TDC, photon counter)
- **Compactness**
- Early digitization of the output => **Low noise**
- Digital => **Temperature and gain stability less critical** wrt analogue
- Fast active quenching => no Afterpulses.
- Possibility to disable individual cells => **Reduction in the dark count rate** (but lower PDE)
- MRI compatible
AX-PET small scale modules with dSiPM

- two “digital” small-scale modules
- identical detector elements as AX-PET coupled to dSiPM
- reduced Nr channels [2 Layers; 2 LYSO and 8 WLS / layer]
dSiPM AX-PET modules: Performance

Light yield spectrum - no coincidence

Confocal plane reconstruction - in coincidence

Results of the characterization measurements:
- **Light yield**: $\sim 1500$ pe (at 511 keV)
- $\Delta E/E \sim 14\%$ @511 keV (after en.calibr.)
- $R_z \sim 1.22$ mm, FWHM (in coincidence)
- $R_{z,\text{mod}} \sim 1.71$ mm, FWHM

achieved performance are perfectly comparable with the AX-PET results
(dSiPM as alternative photodetector)
dSiPM AX-PET: Timing performance

dSiPM as alternative photodetector: **TIMING is the added value!**

10 cm long => **significant path-length dependence** of timing
Need to correct by the axial coordinate

**COINCIDENCE RESOLVING TIME**

- **Corrected**
  - Entries: 19454
  - $\chi^2 / \text{ndf}$: 59.84 / 25
  - Constant: 1135 ± 11.7
  - Mean: 0.000835 ± 0.0009682
  - Sigma: 0.1168 ± 0.0009

- **Raw**
  - Entries: 19454
  - $\chi^2 / \text{ndf}$: 446.7 / 96
  - Constant: 780.4 ± 7.7
  - Mean: 0.03623 ± 0.00133
  - Sigma: 0.1728 ± 0.0011

**not corrected for axial coord.**
(but geometrically constrained in the central part of the crystals)

CRT ~ 406 ps FWHM
module t_res ~ 287 ps FWHM

corrected for axial coord.
( using information from the WLS)

CRT ~ 269 ps FWHM
module t_res ~ 190 ps FWHM
Improving the path-length dependence by introducing **DUAL SIDED READOUT** => Average timing definition

By definition corrects for the path length dependence on the axial coordinate.

Extension to the full 10cm length of the crystals

**COINCIDENCE RESOLVING TIME**

- Entries: 4698
- $\chi^2 / \text{ndf}$: 36.17 / 21
- Constant: $245.2 \pm 6.2$
- Mean: $-0.009822 \pm 0.001775$
- Sigma: $0.08984 \pm 0.00159$

corrected for axial coordinate using the average timing

**CRT ~ 211 ps FWHM**

module $t_{\text{res}} \sim 149$ ps FWHM
dSiPM AX-PET: Timing, Dual side readout

**HORIZONTAL scan**

independent on the horizontal position along the FOV

**AXIAL scan**

independent on axial coordinate

Very good CRT demonstrated. Uniform along the FOV.
**Question 1**: is there a TOF potential in an AX-PET like device?

Christian Joram (CERN), Matthieu Heller (CERN), Thomas Schneider (CERN), Chiara Casella (ETHZ)

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**yes!**

**an axial geometry is perfectly compatible with TOF applications**

need to introduce **correction for the path length dependence**

(either correcting for the axial coordinate or - more powerful - using **dual side readout with average time**)

a proper photosensors + proper readout system is needed

our result with **dSiPM, dual sided readout**: CRT ~ 210 ps FWHM, uniform all along the field of view

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**NIM A 736 (2014) 161-168**

“A high resolution TOF-PET concept with axial geometry and SiPM readout”
**Usage of long axially oriented crystals**

**Question 2**: are there possible alternatives to the WLS strips for the definition of the axial coordinate? which spatial resolution can be achieved?

- **dSiPM dual sided readout crystals**
  - timing difference technique
    \[ \Delta t / \Delta z = 15 \text{ ps/mm} \] (7.5 ps/mm x 2 for dual side)
    too high time resolution required
    not (yet) within reach - EXCLUDED
  
- light sharing technique
  "contrast" function : \((R-L)/(R+L)\)

- original idea of the axial PET (HPD-PET)
  J.Seguinot et al, "Il Nuovo Cimento" C29(04), 2006

- also inspired by recent work from University of Manitoba (group A. Goertzen)
  F. ur-Rehman et al, 2011 IEEE. doi:10.1109/NSSMIC.2011.6153681
Setup

- Tested xtal (3x3x100 mm³)
- Tagging xtal (3x3x3 mm³, LYSO)
- Source holder
- XY table
- Cu plate on Peltier unit (T = 15°C operating temperature)
**Axial coordinate from light sharing**

- The method doesn’t work for AX-PET standard crystals
- Not enough discriminating power in the contrast function

### Detected light yield vs axial position

<table>
<thead>
<tr>
<th>Light yield [p.e.]</th>
<th>Position along crystal [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>0</td>
</tr>
<tr>
<td>2500</td>
<td>10</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
</tr>
<tr>
<td>1500</td>
<td>30</td>
</tr>
<tr>
<td>1000</td>
<td>40</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>0</td>
<td>60</td>
</tr>
</tbody>
</table>

**AX-PET untreated crystal (polished from manufacturer)**

\[ \lambda_{\text{optical}} \sim 400 \text{ mm} \]
Destroying crystals...

**Need to:**
- increase differences in the light yields L vs R
- artificially decrease $\lambda_{\text{optical}}$
- keep sufficiently high light yields

**Empirical approach:**

**Destroying crystals:**
- depolished 1 face, 2 faces (depolishing powder, grade 800)
- mechanical CNC etching (diamond tool), 1 face, 2 faces, 4 faces

Wrapping (to partly recover the losses in light yield)
- teflon
- ESR (Enhanced Specular Reflector, 3M)
- (TiO2 painting on untreated crystals)
Light yield for surface treated crystal

Detected **light yield** vs axial position (one side only)

- **Untreated, ESR wrapping**
- **Etching 4 faces, ESR wrapping**
- **Etching 4 faces, Teflon wrapping**

100 mm long crystal

![Graph showing light yield vs axial position]

\[ \lambda_{\text{eff}} \text{ (ESR)} = 67.8 \pm 0.1 \text{ mm} \]

\[ \lambda_{\text{eff}} \text{ (Teflon)} = 38.5 \pm 0.1 \text{ mm} \]

- **ESR, \( \lambda \sim 70 \text{ mm}, \ LY[0] \sim 2000 \)**
- **Teflon, \( \lambda \sim 40 \text{ mm}, \ LY[0] \sim 1500 \)**

**Staggered pattern** representative of the general results
Axial resolution without WLS

(R-L)/(R+L) for different axial coordinates

(staggered crystal, ESR wrapping)

Error bars: σ of (R-L)/(R+L)

σ/slope = AXIAL RESOLUTION

(R-L)/(R+L)

ESR wrapping

Teflon wrapping

Position along the crystal [mm]

Position along the crystal [mm]

Beam size subtracted

Resolution FWHM [mm]

ESR wrapping

Teflon wrapping

Position along the crystal [mm]

Measured axial resolution without WLS:
dual sided readout on treated crystals
light sharing technique

< R_FWHM > = (4.4 ± 0.1) mm

< R_FWHM > = (3.7 ± 0.1) mm
The achieved results agree with expectation from a Poisson statistics applied on simple exponential description of the light yield.

Poisson-based statistical model

**LYmax = 1500**

![Graph](image1)

**LYmax = 2000**

![Graph](image2)

**ESR, λ ~ 70mm, LY[0] ~ 2000**

**Teflon, λ ~ 40mm, LY[0] ~ 1500**
Are higher spatial resolutions possible?

According to Poisson statistical models

LY[0]=1500pe, 100 mm

LY[0]=1500pe, 60 mm

LY[0]=3000pe, 100 mm

shorter crystals

increased LY
Axial resolution without WLS, 60 mm crystal

- 60 mm long crystal
- mechanical etching, 3mm pitch
- staggered 4 faces
- Teflon wrapped

results with **60 mm long** LYSO crystals!

Resolutions approaching the ones of AX-PET with WLS strips

\[ \lambda \sim 46 \text{ mm} \]

\[ R_{\text{FWHM}} \sim 2.5 \text{ mm} \]

\[ R_{\text{FWHM}} \sim 1.9 \text{ mm} / \text{dSiPM AX-PET small scale} \Rightarrow R_{\text{FWHM}} \sim 1.7 \text{ mm} \]
Timing performance of treated crystals

polished, unwrapped (AX-PET standard)

\[
\langle \text{CRT} \rangle \sim (198 \pm 5) \text{ ps}
\]

intrinsic time res (removing tag contr)

\[
\sim 149 \text{ ps FWHM}
\]
Timing performance of treated crystals

polished, unwrapped (AX-PET standard)

\[ \chi^2 / \text{ndf} = 6.605 / 8 \]
\[ <\text{CRT}> \sim (198 \pm 5) \text{ ps} \]

intrinsic time res (removing tag contr)

\sim 149 \text{ ps FWHM}

100 mm long crystal

treated crystal (4f - aligned)

\[ <\text{CRT}> \text{ FWHM} \sim (405 \pm 5) \text{ ps} \]

\sim 383 \text{ ps FWHM}

deterioration of the absolute timing resolution and non uniformity in the axial direction

\[ <\text{CRT}> \text{ FWHM} \sim (296 \pm 2) \text{ ps} \]

\sim 266 \text{ ps FWHM}
Usage of long axially oriented crystals

**Question2**: are there possible alternatives to the WLS strips for the definition of the axial coordinate?

**yes!**

Method: **Dual side readout** and **light sharing technique** \( ((L-R)/(L+R)) \)

need to “destroy” the crystals (reducing the attenuation length, keeping the highest possible light yield)

- **100mm** crystals, mechanical etching, teflon / ESR wrapping \(\Rightarrow \text{Rz} \sim 4.0 \text{ mm FWHM} \)
- **60 mm** crystals, mechanical etching, teflon / ESR wrapping \(\Rightarrow \text{Rz} \sim 2.5 \text{ mm FWHM} \)

destroyed crystal \(\Rightarrow\) compromize on the timing resolution wrt untreated crystals with **CRT \sim 400 - 300 \text{ ps (not uniform)}**
Usage of long axially oriented crystals beyond AX-PET

AX-TOF-PET
(dual side readout &
average timing introduction)

AX-PET without WLS strips:
- not competitive in spatial resolution with the WLS strips solution
- compact, simple, few nr of channels
- only crystals in the sensitive volume (PET/MRI?)
- room for improvement
  (e.g. shorter crystals?)
  (e.g. higher LY, higher PDE...)
  (e.g. improved timing \[\Delta t/\Delta x \sim 15\, \text{ps/mm}\] with no need of destroing the crystals ...)
Usage of long axially oriented crystals beyond AX-PET

AX-TOF-PET
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AX-PET without WLS strips:
- not competitive in spatial resolution with the WLS strips solution
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THANX for the attention!
treated crystal (4f - aligned)

**TEFLON**

**t_average**

**ESR**

**t_left**

**t_right**

**t_average**

**t_left**

**t_right**
Additional test: 60 mm long LYSO crystals

Axial arrangement of crystals in a PET

**Axial resolution**

- Axial position [mm]
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60

- $R_{\text{FWHM}}$ [mm]
  - 1
  - 1.5
  - 2
  - 2.5
  - 3
  - 3.5
  - 4

**Timing performance**

- CRT Crystal/Tagger
  - CRT [ps]
    - 200
    - 210
    - 220
    - 230
    - 240
    - 250
    - 260
    - 270
    - 280
    - 290
    - 300

- CRT ~ 250 ps FWM

- $R_{\text{intrinsic}}$ ~ 215 ps

Very promising results (axial resolution/timing) with 60 mm long LYSO crystals.
“digital AX-PET modules”: light yield

Light yield (averaged over 8 crystals):
(a) \( LY = (1326 \pm 118) \text{ pe} \)
(b) \( LY = (2159 \pm 93) \text{ pe} \)

Energy resolution (after energy calibration):
(a) \( \Delta E/E \sim 14.2 \% \)
(b) \( \Delta E/E \sim 12.6 \% \)
"digital AX-PET modules" : axial resolution (1/2)

- 22Na source (diam = 0.250 mm)
- Measure reconstructed beam size at different distances
- Extrapolate to zero distance (non colinearity and beam divergence suppressed)
- Positron annihilation physics (i.e. range) subtracted
- Source size subtracted (negligible)

=> Module axial resolution ~ 1.57 mm FWHM
Axial arrangement of crystals in a PET "digital AX-PET modules" : axial resolution (2/2)

Two modules coincidence, 22Na source
Draw LOW => Confocal plane reconstruction => R_meas

\[ R_{intr} = \sqrt{R_{meas}^2 - R_{\rho}^2 - R_{180}^2} \]

limits to the achievable spatial resolution in a PET system, due to the physics of positron emission:

positron range : \( R_{\rho}^2 = [0.54 \text{ mm}]^2 \)
non collinearity : \( R_{180}^2 = [0.0022 \times \text{Diameter}]^2 = [0.33 \text{ mm}]^2 \)

⇒ COINCIDENCE axial resolution ~ 1.21 mm FWHM
⇒ MODULE axial resolution = 1.21 x \( \sqrt{2} \) ~ 1.71 mm FWHM
**TEFLON**

- DSiPM @ 100 mm
- DSiPM @ 0 mm
- DSiPM Sum

\[ \lambda_{\text{eff}} = 40.5 \pm 0.1 \text{ mm} \]

**ESR**

- DSiPM @ 100 mm
- DSiPM @ 0 mm
- DSiPM Sum

\[ \lambda_{\text{eff}} = 71.8 \pm 0.1 \text{ mm} \]

**ESR : higher light yield**

- \( \Rightarrow \) better \( \Delta E/E \)
- \( \Rightarrow \) better timing performance

**Teflon: smaller effective attenuation length**

- \( \Rightarrow \) higher slope in \( (L-R)/(L+R) \)
- \( \Rightarrow \) better spatial resolution (although in principle less uniform)
Staggered vs Aligned Pattern

“quasi-continuos”

“discrete”

5 mm pitch, four faces staggered

5 mm pitch, four faces identical

staggered is preferred because of uniformity!
**Axial Resolution: Toy MC**

**ASSUMPTION:**
Poisson statistics

\[ L \pm \sigma_L ; \sigma_L = \sqrt{L} \]

\[ R \pm \sigma_R ; \sigma_R = \sqrt{R} \]

\[ f = \frac{(L-R)}{(L+R)} \]

\[ \sigma_f : \text{from error propagation} \]

Light yield \( LY[0] \) defines the size of the error bars => Resolution

\[ LY[0] = 1500 \]