Resolving Power of Pixel Detector Timepix for Wide-Range Electron, Proton and Ion Detection

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Resolving Power of Pixel Detector Timepix for Wide-Range Electron, Proton and Ion Detection
Motivation + Goals + Challenges + Status

- Timepix detectors being used to detect and characterize mixed radiation fields such as those found in outer space, near Earth, deep space, upper atmosphere, ion beam radiotherapy → Response/calibration needed
- Particular value by the detector resolving power in terms of particle-type, spectral-(energy loss) and direction/tracking.
- The challenge is to provide resolving power with high sensitivity and wide dynamic range in terms of particle types, stopping power and direction with a single compact device
- Experimental study, tests and calibration of a single Timepix (300 µm Silicon): evaluation of detection response in defined fields of various radiations (electrons, protons, ions) in wide range of fluxes, energies and incident directions

Use of Timepix in space
- Applications:
  - Radiation dosimetry (quantum imaging dosimetry, LET spectra, on line response)
  - Radiation monitoring (miniaturization, integration)
  - Characterization of radiation fields (photon counting, per-px spectrometry, wide range)
- Science/research
  - Space weather
  - Focal plane X-ray imager
  - Micro-tracker/directional camera
  - Gamma-ray Compton camera
  - Neutron detection

Deployments of Timepix in space/orbit
- Applications:
  - NASA - ISS-REM-TPX 2012, IEAP CTU
  - ESA - Proba-V/SATRAM-TPX spacecraft payload 2013, IEAP CTU
  - NASA – BIRD-TPX Orion EFT-1 2014
  - NASA – ISS EPT TPX telescope 2017
- Science/research
  - CZ - X-ray focal plane detector/X-ray telescope on board Czech VZLUSAT-1 cubesat 2016, VZLU/RIGAKU/FEL-IEAP CTU
- Educational
  - GB – TechDemoSat1
Research area/subjects

- Atmospheric phenomena & ionizing radiation
- Sources, variation, characterization of primary & secondary cosmic rays
- Radiation instrumentation/methodology

Experiments/projects/deployment

- Atmospheric balloons
- UAV/drones, remote/terrain vehicles
- DLR aircraft flights
- Dosimetry experiments on board ISS
- Satellite borne payloads/experiments
- Return satellite capsule
- High-altitude radiation stations

Biological satellite BION-M1, return capsule LEO orbit, IBMP RAS Moscow
Cyklotron accelerator

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>Internal</td>
<td>1 - 37</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>H⁺</td>
<td>External</td>
<td>6 - 25</td>
<td>5</td>
</tr>
<tr>
<td>H⁺/H⁺</td>
<td>External</td>
<td>6 - 37</td>
<td>50 - 30</td>
</tr>
<tr>
<td>D⁺</td>
<td>Internal</td>
<td>2 - 20</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>D⁺</td>
<td>External</td>
<td>12 - 20</td>
<td>5</td>
</tr>
<tr>
<td>D⁺/D⁺</td>
<td>External</td>
<td>11 - 20</td>
<td>35 - 20</td>
</tr>
<tr>
<td>³He⁺²</td>
<td>Internal</td>
<td>3 - 55</td>
<td>20</td>
</tr>
<tr>
<td>³He⁺²</td>
<td>External</td>
<td>18 - 52</td>
<td>2</td>
</tr>
<tr>
<td>⁴He⁺²(α)</td>
<td>Internal</td>
<td>4 - 40</td>
<td>40</td>
</tr>
<tr>
<td>⁴He⁺²(α)</td>
<td>External</td>
<td>24 - 38</td>
<td>5</td>
</tr>
</tbody>
</table>

Note: Energy range of internal beams is for the probe radii from 20–50 cm.

Electron microtron accelerator

<table>
<thead>
<tr>
<th>Feature</th>
<th>Before modernization</th>
<th>After modernization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum energy (MeV)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Energy range (MeV)</td>
<td>6 - 25</td>
<td>6 - 25</td>
</tr>
<tr>
<td>Electron current (μA)</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>High frequency source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunable magnetron</td>
<td>2 780 ± 50 MHz</td>
<td>2 786 ± 5 MHz</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Pulse length (μs)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Repetition rate (Hz⁻¹)</td>
<td>400</td>
<td>max. 425 Hz⁻¹</td>
</tr>
<tr>
<td>Resonator freq. (MHz)</td>
<td>2 784 MHz</td>
<td>2 786 MHz</td>
</tr>
<tr>
<td>Power supply freq. (Hz)</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>
Electron Microtron accelerator
Nuclear Physics Institute, Prague, Czech Academy of Sciences

Physics/radiation research at accelerator research facilities

 Highly integrated (contact geometry)
 WidePIX3D 4xTPX tracker

Lead shielding (radiation, EMI)

Palm-top miniaturized particle telescope

Electron beam

4x TPX

Electron Microtron Accelerator

Energetic charged particles

NPI-CAS, Rez near Prague
Electron Microtron Accelerator
3D charged particle tracking
Widepix3D 4xTimepix miniaturized Tracker

Spatial + Time correlated detection
Color value = Time of interaction
21 MeV electrons (NPI Microtron)

21 MeV electrons, NPI Microtron + 4xTimepix WidePIX3D ADV

Color value = pixel layer ordering
600 ns
Medium-energy protons
Cyclotron accelerator, NPI-CAS, Rez near Prague

Timepix chip
Incident beam
Proton beam

Timepix/miniPIX

ADVACAM
Imaging the Unseen

protons: varying E + unfiltered data

30.9 MeV protons
28.8 MeV protons
26.6 MeV protons
19.6 MeV protons
12.7 MeV protons
6.2 MeV protons
Quantum imaging detection, spectrometry, tracking

Energetic charged particles: relativistic ions, secondary reaction/fragmentation products

490 MeV/u $^{28}$Al ions

85 MeV/u $^{28}$Al ions & secondary reaction products

- Deposited energy
- Position of interaction
- $dE/dx \rightarrow$ LET, stopping power
- Direction (limited angular resolution)

C. Granja, CRREAT/NPI-CAS, Prague 22.6.2017
20.4 MeV electrons, 0°
12.6 MeV protons, β = 80°
48 MeV protons, β = 2°
61 MeV/u $^4$He, β = 15°
61.8 MeV/u $^{12}$C, β = 4°
151 MeV/u $^{12}$C, β = 4°
82 MeV/u $^{28}$Si, β = 8°
444 MeV/u $^{28}$Si, β = 3°
Single particle detection and spectrometry
Cluster analysis + Pattern recognition: Heavy charged particles: protons, ions

Charged particles:
- Deposited energy
- Position of interaction

Pixelated cluster morphology / pattern recognition analysis:
- Shape, cluster area: A
- Summed energy, cluster volume: E
- Largest pixel energy, cluster height: H

Light ions /products from nuclear reaction 24 MeV Li ions on Be target
\(^{9}\text{Be}(^{7}\text{Li},^{8}\text{Li})\)

Low-energy protons
VdG accelerator, IEAP CTU Prague

Unwanted events, background, X-rays, scattered particles
Energetic (penetrating) charged particles:
- Deposited energy
- Position of interaction
- $dE/dx \rightarrow$ LET, stopping power
- Direction (ang res $\approx 5$-$10^0$)

Pattern recognition and micro-scale tracking of single charged particles

**Detection Response of Timepix: Micro-scale tracks**

Pattern recognition + cluster analysis parameters + (physics) degrees of freedom

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Value in cluster</th>
<th>Range*</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td># of pixels</td>
<td>1 – few 100’s</td>
<td>px</td>
</tr>
<tr>
<td>E</td>
<td>Deposited energy</td>
<td>Sum of energies of all pixels</td>
<td>5 – $1 \times 10^6$</td>
<td>keV</td>
</tr>
<tr>
<td>H</td>
<td>Height</td>
<td>Largest per-pixel energy</td>
<td>5 – $1 \times 10^3$</td>
<td>keV</td>
</tr>
<tr>
<td>R</td>
<td>Roundness</td>
<td>Extent of circular shape</td>
<td>0 – 1</td>
<td>a.u.</td>
</tr>
<tr>
<td>Lin</td>
<td>Linearity</td>
<td>Extent of track length approaching a straight line</td>
<td>0 – 1</td>
<td>a.u.</td>
</tr>
<tr>
<td>Len</td>
<td>Length</td>
<td>Path length of track across sensor</td>
<td>1 – few 100</td>
<td>px</td>
</tr>
<tr>
<td>W</td>
<td>Width</td>
<td>Transversal width of pixel distribution along track length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LET</td>
<td>Linear energy transfer</td>
<td>Ratio of energy to length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α</td>
<td>Polar angle</td>
<td>Projected angle on the sensor plane</td>
<td>0 - 180⁰</td>
<td>deg</td>
</tr>
<tr>
<td>β</td>
<td>Elevation angle</td>
<td>Elevation angle to the sensor plane</td>
<td>0 - 90⁰</td>
<td>deg</td>
</tr>
</tbody>
</table>

*: Upper limit approximate level

S: Lower limit given by the detector sensitivity and calibration, typically at the level of few keV/px

(§): Upper limit typically up to 1 MeV (linear range of calibration) and 2 MeV (distorted region).

a.u.: arbitrary units
px: pixels

Degrees of freedom:
- Particle type
- Particle energy, stopping power
- Particle direction
Response of cluster analysis parameters: Varying ion energy

Area [\# px]

Energy (volume) [keV]

Height [keV]

Track length [\mu m]

LET [keV/\mu m]

\( ^4 \text{He} \) beam: 20-150 MeV/\( u \): all particles

\begin{align*}
\text{Area} & \quad \# \text{px} \\
\text{Energy (volume)} & \quad \text{[keV]} \\
\text{Height} & \quad \text{[keV]} \\
\text{Track length} & \quad \text{[\mu m]} \\
\text{LET} & \quad \text{[keV/\mu m]} \\
\end{align*}
Response of cluster analysis parameters: Varying ion energy

$^4$He beam: 20-150 MeV/u: all particles

|-------------|-----------------------|--------------|-------------------|--------------|

Distributions and Spectra [#bin]: << minipix TPX 300 um Si >>, HIMAC-Chiba, Sat 10 June 2017, Carlos NP! Prague, beam = 150 MeV u 4He, data dir = minipix\evals\sat10\02
TWO-PARAMETER ANALYSIS

Electrons, protons, ions: all particles

4 energies
protons
bckg/unwanted events

2 energies
bckg/unwanted events
TWO-PARAMETER ANALYSIS

Electrons, protons, ions: all particles

- 25 MeV p
- 48 MeV p
- 60-290 MeV 12C
- 490 MeV 28Si

Graphs showing LET [keV/μm] vs. HL [keV/px] and HEA [keV/deg] for different particle types.
**Timepix: detection response/resolving power**

**Particle types/species, spectral range, direction**

Classification of radiation events in the Timepix detector. The proposed event types are listed with the proposed range of selected values of cluster parameters.

<table>
<thead>
<tr>
<th>#</th>
<th>Event</th>
<th>CAP 1</th>
<th>CAP 2</th>
<th>CAP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X-rays, L.E. e’s, P. energetic e’s, μ’s</td>
<td></td>
<td></td>
<td>H &lt; 140</td>
</tr>
<tr>
<td>2</td>
<td>L.E. p’s</td>
<td></td>
<td></td>
<td>140 &lt; H &lt; 800</td>
</tr>
<tr>
<td>3</td>
<td>L.E. light ions</td>
<td></td>
<td></td>
<td>800 &lt; H &lt; 2500</td>
</tr>
<tr>
<td>4</td>
<td>L.E. heavy ions</td>
<td></td>
<td></td>
<td>2500 &lt; H</td>
</tr>
<tr>
<td>5</td>
<td>E. e’s, μ’s</td>
<td></td>
<td></td>
<td>0 &lt; LET &lt; 1.85</td>
</tr>
<tr>
<td>6</td>
<td>E. p’s</td>
<td></td>
<td></td>
<td>1.85 &lt; LET &lt; 4.0</td>
</tr>
<tr>
<td>7</td>
<td>E. light ions</td>
<td></td>
<td></td>
<td>4.0 &lt; LET &lt; 42</td>
</tr>
<tr>
<td>8</td>
<td>E. heavy ions, HZE</td>
<td></td>
<td></td>
<td>42 &lt; LET</td>
</tr>
</tbody>
</table>

L.E. = low energy, E = energetic, P. = Perpendicular, CAP = cluster analysis parameter
A = area [# px], R = roundness [a.u.], H = height [keV/px], LET = linear energy transfer [keV/μm]
e = electrons, μ = muons, p = protons
Composite materials for radiation shielding
Evaluation + proton beam + mixed field characterization

Set of various composite materials

Proton/light ion cyclotron at NPI Rez

Proton beam

Monoenergetic, size/parallel beam proton field at 3 energies: 4 samples + open beam

acq t = 100 ms

open beam sample A sample C sample G sample H

30.9 MeV

19.6 MeV

7.9 MeV
Composite materials for radiation shielding
Particle flux and spectral (energy loss) characterization

Count rate [#/s]: 30.9 MeV protons

Count rate [#/s]: 19.6 MeV protons

Count rate [#/s]: 7.9 MeV protons

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Cluster volume distribution

Composite materials for radiation shielding
Particle flux and spectral (energy loss) characterization

Back-up slides
Event name: Presentation title: 23

ADVACAM

Timepix in Space, CERN, 13.3.2018

Carlos Granja, Advacam