From Physics to Daily Life: Radiation Detection in the Environment and Classrooms

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PH Department
Spokesman, Medipix2 and Medipix3 Collaborations
Acknowledgements

- Medipix1, Medipix2 and Medipix3 Collaboration members
- CERN KT group
- CERN Medipix team
Outline

• The problem of signal to noise at LHC
• Hybrid pixel at the LHC
• The Timepix chip and some applications
• Medipix3 – moving towards spectroscopic X-ray imaging
• Timepix3 – the electronic bubble chamber
• Conclusions
Understanding signal to noise ratio

The house in the country analogy…..

The LHC vertex detector problem

- 10’s of particles collide every 25(50)ns creating 1000’s of tracks
- All ‘hits’ need to be identified unambiguously in space and time
- The ability to distinguish 2 closely separated tracks in r and phi
- Minimal mass
- Minimal power consumption
- Radiation tolerant detectors and readout electronics.
Fill factor is 100% (away from periphery)
Sensor and ASIC can be optimised separately
Full depletion of sensor allows prompt charge collection
It is relatively straightforward to achieve extremely high SNR – “noise free imaging”
Sensor material can be changed – or replaced by e.g. MCP, Gas gain grid, etc
Standard CMOS can be used allowing on-pixel signal processing
Helping to make sense of this....

20 events piled up in a single LHC bunch crossing...
Hybrid pixel detectors at LHC

3 large vertex trackers in operation
   Alice (10M channels)
   Atlas (~100M channels)
   CMS (~100M channels)

LHCb RICH
   500 photon sensitive tubes

All making important contributions to LHC physics

Upgrades planned for high luminosity or high energy running (Alice, Atlas, CMS)
Trigger free operation of LHCb planned
Moore’s law - transistor feature size

1965: Number of Integrated Circuit components will double every year

1975: Number of Integrated Circuit components will double every 18 months

1996: The definition of “Moore’s Law” has come to refer to almost anything related to the semiconductor industry that when plotted on semi-log paper approximates a straight line. I don’t want to do anything to restrict this definition. - G. E. Moore, 8/7/1996

Medipix chip family – following Moore’s Law

Transistor density per pixel $[\text{trts/}\mu\text{m}^2]$ vs. CMOS process [nm]

- Medipix1 (1998)
- Medipix2 (1998)
- Medipix3 (2006)
- Timepix (2011)
- Medipix3RX (2013)
- Timepix3 (2013)
- Clicpix (2013)
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Medipix2 Collaboration

- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mitthoeogskolan
- MRC-LMB Cambridge
- U INFN Napoli
- NIKHEF Amsterdam
- U INFN Pisa
- FZU CAS Prague
- IEAP CTU in Prague
- SSL Berkeley

http://medipix.web.cern.ch/MEDIPIX/
Medipix chip family – following Moore’s Law

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Aims of the Timepix chip

Camera-like logic (as Medipix2)
- Electronic shutter

Make pixels programmable:
- Particle arrival time (requested by gas detector community – EuDet)
- Time over Threshold
- Particle (photon) counting

Pixel size and matrix dimensions the same as Medipix2
- 55µm square pixels
- 256 x 256 pixels
## Timepix Specifications

<table>
<thead>
<tr>
<th><strong>Pixel matrix</strong></th>
<th>256 x 256</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel size</strong></td>
<td>55 x 55 µm$^2$</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>CMOS 250 nm</td>
</tr>
<tr>
<td><strong>Measurement modes</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Time over Threshold (ToT)</td>
</tr>
<tr>
<td></td>
<td>• Time of Arrival (ToA)</td>
</tr>
<tr>
<td></td>
<td>• Event counting (Medipix mode)</td>
</tr>
<tr>
<td><strong>Readout type</strong></td>
<td>Frame based</td>
</tr>
<tr>
<td><strong>Readout Time</strong></td>
<td>Same as Medipix2</td>
</tr>
<tr>
<td><strong>Minimum threshold</strong></td>
<td>~ 750 e-</td>
</tr>
</tbody>
</table>

- Directly derived from Medipix2 chip
- ToA requested by EUDet Collaborations

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Timepix Pixel Cell Schematic

Analog

Test Input

Testbit

Polarity

4 bits thr
Adj

Mask

THR

Preamp

Input

Digital

Clk_Count

Clk_Countb

Shutter

P0

P1

Timepix Synchronization Logic

Clk_Read

Shutter_int

Conf

8 bits configuration

Ovf Control

14 bits Shift Register

Next Pixel

Previous Pixel
Medipix2/Timepix Chip Architecture

- 14111 µm
- 256 x 256 pixels

- 3328-bit Pixel Column
- 256-bit Fast Shift Register
- 13 8-bit DACs
- 32-bit CMOS Output

5ms readout time (serial @ 200MHz)

300µs readout time (parallel @ 100MHz)

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Timepix miniaturised readout
Image of the astronaut Chris Cassidy working near the Timepix USB on the International Space Station (Courtesy of NASA, photo ref. no. iss036e006175)
4s exposures - ISS

South China Sea

South Atlantic Anomaly

University of Houston, IEAP Prague, NASA
26/09/2014
Map of Dose

Spatial-correlated radiation dose
Earth map @ 400 km altitude

Airline altitude 11 km (Madrid-Bogota): 0.025 μGy/min = 0.036 mGy/d = 0.013 Gy/year

Ground level (Prague): 0.001 μGy/min = 0.0015 mGy/d = 0.0005 Gy/year

REM Orbital Dose Rate Map (μGy/min)
D03-W0094 (S/N 1007)
GMT 2012/320 through GMT 2013/045

0.3 mGy/day → 0.1 Gy/year
3 mGy/day → 1.1 Gy/year
5.5 mGy/day → 5.5 Gy/year

REM Dose Rate Data (μGy/min) measured by Timepix onboard the ISS
Imaging a Carbon ion beam

- 4 Timepix chips configured as a 2x2 quad read out a GEM foil with 3mm thick Ar/CO$_2$ gas volume
- Detector placed in Carbon beam (480MeV/nucleon) within a water phantom and moved in 24 steps
- 1ms frames used to reconstruct beam profile of $10^8$ protons/sec
- Colour scale chosen to show fragments
Imaging a Carbon ion beam

Bragg Peak

Fragment Tail

Width (mm)

Depth (mm)

Height (mm)

20

10

40

60

120

140

S.P. George
F. Murtas
J. Alozy
A.B. Rosenfeld
M. Silari
Timepix summary

- Based on Medipix2
- Reuse Medipix2 readout system, detectors etc
- On-pixel Time of Arrival (ToA) or Time over Threshold (ToT) measurement
- Excellent performance for single particle detection/identification
- Multiple uses – many not explained here
- Limitations:
  - Frame based readout
  - Either ToT or ToA only per pixel
The Medipix3 Collaboration

- University of Canterbury, Christchurch, New Zealand
- CEA, Paris, France
- CERN, Geneva, Switzerland
- DESY-Hamburg, Germany
- Albert-Ludwigs-Universität Freiburg, Germany
- University of Glasgow, Scotland, UK
- Leiden University, The Netherlands
- NIKHEF, Amsterdam, The Netherlands
- Mid Sweden University, Sundsvall, Sweden
- IEAP, Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Universität Erlangen-Nürnberg, Erlangen, Germany
- University of California, Berkeley, USA
- VTT, Information Technology, Espoo, Finland
- ISS, Forschungszentrum Karlsruhe, Germany
- University of Houston, USA
- Diamond Light Source, Oxfordshire, England, UK
- Universidad de los Andes, Bogota, Colombia
- University of Bonn, Germany
- AMOLF, Amsterdam, The Netherlands
- Technical University of Munich, Germany
- Brazilian Light Source, Campinas, Brazil
Medipix chip family – following Moore’s Law

Transistor density per pixel [$trts/\mu m^2$] vs CMOS process [nm]

- Medipix1 (1998)
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‘Colour’ X-ray imaging
Aims of the Medipix3 chip

- Spectroscopic X-ray imaging
- Mitigate effects of charge sharing due to charge diffusion and fluorescence
- Solve using more sophisticated on-pixel signal processing
# Medipix3 Specifications

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<thead>
<tr>
<th><strong>Pixel matrix</strong></th>
<th>256 x 256</th>
</tr>
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<tbody>
<tr>
<td><strong>Pixel size</strong></td>
<td>55 x 55 (\mu\text{m}^2) or 110 x 110 (\mu\text{m}^2)</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>CMOS 130 nm</td>
</tr>
</tbody>
</table>
| **Measurement modes**| • Single pixel  
                       • Charge summing |
| **Gain modes**       | • Super low gain mode  
                       • Low gain mode  
                       • High gain mode  
                       • Super high gain mode |
| **# thresholds**     | • 2 per 55 \(\mu\text{m}\) pixel  
                       • 8 per 110 \(\mu\text{m}\) pixel |
| **Programmable**     | • 2 x 1-bit  
                       • 2 x 6-bit  
                       • 2 x 12-bit  
                       • 1 x 24-bit |
| **counter depths**   | Frame based  
                       • Sequential R/W  
                       • Simultaneous R/W |
| **Readout type**     | Depends on counter depth used |
| **Readout Time**     | ~ 500 e- |
| **Minimum threshold**| ~ 500 e- |
Energy Response Function (CdTe 110µm/2mm)

Conventional counting (SPM)
Charge sharing mitigation (CSM)

~4.4KeV FWHM

Energy (keV)

Normalised differential counts

241Am 60keV

Slide courtesy of T. Koenig, KIT
K-edge imaging

- Iodine: Pulmonary circulation
- Barium: Lung
- Bone: normal structure
- 4 energy CT and PCA
Medipix3 summary

- Medipix3 architecture mitigates charge sharing due to diffusion and fluorescence
- The chip can be connected to sensor pixels on a pitch of 55\(\mu\)m and 110\(\mu\)m in each case with the option of using charge summing
- Fluorescence effects are strongly mitigated by this architecture
- High resolution spectroscopic X-ray imaging becomes feasible
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Transistor density per pixel [trts/\(\mu m^2\)]

CMOS process [nm]

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Aims of the Timepix3 chip

- Provide ‘data push’ readout
- Provide both arrival time and Time-over-Threshold information simultaneously
- Improve time stamp precision to 1.6ns
## Specifications

<table>
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<tr>
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<td>55 x 55 µm²</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 130 nm</td>
</tr>
<tr>
<td>Measurement modes</td>
<td>• Simultaneous 10 bit TOT and 18 bit TOA</td>
</tr>
<tr>
<td></td>
<td>• 18 bit TOA only</td>
</tr>
<tr>
<td></td>
<td>• 10 bit PC and 14 bit integral TOT</td>
</tr>
<tr>
<td>Readout type</td>
<td>• Data driven</td>
</tr>
<tr>
<td></td>
<td>• Frame based</td>
</tr>
<tr>
<td></td>
<td>(both modes with zero suppression)</td>
</tr>
<tr>
<td>Dead time</td>
<td>&gt;475 ns (pulse processing + packet transfer)</td>
</tr>
<tr>
<td>Maximum count rate</td>
<td>85.3 Mhits / s</td>
</tr>
<tr>
<td>(data driven)</td>
<td></td>
</tr>
<tr>
<td>Minimum time</td>
<td>1.56 ns¹</td>
</tr>
<tr>
<td>resolution</td>
<td></td>
</tr>
<tr>
<td>Power pulsing</td>
<td>Yes</td>
</tr>
<tr>
<td>Minimum threshold</td>
<td>~500 e-</td>
</tr>
</tbody>
</table>

¹ ToA precision thanks to Gossupo block from Nikhef (Gromov et al.)

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Cosmics and background in Timepix3

Muon with delta electrons

Highly ionising particle

Note: zoomed images
Cosmics and background in Timepix3

Note: zoomed images
One MIP (fully depleted sensor)
One MIP (not fully depleted sensor)
Conclusions

Hybrid pixels were developed out of the need to make sense of the complicated LHC events. They have made important contributions to LHC physics. The Timepix chip has the advantage of ‘showing’ how particles interact with matter and one can easily ‘see’ the difference between the various particle species. The Medipix3 chip is capable of ‘noise-free’ particle imaging and of spectroscopic imaging. Timepix3 provides both deposited charge and arrival time permitting vector detection in a single sensor layer – a kind of electronic bubble chamber.

Collaboration between different fields of science has been beneficial to all – including the HEP community. A sound and equitable Collaboration Agreement governing IP and licensing issues is an often underestimated asset.
Where Science meets Art