RADIATION DETECTION AND IMAGING WITH THE MEDIPIX FAMILY READOUT ELECTRONICS

Prof. Christer Fröjdh
OUTLINE

• Single particle processing
• The MEDIPIX collaborations
• MEDIPIX2
• TIMEPIX
• MEDIPIX3
• Spectral imaging
• Demonstration
INTEGRATING OR COUNTING

An integrating detector collects the charge released in the sensor
- Signal is proportional to deposited energy
- Dark current is added to the signal
- Good for high fluxes
- Simple electronics

A counting detector generates one pulse for each detected photon
- Spectral information can be retained
- "Noise free" – the noise is seen as an uncertainty in the energy
- Limited count rate
- Complex electronics
THE MEDIPIX COLLABORATION

- Development of hybrid pixel detectors for single photon processing
  - Coordinated by CERN
  - Around 20 member institutes
  - MEDIPIX1
    - 64 x 64 pixels, 170 um
  - MEDIPIX2
    - 256 x 256 pixels, 55 um
    - Window mode
  - TIMEPIX
    - Time-over-threshold
  - MEDIPIX3
    - 256 x 256 pixels, 55 um
    - Spectral mode
    - Charge summing
  - TIMEPIX3
    - Time-over-threshold
    - Time-of-arrival
THE MEDIPIX2 COLLABORATION

Institut de Física d'Altes Energies IFAE Barcelona
University of Cagliari
University of California, Berkeley
Commissariat à l'Energie Atomique CEA
European Organization for Nuclear Research CERN
Czech Academy of Sciences
Czech Technical University in Prague (CTU)
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
European Synchrotron Radiation Facility ESRF
Albert-Ludwigs-Universität Freiburg-i.B.
University of Glasgow
University of Houston
Medical Research Council MRC
Mid-Sweden University
Università di Napoli Federico II
National Institute for Nuclear and High-Energy Physics, NIKHEF
Università di Pisa

Spain
Italy
USA
France
Switzerland
Czech Republic
Czech Republic
Germany
France
Germany
United Kingdom
USA
United Kingdom
Sweden
Italy
The Netherlands
Italy
THE MEDIPIX3 COLLABORATION

Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand
DRT/LIST/DeTeCS/SSTM, CEA, Paris, France
The Medipix Team, Microelectronics Group, PH Department, CERN, Geneva, Switzerland
The Detector Group, DESY-Hamburg, Germany
The Diamond Light Source, Diamond House, Didcot, UK
Freiburger Materialforschungszentrum, Albert-Ludwigs-Universität Freiburg, Germany
Detector Development Group, Dept of Physics and Astronomy, University of Glasgow, Scotland, UK
Institute for Synchrotron Radiation, ISS, Forschungszentrum Karlsruhe, Germany
Biophysical Structural Chemistry, Leiden Institute of Chemistry, Leiden University, The Netherlands
Pixel Team, NIKHEF, Amsterdam, The Netherlands
Mid-Sweden University, Sundsvall, Sweden
Institute of Experimental and Applied Physics, Czech Technical University, Prague, Czech Republic
Instrument Support Group, Detector Systems, ESRF, Grenoble, France
Arbeitsgruppe SPOC, Physikalisches Institut, Universität Erlangen-Nürnberg, Erlangen, Germany
Space Sciences Laboratory, University of California, Berkeley, USA
Microsystems, VTT Information Technology, Espoo, Finland
Physikalisches Institut, Universität Bonn, Bonn, Germany
Departamento de Física, Universidad de los Andes, Bogotá, Colombia
ITER, Cadarache, France
FOM Institute for Atomic and Molecular Physics (AMOLF), Amsterdam, The Netherlands
University of Houston, Houston TX, USA
PUBLICATIONS AND CITATIONS
Data from Web of Science searching on topic.

<table>
<thead>
<tr>
<th>Search key</th>
<th>Publications</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEDIPIX2</td>
<td>442</td>
<td>4279</td>
</tr>
<tr>
<td>TIMEPIX</td>
<td>304</td>
<td>1421</td>
</tr>
<tr>
<td>MEDIPIX3</td>
<td>61</td>
<td>533</td>
</tr>
</tbody>
</table>
MEDIPIX2
THE MEDIPIX2 CHIP

Two thresholds – operating in window mode.

Three adjustment bits

Serial or parallel readout
DIFFERENT SENSORS

- Silicon
  - Different thickness
  - Multi chip modules
- GaAs
  - Semi insulating
  - Epitaxial
- CdTe
- Ge
- Gas detectors

APPLICATIONS

- XRD
- Small animal imaging
- X-ray microscopy
- TEM
- Adaptive optics
- Radiation monitoring
- Phase contrast imaging
- ...
- ...

[Image of a patterned grid with numbers]
A NOISELESS DEVICE WITH PARTICLE IDENTIFICATION

Measurements of natural background radiation with a Medipix2-USB device equipped with a 700 mm thick silicon sensor (10 min exposure time). Various traces and tracks of X-ray photons, electrons and some $\alpha$-particles are displayed. A rare cosmic muon track is clearly seen traversing the sensor horizontally.

Study of the charge sharing in a silicon pixel detector by means of $\alpha$-particles interacting with a Medipix2 device

TIMEPIX
TIMEPIX – DERIVED FROM MEDIPIX2

• Same geometry as MEDIPIX2
• Single threshold
• Improved threshold adjustment
• New operation modes
  • Time-over-threshold
  • Time-of-arrival
TIMEPIX PIXEL CELL

Campbell, M., 10 years of the Medipix2 Collaboration, NIM-A, 633, 2011
TIMEPIX IN TOT MODE

Time over threshold mode – an ADC in each pixel

Pulse height

Pulse Threshold

Time
CLUSTER FORMATION
CS 137 – 662KEV

Compton backscattering

Compton edge

662keV Photopeak

Counts (N)

Energy (keV)

1 mm CdTe, 110 um pixels
DEPTH OF INTERACTION MEASUREMENTS

Experiments at DIAMOND light source with a monoenergetic pencil beam. 1 mm thick CdTe sensor with 110 um pixels

X-ray beam

Sensor

α

Read-out chip
DEPTH PROFILE

![Graph showing depth profile with two lines, one for 65° and another for 70°. The x-axis represents depth (Djup) in micrometers (um), and the y-axis represents counts. The graph shows a peak at around 200 um and a decrease towards 1200 um.]
DEPTH OF INTERACTION

The signal is independent of depth of interaction – Small pixel effect
MEDIPIX3
Charge sharing distorts the spectrum and makes any pulse height measurements unreliable.

The figure shows a simulation of the charge sharing as a function of pixel size.
Charge sharing in high-z materials is a combination of fluorescence and diffusion.
MEDIPIX3

- Analog charge summing on chip
- Configuration for "color" imaging with several thresholds per pixel
- Variable counter depth
- Simultaneous counting and readout
- Selectable gain for operation in different energy regions
<table>
<thead>
<tr>
<th>Matrix configuration</th>
<th>Pixel Operating Modes</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Pitch Mode (55μm)</td>
<td>Single Pixel Mode</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Charge Summing Mode</td>
<td>1+1</td>
</tr>
<tr>
<td>Spectroscopic Mode (110μm)</td>
<td>Single Cluster Mode</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Charge Summing Mode</td>
<td>4+4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Front-end gain mode</th>
<th>Linearity</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super High Gain Mode</td>
<td>~5 ke⁻</td>
<td>2</td>
</tr>
<tr>
<td>High Gain Mode</td>
<td>~9 ke⁻</td>
<td>2</td>
</tr>
<tr>
<td>Low Gain Mode</td>
<td>~12.5 ke⁻</td>
<td>2</td>
</tr>
<tr>
<td>Super Low Gain Mode</td>
<td>~18 ke⁻</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pixel Counter Modes</th>
<th>Dynamic range</th>
<th>Counters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-bit</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6-bit</td>
<td>63</td>
<td>2</td>
</tr>
<tr>
<td>12-bit</td>
<td>4095</td>
<td>2</td>
</tr>
<tr>
<td>24-bit</td>
<td>16777215</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pixel readout mode</th>
<th>Active Counters</th>
<th>Dead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequential Read-Write</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Continuous Read-Write</td>
<td>1</td>
<td>No</td>
</tr>
</tbody>
</table>
MEDIPIX3RX - CHARGE SUMMING

The charge summing algorithm in MEDIPIX3RX dynamically checks the charge generated in any four pixel matrix. The charge is allocated to the pixel with the highest signal:

- Significantly reduced charge sharing
- Increased noise
- Reduced count rate
ZR FLUORESCENCE IN SPM AND CSM

300 um Si, 110 um pixel

Cu

Zr- Kα

Zr- Kβ

Intensity (a.u.)

Energy (keV)
PR FLUORESCENCE IN SPM AND CSM

Counts

keV

2 mm CdTe, 110 um pixel

SPM

CSM
TIMEPIX3
TIMEPIX3 MOTIVATION

Based in the success of the Timepix (2006):
- > 350 original paper citations
- Large range of applications:
  • >10 papers in IEEE- NSS-MIC 2013 use Timepix detectors

Experience gained in the design of the Medipix3 (2009) chip:
- Technology (130nm CMOS)
- Building blocs recycled (CERN’s HD library, DACs, IO PADs…)

Main driving requirements:
- Add simultaneous TIME and CHARGE information per pixel
- Minimize dead time
- Improve time measurements resolution
SPECTRAL IMAGING - OUTLINE

• General properties of spectral imaging
  • Signal-to-contrast
  • Energy resolution

• Material separation
  • Monoenergetic radiation
  • Energy resolving detectors

• Conclusions
SPECTRAL IMAGING

Spectral imaging requires:

• Sufficient contrast to noise ratio over the entire range of interest
  • Poisson statistics mean that less photons gives lower CNR
  • High absorption gives the best CNR
  • Windowing is better than subtraction

• Different spectral absorption properties of the materials of interest
  • Generally speaking an absorption edge is required to separate two materials

• Enough photons over the entire energy range
SPECTRAL IMAGING - CNR

In this experiment the following definition has been used

$$CNR = \sqrt{\frac{2(S_{img} - S_{bg})^2}{(\sigma_{img}^2 + \sigma_{bg}^2)}} \quad (1)$$
SPECTRAL IMAGING MEASURED CNR

- 1 mm thick Al + 0.1 mm Al on half of the image, 10000 photons/pixel

<table>
<thead>
<tr>
<th>Material</th>
<th>K-alpha</th>
<th>% transmission</th>
<th>CNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calculated</td>
<td>measured</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>15,770</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Ag</td>
<td>22,163</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Pr</td>
<td>36,026</td>
<td>82</td>
<td>83</td>
</tr>
<tr>
<td>Gd</td>
<td>42,996</td>
<td>88</td>
<td>85</td>
</tr>
<tr>
<td>Er</td>
<td>49,128</td>
<td>90</td>
<td>89</td>
</tr>
<tr>
<td>W</td>
<td>57,982</td>
<td>92</td>
<td>94</td>
</tr>
</tbody>
</table>
SPECTRAL IMAGING MEASURED CNR

Zr  Ag  Pr  Gd  Er  W
SPECTRAL IMAGING MEASURED CNR

![Graph showing CNR vs. Transmission with data points for Calculated, Simulation, and Measured values.](image-url)
SPECTRAL RESOLUTION - WHICH TWO MATERIALS?

Transmission vs. keV for Series 1 and Series 2.
SPECTRAL RESOLUTION: SILICON AND LEAD

Transmission vs keV graph showing the comparison between Pb 0.015 mm and Si, 2 mm.
SPECTRAL RESOLUTION - ATTENUATION IN FIVE MATERIALS

Attenuation curves have similar shapes except around the absorption edges.
THE TYPICAL SITUATION – SPECTRUM AND ABSORPTION CURVES

The difference is in a quite narrow range of the input spectrum

- High spectral resolution required
- Image subtraction gives very high noise
IMAGE SUBTRACTION - TWO MATERIALS

The basic equation:

$$\phi_{e1} = \phi_{0e1} e^{-\alpha_{e1} t}$$

or

$$\alpha_{e1} t = -\ln \left( \frac{\phi_{e1}}{\phi_{0e1}} \right)$$

If $\alpha$ does not change or the difference is known a material can be eliminated by subtracting the logarithms of the response at two energies

$$\ln \left( \frac{\phi_{e1}}{\phi_{0e1}} \right) = \ln \left( \frac{\phi_{e2}}{\phi_{0e2}} \right) \times \frac{\alpha_{e1}}{\alpha_{e2}}$$
SIM - PALLADIUM AND SILVER

K-edges
- $\text{Pd} = 24.365$
- $\text{Ag} = 25.531$
- Thickness $= 50 \text{ um}$
SIM - PRIMARY IMAGES

24 keV  
25 keV  
26 keV
SIM - AFTER SUBTRACTION

25 keV – 24 keV

26 keV – 25 keV
SIM - CORRECTED FOR FLUORESCENCE
MATERIAL SEPARATION

Experiment:
50 um Ag (upper part)
50 um Pd (lower part)

Imaging at three different energies

Material separation by subtraction
MATERIAL SEPARATION - IMAGES AT THREE ENERGIES

22,16 keV  
25,27 keV  
36,03 keV
MATERIAL SEPARATION – PD AND AG

Pd (25.3 – 22.2 keV)  
Ag (36.0 – 25.3 keV)
EXPERIMENTAL SETUP

- Feinfocus FXE 160.51 nanofocus X-ray tube
- Metal plates to generate fluorescence
- MEDIPIX3RX with 2 mm CdTe sensor, 110 um pixel size
- FITPIX USB readout
- Pixelman software
ENERGY CALIBRATION
INPUT SPECTRA

Normalized Intensity

Photon energy (keV)

Cu
Zr
Sn
Pr
Er
W
MEDIPIX3 ENERGY CALIBRATION

Differential counts (a.u.)

Threshold 1 (dac code)

Cu
Zr
Sn
Pr
Er
W
MEDIPIX3 ENERGY CALIBRATION

![Graph showing the relationship between Threshold1 and Energy (keV). The graph includes a linear fit with the equation p0 = -4.512 and p0 = 0.5811.]

- **Measurements**
- **Linear Fit**
  - $p0 = -4.512$
  - $p0 = 0.5811$
IMAGING
X-RAY TUBE SPECTRUM

- Feinfocus FXE-160.51, Nanofocus X-ray source, W-target
SAMPLE LAYOUT
SPECTRAL RESPONSE, PR+ZR

Counts vs. keV graph showing the spectral response for Pr, Zr, and Pr+Zr.
SPECTRAL RESPONSE, W+SN

Counts vs keV graph showing the response of materials Sn, W, and W+Sn at different keV values.
IMAGE
CONCLUSIONS

• The MEDIPIX collaborations have successfully developed a number of pixel detectors with energy resolution

• Timepix allows particle identification and spectrum reconstruction in heavily charge shared environments

• Medipix3 solves the problem of spectral distortion due to charge sharing

• TImepix3 will allow fast processing of cluster events