Spectroscopic X-ray imaging

Lukas Tlustos
Medipix Collaboration, CERN
MEDIPIX2 Collaboration

- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U d'Auvergne Clermont
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mitt hoegskolan
- 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/
MEDIPIX3 Collaboration

- University of Canterbury, Christchurch, New Zealand
- DRT/LIST/DeTeCS/SSTM, CEA, Paris, France
- CERN, Geneva, Switzerland
- DESY-Hamburg, Germany
- The Diamond Light Source, Diamond House, Didcot, UK
- Freiburger Materialforschungszentrum, Albert-Ludwigs-Universität Freiburg, Germany
- University of Glasgow, Scotland, UK
- Institute for Synchrotron Radiation, ISS, Forschungszentrum Karlsruhe, Germany
- Biophysical Structural Chemistry, Leiden Univ., The Netherlands
- NIKHEF, Amsterdam, The Netherlands
- Mid Sweden University, Sundsvall, Sweden
- IEAP, Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Universität Erlangen-Nurnberg, Erlangen, Germany
- Space Sciences Laboratory, University of California, Berkeley, USA
- VTT Microsystems, Espoo, Finland
- ITER
Hybrid-Pixel Detector

- Charged particle
  - Semiconductor detector
  - Bump-bond contact
  - ASIC

- p+ (p-type
- n- (n-type)
- ASIC
- n-well
- p-substrate

- gm
- I_{in}
- V_{out}

- Sensor chip (e.g. silicon)
- Aluminium layer

- High resistivity n-type silicon
- Flip chip bonding with solder bumps
- Electronis chip

- Single pixel read-out cell
Medipix2

(Current) RO systems
• Standard readout: MUROS2 + NI-DIO32
• Fastest readout: PRIAM (ESRF) 1.5 kHz frame rate
• Most compact, portable: USB1.0 based \leq 4Hz frame rate

ASIC
• 0.25 mm CMOS
• 55 \mu m Pixel, 256 x 256
• Sensitive area \sim 2 \text{ cm}^2
• 3 side buttable
• Serial RO \sim 9.2\text{ms} \text{ @} 100\text{MHz Clock}
• 32bit CMOS Parallel RO \sim 300\mu\text{s Port}

Largest assemblies 2x2 and 1x5

ICFTD, Nov. 2009
Medipix2 Pixel

- Positive und negative input signals → alternative detector materials (GaAs, CdTe …)
- Charge sensitive preamplifier with leakage current compensation per pixel
- 2 Discriminators with globally adjustable threshold
- 3-bit threshold adjustment per pixel
- Counter activation via external shutter signal
- 1 test-bit and 1 mask-bit per pixel
- 13-bit Pseudo-random counter

### Analogue

- Input
- Preamp
- Disc1
- Disc2
- Vth Low
- Vth High
- Test Input
- Ctest
- Testbit
- Maskbit
- 3 bits threshold

### Digital

- Double Disc logic
- Mux
- Shutter
- ClockOut
- Conf 8 bits configuration
- 13 bits Shift Register
- Next Pixel
- Previous Pixel
Medipix Signal Processing

Threshold level $\gg$ electronic noise $\Rightarrow$ No noise counts

Digital integration (counting) $\Rightarrow$ No dark current.

Unlimited dynamic range and exposure time.

Bias Voltage

N$^+$

Si

P$^+$

Common back-side electrode

Pixelated front-side electrode

Amplifier

Comparator

Threshold level

Counter:

Particle count

001

Pixel electronics
Motivation for Spectroscopic Imaging

- Use as much information contained in the X-ray beam as possible
  - Noise reduction, Energy weighting, …
  - Material reconstruction

- Particle recognition → Quantum
- Autoradiography - Discrimination of cosmics
- …
- (Neuron imaging)
Energy Window Medipix2

16.1-19.6 keV

21.6-25.1 keV

29-33.5 keV

Ti/W 38 nm, Ø 24.7 μm
Cu  765 nm, Ø 24.7 μm
Ni   2 μm, Ø 24.7 μm
SnPb 22 μm, Ø 33.0 μm

Kapton 1 μm

Read-out chip ~0.7 mm

Conductive glue

Pcb 1 mm
K-edge Imaging - Simulation

- 20 cm water phantom
- W-tube 120kV, 0.6 mm Ti filter
- Ideal detector w=40 cm, 256 pixels
- Contrast agents
  - Iodine
  - Gadolinium
- Matrix inversion

\[ \frac{I(E)}{I_0(E)} = T(E) = \exp\left(-\sum_j \mu_j(E)a_j\right) \]

\[ \begin{pmatrix} \mu_1(E_1) \\ \mu_2(E_2) \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \cdot \begin{pmatrix} \frac{\alpha}{E_1} \\ \frac{\beta}{E_2} \end{pmatrix} \cdot \begin{pmatrix} \rho \\ \rho Z^k \end{pmatrix}. \]
Statistical Material Recognition

- Material reconstruction using matrix inversion not always possible, matrix to be inverted tends to be close to singular
- Alternatives: Iterative methods, Statistical methods


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K-edge imaging

- Iodine: Pulmonary circulation
- Barium: Lung
- Bone: normal structure

Univ. Canterbury, NZ
Mars bio-imaging
Small animal CT

ICFTD, Nov. 2009
L. Tlustos, CERN
4 energy CT

4 low thresholds chosen
(15, 23, 30, 35 keV)

ICFTD, Nov. 2009
4 energy CT
PCA

Bone = 1 -1 -1 0

Iodine = 1 1 -1

Barium = 1 1 1
Colourise

\[
\begin{pmatrix}
X \\
\end{pmatrix}
\]

\[
+ \\
+ \\
\)

Spectral information

“conventional” information
Spectral enhancement

Iodine: Pulmonary circulation

Barium: Lung

Bone

Possible Future Applications

- Eventually humans
- Improved material recognition
  - Ca-Phosphate vs. Ca-Oxylate
  - Fat vs. glandular tissue
  - Micro-CT in industrial context
- Nanoparticles
  - E.g. Contrast agent loaded Lipoproteines
  - Antibody labeled Lipoproteines → “functional” CT
Limiting Factors

1) Energy dispersion due to charge sharing
   - Double counted / not counted photons, depending on threshold
   - Can be corrected for (De-convolution, Spectrum stripping), but introduces additional noise to the spectral dataset due to uncorrelated datasets - see above
   - Further amplification of noise when using matrix inversion to reconstruct mean Z and mean ρ

2) Only one energy window
   - Uncorrelated datasets for different energy bins
   - Reduced quantum efficiency

3) Fluorescence within detector (GaAs, CdTe, …)
   - Additional distortion of the recorded spectrum
Charge Transport in Planar Si Sensor

20 keV Photons
300 μm Si Sensor
55 μm Pixel Pitch
120 V sensor bias

- Mono-energetic Photon spectrum → continuous spectrum with ± constant background and strong contribution of low pulse heights
- Even when using energy window spectroscopic information degraded

Mono-energetic Photons 20 keV
Charge Summing Implementation

• **Off chip:** Timepix like architecture
  - Digitization of energy deposited in pixel → TOT
  - Sparse data, no overlaps → limited particle flux
  - Fast readout necessary

• **On chip:** Medipix3
  - Communicating pixels
    - Dead time/pileup limit given by shaping time
  - Summing of 4 adjacent pixels
  - 2, 4 (8) Energy bins
TimePix

Continuous clock signal on whole chip ≤ 100 MHz

3 Modes:

1. Counting = Medipix2
2. Time over Threshold clock pulses counted when discriminator high. Measure for energy deposited in pixel.
3. Time of Arrival all clock pulses from first hit until end of shutter signal counted. Time of arrival of first particle per pixel.

Bias Voltage

Common back-side electrode

Pixelated front-side electrode

N⁺ Si P⁺

Particle count

Energy

Threshold level

Amplifier

Comparator

Counter:

Particle count

003

Pixel electronics

Courtesy J. Jakubek, CTU/IEAP

ICFTD, Nov. 2009

L. Tlustos, CERN
Charge deposition studies with various Isotopes → Space Dosimetry

Courtesy L. Pinsky, Univ. Houston
\(^{90}\text{Sr}\)

- \(^{90}\text{Sr}\) 11 μs exposure time and \(\text{Clk}\_\text{Ref}=6.27\) MHz (159.3ns)
- Maximum acquisition time dynamic range of 1.88 ms
Timepix with 3-GEM detector

- DESY testbeam in November 2006 (A. Bamberger, M. Titov)
- 5 GeV e⁻
Medipix3 - Charge Summing Architecture

The winner takes all

- Charge is summed in every 4 pixel cluster on an event-by-event basis

- The incoming quantum is assigned as a single hit
Medipix2/3 - 300 μm GaAs, 650 V
(still simulations)

GaAs, 55μm square x 300μm, 20 keV

\[ \mu_e\tau_e \text{650V/300μm} \approx 1.7 \text{ cm} \]
\[ \mu_h\tau_h \text{650V/300μm} \approx 0.086 \text{ cm} \]

GaAs, 110μm square x 300μm, 20 keV

\[ \text{Ga } K_{\alpha} = 9.2 \text{ keV} \rightarrow 40 \mu\text{m mean free path} \]
\[ \text{As } K_{\alpha} = 10.5 \text{ keV} \rightarrow 15 \mu\text{m mean free path} \]
## Medipix3 Modes of Operation

<table>
<thead>
<tr>
<th>System Configuration</th>
<th>Pixel Operating Modes</th>
<th># Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Pitch Mode → 55 µm x 55 µm</td>
<td>Single Pixel Mode</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Charge Summing Mode</td>
<td></td>
</tr>
<tr>
<td>Spectroscopic Mode → 110 µm x 110 µm</td>
<td>Single Cluster Mode</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Charge Summing Mode</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Front-end Gain Modes</th>
<th>Linearity</th>
<th># Thresholds/Pix</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Gain Mode</td>
<td>~10 keV</td>
<td>2</td>
</tr>
<tr>
<td>Low Gain Mode</td>
<td>~20 keV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pixel Counter Modes</th>
<th>Dynamic range</th>
<th># Counters/Pix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-bit</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4-bit</td>
<td>15</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 Modes</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>
First Medipix3 Assemblies @ CERN

- First 20 300 µm Si detectors bonded to single Medipix3 readout chips (VTT) arrived at CERN ~ one month ago.

- 5 assemblies have been mounted

- Extensive testing going on
  - + HW integration …
  - + Software debugging ….

Images courtesy Gädda Akiko (VTT, Finland)
Charge Summing vs. Single Pixel

Charge Summing Mode

Single Pixel Mode

Very first images, preliminary.

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L. Tlustos, CERN
Spectroscopic behavior (CSM and SPM) Am$^{241}$

- Again, very first measurements
- Low statistics $\leq 0.1$ count/pixel

<table>
<thead>
<tr>
<th>keV</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.9</td>
<td>9.6</td>
</tr>
<tr>
<td>17.7</td>
<td>5.7</td>
</tr>
<tr>
<td>17.9</td>
<td>1.4</td>
</tr>
<tr>
<td>20.8</td>
<td>1.4</td>
</tr>
<tr>
<td>59.5</td>
<td>35.9</td>
</tr>
</tbody>
</table>

• Charge summing works!
MPX3 2\textsuperscript{nd} threshold

- Preliminary
- best guess working point

![Graph showing count vs. threshold DAC](image)
Conclusions & Outlook

• Spectroscopic imaging has a wide range of applications
• High resolution spectroscopic X-ray imaging entered pre-clinical context
  – For the moment limited to low energies ~<40 keV (Si de facto standard sensor material)
• First Medipix3 production run
  – Working!
  – Verification/characterisation under way (16 modes!)
  – High Z materials
  – …..
• Timepix2, first discussions
  – ToA and ToT simultaneously per pixel
  – ….
Description of the detector

Medipix2 ASIC with 300µm Si sensor + USB interface

Neutron conversion structures:

1) LiF+50µm Al foil area
2) 100µm Al foil area
3) PE area
4) PE+50µm Al foil area
5) Uncovered area

\[
\begin{align*}
^6\text{Li} + \text{n} & \rightarrow \alpha + ^3\text{H} \\
^{28}\text{Si} + \text{n} & \rightarrow \alpha + ^{25}\text{Mg} \\
^{28}\text{Si} + \text{n} & \rightarrow \text{p} + ^{28}\text{Al}
\end{align*}
\]
Neutron efficiency calibration

**Fixed HIGH threshold (~200keV)**

**Calibrated efficiency:**
- Thermal: $1.41 \times 10^{-2} - 7.11 \times 10^{-4}$ cm$^2$ s$^{-1}$
- $^{252}$Cf: $1.19 \times 10^{-3} - 1.89 \times 10^{-5}$ cm$^2$ s$^{-1}$
- AmBe: $2.86 \times 10^{-3} - 5.46 \times 10^{-5}$ cm$^2$ s$^{-1}$
- VDG: $7.23 \times 10^{-3} - 5.81 \times 10^{-4}$ cm$^2$ s$^{-1}$

**PE / PE+Al cluster count ratio:**
- $^{252}$Cf: 10.70 ± 0.04
- AmBe: 5.18 ± 0.03
- VDG: 2.51 ± 0.03

Pulse processing (= energy sensitive) imaging ROCs

(tentative & incomplete listing)

<table>
<thead>
<tr>
<th>Technology</th>
<th>MEDIPX2</th>
<th>MPX3 (design)</th>
<th>XPA3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>CMOS 0.25 μm</td>
<td>CMOS 0.13 μm</td>
<td>CMOS 0.25 μm</td>
</tr>
<tr>
<td></td>
<td>counting</td>
<td>counting</td>
<td>counting</td>
</tr>
</tbody>
</table>

| Pixel size [μm] | 55      | 55/110     | 130     |
| Matrix        | 256 x 256 | 256 x 256 | 80 x 120 |
| Pixel no.     | 65536   | 65536      | 9600    |
| Area [mm²]    | 196     | 196        | 162     |
| Max. tiled Area [cm²] | 1.4 x 7 | 6.8 x 6.5 |
| Pixel density [mm⁻²] | 330     | 330        | 60      |
| Pixel noise ENC [e⁻] | 140     | 75e / 150  | 160     |
| Threshold dispersion [e⁻] | 100     | 55 / 100 adj. | 50     |
| Global threshold [e⁻]  | 1000 adj | 1000 adj | 1000 adj |
| Counter depth  | 13      | 1/2/4/8/11/22 | 12     |
| No threshold   | 2       | 1/2/2008   | 2       |
| Read-out scheme | synchronous | synchronous | synchronous |
| Read-out mode   | full frame/ROI | full frame | full frame/ROI |
| Read-out time   | 10 ms, 300 μs | <10 ms | 2 ms (continuous) |
| Frame rate [Hz] | 103     | 100...     | 500     |
| Event rate/pixel [Hz] | ~ 10⁶ | ~ 10⁶ | ~ 10⁶ |
| Poisson event rate [Hz/cm²] | ~ 10⁸ | ~10⁸ / 10⁹ | ~10⁸ / 10⁹ |

<table>
<thead>
<tr>
<th>Pilatus II (single)</th>
<th>Eiger</th>
<th>PIXIE (4th, 2007)</th>
<th>Timepix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>CMOS 0.25 μm</td>
<td>CMOS 0.25 μm</td>
<td>CMOS 0.18 μm</td>
</tr>
<tr>
<td>ToT</td>
<td>counting</td>
<td>counting</td>
<td>counting</td>
</tr>
<tr>
<td>timestamp</td>
<td></td>
<td>27.7 hexagonal</td>
<td>55</td>
</tr>
<tr>
<td>Matrix</td>
<td>60 x 97</td>
<td>256x256</td>
<td>600 x 800</td>
</tr>
<tr>
<td>Pixel no.</td>
<td>5820</td>
<td>65536</td>
<td>480000</td>
</tr>
<tr>
<td>Area [mm²]</td>
<td>172</td>
<td>369</td>
<td>672</td>
</tr>
<tr>
<td>Max. tiled Area [cm²]</td>
<td>43 x 44</td>
<td>big</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Pixel density [mm⁻²]</td>
<td>33</td>
<td>177</td>
<td>720</td>
</tr>
<tr>
<td>Pixel noise ENC [e⁻]</td>
<td>65</td>
<td>135 (design)</td>
<td>50</td>
</tr>
<tr>
<td>Threshold dispersion [e⁻]</td>
<td>85 unadj</td>
<td>&lt;200 unadj</td>
<td>30</td>
</tr>
<tr>
<td>Global threshold [e⁻]</td>
<td>730 unadj</td>
<td>&lt;1250 unadj</td>
<td>200 auto-adj</td>
</tr>
<tr>
<td>Counter depth</td>
<td>20</td>
<td>4/8/2012</td>
<td>15</td>
</tr>
<tr>
<td>No threshold</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Read-out scheme</td>
<td>synchronous</td>
<td>synchronous</td>
<td>synchronous</td>
</tr>
<tr>
<td>Read-out mode</td>
<td>full frame/ROI</td>
<td>full frame</td>
<td>full frame/ROI</td>
</tr>
<tr>
<td>Read-out time</td>
<td>3.6 ms</td>
<td>41/82/123 μs</td>
<td>?</td>
</tr>
<tr>
<td>Frame rate [Hz]</td>
<td>100</td>
<td>8/12/24 kHz</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Event rate/pixel [Hz]</td>
<td>~ 10⁶</td>
<td>~ 5 10⁶</td>
<td>&gt; 10⁵</td>
</tr>
<tr>
<td>Poisson event rate [Hz/cm²]</td>
<td>~ 10⁸</td>
<td>~ 10⁶</td>
<td>~ 10⁸</td>
</tr>
</tbody>
</table>

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L. Tlustos, CERN
XPAD2, XPAD3, Large surface X-Ray Pixel Detector

**XPAD2**
- Pixels 330 x 330 µm²
- 15-bit Counter
- Linear until 2.10⁶ ph/sec/pixel
- 8 modules tiled
- 6.8 x 6.5 cm² HPS Detector
- Pixels size: 330 x 330 µm²
- 400 frames, 2 ms between frames

**XPAD3**
- IBM 0.25 µm
- Pixels 130 µm, 120 x 80 pixels
- Radiation hard
- 13-bit counter/pixel
- Continuous readout during DAQ
- Chip size: 1 x 1.7 cm²

Courtesy Pierre Delpierre, CPPM
Pilatus

**Pilatus Module - Building block of all Pilatus Detectors**

- 1 Silicon Sensor
- 16 PILATUS CMOS Chips
- 487 x 195 pixels = 94965 pixels, active Area 83.8 x 33.6 mm²
- Readout time = 3.6 ms
- Continuously sensitive: no gaps between chips
- Building Block of all Pilatus Detectors
- Frame rate: 300 Hz

**Pilatus 2Module – 24 modules**

- Format: 1475 x 1679 pixels
- Area: 254 x 289 mm²
- Frame rate: up to 30 Hz

**Applications:**
- X-ray diffraction (XRD)
  - Small-angle scattering (SAXS)
  - Macromolecular crystallography
  - Time-resolved experiments

Courtesy Chr. Brönnimann, DECTRIS AG
**EIGER** (preliminary)

- **Technological process**: UMC 0.25 µm
- **Analog Parameters**
  - 30 ns peaking time
  - ~150 ns ret. Zero
  - 8.8uW/pixel
  - Gain: 44.6 μV/e-
- **Chip size**: 19.3 x 20.1 mm² (active 19.2x19.2mm²)
- **Pixel array**: 256 x 256 = 65536
- **Pixel size**: 75 x 75 µm²
- **Transistors, Matrix**: 28.44M
- **Periphery**: >120 000
- **Transistors density**: 430/pixel
- **Detector readout speed**: ~12.5 KHz @ 8 bit mode (Detector size doesn’t matter)
- **Radiation tolerance**: Full radiation tolerant design (>4Mrad)
- **Nominal power supplies**: 1.1 V (analog), 2V (digital), 1.8V (I/O)
- **Counter**: 12 bits, binary, configurable (4,8,12 bit mode)
- **Continuous readout**: yes
- **Threshold adjustment**: 6 bit DAC
- **Overflow control**: yes

~very first image, preliminary – definitely working!

Courtesy R. Dinapoli, PSI
The CMOS counting ASIC

The chip integrates more than 259 million transistors.

It has 480k pixels organized in a honeycomb matrix of 600 columns × 800 lines corresponding to an active area of

24mm² (600×40μm) 27.7mm² (800×34.64μm)

Each pixel is connected to a charge-sensitive shaping amplifier followed by a discriminator and a 15-bit shift register.

A self-calibration circuit is implemented in each pixel to reduce unavoidable DC offset variations from pixel to pixel → a global threshold can be applied to the whole matrix.

Each pixel column can be individually configured for:
• counting the number of events during a given time slot or
• providing, with an external clock, a timestamp to the event or the time over threshold

See talk 24th Nov: R. Bellazzini, X Ray Polarimetry: a new window on the high energy sky

ICFTD, Nov. 2009

Courtesy R.Bellazzini, INFN Pisa
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Pierre Delpierre, CPPM
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