Paul Scherrer Institut
Ian Johnson

SLS Detector group
Eiger, a fast framing, large area pixel detector for X-ray applications
Projects within the SLS Detector group

Synchrotron detectors

Single photon counting

Counter

Number of photons

V_{th}

X-ray free-electron laser detectors

Charge integrating detectors

Total number of electron-hole pairs

Mythen II

Eiger

Gotthard

AGIPD

SwissFEL

A. Mozzanica - Charge integrating silicon detectors for SwissFEL (@ 16:25)
J. Becker (DESY) - AGIPD, A 4.5 MHz camera for the European XFEL (@ 15:10)
H. Billich - Data backend system for fast multi megapixel detectors (Sat. 10:30)
Eiger is aimed towards Diffractive experiments

Typical experimental setup:

- Slits
- Sample
- Flight Tube
- Beam stop
- Eiger Single Chip
- Detector

Typical applications:
- Protein Crystallography
- Small Angle X-ray Scattering (SAXS)
- Coherent Diffractive Imaging (CDI)
- X-ray Photon Correlation Spectroscopy (XPCS)
• X-ray sensitive pixels
  Energy range few keV to 20 keV
• Single photon sensitivity
  Low to no noise
• Sufficient angular coverage
  Large area detectors
• Millions of small (75 um) pixels
• High dynamic range
  Count rates up to 1-2 million counts/pixel/second
• High frame rates
  Tens of kHz

The Eiger chip

<table>
<thead>
<tr>
<th>Chip size</th>
<th>19.3 x 20.1 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel array</td>
<td>256 x 256 = 65536 pixels</td>
</tr>
<tr>
<td>Pixel size</td>
<td>75 x 75 µm²</td>
</tr>
<tr>
<td>Analog Parameters</td>
<td>30 ns peaking time</td>
</tr>
<tr>
<td></td>
<td>Timing: 151 ns (Return to 0@1%)</td>
</tr>
<tr>
<td></td>
<td>Noise: 135 e-rms</td>
</tr>
<tr>
<td></td>
<td>Gain: 44.6 µV/e-</td>
</tr>
<tr>
<td></td>
<td>Static Power: 8.8 µW/pixel (0.6 W/chip)</td>
</tr>
<tr>
<td>Count rate</td>
<td>10⁶ X-rays/pixel/s</td>
</tr>
<tr>
<td>Threshold adjustments</td>
<td>Global threshold + 6 Trimbits/pixel</td>
</tr>
<tr>
<td>Binary counter</td>
<td>Configurable to 4, 8, and 12 bit with overflow control</td>
</tr>
<tr>
<td>Double buffering</td>
<td>Counter values stored in pixel cell</td>
</tr>
<tr>
<td></td>
<td>Negligible dead time (~ 3 µs)</td>
</tr>
<tr>
<td>Frame rates</td>
<td>~23 kHz in 4 bit mode</td>
</tr>
<tr>
<td>Technological process</td>
<td>UMC 0.25 µm;</td>
</tr>
<tr>
<td></td>
<td>Rad tol. Design &gt; 4 MRad</td>
</tr>
<tr>
<td>Transistors matrix</td>
<td>28.44 M</td>
</tr>
<tr>
<td>Periphery</td>
<td>&gt; 120 000</td>
</tr>
<tr>
<td>Transistor density</td>
<td>430/pixel</td>
</tr>
</tbody>
</table>
Hybrid pixel detector

Eiger
Single chip sensor

2x2 cm²

Eiger readout chip
256 x 256 pixels

Si Sensor

Al

Indium bump (~18 um)

A cell in the Readout chip

X-ray (few to a few tens of keV)

Sensor – Chip connected via bump-bonds

Chip - Readout system connected via wire bonds

A PSI bump-bonder
Functionality in each pixel

**Analog Part**
- Preamp/Shaper
- Detector
- Adj. Gain
- Test (x,y)
- Pulse
- Analog output

**Digital Part**
- Discriminator
- Global Threshold
- Enable
- Overflow
- Counter Mode (4, 8, 12 bits)
- Adjust. Gain
- Test (x,y)
- Store
- Reset
- Trimbins/Counter Outs
- 6 Threshold Trimbins
- 12 bit counter (with buffered storage)

**Adjustable Preamp/Shaper**
- Simulated
- Low noise
- Standard
- High speed

- Global threshold + 6 trimbits
- Adjustable gain
- Bump bond connection
- Preamp/shaper
- Trim Bits
- Comparator
- 12 bit counter
- Counter bit buffers
- Overflow logic

8 Toggle flip-flops (MSBs of the counter)

6 D latches (trim bits)

4 Toggle flip-flops (LSBs of the counter)

UMC 0.25 µm Technology
Trimming and Response uniformity

Monochromatic X-rays

Global Threshold ($V_{cmp}$)

Threshold Trim bits

Trim 0

Trim 5

Pulse to the counter

Threshold scan:
4 untrimmed channels

Counts above threshold

Decreasing threshold

$V_{cmp}$ (V)

Inflection points

4 trimmed channels

$V_{cmp}$ (V)

Cu, 8 keV

Threshold Dispersion

Trimmed

$\sigma = 67$ eV

Untrimmed

$\sigma = 279$ eV

Number of channels

Energy (keV)

Counts above threshold

Decreasing threshold

$V_{cmp}$ (V)

Inflection points

4 trimmed channels

$V_{cmp}$ (V)

Cu, 8 keV

Threshold Dispersion

Trimmed

$\sigma = 67$ eV

Untrimmed

$\sigma = 279$ eV

Number of channels

Energy (keV)
Different Gains: for 12 keV X-rays

- Noise sigma: ~580 eV or 160 $e^-$
- Minimum threshold: ~2.5 keV

Energy Calibration

- Simulation
  - Low noise
  - Standard
  - Fast

---

Counts above Threshold vs. $V_{cmp}$ (V)

- Low Noise
- Standard
- Fast

---

X-Ray Energy (keV) vs. $V_{cmp}$ (V)

- Cl (2.6)
- Ti (4.5)
- Cr (5.4)
- Fe (6.4)
- Cu (8)
- Ge (9.9)
- Noise level

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Gain vs. X-Ray Energy (keV)
Monochromatic X-rays

Rate correction for 12 keV X-rays

High rate detection Eff. for 12 keV X-rays

Threshold @ \( \frac{1}{2} \) Energy

Adj. Gain

Simulated

Low noise

Standard

Fast

Incident Rate (kHz)

Detected Rate (kHz)

Rate correction for 12 keV X-rays

Detection Efficiency

Incident Rate (kHz)

Fast \( \tau = 241 \) ns

Standard \( \tau = 355 \) ns

Low noise \( \tau = 653 \) ns

fast \( V = 1.2 \)

standard \( V = 1.3 \)

low noise \( V = 1.4 \)

+1 +1 ≠ 3

= 241 ns

= 355 ns

= 653 ns
Digital data flow in the chip

- Pixel array 256 x 256 (65 k pixels)
- Each counter bit has a local buffer
  - Short 3 µs Between frame dead-time
  - 3 µs -> store and reset the counter
- 32 Super columns
  - 32 bit bus
- Row select (Token shift register)
  - Address 4 bits of a pixel
  - 8 pixels per super column
- 32 Super serializers
  - Serialize the data sent to the pads
- 32 data out pads
  - 100 MHz DDR (6.4 Gbs/chip)
Multi-chip Modules

- Module sensitive area of 38 X 77 mm² (~ Pilatus size)
- 524k pixels per module
  - 2 x 4 chip array
- Parallel Half module based readout
- Maximum frame rates
  - 23 kHz in 4 bit mode
  - 12 kHz in 8 bit mode
  - 8 kHz in 12 bit mode
- Maximum data rates on the readout boards
  - 25 Gb/s for a half module
  - 50 Gb/s for a module
- On board in hardware data processing
- 8 GB of memory on a module
  - four - 2 GB RAMs per module
- Two 10 GbE data links per module
### Eiger systems

<table>
<thead>
<tr>
<th></th>
<th>Number of pixels</th>
<th>On board storage (frames/4 bits)</th>
<th>Data rate(^1) @ 12 kHz</th>
<th>Data rate(^2) @ 1kH</th>
<th>Data rate(^3) @ 100 Hz</th>
<th>Data rate(^4) @ 10 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Module</strong></td>
<td>524 k (512 x 1024)</td>
<td>~32,740</td>
<td>50.3 Gb/s</td>
<td>6.29 Gb/s(^*)</td>
<td>839 Mb/s(^*)</td>
<td>168 Mb/s(^*)</td>
</tr>
<tr>
<td><strong>9M Detector</strong></td>
<td>9.44 M (3072x3072)</td>
<td>~32,740</td>
<td>906 Gb/s</td>
<td>113 Gb/s</td>
<td>15.1 Gb/s(^*)</td>
<td>3.02 Gb/s(^*)</td>
</tr>
</tbody>
</table>

1) 8 bit, equivalent to ~4@23 kHz and 12@8 kHz.  
2) 12 bit.  
3) 16 bit.  
4) 32 bit.  
\(^*\) Foreseeable continuous storage rates (~20 Gb/s).
On board Intelligence

- On board (in firmware) data processing
  - real-time
  - parallel on multi-module systems
  - independent of the detector size
  - reduces a module tens of Gb/s at the source
  - or a 9Ms, hundreds of Gb/s at the source

- Data buffering
  - on board memory for 32 k frames per 4 counter bits

- Image summation
  - extends the dynamic range from 4096 to $4 \times 10^9$
  - 2 ms sub frames (2 M counts/pixel/s)
  - makes long (minutes) high flux data taking possible
  - reduces the quantity of data at the source
  - transparent to the user

- Rate correction
  - performed on the sub-frames
  - more precise, less sensitive to rate fluctuation
  - real-time processing

- Pump and probe series averaging
  - high frame rate exposure series summing
  - alternating pumped and un-pumped
  - no data transfer dead time between series
  - huge reduction of the quantity of data at the source

- Data reduction
  - 2 x 2 pixel rebinning
  - SANS ring intensity averaging (planned)
  - data compression (in thought, question of HDF5 compatibility)
Studied the dynamics of a colloidal suspension
50,000 diffraction patterns in 2.5 seconds,
20 kHz, 45 μs exposure and 5 μs dead-time.

Average of the
diffraction patterns

Intensity
Autocorrelation function
\[ g_2(q, \Delta t) = \frac{\langle I(q,t) I(q,t+\Delta t) \rangle}{I(q,t)^2} \]

Siegert relation,
\[ g_2(q, \Delta t) = 1 + \beta |g_1(q, \Delta t)|^2 \]
Normalized field correlation function
\[ g_1(q, \Delta t) = e^{Dq^2 \Delta t} \]

Without LiCl
10 mM LiCl

Structure factor S(q)
with SAXS

Diffusion coefficient
D(q) via XPCS

*Capturing dynamics with Eiger, a fast framing X-ray detector*
I. Johnson et al., Submitted to the JSR

Eiger Single Chip Development system

"Capturing dynamics with Eiger, a fast framing X-ray detector"
I. Johnson et al., Submitted to the JSR
Summary

- Results
  - Characterization of the chip
  - High frame rate demonstration experiment
- We are working towards 2 x 4 chip modules
- Single module systems @ the SLS
  - Coherent Small Angle X-ray Scattering Beamline (cSAXS)
  - Surface diffraction station (Material Science)
- High performance 9M Eiger @ cSAXS
  - 288 GB of on board memory or 2.5 sec @ highest data rates
  - >100 Hz continuous operation and data to disk
- The chip has been licensed to Dectris
  - many systems around the world
  - 16M Eiger for the Protein Crystallography Beamline (PX)
- Collaboration with the ESRF
  - Single module systems
- We (AIT, Dectris, SLS Detector group) working together to develop a common file structure (HDF5)