EIGER: high frame rate pixel detector for synchrotron and electron microscopy applications
<table>
<thead>
<tr>
<th></th>
<th>MYTHEN II&amp;III</th>
<th>EIGER</th>
<th>GOTTHARD I &amp; II</th>
<th>JUNGFRAU</th>
<th>MÖNCH</th>
<th>AGIPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D/2D</td>
<td>Strip</td>
<td>Pixel</td>
<td>Strip</td>
<td>Pixel</td>
<td>Pixel</td>
<td>Pixel</td>
</tr>
<tr>
<td>Working Mechanism</td>
<td>Photon Counting</td>
<td>Photon Counting</td>
<td>Charge Integrating</td>
<td>Charge Integrating</td>
<td>Charge Integrating</td>
<td>Charge Integrating</td>
</tr>
<tr>
<td>Strip/Pixel size [µm]</td>
<td>50</td>
<td>75×75</td>
<td>25/50</td>
<td>75×75</td>
<td>25×25</td>
<td>200×200</td>
</tr>
</tbody>
</table>

**PSI EIGER: high frame rate pixel detector:**

1) synchrotron
2) electron microscopy
**EIGER: ASIC characteristics**

<table>
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<tr>
<td>Pixel size</td>
<td>75 x 75 um²</td>
</tr>
<tr>
<td>Pixel matrix</td>
<td>256 x 256</td>
</tr>
<tr>
<td>Counter</td>
<td>4/8/12 bit</td>
</tr>
<tr>
<td>Frame rate</td>
<td>23/12/8 kHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>6 Gb/s</td>
</tr>
<tr>
<td>Threshold adj. bits</td>
<td>6</td>
</tr>
<tr>
<td>Threshold dispersion (after trimming)</td>
<td>&lt;10 e⁻</td>
</tr>
<tr>
<td>Noise</td>
<td>100-200* e⁻ RMS</td>
</tr>
<tr>
<td>Rate capabilities (10% deviation)*</td>
<td>500 k counts/pixel/s → 90 Mphotons/mm²/s</td>
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<tr>
<td>Dead time</td>
<td>4 us (with buffering)</td>
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</table>

*Depending on gain setting*
EIGER: 500k pixel single module

- 2x4 chips
- Single 4x8 cm$^2$ silicon sensor
- Sensor thickness 320 μm

No dead area in a single module!

EIGER module equipped with ASICs but no sensor

2x-size pixel

4x-size pixel

Corrected only for geometry

interpolated
EIGER: Readout System

- Image summation: 12 → 32 bit
- Data buffering: preserve high frame rate capability
- Possibility to apply corrections

Half module is basic readout unit. A module is readout as 2 half modules (20 Gb/s)
Very high frame rate detector

<table>
<thead>
<tr>
<th>Dynamic range (bit)</th>
<th>Buffered max frame rate (kHz)</th>
<th>Data buffered (# images)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>22</td>
<td>30000</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>15000</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>7600</td>
</tr>
<tr>
<td>32</td>
<td>2</td>
<td>Online sum</td>
</tr>
</tbody>
</table>

Displayed normalized to 30 imgs/s
High frame rate at synchrotrons: 20 kHz

K. Woll’s group (KIT)

Powder sample with ultra fast heating

MS + microXAS beamlines @ SLS

ID02 @ESRF

XPCS technique

Detector occupancy

Diffraction pattern recorded at 20kHz (45 μs exposure + 5 μs)

Occupancy here defined as: # pixels with hits/# pixels

Occupancy ~ 4%

With optimization of the sample thickness it is expected to gain a factor 5-10 in hits

Diffraction recorded at 20kHz

Occupancy ~ 11%

Obtained from calibration sample: more representative occupancy
Online compression studies

<table>
<thead>
<tr>
<th>Dynamic range (bit)</th>
<th>Continuous frame rate @10 Gb (kHz)</th>
<th>Buffered max frame rate (kHz)</th>
<th>Data buffered (images)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>10.2</td>
<td>22</td>
<td>30000</td>
</tr>
</tbody>
</table>

**2x10 GbE links/module are bottle neck**

We need compression factor \(x2.2\) to go continuous

- **HIT BASED READOUT:** only if OCCUPANCY < 14% module
  - Send address and value only of pixel with hits
  - Typically we have a few % occupancy

- **ZERO COMPRESSION:** instead of writing all the half-bytes that are zeros, write a flag and #half-bytes that are zero:
  - \(0000\ 0000\ 0000\ 0000\ 0001 \rightarrow 1111\ 0100\ 0001\)
  - Real 1111-> 1110, Real 1110-> 1111 0001

This study refers only to powder diffraction data

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Hit based readout</th>
<th>Zero compression</th>
<th>Reference GZIP, level 2 offline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low occupancy</td>
<td>3.2</td>
<td>5.9</td>
<td>11.5 in 8 bit</td>
</tr>
<tr>
<td>High occupancy</td>
<td>1.4</td>
<td>3.4</td>
<td>6.9 in 8 bit</td>
</tr>
</tbody>
</table>
• Modules can be tiled to large area detectors
• Due to the parallel design there is no penalty in performance when moving from a single module to multi module systems

EIGER: Larger systems

2M pixels

9M pixels
PSI Eiger 1.5 and 9M detectors for cSAXS beamline

- 1.5 M in user operation since April 2018
- 9M foreseen user operation Feb 2019
Detector integration concept

Detector: 18 modules
36x10GbE

TCP x36
UDP stream x36
x72 receivers on a server

Control PC
beamline

Storage (GPFS)
Limited to 1.6GB/s currently

TCP x36

Limited to 2GB/s

zmq

Limited to 360Gb/s

writer

Limited to 1.6GB/s currently

zmq

data (metadata added from client)

Phase I: User operation at minimum 25 Hz for 32-bit starting from Feb 2019
Expected: 42 Hz, 1.6GB/s. The detector can send out up to 45 GB/s

• Independent half modules
• Parallel data processing/transfer
• 9 M with 36 half modules (18 modules) 360Gb/s
EIGER: high frame rate pixel detector:
1) synchrotron
2) electron microscopy
EIGER in electron microscopy

- **PEEM - Photo Emission Electron Microscopy - Imaging**
  - ELMITEC, SIM Beamline SLS
  - 20keV Electrons

- **TEM - Transmission electron microscopy - Electron Diffraction/(Imaging)**
  - Prof. Jan Pieter Abrahams C-CINA/PSI
  - 100 – 300 keV

- **Quad:**
  - active area 4x4 cm²

- In vacuum

- For energies <=100 keV, hybrid pixels are an “ideal detector”

- At higher energies, EIGER is appealing thanks to frame rate: scanning/rotation techniques, imaging single electrons, reducing sample drift
EIGER as an electron detector

Electron interaction with a pixel

200-300 keV Multi-pixel cluster

MIP regime

sensor thickness

pixel size

range

lateral jitter

e⁻ in Si

Energy (keV)

distance (µm)

<=100 keV

Energy (MeV/cm)

10

10^2

10^3

10^4

10^5
Low energy electron interaction $\leqslant 20$ keV

- $e^-$ interaction:
  - lose energy due to multiple collisions with atomic electrons
  - Deposit energy in multiple points due to multiple scattering
- Al layer can be etched away
- $e^-$ lose part of their energy in Si backplane

<table>
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<tr>
<th>Material crossed</th>
<th>20 keV $e^-$</th>
<th>10 keV $e^-$</th>
</tr>
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<tr>
<td>Al 1 $\mu$m</td>
<td>2.6 keV</td>
<td>5.0 keV</td>
</tr>
<tr>
<td>Si 1.5 $\mu$m</td>
<td>3.0 keV</td>
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FBK thin entrance window sensors

Sensor produced by FBK Trento:

1. **As implant** tested (~200 nm)
2. As implant low energy still to be tested

*Al has also been etched away*

**Tested with a TEM from J.P. Abrahams’s group**

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<td>Si 500 nm</td>
<td>1.2 keV</td>
<td>2.0 keV</td>
</tr>
<tr>
<td>Si 200 nm</td>
<td>0.5 keV</td>
<td>0.9 keV</td>
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19.5 keV ± 0.9 keV RMS

0.5 keV lost in entrance window
Spatial resolution with low energy electrons

- When setting the threshold to half of the electron energy, we have single pixel resolution
- Fitting with a ErrFunction: resolution is 22 μm, compatible with 75 μm/sqrt(12)
100-300 keV electrons

100 keV: Setting the threshold > 50%, we recover single pixel resolution

The size of interaction is large: high threshold records higher energy hit but not entrance hit

Spatial resolution Best $\sigma = \sim 23$ um

100 keV: Good for imaging and diffraction

200-300 keV: Good for diffraction

Tinti et al, IUCrJ 5(2) (2018)
Conclusions

- We have shown that several EIGER PSI systems are in use for experiments at synchrotrons.
- The high frame rate makes PSI EIGER unique: time-resolved experiments are possible.
- EIGER works well for low energy electrons (<=100keV) both for PEEM and TEM applications.
- The fast frame rate capability makes EIGER interesting also for TEM applications at 200-300 keV.
- We are working to reach even higher frame rates selecting a subsection of the chip or to have compression on board to reach continuous fast frame rate operation.
Acknowledgements

Back: (Marie Ruat,) **Bernd Schmitt**, Sophie Redford, Aldo Mozzanica, **Erik Fröjdh**.

Middle: Jiaguo Zhang, Carlos Lopez, Marie Andrä, **Rebecca Barten**, **Martin Brückner**, Christian Ruder, **Dominic Greiffenberg**, Seraphin Vetter.

Front: Xintian Shi, **Dhanya Thattil**, Gemma Tinti, Anna Bergamaschi, (Marco Ramilli,) **Roberto Dinapoli**, Davide Mezza.

Not in picture: Sabina Chiriotti Alvarez
1MeV electrons

- We expect the peak of the Landau to be around 110 keV: 55 keV threshold
- Calibrated the detector threshold up to 110keV

$^{90}\text{Sr}$ with a momentum selector for electrons

Christian Joram (CERN)

Lukas Gruber (CERN)

- At a threshold >60 keV, mainly single hits are recorded
- We expect a spatial resolution a bit worse than single pixel
**Experiments at synchrotrons**

Protein crystallography PX beamlines

ALL compression findings for powder diffraction does not automatically apply to all experiments

**XPCS average and single** ESRF ID02 beamline


Ptychography cSAXS beamline
### EIGER chip

#### Circuit Diagram

- **Trimbit ins/Counter Outs**
- **Preamp + Shaper**
- **Sensor**
- **Adj. Gain**
- **Global Threshold**
- **Discriminator**
- **Enable Overflow**
- **Counter Mode**
- **Reset**
- **Store**
- **Overflow**

#### Specifications

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Very high frame rate

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Threshold calibration

- Each preamplifier gain covers a different range of photon energies.
- The threshold setting needs to be calibrated into photon energy.
- Threshold is calibrated to be uniform in the detector and its dispersion is negligible (down to 10 e⁻) in comparison to noise.
- The noise at high gain is < 100 e⁻.
- Threshold can be set at > 2 keV (depending on the readout settings).
Online rate correction

Single subframes recorded up to 2kHz frame rate can be corrected online, before summation.

Linearity is restored up to 1.2 Mcounts/pix/s.

Subframes acquired at 500Hz (2ms/subframe)
Rate correction as a function of energy

Monochromatic X-rays

Adj. Gain

Threshold $V_{\text{cmp}}$

Counter

PILE UP

E

I

For the same energy, lower gain improves the rate capabilities

Paralizable counter model:

$$N_{\text{det}} = N_{\text{inc}} \cdot e^{-N_{\text{inc}} \cdot \tau}$$

Linerity at 90% :

200 - 600 kcounts/pixel/s

Rate capability depend on the energy!
Rate corrections in 8 bit mode

\[ N_{\text{det}} = N_{\text{inc}} \cdot e^{-N_{\text{inc}} \cdot \tau} \]

If \( \Phi=1.5 \text{ MHz/pix} \), \( t=80 \text{ us} \), \( N_{\text{inc}}=120 \)

Maximum flux
Chosen for linearity
Margin from 8bit saturation

Errors on corrected value~ 20%:
- Statistical uncertainty in \( N_d \):
  \( \sigma=20\% \)
- Pixel to pixel differences in tau:
  \( \sigma=2 \text{ -15\%} \)
- \( \tau=400 \text{ ns} \)

- \( N_{\text{det}} < N_{\text{inc}} \)
  Rate corrections can be applied to 8bit data as \( N_{\text{inc}} \) does not exceed 8bit depth (254)

- **Rate correction, if wanted in firmware, needs to be implemented for 8bit data**
- If more than 1 image taken in same condition → better to sum before and correct with higher statistics
Charge sharing