Jungfrau, Mönch and Eiger: Detector Development at the Swiss Light Source
Our group is part of the SLS and our job is to build detectors for specific applications at the SLS and SwissFEL to allow users to do new or better science.

uSR, SINQ, SLS

~1500 Staff employees; 30Km from Zurich, task in ETH domain: run large scale user facilities
Hybrid Detectors @ SLS

- **Microstrips**
  - 50 um
  - MYTHEN

- **Pixels**
  - 75 um
  - EIGER
  - 25 um
  - AGIPD

- **200 um**
  - X
  - X

- **Single Photon Counting**
  - GOTTHARD

- **Charge Integrating**
  - JUNGFRAU
  - MÖNCH

See talk Alexander Klyuev
Swiss Mountains

Eiger
(3970 m)

Mönch
(4099 m)

Jungfrau
(4158 m)

Other famous mountains: Mythen, Pilatus and Gotthard…
Example Application: Protein Crystallography

Detector principles:
• single photon counting for synchrotrons
• charge integrating for XFELs and synchrotrons

The Eiger detector

The Jungfrau detector

The Mönch detector

Conclusions
Protein Crystallography

From protein to structure

- Crystallization (cubic Insulin)
- Diffraction experiment
- Phasing
- Electron density map
- Model building, refinement
- Protein expression, purification
- Structure (Insulin)

From protein to structure.
### PilatusII6M at the Protein Crystallography Station

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Modules</td>
<td>60, 12 x 5</td>
</tr>
<tr>
<td>Detector Size [mm]</td>
<td>431 x 448</td>
</tr>
<tr>
<td>Format</td>
<td>6,224,001 pixels</td>
</tr>
<tr>
<td>Pixel size</td>
<td>172 x 172 µm²</td>
</tr>
<tr>
<td>Dynamic range/pixel</td>
<td>20 bits</td>
</tr>
<tr>
<td>Count rate/pixel</td>
<td>~ 1-3 MHz</td>
</tr>
<tr>
<td>Readout time</td>
<td>3.5 ms</td>
</tr>
<tr>
<td>Frame rate</td>
<td>12.5 Hz</td>
</tr>
</tbody>
</table>

Made continuous shutter-less operation possible at PX

Sold and further developed by Dectris
more than 900 protein structures solved at PXI beamline at SLS

~2/3 using PilatusII 6M

compiled by Sandro Waltersperger
Oct 2011
From single photon counting detectors at PSI...

**MYTHEN**
1k to 30k 50μm strips for powder diffraction, small angle scattering, medical imaging...

**PILATUS**
100k to 6M 172μm pixels for protein crystallography, small angle scattering, imaging...

**EIGER**
500k to 9M 75μm pixels, for small angle scattering, CDI, protein crystallography, imaging....

![Diagram with sensor, amplifier, comparator, counter, and digital output connections.](image)
... to charge integrating detectors

Dynamic range: 10000
- voltage swing usually ~1V
- noise usually ~mV

1 photon ~10mV
100 photons dynamic range

Solution:
- dynamic gain switching

main challenge for detector development:
- dynamic range $10^4$ 12keV photons per pixel
- still with single photon resolution

10$^{11}$ X-ray photons
×100 fs

Sensor
Amplifier and reset
Gain switching
Sample and hold
Analog output
External ADC
Preamplifier with gain switching

- CSA in charge integrating configuration
- 3 feedback capacitors
- Common for 1D and 2D, baseline for AGIPD, Gotthard, Jungfrau and Mönch

Logic after comparator to:
- Switch a 2\textsuperscript{nd} time if 1\textsuperscript{st} switch not enough
- Avoid a 2\textsuperscript{nd} switch on spikes due to the 1\textsuperscript{st} one
- Switching has to be FAST (<10ns)

Simulation data

Number of the input photons

output voltage (mV)
Single photon counting hybrid pixel detector for synchrotron applications aimed towards diffraction experiments

- Applications at cSAXS:
  - Scanning Coherent Small Angle X-ray Scattering
  - Coherent Diffractive Imaging
- Protein Crystallography

**The Eiger Detector**

Coherent Small Angle X-ray Scattering

Protein Crystallography

**PILATUS 6M**

**PILATUS 2M**

**EIGER**

The Eiger Module: Eiger 500k

- Sensor 4cm x 8cm, 524k pixels
- 75 micron pixel size
- Dead time free mode of operation
- Electronics is separated in 2 half-modules
  - High frame rates: up to 24 kHz at 4 bit
    12 kHz at 8 bit
    8 kHz at 12 bit
- Readout architecture
  - High speed data transfer: data is sent over 10 GbE connections, one per half module
- Data buffering
  - 8 GB of on board memory per module
  - 32 k frames for 4 counter bits
- Firmware data processing
  - Image summation
    - extends the dynamic range from 4096 (12 bits) to 4x10^9 (32 bits)
  - Rate correction
Eiger Systems

500k module
2x4 chips, ~4x8 cm

Multi-module detectors

First 500k in operation @ PSI

<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) @ 1kHz</th>
<th>Data rate(^3) @ 100 Hz</th>
<th>Data rate(^4) @ 10 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
<td>524 k (512x1024)</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>9M Detector</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@22 kHz or ~12@8kHz
Electronic performance parameters

<table>
<thead>
<tr>
<th>Operation Mode</th>
<th>Noise (e-)</th>
<th>Sigma (e-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LowNoise</td>
<td>121.1±0.07</td>
<td>10.7±0.06</td>
</tr>
<tr>
<td>Standard</td>
<td>160.1±0.08</td>
<td>13.9±0.07</td>
</tr>
<tr>
<td>Fast</td>
<td>185.0±0.1</td>
<td>18.7±0.09</td>
</tr>
</tbody>
</table>

Threshold Dispersion

- Trimmed: σ=67 eV
- Untrimmed: σ=479 eV

@14KeV
Eiger SELFIE: Ptychography of an Eiger chip

Object: An Eiger readout chip

- The object is raster scanned with an out of focus beam
- Diffraction patterns at overlapping positions on the object are recorded
- The information in the overlap is used to recover the phase
- Both the attenuation and phase shift in the object can be reconstructed
Plans and summary for Eiger

• Eiger will be our work horse in the coming few years

• single module (an Eiger 500K) installed at cSAX beamline
• other single module systems foreseen at other beamlines

• 9M currently in production (modules), installation foreseen for early 2014
• will overcome frame rate and pixel size limitations of Pilatus

• we are thinking of a 49M detector in vacuum at a fixed distance for cSAXS not decided yet if this is an Eiger or Jungfrau detector
JUNGFRAU: a 2D detector for SwissFEL

adJUstiNg Gain detector FoR the Aramis User station

JUNGFRAU module:
- **Chip**: 256 × 256 pixels, **Pixel**: 75 × 75 µm²
- **Dynamic range**: $10^4$ 12keV photons per pixel
- **Module**: 2 × 4 chips, 4 cm × 8 cm
- **Systems up to 16 Mpixel at SwissFEL**

Readout:
- **Readout rate**: > 2 kHz
- **Linear count rate capability @ synchrotron**: 25 MHz/pixel

GOAL: detector for XFELs and synchrotrons

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JUNGFRAU: A. Mozzanica et al., JINST, 9, C05010, 2014
Jungfrau pixel architecture

2 main challenges for small pixels

Power consumption per channel

- low power preamp and CDS
- power cycled off-pixel buffer

Space for feedback capacitor limited

- amplifier range optimization
- precharge of feedback capacitors
Noise Characterization

Total noise: $\sim 100$ e$^-$

- Preamplifier: $\sim 91$ e$^-$
- CDS: $\sim 25$ e$^-$
- Readout: $\sim 31$ e$^-$

$\sigma = 100$ e$^-$ $\rightarrow$ $<400$ eV

$\rightarrow$ $5\sigma < 2$ keV
Automatic gain switching:
- White visible light illumination
- Increasing integration time

→ Covers dynamic range of > 4 orders of magnitude!
High Dynamic Range Imaging Via Gain Switching

Works well whether signal is concentrated on part of the chip …

… or if distributed all over the chip!
Summary Jungfrau

Small pixel size: 75 microns
High frame rate: 2kHz
High linear count rate capability:
  • Dead time free 24MHz
  • Quasi infinite for smaller integration times
  • First big not count rate limited hybrid pixel detector

Foresee up to 16M pixel systems for SwissFEL and SLS

Low noise of 120 e⁻ (434 eV) low energies accessible:
  • 3 keV with single photon resolution
  • Less without single photon resolution
    (sensor with thin entrance window)

High energies with scintillators
MÖNCH detector system

- Hybrid pixel detector: 25x25 μm² pixel size
- Goal: low noise and high dynamic range thanks to dynamic gain switching up to 600 12keV photons (or 2 x 10⁴ 400eV photons)

- Optimization for different applications possible:
  - Imaging/Tomography
  - Resonant and nonresonant inelastic X-ray scattering
  - Spectroscopy
  - Laue Diffraction

Current Prototype: MÖNCH 02

- Active area: 4x4 mm²
- 160x160 pixels
- 1x4 mm² optimized for Imaging
Mönch pixel schematics

160 x 160 pixels divided into 4 groups:

- group 1+2 fixed gains
  - gain1: 15 12keV photons
  - gain2: 100 12 keV photons

- group 3+4 dynamic gain switching
  - gain1: 15 12 keV photons
  - gain2: 600 12 keV photons

- CDS gain 1 and 4
The Mönch detector bump bonding

- Bump bonding of 25 micron pixel works well with PSI in-house process
- Limit: 20 microns
Noise measurement

Counts vs noise [eV]

Noise peak of MÖNCH

400 eV

Lowest noise of hybrid pixel detectors:
Noise of 30 electrons rms
3.7 sigma at 400eV
5 sigma at 540eV
Charge integrating detectors: get full information

50 micron pitch, 25 keV
Position dependent charge sharing
Position dependent charge sharing

Diagram showing charge distribution and percentage sharing.
To measure the spatial resolution a 2μm W slit has been scanned in 1μm steps in front of the strips.

- Slit parallel to strips
- Vertical beam size ~100μm
- Strip pitch 20μm, 15keV

\[ \sigma = 1.8 \mu m \]
Kidney stone
12 keV beam
25 um pitch
with GOTTHARD

Interpolation in 1D

25 um pitch
0.5 um bins

Interpolation in 1D
Summary/Outlook Mönch

• Hybrid pixel detectors with 25 um (and less) pixel size are possible
• Extremely low noise: 30 e⁻ Noise (previously only accessible with CCDs and MAPS)
  • Single photon sensitivity down to ~ 400 eV

• Small pixels allow position interpolation
  • Current spatial resolution with interpolation: 3.3 um

Future MÖNCH developments:
• MÖNCH03 is a full 1 by 1 cm² detector optimized for imaging with the presented method
  • Up to 160k pixels
  • 5 kFrames/s

• MÖNCH 1.0 2 by 3 cm² tillable read-out chip for detector modules
  • Dynamic gain switching 20x10³ photons (@400eV)
Summary

- Our single photon counting detectors are state of the art for many synchrotron applications thanks to large area and stability
  - EIGER in advanced commissioning phase
  - MYTHEN for XRPD

- Charge integrating detectors with dynamic gain switching offer performances close to photon counters and work at XFELs
  - Single photon resolution at high gain
  - Poisson limited over the full dynamic range
  - No count rate limitations for SR experiments
  - Low energies accessible with(out) single photon resolution
  - Still a lot of calibration, optimization, validation for real experiments

- Analog single photon readout expands the digital information
  - Work only with low flux
  - Energy dispersive detectors
  - (sub)Micron-resolution by interpolation
  - MÖNCH opens new possibilities in terms of energy and spatial resolution
The SLS Detector Group:
Anna Bergamaschi, Roberto Dinapoli, Dominic Greiffenberg, Dhanya Maliakal, Davide Mezza, Aldo Mozanica, Christian Ruder, Lukas Schädler, Julia Smith, Bernd Schmitt, Xintian Shi, Gemma Tinti

Open positions:
Postdoc for Mönch
Firmware for Eiger

http://www.psi.ch/detectors