First experiments with the JUNGFRAU charge integrating photon detector

International Workshop on Radiation Imaging Detectors :: 24-28 June 2018 :: Sundsvall, Sweden
• Photon detector development at PSI
• The JUNGFRAU detector:
  • a charge integrating detector for SwissFEL
  • pedestal and gain corrections
  • hardware: single modules to larger systems
• FEL applications
  • time-resolved pump-probe phase transitions
• Synchrotron applications
  • pump-probe with storage cells
  • macromolecular protein crystallography
Hybrid photon detector development at PSI

- **Microstrips**
  - 50 um: GOTTHARD
  - 25 um: MÖNCH

- **Pixels**
  - 75 um: JUNGFRAU
  - 200 um: AGIPD

- **Single Photon Counting**
  - MYTHEN

- **Charge Integrating**
  - No specific devices mentioned

- **172 um**: PILATUS

XXX
Hybrid photon detector development at PSI

Microstrips
- 50 um

Pixels
- 25 um
- 75 um
- 200 um

Charge Integrating
- GOTTHARD
- MÖNCH

Single Photon Counting
- MYTHEN

NOW!
- S. Chiriotti
  - Wednesday Poster

Tomorrow 9:40
- D. Greiffenberg
  - Tomorrow 9:40

Today 14:00
- D. Mezza

Today 14:20
- M. André

Now!
- EIGER

172 um
- PILATUS
**JUNGFRAU: a photon detector for SwissFEL**

- **Repetition rate:** 100 Hz
- **Electrons per pulse:** $2 \times 1.24 \times 10^9$
- **Undulators:** 12 x 1060 alternating neodynium magnets
- **Photon energy:** 0.25 - 12 keV
- **Duration of light pulse:** 1 - 60 fs
- **Brilliance:** $1.3 \times 10^{33} \gamma / (s \times 0.1\% \text{ b.w.} \times \text{mm}^2 \times \text{mrad}^2)$
  - $= 10^{10}$ times the SLS

What kind of detector can measure $10^4$ 12 keV photons all arriving within 10 fs?

**Single photon counting**
- every time the signal goes above a threshold, increment a counter
  - ✓ noiseless readout, fluorescence suppression
  - ✦ count loss due to charge-sharing and pile-up

**Charge integrating**
- collect charge throughout the integration window
  - ✓ detects fractions of a photon and pile-up photons
  - ✦ integrates leakage current

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**Key numbers**
- charge
- shares
- time
- threshold
- at half photon
- incoming photons

**Single Photon Counting**
- signal
- threshold
- at half photon
- single photon counting result: 3 photons
- time

**Charge Integrating**
- signal
- +3
- time
- charge integrating result: $5.4 \times$ photonE

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**FELs require charge integrating detectors**
The JUNGFRAU charge integrating detector

How to ensure adequate amplification and limit noise?

**Gain switching**
- Automatically add capacitors to extend the dynamic range
- Noise remains below Poisson statistical limit
- Output: the amplified charge and the amplification factor

Gain switching in action

Noise performance

Poisson statistical limit $\sqrt{N}$
Calibration and pedestal measurement

How to convert JUNGFRAU output to number of photons?

Need to know the six parameters characterise each pixel:
• three offsets (pedestals) regularly measured with dark runs
• three gradients (gains) measured with 3-step lab-based calibration

\[
N_\gamma = \frac{|\text{ADC} - \text{pede}| \times \text{gain [keV/ADU]}}{E_{\text{beam [keV]}}}
\]
Image correction: Fresnel Zone Plate

1. Split gain and ADC
2. Pedestal correct ADC
3. Gain correct to energy
4. Divide by beam energy

\[ N_\gamma = \frac{|ADC - pede|[ADU] \times \text{gain}[\text{keV/ADU}]}{E_{\text{beam}}[\text{keV}]} \]

SLS XIL beamline 92 eV, etched sensor
Image averaged over 10,000 frames of 200 us integration time
From single modules to larger systems

**JUNGFRAU 4 Mpxixels**
- inter module gaps of 36 (vertical) and 8 (horizontal) pixels
- dead area when tiled of 7%
- extra power control board
- water cooled
- control and data in parallel

**First JF4M image**
Xray tube with Korean bookmarks - thank you PAL!

**JUNGFRAU 4.5 Mpxixels**
- SwissFEL ESA diffractometer arm
- in vacuum

**JUNGFRAU 16 Mpxixels**
- two systems currently under construction for SwissFEL ESA+ESB
FEL applications - pump-probe at SwissFEL ESB

in collaboration with M. Camarata et al., U. Rennes

JF1.5M, Bernina beamline, SwissFEL
- pilot experiment in November 2017
- SwissFEL repetition rate 10 Hz, photon energy 6.6 keV (3rd harmonic)
- JF frame rate 100 Hz, integration time 10 us, room temperature

JF1.5M silver behenate powder diffraction

Photons [6 keV]
Semiconductor to metal phase transition of Ti$_3$O$_5$ nanocrystals

- pump-probe technique: 800 nm laser pump, X-ray probe
- delay scan and look for changing positions of diffraction rings
- first time resolved pilot experiment at SwissFEL

- good pedestal stability over 1 week
  - median drift < 10 eV
  - max drift < 200 eV
Pump-probe with a chopped synchrotron beam

- JF1M, ID09 beamline, ESRF
- roadrunner chip delivery system
- chopped 30 μs beam pulse at 10 Hz
- JF storage cells provide time resolution and speed
- 2.6 μs integration, 2.4 μs reset per storage cell
- instantaneous frame rate 0.2 MHz!
JUNGFRAU can be used in high duty cycle synchrotron applications such as MX
But there are challenges...
• requires maximum frame rate of 1.13 kHz
• requires long integration time of 840 us
• requires cooling to -12°C
• requires condensation protection
• requires saving huge amounts of data
• requires offline data conversion

First structure solved by JF - Insulin
October 2016 - thanks K.Nass
Benefits of JUNGFRAU for MX

in collaboration with M. Wang et al., SLS PX1

EIGER rate limited by pile-up → JUNGFRAU enables faster data collection

“Easy” native-SAD in 600 ms
- Thaumatin
- 100°/sec, 60°
- 6 keV, $5 \times 10^{11}$ phs/sec (full beam)

EIGER loses efficiency in the corner of pixels → JUNGFRAU provides better data quality

“Real-life” native-SAD in 60 s
- Aminopeptidase, 101 kDa
- 10°/sec, 600°
- 6 keV, $5 \times 10^{11}$ phs/sec (full beam)

thanks F. Leonarski
The JUNGFRAU detector for photon science
• hybrid silicon pixel detector
• charge integrating
• automatic gain switching reduces noise, extends dynamic range

Pilot experiments at SwissFEL
• first time resolved measurements completed
• construction of large systems underway

JUNGFRAU also for synchrotron applications
• storage cells can give high rates
• brings benefits to MX over photon counting
My thanks go to:

SLS detector group

SLS PX1:
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• Alke Meents

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• Marco Camarata