Inverse LGAD sensors for RIXS spectroscopy at the European XFEL

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X-ray Sensors Joint Workshop, Zürich, 12-16 January 2026

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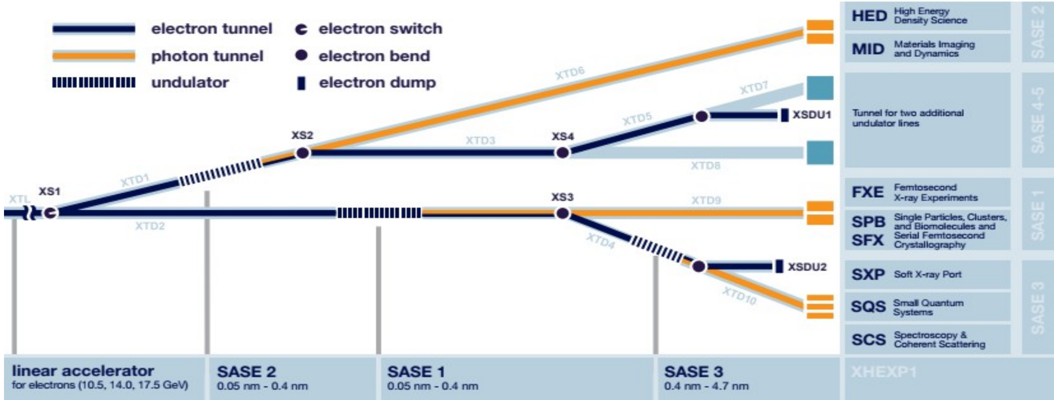
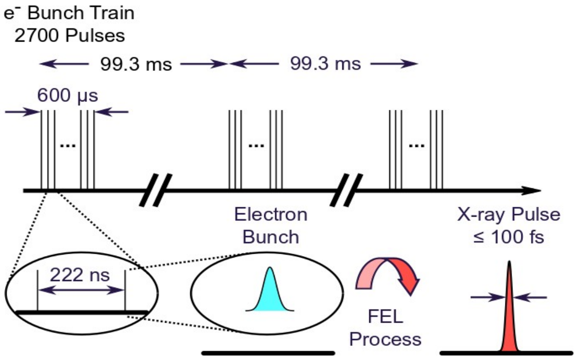
The European XFEL





- Three main undulator systems (SASE 1, 2, 3)
- Supply seven scientific instruments:
  - SPB/SFX, FXE, MID, HED (**‘hard X-ray’**)
    - 6 keV < E < 25 keV
  - SCS, SQS, SXP (**‘soft X-ray’**)
    - 0.25 keV < E < 3 keV

- 10 Hz train rate
- Bunch train internal structure
  - 2700 pulse for 600 µs
  - 4.5 MHz pulse rate (~222 ns spaced)
  - Lasing pulses < 100 fs width
- Pulses ~10^{14} photons

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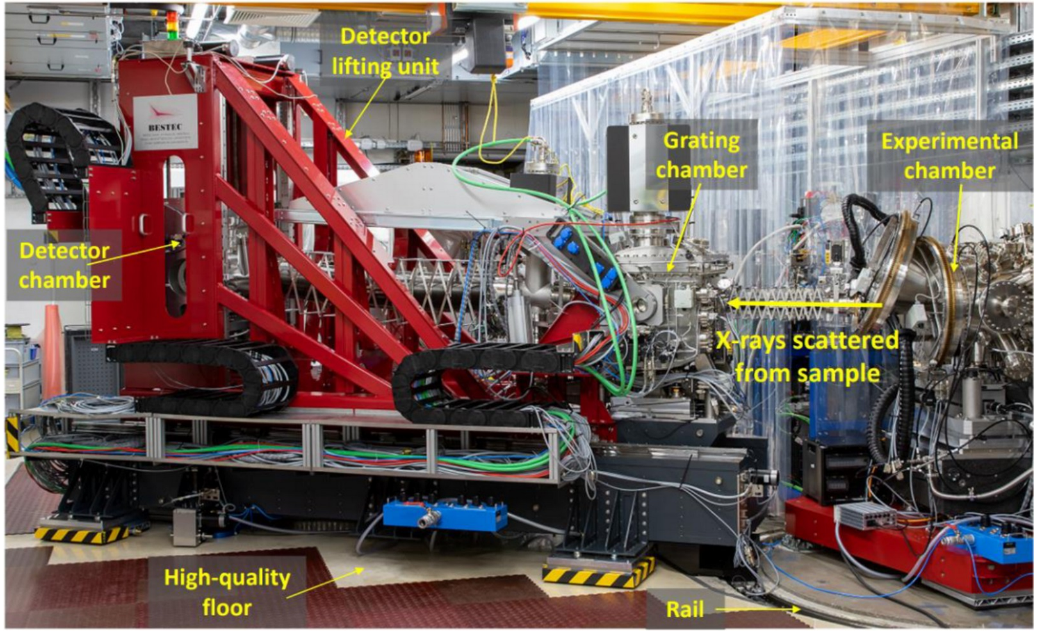
The hRIXS spectrometer @ SCS

- RIXS at the EuXFEL
  - Photon hungry technique
  - High repetition rate light delivery
- Detector requirements:
  - High **S/N** (E > 400 eV)
  - High **acquisition rate** (MHz-level burst).
  - High **spatial resolution** (~5µm in detector).
- Currently, a CMOS detector (Marana-X) is used:
  - limited to 10 Hz;
    - Cannot resolve pulses within a train
  - 11 µm pixel pitch;
  - Single-photon sensitive < 1 keV



J. Schlappa, et. al. European XFEL Users' Meeting 2023

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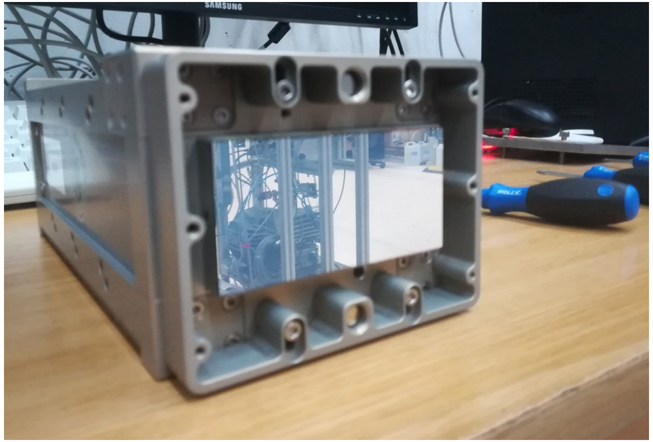
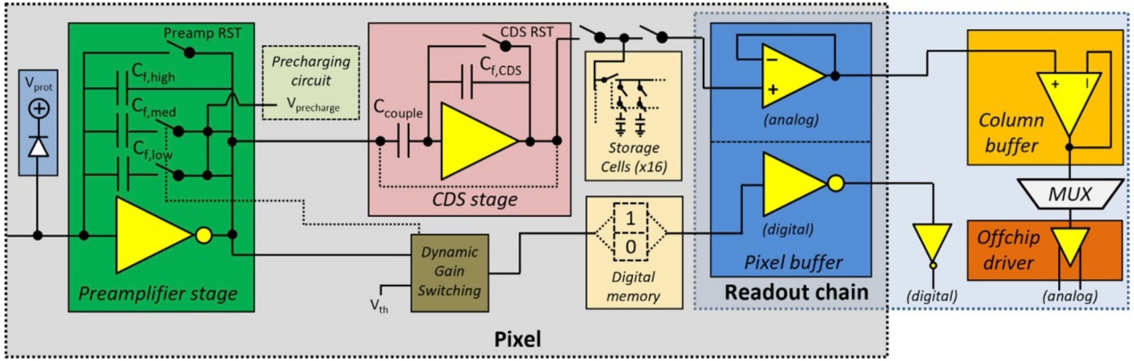
The JUNGFRAU Detector



- **Charge integrating** hybrid pixel detector
- **Dynamic Gain Switching** (DGS) architecture:
  - Single photon resolution down to 3 keV (with Si sensors)
  - Dynamic range up to 10^4 12 keV photons
- Array of 16 storage cells
  - Up to **16 images/train**
  - 'burst' frame rate up to **150 -200 kHz**
- Large area
  - Fully equipped front-end module: (about) 8 cm × 4 cm



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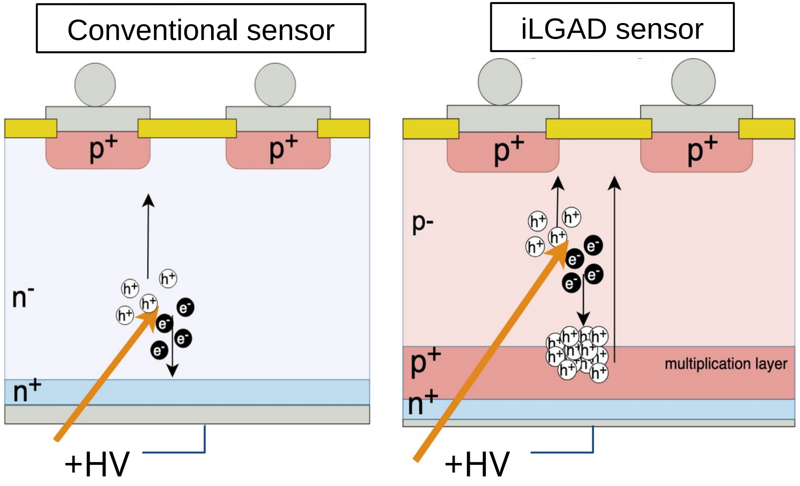
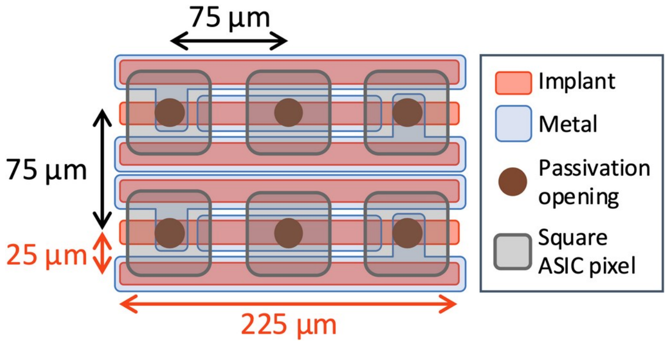
Inverted Low Gain Avalanche Diodes (iLGADs)

- Electrons travel backwards to a multiplication layer with **high local electric field**.
- Avalanche **multiplication of charges** occurs.
- **New e^-/h^+ pairs** are extracted, and holes drift to pixels inducing signal.
- Operational requirements:
  - Bias ~300 V
  - Cooling < -20 °C
- Rectangular pixels (‘strixels’)
  - 25 µm × 225 µm
  - Higher sampling rate in energy dispersive dimension





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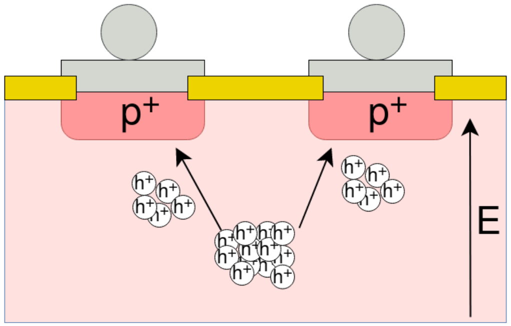
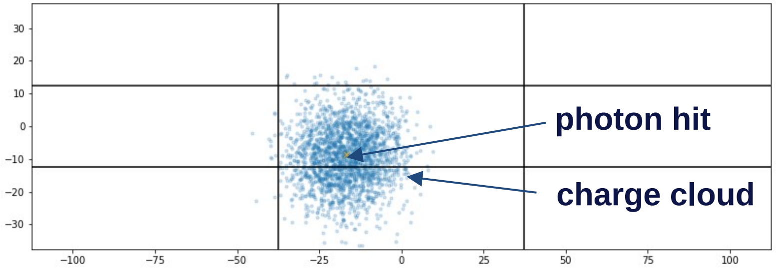
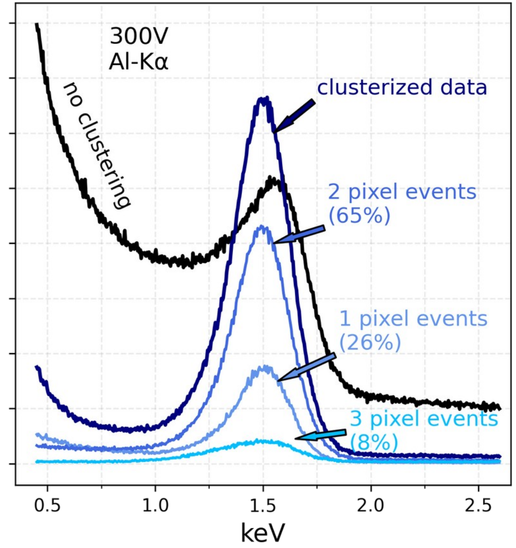
Clustering

- Small pixel pitch along spectroscopic dimension:
  - **Charge is shared** among neighboring pixels
- Photon energy reconstructed via **clustering algorithm**
- **Algorithm** based on two thresholds
  - High threshold (~ 5σ) to identify central pixel
  - Low threshold (~3σ) to identify the neighbors
- Charge sum attributed to the central pixel
- **Hit position finding algorithm** to improve spatial resolution







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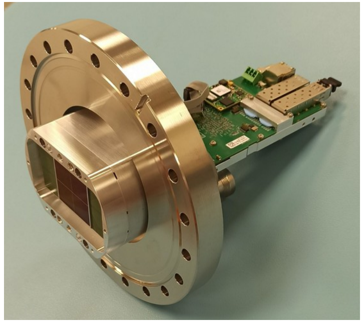
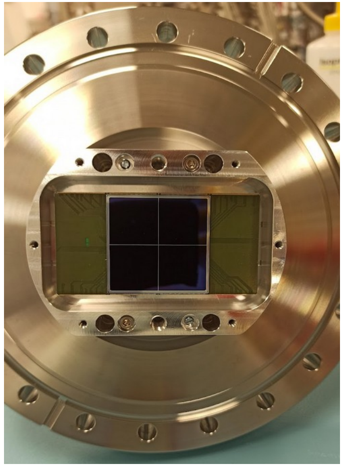
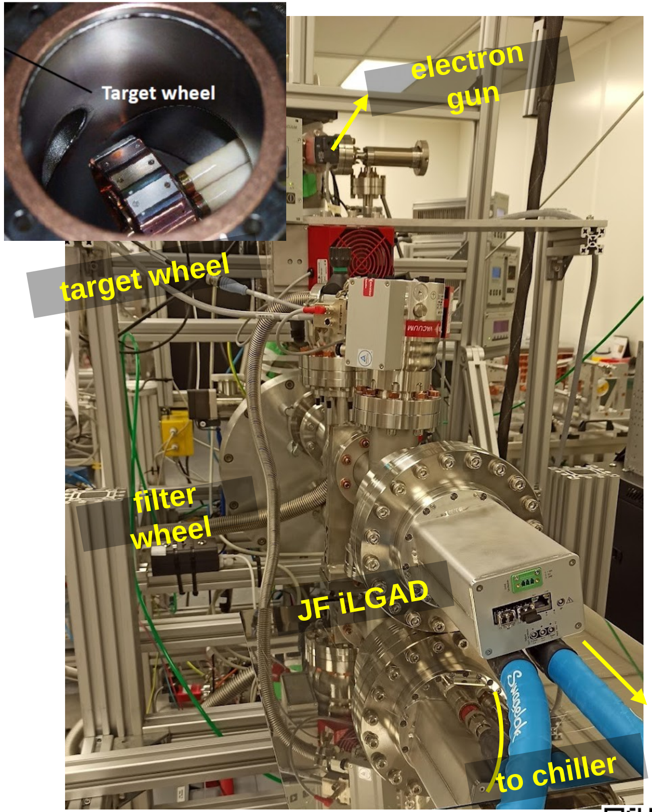
Detector calibration







- Four JUNGFRAU 1.0 ASICs equipped with iLGAD sensor from FBK
- Calibration in the EuXFEL lab prior to usage in the hRIXS spectrometer
- Pulsed X-ray source (PulXar)
  - Electron gun
  - ‘Blanker’ to provide pulsed structure
  - Sets of different **targets** and **filters**
    - Provide X-ray fluorescence lines
- Flat field illumination of Aluminum K_α fluorescence
- Data acquired with 5 μs integration time
- Sensor bias: 300 V, 250 V, 200 V
- Detector cooled to -25 °C

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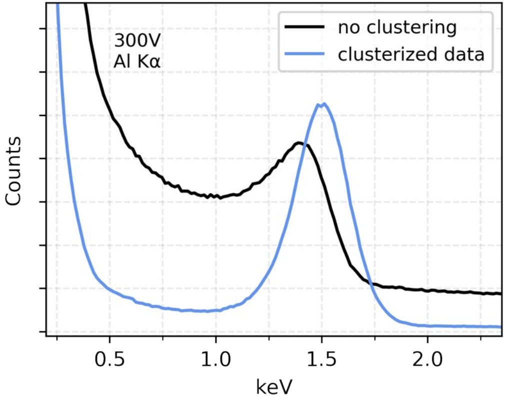
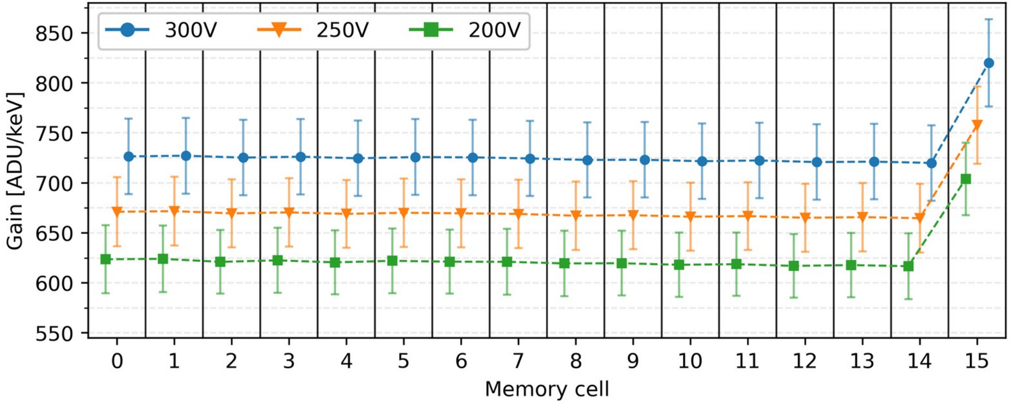
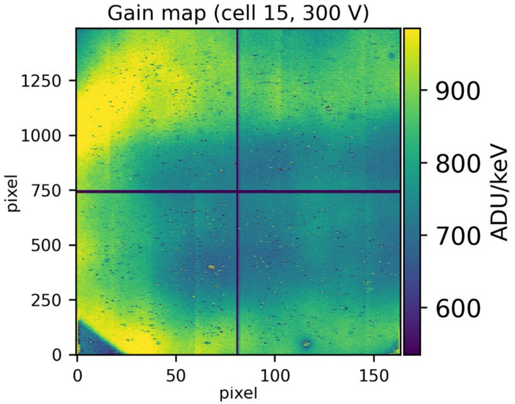
Gain characterization



- Clustered data to establish the peak position
- Average gain stable across memory cells
  - Memory cell 15 has higher capacitance
- Spread of 5 – 10% across the sensor
- Expected dependence from bias voltage





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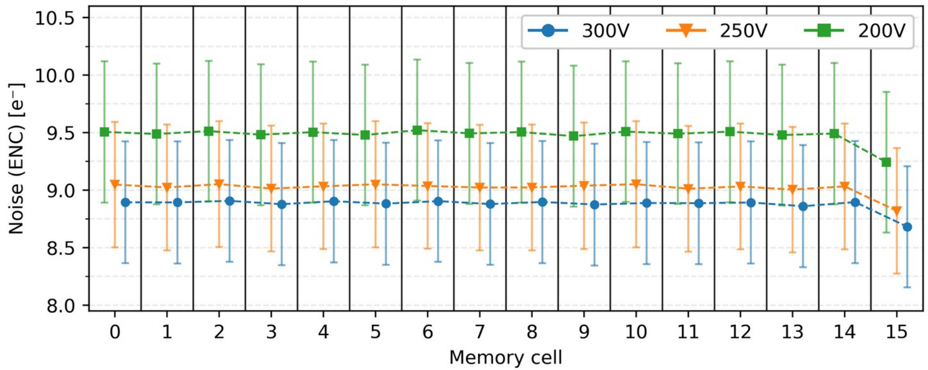
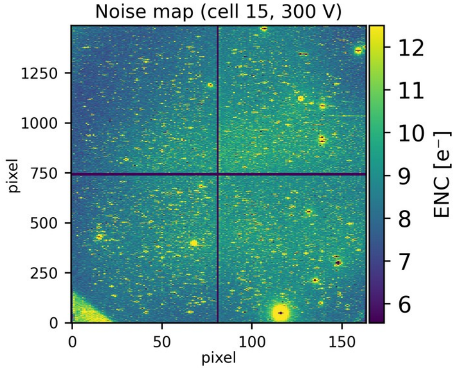
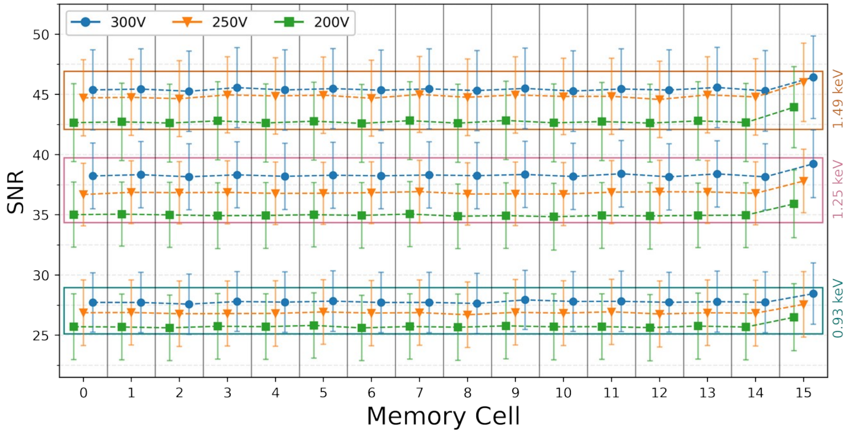
Noise and Signal-to-Noise Ratio







- Noise defined as the RMS of the pedestal distribution with no illumination
- Average noise stable across memory cells
  - Several hot spots
- Dependence from bias voltage (gain)
- Signal-to-Noise Ratio (SNR) can be adjusted with bias voltage
  - SNR ~28 at 930 eV

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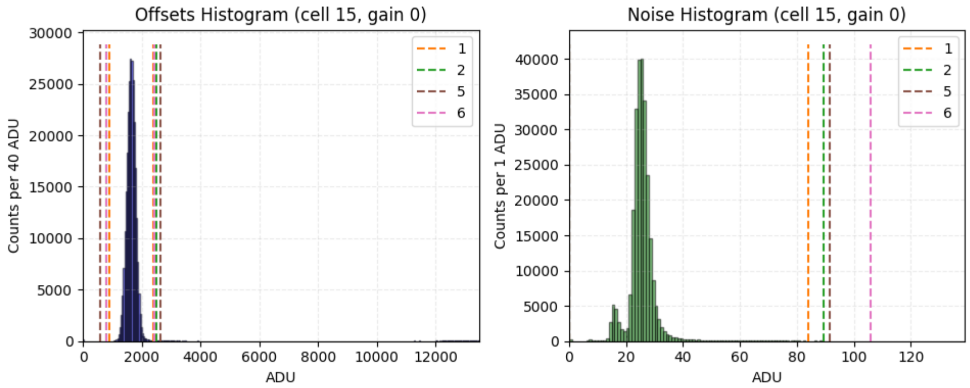
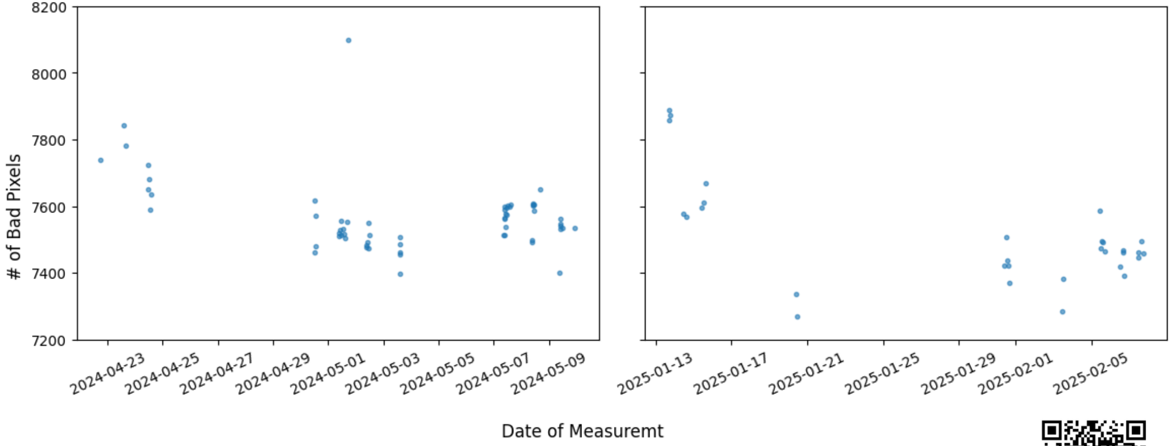
Identifying 'bad' pixels

- False positives can compromise RIXS analysis
- Identify **'bad' pixels:**
    - Outliers in pedestal/noise/gain distribution
    - Failed gain fit
- Number of bad pixels roughly stable
    - for given experimental conditions
    - Still enough fluctuation to affect RIXS measurements





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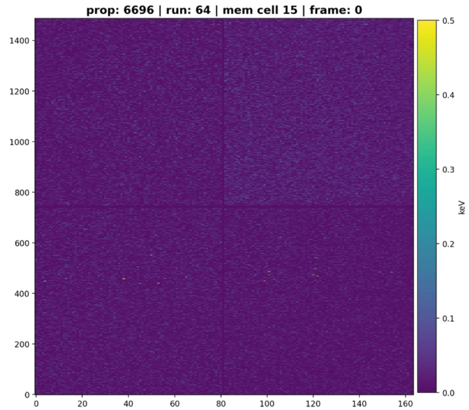
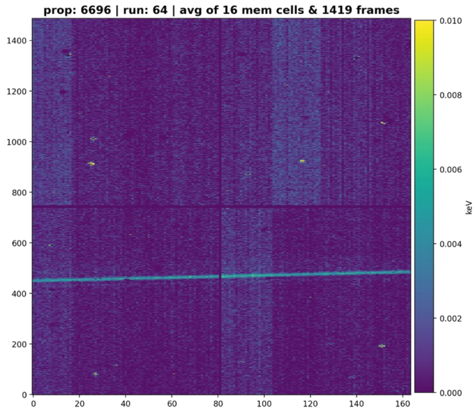
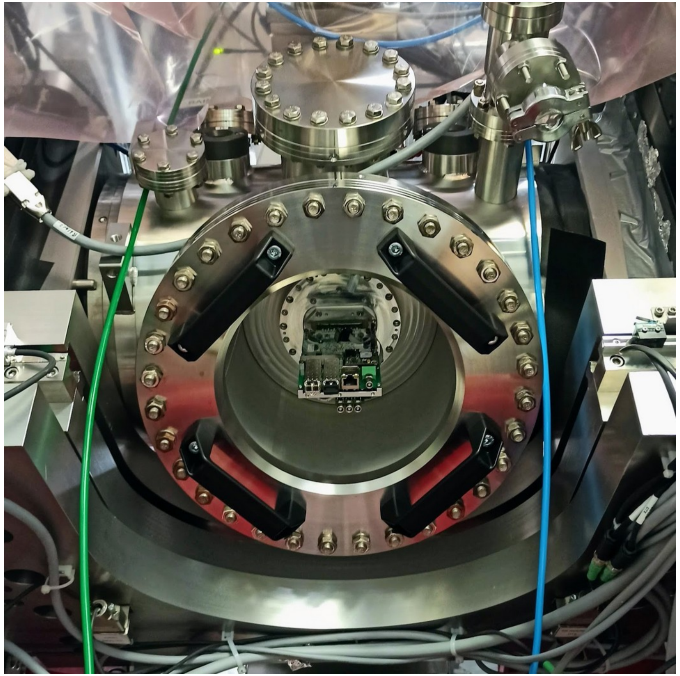
Heisenberg RIXS: Resonant Inelastic X-ray Scattering

Single frame



Averaged frames





- Calibrated detector on hRIXS spectrometer in Nov. 2024
- Two **main goals**:
  - Compare **resolution** with Marana-X
    - Elastic scattering on carbon at 928.5 eV
  - Test **intra-train pump and probe**
    - RIXS on CuO

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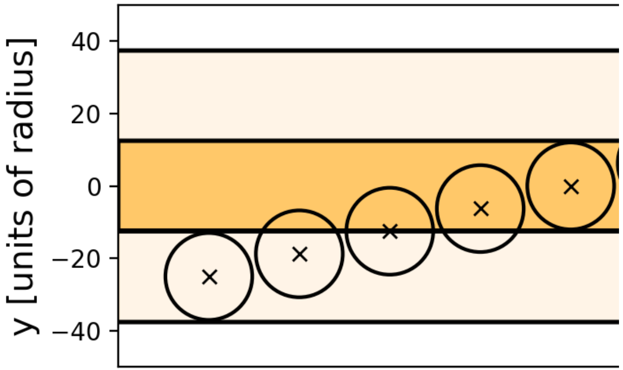
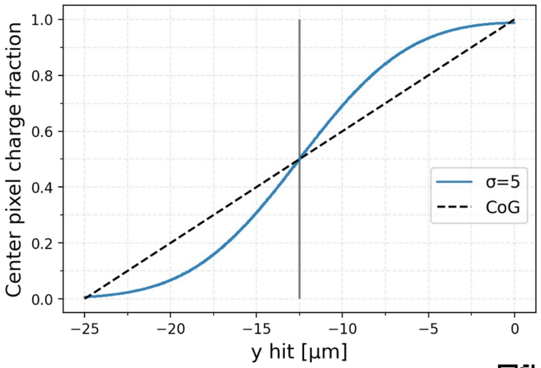
Hit Position Finding Algorithm

- **Center of Gravity (CoG)** used for hit position finding
- Simplest approach experimentally:
  - Hit position **average of pixel center position** each weighted by the corresponding **signal amplitude**
  - Requires no previous specific calibration
  - It incorrectly assumes that charge is linearly shared

$$y_{\mathrm{CoG}} = \frac{\sum_i^N (y_i \times S_i)}{\sum_i^N S_i}$$

- Applied to both JUNGFRAU and Marana-X data





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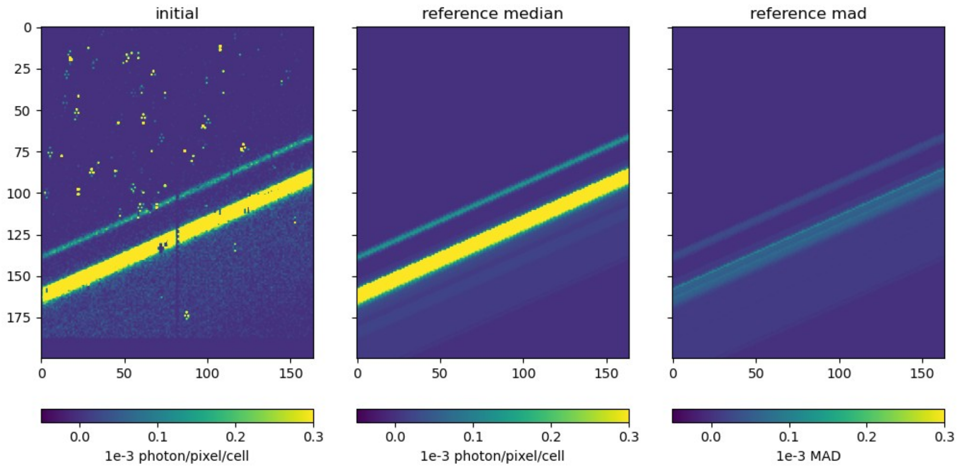
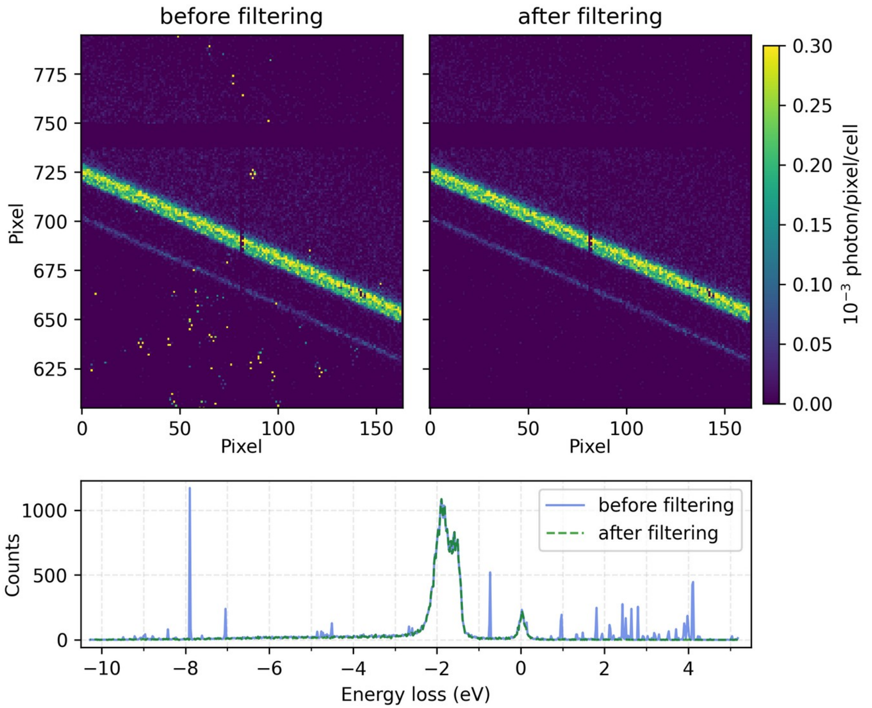
Identifying additional ‘bad’ pixels



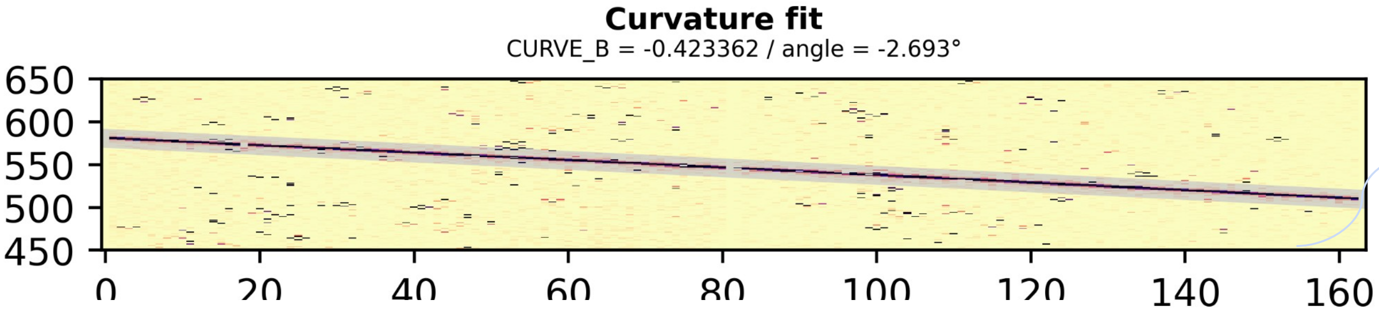


- Bad pixel mask is not 100% effective
- Few not identified pixels spoil spectra
- Additional filtering procedure:
  - Photon count homogeneous along spectral lines
  - Identify **median count** and **mean absolute deviation (MAD)** along spectral lines
  - Use them to filter the images

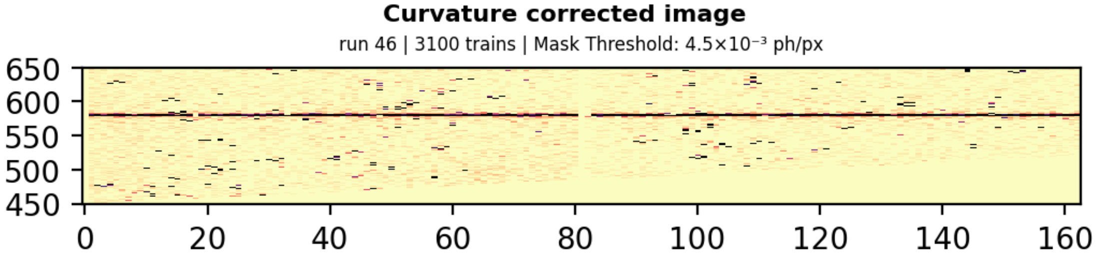
$$\frac{|I - median|}{MAD} > threshold$$

Curvature correction

- Find the parabola coefficients that best fit the data.
- Adjust the y coordinate of each photon applying the determined parabolic equation.



Parabola parameters from fit:
CURVE_A = -0.000081
CURVE_B = -0.423362
intercept = 580.72

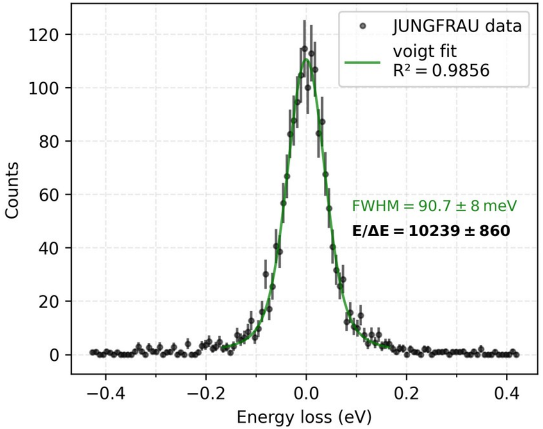



```
def parabola(x, curve_a, curve_b, intercept):
    return CURVE_A*x**2 + CURVE_B*x + intercept
```

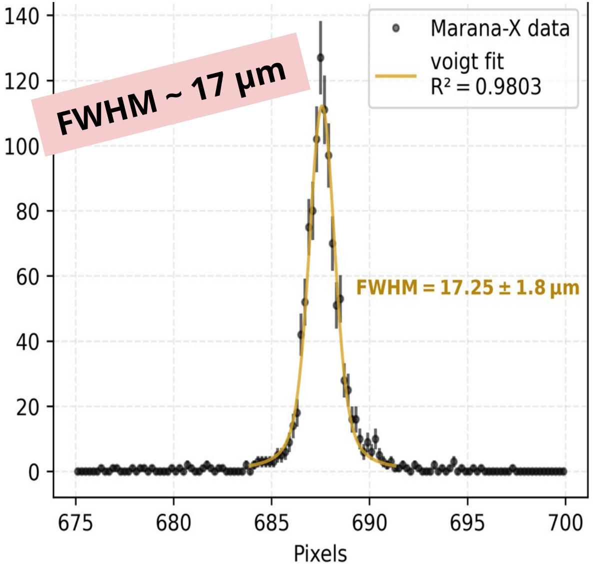
y_curvature_corrected = y + parabola(x)

Resolution

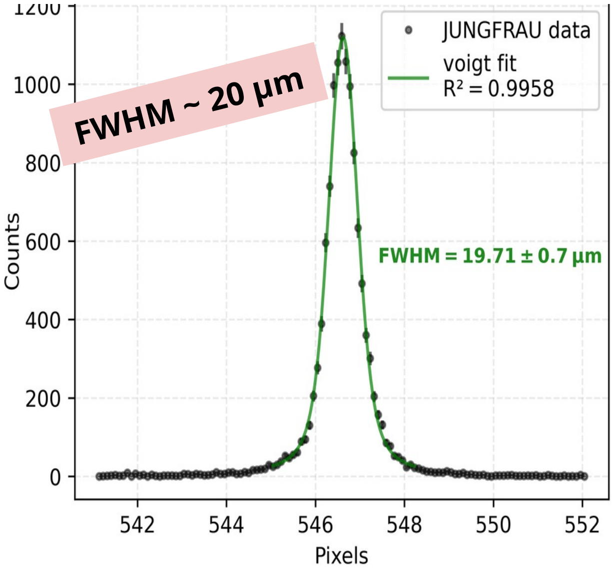
- Resolution is limited by the hRIXS spectrometer, not the detectors.
- Marana-X has smaller pixels (11 μm) than JUNGFRAU (25 μm): There is always charge sharing and interpolation is more precise.



Marana-X



JUNGFRAU iLGAD



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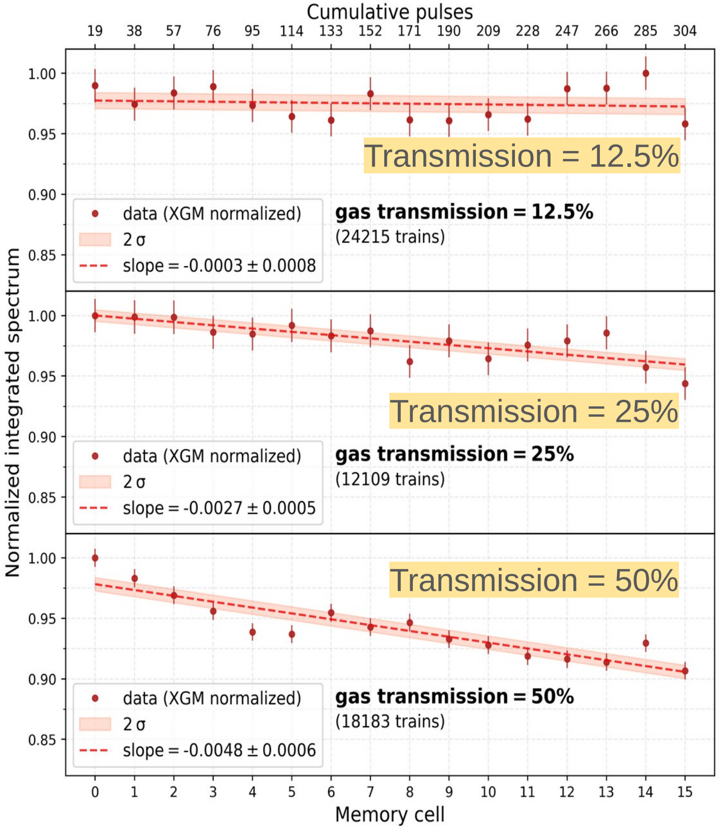
Transient effect on sample



- Deeper memory cells tend to detect less photons emitted from sample.
- This effect increases with beam intensity.
- Seen for both CuO and C tape samples.
- Cause still under investigation

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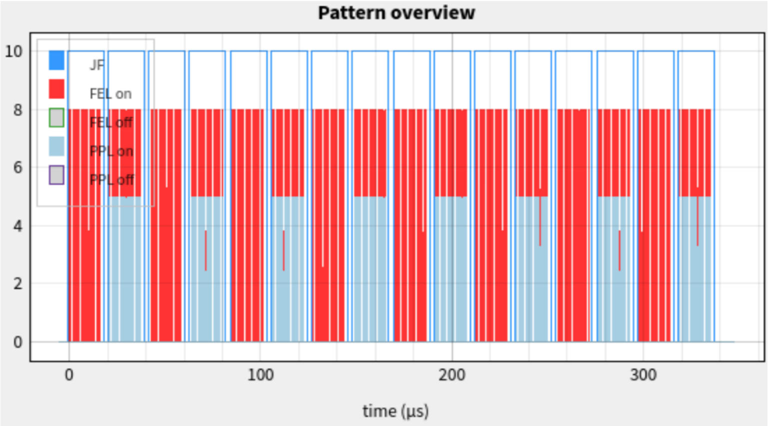
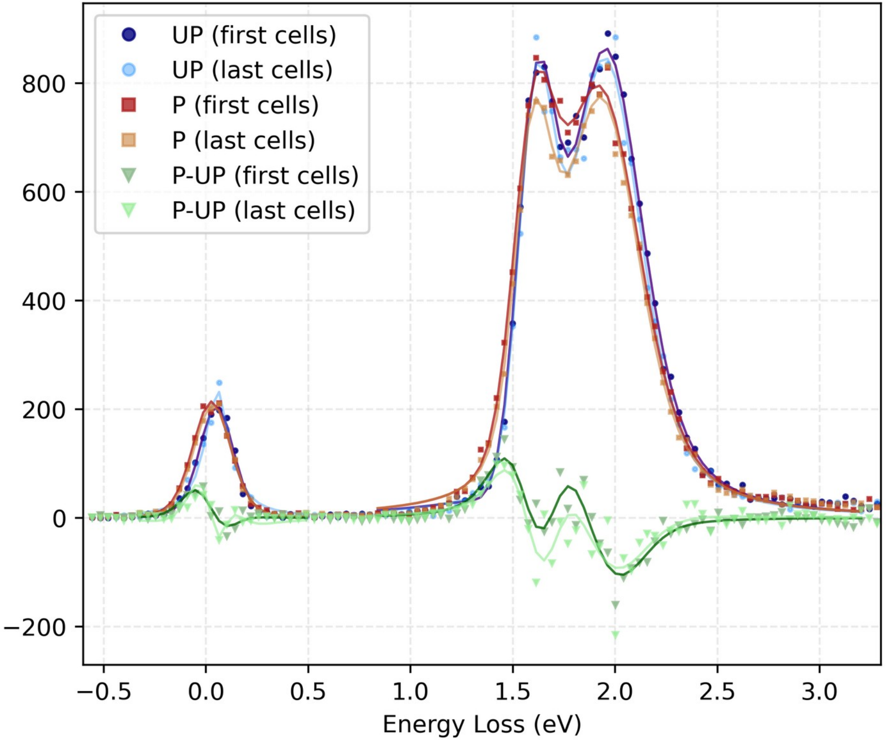
Pump-Probe Laser Effect

- Measurements with consecutive **Pumped (P)** and **Unpumed (UP)** optical laser pulses on alternating memory cells
- Only some microseconds in between pusles → good normalization.
- Observed effects in sample induced by PPL.
- PPL RIXS at ~50 kHz





Conclusions and Outlook

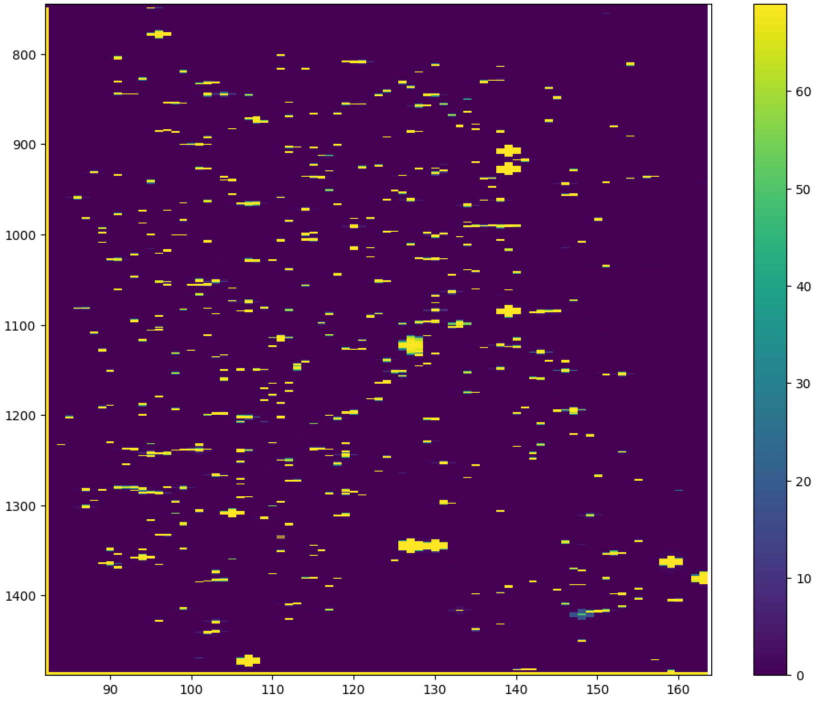
- Detector requirements for hRIXS spectrometer at the EuXFEL:
  - Hit position resolution ~5 µm → ~20 µm achieved
    - Achieved with CoG position finding algorithm
    - Limited by the scientific instrument
  - MHz-level frame rate (burst) → ~ 50 kHz achieved
    - 16 images per train in ‘burst’ mode
  - Single photon sensitivity at ~400 eV → tested at ~928.5 eV
    - S/N ratio > 25
- Performed pump-probe measurements at ~47 kHz (burst)
  - RIXS on CuO
  - High frame rate allowed identification of a transient effect
  - Origin under investigation
- Next steps:
  - Thinner entrance window
  - Higher sampling rates (e.g. 18.75 µm and/or 15 µm)
  - Test position finding algorithms other than CoG
  - PSI started development of MHz-capable JUNGFRAU ASIC

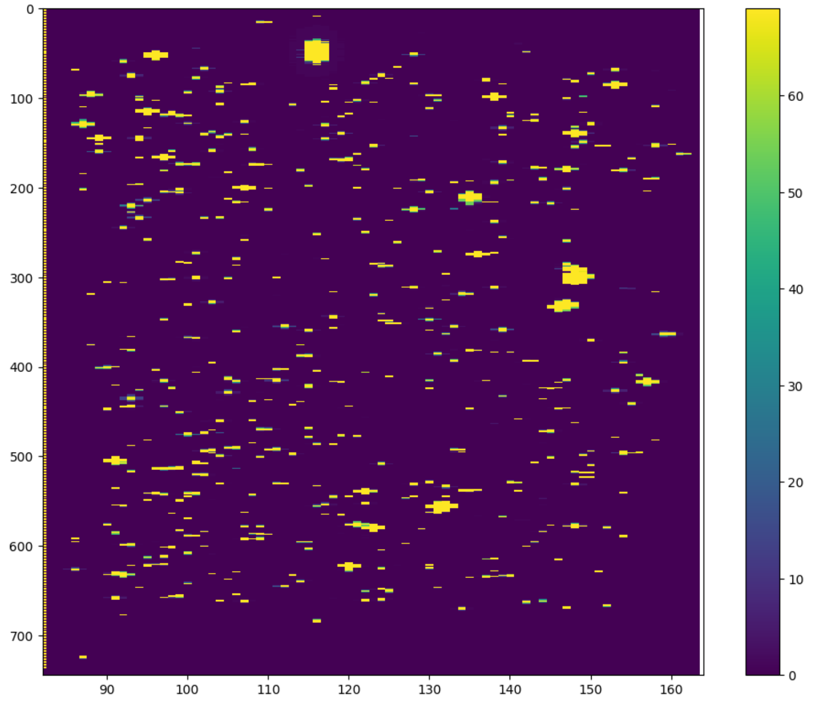
Results submitted for peer review
pre-print available at:
arXiv:2511.12314v1

Thank you.

Backup slides

Stability of Bad Pixels II





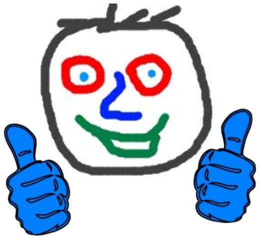
3. hRIXS measurements

Basic Data Analysis Workflow

1. Offset & Gain correction
2. Pixel-strixel remapping
3. Bad pixel masking
4. Clustering
5. Interpolation
6. Frame averaging
7. Curvature correction
8. Image projection
9. Spectrum fit

Working with frames

Working with hits list



	train_id	frame	cell	y_interp	y_interp_curv_corr	y	y_curv_corr	x	E
25	2177489433	0	1	510.728210	580.976850	510	580.248640	161	0.809077
63	2177489433	0	3	494.860718	539.761357	494	538.900639	104	1.089233
65	2177489433	0	3	520.030151	581.325166	520	581.295014	141	1.038226
88	2177489433	0	4	644.500000	695.577986	644	695.077986	118	0.264839
102	2177489433	0	5	536.500000	581.840831	536	581.340831	105	0.391657
...	...	...	...	...	...	...	...	...	...
885960	2177492529	3096	11	460.500000	465.166727	460	464.666727	11	0.809113
885992	2177492529	3096	13	514.500000	581.607543	514	581.107543	154	0.315879
885993	2177492529	3096	13	540.789185	580.420079	540	579.630894	92	1.119770
885994	2177492529	3096	13	558.226746	581.323116	558	581.096370	54	0.990943
886019	2177492529	3096	15	649.500000	675.191623	649	674.691623	60	1.299692

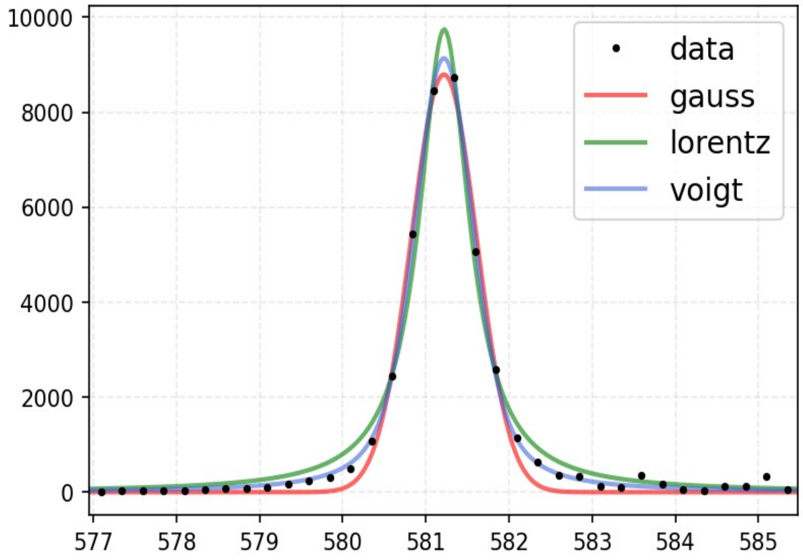
78926 rows × 9 columns

Spectrum fit

9. Spectrum fit

- RIXS spectra is not a gaussian.
- Different broadening mechanisms caused by different to physical processes.
- Best described by a **Voigt** profile: **convolution** between **Gaussian** and **Lorentzian** functions.

$$V(x;\sigma,\gamma) \rightarrow G(x;\sigma) \ast L(x;\gamma)$$



Gauss
FWHM = 23.35μm

Lorentz
FWHM = 18.27μm

Voigt
FWHM = 21.40μm