The performance of the Athena X-ray Integral Field Unit at very high count rates

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Abstract: The Athena X-ray Integral Field Unit (X-IFU) will operate at 90 mK a hexagonal matrix of 3840 Transition Edge Sensor pixels providing spatially resolved high resolution spectroscopy (2.5 eV FWHM up to 7 keV) between 0.2 and 12 keV. During the observation of very bright X-ray sources, the X-IFU detectors will receive high photon rates going up to several tens of counts per second per pixel and hundreds per readout channel, well above the normal operating mode of the instrument. In this contribution, we investigate through detailed End-to-End simulations the performance achieved by the X-IFU up to Crab-like fluxes. Special care is notably taken to model and characterize pulse processing limitations, readout-chain saturation effects, as well as the non-Gaussian degradation of the energy redistribution from crosstalk at the focal plane level (both thermal and electrical). Overall we show that more than 50 % throughput at 1 Crab in the 5 to 8 keV band can be achieved with better than 10 eV average resolution with the use of a Beryllium filter, enabling breakthrough science in the field of bright sources.

X-IFU End-to-End simulations

- The X-ray Integral Field Unit [1, O-17] is a **high resolution imaging spectrometer** in the soft X-ray band (2.5 eV resolution over a 5' field of view) using a matrix of ~ 4000 **Transition Edge Sensor** (TES) pixels voltage biased at 90 mK and read out using **Frequency Domain Multiplexing** (FDM) [2, O-60].
- An End-to-End simulator was developed in the **SIXTE** [3] software environment modeling the full observation process: mirror imaging; X-ray filters, focal plane geometry, detector response.
- Two simulation approaches: *tessim* [4] for **accurate detector physics**; *xifupipeline* for **full instrument simulations** based on response matrices.

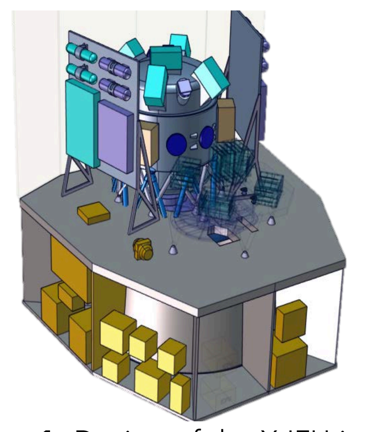

Figure 1: Design of the X-IFU integrated on the instrument module.

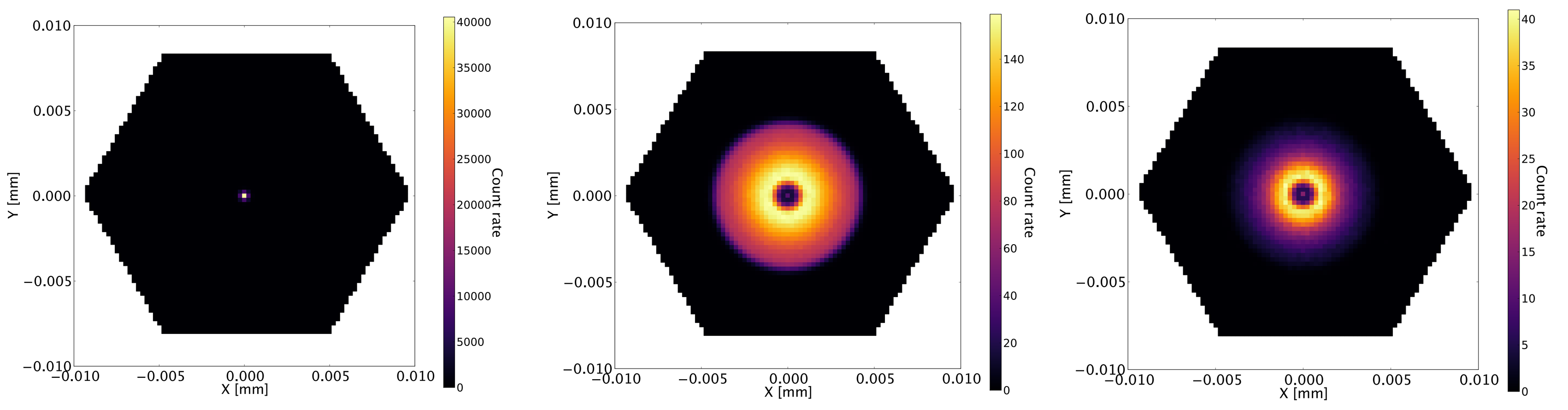

Figure 2: X-IFU point spread function under different configurations. The count rates correspond to a 1 Crab source. Left: On focus observation. Middle: 35 mm mirror defocusing. Right: 35 mm mirror defocusing with a 100 µm thick Be filter. The difference from the previous one is due to the differential effect of defocusing as a function of energy.

Event reconstruction performance

- At high count rates, X-ray pulses get closer together and the energy reconstruction performance is degraded.
- Degradation is characterized by the pixel **electrothermal time constant** (795 µs) and its **effective frequency** (550 Hz).
  - **Secondary pulses rejection** if $T_1 < 10 \times \tau_{etf}$
  - **Resolution degradation** according to [5]:

$$\Delta E(T_2) = \frac{\lim_{T_2 \to \infty} \Delta E}{\sqrt{1 - 1/(2T_2 f_{eff})}}$$

- Assumptions found conservative wrt. *tessim* simulations.
- Behavior characterized using different **event grades**.

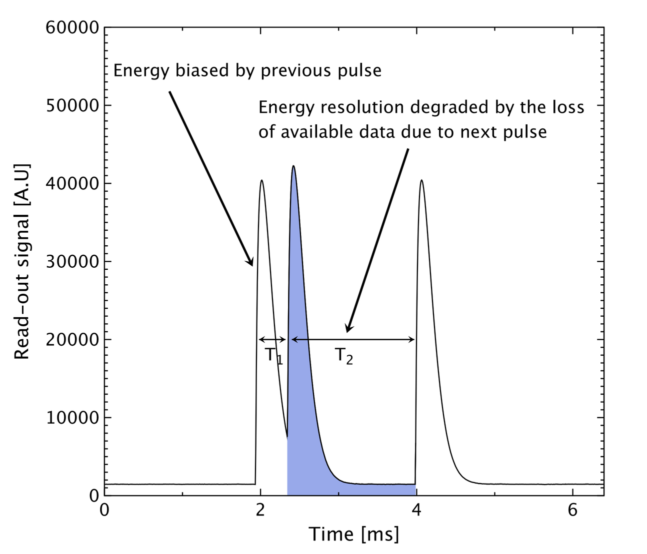

Figure 3: Performance degradation when pulses are too close to one another.

	Time interval since previous pulse	Time interval until next pulse	Energy resolution
High resolution	≥ 7.9 ms	≥ 45.3 ms	2.5 eV
Medium resolution	≥ 7.9 ms	≥ 2.3 ms	3 eV
Limited resolution	≥ 7.9 ms	≥ 1 ms	7 eV
Low resolution	≥ 7.9 ms	-	~ 30 eV

Effect of the front-end SQUID

- The first stage in the amplification of the FDM multiplexed signal is the **front-end SQUID**. Its response being close to sinusoidal, in order to operate it in a linear regime, a **baseband feedback** (BBFB) loop [6] is used to read the signal out. The non-perfect feedback induces:
  - **Intermodulation terms** when pulses from two pixels arrive at the same time and therefore **crosstalk** between the two events.
  - **Loop unlocks** if there are too many coincident high energy events making the error signal exceed the stable operating range of the SQUID.
- Dedicated BBFB simulations were performed.
  - Crosstalk characterized in **look-up tables** implemented in *xifupipeline*.
  - SQUID unlocks predicted if more than **24 keV** are deposited in a channel in a pulse time constant. Appears to be **negligible** up to Crab count rates.

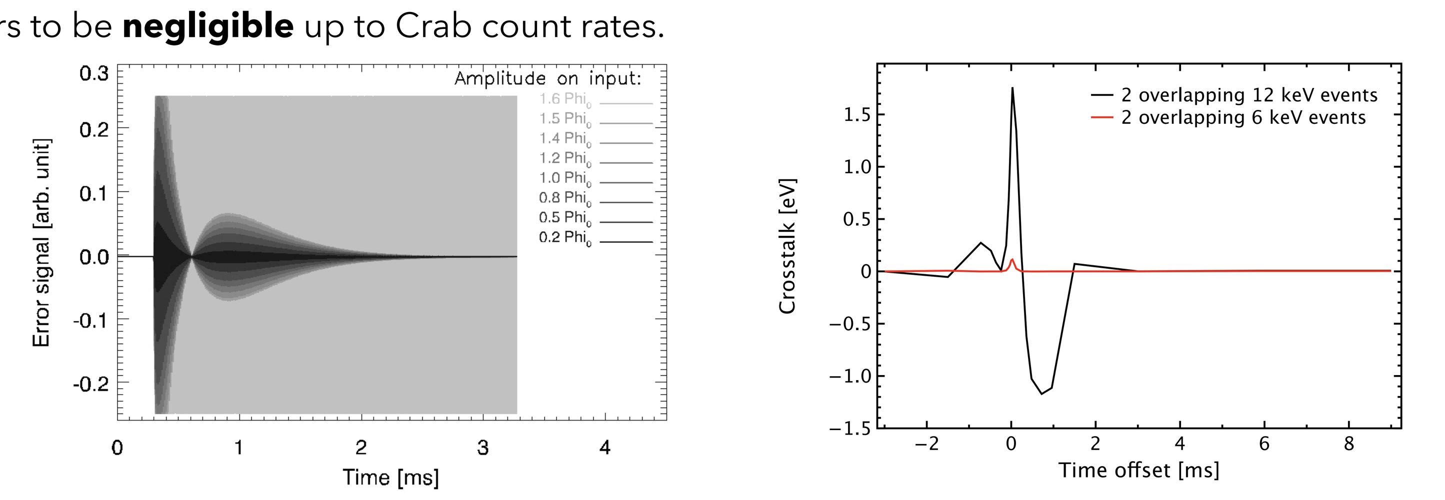

Figure 4: Left: Error signal on the SQUID for the sum of two pulses with varying input amplitudes (1.5 Phi0 corresponds to 12 keV, a BBFB loop gain of 10 is applied). For events > 1.5 Phi0, the loop unlocks. Right: Extract from the non-linear crosstalk lookup table used in *xifupipeline*. This shows the crosstalk level as a function of the time difference between two events of varying energy.

References:

[1] Barret et al. 2016, Proceedings SPIE, Vol 9905, 9905-83
[2] Akamatsu et al. 2016, Proceedings SPIE, Vol 9905, 99055S-5
[3] Wilms et al. 2014, in Proc. SPIE, Vol. 9144, 91445X
[4] Wilms et al., 2016, Proceedings SPIE, Vol 9905, 990564-1
[5] Doriese et al. 2009, AIP Conf. Ser., Vol 1185, 450
[6] den Hartog et al. 2009, AIP Conf. Ser., Vol 1185, 261
[7] Iyomoto et al. 2009, IEEE Trans. Appl. Supercond. 19, 557

Crosstalk at the focal plane level

- **Thermal crosstalk** is modeled as a **scaled transfer** of part of the event energy to the neighboring pixels. The transferred energy will offset the reconstructed energy of nearby events.
  - The level depends on the pixel-to-pixel **distance**.
  - Implemented values **based on measurements** performed on a demonstrator array [7].

Distance	1st neighbor (249 µm)	Diagonal neighbor (352 µm)	2nd neighbor (498 µm)
Crosstalk fraction	10^{-3}	4×10^{-4}	8×10^{-5}

- **Electrical crosstalk** modeled using *tessim* simulations of the first stage readout circuit. Two types of interaction taken into account: **carrier leakage** and **common impedance**.
  - Effect characterized in **look-up tables** as a function of **pixel frequency, energy and grading**.
  - Preliminary verification measurements indicate that the model is conservative but has the right order of magnitude (see Poster PB-3).

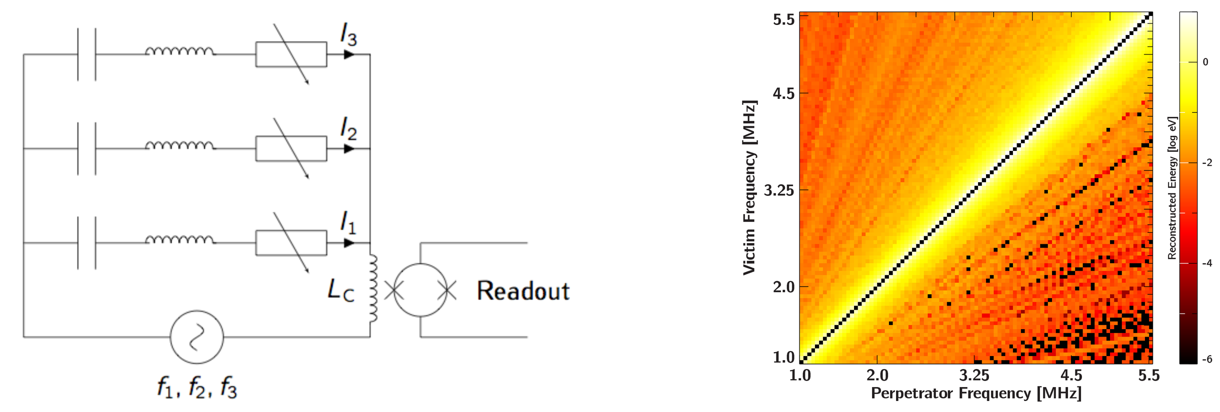

Figure 5: Left: Schematics of the model used for the crosstalk simulations in *tessim*. Right: Slice of the electrical crosstalk look-up table (perpetrator energy equal to 13.8 keV for visibility purposes) used in *xifupipeline* showing the characterization of the frequency dependence of the crosstalk for high resolution events.

- Actual effect on the reconstructed energy of a victim pulse strongly depends on the **time difference** between the perpetrator and victim events due to the use of optimal filters for the energy reconstruction.
  - Key to predict the real effect on the instrument performance.
  - Effect characterized **for all the event grades** (filter lengths) using proper optimal filters.

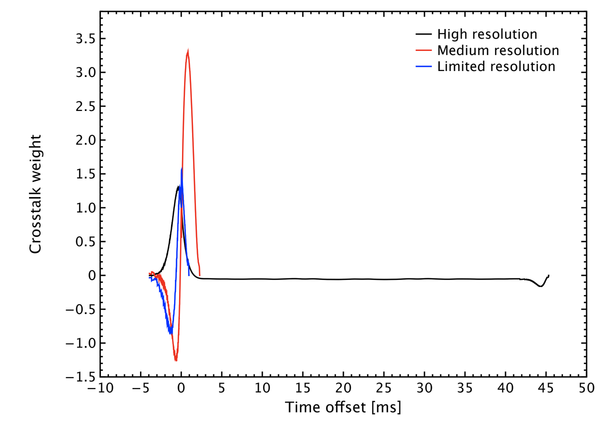

Figure 5: Dependence of the crosstalk level on the difference in arrival time between photons on the victim and perpetrator pixels for different filter lengths.

Performance at high count rates

- All grading and crosstalk effects were characterized and implemented in *xifupipeline*. **Full instrument End-to-End simulations** conducted to estimate the instrument performance under varying configurations.
- Events affected by crosstalk above a certain energy offset limit are first accounted as throughput loss.
  - 0.2 eV for high resolution events (allocation in energy resolution budget).
  - 4 eV for limited resolution events to ensure better than 10 eV final resolution (science need for very bright sources).
  - This assumes an **a priori knowledge** of the crosstalk effect but **no post correction**.

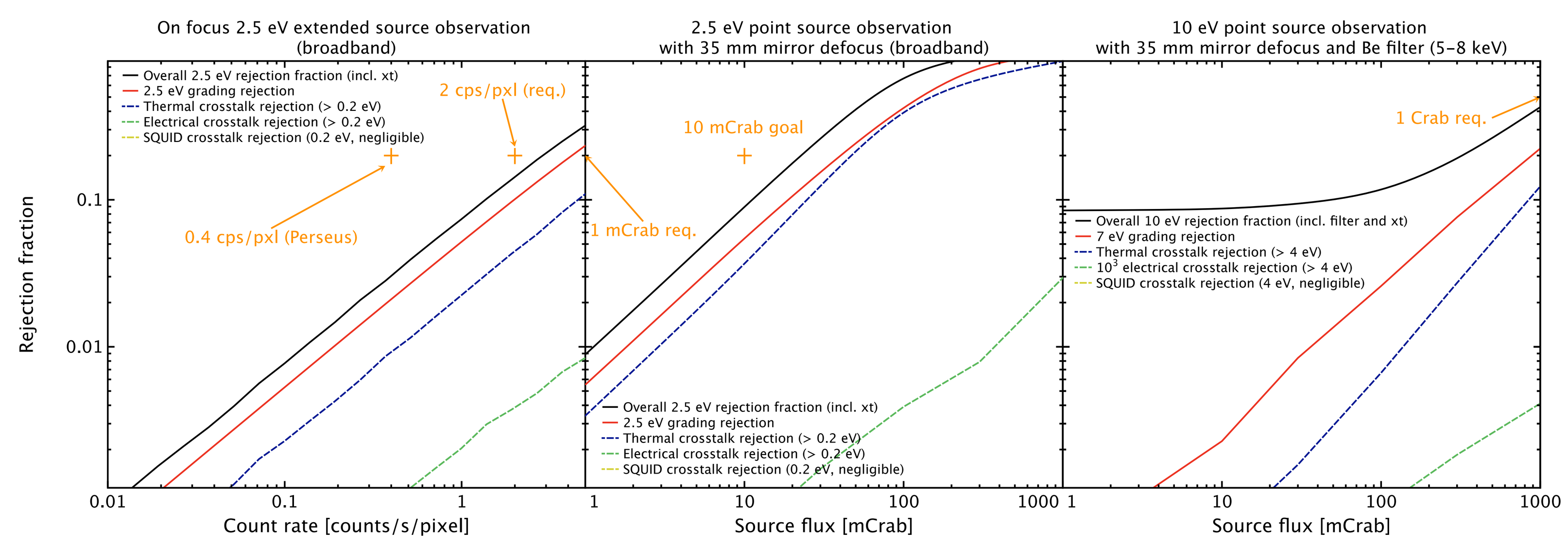

Figure 6: Fraction of events rejected for different types of observations as a function of count rate or source flux. In all cases, the crosstalk due to the front-end SQUID non-linearity was found negligible. Left: High resolution observation of an extended source with a thermal spectrum observed on focus. Middle: High resolution observation for a bright defocused (35 mm) point source with a Crab-like spectrum. Right: ~ 10 eV resolution observation for the same source but with the use of a 100 µm Be filter to only keep the > 3 keV photons for high resolution iron-line spectroscopy at very high count rates.

Brightest X-ray extended sources (2 cts/s/pixel) safely observed on focus. Mirror defocus allows the observation of 20 mCrab sources with 2.5 eV resolution. With a Be filter, 10 eV resolution with > 50 % throughput above 5 keV up to 1 Crab.

- The End-to-End simulator can also be used to see the actual **effect on the energy redistribution** (see Fig. 7).
  - Crosstalk **degrades resolution**, introduces **energy shifts** and **non-gaussianities** depending on cuts used.
  - ~ 5 eV resolution currently predicted at 1 Crab with defocusing and a Be filter.

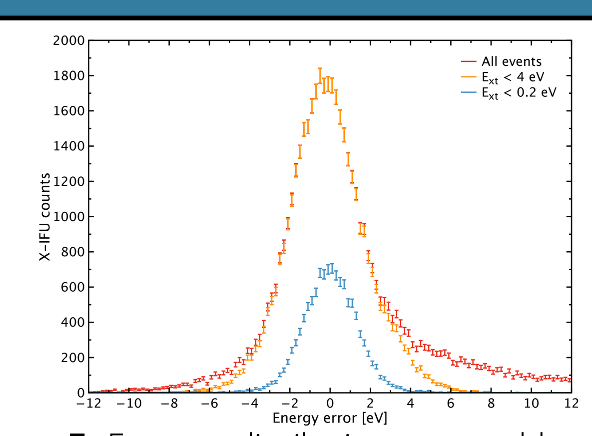

Figure 7: Energy redistribution measured between 5 and 8 keV in a 50 s simulation of a 1 Crab source with 35 mm defocusing and a Be filter.

Detailed diagnostics of the effect of crosstalk at high count rates possible.