Crosstalk in an FDM laboratory set-up and the Athena X-IFU science performance

R. den Hartog[1], C. Kirsch[2], C. de Vries[1], H. Akamatsu[1], T. Dauser[2], P. Peille[3], E. Cucchetti[4], B. Jackson[5], S. Bandler[6], S. Smith[6], J. Wilms[2]

[1] SRON Netherlands Institute for Space Research, Utrecht, The Netherlands
[2] Remeis Observatory, Bamberg and ECAP, Erlangen Centre for Astroparticle Physics, Erlangen, Germany
[3] CNES, Centre National des Etudes Spatiale, Toulouse, France
[4] CNRS, IRAP Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
[5] SRON Netherlands Institute for Space Research, Groningen, The Netherlands
[6] NASA GSFC, Goddard Space Flight Center, Greenbelt, Maryland, USA

The X-ray Integral Field Unit

- One of two instruments on the ESA L2 X-ray mission Athena
- Imaging spectrometer with ~3840 TES's
- Energy range: 0.2 – 12 keV
- Energy resolution: 2.5 eV (FWHM)
- Spatial resolution: ≤ 6 arcsec
- Countrate capability:
  - 1 mCrab (req.), 10 mCrab (goal) with 80% high-resolution throughput
  - 2 cps/pixel for extended sources (req.)
  - 1 Crab with ≤ 10 eV resolution and ≥ 60% throughput (req.)
- Frequency Domain Multiplexed (FDM) readout in 96 channels of ~40 pixels, and carriers in the 1 – 5 MHz frequency range

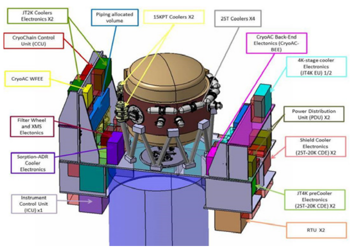

Figure 1. Design impression of the X-IFU instrument

cf. Athena Science Requirements doc., 1.6.0, 14/03/2017

The SIXTE End-to-End simulator

See also Wilms et al., Proc. SPIE 9905-64, 2016

Source model

Athena telescope model

X-IFU instrument model:
- X-IFU focal plane geometry
- TES physics with *TESSIM:*
  - linear *R*(*T*,*I*) plane
  - non-linearity via ETF
  - crosstalk pulses via coupled electrical cricuits
- crosstalk implemented via LUTs in *xifupipeline*
- event-reconstruction, pile-up and grading in *xifupipeline*

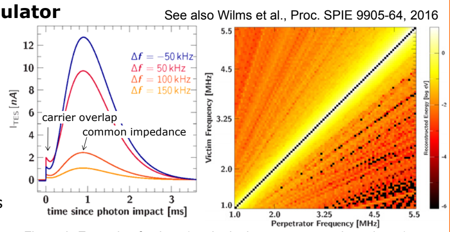

Figure 3. Example of pulses (carrier leakage + common impedance) predicted by TESSIM + electrical model and (a cross section of) a look-up table (LUT) for electrical cross-talk as used in the end-to-end simulations.

Crosstalk: mechanisms

At various points along the read-out chain crosstalk may arise, effectively causing offsets in photon energies measured on pixels due to signals received in neighbors, ultimately degrading the energy resolution of the instrument. Crosstalk is especially harmful for high countrate science cases.

- Defined as offset in inferred energy for one (victim) pixel due to presence of a signals on another (perpetrator) pixel.
- Accounted for by counting events affected above a chosen crosstalk limit as throughput loss
- 4 mechanisms (in blue) implemented in SIXTE E2E simulator

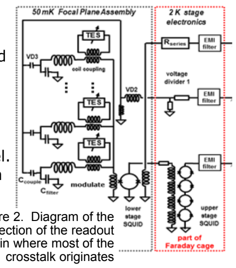

Figure 2. Diagram of the section of the readout chain where most of the crosstalk originates

Table 1. Crosstalk mechanisms

mechanism	dependence	mitigation options	verification status
Thermal leakage (on sensor array)	Interpixel distance on array	Thermalization layer Defocussing	Measured on precursor detectors (Iyamoto et al., IEEE TAS 19, 2009)
Carrier leakage (in TES bias circuit)	$\propto\Delta f^{-2}$; $\propto R^2_{nbr}$; $\propto L_{fltr}^{-2}$ R_{nbr} changes during pulse and scales with (transformer ratio)^2	Increase frequency spacing Δf in bias circuit = - more wires - more DACs	Comparison between measurements and models on recent array
Common impedance (in read-out circuit)	$\propto\Delta f^{-2}$; $\propto L^2_{com}$; $\propto f^2_{carr}$ $\propto L^{-2}_{fltr}$	Lower $L_{com,}$ increase Δf	Modeled
Non-linear amplification (mainly by SQUIDs)	Φ_1 ; Φ_2 ; Δt; Δf per pulse present on input coil	SQUID linearisation = - more GBW in BBFB - more SQUID dyn. range	TBD Computer modeling indicates very low impact
Coupling between parallel r/o circuits	Mutual L and C	Shielding of strategic points in circuit	TBD

Table 2. Summary of crosstalk and throughput for 3 challenging science cases. The throughput depends both on event grading and crosstalk (see poster by P. Peille et al.).

Science case	Source	Count rate	Defocus	Required ΔE (FWHM)	Required Throughput	Crosstalk limit	Percentage of events affected by crosstalk above limit: Thermal	Electrical	Non-linear	Sum	Throughput incl. pile-up
Cas A SNR	extended	2 cps / pixel	0 mm	2.5 eV	80% (high res.)	> 0.2 eV	4.3%	0.4%	< 0.01%	4.5%	85% (high res.)
GRB / WHIM	point	10 mCrab	25 mm	2.5 eV	80% (high res.)	> 0.2 eV	7.4%	< 0.01%	< 0.01%	7.4%	83% (high res.)
Galactic BH	point	1 Crab	25 mm	< 10 eV	50% (5 – 8 keV)	> 4 eV	34.6%	3.5%	0.03%	34.5%	6.3% (5 – 8 keV)
Galactic BH	point	1 Crab	35 mm + Be filter	< 10 eV	50% (5 – 8 keV)	> 4 eV	12.3%	< 0.01%	< 0.01%	12.3%	57% (5 – 8 keV)

Comparison between model and data

- Based on 6 multiplexed pixels from GSFC A2 array, illuminated by Fe^{55}
- Each event triggers readout of all pixels.
- Method to bring crosstalk pulses out of the noise:
  - Stack ~1000 pulses on top of each other, I and Q separately
  - Remove baselines separately (otherwise dominated by I)
  - Remove phase information as our main interest for now is a verification of the amplitude of the crosstalk effects.
  - Each victim is optimally filtered with its 'main' pulse shape

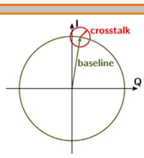

Figure 4. Spinor representation of a crosstalk signal superimposed on the baseline.

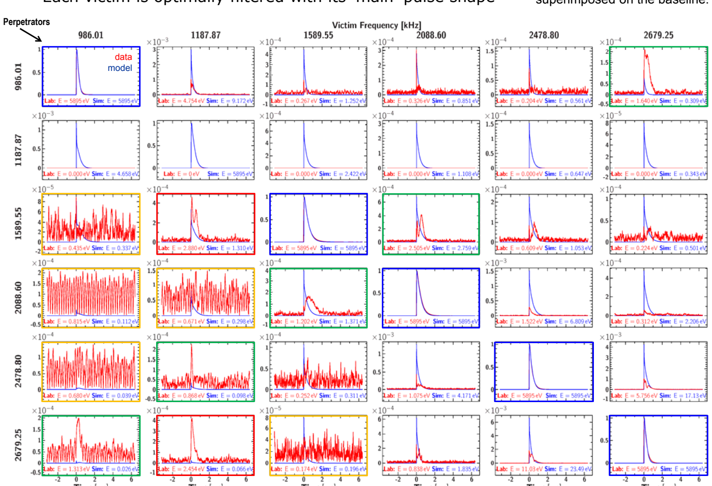

Figure 5. Comparison of average measured pulses (red curves) and pulses modeled with TESSIM and a coupled circuit model (blue curves); no fitting of parameters took place. The vertical scale is relative to the pulse height on the average main event, when the pixel acts as perpetrator. Panels with a blue cadre contain the perpetrator pulse, a red cadre indicates measured crosstalk in excess of the model that is not understood, and in the panels with a green cadre the measured excess crosstalk can be understood as a combination of thermal and electrical crosstalk. An orange cadre indicates that the data is ignored due to excessive noise or interference. The pulses on pixel 1 (on which trigger was not properly set) is set equal to the average pulse on pixel 4, which has very similar device properties.

Conclusions and remaining open issues

Conclusions from the E2E simulations (Table 2):
- Current crosstalk levels are compatible with the resolution and throughput requirements for three of the most stringent science cases.
- If confirmed by experiment, a higher multiplexing factor, a larger setpoint resistance, or smaller frequency range become easier to implement.

Conclusions from the comparison in Figure 5:
- A first attempt was made at a comparison between measured crosstalk data and a detailed electrical model.
- Based on estimated or measured pixel and circuit parameters the shape of the main pulses was accurately reproduced by the models.
- For nearest frequency neighbors – where the electrical crosstalk is expected to be strongest – the model *overestimates* the measured levels by a factor 2 – 4.
- Beyond the first τ modeled and measured crosstalk pulses often fall on top of each other.

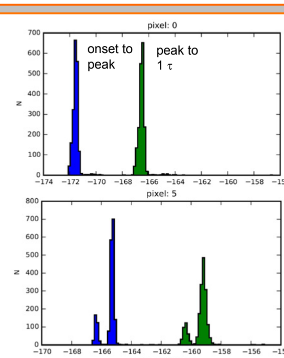

Figure 6. The rotation of phase during a pulse, between the onset and the peak current, and between the peak and the 1 tau moment, is stable to within 1 degree.

Open issues:
- The common impedance in the circuit, one of the main parameters, was not accurately known. It was estimated to be in the range of 1 – 4 nH.
- Due to the high transformer ratio (*TR* = 8) used, the measured crosstalk was also not very sensitive to common impedance at the expected level (independent of *TR*). Carrier leakage crosstalk dominates, as it scales as $R_1^2 \propto TR^4$, where R_1 is the resistance of the perpetrator pixel in the LC circuit.
- A satisfying explanation for the difference in crosstalk pulse shapes and levels between data and models has not yet been found:
  - Pulse-to-pulse variations in the phase changes during the first ~τ can be excluded: the pulse-to-pulse stability at the same moment during the pulse is stable to within ~1° (see Figure 6).
  - The weak link affects the carrier leakage current differently than the resistive part of the TES impedance, but the modeling of the weak link effects falls presently outside the scope of the crosstalk model.

Next steps:
- Repetition of this measurement with lower *TR*, better characterized common impedance, and proper care is taken to separate electrical and thermal crosstalk in frequency space.
- Implement the weak link effect in victim and perpetrator pixels in the crosstalk model.