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. Dauzer\(^2\), P. Peille\(^3\), E. Cucchielli\(^4\), B. Jackson\(^5\), S. Bandler\(^6\), S. Smith\(^6\), J. Wilms\(^2\)

\(^1\)SRON Netherlands Institute for Space Research, Utrecht, The Netherlands
\(^2\)Remoive Observatory, Bamberg and ECAP, Erlangen Centre for Astroparticle Physics, Erlangen, Germany
\(^3\)CNES, Centre National des Etudes Spatiales, 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 \(\sim3840\) TES's
- Energy range: 0.2 – 12 keV
- Energy resolution: 2.5 eV (FWHM)
- Spatial resolution: \(\sim6\) arcsec
- Countrate capability:
  - 1 mCrab (req.), 10 mCrab (goal) with 80% high-resolution throughput
  - 2 cps/pixel for extended sources (req.)
  - 1 Crab with \(\sim10\) eV resolution and \(\geq 60\%\) throughput (req.)
- Frequency Domain Multiplexed (FDM)
  - 96 channels of \(\sim40\) pixels, and carriers in the 1 – 5 MHz frequency range

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 signal 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

Table 1. Crosstalk mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Dependence</th>
<th>Mitigation Options</th>
<th>Verification Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal leakage on sensor array</td>
<td>Interpixel distance on array</td>
<td>Thermatization layer Defocussing</td>
<td>Measured on precursor detectors (Yamamoto et al., IEEE TAS 19, 2009)</td>
</tr>
<tr>
<td>Carrier leakage in TES bias circuit</td>
<td>Increase frequency spacing of bias circuit, more wires, more DACs</td>
<td>Comparison between measurements and models on recent array</td>
<td></td>
</tr>
<tr>
<td>Common impedance in read-out circuit</td>
<td>Lower Leakage, increase offset</td>
<td>SQUID Landauer noise, more SQUID in dynamic range</td>
<td></td>
</tr>
<tr>
<td>Non-linear amplification (mainly by SQUIDs)</td>
<td></td>
<td>TTB</td>
<td></td>
</tr>
</tbody>
</table>

Coupling between parallel IO circuits | Mutual L and C | Shielding of strategic points in circuit | TTB |

The SIXTE End-to-End simulator

Source model
- Athena telescope model
- X-IFU instrument model:
  - X-IFU focal plane geometry
  - TES physics with TESSIM:
    - linear RLC circuit
    - non-linearity via ETF
crosstalk implemented via LUTs in xpspipeline
- Event-reconstruction, pile-up and grading in xpspipeline

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.).

<table>
<thead>
<tr>
<th>Science case</th>
<th>Source</th>
<th>Count rate</th>
<th>Defocus</th>
<th>Required at FWHM</th>
<th>Required Throughput</th>
<th>Crosstalk limit</th>
<th>Percent of events affected by crosstalk above limit</th>
<th>Throughput incl. pile-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas A SNR</td>
<td>extended 2 cps/pixel</td>
<td>0 mm</td>
<td>2.5 eV</td>
<td>80% (high res.)</td>
<td>(&gt;0.2) eV</td>
<td>4.3%</td>
<td>0.4% (&gt;0.01)</td>
<td>4.5%</td>
</tr>
<tr>
<td>Crab/WHIM</td>
<td>point</td>
<td>10 mCrab</td>
<td>25 mm</td>
<td>2.5 eV</td>
<td>80% (high res.)</td>
<td>(&gt;0.2) eV</td>
<td>7.4%</td>
<td>0.01% (&gt;0.74)</td>
</tr>
<tr>
<td>Galactic BH</td>
<td>point</td>
<td>1 Crab</td>
<td>35 mm + Be filter</td>
<td>(&lt;10) eV</td>
<td>50% (5 – 8 keV)</td>
<td>(&gt;4) eV</td>
<td>12.3%</td>
<td>(&lt;0.01) (&gt;0.12)</td>
</tr>
</tbody>
</table>

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 ± modeled and measured crosstalk pulses often fall on top of each other.

Open issues:
- The common impendence in the circuit, one of the main parameters, was not accurately measured. It was estimated to be in the range of 1 – 4 mH.
- 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 \(TR^2\).
- Carrer leakage crosstalk originates 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 \(>>\) can be excluded: the pulse-to-pulse stability at the same moment during the pulse is stable to within \(1\) degree.
  - 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.