TES-Simulations

Jörn Wilms (FAU), P. Peille (IRAP), M. Ceballos (IFCA), T. Brand (ECAP), T. Dauser (ECAP), S.J. Smith (GSFC), B. Cobo (IFCA), S. Bandler (GSFC), R. den Hartog (SRON), J. de Plaa (SRON), E. Pointecouteau (IRAP), D. Barret (IRAP)
X-IFU photon detection process:

- sensitivity described by effective area curves
  (taking into account mirror reflectivity, pixel sensitivity, gaps)

- Two (input/output-compatible) simulation approaches
  - \texttt{xifupipeline}:
    - full imaging implemented
    - fast detection simulation using response matrices
    \implies \text{Well suited for faint sources}
  - \texttt{tessim/sirena}
    - Simulation of TES physics and pulse reconstruction
    - Slower than \texttt{xifupipeline}, but much better physics
    \implies \text{Well suited for bright sources}
    \implies \text{Well suited for engineering studies}

Will soon be able to easily switch simulation between both
Device Simulations: Principle

Calorimeter: measure temperature change in device with temperature $T_0$ connected to heat bath with temperature $T_S$.

Joule heating by current through device $\implies T_0 > T_S$

Absorption: temperature rises: $\Delta T = E_\gamma / C$

$C$: heat capacity

Relaxes back to $T_0$. Typical timescale: $\tau = C/G$.

Resolution given by thermal fluctuations: $\Delta E = 2.35 \sqrt{kT^2C}$

$\implies$ Small (few eV) for $T$ small (mK)
**Device Simulations: Principle**

Negative electrothermal feedback: Operate circuit at Transition Edge between superconduction and normal conduction, voltage bias circuit:

- Absorption $\Rightarrow R \uparrow$
- $\Rightarrow$ Joule power $P_J = I^2 R \downarrow$
- $\Rightarrow$ Faster cooling than for $R = \text{const}$

Typical time constants $75 \mu s \ldots 400 \mu s$

Kinnunen (2011, PhD Jyväskylä)
SLA pulse shapes for 0.1, 1, 2, 3, 5, 10 keV, normalized to top: equal area, bottom: peak current.

- based on GSFC code by S.J. Smith
- numerical solution of differential equations for $T(t), I(t)$ (e.g., Irwin & Hilton, 2005),

$$C \frac{dT}{dt} = -P_b + P_J + P + \text{Noise}$$

$$L \frac{dl}{dt} = V - IR_L - IR(T, I) + \text{Noise}$$

- linear resistance model, $R(T, I; \alpha, \beta)$
- noise treatment: Johnson of circuit, bath, excess noise
- input parameters: $C, G_b, n, \alpha, \beta, m, R_0, T_0, T_b, L_{crit}$

including flexible, FITS-based library of pixel types
SLA pulse shapes for 0.1, 1, 2, 3, 5, 10 keV, normalized to top: equal area, bottom: peak current.

- input parameters: $C$, $G_b$, $n$, $\alpha$, $\beta$, $m$, $R_0$, $T_0$, $T_b$, $L_{crit}$
- including flexible, FITS-based library of pixel types
Tessim

• based on GSFC code by S.J. Smith

Noise terms:

• Johnson noise in the TES
• Johnson noise in the load resistor
• Thermal fluctuation noise
• Excess noise

see Irwin & Hilton (2005) for details

requires special care in numerical integrator

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including flexible, FITS-based library of pixel types
<table>
<thead>
<tr>
<th>Parameter</th>
<th>IXO baseline</th>
<th>DM</th>
<th>LPA</th>
<th>SPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>249 μm</td>
<td>249 μm</td>
<td>249 - 300 μm</td>
<td>75 - 110 μm</td>
</tr>
<tr>
<td>Heat capacity, C @ T&lt;sub&gt;0&lt;/sub&gt;</td>
<td>0.8 pJ/K</td>
<td>0.8 pJ/K</td>
<td>0.8 pJ/K</td>
<td>0.26 pJ/K</td>
</tr>
<tr>
<td>Bath conductance, G&lt;sub&gt;b&lt;/sub&gt; @ T&lt;sub&gt;0&lt;/sub&gt;</td>
<td>200 pW/K</td>
<td>115 pW/K</td>
<td>57 pW/K</td>
<td>300 pW/K</td>
</tr>
<tr>
<td>Temperature exponent, n</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>α</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>β</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>10</td>
</tr>
<tr>
<td>Unexplained noise factor, M</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Resistance, R&lt;sub&gt;0&lt;/sub&gt;</td>
<td>1 mΩ</td>
<td>1 mΩ</td>
<td>1 mΩ</td>
<td>1.1 mΩ</td>
</tr>
<tr>
<td>Current, I&lt;sub&gt;0&lt;/sub&gt;</td>
<td>69.5 μA</td>
<td>52.5 μA</td>
<td>37.1 μA</td>
<td>73.5 μA</td>
</tr>
<tr>
<td>Temperature, T&lt;sub&gt;0&lt;/sub&gt;</td>
<td>90 mK</td>
<td>90 mK</td>
<td>90 mK</td>
<td>90 mK</td>
</tr>
<tr>
<td>Power, P&lt;sub&gt;0&lt;/sub&gt;</td>
<td>4.81 pW</td>
<td>2.76 pW</td>
<td>1.38 pW</td>
<td>5.95 pW</td>
</tr>
<tr>
<td>R&lt;sub&gt;shunt&lt;/sub&gt; *</td>
<td>49 μΩ</td>
<td>90 μΩ</td>
<td>207 μΩ</td>
<td>91 μΩ</td>
</tr>
<tr>
<td>Transformer Turns Ratio *</td>
<td>5.53</td>
<td>4.08</td>
<td>2.69</td>
<td>4.05</td>
</tr>
<tr>
<td>L&lt;sub&gt;crit&lt;/sub&gt;</td>
<td>66 nH</td>
<td>120 nH</td>
<td>276 nH</td>
<td>122 nH</td>
</tr>
<tr>
<td>τ&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>431 μs</td>
<td>0.795 ms</td>
<td>1.87 ms</td>
<td>305 μs</td>
</tr>
<tr>
<td>τ&lt;sub&gt;crit&lt;/sub&gt;</td>
<td>156 μs</td>
<td>286 μs</td>
<td>649 μs</td>
<td>78 μs</td>
</tr>
<tr>
<td>Time constraint for 80% high res.</td>
<td>8.6 ms</td>
<td>112 ms</td>
<td>112 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td>ΔE&lt;sub&gt;FWHM&lt;/sub&gt; (∞ rec length, small signal)</td>
<td>1.69 eV</td>
<td>1.70 eV</td>
<td>1.73 eV</td>
<td>1.54 eV</td>
</tr>
<tr>
<td>ΔE&lt;sub&gt;FWHM&lt;/sub&gt; (high res, small signal)</td>
<td>1.83 eV</td>
<td>1.71 eV</td>
<td>1.76 eV</td>
<td>1.69 eV</td>
</tr>
<tr>
<td>Max slew rate / keV</td>
<td>88 mA/s/keV</td>
<td>36 mA/s/keV</td>
<td>11 mA/s/keV</td>
<td>229 mA/s/keV</td>
</tr>
<tr>
<td>f&lt;sub&gt;eff&lt;/sub&gt; - effective / information bandwidth</td>
<td>970 Hz</td>
<td>560 Hz</td>
<td>280 Hz</td>
<td>1710 Hz</td>
</tr>
</tbody>
</table>

Source: Steve Smith, GSFC, 29-05-2015

* Assumes 1.5 mΩ parasitic from capacitive element, and filter L = 2 μH, T<sub>shunt</sub> = 70mK
Translation to program: (too) many parameters ;-)

Parameters for /home/wilms/pfiles/tessim.par

PixType = SPA  Pixel type
PixID = 1  Number of pixel
PixImpList = test_slow.fits  File name of pixel impact list
Streamfile = stream.fits  File name of output FITS stream
(tstart = 0.)  Start time of simulation [s]
(tstop = 1.)  Stop time of simulation [s]
(sample_rate = 156.25e3)  Sample rate [Hz]
(acbias = y)  AC biased (yes) or DC biased (no)
(T_start = 90.0)  Initial operating temperature [mK]
(Ce = 0.26)  Heat capacity [pJ/K]
(Gb = 300)  Bath conductance [pW/K]
(n = 4.0)  Temperature exponent
(alpha = 100.)  TES sensitivity alpha (T/R*R/dR/dT)
(beta = 10.)  TES current dependence beta (I/R*R/dR/dI)
(m_excess = 0.8)  Magnitude of unexplained (excess) noise
(R0 = 1.1)  Operating point resistance R0 [mOhm]
(I0 = 72.5)  Current [mA]
(Tb = 55)  Heat sink/bath temperature Tb [mK]
(RL = 0.0)  Shunt/load resistor value RL [mOhm]
(Rparasitic = 0.)  Parasitic resistor value Rparasitic [mOhm]
(TTR = 4.11)  Transformer Turns Ratio
(Lin = 238.)  Circuit inductance [nH]
(Lfilter = 2.)  Filter inductance [muH]
(V0 = -1.)  Effective voltage bias [muV]
(imin = -1e-8)  TES current corresponding to 0 ADU [A]
(imax = 5e-5)  TES current corresponding to 65534 ADU [A]
(simnoise = y)  Simulate noise?
triggertype = stream  Trigger type
(triggersize = 1024)  Size of a trigger
(prebuffer = 128)  Size of the prebuffer
(propertiesonly = n)  Display properties of TES and exit without calculation?
(Seed = 0)  Seed for the noise RNG (0 to use system time)
(progressbar = y)  Display progress bar?
(clobber = y)  Overwrite output files?
Configuration control

Solution to large number of parameter problem:
self documentation $\implies$ store all parameters in FITS files output by `tessim`: can reload exact pixel configuration from any stream produced by `tessim`:

First run `tessim` with `propertiesonly=yes`:

```
tessim PixType=LPA1 Ce=0.26 Gb=280 ... propertiesonly=yes
    ... Streamfile=testpixel.fits
```

Later run with

```
tessim PixType=file:testpixel.fits[LPA1]
    Streamfile=simulation PixImpList=impact.fits
```

where ... `[LPA1]`: FITS selection syntax on FITS HDUNAME keyword.

`impact.fits`

`: FITS impact file with TIME and ENERGY columns.`
Iterative Event Detection (Triggering):

- Take derivative of TES stream
  
  \[ \text{trigger} = \]
  
  - stream
  
  - movavg:npts:threshold:suppress
  
  - diff:npts:threshold:suppress

- remove pulses on the go to find others
Iterative Event Detection (Triggering):

- Take derivative of TES stream
  \[ \text{trigger=} \]
  - stream
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  - diff:npts:threshold:suppress

- remove pulses on the go to find others
Event Grading: Resolution depends on distance between different pulses.
Energy calculation: Use optimal filter (Szymkowiak et al., 1993):

$$E \propto \sum \frac{D(f)S^*(f)}{N(f)}$$

where

- $D(f)$: data spectrum,
- $S(f)$: template spectrum,
- $N(f)$: noise spectrum

Caveats:
- exact degradation at higher energies not yet studied for time reasons
- reconstruction algorithms still in development and under optimization, have done first studies using principle component analysis and resistance space optimal filtering