TES-Simulations

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X-IFU

X-ray Integral Field Unit

X-IFU photon detection process:

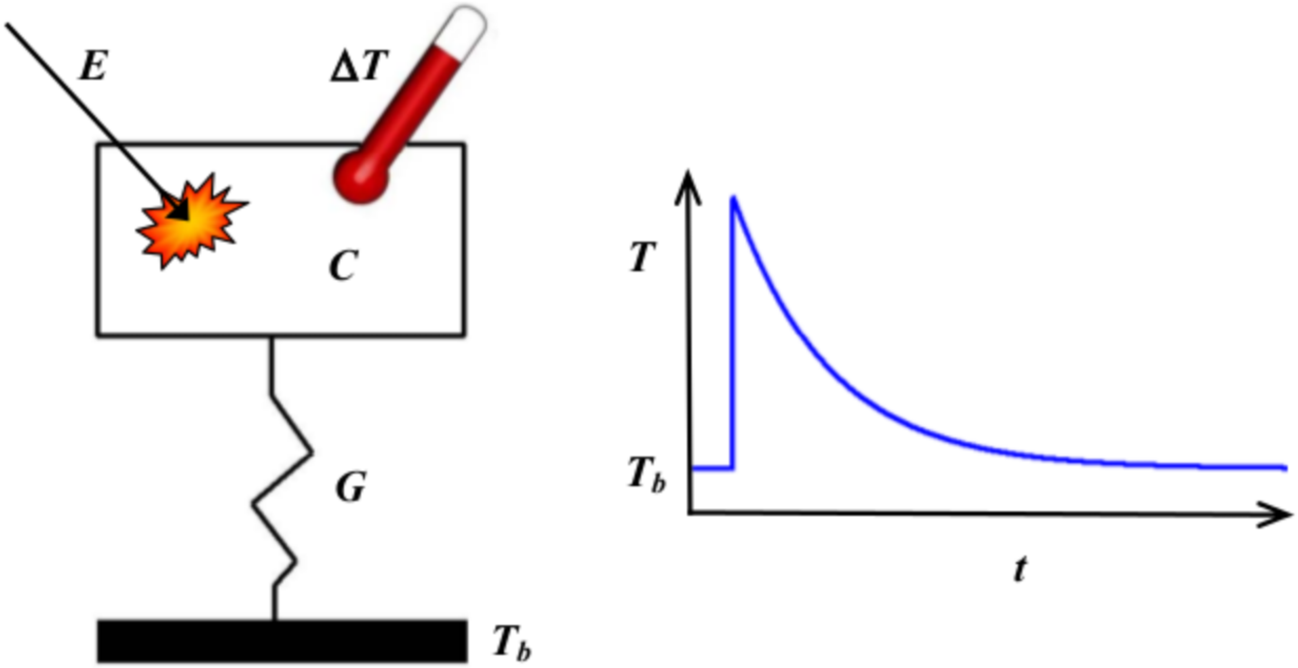
- sensitivity described by effective area curves
  (taking into account mirror reflectivity, pixel sensitivity, gaps)
- Two (input/output-compatible) simulation approaches
  - `xifupipeline`:
    * full imaging implemented
    * fast detection simulation using response matrices

    $\Longrightarrow$ Well suited for faint sources
  - `tessim/sirena`
    * Simulation of TES physics and pulse reconstruction
    * Slower than `xifupipeline`, but much better physics

    $\Longrightarrow$ Well suited for bright sources

    $\Longrightarrow$ Well suited for engineering studies

Device Simulations: Principle



Smith (2006 PhD Leicester)

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

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

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

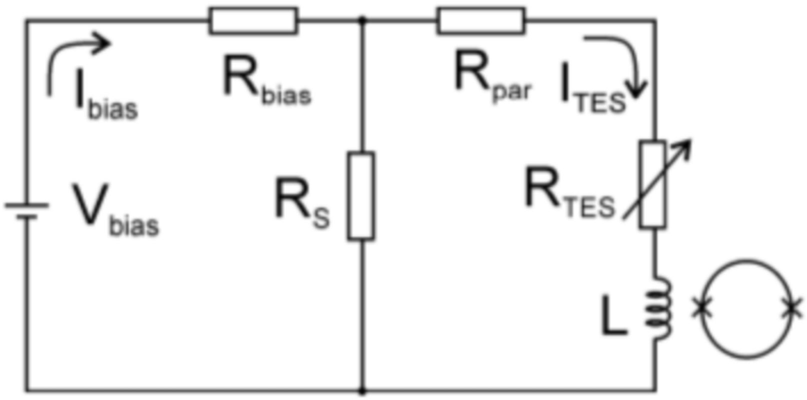
C: heat capacity

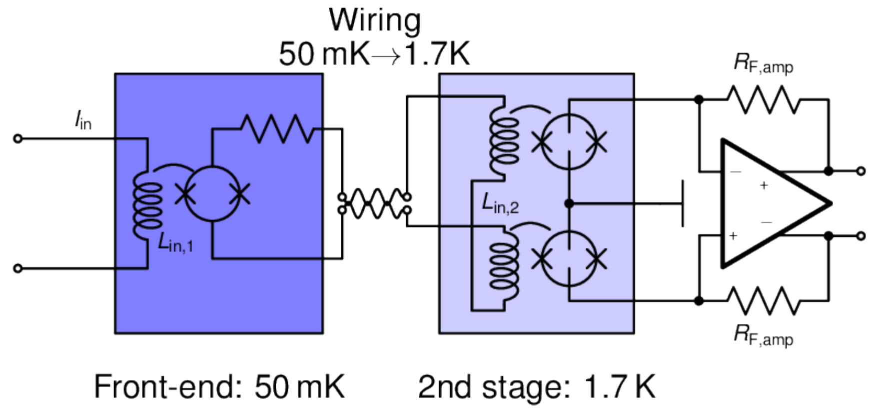
Relaxes back to T_0. Typical timescale: $\tau = C/G$.

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

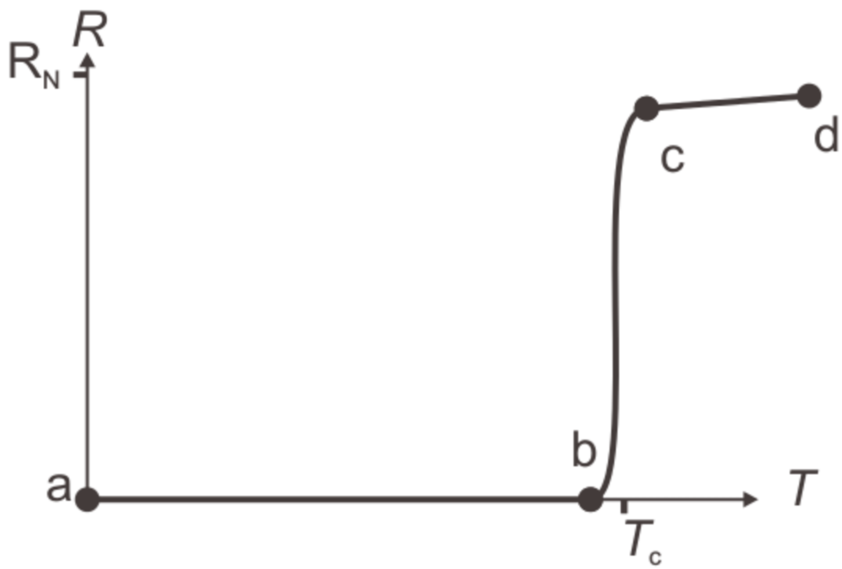
$\Longrightarrow$ Small (few eV) for T small (mK)

Device Simulations: Principle





Kinnunen (2011, PhD Jyväskylä)



negative electrotermal feedback: Operate circuit at Transition Edge between superconduction and normal conduction,

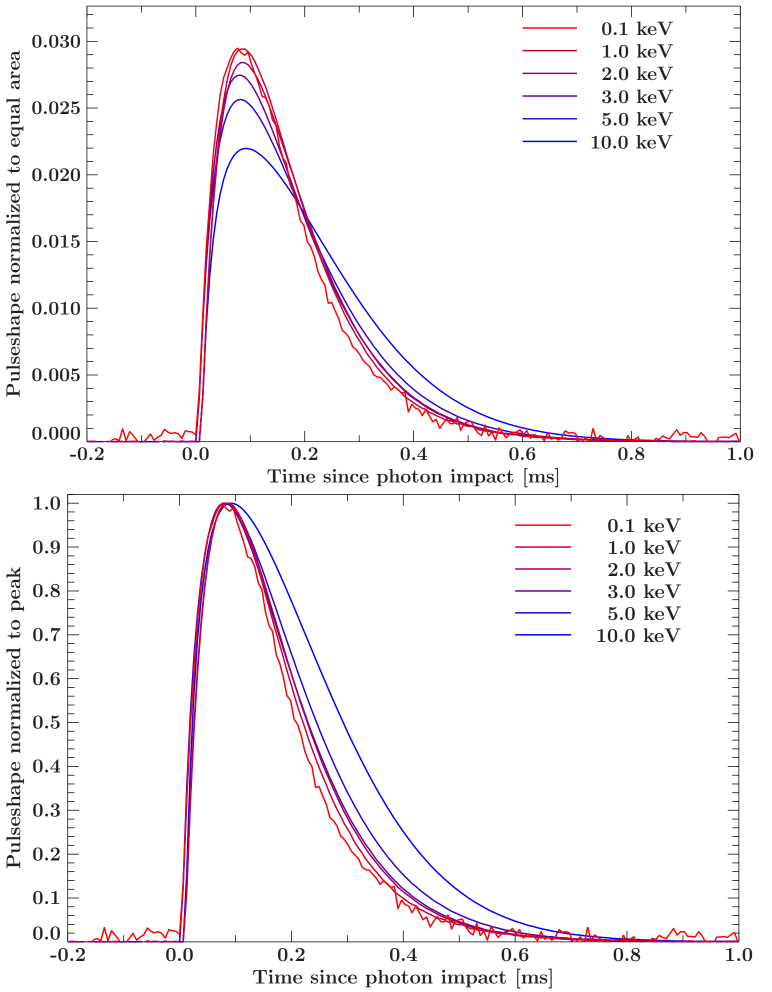
voltage bias circuit:

absorption $\Longrightarrow R \nearrow$

$\Longrightarrow$ Joule power $P_J = I^2 R \searrow$

$\Longrightarrow$ faster cooling than for $R = \text{const}$

Typical time constants 75 μs. . . 400 μs



Typical pulse shapes for 0.1, 1, 2, 3, 5, 10 keV, normalized to top: equal area, bottom: peak current.

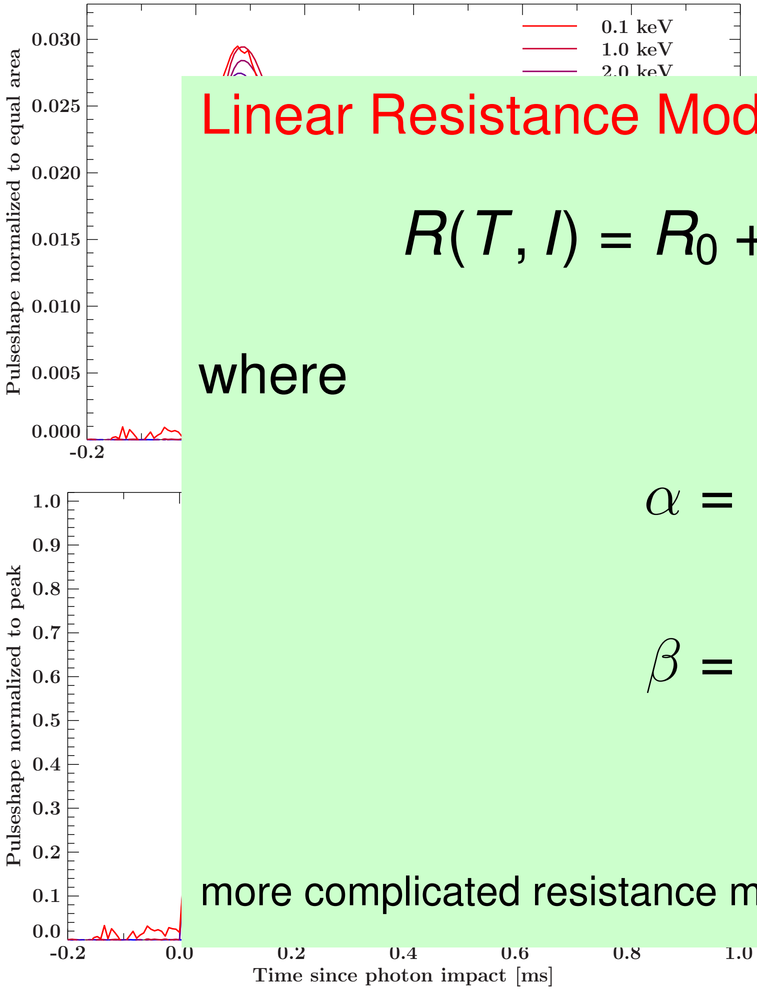
- based on GSFC code by S.J. Smith
- numerical solution of differential equations for $T(t)$, $I(t)$ (e.g., Irwin & Hilton, 2005),

$$C\frac{dT}{dt} = -P_{\mathrm{b}} + P_{\mathrm{J}} + P + \mathrm{Noise}$$

$$L\frac{dI}{dt} = V - IR_{\mathrm{L}} - IR(T, I) + \mathrm{Noise}$$

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

including flexible, FITS-based library of pixel types



Linear Resistance Model:

$$R(T,I) = R_0 + \left.\frac{\partial R}{\partial T}\right|_{I_0} (T - T_0) + \left.\frac{\partial R}{\partial I}\right|_{T_0} (I - I_0) \qquad (1)$$

where

$$\alpha = \left.\frac{\partial \log R}{\partial \log T}\right|_{I_0} = \frac{T_0}{R_0} \left.\frac{\partial R}{\partial T}\right|_{I_0} \qquad (2)$$

$$\beta = \left.\frac{\partial \log R}{\partial \log I}\right|_{T_0} = \frac{I_0}{R_0} \left.\frac{\partial R}{\partial I}\right|_{T_0} \qquad (3)$$

more complicated resistance models also exist (“cross talk”)

...th
...qua-
...lton,

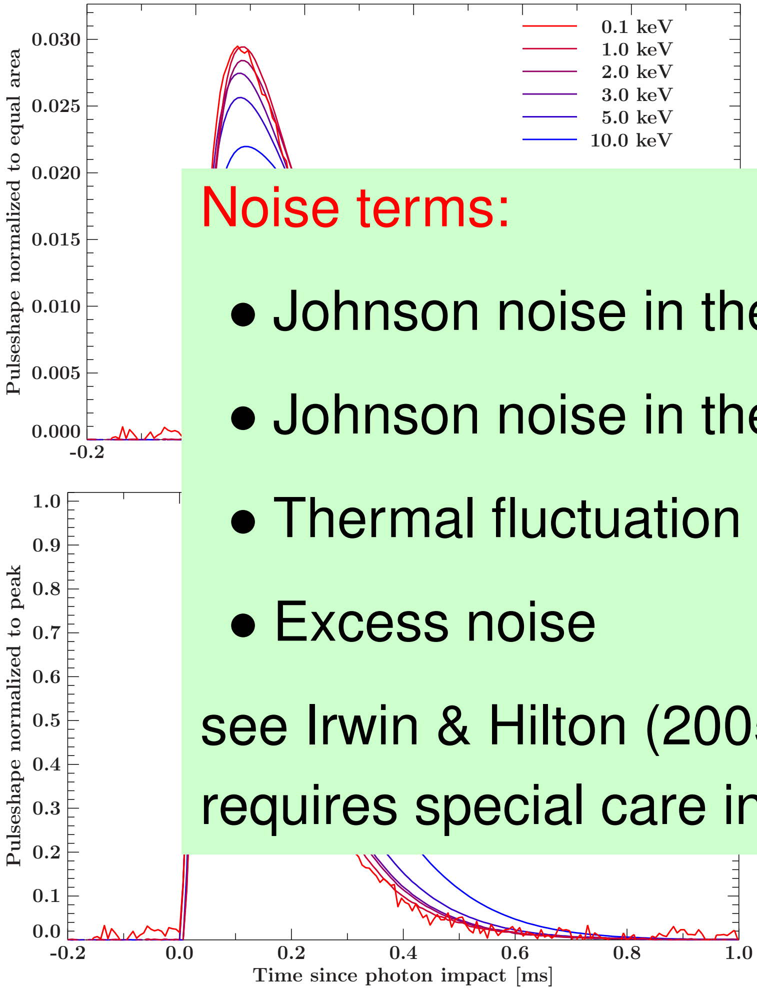
...Noise

..., β)
...t, bath,

- input parameters: C, G_b, n, α, β, m, R_0, T_0, T_b, L_{crit}

including flexible, FITS-based library of pixel types

Typical pulse shapes for 0.1, 1, 2, 3, 5, 10 keV, normalized to top: equal area, bottom: peak current.



Typical pulse shapes for 0.1, 1, 2, 3, 5, 10 keV, normalized to top: equal area, bottom: peak current.

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

- based on GSFC code by S.J. Smith
- … qua- … lton,
- … Noise
- … , β)
- noise treatment: Johnson of circuit, bath, excess noise
- input parameters: C, G_b, n, α, β, m, R_0, T_0, T_b, L_{crit}

including flexible, FITS-based library of pixel types

Parameter	IXO baseline	DM	LPA	SPA
Pixel size	249 µm	249 µm	249 - 300 µm	75 - 110 µm
Heat capacity, C @ T_0	0.8 pJ/K	0.8 pJ/K	0.8 pJ/K	0.26 pJ/K
Bath conductance, G_b @ T_0	200 pW/K	115 pW/K	57 pW/K	300 pW/K
Temperature exponent, n	3.0	3.0	3.0	4.0
α	75	75	75	100
β	1.25	1.25	1.25	10
Unexplained noise factor, M	0	0	0	0.8
Resistance, R_0	1 mΩ	1 mΩ	1 mΩ	1.1 mΩ
Current, I_0	69.5 µA	52.5 µA	37.1 µA	73.5 µA
Temperature, T_0	90 mK	90 mK	90 mK	90 mK
Power, P_0	4.81 pW	2.76 pW	1.38 pW	5.95 pW
R_{shunt} *	49 µΩ	90 µΩ	207 µΩ	91 µΩ
Transformer Turns Ratio *	5.53	4.08	2.69	4.05
L_{crit}	66 nH	120 nH	276 nH	122 nH
τ_{etf}	431 µs	0.795 ms	1.87 ms	305 µs
τ_{crit}	156 µs	286 µs	649 µs	78 µs
Time constraint for 80% high res.	8.6 ms	112 ms	112 ms	4 ms
ΔE_{FWHM} (∞ rec length, small signal)	1.69 eV	1.70 eV	1.73 eV	1.54 eV
ΔE_{FWHM} (high res, small signal)	1.83 eV	1.71 eV	1.76 eV	1.69 eV
Max slew rate / keV	88 mA/s/keV	36 mA/s/keV	11 mA/s/keV	229 mA/s/keV
f_{eff} – effective / information bandwidth	970 Hz	560 Hz	280 Hz	1710 Hz

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

*** Assumes 1.5 mΩ parasitic from capacitive element, and filter L = 2 µH, T_{shunt} = 70mK**

Parameter	IXO baseline	DM	LPA	SPA
Pixel size	249 µm	249 µm	249 - 300 µm	75 - 110 µm
Heat capacity, C @ T_0	0.8 pJ/K	0.8 pJ/K	0.8 pJ/K	0.26 pJ/K
Bath conductance, G_b @ T_0	200 pW/K	115 pW/K	57 pW/K	300 pW/K
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α	75	75	75	100
β	1.25	1.25	1.25	10
Unexplained noise factor, M	0	0	0	0.8
Resistance, R_0	1 mΩ	1 mΩ	1 mΩ	1.1 mΩ
Current, I_0	[illegible]	[illegible]	37.1 µA	73.5 µA
Temperature, T_0	[illegible]	[illegible]	90 mK	90 mK
Power, P_0	[illegible]	[illegible]	1.38 pW	5.95 pW
R_{shunt} *	[illegible]	[illegible]	207 µΩ	91 µΩ
Transformer Turns Ratio *	[illegible]	[illegible]	2.69	4.05
L_{crit}	[illegible]	[illegible]	276 nH	122 nH
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Note: Parameters are outdated!

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

*** Assumes 1.5 mΩ parasitic from capacitive element, and filter L = 2 µH, T_{shunt} = 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*dR/dT)
        (beta = 10.)              TES current dependence beta (I/R*dR/dI)
    (m_excess = 0.8)              Magnitude of unexplained (excess) noise
          (R0 = 1.1)              Operating point resistance R0 [mOhm]
          (I0 = 72.5)             Current [muA]
          (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]
 (thermalBias = n)                Calculate I0 and V0 from thermal power balance?
       (Pload = 0.0)              Residual optical load power [pW]
        (bias = 15)               Bias percentage of normal resistence in the transition
        (imin = -1e-8)            TES current corresponding to 0 ADU [A]
        (imax = 5e-5)             TES current corresponding to 65534 ADU [A]
    (simnoise = y)                Simulate noise?
(stochastic_integrator = n)                Use the stochastich integrator? (default no)
    (twofluid = n)                Option to use the 2 fluid model of RTI transition (default no)
   (frame_hit = n)                Option to use frame hits (default no). Requires time of event and file name
(frame_hit_time = 0.)               Time of frame event (s)
(frame_hit_file = none)             File name of frame hit model
  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?
 (doCrosstalk = y)                Simulate Crosstalk (yes/no)?
 (readoutMode = total)            Readout mode for output current ['total': Absolute value, 'I': I-channel, 'Q':Q-channel]
```

Configuration control

Solution to large number of parameter problem:

self documentation $\Longrightarrow$ 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=LPA Ce=0.26 Gb=280 ...  propertiesonly=yes
          ...  Streamfile=testpixel.fits
```

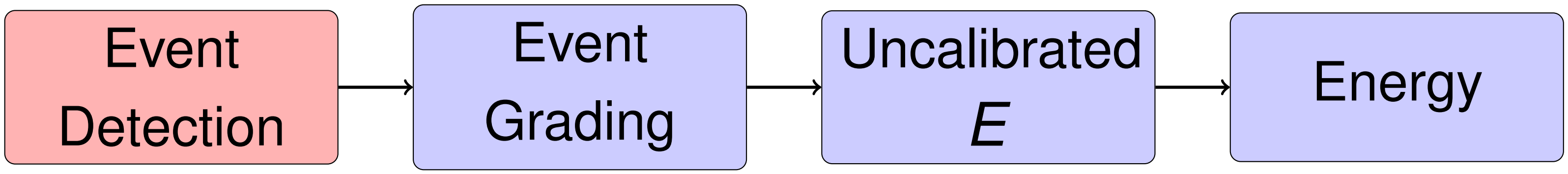
Later run with

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

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

impact.fits

: FITS impact file with `TIME` and `ENERGY` columns.



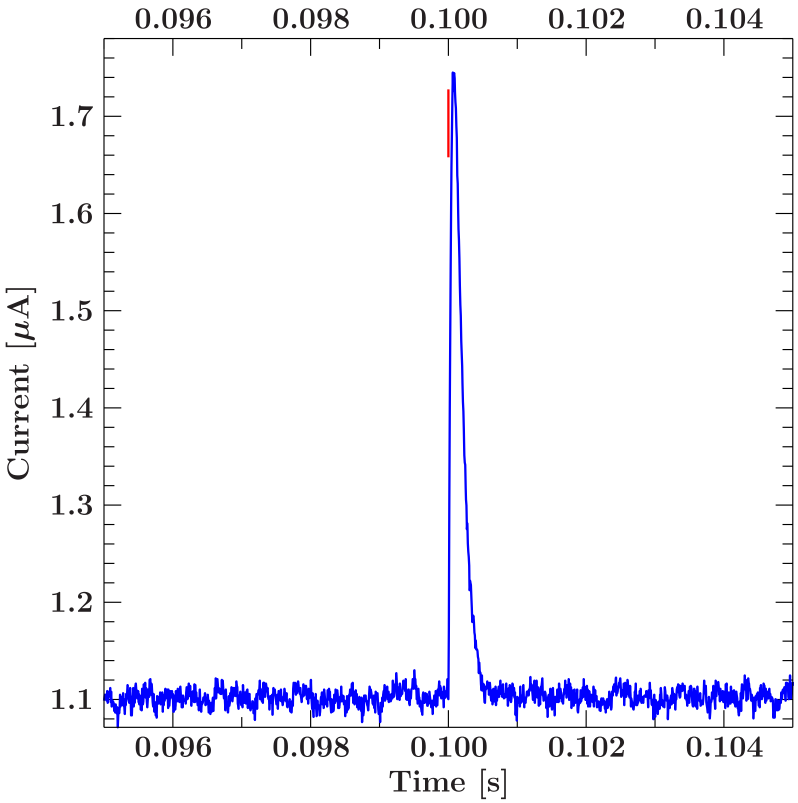
Iterative Event Detection (Triggering):

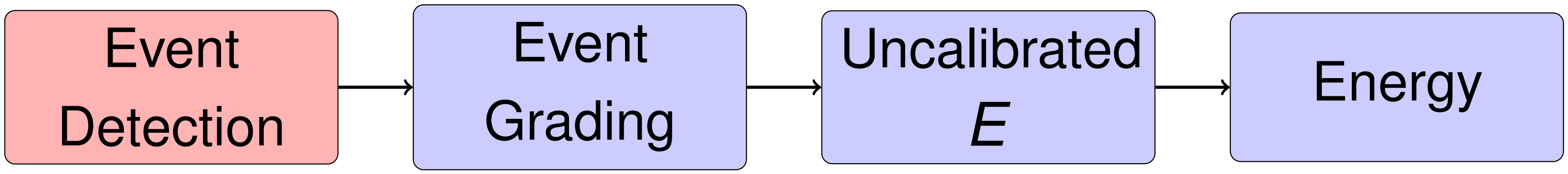
- Take derivative of TES stream

  `trigger=`

  - `stream`
  - `movavg:npts:threshold:suppress`
  - `diff:npts:threshold:suppress`

- remove pulses on the go to find others





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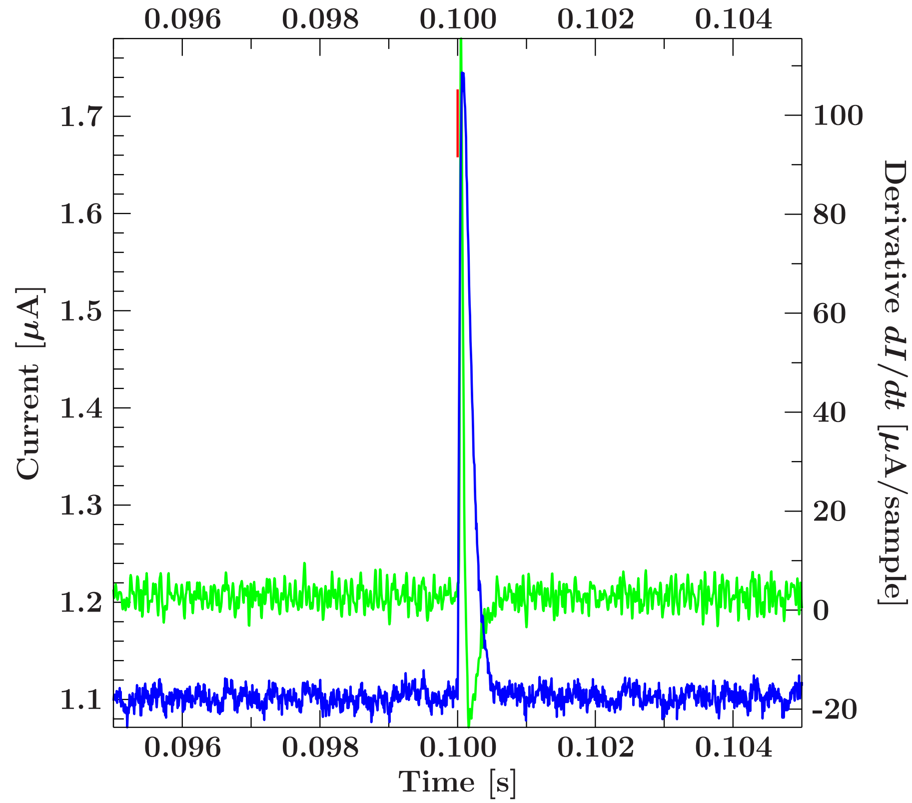
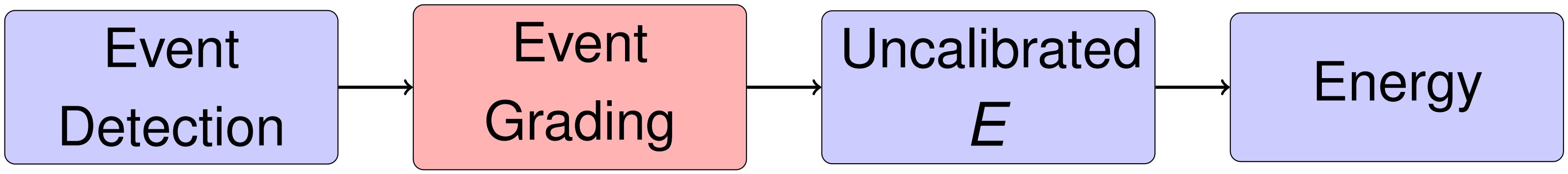
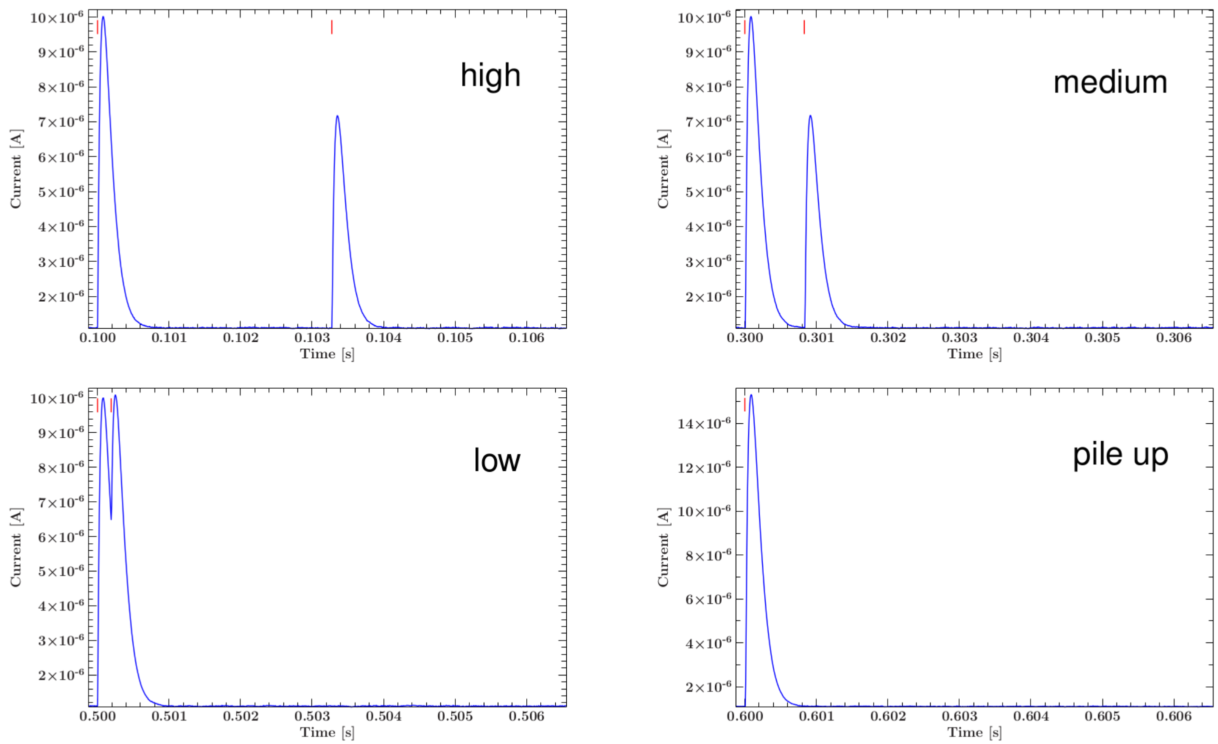
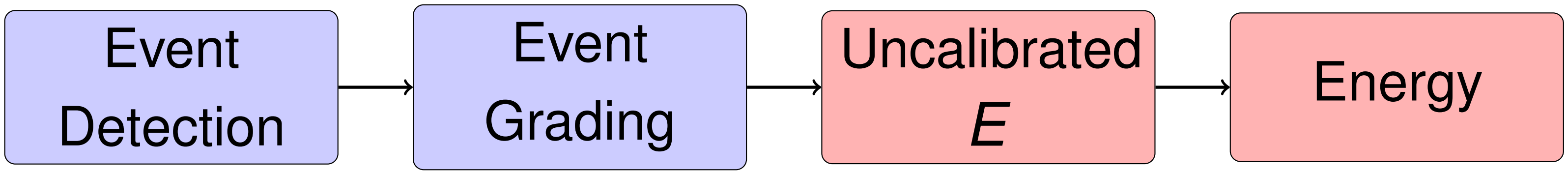


Trigger



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