Time-domain modeling of TES microcalorimeters under AC bias

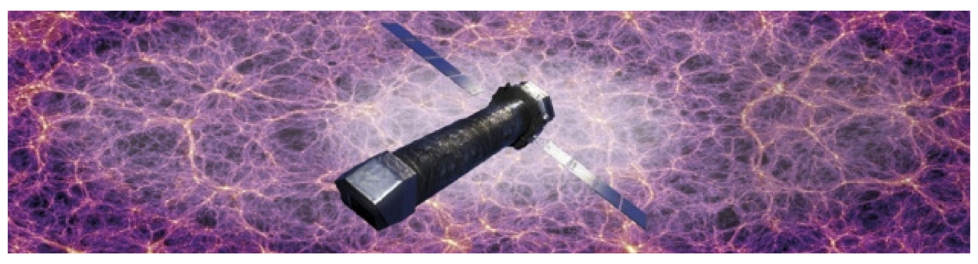
C. Kirsch[1],
L. Gottardi[2], M. Lorenz[1], T. Dauser[1], R den Hartog[2], B. Jackson[2], P. Peille[3], S. Smith[4], J. Wilms[1]

[1]Remeis-Observatory / ECAP, Bamberg, Germany, [2]SRON, Utrecht, Netherlands, [3]CNES, Toulouse, France, [4]NASA GSFC, Greenbelt, USA

Abstract

We present developments in the simulation of Transition-Edge Sensor (TES) microcalorimeters under AC bias for the purpose of detector studies. The presented model extends the TES differential equation system by describing the TES as a resistively shunted junction, using the Josephson equations instead of a parametrized resistance. To demonstrate the performance of this model, we compare simulated and measured IV curves of a pixel characterized for the *Athena* X-ray Integrated Field Unit (X-IFU) and showcase the signal generated by a simulated X-ray pulse.

Athena X-IFU



- Instrument on planned *Athena* X-ray observatory, launch early 2030s [4, 2]
- Array of more than 3000 TES Microcalorimeters
- Operates pixels in frequency domain multiplexing (FDM)
  $\Longrightarrow$ pixels operated under AC bias (1-5 MHz) [1]

For instrument development: Dedicated end-to-end simulator `xifusim` (⇒ **Poster #251, M. Lorenz**) including TES physics, cryogenic read-out and on-board data processing.

In current simulator: TES modeled by linear transition $R(T, I)$ [6] ⇒ How to improve?

TES RSJ Model

- TESs under AC bias have been found to behave like a weak link between superconducting leads [5]
- In the steady state, TESs modeled as a resistively-shunted junction (RSJ) have been used to explain measured TES resistances and inductances [3]
- This poster: Model TES as RSJ in the time-domain, with the goal of simulating pulses of a calorimeter

Model:

- Electrical circuit: AC bias voltage with RLC filter tuned to bias frequency and TES
- TES replaced with Josephson junction shunted by TES normal resistance R_N
- Junction satisfies Josephson equations:

$$V_{\mathrm{TES}} = \frac{\hbar}{2e}\frac{\partial\varphi}{\partial t}, \quad I_J(t) = I_C(T)\sin\varphi(t), \qquad (1)$$

with critical current $I_C(T)$ taken from fit to measured values (Fig. 1, right)

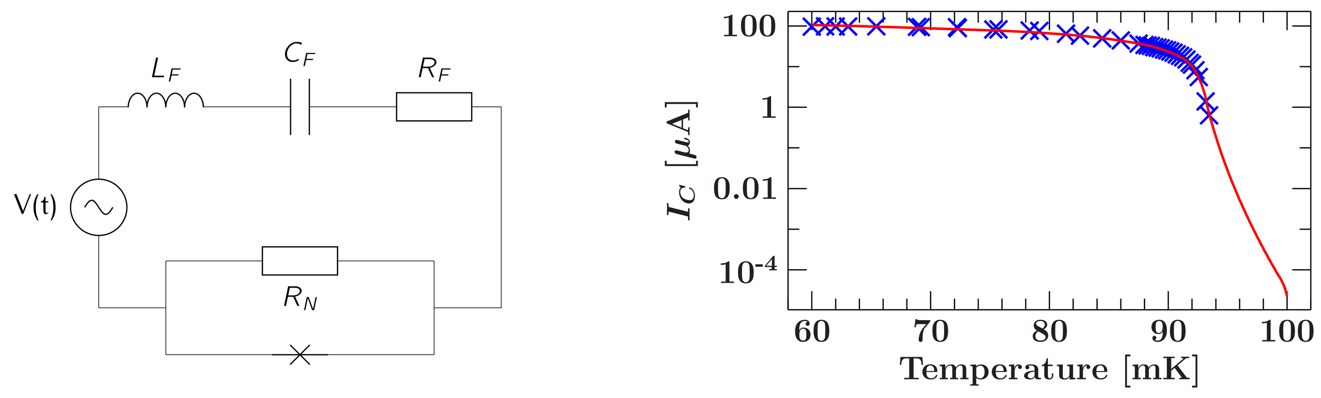


Figure 1: *Left:* TES electrical circuit. *Right:* TES critical current values, with data points as crosses and an extended model fit [5, 3]

TES equation system

$$\frac{\partial Q}{\partial t} = I(t) \qquad (2)$$

$$V_{\mathrm{TES}} = (I_c(T)\sin(\varphi(t)) + I(t)) \cdot R_N \qquad (3)$$

$$\frac{\partial I}{\partial t} = \left(V(t) - \frac{Q(t)}{C_F} - R_F I(t) - V_{\mathrm{TES}}\right)\cdot\frac{1}{L_F} \qquad (4)$$

$$\frac{\partial\varphi}{\partial t} = \frac{2e}{\hbar}V_{\mathrm{TES}} \qquad (5)$$

$$\frac{\partial T}{\partial t} = \left(V_{\mathrm{TES}}\cdot I(t) + P_{\mathrm{phot}} - P_{\mathrm{bath}}\right)\cdot\frac{1}{C} \qquad (6)$$

$$P_{\mathrm{bath}} = K\left(T^n - T^n_{\mathrm{bath}}\right) \qquad (7)$$

AC Behavior

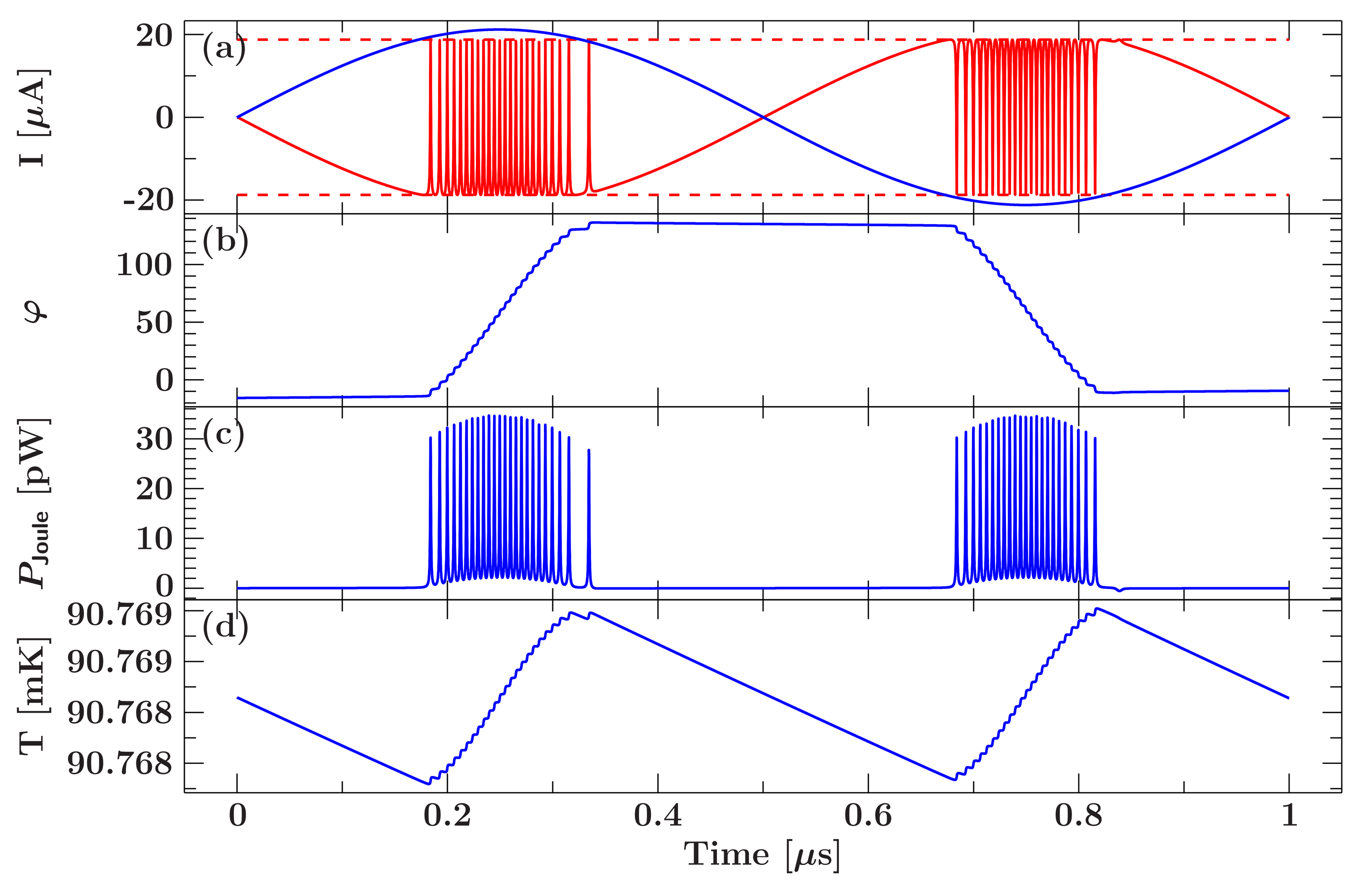


Figure 2: Behavior of the RSJ system during a single period of a 1 MHz pixel. *(a)* Current I (*blue*) and I_J from Eq. 1 (*red*) alongside $\pm I_C(T)$ (*red dashed lines*)

$|I| < I_C(T)$

- V_{TES} very small, as $I_J \approx -I$
- TES effectively superconducting
- No Joule heating

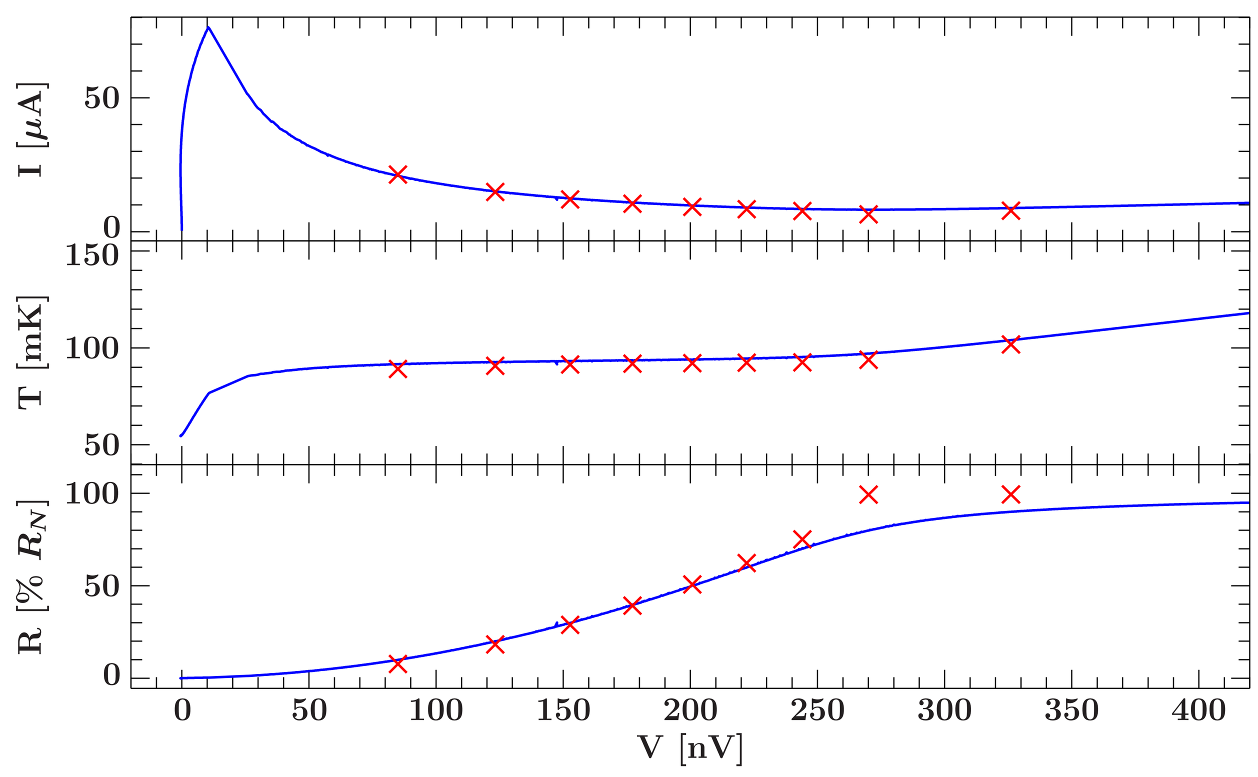
$|I| > I_C(T)$

- V_{TES} much larger, drives φ
- Creates effective TES resistance
- Pulses of Joule heating

IV Curve

First order test:

- use existing IV curve of modeled pixel as starting points to a simulation
- compare stable points reached in simulation with measured IV curve at same bias voltage



$\Longrightarrow$ General agreement, although model temperatures trend slightly lower and highest bias points already reached 100 % R_N

Figure 3: Stable points of the RSJ model for selected applied voltages (*red crosses*) in comparison with a measured IV curve of the modeled pixel (*blue lines*)

X-ray Pulses

- Simulate X-ray pulses via setting P_{phot} in Eq. 6 (Here: Instant absorption of full photon energy)

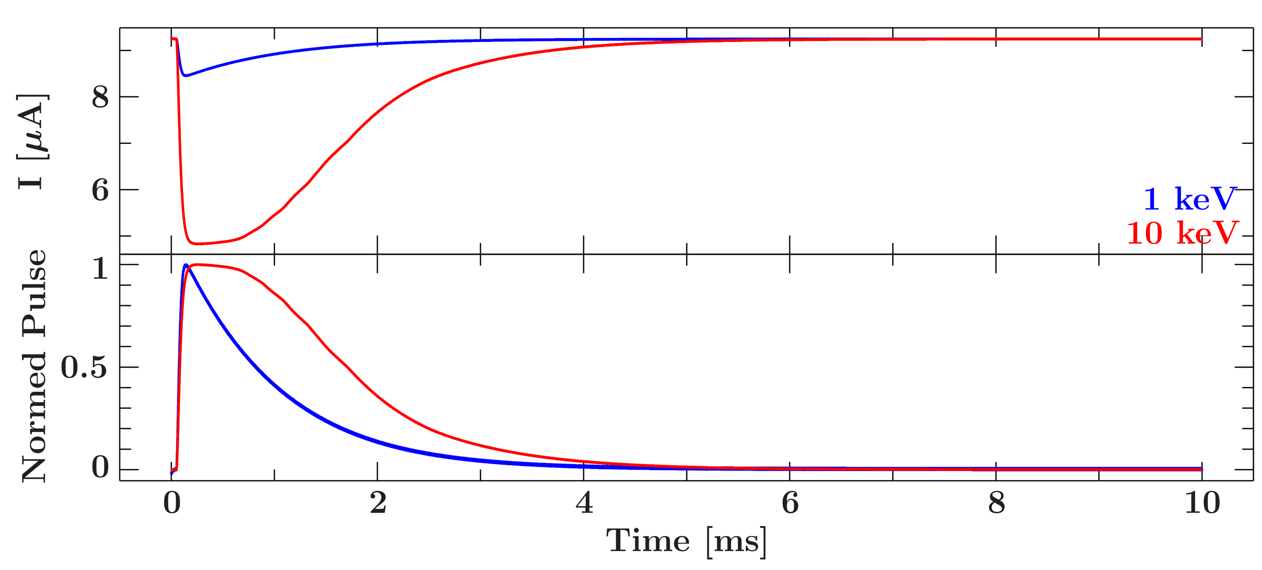


Figure 4: Two X-ray pulses simulated for a pixel biased at 50 % R_N. The two panels show the RMS current of the TES and the pulses normed to equal peak value respectively. The pulse energies are 1 keV (*blue*) and 10 keV (*red*)

- 1 keV pulse shows characteristic TES pulse shape with duration of ~ 4 ms
- 10 keV pulse shows extended peak $\Longrightarrow$ TES reaches normal resistance during pulse, due to bias high in the transition (50 % R_N)

$\Longrightarrow$ Future work: Compare with measured pulses and other models such as linear resistance or tabulated $R(T, I)$ (⇒ **Poster #97, L. Gottardi**)

Acknowledgements

This research has made use of ISIS functions (ISISscripts) provided by ECAP/Remeis observatory and MIT (http://www.sternwarte.uni-erlangen.de/isis/). We thank John E. Davis for the development of the SLXfig module used to prepare the figures.
This work has been funded by the Bundesministerium für Wirtschaft und Technologie under DLR grant number 50 QR 1903.

References

[1] Akamatsu H., Gottardi L., van der Kuur J., et al., 2016, In: Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, Vol. 9905. Proc. SPIE, p. 99055S
[2] Barret D., Lam Trong T., den Herder J.W., et al., 2018, In: Proc. SPIE, Vol. 10699. SPIE Conf. Ser., p. 106991G
[3] Gottardi L., Kozorezov A., Akamatsu H., et al., 2014, Appl. Phys. Lett. 105, 162605
[4] Nandra K., Barret D., Barcons X., et al., 2013, arXiv e-prints arXiv:1306.2307
[5] Sadleir J.E., Smith S.J., Bandler S.R., et al., 2010, Phys. Rev. Lett. 104, 047003
[6] Wilms J., Smith S.J., Peille P., et al., 2016, In: Proc. SPIE, Vol. 9905. SPIE Conf. Ser., p. 990564

For more information: christian.ck.kirsch@fau.de

LaTeX TikZposter