Comparing Complex Impedance and Bias Step Measurements of Simons Observatory Transition Edge Sensors

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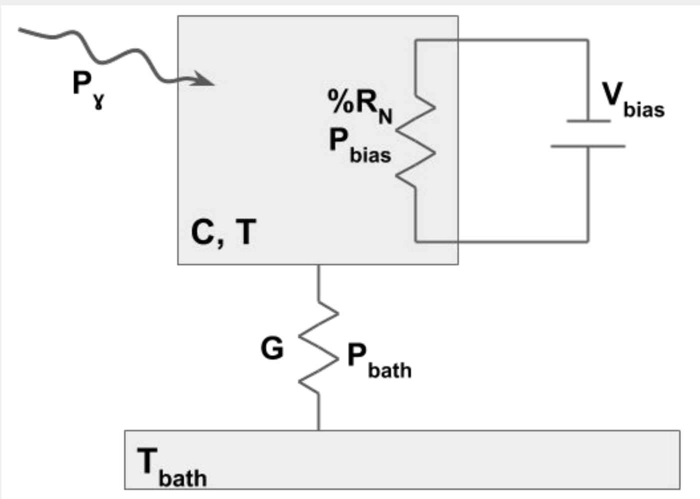
Simons Observatory Detectors

- The Simons Observatory [1]
  - Improve cosmological constants constraints
  - Probe sum of neutrino masses
  - Detect high-redshift galaxy clusters
  - Characterize dark matter via grav. lensing
- Small and Large Aperture Telescopes [2]
  - ~0.5 m (SAT) and ~6 m (LAT) respectively
  - Altitude 5190 m on Cerro Toco, Chile
- ~70,000 Transition Edge Sensors (TESs)
  - Dichroic LF, MF, and UHF arrays
  - 30/40, 90/150, 230/290 GHz
- Single prototype TESs used for optimization [3]
- Detector time constants driven by:
  - Rotating, cryogenic half-wave plate (SAT)
  - Nyquist sampling of beam on sky (LAT)
- Time constant measurement methods:
  - Bias steps good for fast effective thermal response characterization in the field
  - Complex impedance slower but probes fundamental device parameters

Frequency Band	Target $P_{\rm sat}$ Range	Target $f_{\rm 3dB,min}$
LF-1 27 GHz	0.6 – 1.0 pW	150 Hz
LF-2 39 GHz	2.7 – 4.4 pW	150 Hz
MF-1 90 GHz	2.0 – 3.3 pW	150 Hz
MF-2 150 GHz	5.4 – 9.0 pW	166 Hz
UHF-1 220 GHz	16.9 – 28.1 pW	245 Hz
UHF-2 275 GHz	22.4 – 37.3 pW	279 Hz

Background and TES Model

- Irwin & Hilton Single Thermal Block Model [4]
  - Bolometer island suspended from bath
  - Superconductor biased on transition
  - Negative electrothermal feedback

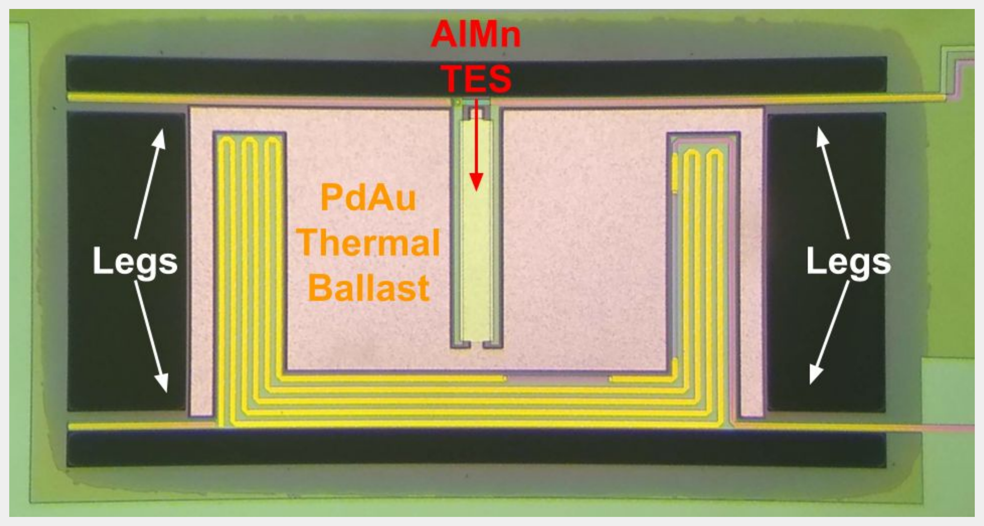


- Saturation power tuned by changing G
- Effective thermal time constant
  - Function of C, G, P_{bias}, and TES properties
  - Tune at expected P_{bias} by changing C

$$\frac{1}{2\pi\tau_{\rm eff}} = f_{\rm 3dB} = f_{\rm nat}\left(1+\frac{\mathscr{L}}{1+\beta}\right) = \frac{G}{2\pi C}\left(1+\frac{1}{(1-\beta)}\frac{\alpha P_{\rm bias}}{T_c G}\right)$$

- Complex impedance
  - Probe fundamental TES parameters α, β, C
  - Low frequency limit reduces to Z_{TES}~ -R
  - High frequency limit reduces to Z_{TES}~ R(1+β)

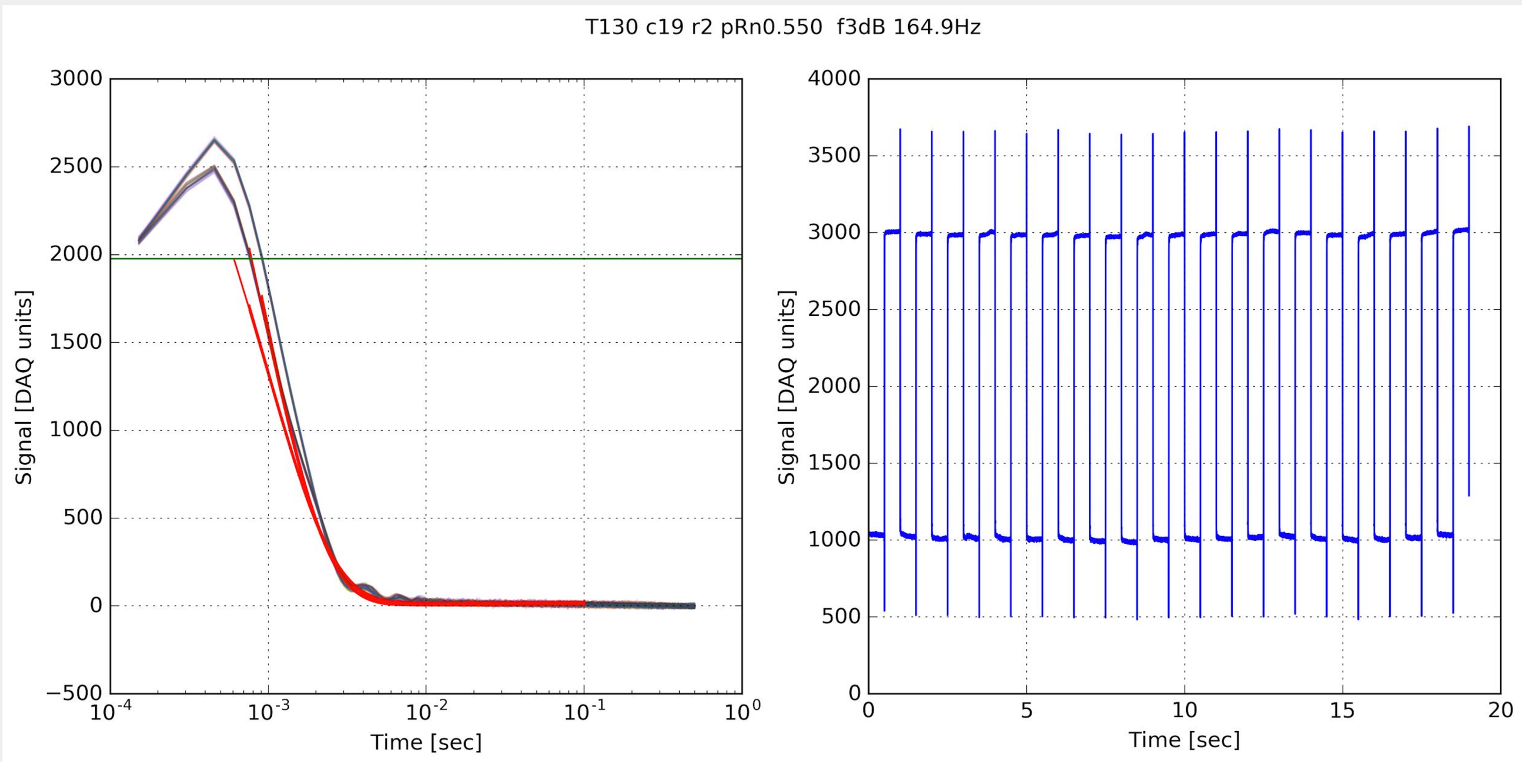
$$Z_{\rm TES}(f) = R(1+\beta) + \frac{R(2+\beta)\mathscr{L}}{(1-\mathscr{L})+if/f_{\rm nat}}$$



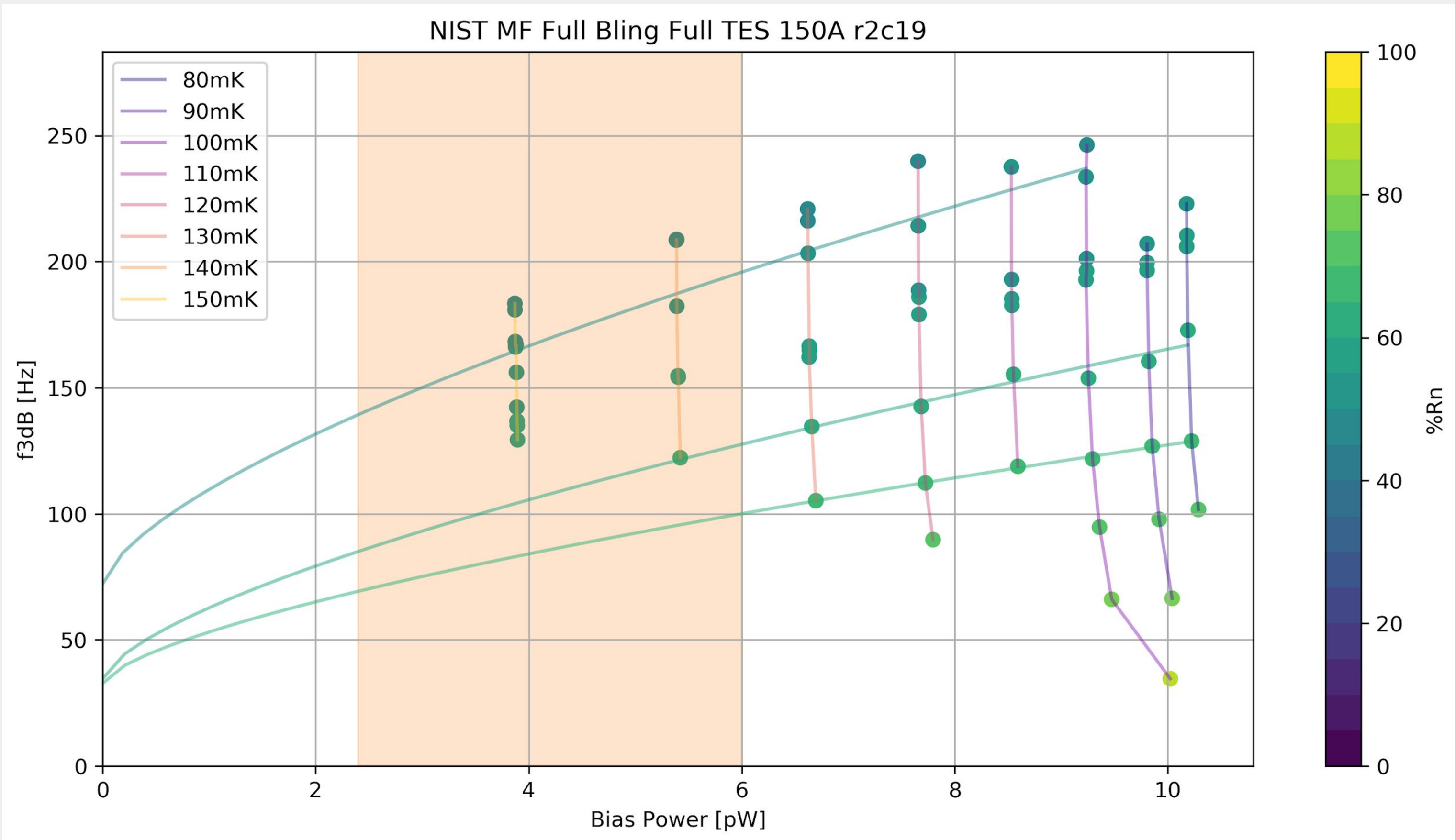
NIST SO MF-2 150 GHz TES Bolometer

Bias Step Measurements

- Bias step acquisition with Multichannel Electronics (MCE) readout system
  - TES at T_{bath} biased onto transition to $\%R_N$ with DC P_{bias}
  - Small amplitude square wave applied on top of DC bias
  - TES rebiased to another $\%R_N$ and another bias step is acquired
  - Quickly sample TES response with MCE (~6.4 kHz)

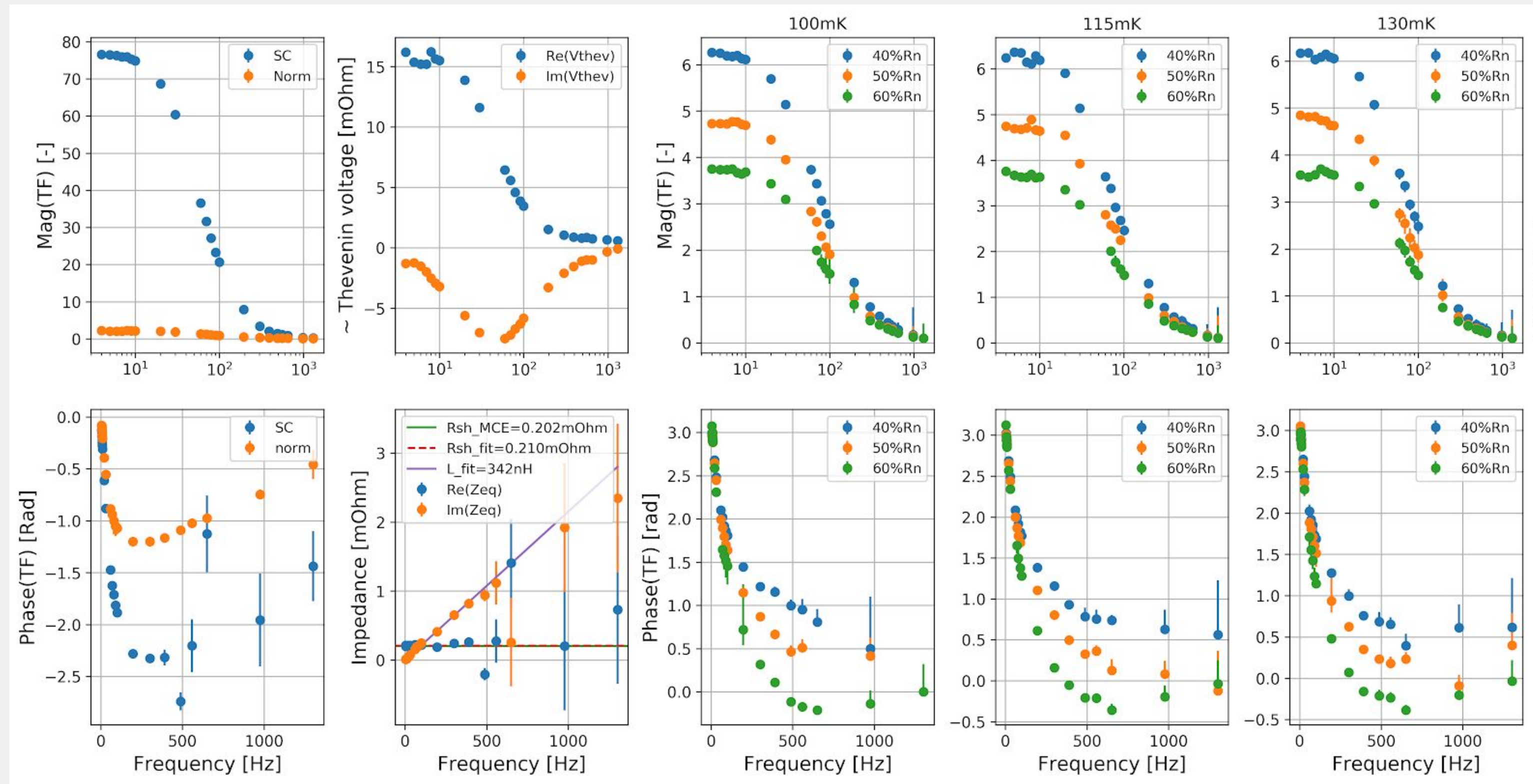


- Extracting the effective thermal time constant
  - Bolometer time streams split at each step of the square wave
  - Single pole exponential fit applied to each step
  - Beginning of fit determined by amplitude of square wave
- Mapping the effective thermal time constant
  - Measurements at multiple T_{bath} simulate variety of loading conditions
- Confirm bolometer performance meets requirements
  - Estimate natural time constant by extrapolating to P_{bias}= 0 pW
  - Fit constant $\%R_N$ datasets to two-fluid model [5,6]

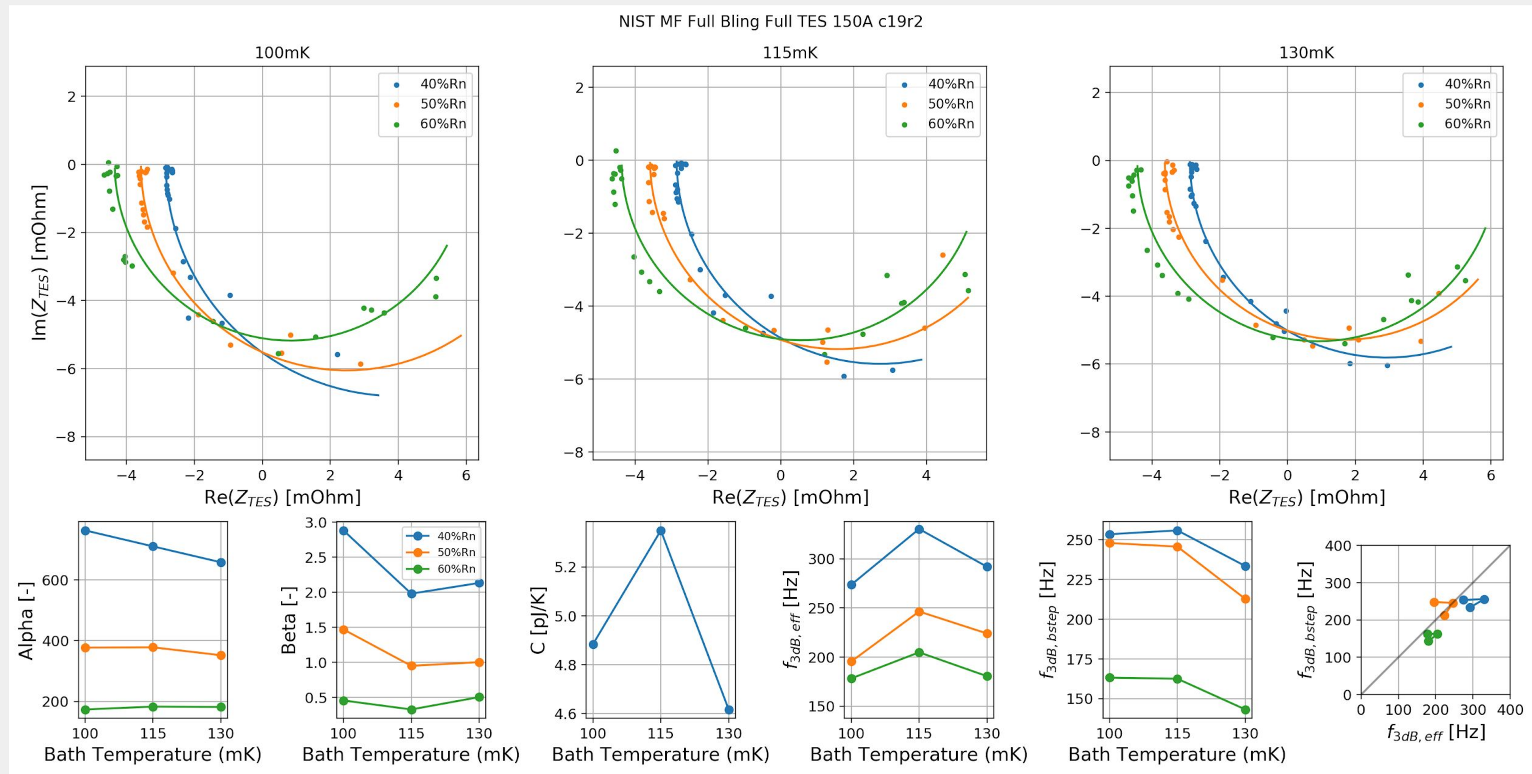


Complex Impedance Measurements

- Complex impedance acquisition with MCE arbitrary waveform generator (AWG)
  - TES at T_{bath} biased onto transition to $\%R_N$ with DC P_{bias}
  - Small amplitude digitized sine waves applied on top of DC bias
    - Stimulation frequencies ranging from 4 Hz to ~ 1.3 kHz
  - Quickly sample TES response with MCE (~7.8 kHz)
- Transfer functions (TFs)
  - Fit amplitude and phase of bolometer response to stimulation [7]
  - Relative amplitude and phase of input and output gives complex-valued TF
  - Use superconducting and normal TFs for bias circuit calibration/removal

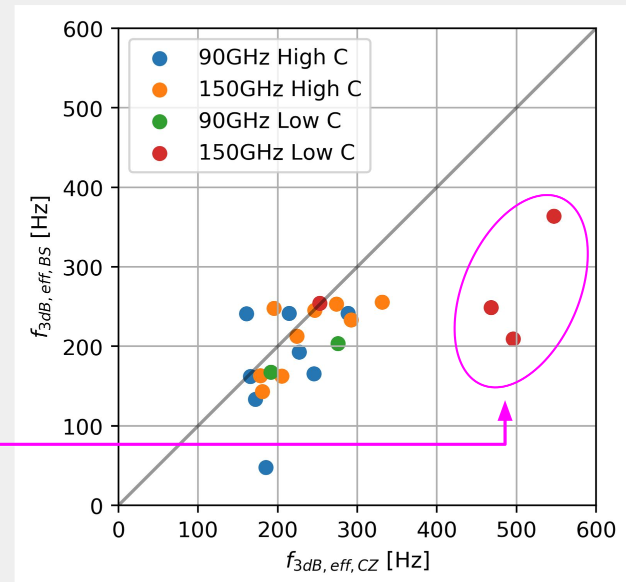


- TES complex impedance (Z_{TES})
  - Z_{TES} from TFs using bias circuit calibration and R_N from IV-curve measurement
  - Fit model for α, β, C as function of $\%R_N$ and T_{bath}
  - Heat capacity constrained as constant for all $\%R_N$ fits at a given T_{bath}
  - Propagate sinusoid fitting errors analytically to Z_{TES} and input to model fit
  - IV-curve measurements of R_N, T_c, G, and P_{bias} assumed negligible uncertainty
  - Derived effective thermal time constant roughly agrees with bias steps



Conclusions

- Time constants measured via bias step and complex impedance
- Both methods roughly consistent and fit well to single island bolometer model
- Bias step fits become less reliable for fast detectors
  - Can be improved by increasing sampling rate
- Complex impedance fits can be improved with higher stimulation frequencies.
  - CZ fits of fast devices poorly constrain β and therefore f_{3dB}
  - f_{3dB} limited by fastest bolometer excitation frequency
- Effective thermal time constants meet expectations and SO requirements



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