Precision characterization of thermal circuits and noise of TES microcalorimeters

Avirup Roy[1], Felix Jaeckel[1], Conjeepuram Ambarish[1], Nick Christensen[1], Dan McCammon[1], Mari McPheron[1], Kari Nelms[1], Dallas Wulf[1]
[1]University of Wisconsin Madison, Madison, WI, 53706 USA

Kelsey Morgan[2], Daniel Schmidt[2], Daniel Swetz[2], Joel Ullom[2]
[3]National Institute of Standards and Technology, 25 Broadway, Boulder, CO 80305

Jay Chervenak[3], Megan Eckart[3,4], Stephen Smith[3], Nick Wakeham[3]
[3]NASA - Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA
[4]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550

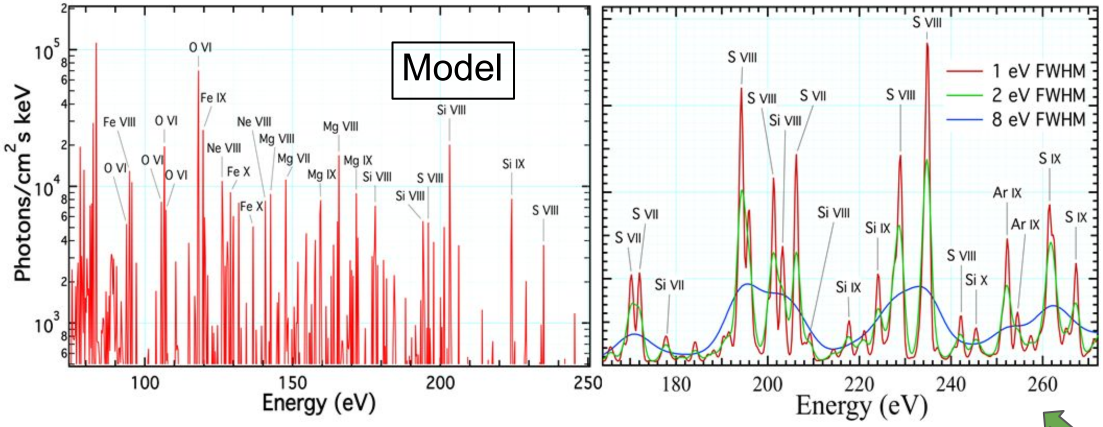
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

NIST

NASA

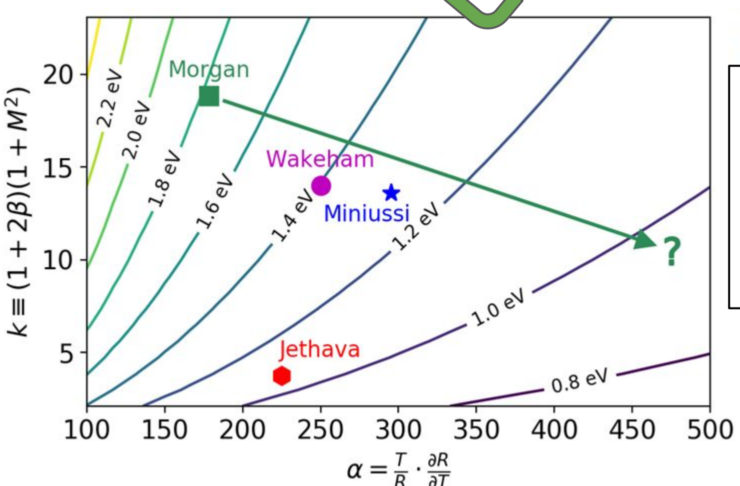
22-26 JULY 2019 MILANO
LTD18
LOW TEMPERATURE DETECTORS

Motivation



- Clear understanding of the physics of the ISM and CGM are key to solving many open astrophysical questions (missing metals and baryons)
- Significant **diffuse hot gas close to 10^6K** is observed both in the local ISM and beyond.
- Bulk of the emission for such plasma is in narrow lines **below 600 eV**.
- Need **<2 eV spectral resolution** and large area detection area: e.g. **256 pixels at 1 mm^2** each

- Require low C, high α, low β & M^2.
- **A better understanding of the transition surface and "excess" noise would help. We need precise measurements!**

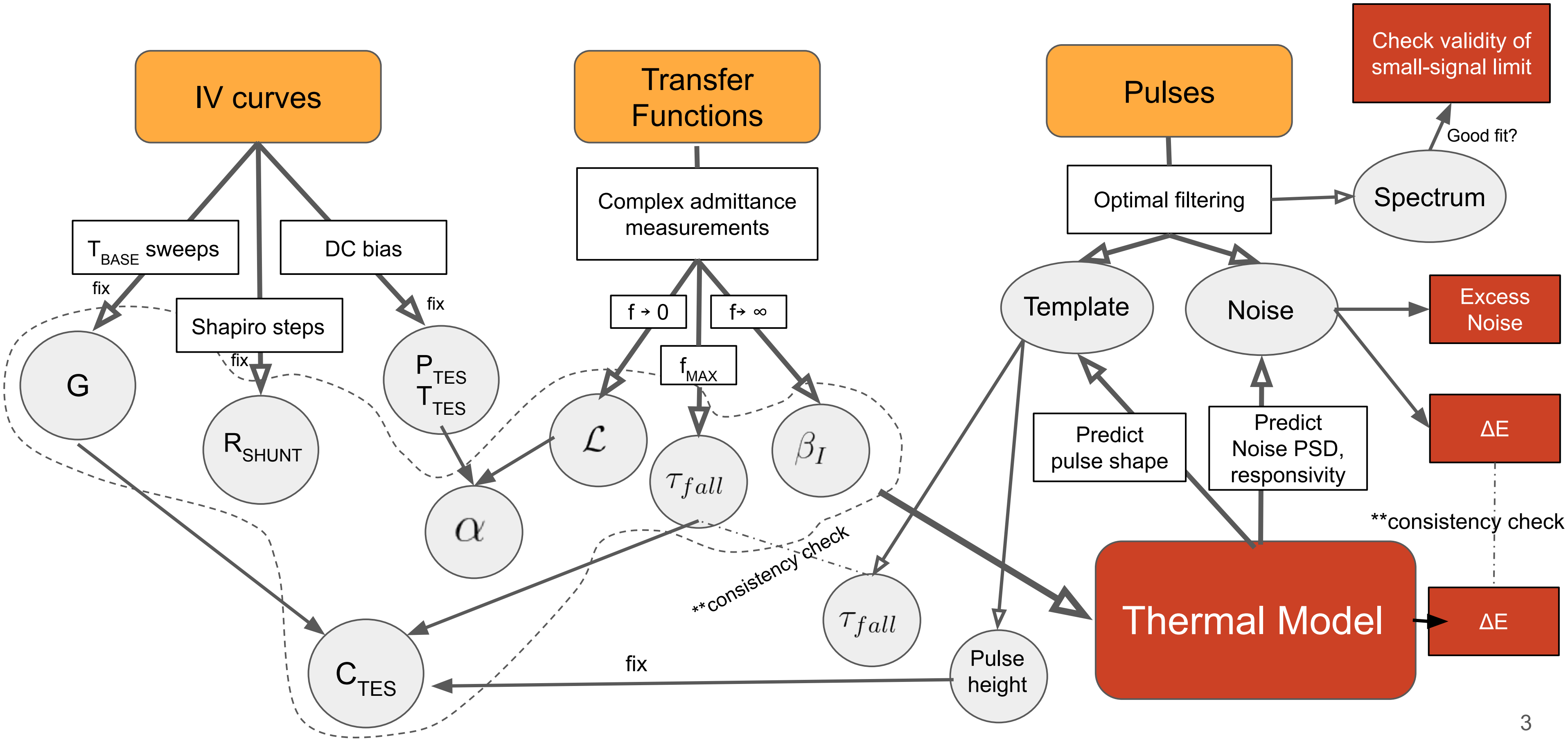


$$\Delta E_{FWHM} \propto \left(\sqrt{k}T^2 C/\alpha\right)^{1/2}$$

Notional pixel design: 1mm^2, 200 nm Au absorber C_{abs}=1.0 pJ/K T_{bias}=50mK, T_{TES}=70mK G_{TES}=35pW/K, C_{TES}=0.21pJ/K

See poster PA 218-235 (Dan McCammon et al.)

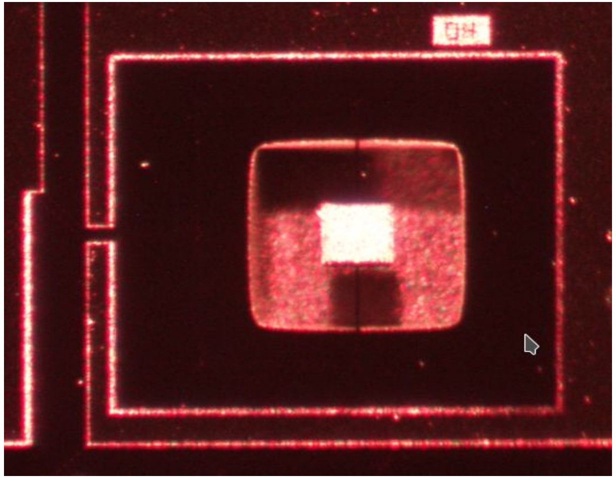
Toolbox

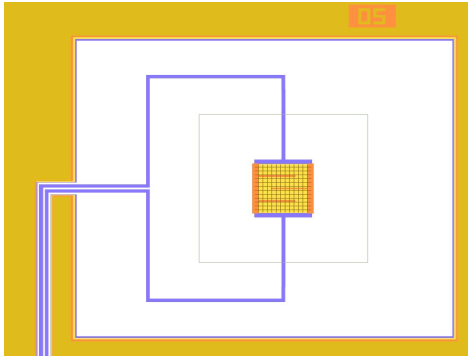


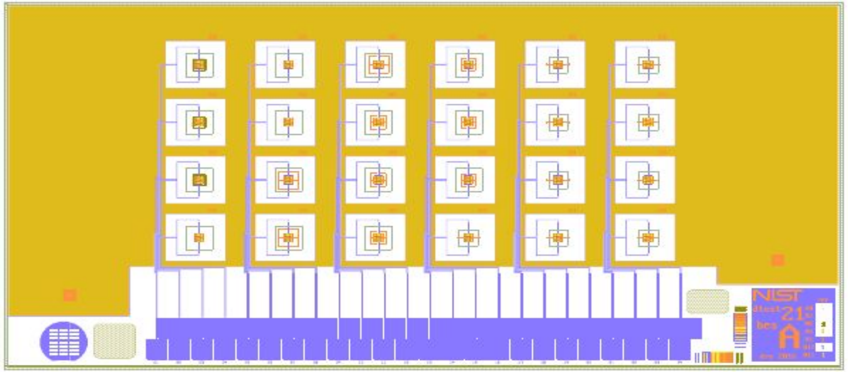
Check validity of small-signal limit
IV curves
Transfer Functions
Pulses
Good fit?
Complex admittance measurements
Optimal filtering
Spectrum
T_{BASE} sweeps
DC bias
fix
fix
Shapiro steps
fix
$f \to 0$
$f \to \infty$
f_{MAX}
Template
Noise
Excess Noise
G
R_{SHUNT}
P_{TES}
T_{TES}
$\mathcal{L}$
τ_{fall}
β_I
Predict pulse shape
Predict Noise PSD, responsivity
ΔE
α
**consistency check
**consistency check
τ_{fall}
Thermal Model
ΔE
fix
C_{TES}
Pulse height

Device under test

- 150 μm x 150 μm Mo/Cu TES
  Tc ~ 75 mK
- Absorbers: 3.4 μm Bi (evaporated)
- ΔE at 1.25keV: 1.0 to 1.5eV (typical)



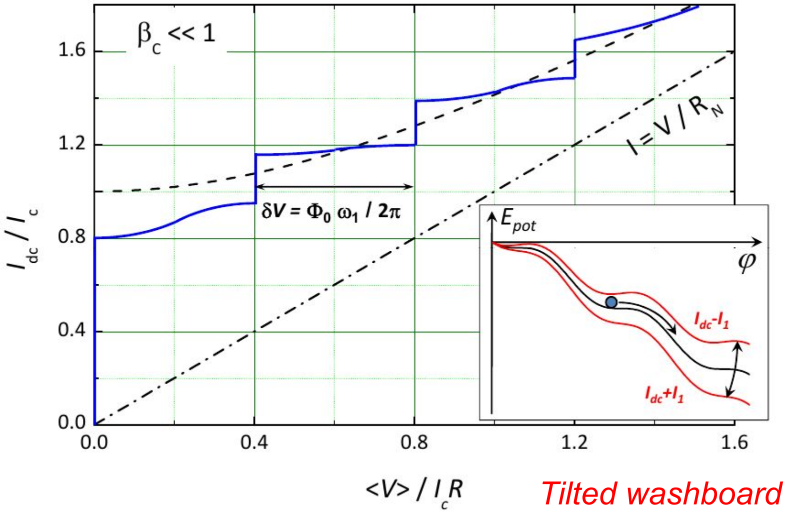




Shapiro steps

ASC 2016:

Jack Sadleir, "Unexpected nonlinear effects in superconducting transition-edge sensors." (2016)



Tilted washboard potential

Apply AC bias to device

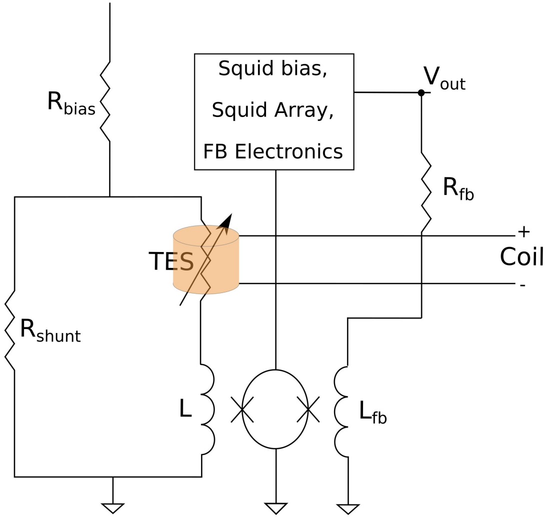
$$V(t) = V_{DC} + V_{AC}cos(\omega t)$$

or:

Apply AC bias to field coil

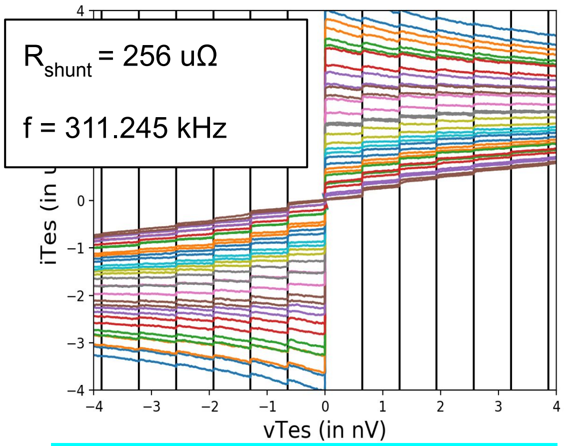
Step size:

$$V_n = n\frac{\hbar\omega_{AC}}{2e}$$



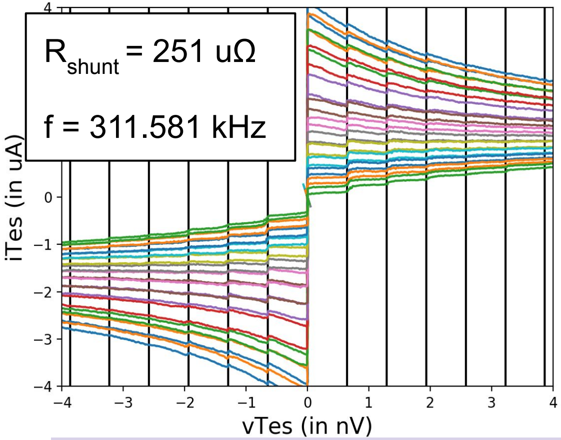
Determination of shunt resistance

Mo/Cu - Mo leads

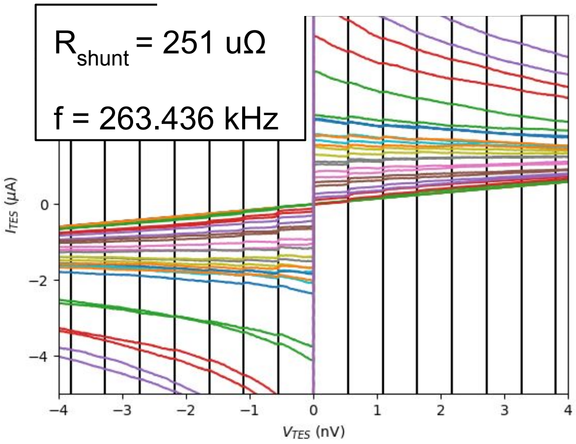


shunt resistor A

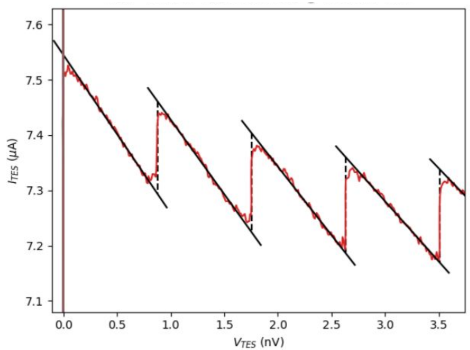
Mo/Cu - Mo leads

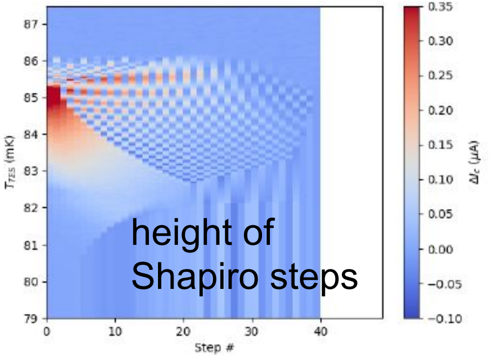


Mo/Au - Nb leads



shunt resistor B



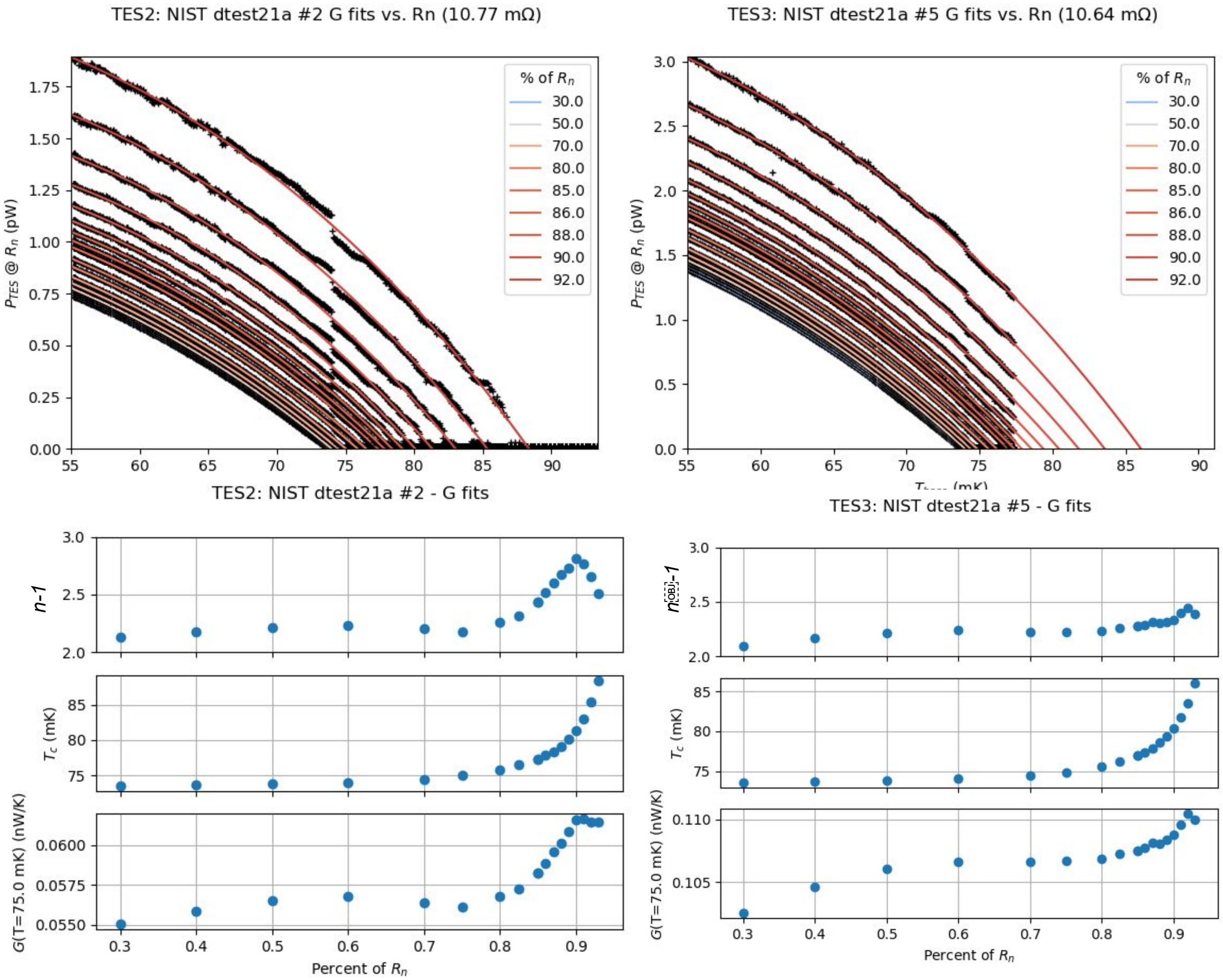


See Yu Zhou et al.: "Mapping TES Temperature Sensitivity and Current Sensitivity as a Function of Temperature, Current, and Magnetic Field with IV Curve and Complex Admittance Measurements," (2017): 074503.

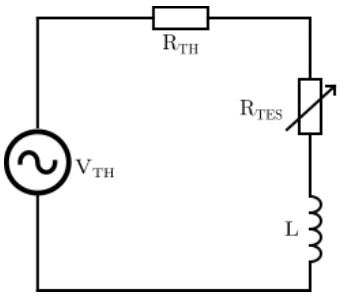
Measuring G

$$I_0^2 R_0 = \kappa(T_0^n - T_b^n)$$

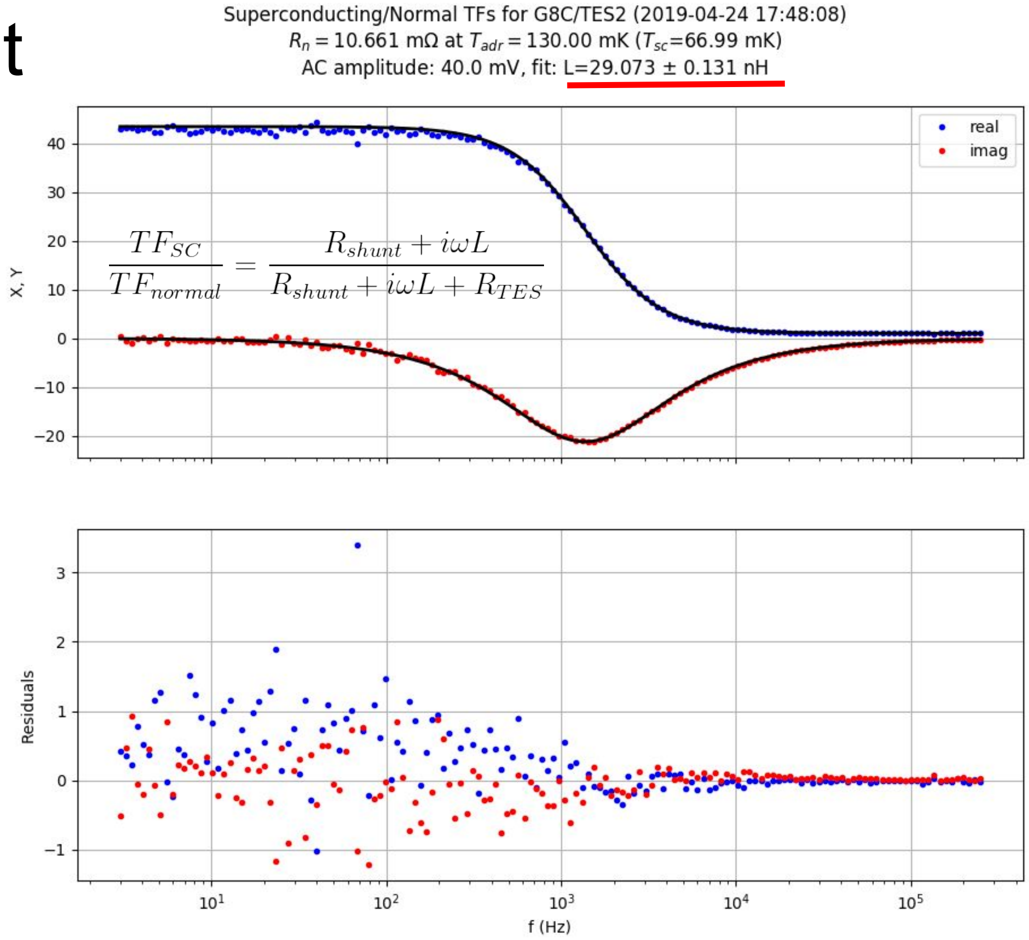
$$G \equiv \frac{dP}{dT} = n\kappa T_0^{n-1}$$



Thévenin circuit treatment



$$Z_{TH} = R_{TES}\frac{TF_{normal}}{TF_{SC} - TF_{normal}}$$



R_{SHUNT} and R_{TES} independently fixed from Shapiro steps and IV curves.

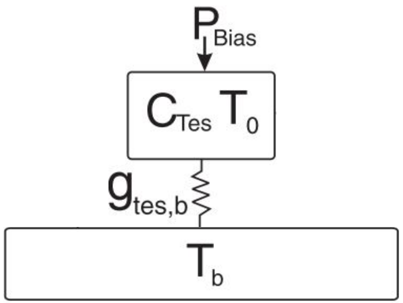
1. Thevenized circuit accurately accounts for circuit strays
2. Complex impedances can be measured from ratios of SC and Normal transfer functions
3. Consistency check:
   $$\frac{TF_{SC}}{TF_{normal}} = \frac{R_{shunt} + i\omega L}{R_{shunt} + i\omega L + R_{TES}}$$
   Fits with a single free parameter (inductance L) out to 250 kHz.

Lindeman, Mark A., et al. "Impedance measurements and modeling of a transition-edge-sensor calorimeter." *Review of Scientific Instruments* 75.5 (2004): 1283-1289.

Thermal models

One-block basic model

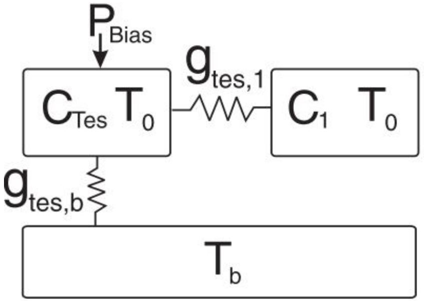
$$Z_{TES}(\omega) = R_0(1+\beta_I) + \frac{\mathcal{L}}{1-\mathcal{L}}\frac{R_0(2+\beta_I)}{(1+i\omega\tau_I)} \qquad \mathcal{L} = \frac{P_0\alpha}{GT_0}$$



Two-block hanging model

$$Z_{TES,H}(\omega) = R_0(1+\beta_I) + \frac{\mathcal{L}_\mathcal{H}}{1-\mathcal{L}_\mathcal{H}}\frac{R_0(2+\beta_I)}{\left(1+i\omega\tau_I - \frac{g_{tes,1}}{g_{tes,1}+g_{tes,b}(1-\mathcal{L}_\mathcal{H})}\right)}\frac{1}{1+i\omega\tau_1}$$

$$\mathcal{L}_\mathcal{H} = \frac{P_0\alpha}{(g_{tes,1}+g_{tes,b})T_0} \qquad \tau_1 = \frac{C_1}{g_{tes,1}} \qquad \tau_I = \frac{C_{tes}}{(g_{tes,1}+g_{tes,b})(1-\mathcal{L}_\mathcal{H})}$$



Multi-body models easily numerically solved using the matrix method (E. Figueroa-Feliciano)

Irwin, K. D., and G. C. Hilton. "Cryogenic particle detection." *Topics in Applied Physics* 99 (2005): 63-149.

Maasilta, Ilari J. "Complex impedance, responsivity and noise of transition-edge sensors: Analytical solutions for two-and three-block thermal models." *AIP Advances* 2.4 (2012): 042110.

Figueroa-Feliciano, Enectali. "Complex microcalorimeter models and their application to position-sensitive detectors." *Journal of Applied Physics* 99.11 (2006): 114513.

Measuring complex admittance

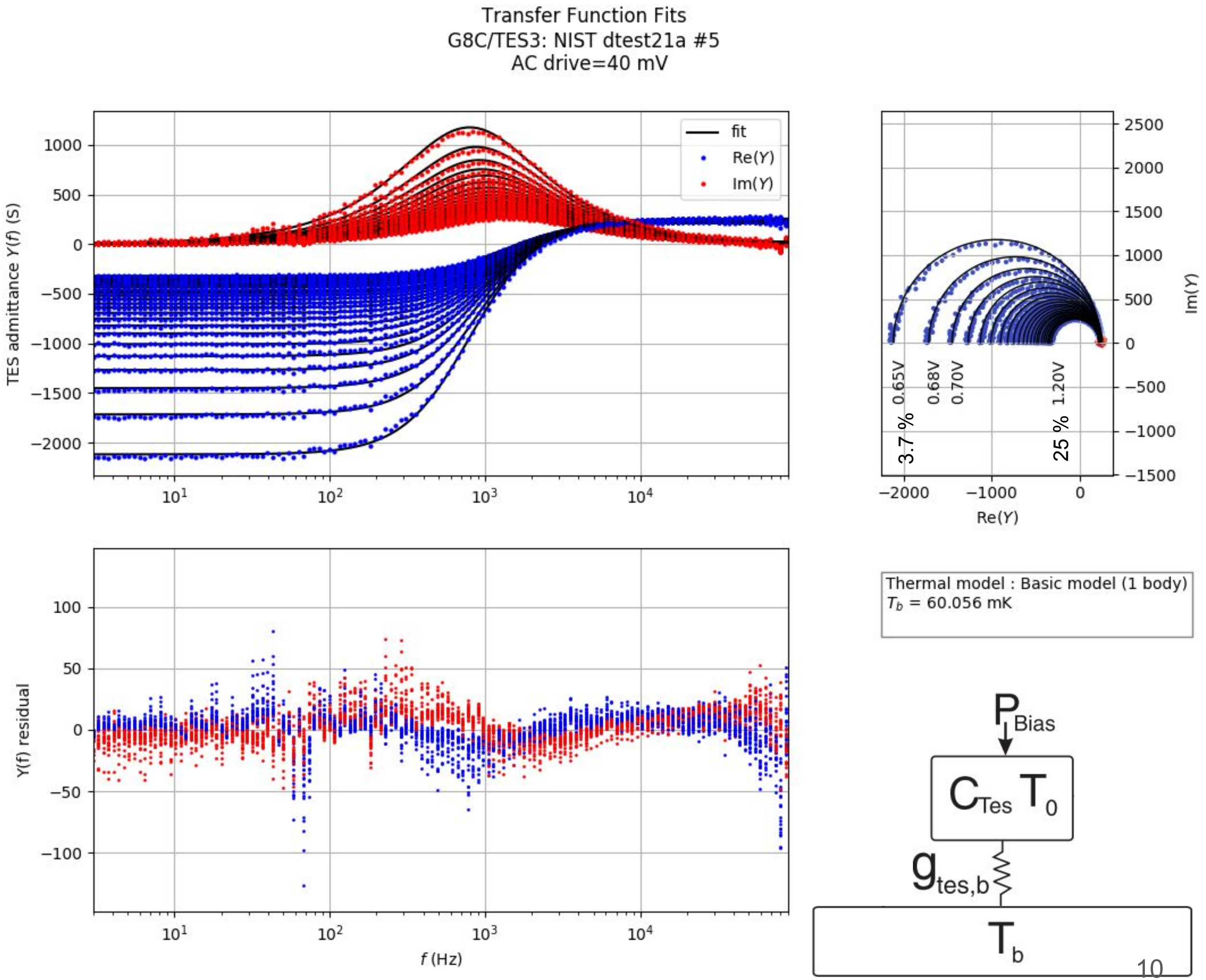
I_0 , R_0, T_0 are determined by fitting local cubic splines of TES IV sweeps at bias points used in taking TFs

$$\beta_I = \frac{1}{R_{TES}\Re(Y(\omega_\infty))} - 1$$

$$\mathcal{L} = 1 - \frac{1 + \beta_I R_{TES}\Re(Y(\omega \to 0))}{1 + R_{TES}\Re(Y(\omega \to 0))}$$

$$\alpha = \frac{\mathcal{L} G T_0}{I_0^2 R_0}$$

$$\tau = \frac{1}{2\pi f_{max}}\Big|_{\Im(Y(f=f_{max}))'=0}$$

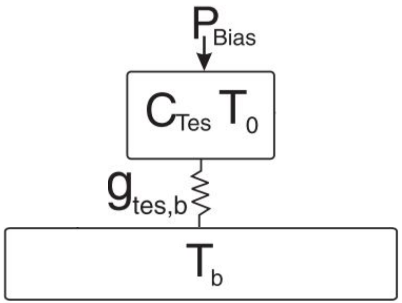


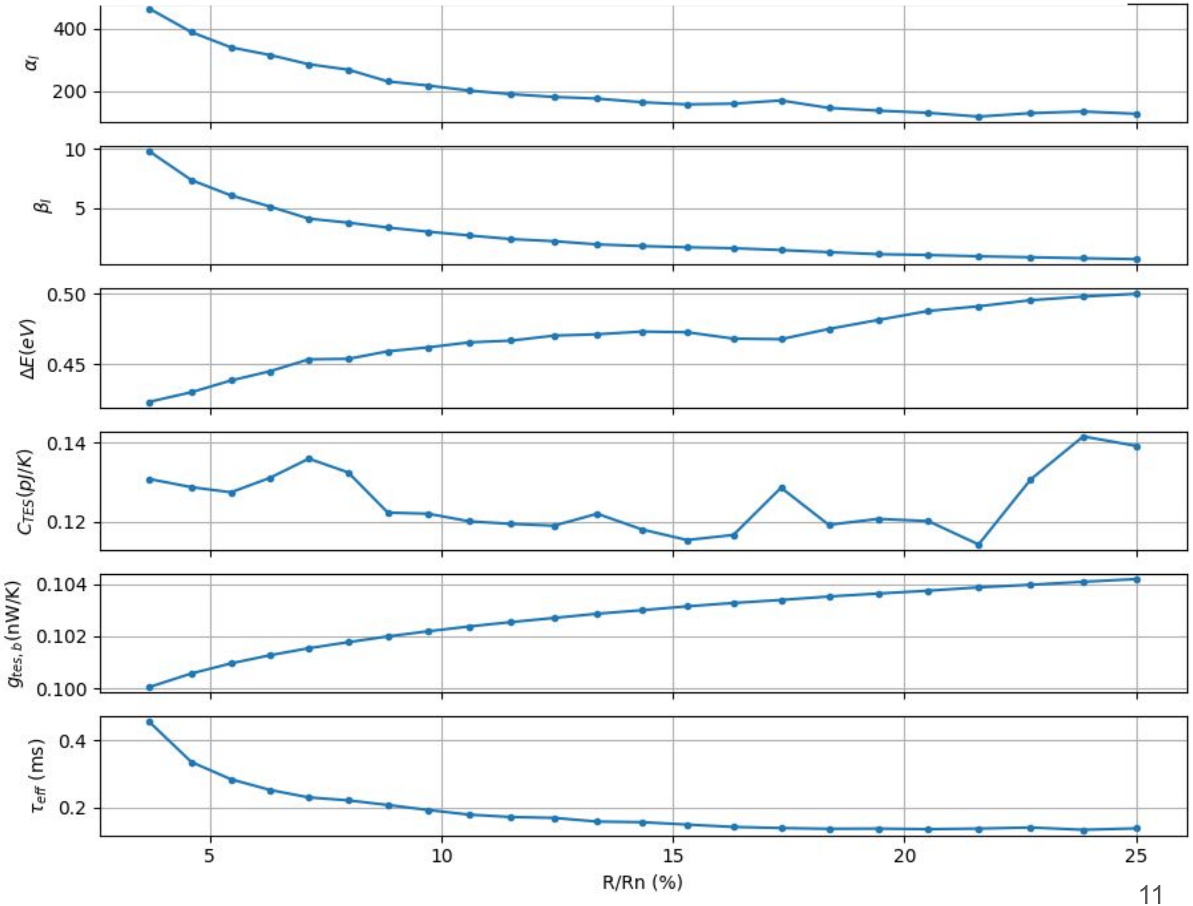
Fit results: single body model

Free fit parameters:

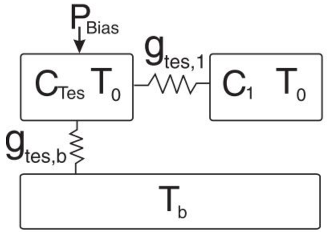
1. α - (vary within 5% of DC value)
2. β - (vary within 5% of high f limit)
3. Cтes - (seed value of Gτ$_{tes}$)

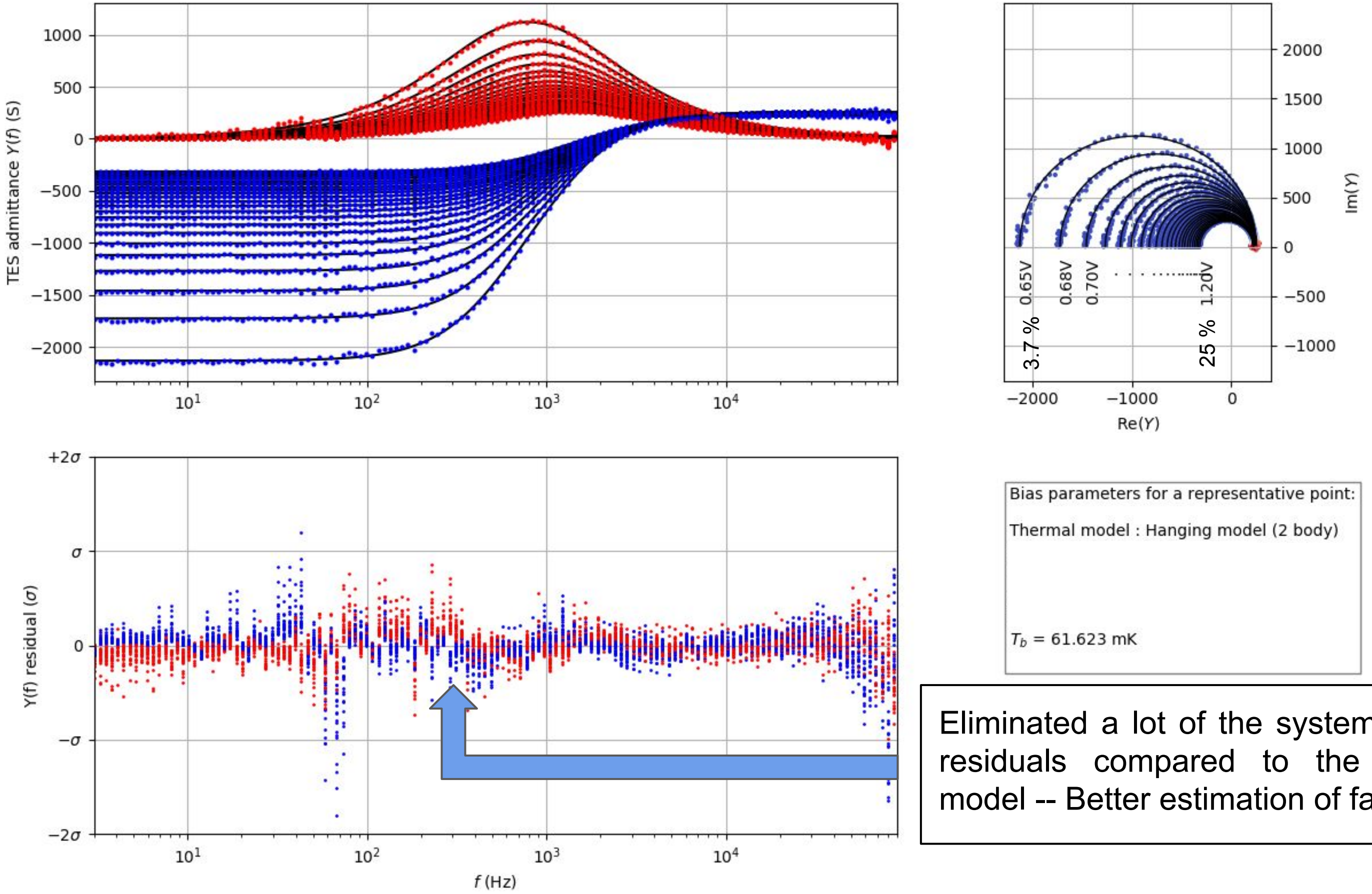
Fixed: G, R_0, T_0, P_0





Complex admittance fits: 2 body model





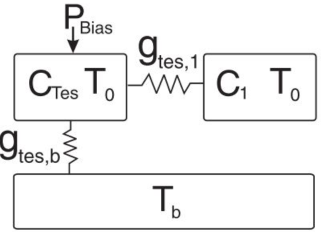
Bias parameters for a representative point:

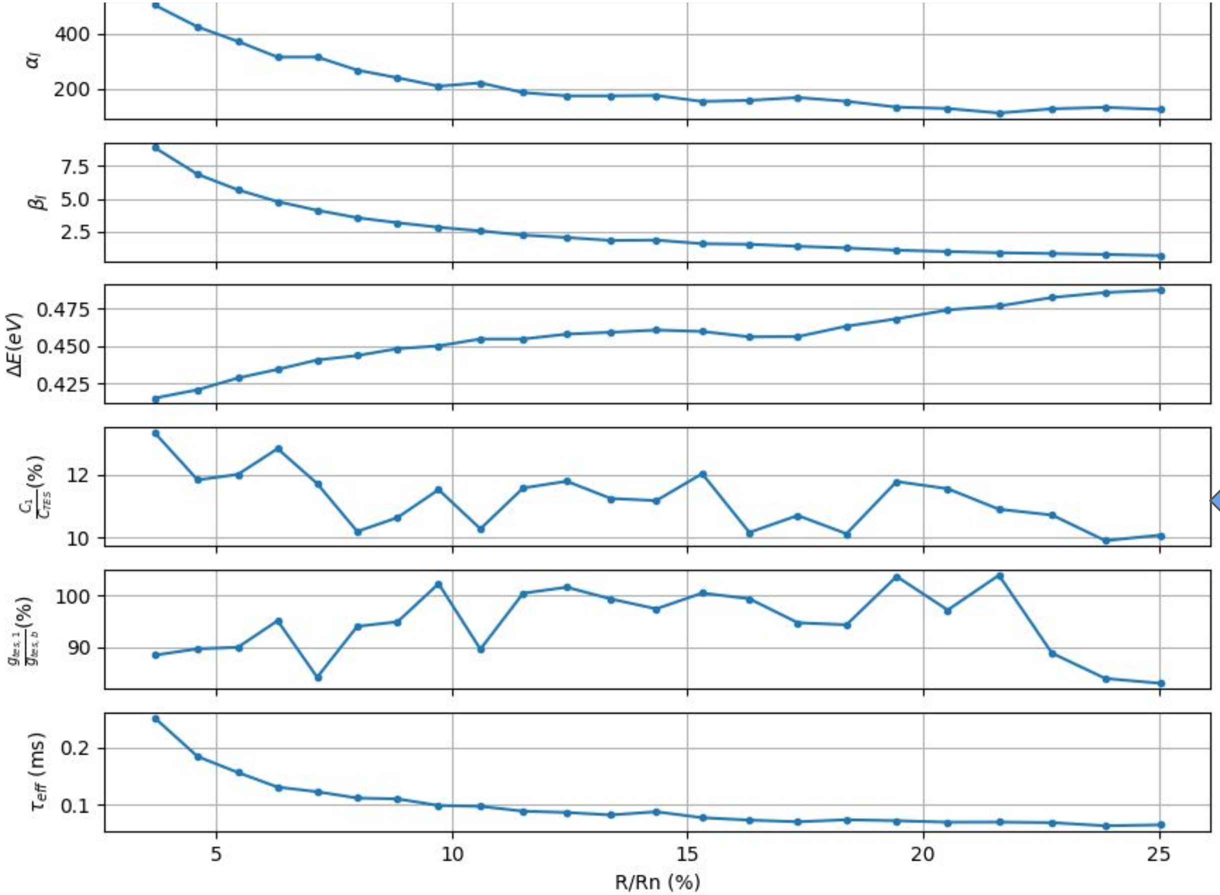
Thermal model : Hanging model (2 body)

T_b = 61.623 mK

Eliminated a lot of the systematics from residuals compared to the one-body model -- Better estimation of fall time.

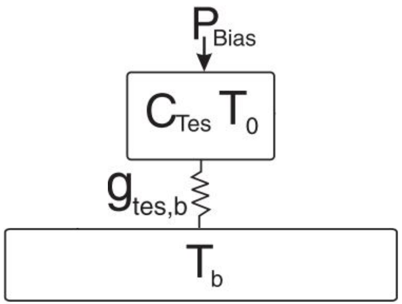
Fit results: 2-body model

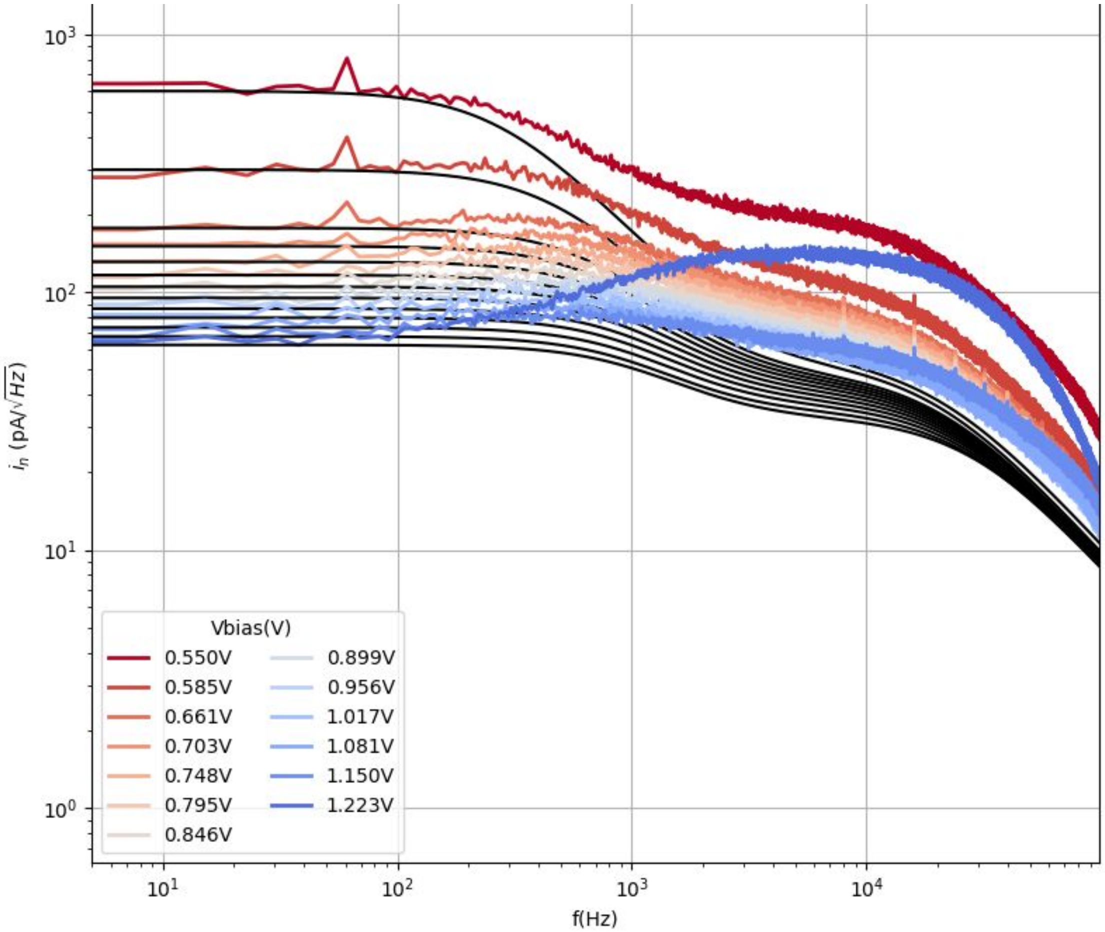




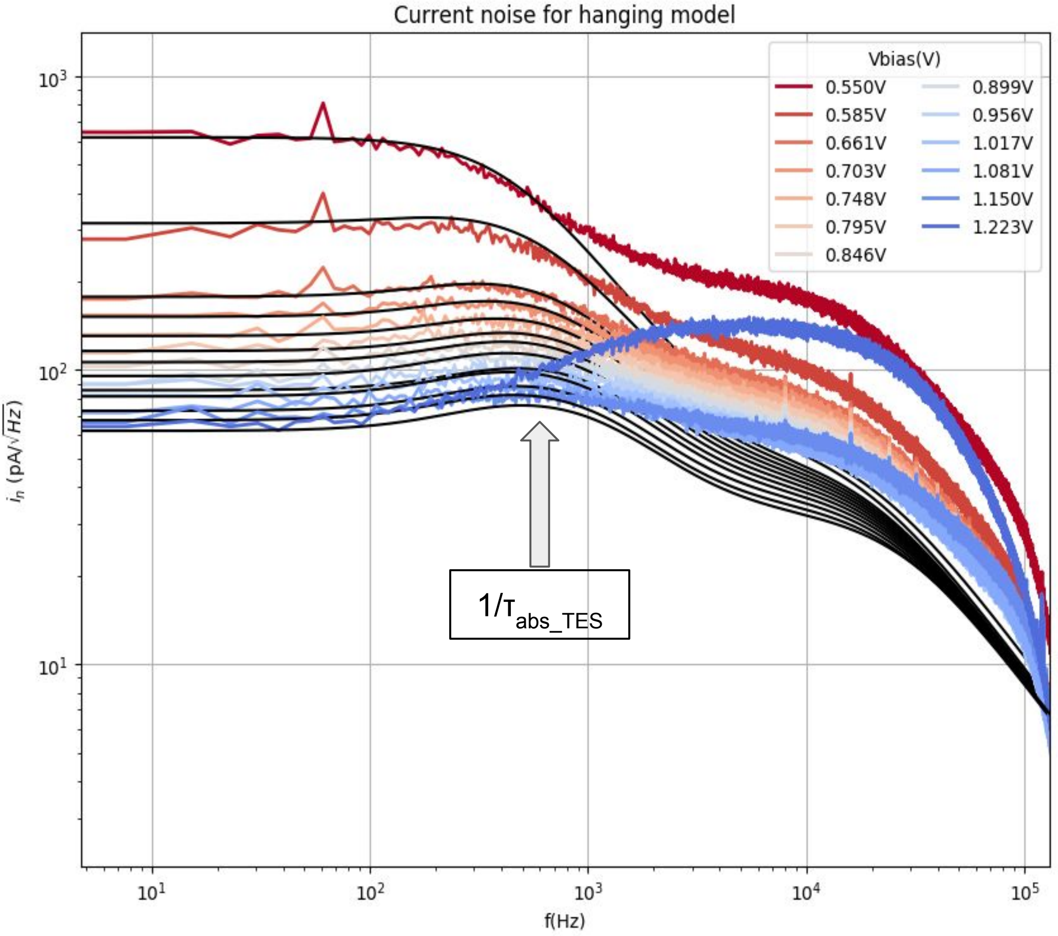
The extra ~10% C of the hanging body can be attributed to bismuth absorber on top of gold

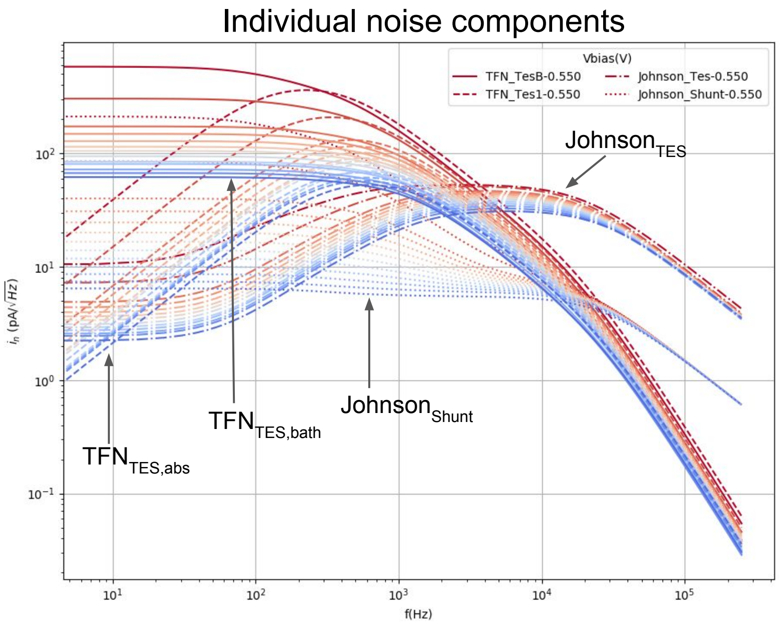
Current noise: single body model





Current noise: 2 body model (no $1+M^2$)

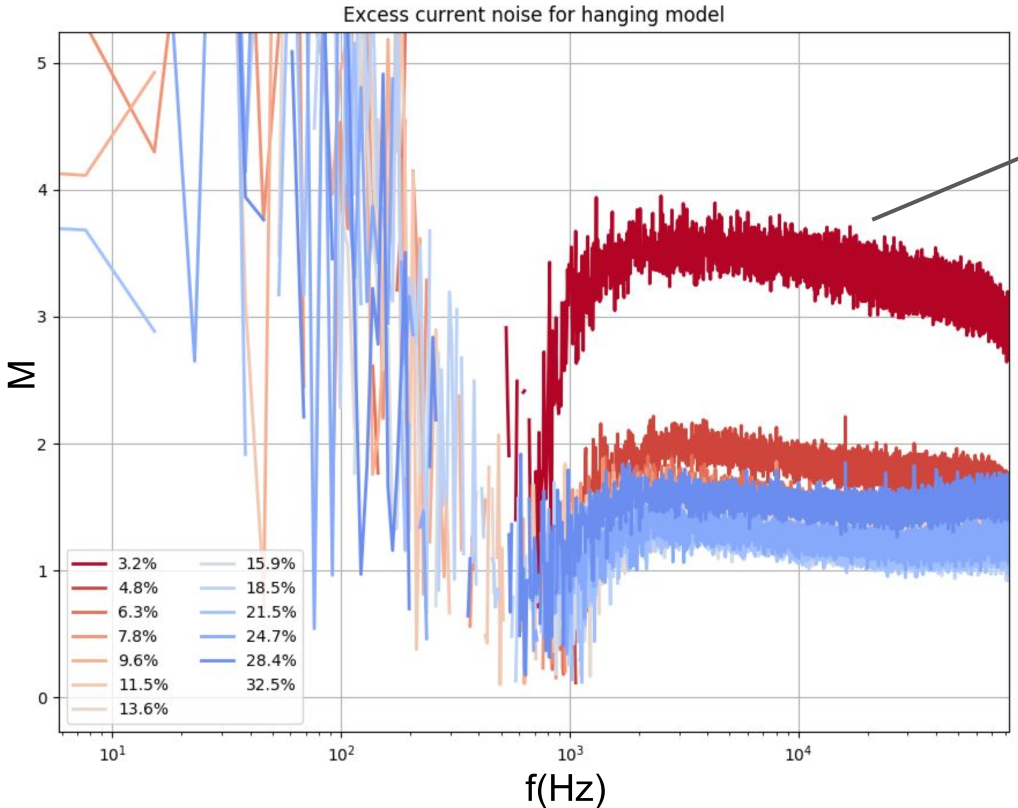


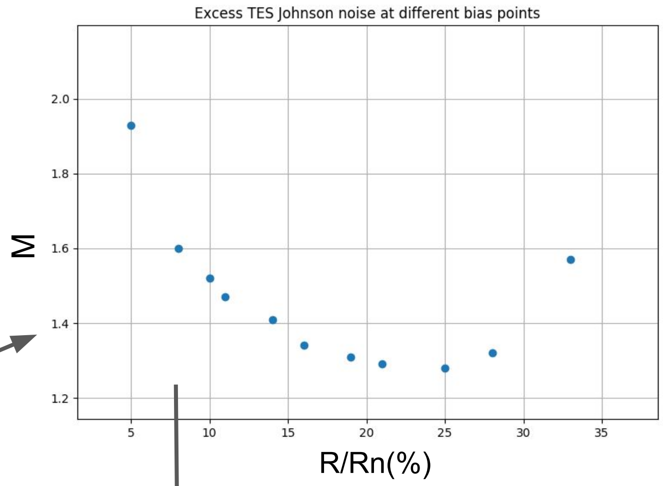


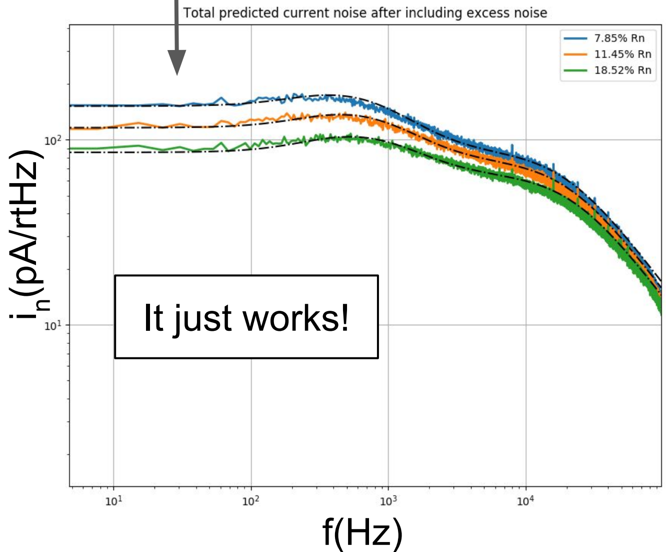
Two-body model correctly predicts bump at 500 Hz, corresponding to $1/\tau_{abs\_TES}$. Excess seen at 10kHz has shape of TES Johnson noise.

Excess Noise

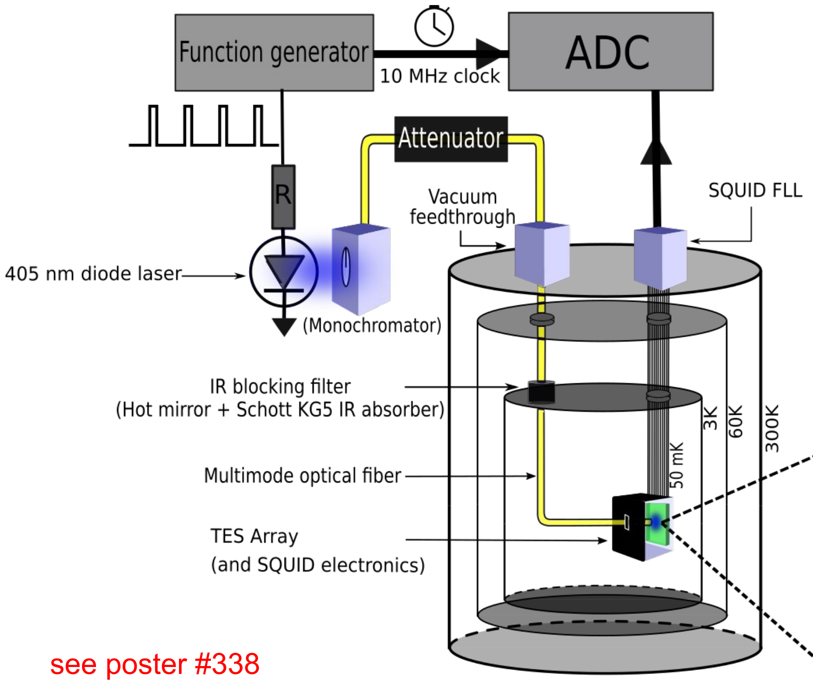
$$\frac{S_{P,measured}(\omega)}{S_{P,predicted}(\omega)}\Big|_{JohnsonTES} = 1 + M^2$$

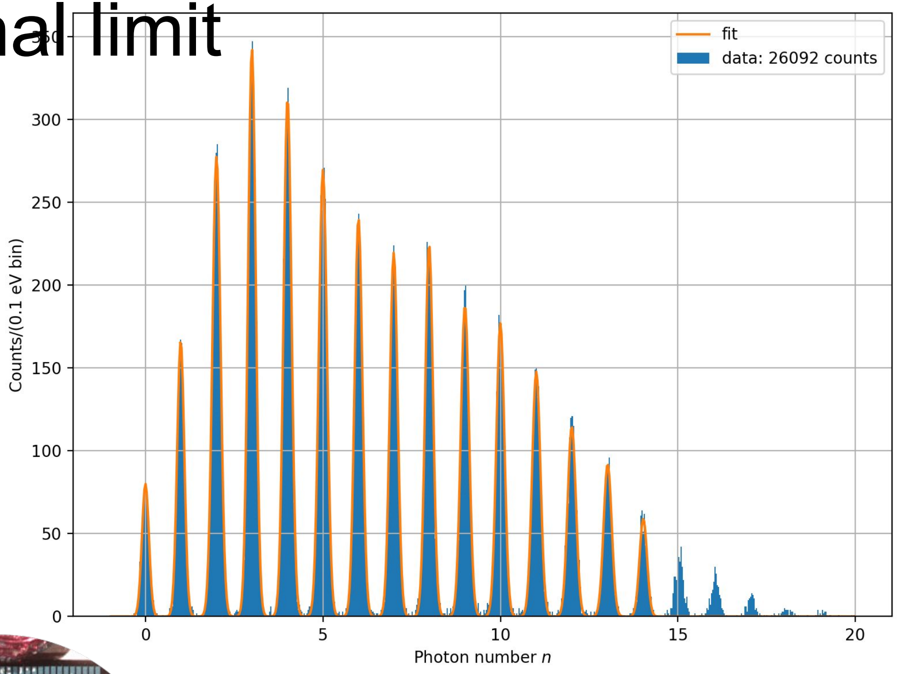


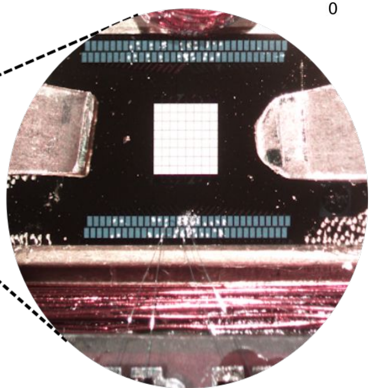




Pulse shape in the small signal limit







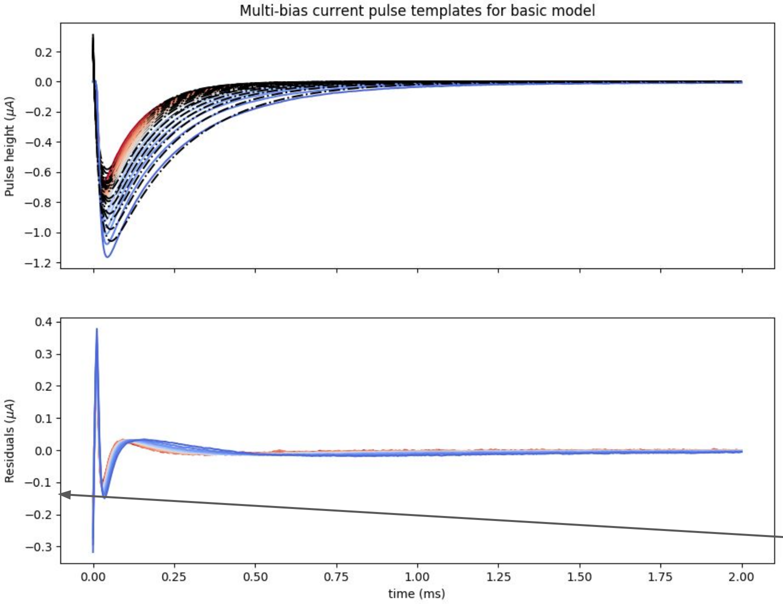
Obtain pulse shape in small signal limit

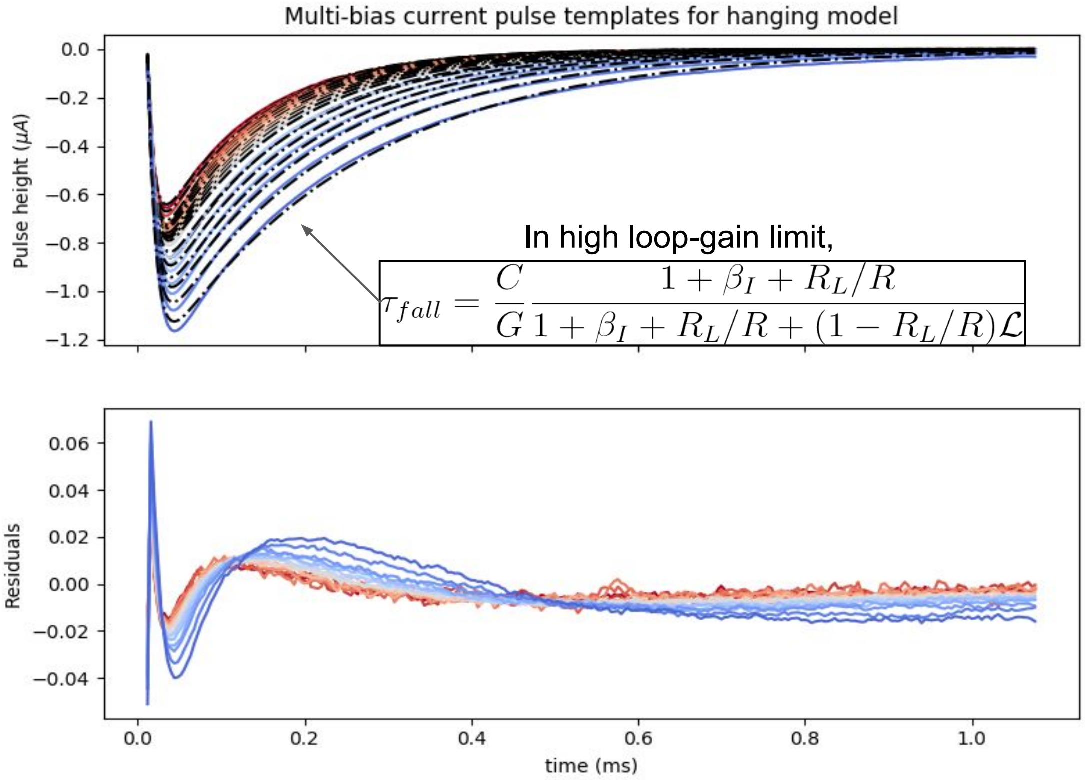
Photon number resolution gives absolute pulse energy calibration

see poster #338
(Felix Jaeckel et al.)

Photon pulses

Bunches of 3 eV photons made by the laser pulser form pulse templates
Note: This is not a fit but a prediction of pulse shape using derived parameters from TF fits.





In high loop-gain limit,

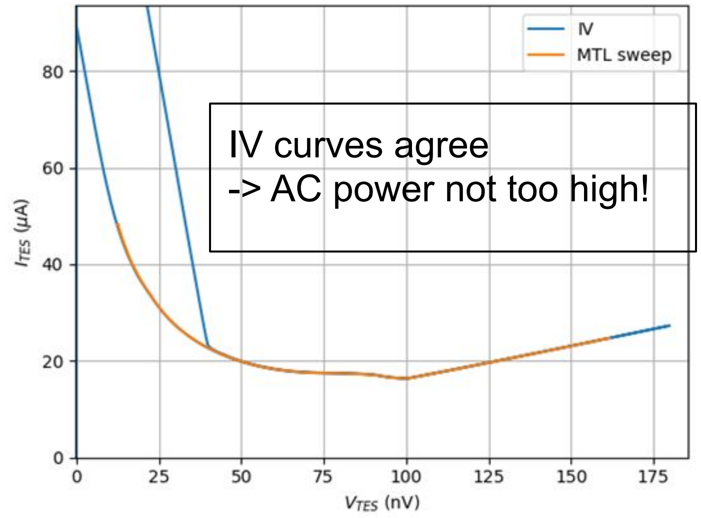
$$\tau_{fall} = \frac{C}{G} \frac{1 + \beta_I + R_L/R}{1 + \beta_I + R_L/R + (1 - R_L/R)\mathcal{L}}$$

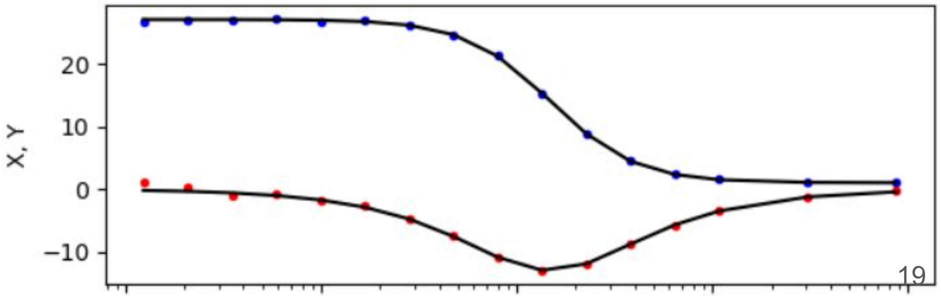
Basic model doesn't fit pulses very well
(10x worse on residuals)

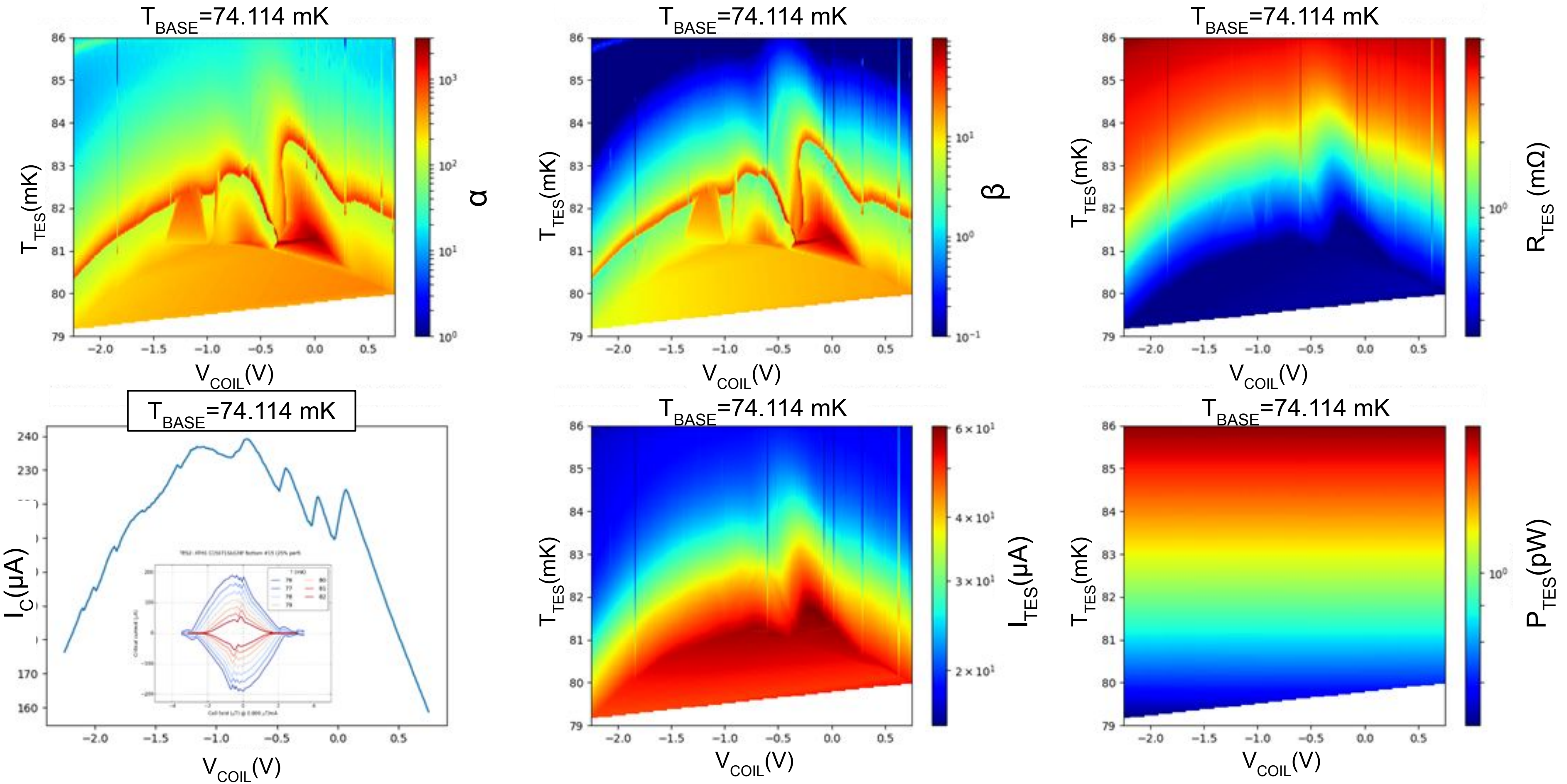
Complex impedance with multitone lock-in

Measure complex impedance across the transition surface quickly and efficiently (Mark Lindeman 2008)

- Excite with $V_{bias} = V_{DC} + \sum_i A_i \sin(\omega_i t)$ and demodulate V_{squid} at all ω_i of interest
- We do it in real time with DAQ & software lock-in on a PC (~ 20 frequencies simultaneously)
- Final lock-in LP filtering using non-causal forward-backward filter to avoid phase shifts
- Sweep bias and keep other parameters fixed
- Record accurate DC level to track bias point







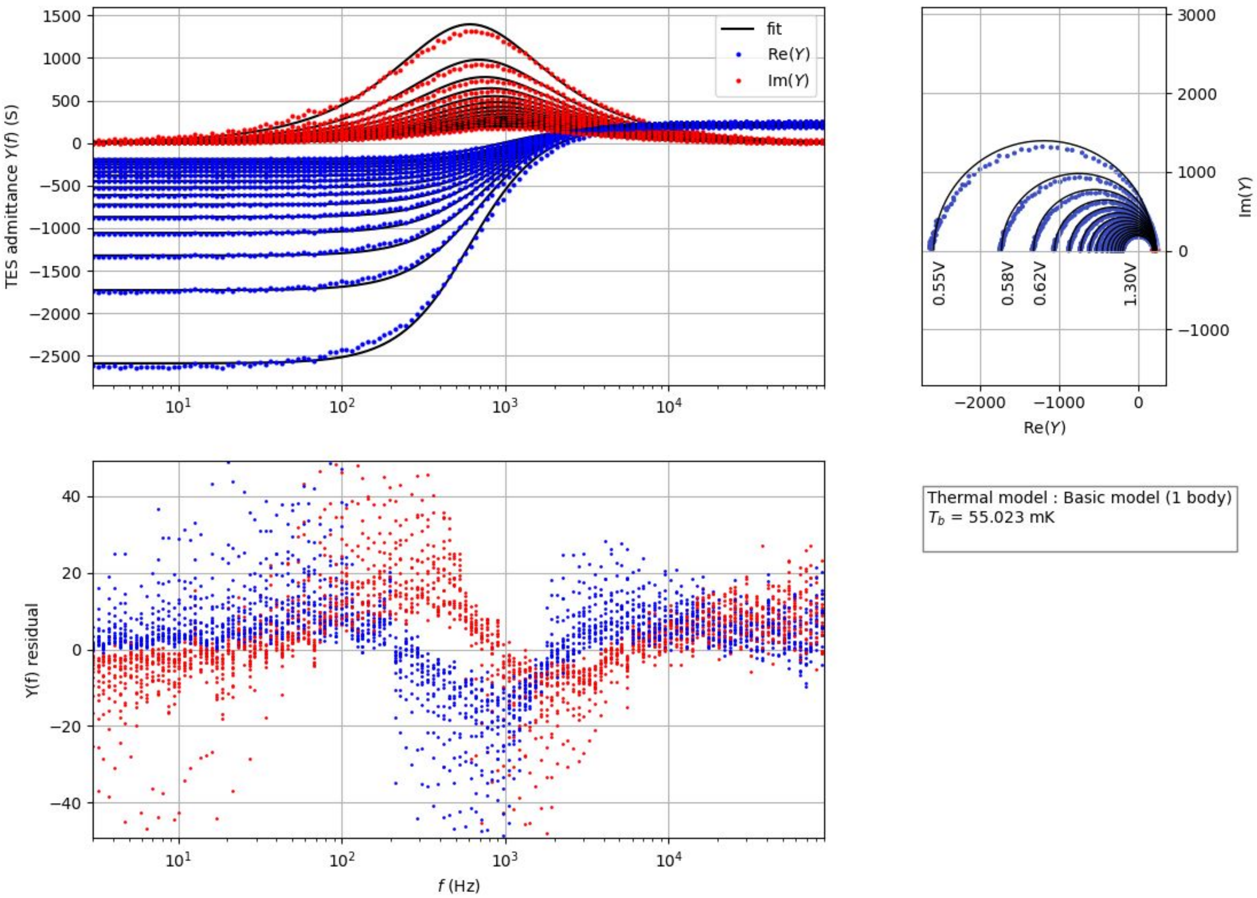
Measured and fit 50,000 TF overnight to produce detailed maps of α, β, R_{tes} vs applied magnetic field and operating temperature

Conclusions

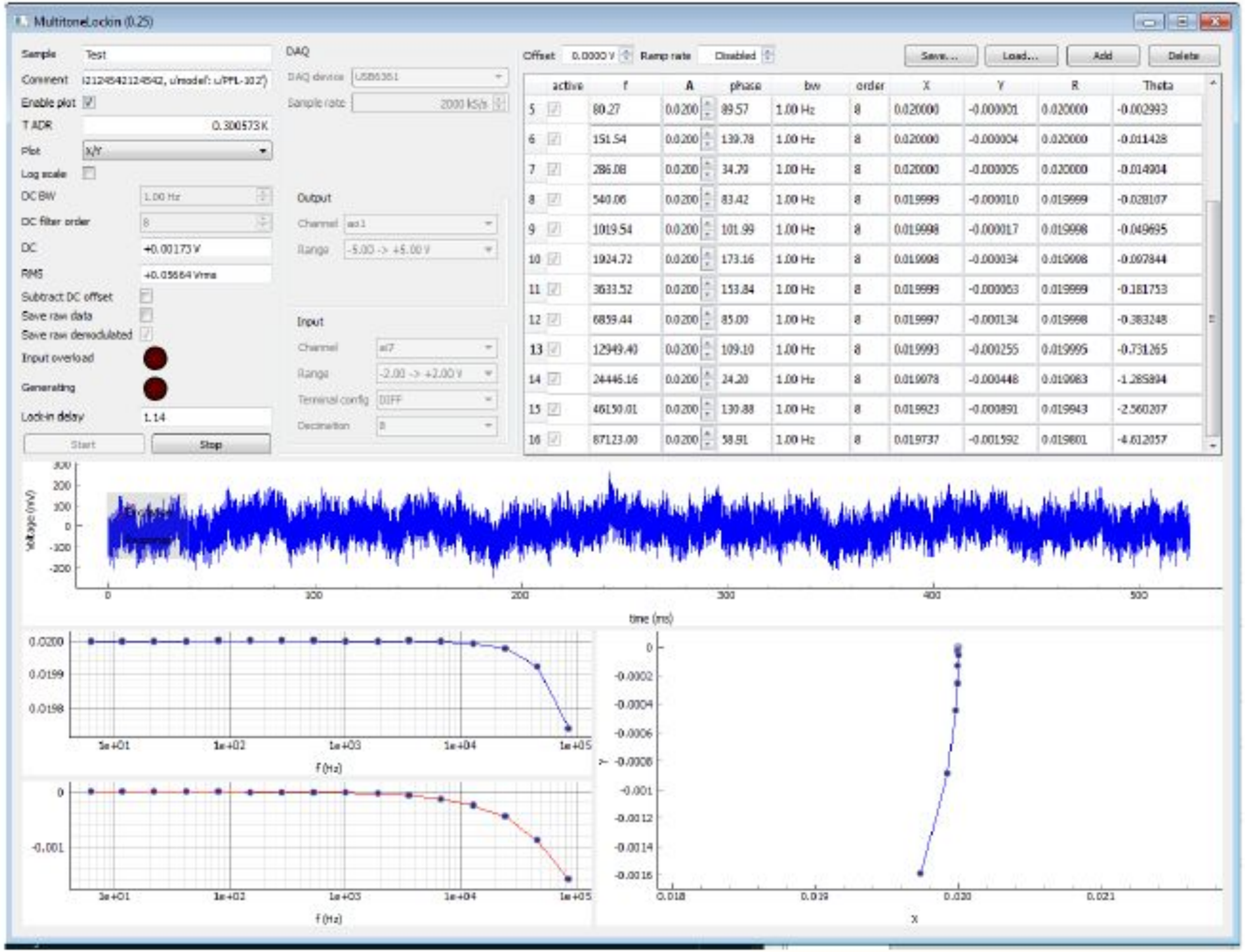
1. Shapiro steps give repeatable, high accuracy determination of shunt resistance.
2. Thevenin equivalent circuit method results in accurate impedance measurements.
3. Small signal pulses (e.g. photon pulser) help inform thermal model.
4. Devices investigated here described well by two-body model does a good job.
5. More work remains to be done to fully close the loop.

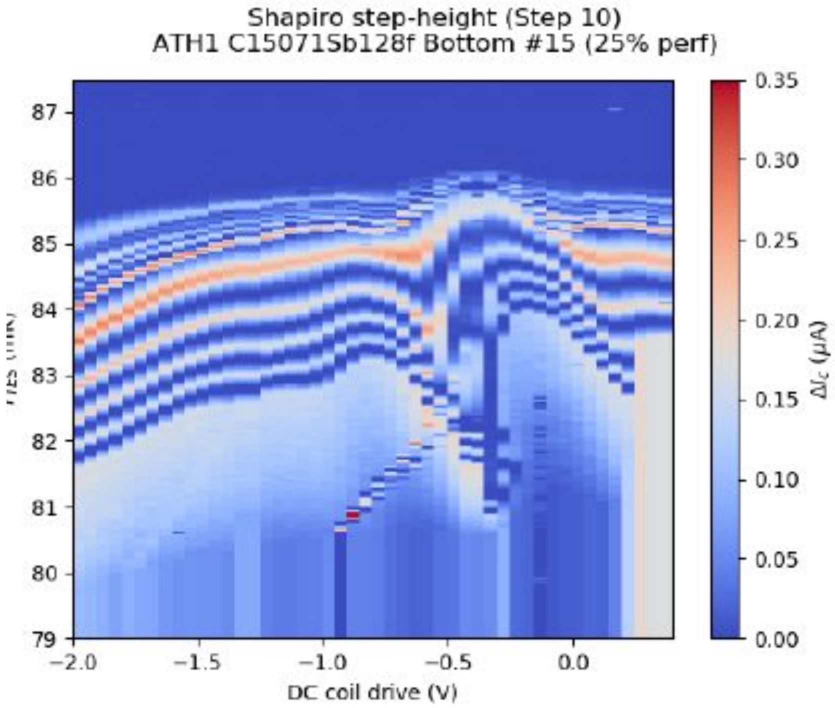
BACKUP

Transfer Function Fits
G8C/TES2: NIST dtest21a #2
AC drive=40 mV

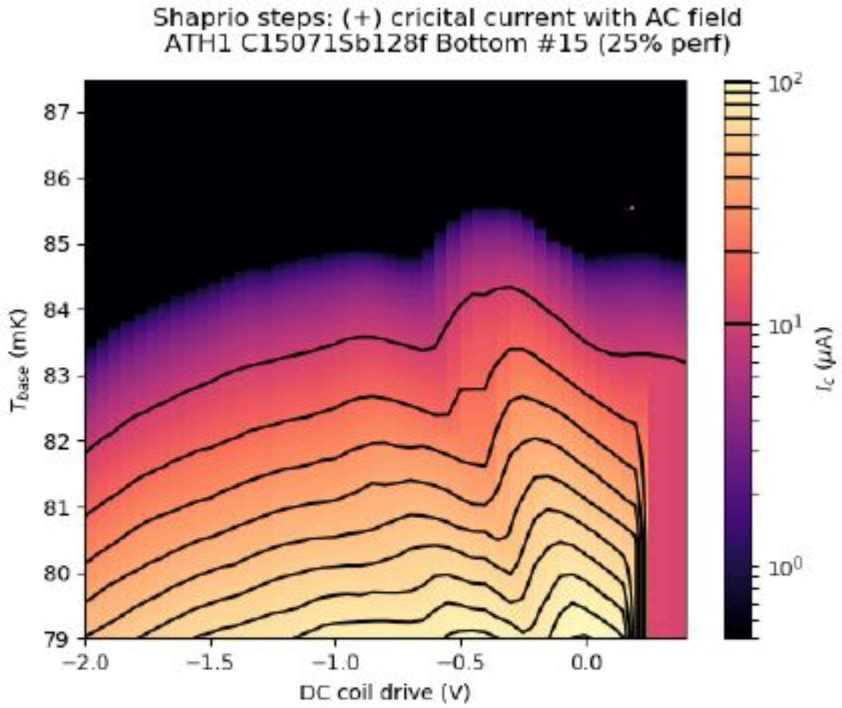


Thermal model : Basic model (1 body)
T_b = 55.023 mK


MultitoneLockin (0.25)
Sample
Test
Comment
Enable plot
T ADR
0.300573 K
Plot
X/Y
Log scale
DC BW
1.00 Hz
DC filter order
8
DC
+0.00173 V
RMS
+0.05664 Vrms
Subtract DC offset
Save raw data
Save raw demodulated
Input overload
Generating
Lock-in delay
1.14
Start
Stop
DAQ
DAQ device
USB6361
Sample rate
2000 kS/s
Output
Channel
ao1
Range
-5.00 -> +5.00 V
Input
Channel
ai7
Range
-2.00 -> +2.00 V
Terminal config
DIFF
Decimation
8
Offset
0.0000 V
Ramp rate
Disabled
Save...
Load...
Add
Delete
active f A phase bw order X Y R Theta
5 80.27 0.0200 89.57 1.00 Hz 8 0.020000 -0.000001 0.020000 -0.002993
6 151.54 0.0200 139.78 1.00 Hz 8 0.020000 -0.000004 0.020000 -0.011428
7 286.08 0.0200 34.79 1.00 Hz 8 0.020000 -0.000005 0.020000 -0.014904
8 540.06 0.0200 83.42 1.00 Hz 8 0.019999 -0.000010 0.019999 -0.028107
9 1019.54 0.0200 101.99 1.00 Hz 8 0.019998 -0.000017 0.019998 -0.049695
10 1924.72 0.0200 173.16 1.00 Hz 8 0.019998 -0.000034 0.019998 -0.097844
11 3633.52 0.0200 153.84 1.00 Hz 8 0.019999 -0.000063 0.019999 -0.181753
12 6859.44 0.0200 85.00 1.00 Hz 8 0.019997 -0.000134 0.019998 -0.383248
13 12949.40 0.0200 109.10 1.00 Hz 8 0.019993 -0.000255 0.019995 -0.731265
14 24446.16 0.0200 24.20 1.00 Hz 8 0.019978 -0.000448 0.019983 -1.285894
15 46150.01 0.0200 130.88 1.00 Hz 8 0.019923 -0.000891 0.019943 -2.560207
16 87123.00 0.0200 58.91 1.00 Hz 8 0.019737 -0.001592 0.019801 -4.612057
Voltage (mV)
time (ms)
f (Hz)
f (Hz)
Y
X

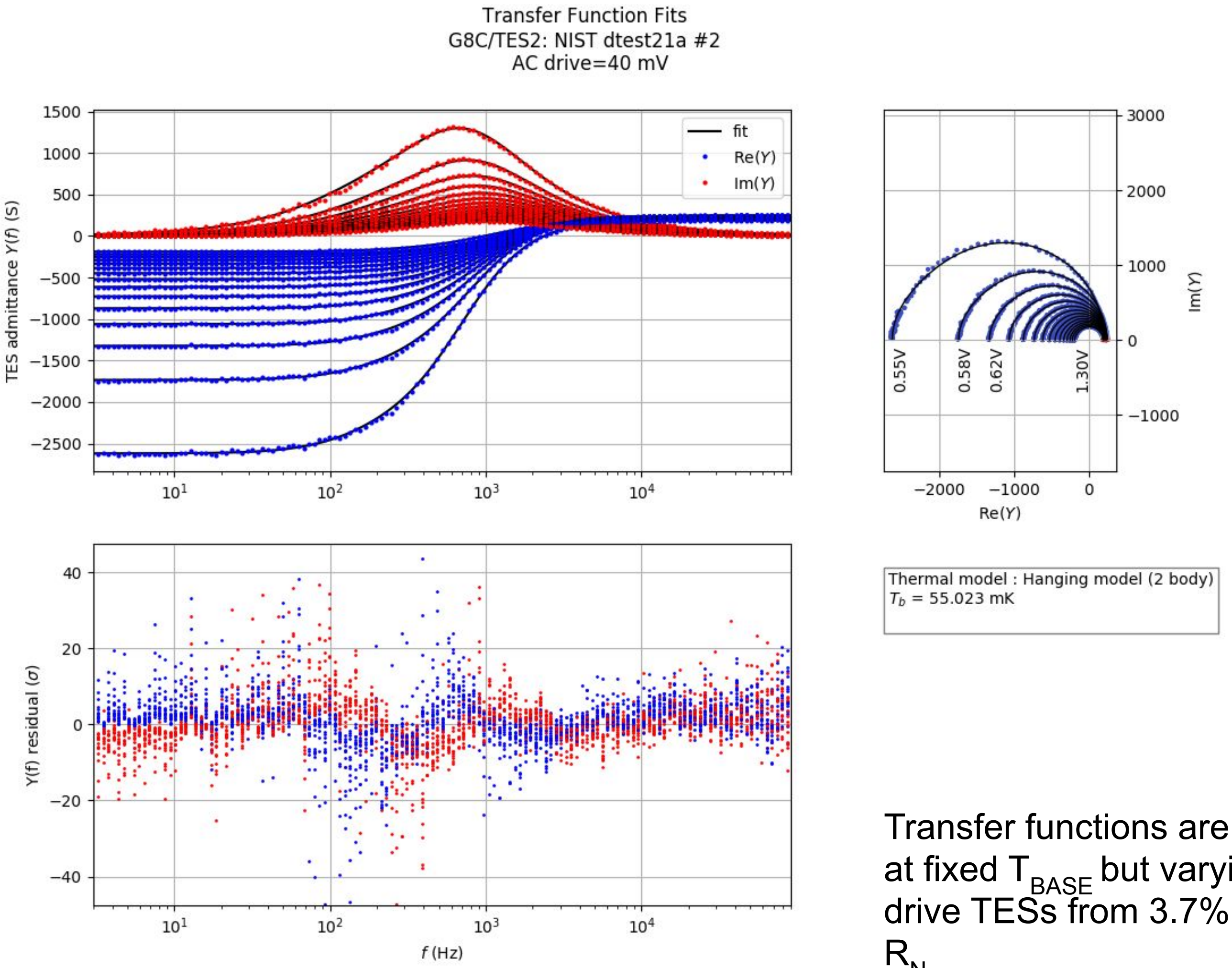


Shapiro step-height (Step 10)
ATH1 C15071Sb128f Bottom #15 (25% perf)
87
86
85
84
83
82
81
80
79
−2.0
−1.5
−1.0
−0.5
0.0
DC coil drive (V)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
ΔI_c (μA)



Shaprio steps: (+) cricital current with AC field
ATH1 C15071Sb128f Bottom #15 (25% perf)
87
86
85
84
83
82
81
80
79
T_{base} (mK)
−2.0
−1.5
−1.0
−0.5
0.0
DC coil drive (V)
10^2
10^1
10^0
I_c (μA)

TES: TES2
Model:
two-body



Transfer functions are recorded at fixed T_{BASE} but varying V_{BIAS} to drive TESs from 3.7% R_N to 25% R_N

Variables: α, β, Cᴛes

Fixed: G