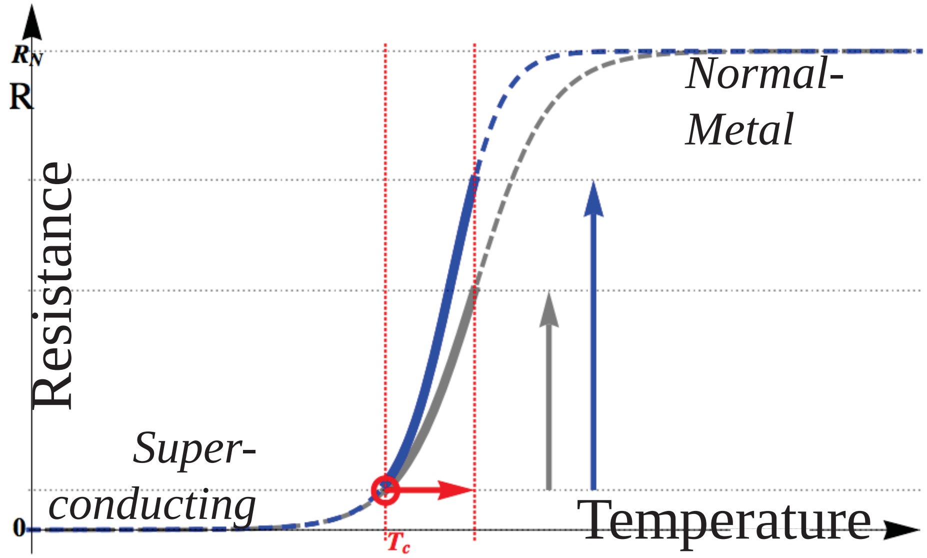
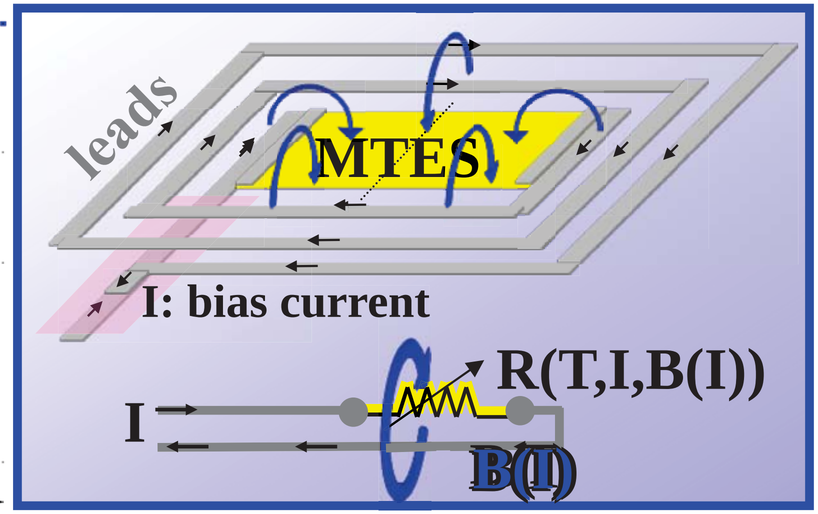
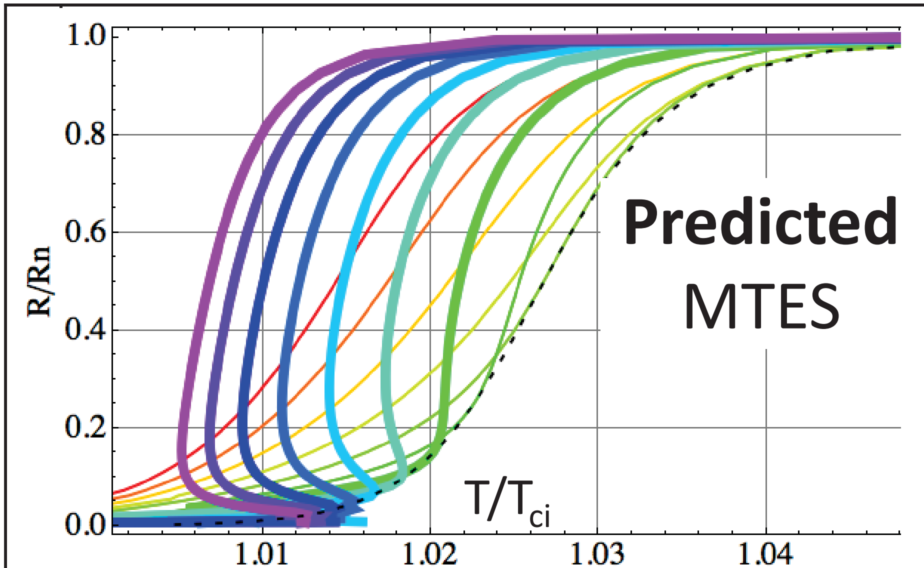
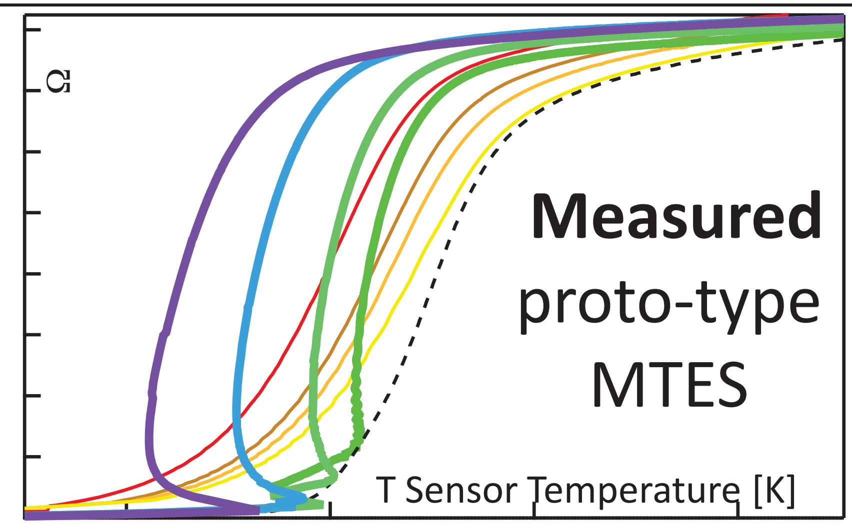
The Magnetically Tuned Transition-Edge Sensor









1	Sharper field-tunable resistive transitions	✓ Yes!
2	Increased X-ray pulse signal size.	✓ Yes!
3	Faster X-ray pulse decay times	✓ Yes!
4	Increased Signal to Noise	✓ Yes!
5	Reduction in Johnson Noise	?
6	Reduction in ΔE_{FWHM}	?

Predicted MTES properties	Measured on Proto-type MTES device	Comments
At B_a=0, β decreases as |g| decreases.	✓ yes	From Z and IV measurements.
β further reduced for B_a>0 and g<0.	✓ yes	From Z and IV measurements.
MTES β reduced by more than a factor of 10. *	✓ yes	From Z measurements
β reduced over the entire operating bias trajectory.	✓ yes	Measured from R/R_N = 0.05 to 0.95
β reduction accompanied by a desirable increase in α.	✓ yes	Decrease in β/α.
Increase in X-ray pulse signal size.	✓ yes	Increased pulse heights until saturation
Faster X-ray pulse decay times	✓ yes	MTES 5 times faster
Decrease in NEP §	✓ yes	Magnetic tuning dropped NEP from 1.6 eV to 0.24 eV at 6 keV.
β can be even assume negative values	✓ yes	From IV and Z measurements
It is possible to stably bias the MTES in this negative β regime.	✓ yes	From Z measurements
Reduction in Johnson Noise §	? (untested)	Suffered from increase pickup noise due to prototype design
Reduction in ΔE_{FWHM} §	? (untested)	Pickup noise and heat capacity too small for the radically increased responsivity.

*: if resistively shunted junction weak-link model is satisfied

§ : if higher order nonlinear nonequilibrium Johnson noise terms are negligible and no new introduced noise sources.

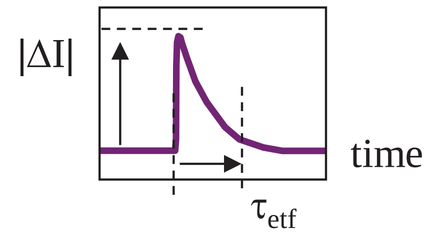
A "better" TES? Where do we start?

Small Signal Limit TES Calorimeter Expressions

$$\Delta I(t) \approx \boxed{\frac{\alpha}{1+\beta}} \frac{I_0 R_0}{T_0} \frac{E_\gamma}{C} \exp\left(-t/\tau_{etf}\right)$$

$$\tau_{etf} = \frac{\tau}{1+\mathscr{L}} \qquad \tau = C/G \qquad \mathscr{L} = \boxed{\frac{\alpha}{1+\beta}} \frac{I_0^2 R_0}{T_0 G}$$

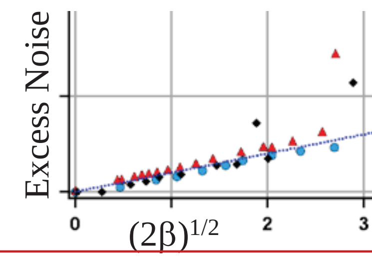
Measured Signal



$$V_n = \sqrt{4 k_B T_0 R_0 \boxed{(1+2\beta} + \theta^2)(1+M^2)}$$

K. D. Irwin 2006

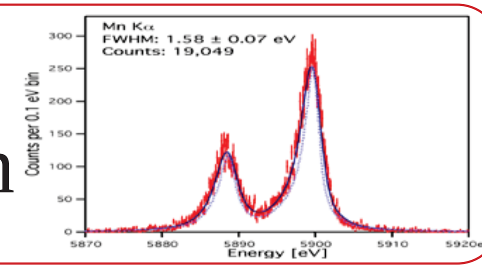
Johnson Noise



$$\Delta E_{FWHM} \approx \boxed{\left(\frac{1+2\beta}{\alpha^2}\right)^{1/4}} 2.355 \sqrt{4 k_B C T_0^2 \sqrt{n F (1+M^2)}}$$

K. D. Irwin G.C. Hilton 2005

Energy Resolution



The Goal: decrease β while maintaining a large (or larger) α

Goal: $\beta\Downarrow$, $\alpha\Uparrow$ ➡

- -larger signal size
- -faster recovery time
- -reduced Johnson Noise
- -improved energy resolution

Including Magnetic Field Effects in the TES R(T,I,B)

For the first time we include the magnetic field dependence in the TES response using our theoretical model. In other words, we express the TES resistance R as function of temperature T, current I, *and magnetic field B.*

We then expand the R(T,I,B) function about a operating point $\mathbf{v_0} = (R_0, T_0, I_0, B_0)$

substitute the definitions for deviations from this operating point $\delta T = T - T_0\ ,\ \delta I = I - I_0\ ,\ \delta B = B - B_0$

$$R(T,I,B) \approx R_0 + \frac{\partial R}{\partial T}\,\delta T + \frac{\partial R}{\partial I}\,\delta I + \frac{\partial R}{\partial B}\,\delta B$$

We then use our successful theoretical model describing the magnetic self-fielding effect which expresses total field B as a sum of a constant applied field B_a and the self-field g I where g is a geometric "self-fielding factor" and TES current I;

$$\mathbf{B} = B\,\hat{\mathbf{z}} \qquad B_{self} = B_{self\ I\ injection} + B_{self\ internal}$$

$$B = B_a + B_{self} = B_a + g\,I \qquad \delta B = g\,\delta I$$

with device parameters definitions

$$\alpha \equiv \frac{T_0}{R_0}\frac{\partial R}{\partial T} \qquad \beta_I \equiv \frac{I_0}{R_0}\frac{\partial R}{\partial I} \qquad \gamma \equiv \frac{B_0}{R_0}\frac{\partial R}{\partial B} \qquad R(T,I,B) \approx R_0\left(\alpha\frac{\delta T}{T_0} + \beta_I\frac{\delta I}{I_0} + \gamma\frac{\delta B}{B_0}\right)$$

collecting terms, we write in a familiar form:

$$\beta \equiv \beta_{meas} = \beta_I + \beta_B$$

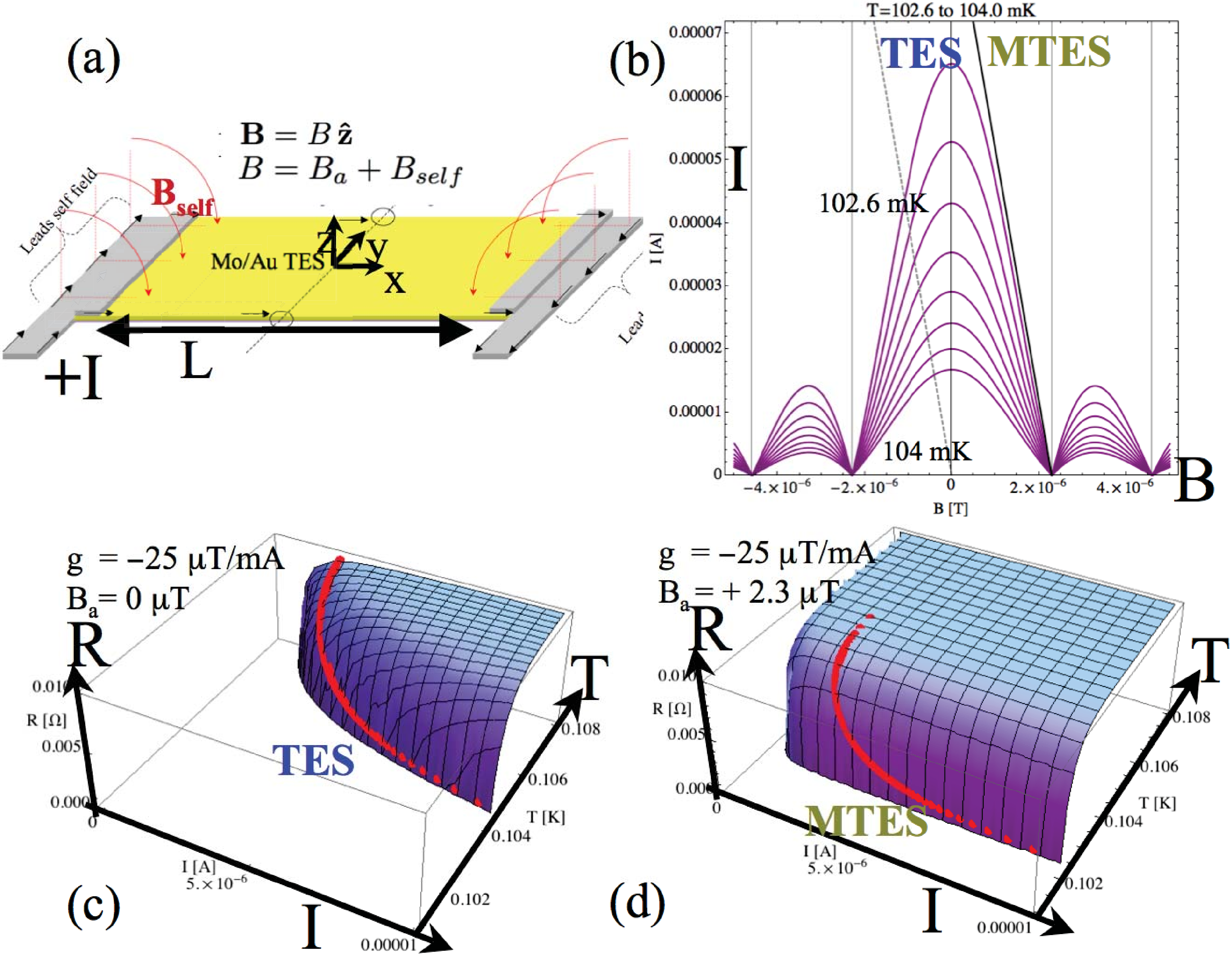
NEW

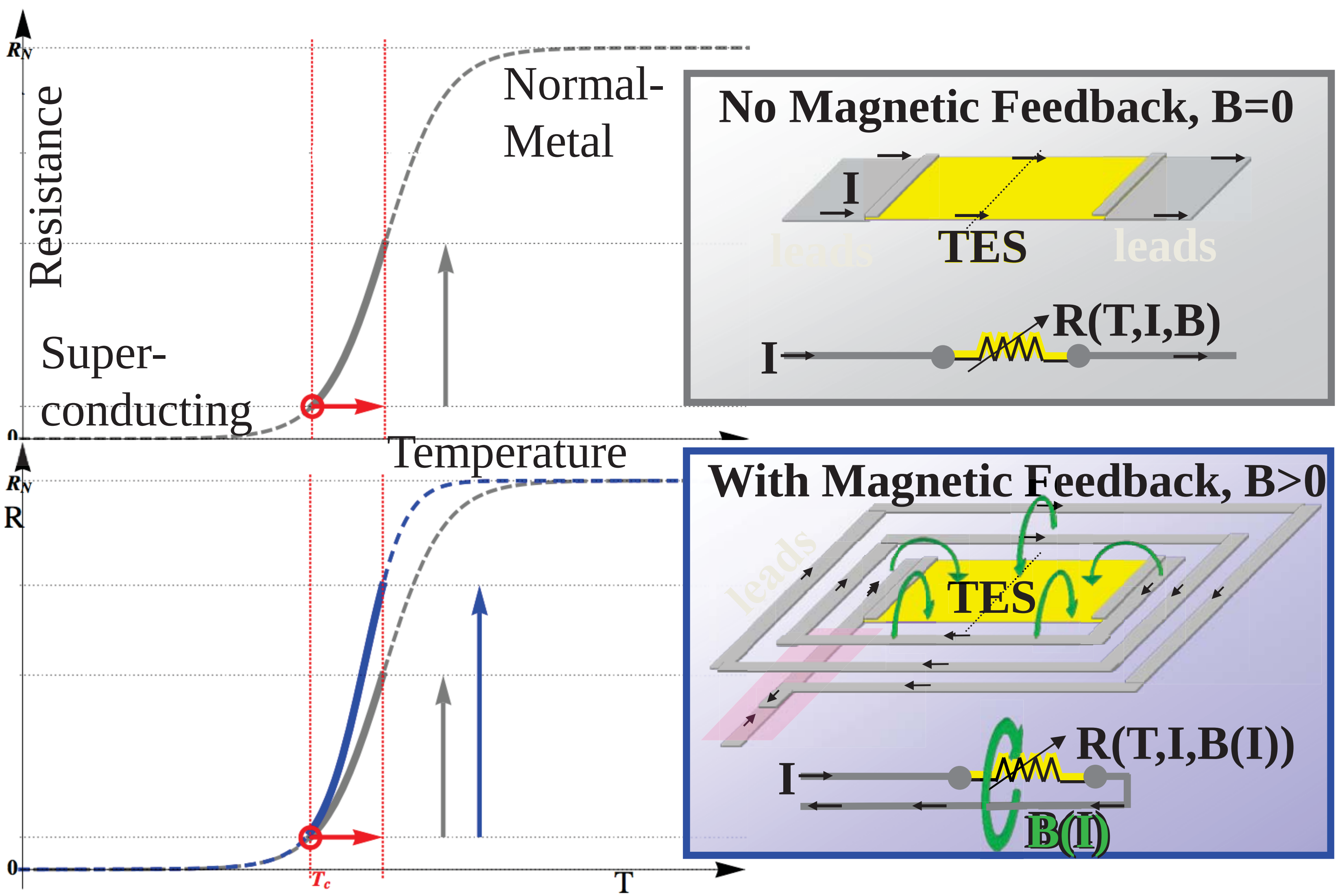
$$R(T,I,\underline{B}) \approx R_0 + \alpha\frac{R_0}{T_0}\,\delta T + \beta\frac{R_0}{I_0}\,\delta I$$

$$\boxed{\beta = \beta_I + \frac{g\,I_0}{R_0}\frac{\partial R}{\partial B}}$$

GREAT !!!!

Magnetically tune **the TES to lower β.**


(a)
$\mathbf{B} = B\,\hat{\mathbf{z}}$
$B = B_a + B_{self}$
$\mathbf{B}_{\mathbf{self}}$
Leads self field
Mo/Au TES
z
y
x
L
+I
(b)
T=102.6 to 104.0 mK
TES
MTES
I
102.6 mK
104 mK
B
I [A]
B [T]
0.00007
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0
$-4.\times10^{-6}$
$-2.\times10^{-6}$
0
$2.\times10^{-6}$
$4.\times10^{-6}$
(c)
g = −25 μT/mA
B_a = 0 μT
R
T
TES
R [Ω]
0.005
T [K]
0.108
0.106
0.104
0.102
I [A]
$5.\times10^{-6}$
0.00001
0
I
(d)
g = −25 μT/mA
B_a = + 2.3 μT
R
T
MTES
R [Ω]
0.005
T [K]
0.108
0.106
0.104
0.102
I [A]
$5.\times10^{-6}$
0.00001
0
I



R_N
Resistance
Normal-
Metal
Super-
conducting
0
Temperature
No Magnetic Feedback, B=0
I
TES
leads
leads
R(T,I,B)
I
R_N
R
0
T_c
T
With Magnetic Feedback, B>0
leads
TES
R(T,I,B(I))
I
B(I)

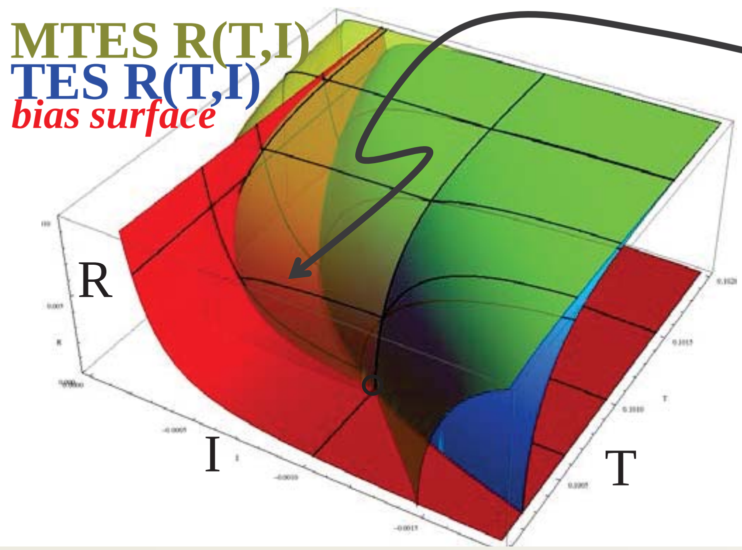
MTES = "magnetically tuned TES"... *reduced β AND increased α*

J.E. Sadleir et al. (Wednesday 11:15am)

$$\beta \equiv \beta_{meas} = \beta_I + \beta_B$$

$$R(T,I,B) \approx R_0 + \alpha \frac{R_0}{T_0}\delta T + \beta \frac{R_0}{I_0}\delta I$$

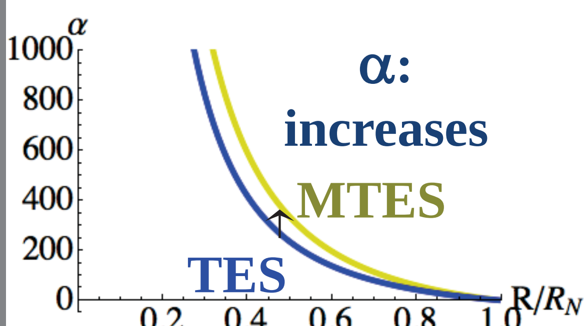
$$\boxed{\beta = \beta_I + \frac{g\, I_0}{R_0}\frac{\partial R}{\partial B}}$$

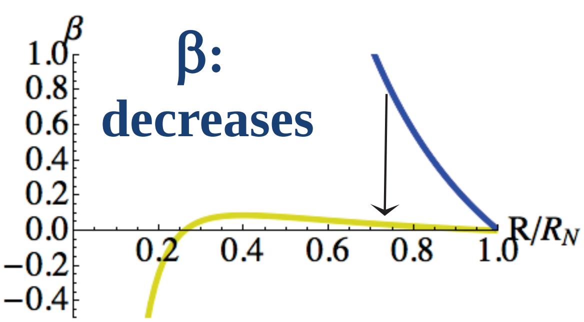


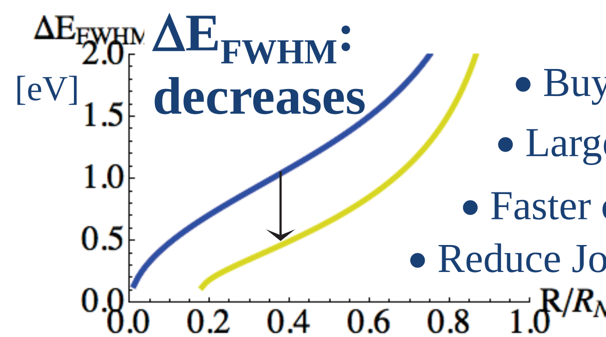
Magnetically tuning the
TES R(T,I) surface ⇒MTES R(T,I) surface

(Blue)⇒ **(Yellow)**

(1) made the $R(I)|_T$ contours $\partial R/\partial I \approx 0 \Rightarrow \beta \approx 0$.
(2) maintained a large α (a large $\partial R/\partial T$)



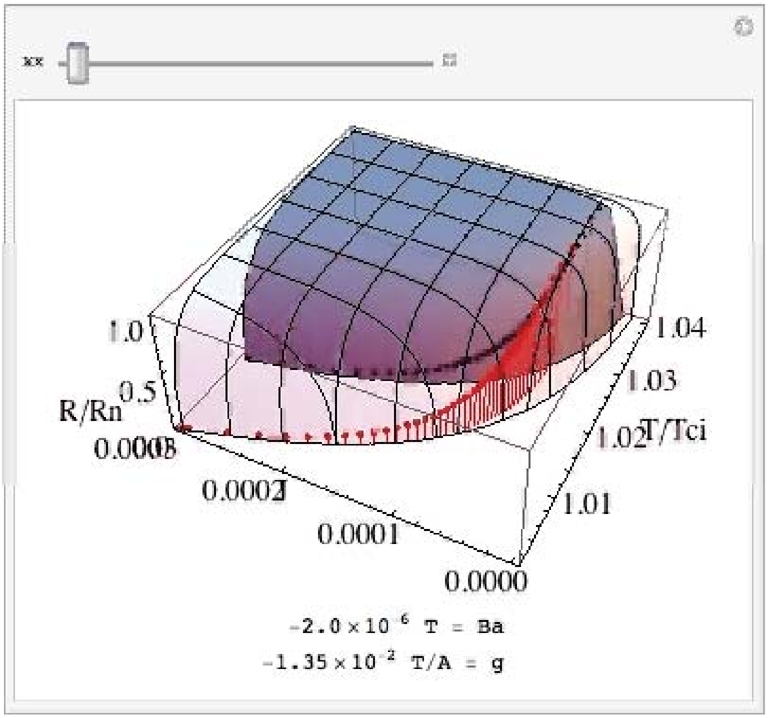




- Buys margin
- Larger signals
- Faster count rates
- Reduce Johnson Noise

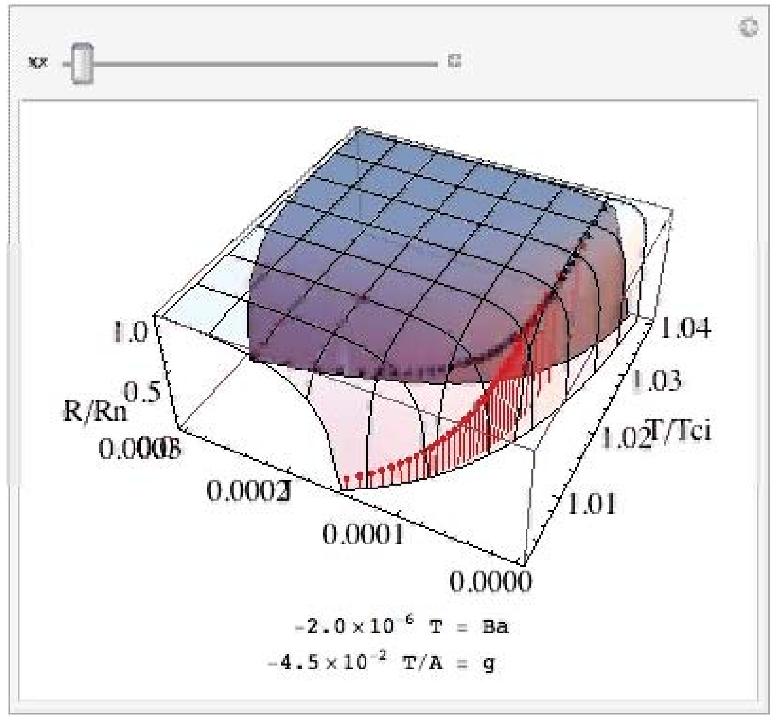
Moderate self-fielding g

beta → 0 at small R/Rn



Large self-fielding g

beta → ***Negative*** at small R/Rn



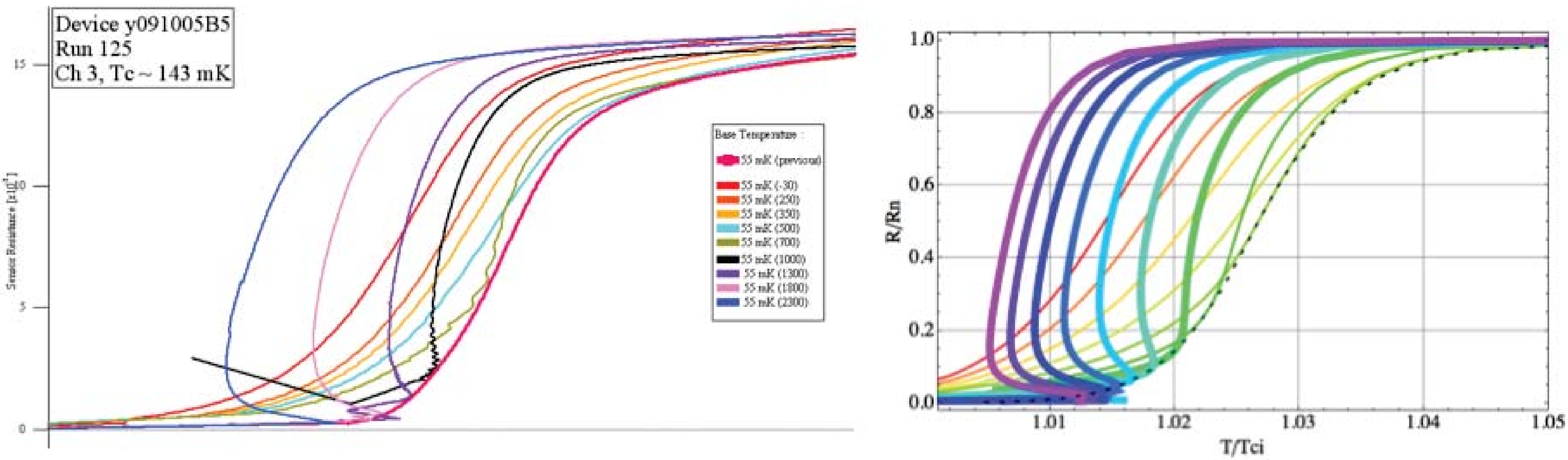


Fig. 8: Left: Measured $R_{IV}(T)$ for a fixed self-fielding constant but varying applied B. Right: the equivalent calculated curves; except that the black dashed curve represents no B and no self field. The apparent dR/dT = $\alpha_{IV} = (2\alpha x - n\beta)/(2+\beta)$, thus we have demonstrated that engineering the self-fielding can create a device with lower, and even negative, values for β.

$$\alpha_{\mathrm{IV}} = \frac{\left(J_0 \frac{\partial R_{\mathrm{th}}}{\partial J}\, \alpha - T_0\, \beta\, \frac{\partial R_{\mathrm{th}}}{\partial T}\right)}{\frac{\partial R_{\mathrm{th}}}{\partial J}\, J_0 - R_0\, \beta}$$

$$\alpha_{\mathrm{IV}} = \frac{2\,\alpha + \beta\left(1 + n\left(\frac{1}{\phi} - 1\right)\right)}{2 + \beta}$$

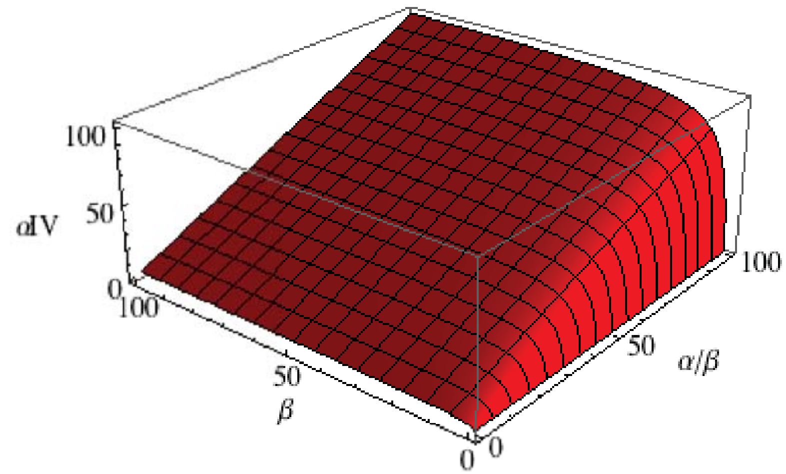
$$R_{\mathrm{th}} = \frac{P_{\mathrm{bath}}}{J^2}$$

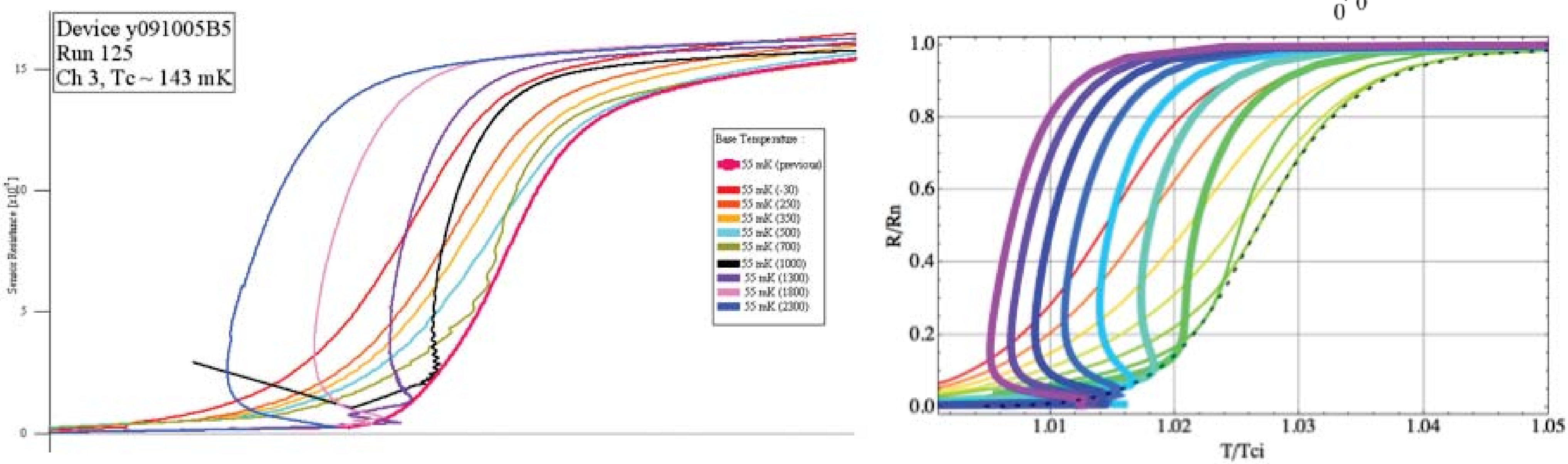
$$P_{\mathrm{bath}} = \frac{G}{n\, T^{n-1}}\left(T^n - T_b{}^n\right)$$

$$R_{\mathrm{th}} = \frac{G}{J^2\, n\, T^{n-1}}\left(T^n - T_b{}^n\right)$$

$$\phi = \left(1 - \left(\frac{T_b}{T}\right)^n\right)$$

in the limit with Tb << T then ϕ goes to 1.





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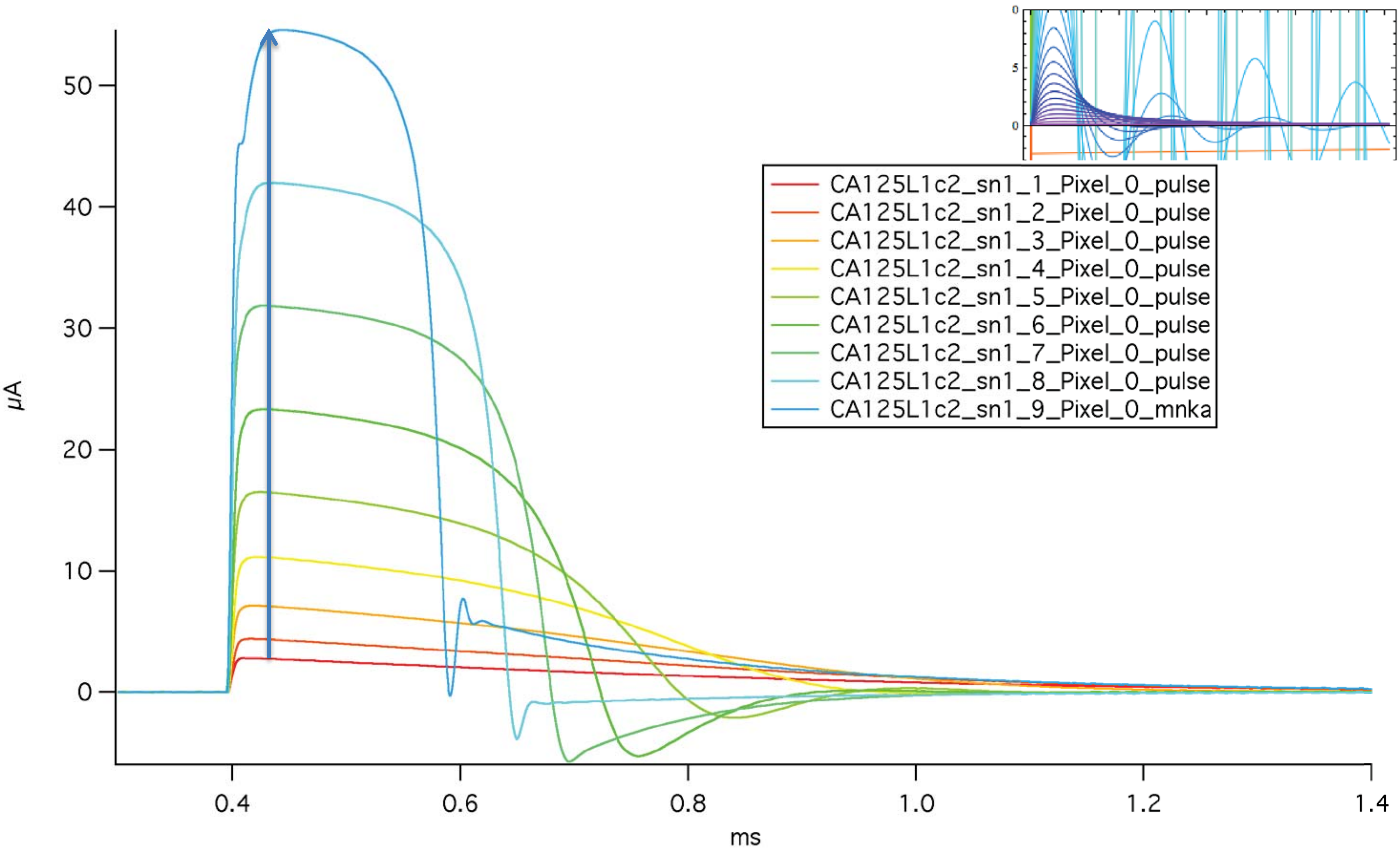
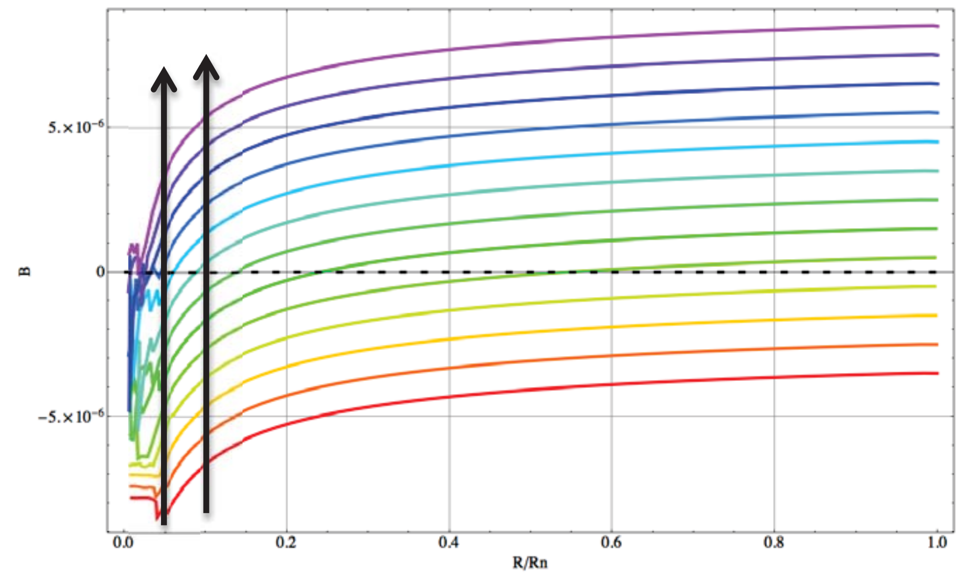
Magnetic Tuning Increasing Signal Size untill saturation



L=W=30um

g = -30 uT/mA

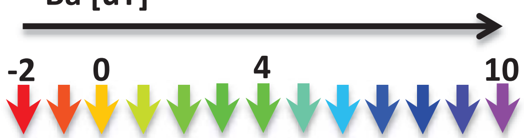


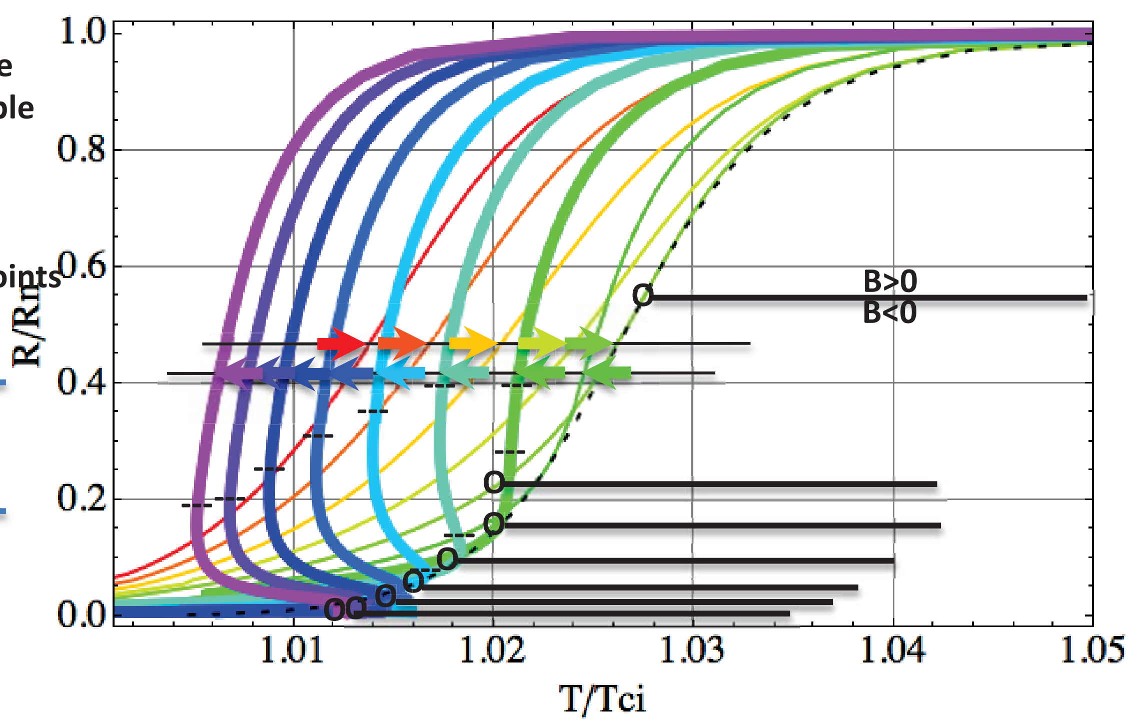
O

Landmarks:
R/Rn=0.1, 0.5, 0.9
B=0,+-.deltaB,+-3/2deltaB,
+-2deltaB,..., +-Bs/2.
beta=0
Overdamped stable
Underdamped stable
Overdamped unstable
Underdamped unstable

dIc/dT=0, and <0.

1/g versus dIc/B at points



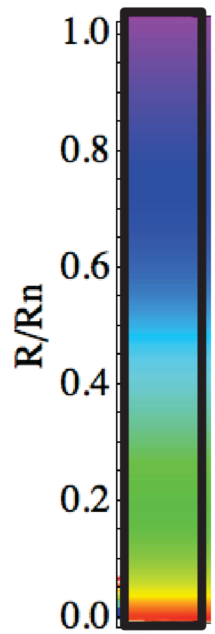


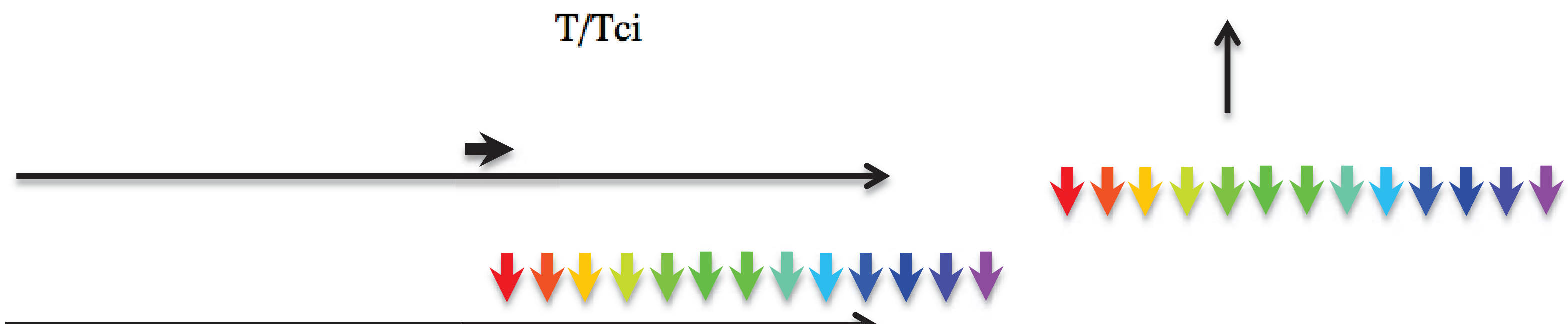
Beta < 0, Ba=4uT

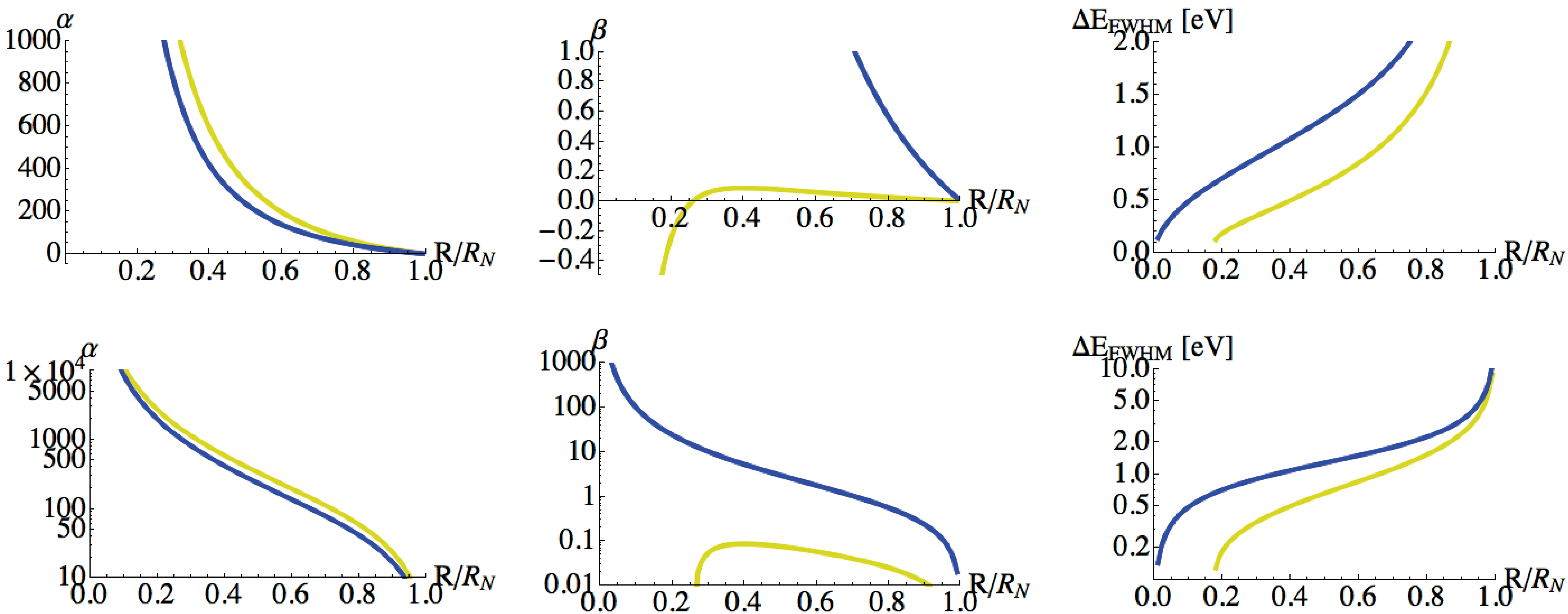
Beta < 0, Ba=5uT

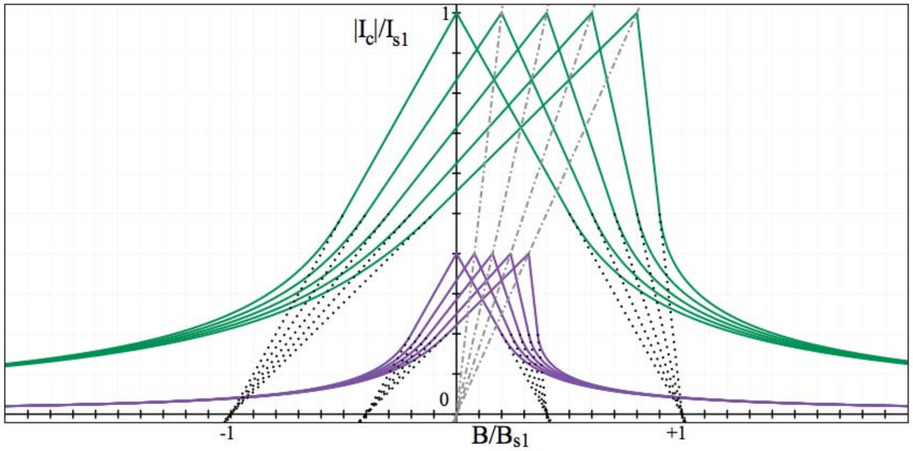
Beta < 0, Ba=9uT

Beta < 0, Ba=10uT

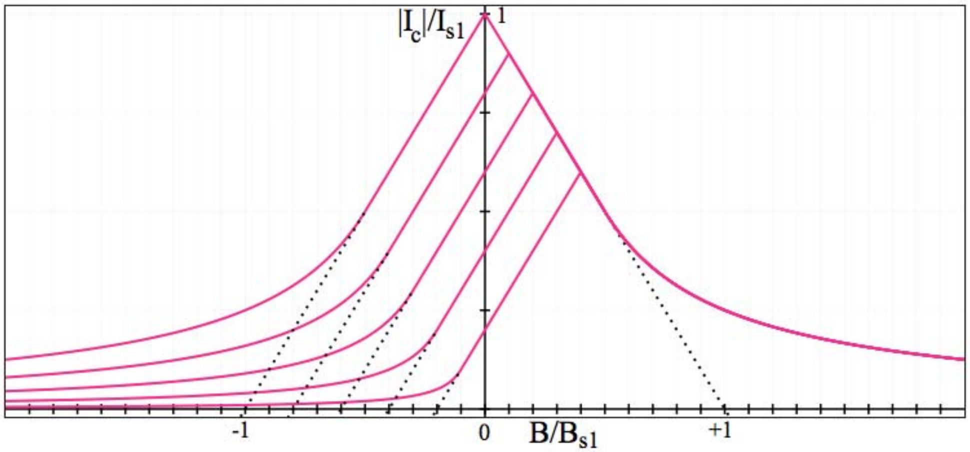




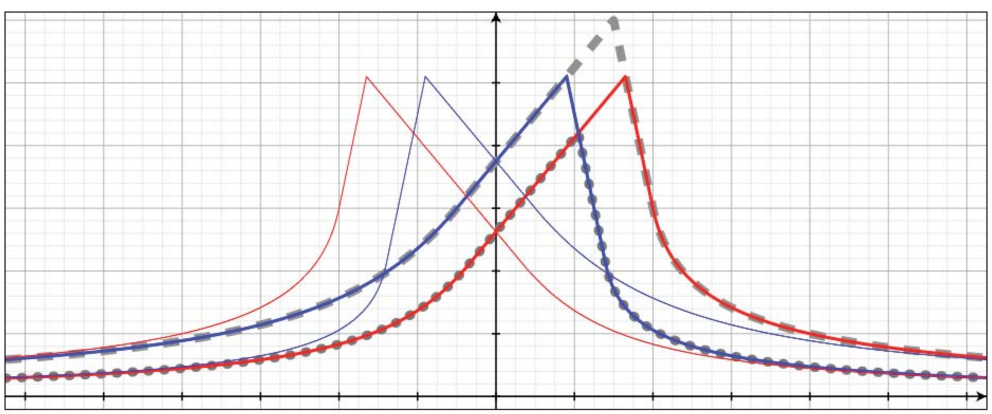

α
1000
800
600
400
200
0
0.2
0.4
0.6
0.8
1.0
R/R_N
β
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
ΔE_FWHM [eV]
2.0
1.5
0.5
0.0
1 × 10^4
5000
500
100
50
10
0.1
0.01
10.0
5.0
0.2



Asymmetric Current Injection



Asymmetric Edges



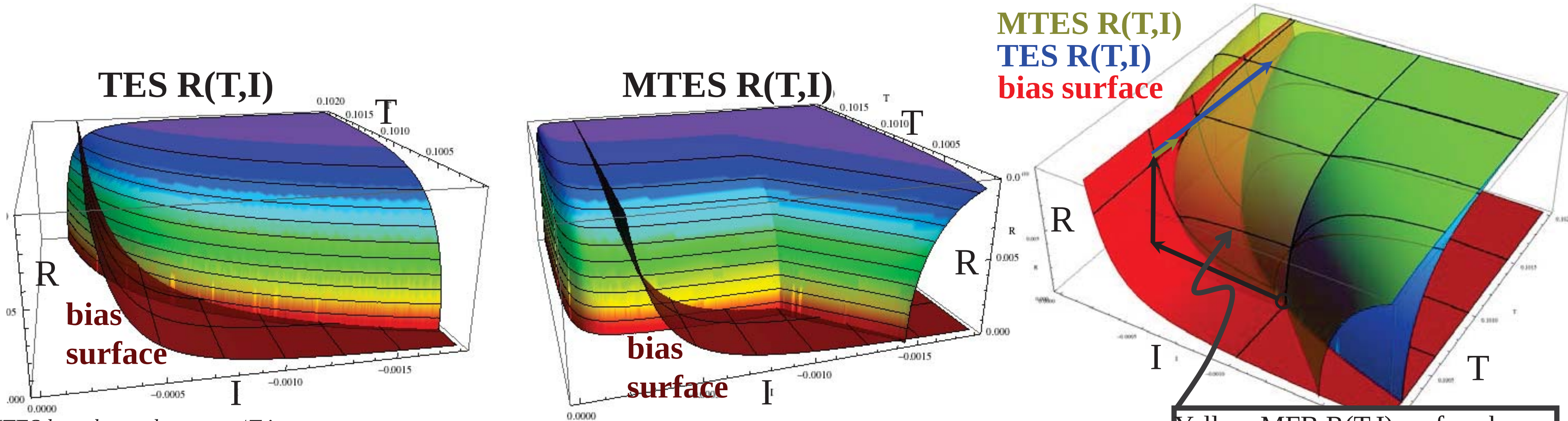
Asymmetric Current Injection
&
Asymmetric Edges

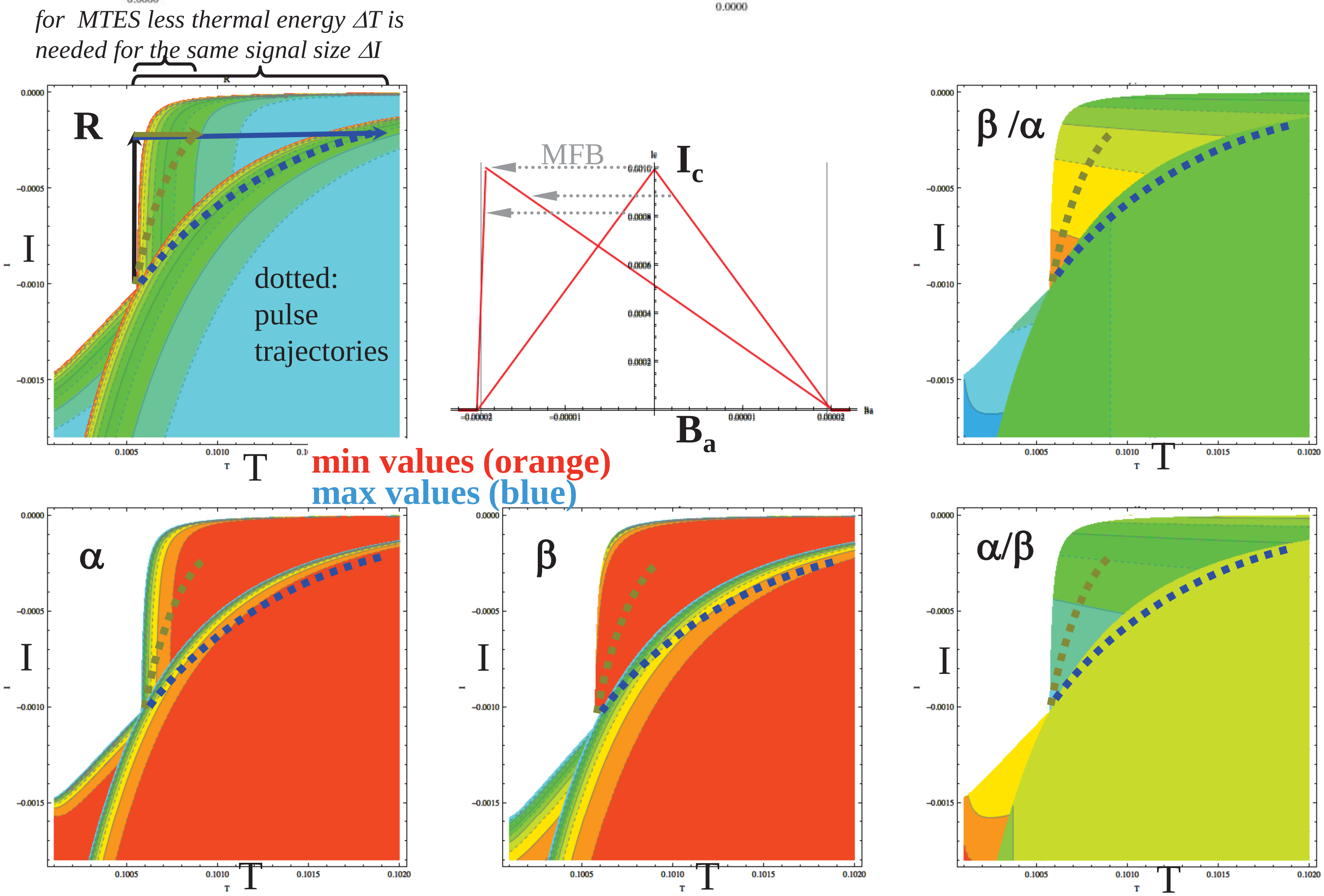
$$\beta \equiv \beta_{meas} = \beta_I + \beta_B$$

	β	β_I	β_B	B_a	g	
R(B) increases β	$\beta > \beta_I$	(+)	(+)	$B_a = 0$	$g \neq 0$	Typical TES devices
β reduced ! ★	$\beta \rightarrow \beta_I$	(+)	$\beta_B \rightarrow 0$	$B_a = 0$	$g \rightarrow 0$ $\lvert g \rvert$ *small*	Reduce self field designs
β further reduced!!! ★★★★	$\beta \rightarrow 0$ or < 0	(+)	$\beta_B << 0$ *large (–)*	$B_a > -g\,I$ *large (+)*	$g << 0$ $\lvert g \rvert$ *large*	a large self-field and applied field
β reduced !! ★★	$\beta \rightarrow 0$ or < 0	(+)	$\beta_B < 0$	$B_a = 0$	$g << 0$ $\lvert g \rvert$ *large*	$\beta_B<0$ & $B_a=0$ using edge modification

$$\boxed{\beta = \beta_I + \frac{g\,I_0}{R_0}\frac{\partial R}{\partial B}}$$

$$\beta_I \equiv \frac{I_0}{R_0}\frac{\partial R}{\partial I}$$





Yellow MFB R(T,I) surface has:
(1) made the $R(I)|_T$ contours $\partial R/\partial I \approx 0$ therefore $\beta \approx 0$.
(2) maintained a large α (a large $\partial R/\partial T$)
(3) created the desired large α/β condition over the entire pulse trajectory

Overlaid contour plots of parameter values with and without Magnetic Feedback (MFB). Same range in current I and temperature T as above.

- Want to make a calorimeter. Want a response that is sensitive to
- Understanding of the exotic TES physics effects led to my recommendation to use MoAu as the sensor material for a MPT thermometer. Given the best results to date.

Other reasons we need superconducting knowledge

- Superconducting absorbers (have low heat capacity, the design challenge is to minimize the long lived quasiparticles or energy traps).
- Superconducting leads to bring the signal in and out of the low temperature detector signals.
- MoAu basic understanding lead me to suggest using this material for Magnetic Penetration depth Thermometer (MPT). It remains the best result to date of any MPT sensor.