

Demonstration of an Ultra- Stable Thermal Platform

Colin Green¹, Dmitri Sergatskov¹, and R. V. Duncan^{1,2}

¹ University of New Mexico (UNM)

² California Institute of Technology (Caltech)

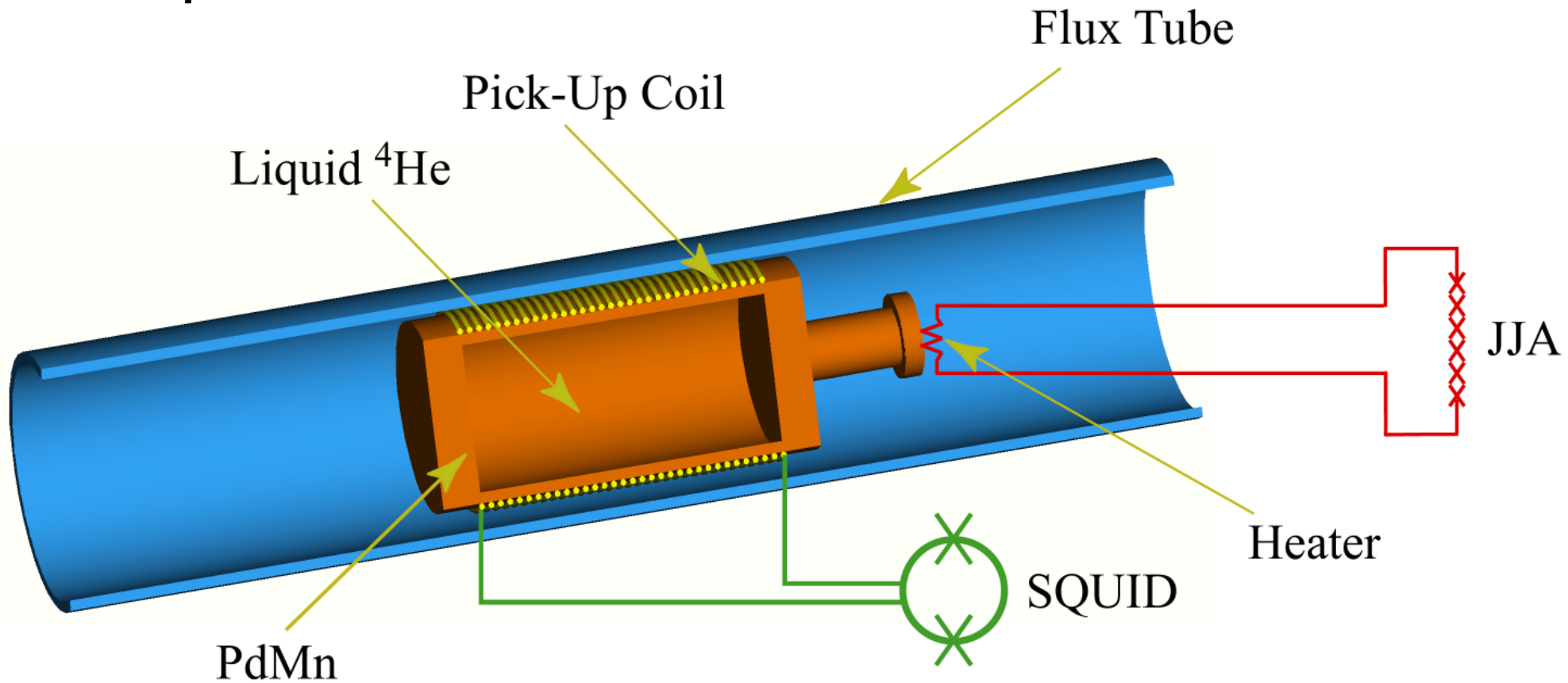
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New Ultra-Stable Platform

Concept from QFS 2000 ...



The helium sample is contained within the PdMn thermometric element. Power dissipation is precisely controlled with the rf-biased Josephson junction array (JJA). Stabilize to $\delta T \sim 10^{-11}$ K.

Why Do This?

Improved blackbody standard for cosmology

- On Earth, hold T_λ to within a nK
- Weightless, hold T_λ to within 50 pK
- Anisotropy stability studies
- Radiant energy studies
- Universe cools at ~ 200 pK / year

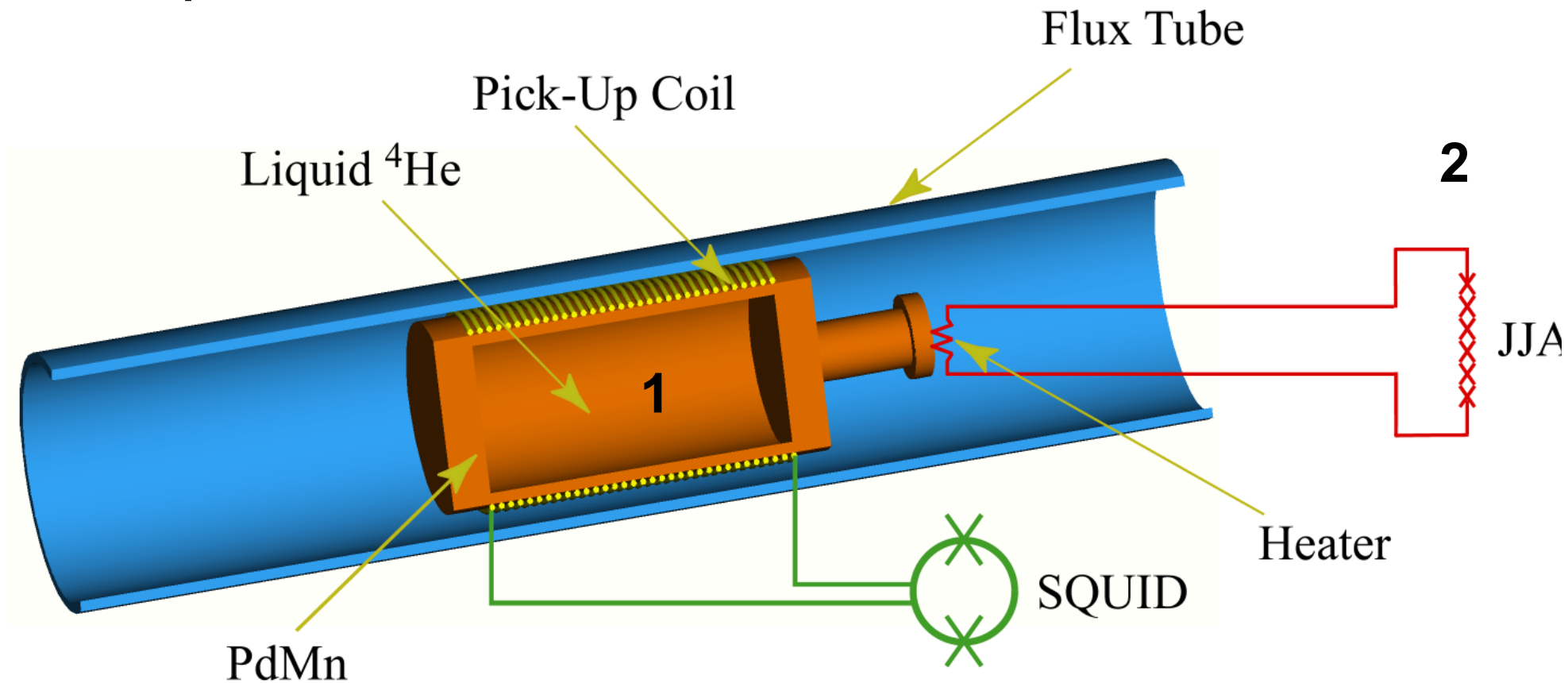
Critical Fluctuations Studies

- At $\varepsilon \approx 10^{-10}$ $\xi \approx 1$ mm
- $\delta t \sim \xi^2/D_\psi \sim 0.1$ s
- Fluctuations within thermometry BW

(Work on sputtered PdMn films has progressed nicely, but is not reported here)

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1. Paramagnetic Susceptibility Thermometry

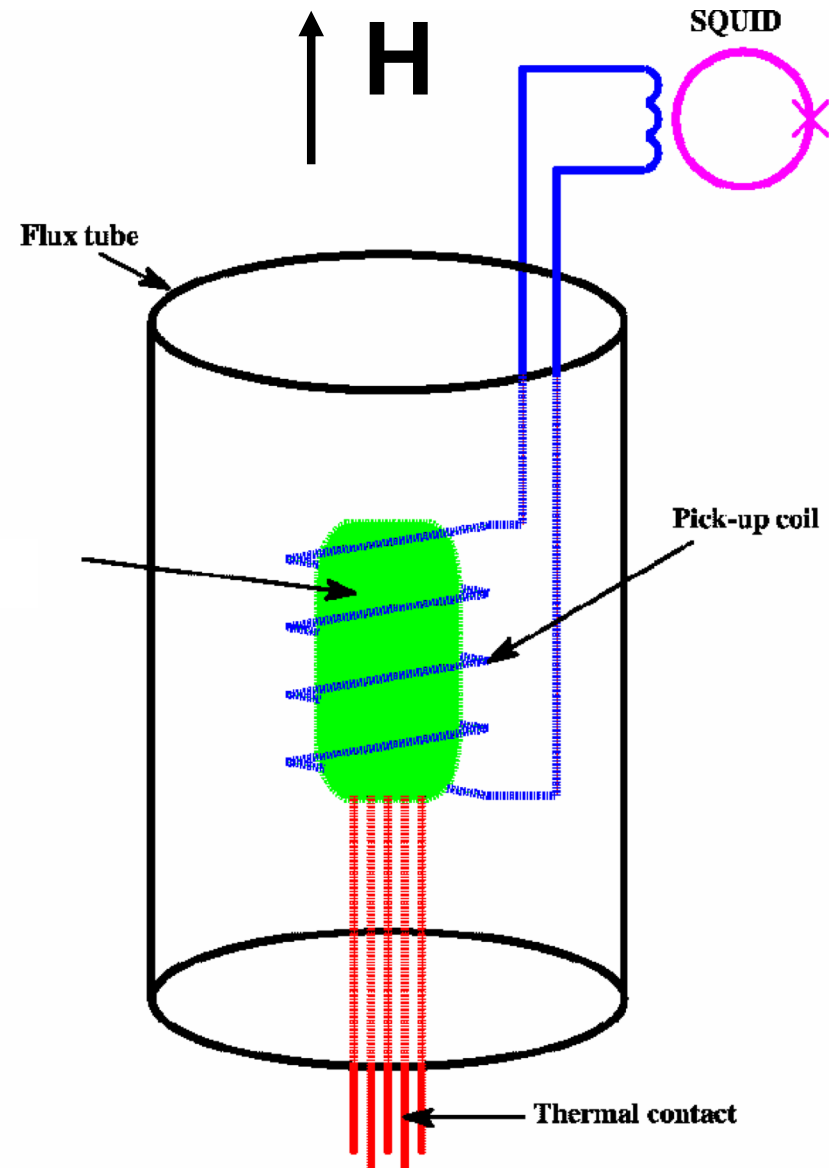
Magnetic flux is trapped in a niobium tube

A paramagnetic substance with $T > T_c$ is thermally anchored to the platform

$$M = H \chi(T)$$

$\chi(T) = \Gamma [(T - T_c)/T_c]^{-\gamma}$ so small changes in T create large changes in M , and hence in the flux coupled to the SQUID

Gifford, Web, Wheatley (1971)
Lipa and Chui (1981)

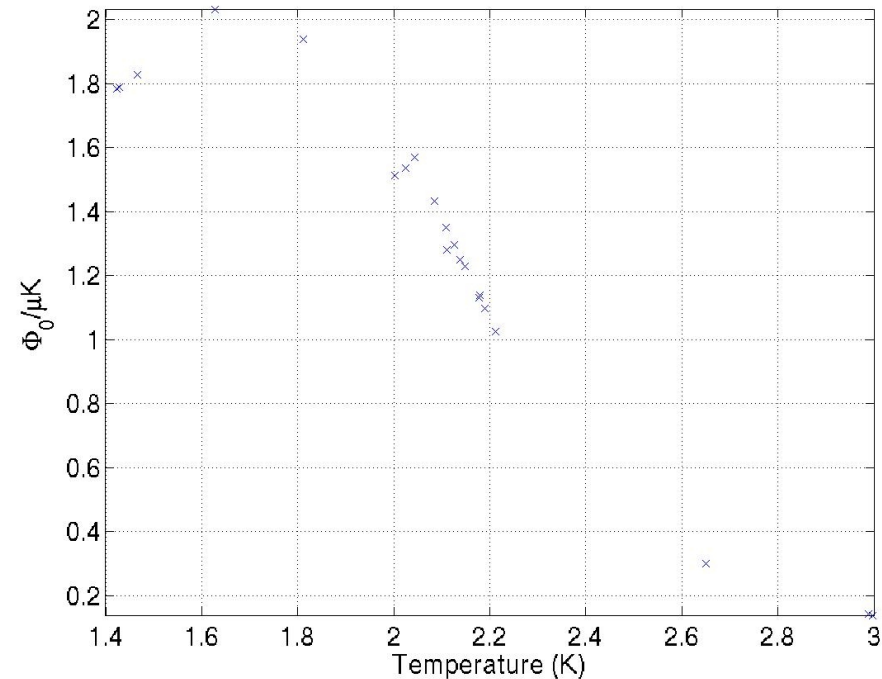


Sensitivity of Paramagnetic Susceptibility Thermometry

- Calibrate $\Delta T = \Delta\Phi / s$
- $\phi_o = h/(2e) \approx 2.07 \times 10^{-15}$ Wb (Wb = T m² = V/Hz)
- $s = dM/dT = Hd\chi/dT$
 $= -\gamma\Gamma HT_c^{-1}[(T - T_c)/T_c]^{-\gamma-1}$

adjust s by...

changing $T_c(x)$ in Pd_{1-x}Mn_x,
here $T_c(x=0.6 \text{ at.}\%) \approx 1.60$ K
changing H



PdMn: Klemme *et al.*, JLTP 116, 133 (1999)

Nelson, Sergatskov, & Duncan, JLTP 127 173 (2002)

Fundamental Noise Sources

Heat fluctuations in the link

one independent measurement

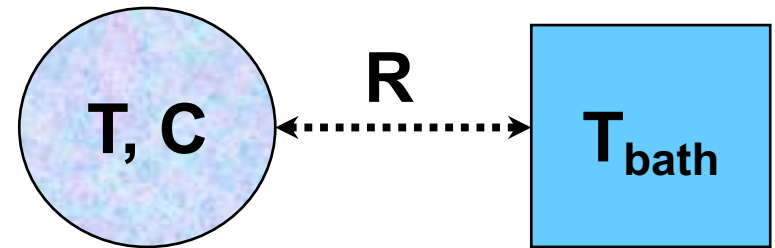
per time constant τ , $\tau = RC$

$$\langle (\delta T_Q)^2 \rangle \sim \tau / C$$

$$\langle (\delta T_Q)^2 \rangle = 4Rk_B T^2$$

so $\delta T_Q \sim \sqrt{R}$ and $\delta T_Q \sim T$

See: Day, Hahn, & Chui, JLTP 107, 359 (1997)



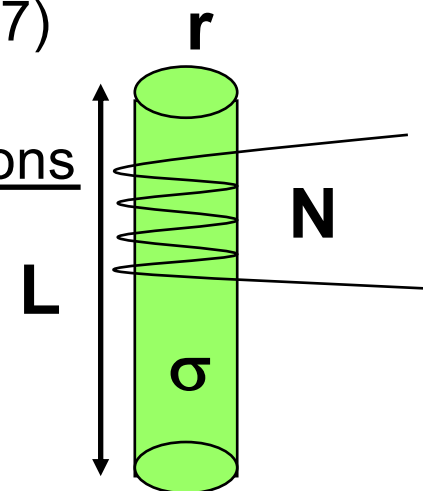
Thermally induced electrical current fluctuations

mutual inductance creates flux noise

$$\langle (\delta \Phi)^2 \rangle \sim T N^2 \sigma r^4 / L$$

$$\delta T_M = \delta \Phi / s, s \approx 1 \phi_0 / \mu K$$

so $\delta T_M \sim \delta \Phi \sim \sqrt{T}$



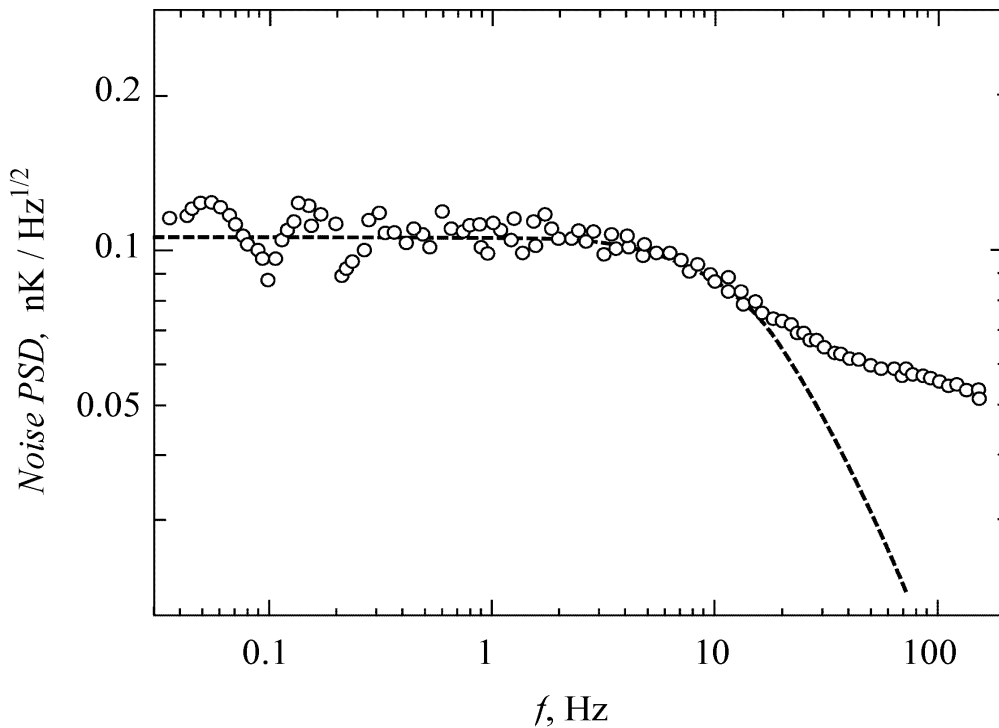
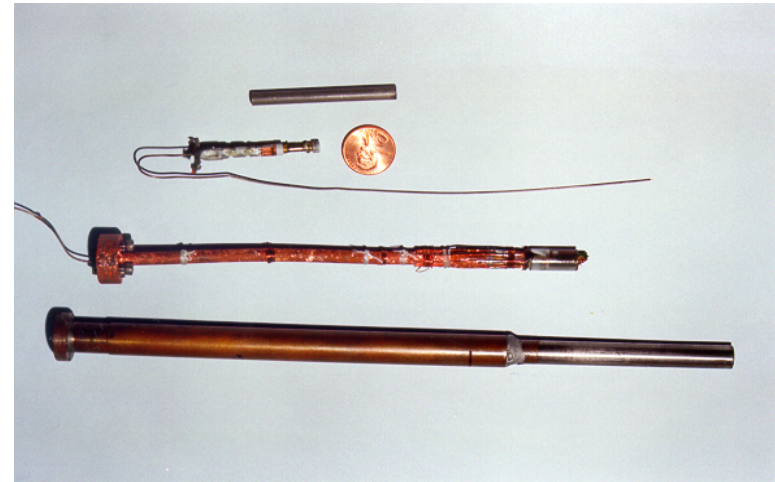
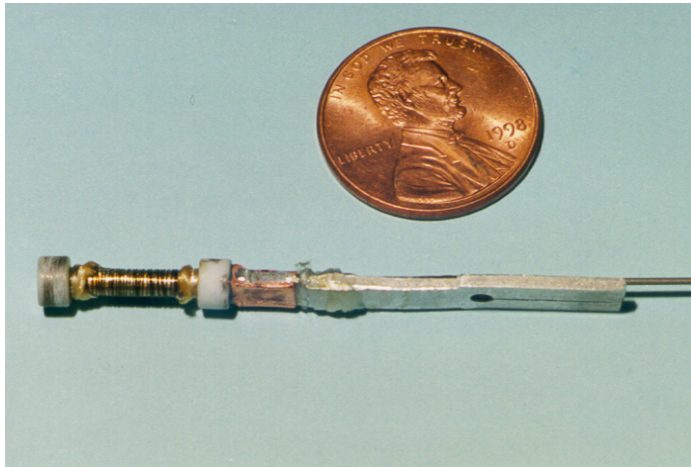
SQUID noise

$\langle (\Delta \Phi_{SQ})^2 \rangle^{1/2} \approx 4 \mu \phi_0 / \sqrt{\text{Hz}}$ with shorted input

external circuit creates about three times this noise level

so $\Delta \Phi \approx 12 \mu \phi_0 / \sqrt{\text{Hz}}$ and $\delta T_{SQ} \approx 12 \text{ pK} / \sqrt{\text{Hz}}$

Heat Fluctuation Noise Across the Link



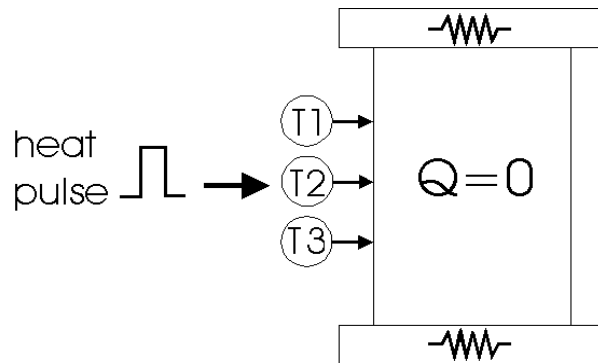
$R = 40 \text{ K/W}$

**$\langle (\delta T_Q)^2 \rangle = 4Rk_B T^2$
so $\delta T_Q = 0.10 \text{ nK}/\sqrt{\text{Hz}}$**

**3 dB point at 10 Hz,
suggesting $\tau \approx 50 \text{ ms}$**

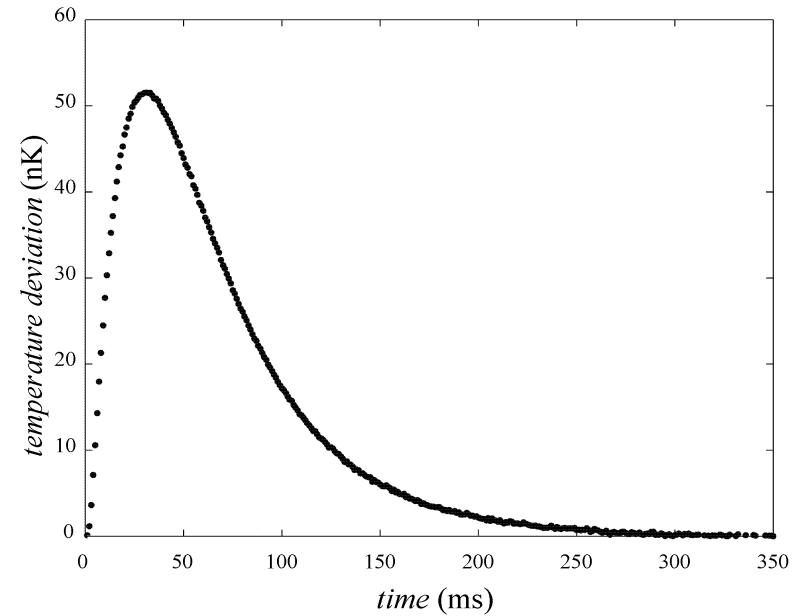
(collaboration with Peter Day)

HRT Time Constant



Method:

- Controlled cell temperature with T1
- Pulsed a heater located on T2
- Cell in superfluid state
- Contact area of only 0.05 cm^2



- Rise time $\sim 20 \text{ ms}$
- Decay time = 48 ms

Collaboration with Peter Day

Reduce the Heat Fluctuation Noise

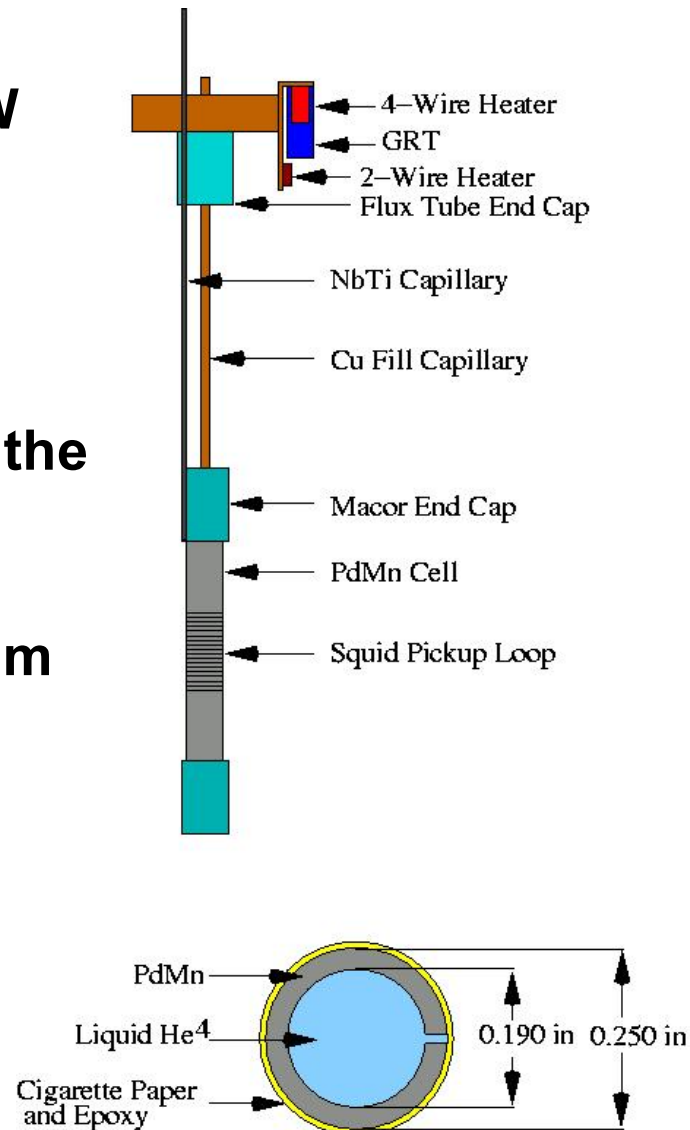
Reduce R from 40 to 0.25 K/W

Now $\delta T_Q \approx 7 \text{ pK}/\sqrt{\text{Hz}}$

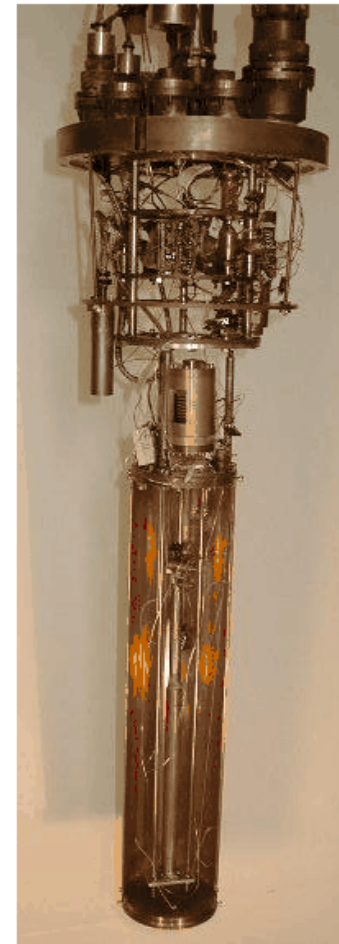
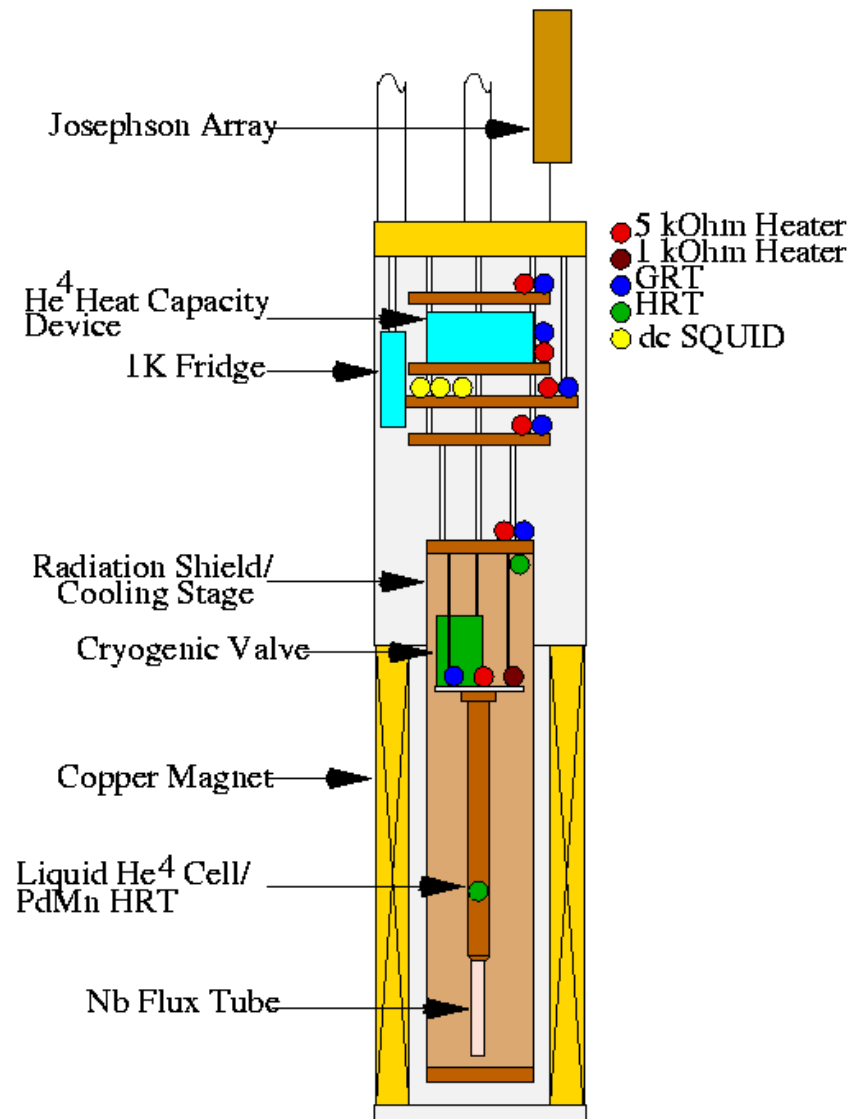
Minimize δT_M with a gap to reduce mutual inductance to the SQUID loop

α is PdMn thickness = 0.76 mm

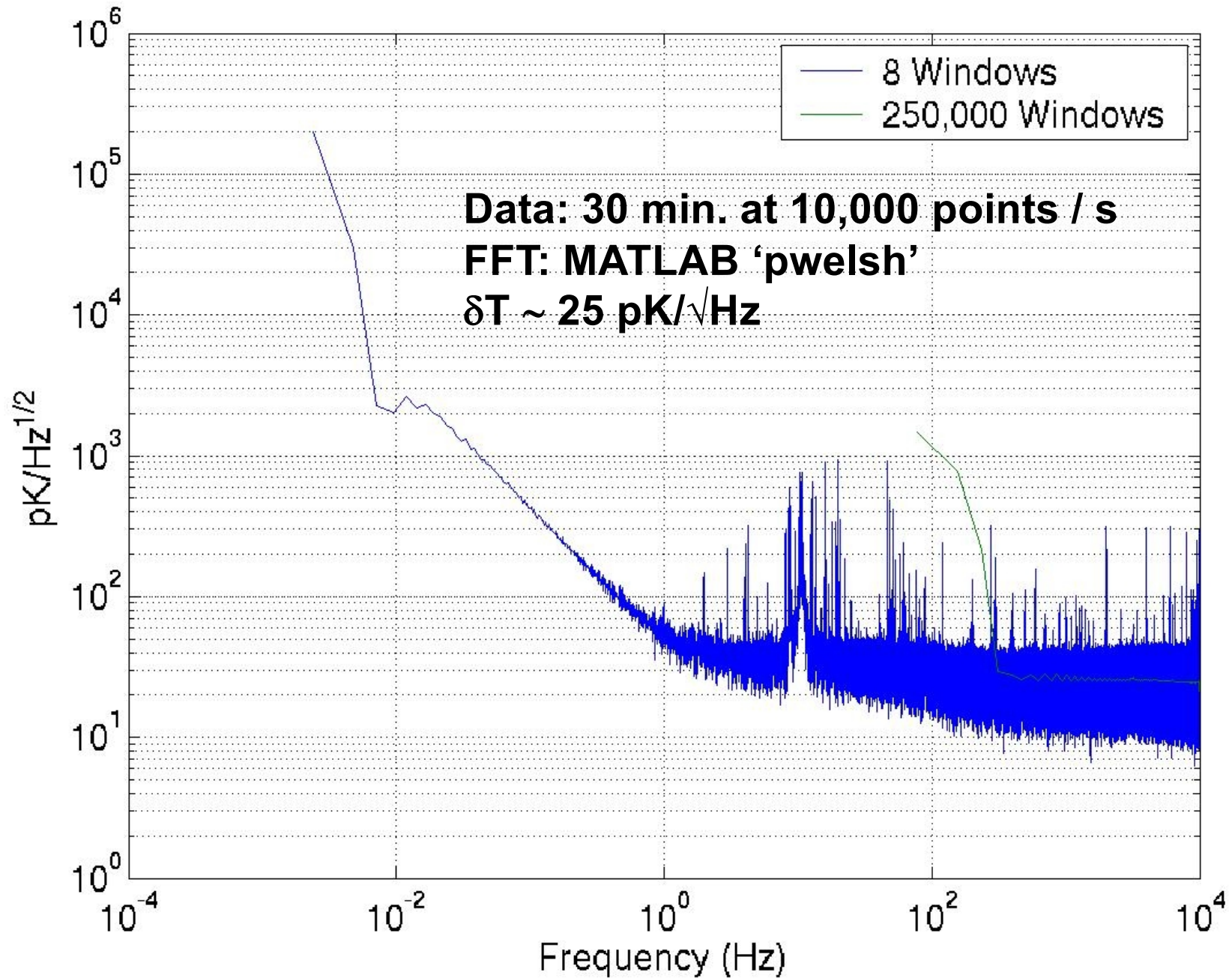
$$r^4 \rightarrow 4 r \alpha^3 \quad r^3/(4\alpha^3) \approx 18$$



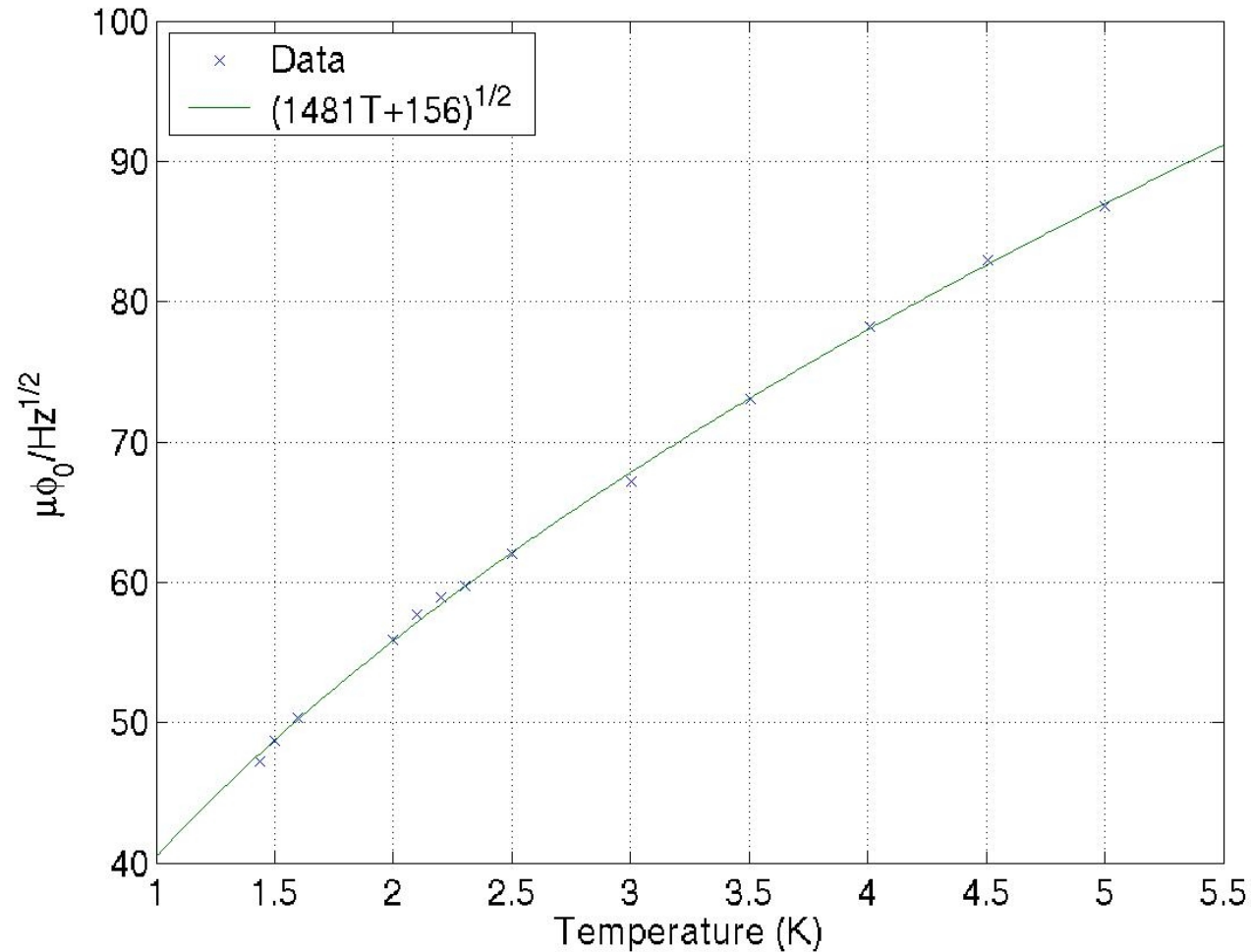
The Cryostat



Typical Noise Spectrum, T = 1.6 K

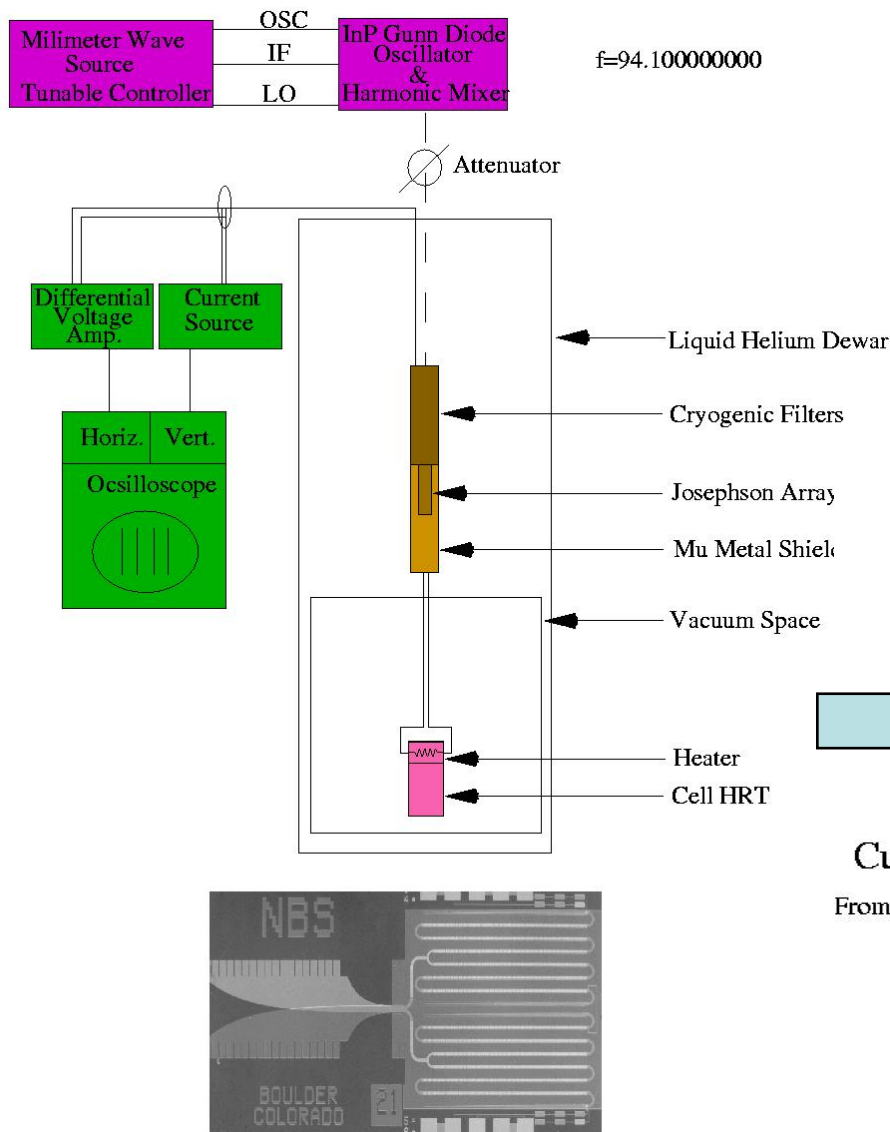


Thermally Driven Electric Current Fluctuations



Thermal current fluctuations: $\delta\Phi = 38 \mu\phi_0/(\text{Hz K})^{1/2} \sqrt{T}$
SQUID circuit noise: $\delta\Phi_{\text{SQ}} = 12.5 \mu\phi_0/\sqrt{\text{Hz}}$

2. RF-biased Josephson Junctions for Heater Control



$$V_n = n (h/2e) f$$

$$h/2e = \phi_0 = 2.07 \mu\text{V}/\text{GHz}$$

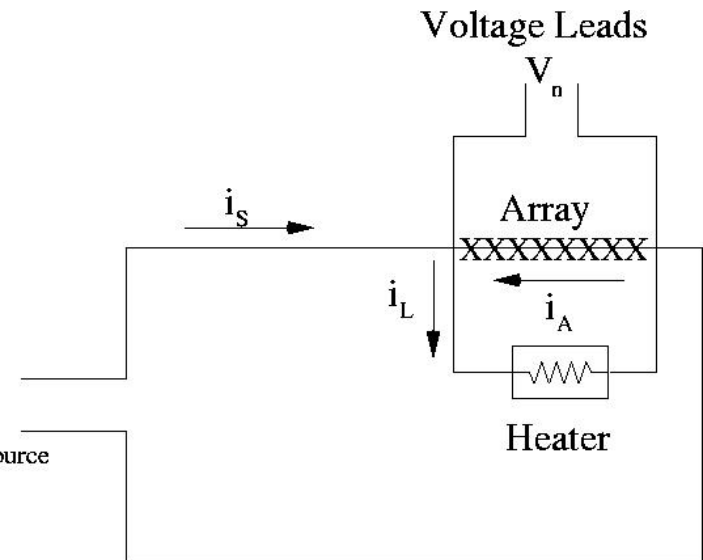
$$f = 94.100000000 \text{ GHz}$$

$$R_{el} = 1,015 \Omega$$

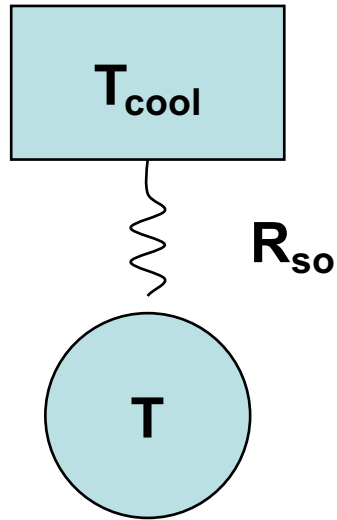
$$P_n = V_n^2 / R_{el} = 37.3 \text{ n}^2 \text{ pW}$$



Current Leads
From external current source

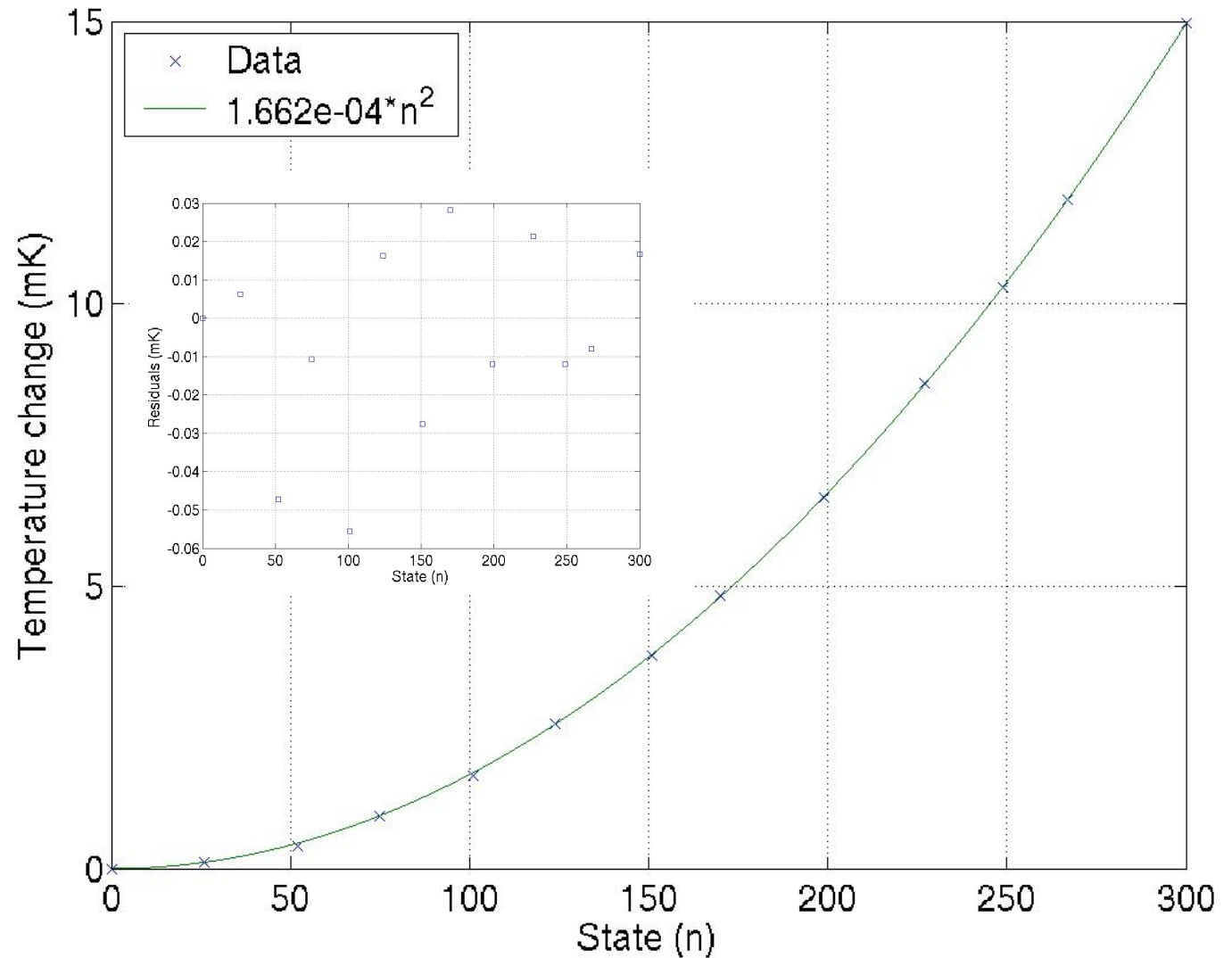


Standoff vs. Josephson Quantum Number

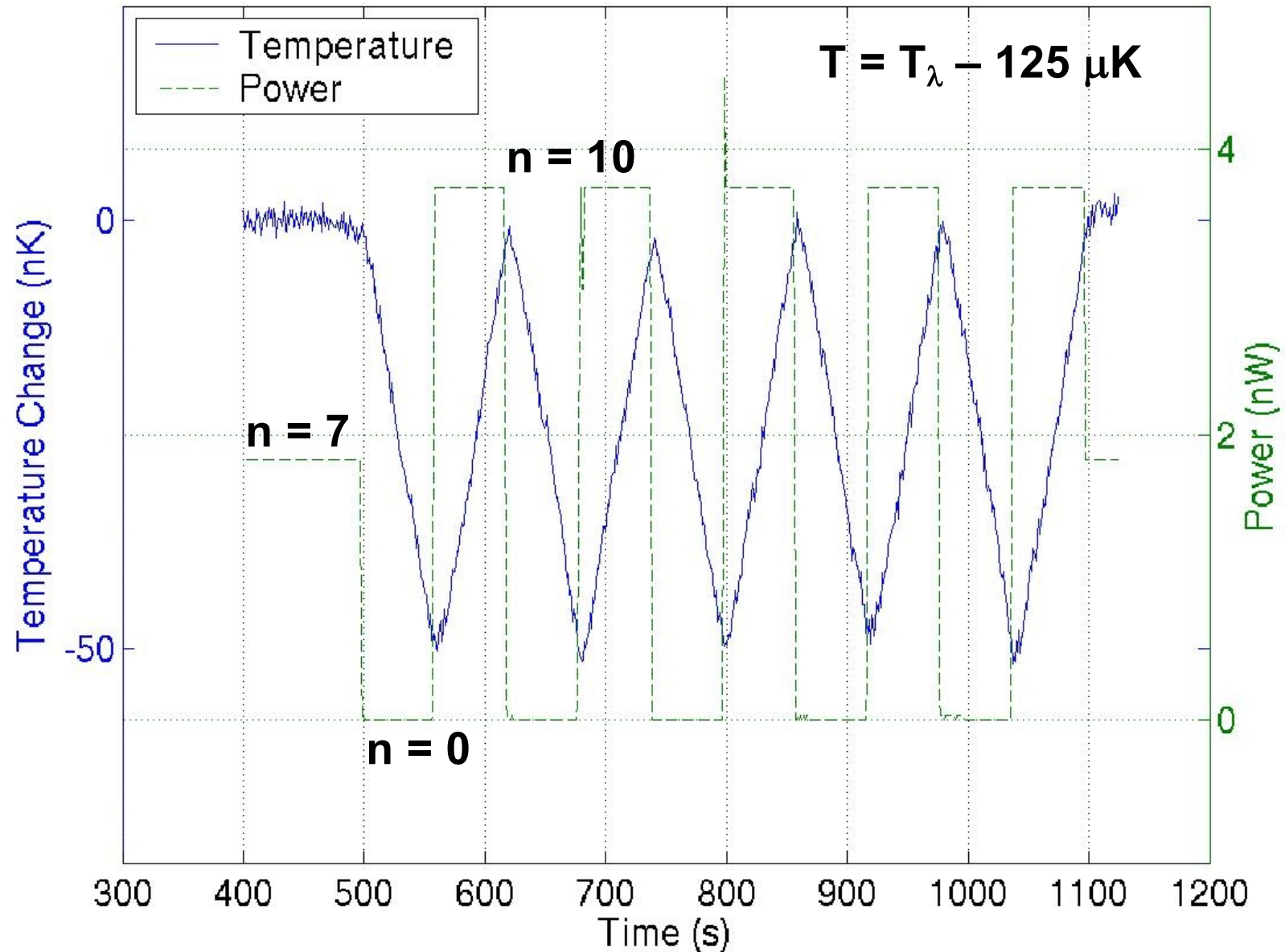


$$R_{\text{el}} = 1,015 \Omega$$

$$R_{\text{so}} = 4,456 \text{ K/W}$$



A New 'Fixed-Point' Standard



Conclusions

- Fundamental noise sources in PST identified and reduced
- Lowest noise $\sim 25 \text{ pK}/\sqrt{\text{Hz}}$ at 1.6 K
- New rf-biased Josephson junction heater controller developed
- Technology in place now to develop a reference standard more stable than the CMB temperature ($< 200 \text{ pK}/\text{year}$ drift) in a weightless lab, provided that T_λ does not vary with the cosmic expansion

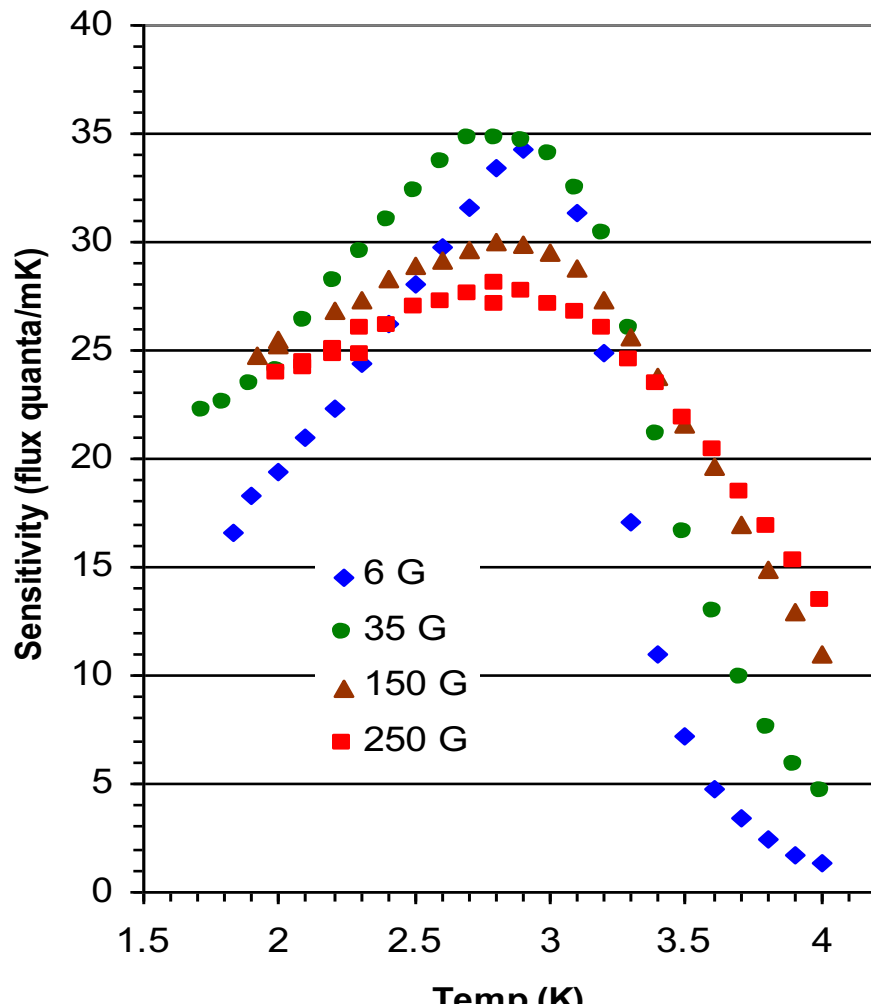
PdMn0.9% Thin Film Magnetic Susceptibility

Thermometry

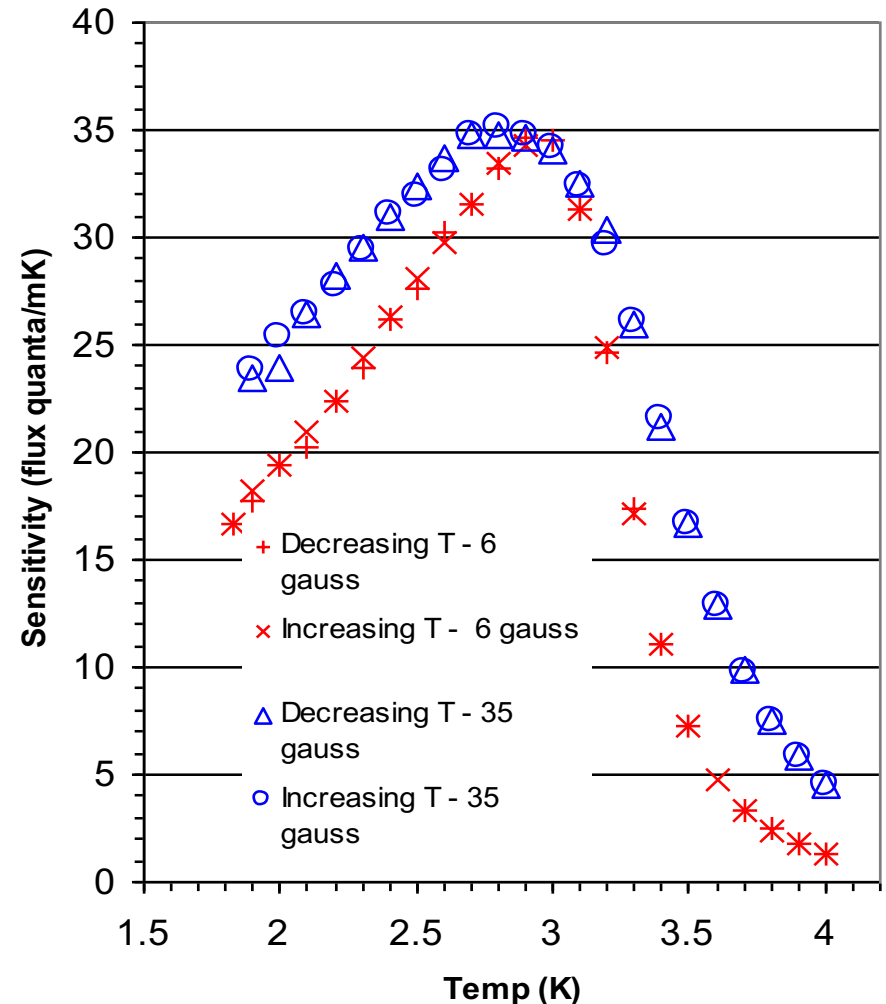
See R.C. Nelson *et al.*, JLTP (2002)

For thermometry, See Duncan *et al.*, 2nd Pan Pacific Basin Workshop, 2001.

Thin film sensitivity vs. T and H



No hysteresis was observed



New Data, PdMn0.4%, 6.67 μm thick films

$$T_c = 1.17 \pm 0.01 \text{ K}$$

$$\gamma = 1.41 \pm 0.01$$

Data by...
Ray Nelson
Colin Green
Dmitri Sergatskov
R. V. Duncan

