# Demonstration of an Ultra-Stable Thermal Platform

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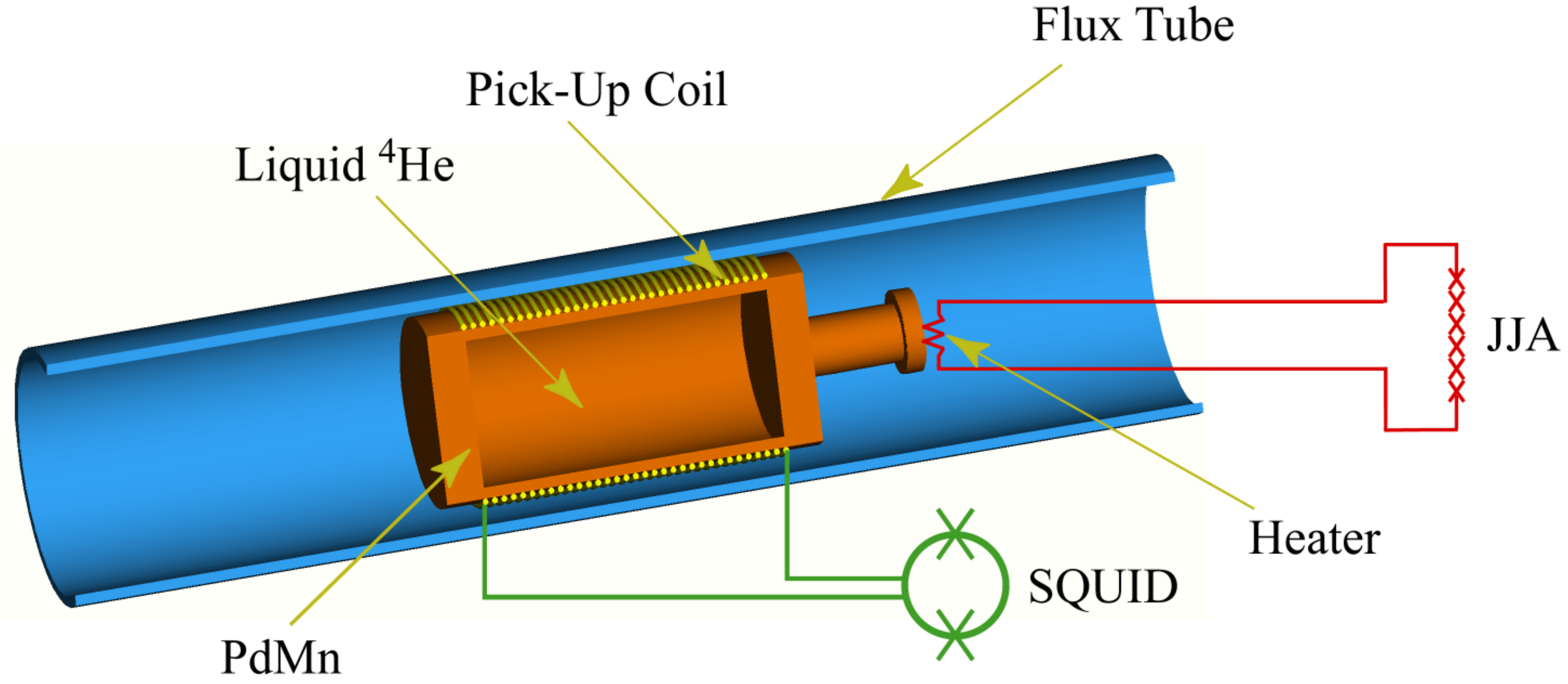
# New Ultra-Stable Platform

**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 $T_\lambda$ to within a nK
- Weightless, hold $T_\lambda$ to within 50 pK
- Anisotropy stability studies
- Radiant energy studies
- Universe cools at ~ 200 pK / year

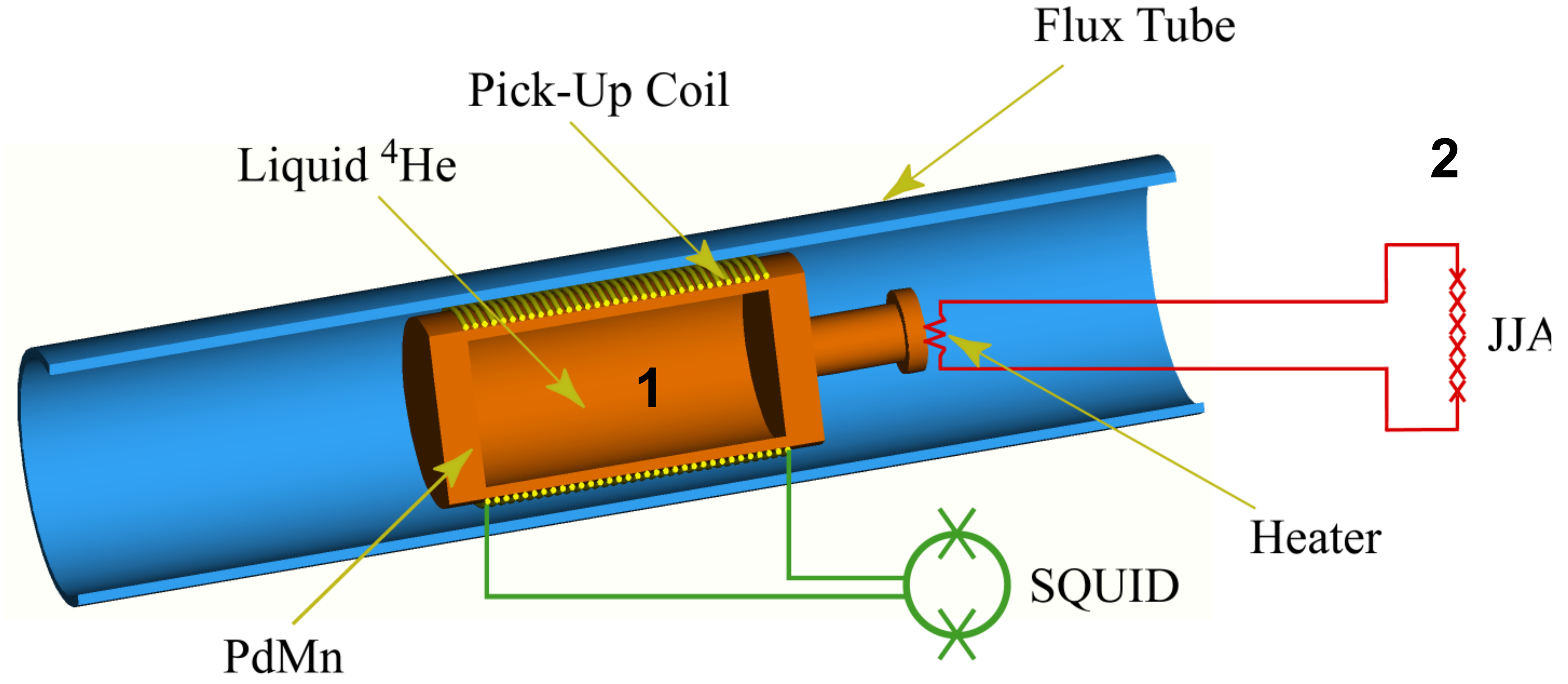
**Critical Fluctuations Studies**

- 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)

# 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.**

# 1. Paramagnetic Susceptibility Thermometry

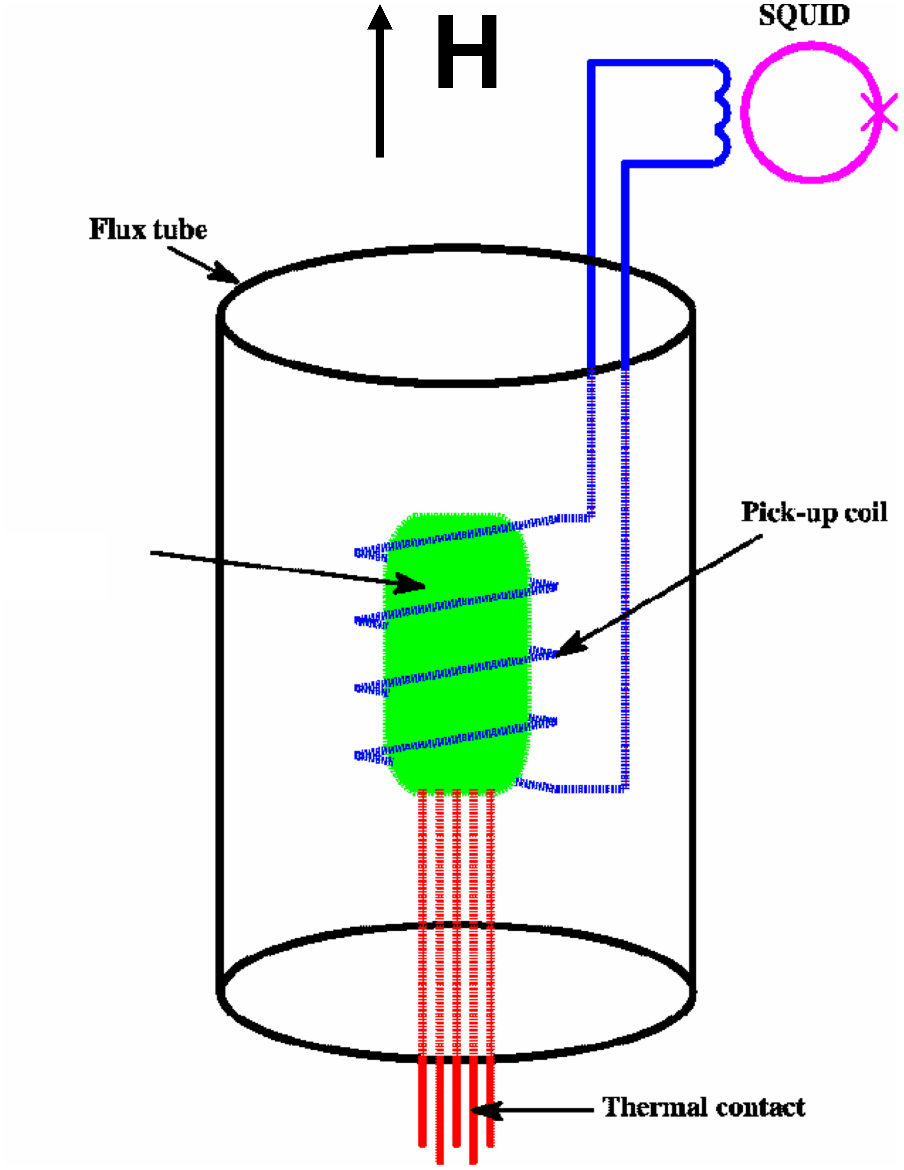
**Magnetic flux is trapped in a niobium tube**

**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)**



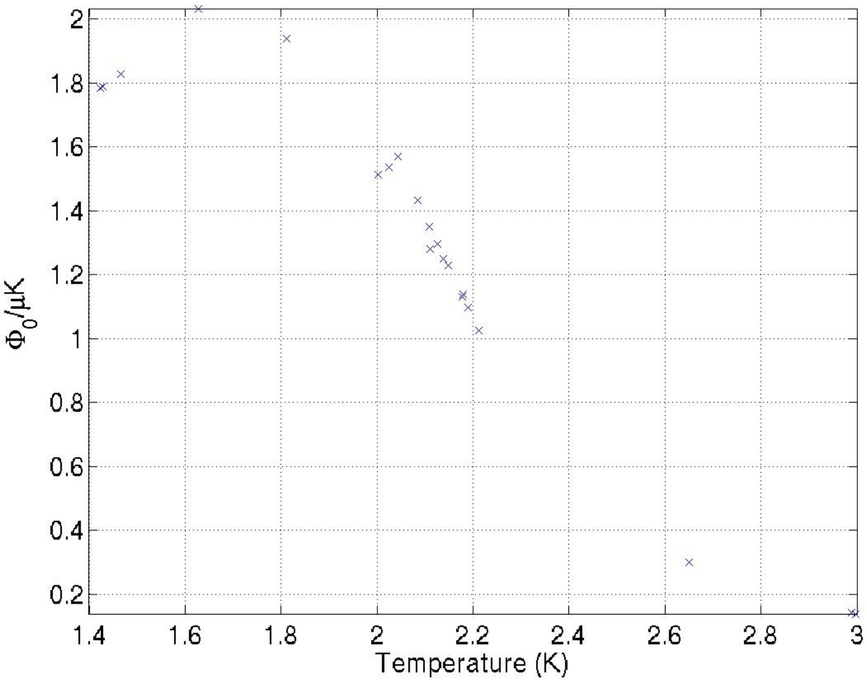
# Sensitivity of Paramagnetic Susceptibility Thermometry

- **Calibrate $\Delta T = \Delta\Phi / s$**
- **$\phi_o = h/(2e) \approx 2.07\times10^{-15}$ Wb (Wb = T m$^2$ = V/Hz)**

- **$s = dM/dT = H d\chi/dT$**

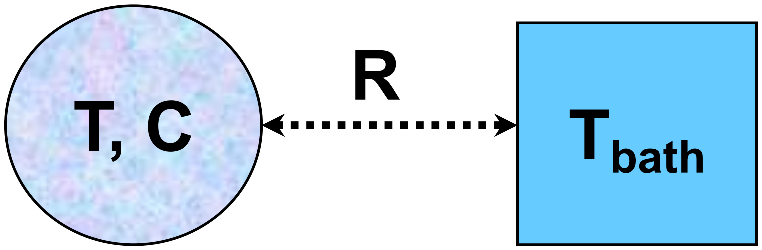
  **$= -\gamma\Gamma H T_c^{-1}[(T - T_c)/T_c]^{-\gamma-1}$**

**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**



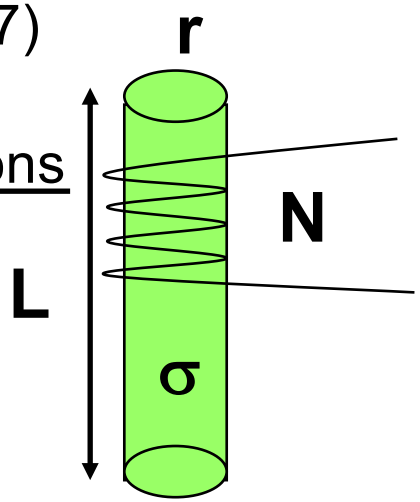
**PdMn: Klemme *et al.*, JLTP 116, 133 (1999)**
**Nelson, Sergatskov, & Duncan, JLTP 127 173 (2002)**

# Fundamental Noise Sources



Heat fluctuations in the link

one independent measurement
per time constant $\tau$, $\tau$ = RC
$(\text{noise})^2 \sim \tau / C$
$\langle(\delta T_Q)^2\rangle = 4Rk_BT^2$
so $\delta T_Q \sim \sqrt{R}$ and $\delta T_Q \sim T$
See: Day, Hahn, & Chui, JLTP 107, 359 (1997)



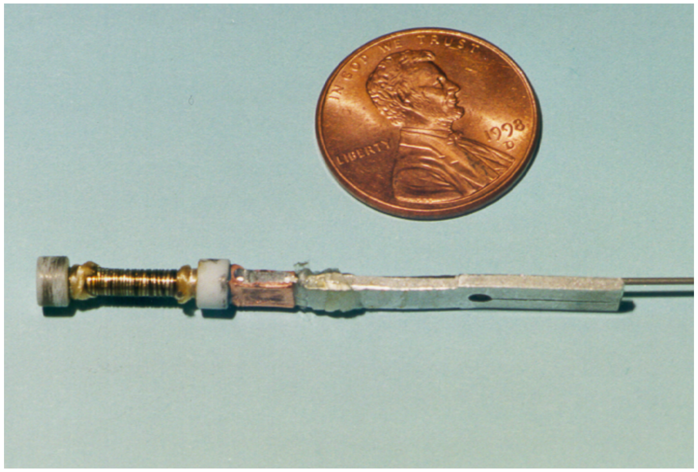
Thermally induced electrical current fluctuations

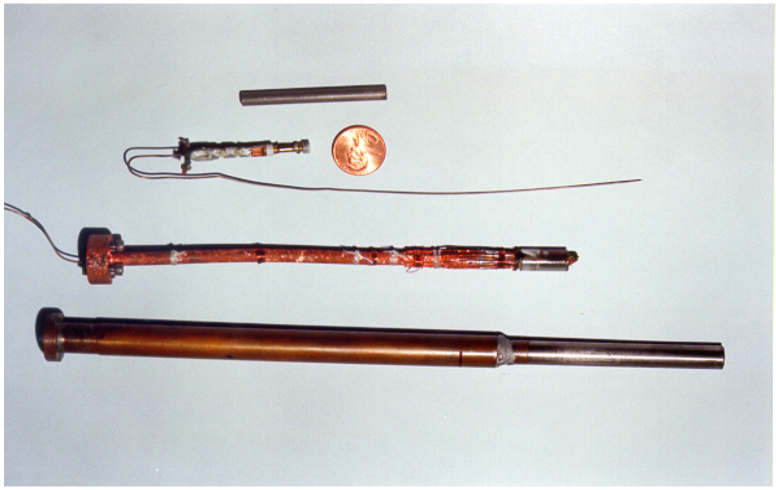
mutual inductance creates flux noise
$\langle(\delta\Phi)^2\rangle \sim T\,N^2\,\sigma\,r^4 / L$
$\delta T_M = \delta\Phi / s$, $s \approx 1\ \phi_o/\mu K$
so $\delta T_M \sim \delta\Phi \sim \sqrt{T}$

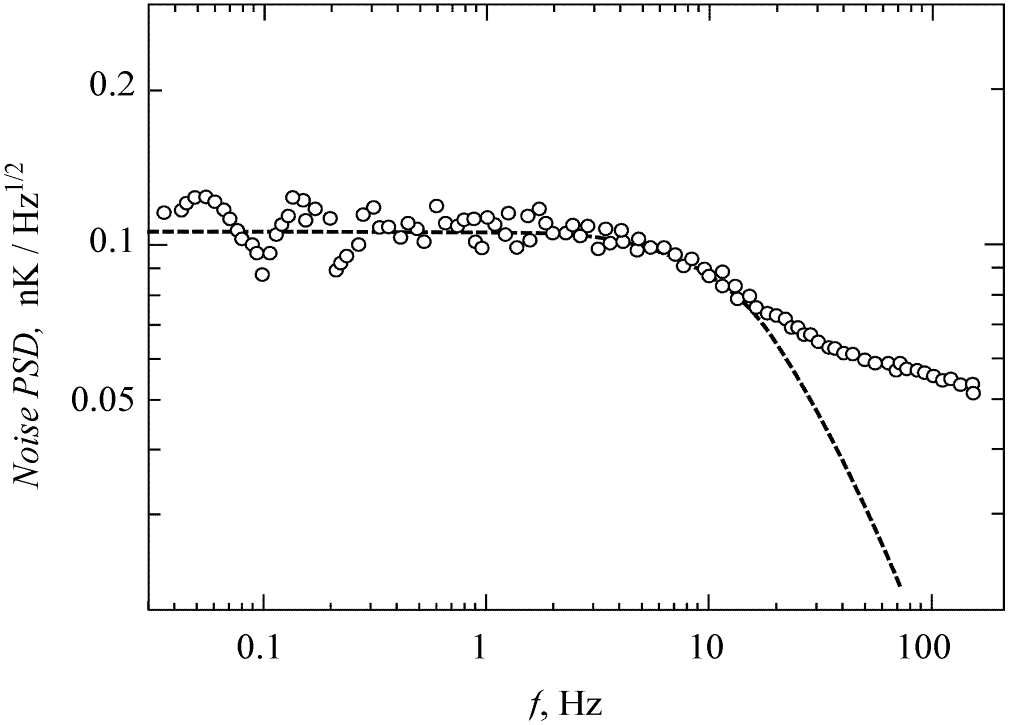
SQUID noise

$\langle(\Delta\Phi_{SQ})^2\rangle^{1/2} \approx 4\ \mu\phi_o/\sqrt{Hz}$ with shorted input
external circuit creates about three times this noise level
so $\Delta\Phi \approx 12\ \mu\phi_o/\sqrt{Hz}$ and $\delta T_{SQ} \approx 12\ pK/\sqrt{Hz}$

# Heat Fluctuation Noise Across the Link







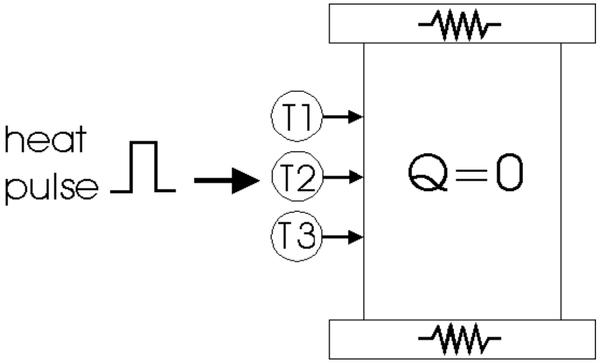
**R = 40 K/W**

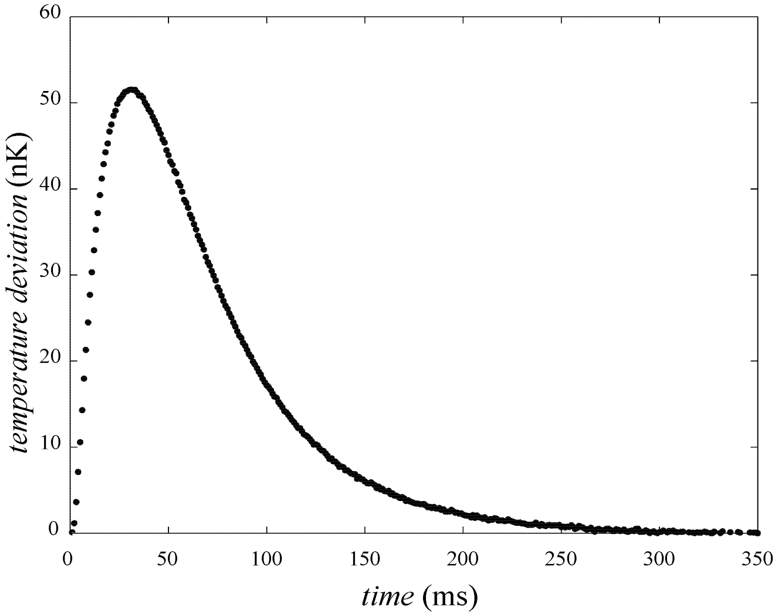
**$\langle(\delta T_Q)^2\rangle = 4Rk_BT^2$**
**so $\delta T_Q = 0.10$ nK/√Hz**

**3 dB point at 10 Hz,**
**suggesting $\tau \approx 50$ 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 ~ 20 ms**
- **Decay time = 48 ms**

**Collaboration with Peter Day**

# Reduce the Heat Fluctuation Noise

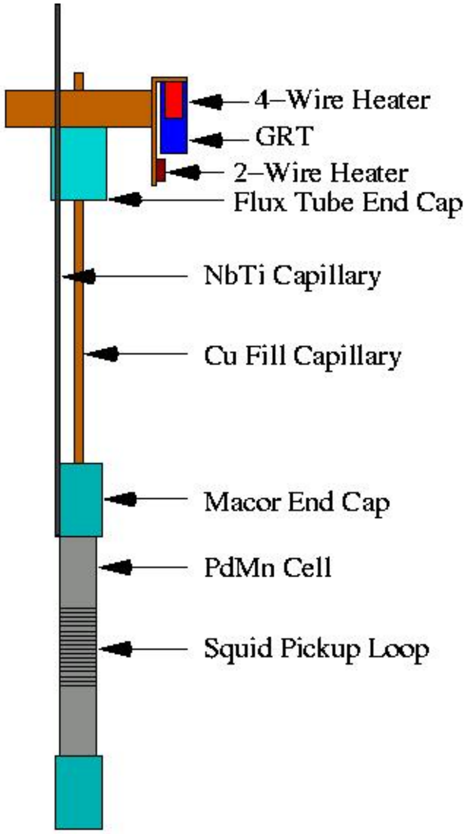
**Reduce R from 40 to 0.25 K/W**

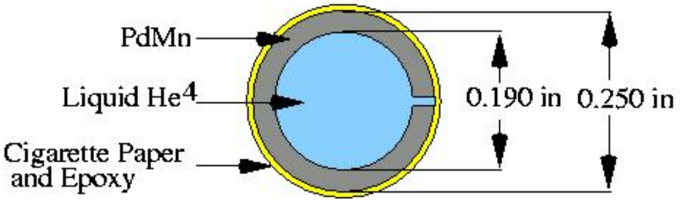
**Now $\delta T_Q \approx 7\ \mathrm{pK}/\sqrt{\mathrm{Hz}}$**

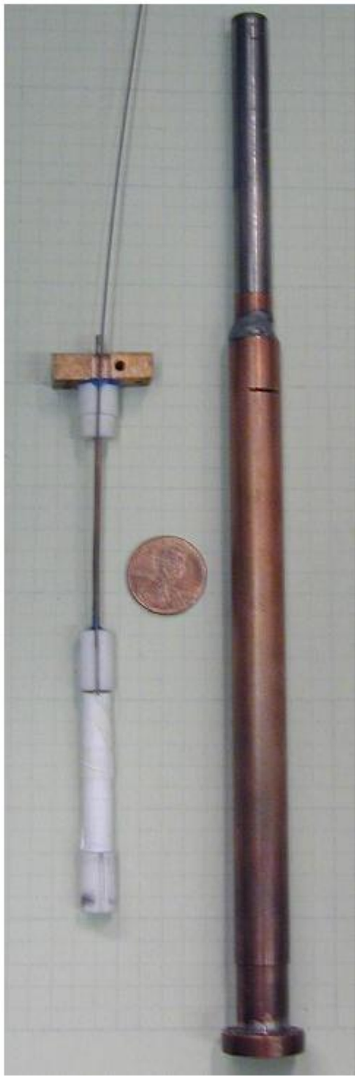
**Minimize $\delta T_M$ with a gap to reduce mutual inductance to the SQUID loop**

**$\alpha$ is PdMn thickness = 0.76 mm**

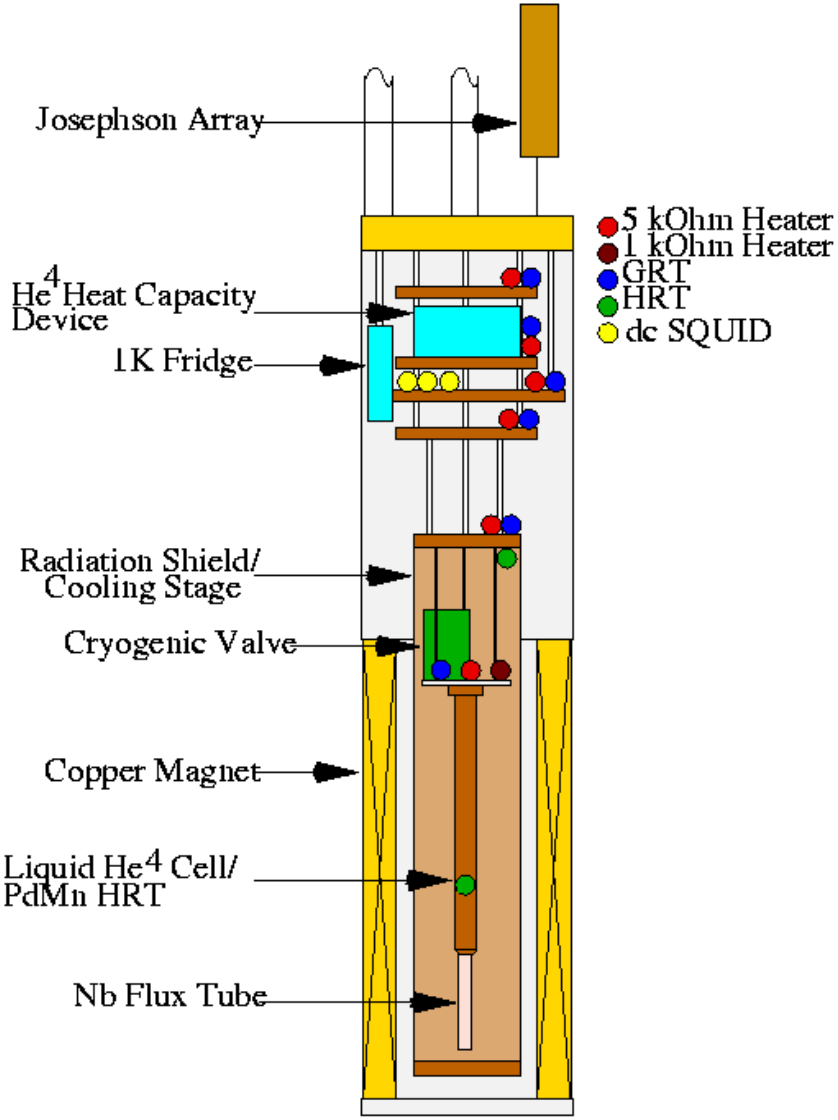
**$r^4 \rightarrow 4 r \alpha^3$ $r^3/(4\alpha^3) \approx 18$**

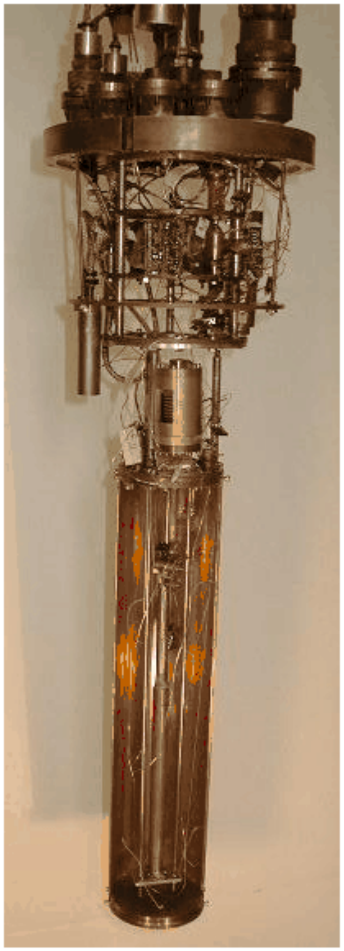




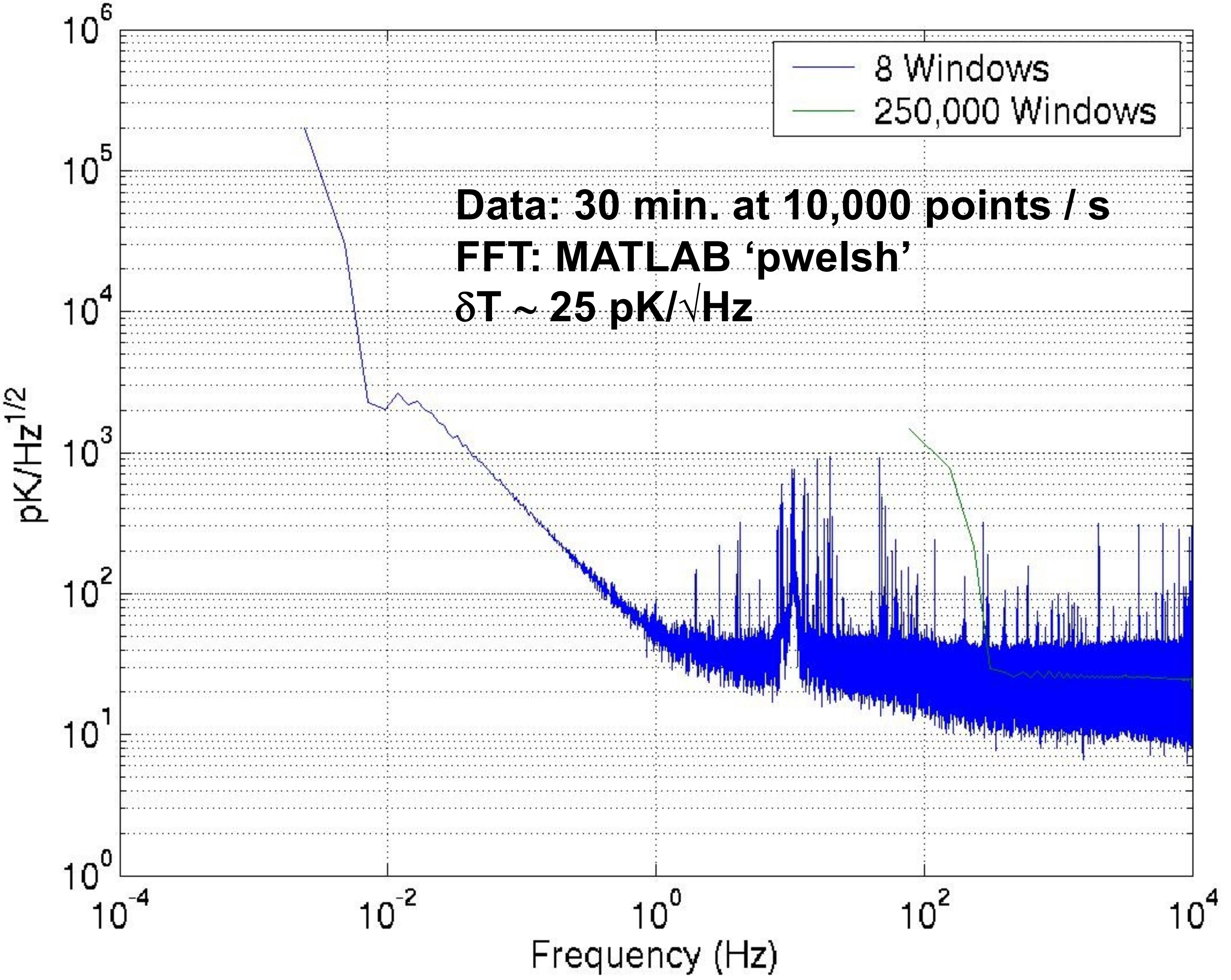


# The Cryostat



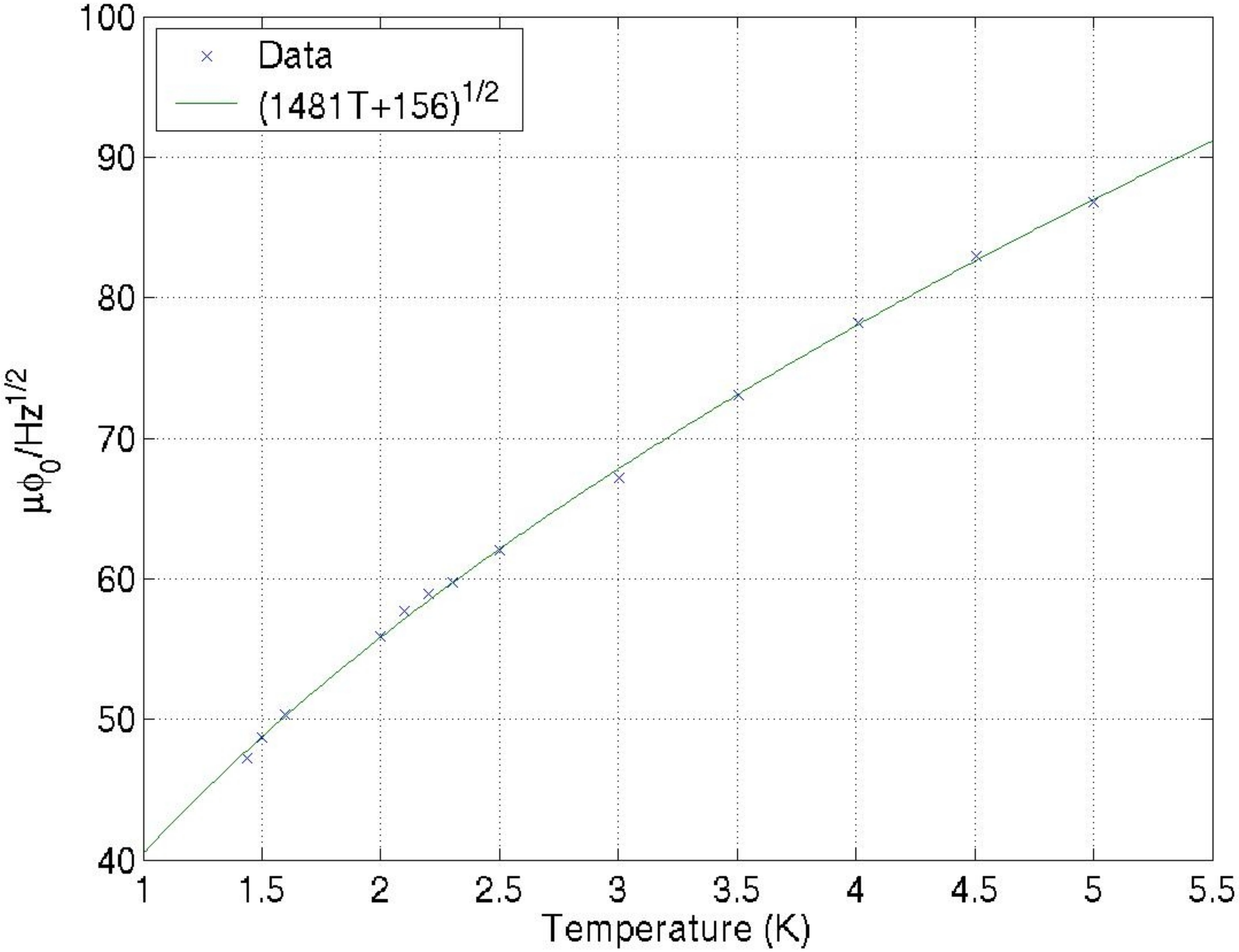


# Typical Noise Spectrum, T = 1.6 K



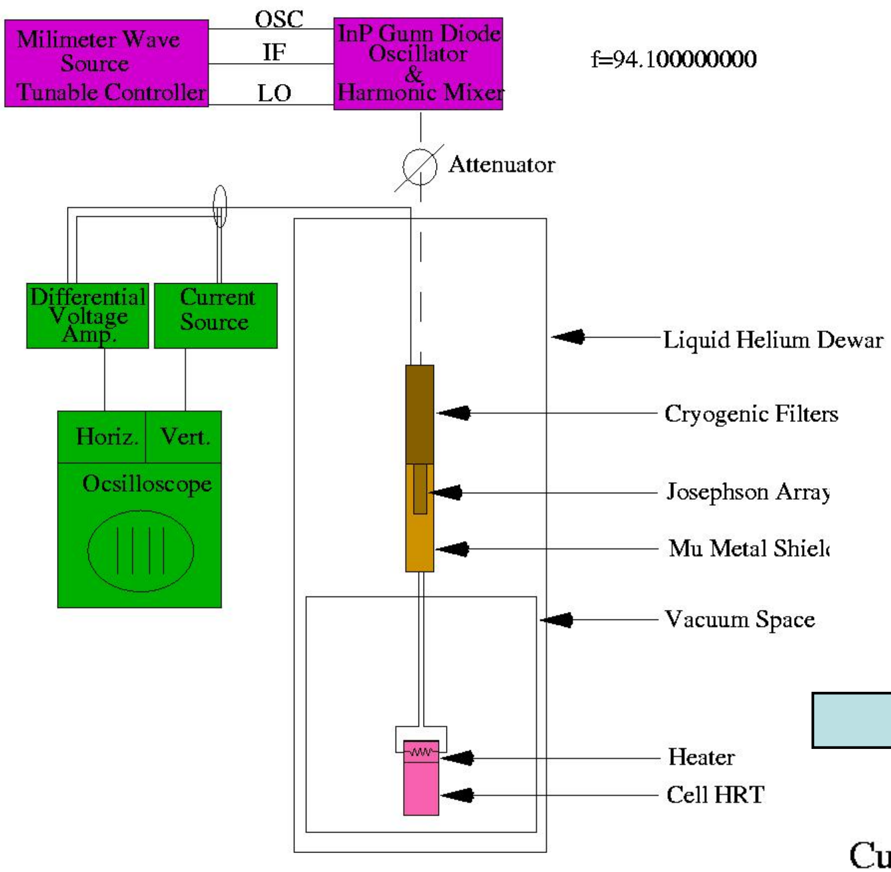
**Data: 30 min. at 10,000 points / s**
**FFT: MATLAB ‘pwelsh’**
**$\delta T \sim 25$ pK/√Hz**

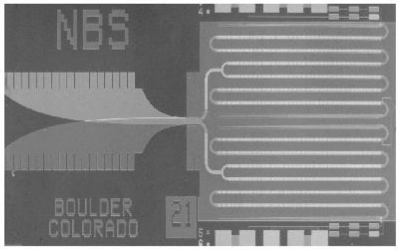
# Thermally Driven Electric Current Fluctuations



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

# 2. RF-biased Josephson Junctions for Heater Control





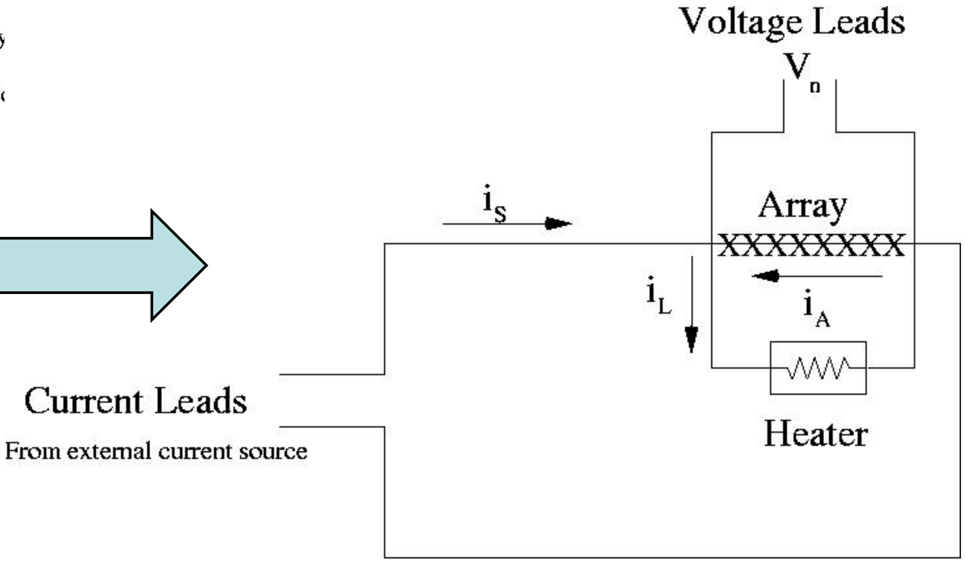
$V_n = n\,(h/2e)\,f$

$h/2e = \phi_o = 2.07\ \mu V/GHz$

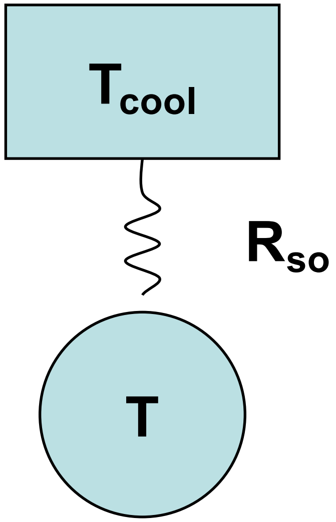
$f = 94.100000000\ GHz$

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

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

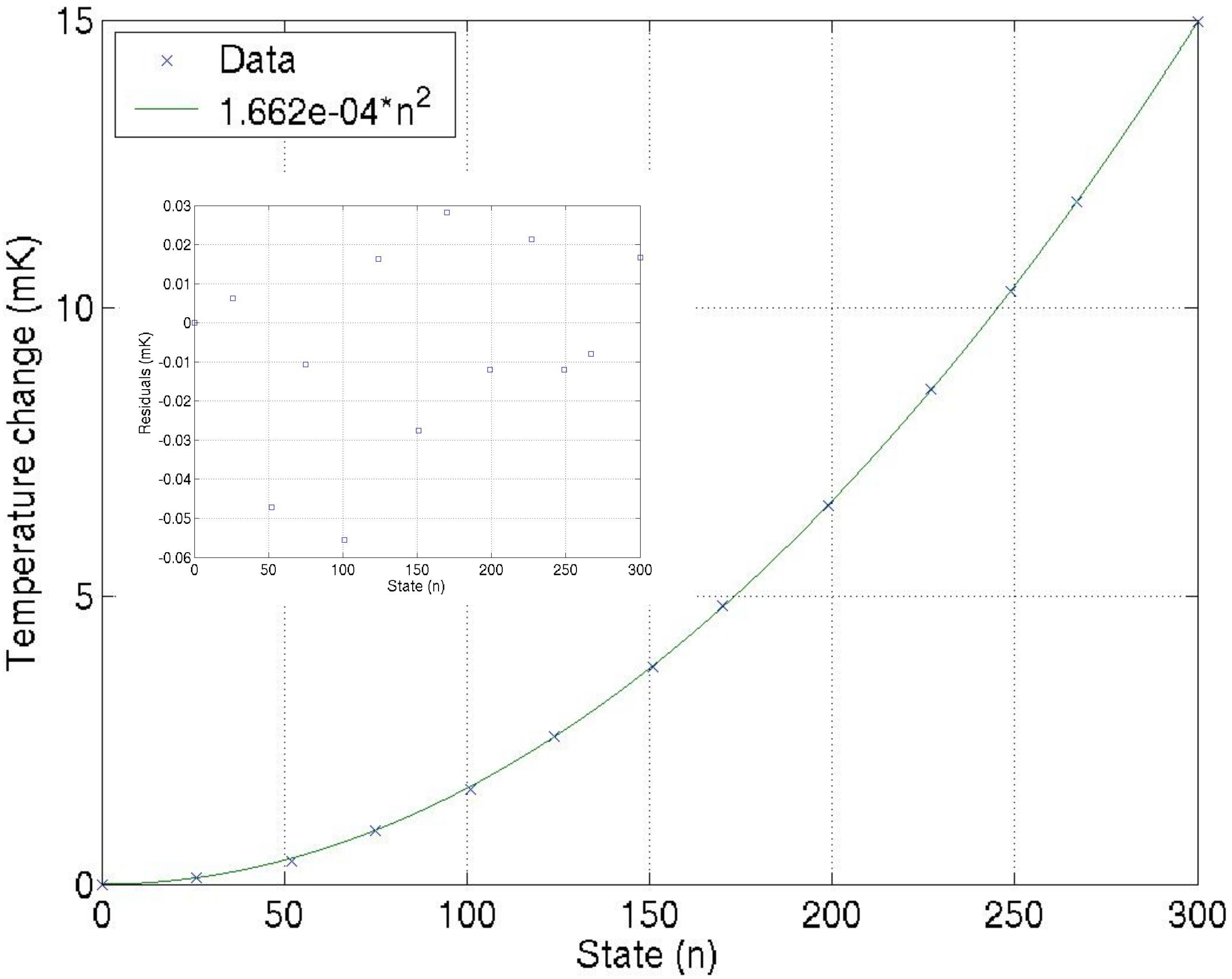


# Standoff vs. Josephson Quantum Number

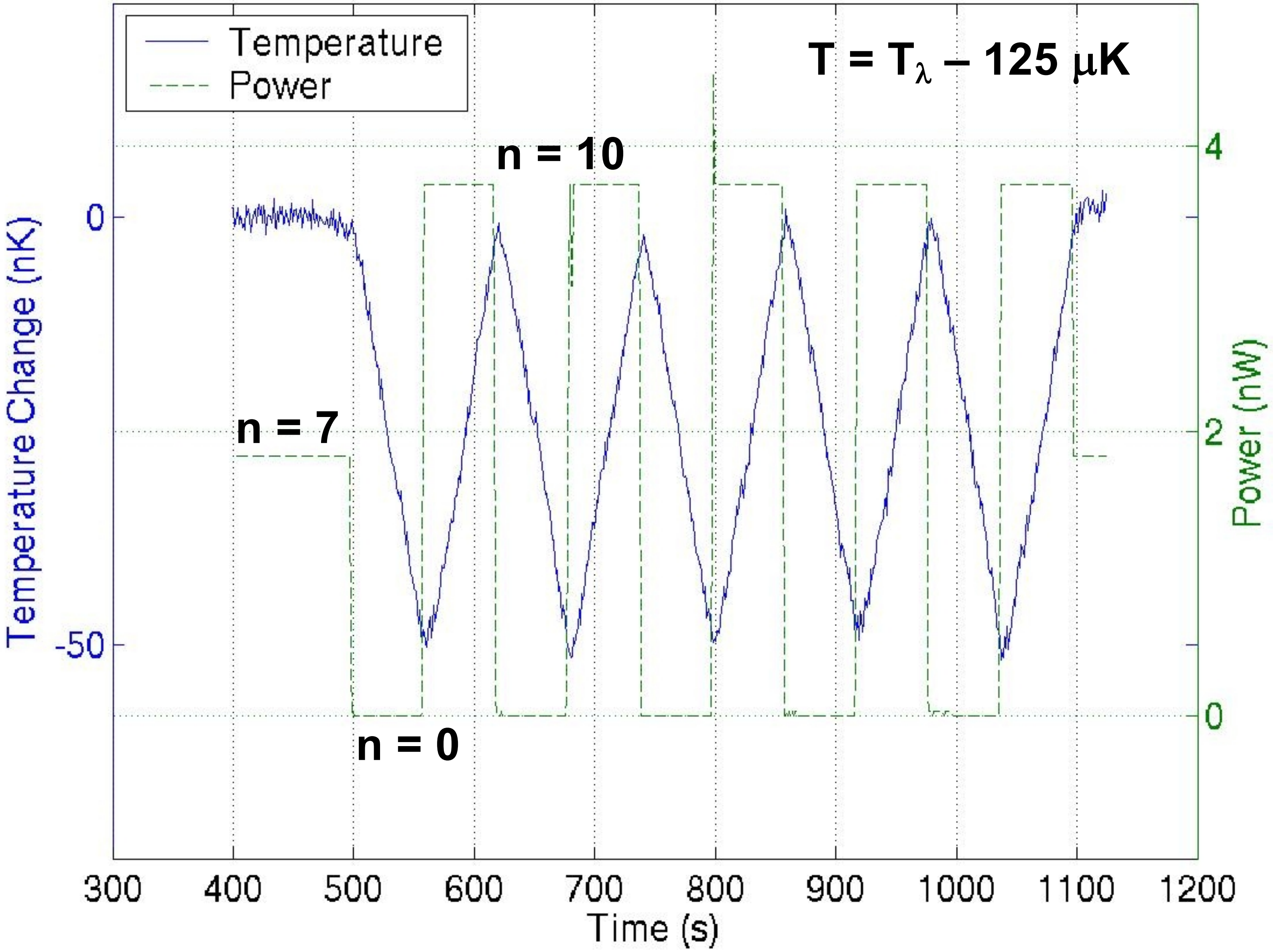


$R_{el}$ = 1,015 Ω

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



# A New ‘Fixed-Point’ Standard



# Conclusions

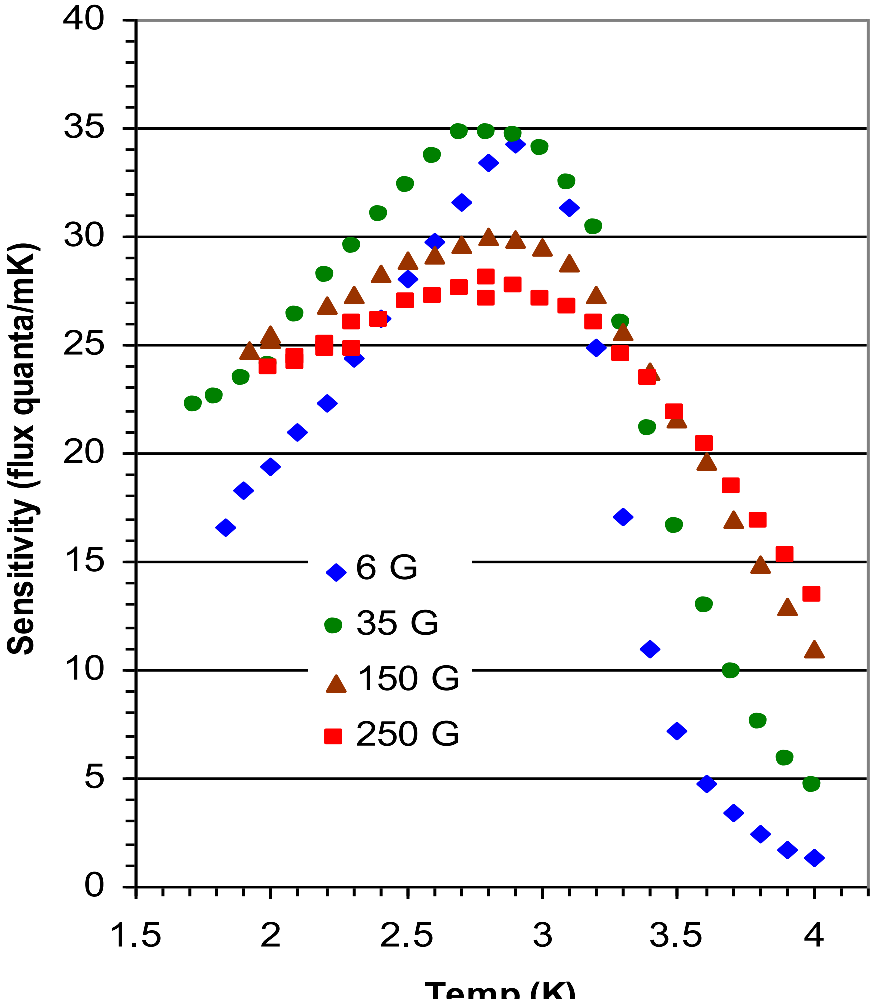
- Fundamental noise sources in PST identified and reduced
- Lowest noise $\sim$ 25 pK/$\sqrt{\text{Hz}}$ at 1.6 K
- New rf-biased Josephson junction heater controller developed
- Technology in place now to develop a reference standard more stable than the CMB temperature (< 200 pK/year drift) in a weightless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

# PdMn0.9% Thin Film Magnetic Susceptibility Thermometry

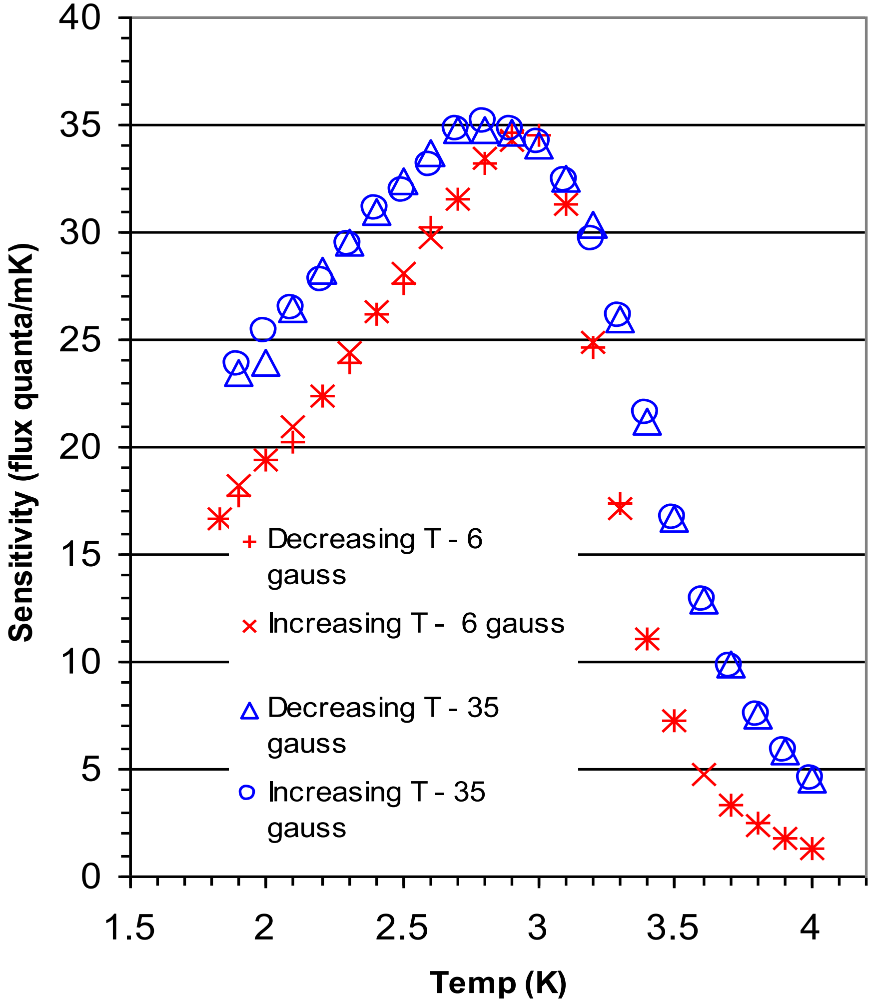
See R.C. Nelson *et al*., JLTP (2002)

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 ± 0.01 K**

**$\gamma$ = 1.41 ± 0.01**

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