Helium-4 Experiments Near T_λ in a Low-gravity Simulator

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* *This research described in this poster was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration*

ABSTRACT

We report on our latest measurements of gravity reduction in the low-gravity simulator. We made these measurements using a new thermal conductivity cell design that is 0.5cm in diameter and 0.5cm in height. Gravity reduction was verified by measuring both the reduction in the T_λ variation across the cell and the suppression of thermal convection as a function of the magnetic field. Full gravity cancellation was achieved in the simulator with B(dB/dz) ~ 21 (T^2/cm), agreeing well with the calculated value and the valve found from levitating drops of helium.

We also report on the measurements of thermal boundary resistance and T_λ depression by a heat current in both 1g and 0g environments.

OVERVIEW

- What is low-gravity simulator?

  Cryostat + High field superconducting magnet to counter gravity

- Why to cancel gravity?

  Variation in T_λ due to induced hydrostatic pressure
  Thermal convection in normal fluid

- Effect of B force on transition?

  Theory: Like gravity *(Ginzburg & Sobyanin, 82)*
  Experiment: Unknown

➩ Applications

Study the superfluid transition and properties of helium in a heat current and a reduced gravity environment (<0.01g)

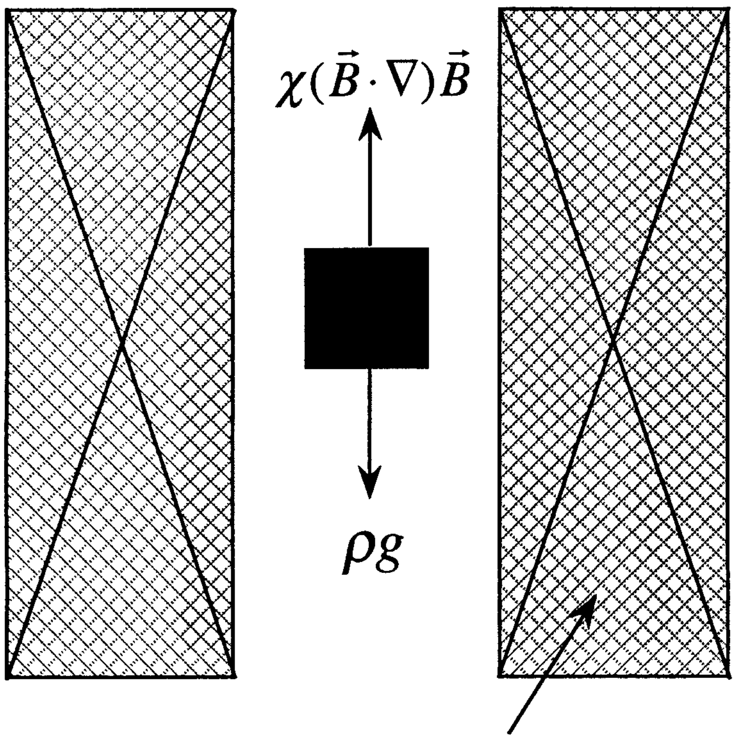
- *hysteresis of superfluid transition*
- *nonlinearity of thermal conductivity*
- *depression in transition*
- *thermal expansion coefficient*

Benefits from low-g simulator

- *Closer approach to T_λ without entering superfluid/normal fluid state*
- *Suppress thermal convection to allow larger heat current and taller cell*
- *Better comparison with theories assuming zero gravity*
- *Bridge between 1g and μg*

Low-gravity Simulator

- Helium-4 is weakly diamagnetic
- Full Cancellation: $B(\partial B/\partial z) \approx 21\,T^2/cm$

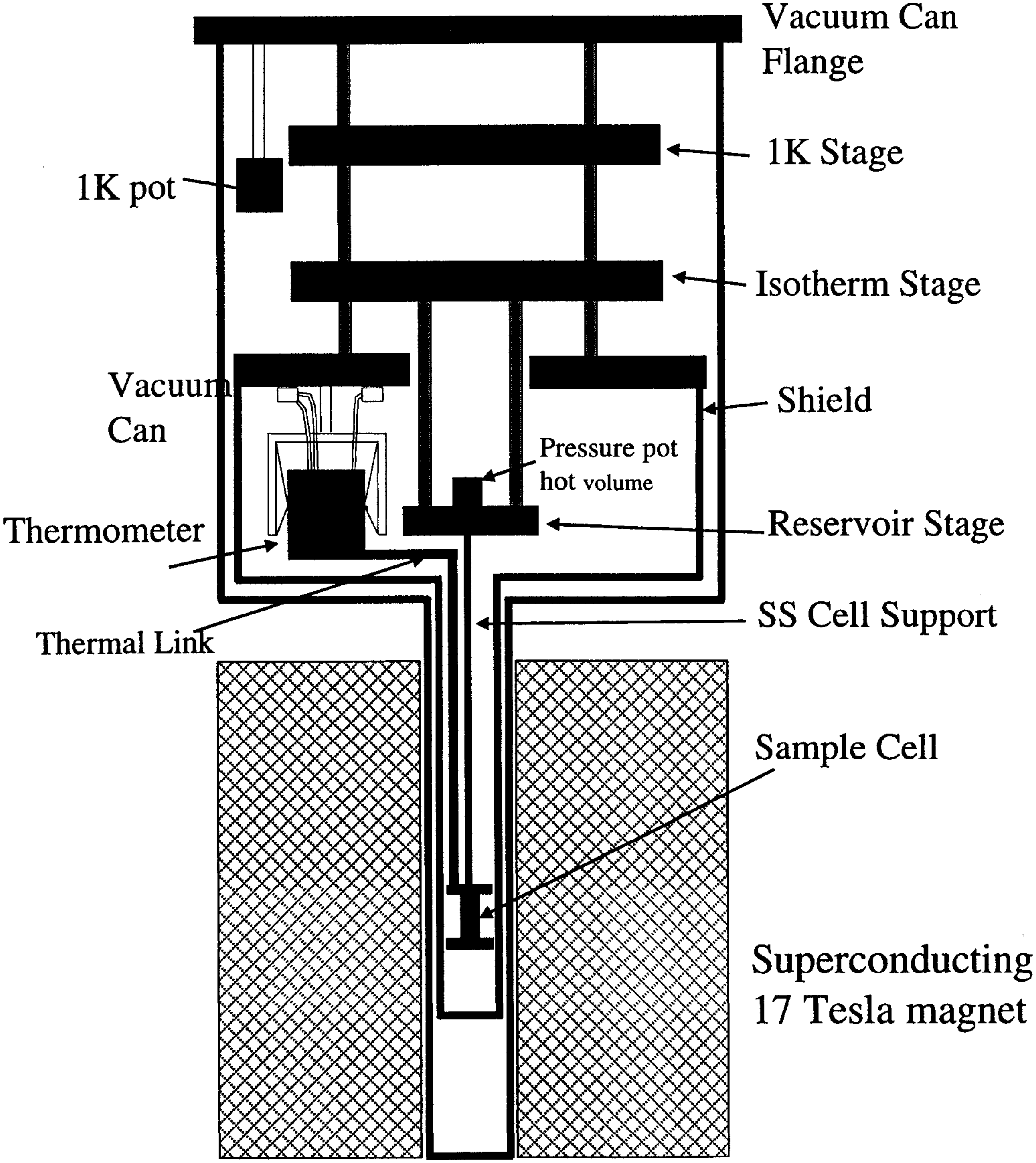


17T superconducting magnet
(From Oxford Instruments)

Magnet:

- Run in persistent mode
- Maximum B(dB/dz)~23 T^2/cm
- Rated fields:
  15.2 T @ 4.2K
  16.6 T @ 2.2K
- 3.2cm-Dia. bore
- Produce 0.01g in a sample volume of 0.5cm dia. and 0.5cm high

Apparatus

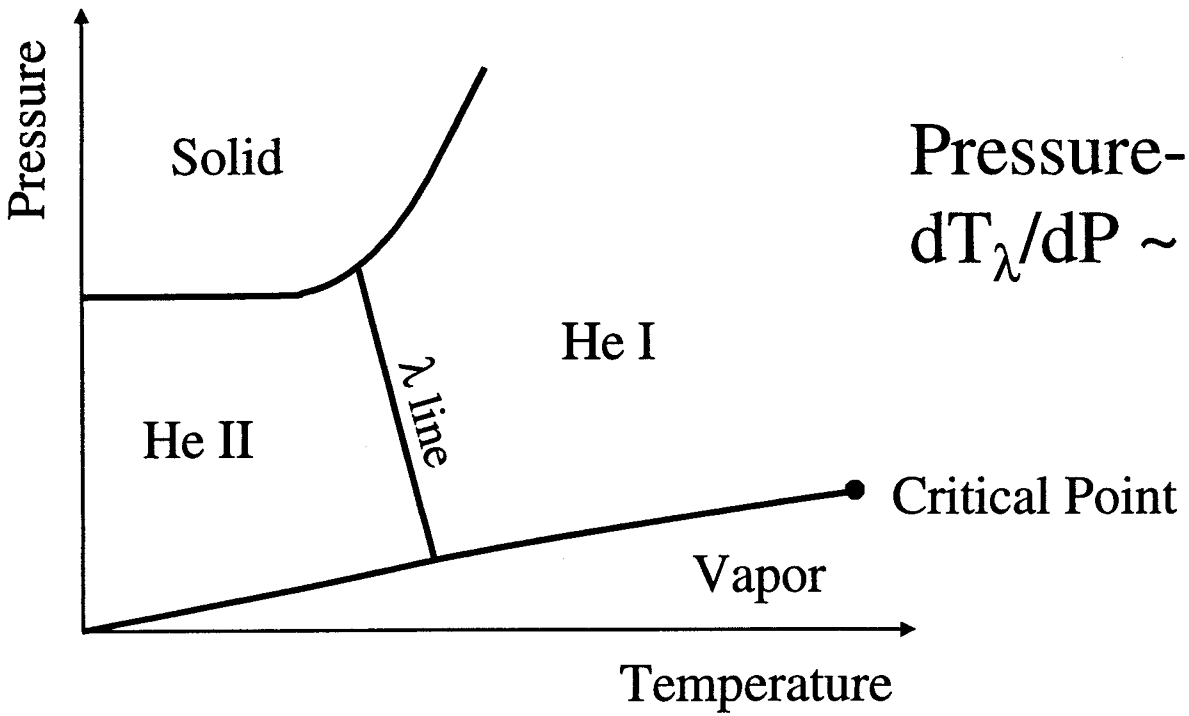

Vacuum Can
Flange
1K Stage
1K pot
Isotherm Stage
Vacuum
Can
Shield
Pressure pot
hot volume
Thermometer
Reservoir Stage
SS Cell Support
Thermal Link
Sample Cell
Superconducting
17 Tesla magnet

Gravity Effect on T_λ

Hydrostatic pressure

→ Variation in T_λ

$$T_\lambda(z) = T_\lambda(0) + z\,\rho g(d\,T_\lambda/dP)$$
$$= T_\lambda(0) + z\,(1.273\ \mu K/cm)$$

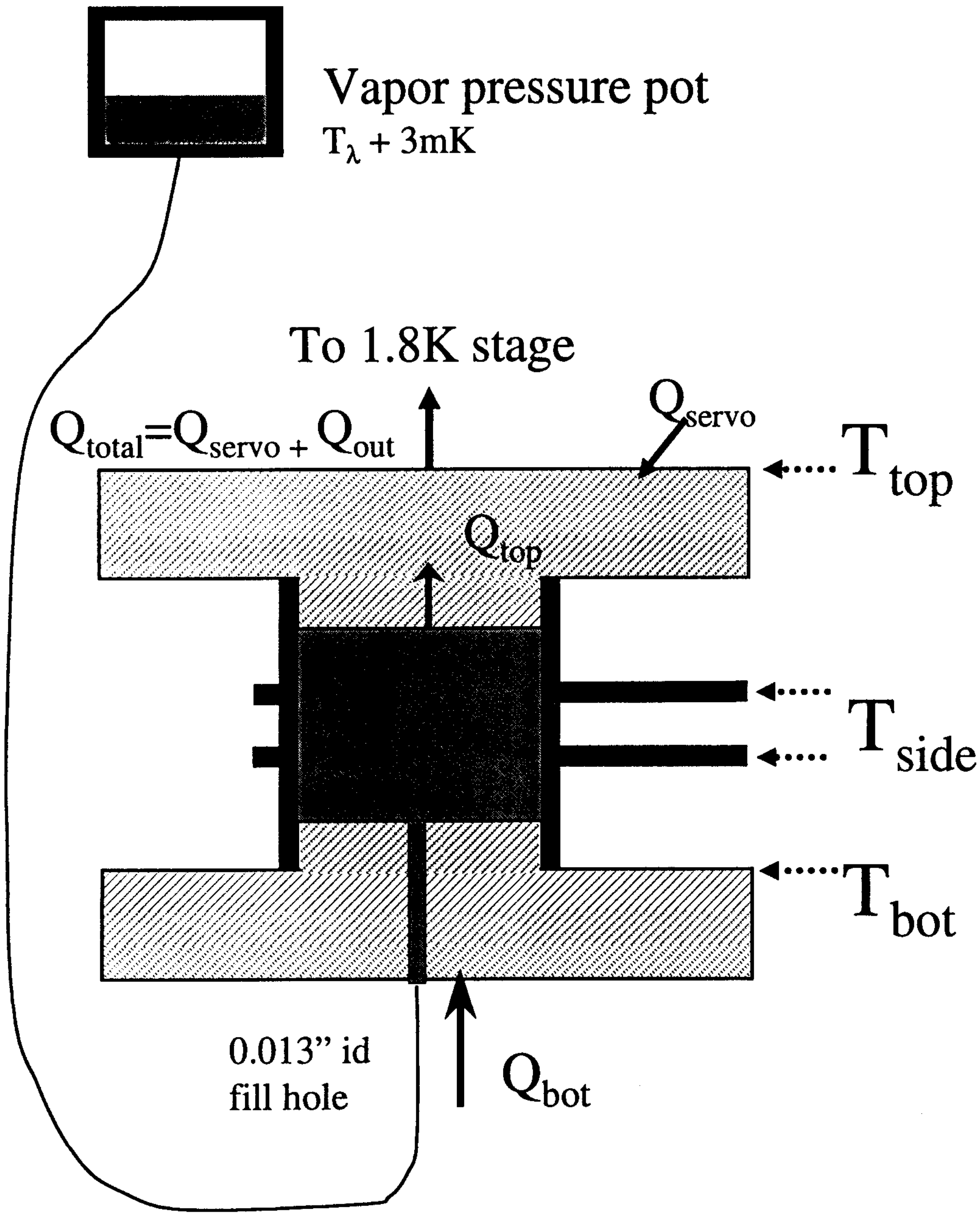


Pressure-dependent λ line

$dT_\lambda/dP \sim 8.7$ mK/bar

Thermal conductivity cell:

Based on ***DYNAMX*** design



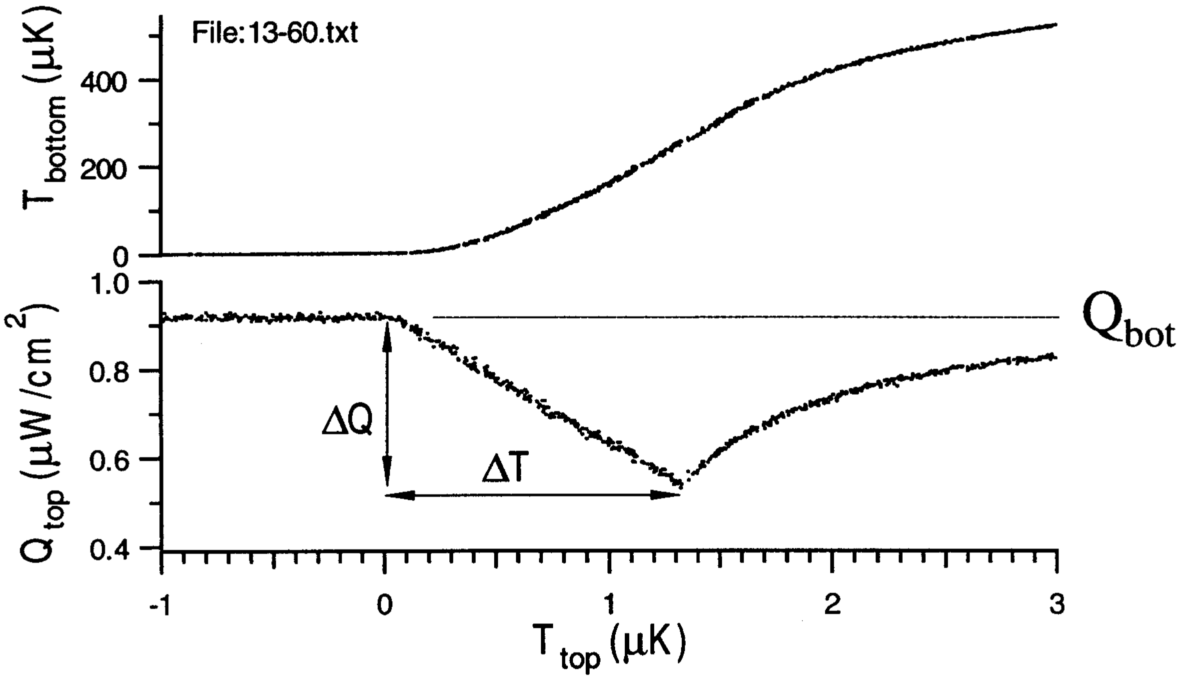
Cell Characteristics

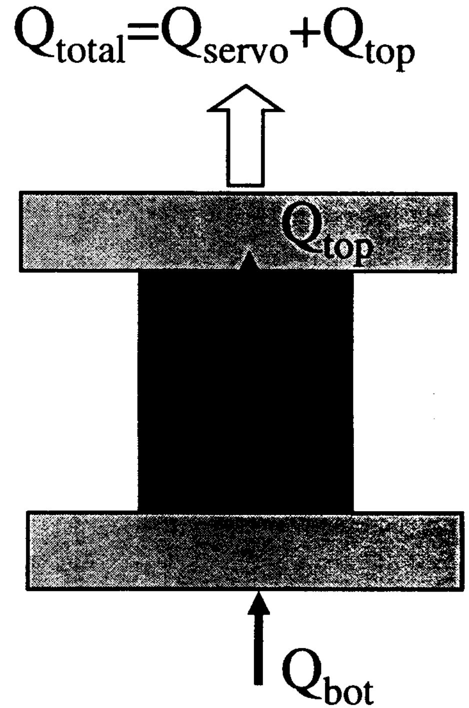
- ✓ ***Sidewall:*** *0.020" Vespel*
- ✓ ***Endcaps:*** *OFHC annealed copper*
- ✓ ***Side Probes:*** *Two annealed 0.002" high purity copper foils*
- ✓ ***Thermometers:*** *6nK resolution He-4 melting curve thermometers (MCT)*
- ✓ ***Dimensions:*** *0.5cm did., 0.5cm tall*
- ✓ ***Epoxy seal****, top end cap assembled first and inspected*

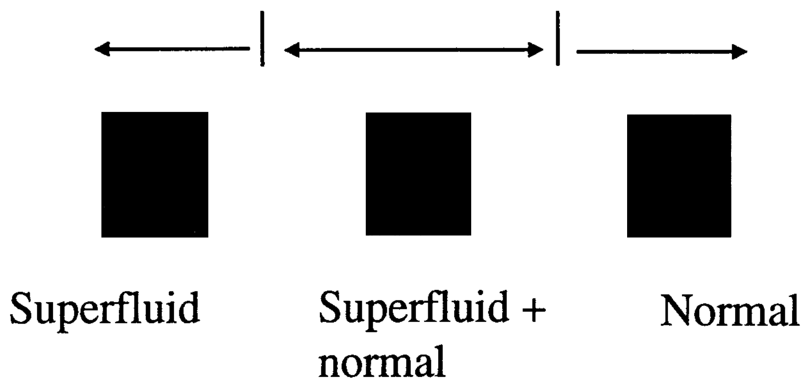
Gravity Reduction: I. Reduction in ΔT_λ

(ΔT_λ is the difference of Tl between the top and bottom of the cell)

By ramping cell top temperature (1g data) *Ramp Rate: 0.55nK/s*







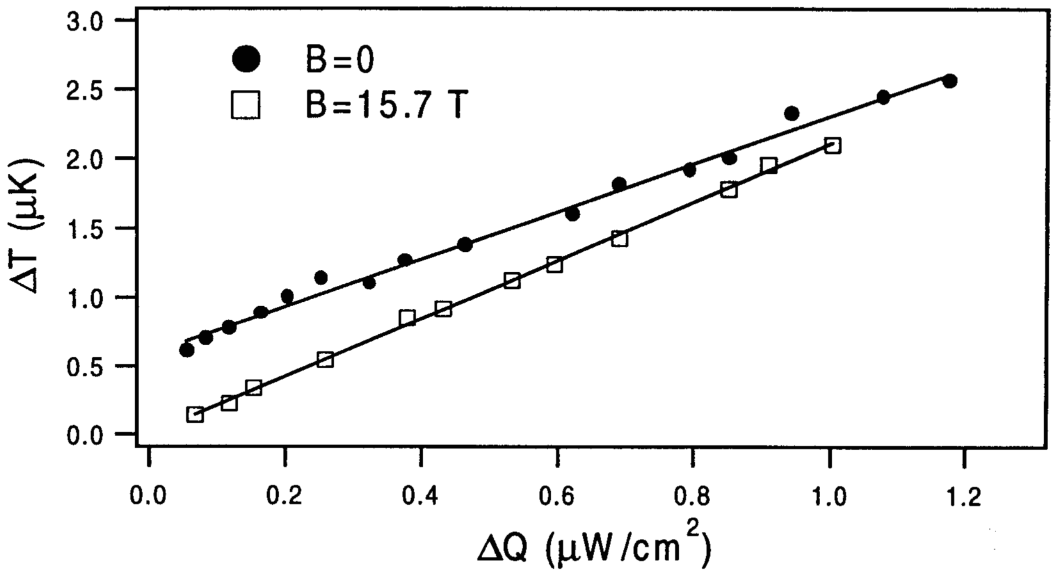
Q_{top} is obtained by measuring Q_{servo} and assuming constant Q_{total}

Gravity Reduction: I. Reduction in ΔT_λ

$$\Delta T = \Delta T_\lambda + R_b \, \Delta Q$$

$$\Delta T_\lambda = 1.273 \, L \, a/g$$

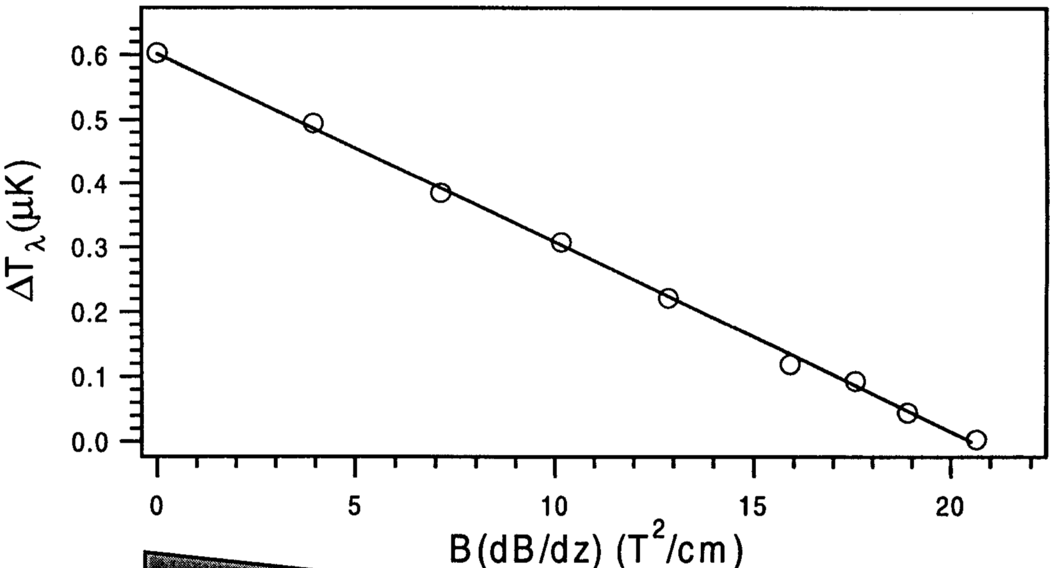
↑ T_λ difference across the cell



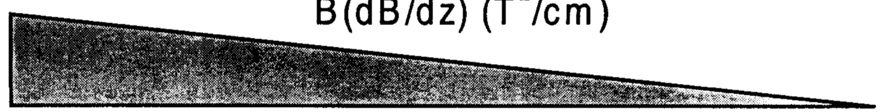
Full Cancellation

$B\,dB/dz = 21.0 \pm 0.2 \; T^2/cm$

OR $\quad B = 15.7 \pm 0.2$ Tesla



Effective Gravity 1g

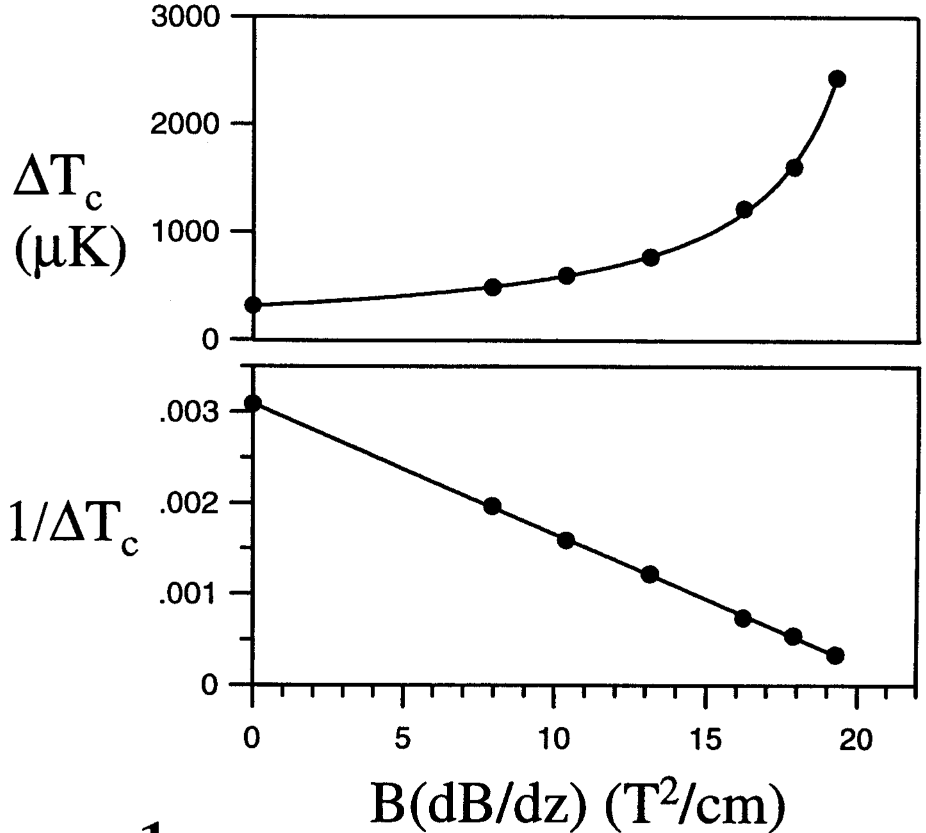


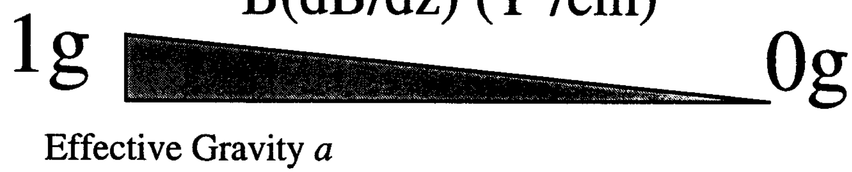
0g

Gravity Reduction: II. Suppression of Convection

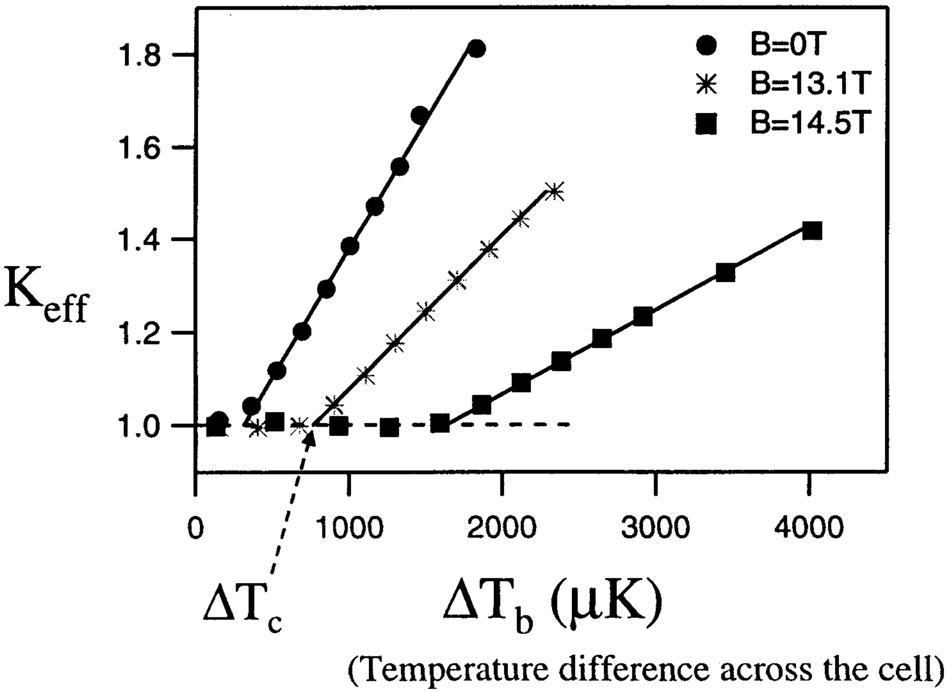
Critical temperature is inversely proportional to effective gravity a

$$\Delta T_c \sim 1/a$$





Effective thermal conduction

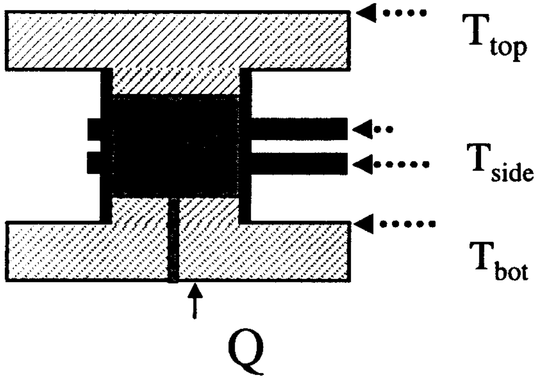


Full cancellation:
$B(dB/dz) \sim 21.6\ T^2/cm$

Field-Dependent Thermal Resistance

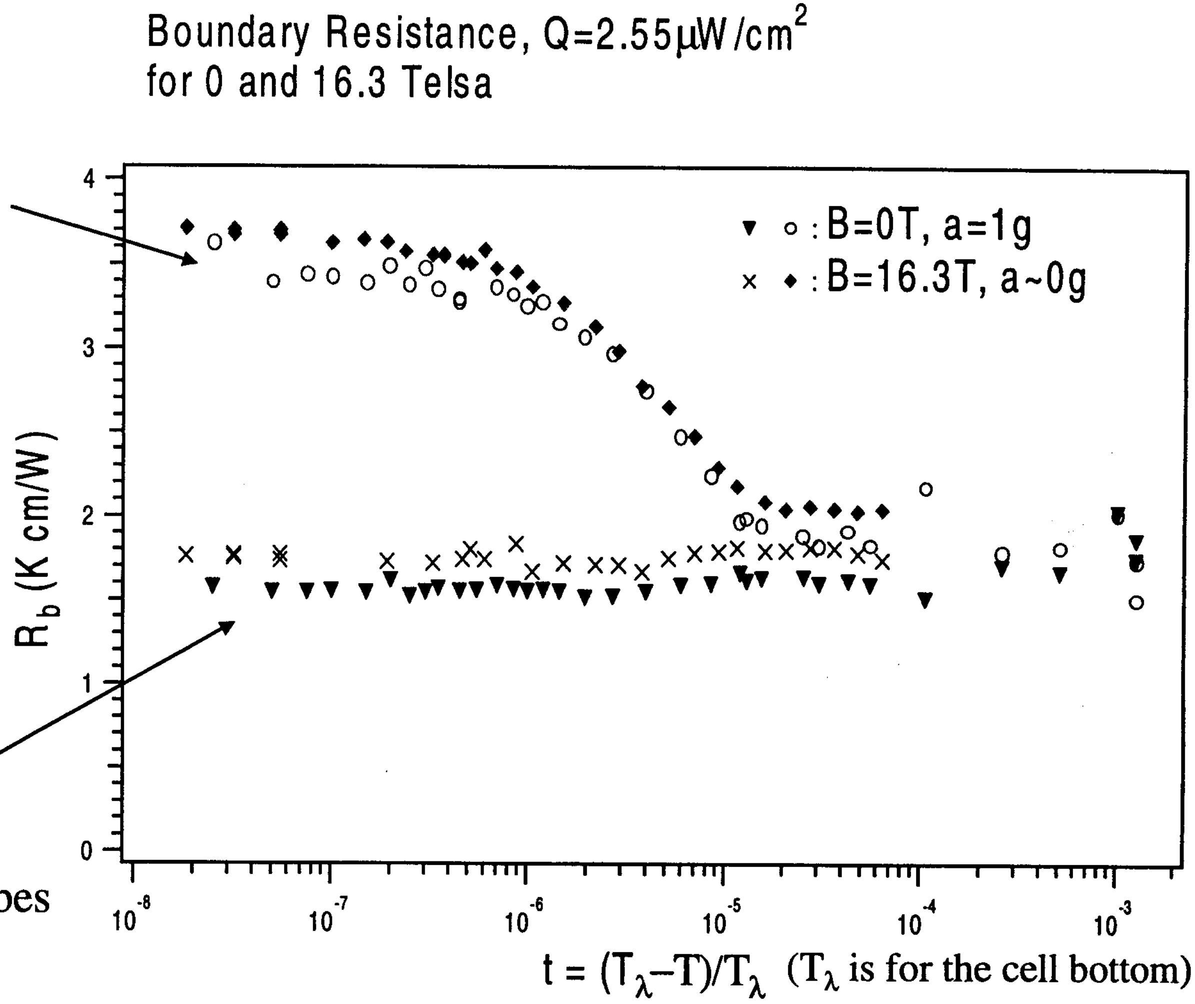
R_{tb}

between top and bottom probes



R_{ts}

Between top and side probes



✓ The fill hole reduces the thermal resistance by increasing the surface area at the cell bottom

✓ Thermal resistance is increased by magnetic field

✓ Gaps between sidewall and end plate show similar effect

(See, Murphy and Meyer, *JLTP 105, 185 (1996))*

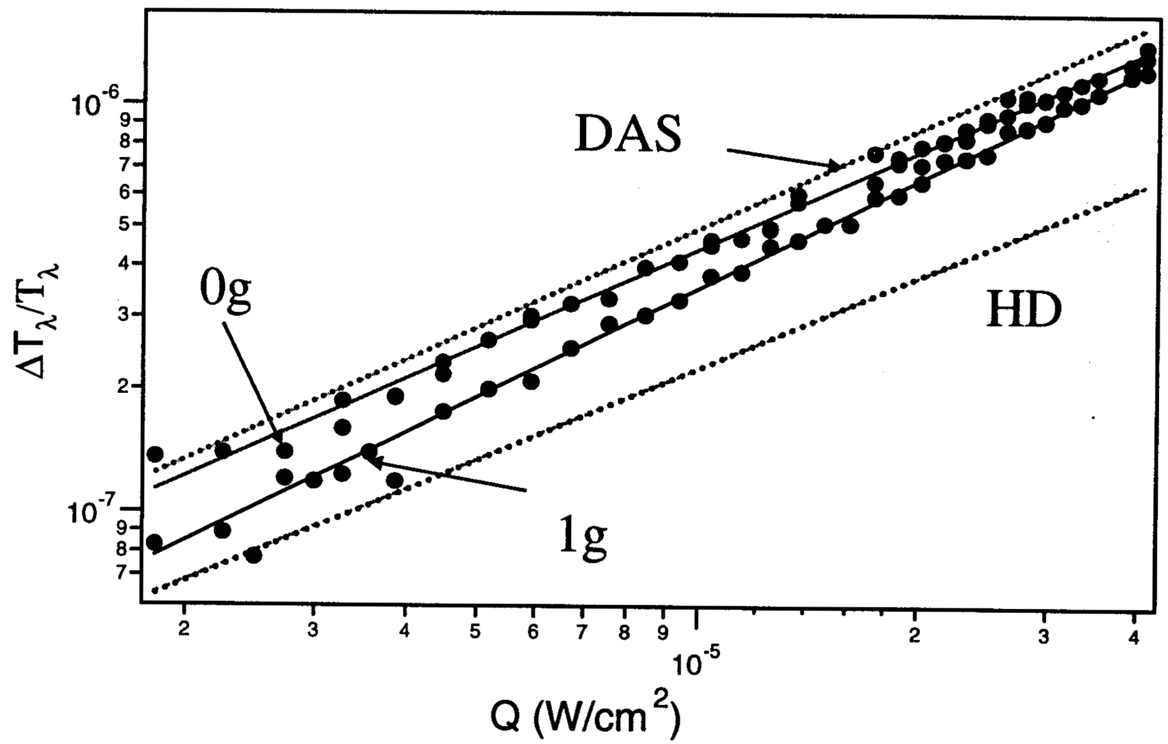
T_λ (or Tc) depression by heat current

***Measurement**: Mapping the transition temperature at the cell bottom (T_λ^b) to the side probe while ramping the cell top temperature*

$\tilde{Q} = 0.408\,\mu\ \mathrm{W/cm^2}$

$$\frac{\Delta T_\lambda}{T_\lambda} = \left(\frac{Q}{Q_0}\right)^x$$

	Q_0	x
1g	*182*	*0.89*
0g	*902*	*0.80*



Experiments: Duncan, Ahlers, and Steinberg, *PRL 60, 1522 (1988)* (DAS)
F. Liu and Ahlers, *PRL 76, 1300 (1996)*
Moeur et al (DYNAMX), *PRL 78, 2421 (1997)*

Theories: Onuki, JLTP 50, 433 (1983)
Haussmann and Dohm, *PRL 67, 3404 (1991)*

CONCLUSIONS:

✓ Gravity reduction has been verified using two independent measuring techniques

✓ Full Gravity cancellation was achieved in our low-g simulator with $B(dB/dz) \sim 21\ T^2/cm$

✓ Abnormal behavior of thermal resistance at cell bottom caused by the fill hole in the bottom end cap

✓ Thermal resistance increased with increasing magnetic field

✓ Depression of the transition by a heat current (1g and 0g) agreed qualitatively with DAS measurements and the theories.