Superfluid helium weak links: physics and applications

Richard Packard
University of California,
Berkeley

Collaborators

^3He

Alex Loshak
Sergei Pereversev
Scott Backhaus
Alosha Marchenkov
Ray Simmonds
Seamus Davis

^4He

Emile Hoskinson
Yuki Sato

Supported by NSF and NASA

What is a superfluid weak link?

Josephson Equations

Generic technique for observing the physics

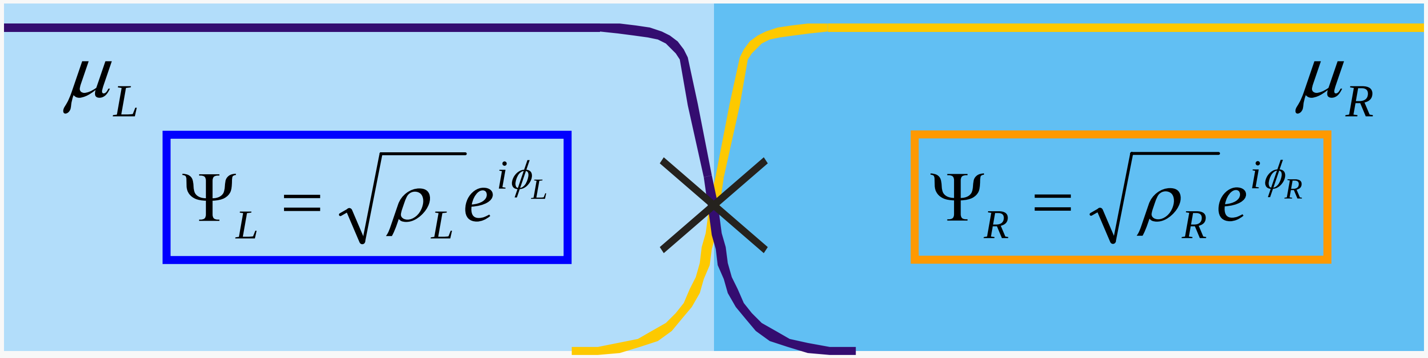
^{3}He

- **Josephson oscillations (the quantum whistle)**
- **The current-phase relation**
- **The ^{3}He superfluid gyroscope**

^{4}He

- **Quantized phase slips**
- **Search for phase slip sound**
- **Josephson oscillations again!**
- **The current phase relation**
- **The coherence question**
- **Prospects for a practical gyroscope**

A superfluid weak link:



$$\Delta\phi = \phi_R - \phi_L$$

$$I = I_c \sin(\Delta\phi)$$

$$\frac{d\Delta\phi}{dt} = \frac{-\Delta\mu}{\hbar}$$

$$if \;\; \Delta\mu = const., \; I = I_c \sin\left(\frac{\Delta\mu}{\hbar} t\right),$$

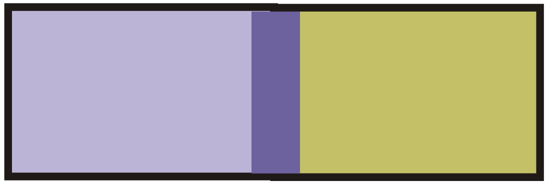
$$f_j = \frac{\Delta\mu}{h}$$

superconductor $\Delta\mu = -2eV$

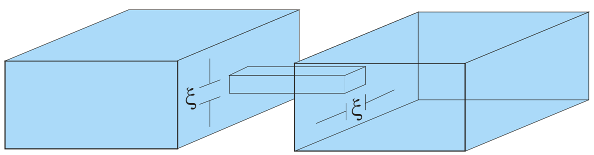
superfluids $\Delta\mu = m(\Delta P/\rho - s\Delta T)$

Criterion for weak link barrier dimensions

Josephson Junction:

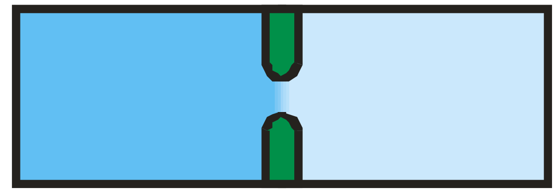


Superconducting weak link:



$$f_j = \frac{2eV}{h} = 483THz/Volt$$

Superfluid weak link:



$$f_j = \frac{2m_3}{h}\left(\frac{\Delta P_{dc}}{\rho}\right) or \frac{m_4}{h}\left(\frac{\Delta P_{dc}}{\rho} - s\Delta T\right)$$

$$f_{j3} = 183Hz/mPa \;\; or \;\; f_{j4} = 68.7Hz/mPa$$

Size of barrier must be on the order of or less than the coherence length ξ

For superfluid ^{3}He, ξ(T=0) ~ 70nm

For superfluid ^{4}He, ξ(T=0) ~ 0.1nm

$$\xi_3 = \frac{60nm}{\left(1 - T/T_c\right)^{1/2}}$$

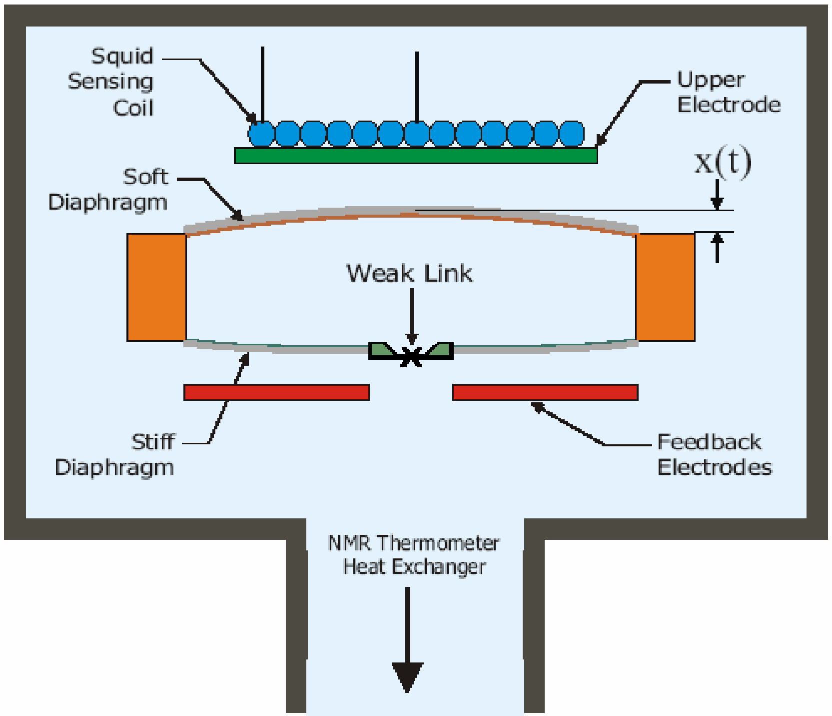
For ^3He cool to below 1mK

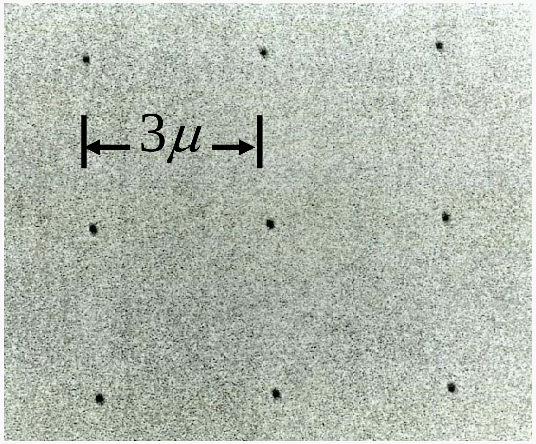
$$\xi_4 = \frac{0.3nm}{\left(1 - T/T_\lambda\right)^{0.67}}$$

For ^4He cool to below 2K

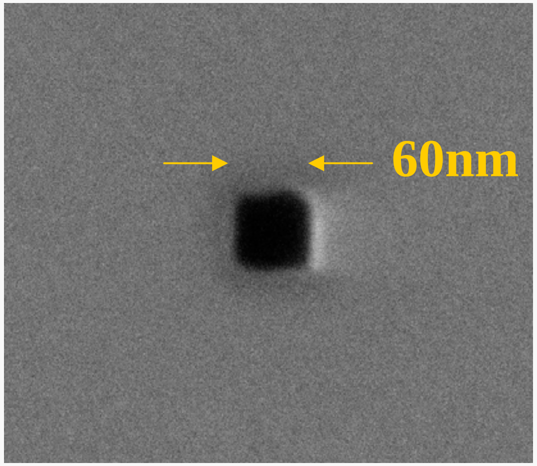
Use ^3He to exploit longer healing length

Experimental Cell Design



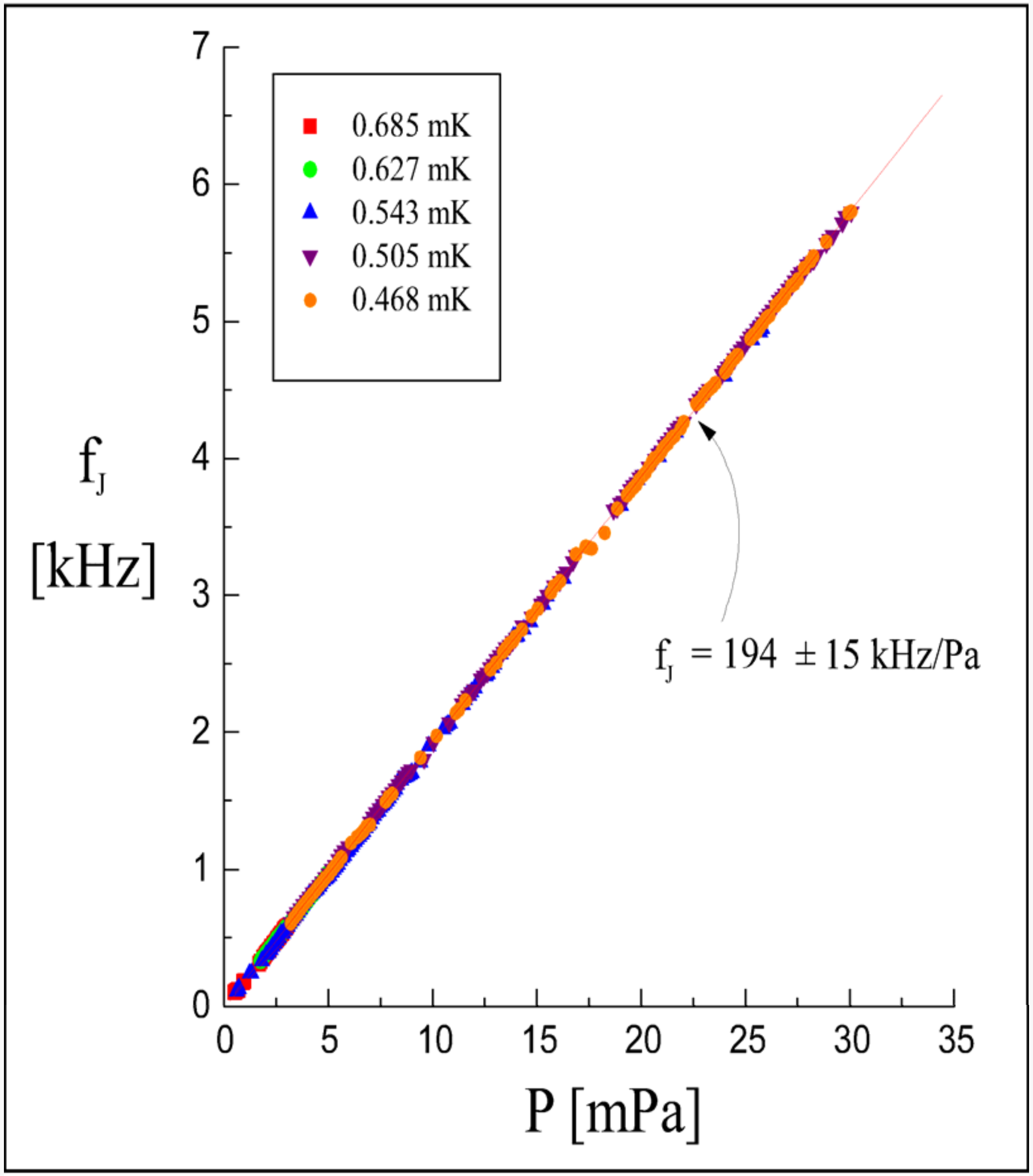


4225 holes in a 50 nm thick silicon nitride membrane



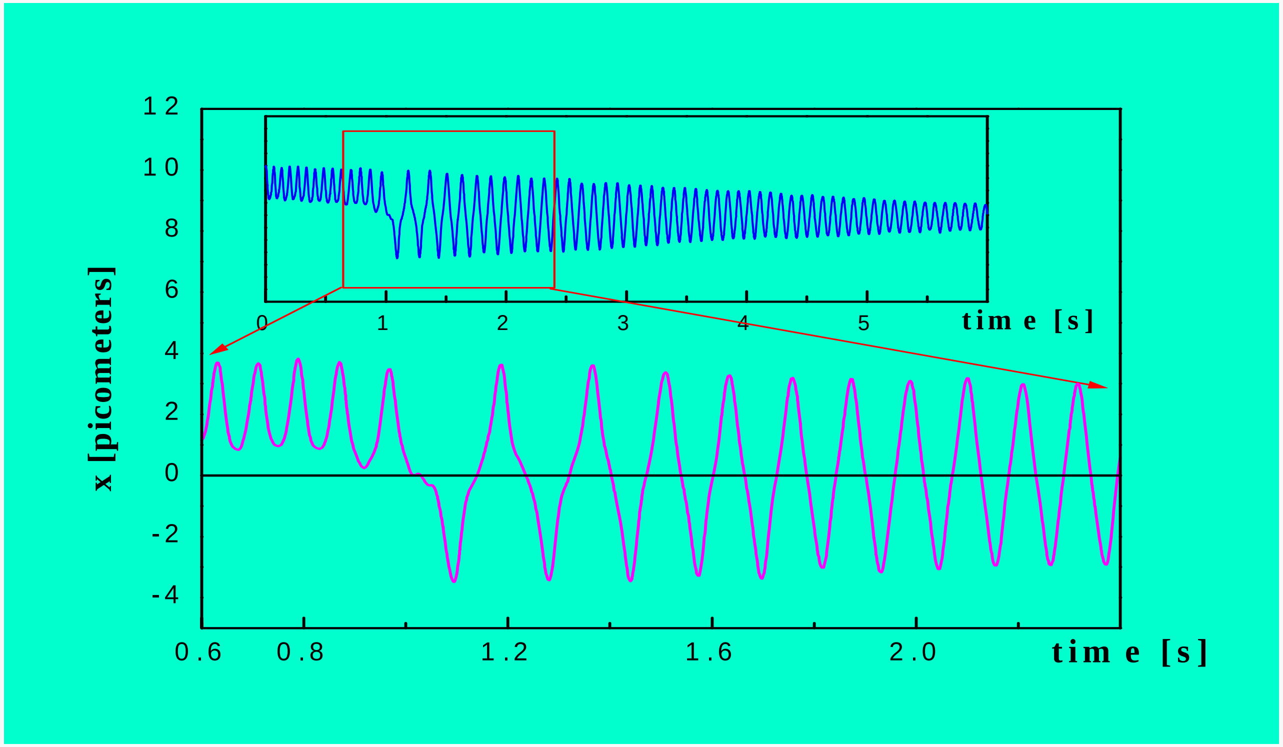
Able to detect ~ 10^{-15} m

AC Josephson Effect



S. V. Pereversev *et al.* Nature **388**. 449-451 (1997)

Determination of the current-phase relation



$$\left.\begin{array}{l}\dfrac{d\varphi}{dt} = -\dfrac{2m_3}{\eta\rho}\Delta P(t) \\ \Delta P = \lambda x(t)\end{array}\right\} \Rightarrow \quad \varphi(t) = \varphi(0) - \left(-\frac{2m_3\lambda}{\eta\rho}\right)\int_0^t x(\tau)d\tau$$

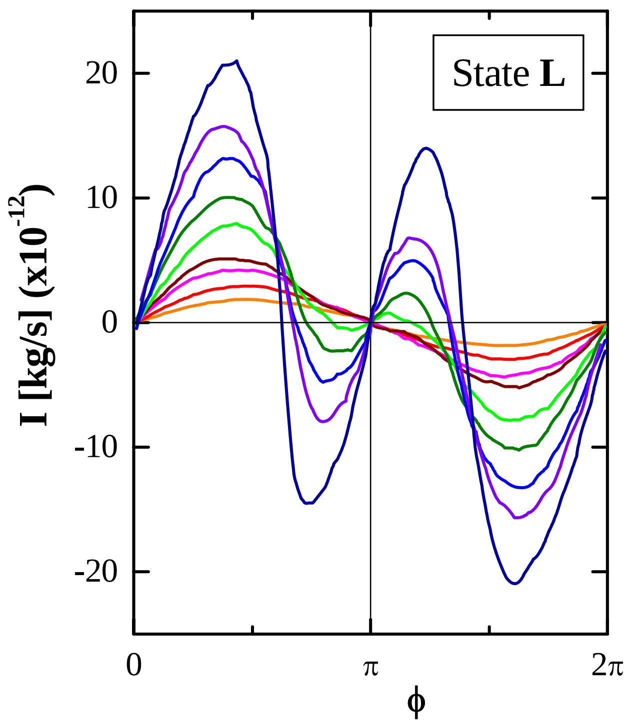
&

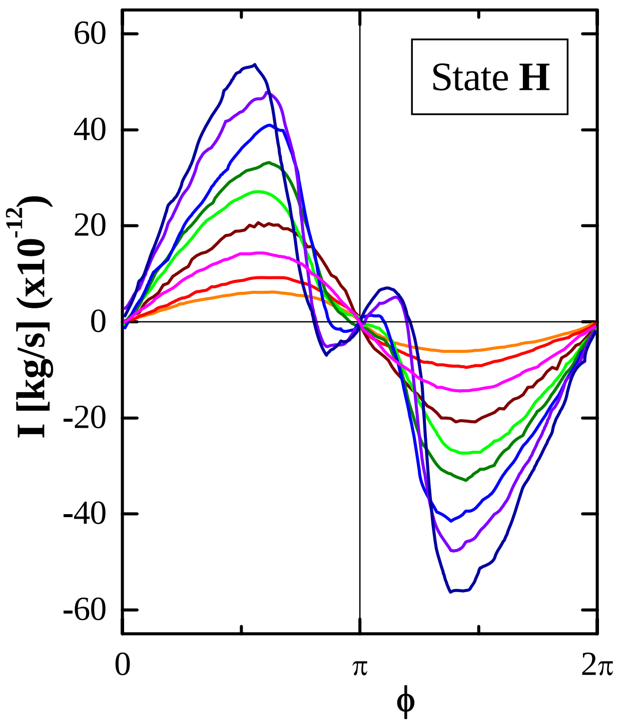
$$I(t) = A\rho\frac{dx}{dt}$$

Eliminate common variable time and plot ...

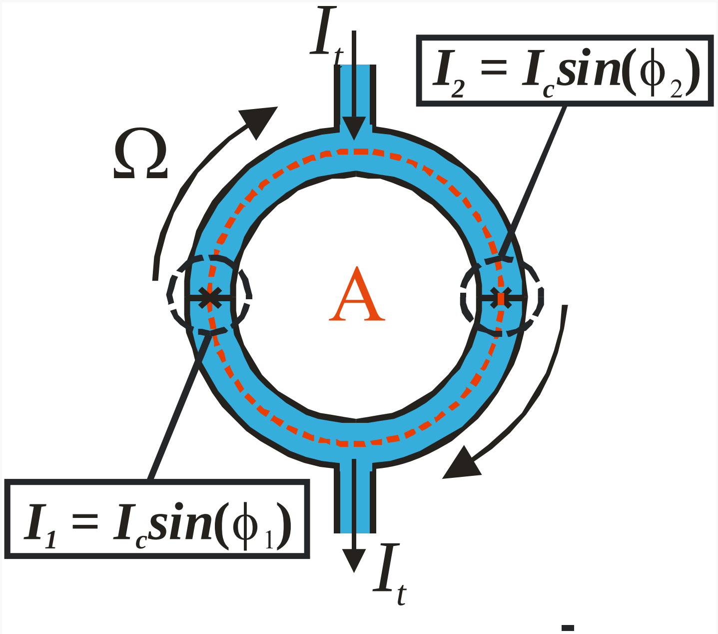
Two Distinct Current-Phase Relations.

Experimental Data.



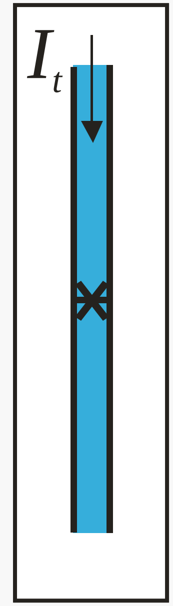


Superfluid dc-SQUID: a gyroscope



$$\nabla \phi = \frac{m_4}{\eta} v_s$$

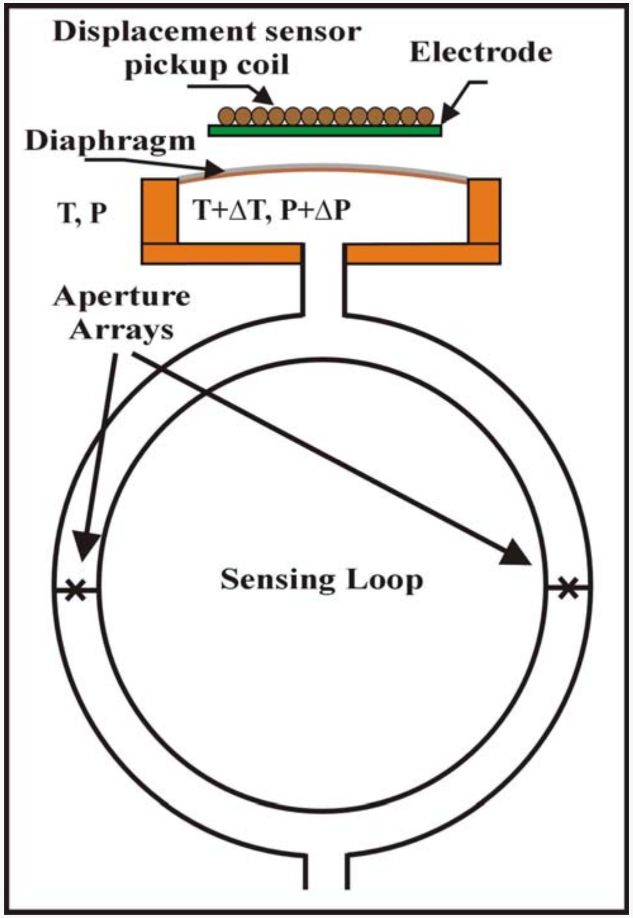
$$\oint \vec{\nabla}\phi \bullet d\vec{\lambda} = 2\pi n$$



$$I = I_c^* \sin(\phi)$$

$$I_c^* = 2 I_c \cos\left(\frac{2\pi \vec{\Omega} \cdot \vec{A}}{h/2m_3}\right)$$

The critical current is modulated by the rotation flux

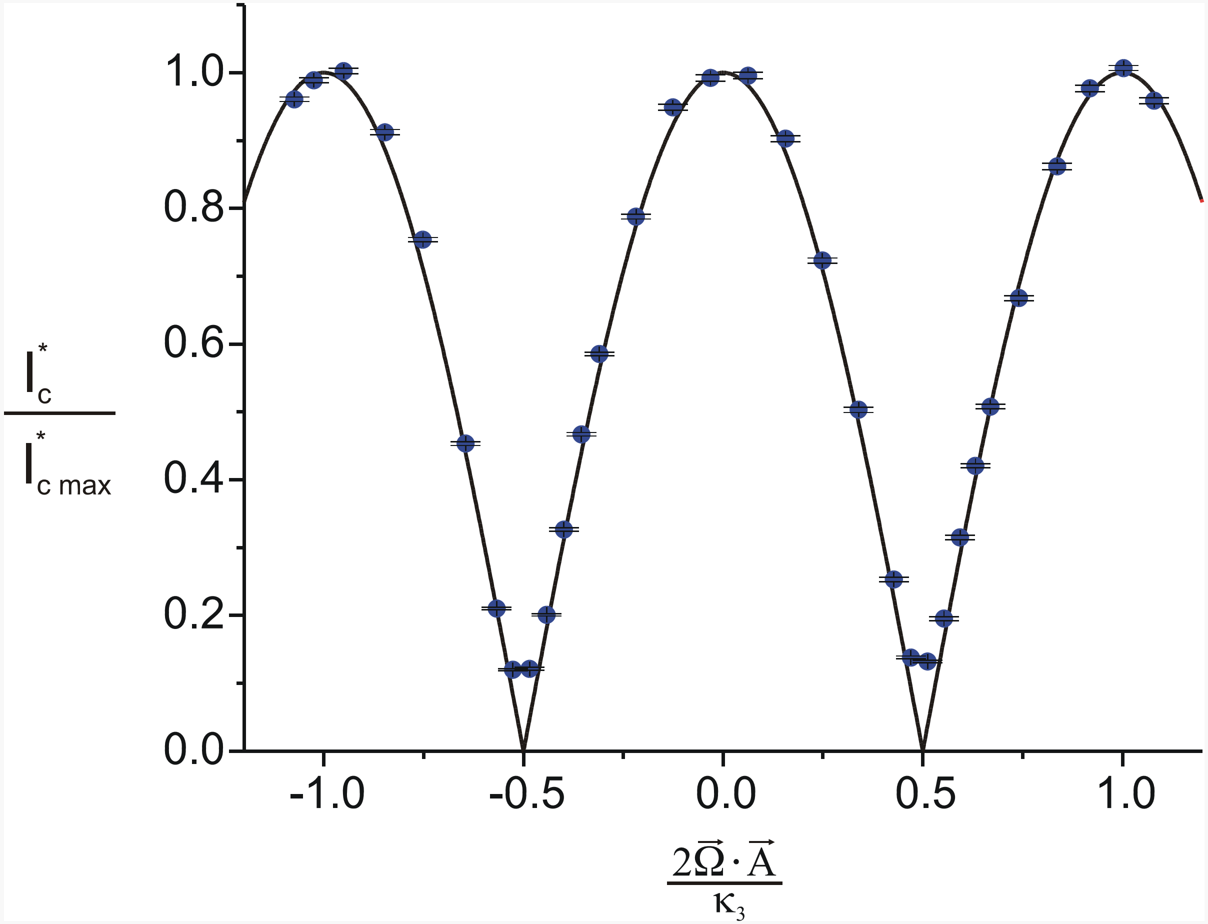

Displacement sensor
pickup coil
Electrode
Diaphragm
T, P
T+ΔT, P+ΔP
Aperture
Arrays
Sensing Loop

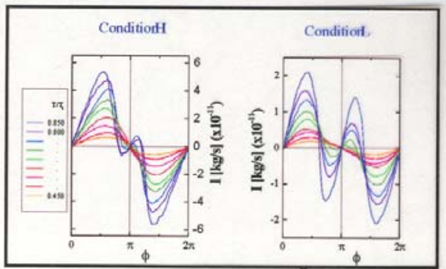
Superfluid ^{3}He gyroscope

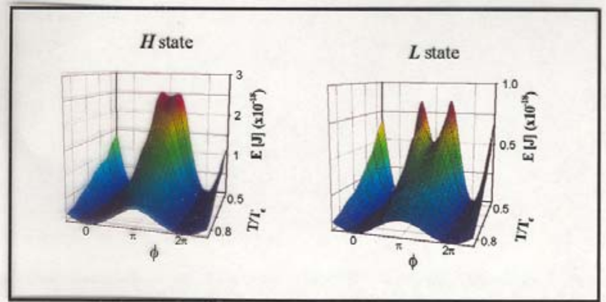
Whistle amplitude vs. reorientation wrt the Earth's axis

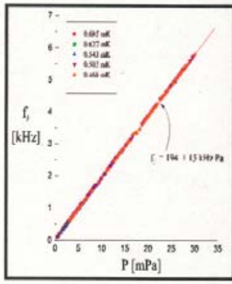
prediction

$$I_c^* = 2I_c \cos\left(\frac{2\pi\vec{\Omega}\cdot\vec{A}}{h/2m_3}\right)$$

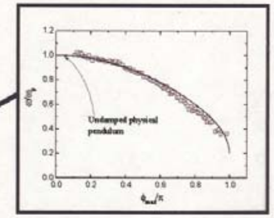


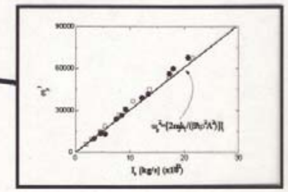


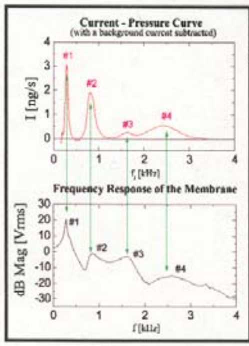


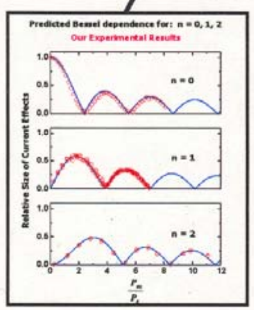


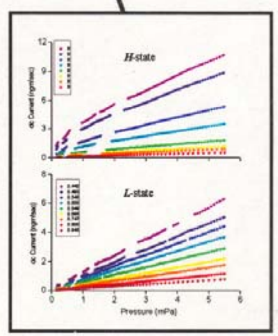
Superfluid ^{3}He Weak Link

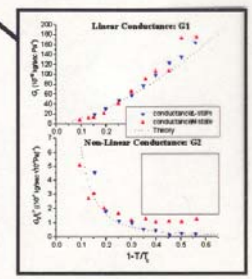










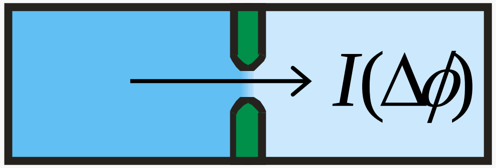


Physics Department
University of California, Berkeley

Richard E. Packard
packard@socrates.berkeley.edu
Ultra Low Temperature Physics

What about ^{4}He?

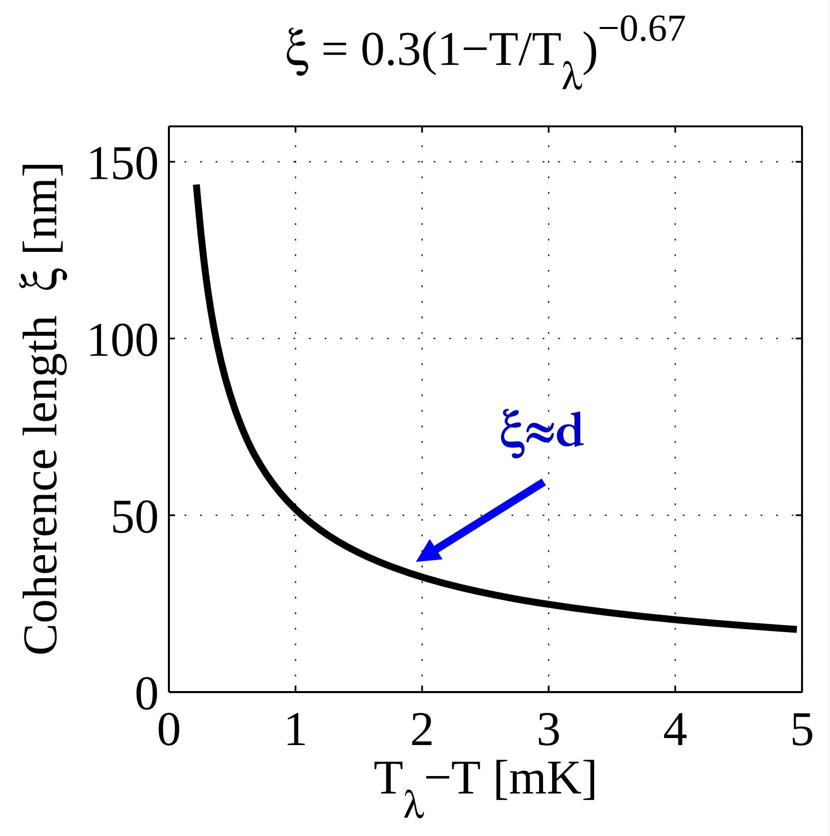
Variation of coupling strength via the healing length, $\xi_4(T)$



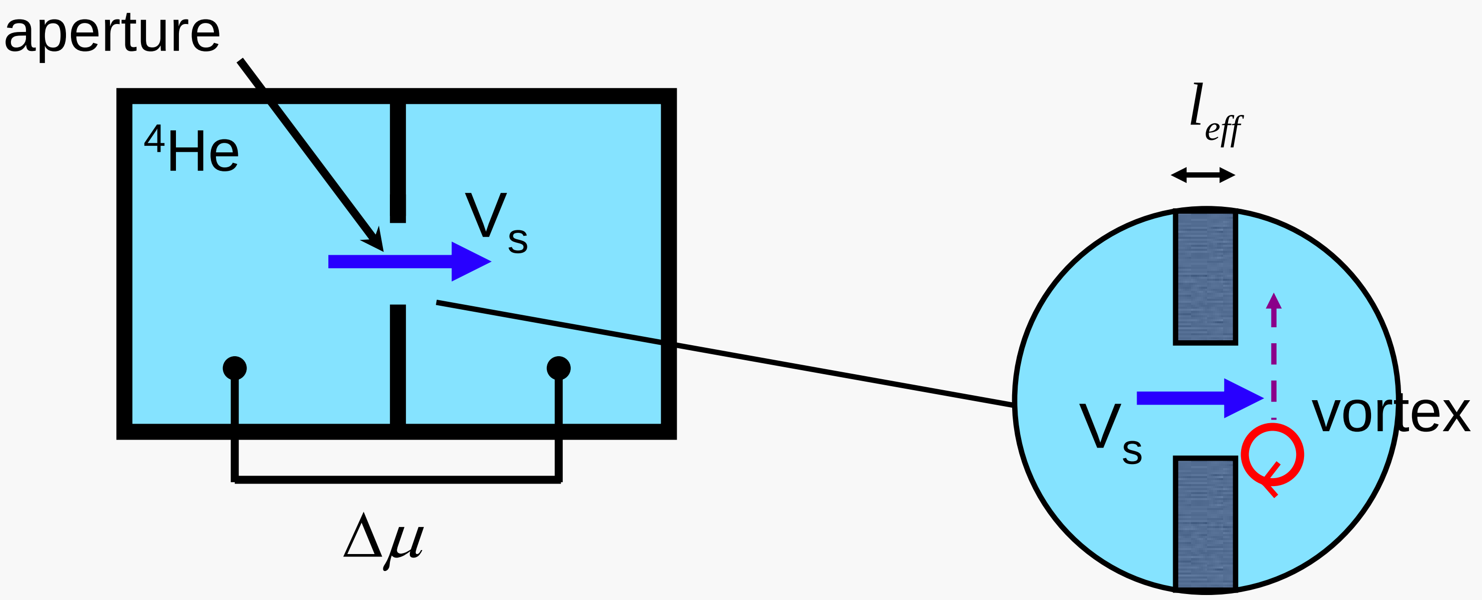
$$\xi_4 = \frac{0.3nm}{\left(1 - T/T_\lambda\right)^{0.67}}$$

Strong coupling: $\xi_4 < d$

Weak coupling: $\xi_4 > d$



A superfluid "strong link"

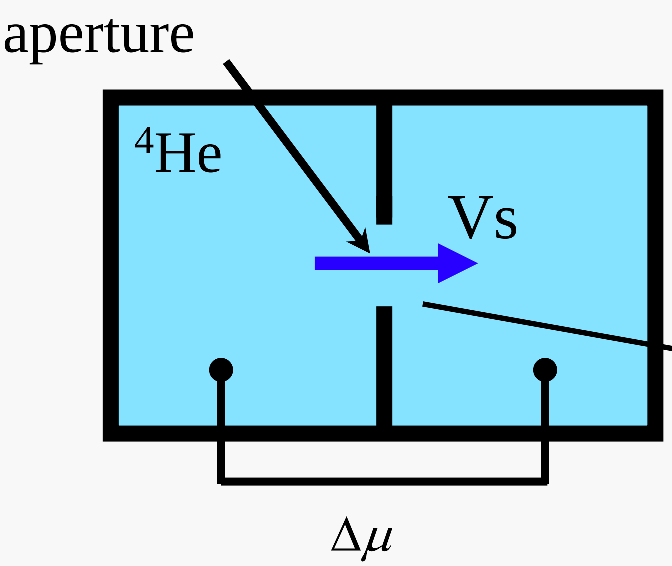


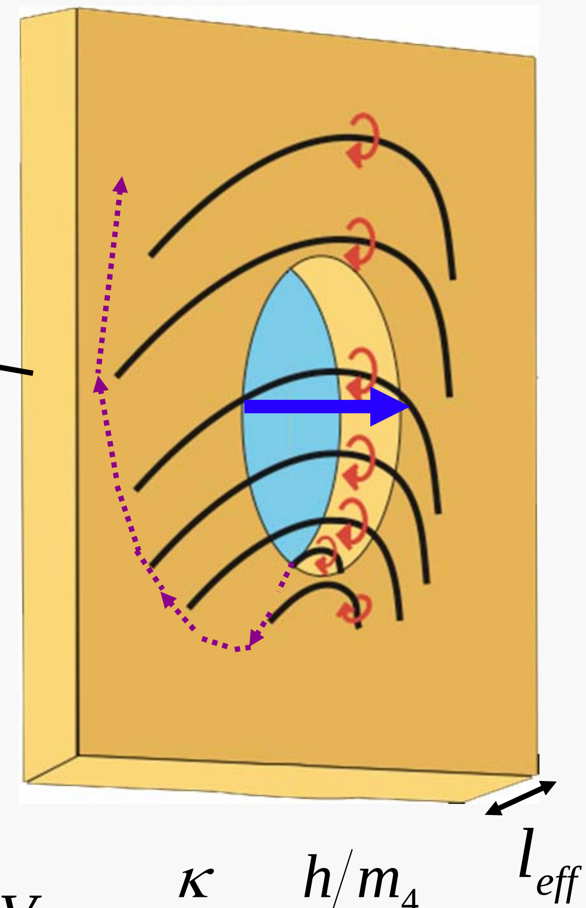
1. Δμ drives superfluid ^{4}He through an aperture
2. V_s increases till it reaches V_c
3. At V_c, a vortex is nucleated and the flow velocity drops by a fixed amount V_{slip}

$$V_{slip} = \frac{\kappa}{l_{eff}} = \frac{h/m_4}{l_{eff}}$$

2π phase slip

2π Phase Slip





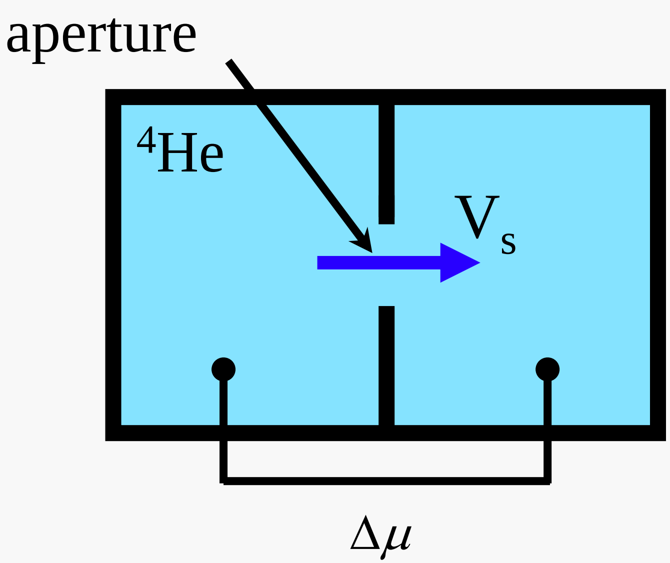
1. $\Delta\mu$ drives superfluid ^{4}He through an aperture

2. V_s increases till it reaches V_c

3. At V_c, a vortex is nucleated and the flow velocity drops by a fixed amount V_{slip}

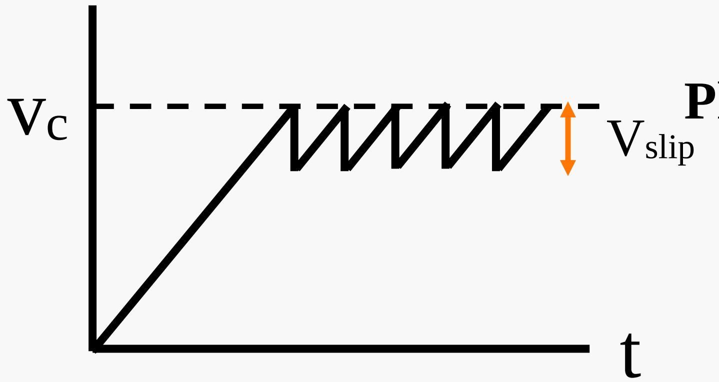
$$V_{slip} = \frac{\kappa}{l_{eff}} = \frac{h/m_4}{l_{eff}}$$

Phase Slip Oscillations



What happens if we keep applying $\Delta\mu$?

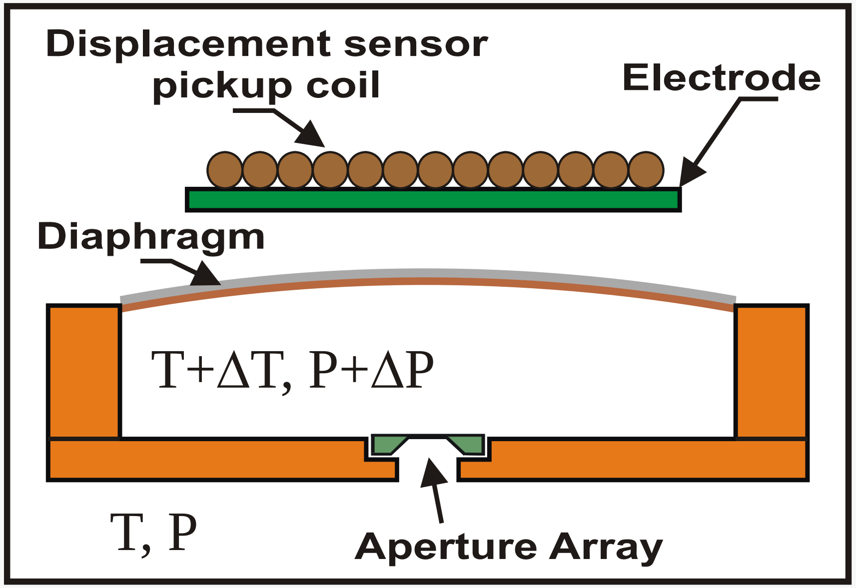
1. V increases till it reaches V_c
2. Phase slip event takes place and V drops by V_{slip}
3. V increases again due to $\Delta\mu$ to repeat the same process

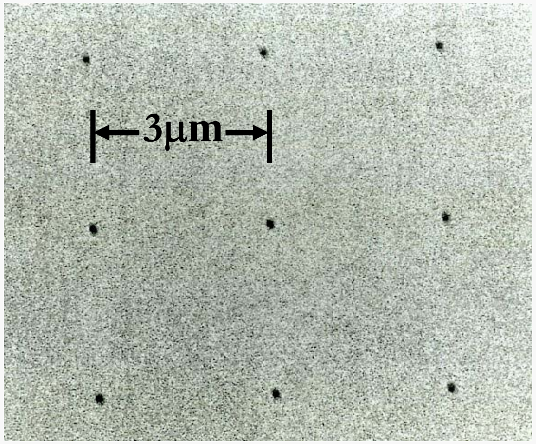


Phase slips occur at Josephson Frequency

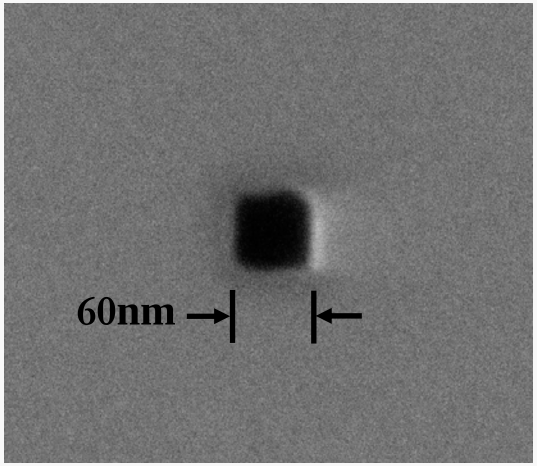
$$f_j = \frac{\Delta\mu}{h}$$

Generic apparatus





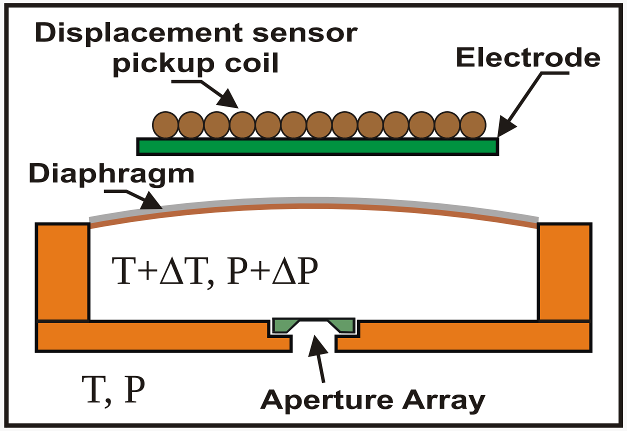
4225 holes in a 50 nm thick silicon nitride membrane



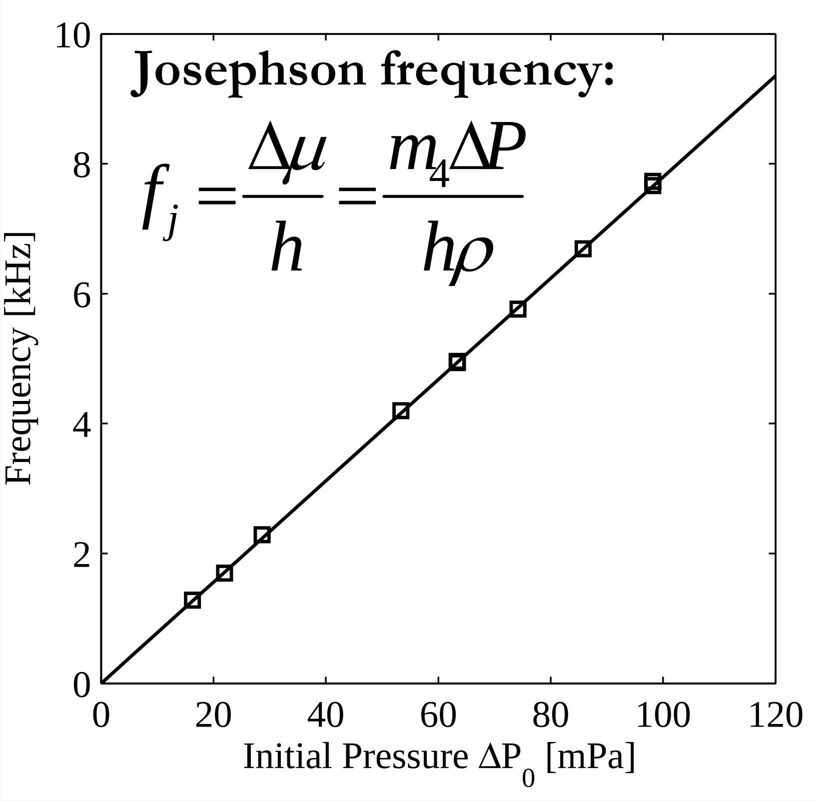
Demonstration of Josephson frequency relation when $\Delta\mu = m_4\Delta P/\rho$

Chemical potential difference

$$\Delta\mu = m_4\left(\Delta P/\rho - s\Delta T\right)$$

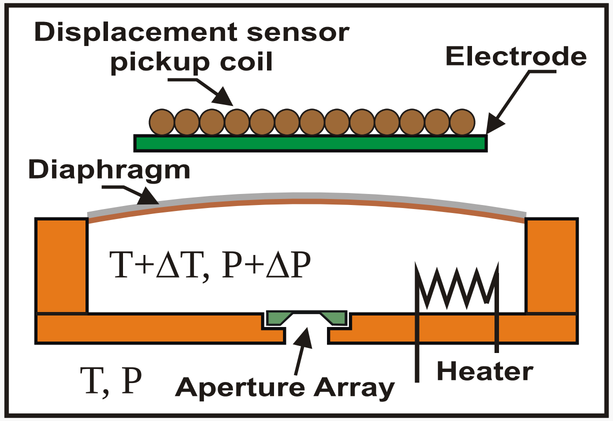


ΔT = 0 at beginning of transient

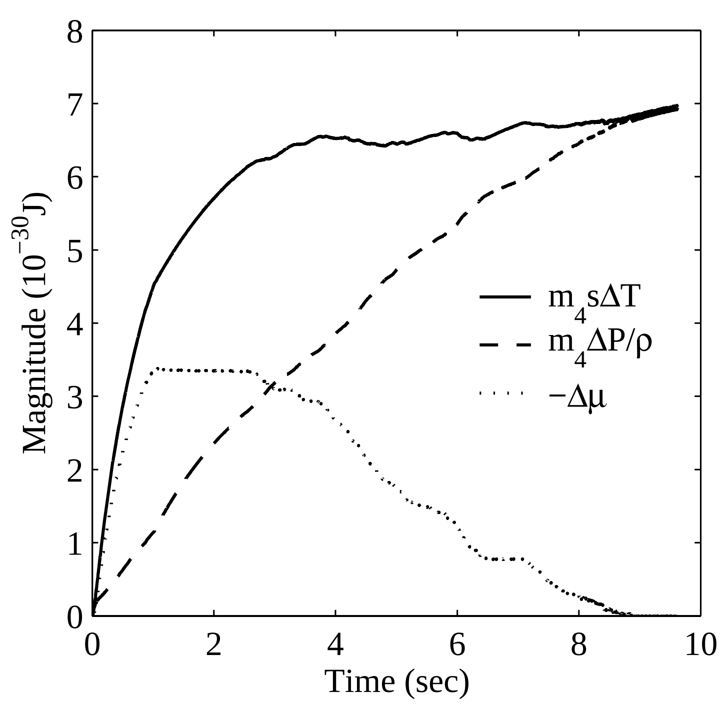


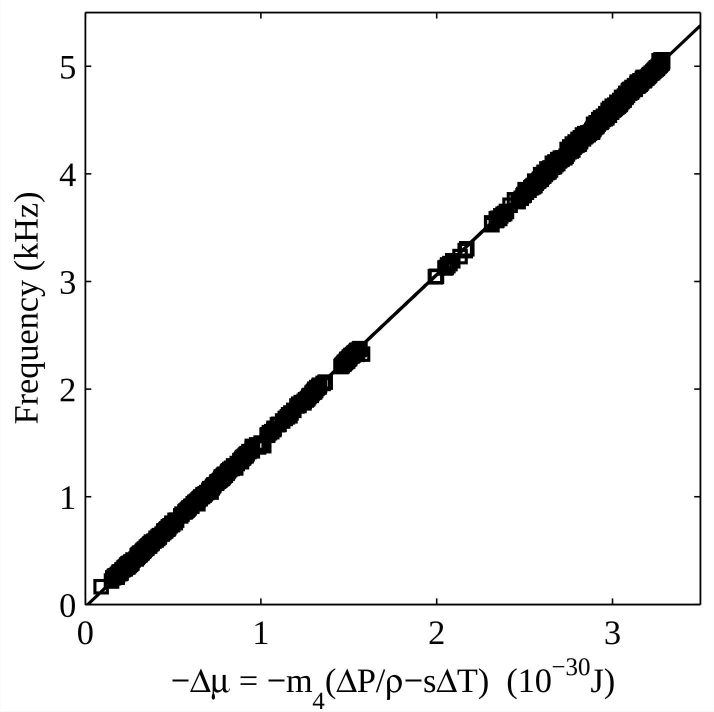
E. Hoskinson, R. E. Packard, T. M. Haard, Nature **433**, 376 (2005)

Thermally driven quantum oscillations



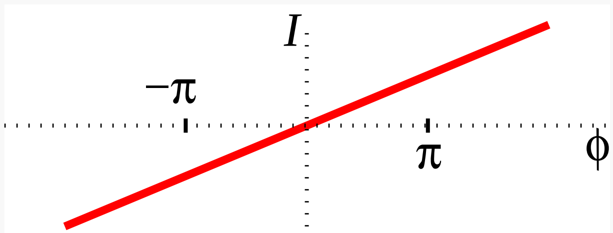
$$\Delta\mu = m_4\left(\Delta P/\rho - s\Delta T\right) \qquad f_j = \Delta\mu/h$$





E. Hoskinson, R. E. Packard, PRL **94**, 155303 (2005).

How do you get from a sawtooth to a sinusoid?



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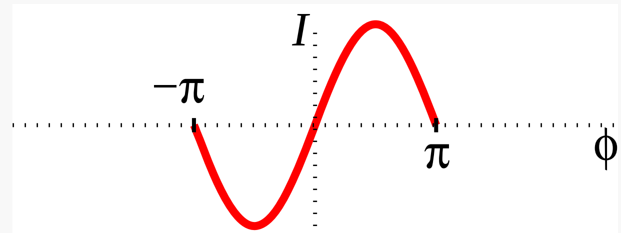
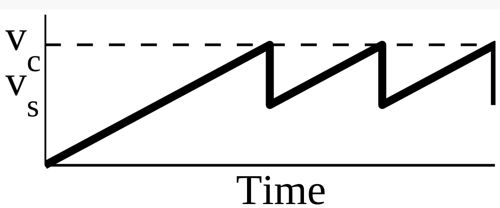
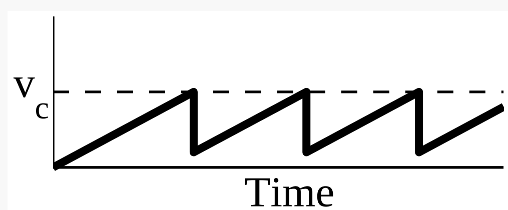


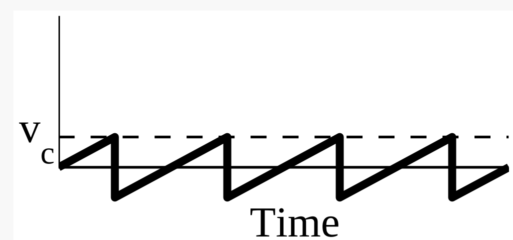
$$I \propto \rho_s v_s \propto \Delta\phi \propto \Delta\phi$$

$$I = I_c \sin \Delta\phi$$





$$When\ \ V_c \approx \frac{1}{2} V_{slip}\ \ , \xi \approx d$$



Determining the current-phase relation

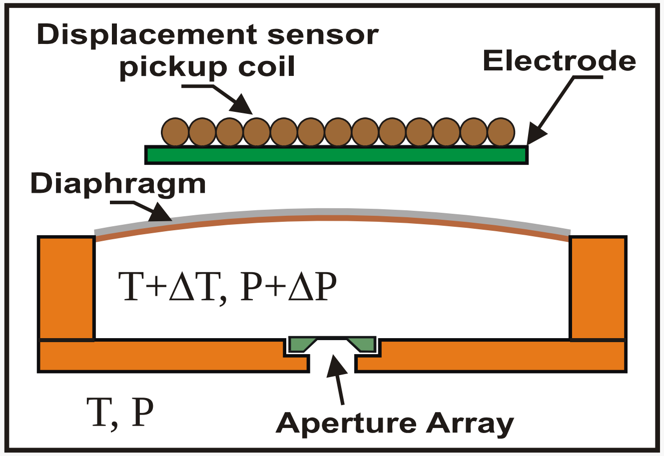
$$I(t) \propto \dot{x}(t)$$

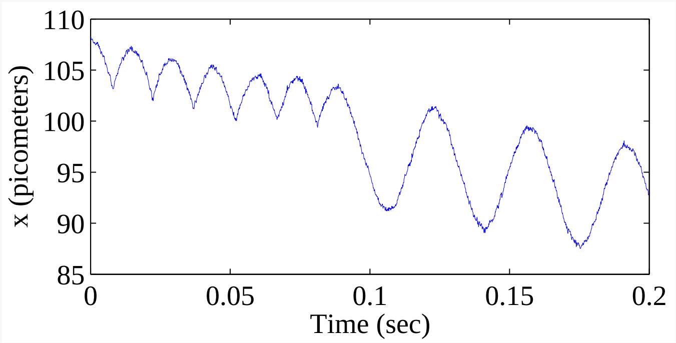
$$\dot{\phi}(t) \propto \Delta\mu \propto \left(\frac{\Delta P}{\rho} - s\Delta T \right)$$

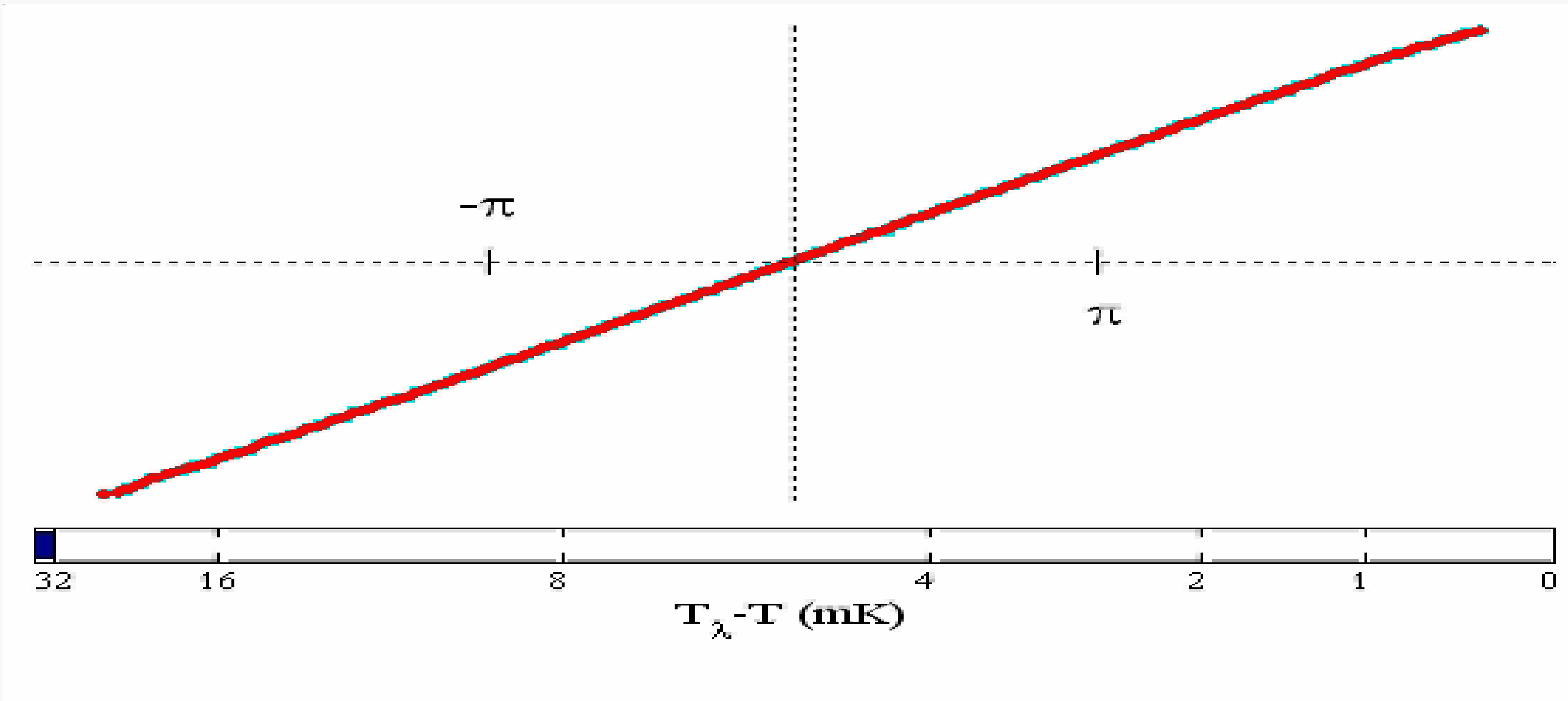
$$\phi(t) = -\eta^{-1} \int \Delta\mu(t)\, dt$$

given $I(t)$ and $\phi(t)$

eliminate t to get $I(\phi)$


Displacement sensor
pickup coil
Electrode
Diaphragm
T+ΔT, P+ΔP
T, P
Aperture Array


110
105
100
95
90
85
x (picometers)
0
0.05
0.1
0.15
0.2
Time (sec)

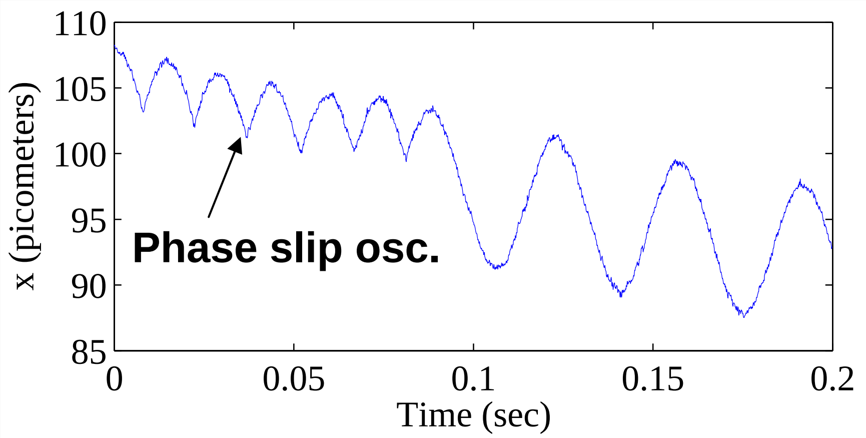

−π
π
32
16
8
4
2
1
0
T_λ-T (mK)

ovie

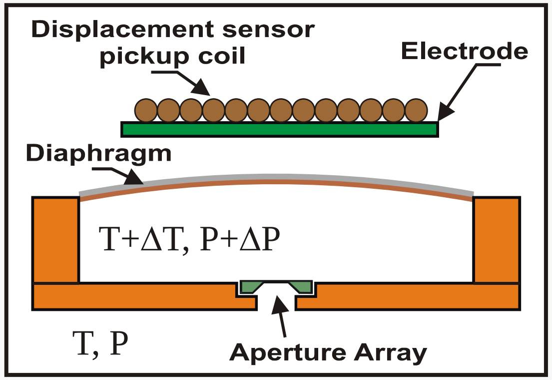
Are the phase slip oscillations synchronicity or quantum phase rigidity?

- A Fourier transform of the quantum whistle shows very narrow spectral width.
- Does the periodicity evolve over time or is it present from the first instant?

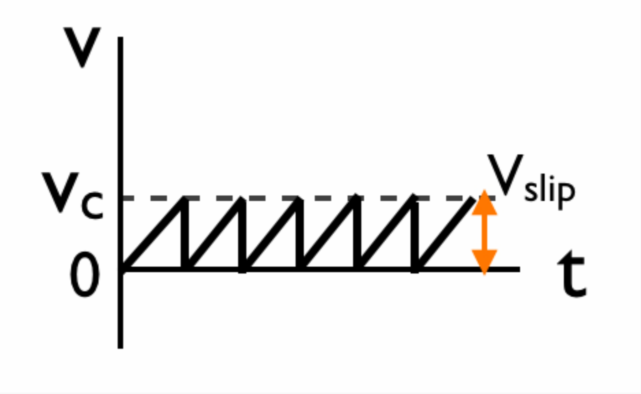
The end of an impulse transient



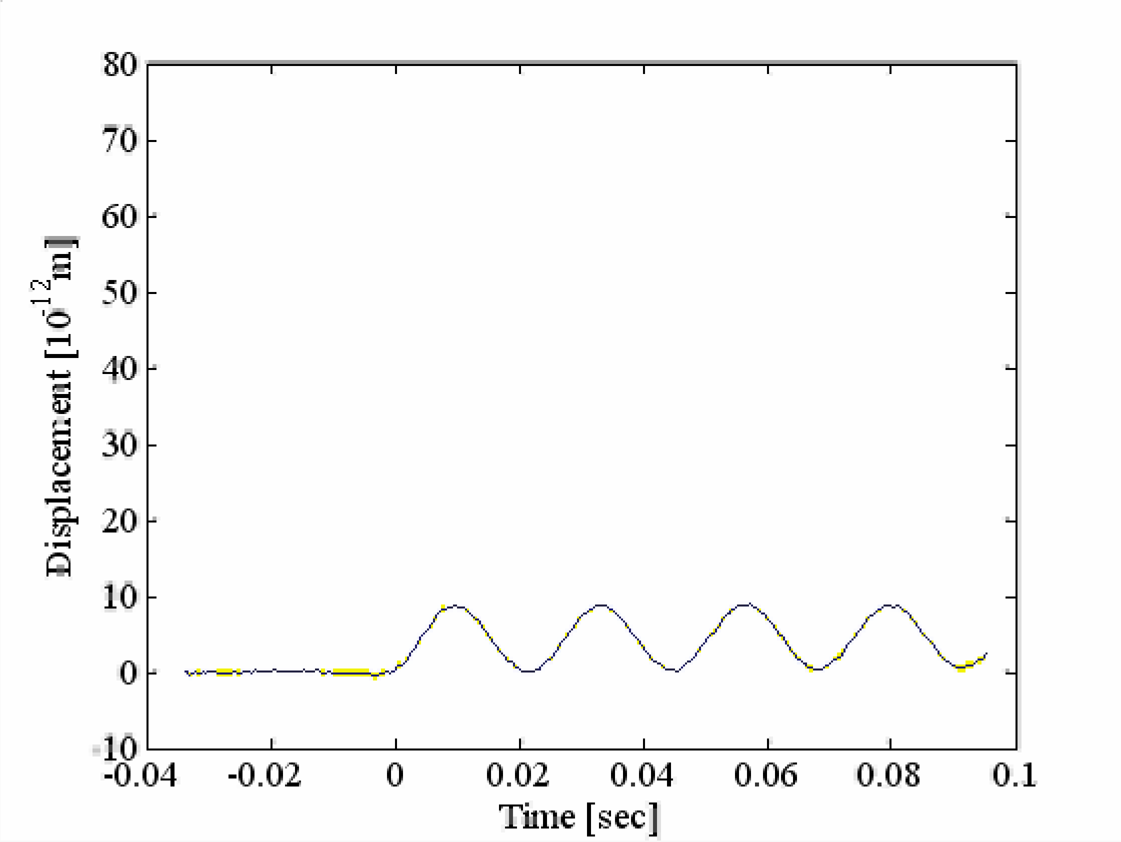
The magnitude of the slips implies that all 4225 apertures slip together.



$$V_{slip} = V_c$$

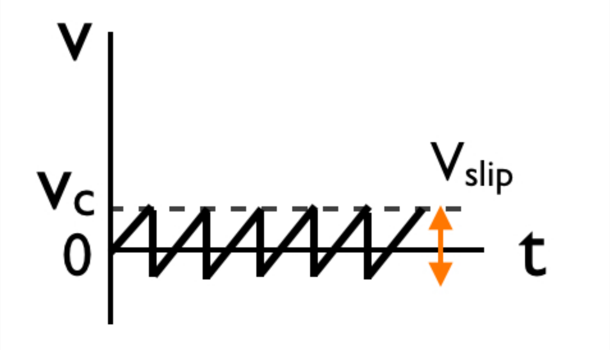


The slip removes all of the energy

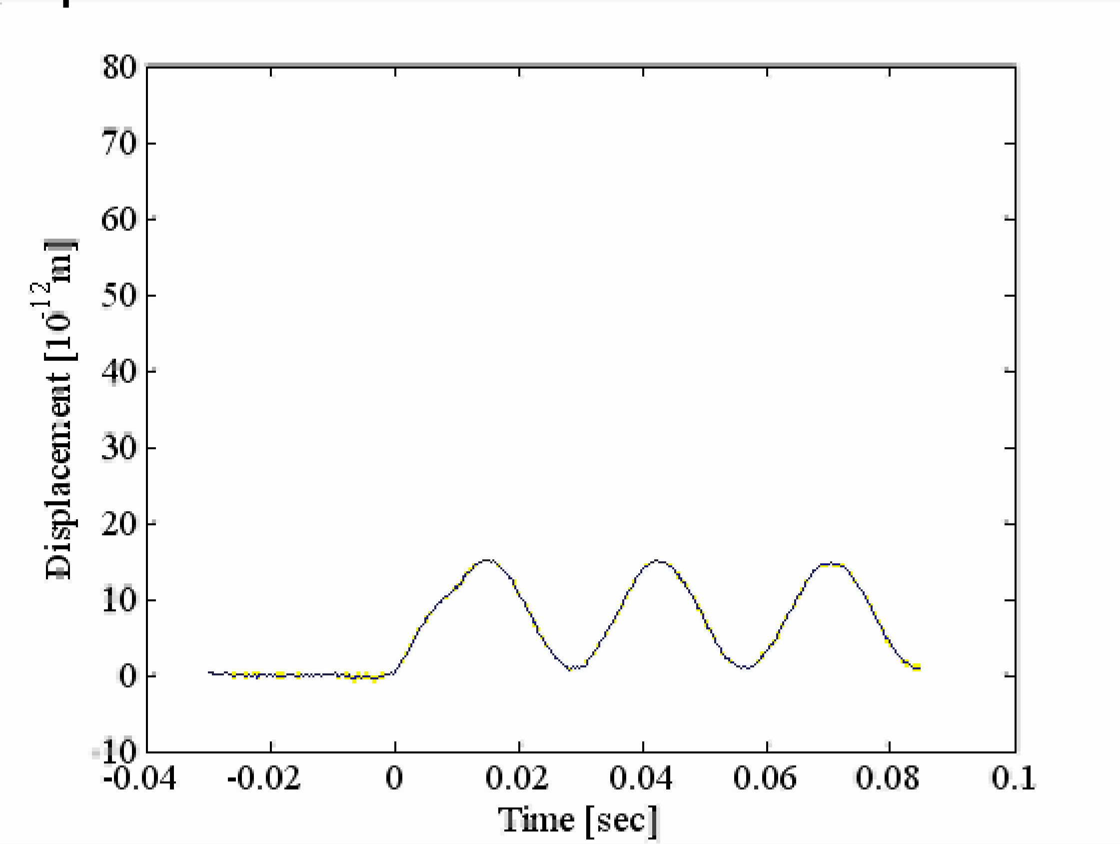


Movie

$$2V_c > V_{slip} > V_c$$

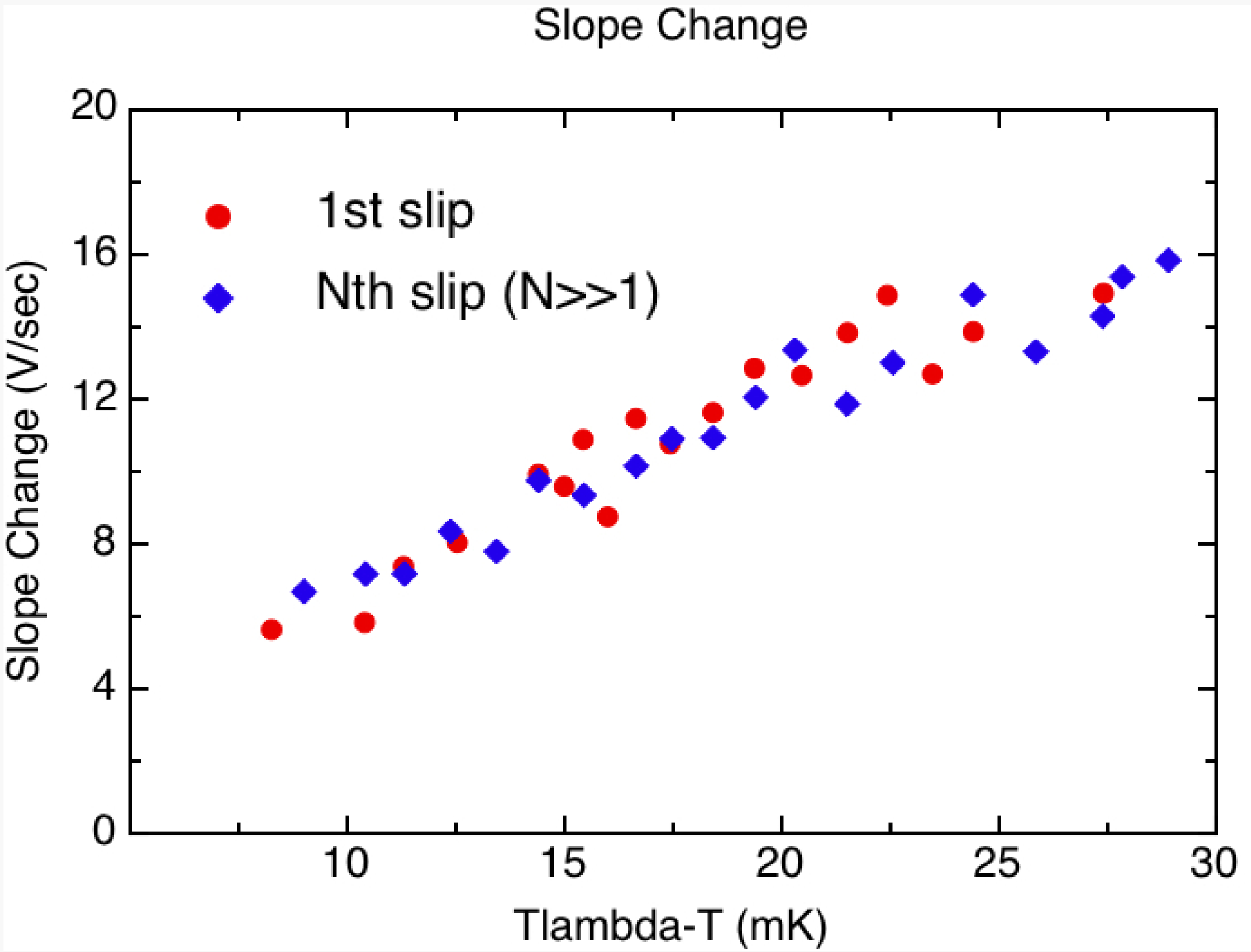


Slips remove some but not all of the energy

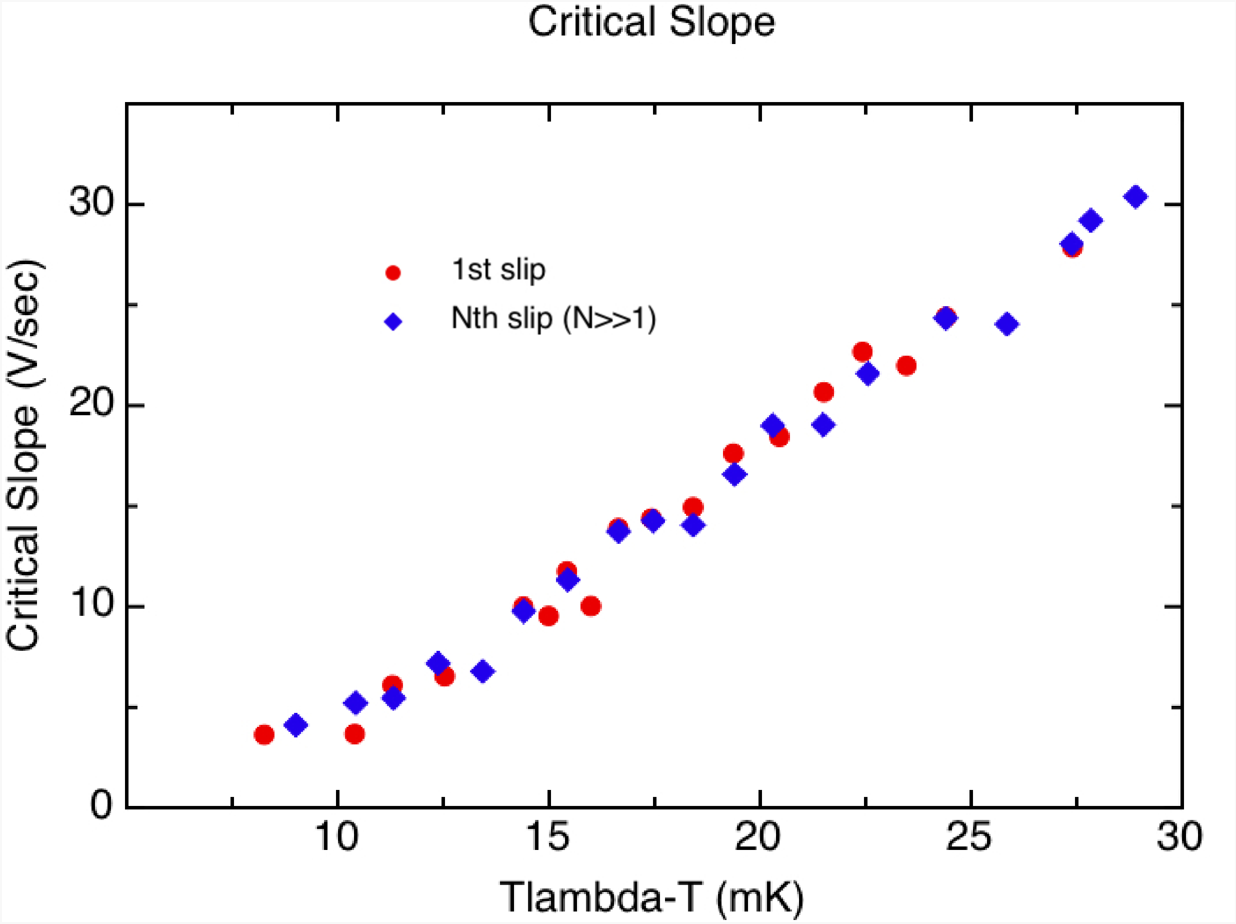


Movie

Equality of 1st and Nth slip



Equality of 1st and Nth slip

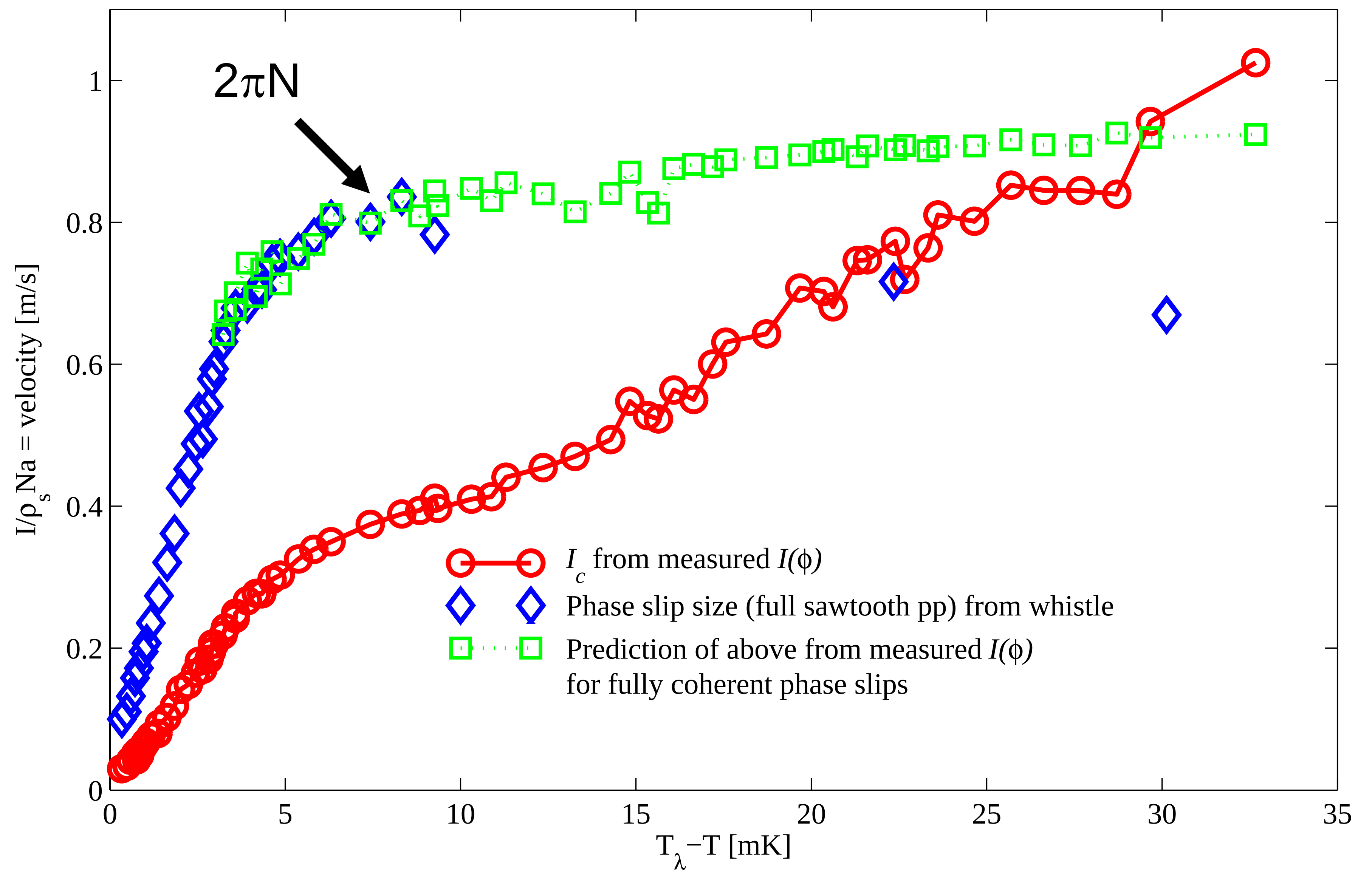


- Slip size is the same for the 1st slip and the Nth. Maybe synchronization plays no role.
- Synchronization cannot be ruled if the interactions are strong.

More Questions

- Is phase slippage a global process wherein a single vortex filament passes over the complete array?
- Is phase slippage a cooperative process wherein each aperture slips but they all are locked together? N vortex events
- Does phase slippage in one aperture trigger an “avalanche” slip in all N?

Slip size is not 2πN as T decreases



One more mystery

- Why does the slip size decrease as T is lowered?

Next step is to build a superfluid ^{4}He dc squid gyroscope

Future possibilities:

A superfluid gyroscope operating near 2K cooled by a mechanical cryocooler

Useful for geodesy, seismology and navigation

Summary

^3He: Arrays of nanometer size apertures behave as ideal Josephson weak links. Quantum coherent dynamics

Josephson oscillations, Shapiro steps, plasma mode.
Discovery of novel dissipation, novel I(ϕ) relation
Proof-of-principle of superfluid dc-SQUID gyroscope

^4He: Aperture arrays behave quantum coherently near T_λ

The current-phase relation has been mapped from the "strongly coupled" linear regime to the "weakly coupled" Josephson I(ϕ) regime.

Near T_λ all apertures phase slip coherently. Dynamics unknown.

At lower temperatures the phase slip sound amplitude decreases but the quantum whistle remains well defined. Why??