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Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Keith Schwab
UU	UU	UU	UU		19b. TELEPHONE NUMBER 626-395-2986

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 25-May-2021

Agency Code: 21XD

Proposal Number: 74781ELII

Agreement Number: W911NF-19-1-0212

INVESTIGATOR(S):

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DUNS Number: 009584210

EIN: 951643307

Report Date: 14-Jan-2020

Date Received: 20-May-2021

Final Report for Period Beginning 15-Mar-2019 and Ending 14-Dec-2019

Title: Investigation of Unexpected Transport of Superfluid Helium Through Graphene

Begin Performance Period: 15-Mar-2019

End Performance Period: 14-Dec-2019

Report Term: 0-Other

Submitted By: Keith Schwab

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0

STEM Participants:

Major Goals: We have observed unexpected transport of superfluid helium-4 in an apparatus designed to study superflow through nanoporous membranes. This small award was to help fund further experiments to pin down if this superflow was infact through graphene membranes, or some artifact of the measurement system. In the end, we have been unable to make a concrete conclusion and this requires further study. The student involved in the work abandoned the experiment and the PI is currently looking for a way to continue the study.

Accomplishments: We performed a number of experiments to attempt to identify if the superflow was through the graphene or around some other path in the apparatus. We were unable to make a concrete conclusion.

Training Opportunities: A Caltech PhD student worked on this experiment and received training in low temperature physics techniques.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Keith Schwab
Person Months Worked: 6.00

Funding Support:

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Anthony Ardizzi

Person Months Worked: 6.00
Project Contribution:
National Academy Member: N

Funding Support:

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Keith Schwab
Signature Date: 5/20/21 5:50PM

Transport Through 2D-Materials

a Superfluid Josephson Junction

Caltech

Anthony Ardizzi
10/15/2018
Advisor: Keith Schwab
Committee Members: Keith Schwab, Stevan Nadj-Perge,
Michael Roukes, Thomas Rosenbaum

Outline

1. Background Physics
    i. Helium
    ii. Superfluids and Quantum Condensates
    iii. Josephson Junctions
    iv. Materials

2. Experimental Apparatus and Measurement Scheme

3. Superfluid transport data and Hydrodynamic Modelling

4. Future Directions

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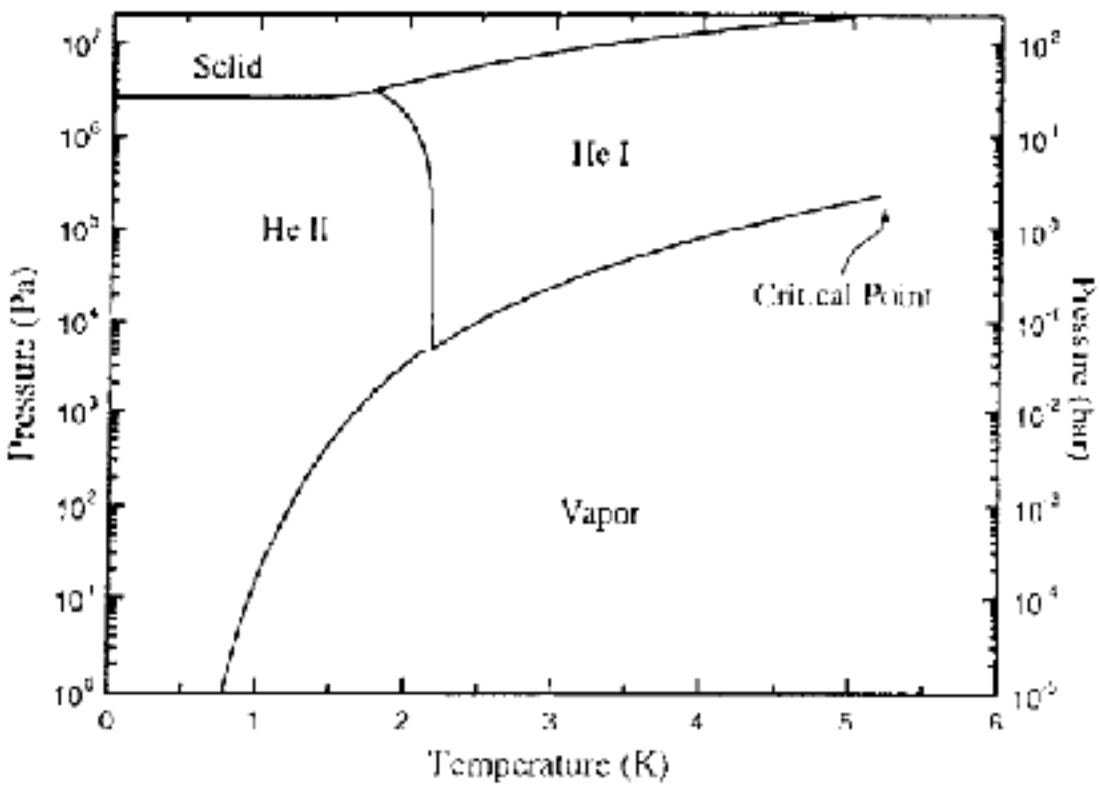
Background Physics - Helium

4He Phase Diagram (Donnelly and Barenghi 1998)

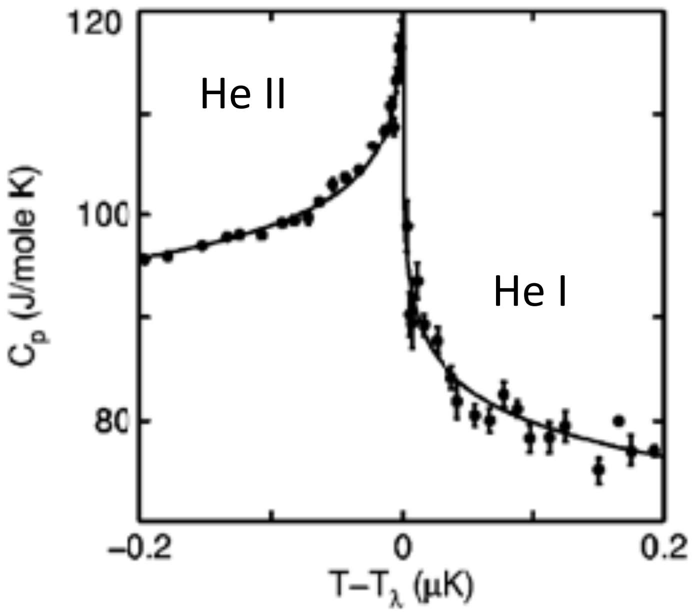


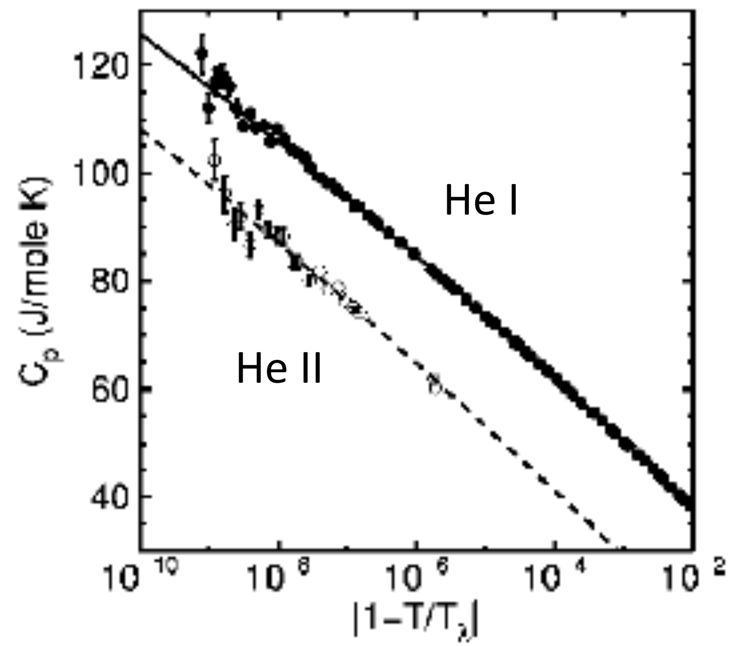
BEC Condensation Estimate

$$T_b = \frac{2\pi\hbar^2}{m_4 k_b}\left(\frac{N}{2.612V}\right) \sim 3.1\text{K}$$

Background Physics – Superfluids and Quantum Condensates

- 4He condenses to a "superfluid" at T_λ=2.17K





Lipa et al, Phys. Rev. B. 2003

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Background Physics – Superfluids and Quantum Condensates

- Full hydrodynamic system of equations was first treated by (Landau 1941), (Landau and Lifshitz 1959) and (Khalatnikov 1965).

Two-Fluid Model

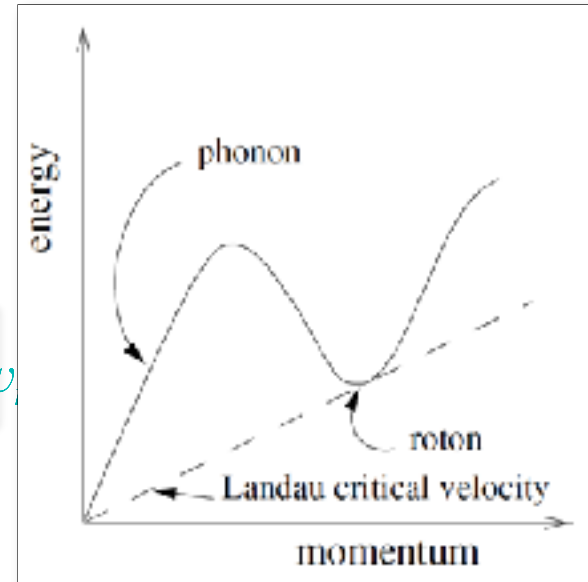
$$\rho_s + \rho_n = \rho$$

$$\rho_s \boldsymbol{v}_s + \rho_n \boldsymbol{v}_n = \boldsymbol{j}$$

$$\rho_s \left(\frac{\partial \boldsymbol{v}_s}{\partial t} + (\boldsymbol{v}_s \bullet \nabla) \boldsymbol{v}_s \right) = -\frac{\rho_s}{\rho} \nabla P + \rho_s \sigma \nabla T$$

$$\rho_n \left(\frac{\partial \boldsymbol{v}_n}{\partial t} + (\boldsymbol{v}_n \bullet \nabla) \boldsymbol{v}_n \right) = -\frac{\rho_n}{\rho} \nabla P - \rho_s \sigma \nabla T + \eta_n \nabla^2 v_n$$

$$\mathrm{curl}(v_s) = 0$$



$$v_L \approx 60 \frac{\mathrm{m}}{\mathrm{s}}$$

- The non-viscous flow was explained by the shape and sharpness of the dispersion spectrum derived by Landau

Background Physics – Superfluids and Quantum Condensates

- More complete microscopic description from (Onsager 1949), (London 1938 and 1954) and eventually Feynman (1955,1972) and (Anderson 1966).

$$\psi(\boldsymbol{r},t) = \sqrt{\frac{\rho_s}{m_4}} e^{i\varphi(\boldsymbol{r},t)}$$

$$v_s = \frac{\hbar}{m_4}\nabla\varphi$$

$$\hbar\frac{\partial\varphi}{\partial t} = -\frac{\partial H}{\partial N} \qquad \hbar\frac{\partial N}{\partial t} = -\frac{\partial H}{\partial\varphi}$$

$$\frac{\partial\,\Delta\,\varphi}{\partial t} = -\frac{\Delta\,\mu}{\hbar}$$

Josephson Anderson Equation

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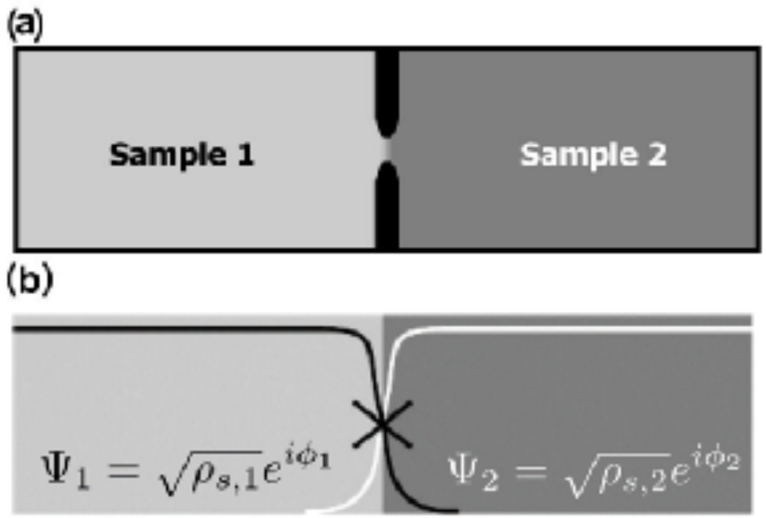
Background Physics – Josephson Junctions

- Quantum devices can follow when quantum phase can be measured -> Josephson Junction

$$i\hbar\frac{\partial \psi_1}{\partial t} = \mu_1\psi_1 + K\psi_2$$

$$i\hbar\frac{\partial \psi_2}{\partial t} = \mu_2\psi_2 + K\psi_1$$



DC Josephson Equation: $I = I_0 \sin \Delta\phi$

Josephson Anderson Equation: $\frac{d\Delta\phi}{dt} = -\frac{\Delta\mu}{\hbar}$

Josephson Frequency: $f_J = \frac{\Delta\,\mu}{\hbar}$

Sato and Packard, Rep. Prog. Phys. 2012

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Background Physics – Josephson Junctions

Superconductivity

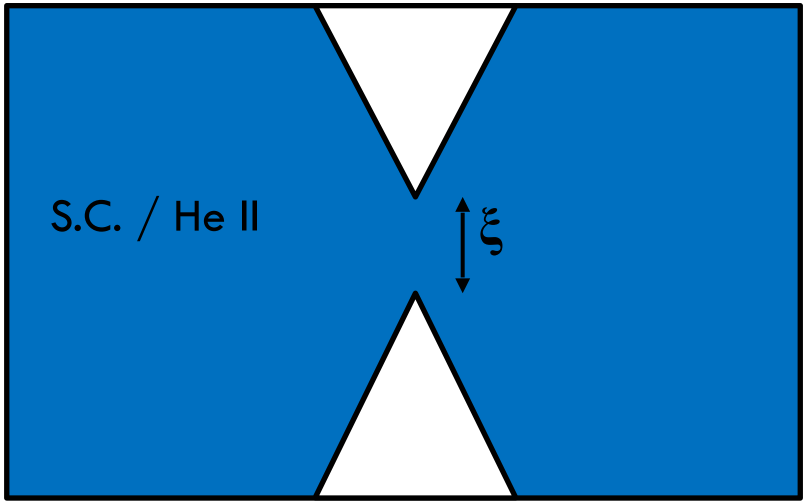
- Macroscopic Quantum System
- Zero Electrical Resistance
- Electrical Current
- Chemical Potential (Voltage)
- Critical Current Density
- **SQUIDs, Qubits**
- Quantum Tunnelling of Cooper Pairs
  - Cooper pair mass $2m_e$
  - Barrier Energy $E_b \approx 1eV$

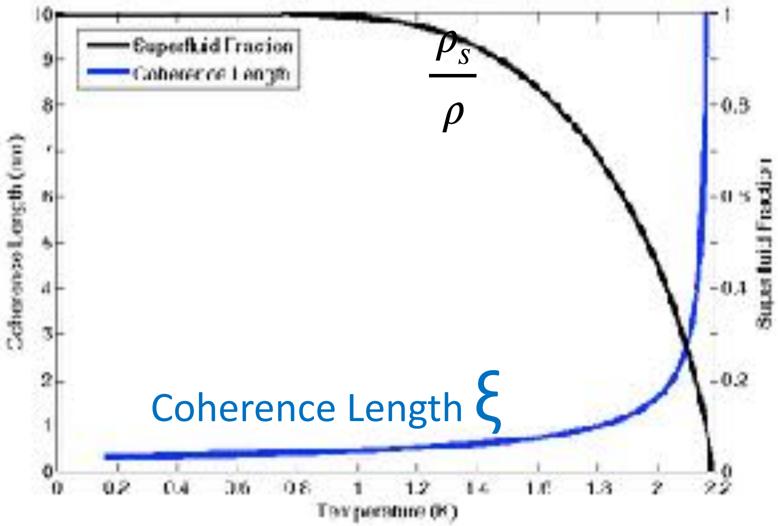
Superfluidity

- Macroscopic Quantum System
- Zero Viscosity
- Mass Current
- Chemical Potential (Pressure)
- Critical Flow Velocity
- **SHeQUIDS, Gyroscopes… Qubits?**
- 4He Particles too massive to tunnel
  - Helium mass $m_4 \approx 7000 m_e$
  - Graphene barrier $E_G \approx 20eV$

Background Physics – Josephson Junctions

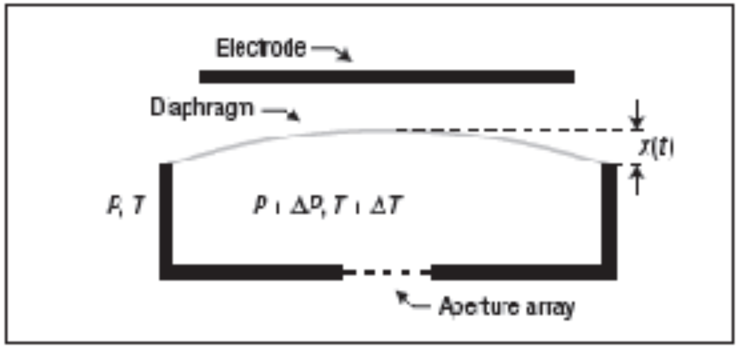
- Leads to “Dayem Bridge” junction design for superfluids

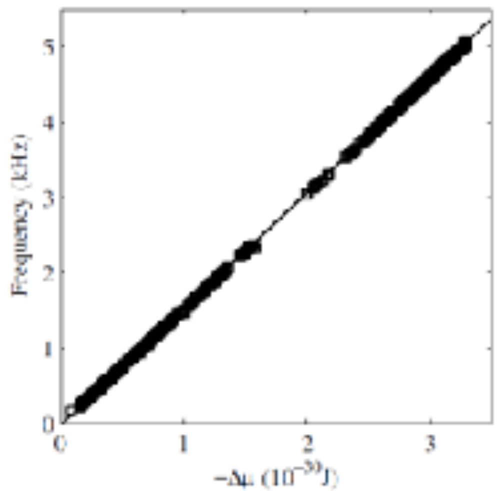


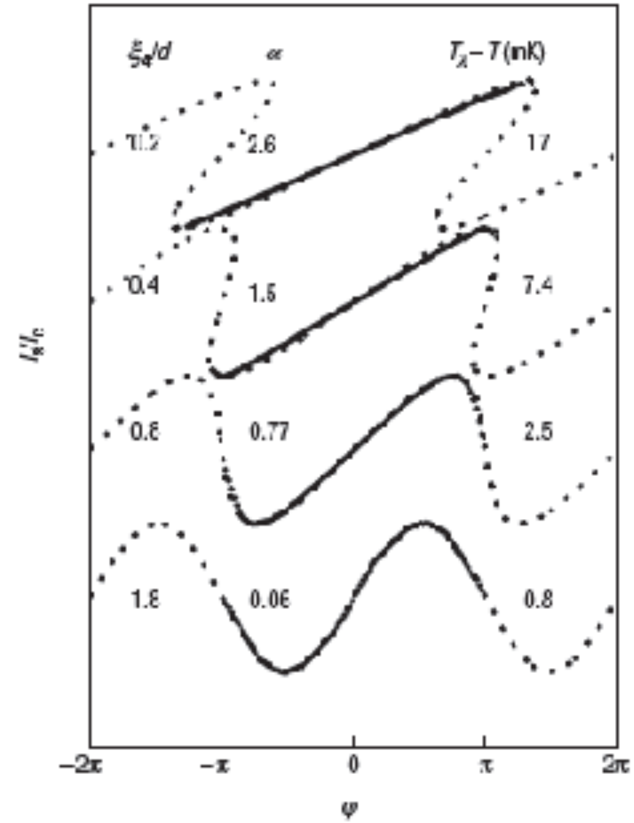


Background Physics – Josephson Junctions

- Josephson oscillations have been observed in superfluid 4He, only within ~10mK of T_λ



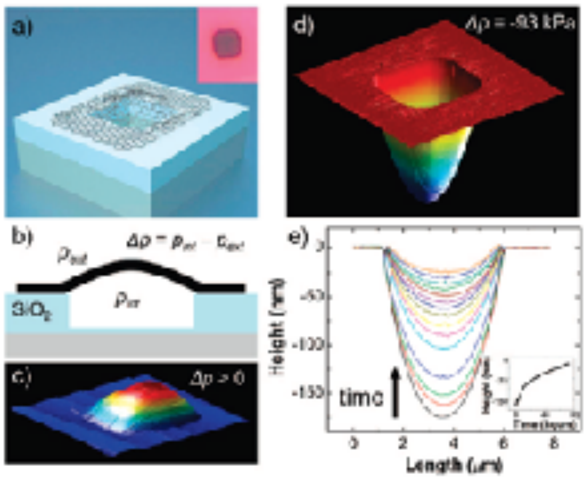




Hoskinson et al, Nature Physics 2006

Background Physics – Materials: Graphene

- Graphene appears to be completely impermeable to all atomic matter
  - WKB approximation, 20eV barrier -> tunneling suppression by ~e^{-500} for conservative barrier parameters



(2008 Bunch et al)

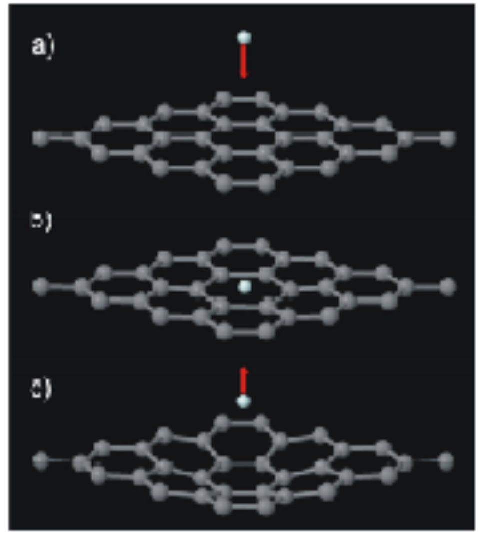
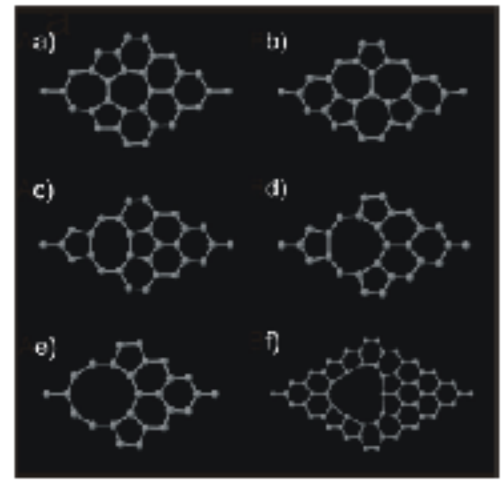
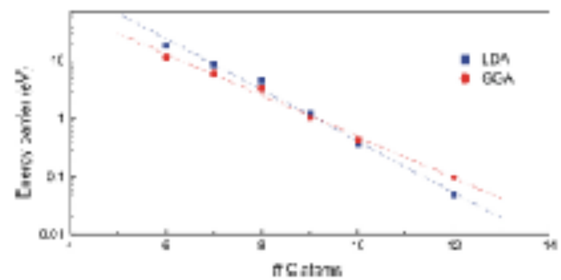


FIG. 2. (Color online) Reflection of a He atom with a kinetic energy of 18.0 eV from a graphene surface. a) The He atom approaches the perfect graphene layer. b) The He atom comes to rest before penetrating the graphene layer. Note that the relaxation of the graphene layer is very small at this moment. c) The He atom is reflected back and the surface starts to relax.





(2008 Leenaerts et al)

Background Physics – Materials: Carboxy Fantrip

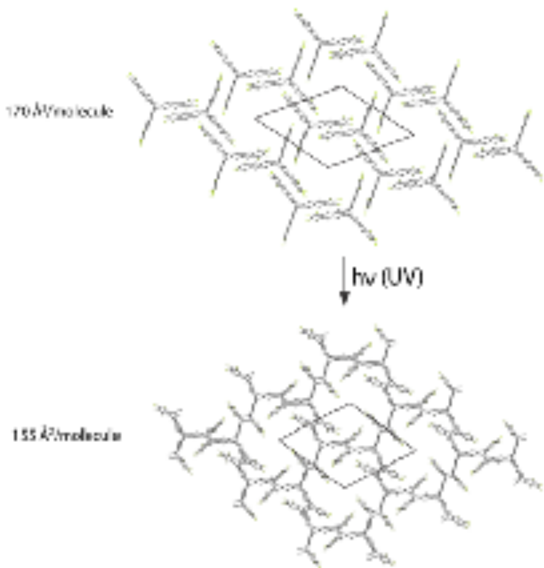
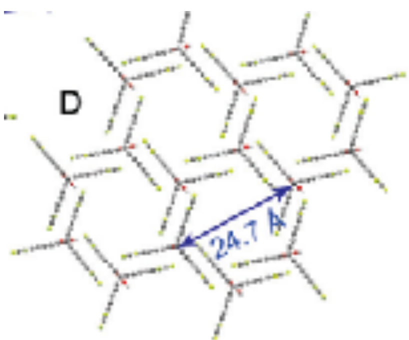


Figure 3.7. Change of MMA upon polymerization of carboxy fantrip.



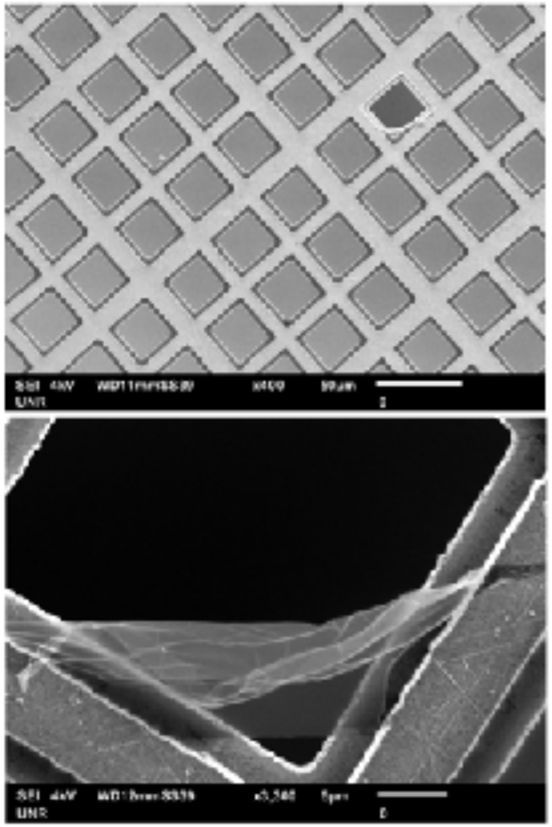


Figure 3.11. SEM images of poly(carboxy fantrip) spanning 25 × 25 μm² holes on a TEM grid.

Murray et al, J. Am. Chem. Soc 2015

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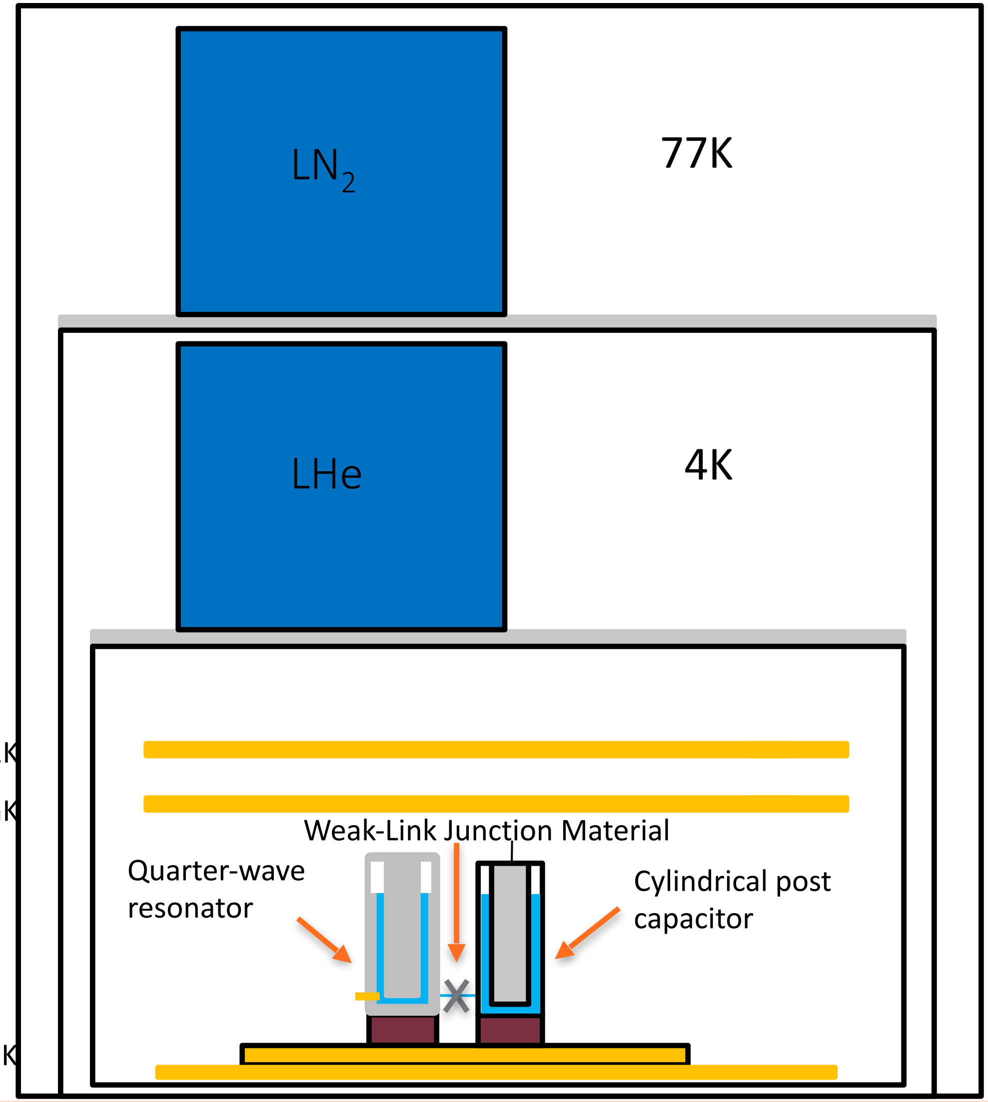
Experimental Apparatus and Measurement Scheme - Cryogenics



^{4}He Fridge - 2K

^{3}He Fridge - 400mK

rcoal pumped

^{3}He Fridge - 287mK

Chase Research Cryogenics LTD.

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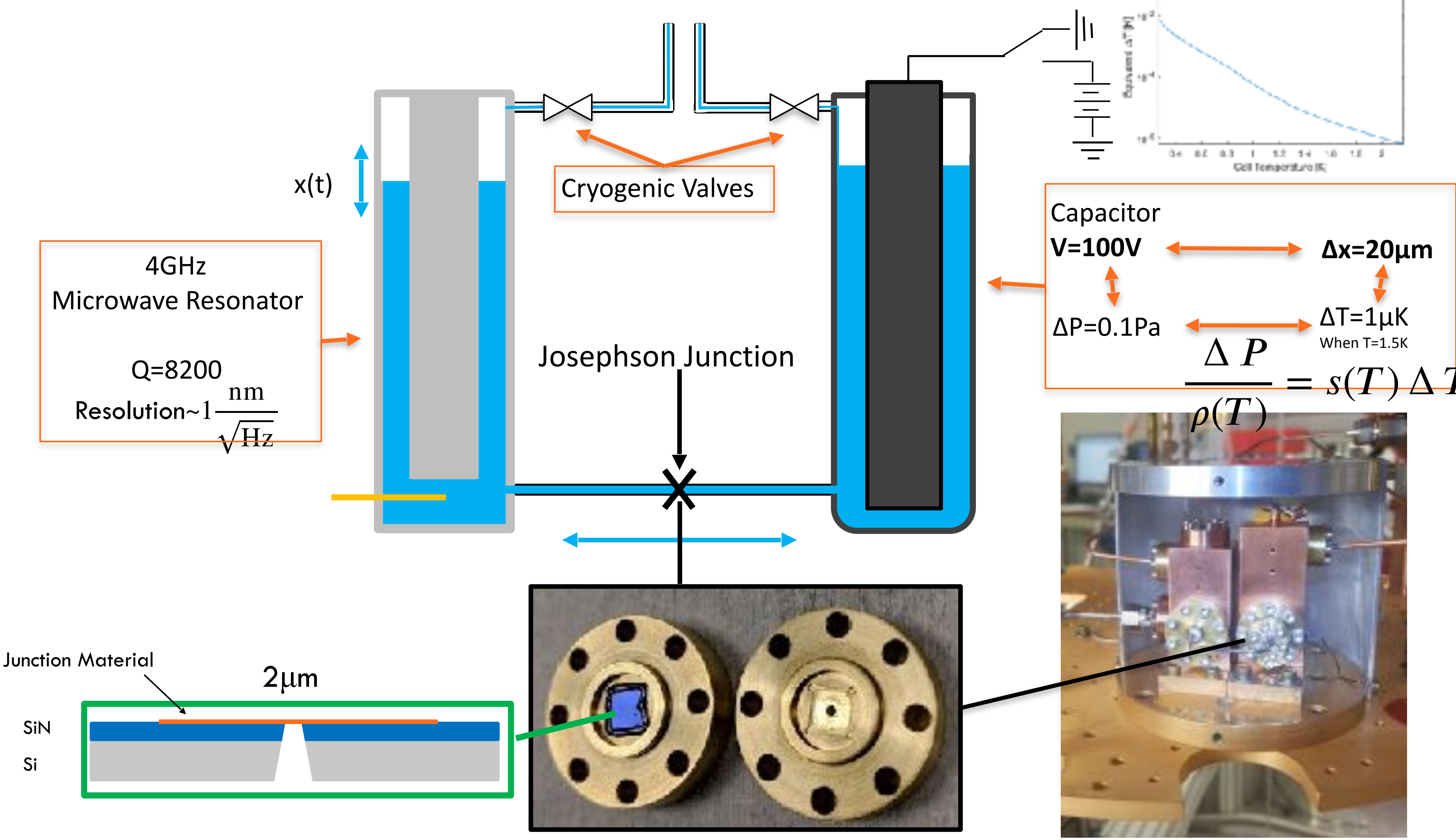
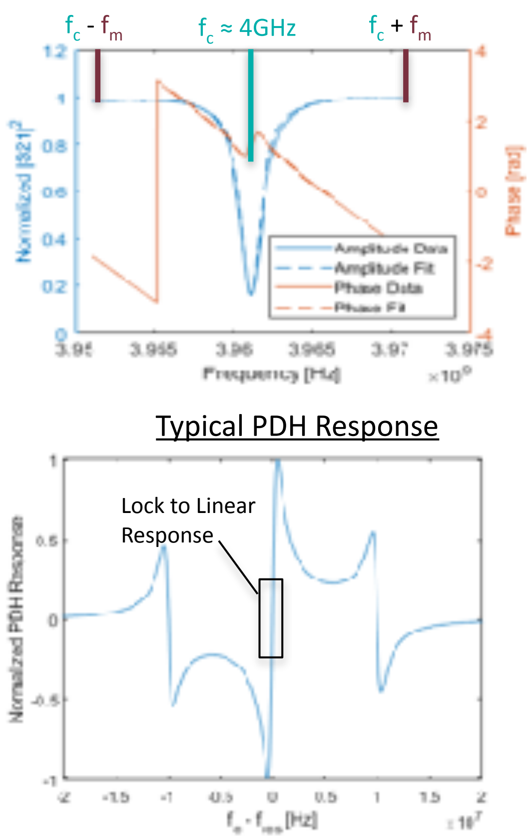
U-Tube Liquid Level Meter

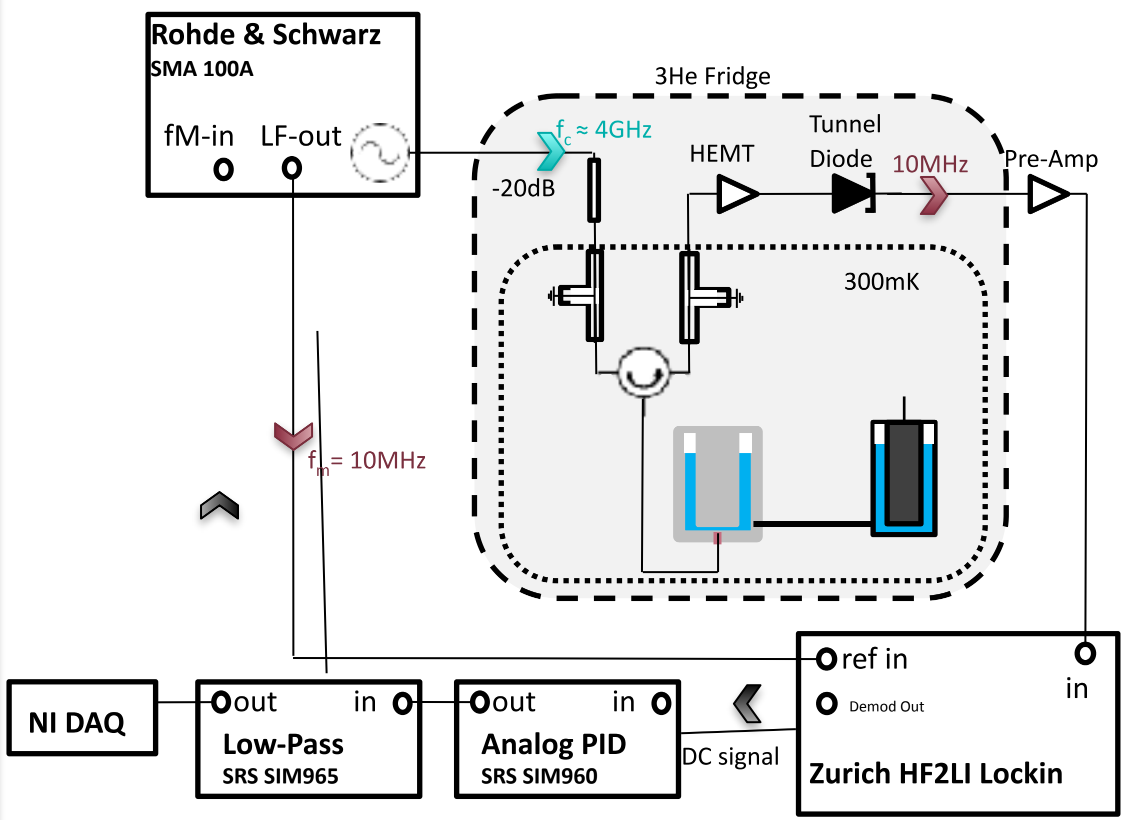


Experimental Apparatus and Measurement Scheme – PDH Microwave Scheme

Pound-Drever-Hall



PDH PID Circuit



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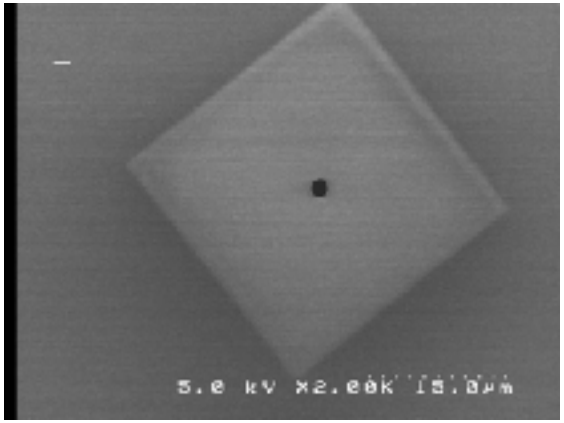
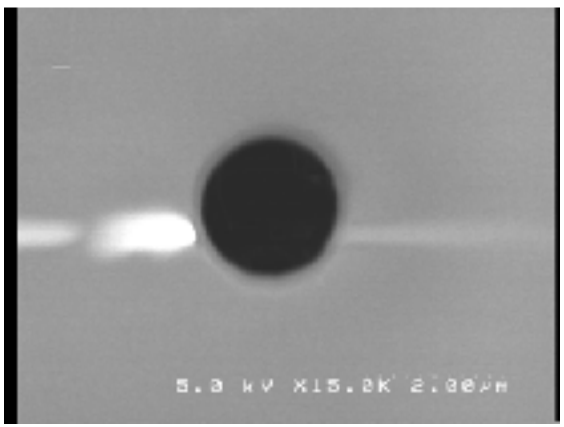
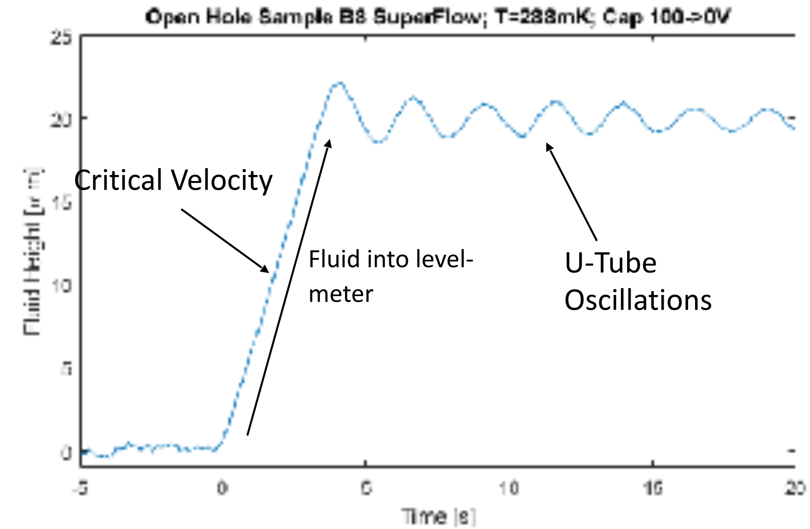
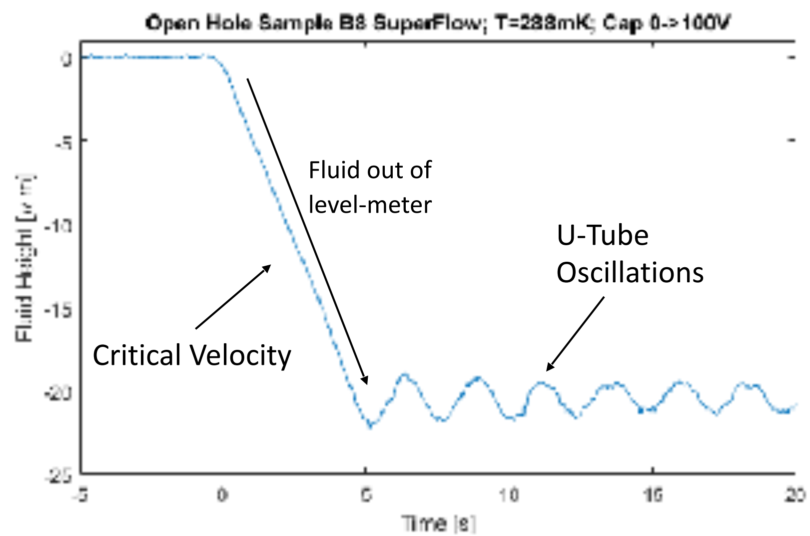
Transient Data - 2µm diameter hole

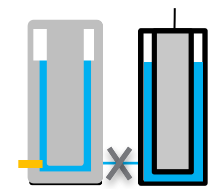
SEM Images



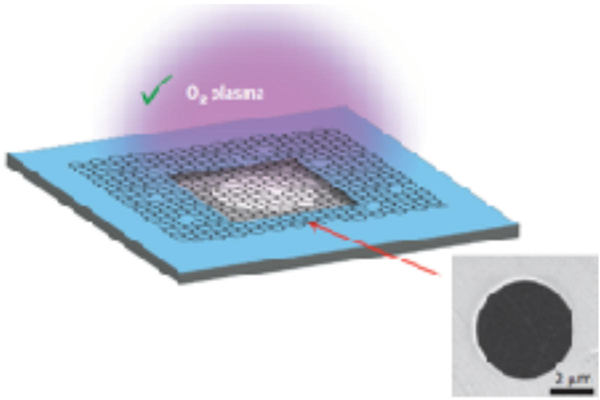


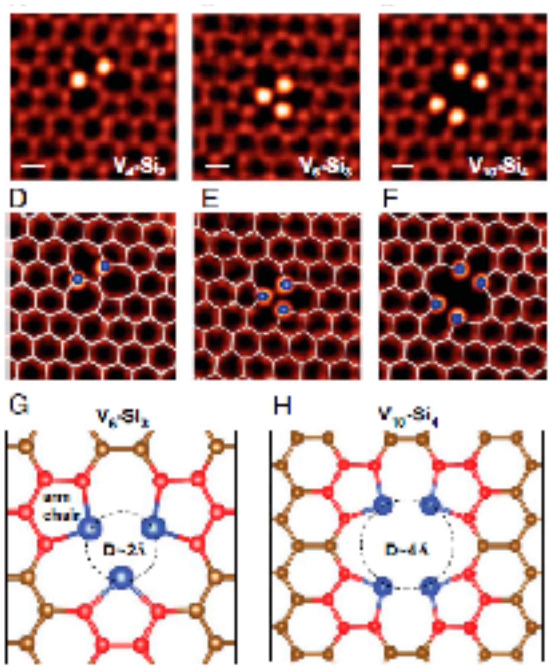


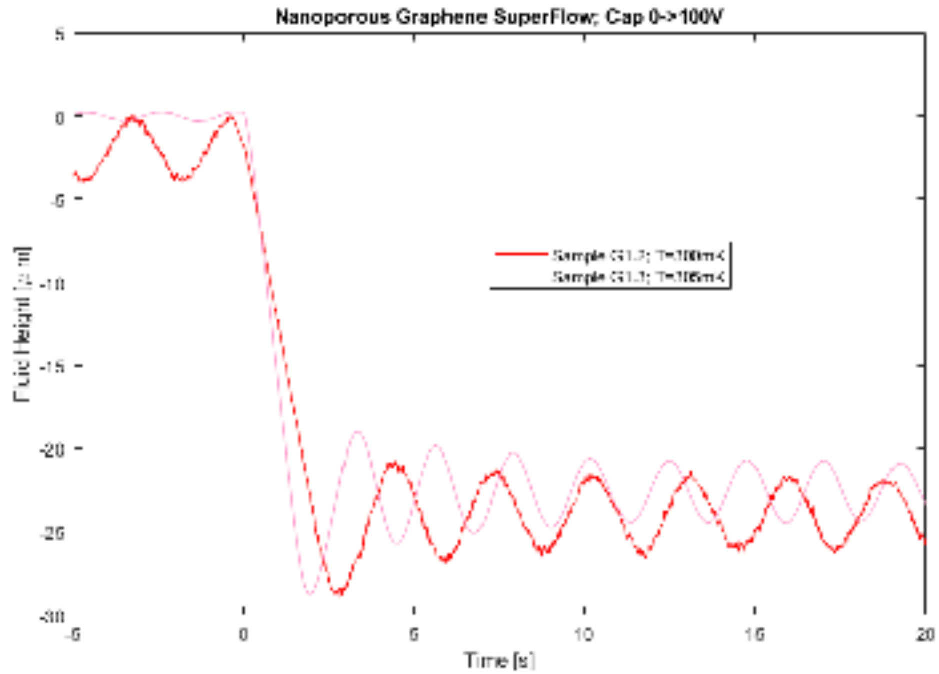




Transient Data – Nanoporous Graphene







Lee et al, Proc Natl Acad Sci USA 2014
Sumedh et al, Nature Nanotech 2015

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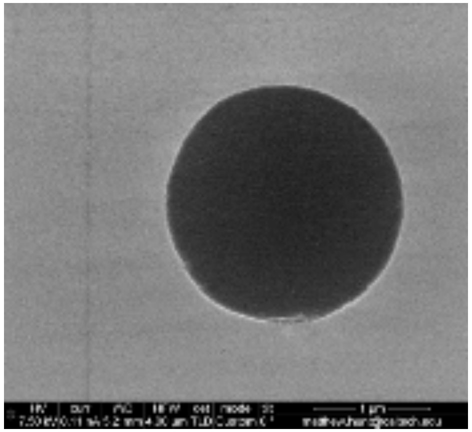
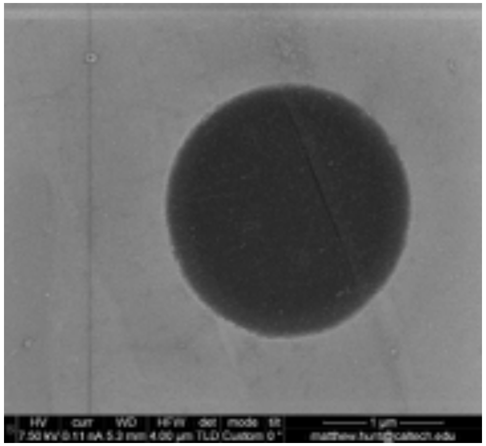
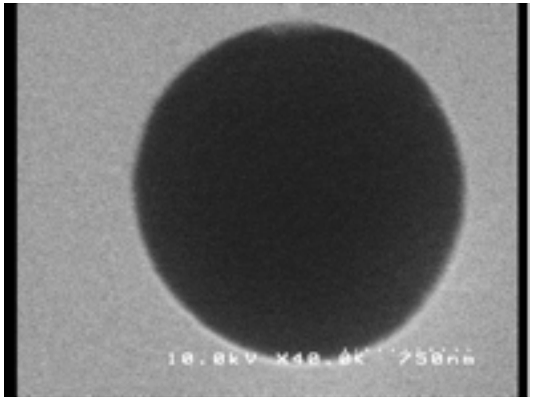
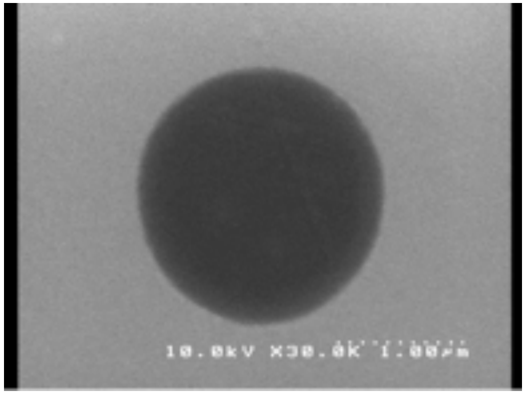
SEM Before and After Measurement (all at Caltech)

	Sample G1.2	**Sample G1.3**
Before Cooldown		
After Cooldown		

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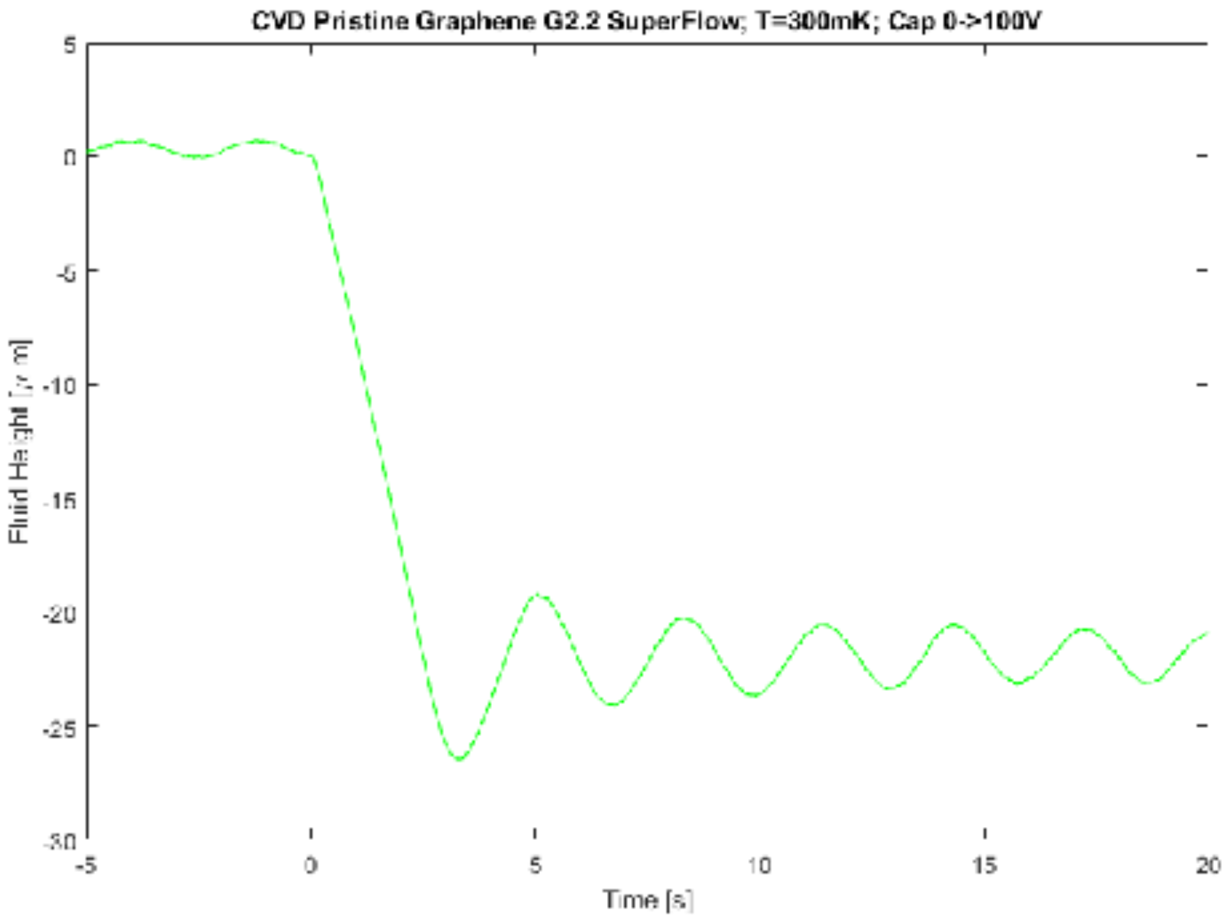
Transient Data – Crystalline CVD Graphene



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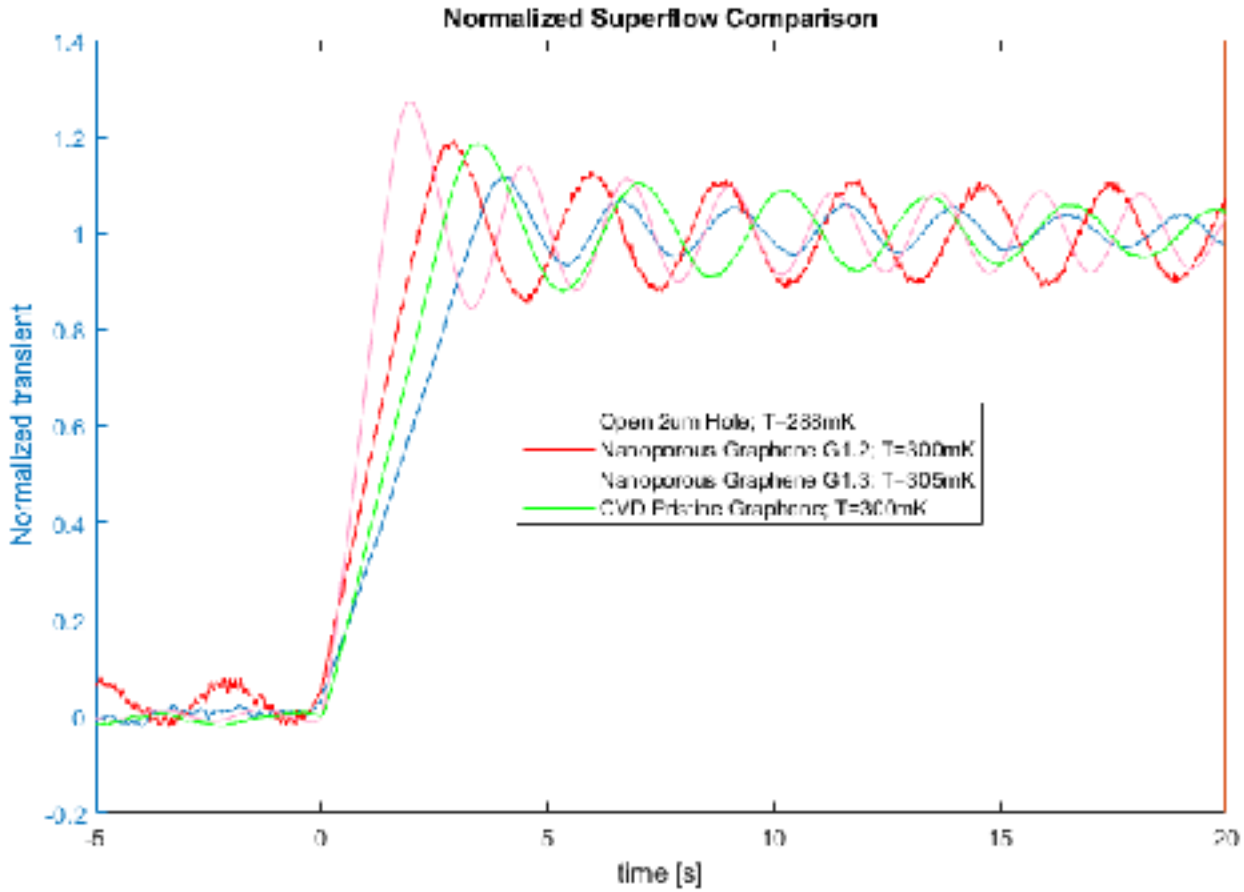
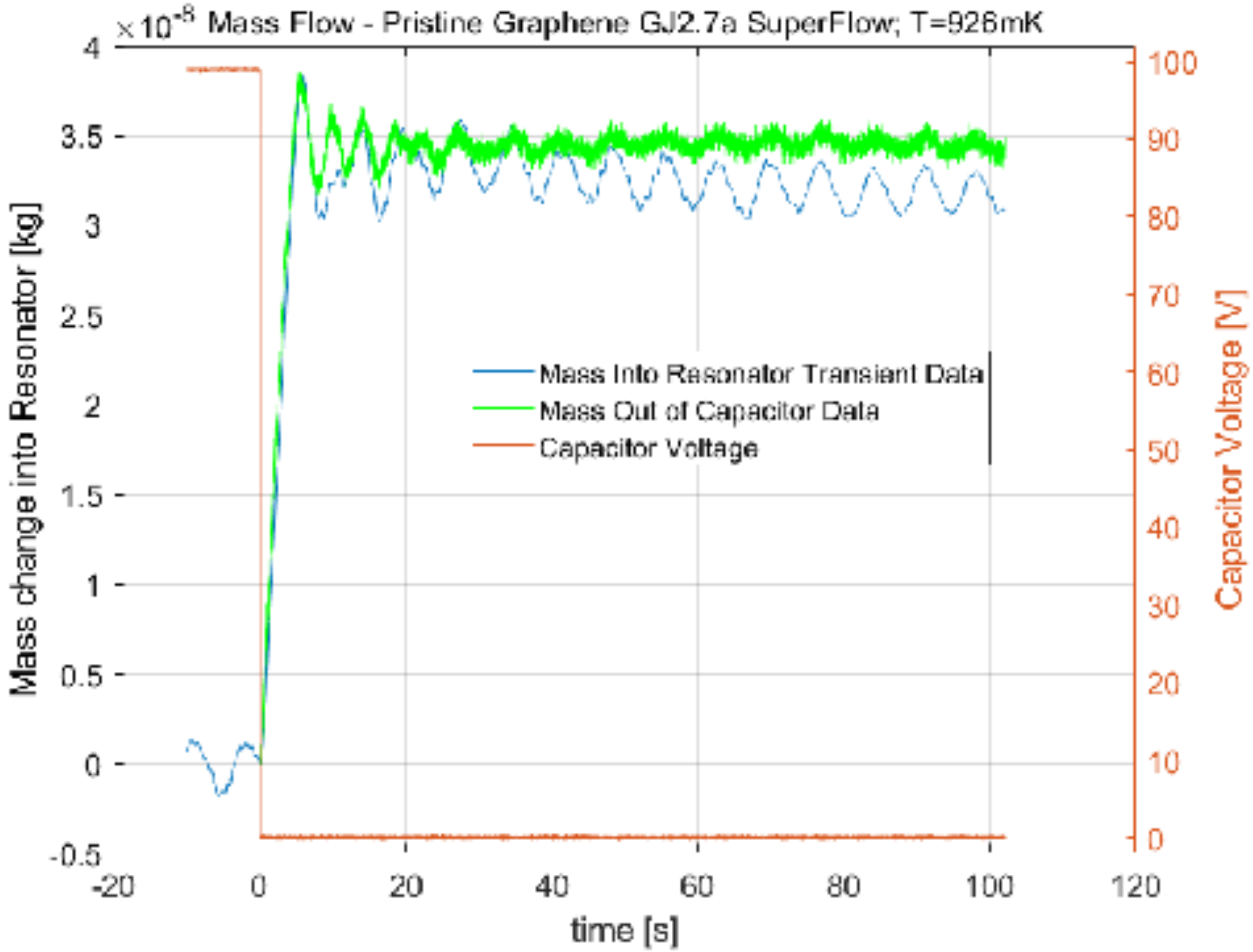
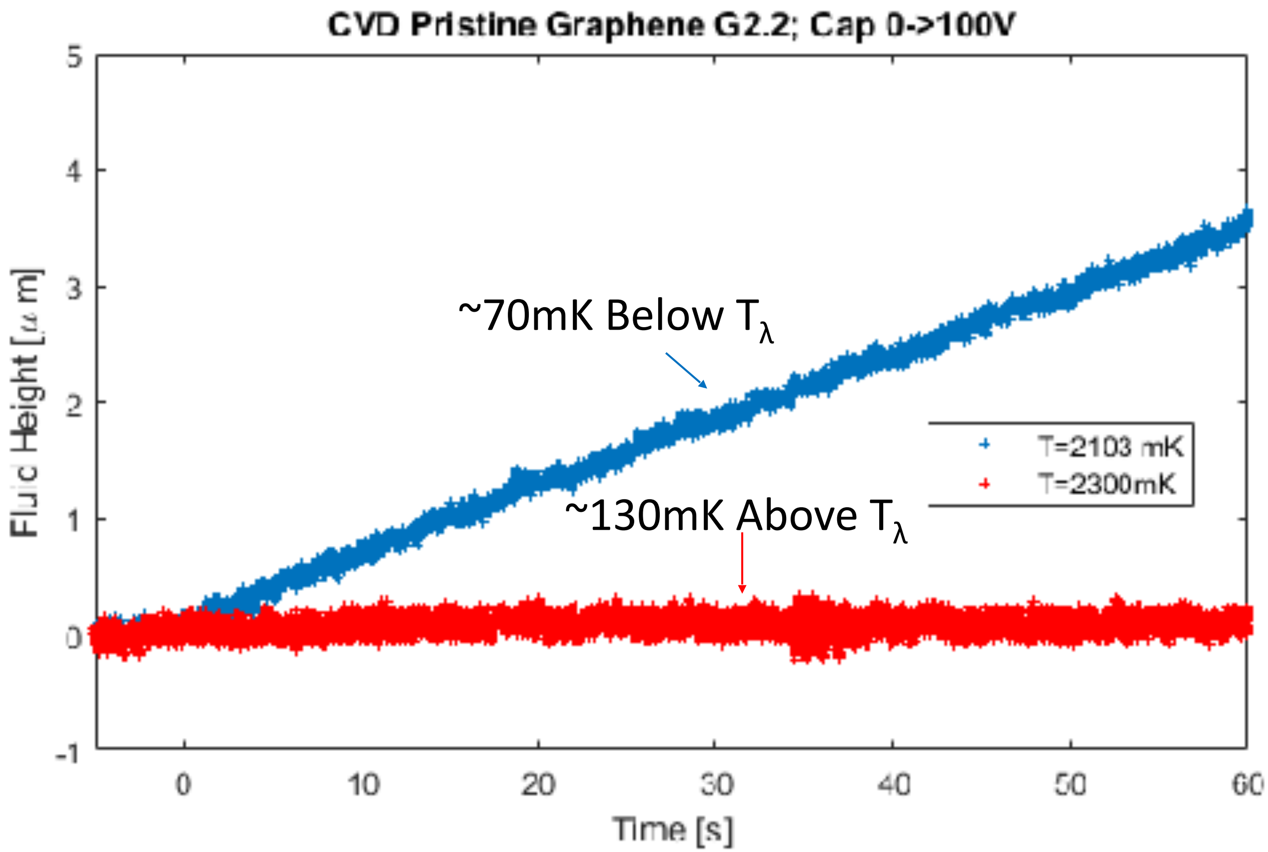
Transient Data – Crystalline CVD Graphene



Transient Data – Exfoliated Graphene

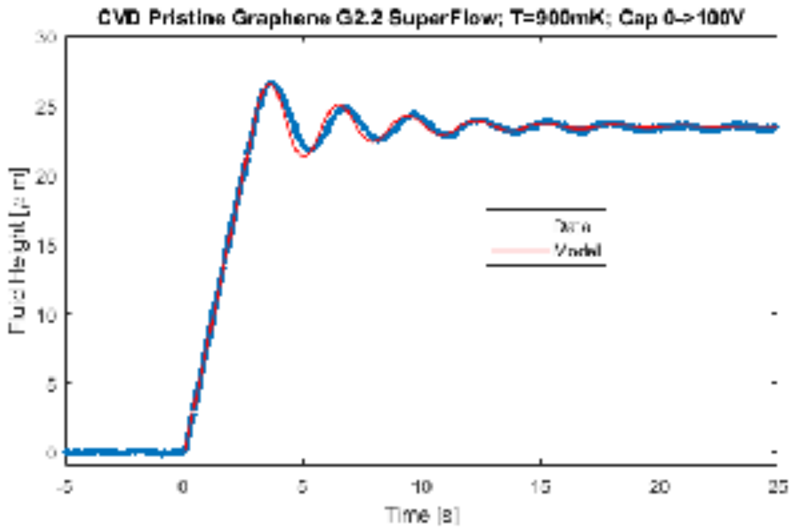


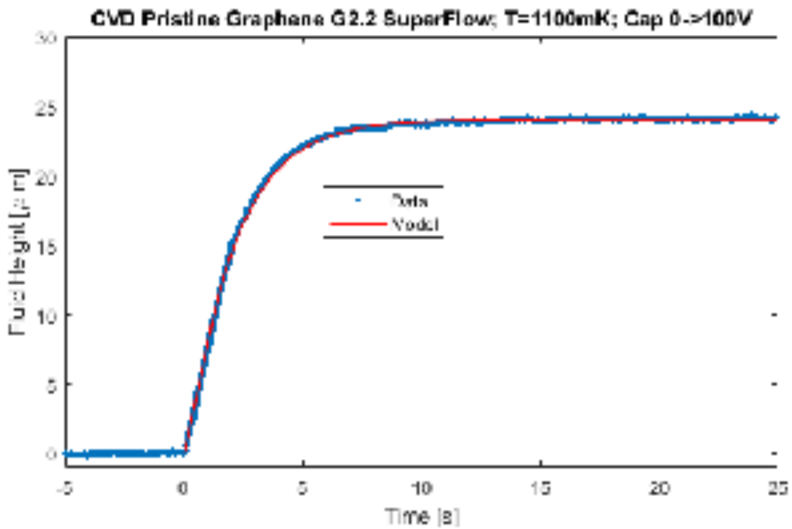
Transient Data – Normal Fluid Through Graphene



Gas flow measurements at room temperature also show at least 10^4 reduction (limited by leak cart background)

Transient Data – Crystalline CVD Graphene – Superflow Model

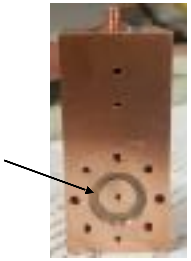


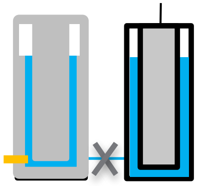


Relevent Model Parameters

- Junction Inductance
  - Consistent with 2μm hole
- Critical Velocity
  - Consistent with 2μm hole ~25m/s
- Kapitza Resistance
  - Consistent with approximate sinter area
- Capacitor Pressure
  - Consistent with estimate ~0.1Pa
- Resonator and PDH parameters
  - Taken from fitting

Silver Sinter





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Future Directions

Immediate:

- Final verification of graphene super-leak using sealed, exfoliated graphene flakes from Jim Hone
- Theoretical explanation of graphene super-leak phenomenon

Remainder of PhD:

- Transport properties of multilayer graphene. Eventual weak-link?
- Transport through other 2D materials, such as MoS_2, BN, Carboxy Fantrip, etc.
- Complete hydrodynamic modelling overall full temperature range, including Josephson effects

Time Permitting:

- Implementation of a high-Q superconducting quarter-wave resonator as a fluid level-meter
- Theoretical investigation of Superfluid Qubits and other potential superfluid technologies

Next Generation of Students:

- Building superfluid quantum devices

Thank You

Professor Keith Schwab
Dr. Jeffrey Bottimer

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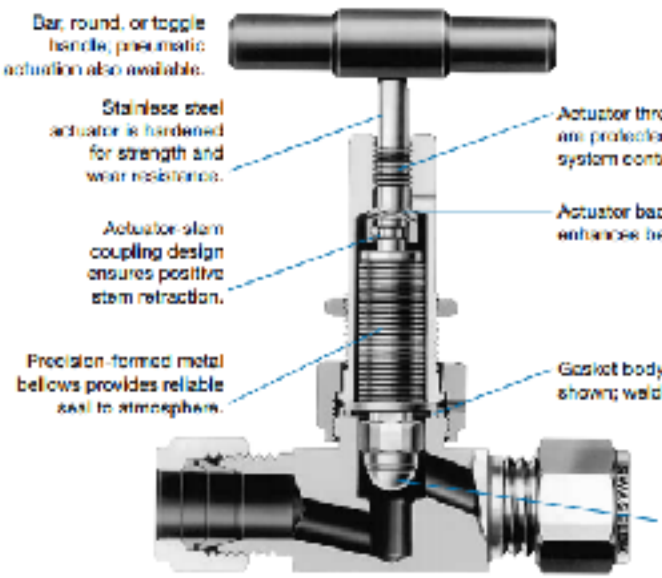
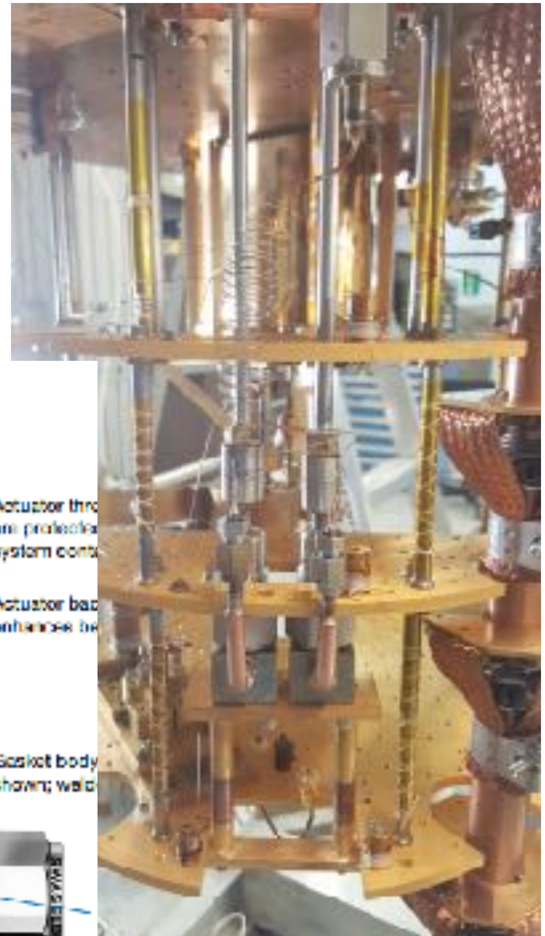
Cryogenic Valves





https://www.swagelok.com/downloads/webcatalogs/en/MS-01-22.pdf

Superfluid Qubits

PRELIMINARY FORMALISM ON SUPERFLUID QUBIT EQUATIONS

THOUGHTS ON HOW TO IMPLEMENT AND COUPLE TO A SUPERFLUID QUBIT