Volume Dependency of Magnetically Levitated Superfluid He-4 over 0.5 mm in Vacuum

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Introduction, Background, and Motivation:

We are investigating how to procedurally put over half-millimeter-sized superfluid liquid Helium-4 (He-4) droplets into a vacuum as well as understand the drop's survivability based on the input volume of T6 He-4 gas. Our work is built upon Charles D. Brown II's dissertation [1], where they sustained droplets of 250 microns in radius in a vacuum; the droplets were used to examine optical whispering gallery modes (WGMs) via coupling a laser into the droplet to study Optomechanics, e.g., surface modes, breathing modes, and optical modes. However, initial research was limited by the size of the drop. Our goals in this set of experiments were to sustain larger droplets (>0.5mm) in a vacuum, which hasn't been done, and to understand the characteristics of this process. Overall, our group wants to optimize the He-4 droplet experiment apparatus to benefit future experiments in optomechanics and quantum optics by increasing radius and thus higher modes of resonance and finesse

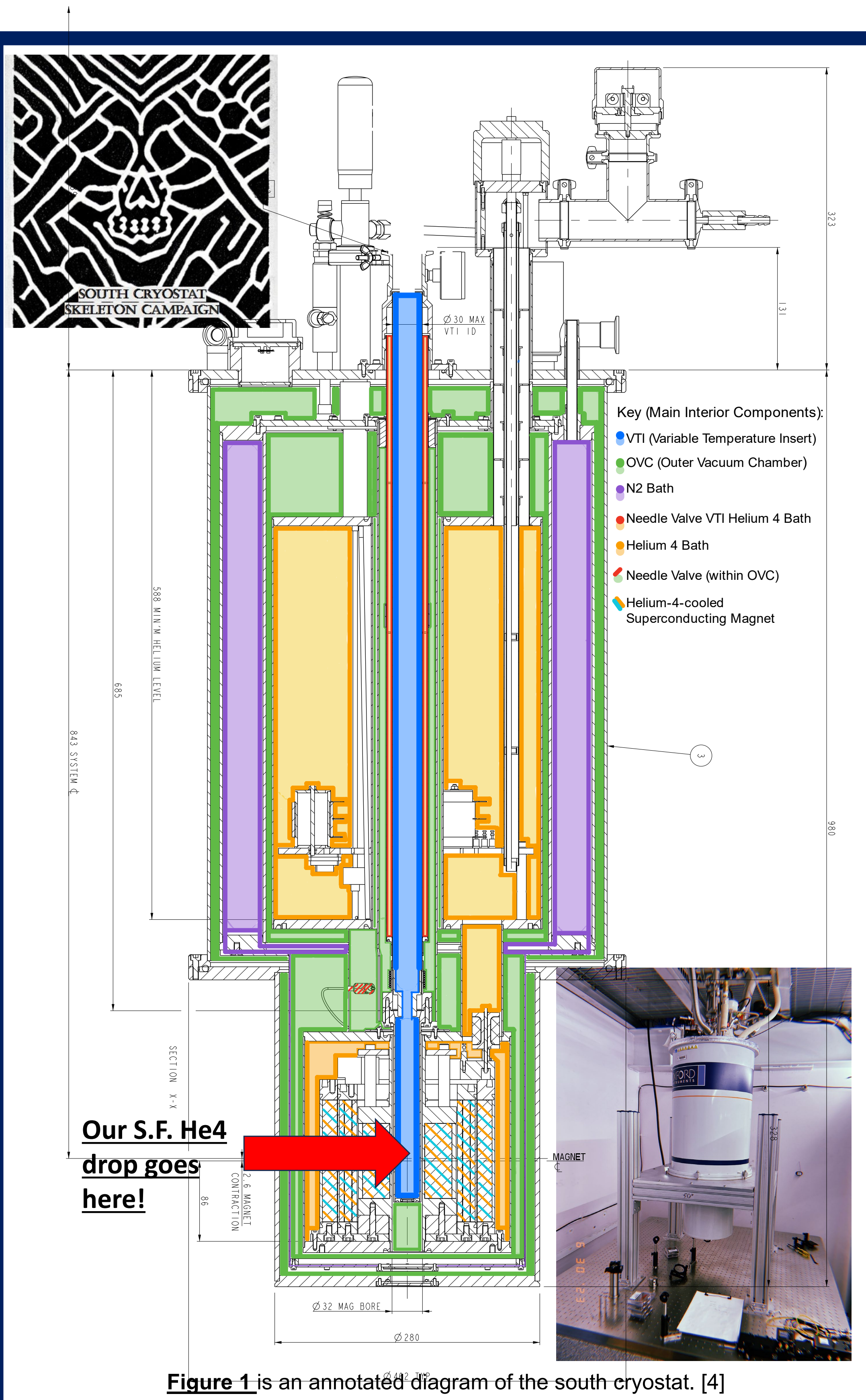
Experimental Apparatus: The South Cryostat; The Skeleton Campaign

The cryostat, in **Figure 1**, is a cryogenic chamber that ensures:

- stable temperatures near absolute zero.
- supercooling the superconducting electromagnet
- magnetic levitation
- ensuring vacuum conditions in multiple chambers

Components:

- **The Outer Vacuum Chamber (OVC)** (in green) ensures there is minimal heat transfer between exterior, internal chambers, and sample space via convection.
- **The Liquid nitrogen bath** (in purple) is an outer chamber that is 77K (-200 C) which reduces the radiation heat load on the He-4 bath and VTI.
- **The Liquid Helium-4 Bath** (in orange) is in the inner chamber at 4K (-269 C) which cools the cryostat via conduction while also submerging and cooling our super-conducting magnet in liquid He-4 (the striped portion near the bottom).
- **The Needle Valve (NV) and VTI He4 Bath,** (red striped and orange fill with a red outline) is the valve that controls liquid He-4 flow and further cools the VTI/sample space via convection. It is controlled manually and sets the base temperature to approximately 1.34K (-273.66 C).
- **The Variable Temperature Insert (VTI)** (in blue) is where our gas sample is pumped into the sample space. The space toward the bottom is surrounded by the super-conducting electromagnet and is where the field is strongest and where the drop forms.

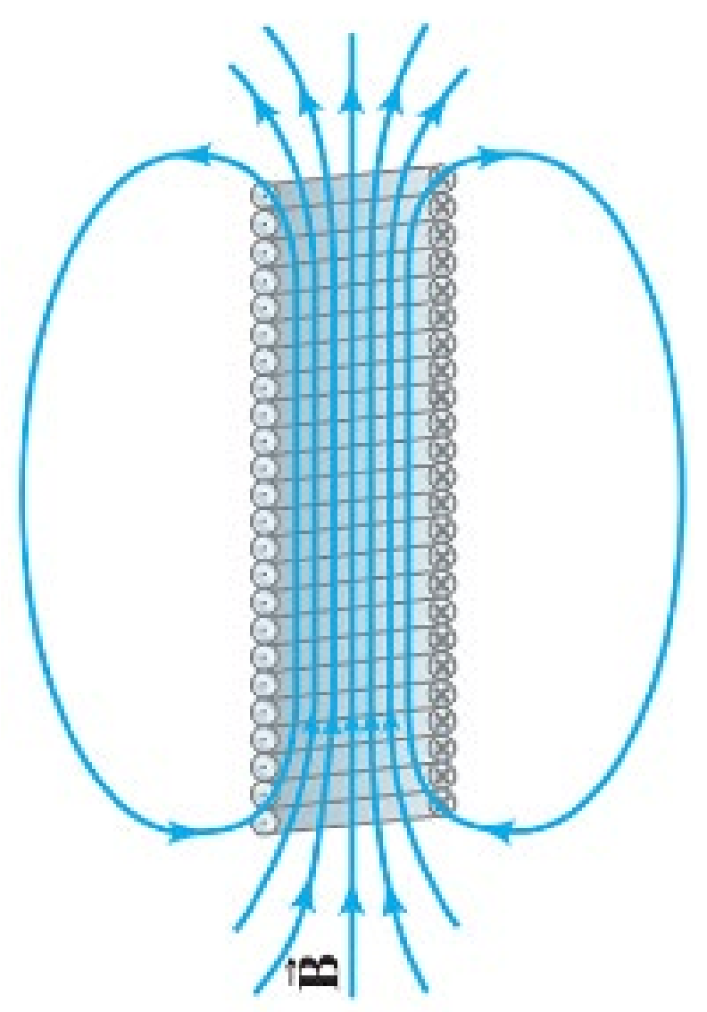


Our S.F. He4 drop goes here!

Figure 1 is an annotated diagram of the south cryostat. [4]

Superfluid, Magnetic Levitation, and Magnetic Potentials:

- **Superfluid (S.F.):** He-4 transitions from liquid to superfluid at 2.17K. He-4 S.F. makes an ideal optical resonator because of its:
  - chemical & structural purity (impurities freeze to the walls)
  - having zero viscosity
  - low non-linear mechanical energy loss,
  - low acoustic impedance
  - doesn't absorb visible or infrared light
- **Magnetic Levitation** is used to isolate our drops from the environment, counter the force of gravity, and minimize mechanical energy loss. We use a superconducting electromagnet in the shape of a solenoid like in Figure 2 [3].
- **Magnetic Potentials** are formed by the magnet's 'strength' in space and depict our magnetic trap. Figure 3 [1] shows a trap similar to ours. The drop sits in equilibrium (not in motion). If the drop were to move from the trap, it requires energy. If too much energy is applied (either internally or externally), it can 'fall out' of the trap. We've seen the drop 'fall out' as we attempted to put the drop into vacuum. We are still researching the cause of why the drop falls out.



$$B = \mu_o \left(\frac{N}{l}\right) I$$

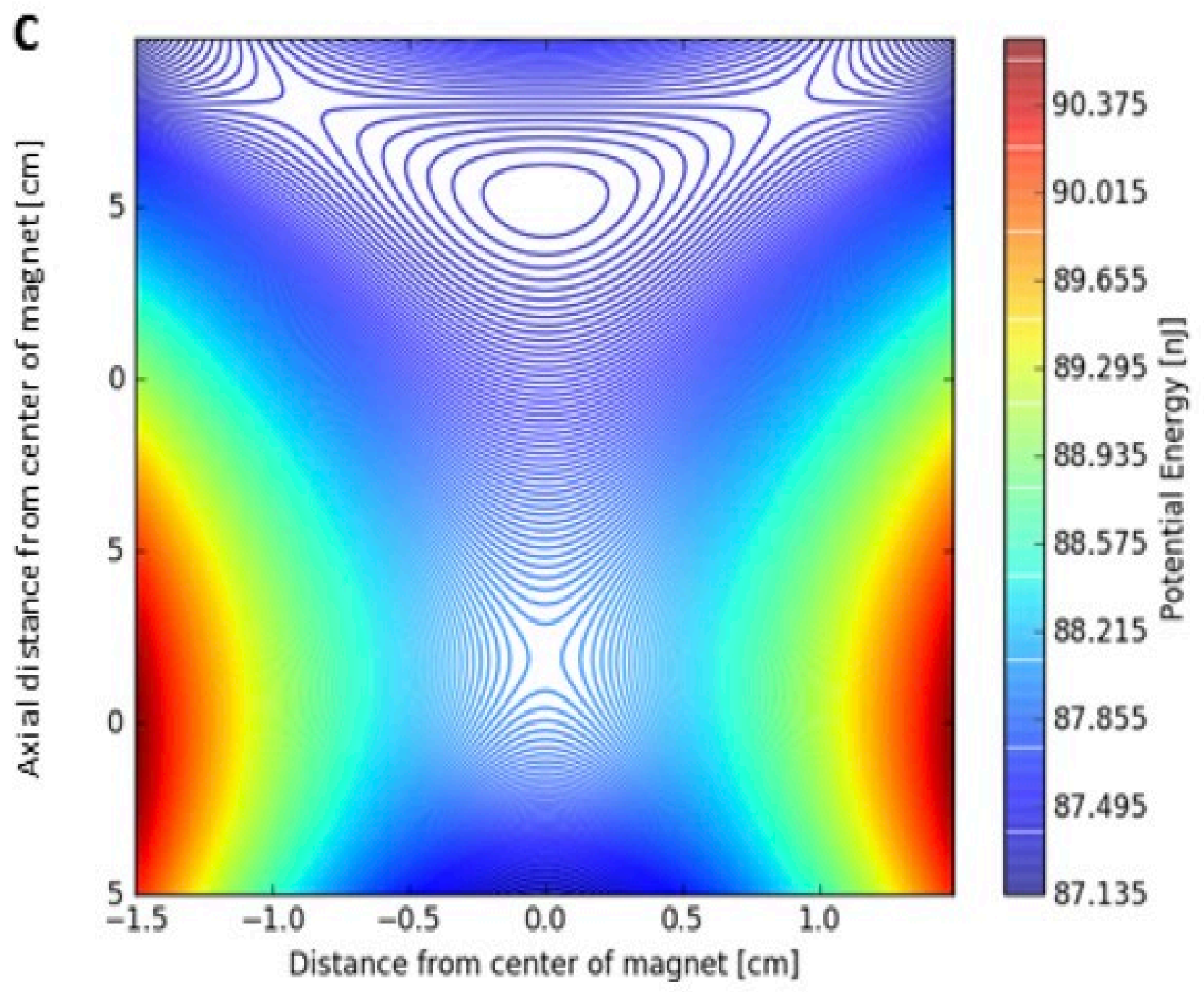


Figure 2 (above left) [3] is a depiction of a solenoid like our cryostats' magnet. The equation shows the current, number of turns, length, and permeability of free space.

Figure 3 (above right), a magnetic potential diagram from Dr. Brown's thesis [1], shows the energy required to move the drop. This paints an estimate of the force required to have a drop 'fall out' in relation to space.

Methods of Drop Formations:

Figure 4 - Pump Method

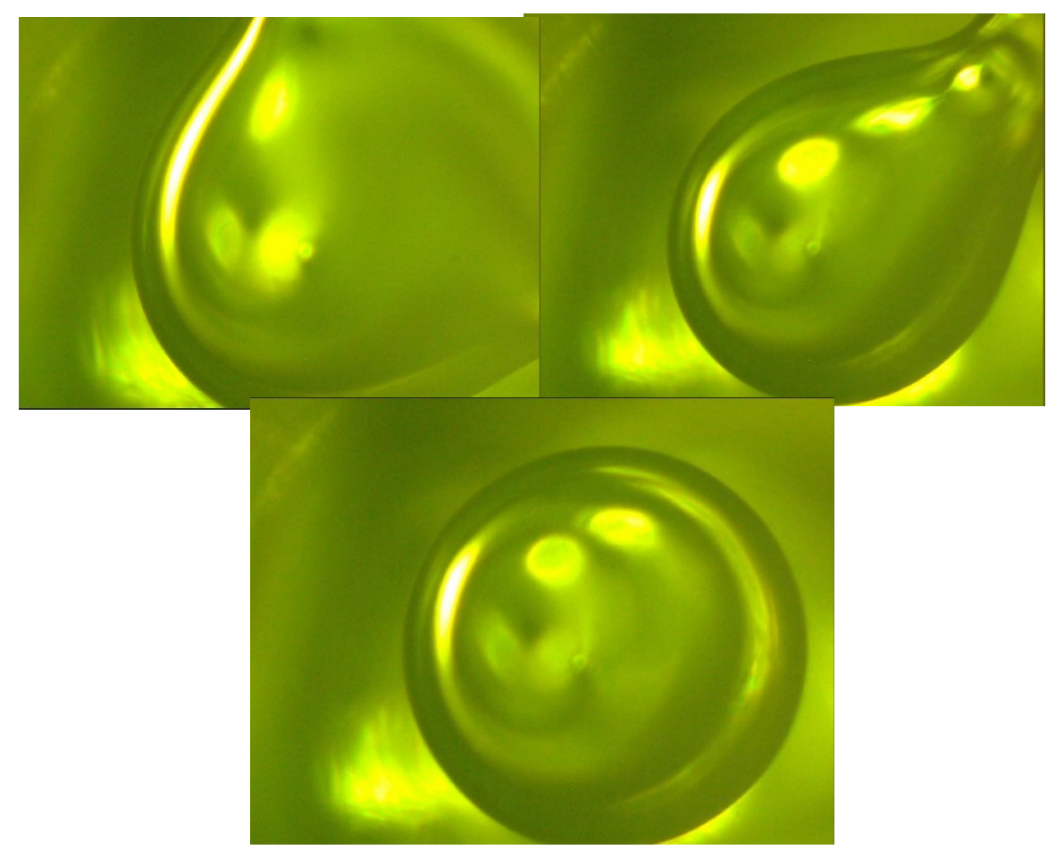


Figure 5 - Drip Method

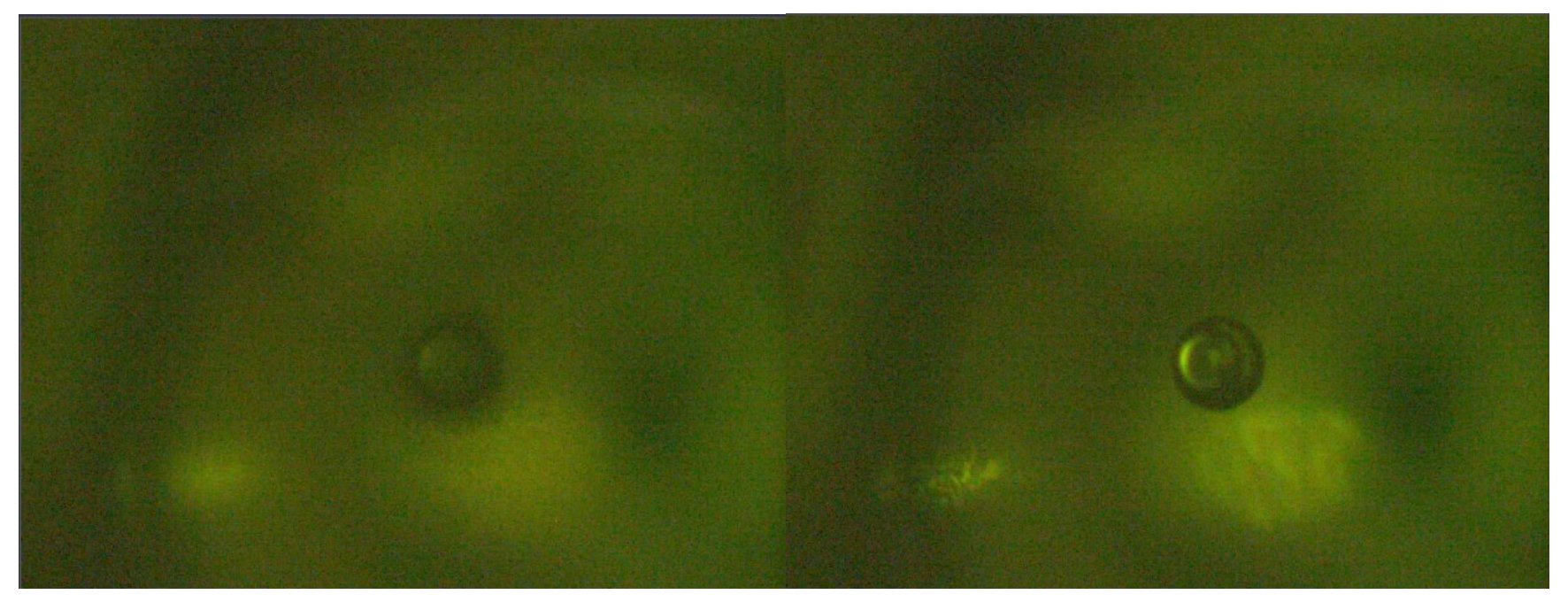
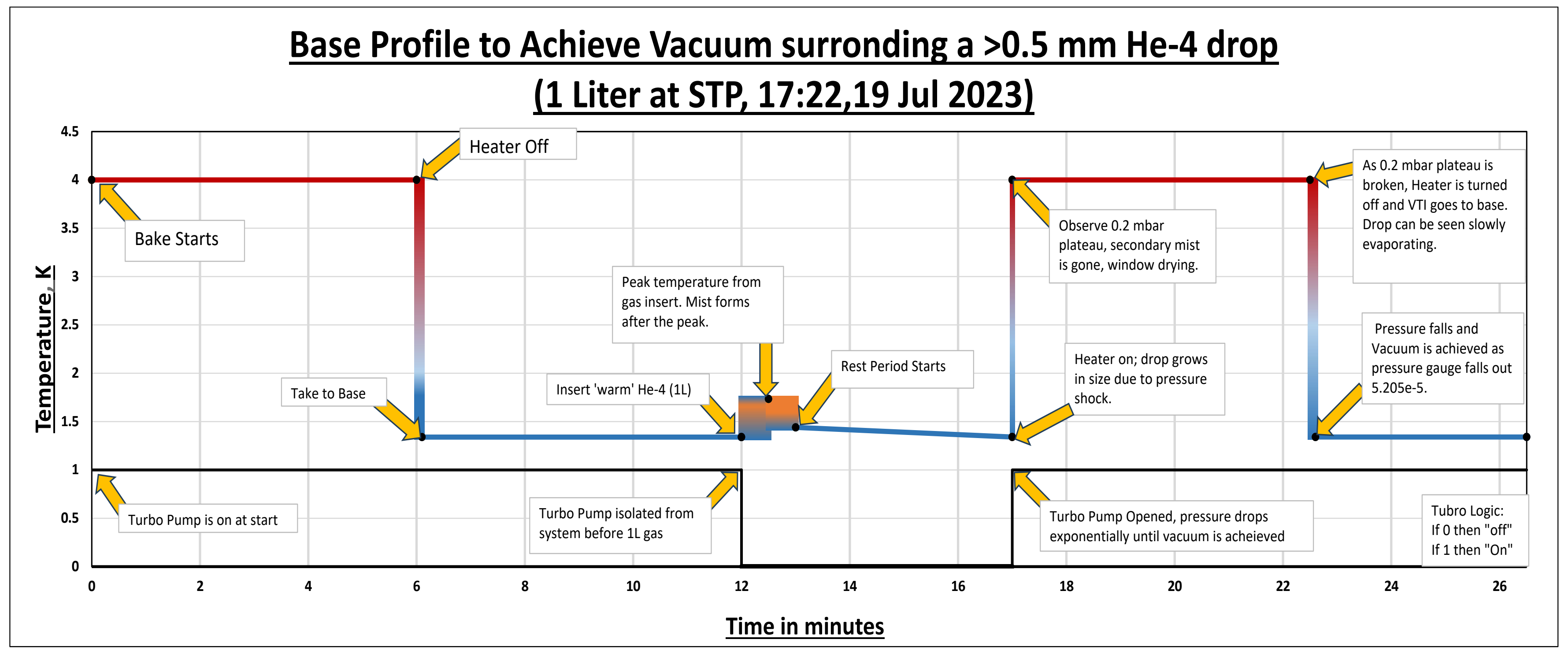


Figure 6 - Mist Method

Profile to create a Vacuum surrounding the He4 Drop in the VTI:

On July 17, 2023, after qualitative analysis, we created a drop that survived a vacuum by mist method, the first time ever a vacuum has been achieved for a drop this size. Afterward, we developed this reproducible baseline using adjustable cryostat parameters.


Base Profile to Achieve Vacuum surronding a >0.5 mm He-4 drop
(1 Liter at STP, 17:22,19 Jul 2023)

Bake Starts

Heater Off

Take to Base

Insert 'warm' He-4 (1L)

Peak temperature from gas insert. Mist forms after the peak.

Rest Period Starts

Observe 0.2 mbar plateau, secondary mist is gone, window drying.

Heater on; drop grows in size due to pressure shock.

As 0.2 mbar plateau is broken, Heater is turned off and VTI goes to base. Drop can be seen slowly evaporating.

Pressure falls and Vacuum is achieved as pressure gauge falls out 5.205e-5.

Turbo Pump is on at start

Turbo Pump isolated from system before 1L gas

Turbo Pump Opened, pressure drops exponentially until vacuum is acheieved

Tubro Logic: If 0 then "off" If 1 then "On"

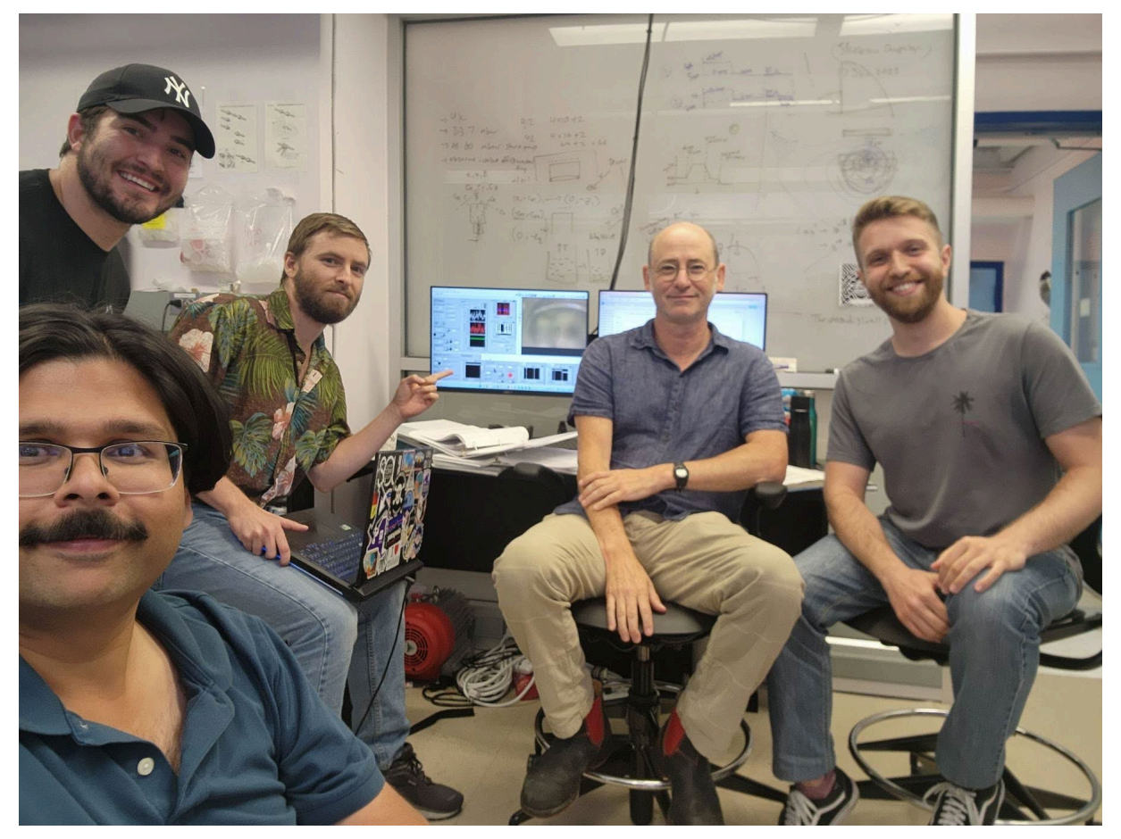


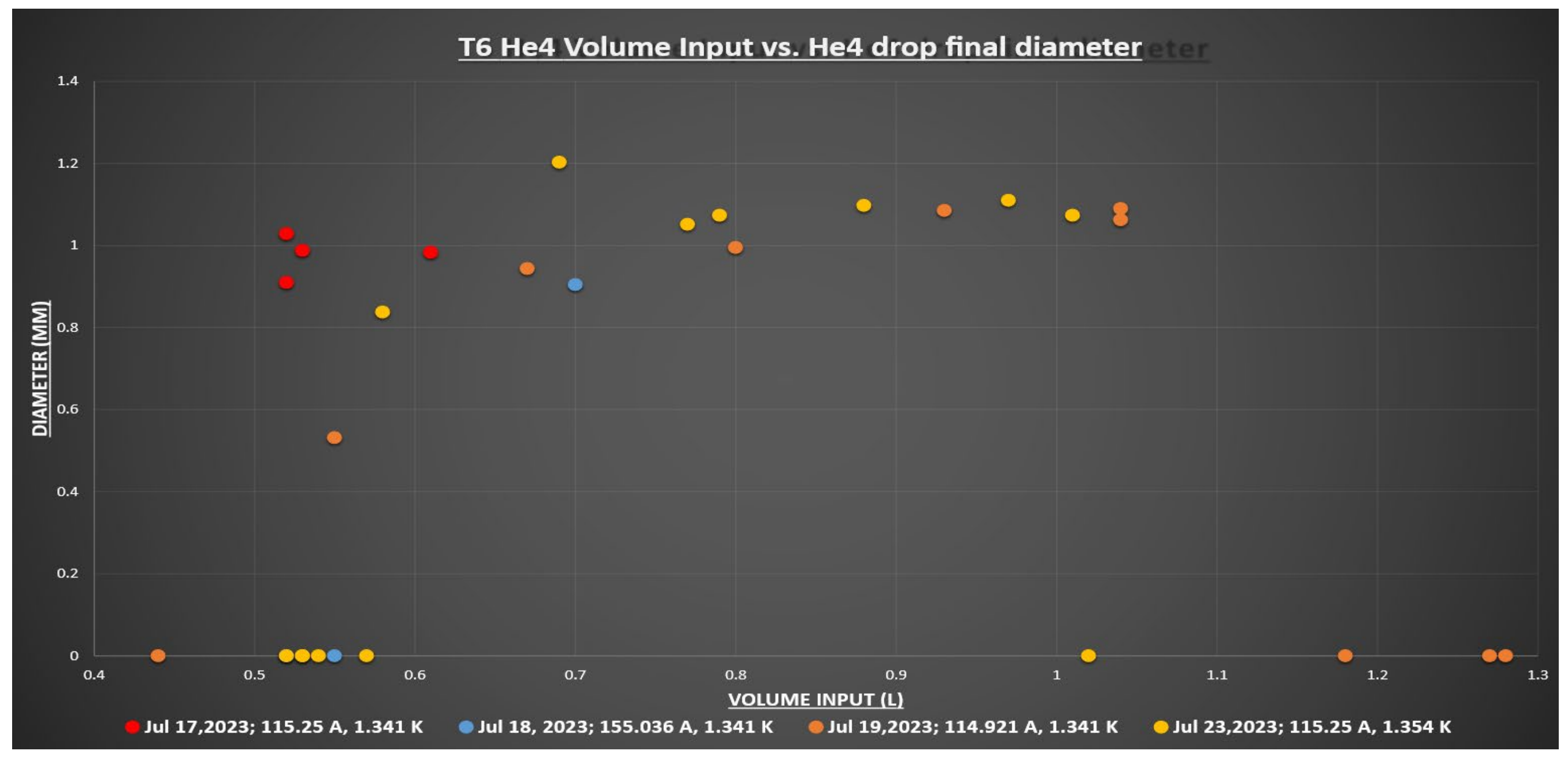
Figure 7 (to the left) is the baseline procedure used to reproduce He4 drops in a vacuum.

Figure 8 (above) is our lab team after successfully putting a 1mm He4 drop into a vacuum for the first time! Pictured (Left to right) Y.S.S. Patil, V.M. Gallegos, T.L. Human, J.G.E. Harris, I. Brandao,

Input Volume of T6 He4 gas & the ability to create a vacuum surrounding the Drop:

After successfully reproducing putting a He-4 drop in a vacuum, our lab elected to explore the parameter space. The first variable we altered was the input volume of T6 He-4 gas, in **Figure 8,**

- Other parameters were near constant.
- Data shows there's a boundary where drops "fall out."
- There is a boundary condition around 0.5 L and 1.0 L.
- Ultimately, we can deduce that more gas, up to ~1.0L, put into our cryostat allows for a larger drop with some deviations.
- However, this volume dependency varies with small unintentional changes, seen in experimental iterations.



Final Results, Implications, and Future Work:

- **Final Results:** After putting the ~1mm He-4 drop in a vacuum and evaluating the drop size in relation to the input volume, it's clear there are limits to the drop size due to input volume and that small variations in changeable variables may play a role in optimizing the size of the drop in a vacuum.
- **Implications:** There is still much to learn about levitated He-4 drops in a vacuum; however, the ability to keep the drop levitated may depend and be limited by the design of the electromagnet or the changes occurring within the He-4 as it transitions to superfluid while levitated. Our lab will continue research into phenomena referencing the works of low-temperature helium works like Donnelley [2] and Po=bell [5] to optimize drop size further.
- **Future Work:** These experiments provide a basic framework to further change parameters and optimize drop sizes for optical coupling, deriving magnetic potentials for our magnet, and driving higher modes of resonance. Changes include evaluating other variables such as volume fill rate, bake temperature, base temperature, etc. to optimize the drop size. This work is the basis for the proceeding WGMs experiment, the finesse of the actual WGMs, and higher modes of resonance, which may help shape the field of optomechanics and quantum optics.

References:

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2. Donnolley, R. & Barenghi, C. *"The Observed Properties of Liquid Helium at Saturated Vapor Pressure."* Journal of Physical and Chemical Reference Data 27. 15 October 2009.
3. Giancoli, D.C. *"Physics for Scientists & Engineers with Modern Physics, 5th Edition."* Pearson Education Inc. 2020.
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