
CERN

Superfluid Helium Properties
Visualization of Common Effects

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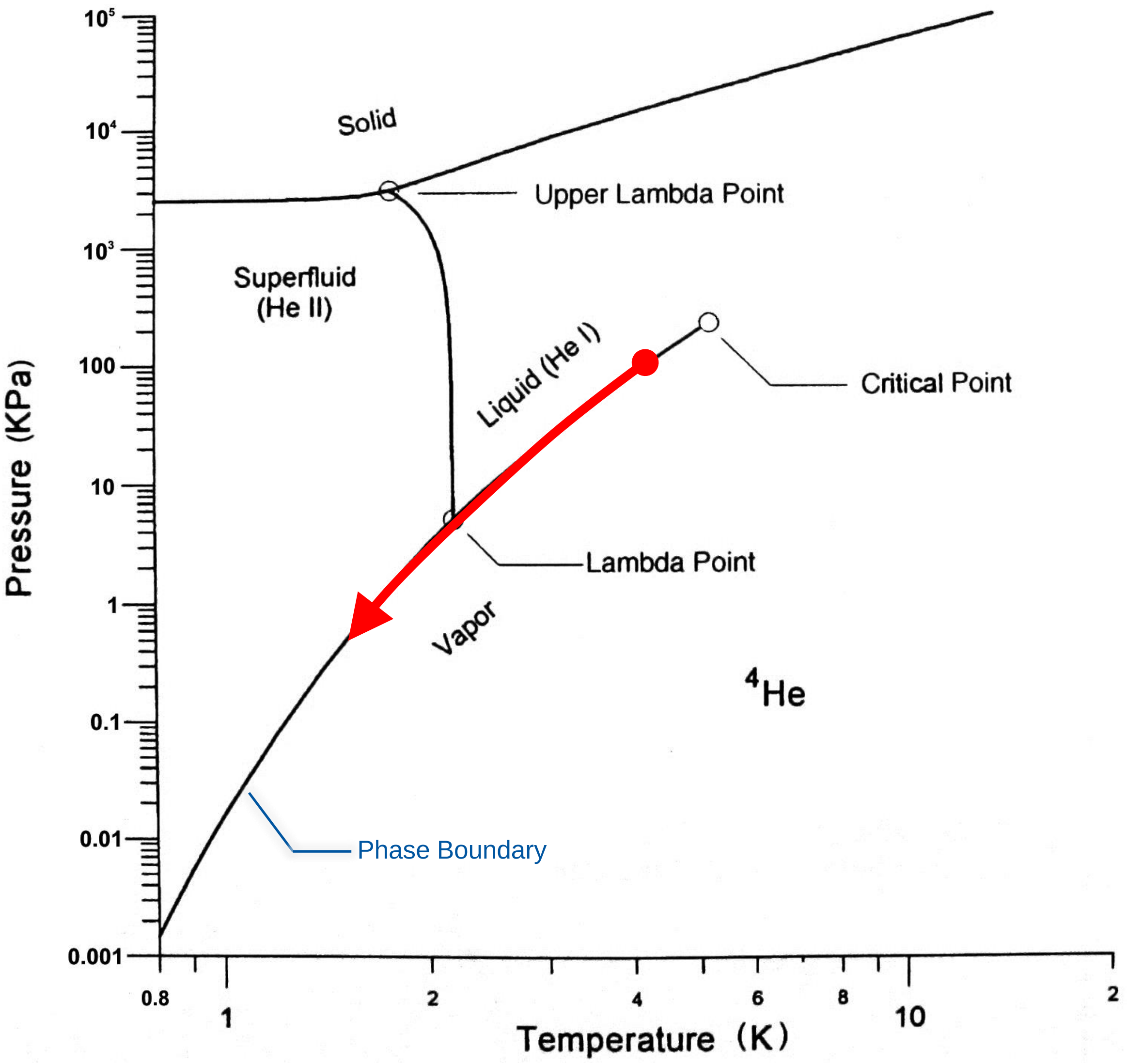
Contents

- Introduction to helium as a cryogenic liquid
- Glass cryostat – visualize liquid helium
- Phase transition of He I to superfluid He II – some properties
- Two-Fluid model of superfluid helium
- Demonstration:
  - Cooldown of He I => transition to He II
  - Superleak in porous materials
  - Fountain effect
  - Superfluid film flow
  - Trapped gas volume - condensation

History of Helium

- 1868 first discovered in the solar spectrum (P. Janssen)
- 1895 formal discovery of He from uranium ore (P. Cleve, N. Langlet)
- 1903 helium in natural gas, concentration ≤ 7 vol.% (E. Haworth)
- 1908 first liquefaction of helium at 4.2 K =>60 g of ^{4}He (H. Kamerlingh-Onnes)
- 1932 first industrial helium liquefier installed (C. Linde)
- 1937 discovery of superfluidity in ^{4}He (P. Kapitza, J. Allen and D. Misener)
- 1938 introduction of a Two-Fluid model (L. Tisza)
- 1941 mathematical theory of superfluidity (L. Landau)

Phase Diagram of ^{4}He

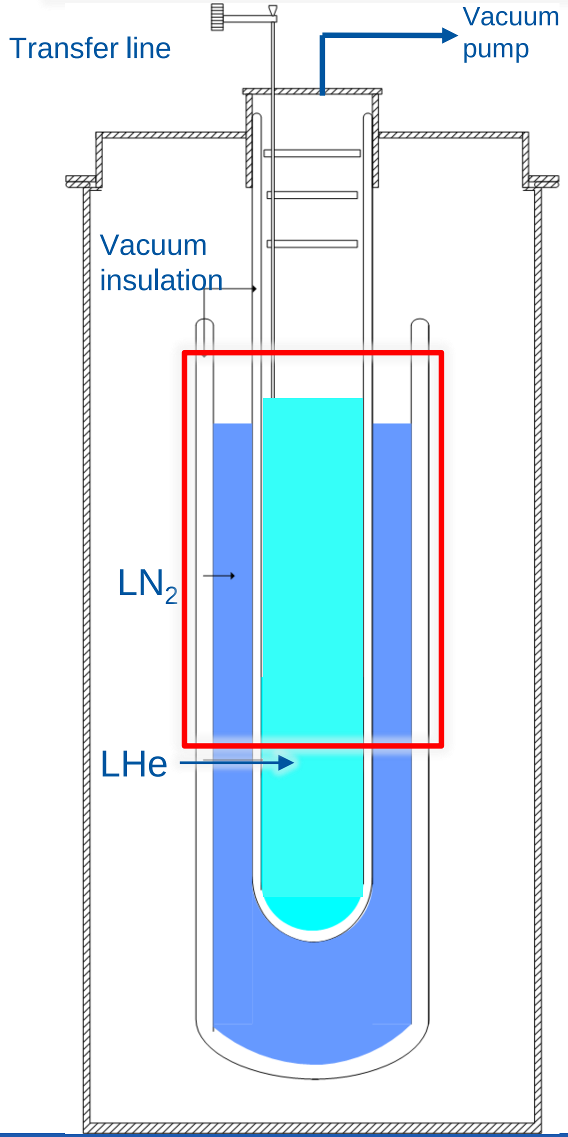


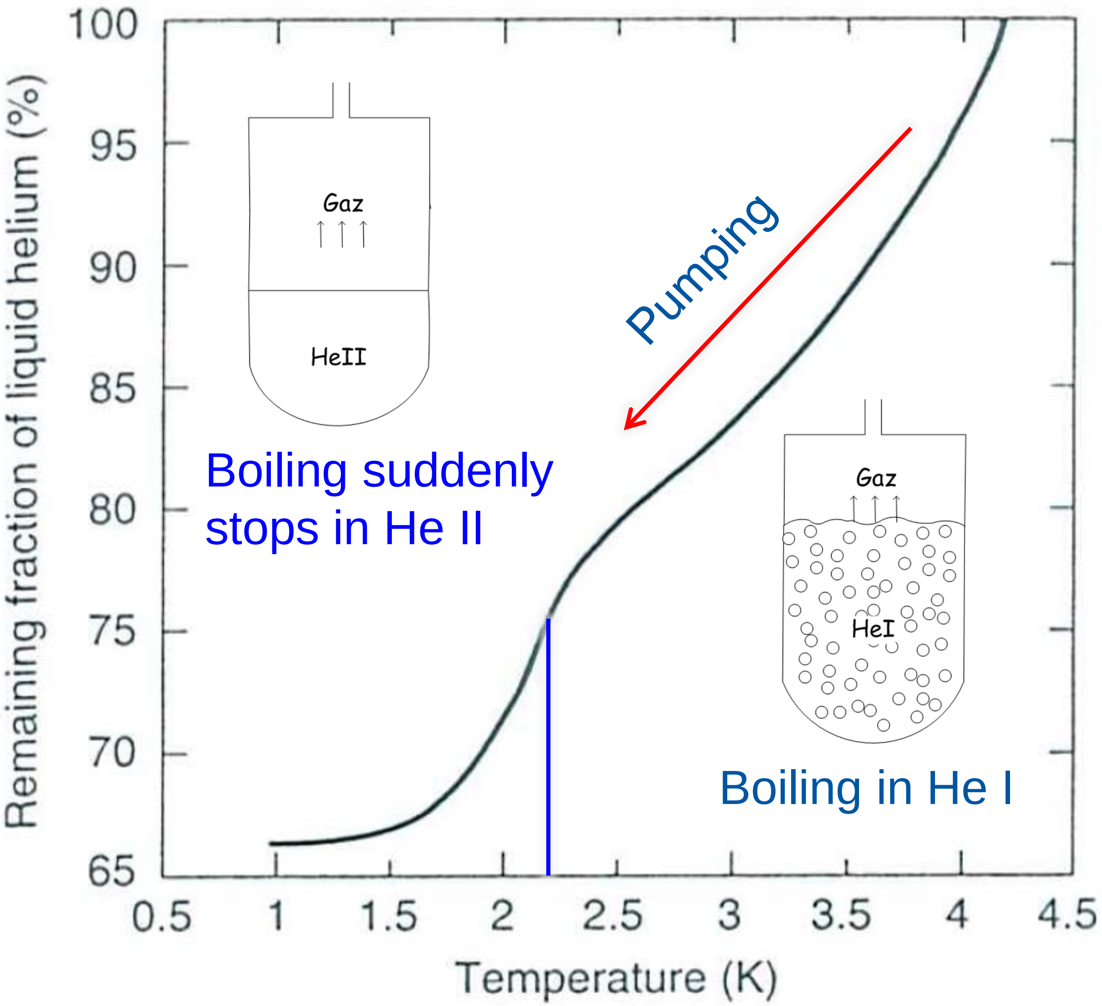
$T_\lambda \approx 2.1768$ K @

$p_\lambda \approx 50.41$ mbar

From Weisend, Handbook of Cryogenic Engineering, 1984.

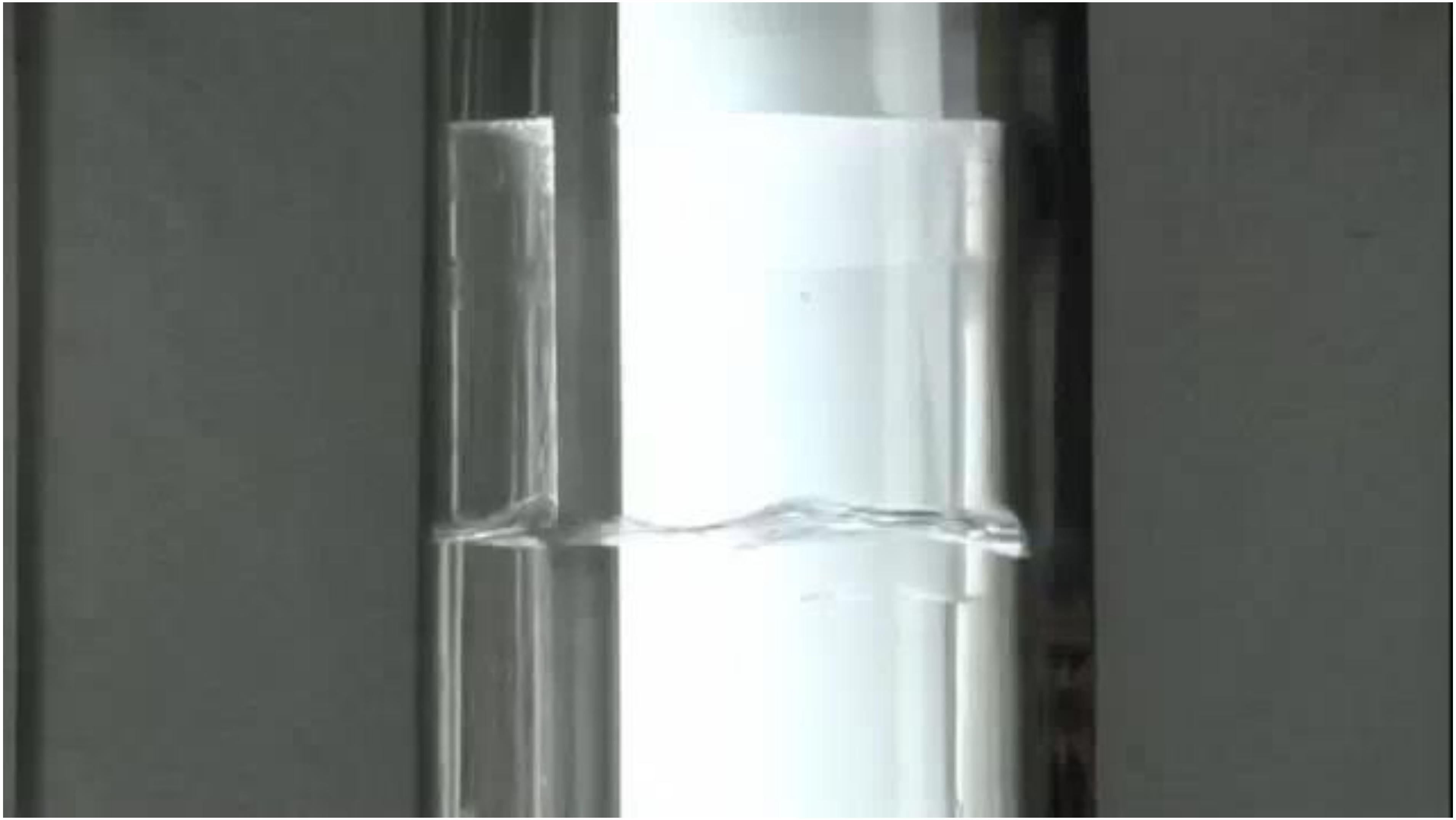
Glass Cryostat Set-up





From Ekin, Experimental Techniques for Low Temperature Measurements, 2006.

Boiling Effects During Cooldown / Pumping on the He Vapor Space

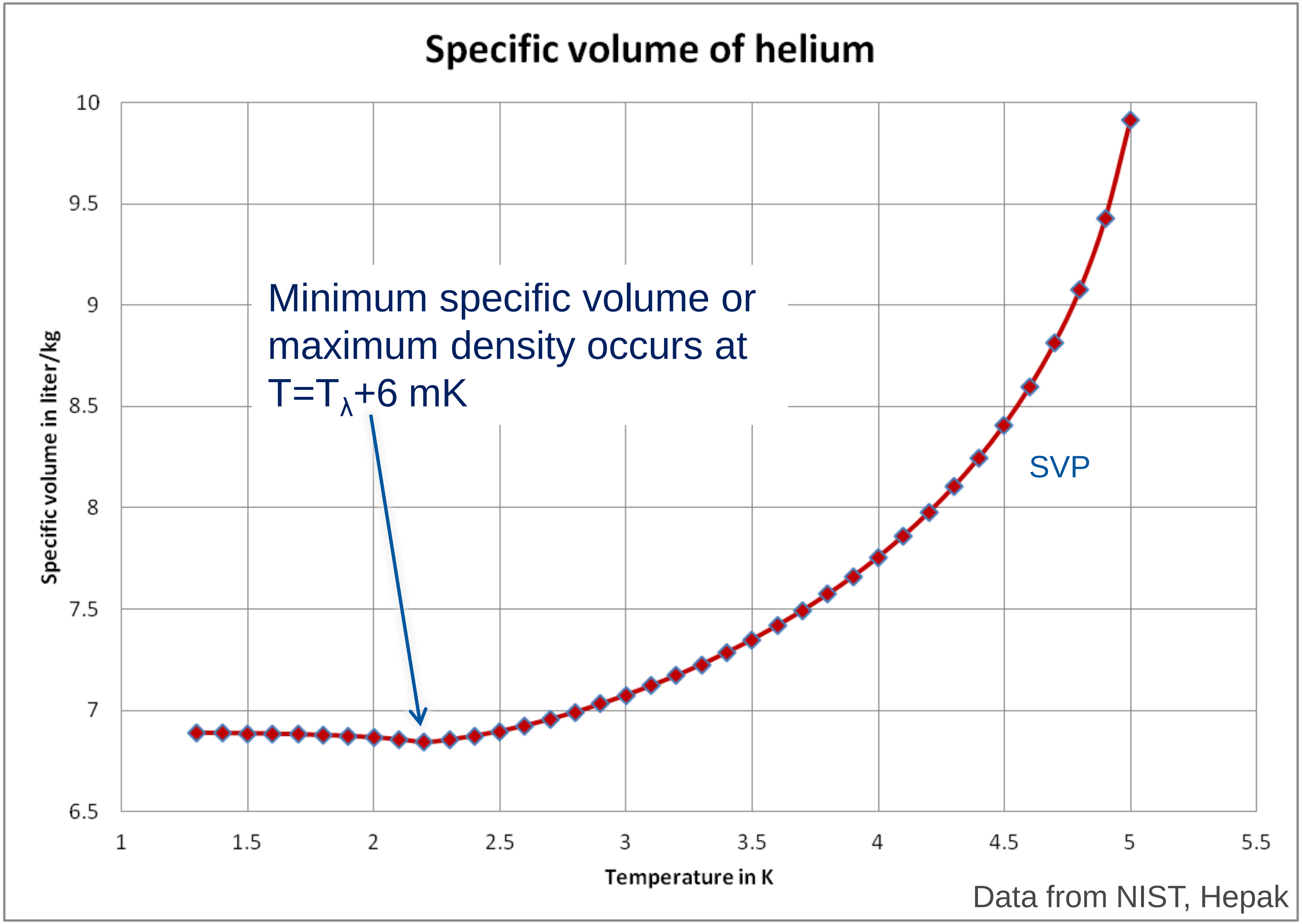


Effects in Superfluid Helium

Superfluid helium – some properties

- No vapor bubbles in the liquid
- Minimum specific volume at $T \approx T_\lambda + 6$ mK
- λ point => peak in heat capacity
- Vanished viscosity in capillary flow
- Very high thermal conductivity => effective cooling of SC cavities & magnets
- Uniform temperature in the liquid => minimal temperature gradients

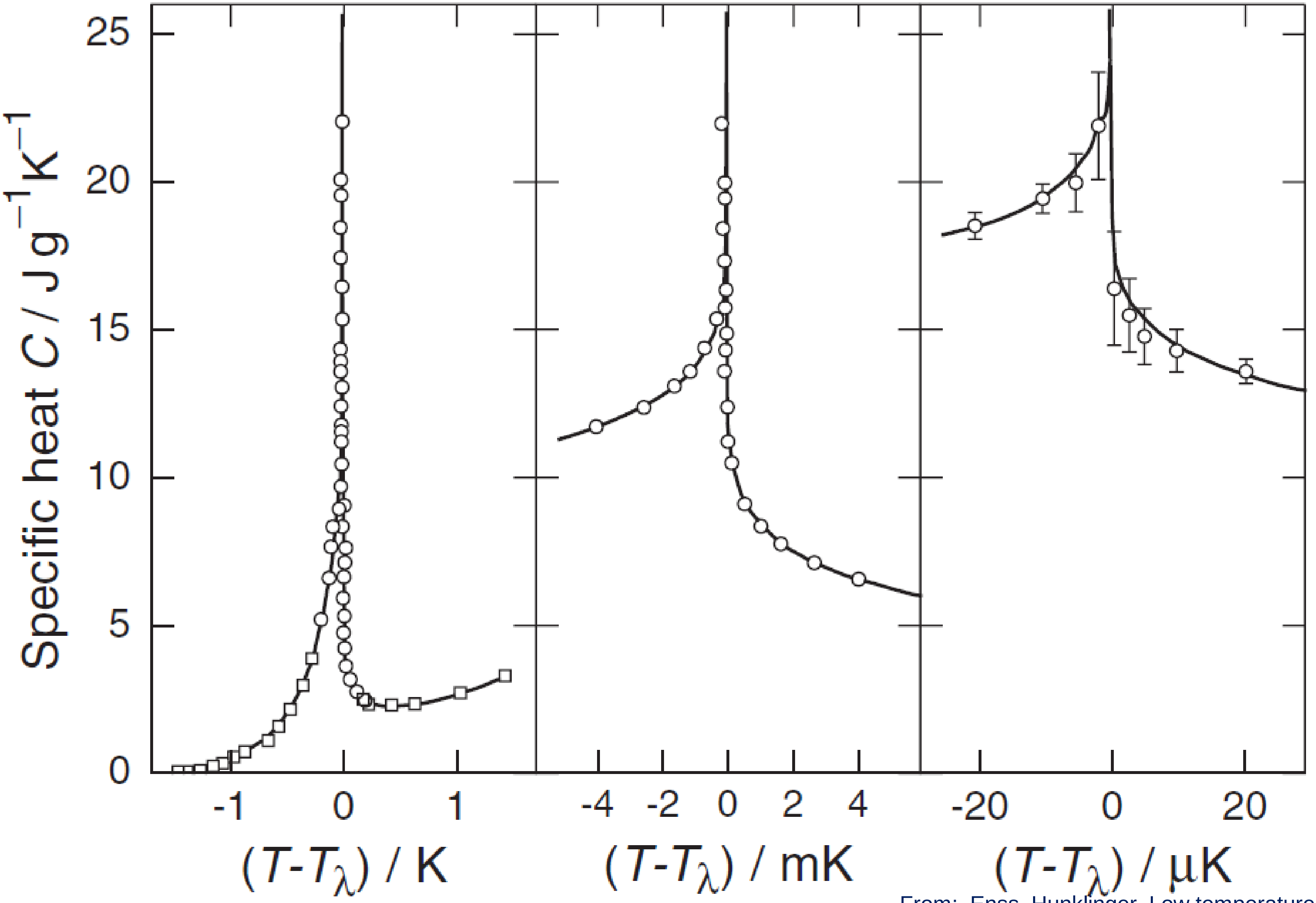
Specific Volume of ^{4}He



Minimum specific volume or maximum density occurs at $T=T_\lambda+6$ mK

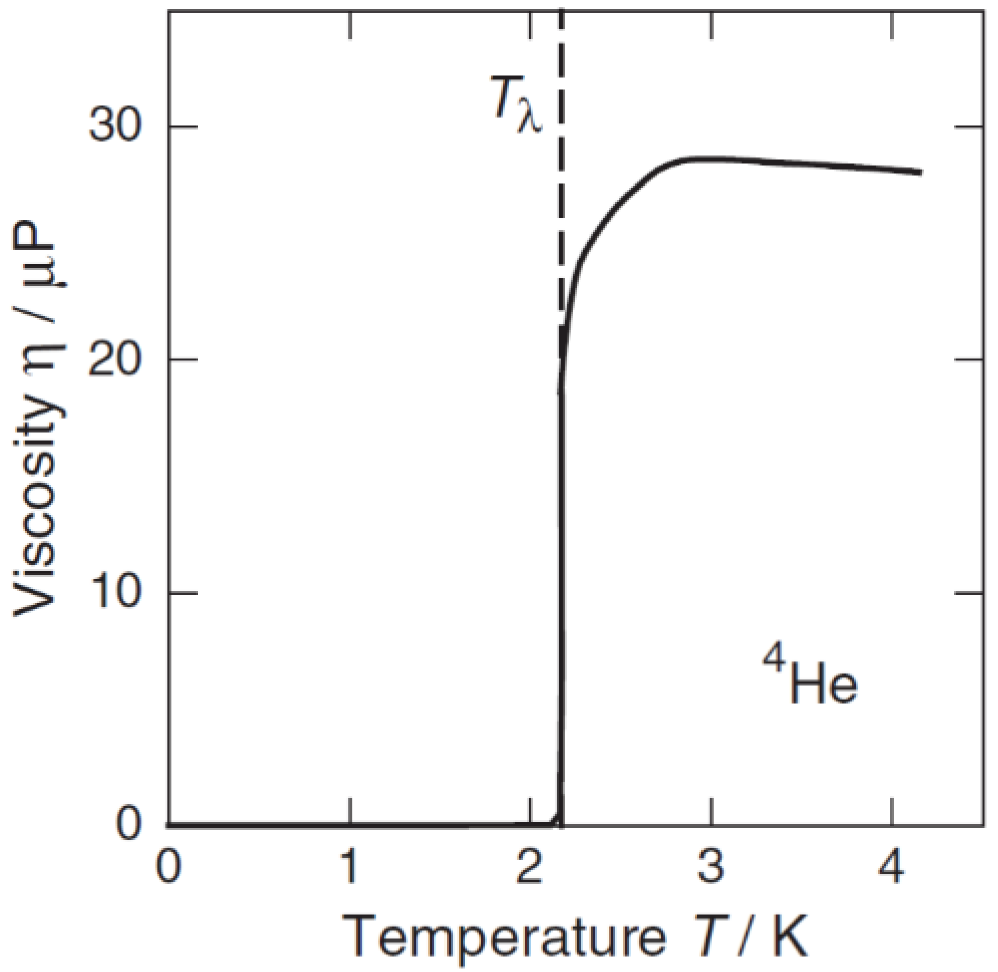
Data from NIST, Hepak

Heat Capacity – Lambda Point



From: Enss, Hunklinger, Low temperature physics, 2005.

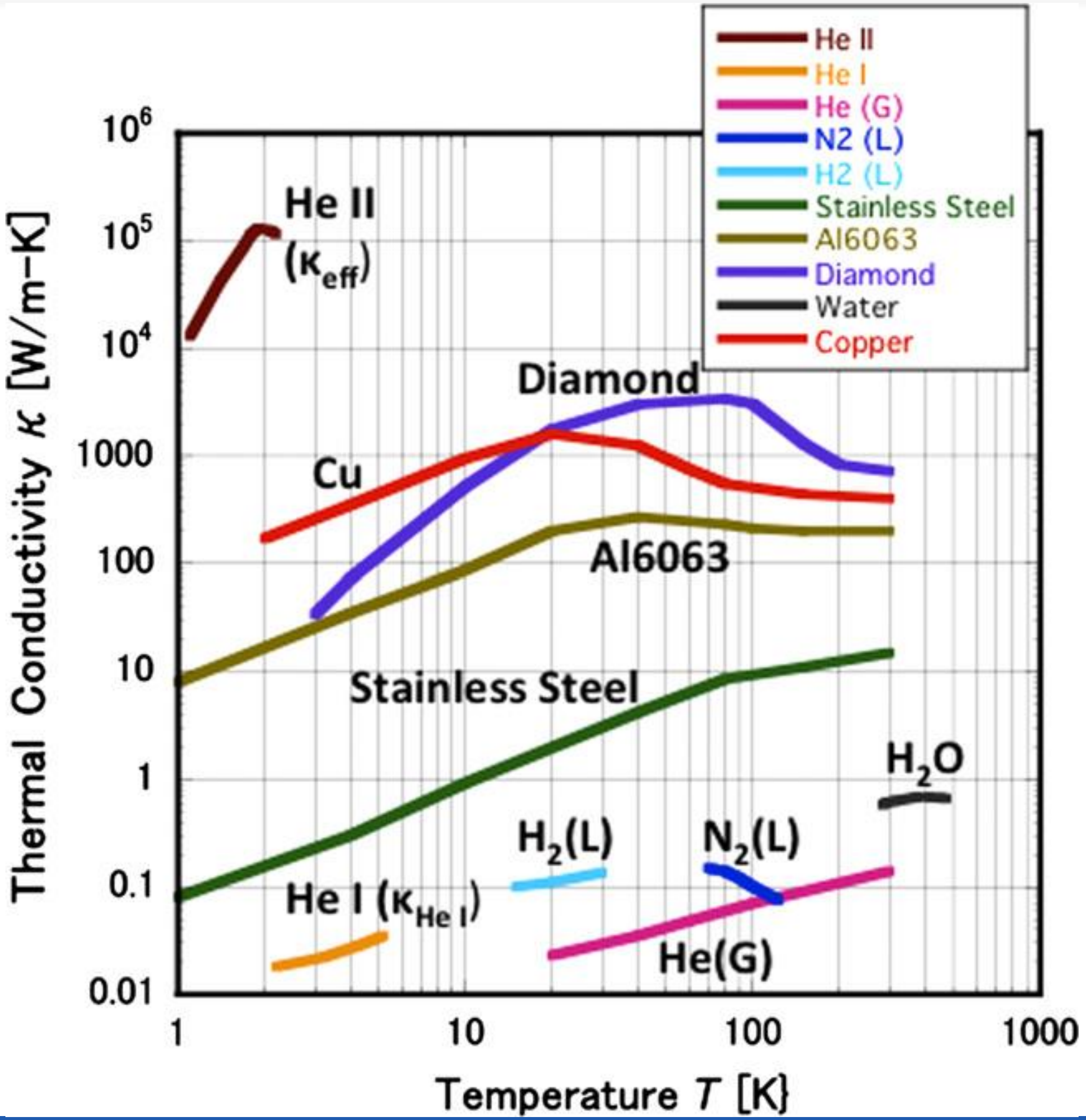
Viscosity of He II



From: Enss, Hunklinger,
Low temperature physics, 2005.

The observed viscosity of He II is depending on the method of measurement !

Thermal Conductivity at Low Temperatures



Murakami, Experimental study of thermo-fluid dynamic effect in He II cavitating flow, Cryogenics, 2012.

Thermal Conductivity of He II

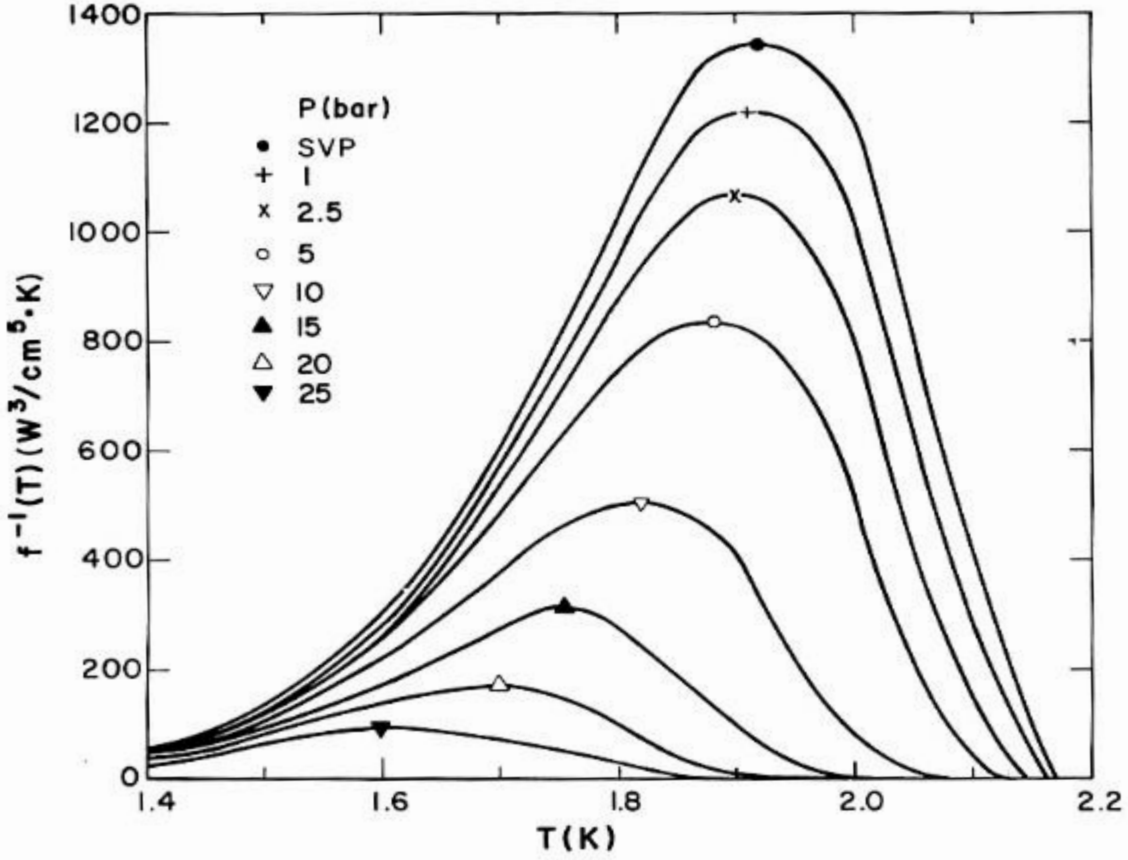


Fig. 5.3. Heat conductivity function for turbulent He II. Symbols indicate the location of the peak value.

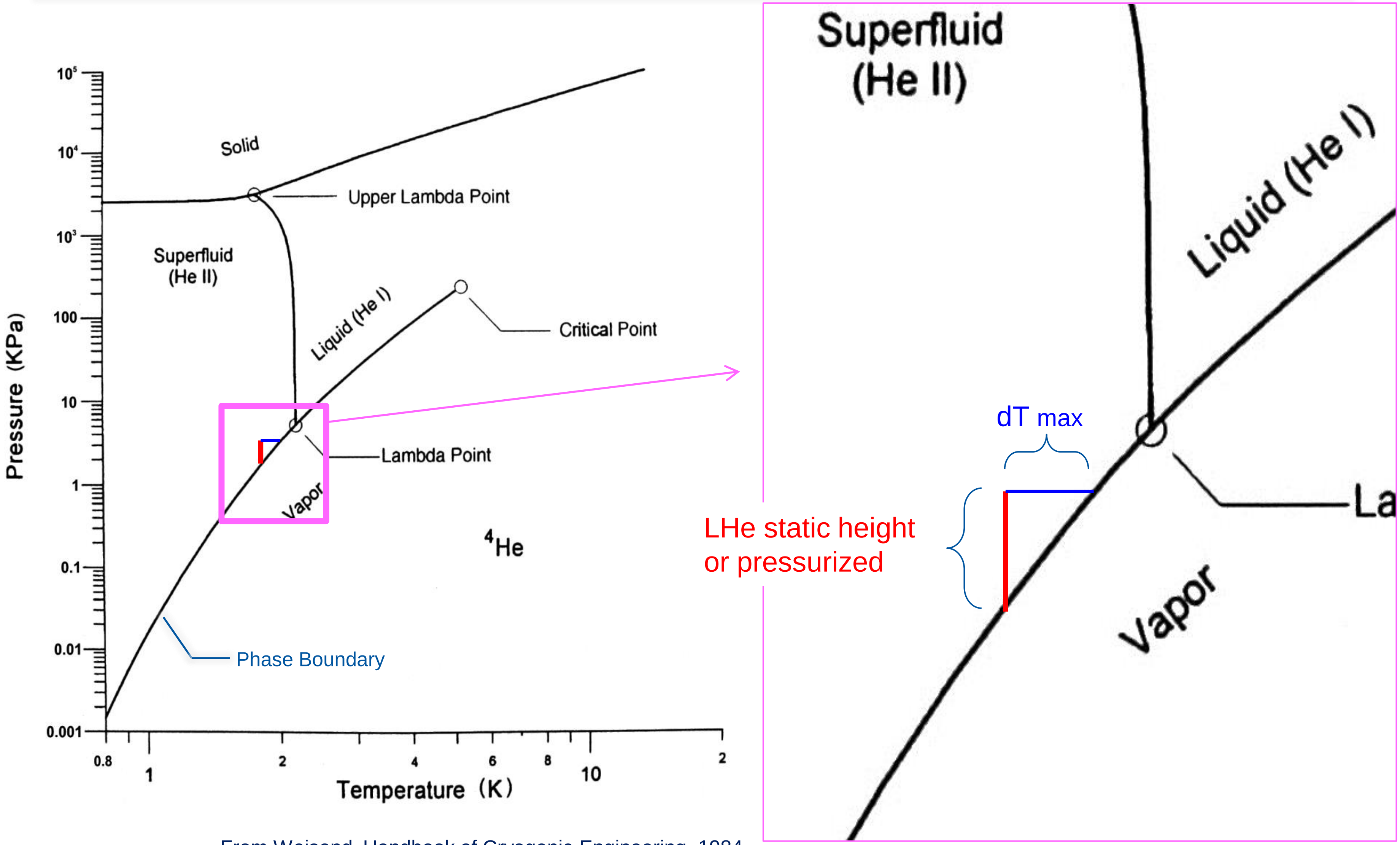
For channels d>1 mm

$$\dot{q}^m = f^{-1}(T) \cdot \frac{dT}{dx}$$

m = 3 … 3.4

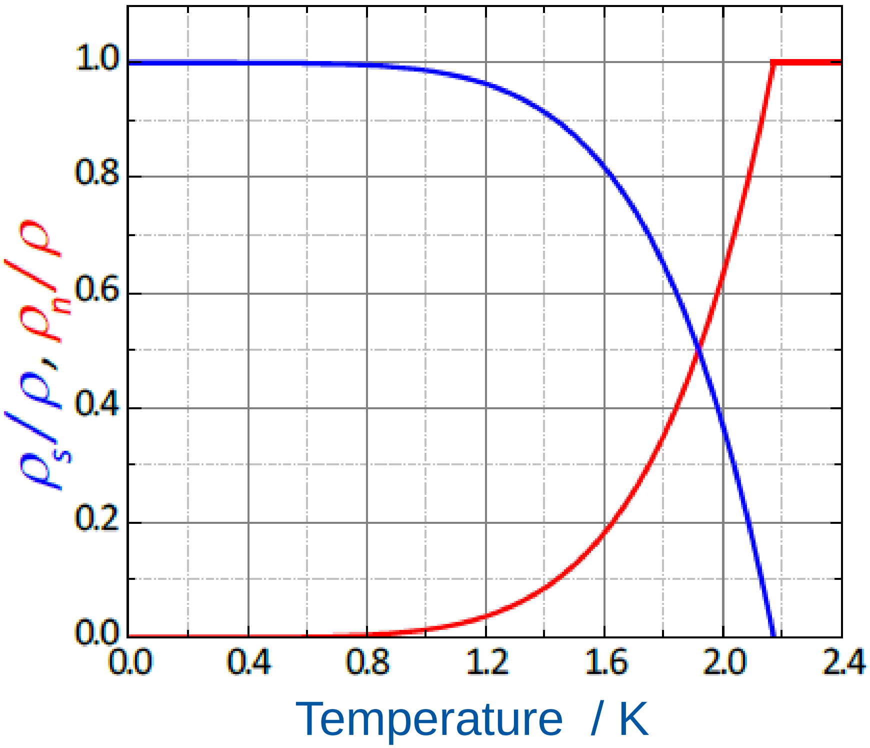
From: Van Sciver, Helium Cryogenics, 1986

Subcooling by Static Height



From Weisend, Handbook of Cryogenic Engineering, 1984.

Two-fluid Model of He II



- Anomalous properties of He II can be well described by two-fluid model (I.Tisza, 1938),

- Formal description of He II as the sum of a normal and a superfluid component.

- Ratio ρ_s/ρ_n depends on temperature

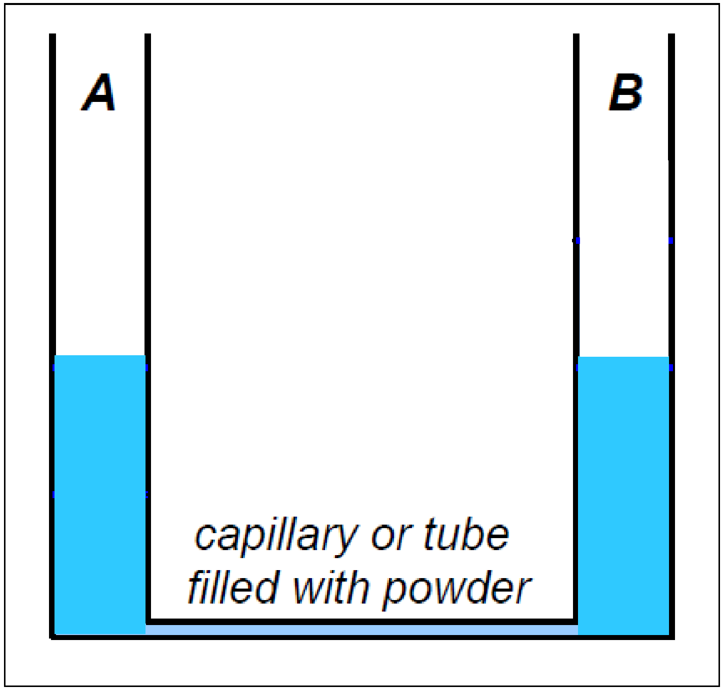
- Superfluid component: no entropy S_s=0, zero viscosity: η_s=0
- Normalfluid component: carries total entropy: S_n=S finite viscosity: η_n=η_n

From Gross, Marx, Wather-Meissner Institut, 2009.

Thermo-mechanical Effect

1963 film by Alfred Leitner, Michigan State University

Thermo-mechanical Effect

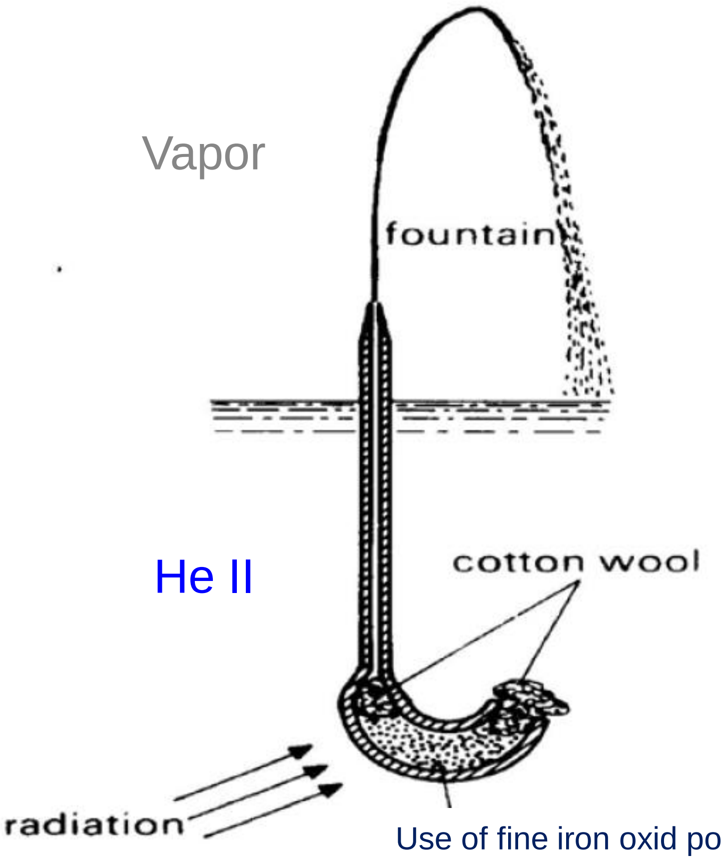


- starting point: same fill level and temperature *T* of container A and B

Inverse effect: superfluid helium fountain

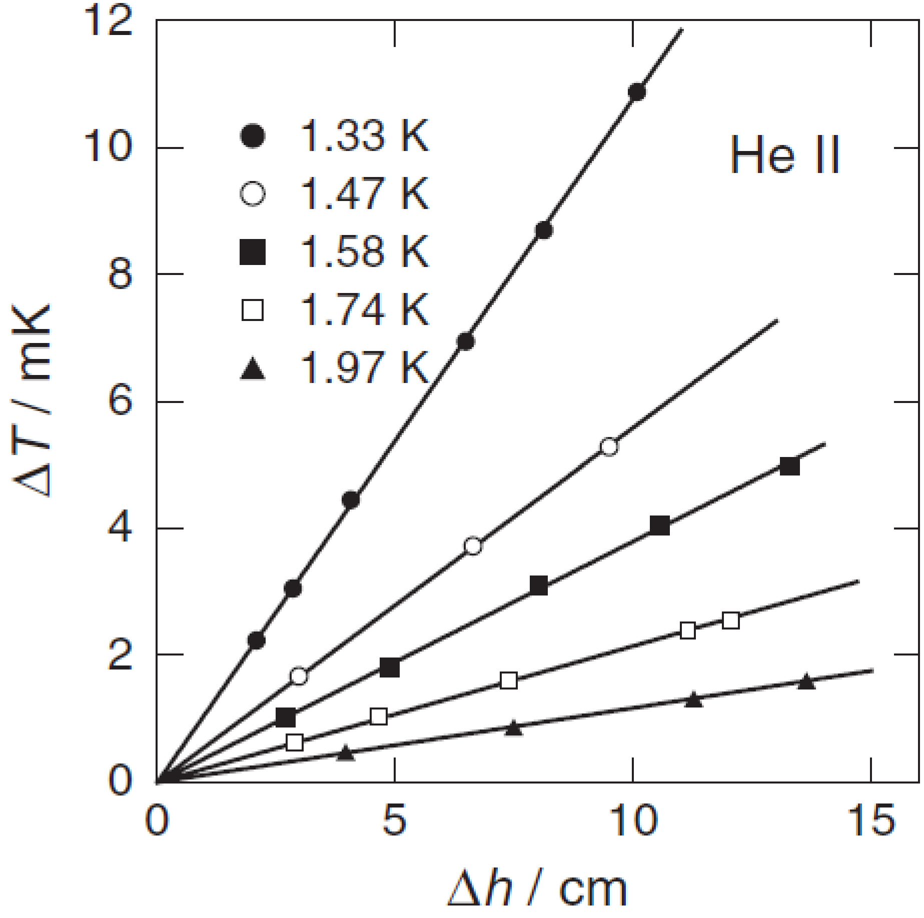
From Gross, Marx, Wather-Meissner Institut, 2009.

Fountain Pressure



Use of fine iron oxid powder
as a porous plug ~ 1 µm

From J. Allen, 1937

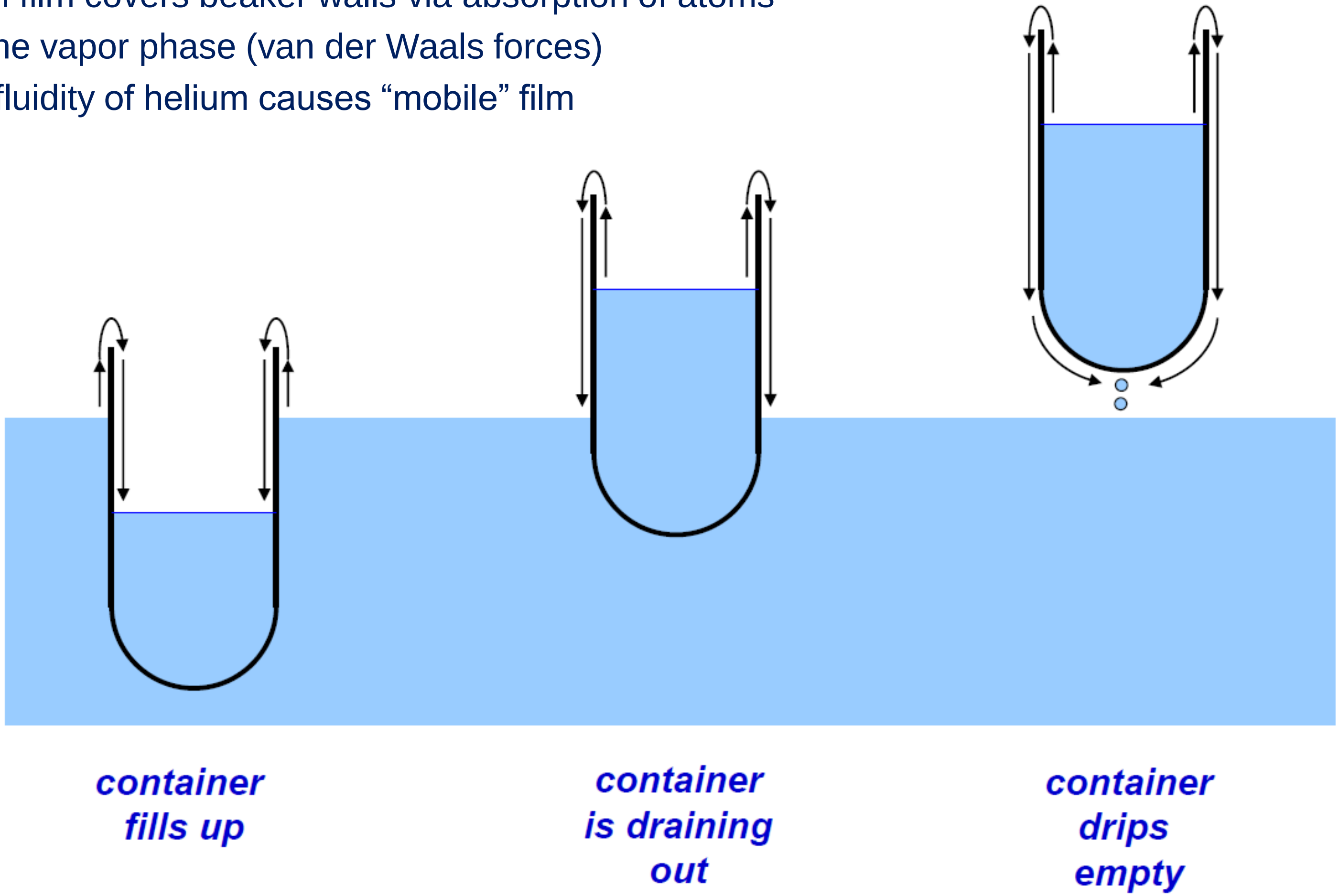


From Enss, Hunklinger, Low temperature physics, 2005.

Fountain Effect

Superfluid Film Flow

- Helium film covers beaker walls via absorption of atoms from the vapor phase (van der Waals forces)
- Superfluidity of helium causes “mobile” film



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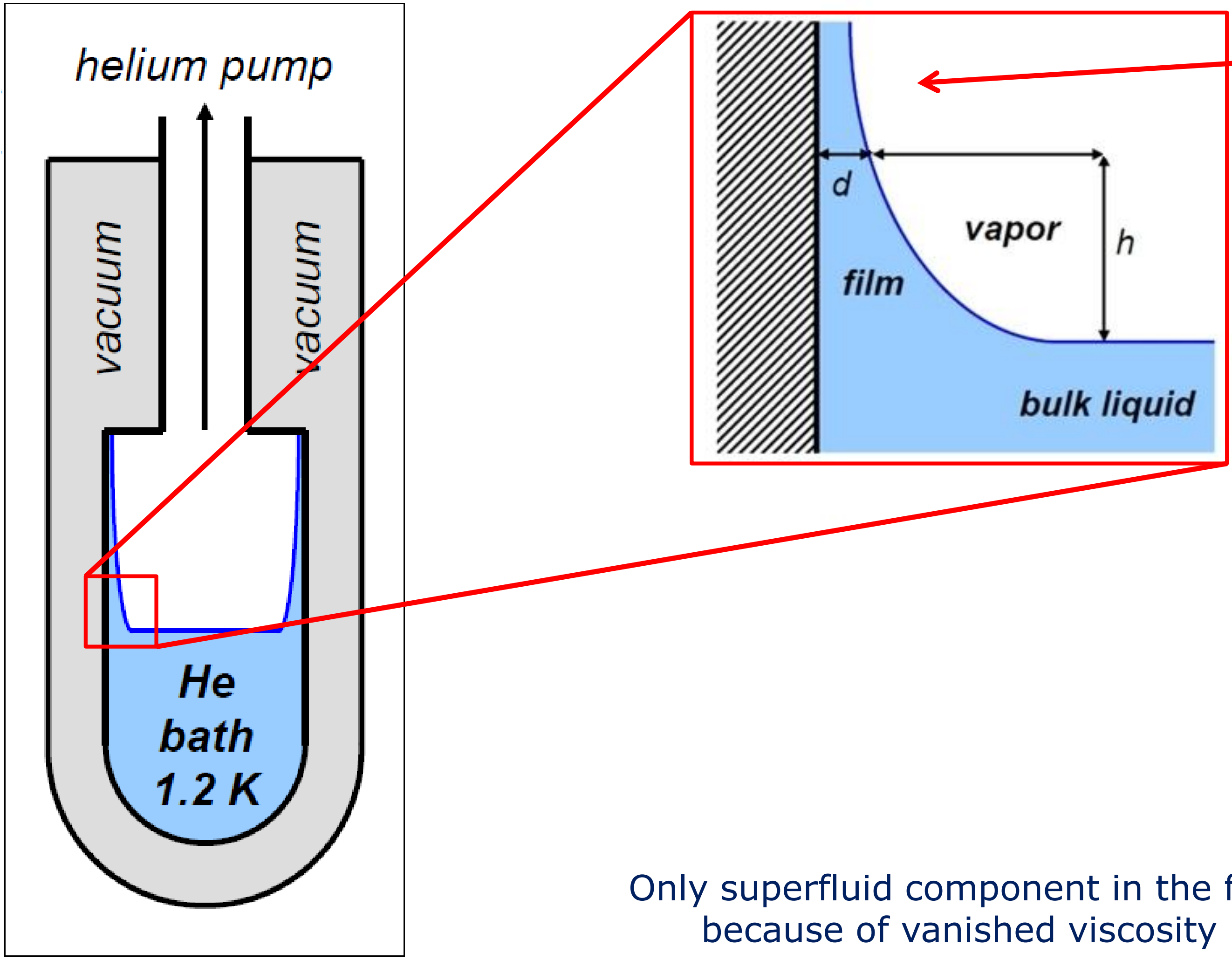
Superfluid Film Flow



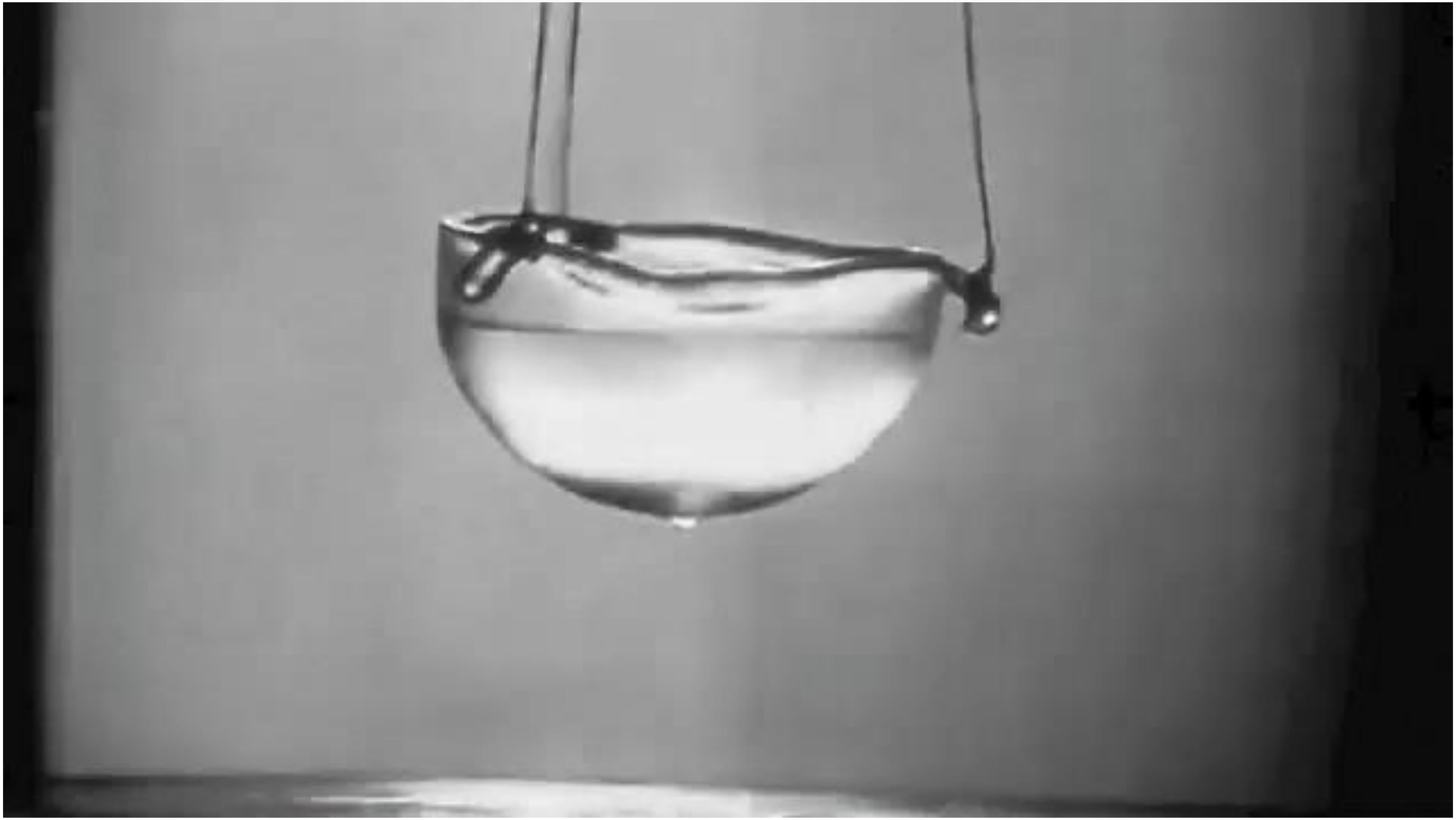
Super leak !

Rollin film for
d>2.1 Monolayer
≈1 nm

Only superfluid component in the film
because of vanished viscosity

From Gross, Marx, Wather-Meissner Institut, 2009.

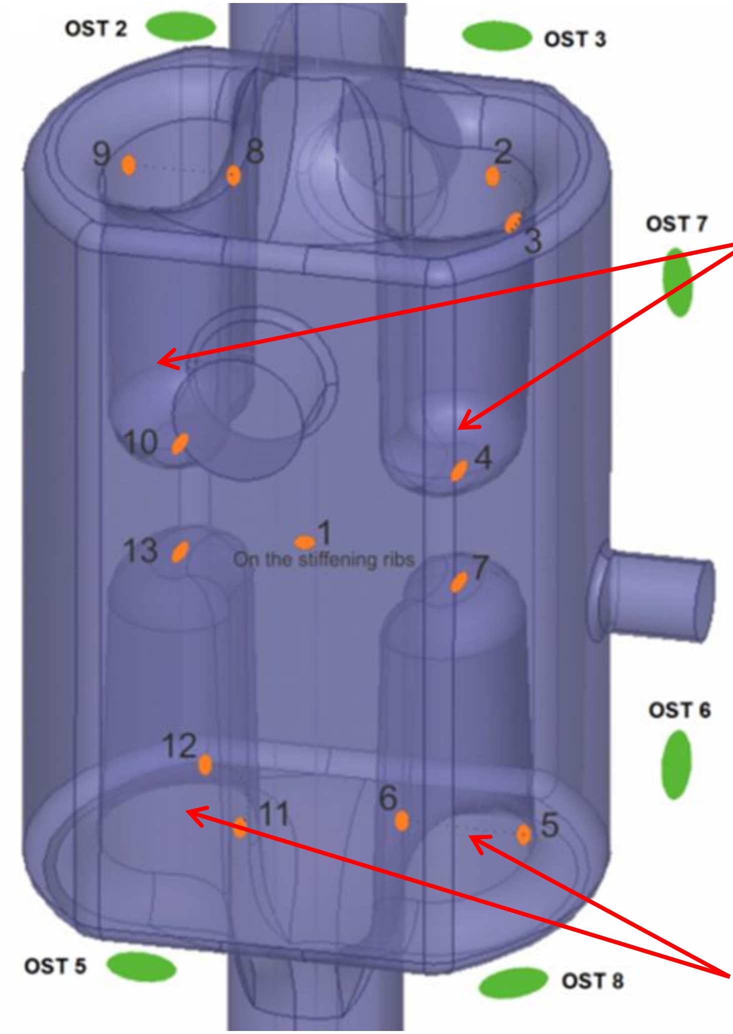
Rollin Film



1963 film by Alfred Leitner, Michigan State University

Trapped Volume in Liquid Helium

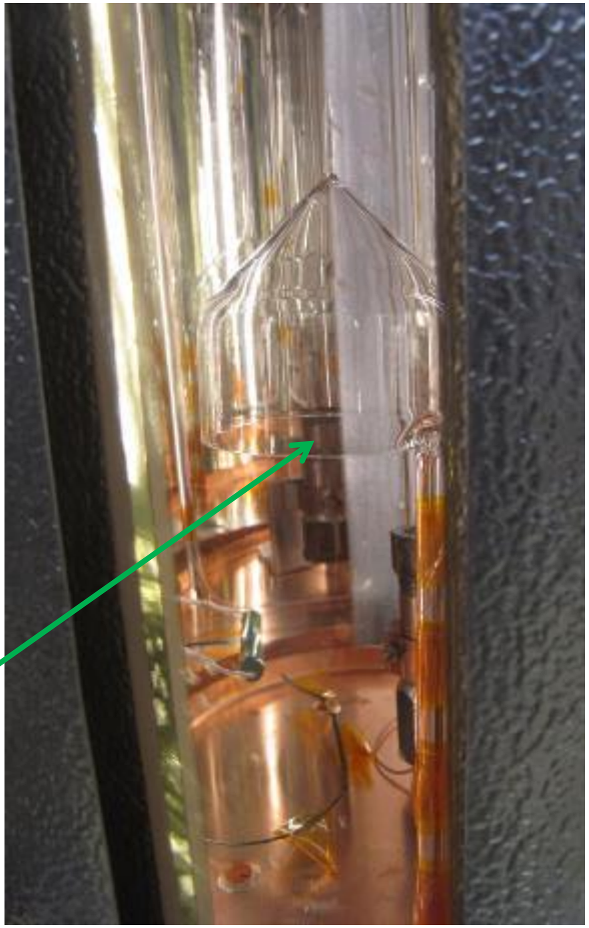
Trapped volume of a CRAB cavity



Two deep-drawn structures from top

Two deep-drawn structures from bottom

Set-up with glass beaker



Upside down installed glass beaker representing the trapped gas volume

Filled Cryostat at Saturation Condition

LHe at 4.2 K and 1.0 bar abs.

In saturated bath conditions.

No condensation of vapor in t=8 h.

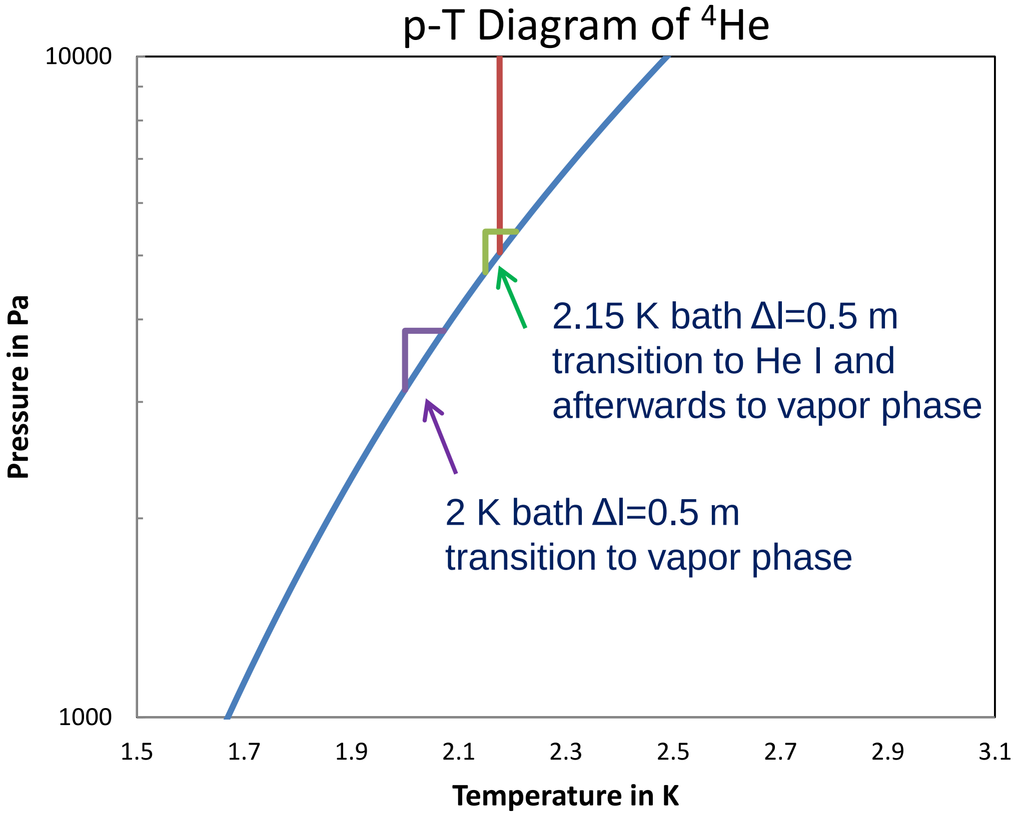
Possible reasons for “steady” interface:

- Small remaining heat load due to thermal radiation to the glass beaker
- Lowering of the outer He II liquid level during the 8 h

Superfluid Transition => Options for Reduced Condensation Speed

Main restriction:

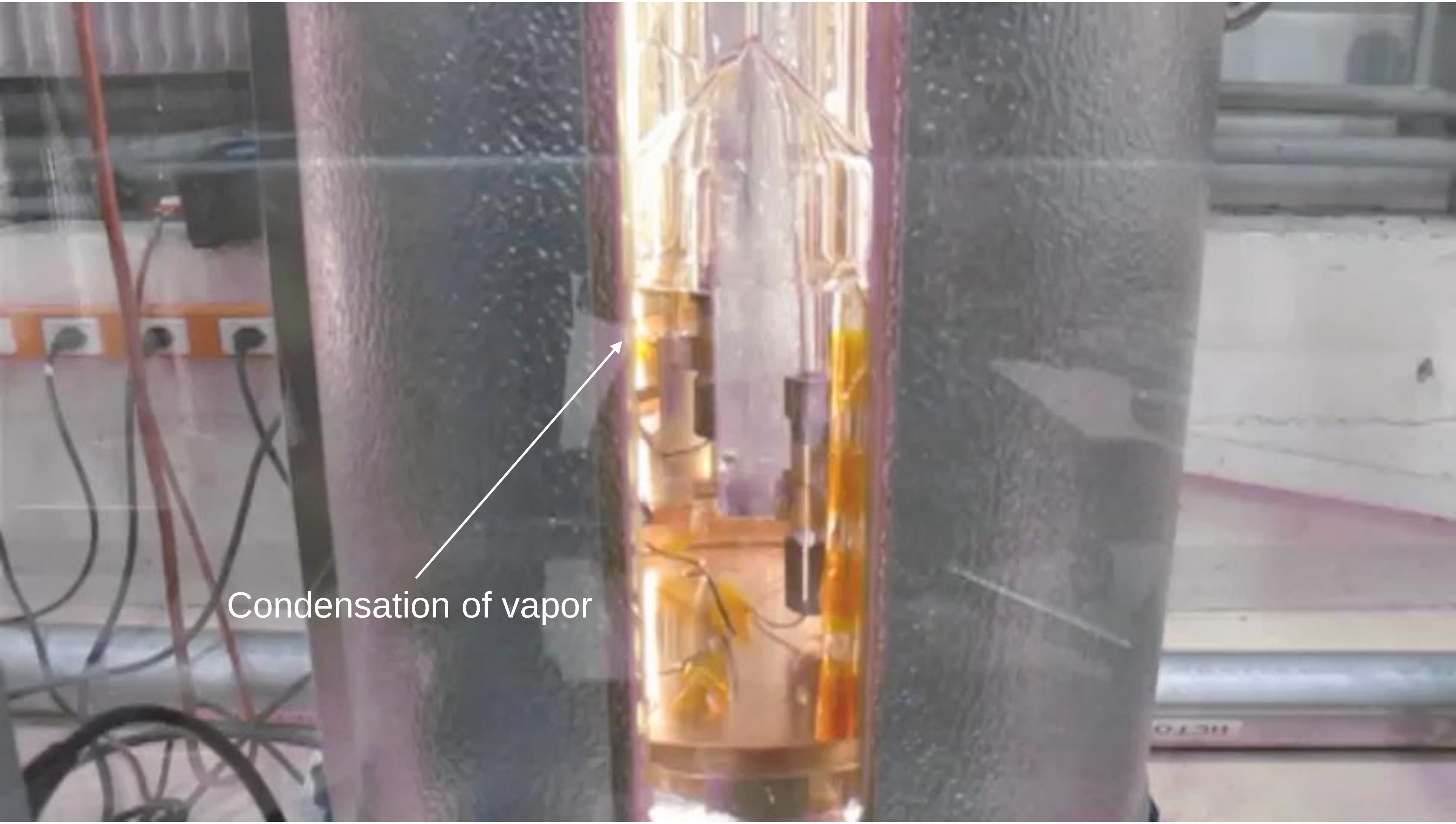
- thermal conductivity in the vapor phase
- He I intermediate layer while passing the phase transition => caused by subcooling (static height) at the vapor liquid interface in the beaker



2.15 K bath Δl=0.5 m
transition to He I and
afterwards to vapor phase

2 K bath Δl=0.5 m
transition to vapor phase

Superfluid Transition p < 50.4 mbar



Condensation of vapor

He II Heat Transport => Kapitza Spider

First and Second Sound in He II

Pressure waves

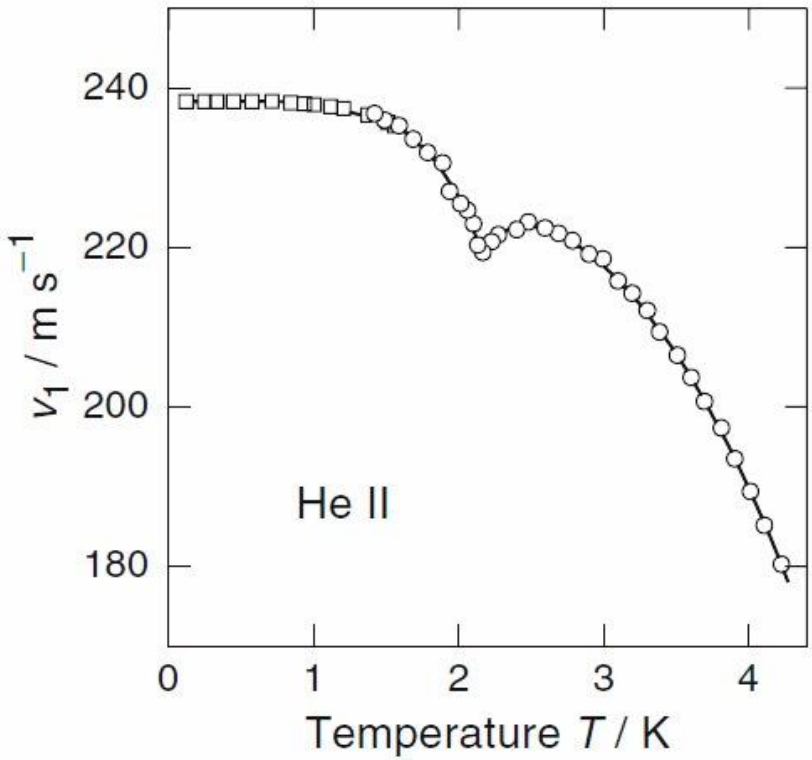
First sound v_1

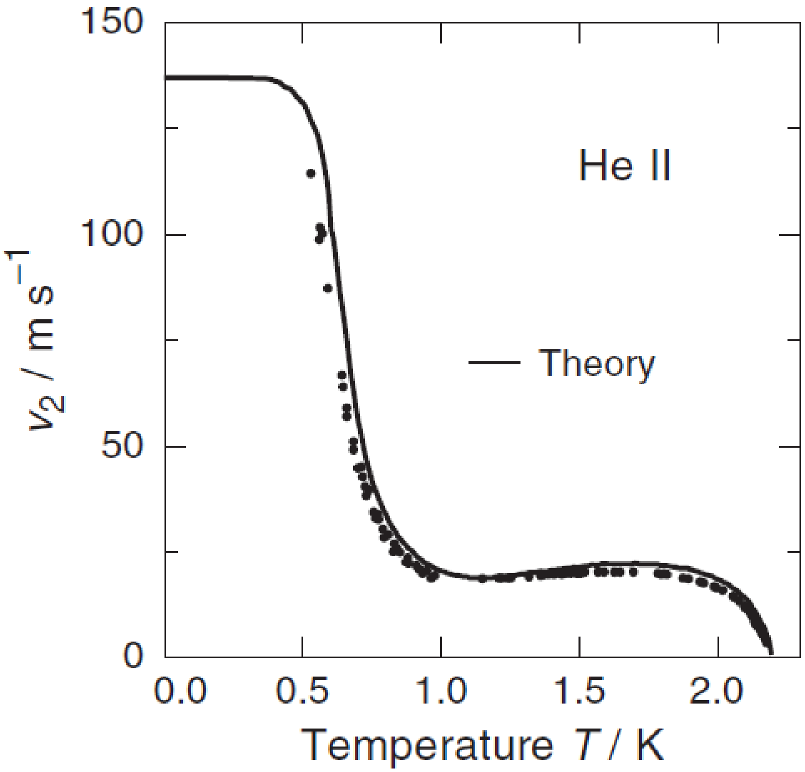
Temperature waves

Second sound v_2

Below the λ point the two components move in phase

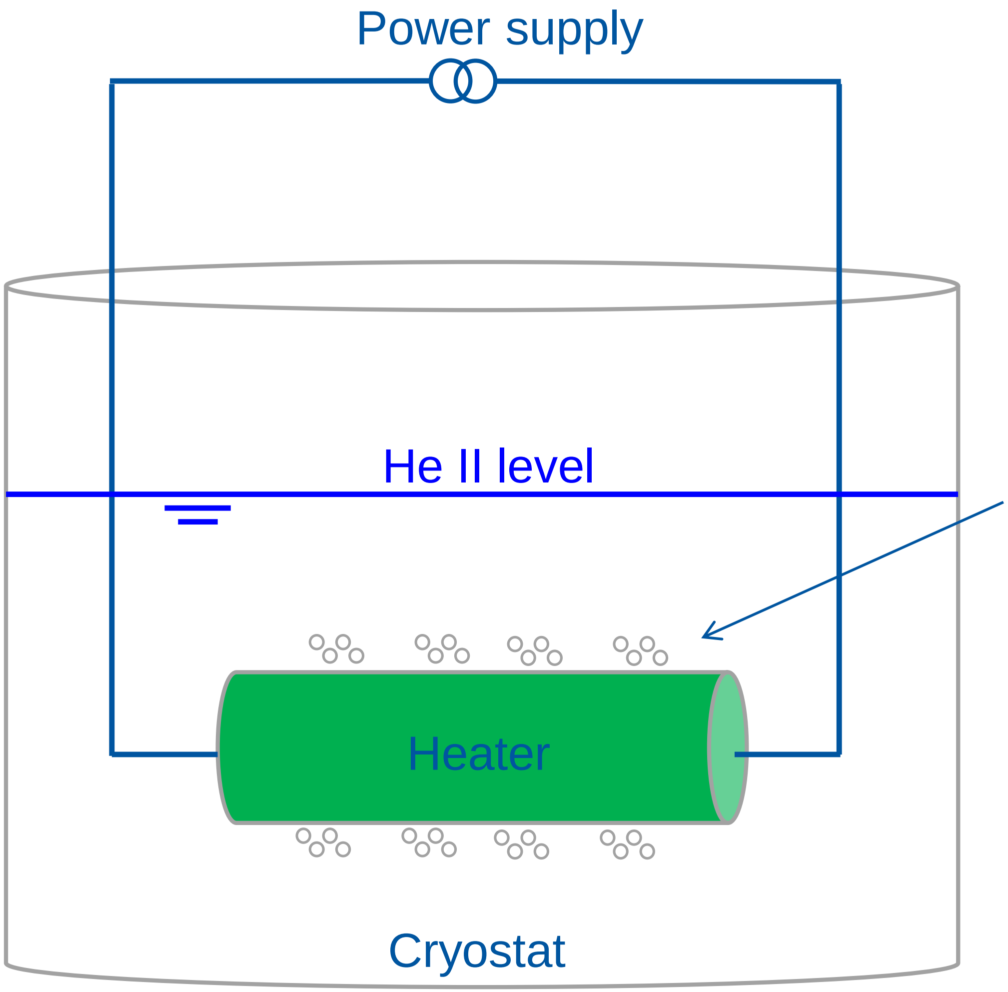
The two components move antiphase





From Enss, Hunklinger, Low-temperature physics, 2005.

Critical Heat Flux – Steady State Condition



Heat and mass flow are limited by a critical velocity:

$v > v_{cr}$

Superfluid behavior becomes non-linear (mutual friction)

$k \downarrow$ and $\eta \uparrow$

Formation of vapor bubbles at the surface of the heater

In He II re-condensation of the vapor

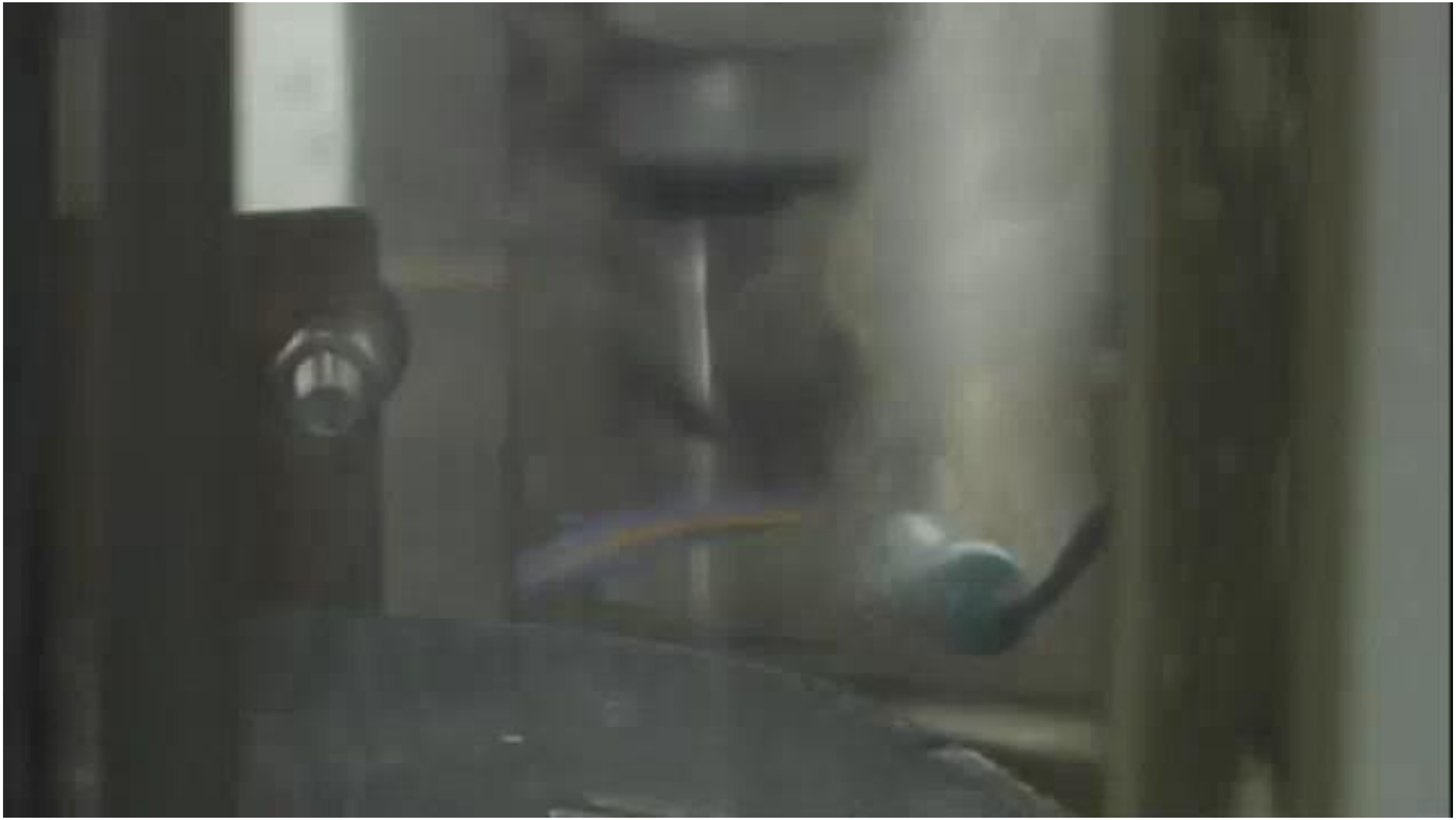
Surface tension let the bubbles implode

Implosion speed exceeds v_1

Shock wave => cavitation

Critical Heat Flux in He II ($T<T_\lambda$) – Steady State Condition

Normal Fluid Cooling ($T>T_\lambda$) – Steady State Condition

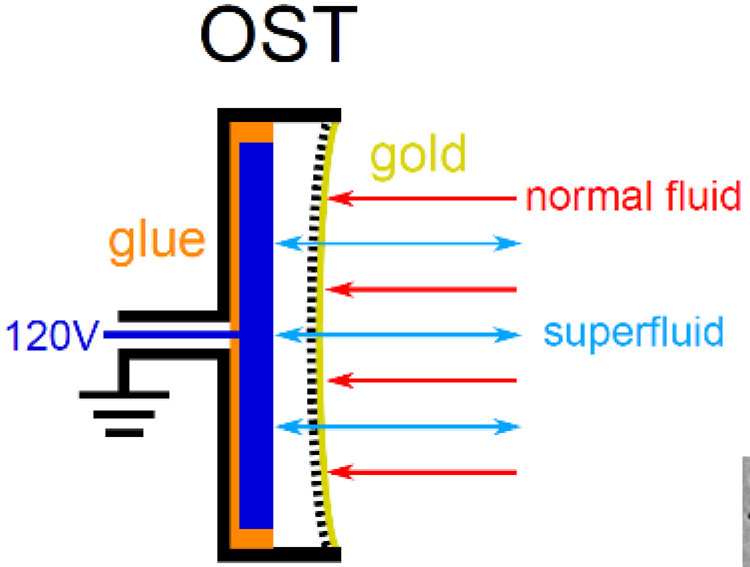


From Transient to Quasi Steady State Condition

Transient heat flux => measurements in He II

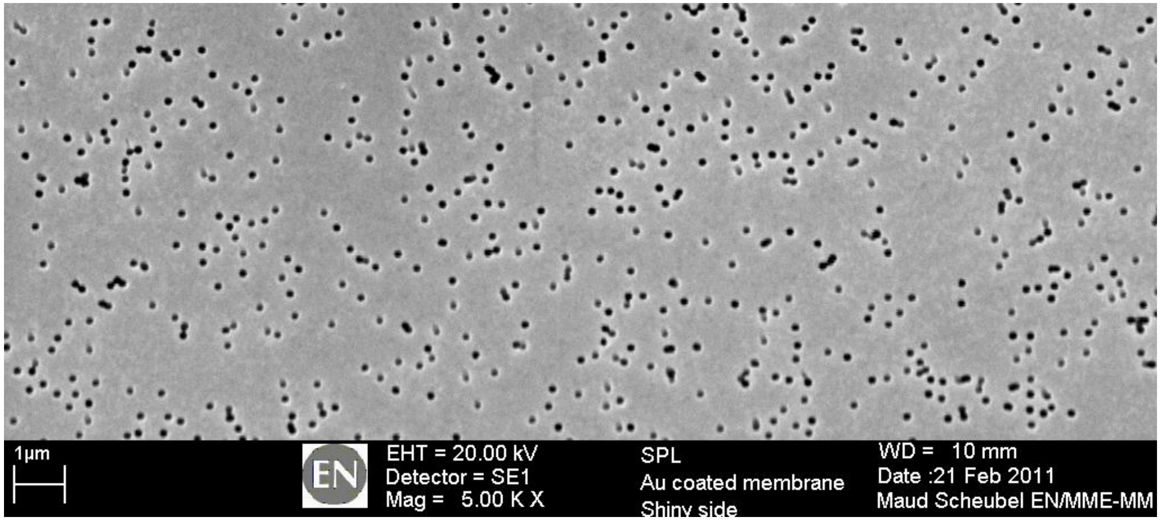
- Short heat pulses with duration in the range of milliseconds
- Heat fluxes up to kW/cm^2 **»** steady state critical values ~1.5 W/cm^2
- Detection of second sound wave with Oscillating Superleak Transducers

Oscillating Superleak Transducer (OST)



Courtesy: Hannes Vennekate

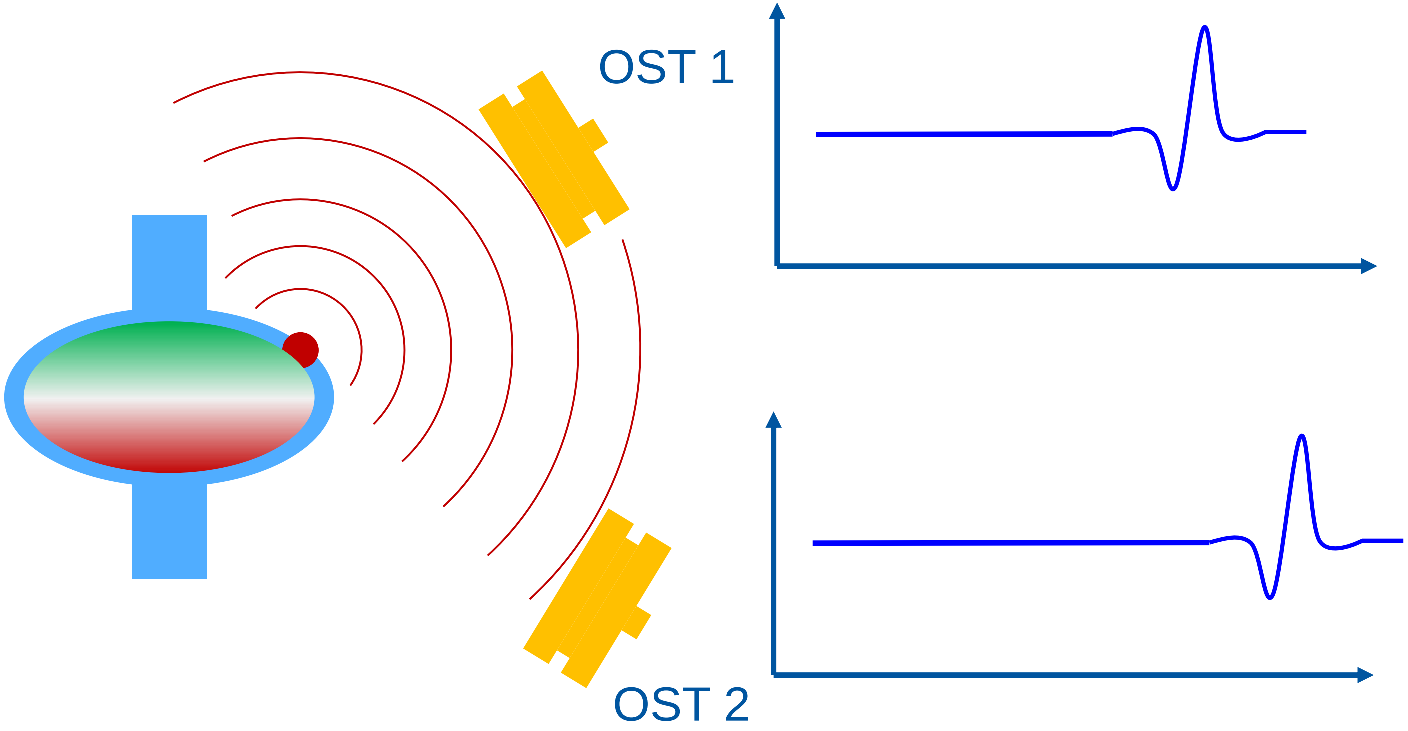
Membrane structure
Holes are of diameter 0.1 µm



Benedikt Peters, BE-RF/SRF

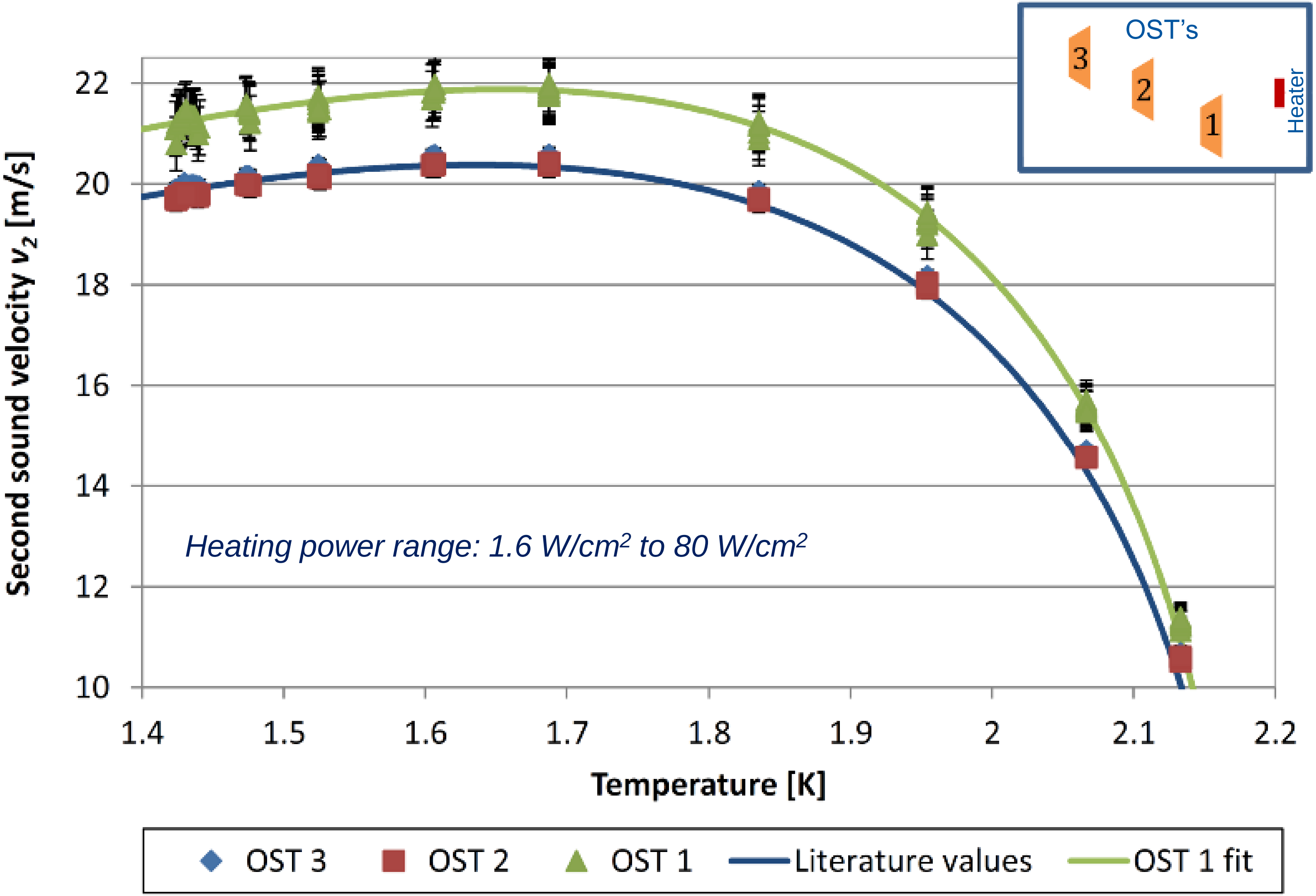
OST – Quench Spot Localization

Detection and localisation of quenches on superconducting RF cavities by the measurement of the second sound with OSTs



Benedikt Peters, BE-RF/SRF

OST Signal Detection



Heating power range: 1.6 W/cm^2 to 80 W/cm^2

Benedikt Peters, BE-RF/SRF

Critical Heat Flux – Transient Condition

RF heater in He II @ 1.8 K,
0.3 m hydrostatic height,
=> slightly pressurised liquid
no heating power

Electrical breakdown in He II

Boiling can be observed above the surface for heating powers above 88 W/cm^2 up to 700 W/cm^2 (measurement limit right now).

Duration of the heat pulse t=3 ms

From Transient to Quasi Steady State Condition

Transient heat flux => measurements in He II

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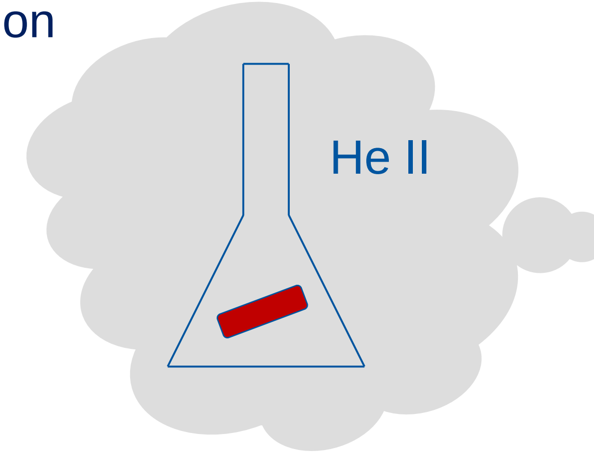
- Detection of second sound wave with Oscillating Superleak Transducers

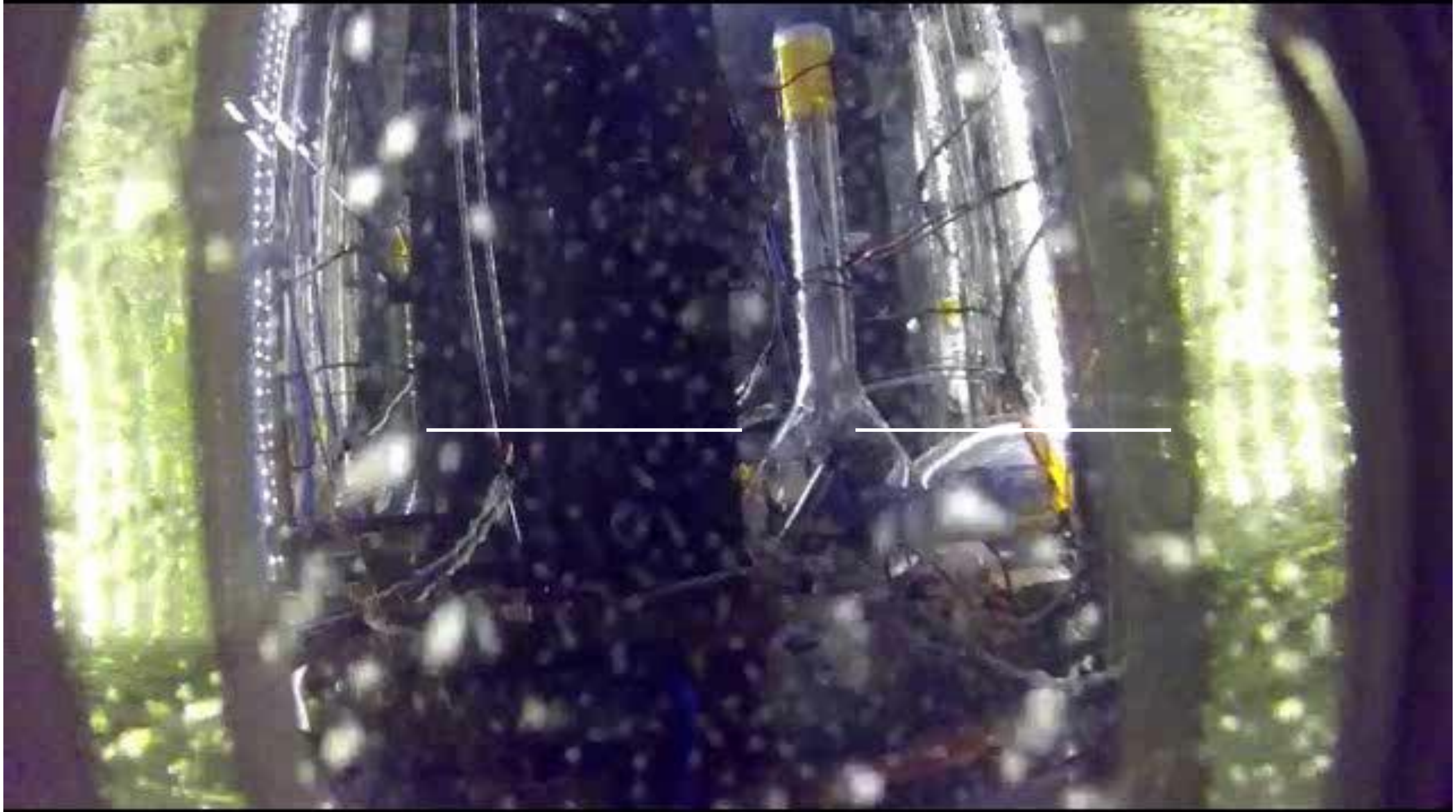
He II - Critical heat flux in a reduced cross section

- Flask immersed in He II
- Heat flux exceeding the critical conditions in the restriction



Critical Heat Flux – Quasi Steady State Condition, Constant Heat Load

Boiling effects only in the restricted cross section, not at the heater surface



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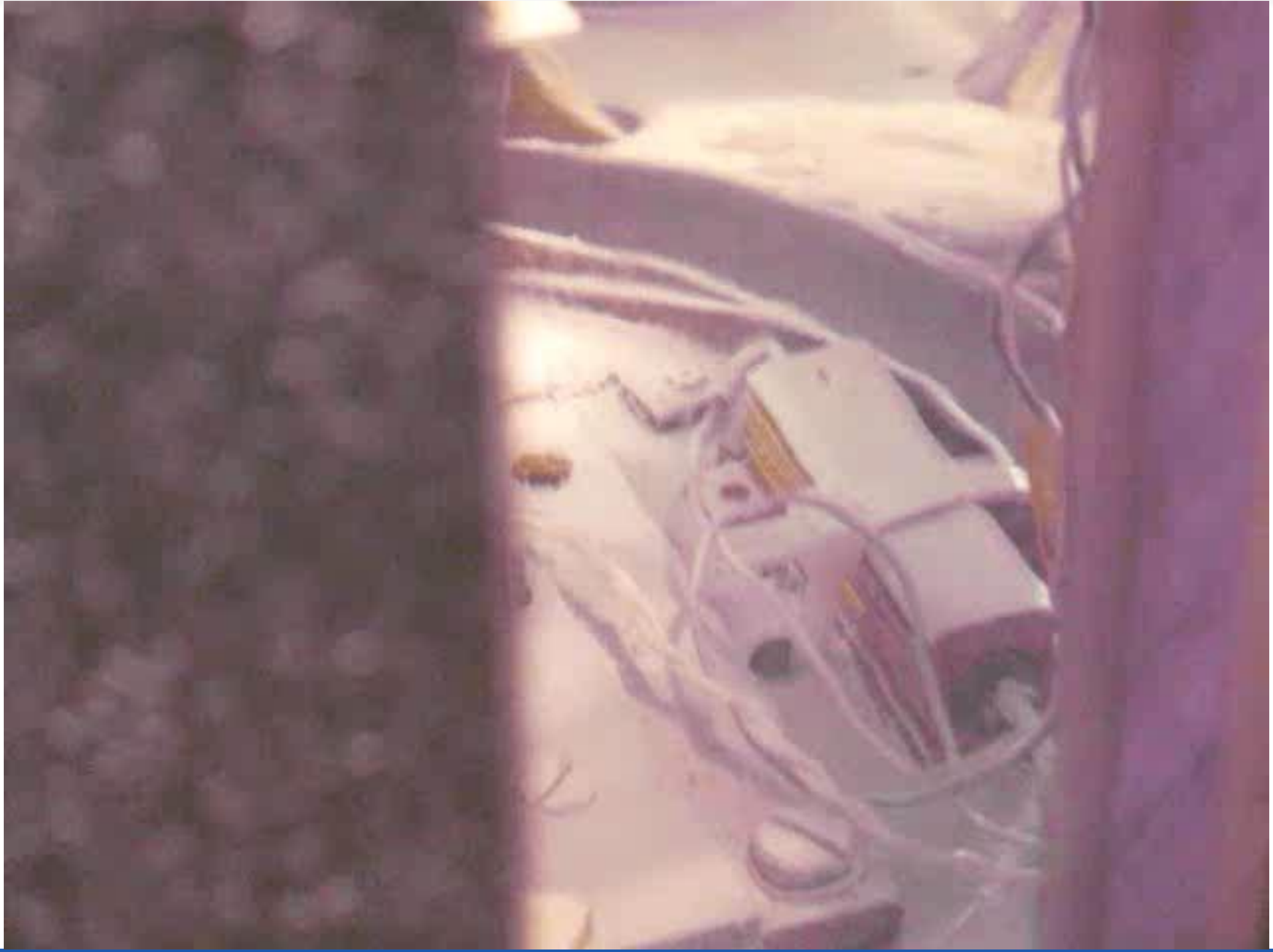
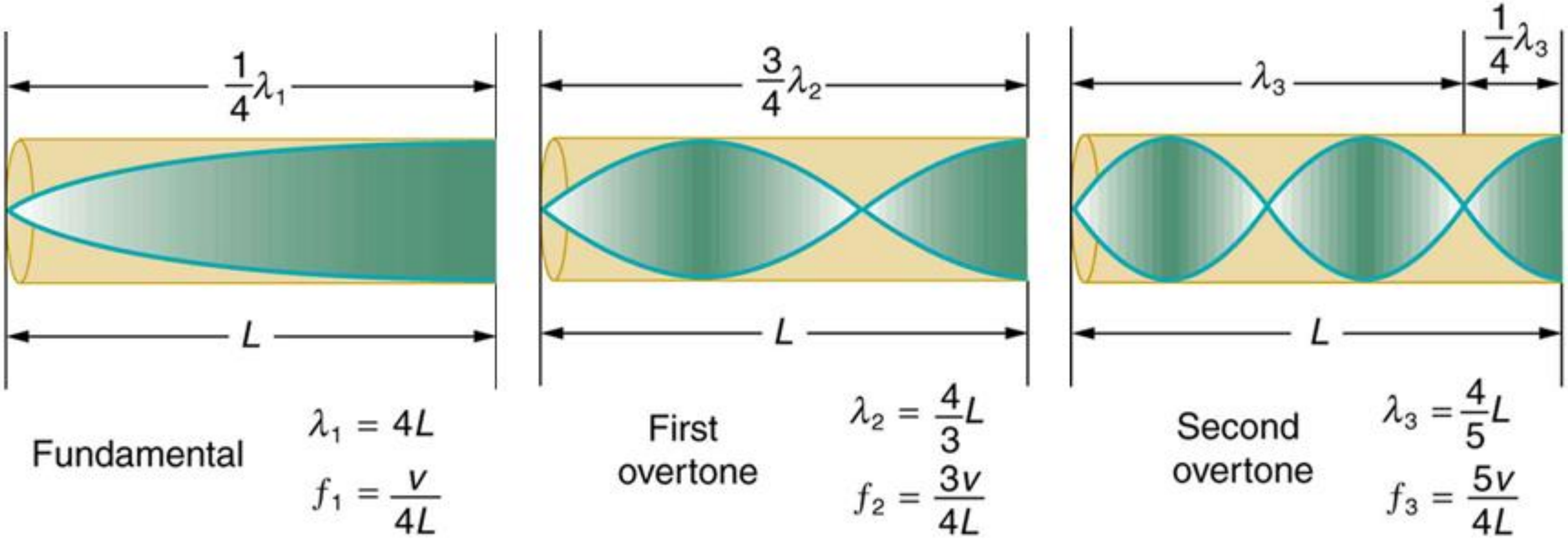
He II – Steady state heat flux - Tracer particles by frozen air

Visualisation of Motion in He II – Tracer Particles



Acoustic Oscillations

Quarter wave resonator “resonance at one open end”



From: openstax college, Rice University, Sound Interference and Resonance, Download for free at http://cnx.org/content/col11406/latest/.

Thermally Driven Acoustic Oscillations (Taconis)

Gas in contact with a wall that is subjected to a temperature gradient

$$Y_C = r \cdot \sqrt{\frac{v_1 \ \cdot \rho_{vap}}{l_{cold} \ \cdot \ \nu_{vap}}}$$

$$\alpha = \frac{T_{hot}}{T_{cold}}; \qquad \xi = \frac{L_{hot}}{L_{cold}}$$

Typical frequencies 5 to 40 Hz

Conditions:

Stand pipe of a transfer line

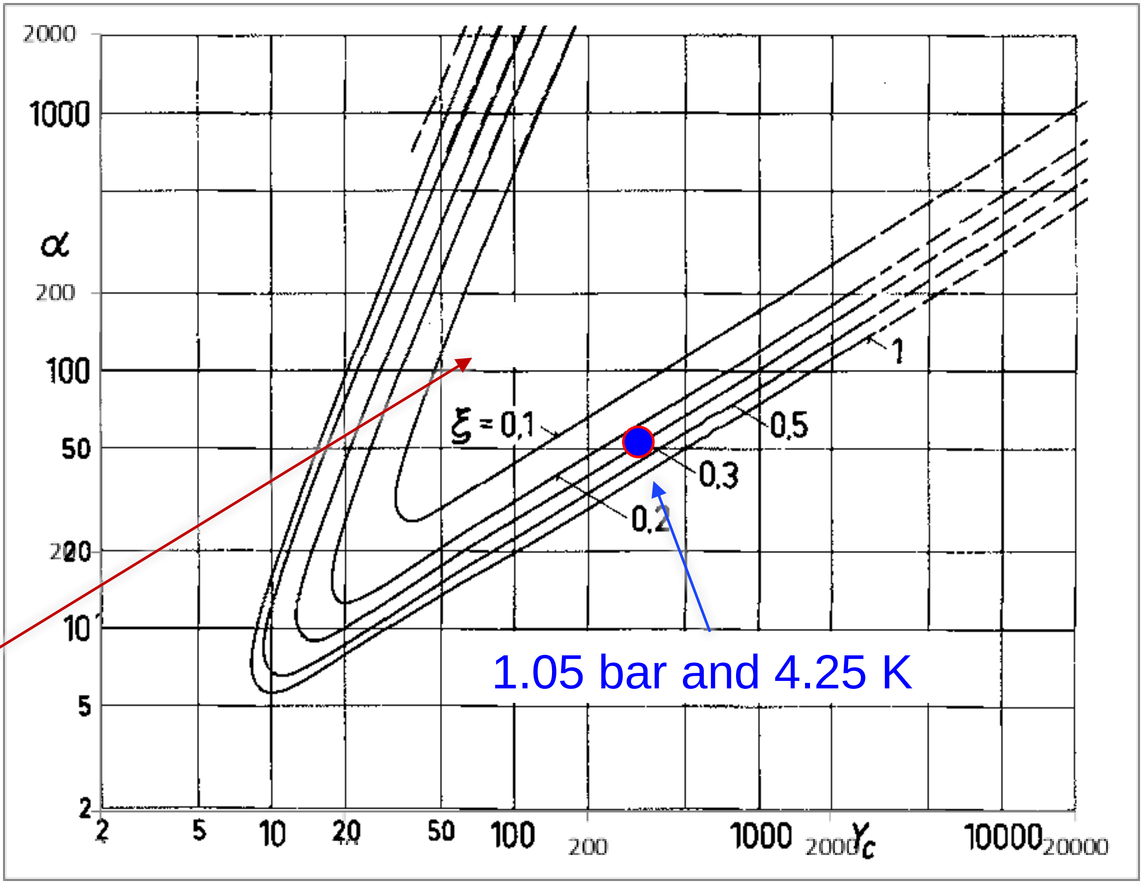
T_{warm}=280 K

T_{cold} =2.1 K saturated bath

L_{cold} =0.35 m

L_{warm}=0.35 m

r_{Tube} =5 mm inner tube radius



1.05 bar and 4.25 K

Stability curves from: N. Rott, Thermally Driven Acoustic Oscillations. Part II: Stability Limit for Helium, J. of Apl. Math. And Physics, Vol. 24

Thermally Driven Acoustic Oscillations (Taconis)

Stainless steel tube

$Ø_{inside}$=10 mm at 100 mm

above liquid level

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