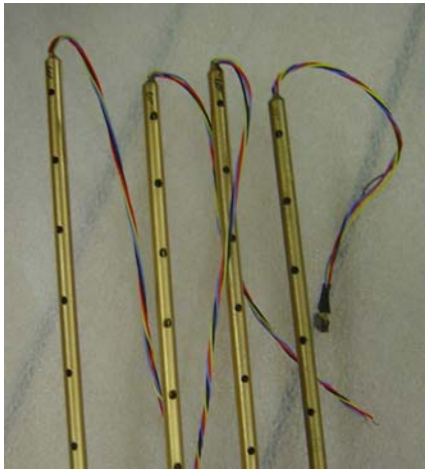
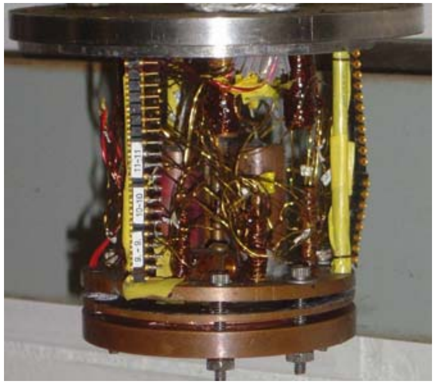


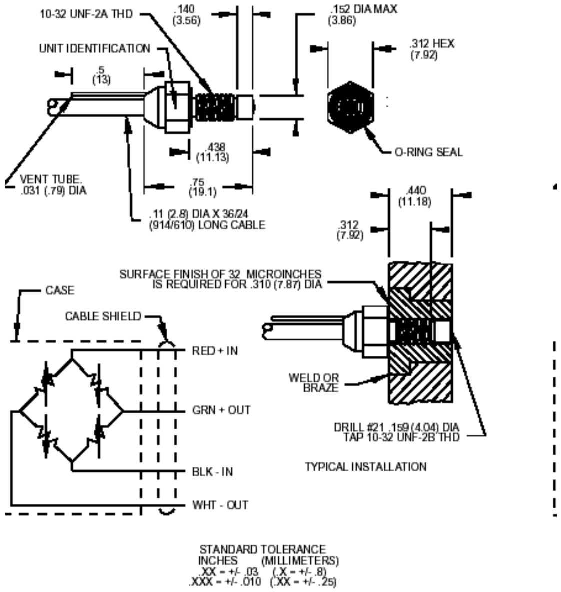
4.2 Instrumentation: Pressure, Flow, & Level



Pressure

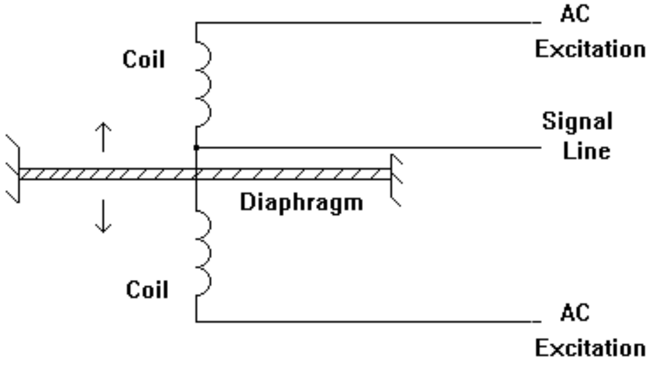
- Piezoresistive transducers
  - Resistance bridge – 4 active arm strain-gauge
  - Calibration required <u>at temperature</u>
  - Example: Endevco 8510B
  - Typical price: ~ $1K per each
- Pressure capillary extension
  - Extend capillary from cold environment up through cryostat to room temperature environment
  - Ensure leak-tight
  - Check mean free path length for low pressure (vacuum) applications

Actual size



Pressure

- Variable reluctance transducers
  - Magnetically permeable stainless steel diaphragm clamped between inductive pick-up coils
  - Diaphragm displacement changes induction of both coils
  - AC bridge / amplifier circuit converts inductive change to proportional DC output voltage



Variable Reluctance Circuit

Cryogenic flow metering techniques

Single phase flows

1. Pressure drop devices based on Bernoulli Principle
    a) Venturi
    b) Orifice plate
    c) Pitot tube

$$\left.\begin{array}{l}\text{a) Venturi}\\ \text{b) Orifice plate}\\ \text{c) Pitot tube}\end{array}\right\}\ \Delta p = \frac{1}{2}\rho v^2$$

2. Friction pressure drop (packed screens)
3. Hot wire anemometers based on h = f(v)
4. Acoustic flow meters based on Doppler effect
5. Turbine flow meters where frequency ~ velocity
6. Optical techniques (Laser Doppler)

Two phase flows

1. Void fraction measurement (A_v/A)
    a) Capacitance measurement
    b) Optical characterization
2. Quality measurement (m_v/m)

These techniques are for the most part all used in classical fluid flows.

The unique "cryogenic" features have to do with instrumentation used to detect signal and need for low heat leak.

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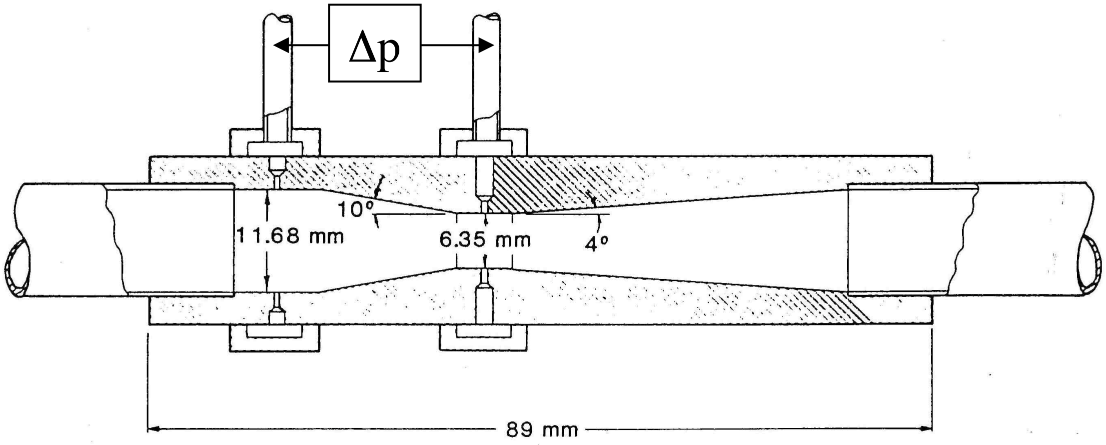
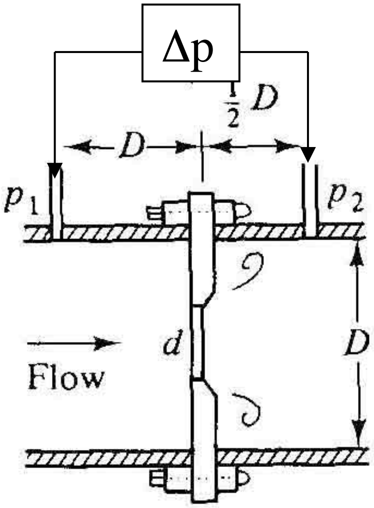
Pressure drop devices



Venturi



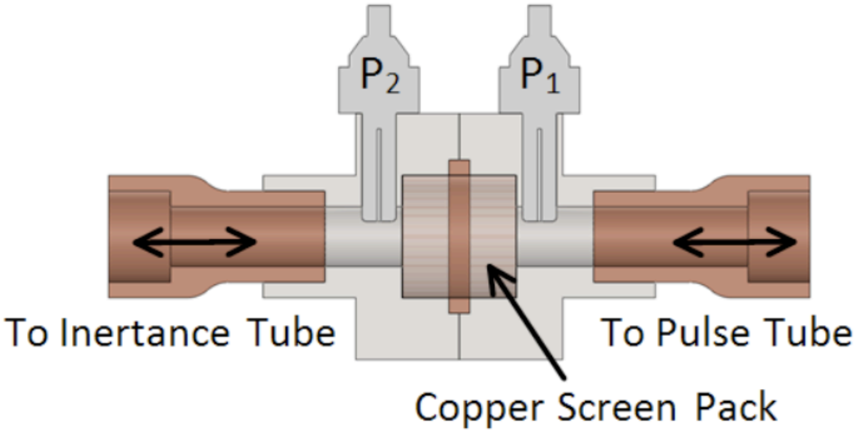
Orifice

- Venturi flow meters have advantage over orifice plate due to low loss coefficient

$$\dot{V} = A_t v_t = C_d A_t \left[\frac{2\Delta p/\rho}{1-\beta^4}\right]^{1/2} \qquad \text{where } \beta = D_t/D$$

- C_d is the discharge coefficient (~ 1 for venturi & 0.6 for orifice)
- Pressure transducer should be located at low temperature, if possible
- Requires determination of density at meter inlet

Packed Screen (AC) Gas flow meters



- Pressure drop is proportional to, and in phase with the mass flow rate
- Other impedance contributions to pressure drop are negligible
- Pressure transducers (Endevco, PCB Piezotronics) can be calibrated for use at cryogenic temperatures

Hot Wire Anemometers

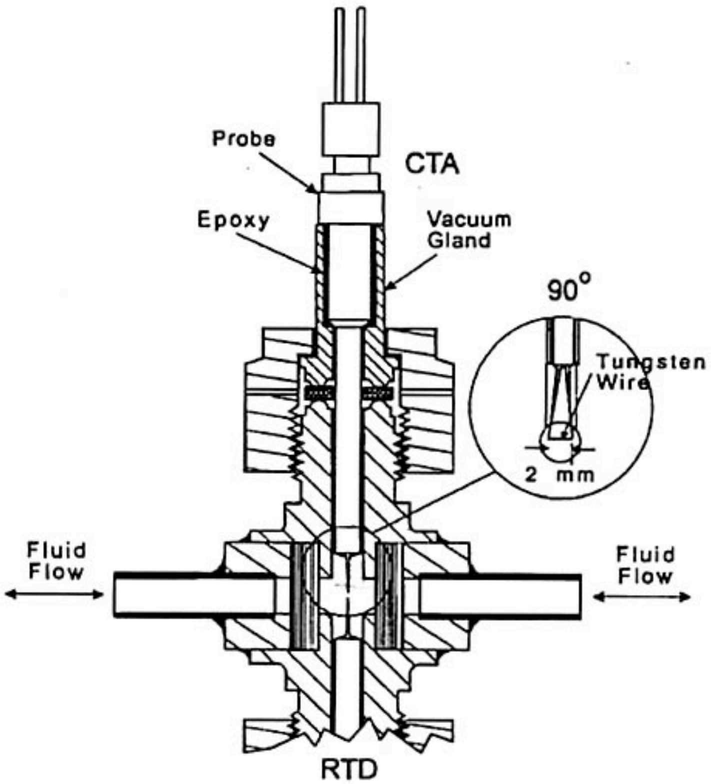


FIGURE 5. MODIFIED VACUUM ASSEMBLY WITH CTA AND RTD PROBES IN PLACE

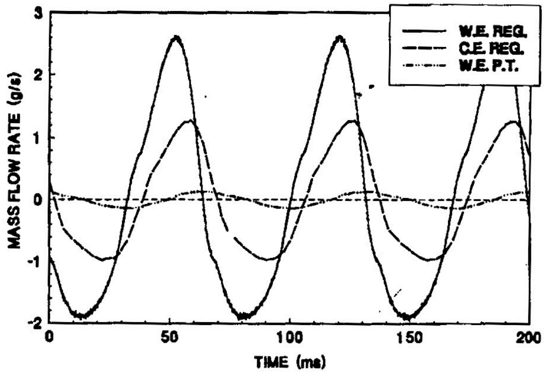
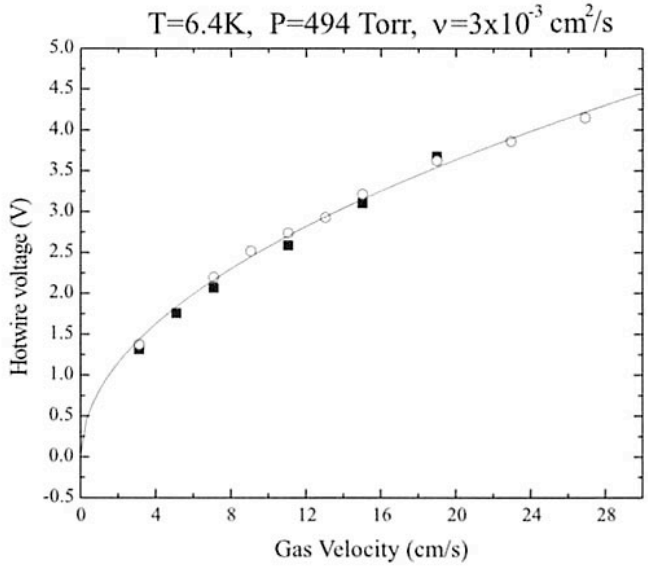
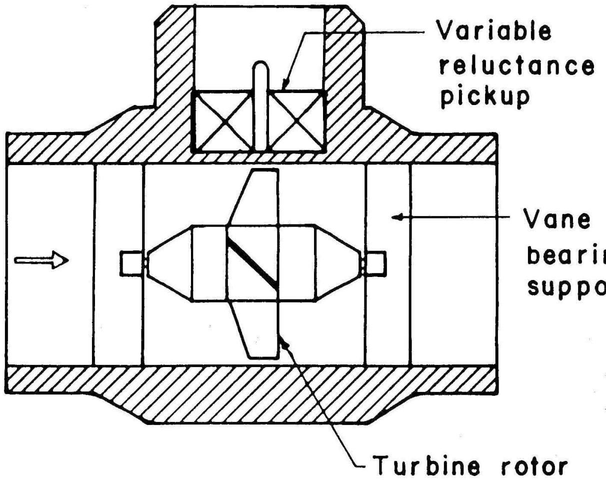


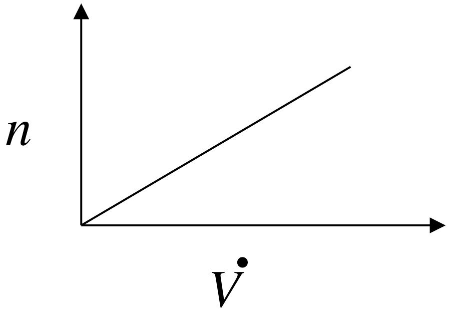
FIGURE 12. MASS FLOW RATES AT THREE LOCATIONS IN A PULSE TUBE REFRIGERATOR



Turbine flow meters

- Rotation speed is proportional to volumetric flow rate
- Linear response function allows a wide range of operation

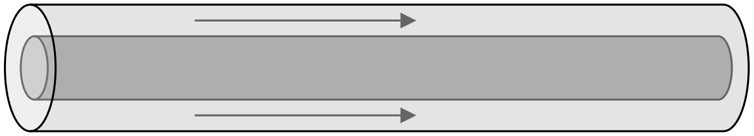




$$\dot{V} = \frac{\pi D_b A_f}{\tan \theta_b} n = Kn$$

Two phase flow measurement

- Measurement of flow quality (m_v/m) in a two phase mixture (liquid + vapor) is difficult.
  - Vapor velocity and liquid velocity may be different
  - Flow regime is not known
- Measurement of void fraction (A_v/A) is more straightforward
  - Capacitive meter based on different dielectric constant



Co-axial capacitor

  - Optical techniques
- Total mass flow rate can be determined in some part of the circuit where the fluid is single phase using a conventional flow meter

RF Void Fraction Measurement

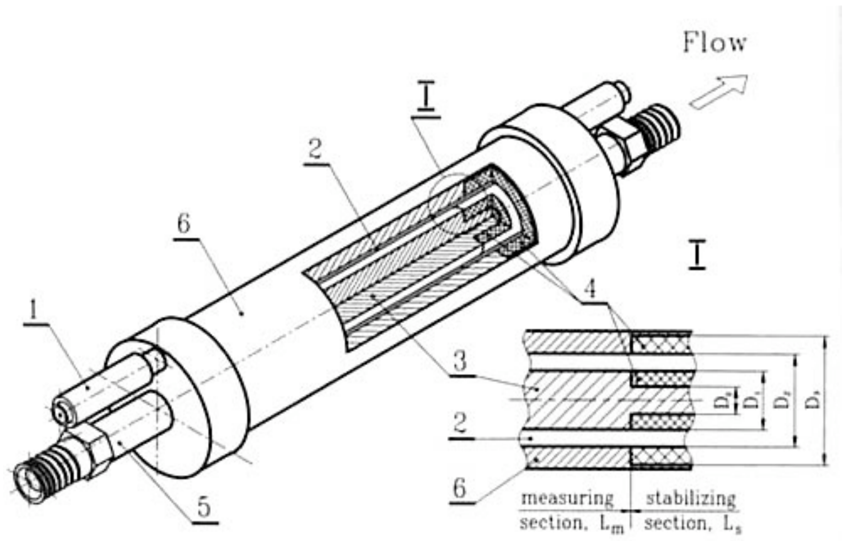


Fig. 1. Typical design of the RF-void fraction sensor with annular cross-section. 1 – RF-connector; 2 – annular channel for the two-phase flow; 3 – central electrode; 4 – dielectric inserts; 5 – input node for the flow; 6 – body of the sensor.

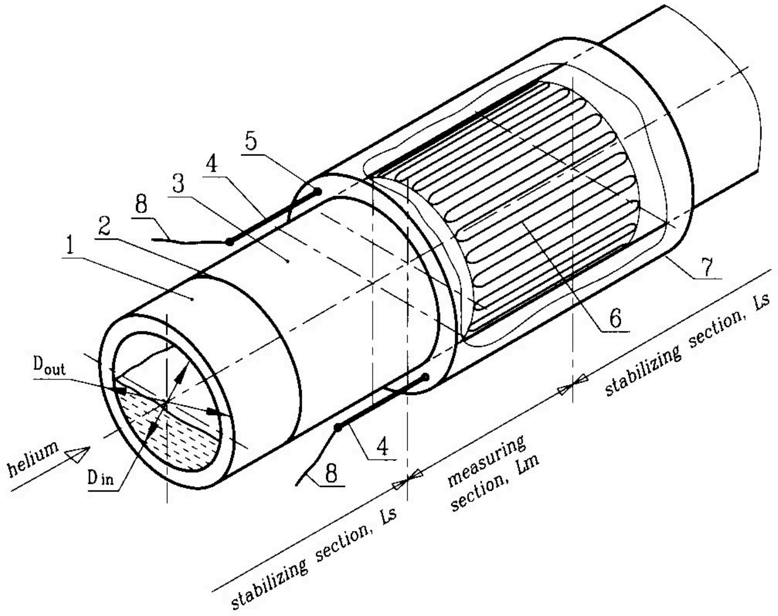


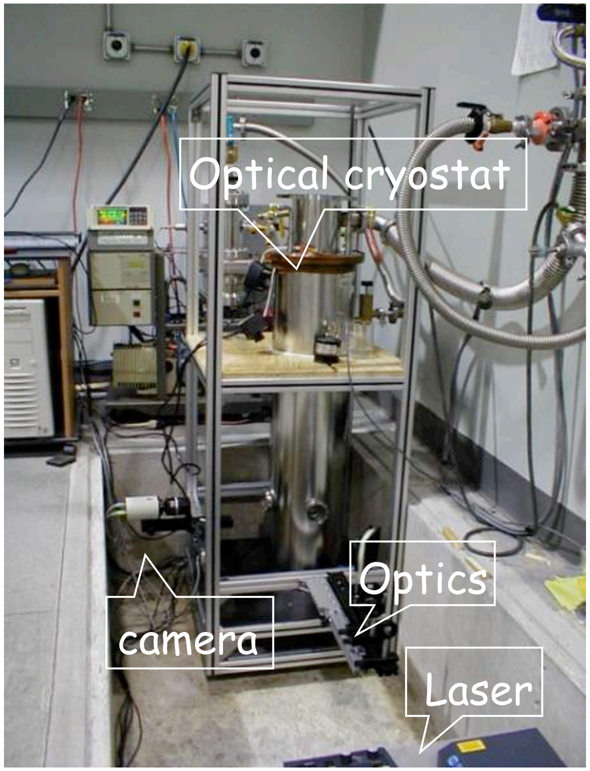
Fig. 2. RF-void fraction sensor with round cross-section. 1 – stainless steel tube; 2 – RF-welding; 3 – glass tube; 4 – rod of connection; 5 – insulating inserts; 6 – meander line; 7 – cooper shield; 8 – RF-cables.

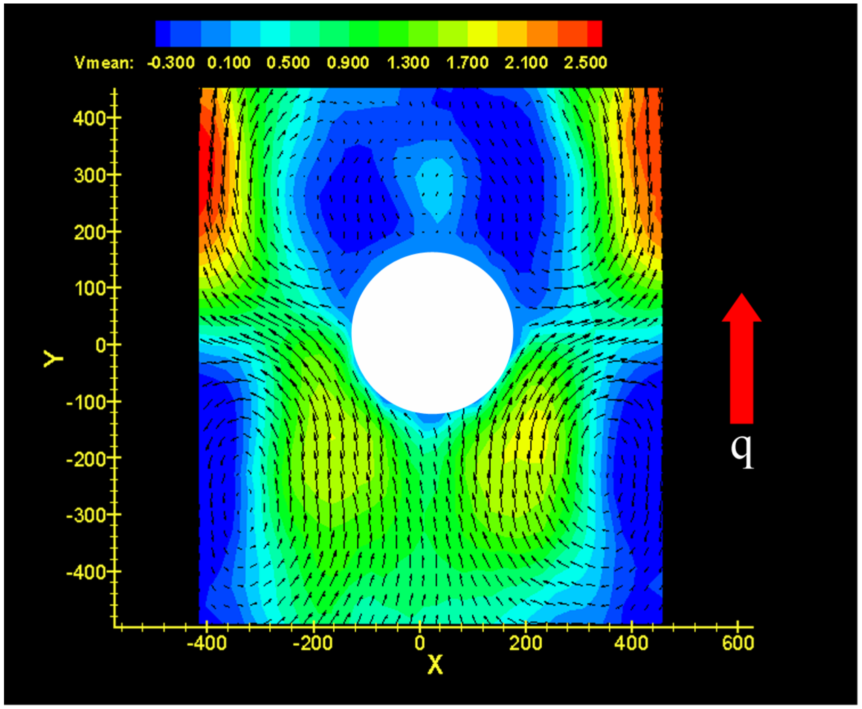
$$\varepsilon = \varepsilon_g \varphi + \varepsilon_l (1 - \varphi)$$

$$\varphi = \frac{A_g}{A_g + A_l}$$

Liquid Helium Flow Visualization

- Heat transfer in superfluid observed by PIV technique
  - This is the first time motion of fluid components in superfluid helium has been observed





Normal fluid convection around cylinder
Diameter = 6.35 mm

2-phase Helium Flow Visualization

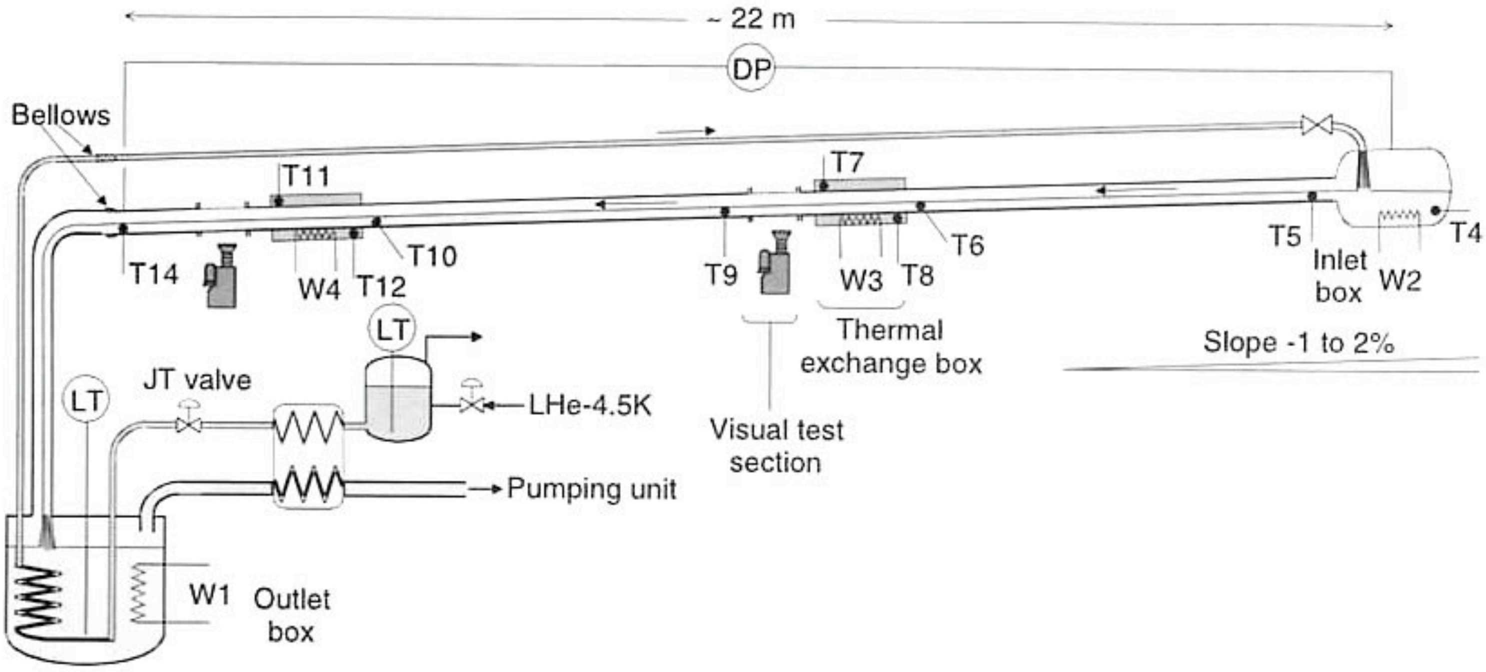


Fig. 1. Flow scheme of cryoloop.

2-phase Helium Flow Visualization

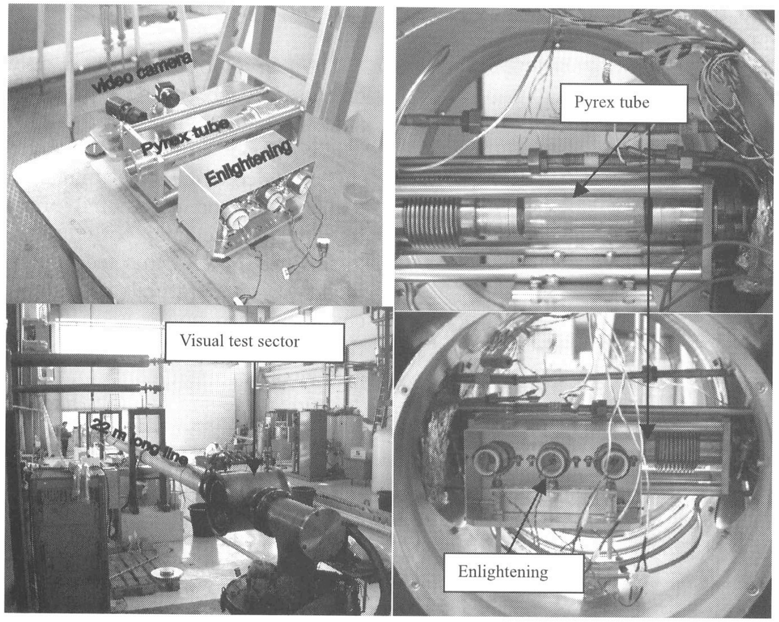
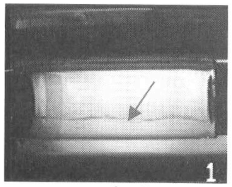
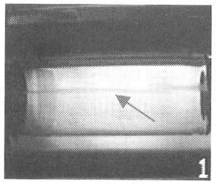


Fig. 2. Photos of the cryoloop and of the visual test section.



number 1



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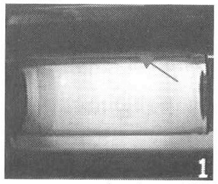

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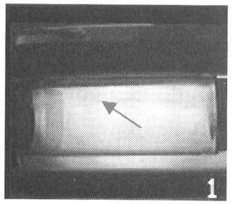

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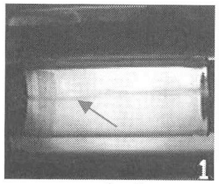

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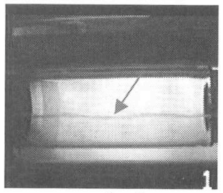
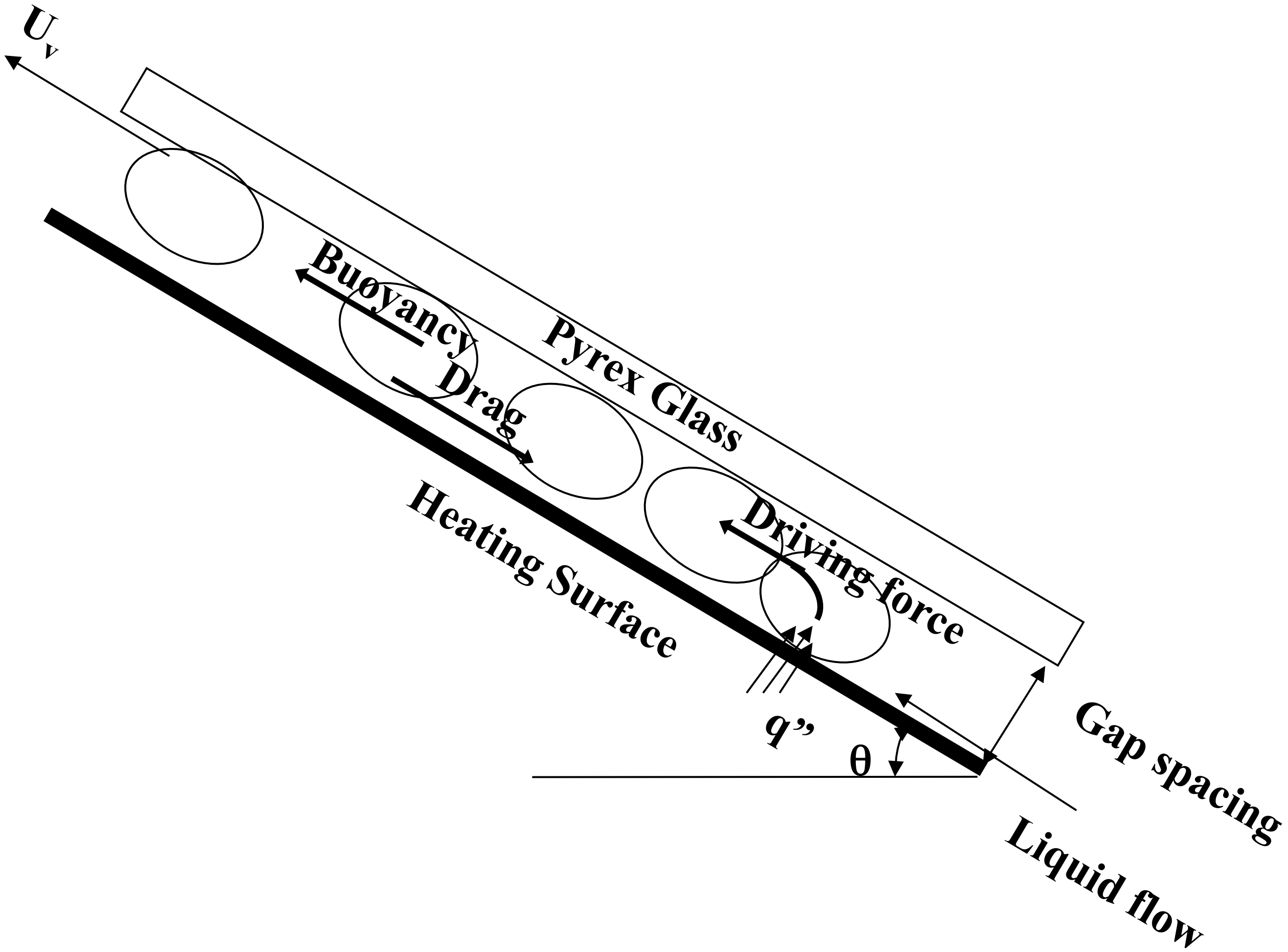


number 6

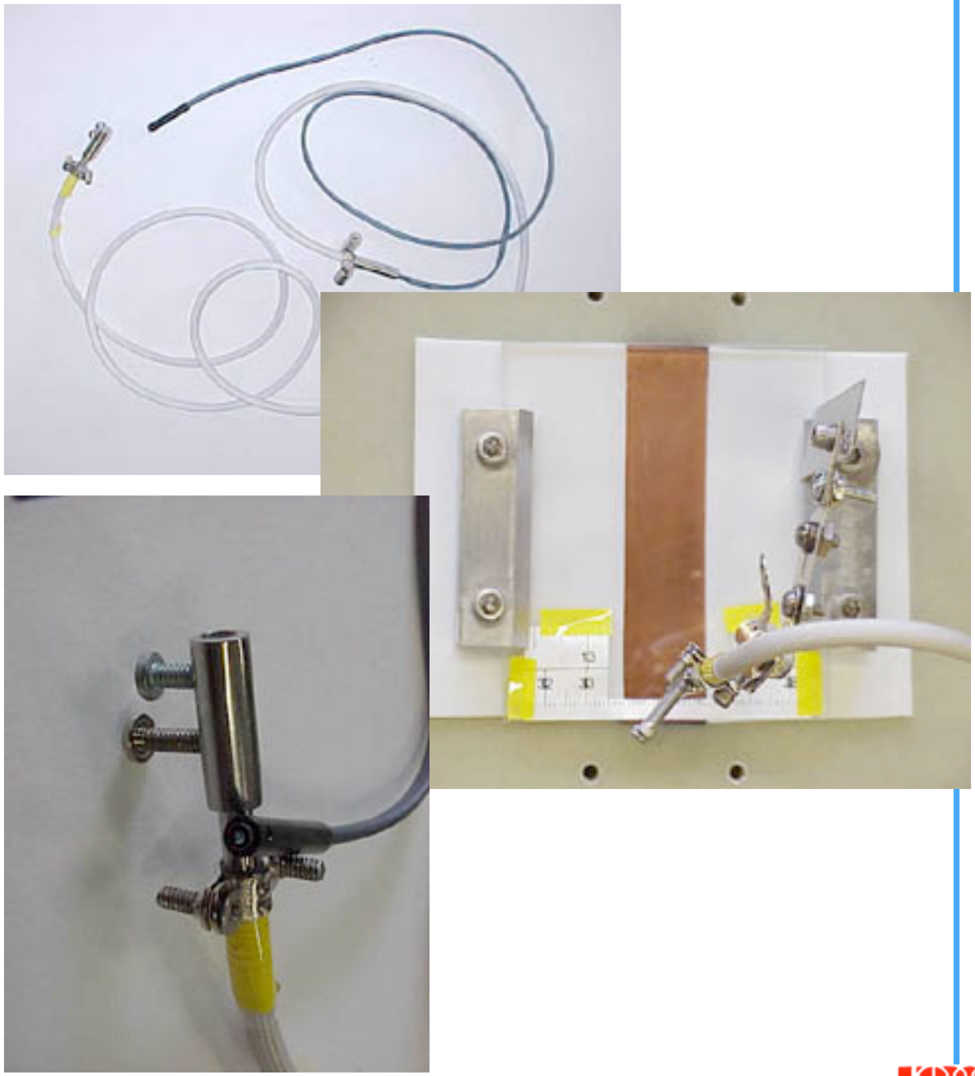
CHF Investigation: modeling

- A physical description of void fraction growth or force balance requires knowledge of bubble size, frequency, spacing and velocity



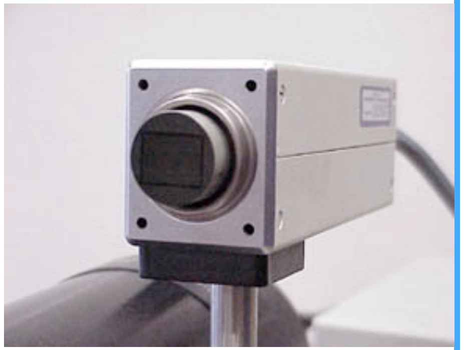
Visualization: Optical fibers

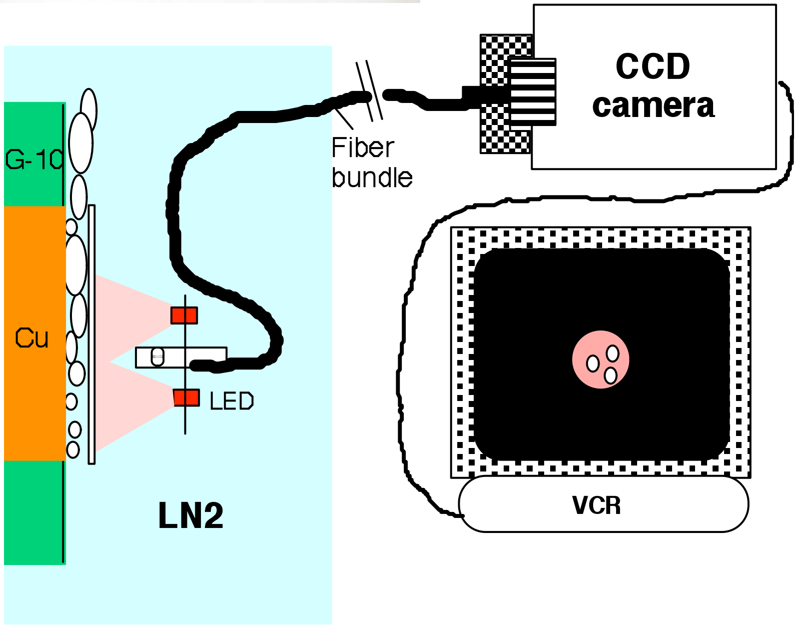
- Fiber bundle: 40,000 20 µm strand bundle chosen over solid core
  - Avoid multi-mode distortion in larger diameters
  - Maximum flexibility
- PVC protective sheath replaced by braided fiberglass sheath in LN_2
- Fused ends covered by stainless steel tubes for mounting & focusing



Visualization: Image Capture

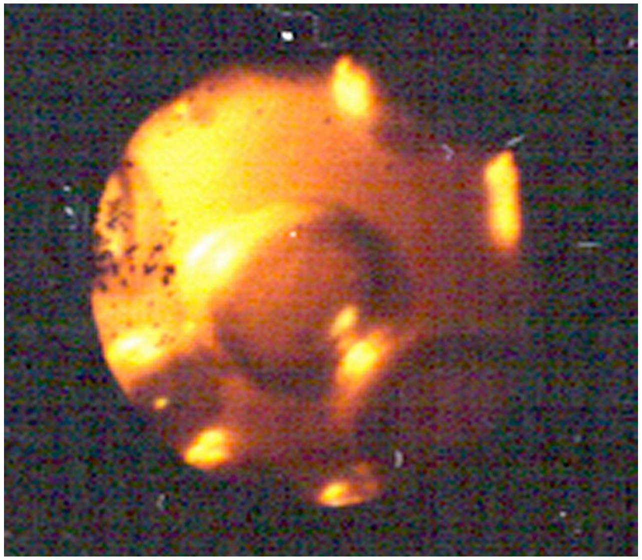
- Phillips CCD camera
  - Direct fiber to fiber image transfer.
  - Camera pixel density provides ~ 10,000 pixels for 1.9 mm diameter image.
  - Minimal illumination required: 4 - LED array provides more illumination than necessary (especially with illumination increase when submerged in LN_2).





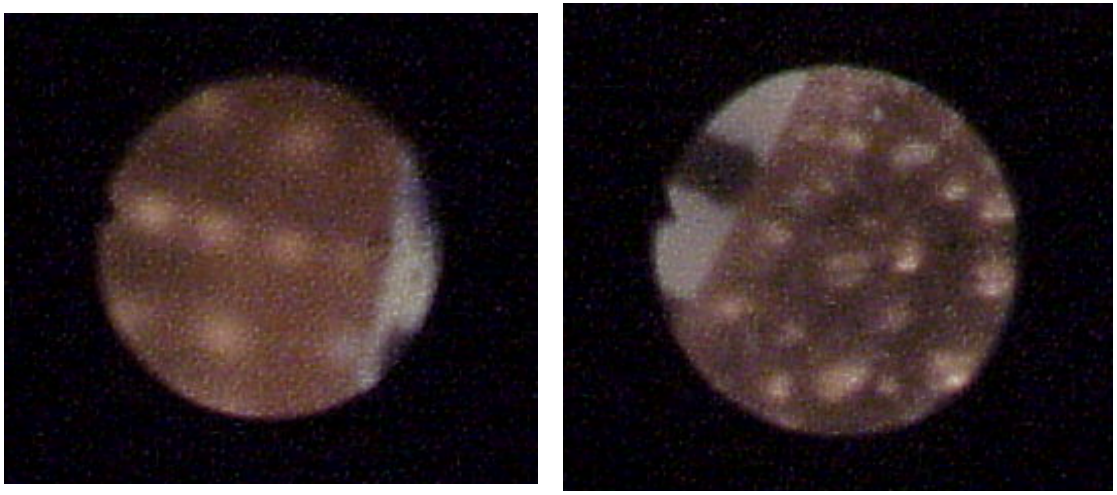
Visualization: Image Capture

- Questar QM100 Images



SLR:

- Ektachrome P1600, pushed to 6400.
- 1/250 s shutter speed
- halogen lamp illumination
- horizontal channel - slow bubble motion



Digital camcorder ‘still’

- 1/3000 s shutter speed
- halogen lamp illumination
- black line spacing in upper right is 1 mm.
- vertical channel - ‘fast’ bubble capture

Visualization: Image capture

- Aperature speed of 1/500 s
- Excellent image quality captured on vhs tape - quality reduced upon digitization
- Note regular spacing of bubbles (vertical channel flow)

Visualizing Phase Change

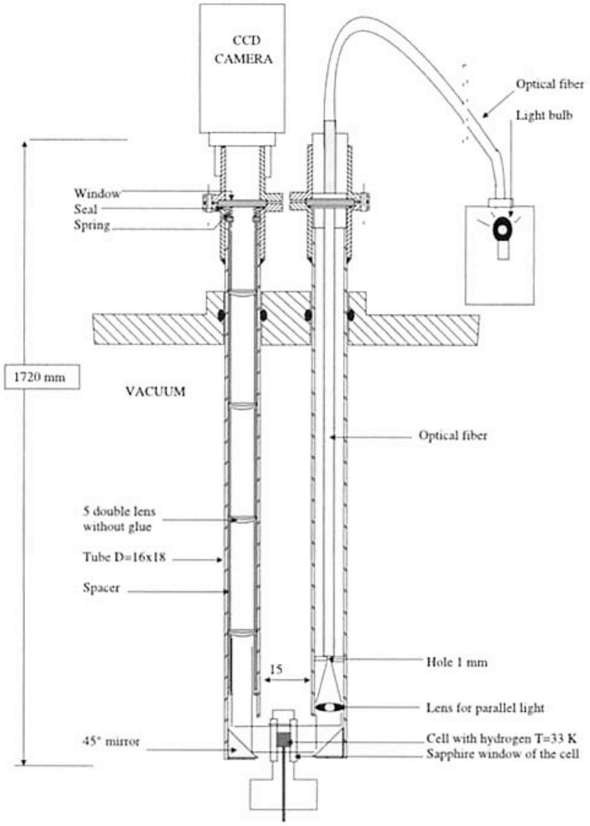
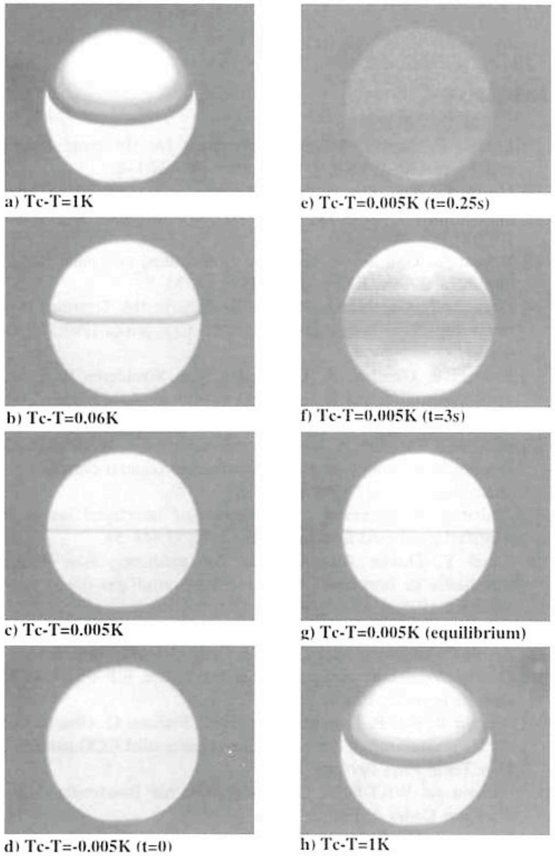


Fig. 8. A schematic of the optical system.



a) Tc-T=1K

b) Tc-T=0.06K

c) Tc-T=0.005K

d) Tc-T=-0.005K (t=0)

e) Tc-T=0.005K (t=0.25s)

f) Tc-T=0.005K (t=3s)

g) Tc-T=0.005K (equilibrium)

h) Tc-T=1K

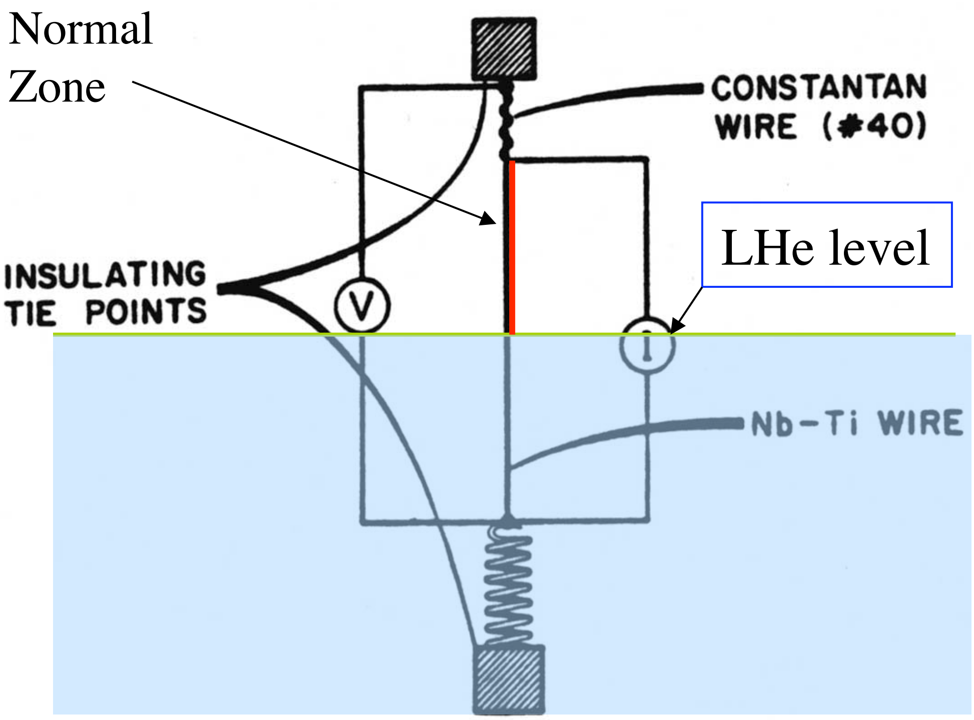
Fig. 9. Hydrogen phase transition under gravity in diffuse light.

Liquid level measurement techniques

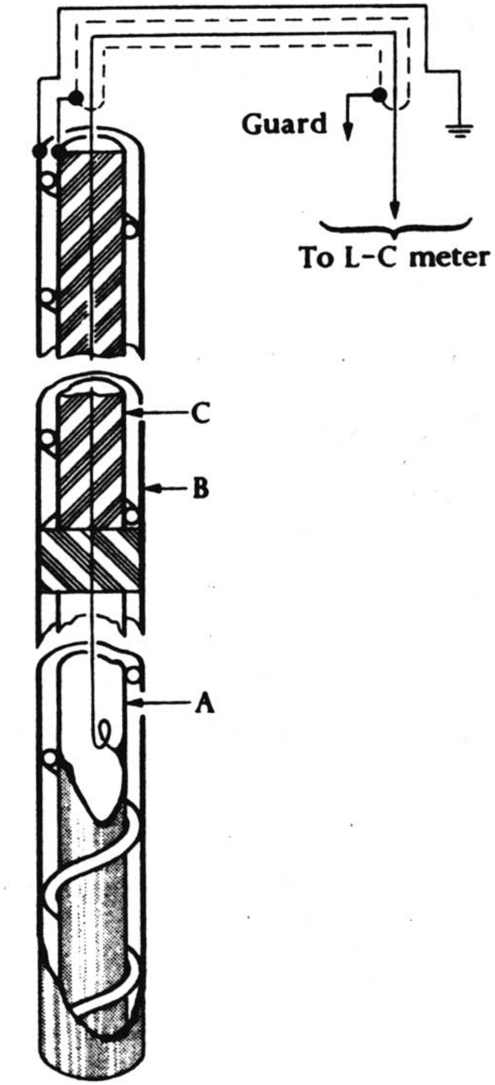
- Continuous level measurement
    - Superconducting wire level device
    - Capacitive level measuring systems
    - Transmission line system
    - Ultrasonic level measurement
    - Hydrostatic (head) level measurement
- Discrete level measurement
    - Liquid-vapor detectors (resistive, superconducting)
    - Acoustic “Dip stick” method
- Mass measurement (gauging)

Superconducting wire level meters

- Developed by Efferson (1970), but now a commercial product
- Heater drives the normal zone of SC wire to the liquid interface, where it stops due to improved heat transfer
- Units are most often calibrated in LHe at 4.2 K
- Variable performance in He II due to improved heat transfer
- Some SC level meters based on HTS materials have been developed for LN_2



Capacitive Level Gauges



Most are custom, some are available as a prototype commercial units, particularly for high dielectric constant fluids (e.g. LN_2)

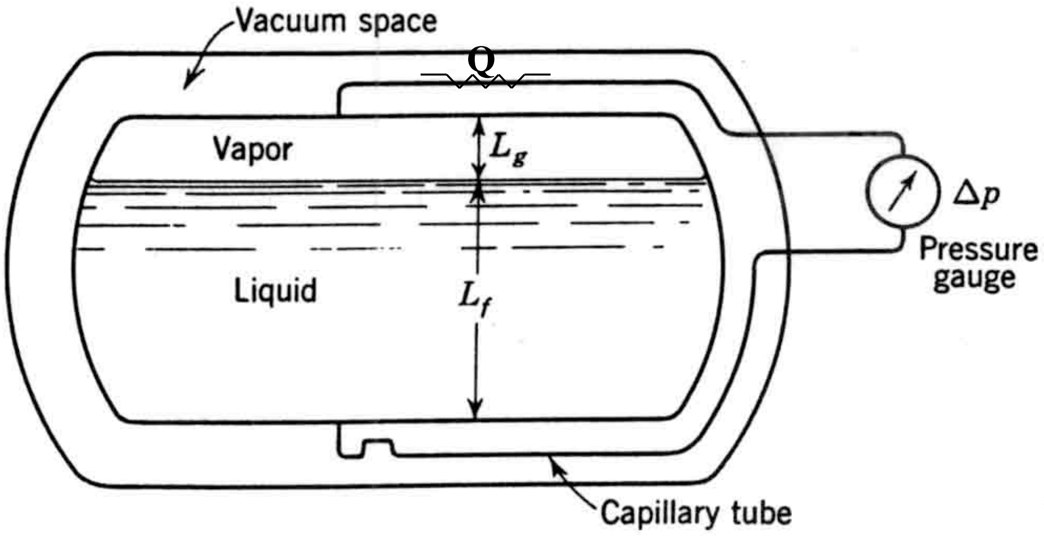
Measurement Methods:

- AC Bridge
- High frequency oscillator
- Time constant method
- Phase-lock loop technique

In-situ calibration necessary

$$\text{Sensitivity} = \frac{dC}{dH_f} = \frac{2\pi\varepsilon_0\left(\kappa_f - \kappa_g\right)}{\ln\left(D_0 / D_i\right)}$$

Differential pressure (head) gauge



Requirements

- No liquid in vertical leg of lower capillary tube
- dp/dL = $\Delta\rho\, g$

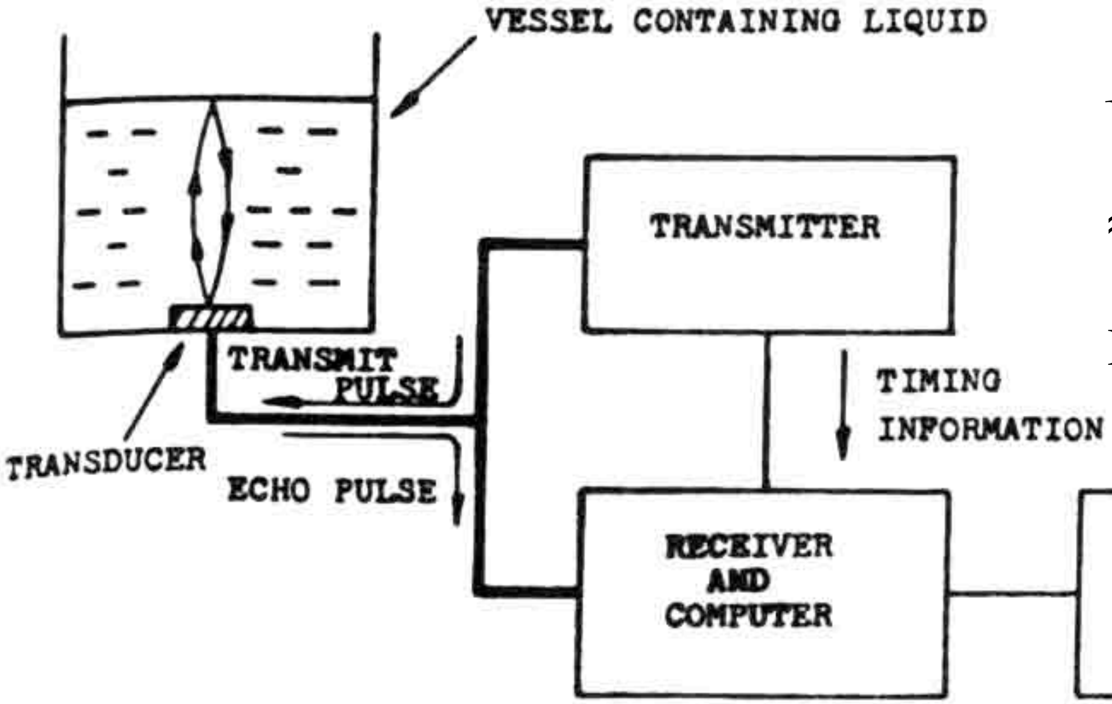
  = 1.06 $(\mathrm{Pa/mm})_{\mathrm{helium}}$
- Heat load may be large to keep vapor line dry

$$L_{liquid} = \frac{\left(\Delta p/g\right) - \rho_g L_{total}}{\rho_l - \rho_g}$$

	He	H_2	Ne	N_2	O_2	Ar
ρ_l	125	70.8	1240	807	1141	1394
ρ_g	16.7	1.33	9.4	4.6	4.47	5.77

Ultrasonic level measurement

Signal travels at sound speed



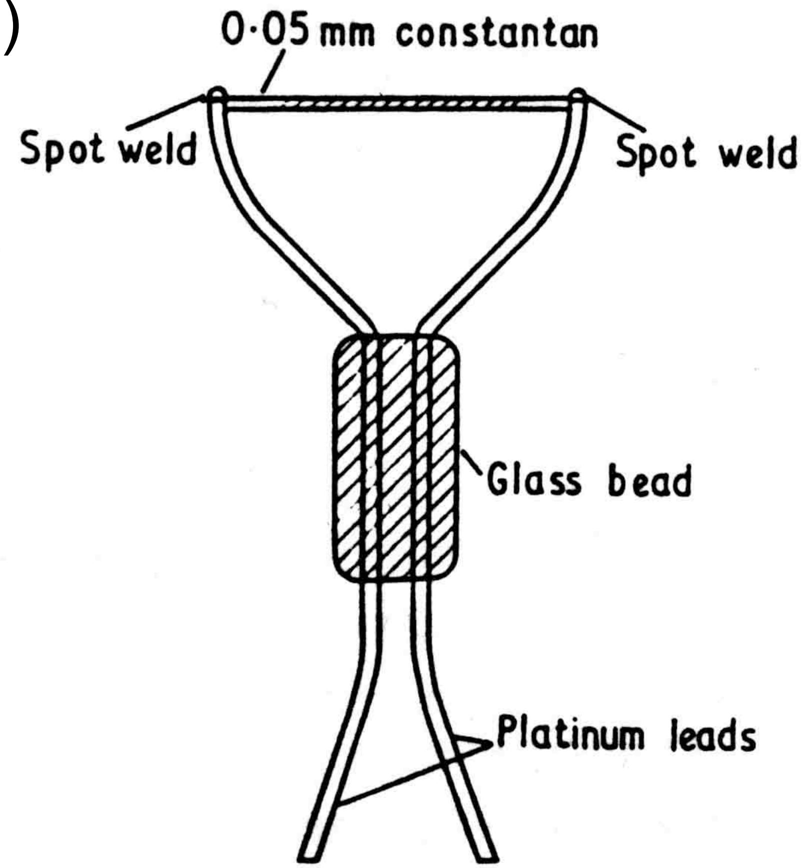
$$v = \sqrt{\gamma RT}$$

≈ 200 m/s for LHe

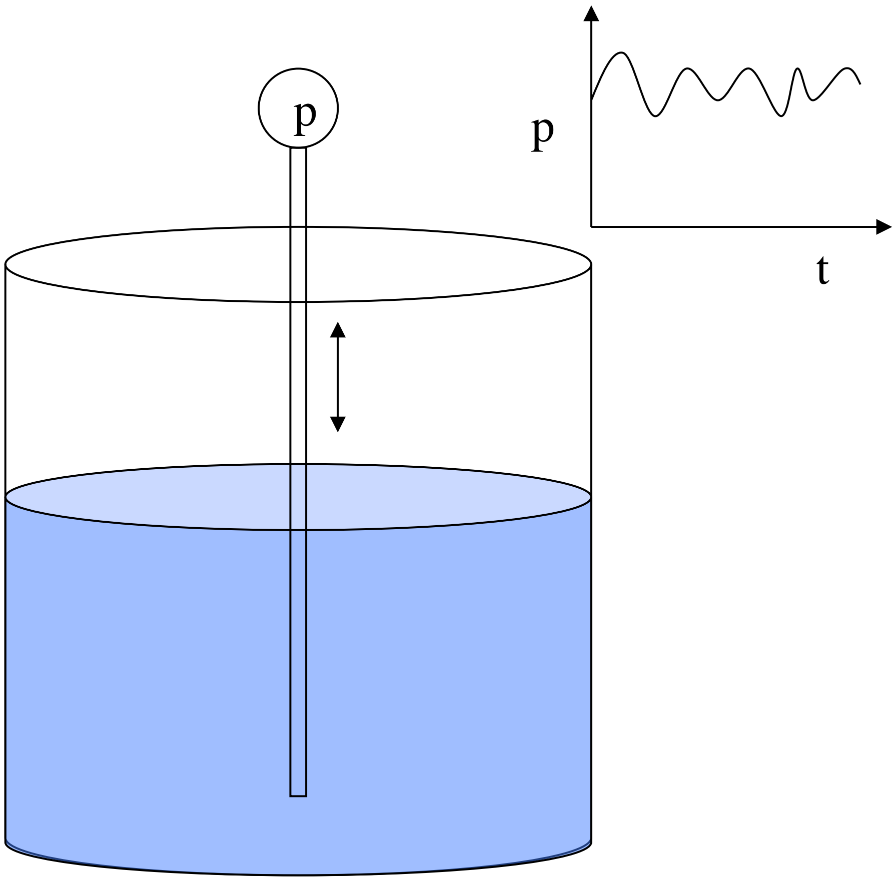
Level ~ resonant frequency

Discrete level measurement techniques

- Liquid vapor detection (LVD)
- Types of devices:
  - Superconducting thin films (SnAu)
  - Hot wire or film
  - Semiconductors
- Operating current must be sufficient to self heat the sensor in vapor, but not in liquid
- Sensor must be small to minimize heat generation in liquid



“Dip Stick” level measurement



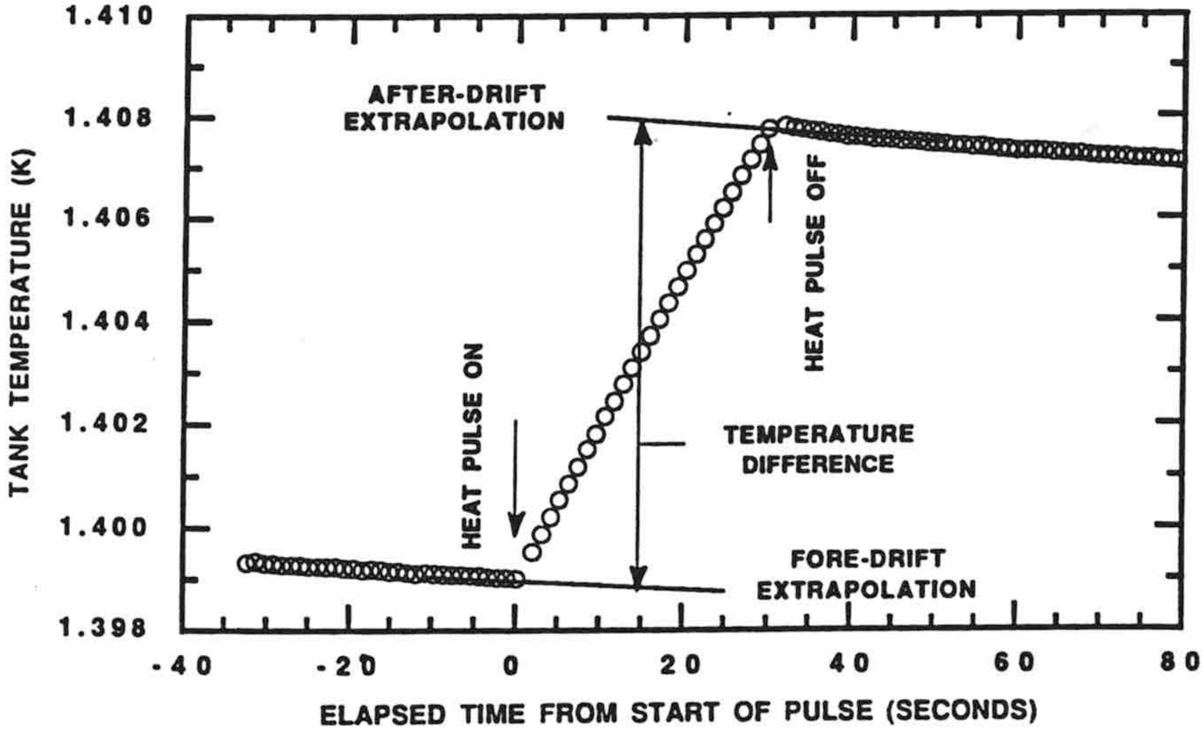
Acoustic oscillation changes frequency & amplitude when capillary leaves liquid

Heat Pulse Mass Gauging

- Measurement of He II volume (mass) by heat pulse technique

→ mass = Q/Δh

- Technique used extensively for space based He II cryostats but also pressurized He II systems for superconducting magnets



From Volz, et al
Advances in Cryo. Engn.
Vol 35 (1990)

Summary of Level Measurement Techniques

		Availability	**Readout**	**Range of heat Deposition**
Continuous Level Measurement				
	Capacitive gauge	Prototype	Frequency	Less than 1mW
	Superconducting wire	Commercial	Voltage	Tens of mW's
	Transmission line	Development	Frequency	On the order of μW
	Heat transfer based	Development	Power/temperature	Tens of mW's
	Floats	Development	Visual/voltage	Negligible
	Hydrostatic	Development	Pressure	On the order of mW's
	Ulrasonic	Development	Frequency	Less than 1 μW
Liquid-Vapor Detectors				
	SC wire	Development	Voltage	On the order of mW's
	Resistive	Development	Voltage	On the order of mW's
	Ultrasonic	Development	Frequency	Less than 1 μW
	Optical	Development	Light intensity	Less than 1 μW
Mass gauging				
	Internal energy change	Development	Temperature	On the order of 1 Joule