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Instrumentation

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Goals

- Describe measurements & instrumentation in cryogenic systems
- Give examples of typical temperature, pressure, flow and level sensors used in cryogenic systems
- Discuss the proper installation of sensors, wiring and feed throughs in cryogenic instrumentation
- Describe Thermal Acoustic Oscillations

Introduction

- The correct measurement of properties such as temperature, pressure, flow, level and vacuum in cryogenic systems is a key factor in the success of cryogenic systems.
- Measurements will allow us to understand if our cryogenic components are working properly, enable us to control them and permit the collection of scientific data.
- There are many subtleties in the selection and installation of cryogenic sensors.
  - Poor sensor selection and installation can result in wildly inaccurate readings or sensor failure
- Think about instrumentation as a complete system – sensor, wiring, feed through, DAQ rather than just the sensor itself.
  - Total system cost per measuring point can be ~ $500 - $1000

Introduction

- Define system & sensor requirements:
  - Range
  - Accuracy
  - Time response
  - Sensor environment (e.g. presence of magnetic or radiation fields)
  - Precision – what is the smallest change detected by the sensor?
  - Reliability
  - Cost

Instrumentation Rules of Thumb

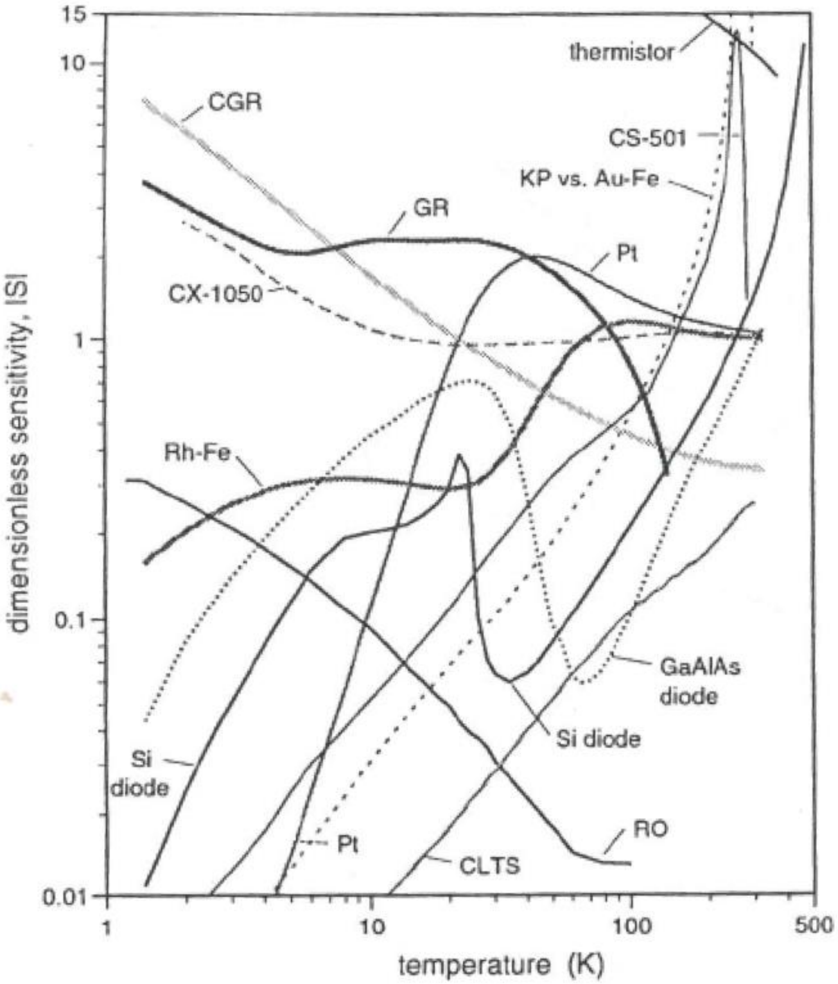
- Don't use more accuracy & precision than required
- Use commercially produced sensors whenever possible – there is a lot available
- When possible, mount sensors outside cryostat at 300 K (e.g. pressure transducers, flow meters)
- For critical devices inside of cryostats, install redundant sensors whenever feasible
- Be sure to consider how to recalibrate sensors
- If at all possible avoid, cold instrumentation feed throughs
  - SNS experience
- Once R&D is done, minimize number of sensors in series production of cryostats

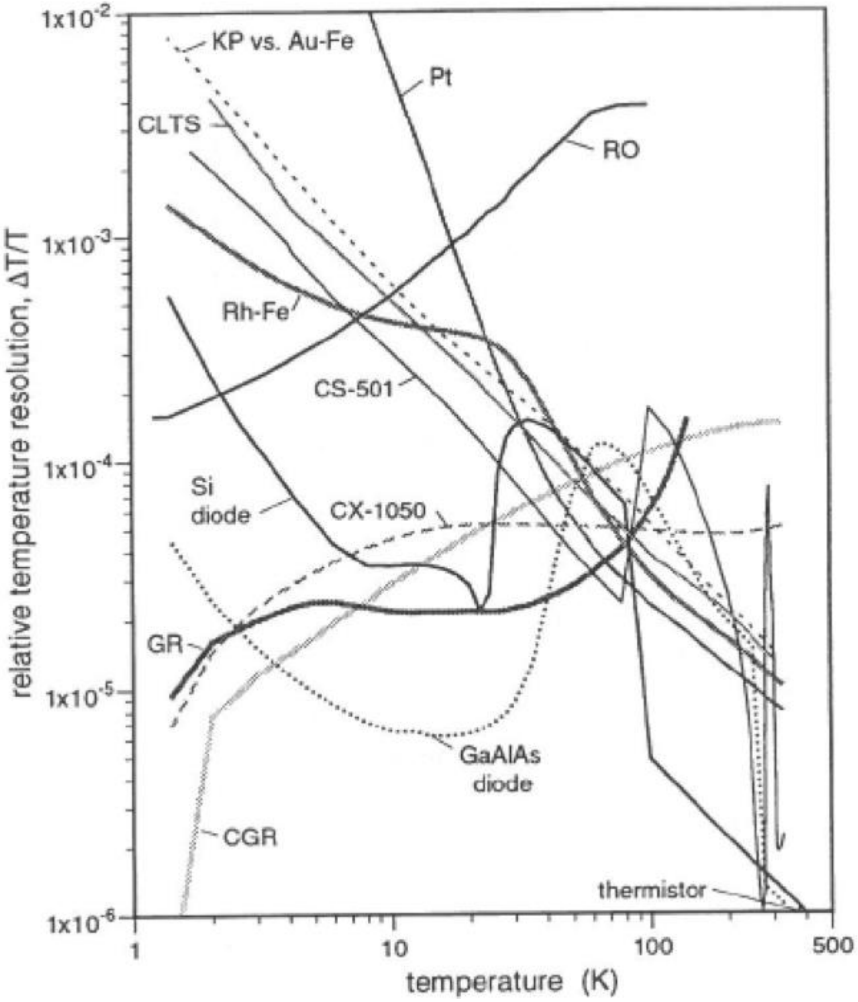
Temperature Measurement

- Measure some property – typically resistance or voltage drop that changes with temperature
- Commercial Temperature Sensing Options
  - Silicon Diodes (300 K - ~1 K)
  - Pt Resistors (300 K - ~ 30 K)
  - Ge Resistors (100 K < 1 K)
  - Carbon Glass resistors (300 K ~ 1 K) best below 100 K
  - Ruthenium Oxide (40 K - < 1 K)
  - Cernox (300 K < 1 K)
  - Thermocouples
- Take care not to put so much power in the sensor that it "self heats" and gives a false reading. Follow the vendor' s recomendations

Typical Cryogenic Temperature Sensor Characteristics

(from LakeShore Cryotronics)





Temperature Sensor Overview

(from Handbook of Cryogenic Engineering)

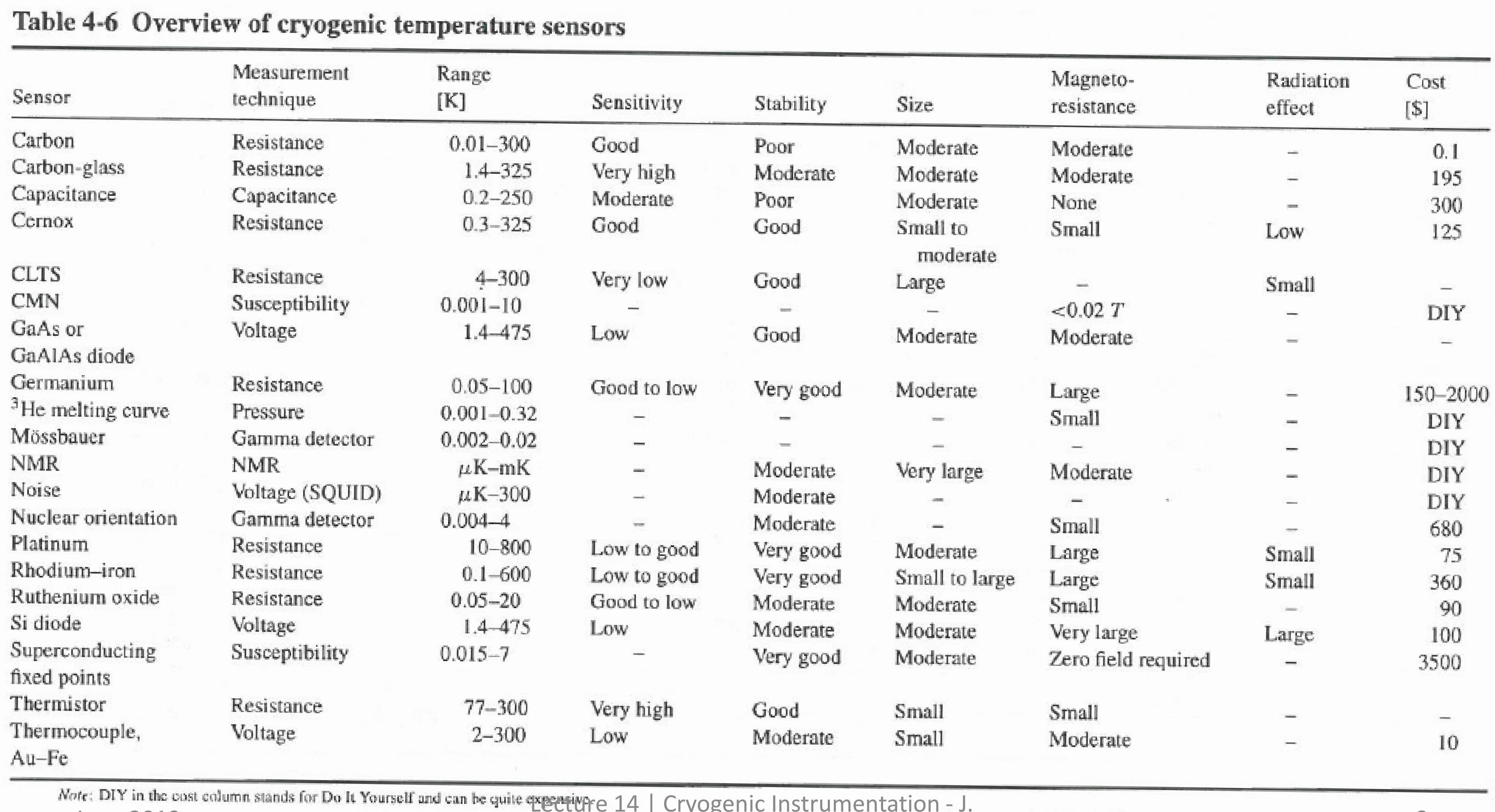
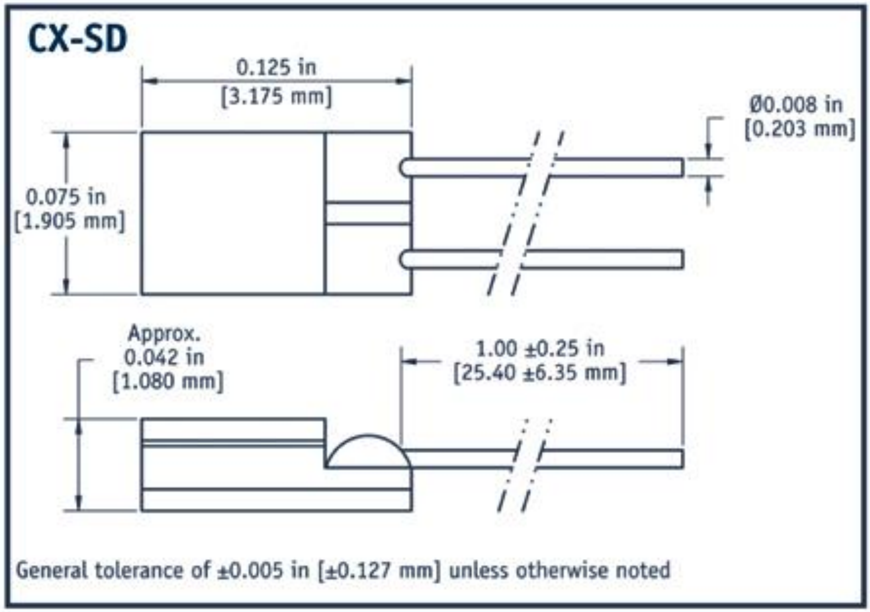


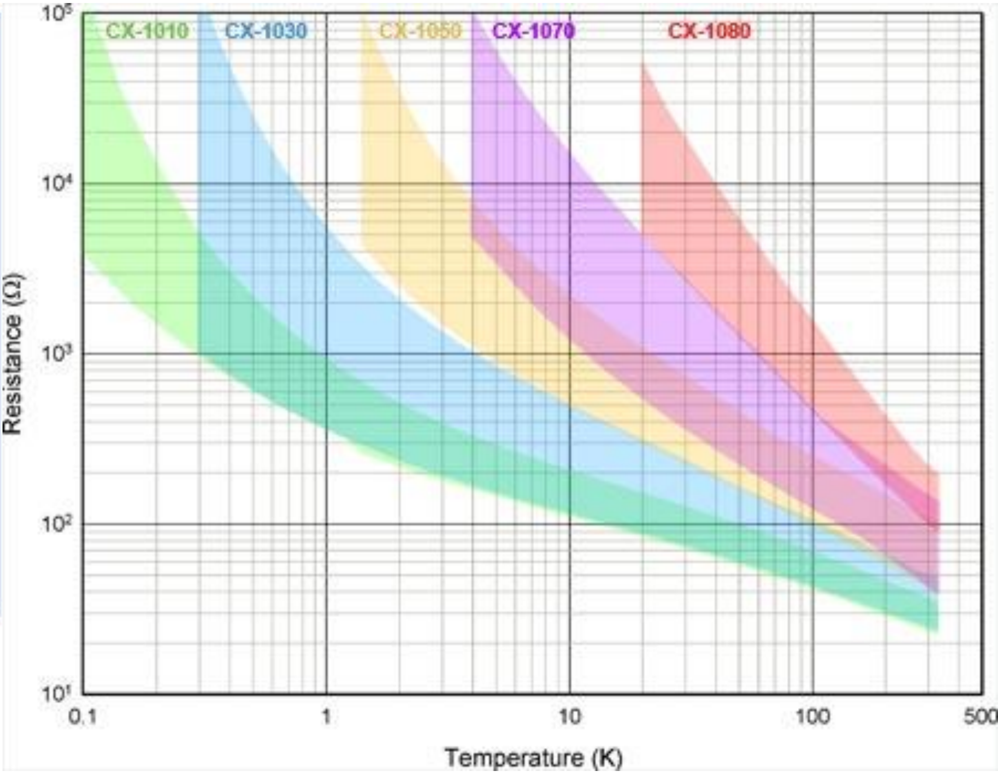
Table 4-6 Overview of cryogenic temperature sensors

Sensor	Measurement technique	Range [K]	Sensitivity	Stability	Size	Magneto-resistance	Radiation effect	Cost [$]
Carbon	Resistance	0.01–300	Good	Poor	Moderate	Moderate	–	0.1
Carbon-glass	Resistance	1.4–325	Very high	Moderate	Moderate	Moderate	–	195
Capacitance	Capacitance	0.2–250	Moderate	Poor	Moderate	None	–	300
Cernox	Resistance	0.3–325	Good	Good	Small to moderate	Small	Low	125
CLTS	Resistance	4–300	Very low	Good	Large	–	Small	–
CMN	Susceptibility	0.001–10	–	–	–	<0.02 *T*	–	DIY
GaAs or GaAlAs diode	Voltage	1.4–475	Low	Good	Moderate	Moderate	–	–
Germanium	Resistance	0.05–100	Good to low	Very good	Moderate	Large	–	150–2000
^{3}He melting curve	Pressure	0.001–0.32	–	–	–	Small	–	DIY
Mössbauer	Gamma detector	0.002–0.02	–	–	–	–	–	DIY
NMR	NMR	μK–mK	–	Moderate	Very large	Moderate	–	DIY
Noise	Voltage (SQUID)	μK–300	–	Moderate	–	–	–	DIY
Nuclear orientation	Gamma detector	0.004–4	–	Moderate	–	Small	–	680
Platinum	Resistance	10–800	Low to good	Very good	Moderate	Large	Small	75
Rhodium–iron	Resistance	0.1–600	Low to good	Very good	Small to large	Large	Small	360
Ruthenium oxide	Resistance	0.05–20	Good to low	Moderate	Moderate	Small	–	90
Si diode	Voltage	1.4–475	Low	Moderate	Moderate	Very large	Large	100
Superconducting fixed points	Susceptibility	0.015–7	–	Very good	Moderate	Zero field required	–	3500
Thermistor	Resistance	77–300	Very high	Good	Small	Small	–	–
Thermocouple, Au–Fe	Voltage	2–300	Low	Moderate	Small	Moderate	–	10

Note: DIY in the cost column stands for Do It Yourself and can be quite expensive.

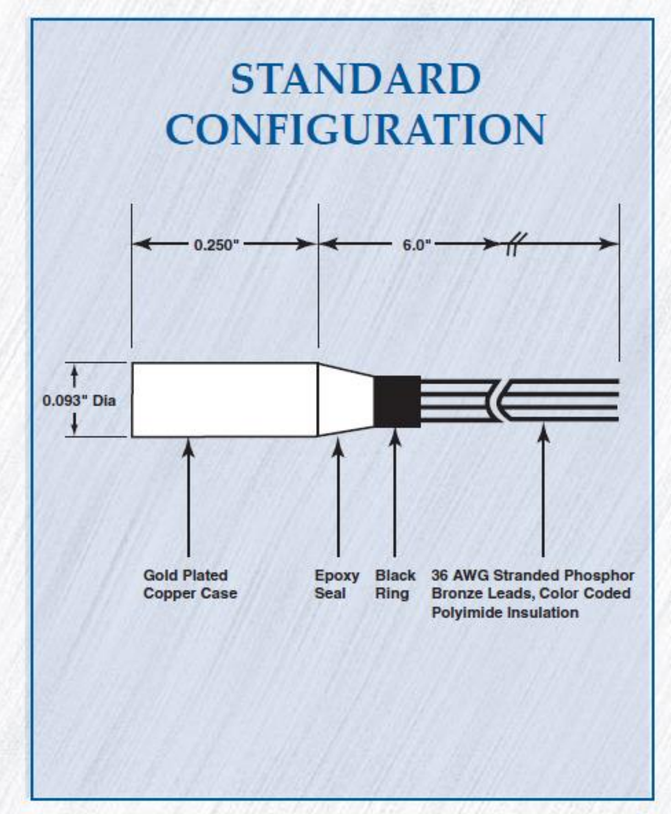
Cernox Temperature Sensors
LakeShore Cryotronics

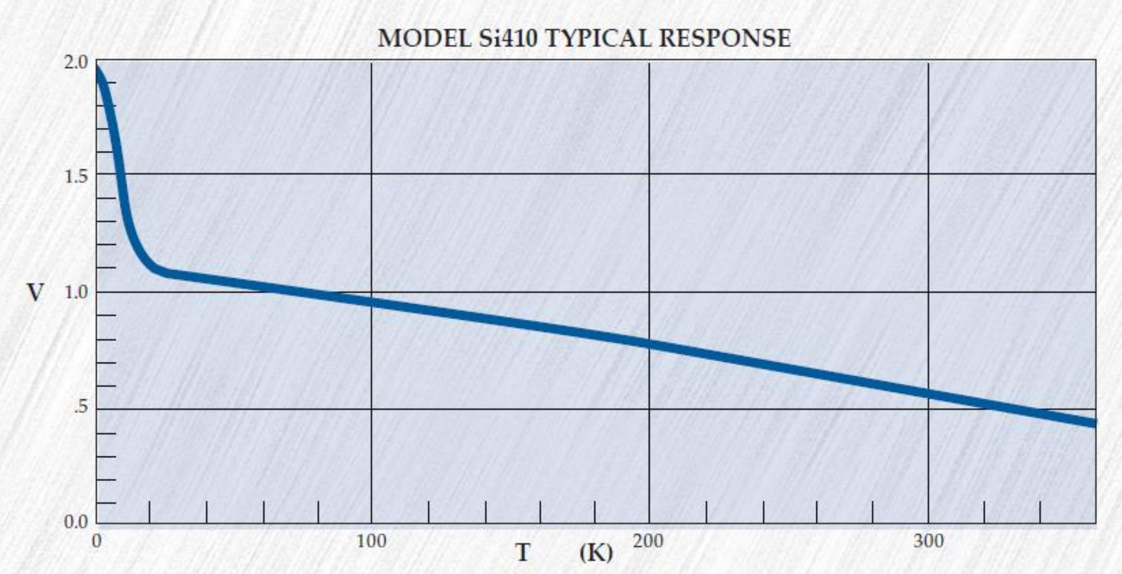




Very responsive at LHe Temps
Expensive
Requires individual calibration for best results
Very good in ionizing radiation environments

Si410 Silicon Diode Scientific Instruments



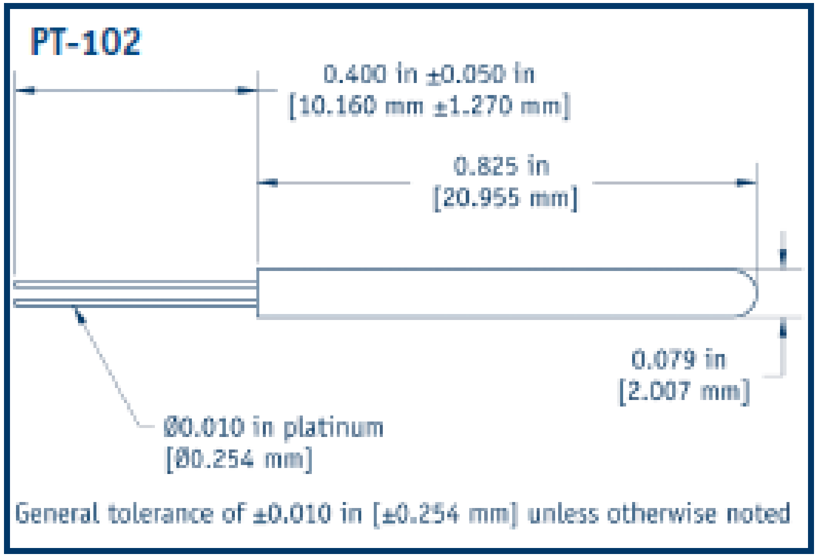


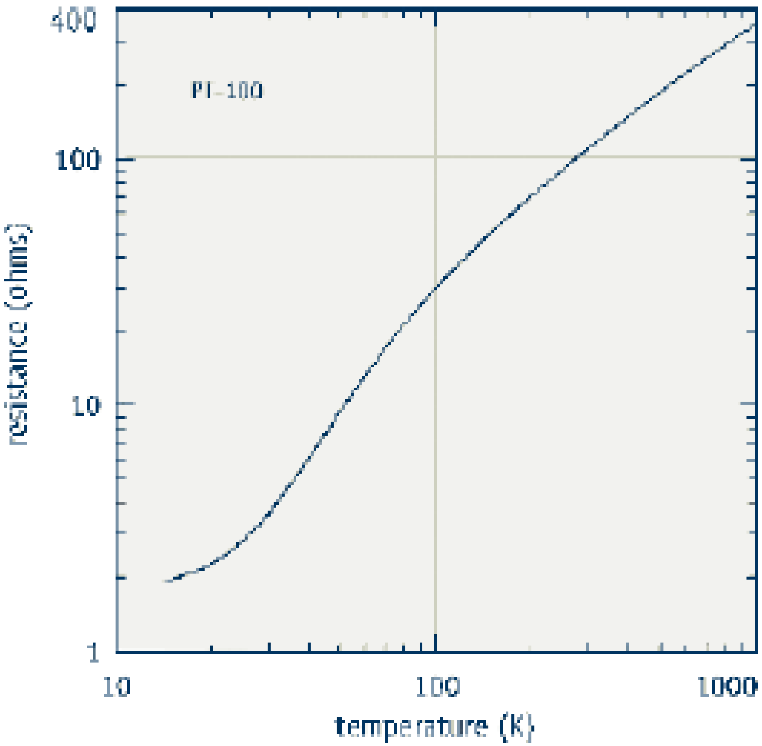
Can both be individually calibrated or used with typical curves

Relatively low cost, frequently used in cryogenic plants

Not suitable for radiation environments

Platinum Resistors





From Lakeshore Cryotronics Catalog

Good down to ~ 30 K
Works well in ionizing radiation fields
Can be calibrated with good accuracy to common calibration curves
Relatively low cost
Excitation is generally 1 mA DC

Temperature Sensor Wiring

- Four wire measurements (V+, V-, I+,I-) should be used for temperature sensors to avoid impact of lead resistance on measurement'
- Wires should be in twisted pairs (V+,V-) and (I+,I-) to reduce noise pickup
- Wires will connect from 300 K to cryogenic temperatures so must be have small cross sections, and low thermal conductivity
  - 36 gage manganin wire is a frequent choice
    - see thermal conductivity integrals
  - Avoid using wires that are too fine as this will result in breakage and poor reliability
  - Heat sink wires at an intermediate temperature
- Don't over constrain the wires - allow room for movement and shrinkage during cool down to avoid breakage

Heat Sinking of Wires

- Critical to the proper use of temperature sensors in vacuum spaces
  - You want to measure the temperature of the sensor not that due to heat leak down the wire
  - Small heat capacities at cryogenic temperatures means small heat leaks can easily impact sensor temperature
  - Heat sink wire at intermediate temperature and also at point where temperature is measured

Required Wire Heat Sinking for Proper Temperature Measurement

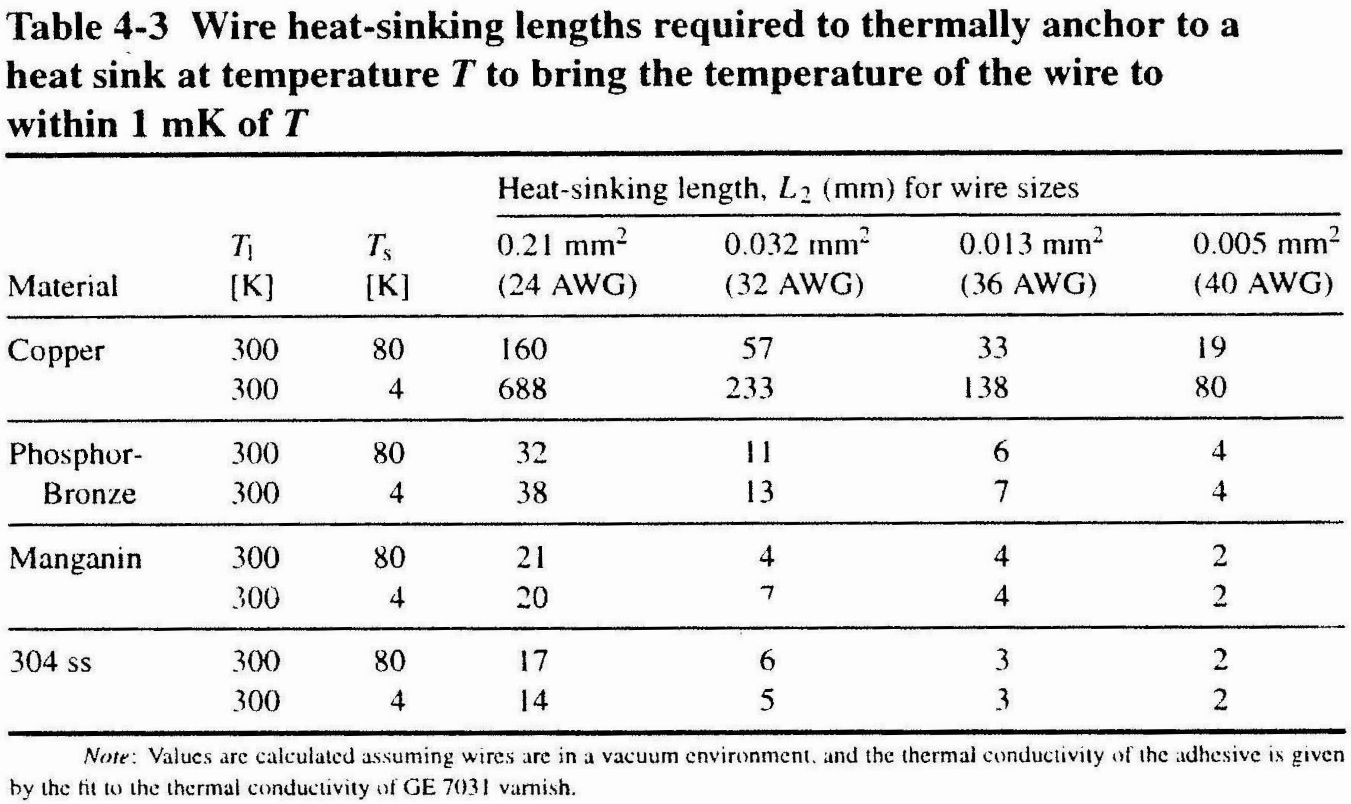


Table 4-3 Wire heat-sinking lengths required to thermally anchor to a heat sink at temperature *T* to bring the temperature of the wire to within 1 mK of *T*

Material	T_1 [K]	T_s [K]	Heat-sinking length, L_2 (mm) for wire sizes 0.21 mm^2 (24 AWG)	0.032 mm^2 (32 AWG)	0.013 mm^2 (36 AWG)	0.005 mm^2 (40 AWG)
Copper	300	80	160	57	33	19
	300	4	688	233	138	80
Phosphor-Bronze	300	80	32	11	6	4
	300	4	38	13	7	4
Manganin	300	80	21	4	4	2
	300	4	20	7	4	2
304 ss	300	80	17	6	3	2
	300	4	14	5	3	2

Note: Values are calculated assuming wires are in a vacuum environment, and the thermal conductivity of the adhesive is given by the fit to the thermal conductivity of GE 7031 varnish.

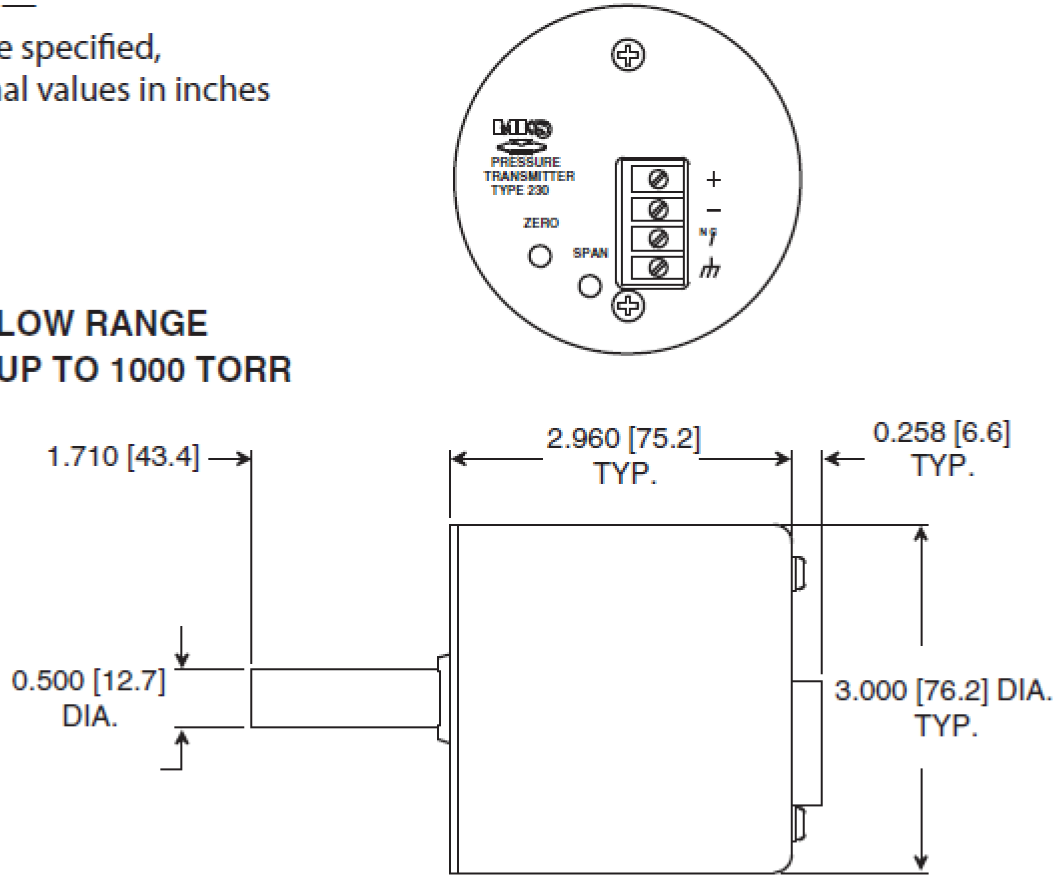
From "Cryogenic Instrumentation" – D.S. Holmes and S. Courts
Handbook of Cryogenic Engineering

Pressure Measurement

- Carry out at room temperature where possible (using a capillary tube)
- Problems with room temperature pressure measurement
  - Thermal Acoustic Oscillations (recall Lecture 13)
  - Time response will be too slow for high speed transients but for most operations this isn't an issues
    - High speed pressure pulse due to magnet quenching is an exception
- Some cold pressure transducers exist that solve these problems
- There are a wide range of 300 K commercial pressure transducers that exist
  - Many are based on capacitive sensors or strain gage bridges mounted on diaphragms that change shape with pressure

MKS Baratron Pressure Transducer

Dimensional Drawing —
Note: Unless otherwise specified, dimensions are nominal values in inches (mm referenced).

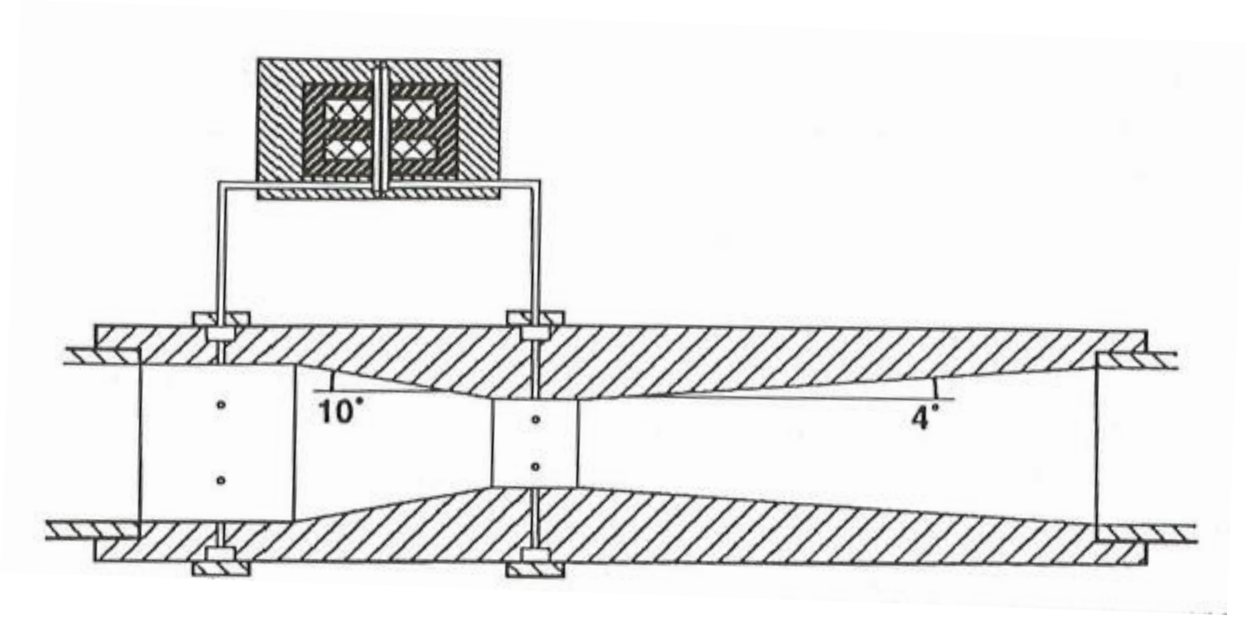


300 K operation
Uses a capacitive sensor
Accurate up to 0.3 % of reading

Flow Measurements

- A variety of techniques are available mostly the same ones as used in standard fluid mechanics including:
  - Venturi Meters
  - Turbine Flowmeters
  - Coriolis Flowmeters
  - Orifice plate Flowmeters
- Comments
  - Insure that the devices are calibrated for operation at the temperatures and pressures that you are expecting (use appropriate fluid properties)
  - Beware of situations that can result in unplanned two-phase flow
  - Allow sufficient length for flow straightening if required (e.g. Venturi)
  - If possible install the flow meters in the 300 K portions of the flow

Venturi Flow Meter



Note use of cold DP transducer

A more common approach is to use capillary tubes and a warm transducer

From The Handbook of Cryogenic Engineering

Coriolis Flow Meter

Figure 1 Coriolis meter sensor and transmitter

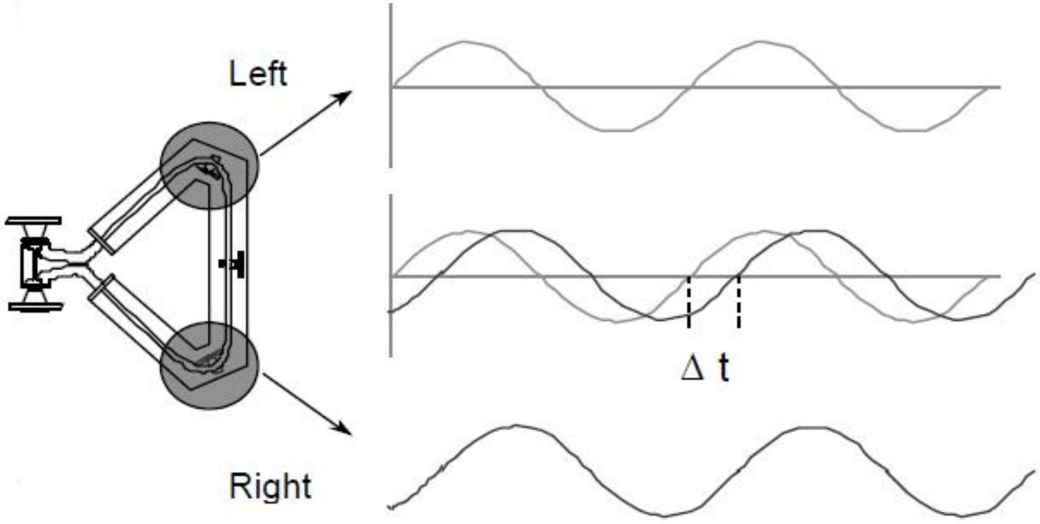


Figure 2 Coriolis flow meter operation

Tested down to 1.7 K at CERN LHC
Flow produces vibrations in the flow tubes that have a phase offset directly related to mass flow

From *Development of a mass flowmeter based on the Coriolis acceleration for liquid, supercritical and superfluid helium*
de Jonge T. et al. Adv. Cryo. Engr. Vol 39 (1994)

Flow Meter Comparisons

(From M. Süßer – Adv.Cryo.Engr. Vol.57B – 2010)

TABLE 2: Comparison of different mass flow meters

	Venturi	**Orifice**	**V-Cone**	**Coriolis**
Space requirements	Inline mounting	Inline mounting	Inline mounting	Additional space
Straight upstream length	Effects of upstream conditions	Effects of upstream conditions(5)	Effects of upstream conditions(6)	No effects of upstream conditions
Connections	Capillaries	Capillaries	Capillaries	Electrical wiring
Turn down	3 - 5	3 - 5	3 - 5	50 (1)
Reliability	Very high	Very high	Very high	No inform.(2)
Cost of capital(3)	High	High	High	Medium
Cost of operation	Less	High	Medium	High (1)
Magnetic field influence	No	No	No	Yes
Dynamic measurements	Errors due frequency amplitude	Errors due frequency amplitude	Errors due frequency amplitude	Depending on frequency
Uncertainty(4)	5%	5%	5%	2%
Capillary effects	yes	yes	yes	no
Pressure overload capability	high	high	high	medium

(1): Using a device with higher nominal flow rate, the pressure drop could be reduced in compensation the turn down is reduced too and the required installation space enlarged

(2): There is no information in the literature about the long term experience at low temperature conditions

(3): Pressure transducer, differential pressure transducer and temperature measurement necessary

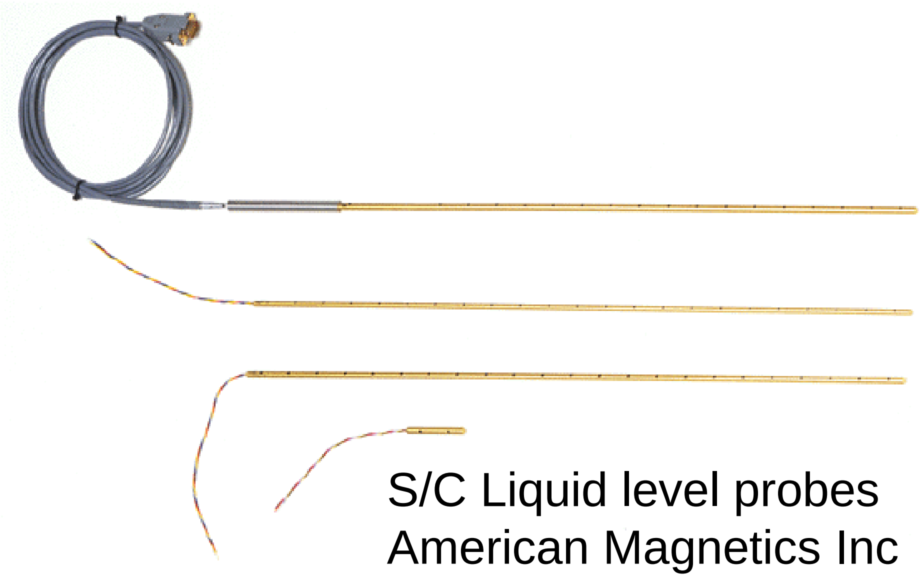
(4): Stationary flow conditions without any capillary effect

(5): Upstream length enlarged factor 2 compared to Venturi tubes

(6): Upstream length reduced [illegible]

Level Measurements

- Measuring the level of cryogenic baths is important to proper operations
- Options include:
  - Capacitance gauges (LN_2, LOX, LH_2)
  - Superconducting level probes (LHe)
    - Installing redundant or easily replaceable s/c level probes is highly recommended
  - Differential pressure techniques
  - Floats (LN_2)



S/C Liquid level probes
American Magnetics Inc

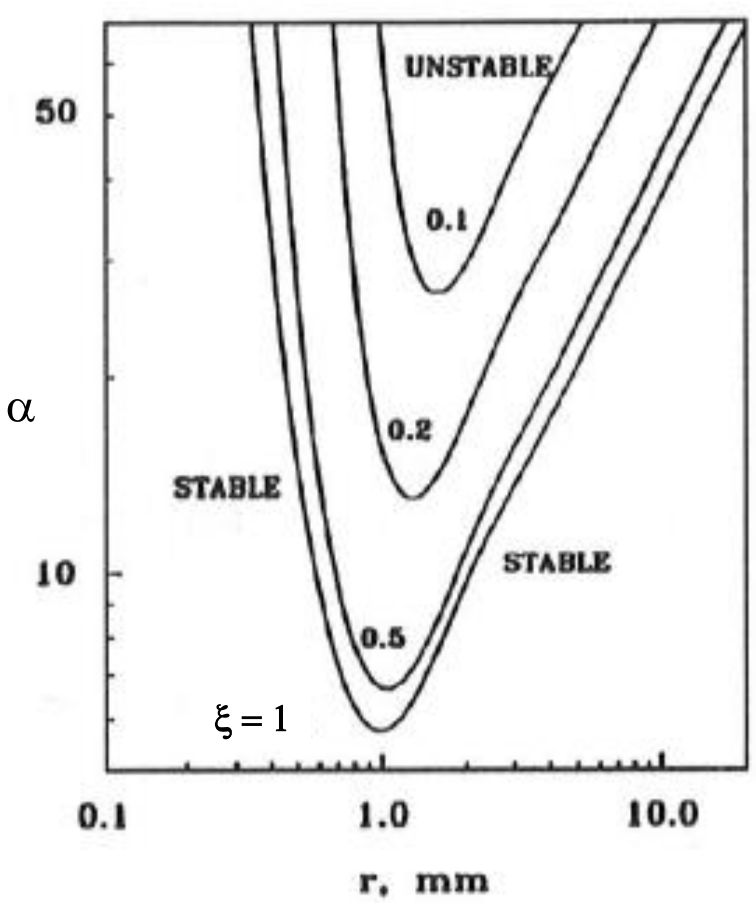
Feedthroughs

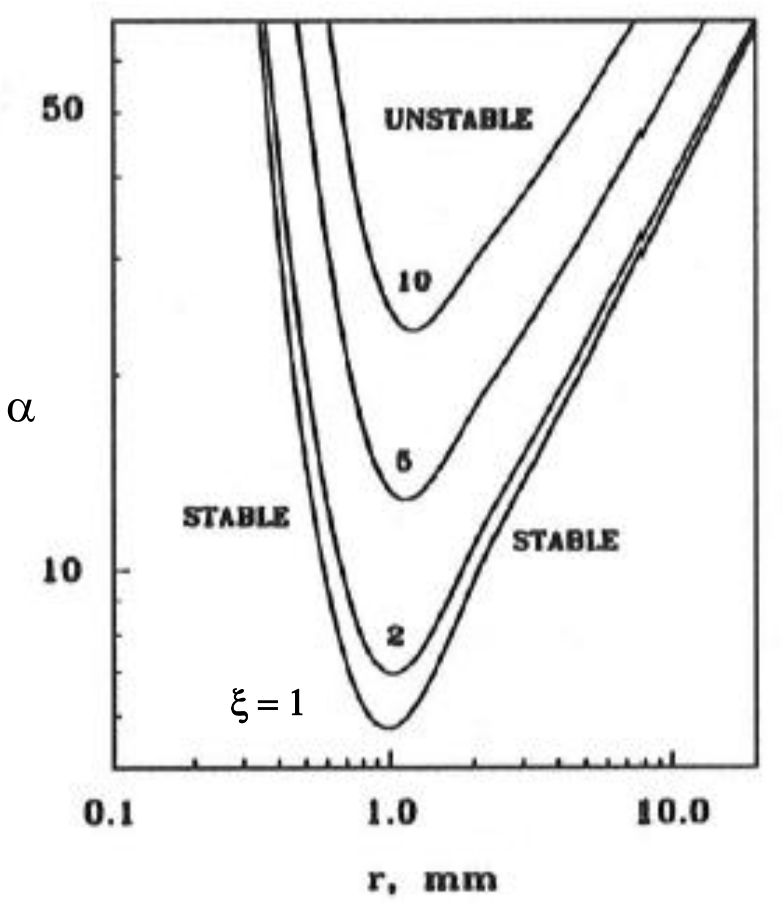
- Instrumentation feedthroughs are best done at 300 K
- Avoid cryogenic instrumentation feedthroughs if at all possible
  - If you can’t, significant testing and validation will be needed
- In test and prototype cryostats always put in more feedthroughs (or blank flanges) than you think you’ll need
- GHe at 300 K and 1 bar has poor dielectric strength use spacing of pins or potting of feedthrough if this will cause problems (e.g. in voltage taps of S/C magnets)
- Beware of possible thermal acoustic oscillations being set up in pressure taps and other sealed tubes

Thermal Acoustic Oscillations (TAOs)

- Occurs in a tube that connects room temperature and cryogenic temperatures and is sealed at the room temperature end
- The thermal gradient establishes standing pressure oscillations in the fluid in the tube.
- These oscillations can cause very high pressure spikes as well significant heating at the low temperature end due to friction.
- This can cause significant problems in cryogenic systems
- Such scenarios should be avoided but the enabling geometry is fairly common in cryogenic systems
  - Valved off lines
  - Pressure taps
  - Instrumentation
- There have been studies to determine stable (non-oscillating geometries)

Stability Curves for TAOs in He





Y. Gu
PhD Thesis
University of Colorado 1993

Using the Stability Curves

$$\alpha = \frac{T_H}{T_c}$$

$$\xi = \frac{L_H}{L_C}$$

Where the division between L_H and L_C is the point in the tube where $T = (T_H + T_C)/2$

These curves are for a 1 meter long tube. To use them with other lengths use the Adjusted radius:

$$r' = \frac{r}{\sqrt{L}}$$

Stability on the left hand side of the plots is due to viscous damping and stability on the right hand side of the plots is due to inertial damping

Other Approaches to Removing TAOs

- Add volume to the warm end
- Install a check valve between the warm and cold end (near boundary between the two) – this converts the problem to a closed cold tube with no TAOs
- Heat sink the closed end (thus changing T_H/T_C)
- Allow flow through the warm end

Commercial Sources of Cryogenic Instrumentation

- Don’t reinvent the wheel – there is a lot already available. Catalogs can help you choose the correct sensor for your application
- Two US Sources:
  - Lakeshore Cryogenics

    http://www.lakeshore.com/
  - Scientific Instruments

    http://www.scientificinstruments.com/
- Possible Cold Pressure Transducers
  - http://www.omega.com/
  - http://www.gp50.com/
- Cryogenic Society of America Buyer’s Guide
  - http://www.cryogenicsociety.org/buyers_guide/