PSI Center for Neutron and Muon Sciences

Cryogenics I

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5th ISSE Training School Lund, 20 January 2026

Agenda

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Cooling mechanisms

- Cooling with liquid and vapour
- Latent heat and vapour pressure
- Cooling by evaporation
- Cooling by vapour
- Cooling with gas
- Joule Thomson effect
- Heatpumps - Stirling cooler
- GM cooler

Heat transfer

- Conduction
- Radiation
- Convection

Cryostats

- Cold finger cryostats radiative heat load
- Flow cryostats
- Cold finger closed cycle
- Top loading cryostats
- Top loading closed cycle
- Joule Thomson top loading CCR
- Orange Cryostat

Cooling with Liquid and Vapour

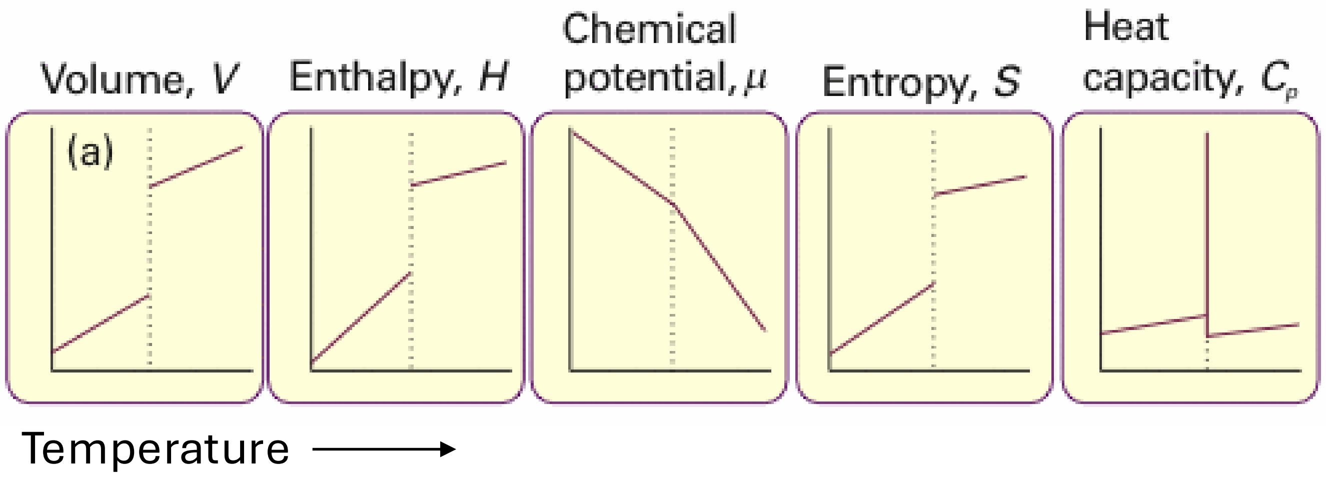
Cooling with Cryogens

- Utilize cryogenic liquids for cooling
- Cryogenic liquids are liquids with a boiling point below approximately -150°C

Fluid	Freezing (K)	Boiling (K)
Helium-4		4.214
Hydrogen	14.01	20.27
Neon	24.5	27.09
Nitrogen	63.15	77.36
Argon	83.81	87.24
Oxygen	54.3	90.18

How can a boiling liquid be used for cooling?

Latent heat of evaporation



liquid to gas transition requires heat transfer from surrounding.

Energy required to free molecules or atoms from bonds

Enthalpy of evaporation

$$L = \Delta H = \Delta U + p\Delta V$$

Change of internal energy

Work done by expanding gas

Energy required/released to change the entropy of the system

$$L = (\Delta S_{gas} - \Delta S_{liquid})T$$

Latent Heat of Helium and Nitrogen

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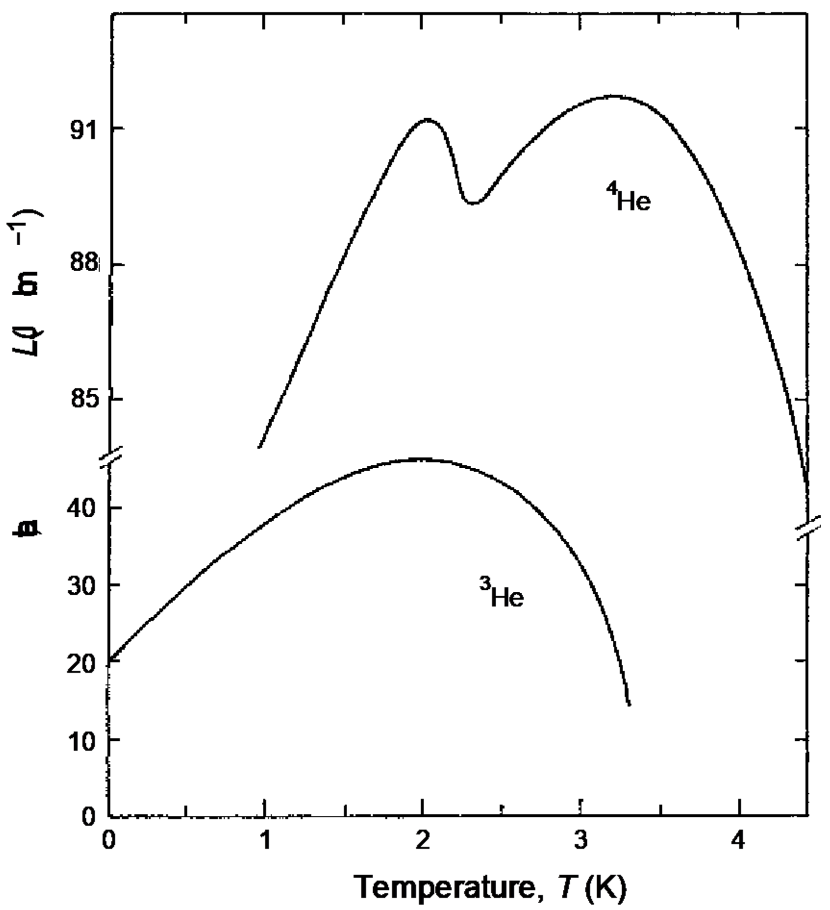
prop. @ Norm.press	Nitrogen	Helium-4	Helium-3
boiling point (K)	77.3	4.22	3.19
latent heat (J/g)	198	20.9	7
volume ratio Gas/liq	694	750	750
liquid density (g/cm^3)	0.808	0.125	0.055

Atkins' Physical Chemistry, Enss Hunklinger,Low temperature Physics

A heat load of 1W
to a He4 bath will
result in an evaporation rate of
1.4ll/h ➔ 1scm/h = 16 ln/min

3l of liquid Helium cools
100g of Cu from RT→4K



F. Pobell, Matter and Methods at Low Temperatures

Vapour pressure curve

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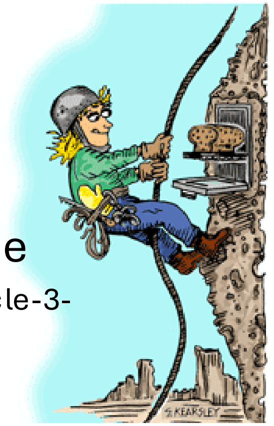
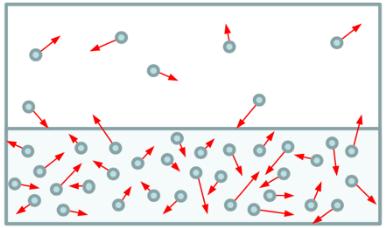
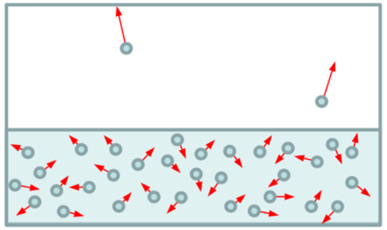


The high Art of baking at high altitude
https://www.exploratorium.edu/cooking/icooks/article-3-03.html



In a boiling liquid the pressure of the gas reaches saturation (Thermal equilibrium)



reducing the vapor pressure (pump)
➔ Boiling point of liquid is reduced

$$T_{\text{boiling}} = \left(\frac{1}{T_0} - \frac{R\ln(\frac{p}{p_0})}{L}\right)^{-1}$$

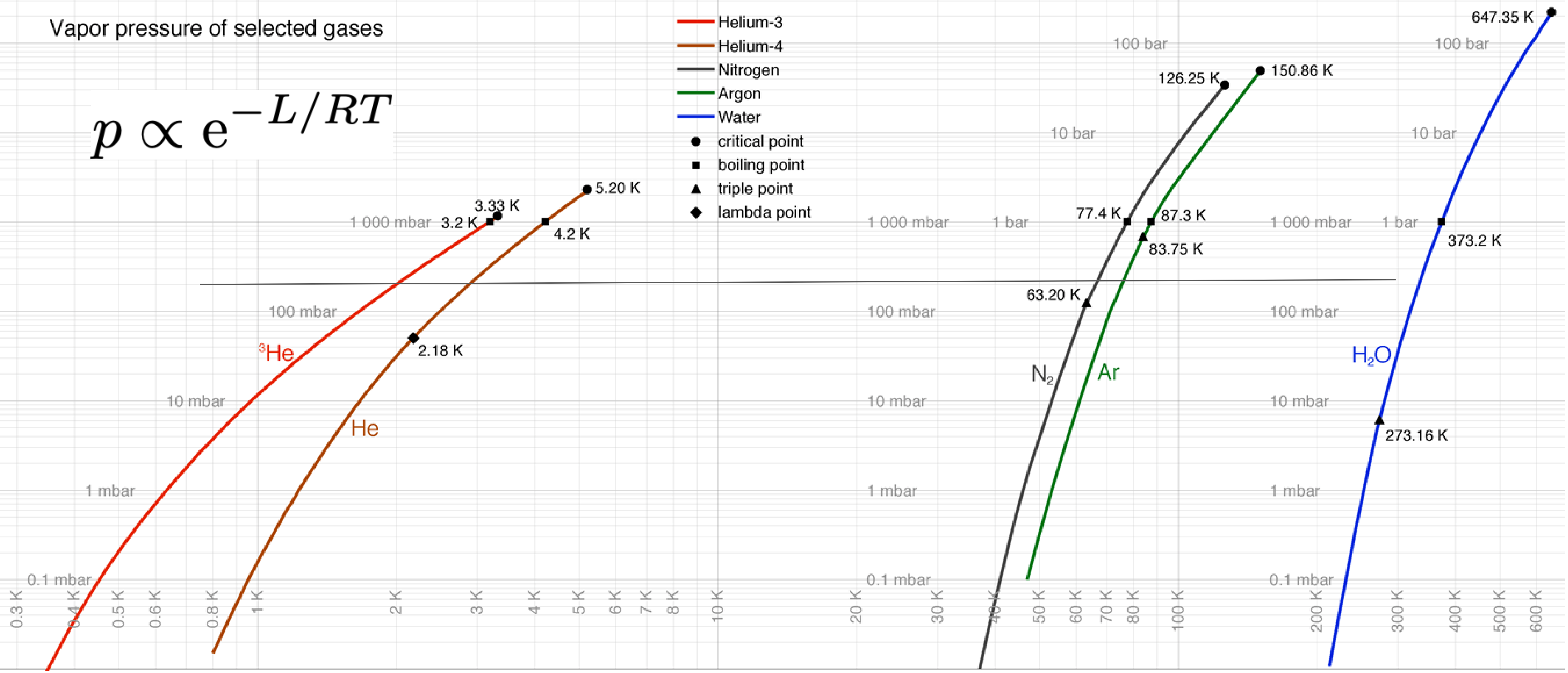
$$p_{\text{vap}} \propto \mathrm{e}^{-L/RT}$$

$$\left[\frac{dp}{dT}\right]_{\text{vap}} = \frac{S_{\text{gas}} - S_{\text{liq}}}{V_{\text{m,gas}} - V_{\text{m,liq}}} = \frac{L}{T(V_{\text{m,gas}} - V_{\text{m,liq}})} \approx \frac{L}{TV_{\text{m,gas}}} = \frac{Lp}{RT^2}$$

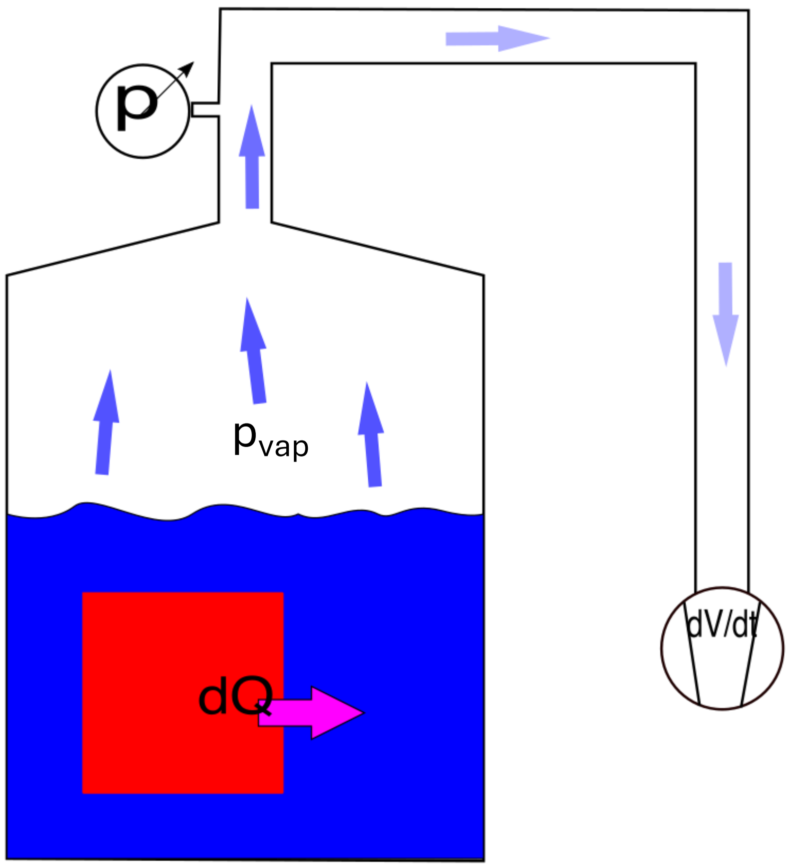
Clausius-Clapeyron

Vapour pressure curve

$$p \propto \mathrm{e}^{-L/RT}$$



Cooling by Evaporation



Cooling power

$$\dot{Q} = \frac{dQ}{dt} = \frac{dn}{dt}L \propto Lp_{\mathrm{vap}} \propto \mathrm{e}^{-1/T}$$

Recap vacuum pumps:

Pumping speed $S_0 = \frac{dV}{dt}$

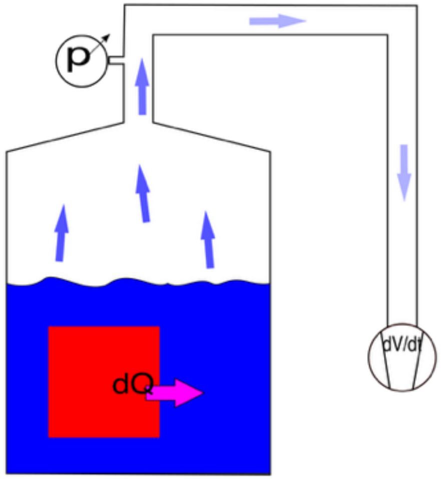
Throughput : $q_{pV} = S_0 \cdot p = \frac{dV}{dt}p$

Cooling power calculation

$$\frac{dQ}{dt} = \frac{dn}{dt}L$$

$$\frac{dn}{dt} = d\left(\frac{pV}{RT}\right)/dt = \frac{1}{RT}p\frac{dV}{dt}$$

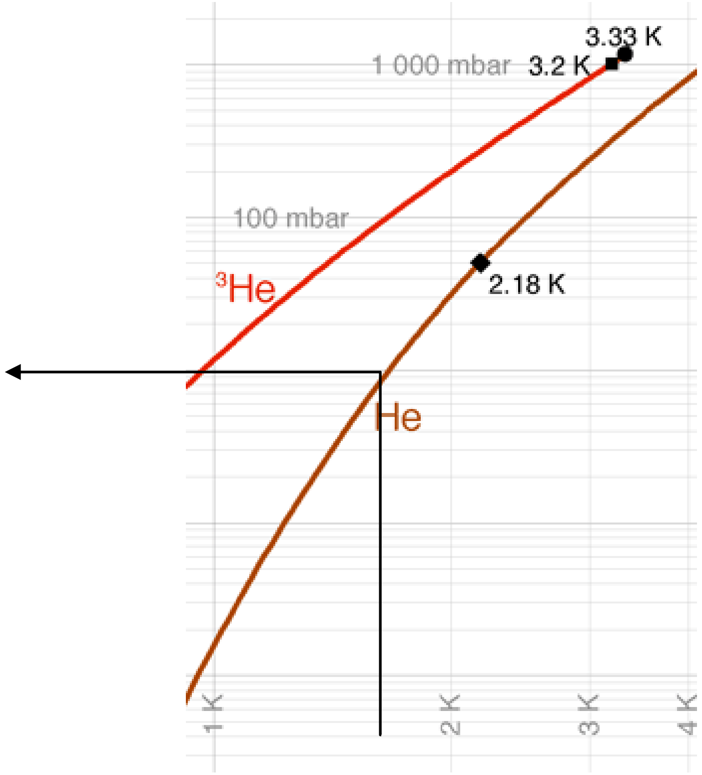
Cooling by evaporation – Example



liquid 4He cooled cryostat
T = 1.7K cooling power 100mW

P_{vap} = 10mbar

$$\frac{dQ}{dt} = \frac{dn}{dt} L$$
$$\frac{dn}{dt} = d\left(\frac{pV}{RT}\right)/dt = \frac{1}{RT} p \frac{dV}{dt}$$



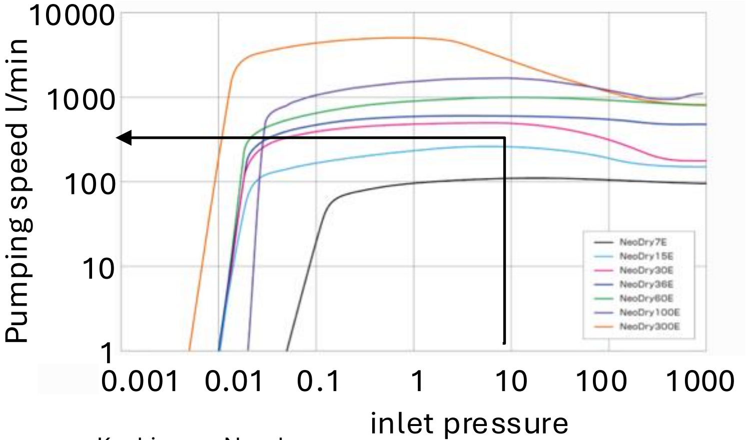
$$\dot{Q} = L M_{\mathrm{He}} \frac{1}{RT} p_{\mathrm{vap}} \frac{dV}{dt}$$

Pumping speed

$$S_0 = \frac{\dot{Q} RT}{L M_{\mathrm{He}} p_{\mathrm{vap}}}$$

$$S_0 = \frac{0.1\,\mathrm{W} \cdot 8.314\,\mathrm{J(molK)^{-1}} \cdot 300\,\mathrm{K}}{20\,\mathrm{Jg^{-1}} \cdot 4\,\mathrm{gmol^{-1}} \cdot 1000\,\mathrm{Pa}}$$

S_0 = 11 scm/h = 187 ln/min



Cooling with Gas

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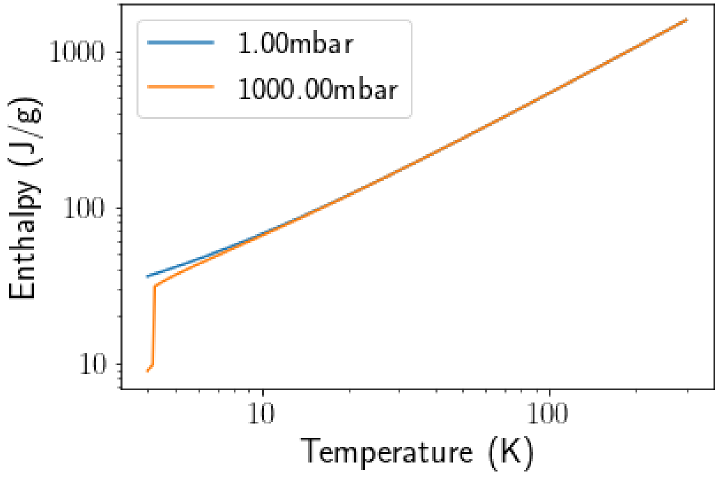
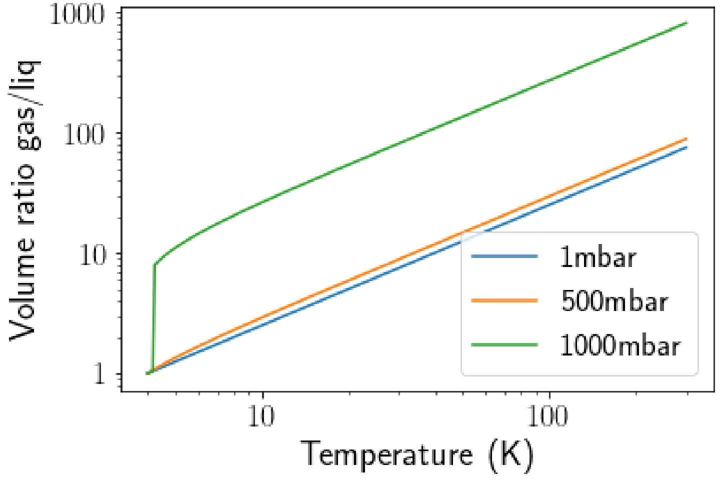




$$L = 21\,[\mathrm{J/g}]$$

$$H(T > 4.2\,\mathrm{K}) = 5.2\,T[\mathrm{K}] + 15.1[\mathrm{J/g}]$$

Liquid required to cool 1kg of material from 300K to 4K

	Spec Heat integral [kJ]	He liq.liter Evap cooled	He liq.liter Enth cooled
Copper	80	39	0.8
Stainless	92	35	0.9
Al	178	67	1.7

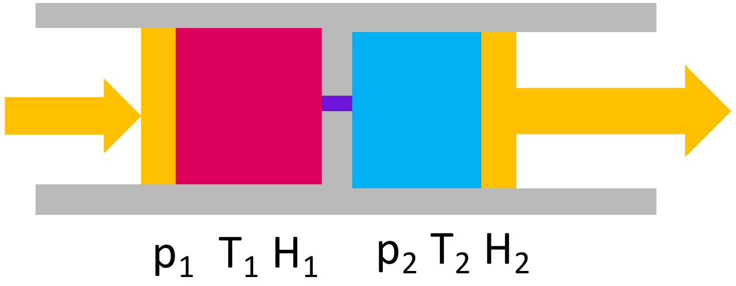
Slow cooling saves Helium and avoids trouble

$$\frac{m_{\mathrm{liq}}}{m_{\mathrm{solid}}} = \int_{4.2}^{300} \frac{c_{\mathrm{solid}}(T)}{5.2T + L} dT$$

Joule Thomson effect

isenthalpic expansion of a real gas or liquid

throttled gas expansion
will lead to a temperature change



$$H_1 = H_2$$

$$U_1 + p_1 V_1 = U_2 + p_2 V_2$$

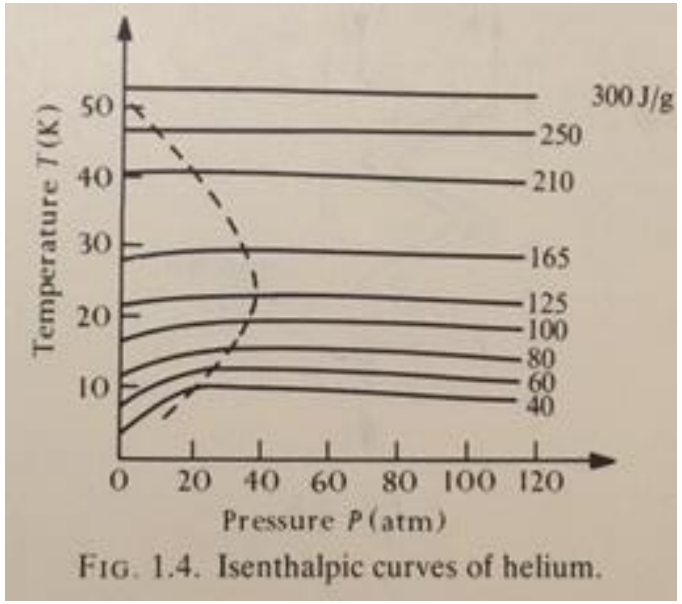
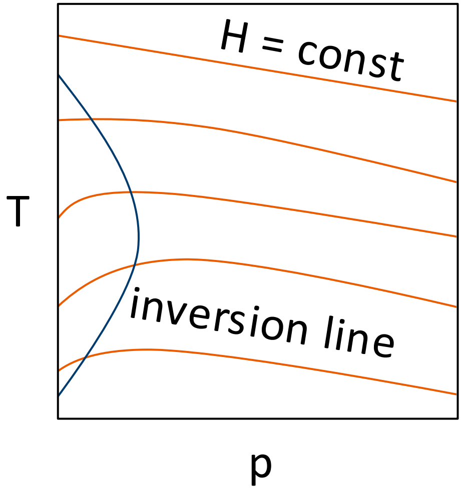


FIG. 1.4. Isenthalpic curves of helium.

Gas	max inv. Temp (K)
Nitrogen	621
Argon	794
CO_2	1500
Hydrogen	205
Helium	45
Neon	250

work during expansion against inner energy



JT-coefficient

$$\mu = \left(\frac{\delta T}{\delta p}\right)_H$$

μ>0 cooling

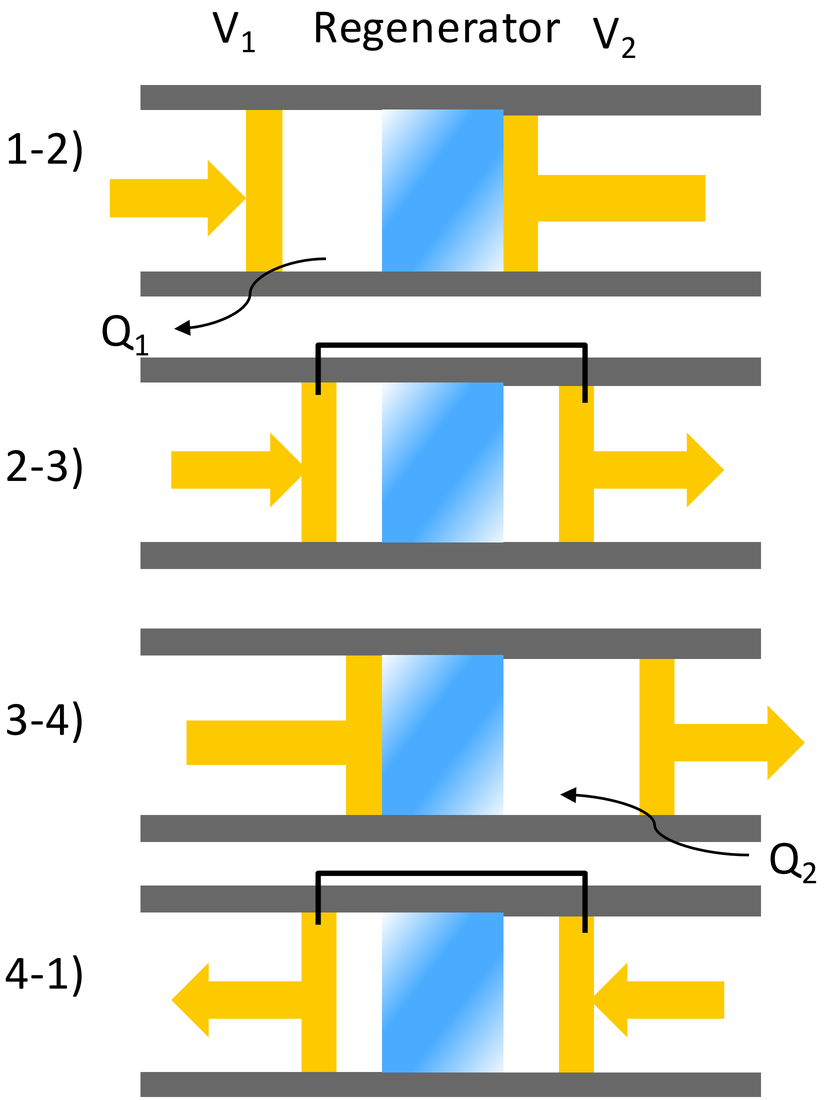
μ<0 warming

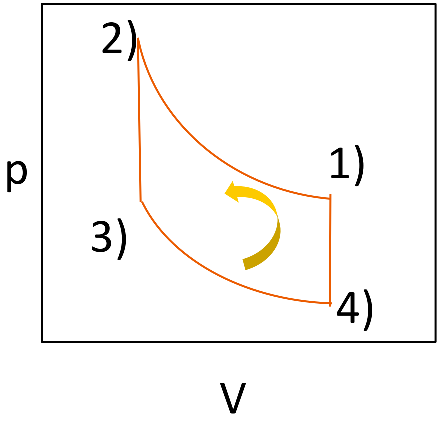
$$\mu_{\mathrm{JT}} = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]$$

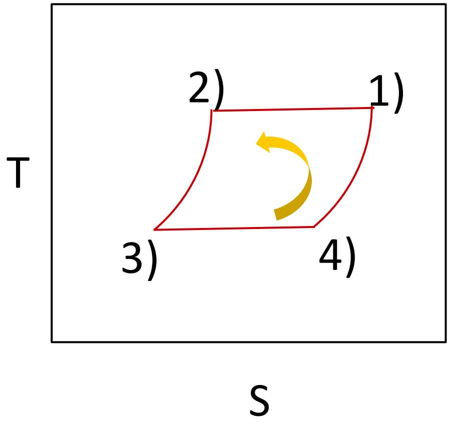
$$\approx \frac{1}{c_p}\left(\frac{2a}{RT} - b\right)$$

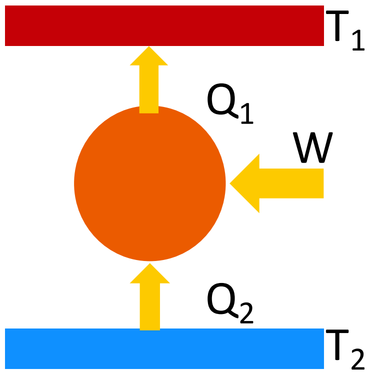
Cooling Cycles

closed cycle refrigeration (stirling cooler)









Carnot Cycle

$$Q_1 = Q_2 + W$$

$$\frac{Q_1}{T_1} \geq \frac{Q_2}{T_2}$$

$$W \geq Q_2\left(\frac{T_1}{T_2} - 1\right)$$

T_2 = 4.5K

T_1 = 300K

Q_2 = 1W ➔ W > 66W

Stirling Cooler – Example

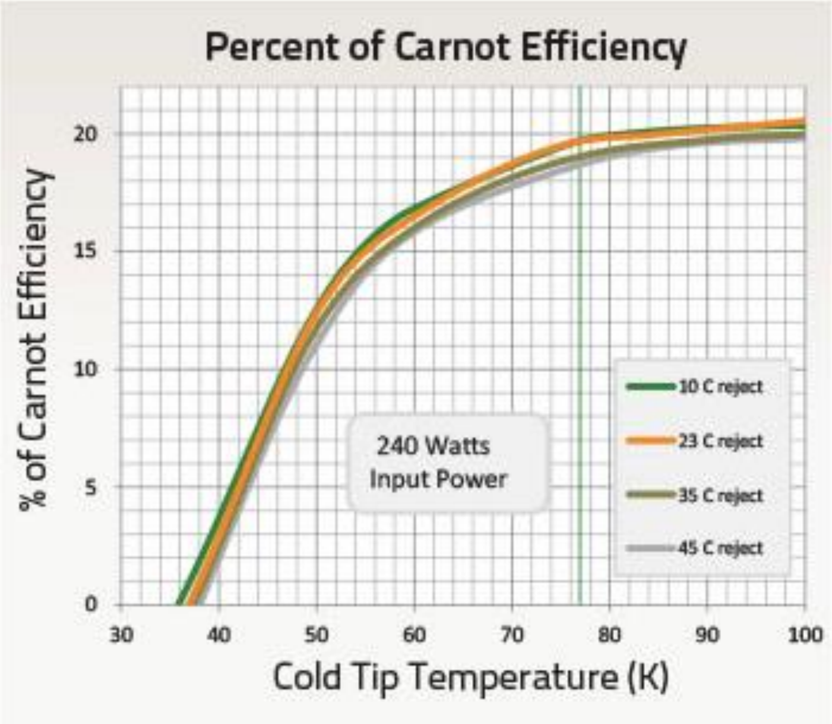
Cooling power@ 77K : 16W

Required input ideal process

Q = 16W(300K/77K-1) = 46W

Actual power input: 240W

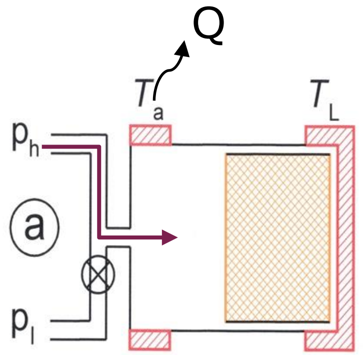
Efficiency : ~20% (46W/240W)



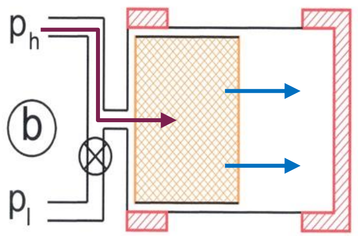
- Very compact
- Long lifetime
- Operates at 50Hz
- Large vibrations

https://www.sunpowerinc.com/products/stirling-cryocoolers/cryotel-cryocoolers/gt

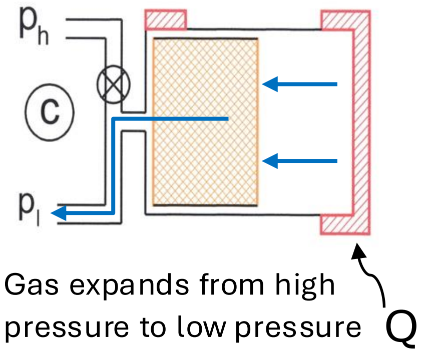
Gifford- McMahon Cycle



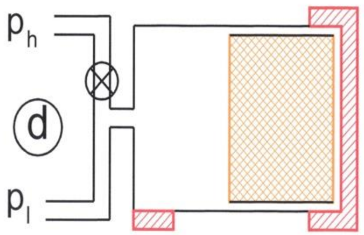
High pressure gas enters at warm end



Piston moves regenerator from lowT region
Gas passes and cools and V decreases
More gas flows from high pressure end



Gas expands from high pressure to low pressure
Expansion ideally isentropic
➔ Cooling of the gas that remains



Regenerator moves to lowT region
Cold gas cools the regenerator

https://en.wikipedia.org/wiki/Cryocooler#/media/File:GM_Cycle_Cryocooler02.jpg

Characteristics

- Efficiency not very high
- Spatial separation of compressor and cold end

→ Use efficient high-speed compressor (50/60Hz) + low speed displacer (0.5-2Hz)

→ low vibration levels

- No low temperature seals or valves
- Well suited for multistage systems

Windmeier, Cryogenic Technology, Wiley-VCH
DOI: 10.1002/14356007.b03_20.pub2
Timmerhaus, Advances in Cryogenic Engineering, Springer, DOI: 10.1007/978-1-4757-0522-5

Thermal Conduction

Thermal Conductivity

- transport property, the property of heat conduction
- sets the relation between a heat current density and the resulting temperature gradient

$$j = \dot{q} = -\kappa \frac{dT}{dx}$$

j: heat current per unit area [Wm^{-2}]
thermal conductivity [$W(Km)^{-1}$]
in general, anisotropic (tensor)

$$\frac{\dot{Q}}{A} = -\kappa \frac{\Delta T}{l}$$

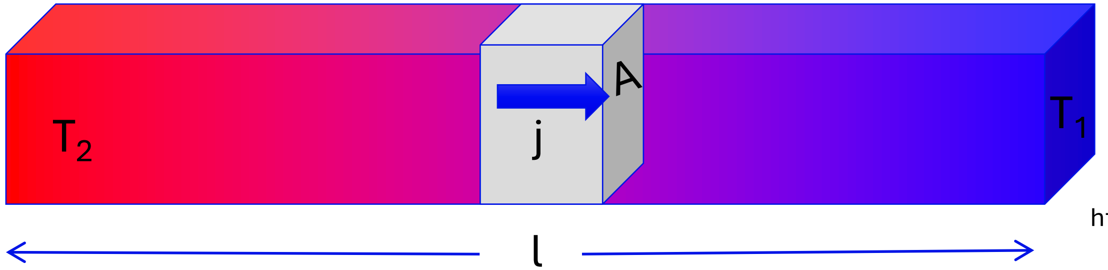
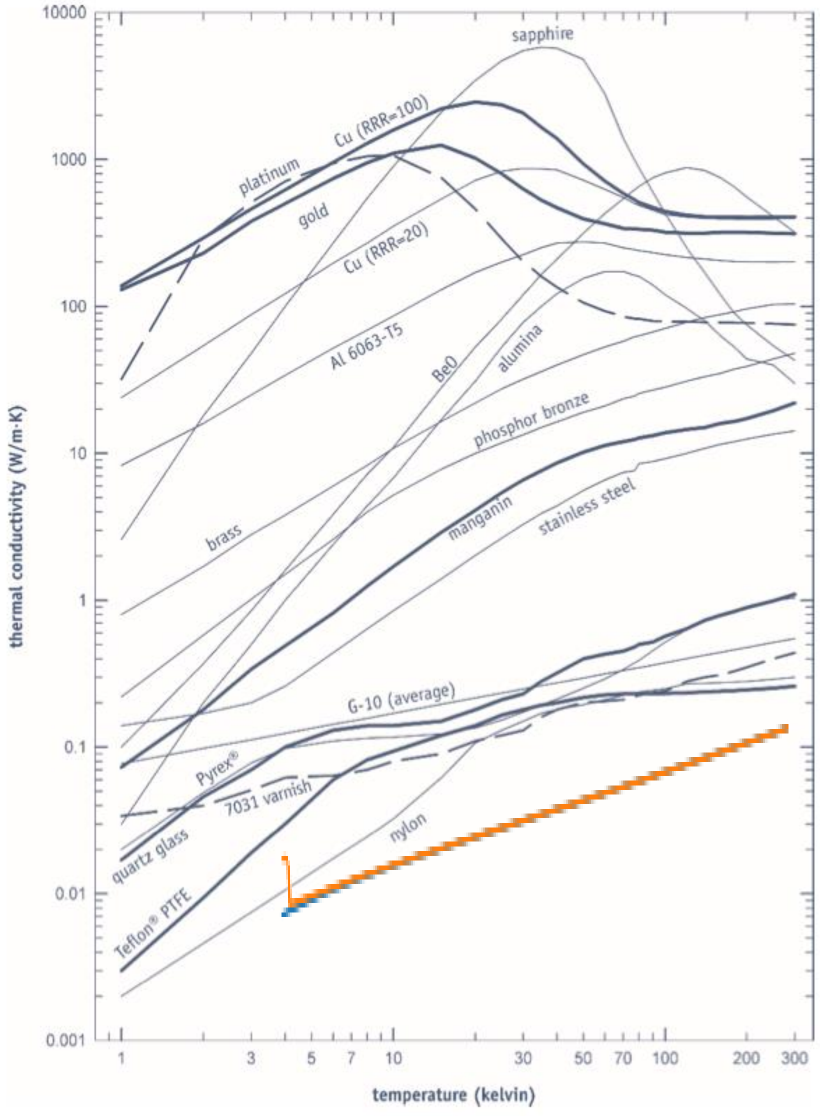
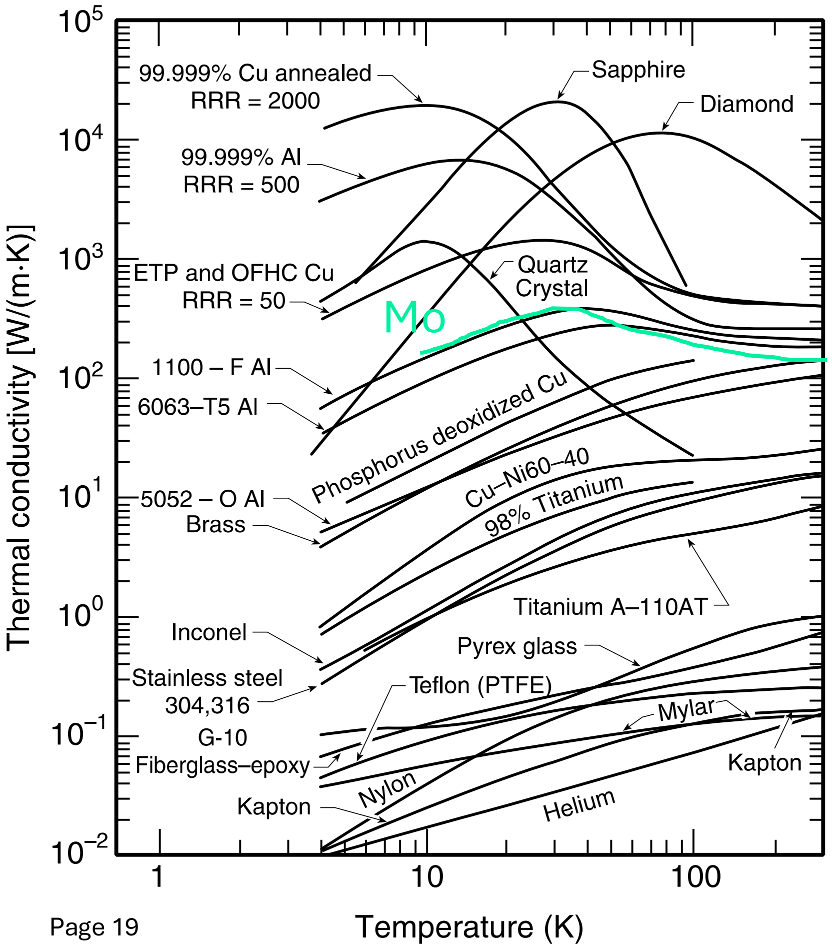


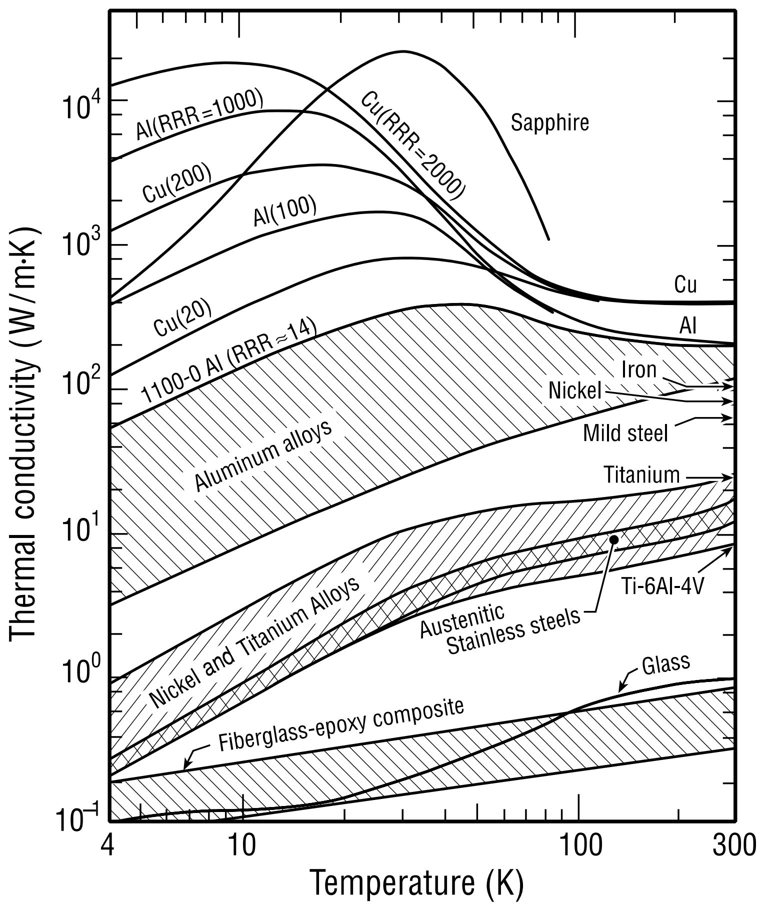
Figure 1—Thermal conductivity of selected materials



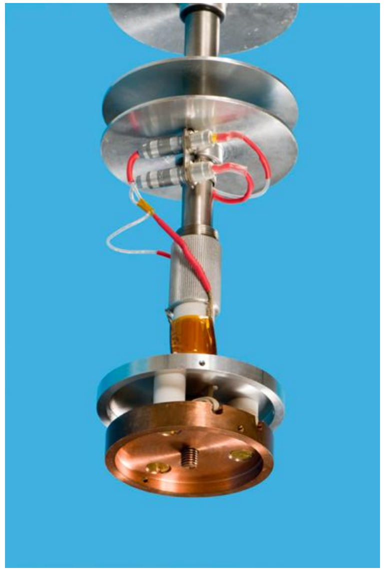
http://www.lakeshore.com/Documents/LSTC_appendixI_l.pdf

Thermal conductivity





Sapphire has a higher conductivity than copper in the range of 10-100K but can be used as thermal insulator at high or low temperatures



https://www.isis.stfc.ac.uk/Pages/CCR-Hot-Stage.aspx

Thermal Conductivity

"banana boat" equation

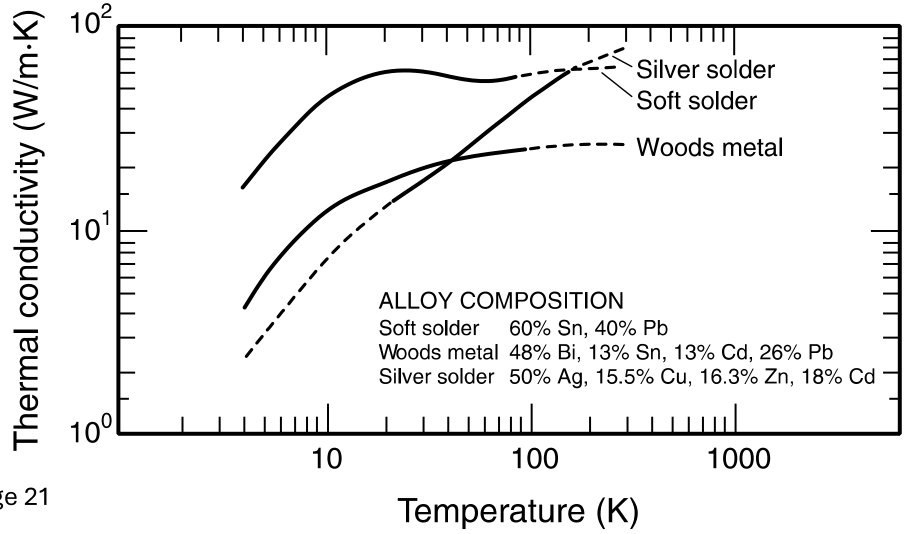
$$\kappa \approx \text{capacity} \times \text{velocity} \times \text{free path of travel}$$

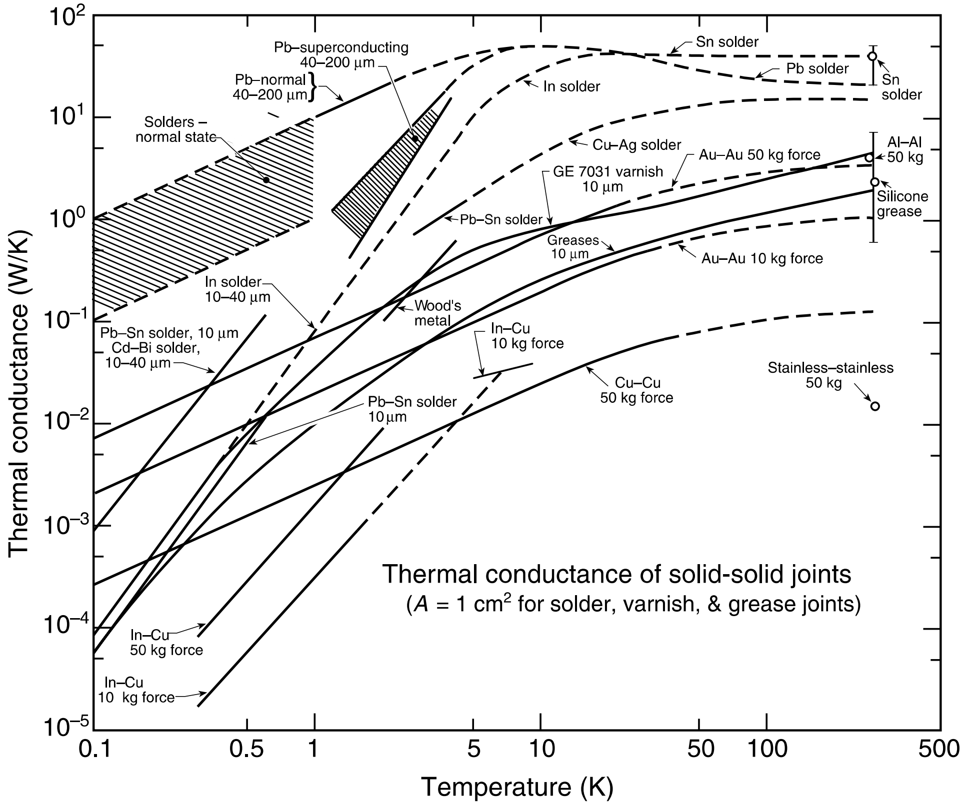
$$\kappa = \frac{1}{3} C\, v\, l$$

joining materials

Welding (best)   heatflow~Area
soldering   heatflow~Area
gluing   heatflow~Area
pressing (k~p)➔ heatflow ~ Force

low p: use grease
medium p: use indium >1MPa
high pressure: use gold plated

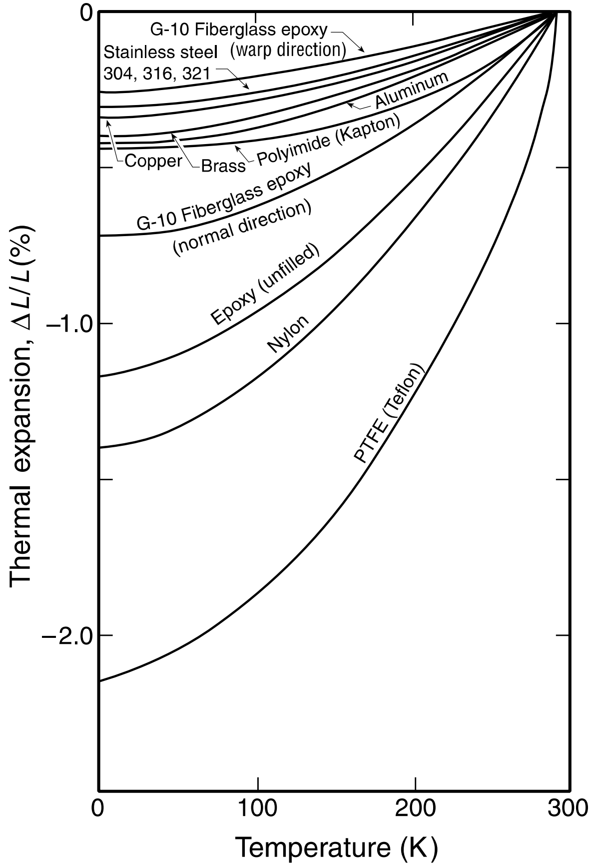


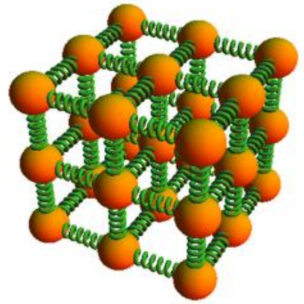


$$\dot{Q}(T) = \dot{Q}(445\,\mathrm{N}4\,\mathrm{K}) = \left(\frac{F}{445\,\mathrm{N}}\right)\left(\frac{T}{4.2\,\mathrm{K}}\right)^{\gamma}$$

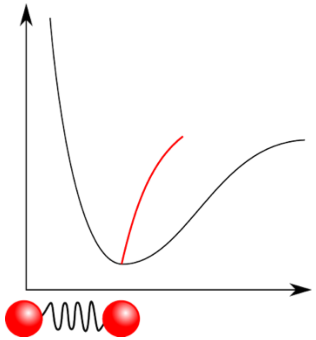
Ekin

Thermal expansion



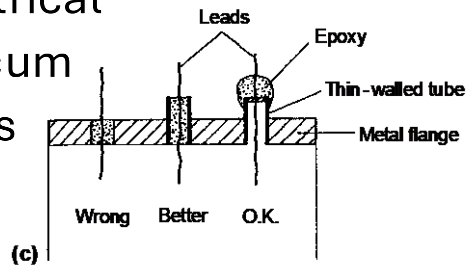


atoms are arranged in a regular lattice
held together by bonding forces
➔ they have some springiness

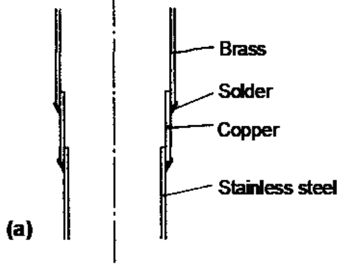


in a real potential
average position is energy
dependent (T dependent)
➔ thermal expansion

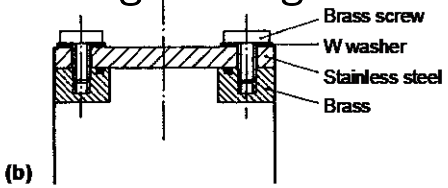
Electrical
Vaccum
feeds



joining cryo tubing



self tightening seal

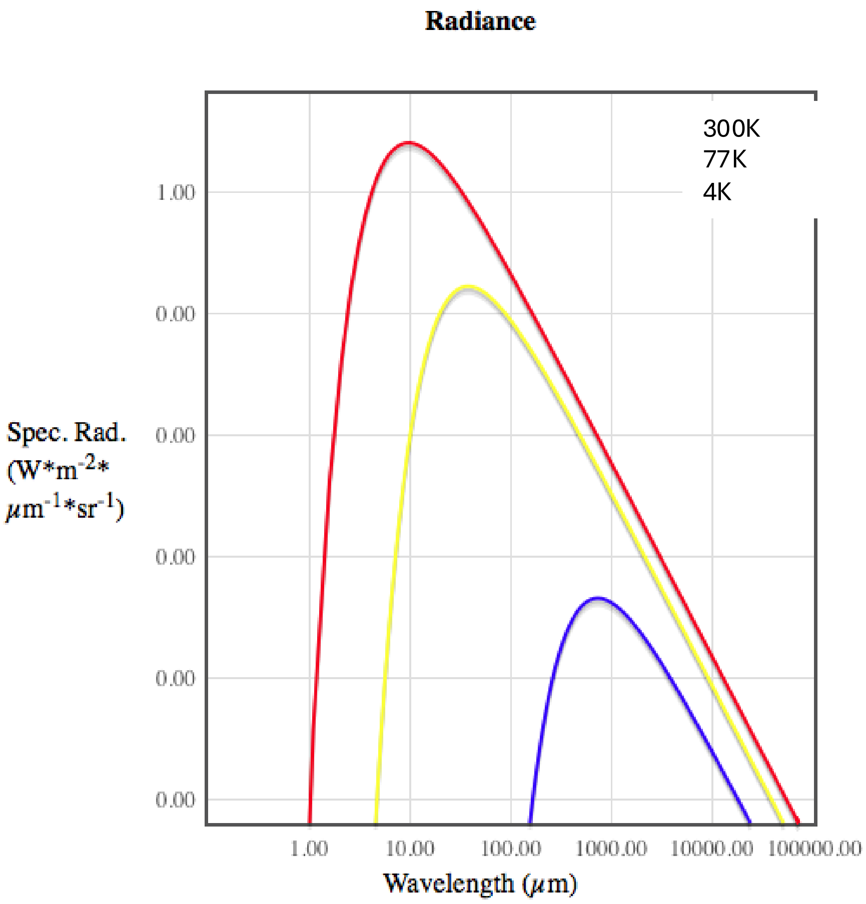


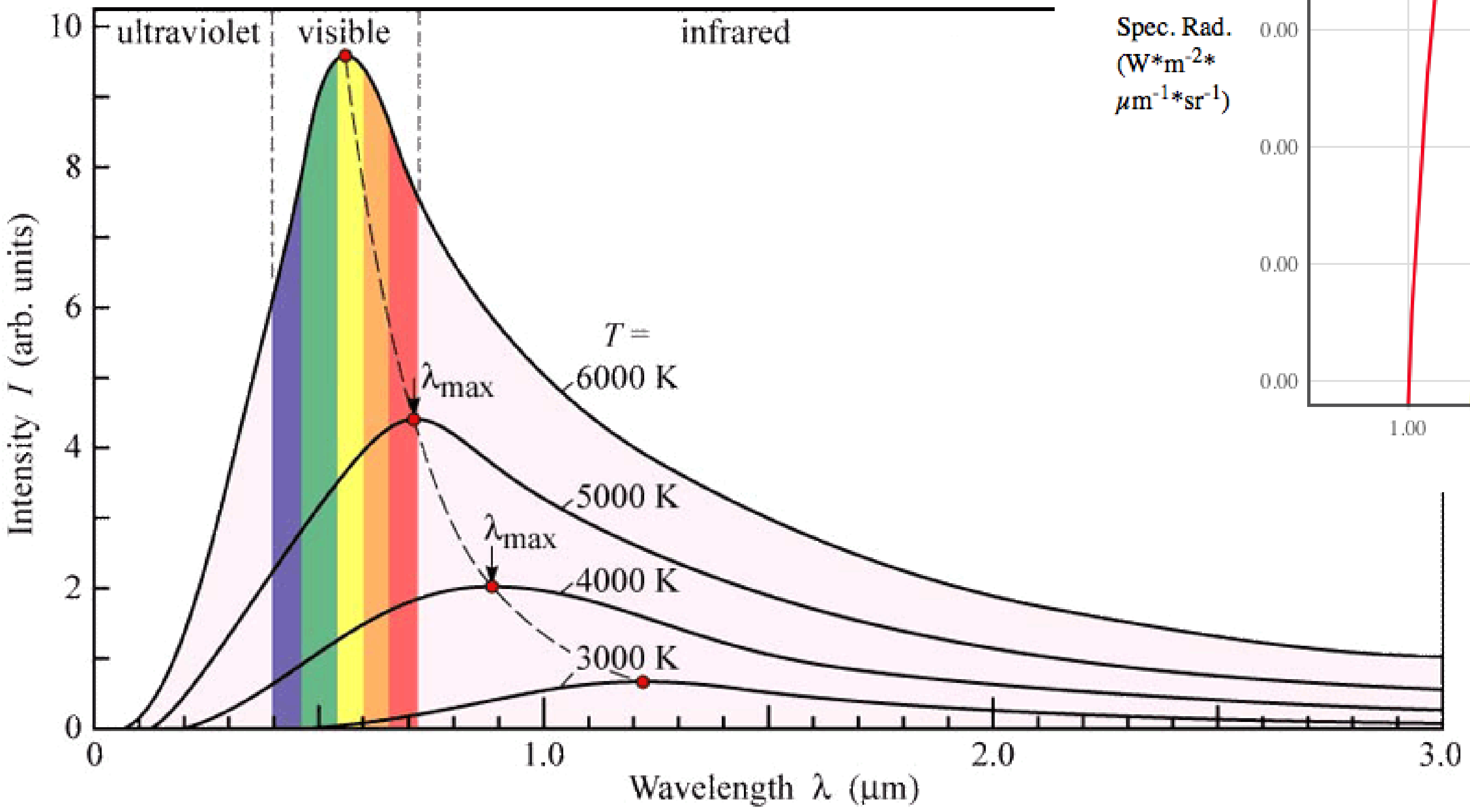
Pobell

Radiative Heat Transfer

Blackbody Radiation

- Any material emits radiation
- The intensity and wavelength depends on the temperature





Radiation Heat Load

radiation power of a black body radiator
(Stefan-Boltzmann law)

$$P = \sigma \cdot A \cdot T^4$$

Stefan-Boltzmann constant

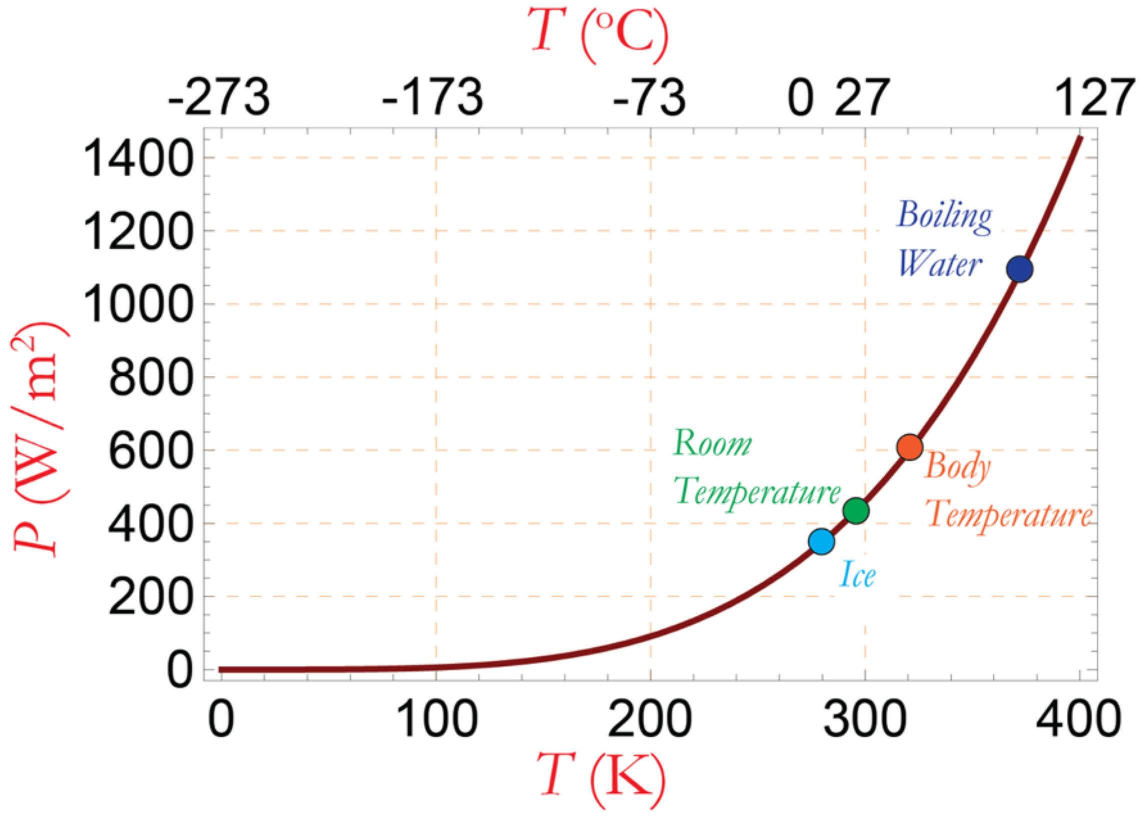
$$\sigma = 5.670373 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2\,K^4}}$$

A .. Surface Area

for a grey (non-ideal) body

$$P = \epsilon \cdot \sigma \cdot A \cdot T^4 \quad \epsilon = \frac{P_{\text{grey}}}{P_{\text{black}}}$$

material	typ. ε
paint	0.9
glass	0.9
Copper polished	0.05
Copper oxidized	0.85
Aluminium foil	0.04
Aluminium as bought	0.1



Radiation Heat Transfer

heat transfer between surface A_1 and A_2
P… radiation power
F… view factor

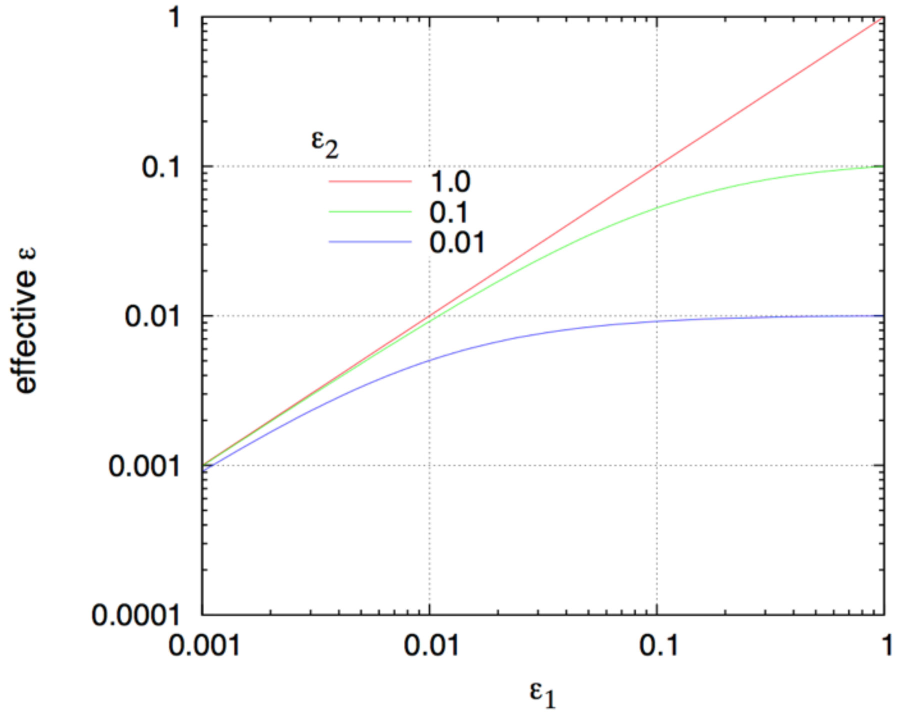
$$\dot{Q} = A_1 \cdot P_1 \cdot F_{1\to2} - A_2 \cdot P_2 \cdot F_{2\to1}$$

using $A_1 \cdot F_{1\to2} = A_2 \cdot F_{2\to1}$

$$\dot{Q} = \sigma \cdot A_1 \cdot F_{1\to2}(T_1^4 - T_2^4)$$

for 2 long concentric cylinders:

$$\dot{Q} = \sigma \cdot \frac{A_1}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}(\frac{1}{\epsilon_2} - 1)}(T_2^4 - T_1^4)$$



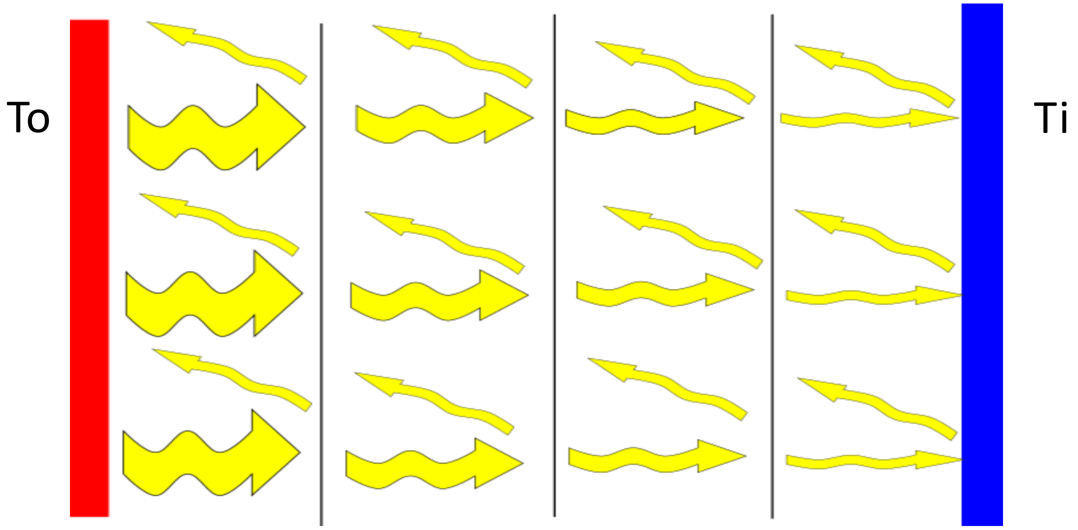
T of hot surface (K) neglecting T_{cold}	max. heat load (mW/cm^2)
300	46
77	0.2
4	1.4×10^{-6} ($1 nW/cm^2$)

Multilayer Super Insulation

$$\dot{Q} = \frac{\varepsilon \sigma A (T_o^4 - T_i^4)}{N+1}$$

- N = number of shields

- Adding 1 shield will half the heat load
- Shield material and thickness is not important
- Shields are thermally floating



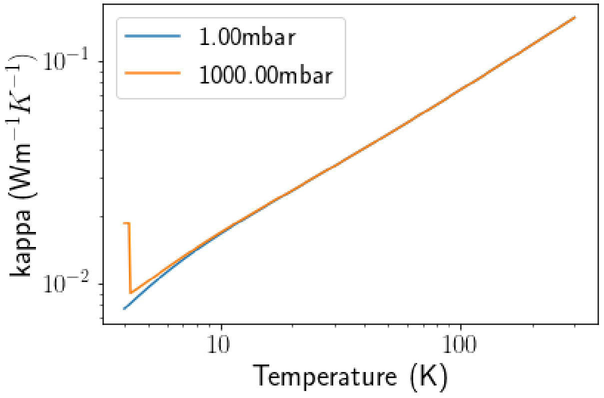
https://fys.kuleuven.be/iks/wi/WITCH/images/photos/cryo_oxf02.jpg/image_large

Heat Transfer by Convection

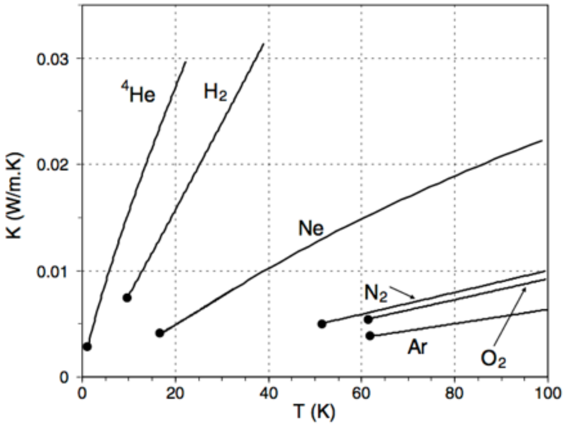
Exchange Gas

hydrostatic limit

l << d; l..mean free path



thermal conductivity independent of pressure

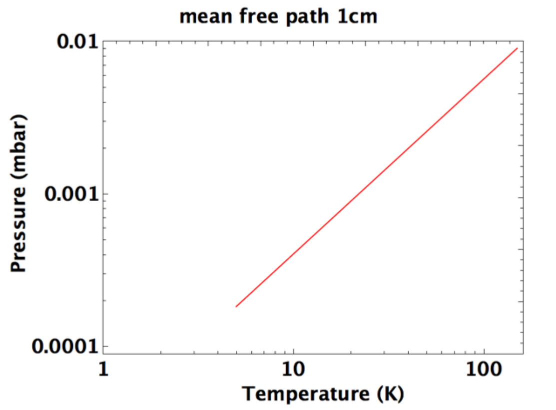


Catarino, *Cryogenics* **48** (2008),17-25

mean free path for Helium

$$l[\mathrm{cm}] = 2.87 \times 10^{-3} \frac{T[\mathrm{K}]^{1.147}}{p[\mathrm{Pa}]}$$

Ekin 2006



free molecular regime

l >> d; l..mean free path

thermal conductivity is a function of pressure and energy transfer to the surfaces (accommodation coefficients)

For 2 surfaces with 1 Surface at room temperature and Helium as gas:

$$\dot{Q}[\mathrm{W}] = 2.1 \frac{0.5}{1 + 0.5\frac{A_i}{A_o}} A_i[\mathrm{m}^2] p[\mathrm{Pa}] \Delta T[\mathrm{K}]$$

for T_{low} : 4K

A : $1 m^2$

p : 10^{-7}mbar

heat load: 2mW

White&Meeson, 2002

Summary

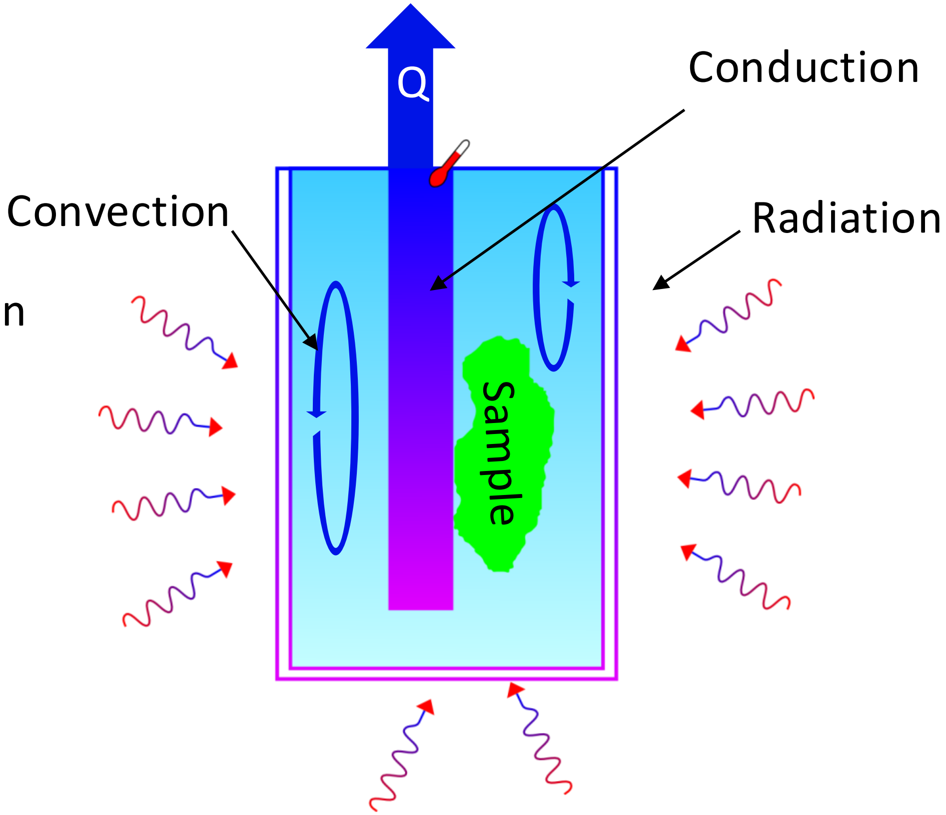
Cooling mechanisms

Cooling by evaporation	Gas cooling	Closed cycle cooling
Latent heat	Enthalpy of	Cyclic Heat pump
Vapor pressure	warming gas	GM-coolers

Heat Transport mechanisms

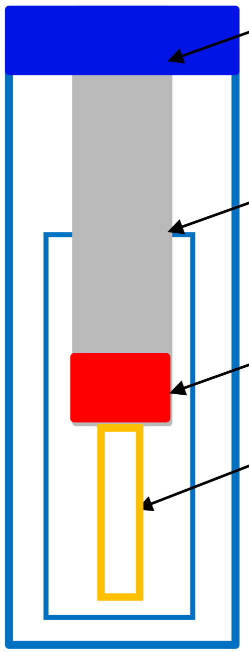
We did not talk …

- Peltier cooling/heating
- Cooling by dilution or solution
- Radiative cooling
- Magnetic cooling (adiabatic demagnetisation)



Cryostats

Cold finger cryostats – radiative heat load



Assume a sample container @4K
Al length = 60mm; diam 30x0.5mm

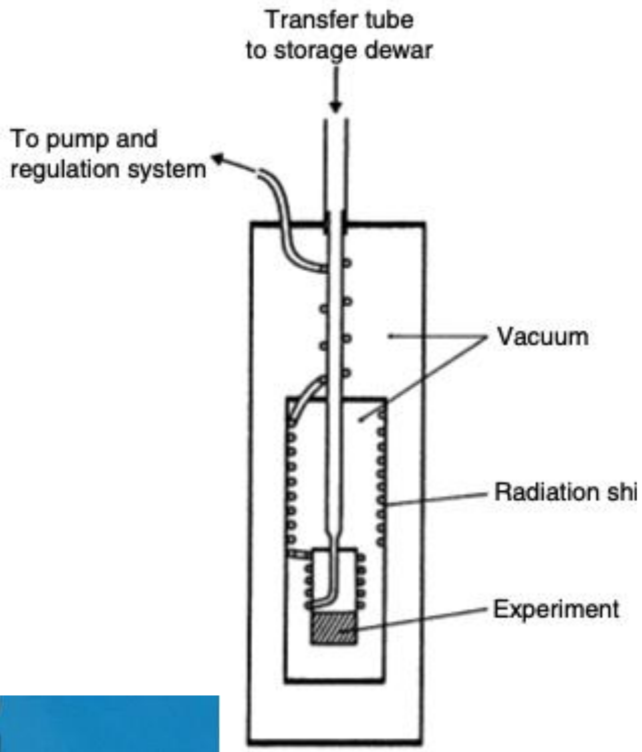
Thermal conductivity Al : k = 0.1W/Kcm
Rad. heat load from 77K :0.2mW/cm^2

Cylinder surface area: 64 cm^2

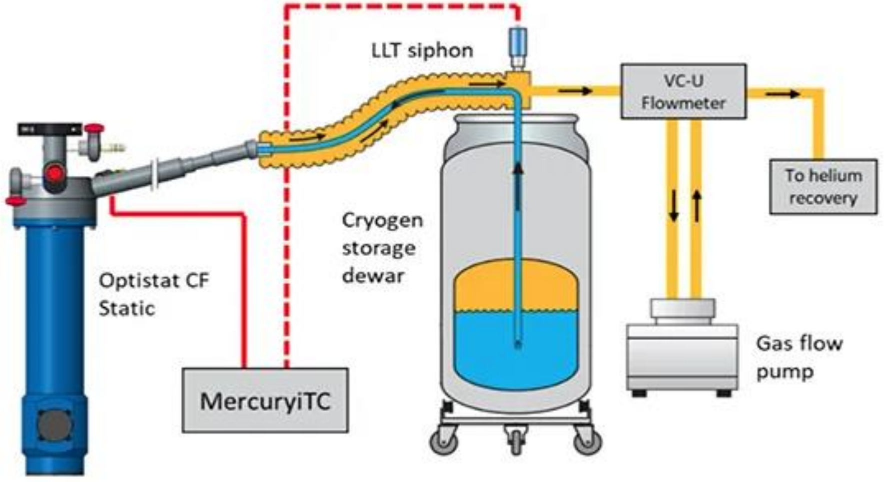
Heat load : 13 mW
Thermal gradient: $\Delta T = \frac{\dot{Q} \cdot l}{\kappa \cdot A}$

dT = 1.6K

Cold Finger Cryostat – Helium Flow



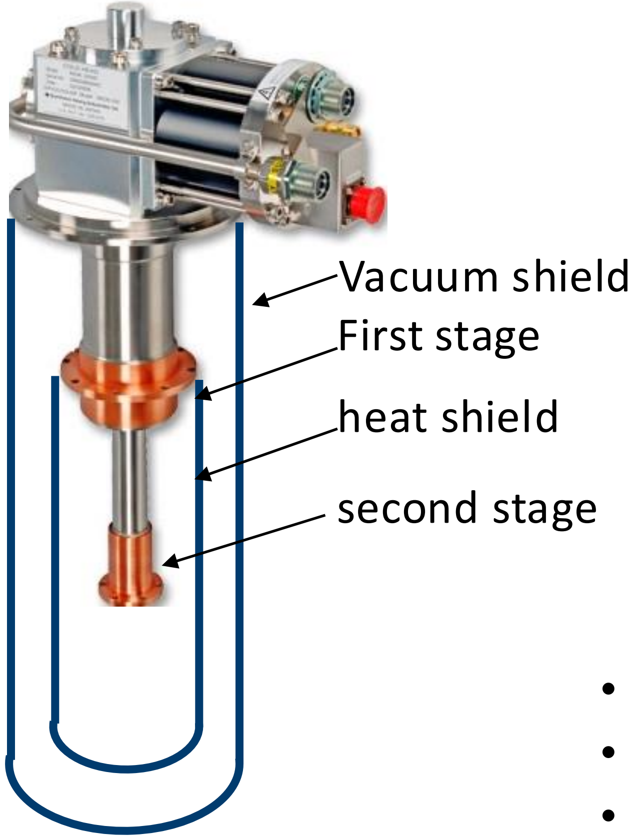
Pobell, ISBN: 978-3-540-46356-6

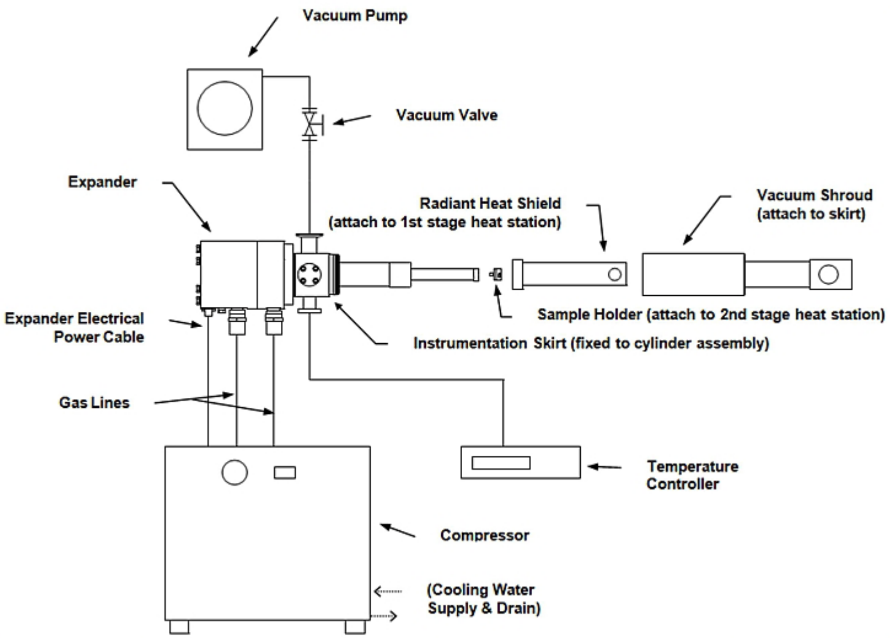


- Full setup requires a storage dewar and low loss transfer line
- Operates by using a mix of He-gas and He-liquid
- Base temperature ~2.3K
- Lower Temperature require JT-stage

Lakeshore flow cryostat

Cold finger cryostats – GM closed cycle



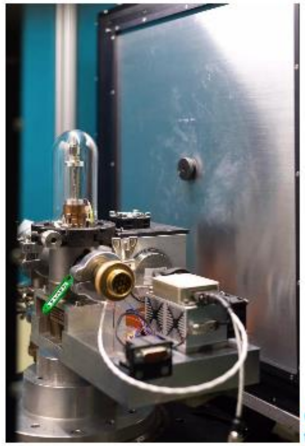


www.arscryo.com

- heavier than a flow cryostat
- simple to set-up and operate
- No liquid Helium infrastructure
- For GM-coolers independent on the operation position (works also up side down)
- Tbase ~4K

Cold Finger Cryostat – examples

Stirling cooler BERII HZB



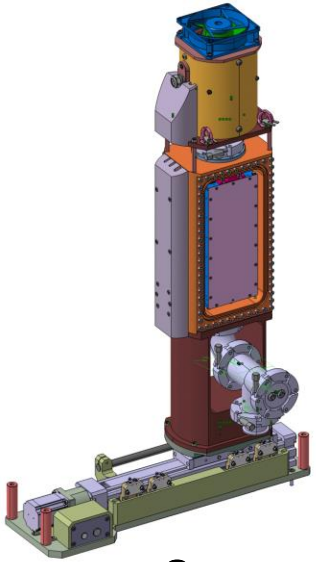
Cryostat (CC-SE5) in front of transmission detector of E11

Mini refrigerator (AIM Stirling cooler SL400) in a the custom made assembly for space restricted environments, i.e. between the transmission and backscattering detectors of „FALCON“

Specifications

Cold finger	*60 .. 320 K*
High temperature option with quartz sample tube	*80 .. 450 K*
Cooling performance	*t(≤ 70 K) ≈ 1.5 h*

Stirling cooler BerylliumFilter FOCUS@PSI



Operate at <100K

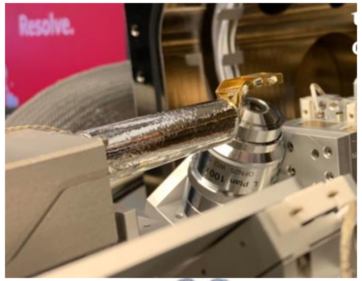
Nitrogen JT cooler

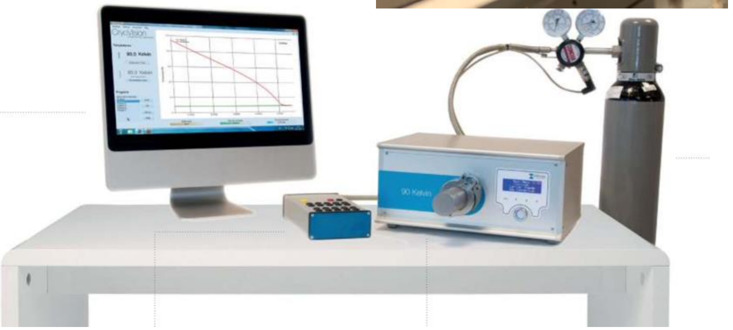
Uses recuperating compressor or Gas bottle

No moving parts

Extremely fast cooldown

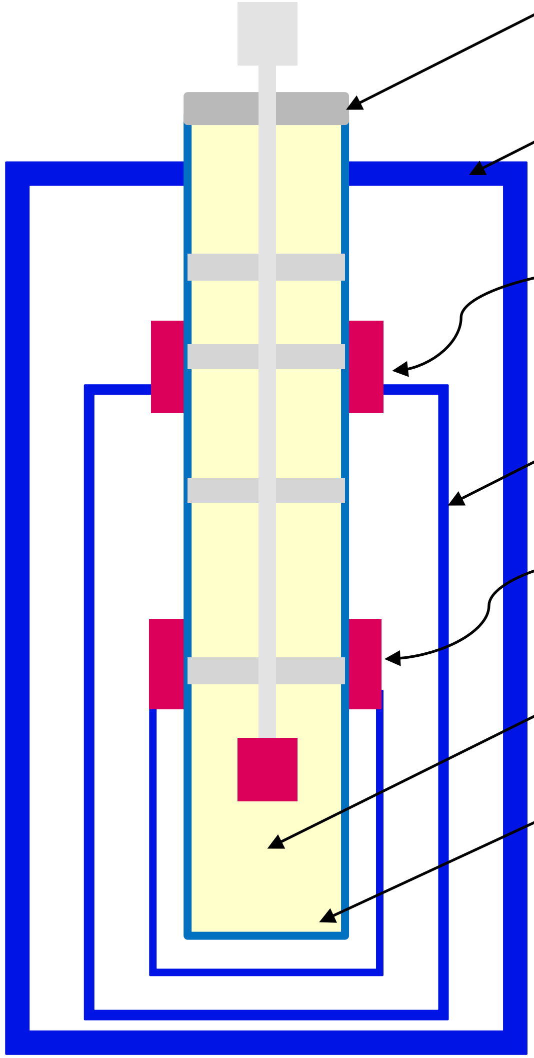
Tbase <90K





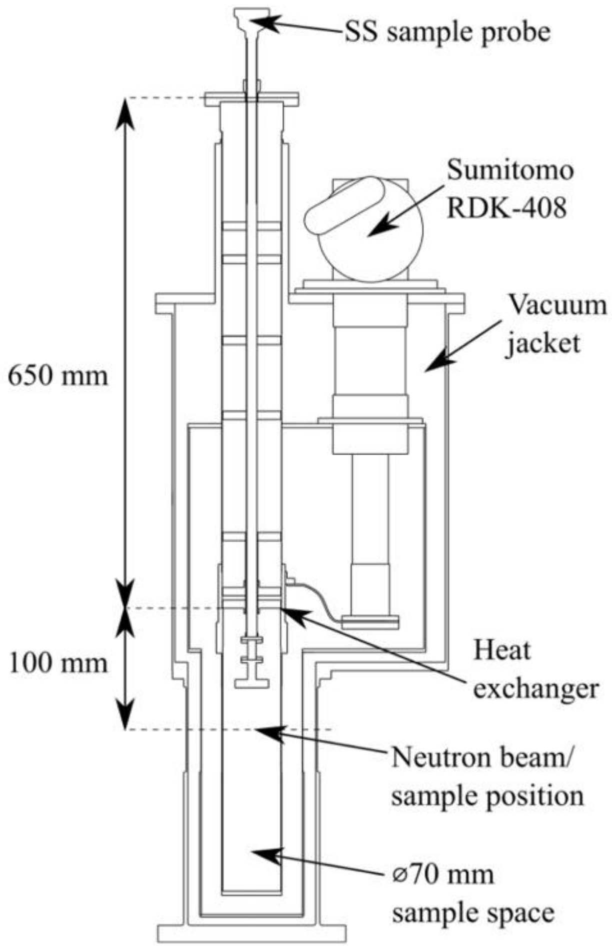
https://www.elliotscientific.com/Kryoz-CryoLab-S-SP-MSG

Top Loading Cryostats



- simple sample mounting
- Sample thermalisation via exchange gas
- Small thermal gradients at the sample
- Fast sample change
- Slower cooling
- Easily extendable (Magnet, sample stick)

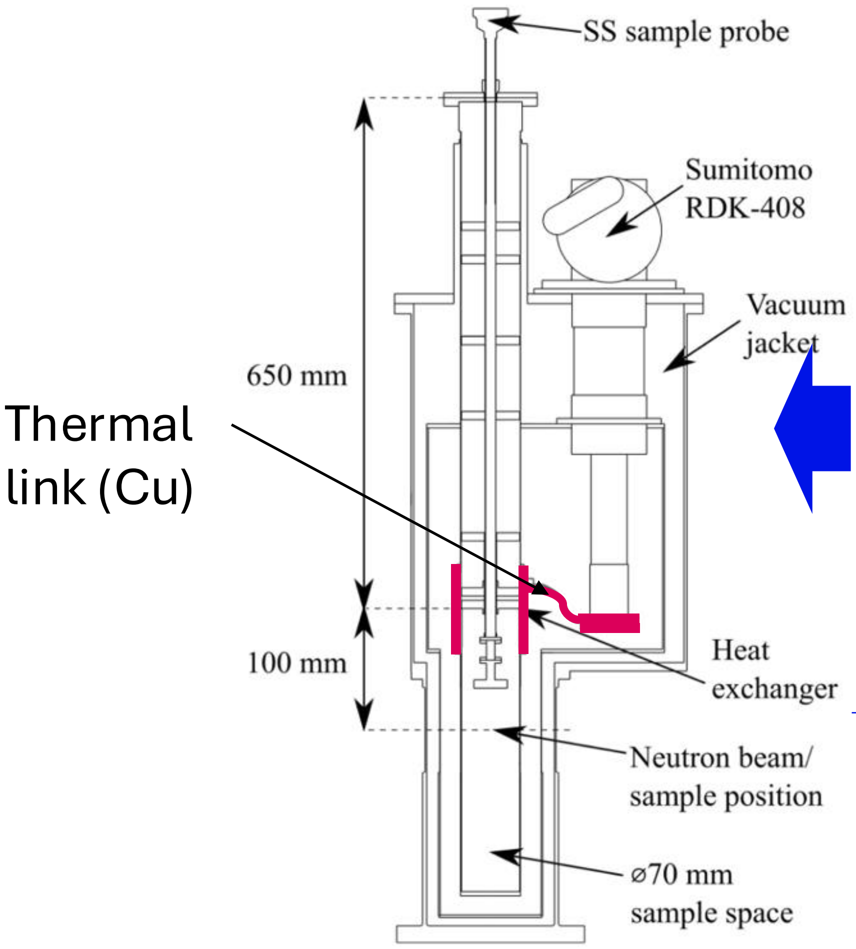
Top Loading Cryostats – Cryocooler



- Thermalise sample stick at 2 positions
- Direct connection to the Cryocooler stages
- Fast cooling
- Simple construction
- Easy to handle and maintain
- Needs compressor and "flex" lines
- Precool near the instrument
- Tbase <~4K

A S Scientific top-loading cryofurnace (see ref https://doi.org/10.1107/S1600576719016704

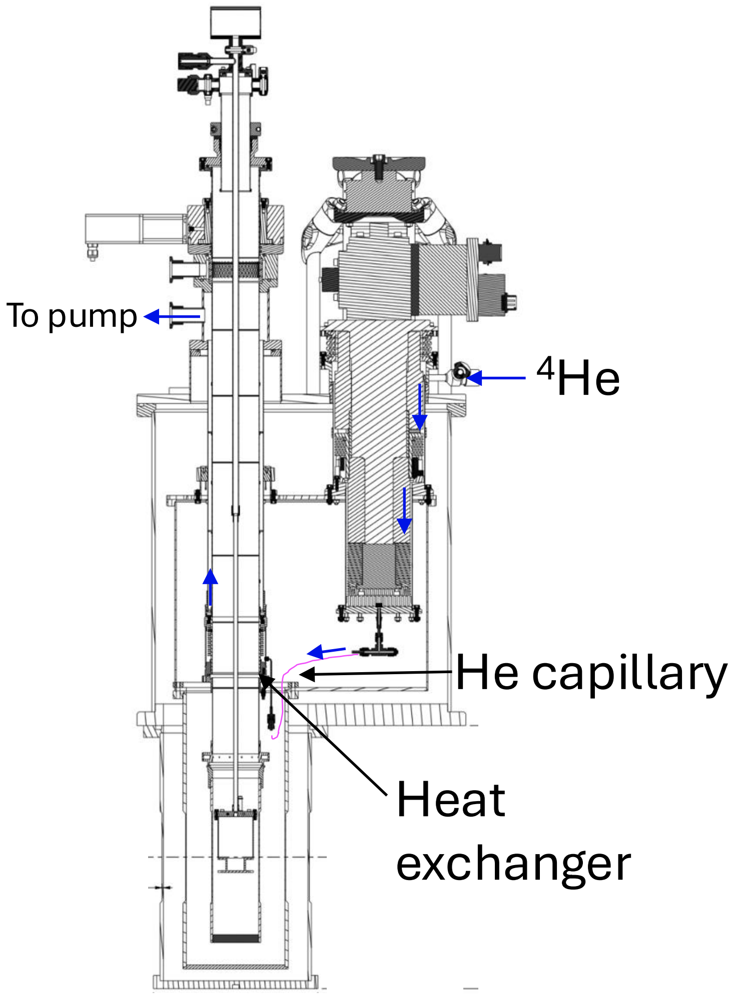
Top Loading Cryostats – Cryocooler



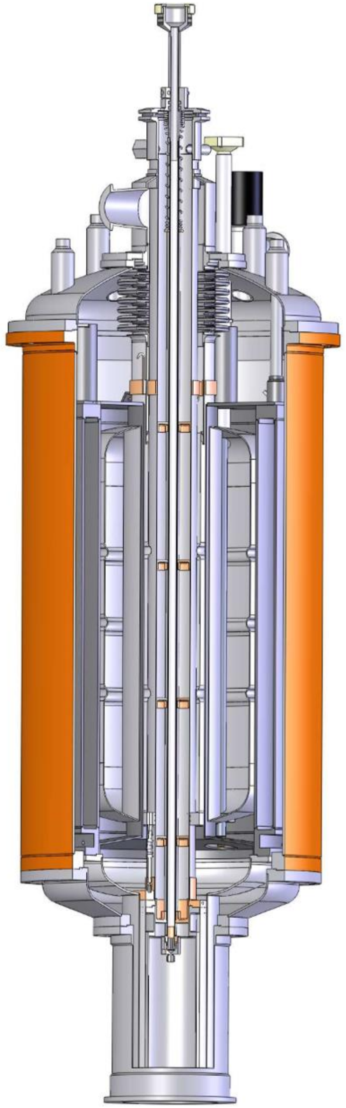
A S Scientific top-loading cryofurnace (see ref https://doi.org/10.1107/S1600576719016704

- Thermalise sample stick at 2 positions
- Direct connection to the Cryocooler stages
- Fast cooling
- Simple construction
- Easy to handle and maintain
- Needs compressor and "flex" lines
- Precool near the instrument
- Tbase <~4K

- Add JT stage to reach
- Tbase <1.8K
- Limited cooling power
- ➔ slow
- Requires small gas handling



Top Loading Cryostats – Orange Cryostat



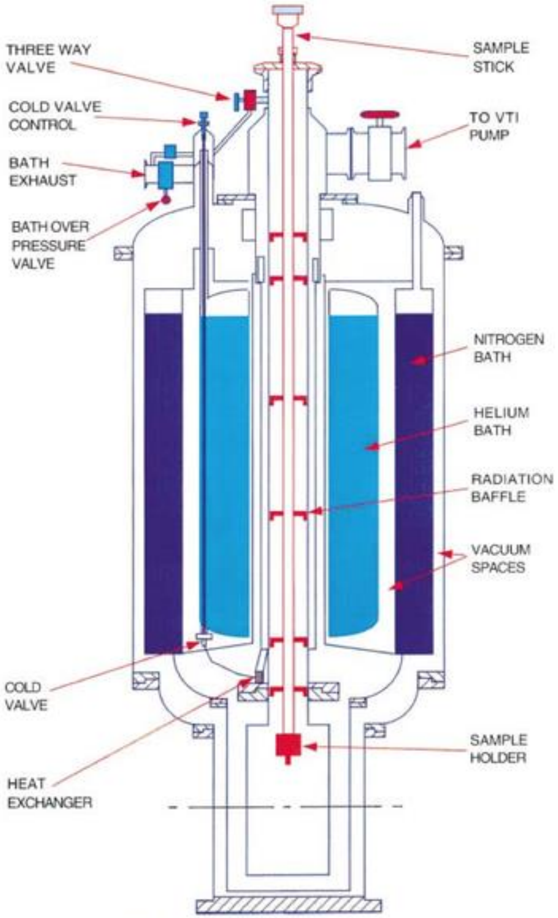
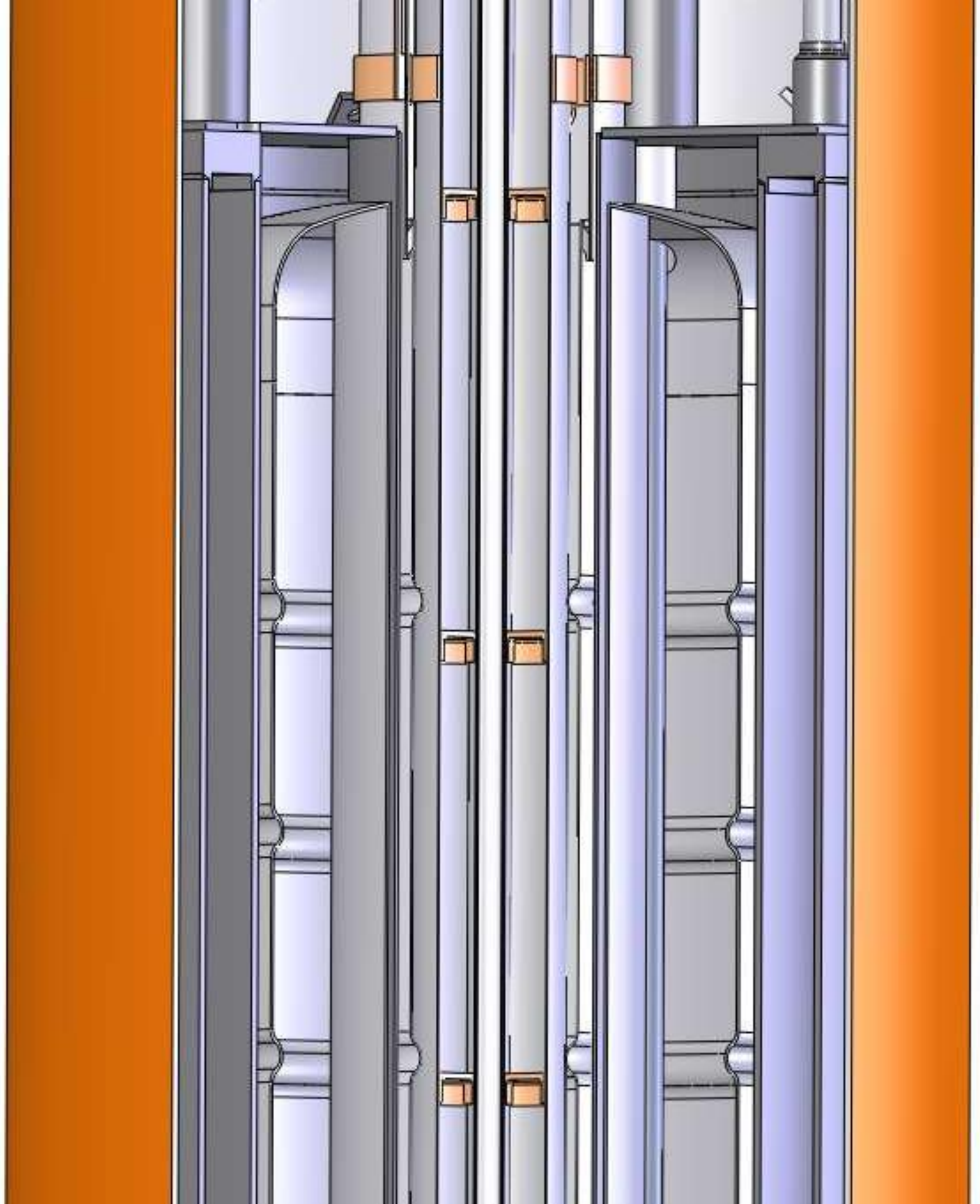
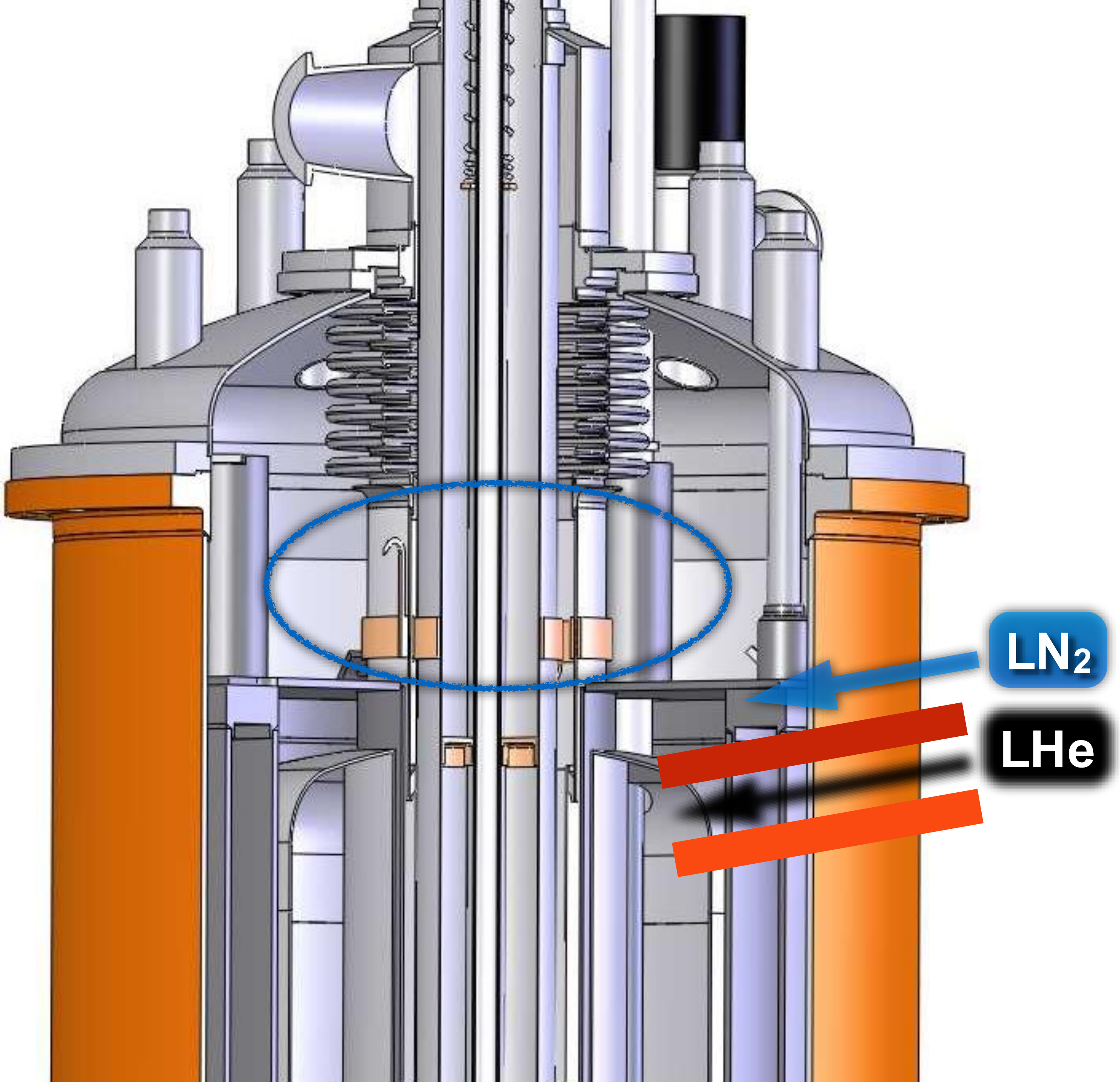


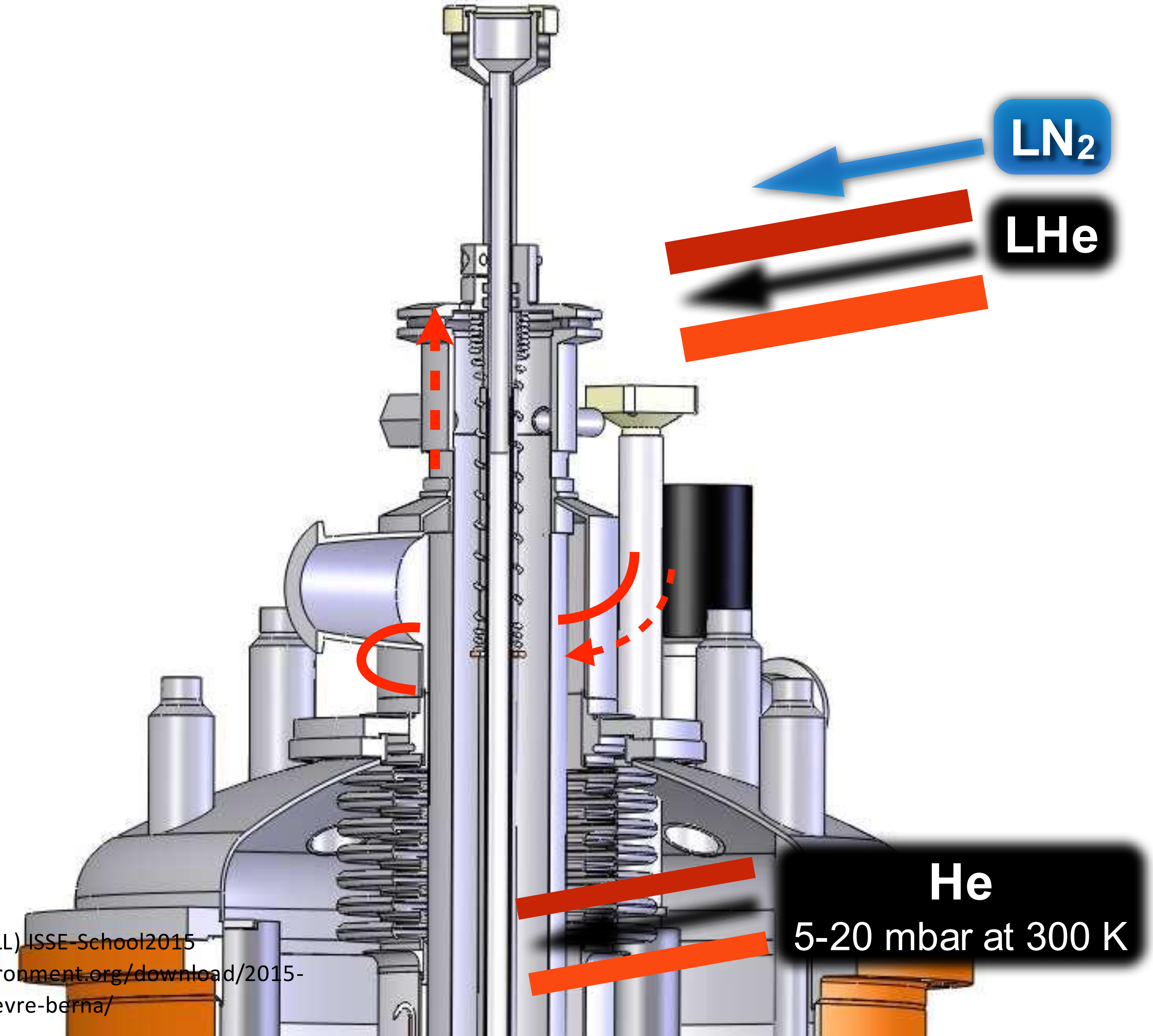
Fig. 2. Schematic of Orange Cryostat.

- Nitrogen bath for the thermal shielding
- Helium bath serves as reservoir to cool sample space via a JT-stage
- A load of Helium and Nitrogen lasts about 1-2days.
- Can be operated to 4K without pump
- Fast cooling can be transported and installed when cold



PSI





PSI

E. Lelievre-Berna (ILL) ISSE-School2015
https://sampleenvironment.org/download/2015-se-school-eddy-lelievre-berna/

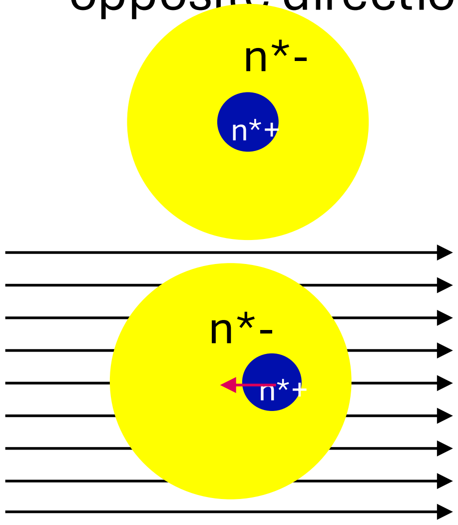
Bonus

Electric Fields

Electric fields in Matter

induce dipole moment

- E-field applied to atom (neutral) pushes nucleus (+) and electrons (-) in opposite direction

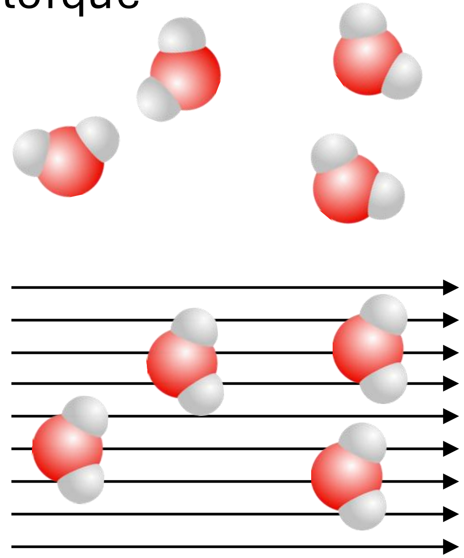


$$|p| = \alpha |E|$$

Polarizability a is isotropic

Permanent dipole moment

Pos and neg part of dipole experience forces in opposite directions ➔ torque



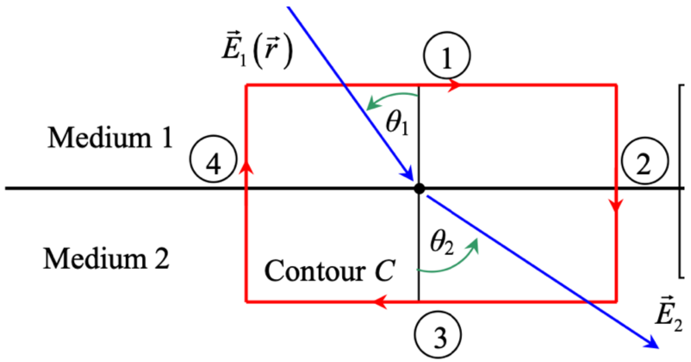
Polarizability a is anisotropic

$$p_x = \alpha_{xx}E_x + \alpha_{xy}E_y + \alpha_{xz}E_z$$

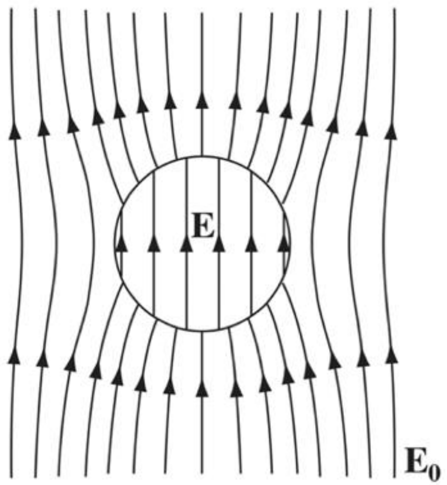
$$p_y = \alpha_{yx}E_x + \alpha_{yy}E_y + \alpha_{yz}E_z$$

$$p_z = \alpha_{zx}E_x + \alpha_{zy}E_y + \alpha_{zz}E_z$$

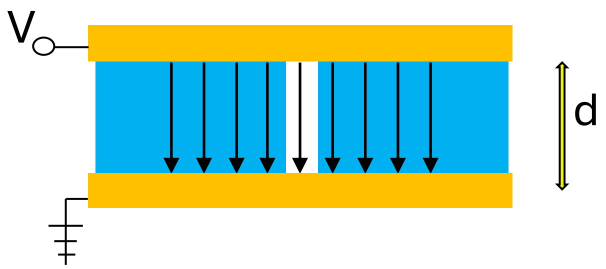
Electric fields in Matter – boundary effects



Tangential component not affected



Parallel Plate Capacitor

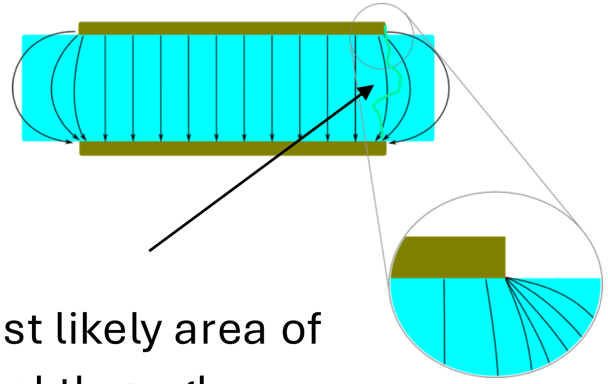


- Electric field easy to calculate $E = \frac{V}{d}$
- Field direction well defined
- Field strength constant (not on edges)
- Field inside the Dielectric

$$D = \varepsilon_0 \varepsilon_r E$$

https://hep.physics.illinois.edu/home/serrede/P435/Lecture_Notes/P435_Lect_10.pdf
http://www.phys.nthu.edu.tw/~hf5/EM/lecture%20note/EM04.pdf

Limiting effects – electric breakdown



Most likely area of breakthrough
Field enhancement at edge factor 3-4

Material	Breakdown field kV/mm
PTFE	45
Kapton	118
Mylar	75
Sapphire	35

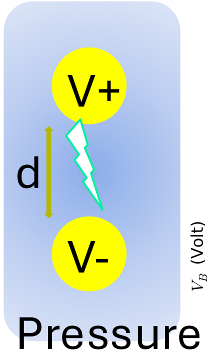
Intrinsic breakdown
collision ionisation of conduction electrons
emission from bulk impurity centres
field emission from the electrodes.

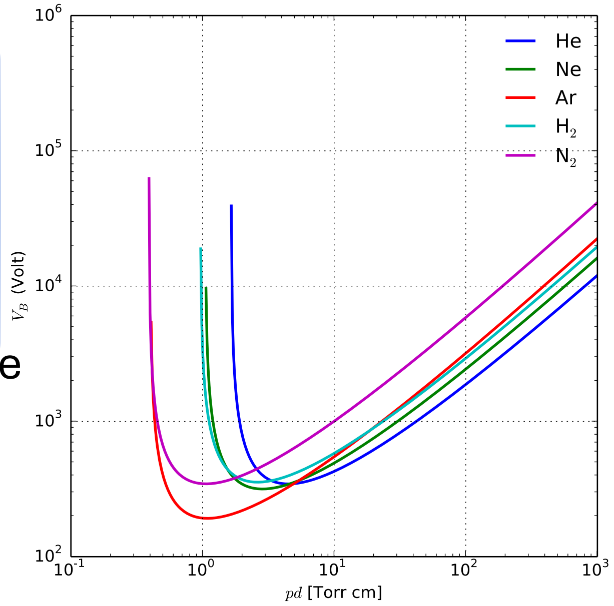
Thermal breakdown
Temperature increases the dielectric loss
Increase in dissipation (Joule heating)
Thermal run away

Discharge breakdown
Porosity in the sample

Beak down – in exchange gas

- Cooling the samples by conduction limits applicable field
- Paschen Law relates beakdown voltage to the pressure distance product
- Lowest breakdown voltage of Helium gas: 300V
- Stressareas (edges) worsen the effect

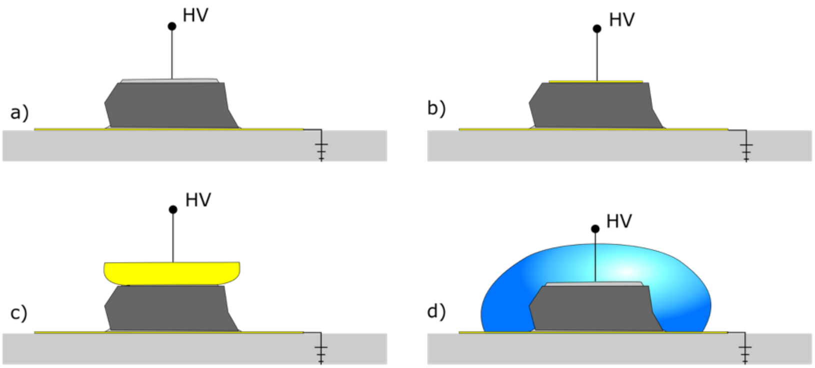




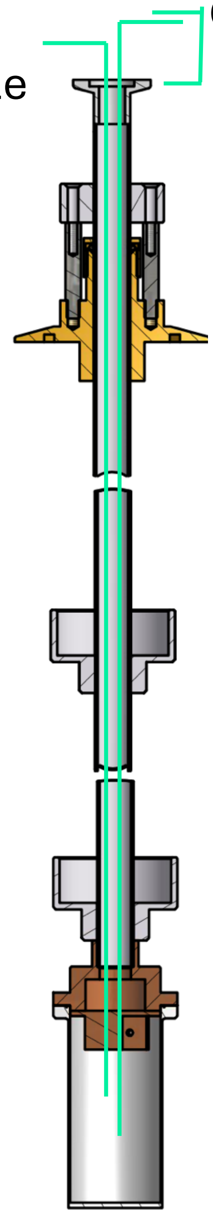
Solutions:

- Experiments in Vacuum
- Work on electrode design
- Immerse sample and electrode in stronger dielectric material (oil)

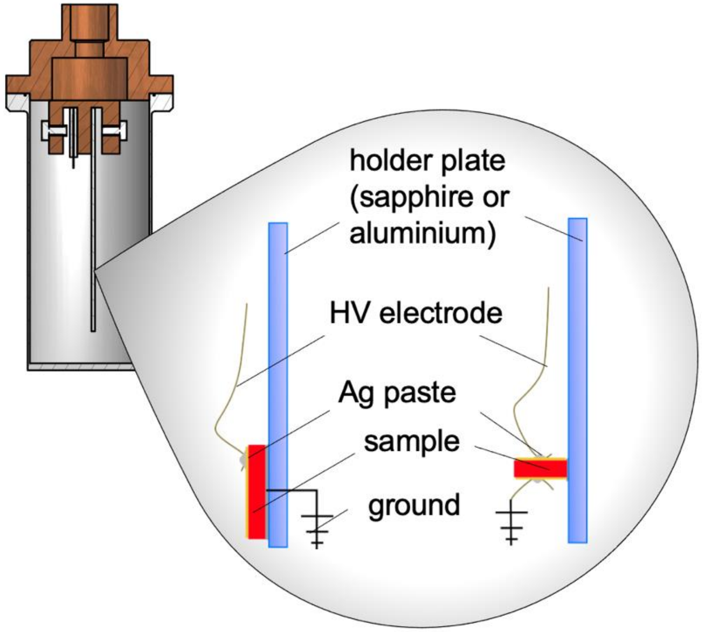
e.g. Fomblin (fluorinated Grease) for low Neutron background

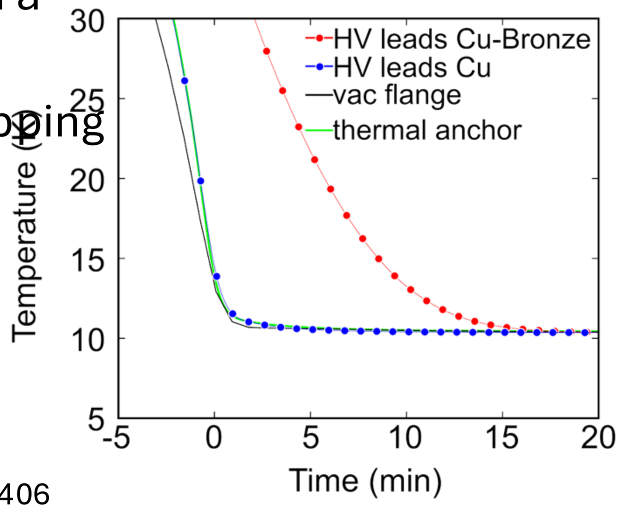


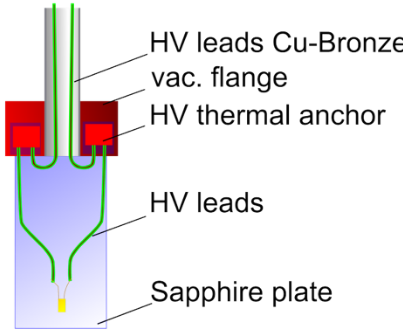
HV stick PSI – Design principles



- Sample is installed in a Vacuum container
- Parallel plate geometry
- Sample is mounted to a sapphire plate
- Alignment of E to B or Scattering plane can be chosen easily
- Sample thermalisation via Electrodes
- Ground the sample with a grounding plug
- Change polarity by swapping electrodes
- Typ. 50kV/cm (V_{max}:5kV)

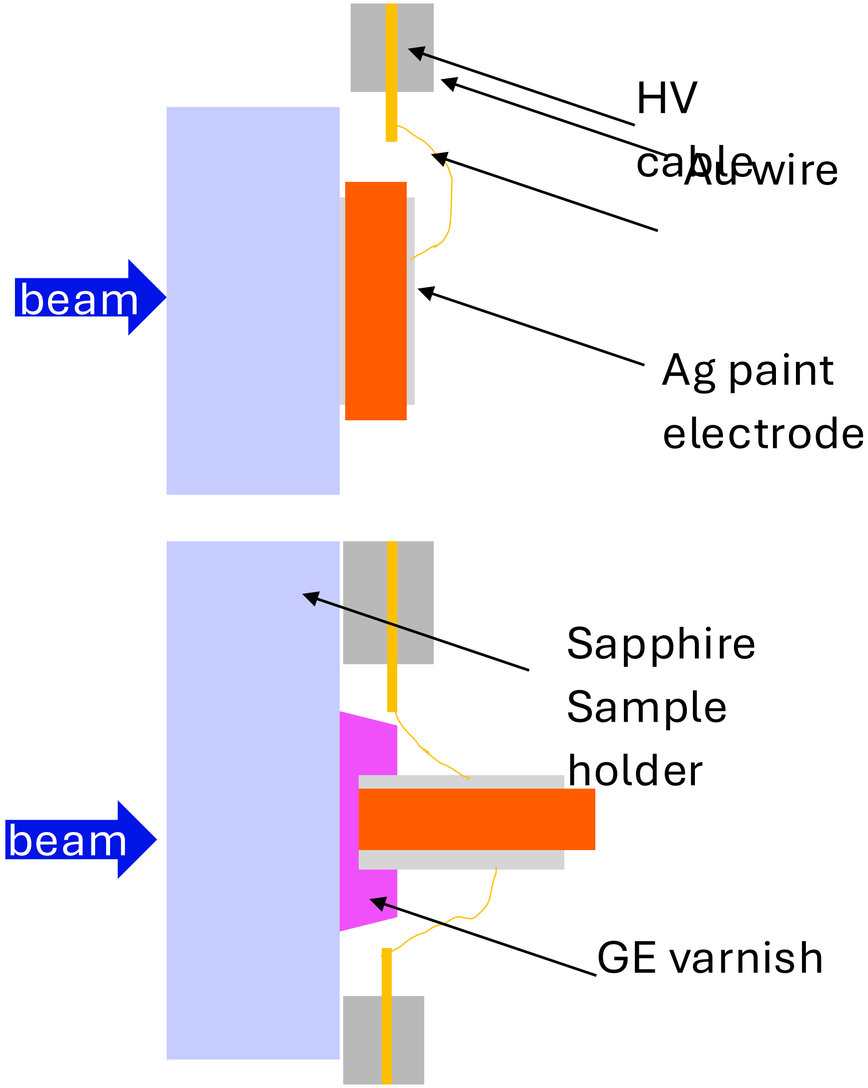


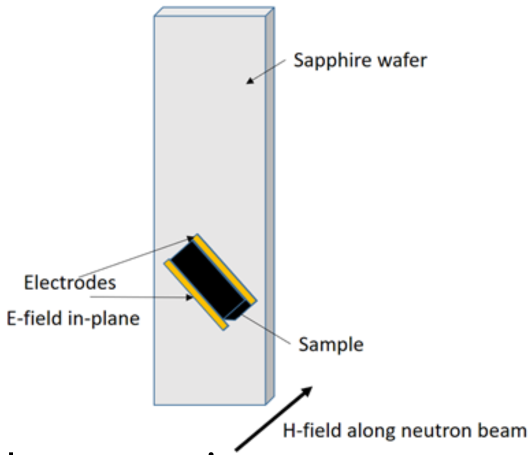




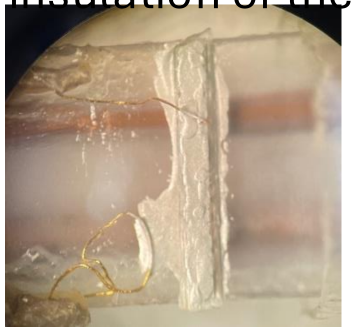
M. Bartkowiak, https://doi.org/10.1063/1.4865406

HV stick PSI – Sample preparation





- Electrodes and connections are prepared with silver paint
- Additional material in the beam (e.g. cables) are shielded with Cadmium foil
- Multiple Layers of Kapton tape (~3) are used for electric insulation of the Cadmium



Electric fields in Liquids

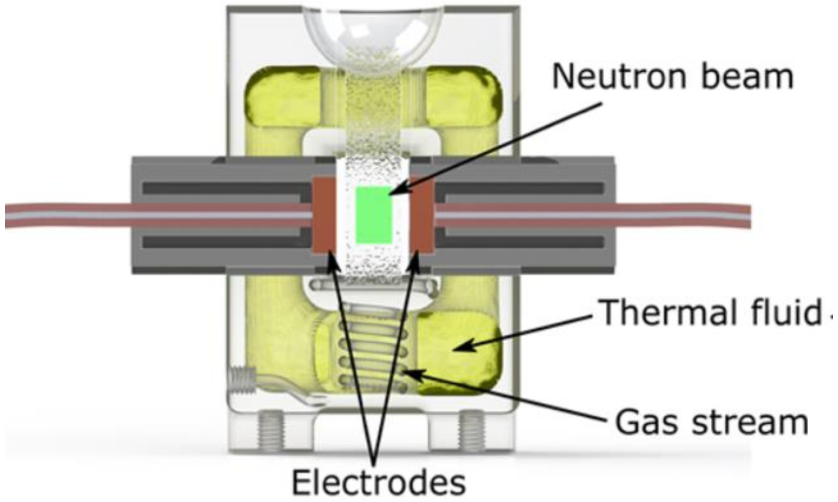
Corrosion if electrodes in direct contact

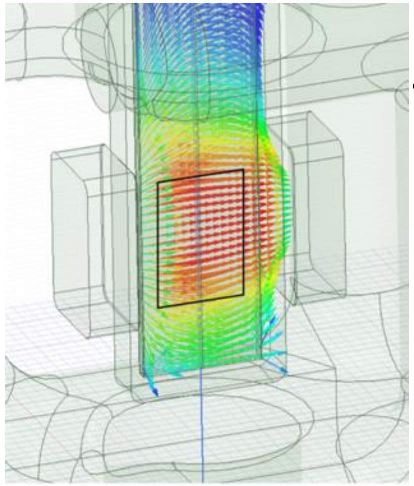
Complicated to make a simple container

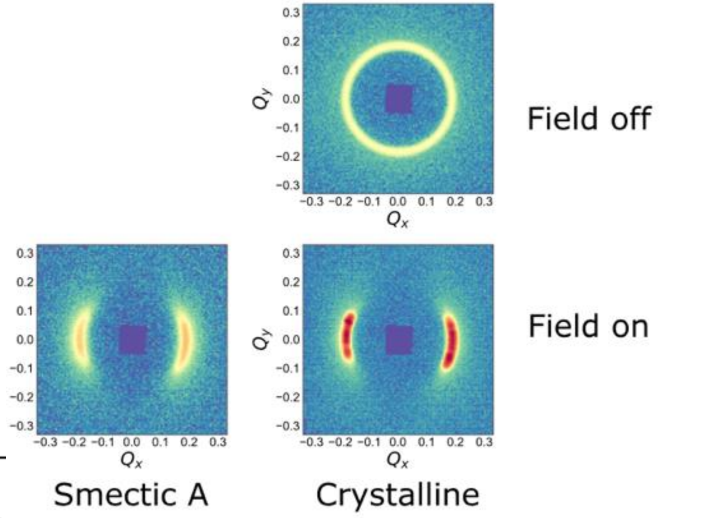
Standard container are glass cuvettes

D.W. Hayward Rev. Sci. Instrum. **92**, 033903 (2021);
doi: 10.1063/5.0040675

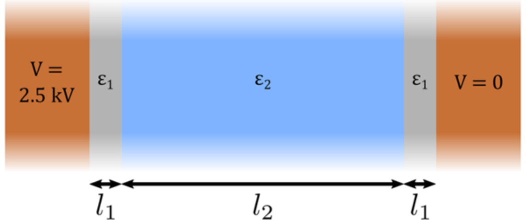
- With 10kV ~1-2kV/cm achieved in sample
- No current flowing in cell due to insulating cuvettes
- Avoid motion of charged constituents of a solution apply alternating Voltage kHz
- Dipole follows but diffusion is much slower







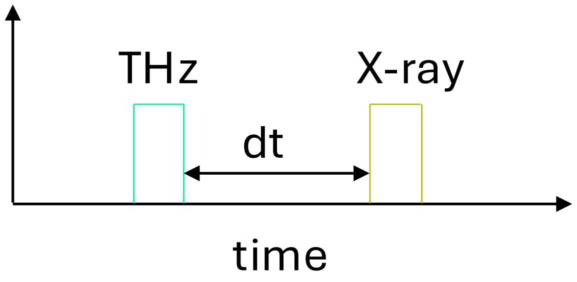
Domain alignment in liquid crystal

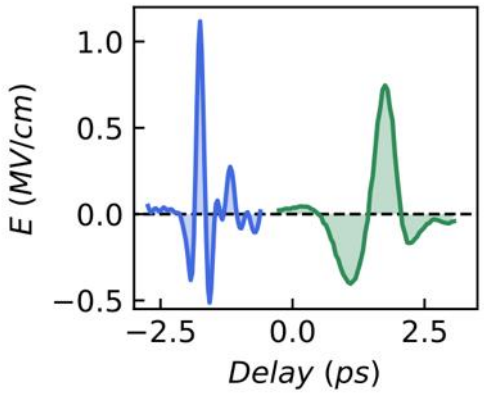


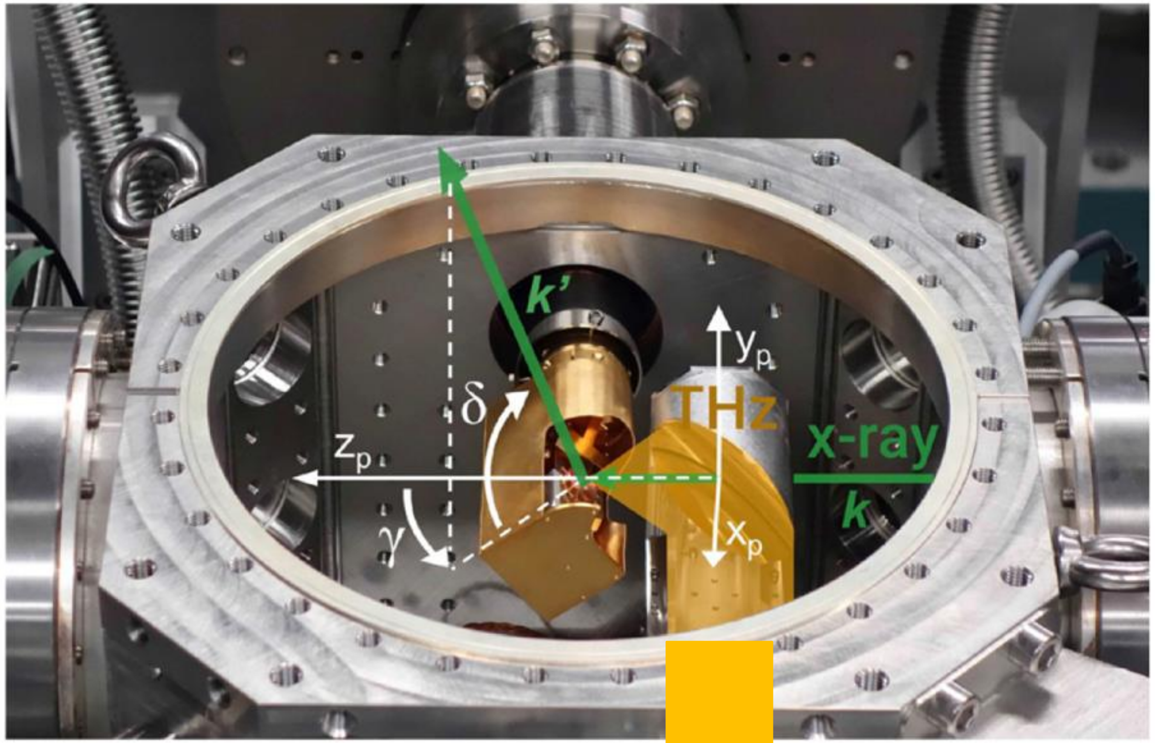
$$E_2 = \frac{-\varepsilon_1 \Delta V}{2 l_1 \varepsilon_2 + l_2 \varepsilon_1}$$

THz Pump x-ray probe

Pump probe scheme







- Cold finger cryostat
- No radiation shielding on the THz input
- Sample temperature 5K – 500K
- Field maxima of 1MV/cm are reachable

0.1THz-30THz
Pump pulse
Length: 100fs

R. Mankowsky J. Phys.: Condens. Matter **33** (2021) 374001 (16pp)

Backup Slides

Basic definitions

PSI

specific heat

Specific heat: the amount of heat required to raise the temperature od a solid of mass m by 1 Kelvin

$$c_V = \frac{dU}{dT} = \frac{1}{m} dQ/dT$$

inner energy

total energy contained in a system

energy related to the motion of system particles

$$dU = TdS - pdV$$

$$= dQ|_V = mc_V dT$$

entropy

a measure of disorder in a system

accounts for the energy unavailable to do work

$$\Delta S = \frac{Q}{T} \qquad dS = \left.\frac{dH}{T}\right|_p$$

"... handy way to calculate heat transfers" [G. Walker "Cryocoolers"]

enthalpy

"heat content"

energy for isobaric process

easier for calculations in flow systems

$$H = U + pV$$

$$dH = dU + Vdp + pdV$$

$$dH = dQ + Vdp$$

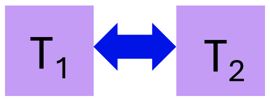
$$dH = C_p dT$$

Laws of thermodynamics

0^{th} law

definition of equilibrium

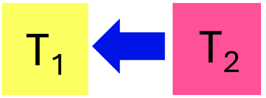
Equilibrium



$T_1 = T_2$

$dQ = 0$

not in equilibrium

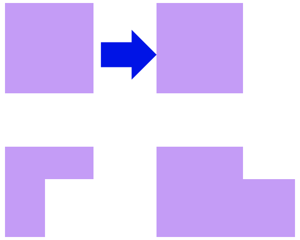


$T_1 < T_2$

$dQ \neq 0$

1^{st} law

energy conservation

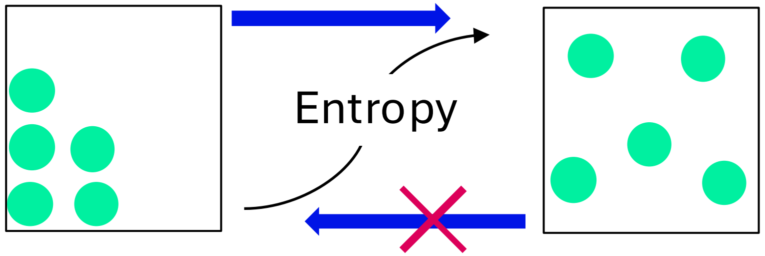


$dU = Q - W$

U..internal energy
Q..heat added to system
W..work done by the system

2^{nd} law

time has a direction
heat flows from high to low temperatures
entropy of an isolated system approaches maximum



3^{rd} law

the entropy at zero temperature converges to a constant value

$$\Delta S_{T \to 0} = 0$$

T=0 cannot be reached