Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)

MEPAS 2015

CRYOGENIC SYSTEMS

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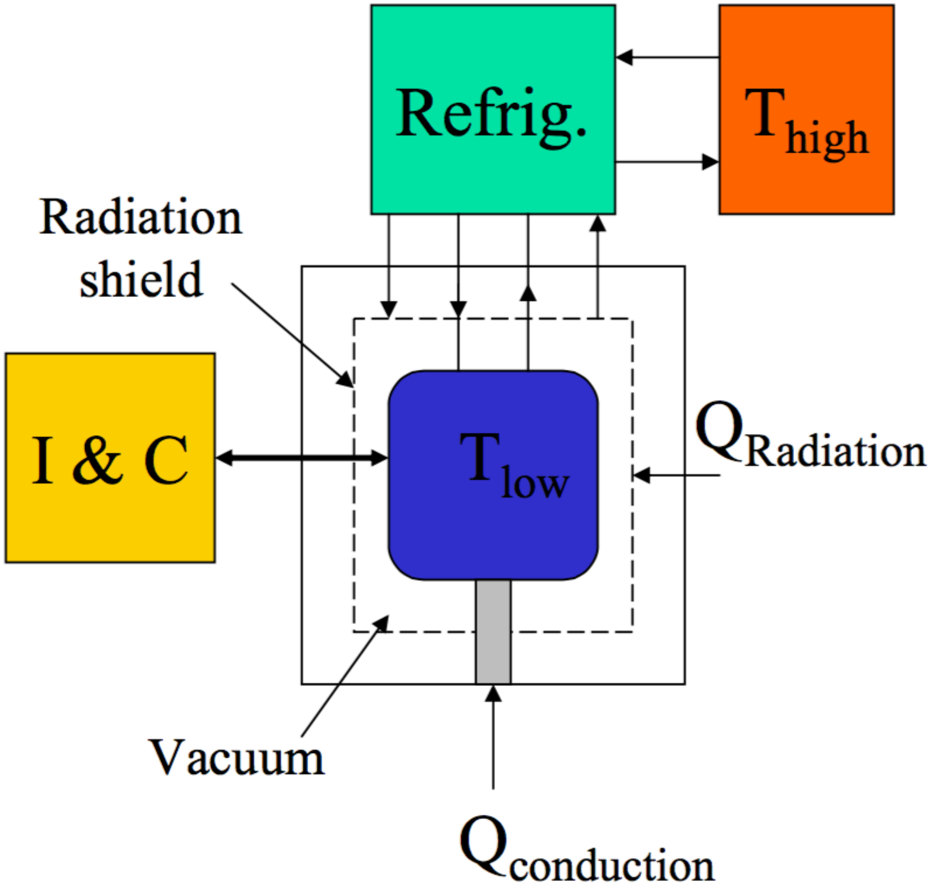
Cornell Laboratory for Accelerator-based
ScienceS and Education (CLASSE)

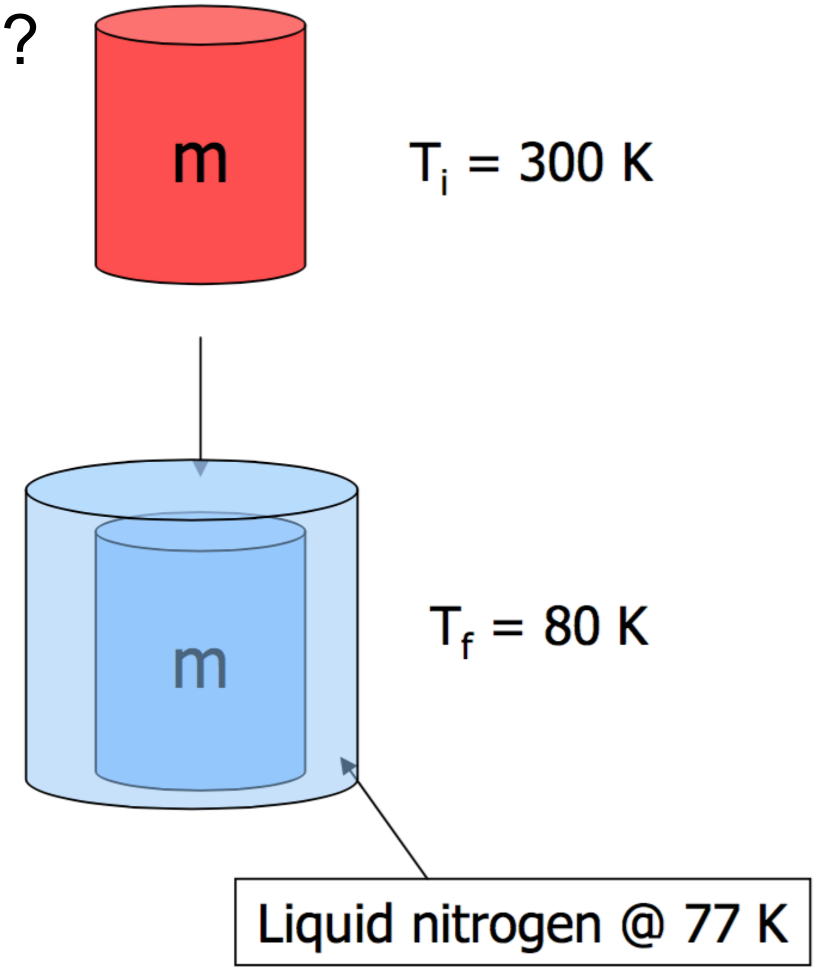
A typical cryogenic system

- Goal: provide a low temperature environment
- Needed: source of refrigeration
- What to obey:
  - Heat transfer
  - Thermal insulation
  - Heat exchange
  - Structural support
  - Instrumentation and controls
  - Safety



Let's start easy

- Let us take a piece of metal and cool it down
- How much heat do we remove?
- $Q = m \cdot c \cdot T$
- Or if c is not constant:
- $Q = m \int_{T_i}^{T_f} c(T) dT$
- Two questions:
  - What temperature does the metal have?
  - What property of the metal did we change during cool-down?



Laws of thermodynamics (I)

- 0^{th} fundamental law of thermodynamics:

bodies in thermal contact have the same temperature

- 1^{st} fundamental law of thermodynamics

The increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by the system:

$$dU = dW + dQ \qquad U = \frac{1}{n}\sum E_i$$

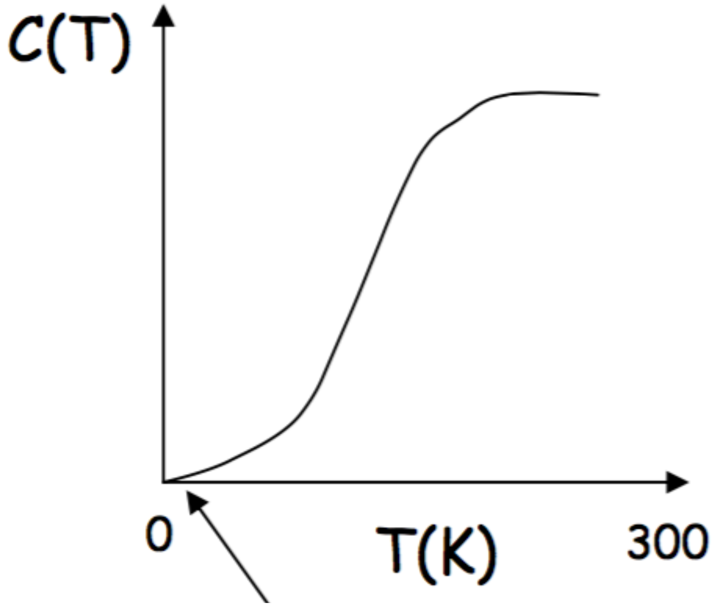
...more to come later

Heat capacity of solids

- Specific heat is more generally defined as

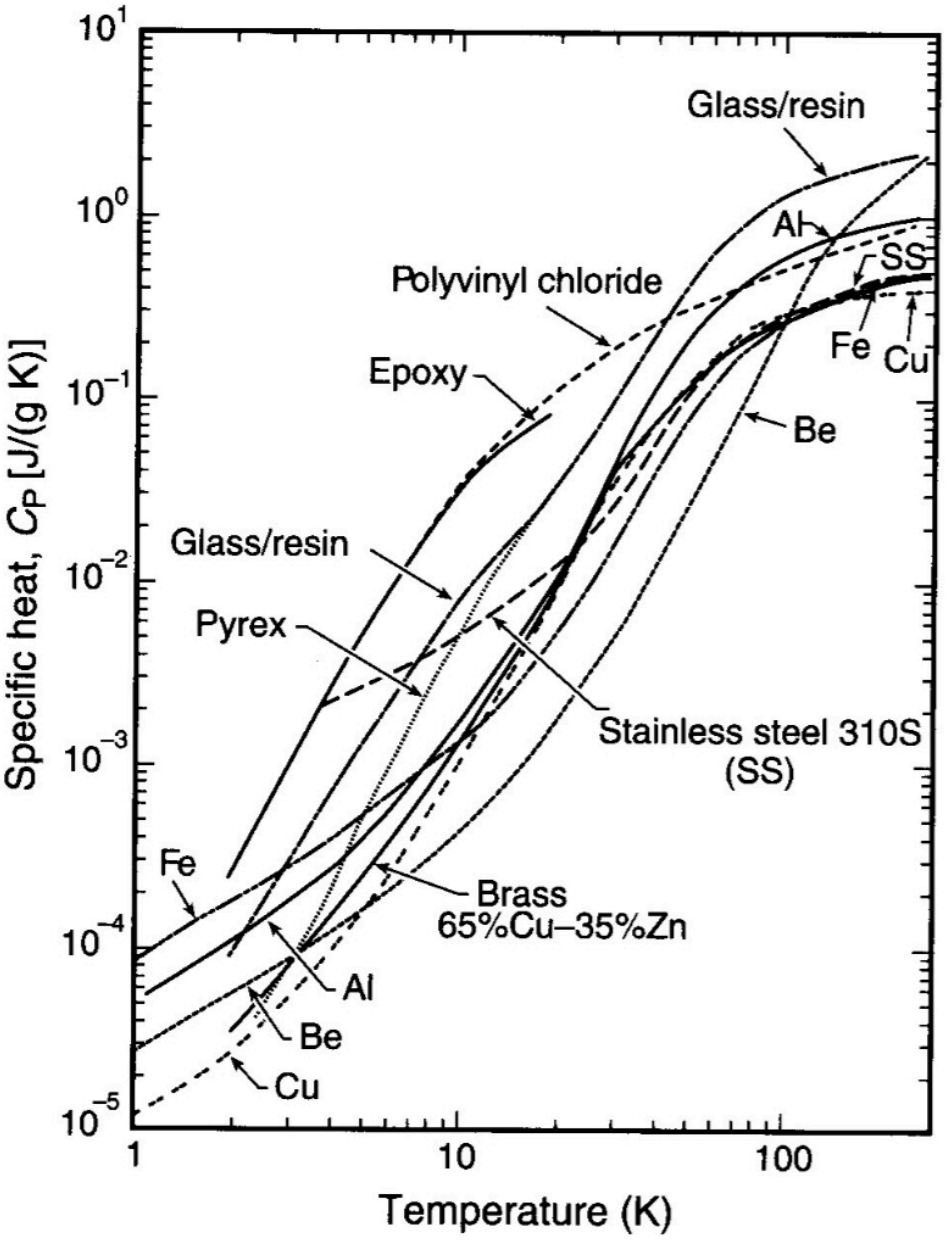
$$C_V = \left.\frac{dU}{dT}\right|_V \qquad C_p = T\left.\frac{dS}{dT}\right|_p$$

- $C_p - C_V \approx 0$ for solids and incompressible fluids
- $C_p - C_v \approx \mathrm{R} = 8.31\,\frac{J}{molK}$ for gasses



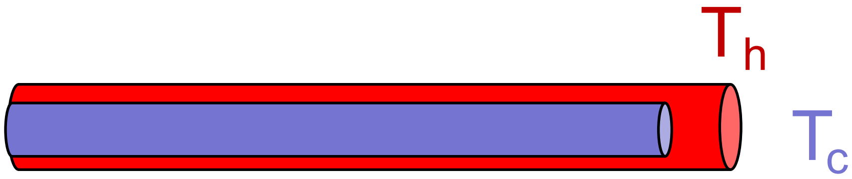
Specific heat at low temperatures

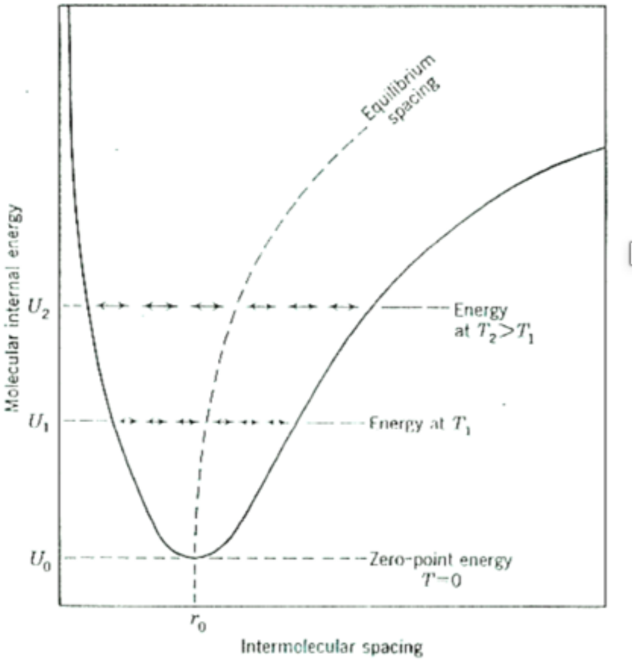
- c_p usually decreases by an order of magnitude from room temperature (RT) to 77K (LN_2)
- Down to 4 K (LHe) there are another 2 orders of magnitude!
- General characteristics:
  - c_p ~ const. at RT
  - $c_p \sim T^3$ for T<100 K
  - c_p ~ T for metals below 1K



Thermal Contraction

- Materials change dimensions with temperature

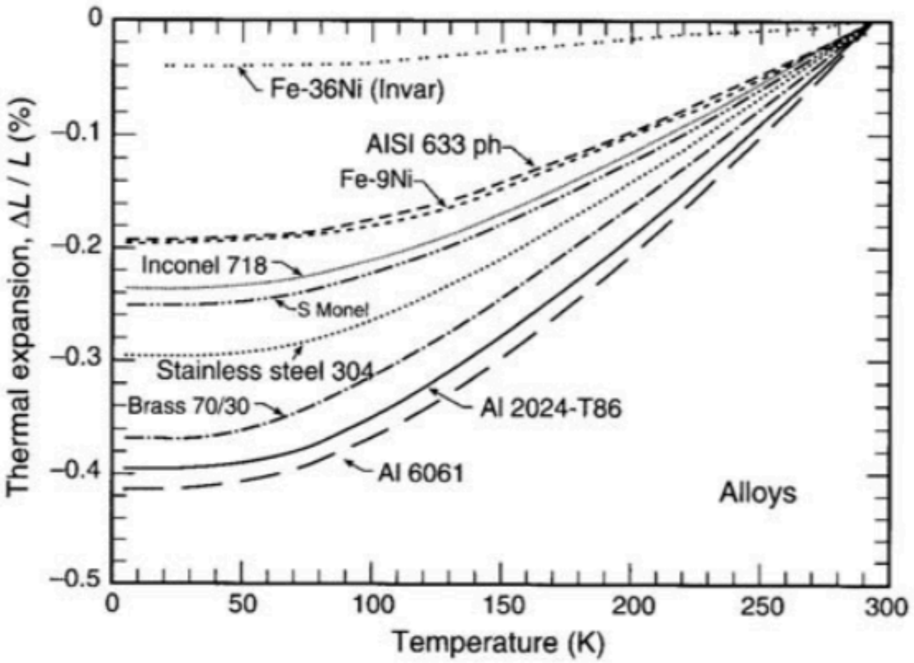


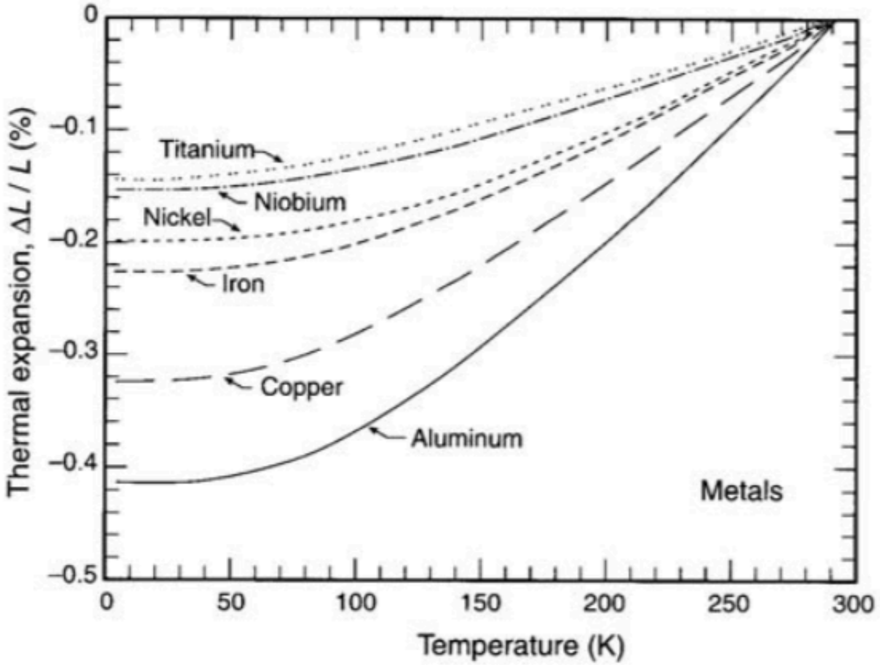


- This is captured by the expansion coefficient (CTE):

$$\alpha = \frac{1}{L} \cdot \frac{dL}{dT}$$

CTE of some materials





- At LN_2 most CTEs become constant. This is why people say: the mechanical properties freeze in at LN_2

$$\frac{\Delta L}{L} = \frac{L_T - L_{295K}}{L_{295K}}$$

Table of CTEs

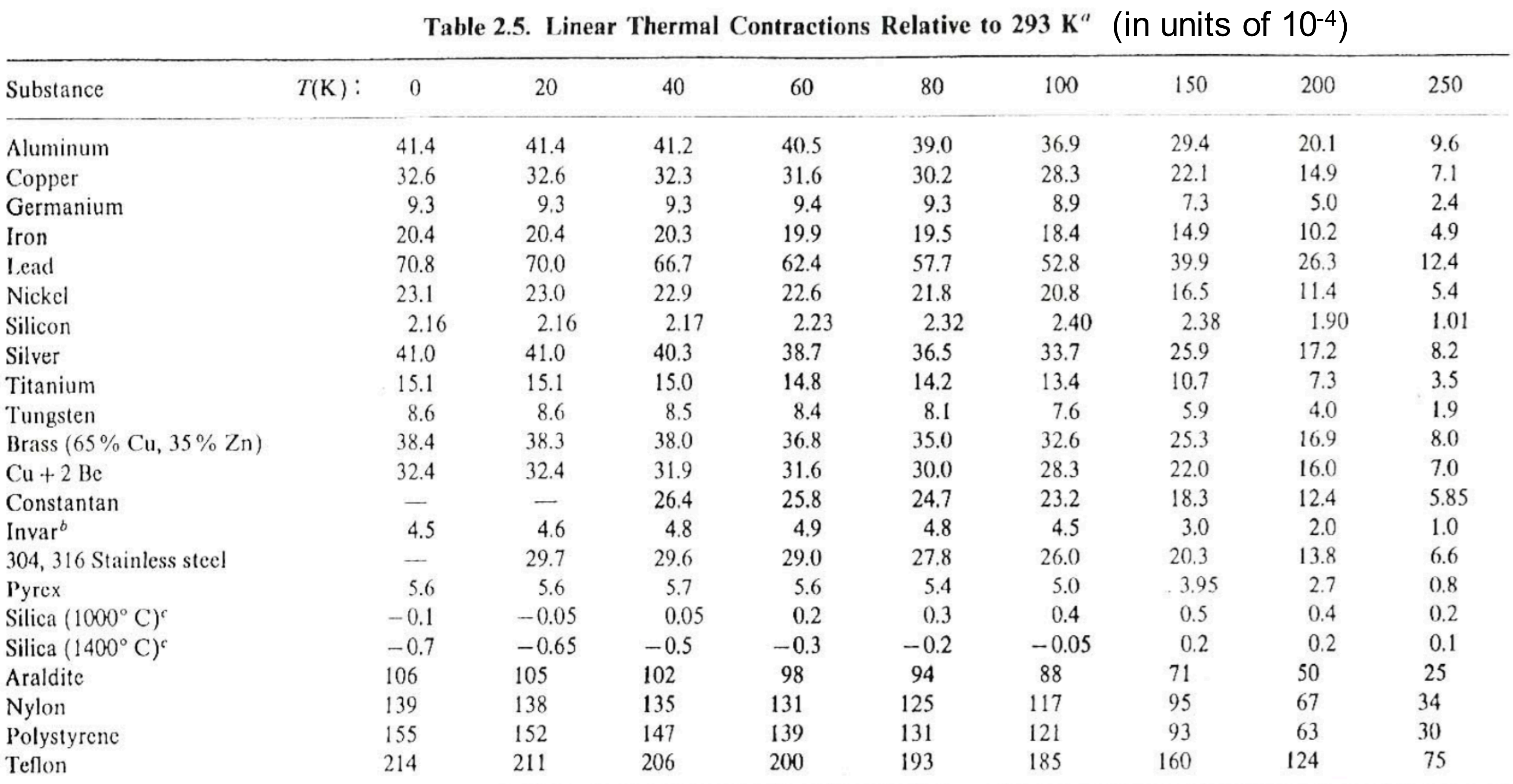
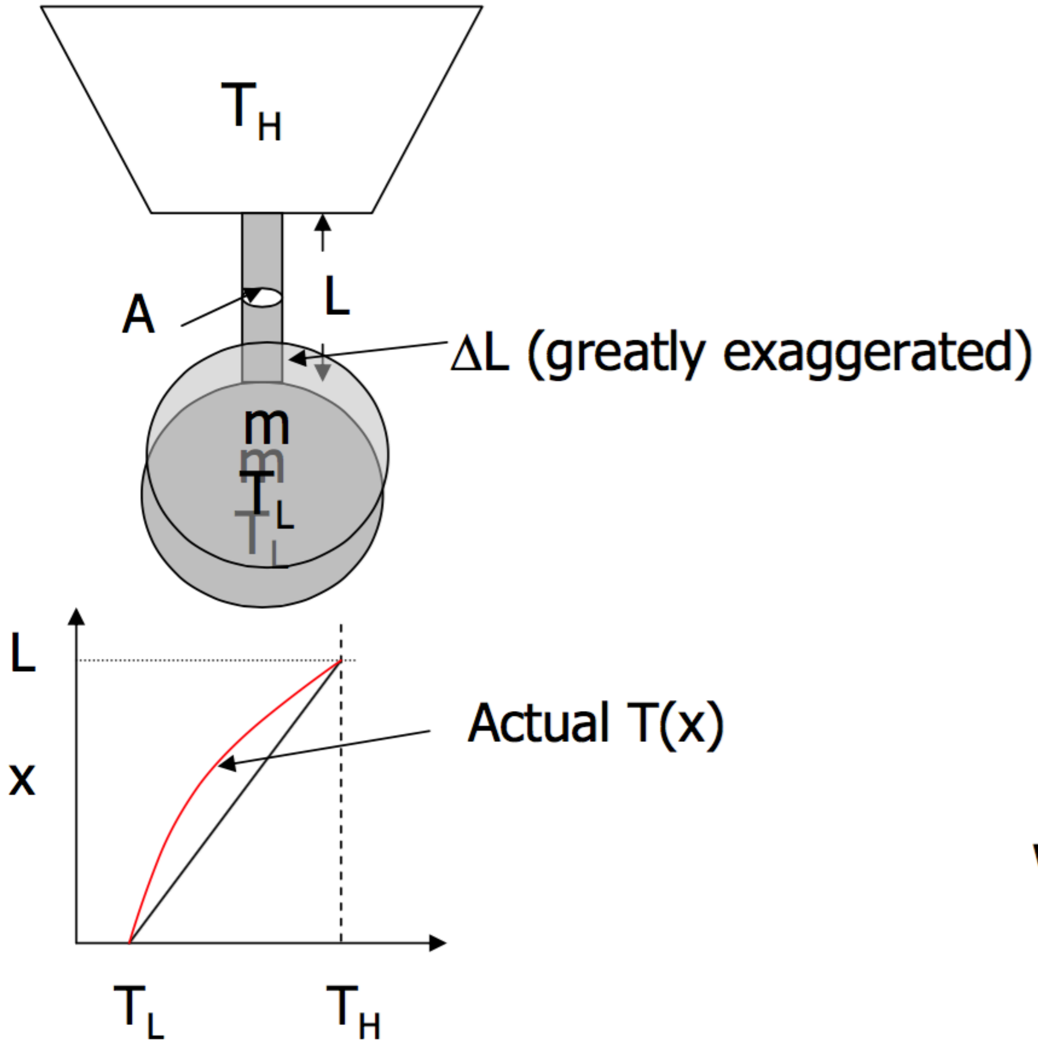


Table 2.5. Linear Thermal Contractions Relative to 293 K[a] (in units of 10^{-4})

Substance	T(K): 0	20	40	60	80	100	150	200	250
Aluminum	41.4	41.4	41.2	40.5	39.0	36.9	29.4	20.1	9.6
Copper	32.6	32.6	32.3	31.6	30.2	28.3	22.1	14.9	7.1
Germanium	9.3	9.3	9.3	9.4	9.3	8.9	7.3	5.0	2.4
Iron	20.4	20.4	20.3	19.9	19.5	18.4	14.9	10.2	4.9
Lead	70.8	70.0	66.7	62.4	57.7	52.8	39.9	26.3	12.4
Nickel	23.1	23.0	22.9	22.6	21.8	20.8	16.5	11.4	5.4
Silicon	2.16	2.16	2.17	2.23	2.32	2.40	2.38	1.90	1.01
Silver	41.0	41.0	40.3	38.7	36.5	33.7	25.9	17.2	8.2
Titanium	15.1	15.1	15.0	14.8	14.2	13.4	10.7	7.3	3.5
Tungsten	8.6	8.6	8.5	8.4	8.1	7.6	5.9	4.0	1.9
Brass (65% Cu, 35% Zn)	38.4	38.3	38.0	36.8	35.0	32.6	25.3	16.9	8.0
Cu + 2 Be	32.4	32.4	31.9	31.6	30.0	28.3	22.0	16.0	7.0
Constantan	—	—	26.4	25.8	24.7	23.2	18.3	12.4	5.85
Invar[b]	4.5	4.6	4.8	4.9	4.8	4.5	3.0	2.0	1.0
304, 316 Stainless steel	—	29.7	29.6	29.0	27.8	26.0	20.3	13.8	6.6
Pyrex	5.6	5.6	5.7	5.6	5.4	5.0	3.95	2.7	0.8
Silica (1000° C)[c]	−0.1	−0.05	0.05	0.2	0.3	0.4	0.5	0.4	0.2
Silica (1400° C)[c]	−0.7	−0.65	−0.5	−0.3	−0.2	−0.05	0.2	0.2	0.1
Araldite	106	105	102	98	94	88	71	50	25
Nylon	139	138	135	131	125	117	95	67	34
Polystyrene	155	152	147	139	131	121	93	63	30
Teflon	214	211	206	200	193	185	160	124	75

Thermal contraction of the support



- The change in length of a support is determined by the temperature distribution along the support
- Tabulated ΔL/L values are for uniform temperature of support
- For non-uniform temperature

$$\Delta L = \int_0^L dx \int_{T(x)}^{T_H} \alpha(T)\,dT$$

Where T(x) is defined according to,

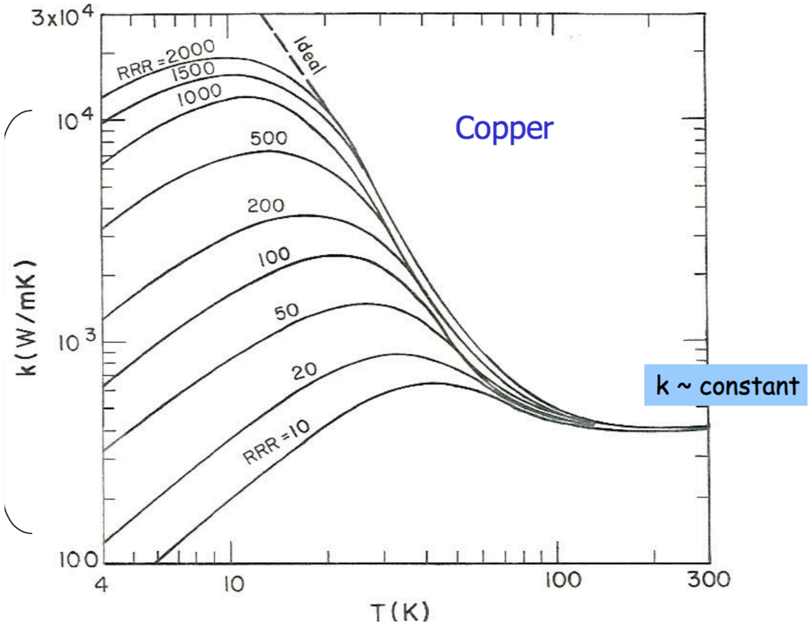
$$\int_{T_x}^{T_H} k(T)\,dT = \left(\frac{x}{L}\right)\int_{T_L}^{T_H} k(T)\,dT$$

Thermal conductivity

- Thermal conductivity is defined as the relation between the temperature gradient and the heat flux.

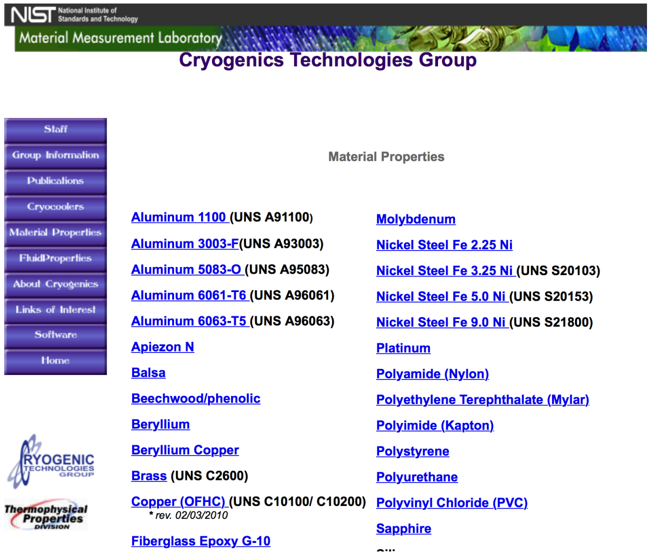
$$\dot{Q} = -k(T)A\frac{dT}{dx}$$

- k usually is a strong function of the temperature
- Thermal conductivity has two contributions:
  Phonons (dominant for insulators)
  Electrons (dominant for metals)
- For metals, this means, electron properties depend on temperature and impurities



Some thermal conductivities

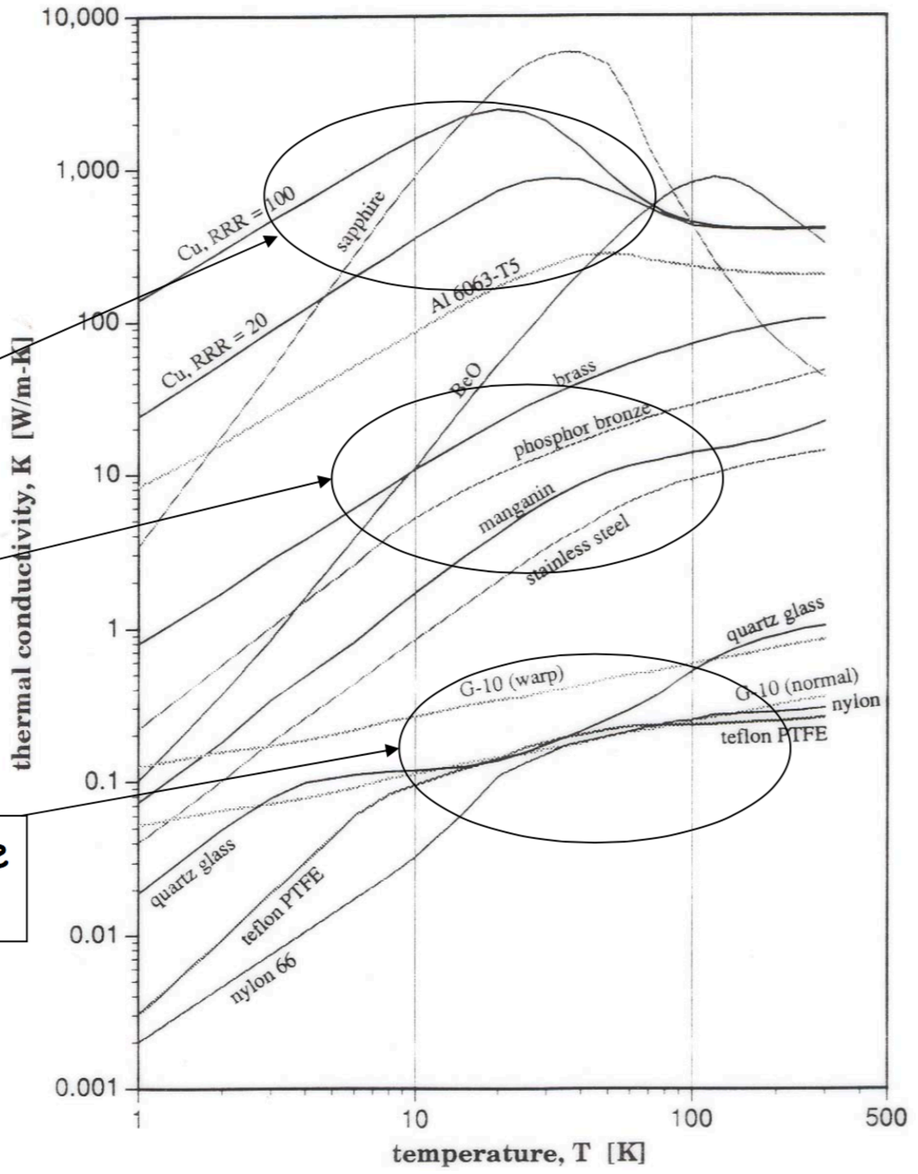
Good source of cryogenic data:
http://www.cryogenics.nist.gov/MPropsMAY/material%20properties.htm



Cryogenics Technologies Group

Material Properties

- Aluminum 1100 (UNS A91100)
- Aluminum 3003-F(UNS A93003)
- Aluminum 5083-O (UNS A95083)
- Aluminum 6061-T6 (UNS A96061)
- Aluminum 6063-T5 (UNS A96063)
- Apiezon N
- Balsa
- Beechwood/phenolic
- Beryllium
- Beryllium Copper
- Brass (UNS C2600)
- Copper (OFHC) (UNS C10100/ C10200)
  - * rev. 02/03/2010
- Fiberglass Epoxy G-10
- Molybdenum
- Nickel Steel Fe 2.25 Ni
- Nickel Steel Fe 3.25 Ni (UNS S20103)
- Nickel Steel Fe 5.0 Ni (UNS S20153)
- Nickel Steel Fe 9.0 Ni (UNS S21800)
- Platinum
- Polyamide (Nylon)
- Polyethylene Terephthalate (Mylar)
- Polyimide (Kapton)
- Polystyrene
- Polyurethane
- Polyvinyl Chloride (PVC)
- Sapphire



Pure metals and crystalline insulators

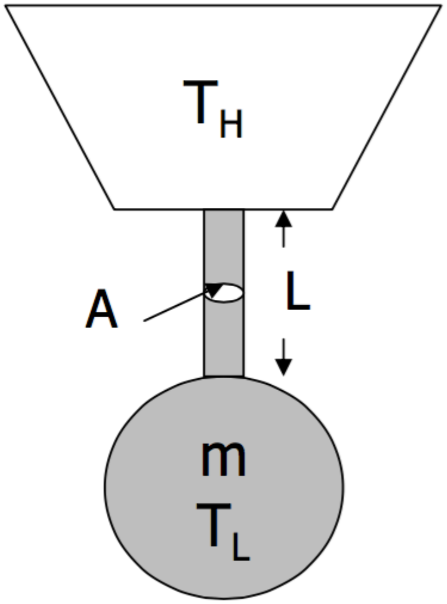
Alloys

Non-crystalline Non-metallics

... speaking of support structures...

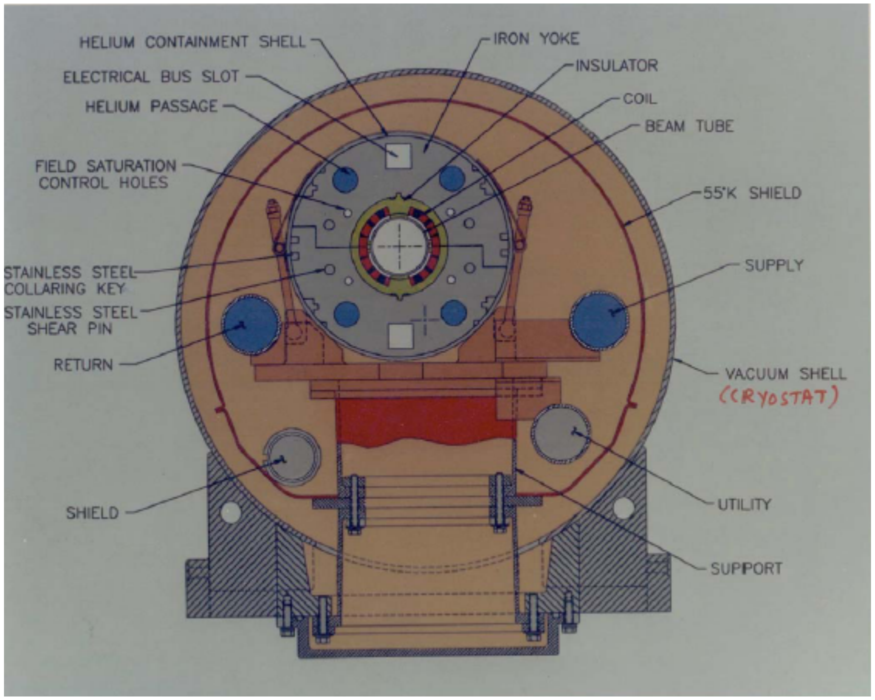
- It will not only move your cold mass as you cool-down,
- It will also add a heat load to the cold mass:

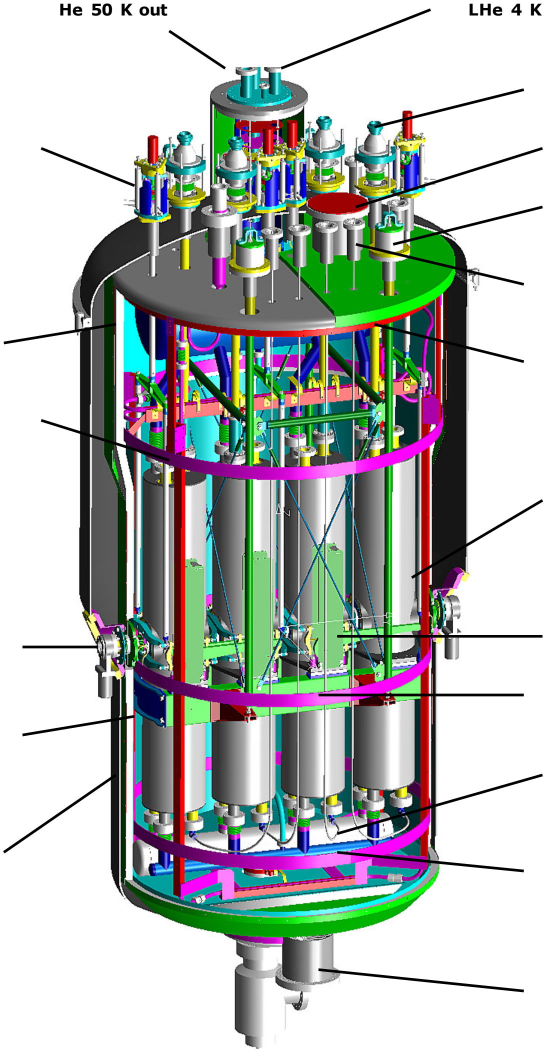
$$Q = \left(\frac{A}{L}\right)\int_{T_L}^{T_H} k(T)\,dT$$



- But there are limitations on A,L and the choice of material
- So: how would you design a support?
- Typical material used: G10

Examples of supports




He 50 K out

LHe 4 K in

Piezo & Stepper Motor (Tuner)

RF Power Input

Rupture Disc

Cavity Alignment

RF Field Probe

MLI Insulation

LHe Reservoir

Shield Cooling (part. Removed)

Cavities

Beam Axis

Tuner

Girder

Mangnetic Shielding

Additional Pumping

Cryostat Vessel

Thermosyphon

Pumping Port (Insulating Vacuum)

A design help: conductivity integrals

- Heat transfer is given by:

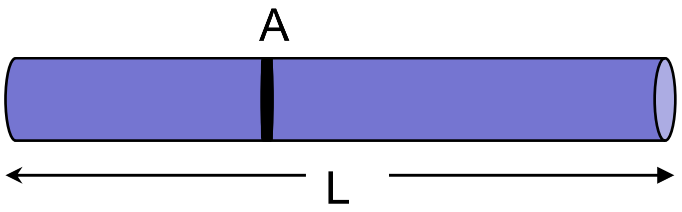
$$Q = \left(\frac{A}{L}\right)\int_{T_L}^{T_H} k(T)\,dT$$

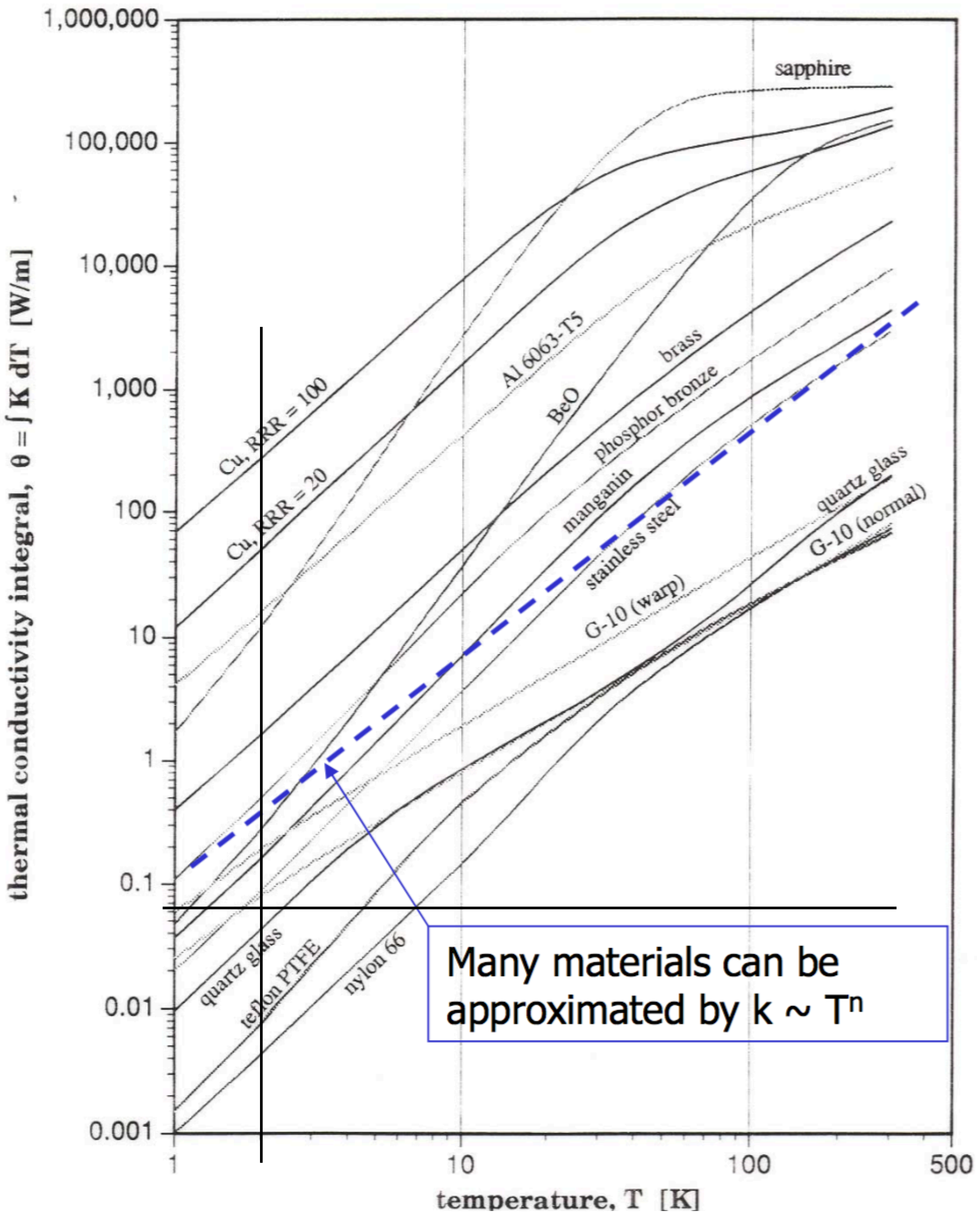
- For convenience, you can precalculate the conductifity integrals:

$$\theta(T_1,T_2) = \int_{T_1}^{T_2} k(T)\,dT$$

- So Q becomes

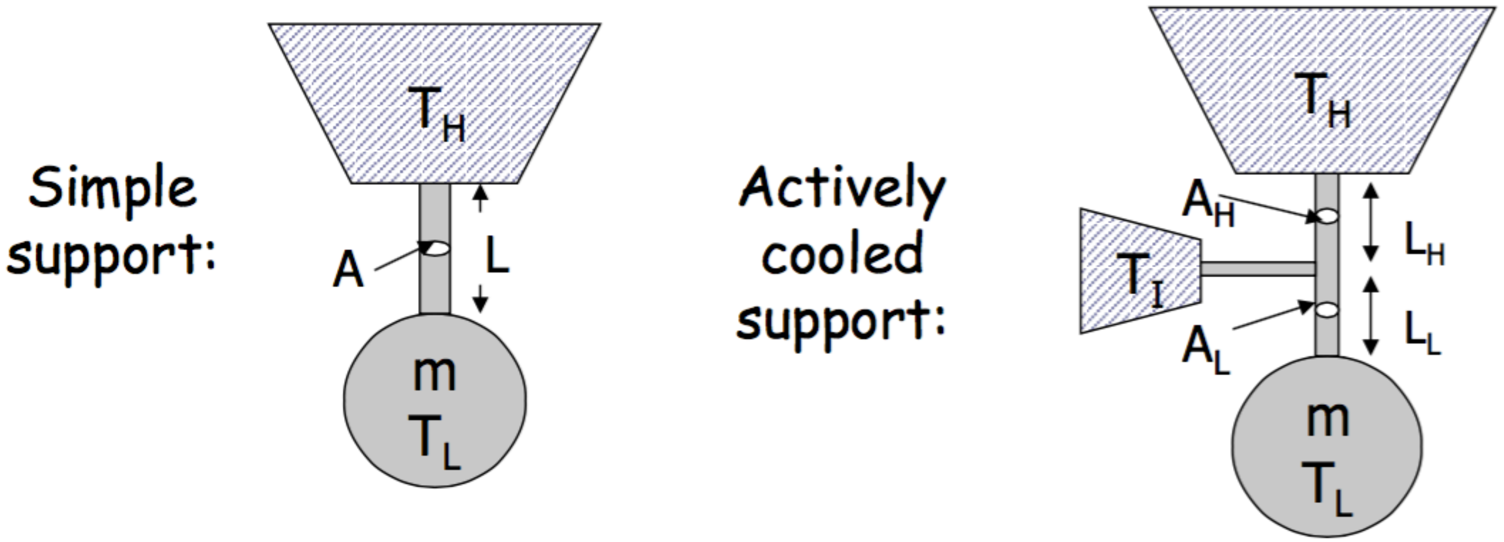
$$Q = \theta(T_1,T_2)\frac{A}{L}$$



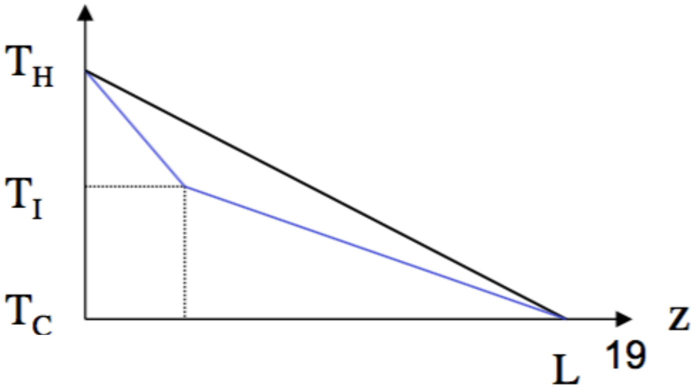


Many materials can be approximated by k ~ T^n

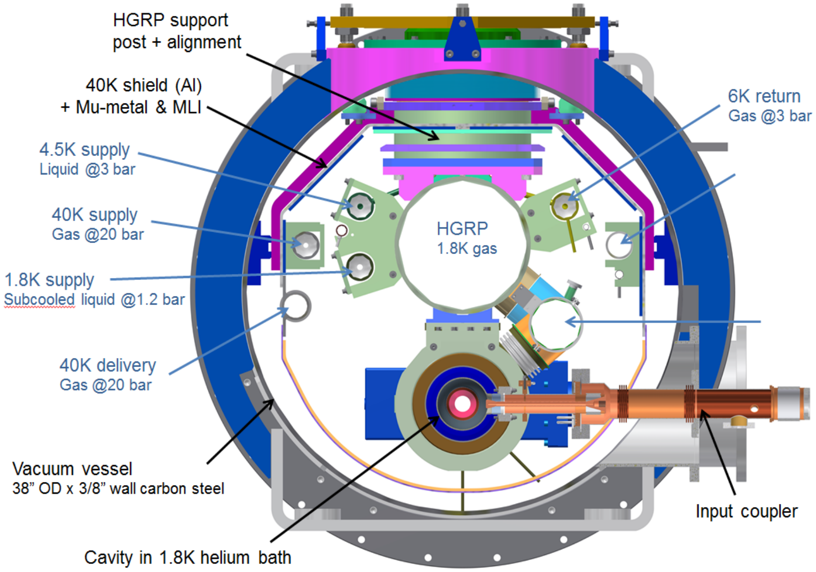
Thermal anchoring

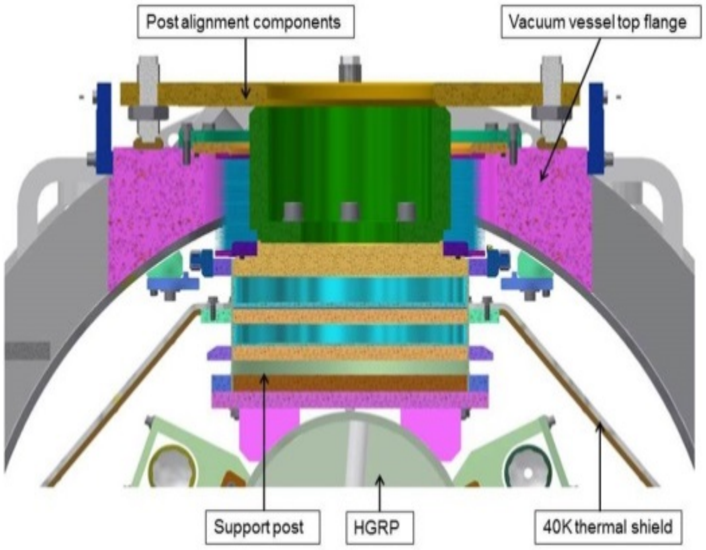


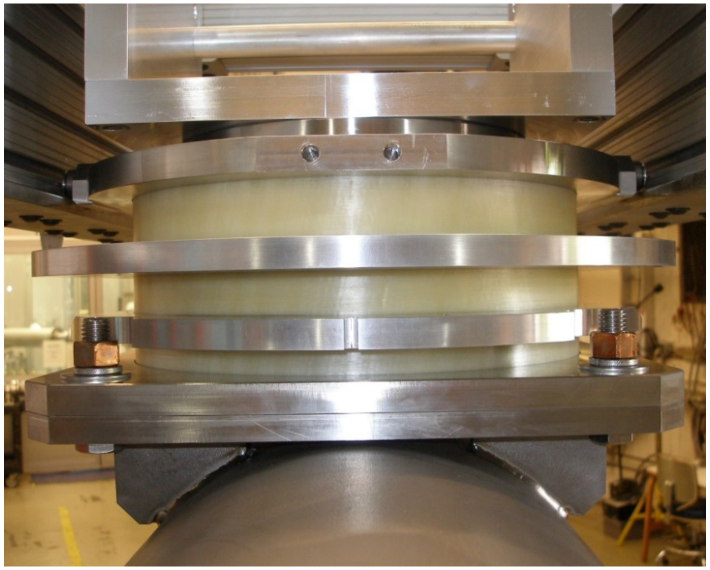
- By intercepting the support at an intermediate temperature, heat transfer can significantly be reduced!
- But: where to position it,
- at what temperature?



Composit posts/ anchoring







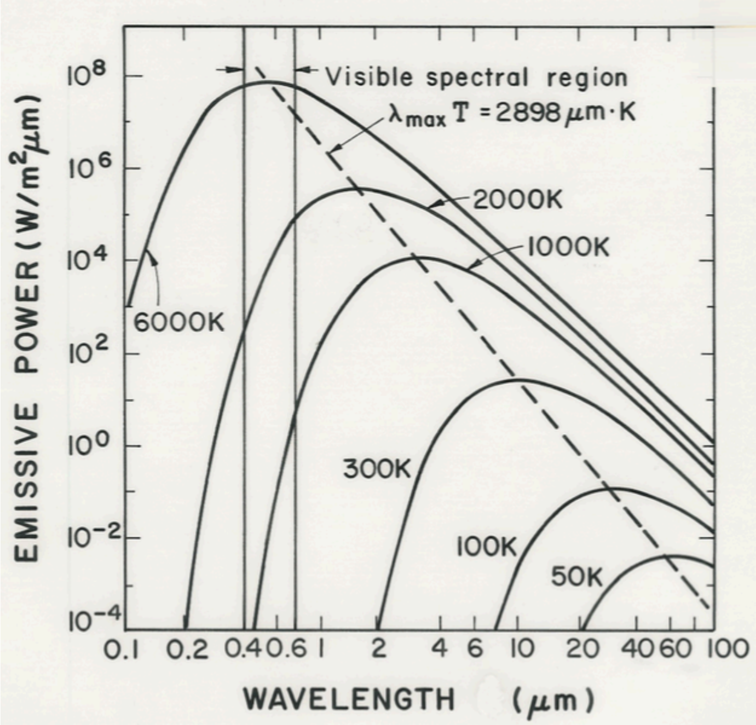
Radiation heat

- Planck's law of black body radiation

$$I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- Believe it or not: this is still a factor at 300 K and below!
- If you are just interested in the total power transfer, you can integrate over the wavelength which gives you the Stephan Boltzmann law

$$Q = \sigma T^4, \sigma = \frac{2\pi^5}{15}\frac{k^4}{c^2h^3}$$



Heat transfer from radiation

- If you have two surfaces facing each other, this is the net heat transfer:

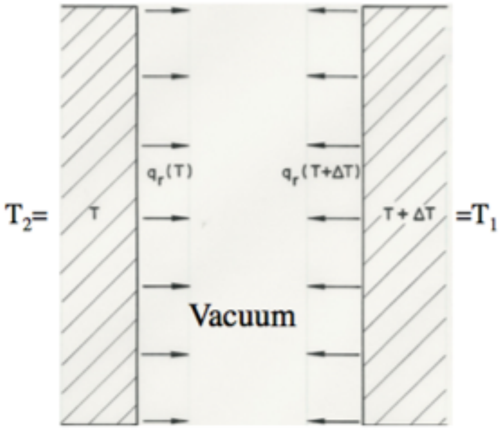
$$Q_R = \sigma A\left[(T+\Delta T)^4 - T^4\right]$$

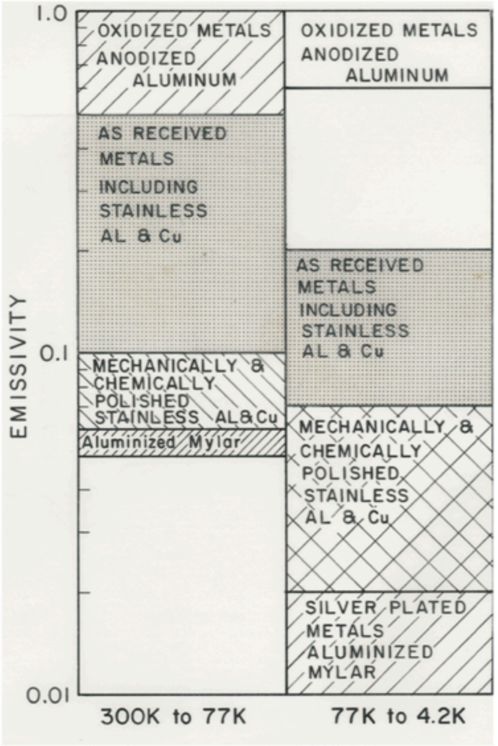
- But: are all bodies black?
- No! Materials have emissivity!

$$Q_R = \varepsilon\sigma T^4$$

- So the heat exchange of two, non-black surfaces is given by

$$Q_R = \frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2}\sigma\left(T_1^4 - T_2^4\right)$$





Heat transfer from radiation

- Is this relevant?
- What is the heat transfer from 300 K to 4K if the emissivity of both surfaces is .05?

$$Q_R = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \sigma (T_1^4 - T_2^4) \qquad \sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$

- Please calculate!

Heat transfer from radiation

- Is this relevant?
- What is the heat transfer from 300 K to 4K if the emissivity of both surfaces is .05?

$$Q_R = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \sigma (T_1^4 - T_2^4) \qquad \sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$

- Please calculate!

=> It‘s ~115 W/m^2

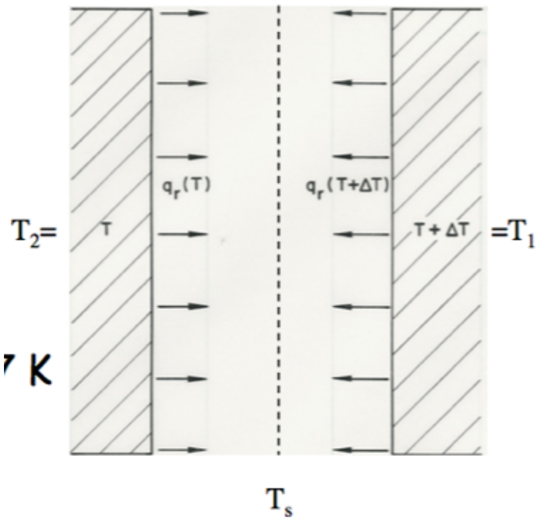
- What can we do about it?

Multi-Layer Insulation (MLI)

- Let us investigate what a radiation shield (passive) does:

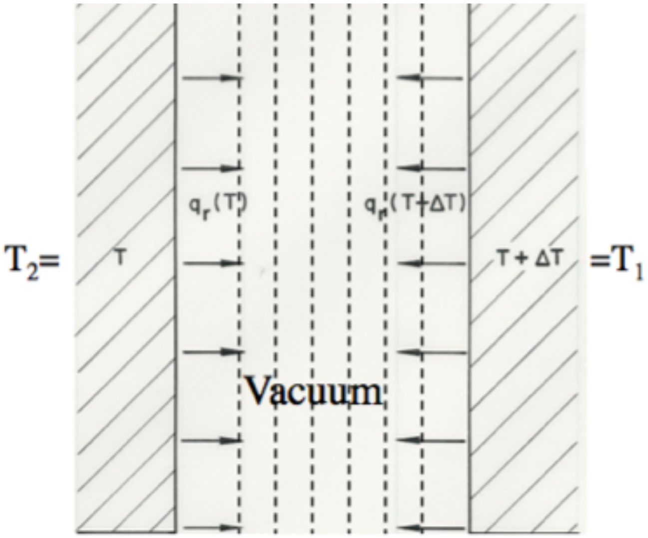
$$Q_{1\rightarrow s} = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \sigma (T_1^4 - T_s^4)$$

$$Q_{s\rightarrow 2} = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \sigma (T_s^4 - T_2^4)$$

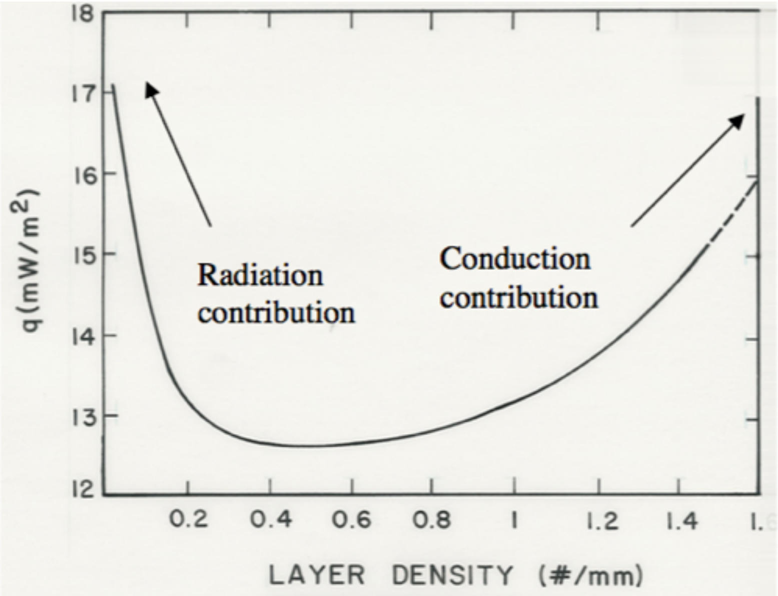


- And as there is no cooling at T_S, so $Q_{1\rightarrow s} = Q_{s\rightarrow 2}$, and this turns out to be smaller than $Q_{1\rightarrow 2}$
- For n passive layers, you get

$$Q_{MLI} = \frac{\varepsilon}{(n+1)(2-\varepsilon)} \sigma (T_1^4 - T_2^4)$$



MLI

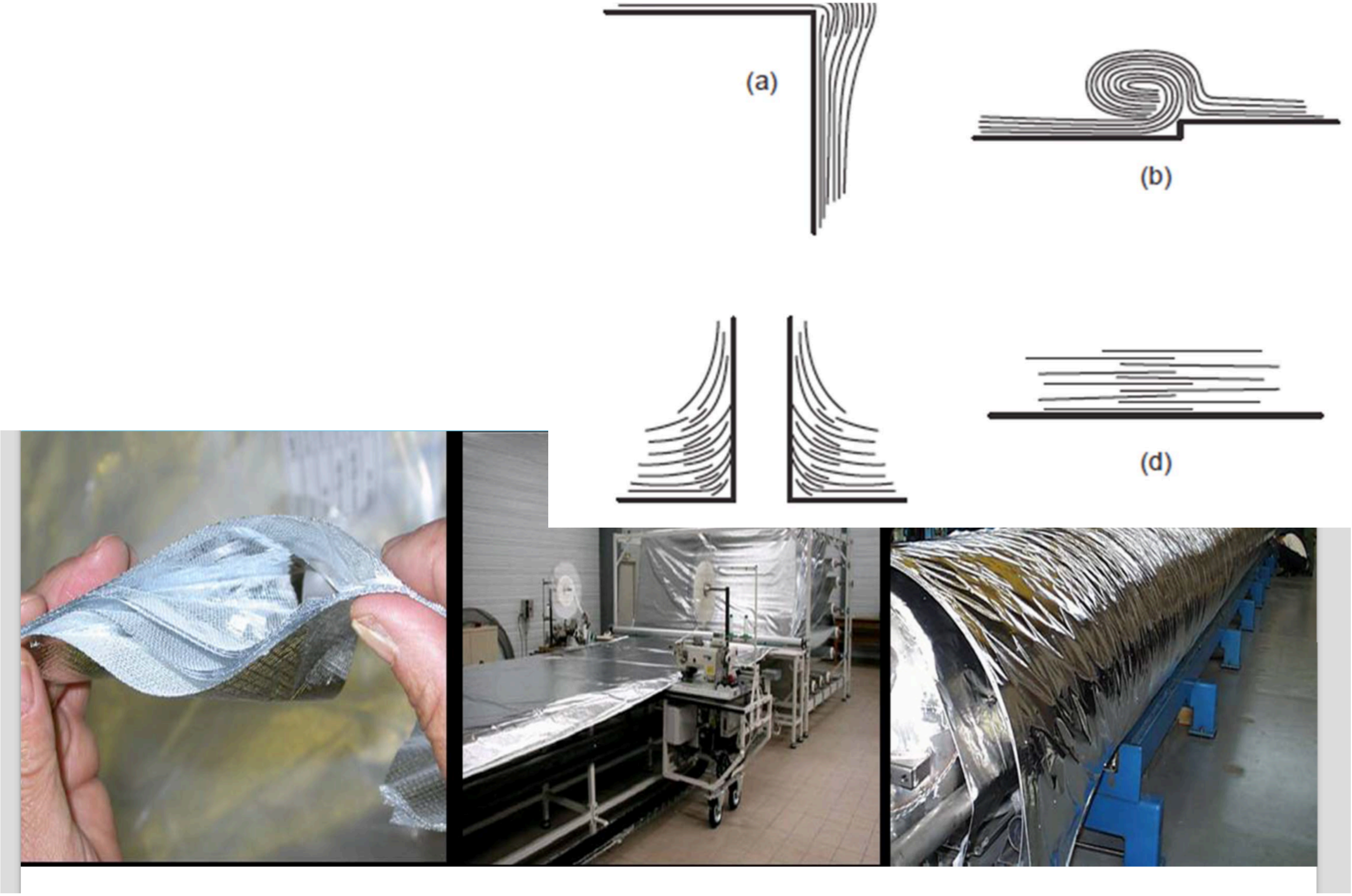


Multi-layer Superinsulation Package

- Make sure you don‘t pack the MLI too tightly!

Function	Specification	Properties and Justification
Insulation 300 K to 77 K	10 foil + 10 spacer layers	1.0 to 1.5 W/m^2
	20 foil + 20 spacer layers	0.8 to 0.9 W/m^2
	30 foil + 30 spacer layers	0.6 to 0.7 W/m^2
	40 foil + 40 spacer layers	0.55 to 0.6 W/m^2
Insulation 77 K to 4 K	10 foil + 10 spacer layer	0.05 W/m^2

And there is more about MLI



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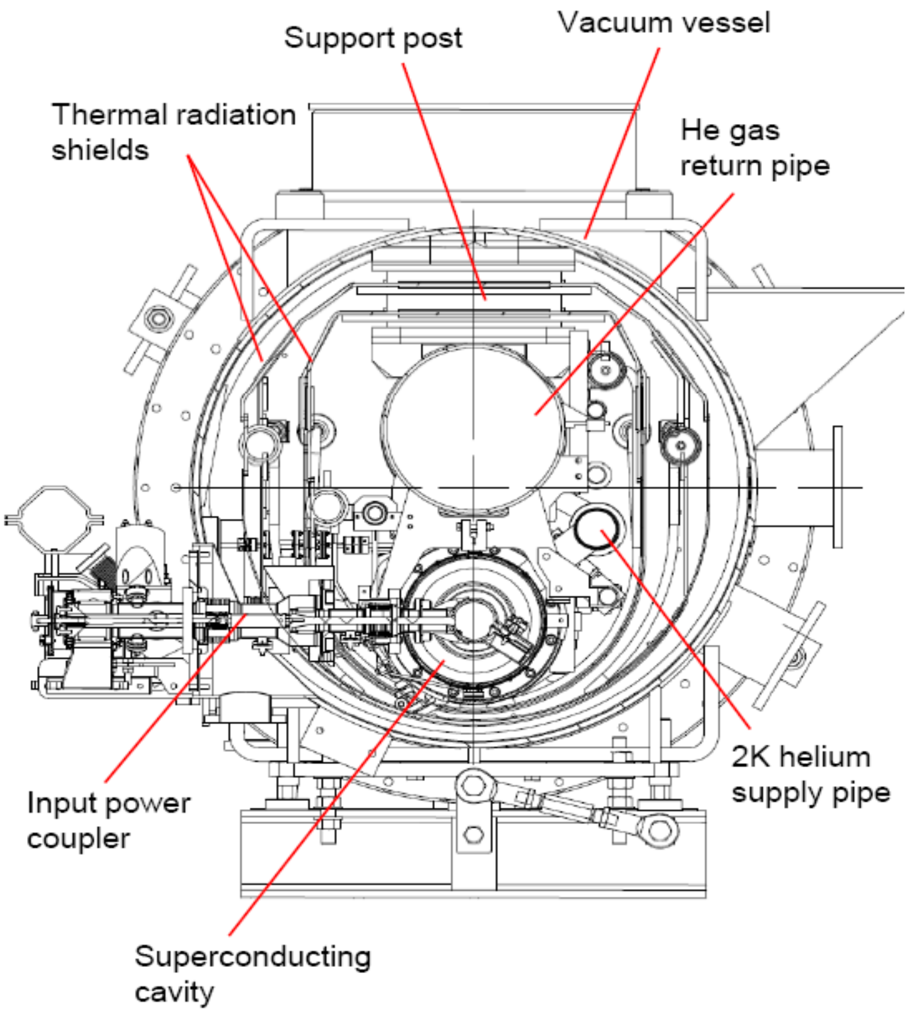
From what we learned, we can build a cryostat

- Vacuum vessel (Iron pipe)
  - Outer diameter = 965.2mm, Length=11.8m
  - Connection between cryomodules
    - Vacuum bellow
  - Total length=12.7m
  - Magnetic shielding
- Support post
  - Supporting the all cold mass in the vacuum vessel
  - Material : FRP(G-10)
- Thermal radiation shield
  - Aluminum plate ＋Muti-layer insulation of aluminum-evaporated film (Super Insulation)
  - 40K-80K, 4K-5K helium gas cooling



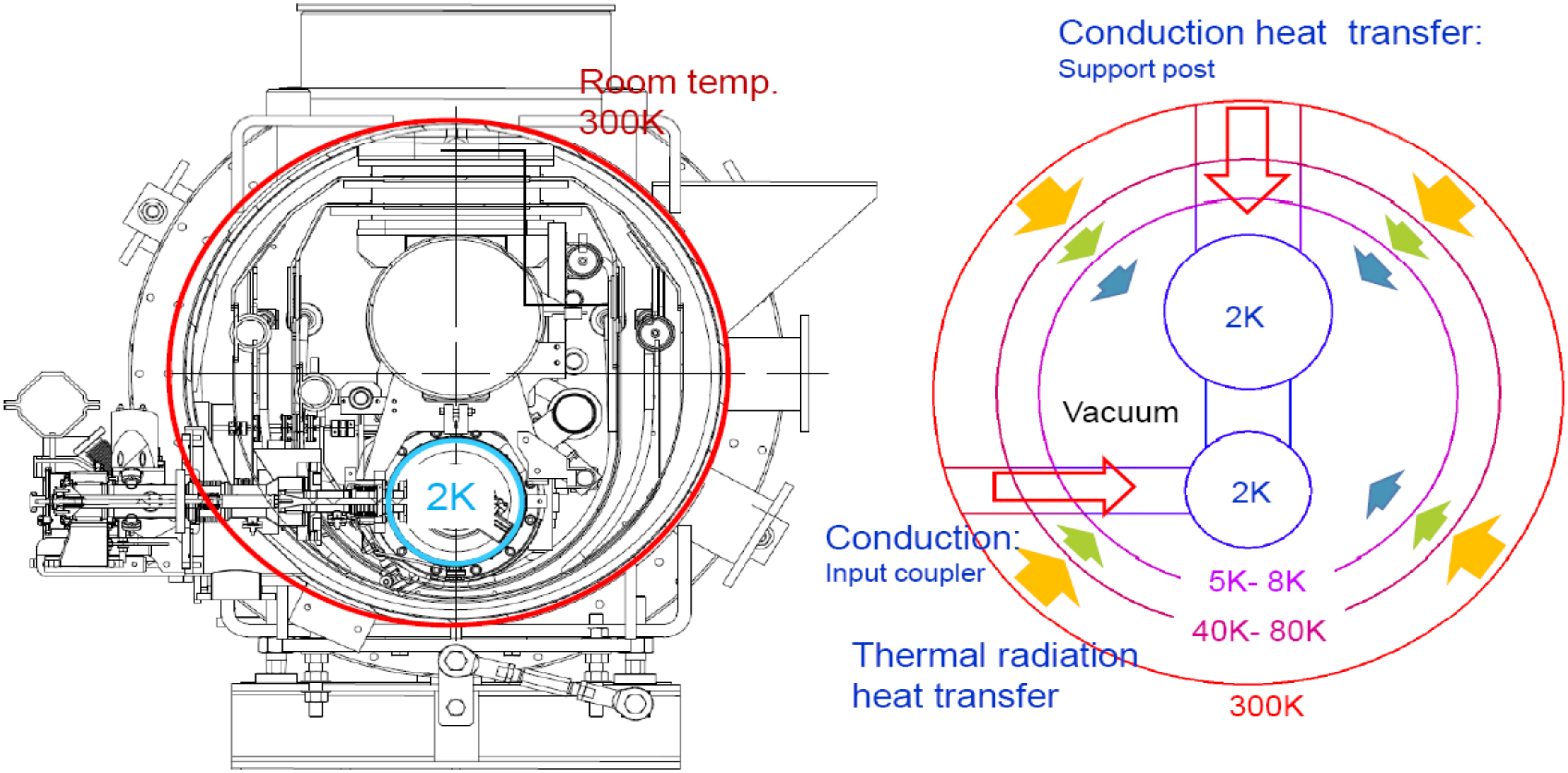
DESY-TESLA-TYPE-III
Cryomodule Cross Section

But hey! Why do we have a vacuum vessel?

What type of vacuum de we need here?

Figure of Merrit for a cryo-module

Making thermal insulated environment for superconducting cavity



A typical heat load table (ILC)
Figures are in W

	2K		5-8K		40-80K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF load		7.5				
Thermal radiation	0.0		1.4		32.5	
Supports	0.6	0.0	2.4		6.0	
Input coupler	0.5	0.2	1.5	1.3	15.5	66.1
HOM coupler (cables)	0.0	0.2	0.3	1.8	1.8	9.0
HOM absorber	0.1	0.0	3.1	0.5	3.3	10.9
Beam tube bellows		0.4				
Current Leads	0.3	0.3	0.5	0.5	4.1	4.1
HOM to structure		1.2				
Coax cable (4)	0.07					
Instrumentation tapes	0.07					
Diagnostic cable			1.4		2.8	
Sum	1.7	9.7	10.6	4.2	59.2	90.1

End of Lecture I

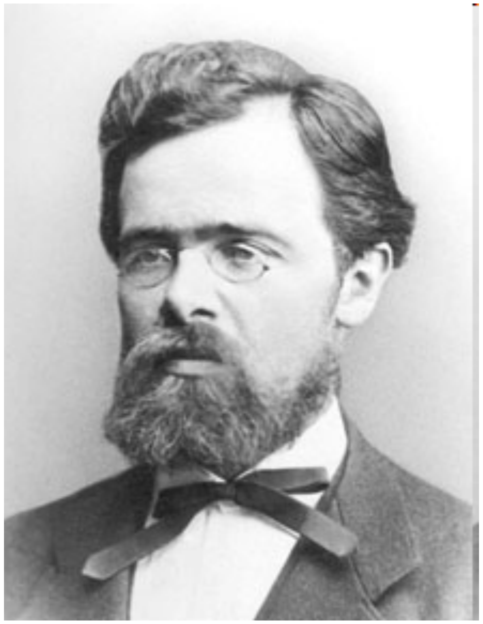
Cryo-Module Basics

Next: Lecture II

Refrigeration, Liquefaction and Properties of Helium

About the physics at low temperature

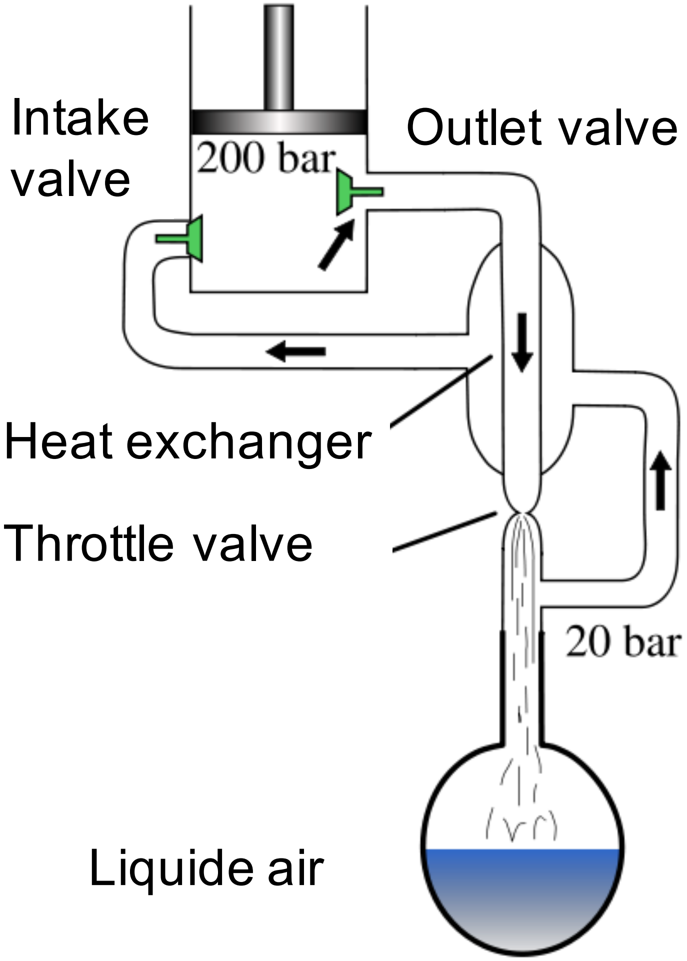
Low temperature physics started with **Carl von Linde**



- 1868-78 Prof. in Mechanical Engineering Polytechnikum München (TUM)
- 1874 first cooling device
- 1879 foundation of “Linde's Eismaschinen” (now Linde AG)
- 1892-1910 Profesor, Polytechnikum München
- 1895 first liquefaction of air
- 1901 Liquefaction of O_2 und N_2 on an industrial scale

Linde's process to liquefy air based on heat exchangers

- Air gets compressed
- Heat generated by that gets chilled by water
- Expansion of the air in a throttle
- => cooling due to the Joule-Thomson effect (expansion from 200 to 20 bar results in 45 K)
- Process can also be used to liquefy Hydrogen
- But: Helium cannot!



Liquefaction of Helium

- First successfully done by Heike Kammerlingh Onnes
- 1908 in Leiden (Netherlands)
- Nobel price 1913

And people asked: why do we need liquid helium?

But let's come back to the Joule-Thompson effect…

Laws of thermodynamics (II)

- 0^{th} fundamental law of thermodynamics:

bodies in thermal contact have the same temperature

- 1^{st} fundamental law of thermodynamics

The increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by the system:

$$dU = dW + dQ \qquad U = \frac{1}{n}\sum E_i$$

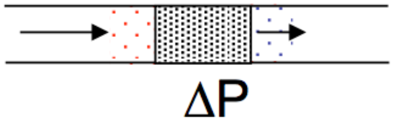
In open systems, the enthalpy is a more appropriate quantity for the energy:

$$H = U + p \cdot V$$

when you allow a gas to expand, H is constant

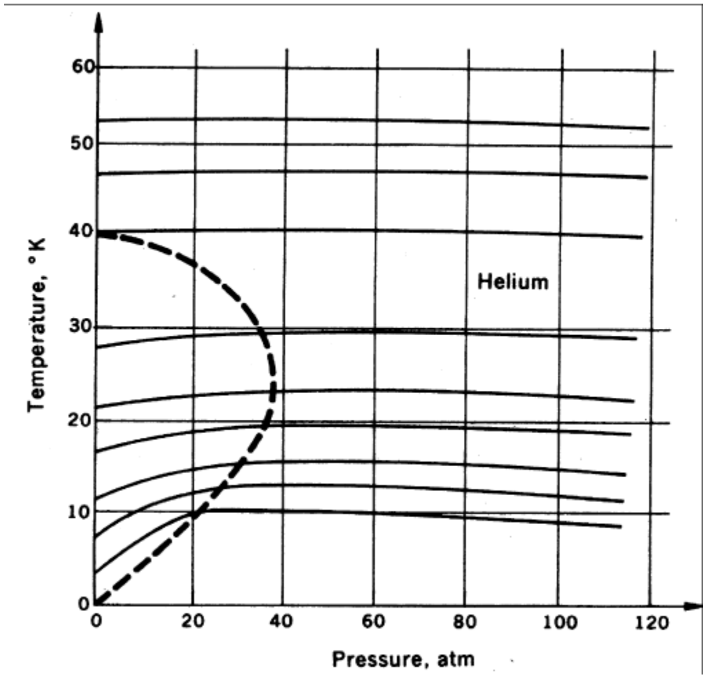
Joule Thomson Coefficient

- 1885 - Joule & Thomson (Lord Kelvin) confirm that a gas flow through a restriction experiences a temperature drop along with the pressure drop.



- The Joule-Thomson coefficient: $\mu_j = \left.\frac{dT}{dP}\right|_h$ characterizes the phenomenon.
- When $\mu_j > 0$, cooling accompanies a pressure drop.

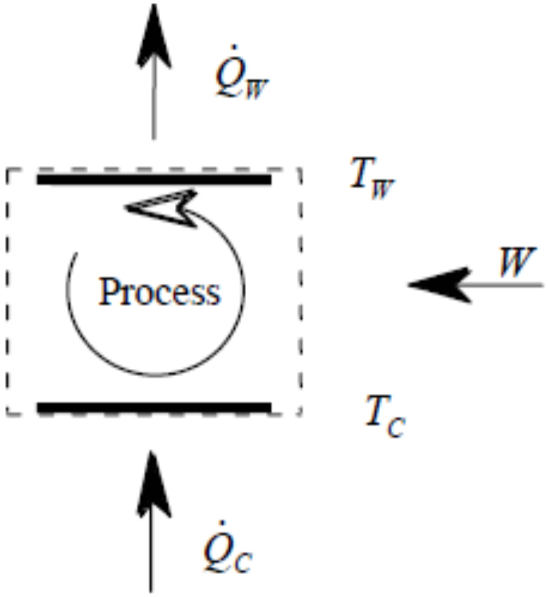
Gas	Maximum Joule-Thompson inversion temperature [K]
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Oxygen	761



Laws of thermodynamics (II)

- 2nd fundamental law of thermodynamics

Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.



$$\frac{Q_w}{T_w} + \frac{Q_c}{T_c} \leq 0$$

This limits the options of transferring energy according to the 1st law

=> Gives rise to the definition of the entropy

Entropy

The entropy of an isolated system increases in all real processes and is conserved in reversible processes

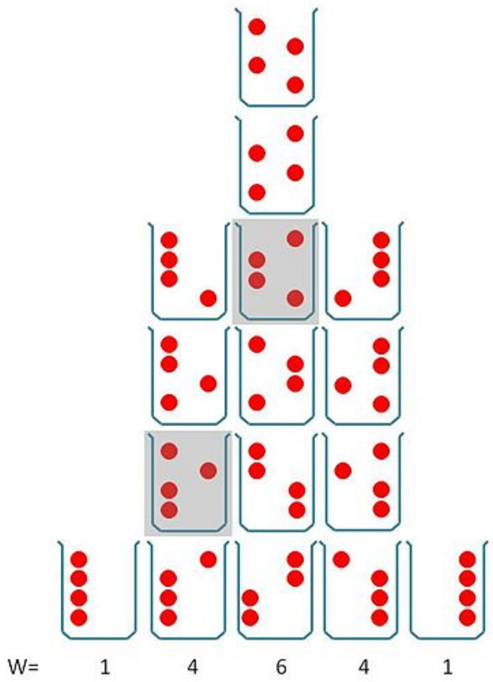
- Definition of the entropy (change)

$$\Delta S = \frac{\Delta Q}{T}$$

- Entropy also measures the disorder in a system. The statistical definition is:

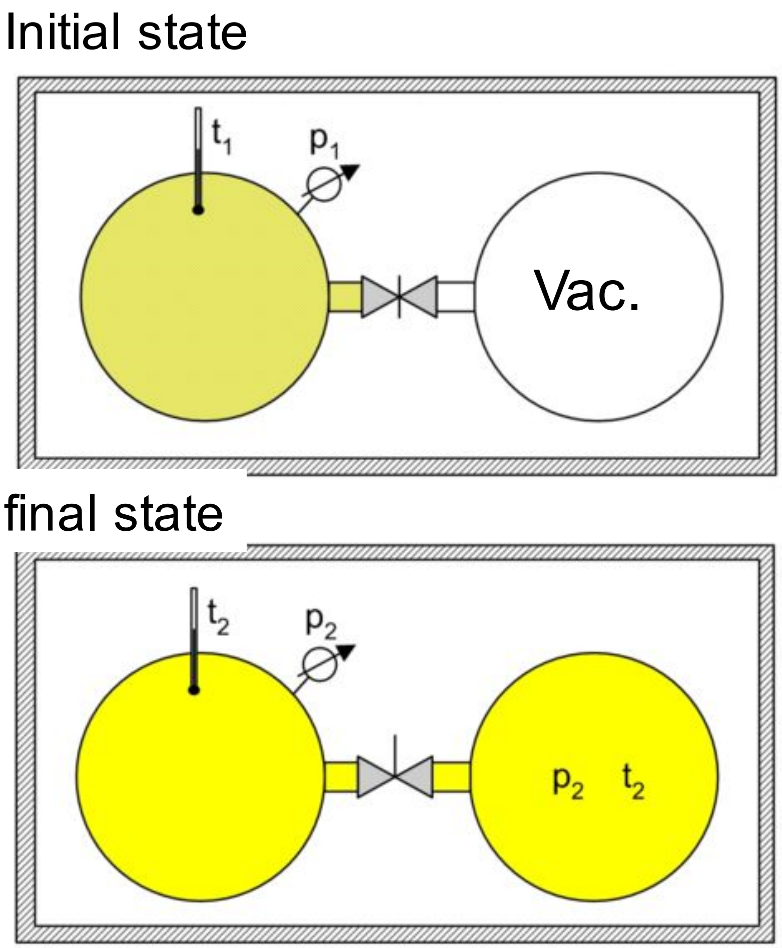
$$S = k_B \ln W$$

(W is the number of microscopic states)

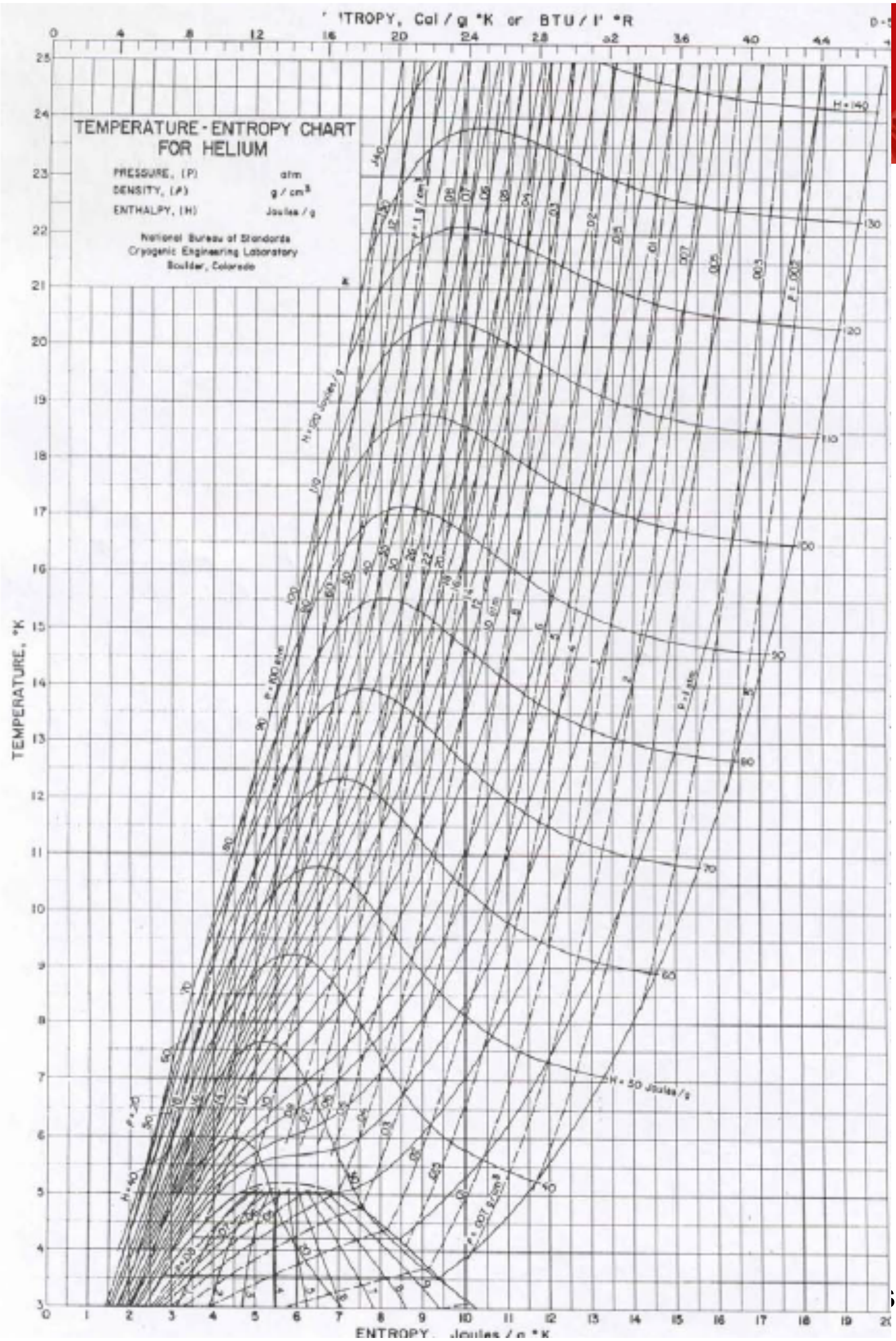


To fill this with life

- What happens to the entropy?
- Is this process reversible?



TS Diagram



- Gives thermodynamic properties of a specific material
- Contains a lot of information!

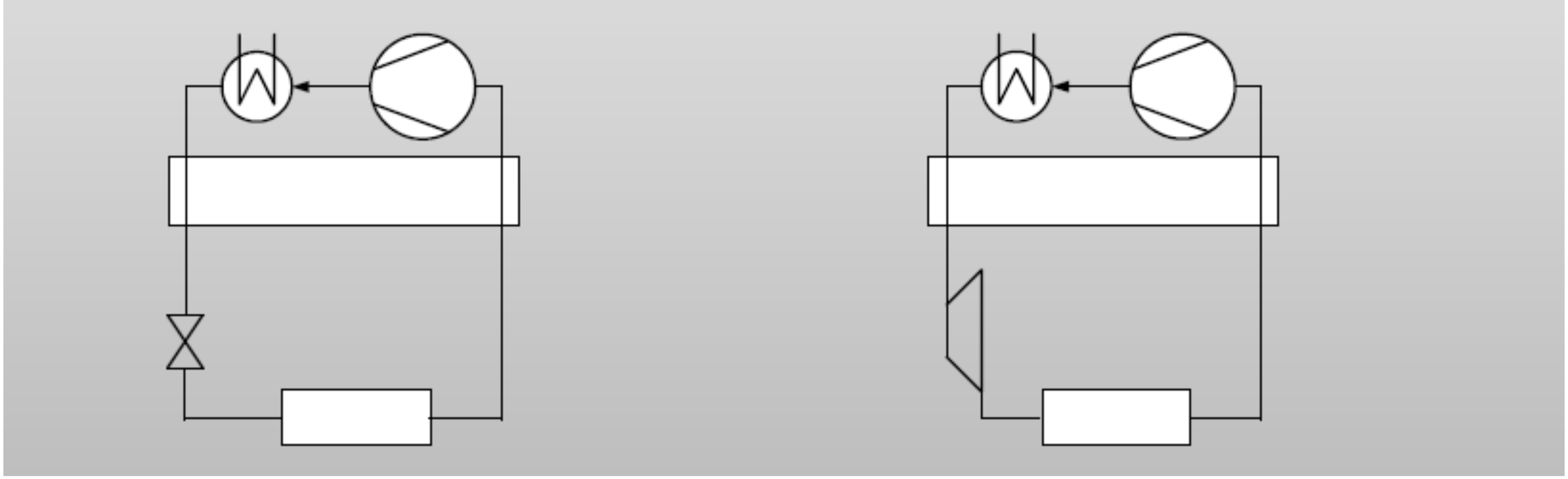
Get oriented:

- Find lines of constant p
- Find lines of constant T
- Constant h
- Where is the 2 phase region?
- Quality of the liquid?
- Critical point?

Two basic processes

Joule-Thomson effect:
isenthalpic expansion

Expander: isentropic
expansion



Expansion without heat transfer

$$\Delta H = 0$$

Expansion while delivering mechanical work

$$\Delta S = 0$$

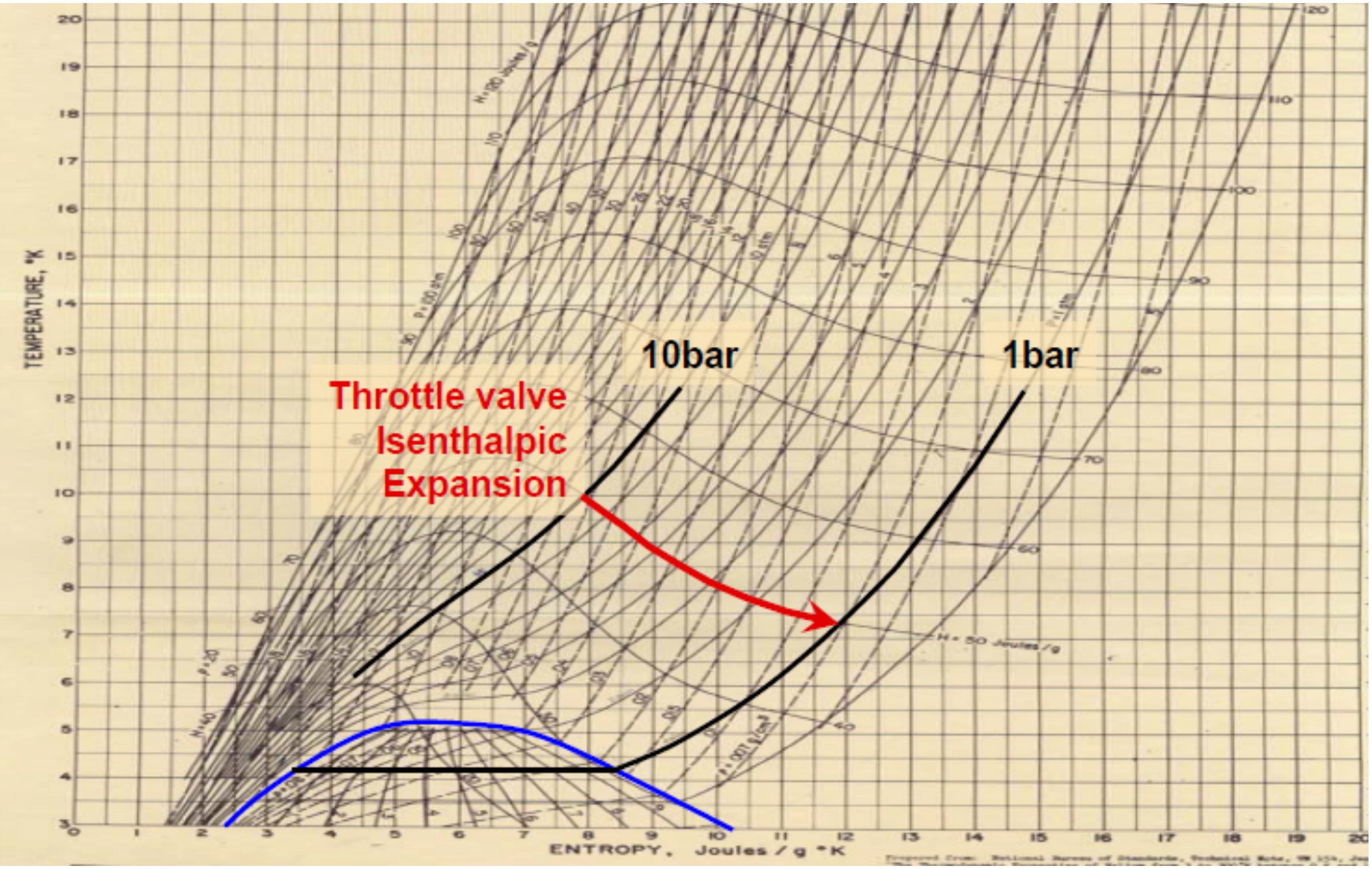
Joule Thomson effect
TS Diagram

p_1

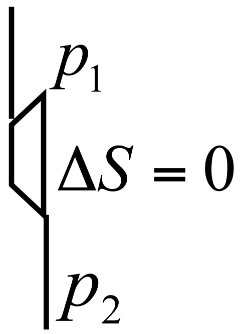
$\Delta h = 0$

p_2

$\Delta S >> 0$



Expander
TS Diagram

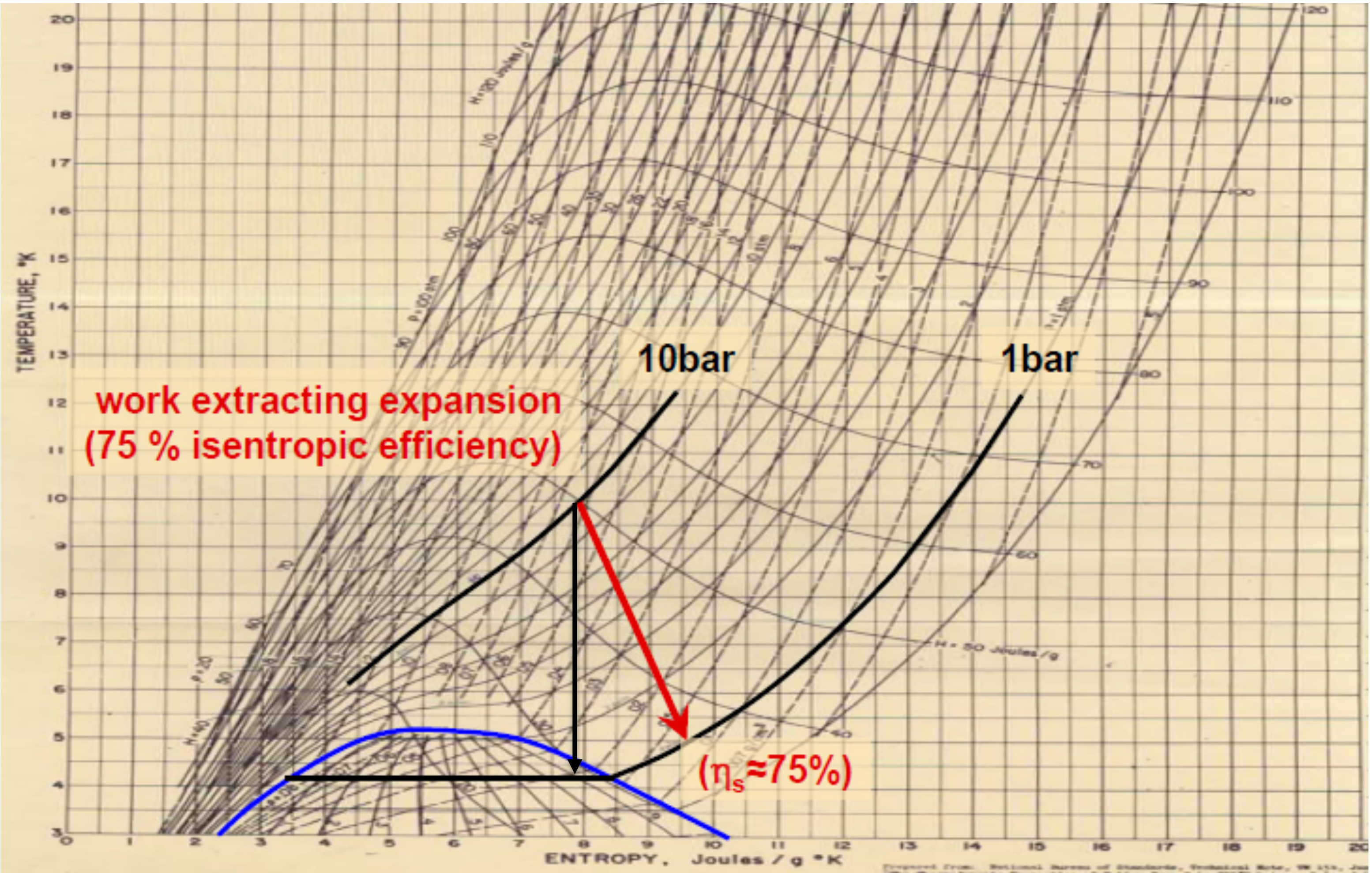


p_1

$\Delta S = 0$

p_2

$$S_2 = \frac{1}{\eta_S} S_1$$



work extracting expansion
(75 % isentropic efficiency)

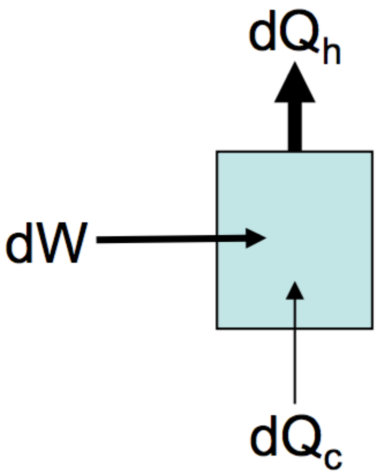
10bar

1bar

(η_s≈75%)

Principle of a refrigerator

- ‘Moving’ heat from a cold reservoir to a warm reservoir requires energy



The amount of heat moved is associated with an amount of entropy by the relationship:

$$dQ = TdS$$

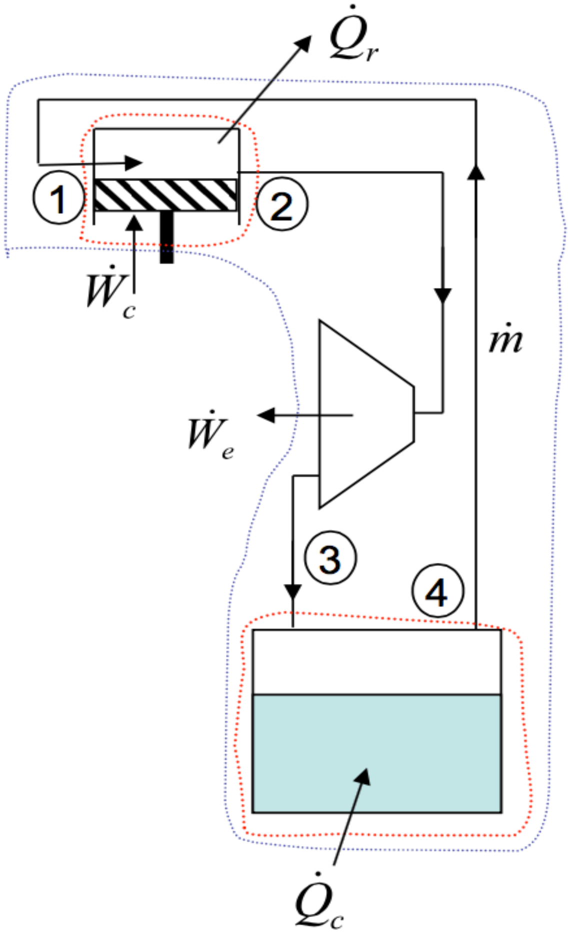
• In an ideal process, the entropy associated with the two heat flows is the same, that is:

$$dS = \frac{dQ_c}{T_c} = \frac{dQ_h}{T_h}$$

- In an ideal process the amount of work (energy) required to ‘move’ the heat is

$$dW = dQ_h - dQ_c$$

The ideal refrigerator



- In steady state, the 1st law around the whole system gives:

$$\dot{W}_c - \dot{W}_e = \dot{Q}_r - \dot{Q}_c \quad or \quad \dot{W}_{net} = \dot{Q}_r - \dot{Q}_c$$

- The 2nd law around the compressor gives:

$$\dot{Q}_r = T_H \dot{m} \left(s_1 - s_2 \right)$$

- The 2nd law around the evaporator gives:

$$\dot{Q}_c = T_c \dot{m} \left(s_4 - s_3 \right)$$

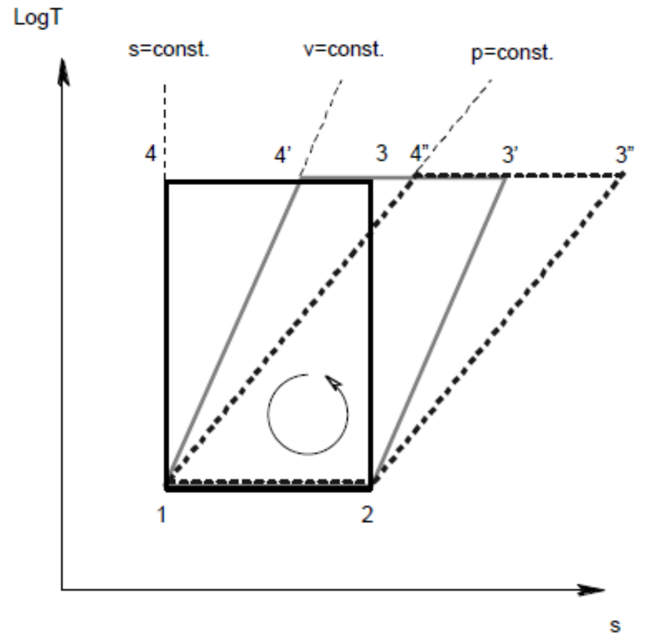
- Combining, and noting that $s_1=s_4$ and $s_2 =s_3$ we have:

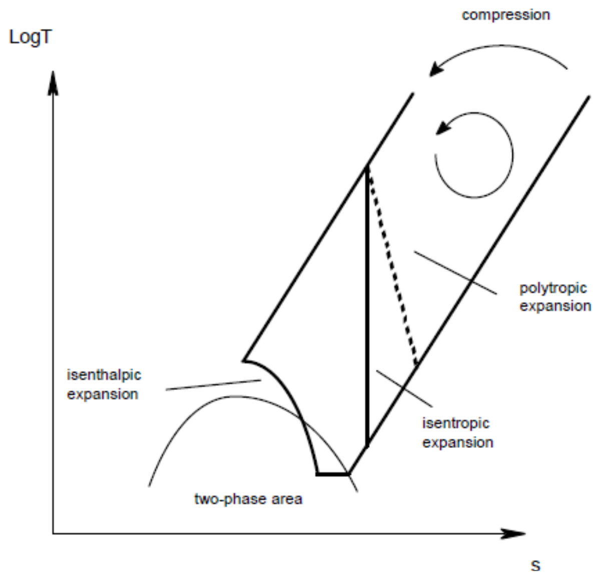
$$\frac{\dot{W}_{net}}{\dot{m}} = \left(T_H - T_c\right)\left(s_4 - s_3\right) = \frac{\Delta S}{\dot{m}}\left(T_H - T_c\right) = \frac{\dot{Q}_c}{\dot{m}}\left(\frac{T_H}{T_C} - 1\right)$$

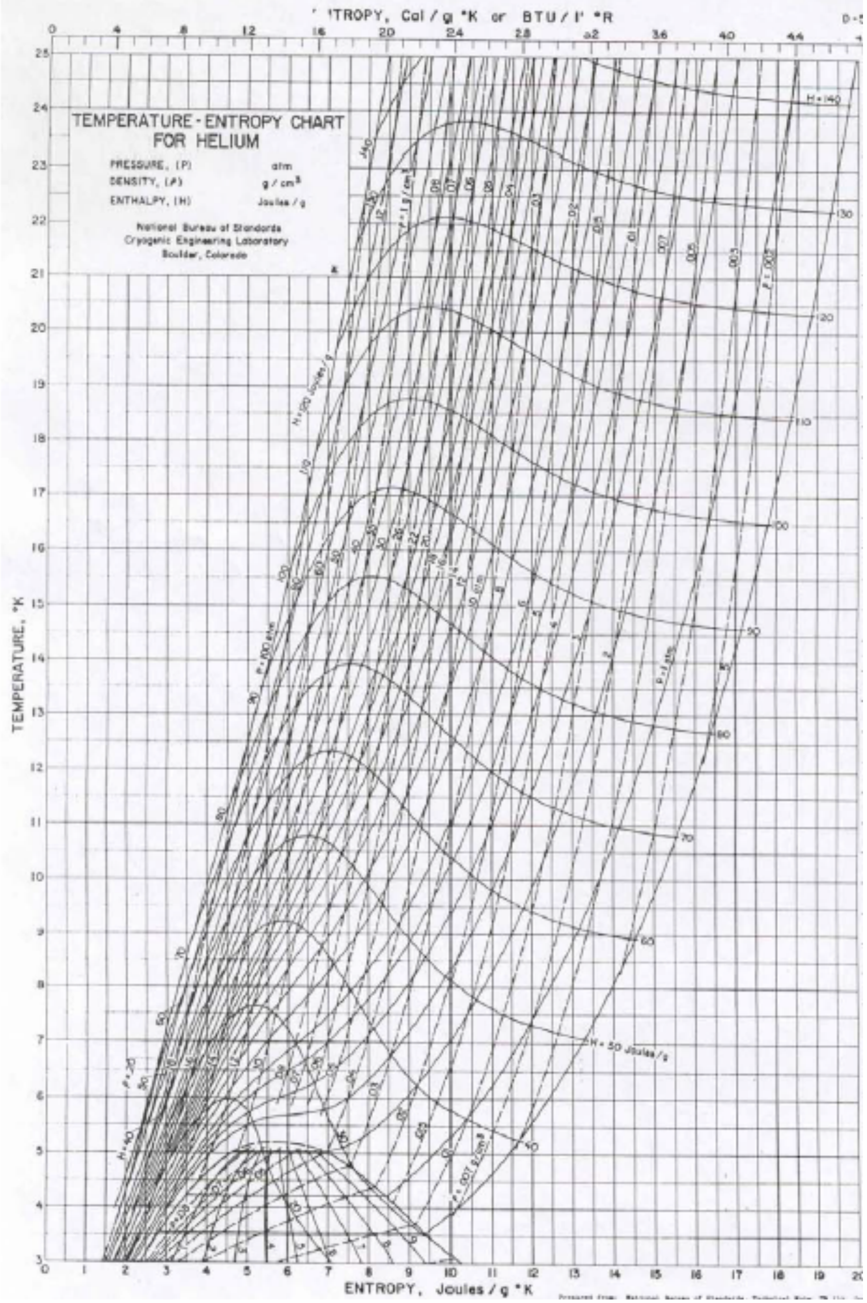
- The coefficient of performance (COP) for the refrigerator is then

$$COP_{ideal} \equiv \frac{\dot{Q}_c}{\dot{W}_{net}} = \left(\frac{T_H}{T_C} - 1\right)^{-1} = \frac{T_C}{T_H - T_C}$$

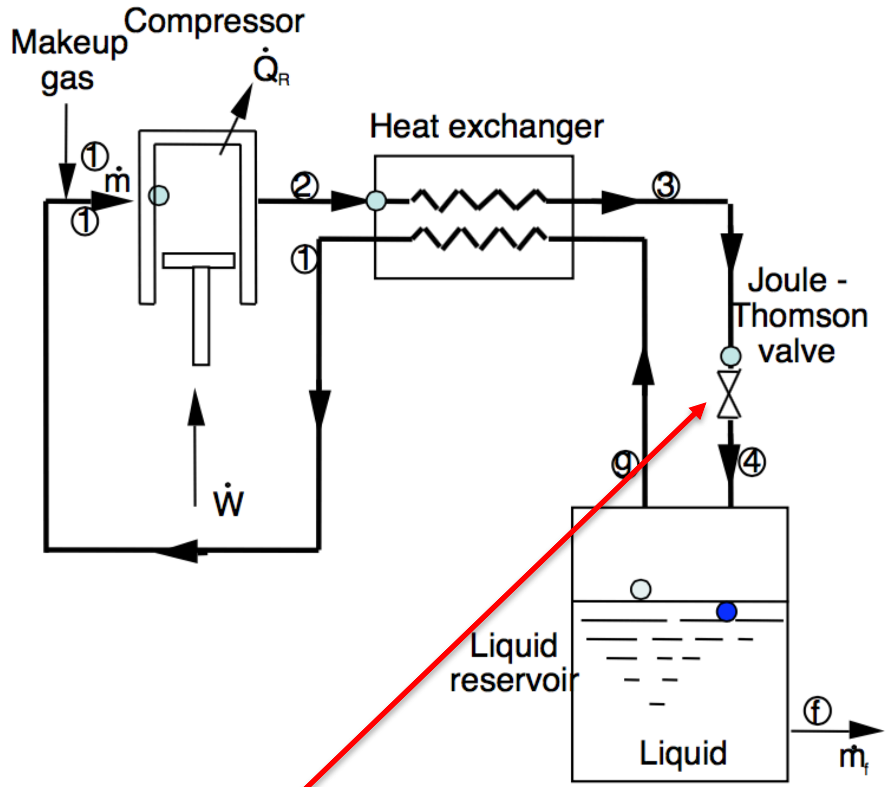
Thermodynamic Processes

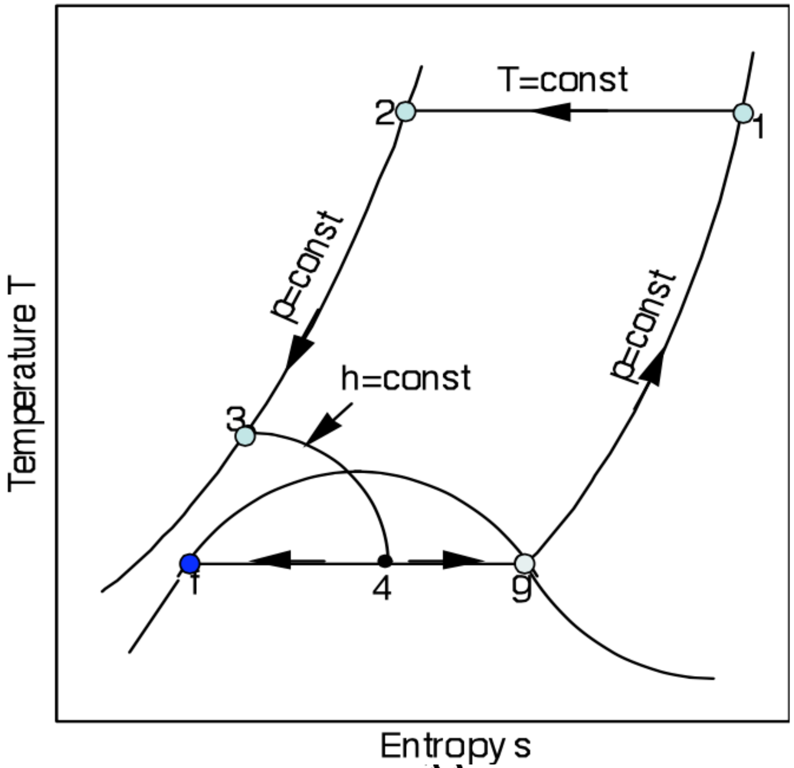


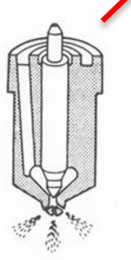


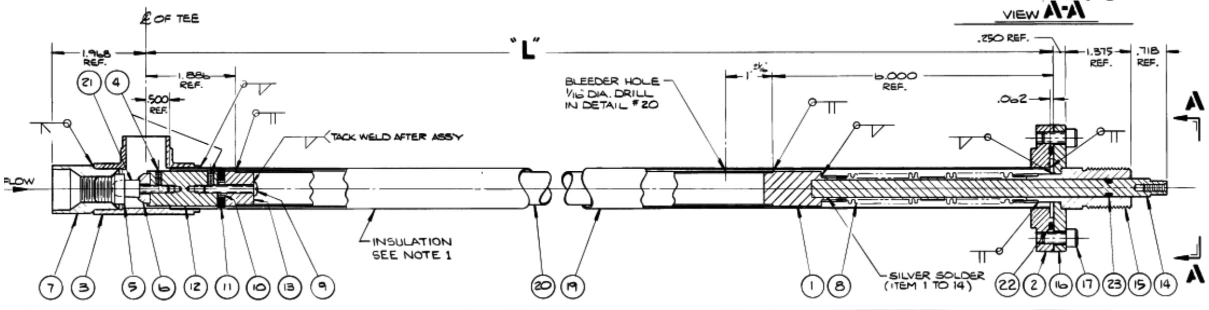


The Linde Cycle

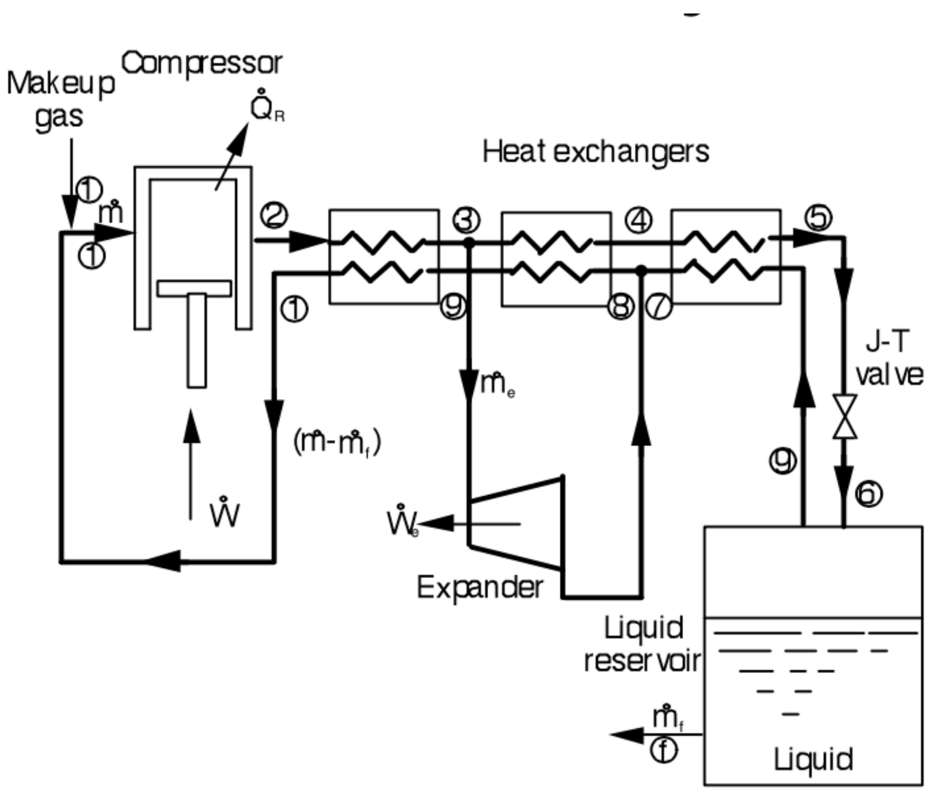


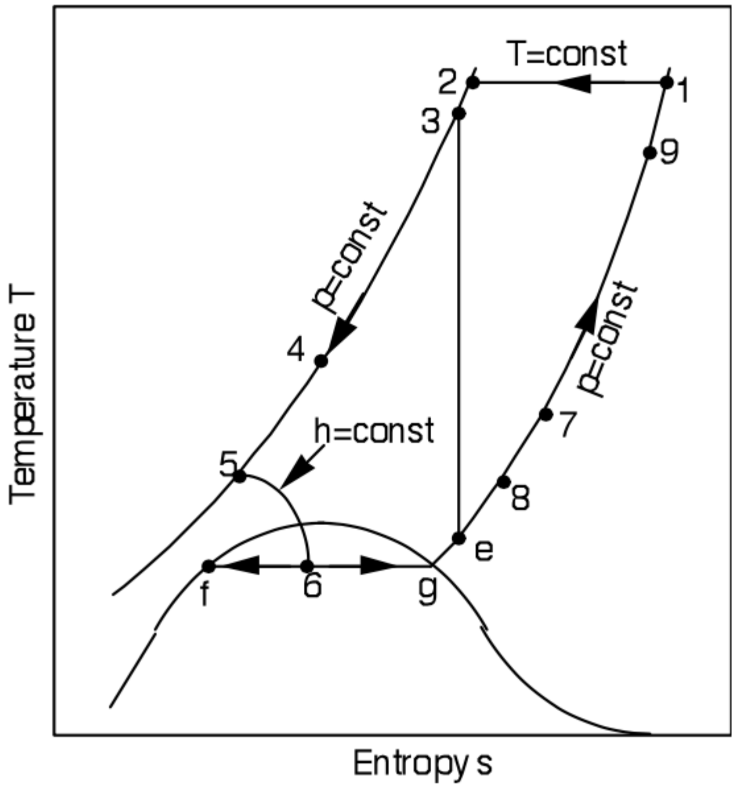




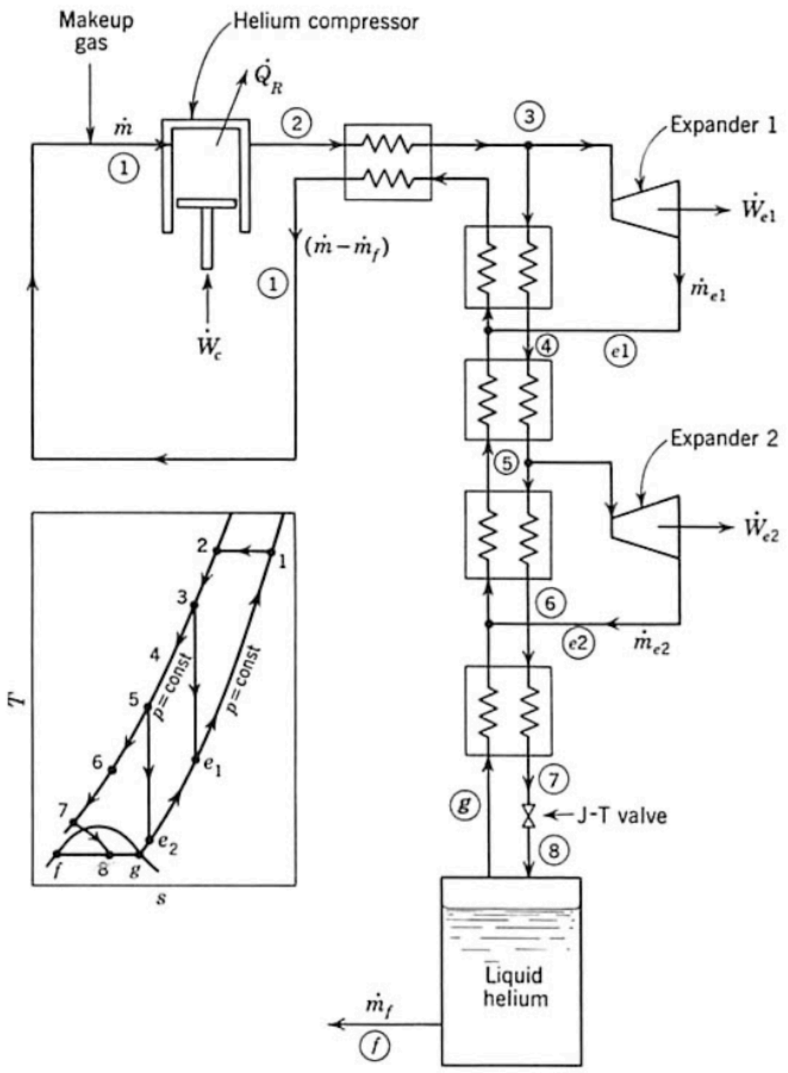


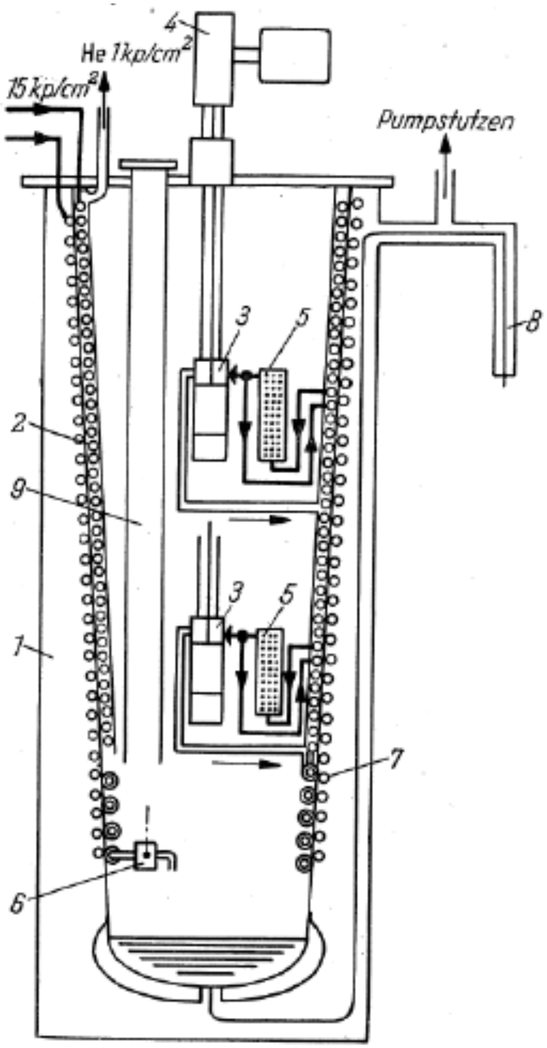
Claude Cycle





Collins Liquefier

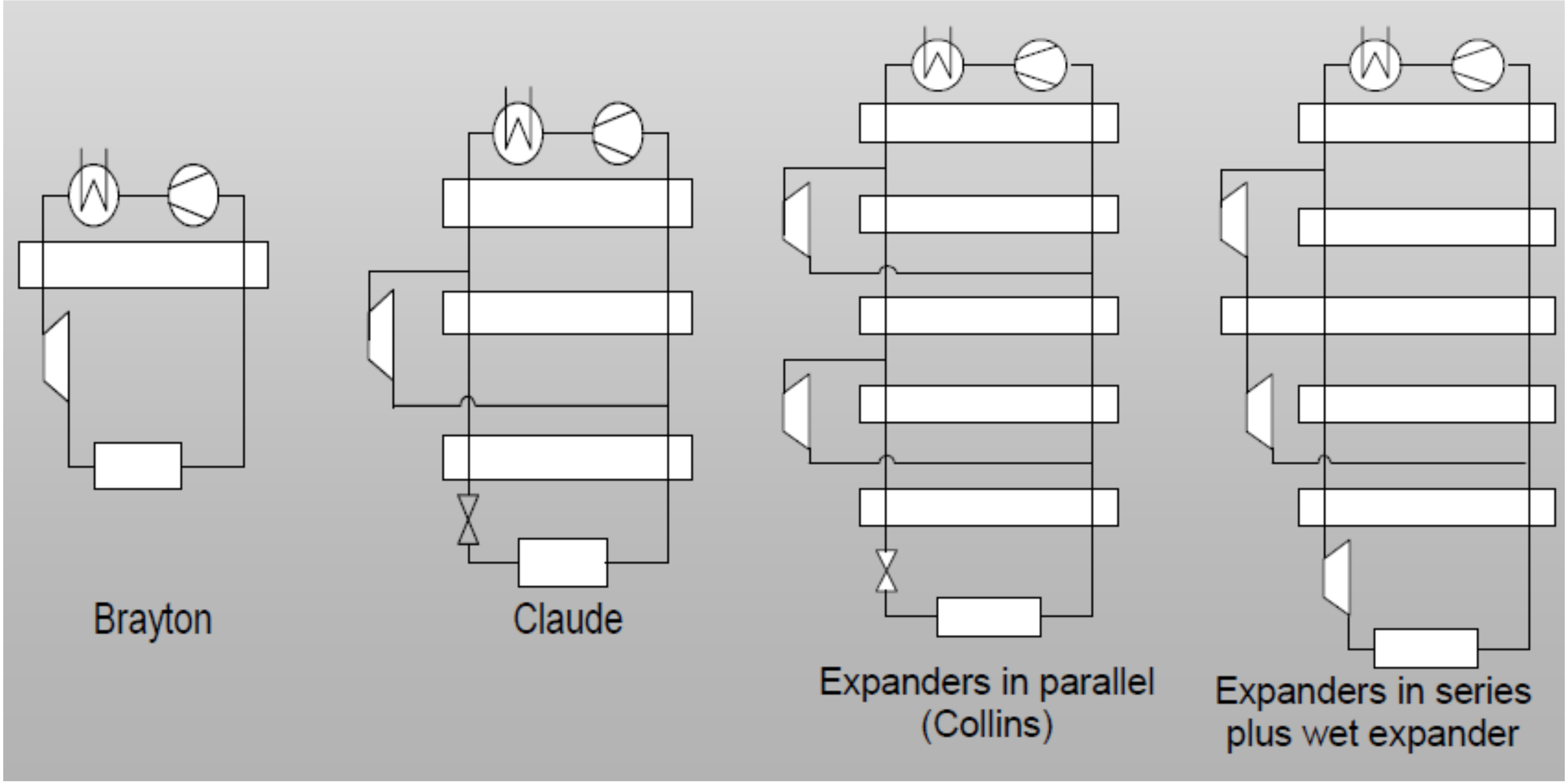




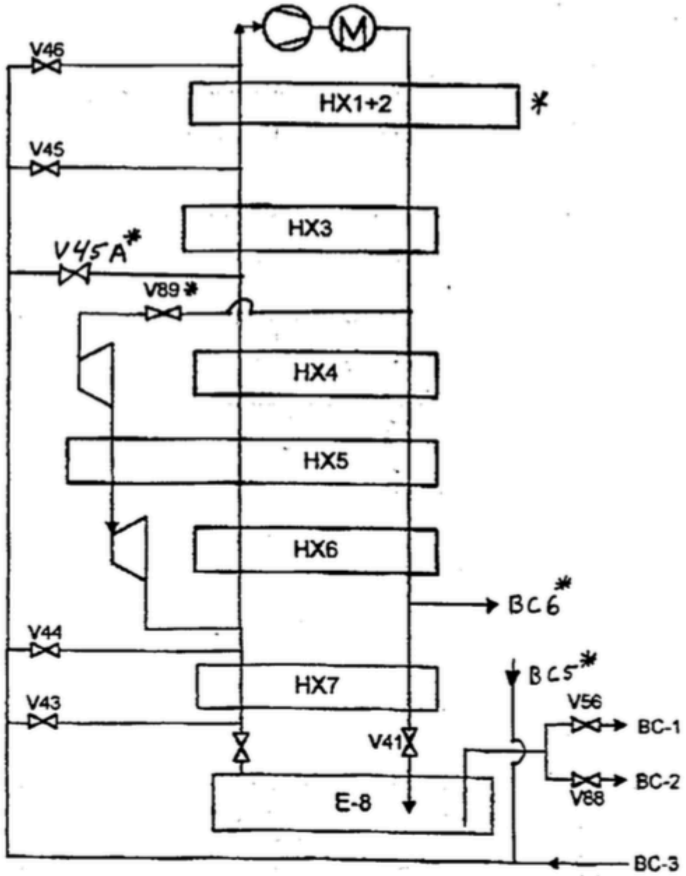
Collins liquefier, MIT (1946)

- First commercially available liquefier

And more combinations....

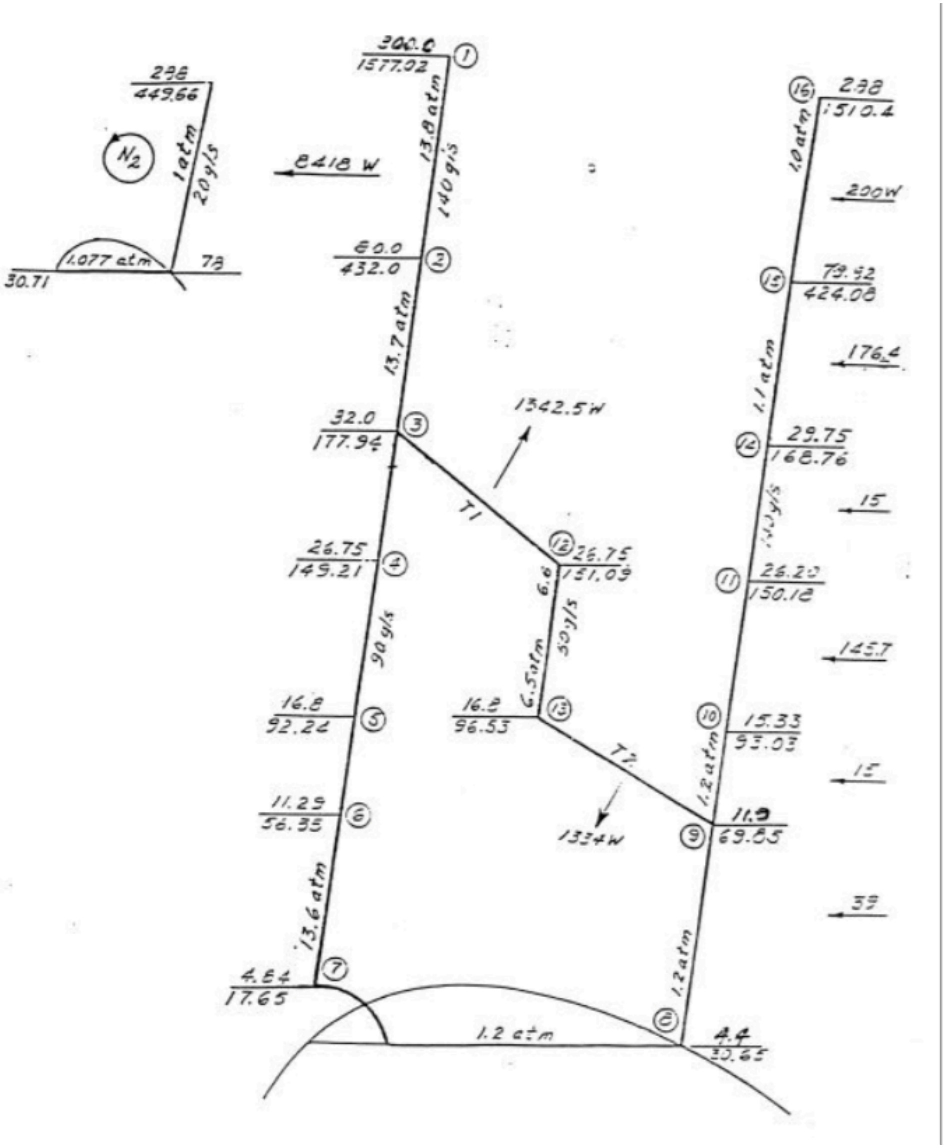


1.2 kW @ 4.5K (1980)

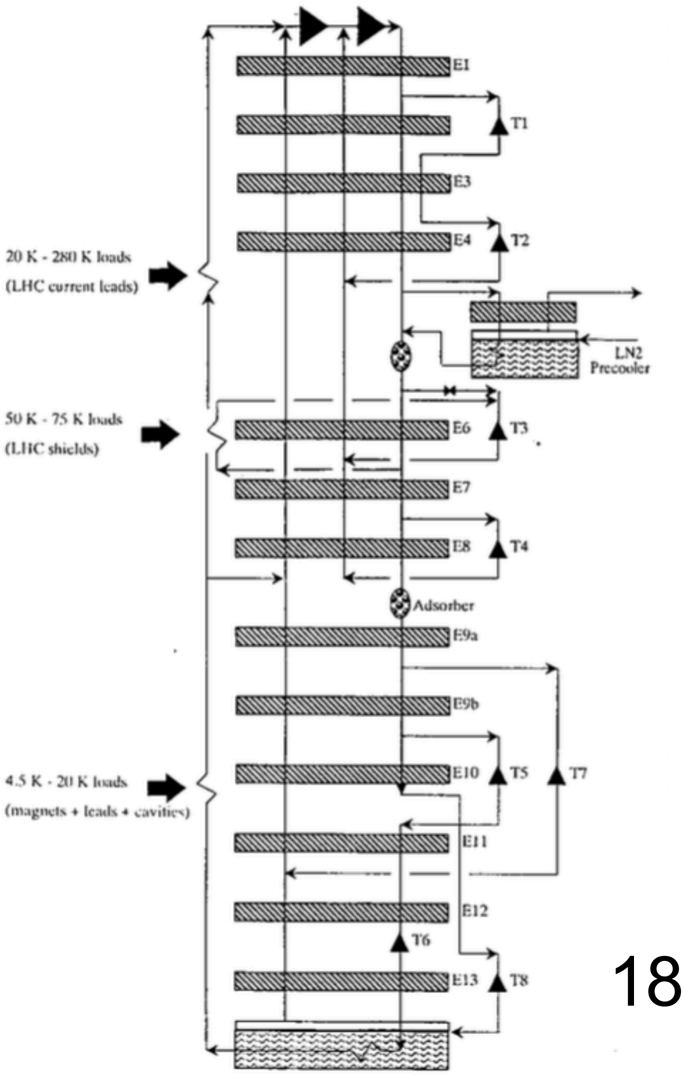


CTI 4000 Upgrade 12 / 2 / 99

* Indicates new or changed component



The LHC refrigeration pant

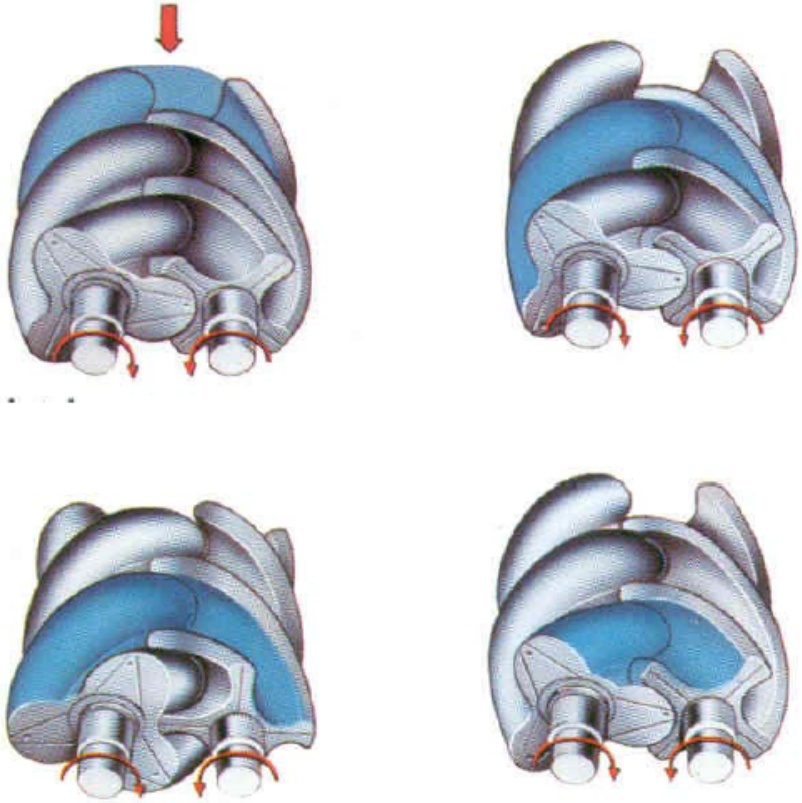


- Note:
  - Large number of expansion turbines – some in series with HP stream
  - Medium pressure return
  - Heat loads at intermediate temperatures
  - Designed to have high % Carnot (roughly 30%)

18 kW @ 4.5K

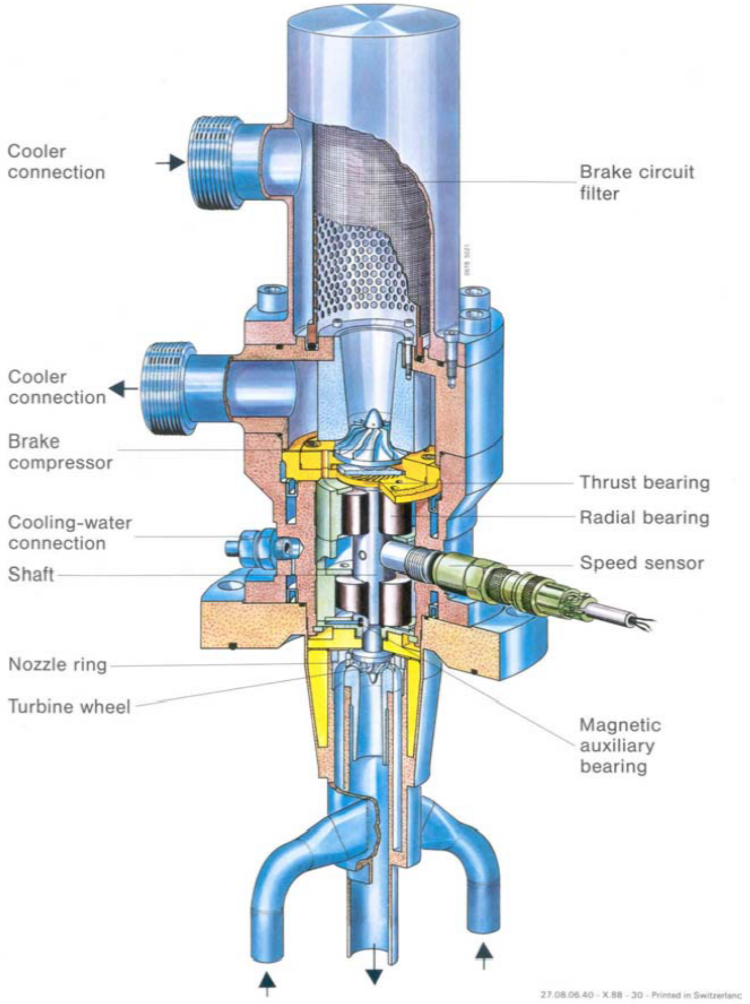
Main Compressor

- Typically a 2 stage, oil flooded screw compressor
- Compression from 1 to 15..20 bar
- Oil removal can be critical



Turbine expander

- Typically 5000 rps
- Gas-bearing, magnetic guidance
- Throttle gas circuit
- Helium contaminations can kill the turbine
- Quick pressure changes, too



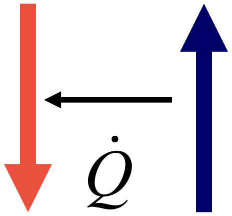
Turbine Expander

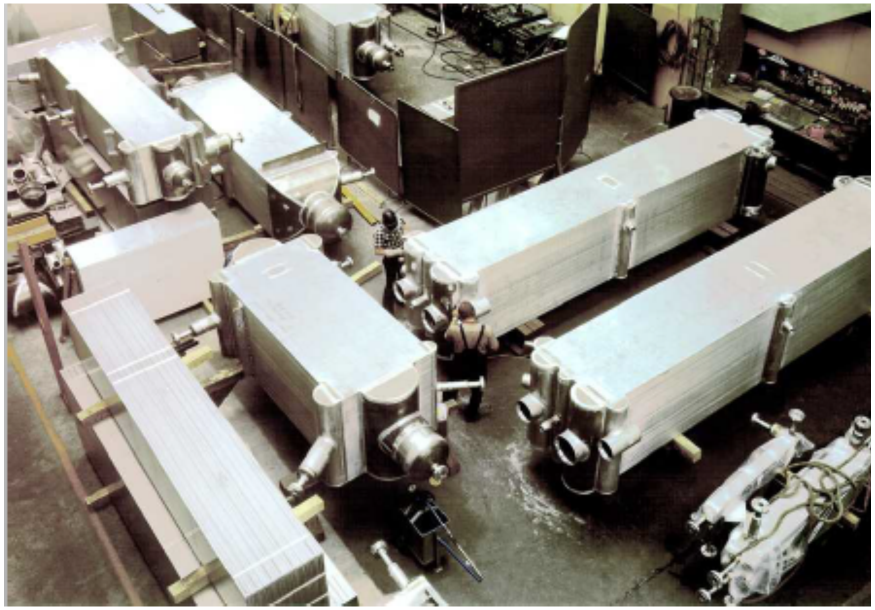
Isentropic effiziency

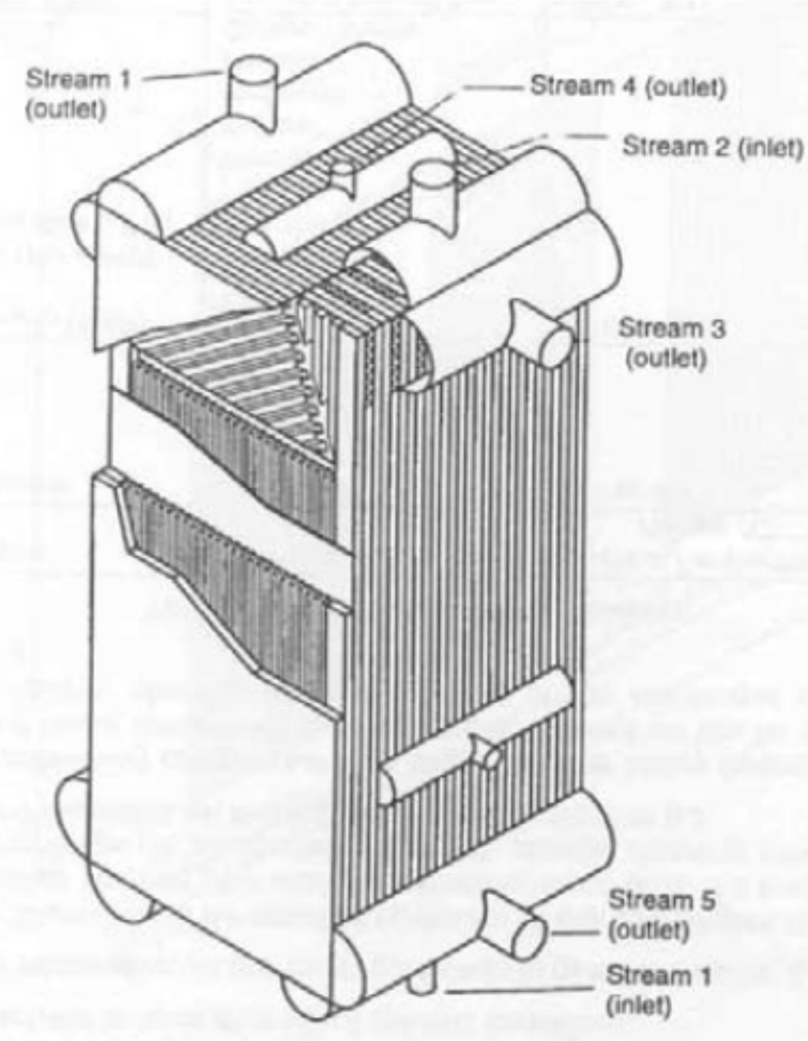
$$\eta_S \sim 65...80\%$$

Heat Exchangers

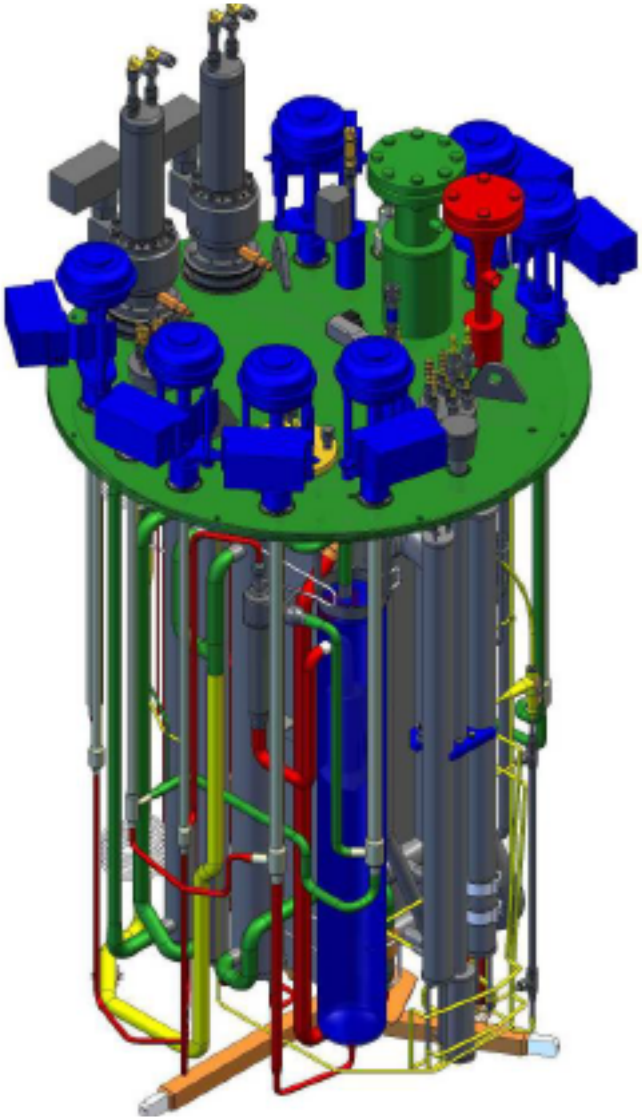
$$\Delta T \approx 3K$$





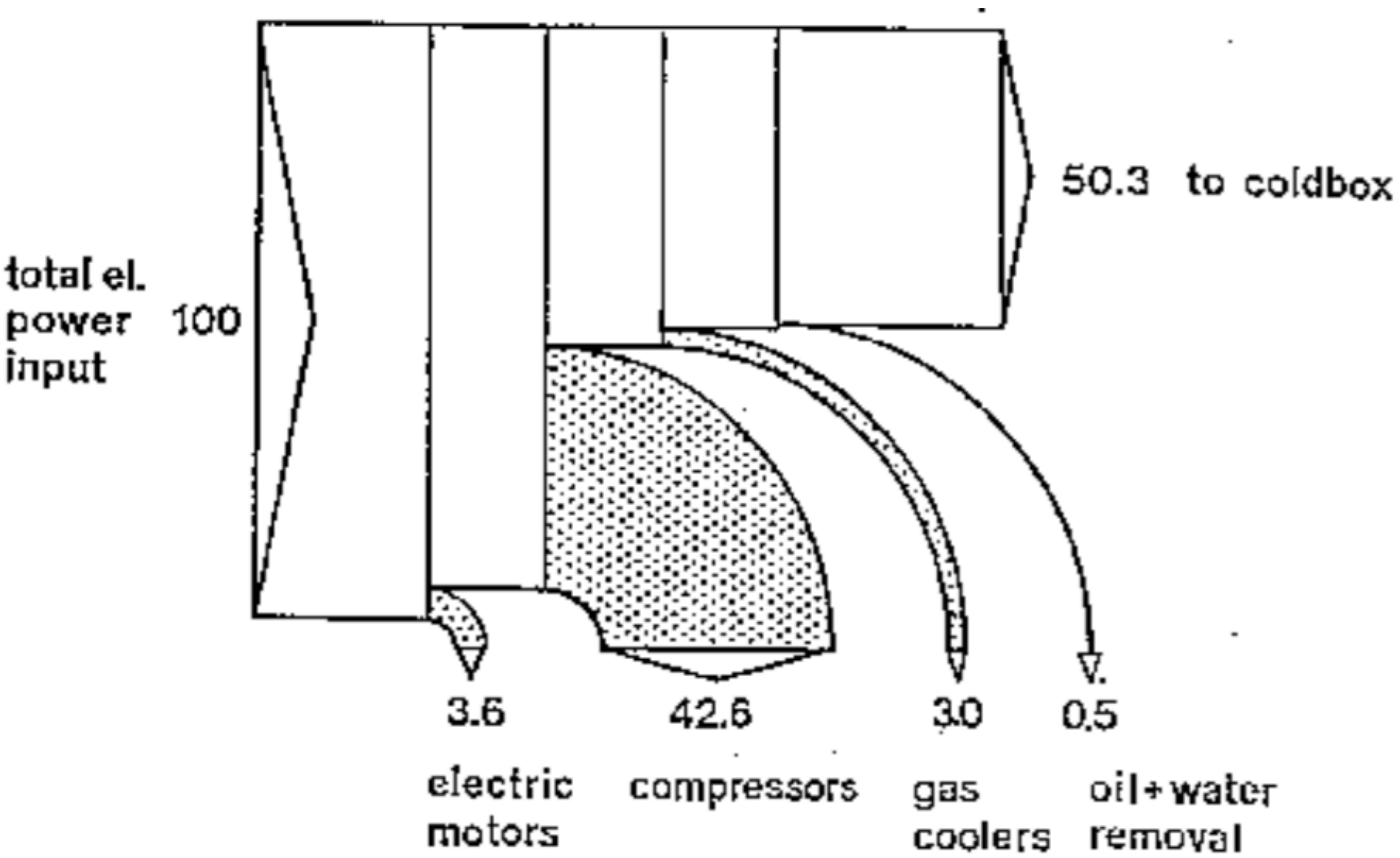


A typical (small size) Cold-Box

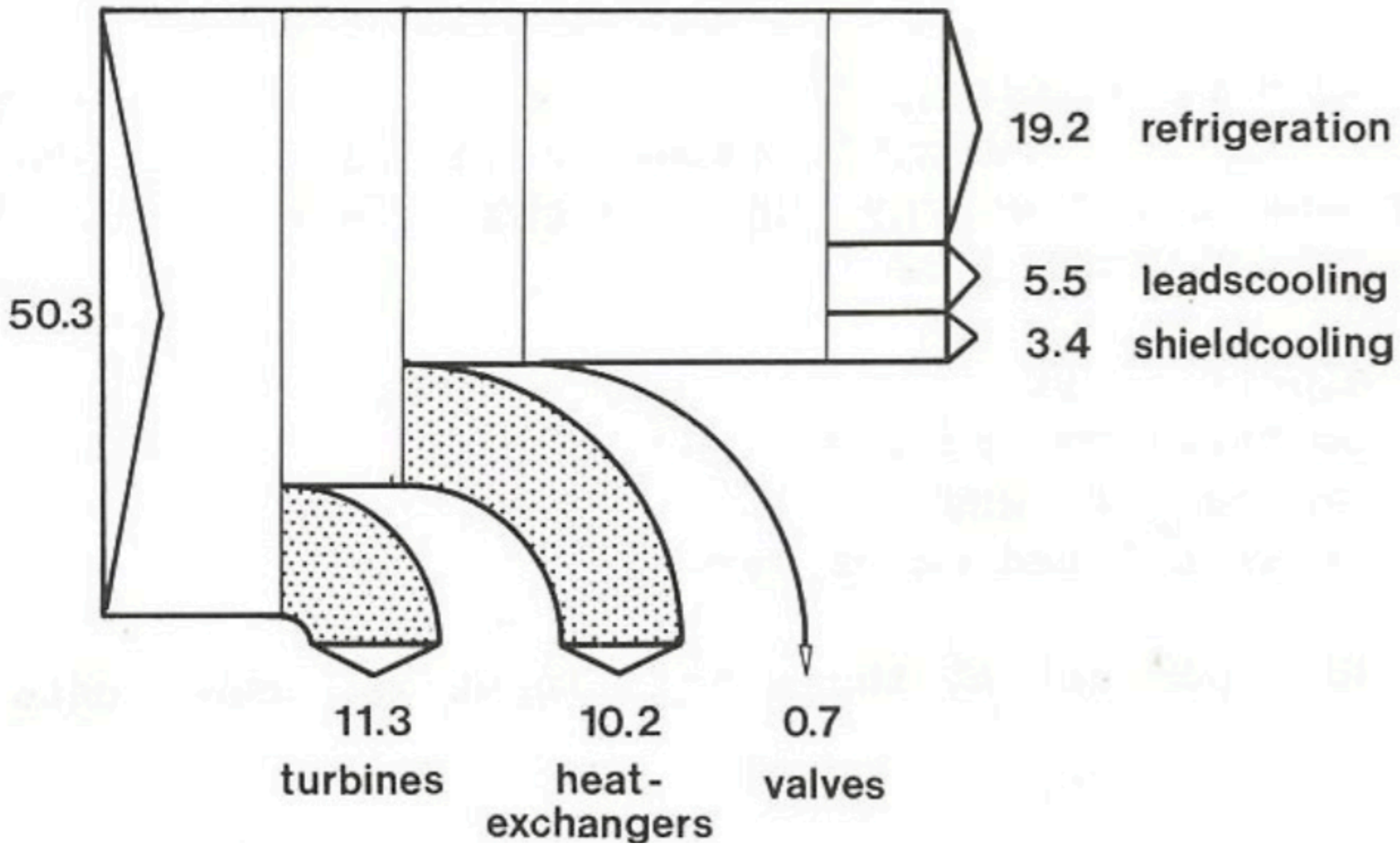


Cold Box for LHC (18kW@4K)

HERA Cryogenic loss analysis

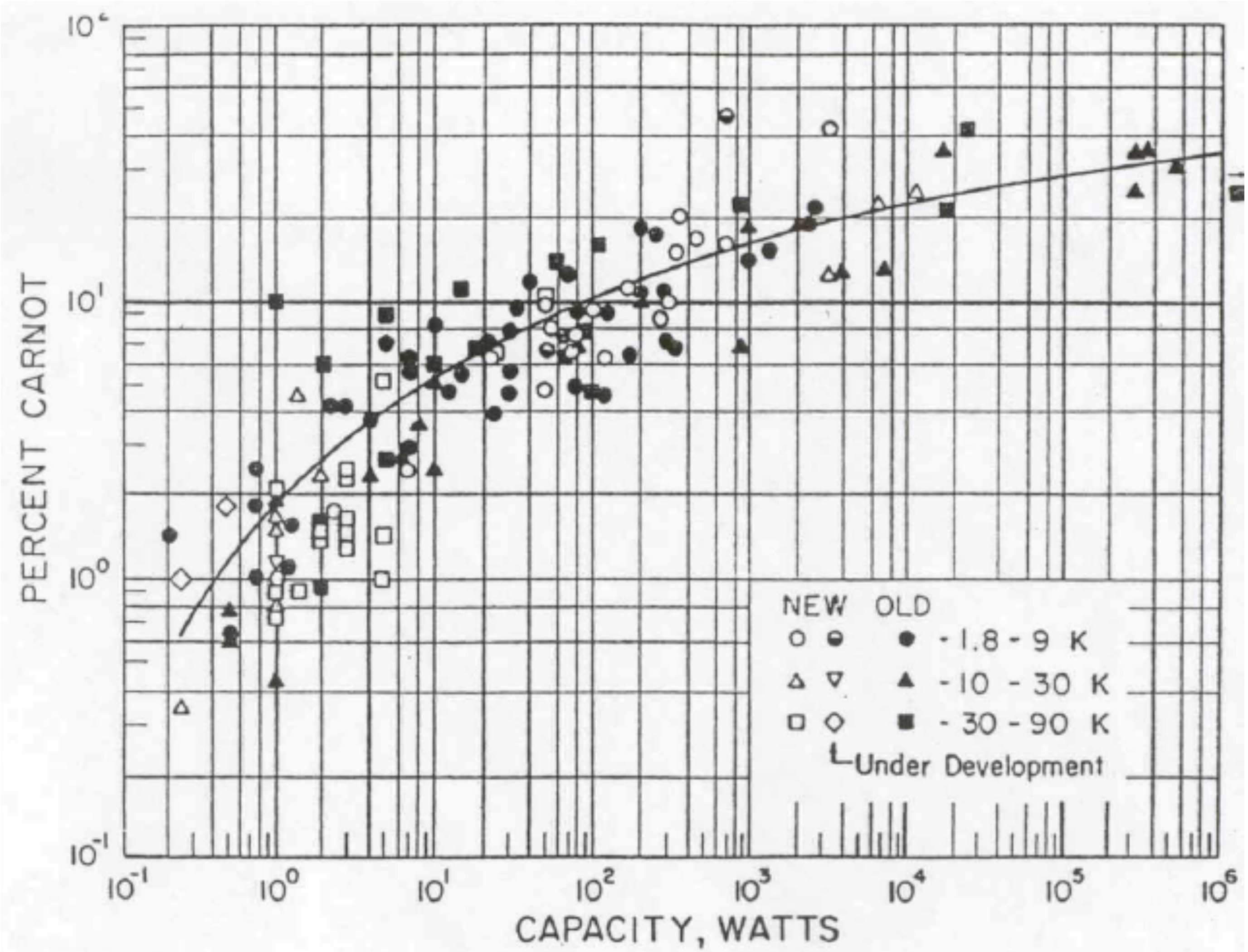


HERA Cryogenic loss analysis

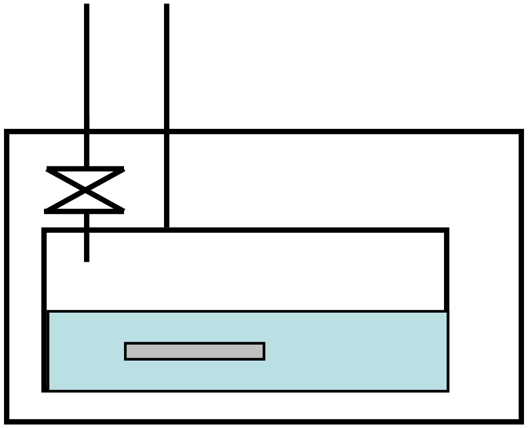


Efficiency of refrigerators

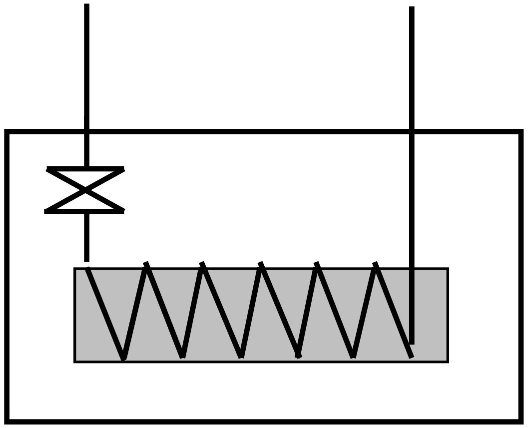
$$\eta_C = \frac{T_h - T_c}{T_h}$$



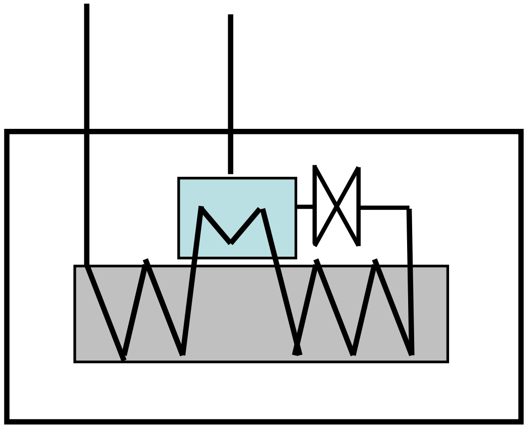
Types of cryogenic cooling



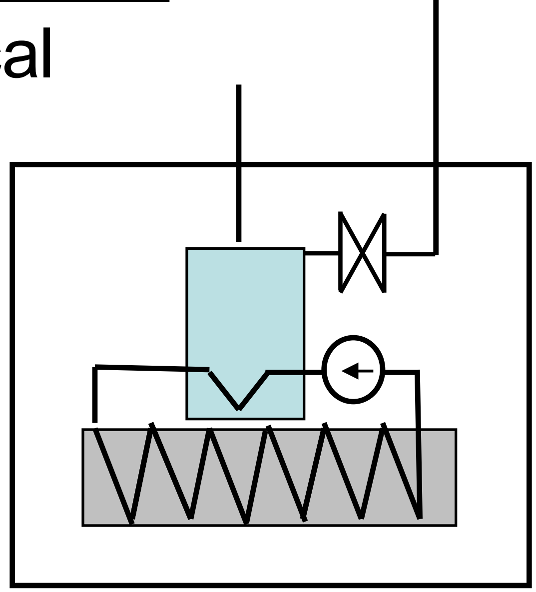
Bath cooling



Subcritical

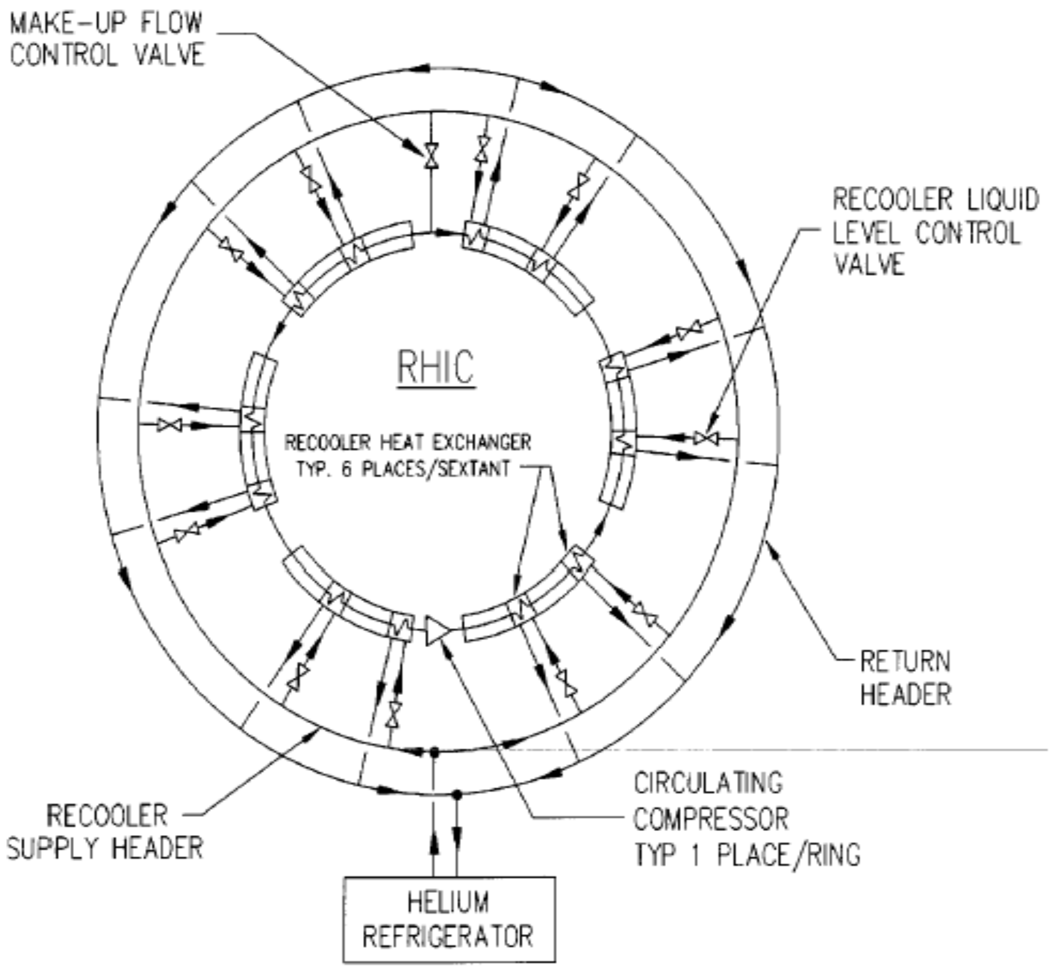


Supercritical with Recooler

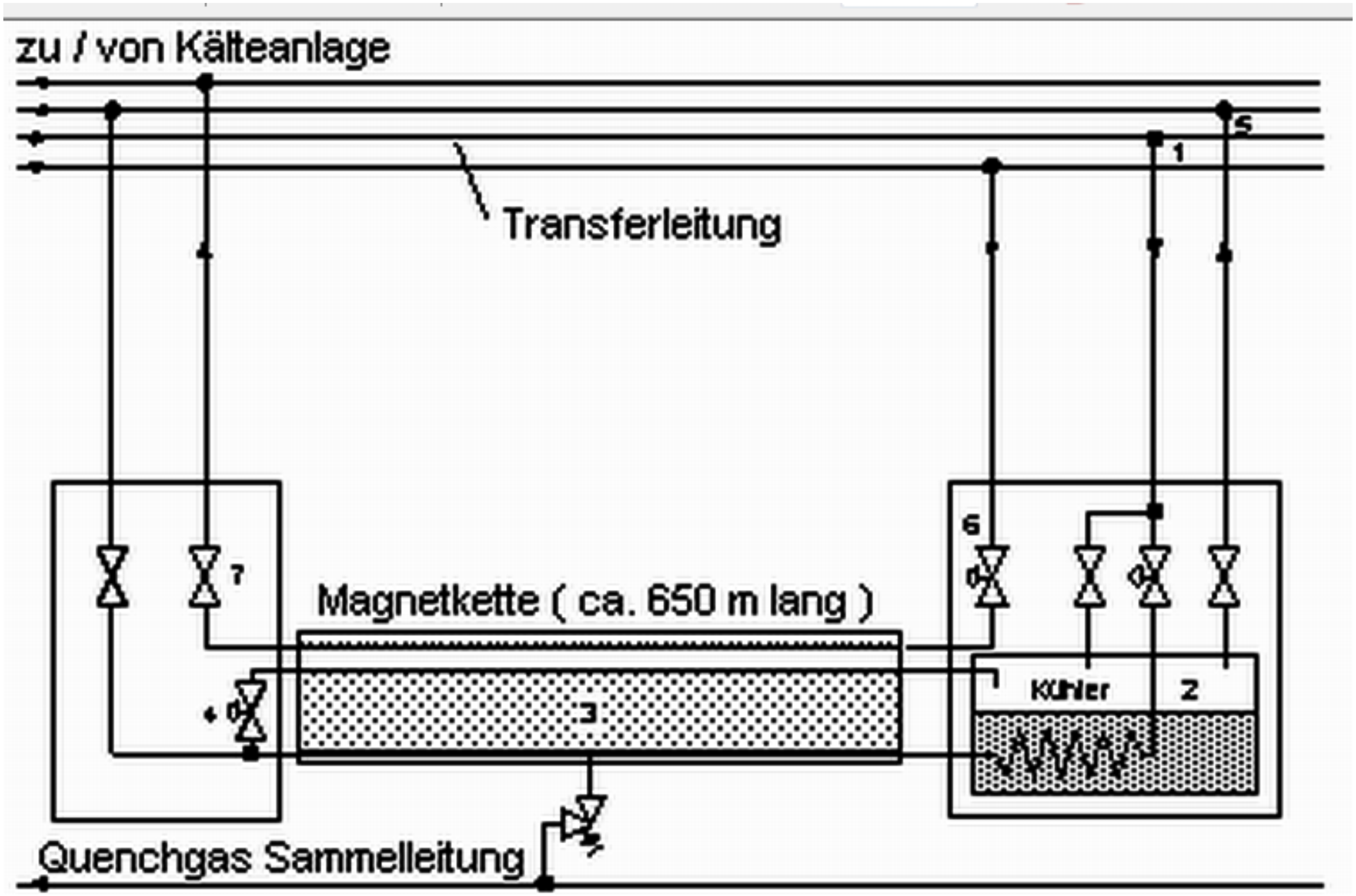


Supercritical using a pump

Magnet cooling @ RHIC

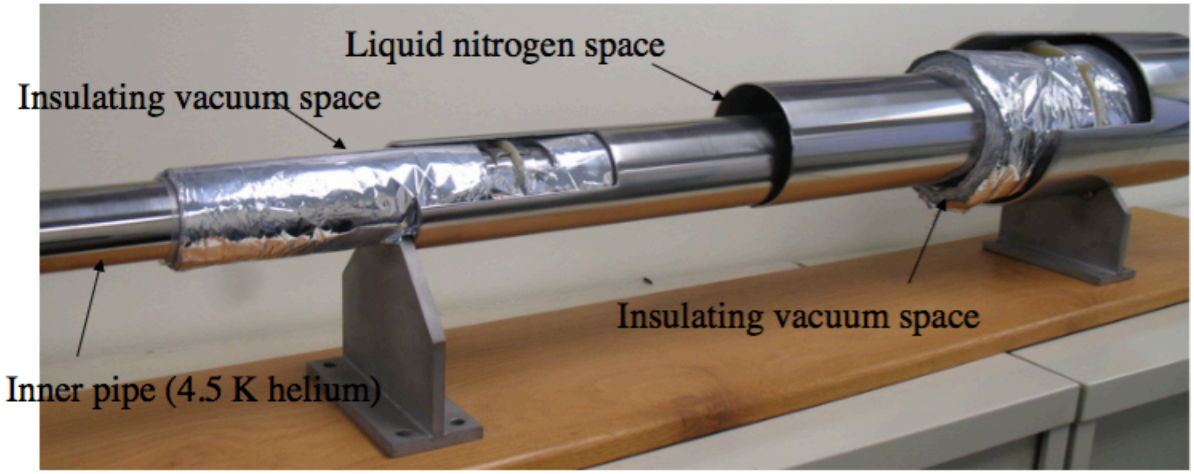


HERA magnet cooling



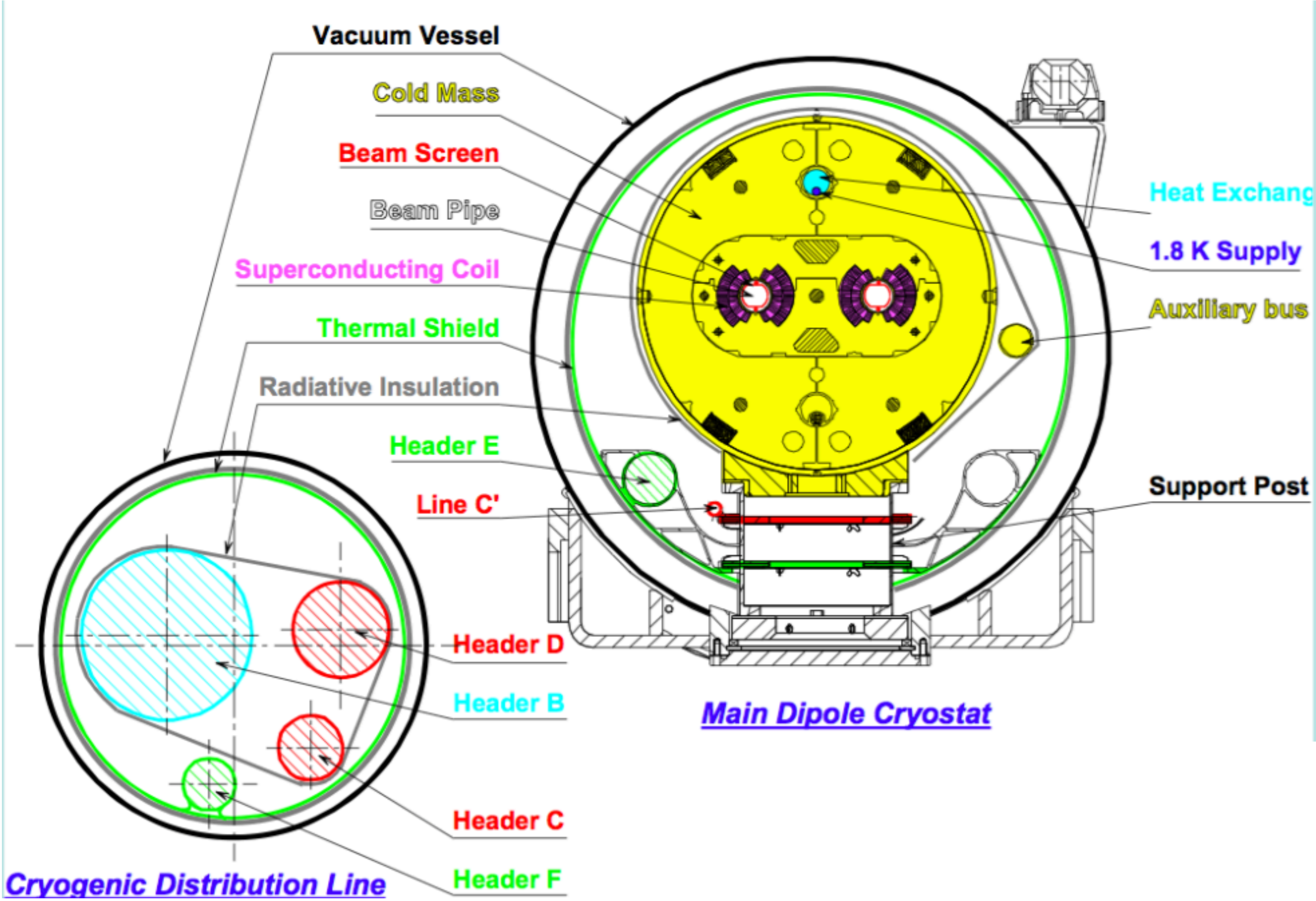
How Cryogens are distributed

Fermilab’s 4.5 K transfer line

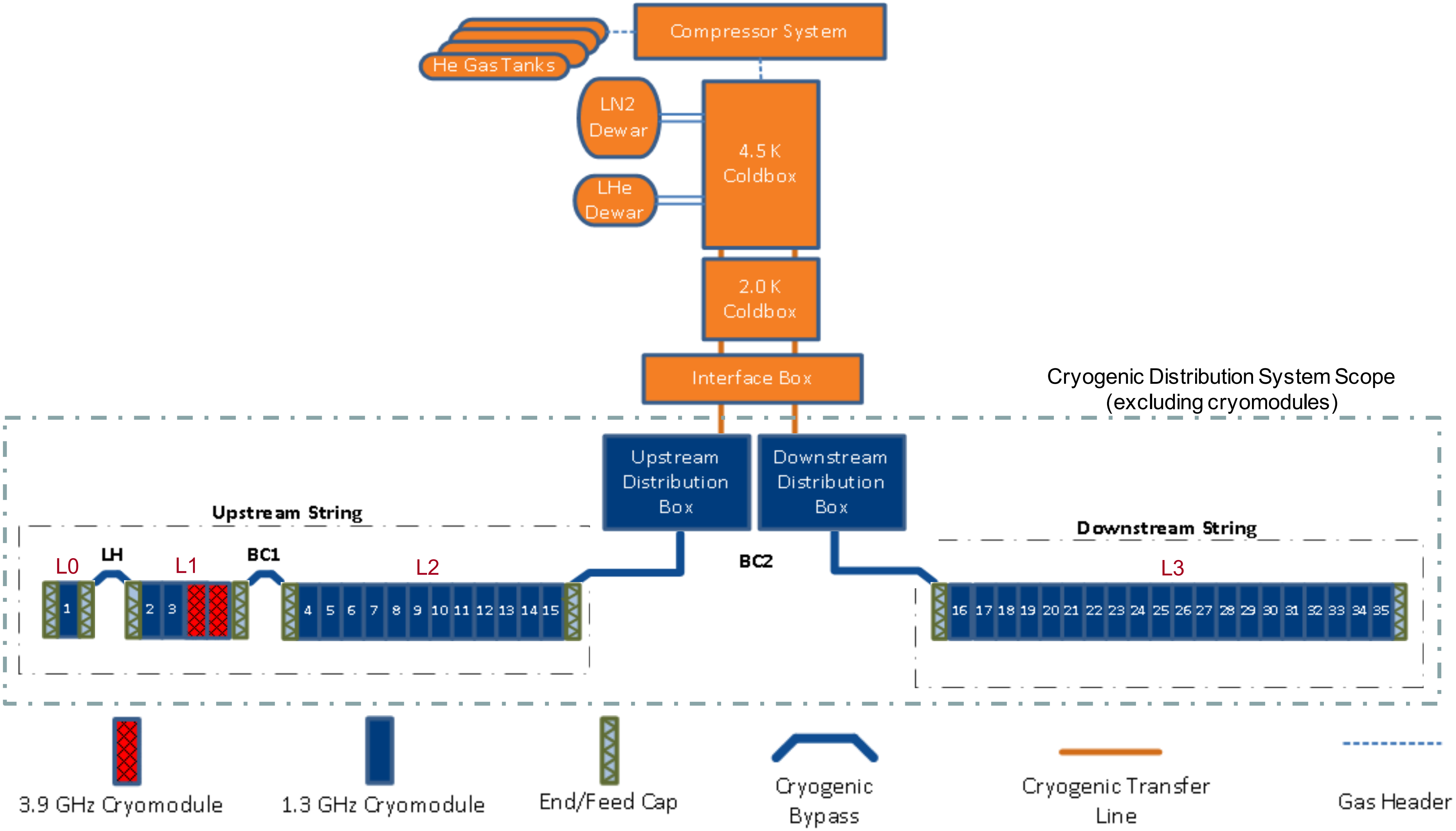


- Supplies 4.5 K, supercritical (3 bar) helium over 6 km to “satellite” refrigerators
- Also provides LN2

The LHC cryogenic distribution line

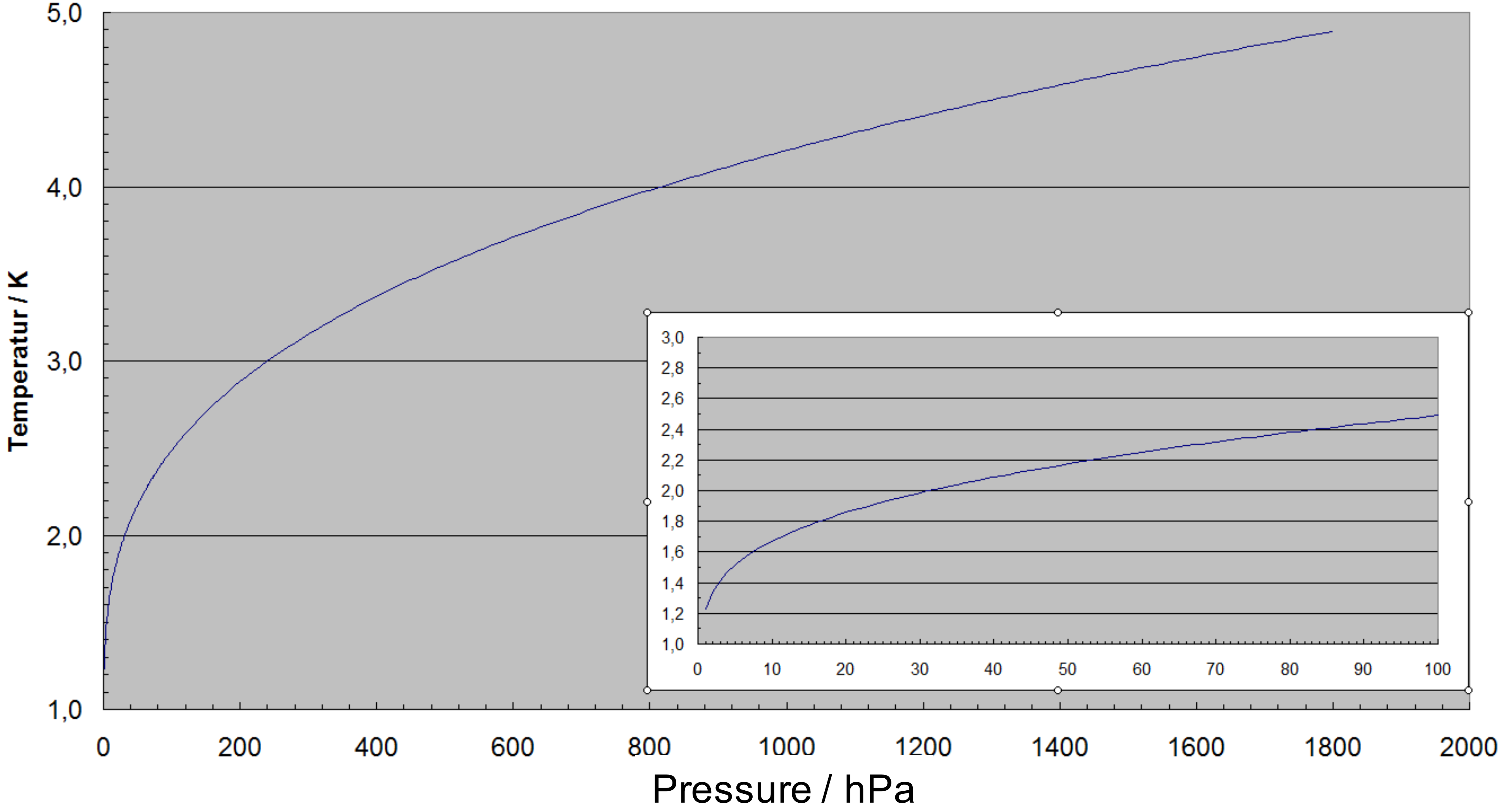


LCLS-II Cryogenic System Overview



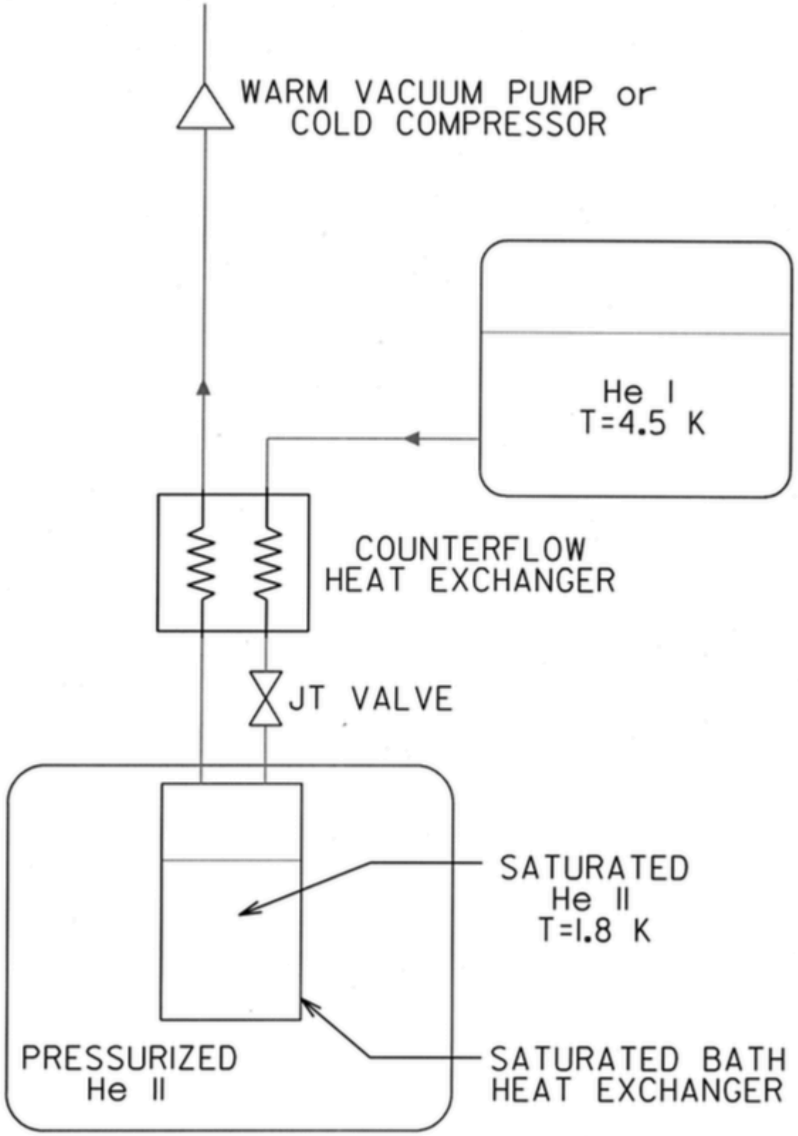
How to get below 4 K?

- Boiling curve of helium

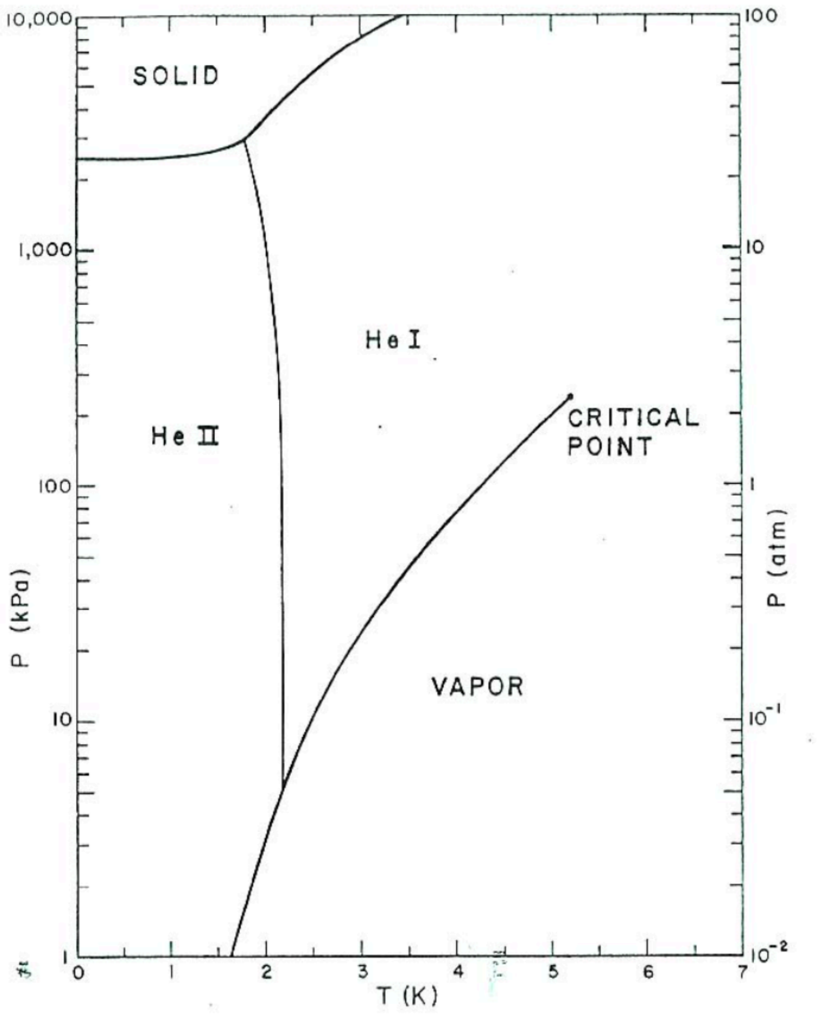


2 K Pump Skids (8 g/s, 125 kW)

- State of the art are colc
compressors

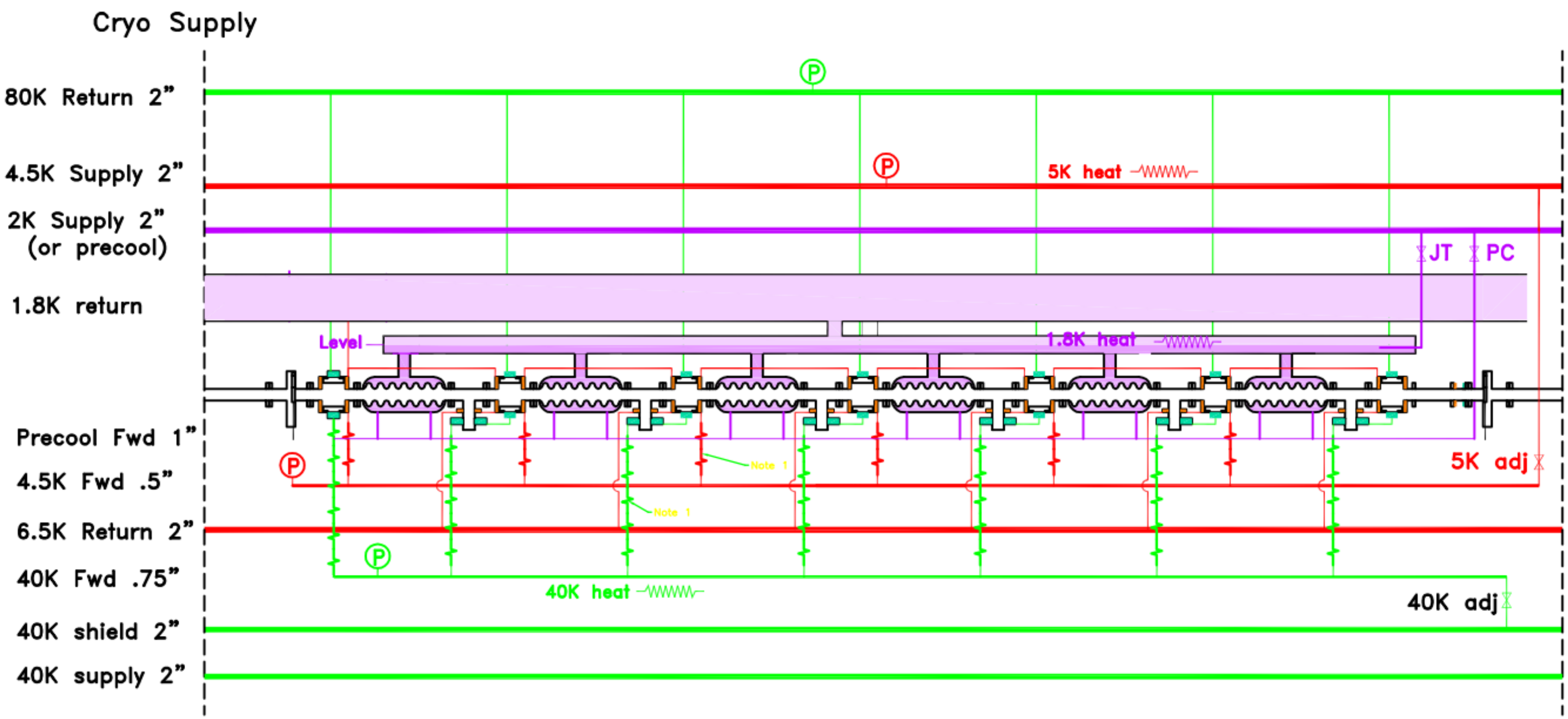


Helium Properties

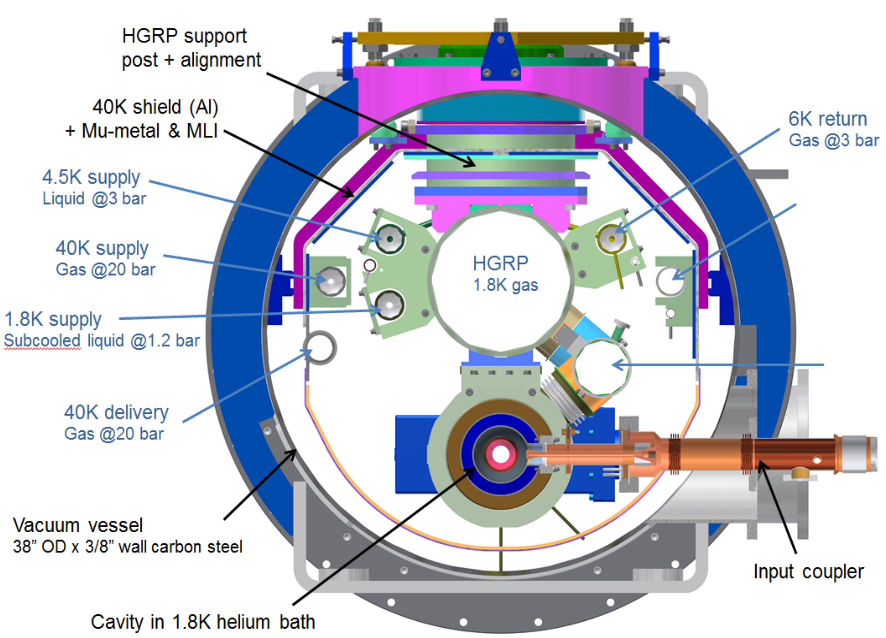


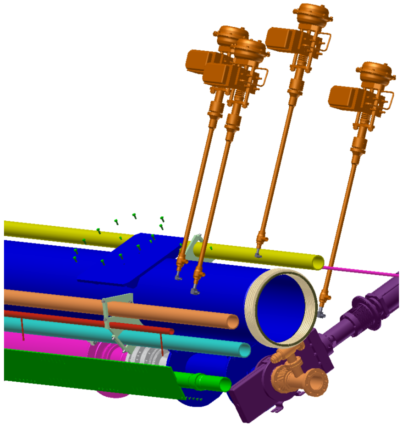
- Two Liquid phases
  - He I – Neutonian fluid
    - $T_\lambda < T < T_c = 5.2$ K, $P_c = 0.226$ MPa
  - He II – quantum fluid
    - $T < T_\lambda = 2.176$ K @ SVP
    - T_λ (solid line, 3 MPa) = 1.76 K
- Solid phase only under external pressure P > 2.5 MPa
- Important point: no triple point

Cryogenic sketch of an SRF Module



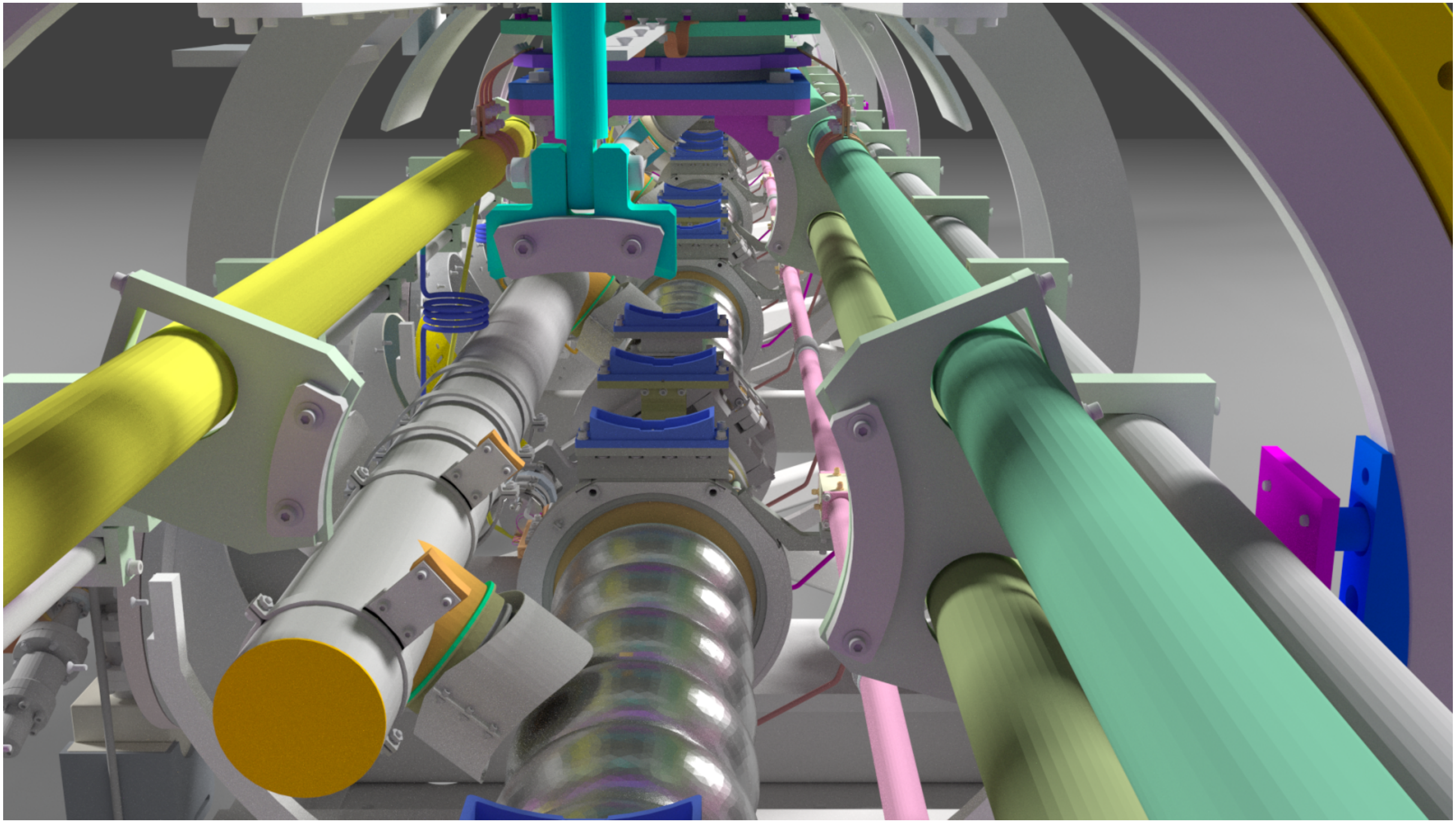
Cryogenic sketch of an SRF Module



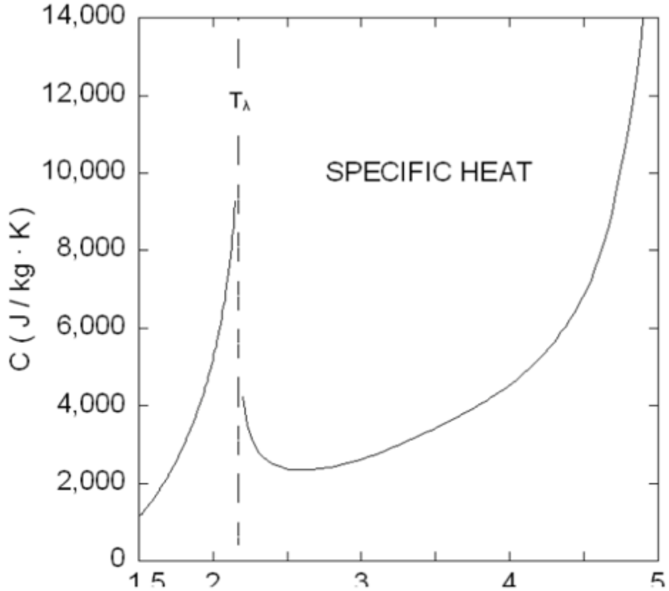


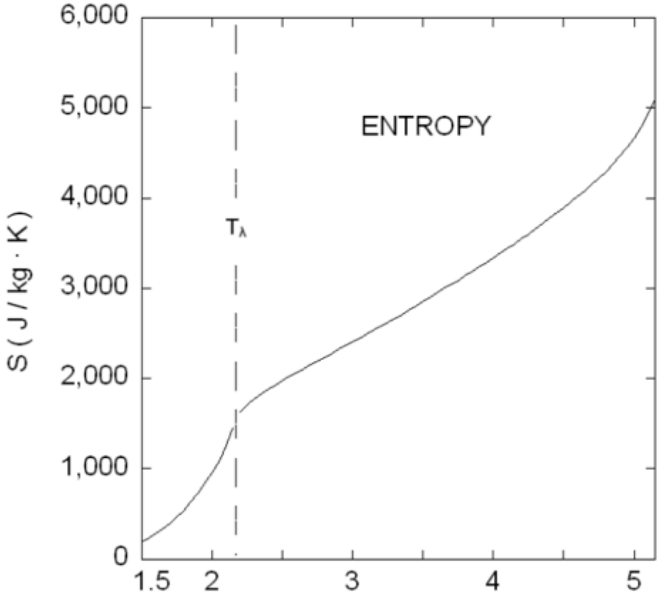
1 line for 2K supply	subcooled liquid @1.2 bar	- 2K helium bath for cavities via 2K-2 phase line - pre-cool gas for cool-down - 90% heat load from RF losses in the cavities
2 lines for 4.5-6K	3.0 bar He liquid Single phase flow	- Thermal intercept for HOM absorbers and couplers - 2/3 dynamic heat load
3 lines for 40-80K	20 bar He gas	- Thermal intercept for HOM absorbers and couplers - 40K thermal shield - 90% heat load from HOM

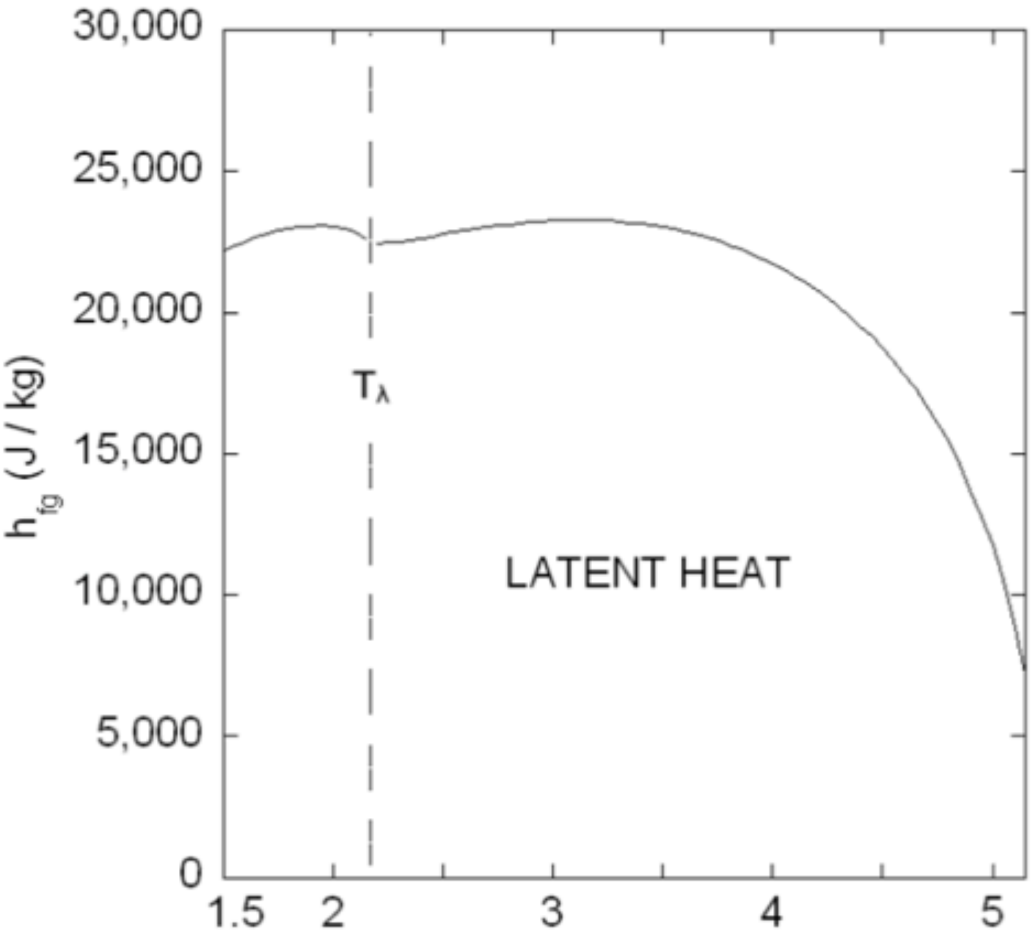
Cornell's ERL Main Linac Cryomodule



Properties of helium

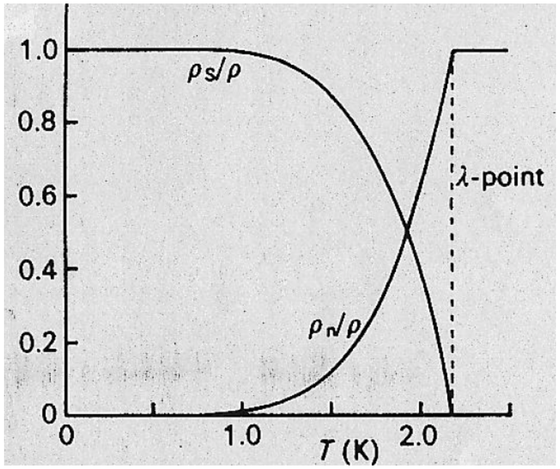


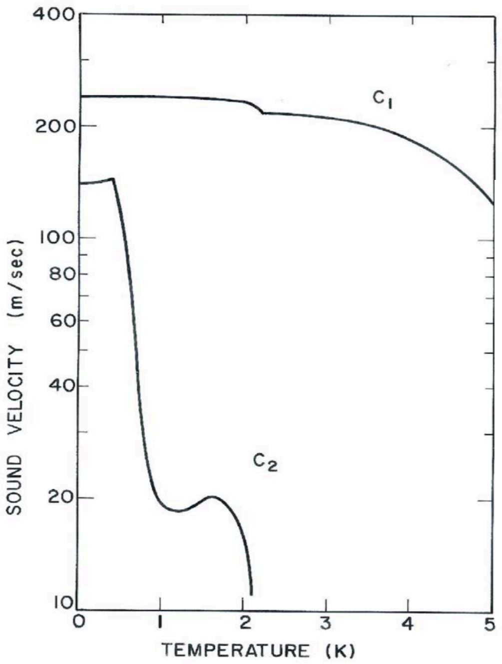


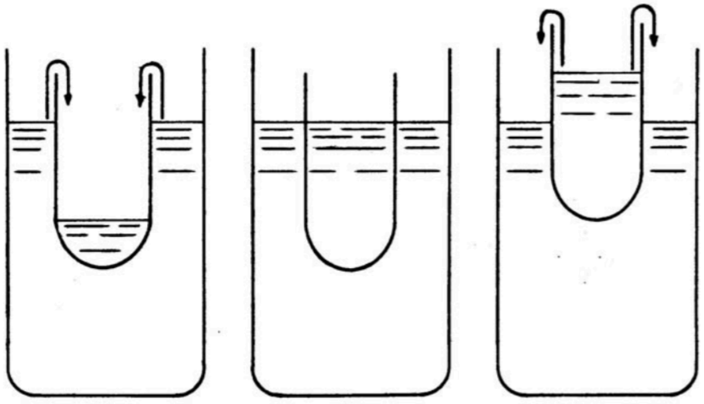


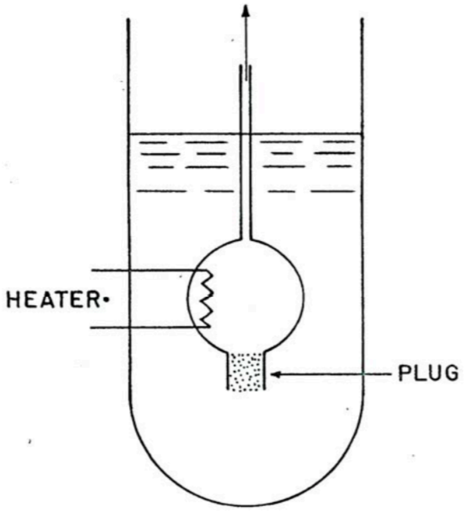
Helium-II

- Helium II is a superfluid (similar to a superconductor:
  - no viscosity
  - great heat conductivity
  - film flow
  - fountain effect
  - has 2nd sound

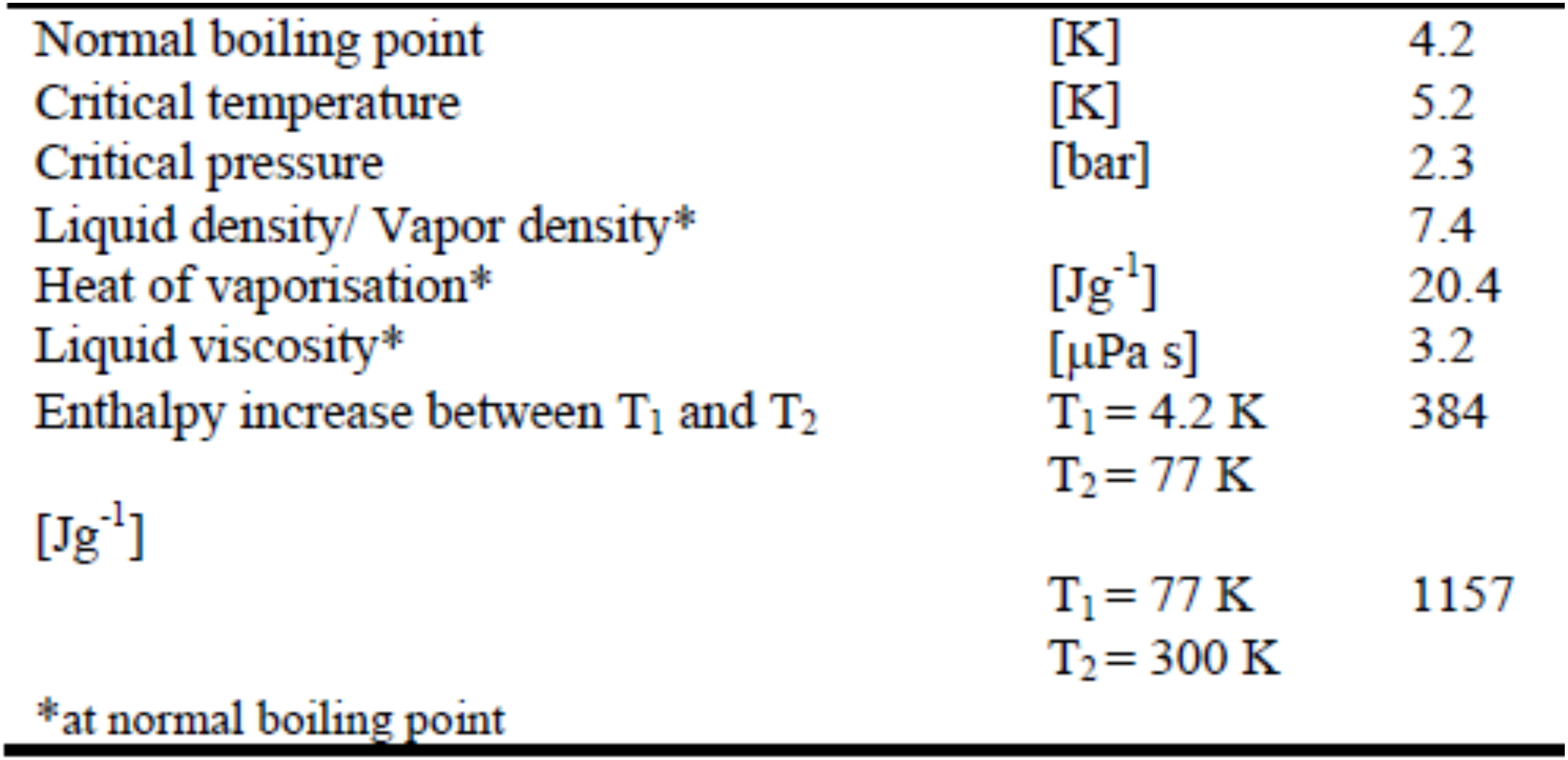








Some Helium properties



Normal boiling point	[K]	4.2
Critical temperature	[K]	5.2
Critical pressure	[bar]	2.3
Liquid density/ Vapor density*		7.4
Heat of vaporisation*	[Jg^{-1}]	20.4
Liquid viscosity*	[μPa s]	3.2
Enthalpy increase between T_1 and T_2 [Jg^{-1}]	$T_1 = 4.2$ K $T_2 = 77$ K	384
	$T_1 = 77$ K $T_2 = 300$ K	1157

*at normal boiling point

Thank you!

Who needs this?

Homework #1: **Thermal radiation:**

Assume you have two surfaces with identical emissivity being 0.1. One surface is at 300K while the second surface is cooled to 77 K.

a) What is the heat transfer through radiation?

b) If you insert a passive layer of shielding material (again e=0.1), what is the heat transfer from 300 K to 77 K now?

c) At which temperature will that passive layer settle in?

d) Why do people usually use 30 layers of MLI between 300 K and 77 K, but only 10 layers between 77 K and 4 K? try to quantify the difference.

Who needs this?

Homework #2: Safety and boil-off:

You have a helium dewar (size 250 l). After doing your experiment, you have 100 liters left. You decide to close all valves and leave the dewar on it's own over the weekend. When you returned on Monday, you realized that the pressure went from 1 bar on Friday to 1.5 bar on Monday morning.

a) What is the temperature of the helium?

b) How much helium has been evaporated to get to 1.5 bar?

c) How much heat was leaking into the dewar over the weekend? Assume a mean (temperature independent) latent heat (what's the value?) and use the density of liq. Helium of 125 g/l.

d) Now you open the valve to release the pressure into a recovery system. What process is this? Will you get more or less than 75 l of gas? Why?

e) Assume you have a gas cylinder, 200 bar at room temperature, full of helium. You connected the cylinder to your liquefier which accepts the gas at 1 bar. What should you open the valve slowly?