CERN

Introduction to Cryogenics

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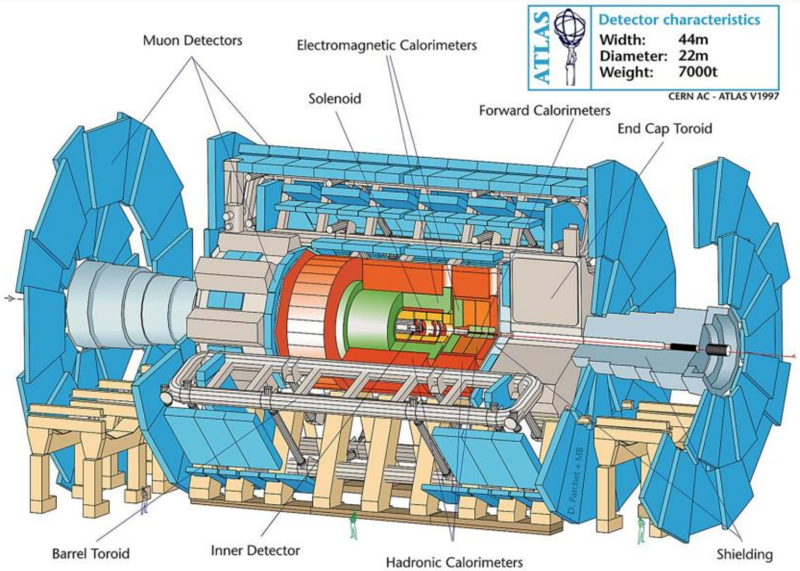
Contributions from S. Claudet and Ph. Lebrun

CAS@ESI: Basics of Accelerator Physics and Technology, 7 - 11 Oct. 2019, Archamps

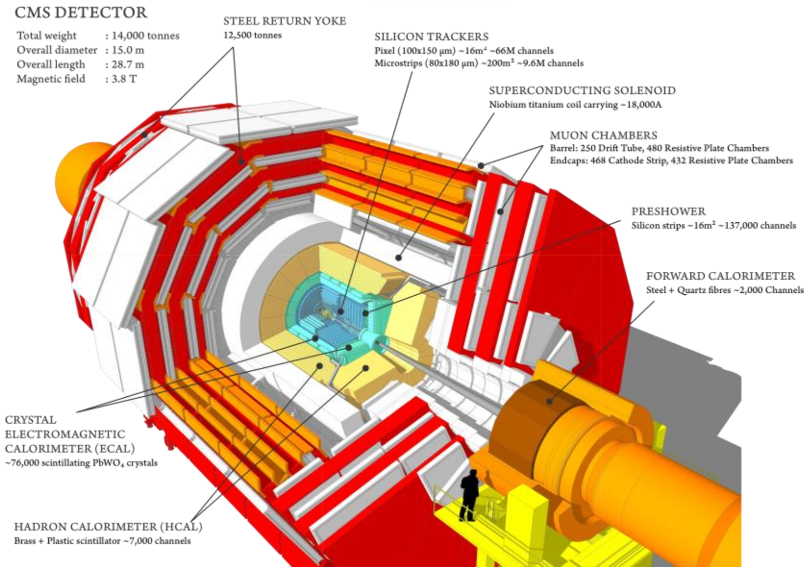
Content

- Introduction to cryogenic installations
- Safety aspects => handling cryogenic fluids
- Motivation => reducing thermal energy in a system
- Heat transfer and thermal insulation
- Helium cryogenics, He I => He II
- Conclusions
- References

Overview of cryogenics at CERN - Detectors



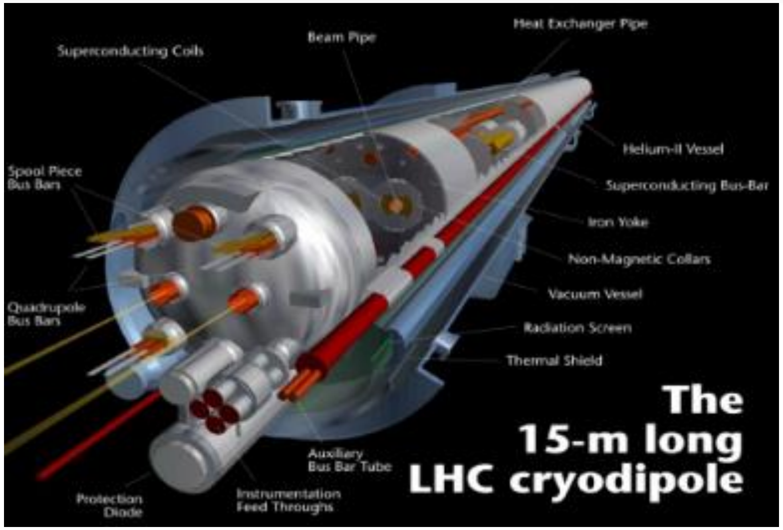
From: CERN-DI-9803026

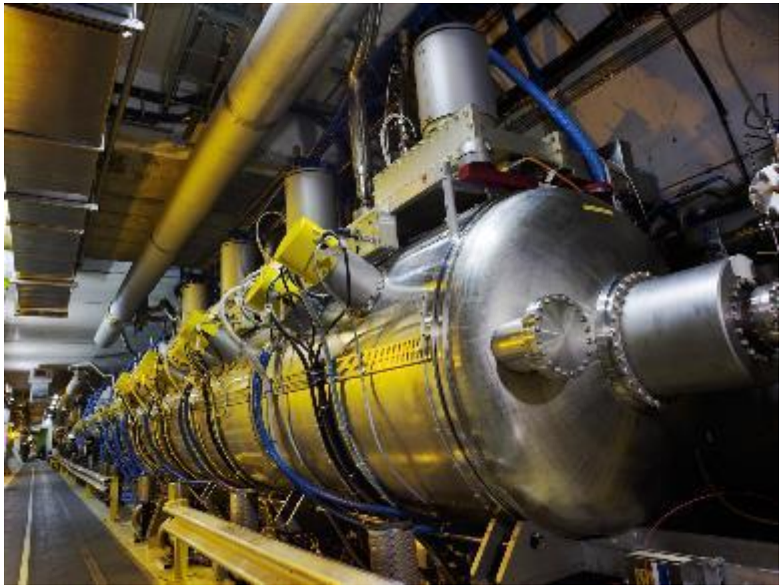


From: http://cms.web.cern.ch/news/cms-detector-design

- Superconducting coils of LHC detectors @ 4.5 K (ATLAS, CMS)
- LAr Calorimeter - LN_2 cooled
- Different types of cryogens (Helium, Nitrogen and Argon)

Overview of cryogenics at CERN - LHC





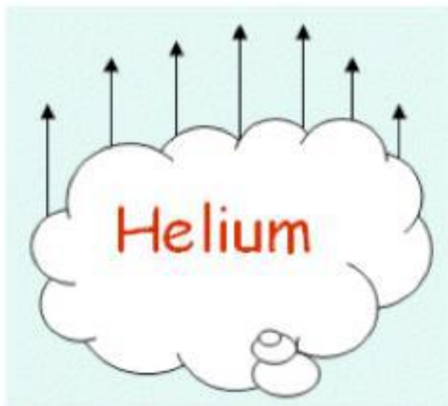
- Helium at different operating temperatures (thermal shields, beam screens, distribution and magnets,…)
- Superconducting magnets of the LHC accelerator
- Accelerating SC cavities

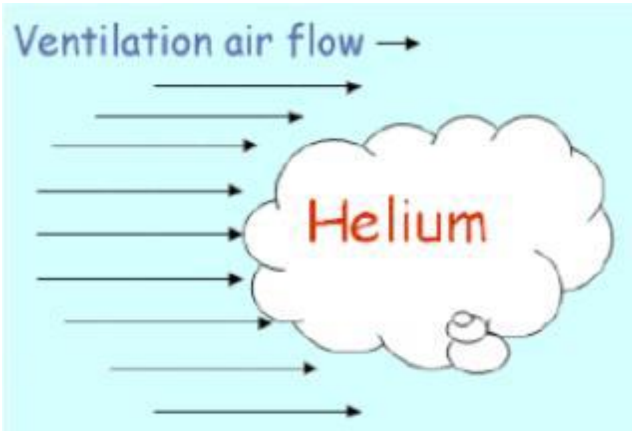
Safety aspects in cryogenics

Cryogenic fluids - Thermophysical properties

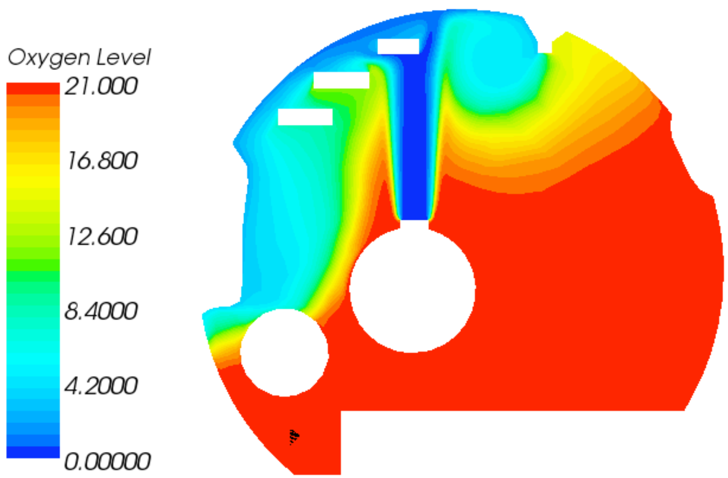
Fluid	^4He	N_2	Ar	H_2	O_2	Kr	Ne	Xe	Air	Water
Boiling temperature (K) @ 1.013 bar	4.2	77.3	87.3	20.3	90.2	119.8	27.1	165.1	78.8	373
Latent heat of evaporation @ T_b in kJ/kg	20.9	199.1	163.2	448	213.1	107.7	87.2	95.6	205.2	2260
Volume ratio $gas_{(273\ K)}$ / liquid	709	652	795	798	808	653	1356	527	685	-----
Volume ratio saturated vapor to liquid (1.013 bar)	7.5	177.0	244.8	53.9	258.7	277.5	127.6	297.7	194.9	1623.8
Specific mass of liquid (at Tb) – kg/m^3	125	804	1400	71	1140	2413	1204	2942	874	960

Cryogenic hazardous events – Discharge of helium





Safer location on the floor



Simulated blow out in the LHC tunnel cross section

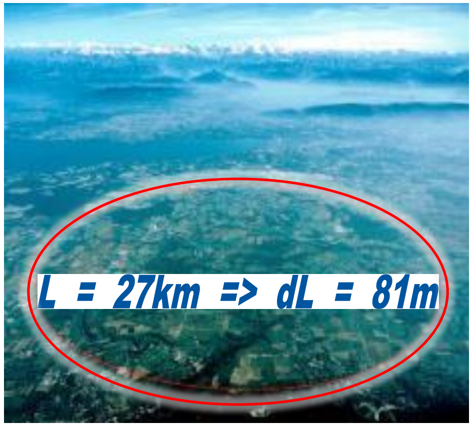
- Displacement of oxygen => Asphyxiation risk!
- Opposite behavior for e.g. argon and nitrogen!

Technical risks

Embrittlement

- Some materials become brittle at low temperature and rupture when subjected to mechanical force

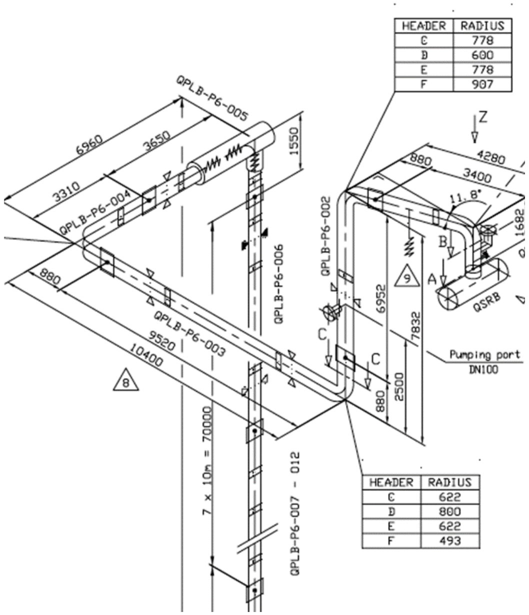
  (carbon steel, ceramics, plastics)



Thermal contraction (293 K to 80 K)

- Stainless steel: 3 mm/m
- Aluminum: 4 mm/m
- Polymers: 10 mm/m

- Requires compensation for transfer lines, QRL …



Condensation of atmospheric gases

- Inappropriate insulation or discharge of cryogens
- Observed at transfer lines and during filling operations (liquid air ~50 % O_2 instead of 21 % in atmospheric air)

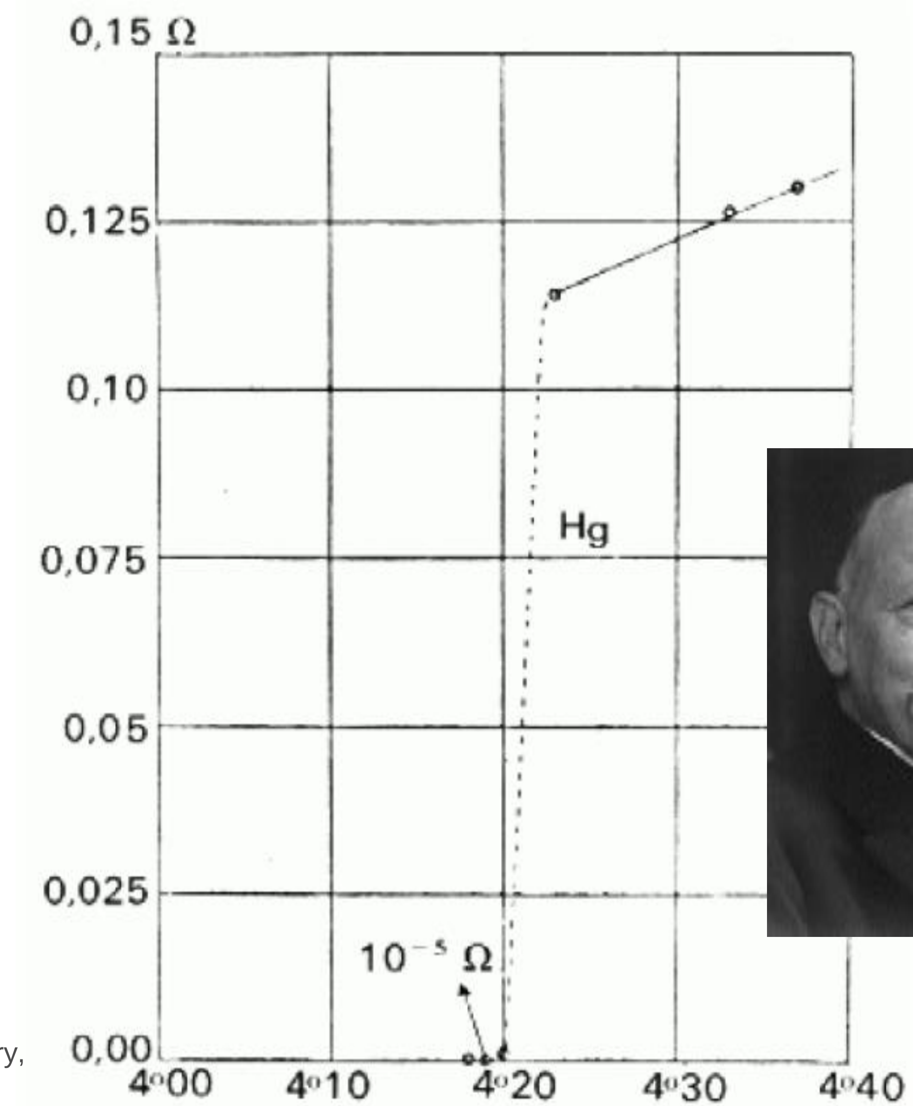
Cryogenics and Superconductivity

Characteristic temperatures of low-energy phenomena

Phenomenon	Temperature
Debye temperature of metals	few 100 K
High-temperature superconductors	~ 100 K
Low-temperature superconductors	~ 10 K
Intrinsic transport properties of metals	< 10 K
Cryopumping	few K
Cosmic microwave background	2.7 K
Superfluid ^4He	2.17 K
Bolometers for cosmic radiation	< 1 K
ADR stages, Bose-Einstein condensates	~ μK

Superconductivity

- H. Kamerlingh Onnes
- Liquefied helium in 1909 at 4.2 K with 60 g He inventory
- Observed in 1911 for the first time superconductivity of mercury
- Nobel prize 1913



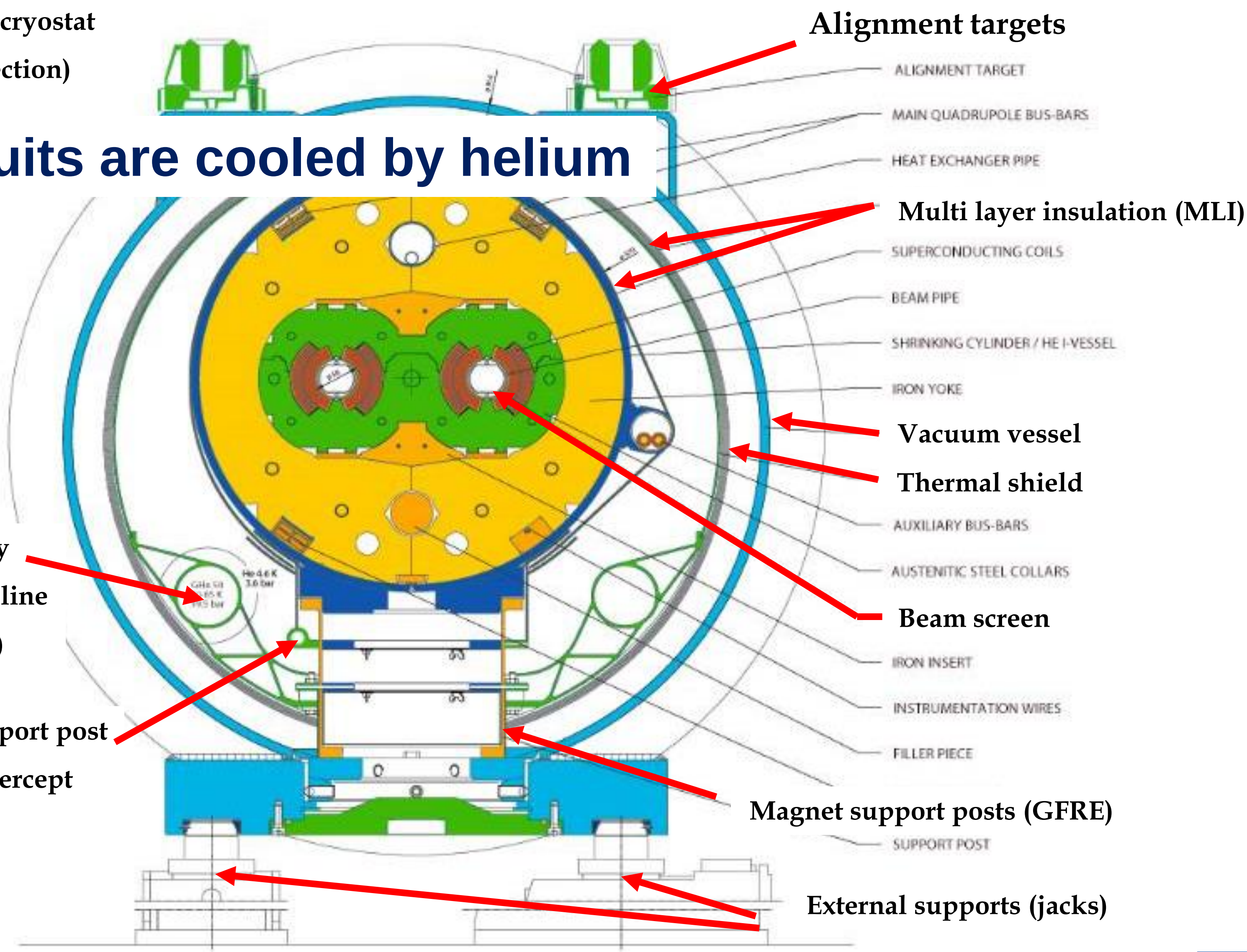
Historic graph showing the superconducting transition of mercury, measured in Leiden in 1911 by H. Kamerlingh Onnes.

Cryogenic application: Dipole magnets of the LHC

LHC main cryostat

(Cross-section)

All circuits are cooled by helium



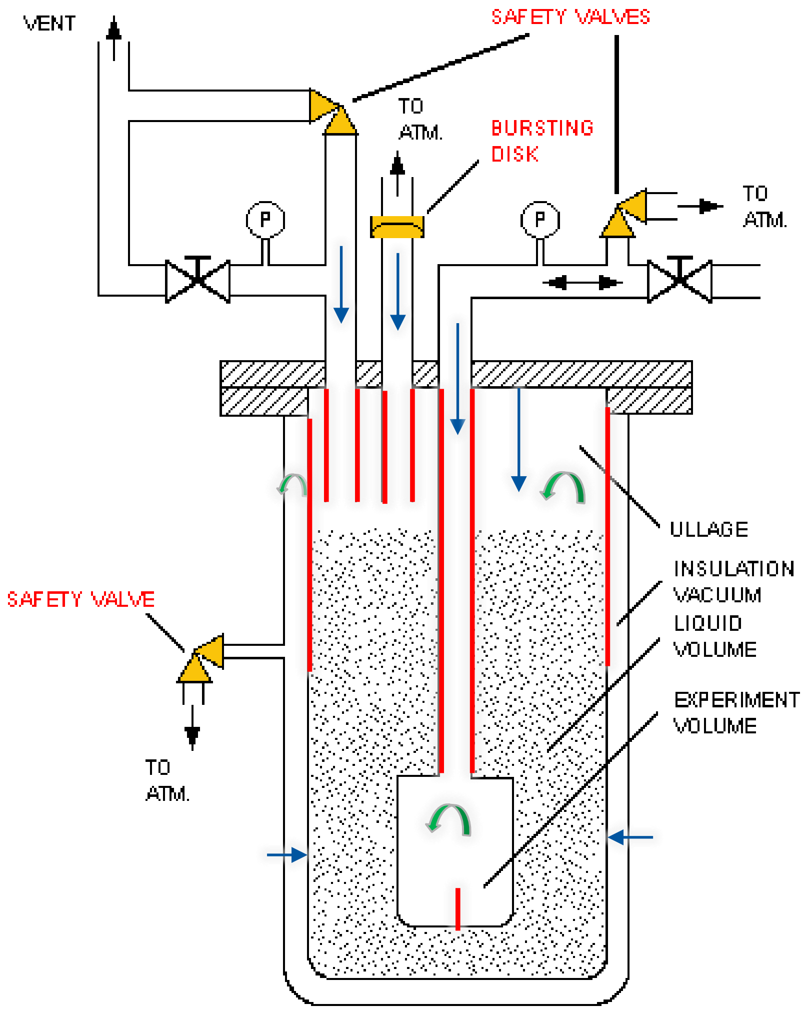
Heat Transfer and Thermal Insulation

Heat transfer: General

- Solid conduction:

- Thermal radiation:
  (with and without MLI)

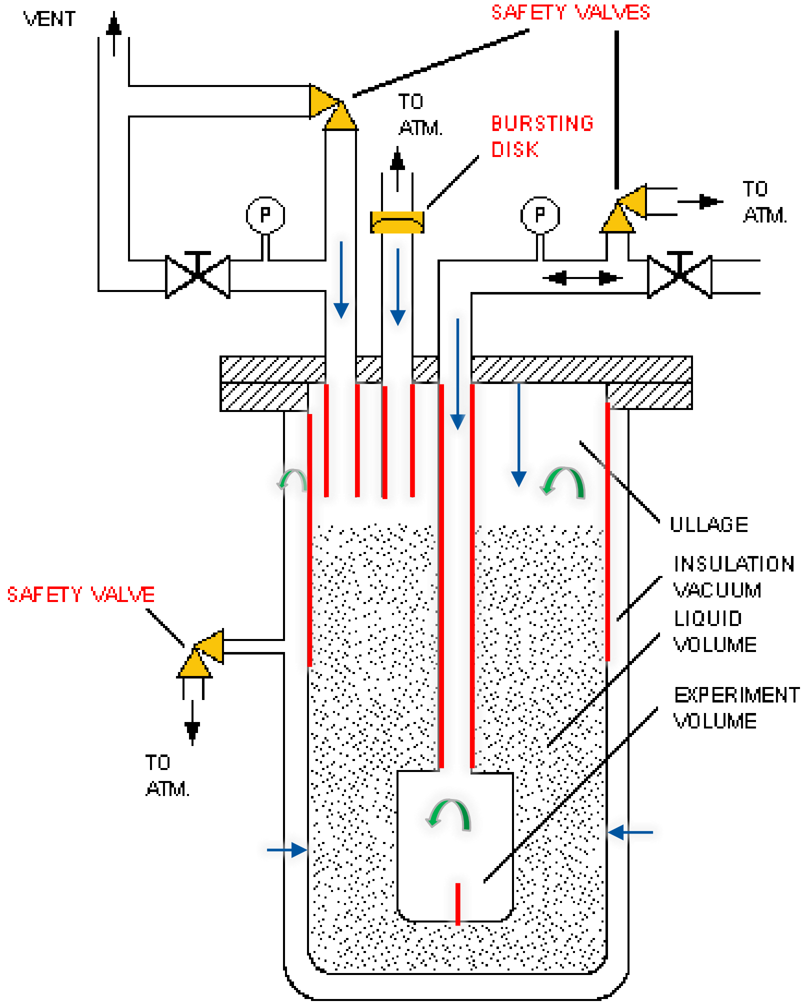
- Natural convection:
  Negligible with insulation vacuum for $p < 10^{-6}$ mbar



Source: Edeskuty, Safety in the Handling of Cryogenic Fluids

Heat transfer: General

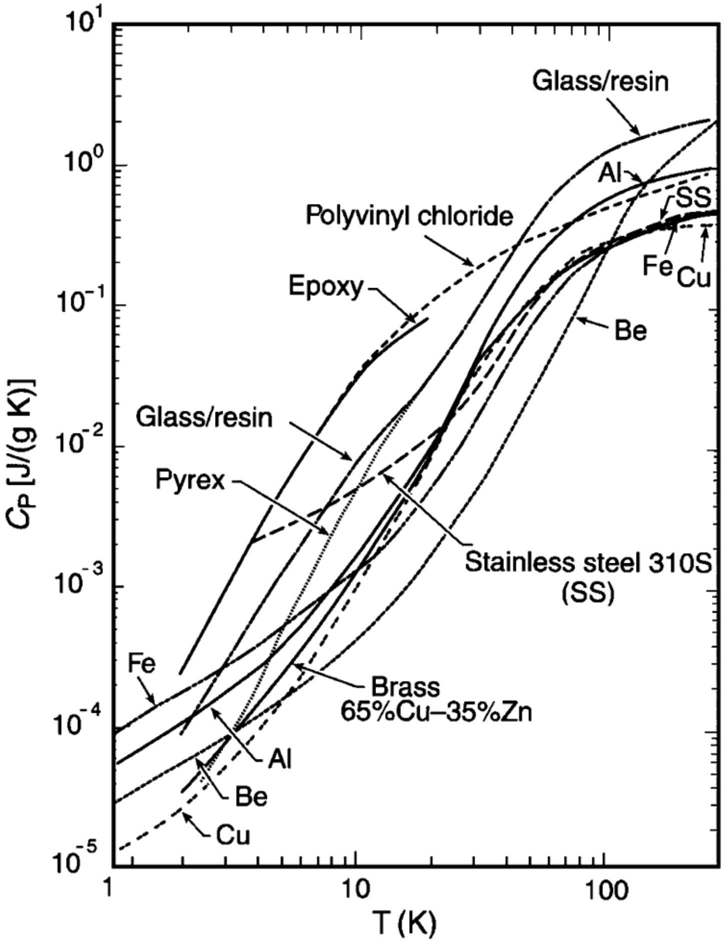
Choosing the right materials in terms of mechanical strength and low-temperature properties is essential.



Source: Edeskuty, Safety in the Handling of Cryogenic Fluids

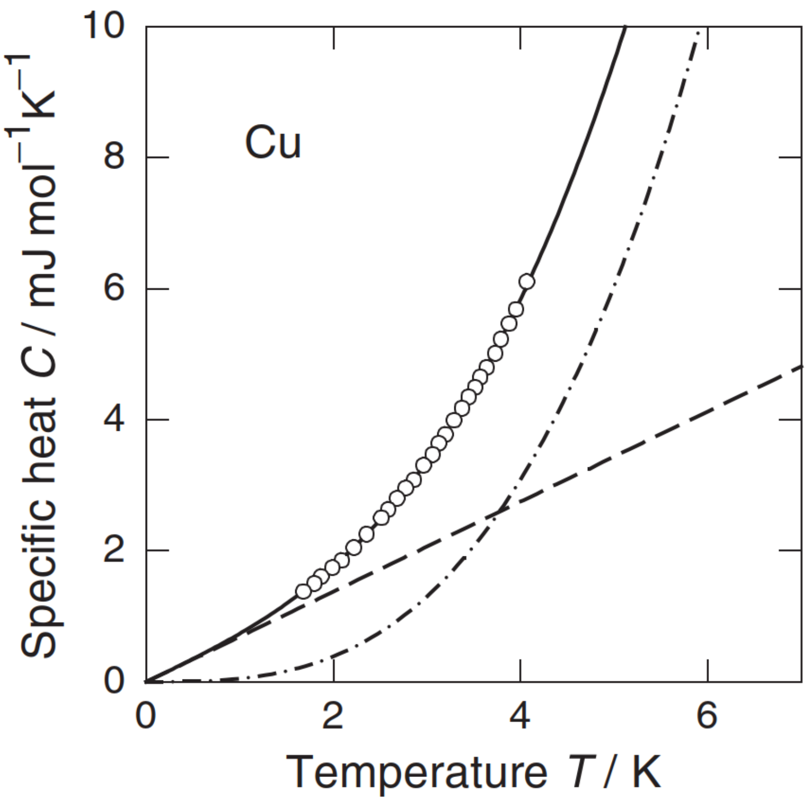
Heat capacity of materials

Discrete lattice vibrations => Phonon



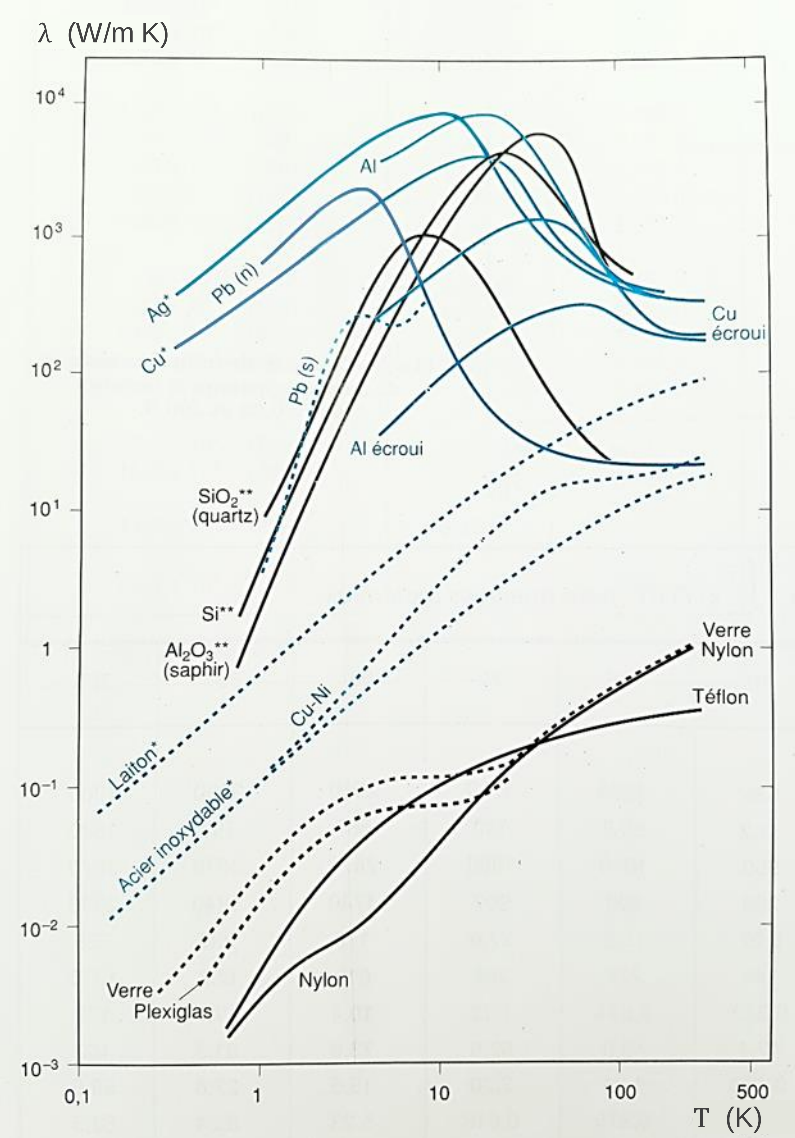
Source: Ekin, Experimental Techniques for Low-Temperature Measurements.

Metals have a contribution of free electron gas => dominant at very low temperature



Source: Enss, Low temperature physics.

Thermal conductivity, solid conduction



Heat transport in solids

Fourier's law: $\dot{Q} = -\lambda(\mathrm{T})\,\frac{A}{l}\,\nabla T$

Pure dielectric crystals: phonons

Dielectrics/Insulators: phonons

Pure metals: free electron gas and phonons

Alloyed metals: electrons and phonons

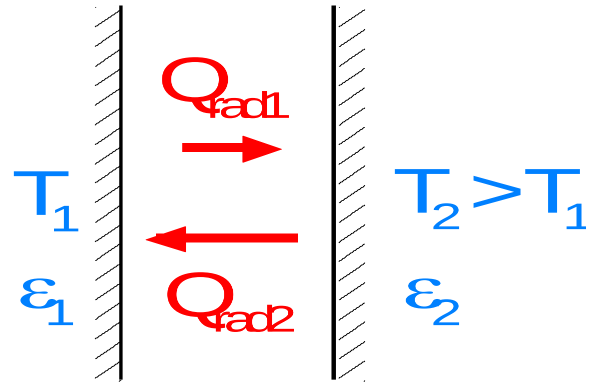
From: Cryogenie, Institut International du Froid, Paris

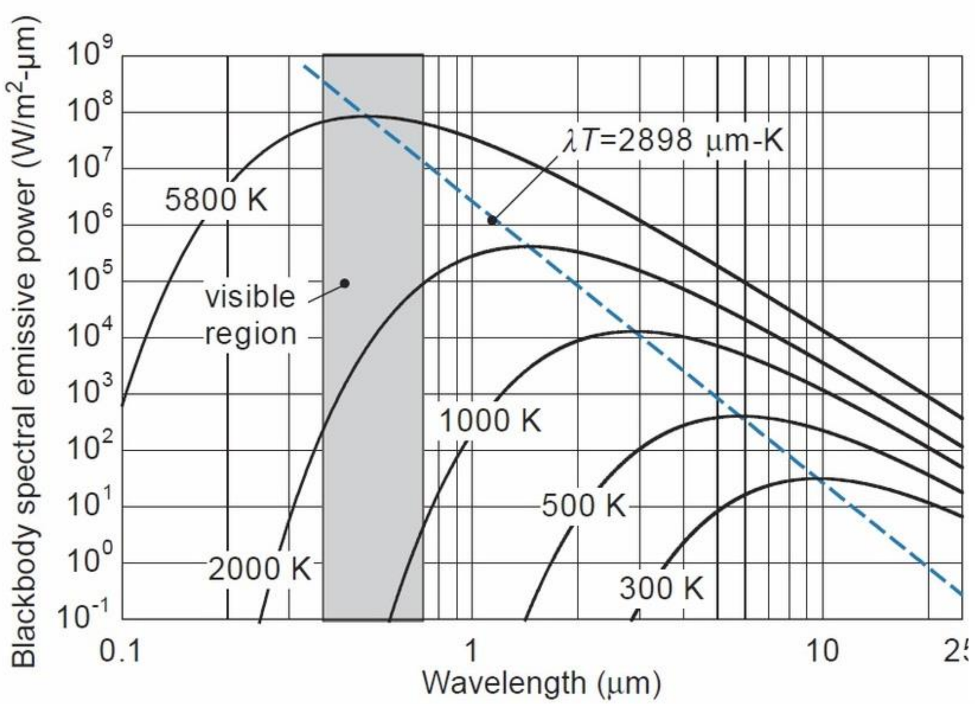
Radiative heat transfer – Black body

- Wien's law (Maximum of black body power spectrum)

$$\lambda_{max}T = 2898\ \mu\text{m K}$$

=> $10\ \mu\text{m}$ for $T = 300\ \text{K}$





Source:
https://www.researchgate.net/figure/Blackbody-spectral-emissive-power-as-a-function-of-wavelength-for-various-values-of_fig4_320298109

Radiative heat transfer

- Wien's law (Maximum of black body power spectrum)

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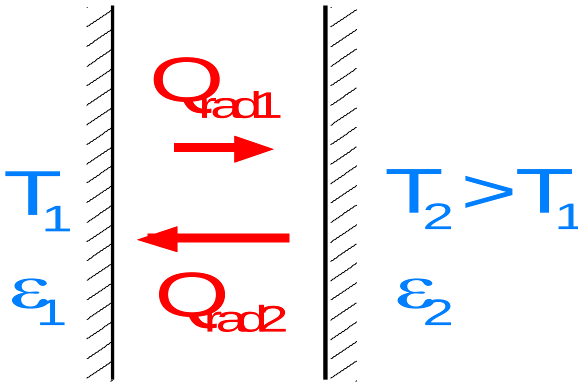


- Stefan-Boltzmann's law
  - Black body $\dot{Q}_{rad} = \sigma A T^4$
  - "Gray" body $\dot{Q}_{rad} = \varepsilon \sigma A T^4$
  - "Gray" surfaces at T_1 and T_2 $\dot{Q}_{rad} = E \sigma A (T_1^4 - T_2^4)$

$\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4) (Stefan-Boltzmann's constant)

ε - emissivity of surface

E - function of ε_1, ε_2, geometry

Emissivity of technical materials at low temperatures

	Surface at 77 K	Surface at 4.2 K
Stainless steel, as found	0.34	0.12
Stainless steel, mech. polished	0.12	0.07
Stainless steel, electropolished	0.10	0.07
Stainless steel + Al foil	0.05	0.02
Aluminium, as found	0.12	0.07
Aluminium, mech. polished	0.10	0.06
Aluminium, electropolished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mech. polished	0.06	0.02

From: Ph. Lebrun, CAS School on Vacuum in Accelerators, 2006

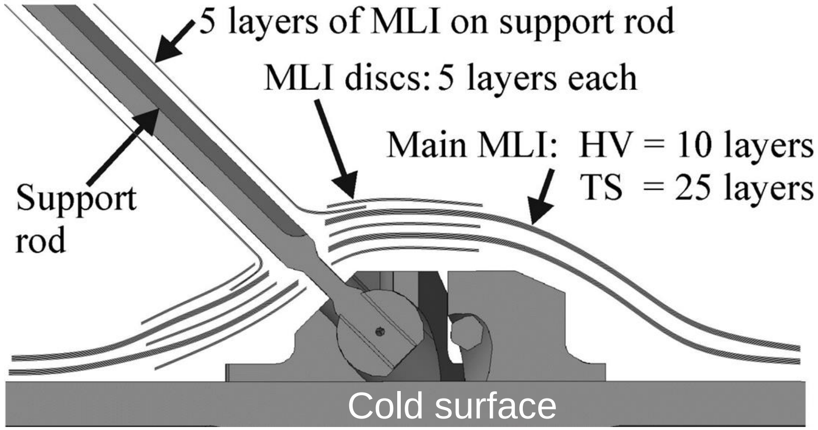
Condensed layers from gas phase easily vary these values !

Multi-layer insulation (MLI)

Complex system involving three heat transfer processes

- $Q_{MLI} = Q_{radiation} + Q_{solid} + Q_{residual}$
- With *n* reflective layers of equal emissivity, $Q_{radiation} \sim 1/(n+1)$
- Parasitic contacts between layers, Q_{solid} increases with layer density
- $Q_{residual}$ due to residual gas trapped between layers, scales as 1/n in molecular regime
- Non-linear behavior requires layer-to-layer modeling

Large surface application



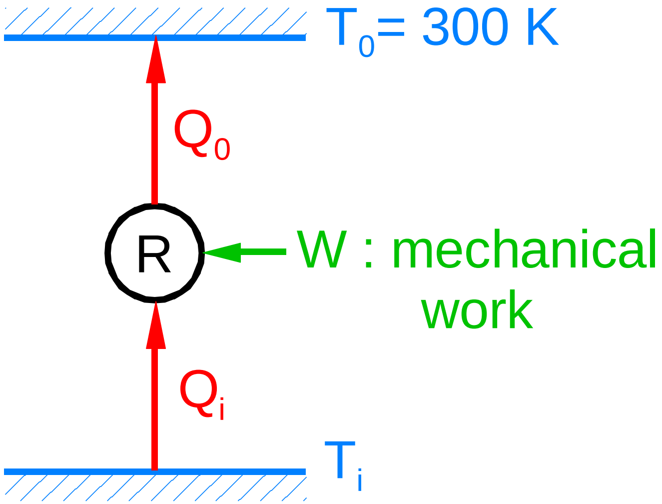
Solutions for penetrations and support structures

Typical heat fluxes between flat plates (cold side vanishingly low)

Configuration	W/m^2
Black-body radiation from 293 K	420
Black-body radiation from 80 K	2.3

Refrigeration and Liquefaction

Thermodynamics of cryogenic refrigeration



First principle [Joule] $Q_0 = Q_i + W$

Second principle [Clausius] $\frac{Q_0}{T_0} \geq \frac{Q_i}{T_i}$

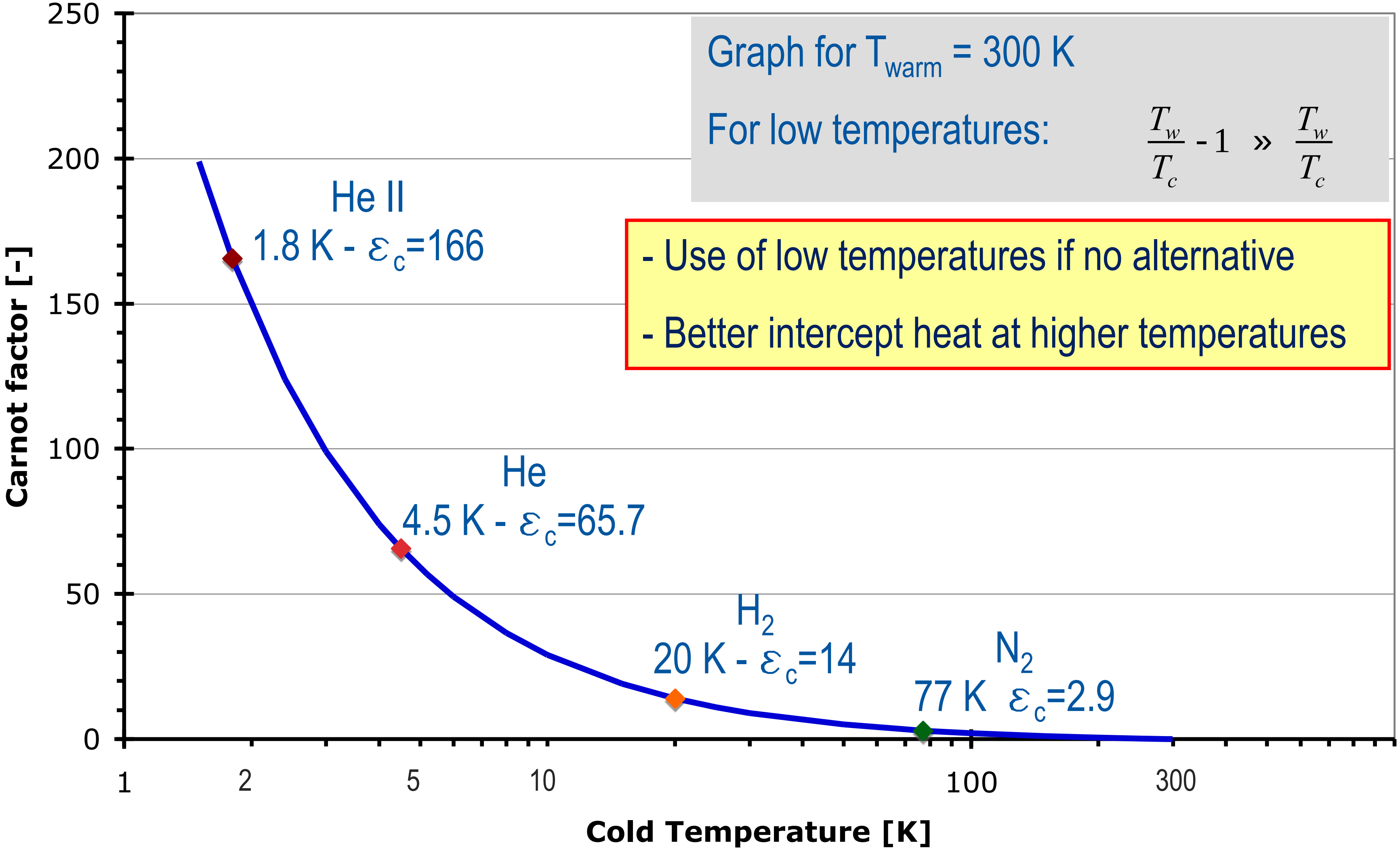
(= for reversible process)

Hence, $W \geq T_0 \cdot \frac{Q_i}{T_i} - Q_i$ which can be written in different ways:

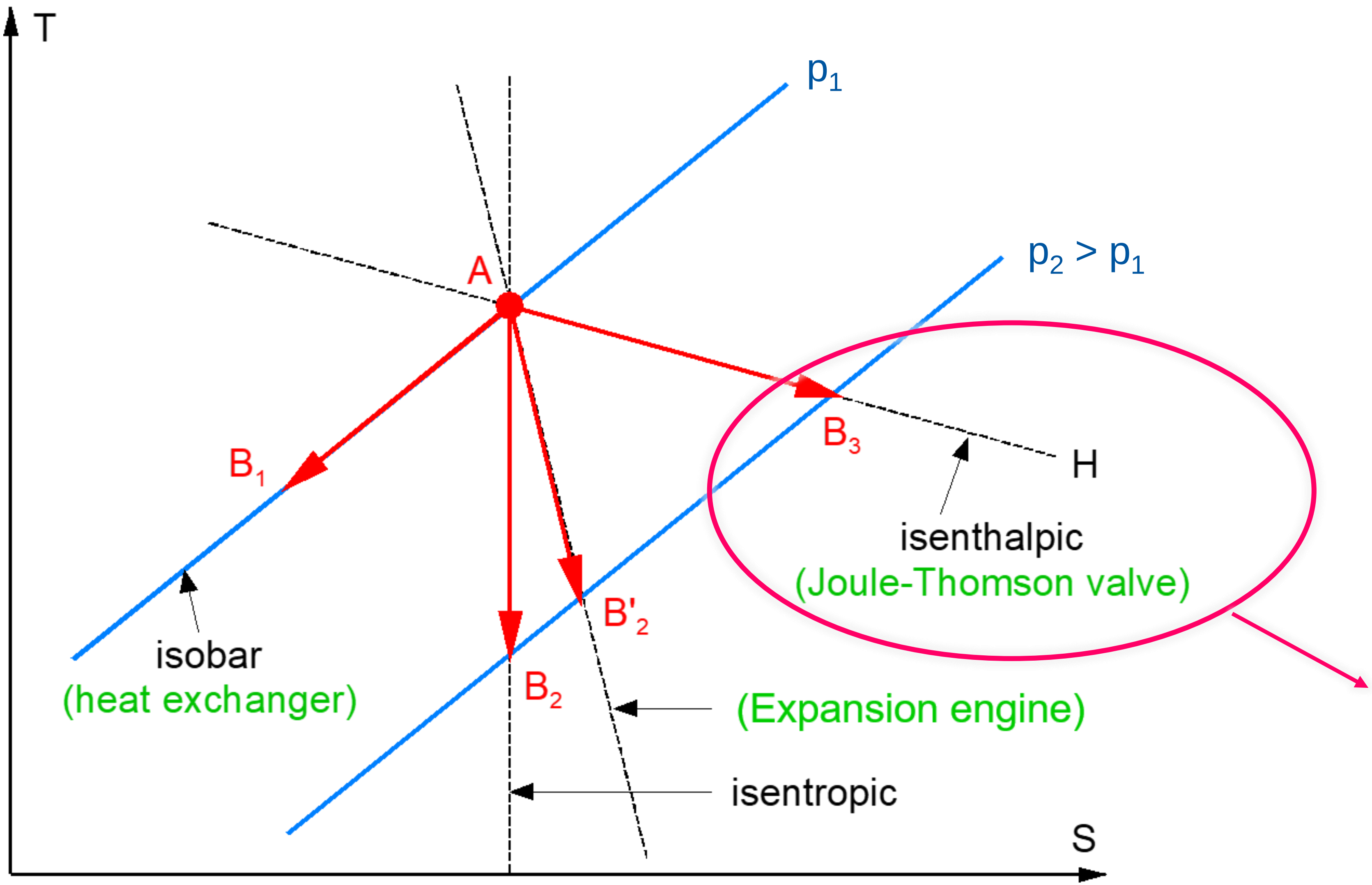
① $W \geq T_0 \cdot \Delta S_i - Q_i$ introducing entropy S as $\Delta S_i = \frac{Q_i}{T_i}$

② $W \geq Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right)$ ← Carnot factor

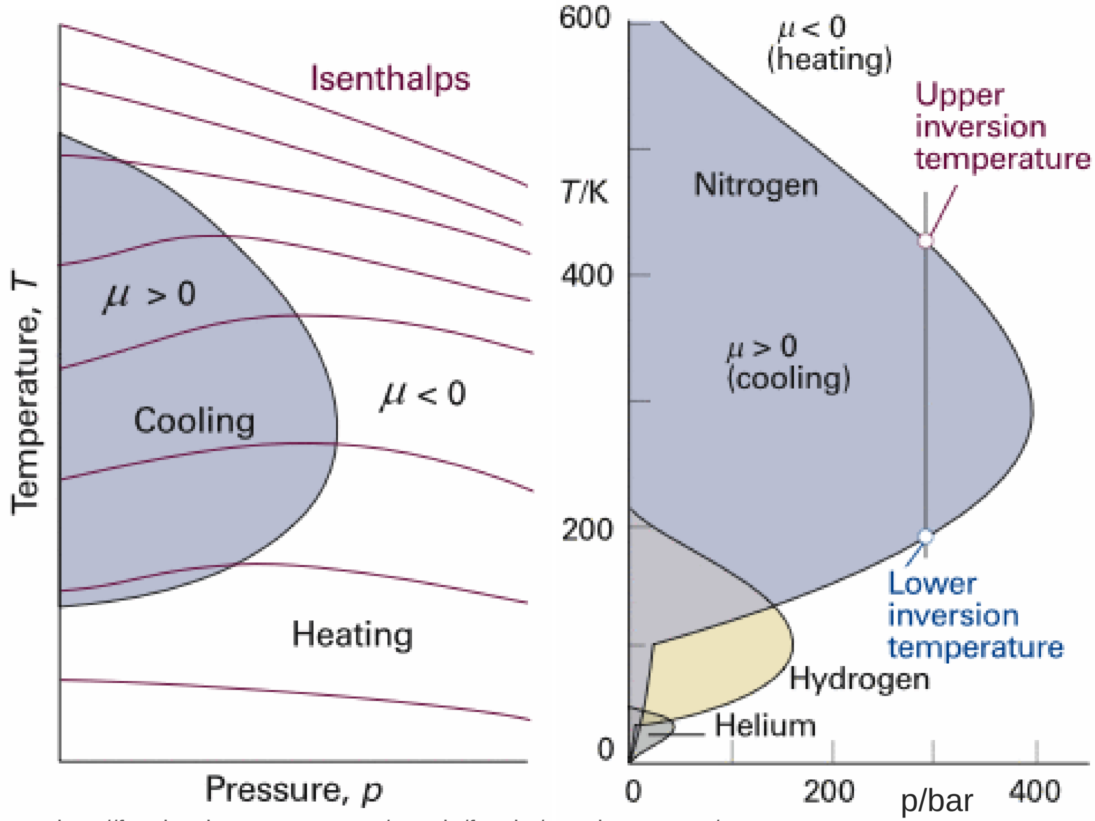
Thermodynamics of cryogenic refrigeration



Elementary cooling processes in a T-s diagram



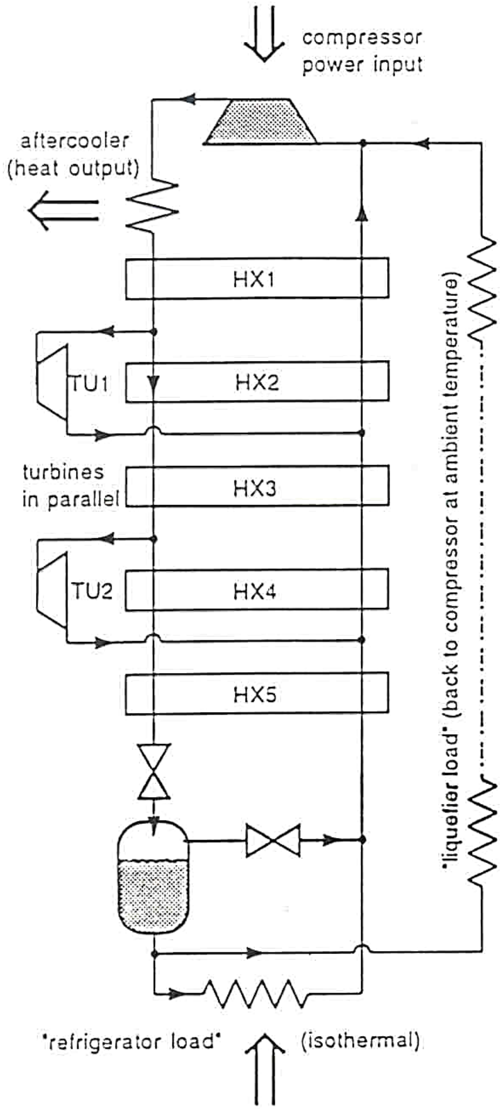
Maximum Joule-Thomson inversion temperatures

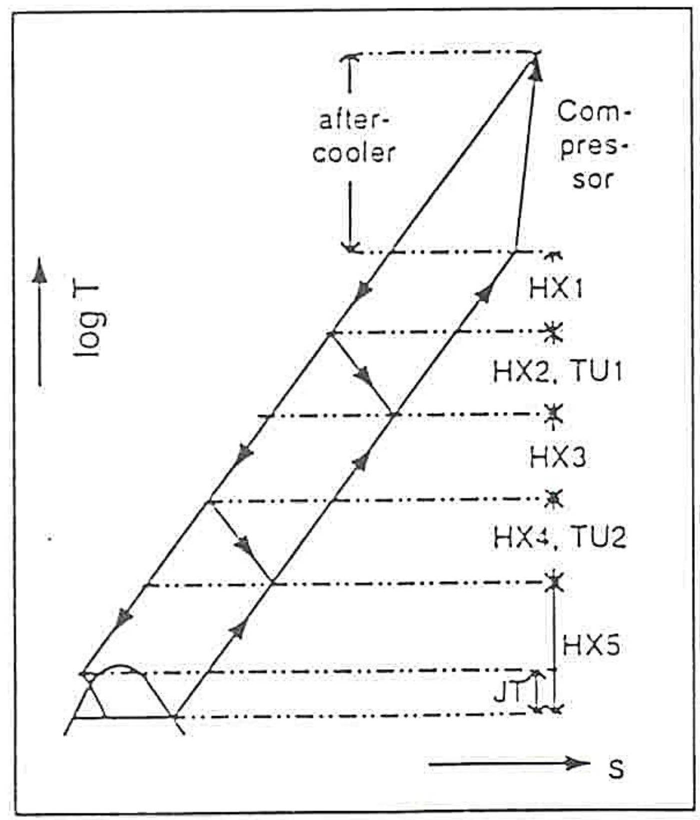


Source: http://faculty.chem.queensu.ca/people/faculty/mombourquette/
Chem221/3_FirstLaw/ChangeFunctions.asp

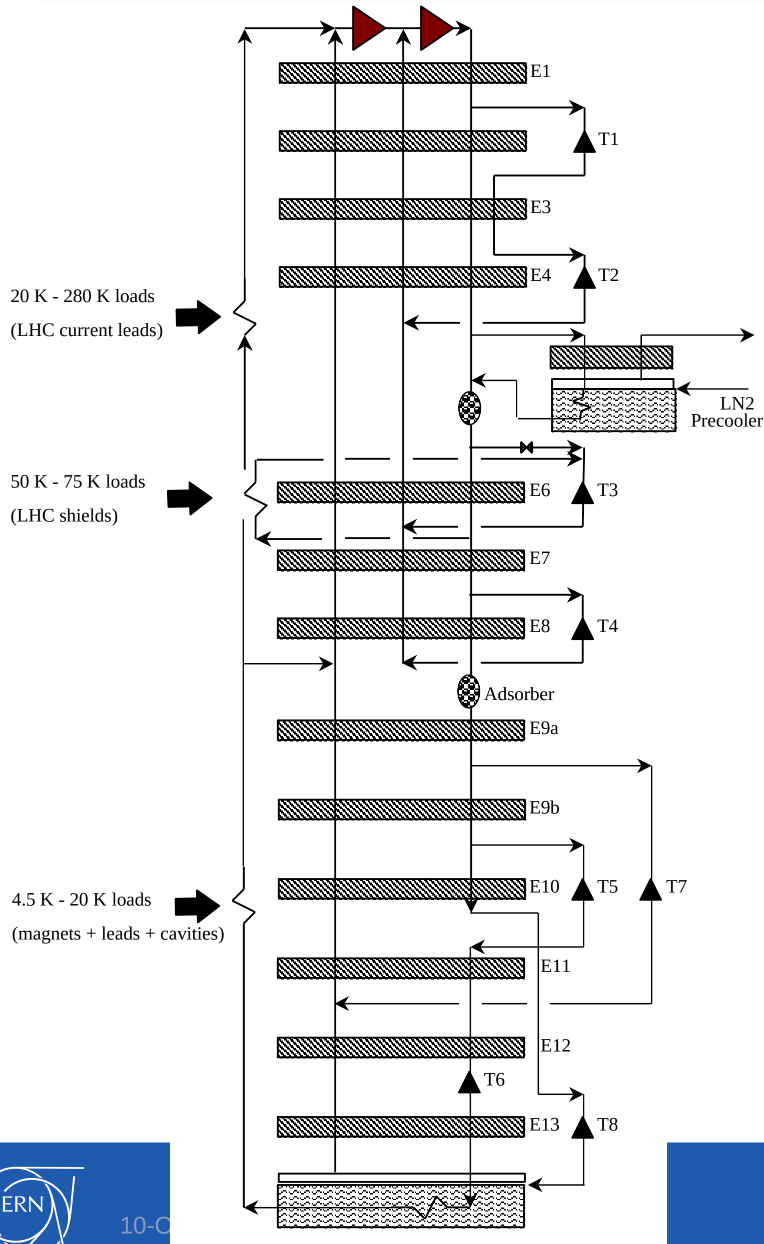
- Air can be cooled down and liquefied by J-T expansion from room temperature,
- Helium and hydrogen need precooling down to below the inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

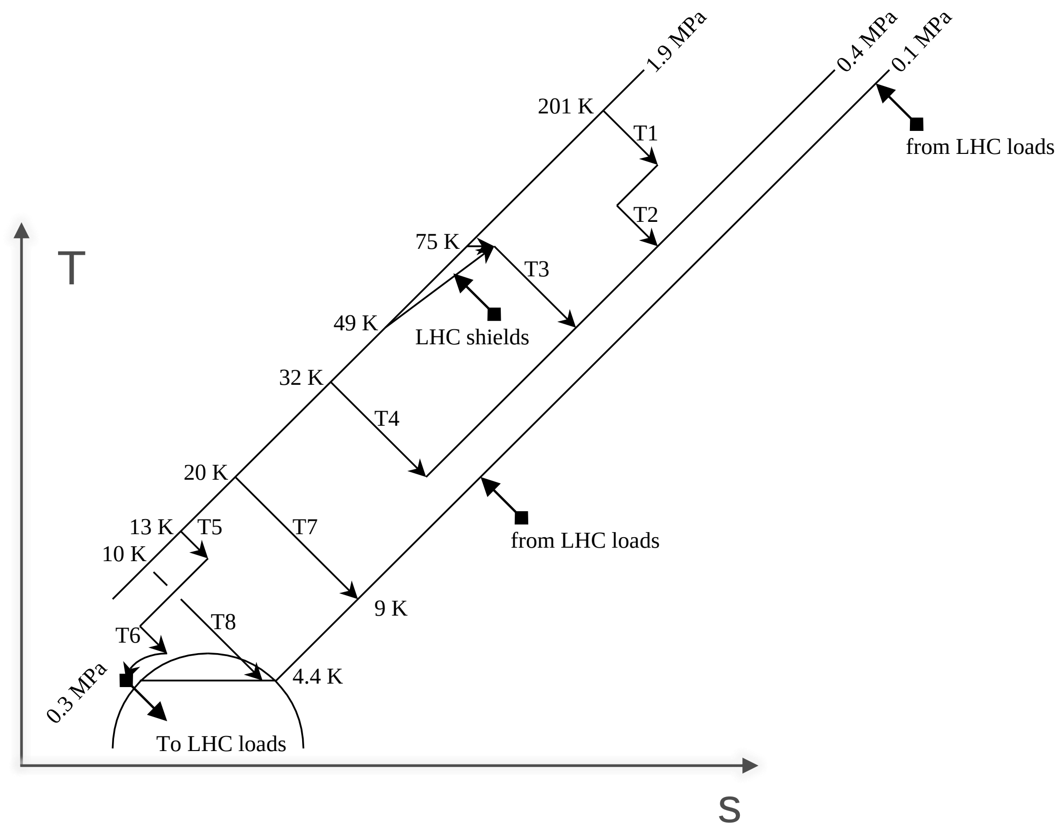
Two-stage Claude cycle



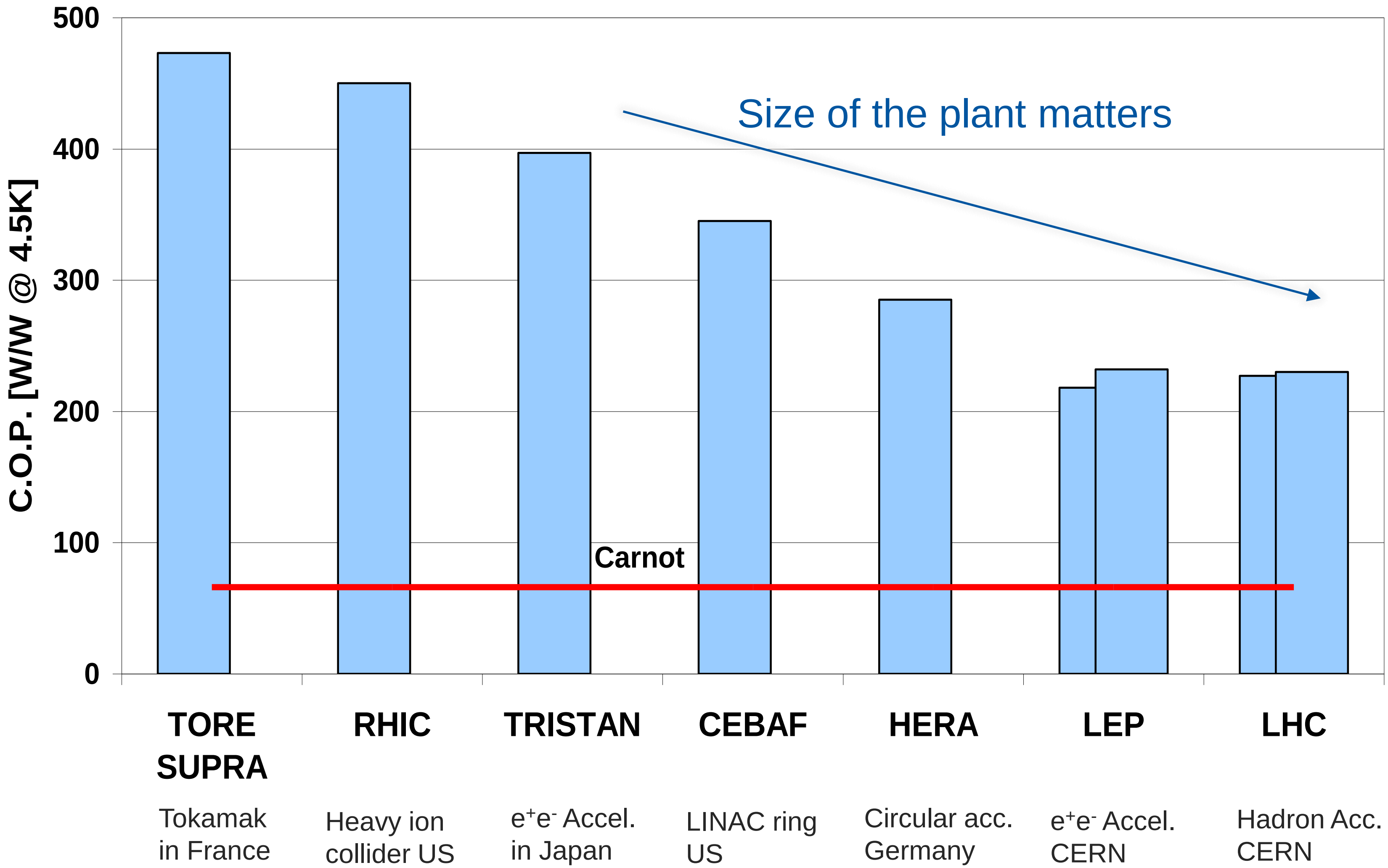


Process cycle & T-s diagram of LHC 18 kW @ 4.5 K cryoplant





COP of large cryogenic helium refrigerators



LHC 18 kW @ 4.5 K helium cryoplants

Th. shields: 33 kW @ 50 K to 75 K
Beam screen: 23 kW @ 4.6 K to 20 K
Current leads: 41 g/s liquefaction

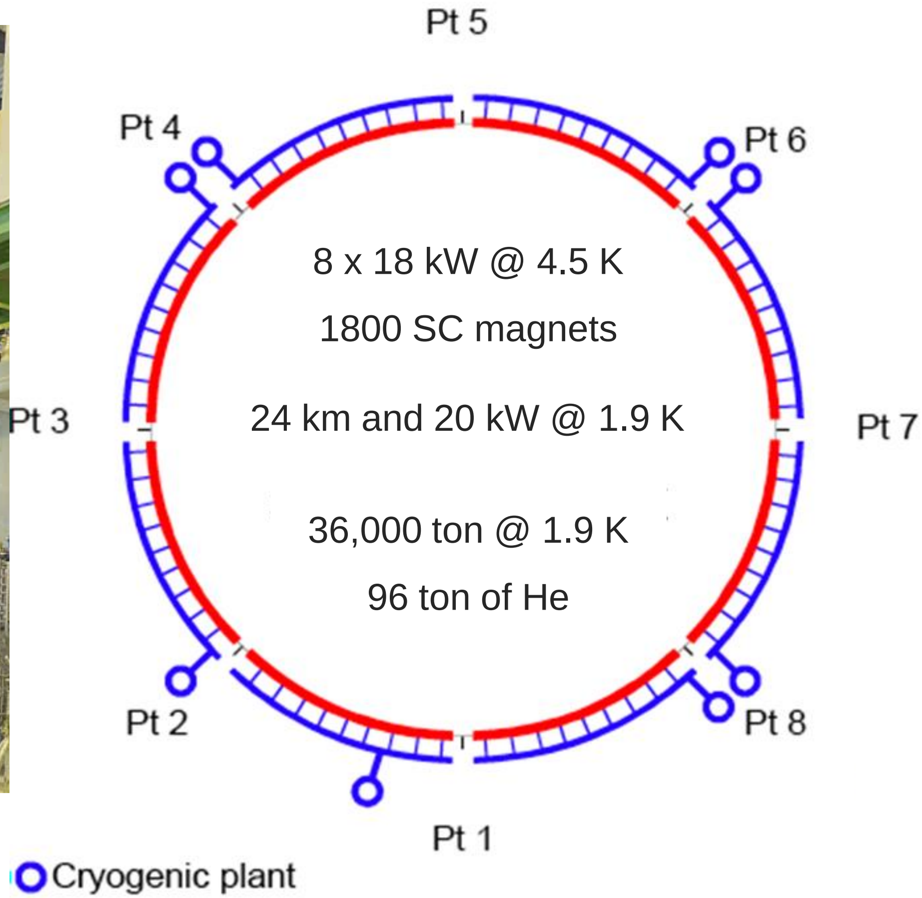
4 MW compressor power
COP 220-230 W/W @ 4.5 K

Air Liquide ↑

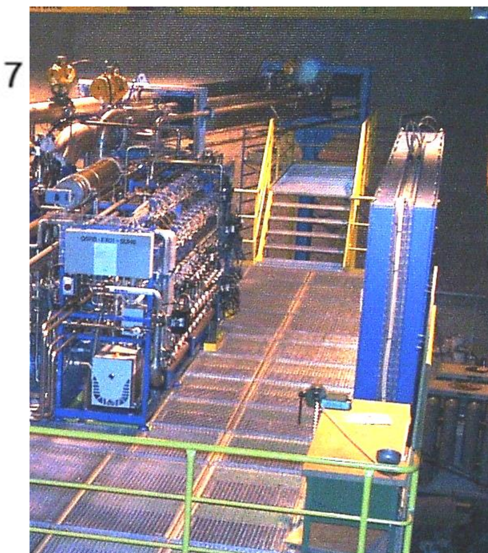
Linde →

LHC 18 kW @ 4.5 K helium cryoplants

K to 75 K
K to 20 K
action
essor power
0 W/W @ 4.5 K

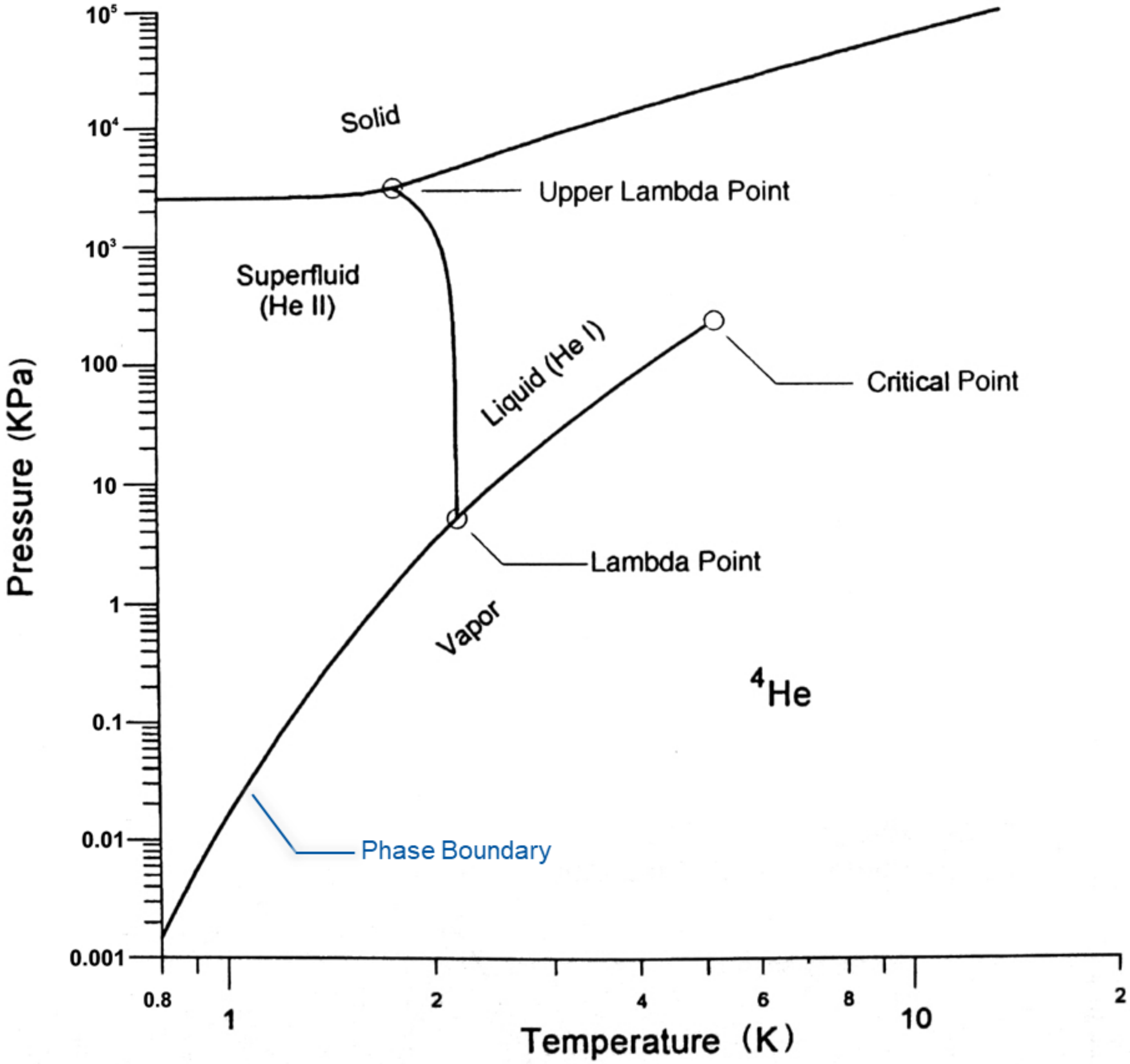


Air Liquide



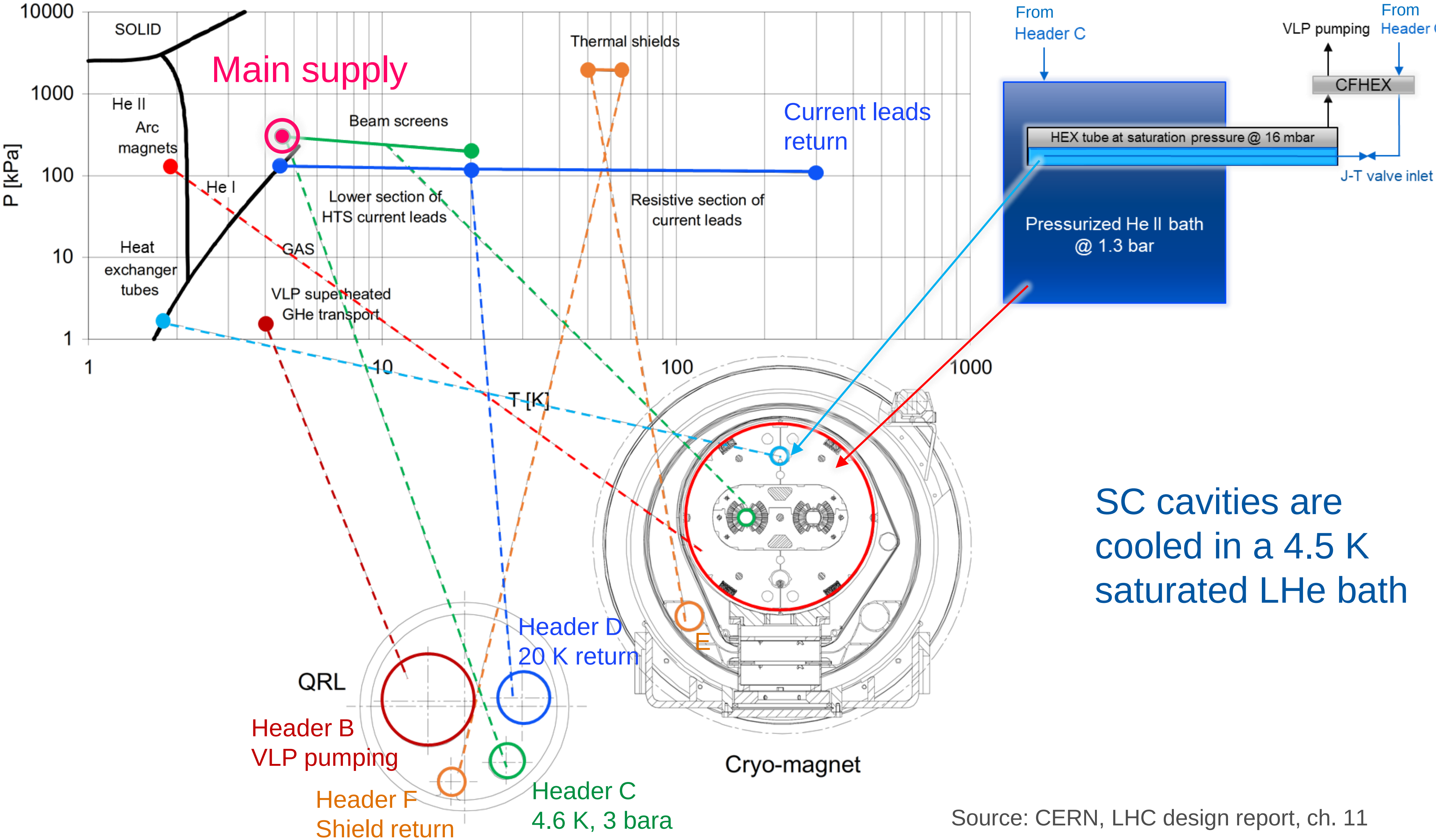
Linde

^{4}He phase diagram



From Weisend, Handbook of Cryogenic Engineering, 1984.

LHC Cooling scheme



SC cavities are cooled in a 4.5 K saturated LHe bath

Source: CERN, LHC design report, ch. 11

Cryogenic Fluid Properties

He I and He II

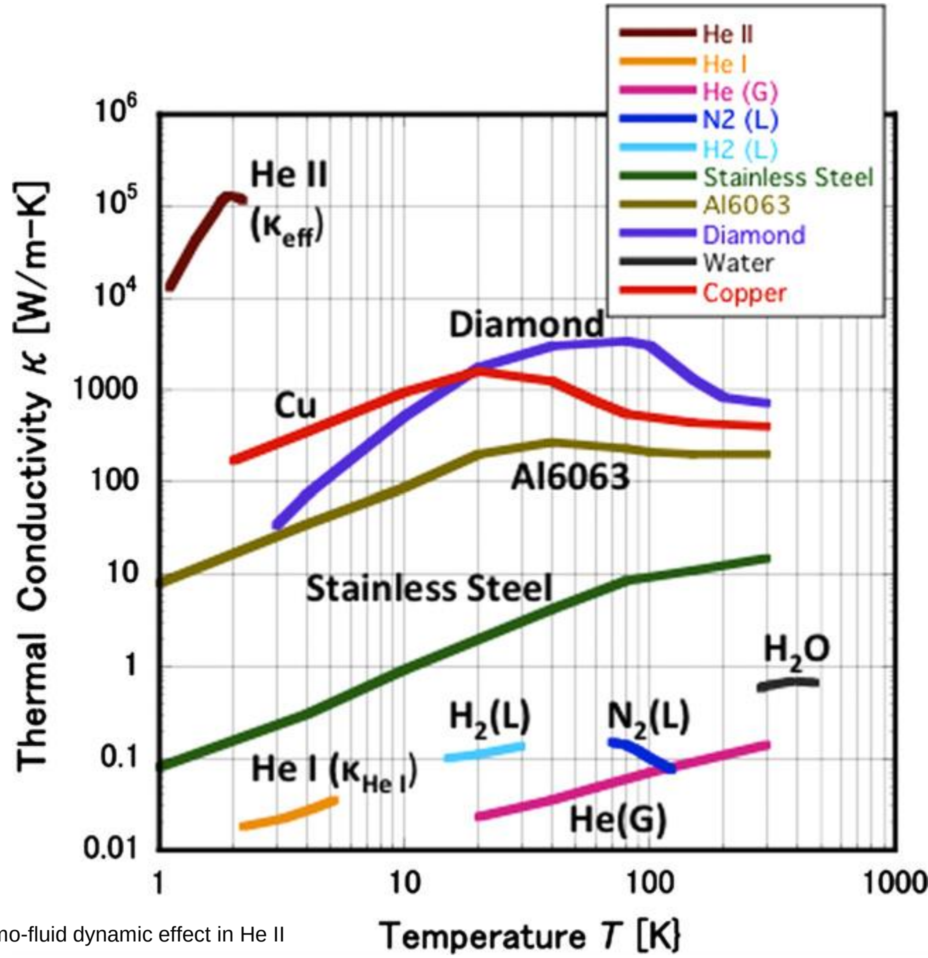
From He I to He II

Normal fluid helium => He I

- Like a standard fluid: viscosity etc.

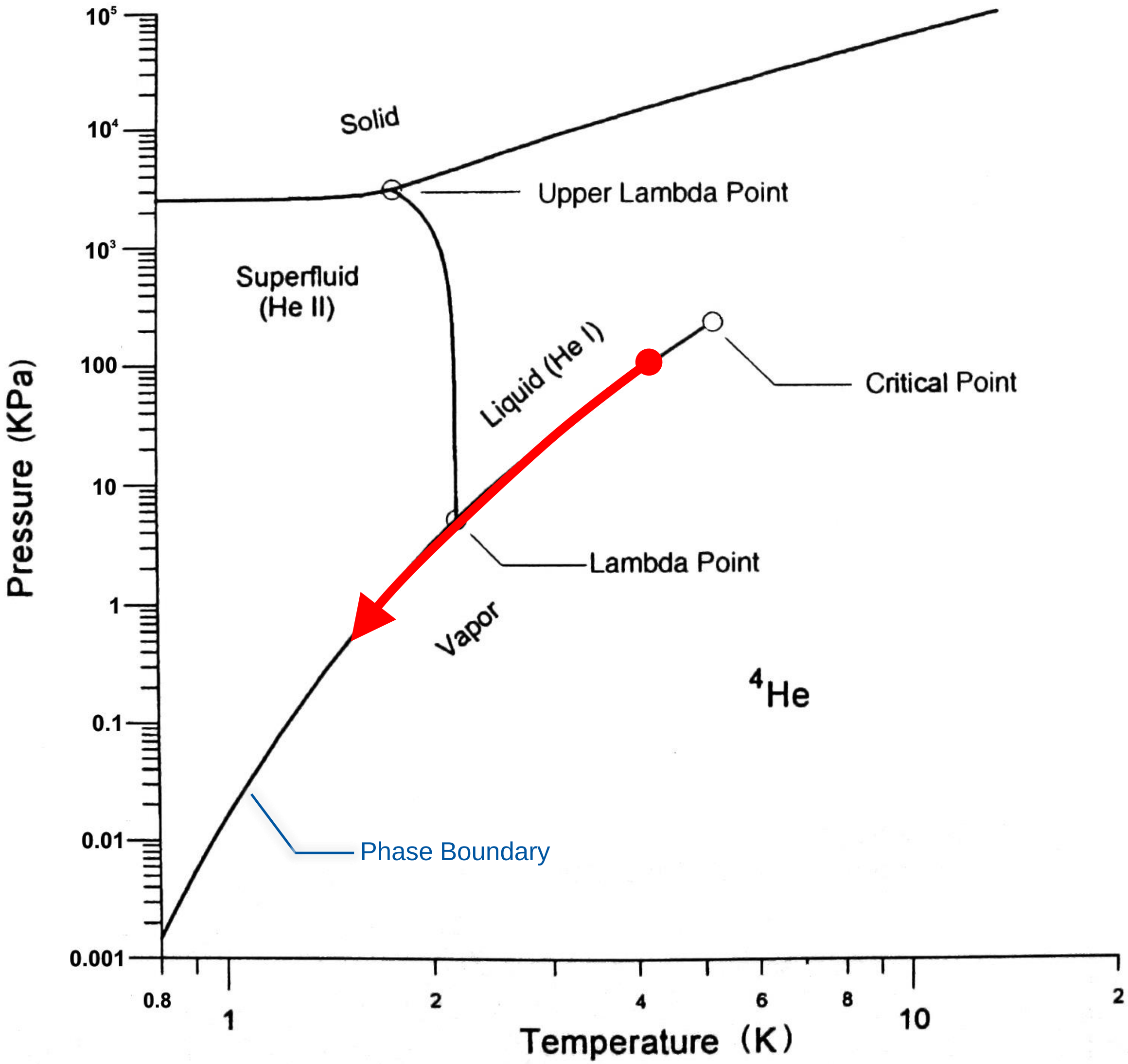
Superfluid helium => He II

- Temperature < 2.17 K
- Peak in heat capacity c_p at T_λ
- Very high thermal conductivity
- Low / vanishing viscosity



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

Phase diagram of ^4He

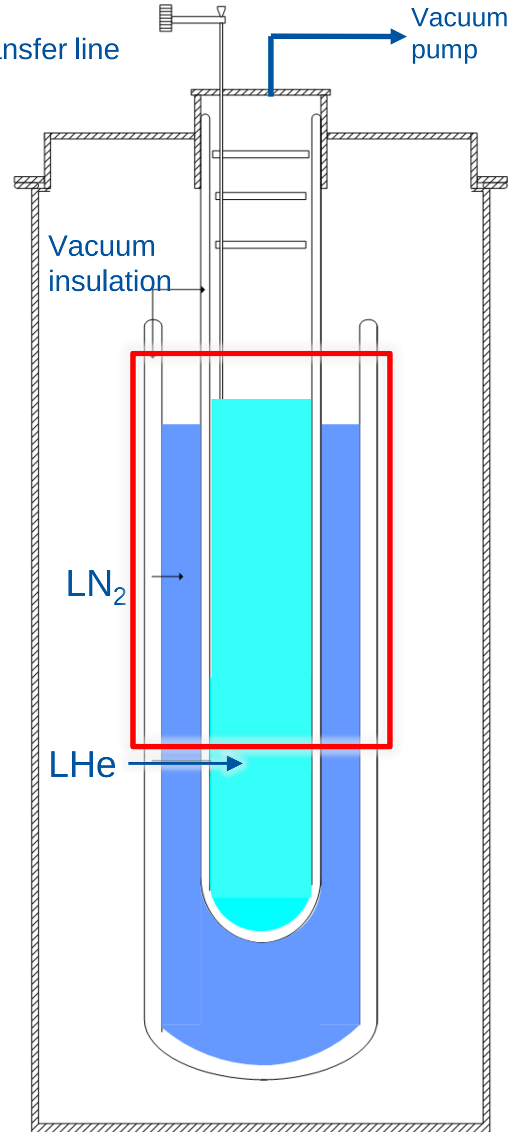


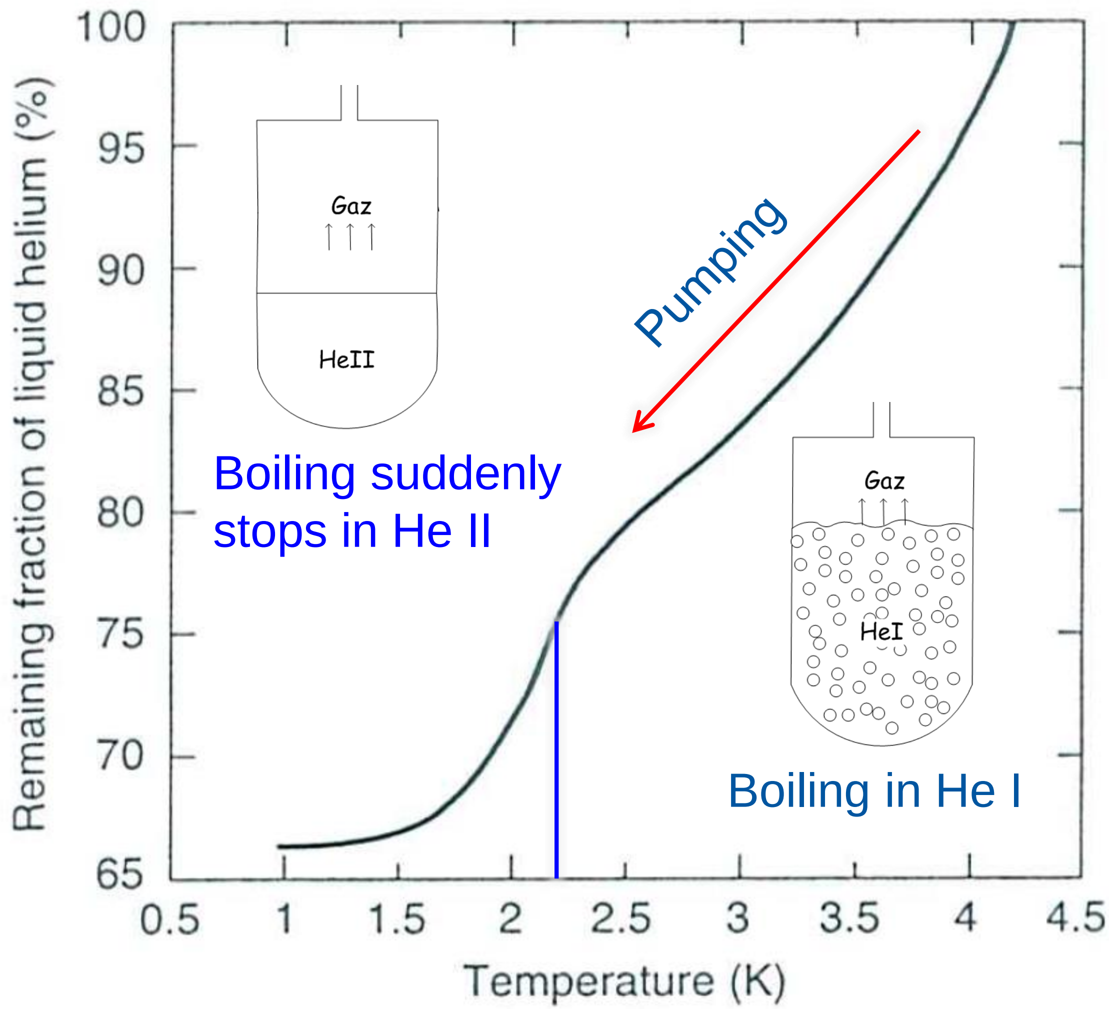
$T_\lambda \approx 2.1768$ K @

$p_\lambda \approx 50.41$ mbar

From Weisend, Handbook of Cryogenic Engineering, 1984.

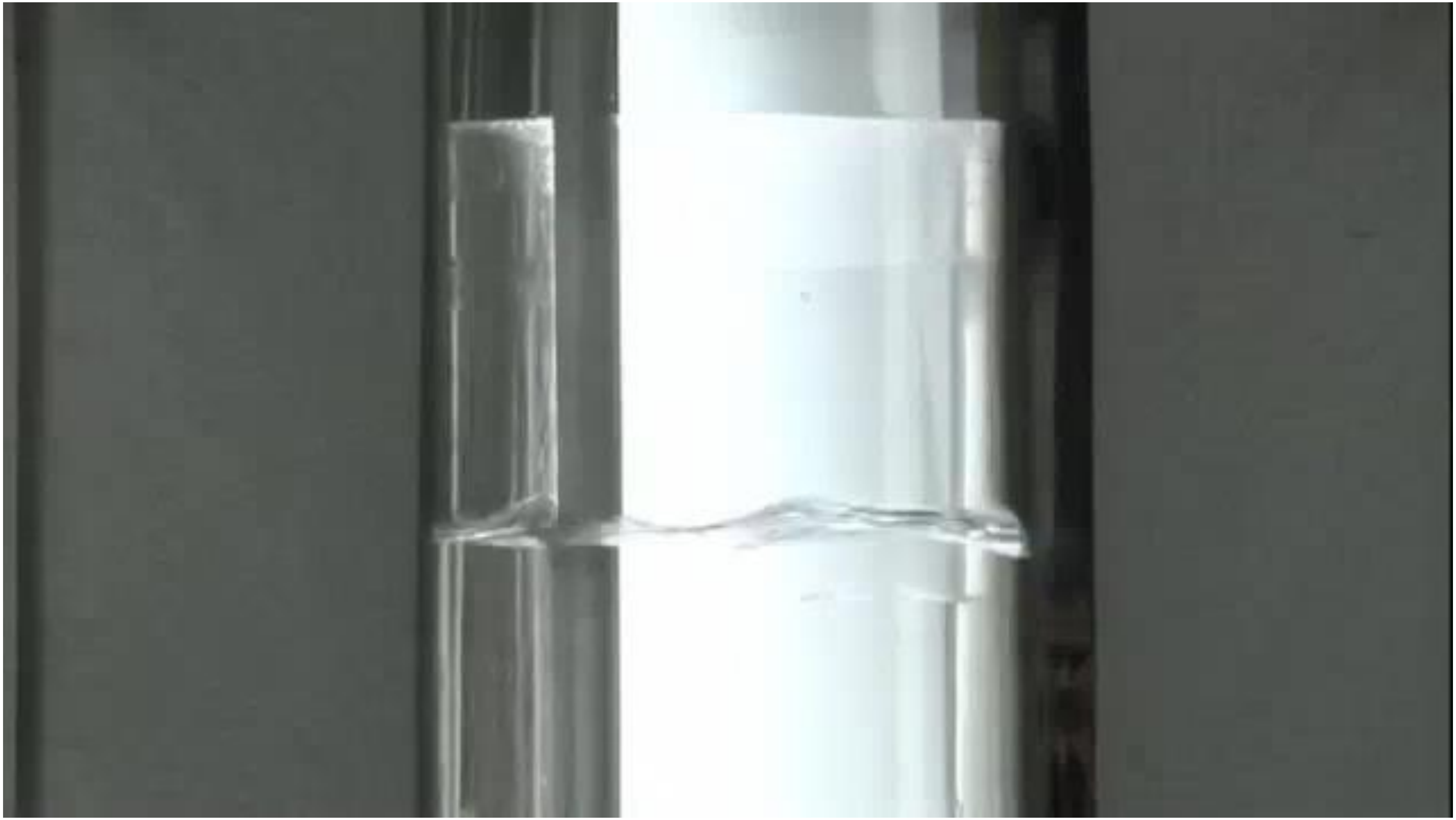
Glass cryostat set-up





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

Boiling effects during cooldown / Pumping on the He vapour



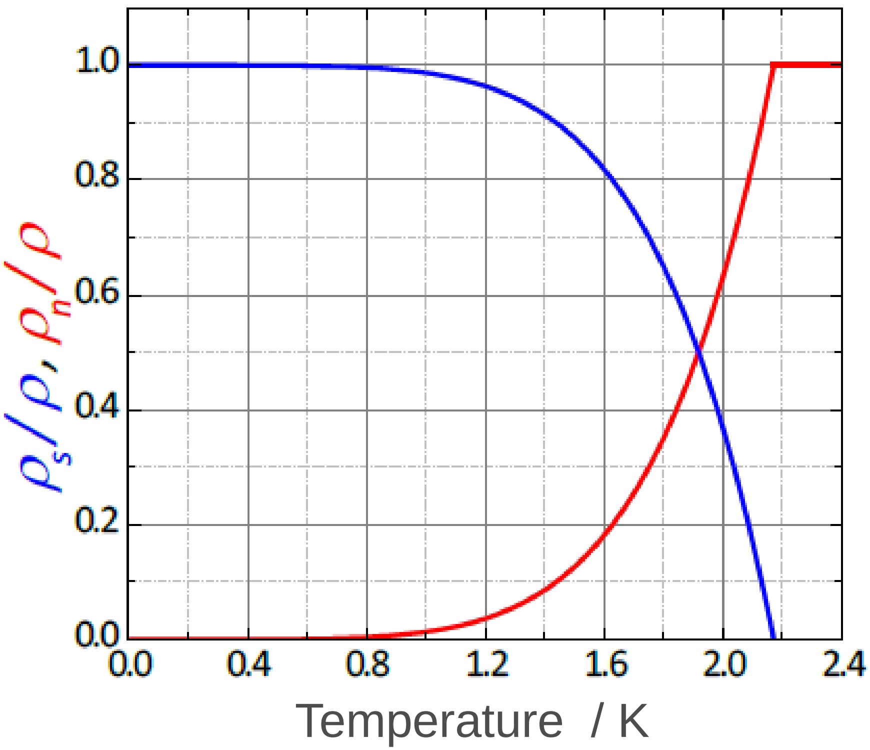
How to explain that unique behaviour ?

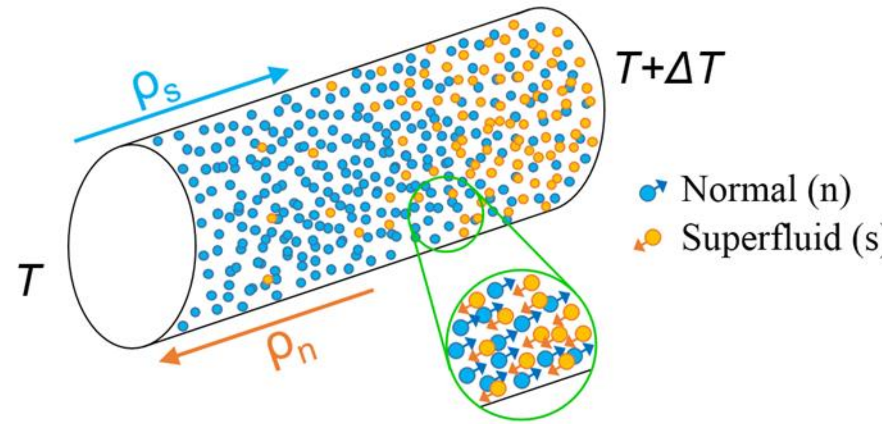
Two fluid model of L. Tisza:

He II is composed of two components

Two-fluid model of He II by Tisza, 1938

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





- ✓ Formal description of He II as the sum of a **normal** and a **superfluid** component.
- ✓ Ratio ρs/ρn depends on temperature

Superfluid component:

- no entropy: $S_s = 0$
- zero viscosity: $\eta_s = 0$

Normal component:

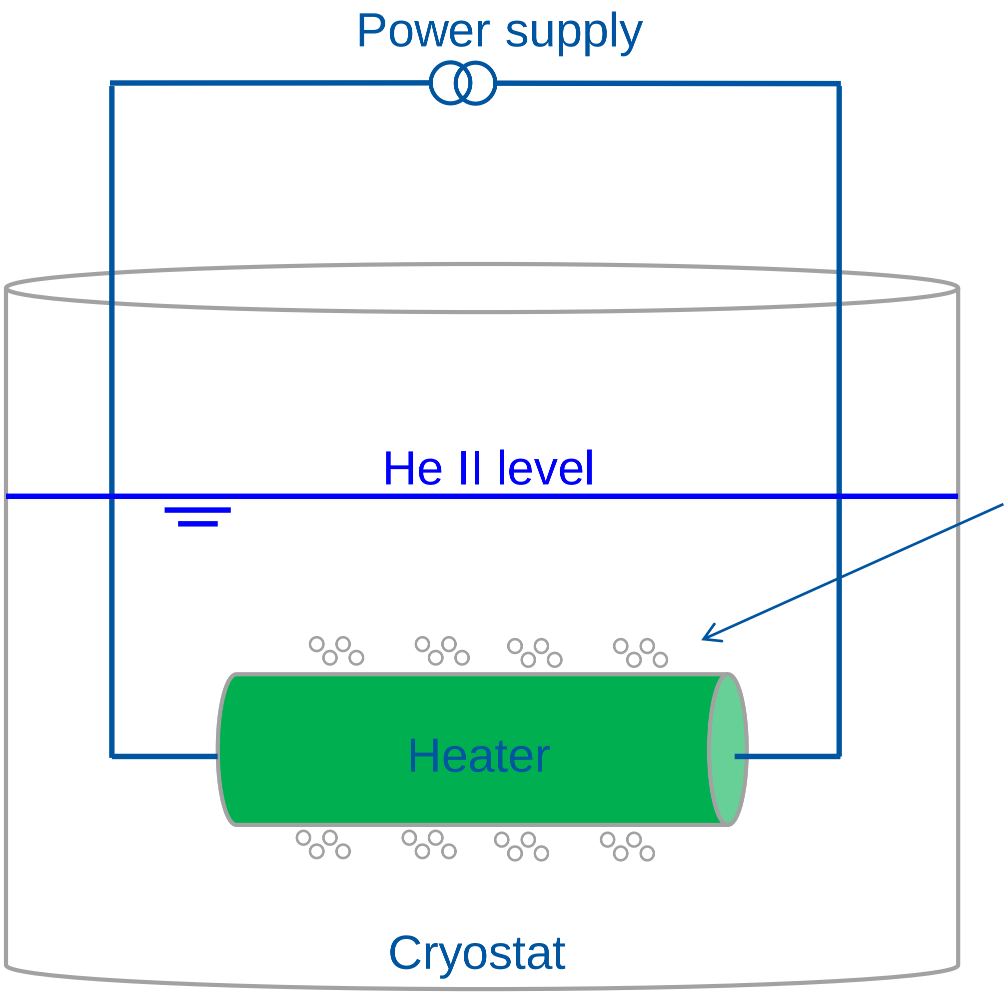
- carries total entropy: $S_n = S$
- finite viscosity: $\eta_n = \eta_n$

He II in practice

Superleak below T_λ

1963 film by Alfred Leitner, Michigan State University

Critical heat flux in He II



Heat and mass flow are limited by a critical velocity:

$v > v_{cr}$

Superfluid behavior becomes non-linear (mutual friction)

k ↓ and η ↑

Formation of vapor bubbles at the surface of the heater

In He II re-condensation of the vapor

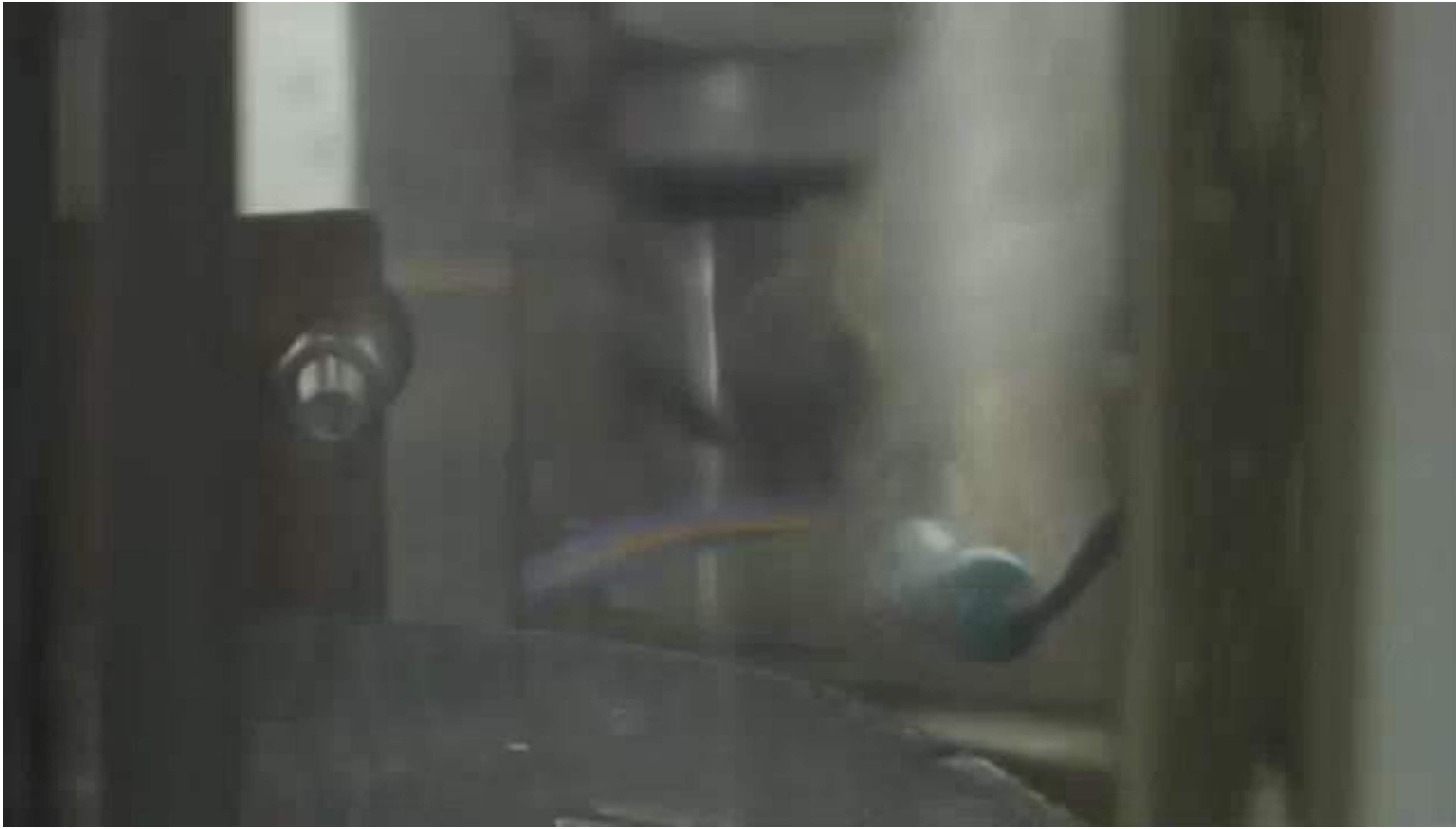
Surface tension let the bubbles implode

Implosion speed exceeds v_1

Shock wave => cavitation

Critical heat flux in He II ($T<T_\lambda$)

Normal fluid cooling (T>T_λ)



Concluding remarks

- Cryogenics serving superconducting systems is now part of all major accelerators and future projects,
- While advanced applications tend to favour “T< 2 K”, many almost industrial applications are based on “4.5 K” and R&D continues for “high temperature” applications,
- Even though cryogenic engineering follows well defined rules and standards, there are still variants depending on boundary conditions, continents, project schedule …
- I could only recommend that demonstrated experience is evaluated and adapted to specific requirements you may have !

Some references

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    - G. Vandoni, *Heat transfer*
    - Ph. Lebrun, *Design of a cryostat for superconducting accelerator magnet*
    - Ph. Lebrun & L. Tavian, *The technology of superfluid helium*
- Proceedings of ICEC and CEC/ICMC conferences
- CERN, HSE, Cryogenic Safety courses 1-3

Thank you for your attention.

www.cern.ch

Spare slides

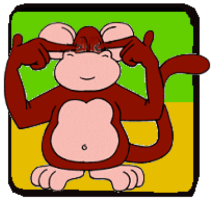
Overview of cryogenics at CERN - Infrastructure

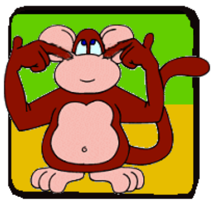
- Refrigeration plants (warm compressor stations and cold boxes – e.g., LHC, ATLAS, CMS)
- Refrigeration units (e.g., LHC cold compressor units)
- Liquefiers (Central Liqu., SM18, ISOLDE, CAST...)

Overview of cryogenics at CERN - Infrastructure

- Storage vessels: GHe or LHe
- Networks of distribution lines (warm and cryogenic)
- Q stands for Cryogenics

Cryogenic hazardous events – Warning signs





- Eyes -
- Ears -
- Nose -

Liquid or gaseous cryogens are odourless and colourless.

Surface temperatures are not obvious

The human senses do not warn!

OFTEN ONLY secondary signs:

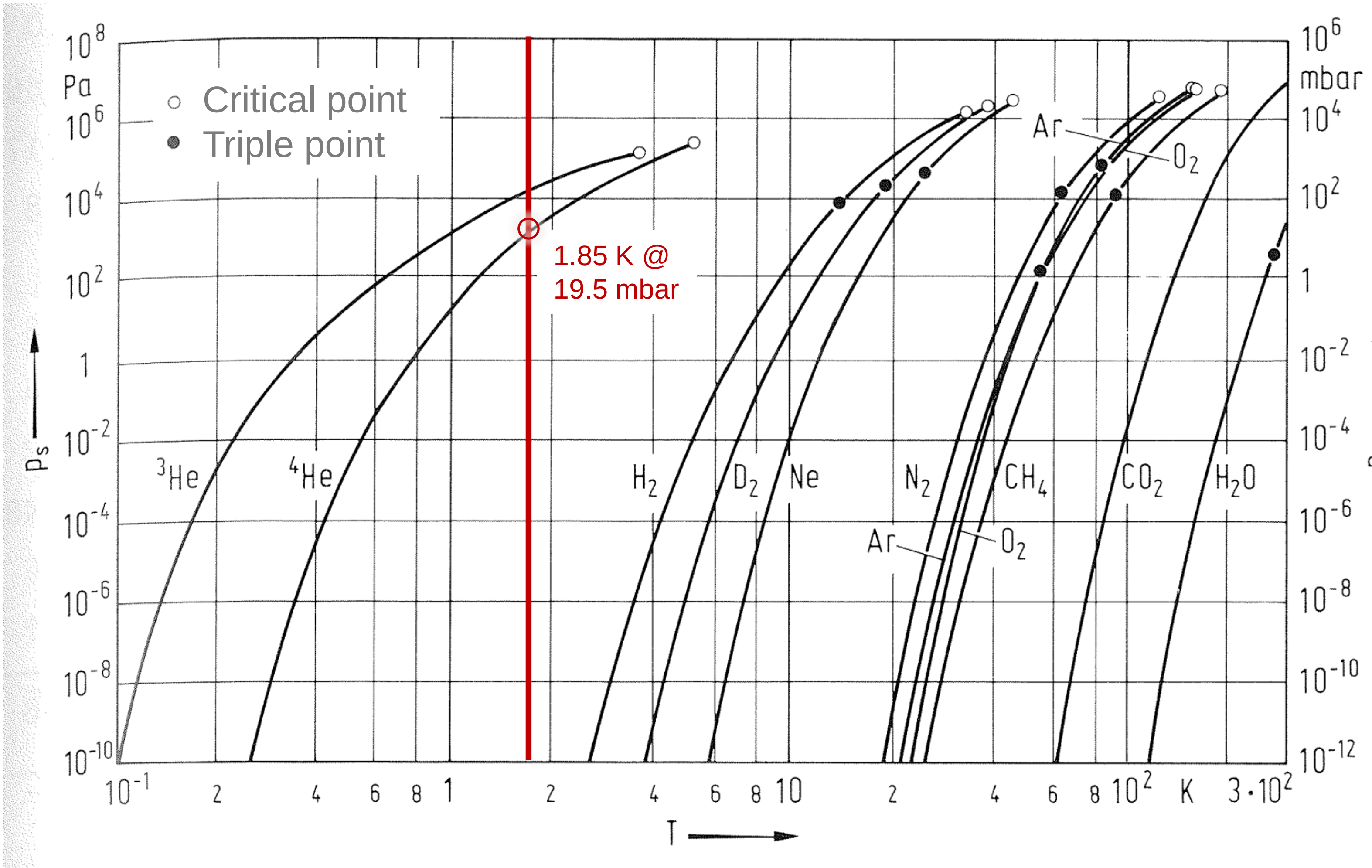
Ice, water, air condensation (!) → indicates cold surfaces

Fog → may indicate a leak of liquid or gazeous cryogens

Risk of cold burn / Frost bite

Source: Sever et al. (2010). Frostbite Injury of Hand Caused by Liquid Helium: A Case Report. Eplasty. 10. e35.

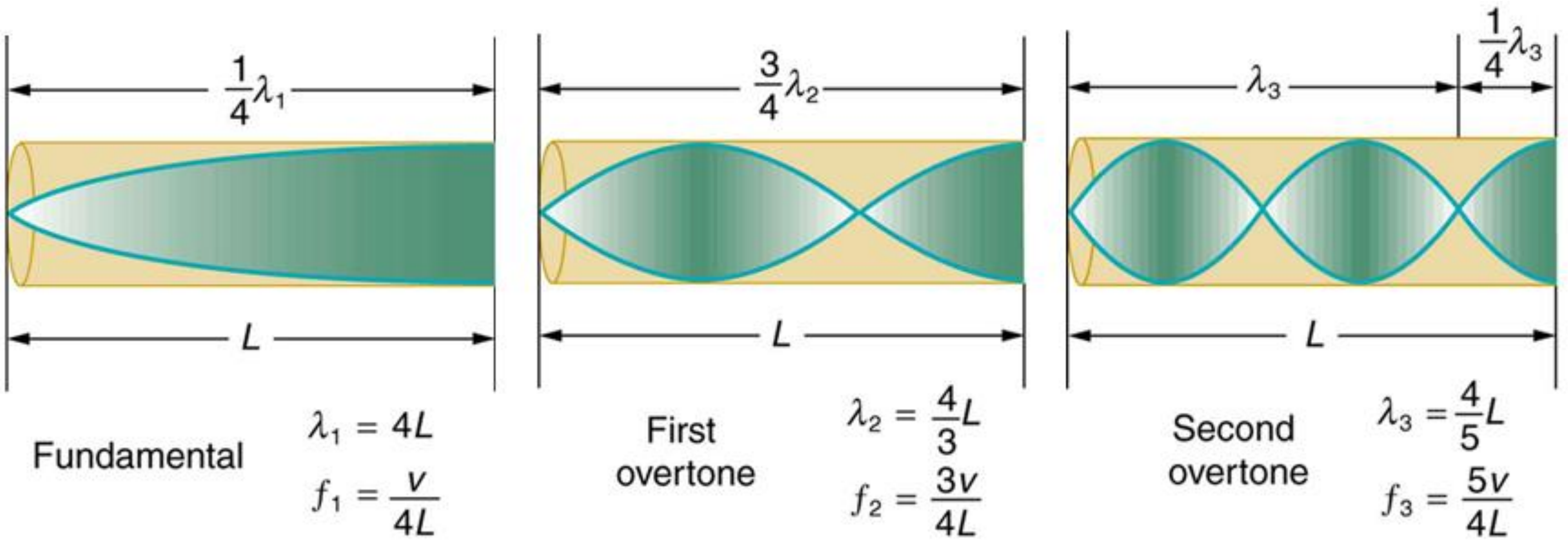
Vapor pressure curves of common gases



Source: Haefer; Kryovakuumtechnik, 1981

Thermo-acoustic oscillations

Quarter wave resonator “resonance at one open end”



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

Thermo-acoustic oscillations (TAO or Taconis)

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

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

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

Typical frequencies 10 to 40 Hz

Conditions:

Stand pipe of a transfer line

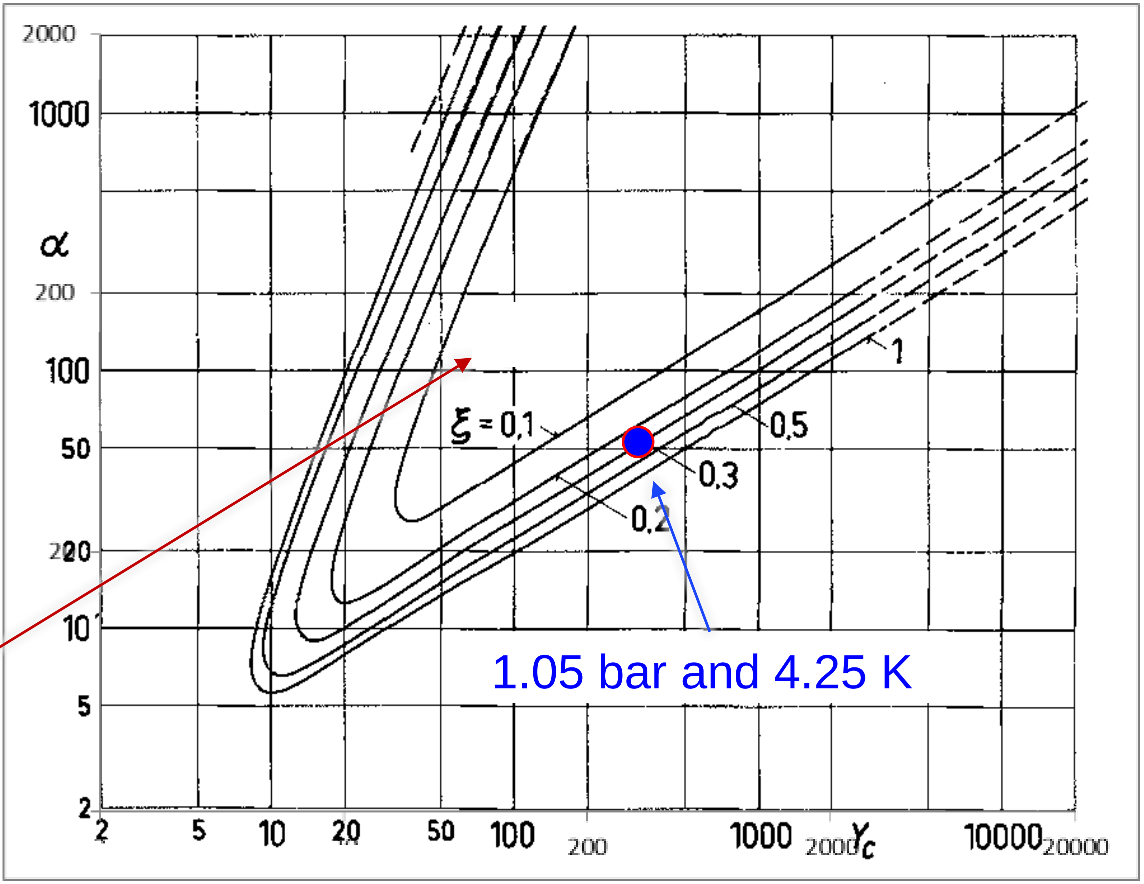
T_{warm} = 280 K

T_{cold} = 2.1 K saturated bath

L_{cold} = 0.35 m

L_{warm} = 0.35 m

r_{Tube} = 5 mm inner tube radius



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

Thermo-acoustic oscillations (TAO or Taconis)

- Oscillations are more likely and stronger at lower pressure
- Δp= ±0.3 bar
- Reduction/attenuation by:
  - restriction and warm buffer
  - insert in tube
  - closing bottom of tube by liquid

Heat capacity of materials vs. cooldown

Amount of cryogen required to cool down 1 kg iron to sat. temperature

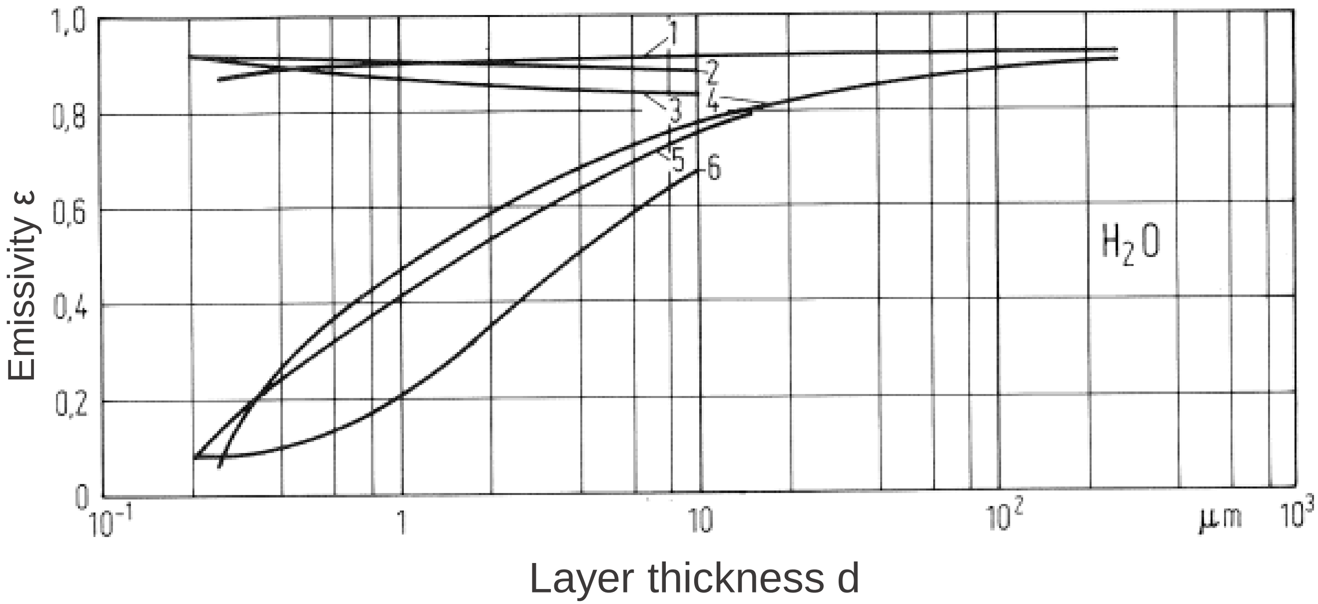
Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 liter	0.75 liter
LHe from 77 to 4.2 K	1.46 liter	0.12 liter
LN_2 from 290 to 77 K	0.45 liter	0.29 liter

Vaporization of normal boiling cryogens under 1 W applied heat load

Cryogen	[mg/s]	[l/h] (liquid)	[l/min] (gas NTP)
Helium	48	1.38	16.4
Nitrogen	5	0.02	0.24

Emissivity of technical materials at low temperatures

Emissivity of cold surface coated with water condensate dependent on layer thickness



Source: Haefer, Kryovakuumtechnik, 1981

	Cold surface, 77 K	Gas inlet
1	Al + Cat-a-Lac	Uniform over time, 0.06 Pa
2	Ni + Black Velvet 101-C10/3M	Sporadic
3	Ni + Black Velvet 101-C10/3M	Uniform over time, 0.1 Pa
4	Al, polished, ε = 0.07	Uniform over time, 0.06 Pa
5	Ni, polished	Sporadic
6	Ni, polished	Uniform over time, 0.1 Pa

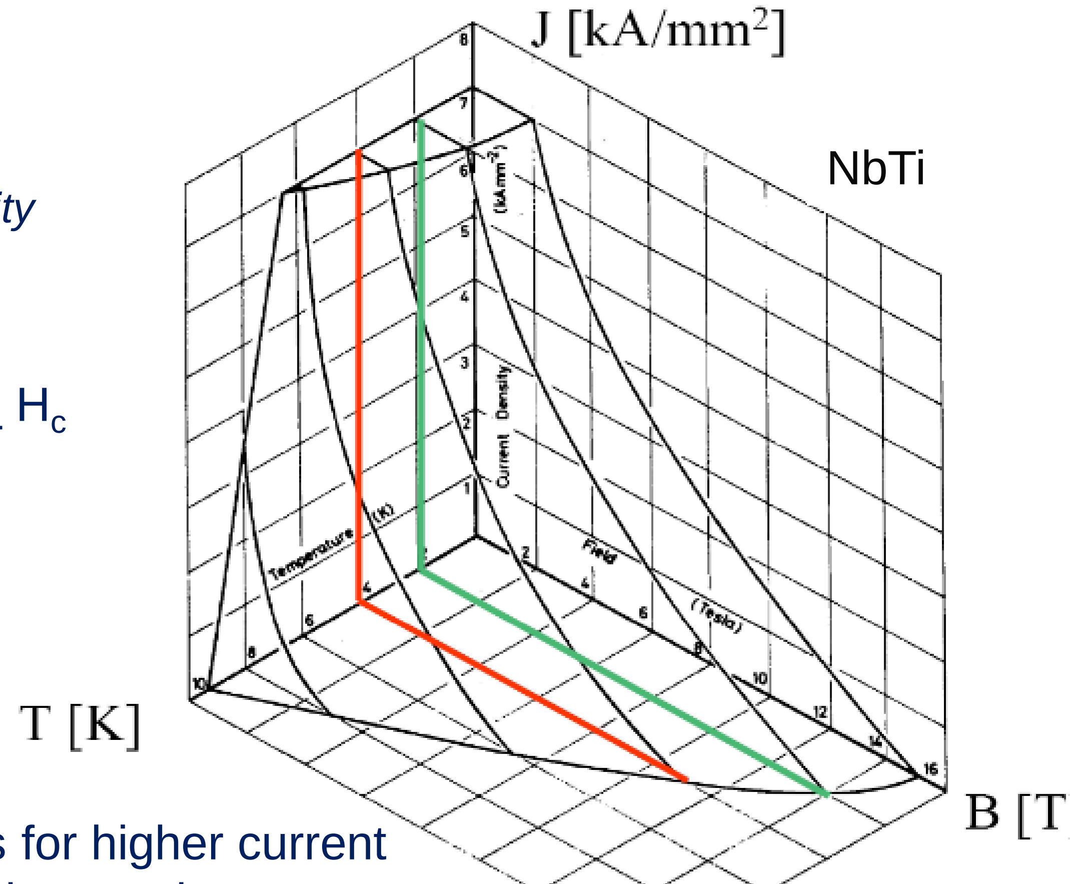
Superconductivity – Properties

Three essential parameters of SC :

- Critical Temperature : T_c
  For T_c>23.2 K *one calls it*
  High Temperature Superconductivity (HTS)

- Critical magnetic field strength: H_c

- Critical current density: j_c

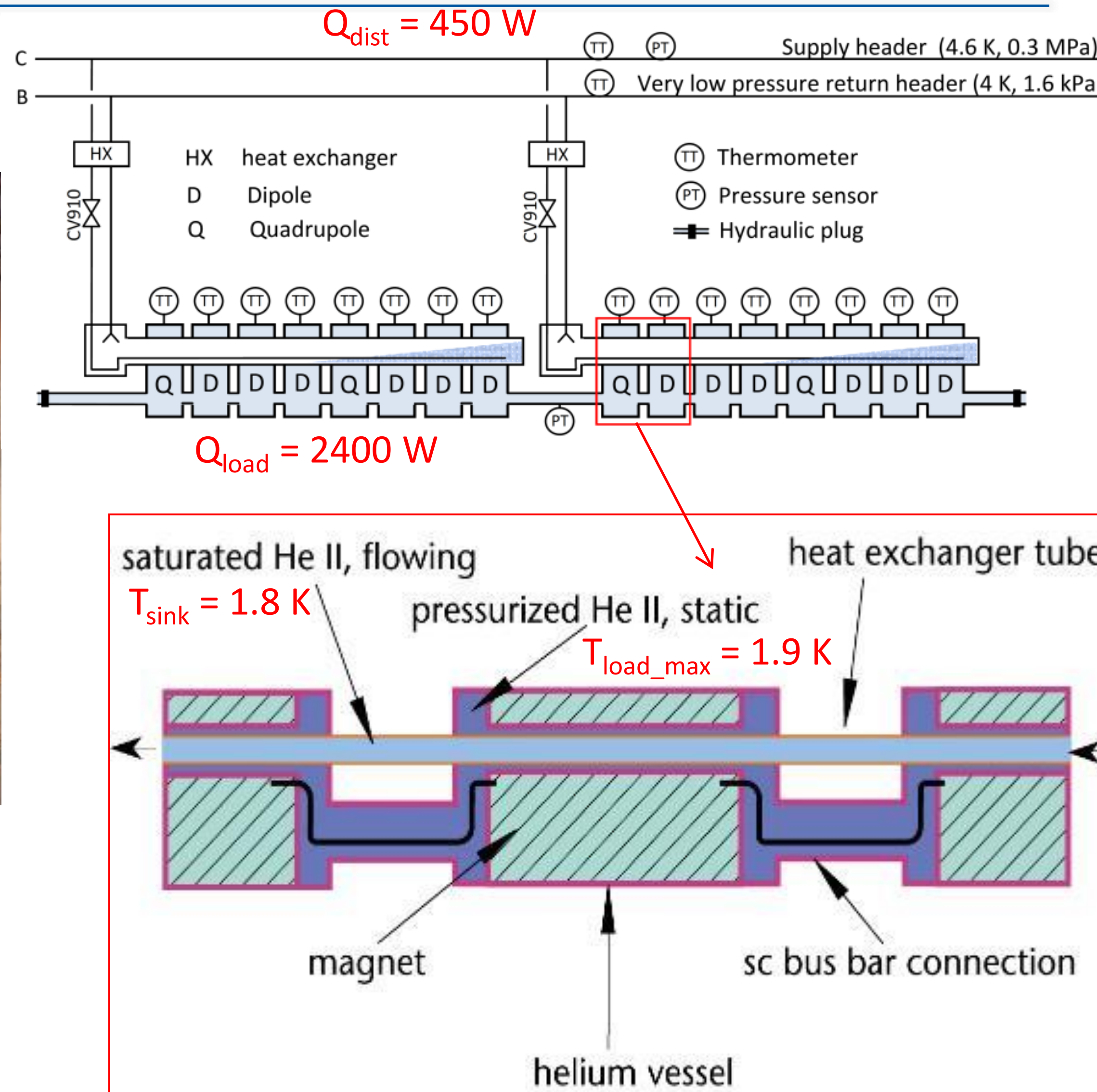


- Lowering the temperature allows for higher current density and higher magnetic field strength.
- Temperature stability and homogeneity are crucial.

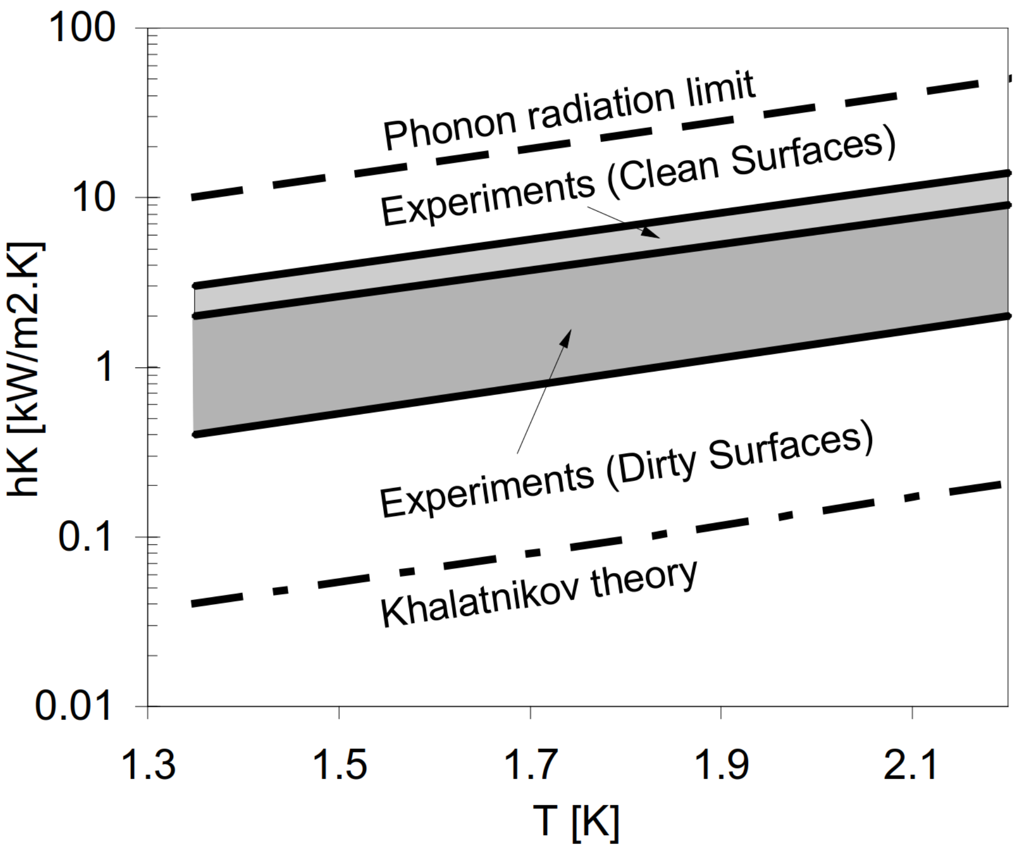
LHC cryogenic distribution scheme - QRL

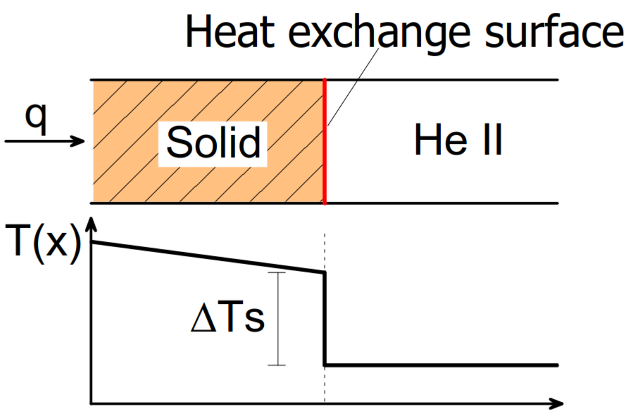
Pressurized/saturated He II

37’500 tons at 1.9 K



Interface heat transfer at very low temperature



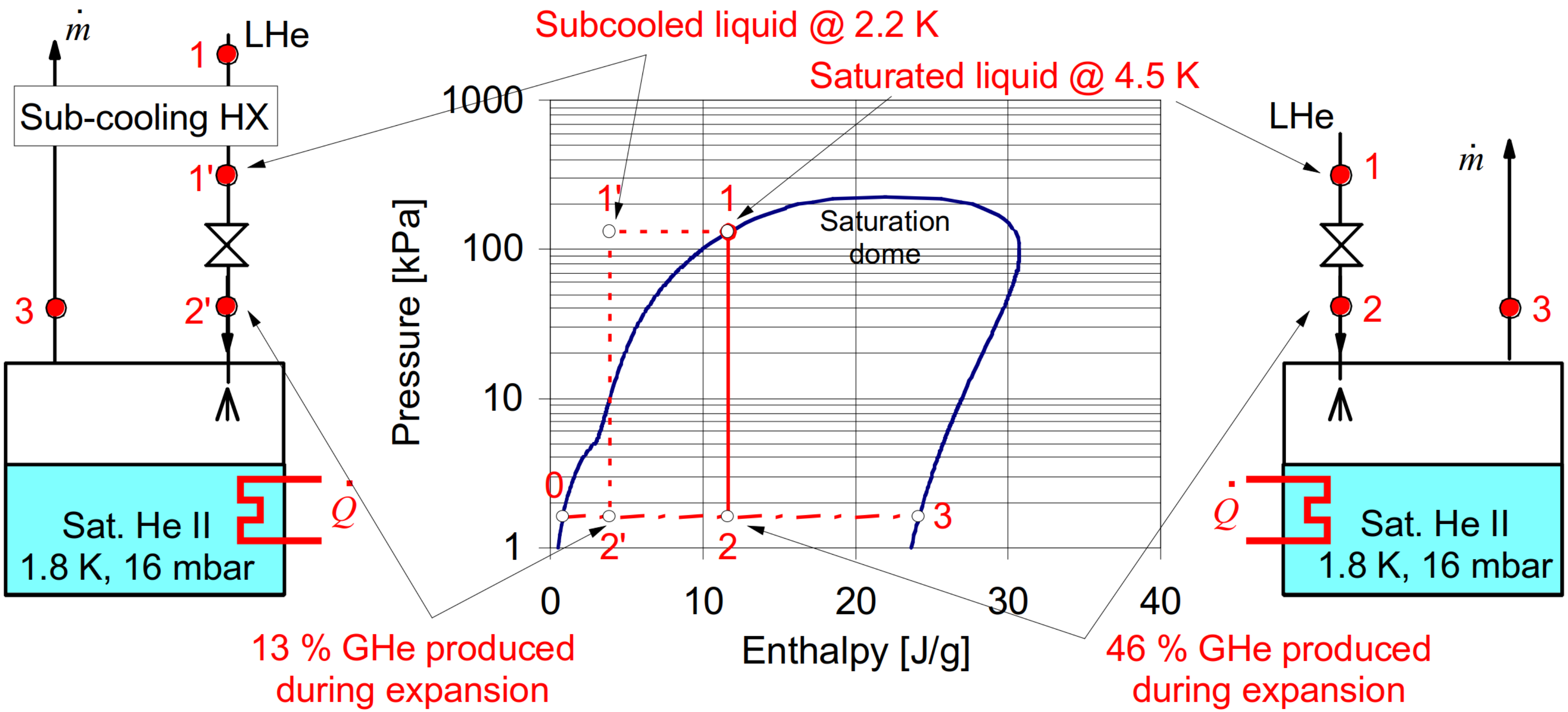


Valid for small heat flux

(when $\Delta T \ll T$)

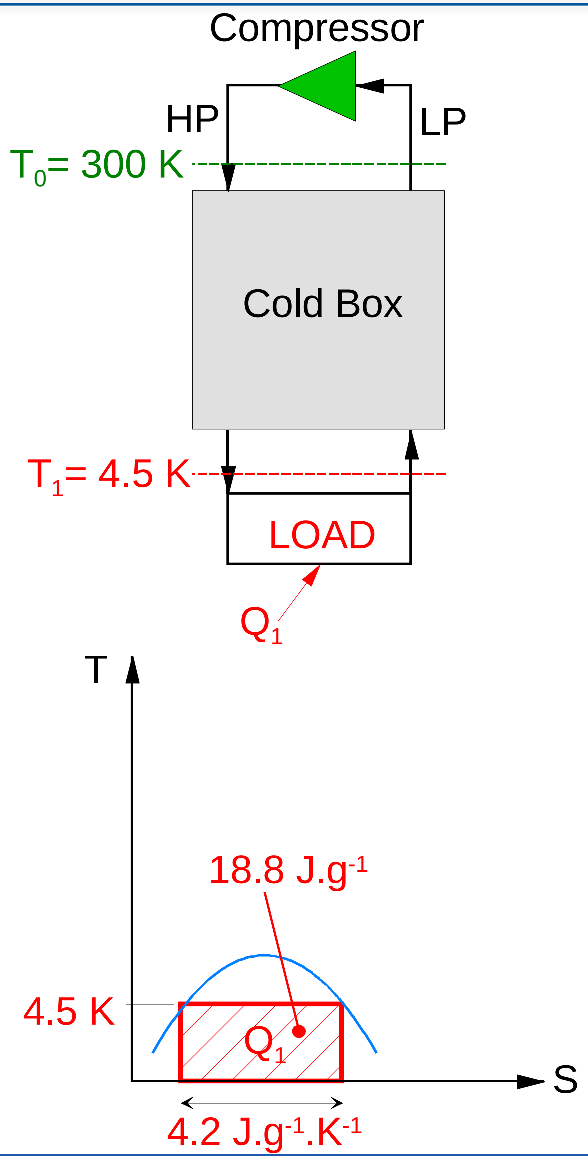
Source: Ph. Lebrun, Cooling with Superfluid Helium

The effectiveness of J-T expansion

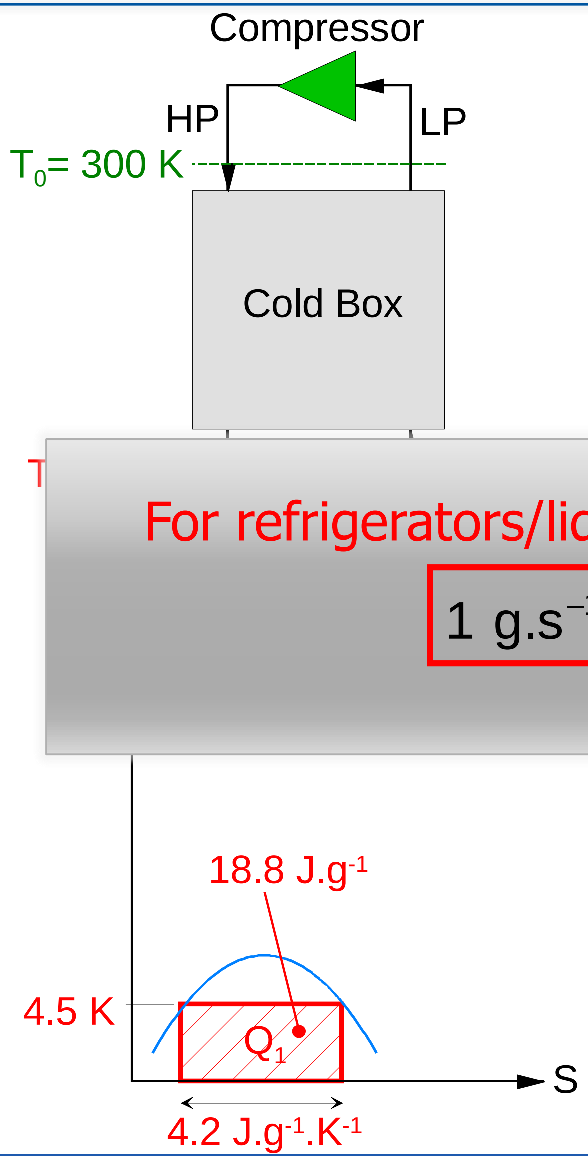


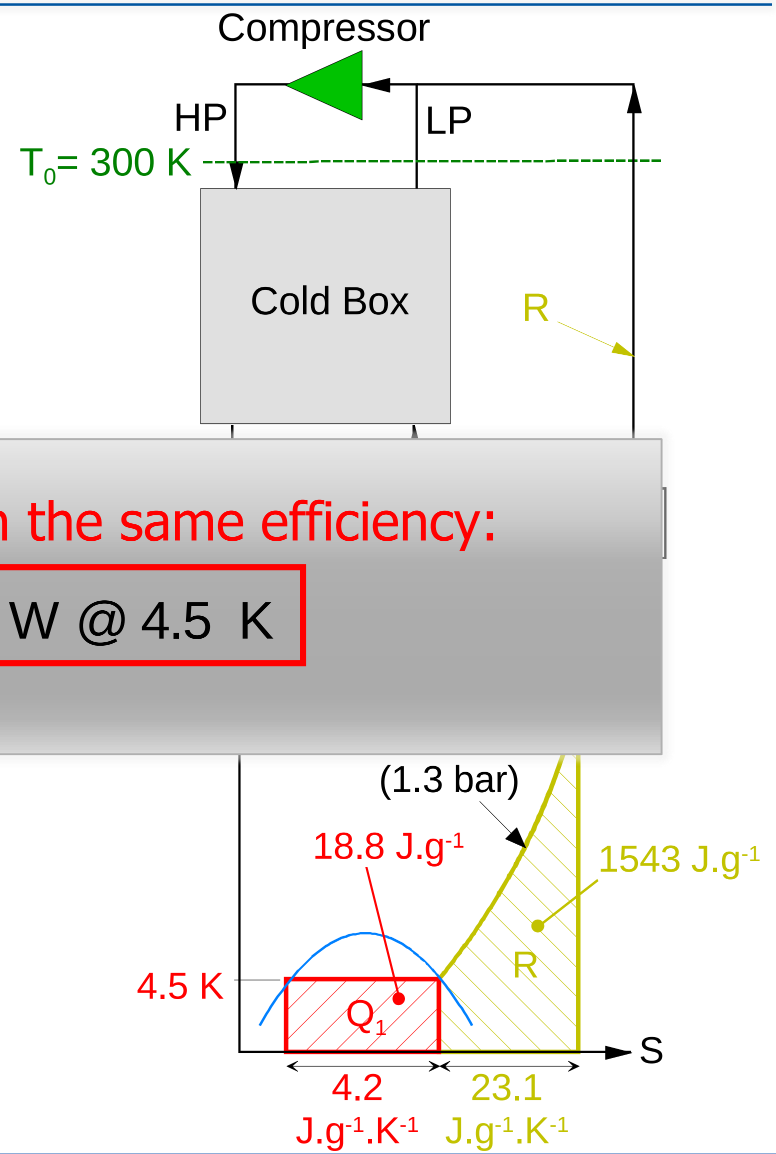
Source: Ph. Lebrun, Cooling with Superfluid Helium

Refrigerator



Refrigerator | Liquefier

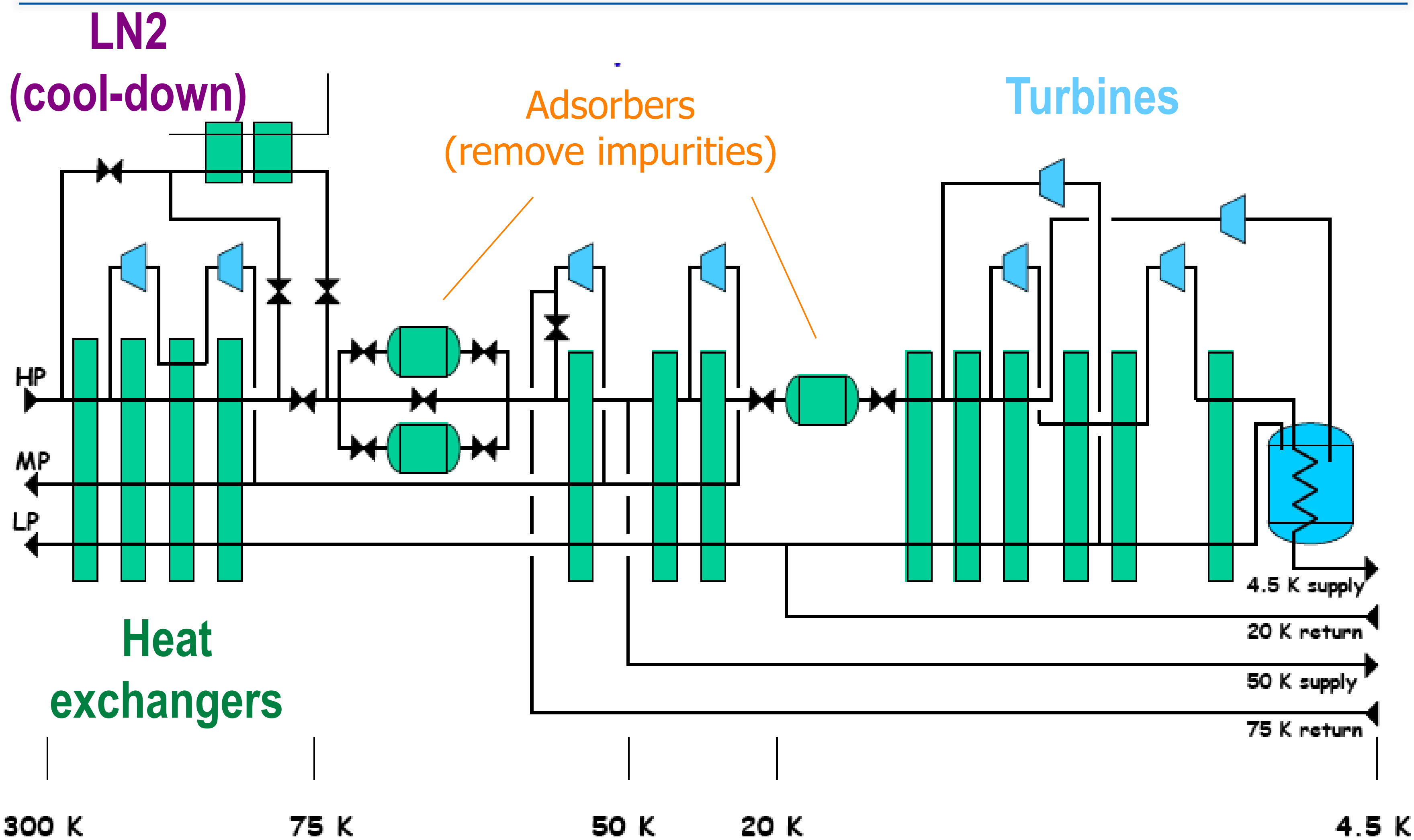




For refrigerators/liquefiers with the same efficiency:

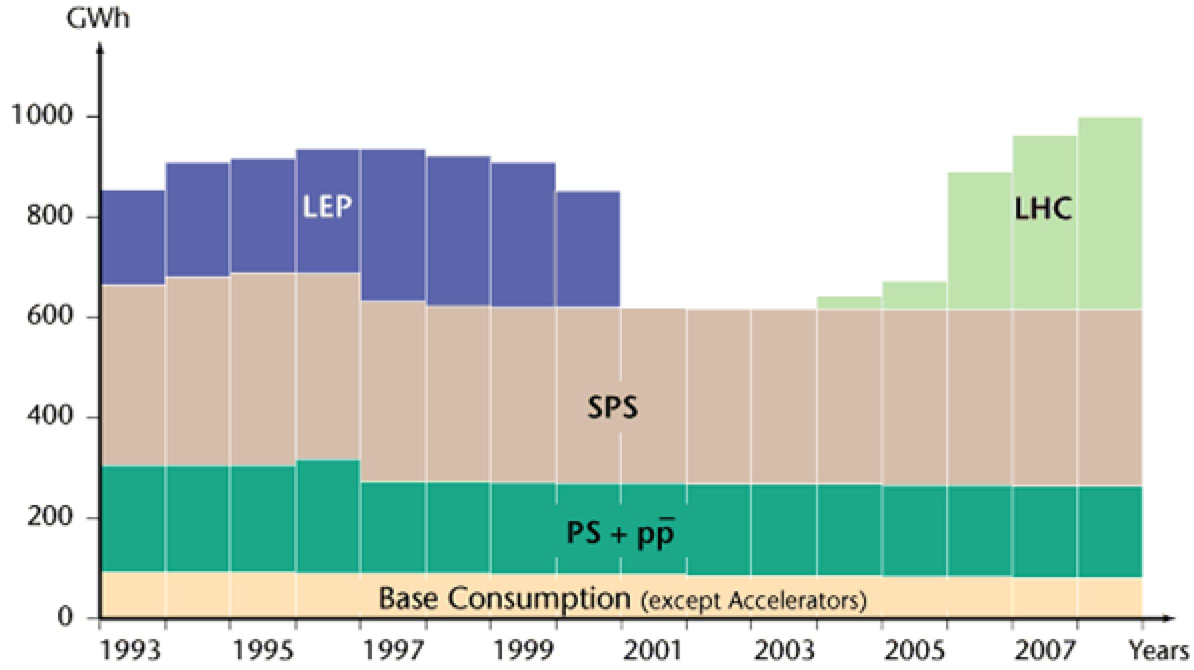
$$1\ \mathrm{g.s^{-1}}\ \mathrm{LHe} \equiv 100\ \ \mathrm{W}\ @\ 4.5\ \ \mathrm{K}$$

Process diagram, LHC refrigerator 18 kW @ 4.5 K



Energy consumption CERN, LHC and Cryo

CERN in total is around 200 MW with LHC contributing to 115 MW

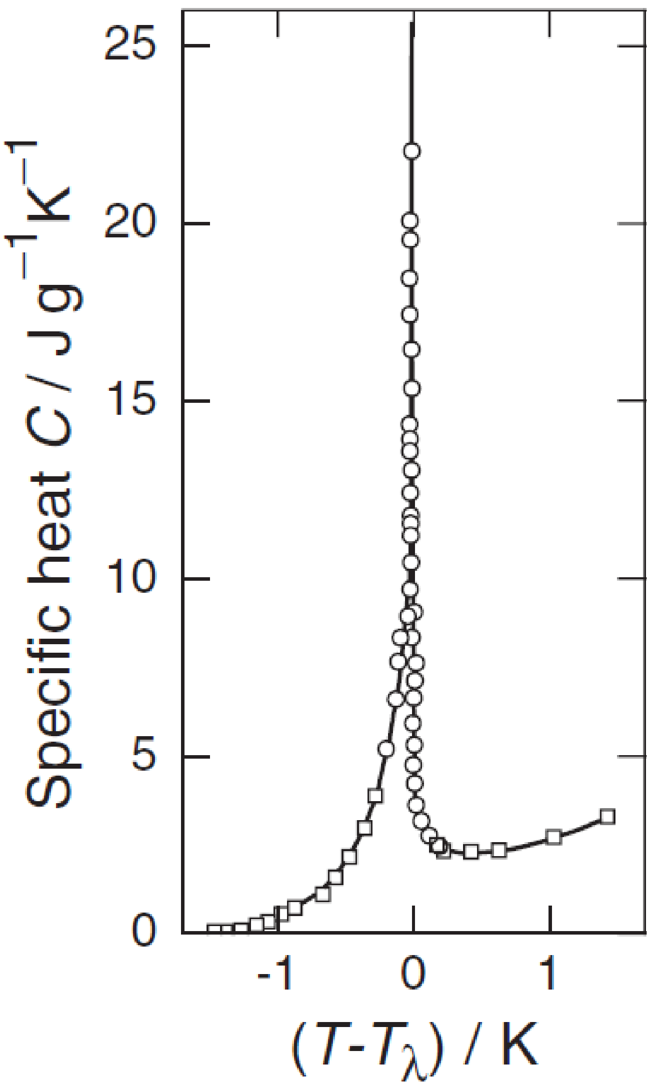


Source: https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.energy_consumption

When the LHC is up and running the total average power for the whole CERN site will peak during July at about 180 MW of which:

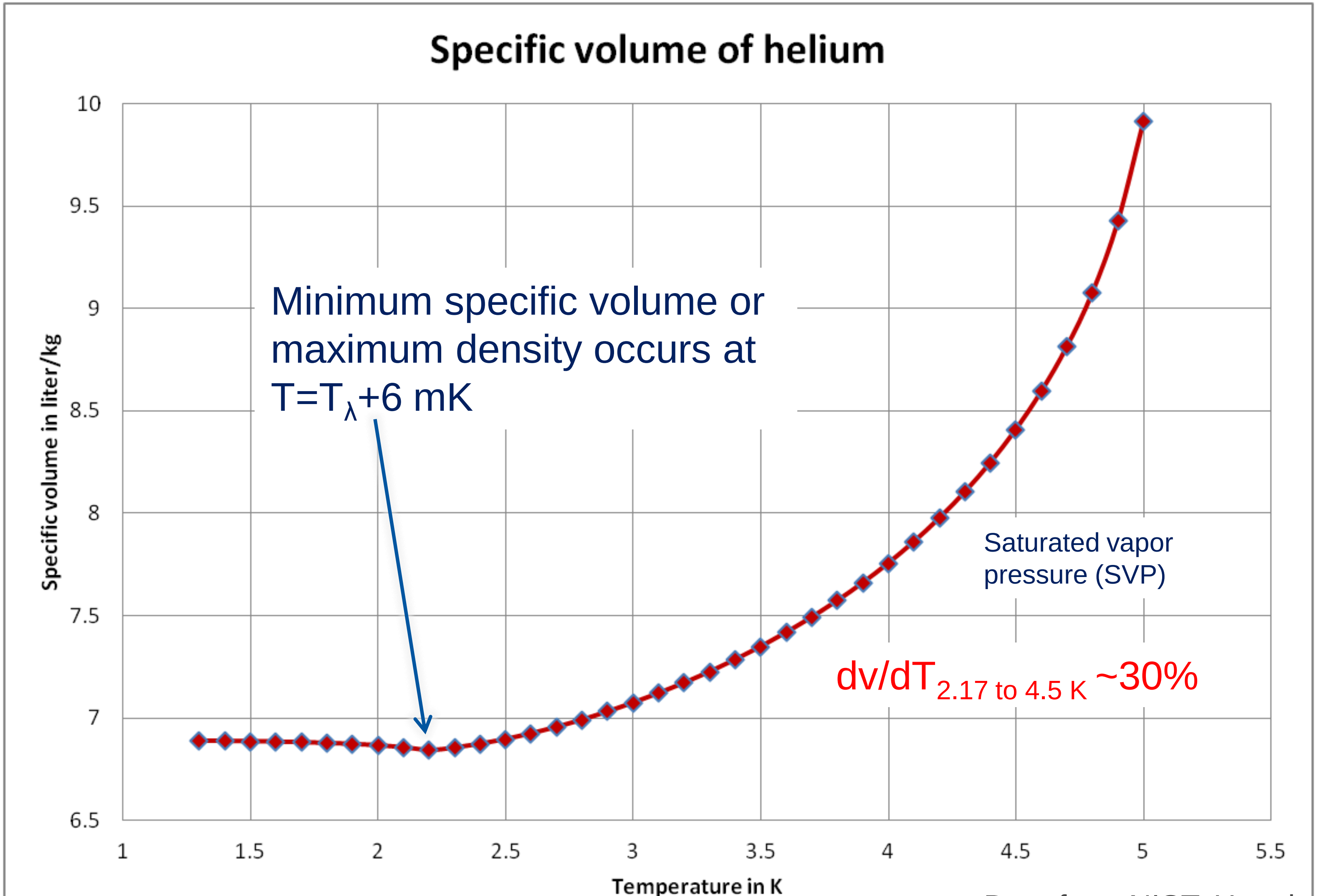
- LHC cryogenics 27.5 MW (40 MW installed)
- LHC experiments 22 MW

Heat capacity – Lambda point



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

Specific volume of ^4He



Data from NIST, Hepak