CERN

Introduction to Cryogenics

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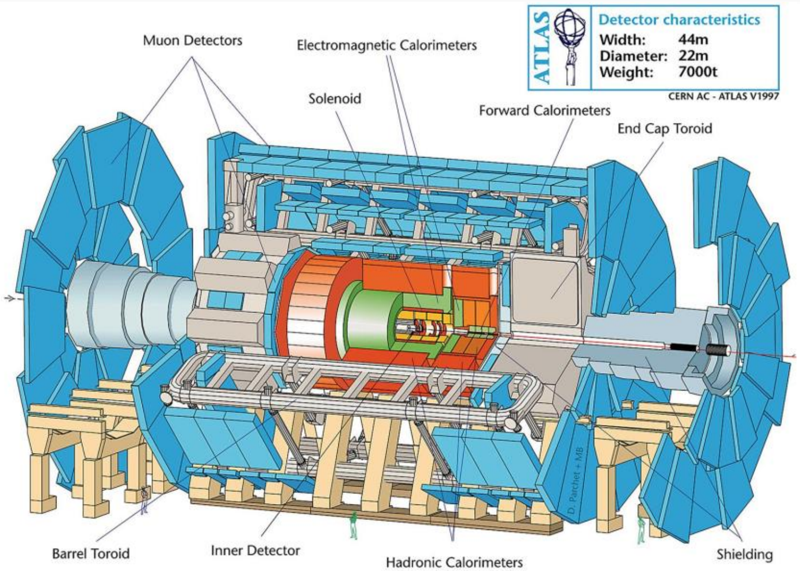
Contributions from S. Claudet and Ph. Lebrun

CAS: Basics of Accelerator Physics and Technology, 2021.

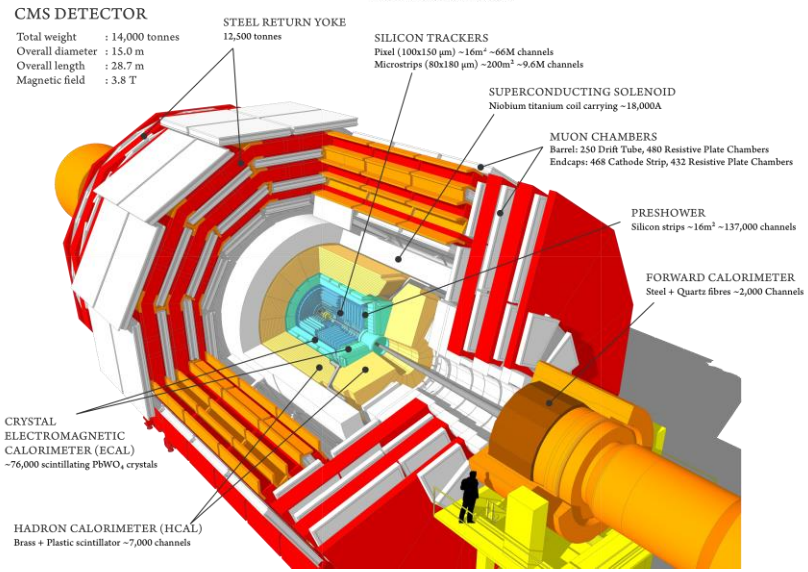
Content

- Introduction to cryogenic installations
- 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



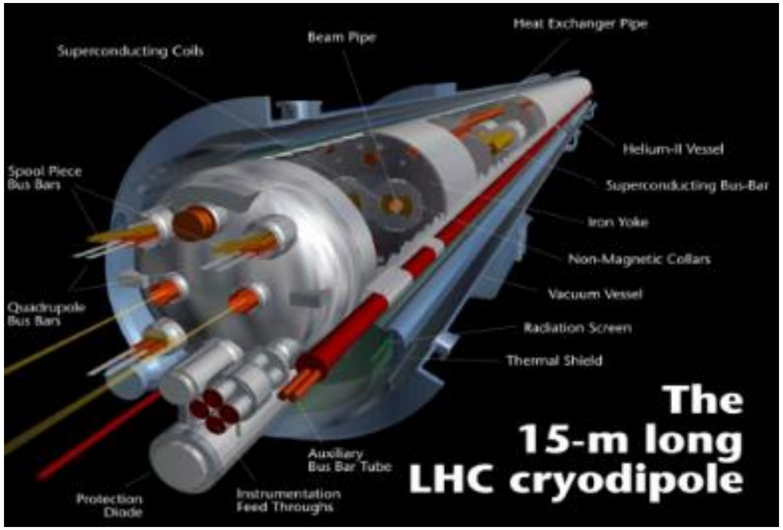
From: CERN-DI-9803026

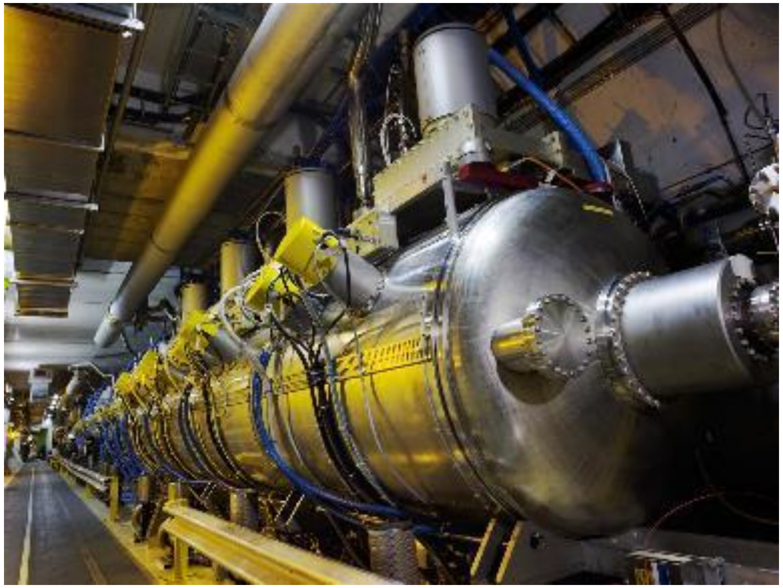


From: http://cms.web.cern.ch/news/cms-detector-design

- 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

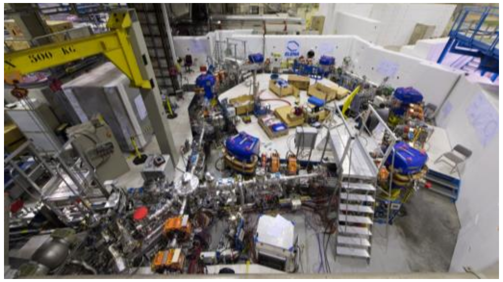




- Helium at different operating temperatures (thermal shields, beam screens, distribution and magnets,…)
- Superconducting (SC) magnets of the LHC ring
- Accelerating SC cavities

Overview of cryogenics at CERN

- North area =>
- SM18
- Antimatter Factory =>
- HIE-Isolde
- Test facilities =>
- Neutrino Platform
- …



Sources: CERN-PHOTO-201509-239, CERN-EX-0606017, CERN-PHOTO-201607-170-3, OPEN-PHO-ACCEL-2016-016-7, CERN-PHOTO-201703-077-4

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

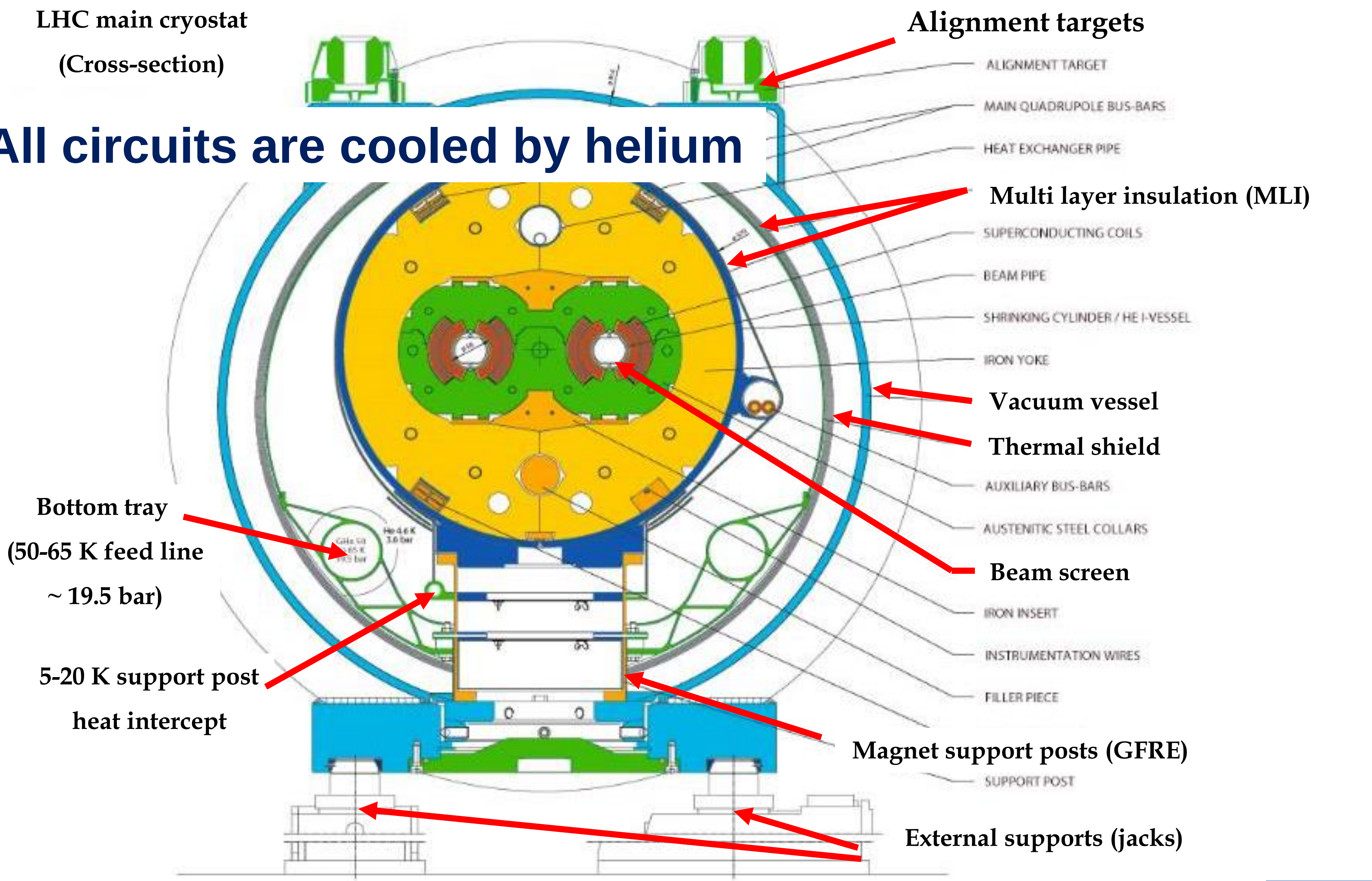
Cryogenics and Superconductivity

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
Cryo-pumping	few K
Cosmic microwave background	2.725 K
Superfluid ^4He	< 2.17 K
Bolometers for cosmic radiation	< 1 K
ADR stages, Bose-Einstein condensates	~ μK

Cryogenic application: Dipole magnets of the LHC

All circuits are cooled by helium



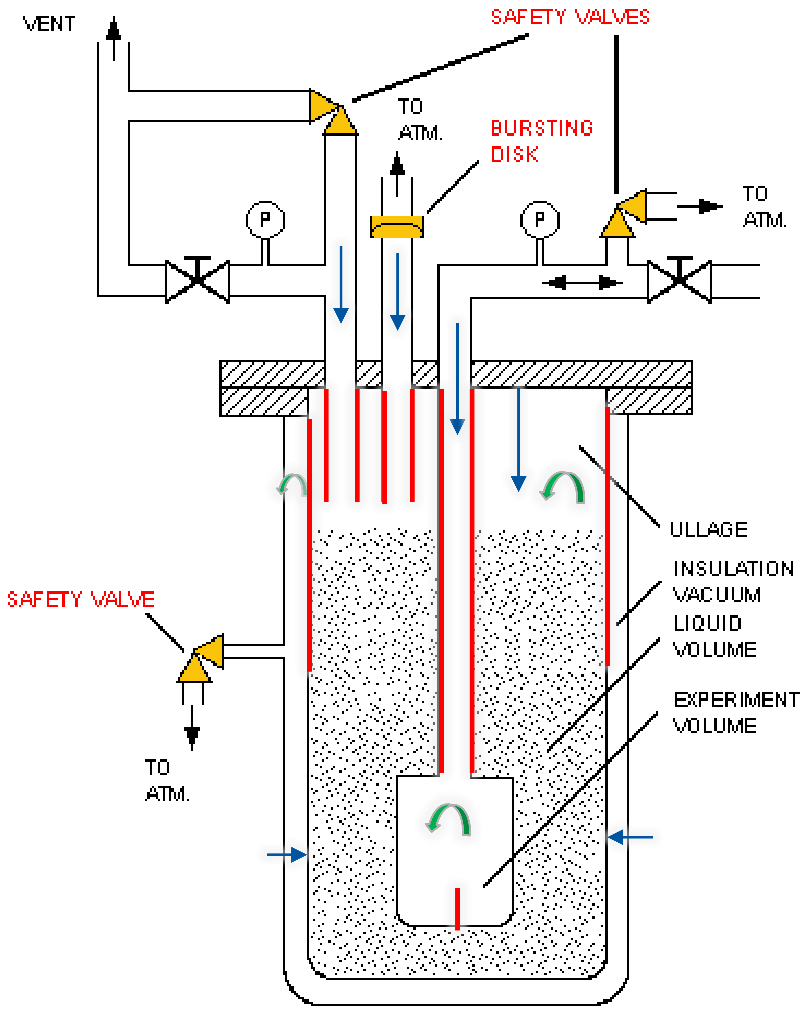
Heat Transfer and Thermal Insulation

Heat transfer: General

- Solid conduction:

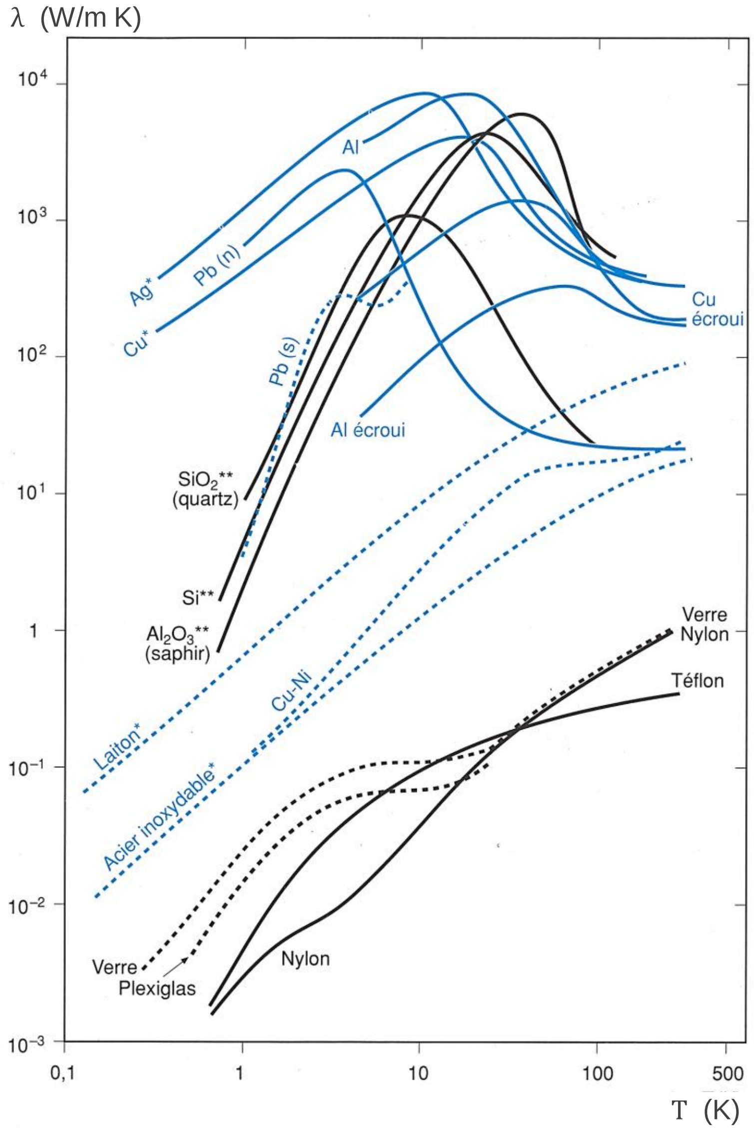
- Thermal radiation:
  (with and without MLI)

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



Source: Edeskuty, Safety in the Handling of Cryogenic Fluids

Thermal conductivity, solid conduction – how to cool?



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

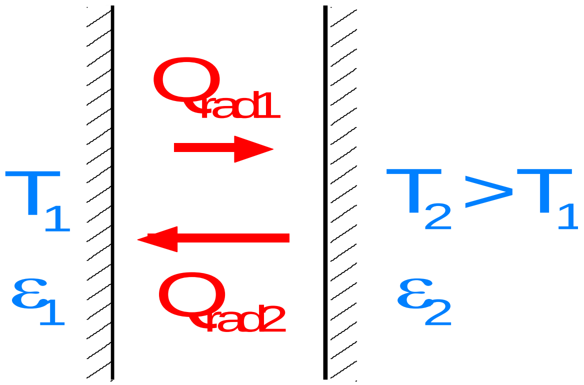
From: Cryogenie, Institut International du Froid, Paris

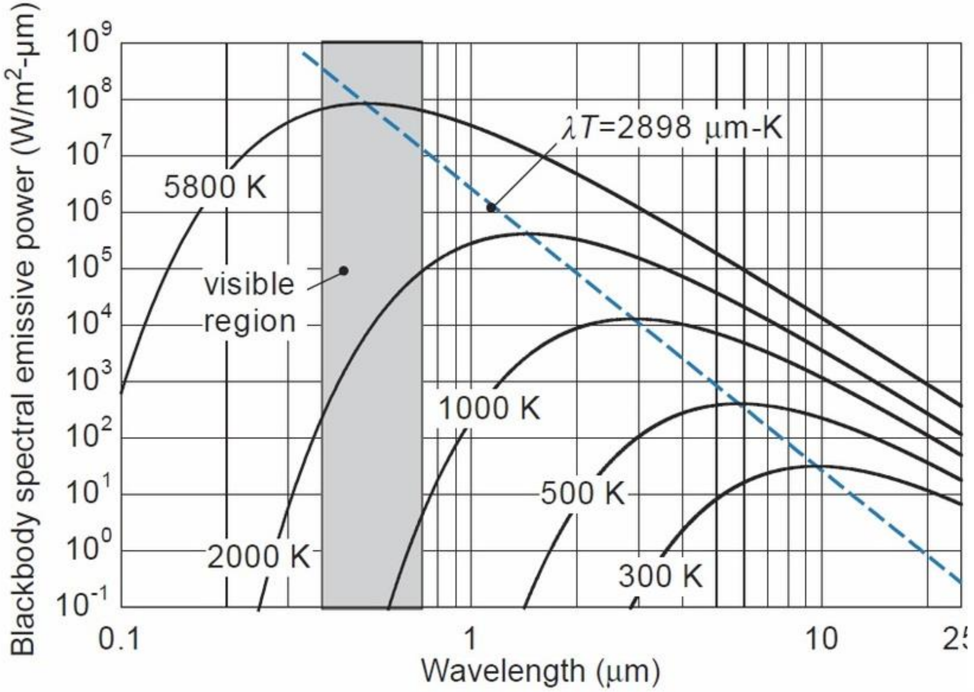
Radiative heat transfer – Black body

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

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

$$\Rightarrow 10\ \mu\mathrm{m} \quad \text{for}\ T = 300\ \mathrm{K}$$





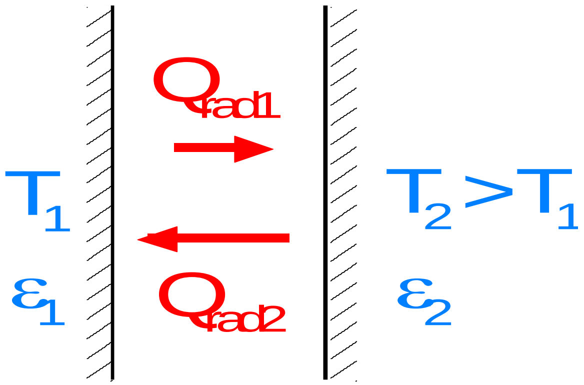
Source: https://www.researchgate.net/figure/Blackbody-spectral-emissive-power-as-a-function-of-wavelength-for-various-values-of_fig4_320298109

Radiative heat transfer – Grey body

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

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

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



- Stefan-Boltzmann's law

Black body $\quad \dot{Q}_{rad} = \sigma A T^4 \quad$ σ = 5.67 x 10^{-8} W/(m^2 K^4) (Stefan-Boltzmann's constant)

- "Grey" body $\quad \dot{Q}_{rad} = \varepsilon \sigma A T^4 \quad$ ε - emissivity of surface

- "Grey" surfaces at T_1 and T_2 $\quad \dot{Q}_{rad} = E \sigma A (T_1^4 - T_2^4) \quad$ 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

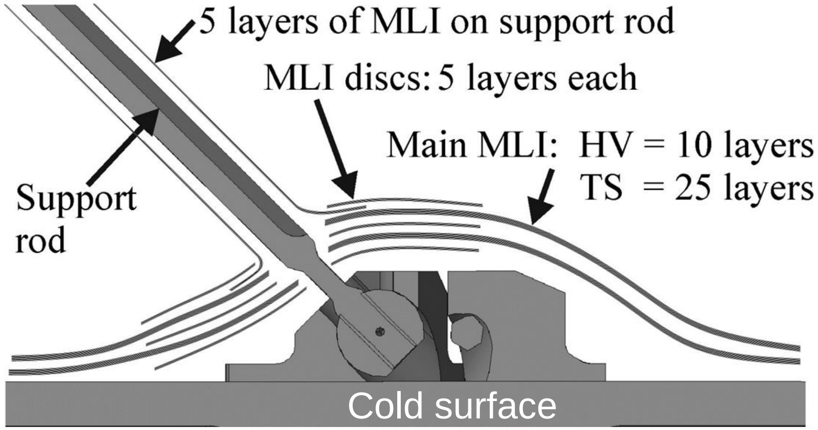
From: Ph. Lebrun, CAS School on Vacuum in Accelerators, 2006

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



Solutions for penetrations and support structures

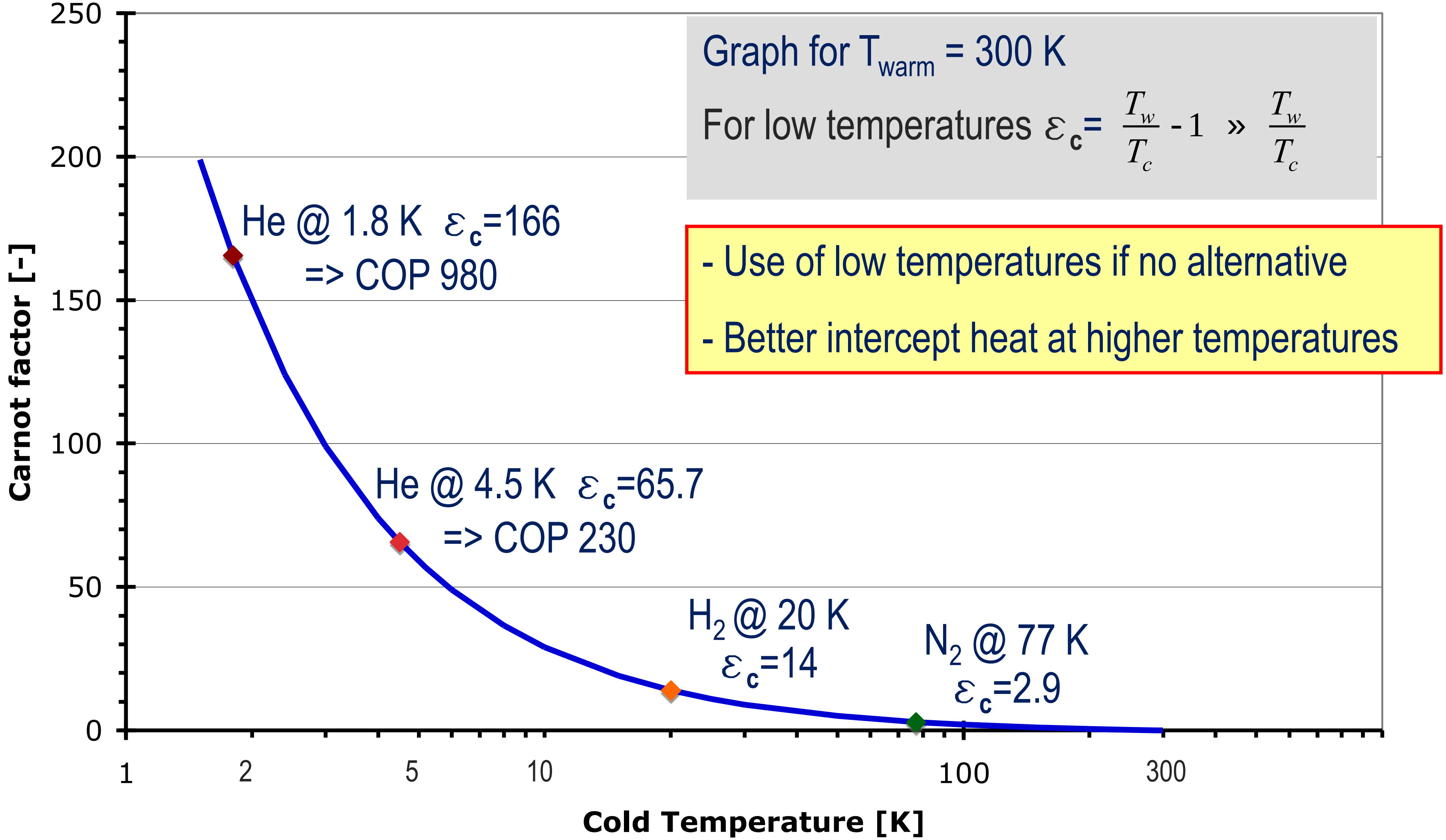
Large surface application

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

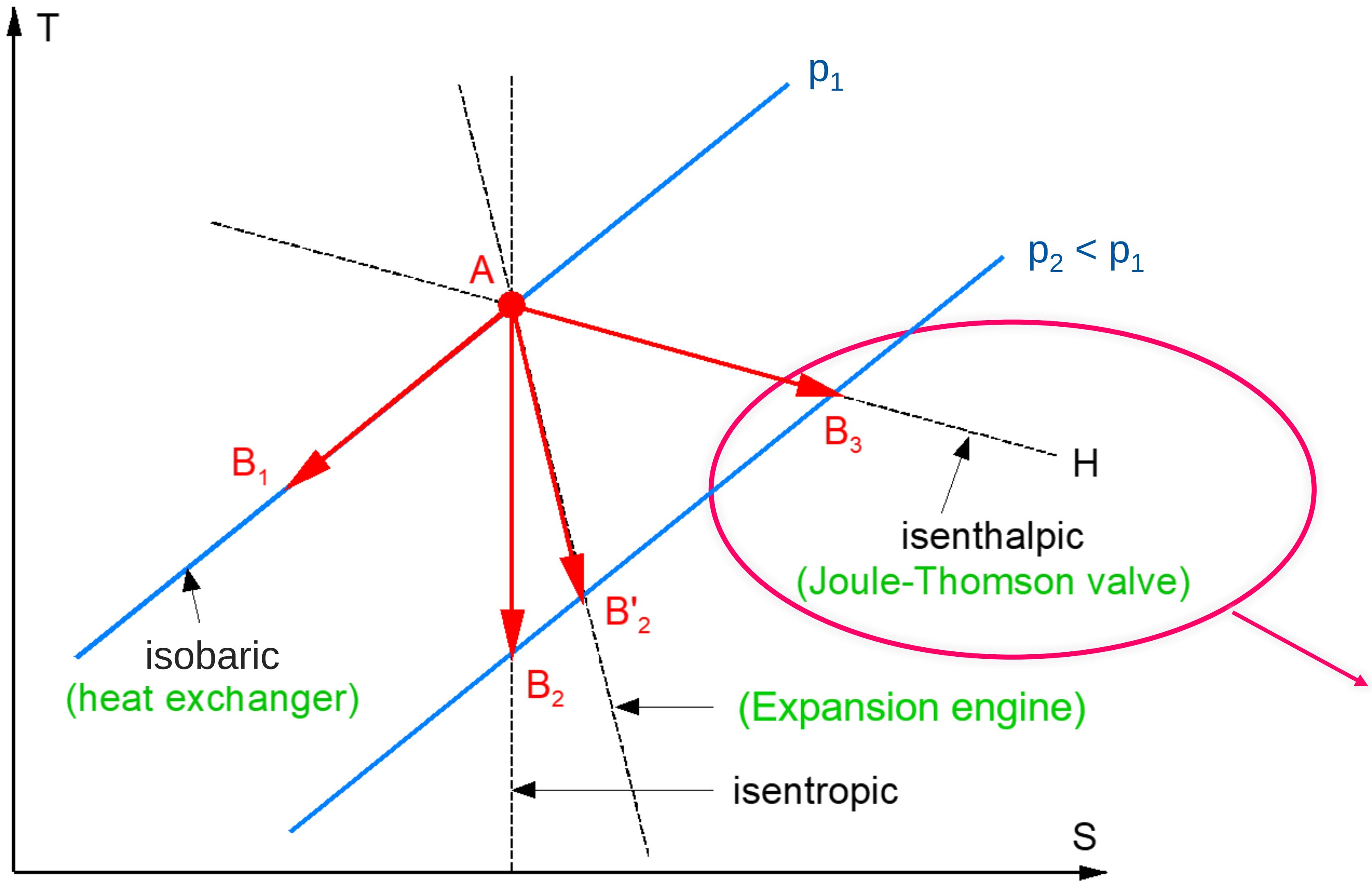
Configuration	W/m^2
Black-body radiation from 293 K	420
Black-body radiation from 80 K	2.3

Refrigeration and Liquefaction

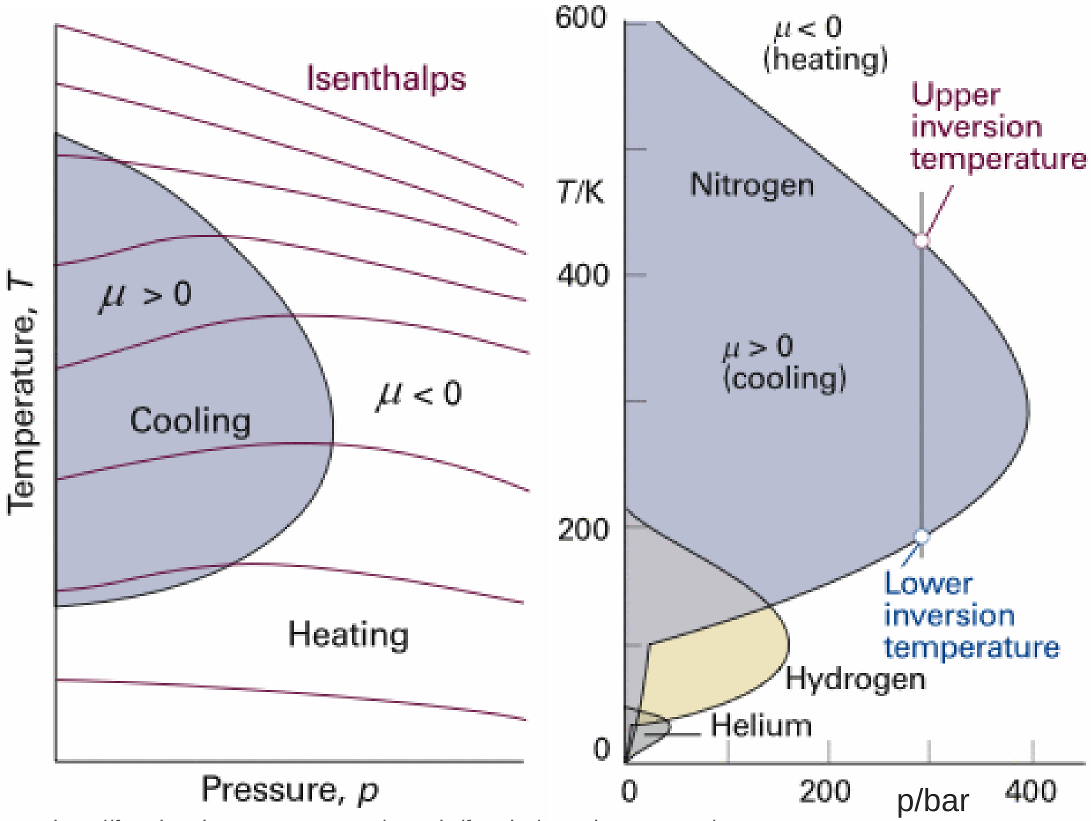
Thermodynamics of cryogenic refrigeration



Elementary cooling processes in a T-s diagram

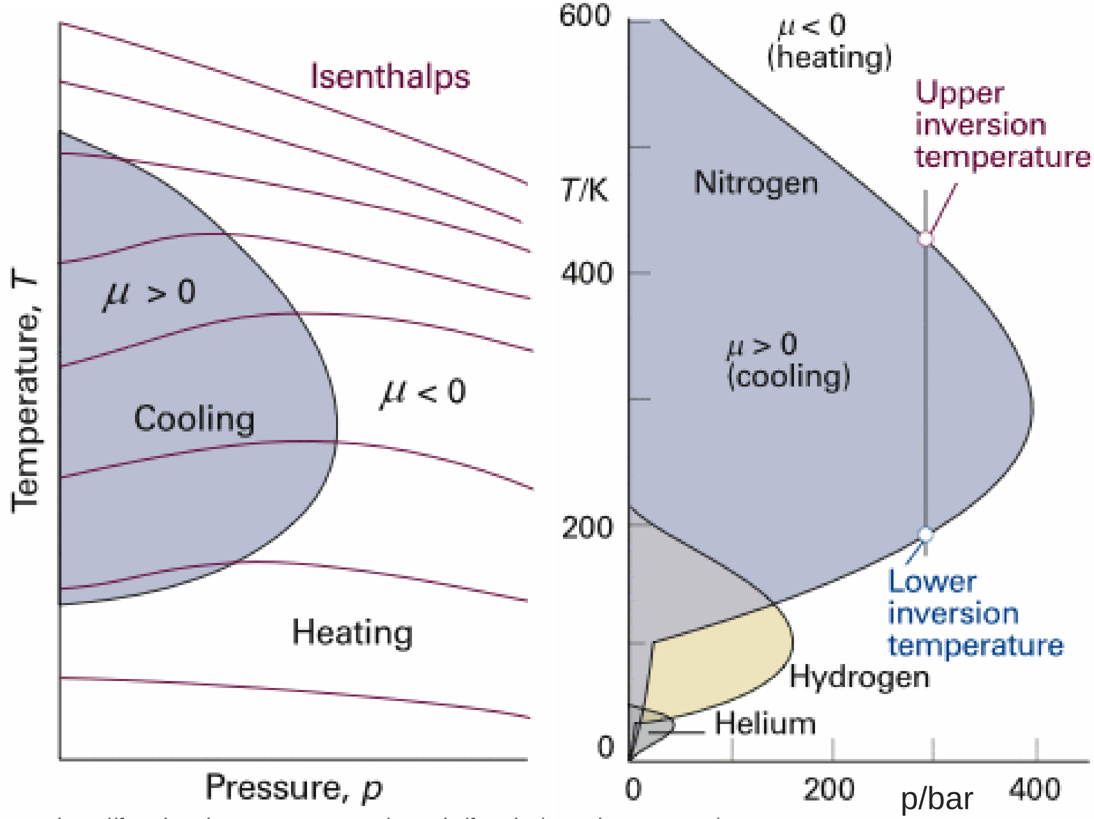


Maximum Joule-Thomson inversion temperatures



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

Maximum Joule-Thomson inversion temperatures



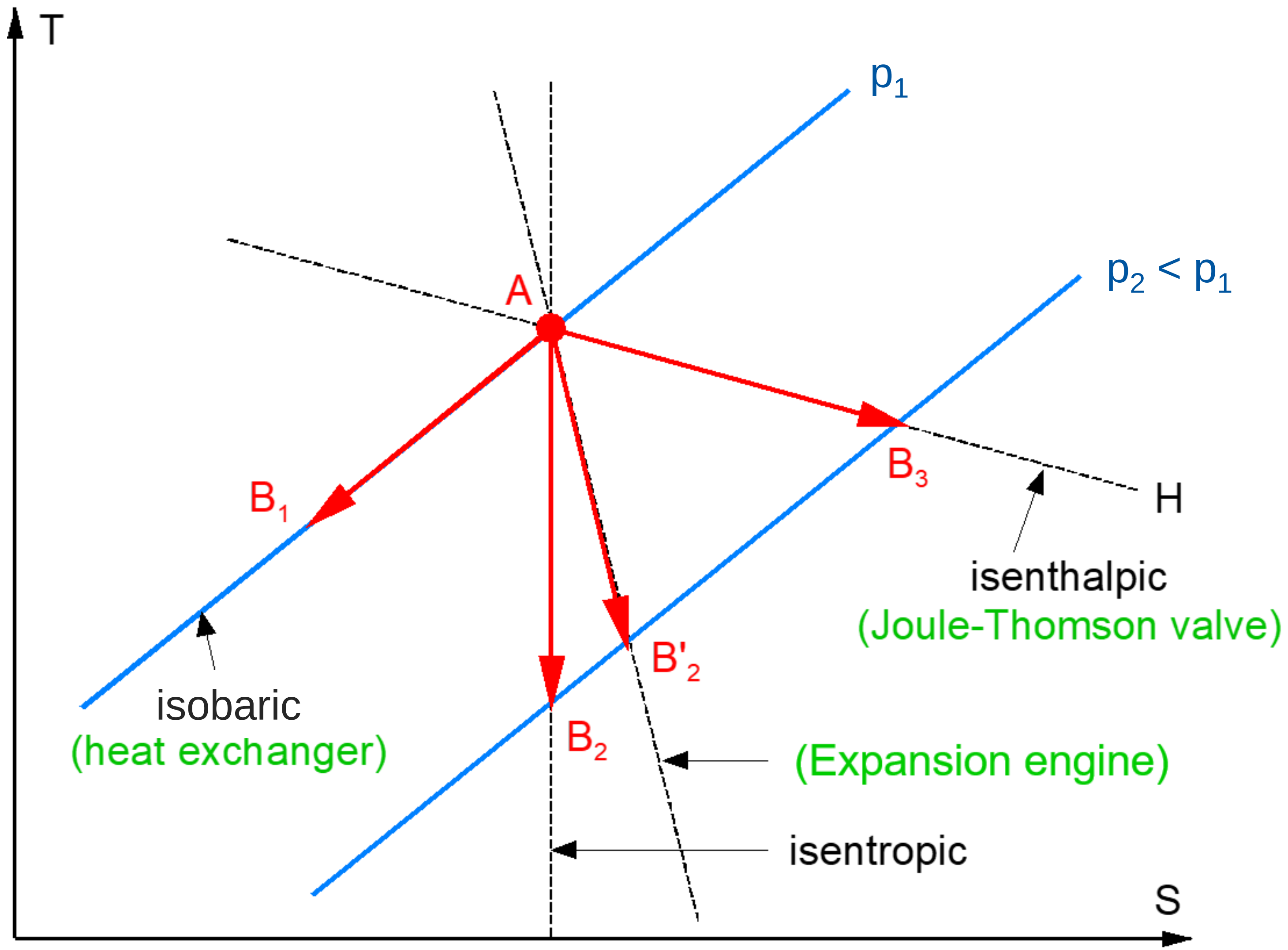
Source: http://faculty.chem.queensu.ca/people/faculty/mombourquette/Chem221/3_FirstLaw/ChangeFunctions.asp

Cryogen	Max. inversion temperature [K]
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Argon	723

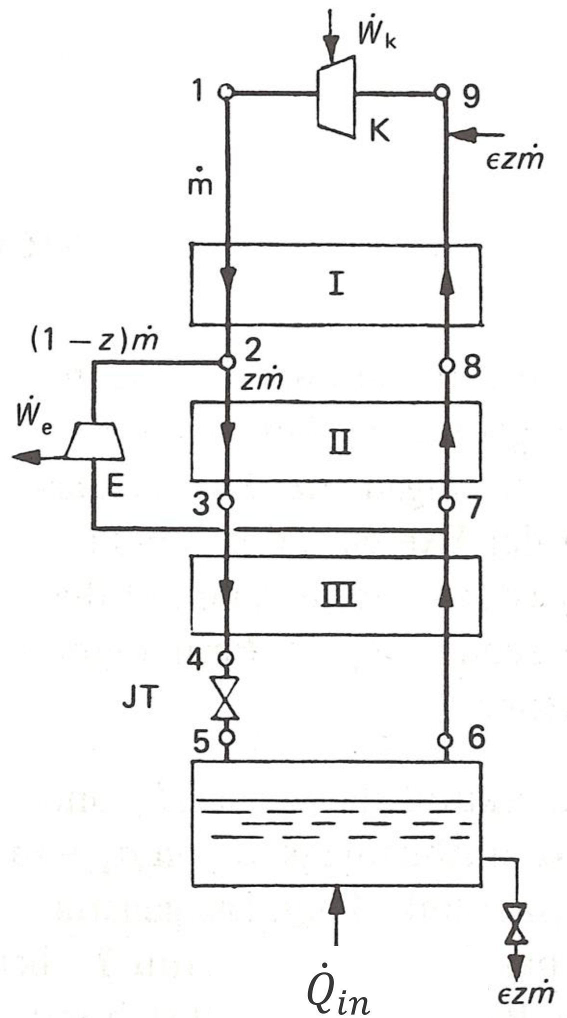
Source: Refprop® NIST

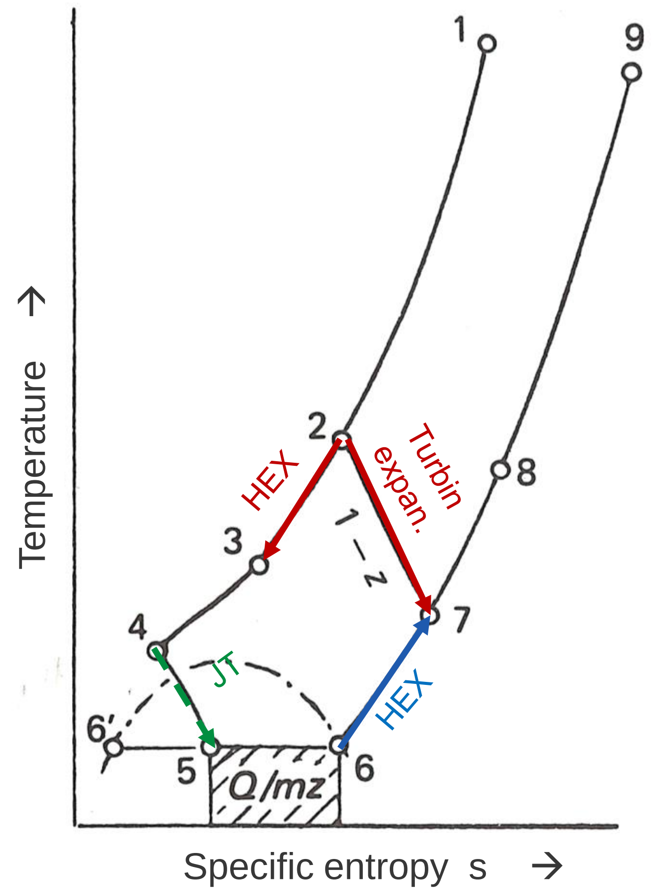
- Air can be cooled down and liquefied by J-T expansion from room temperature,
- Helium and hydrogen need precooling down to below the inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

Combining all three processes in a cryoplant



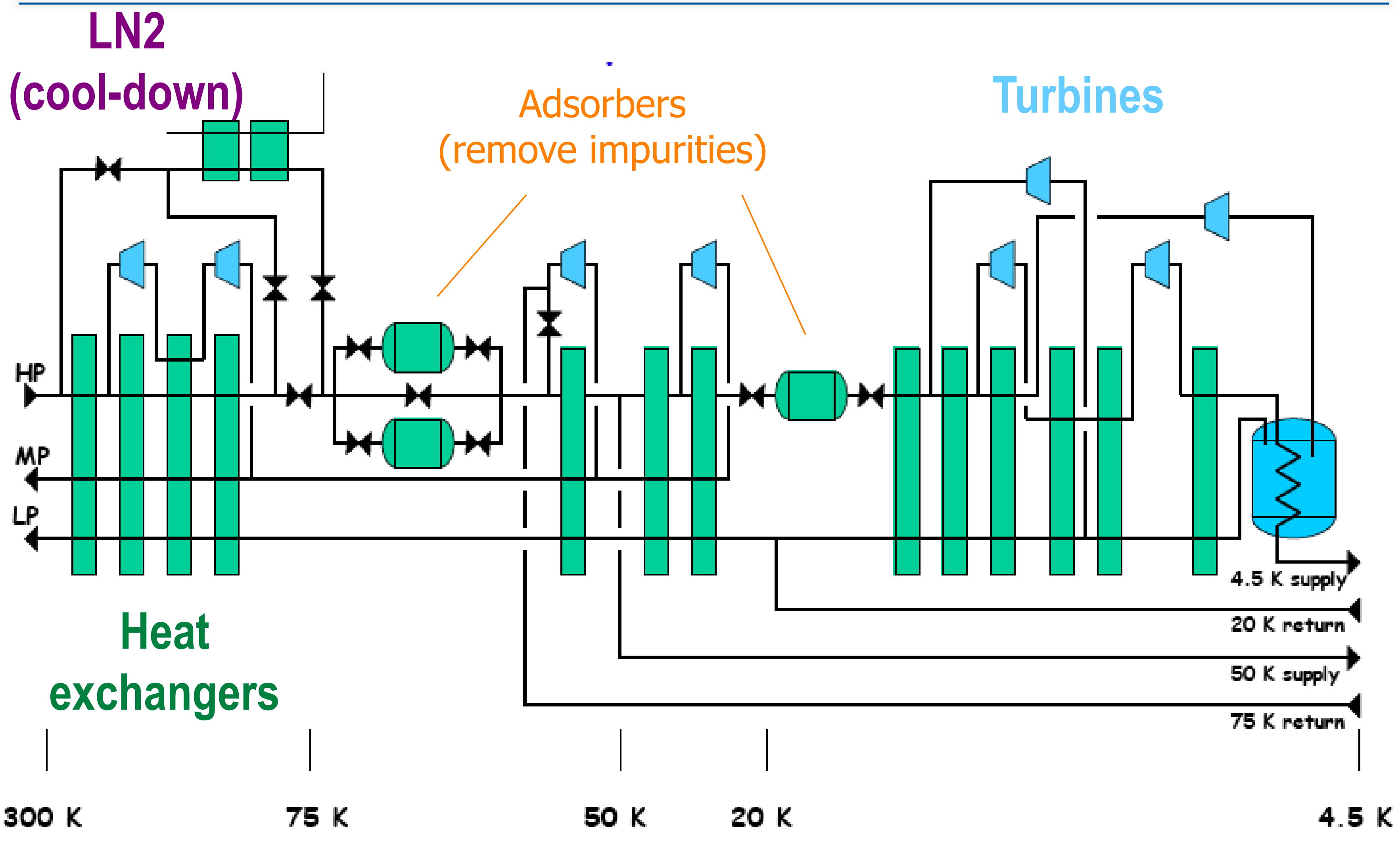
Claude cycle (Turbo Brayton + JT)



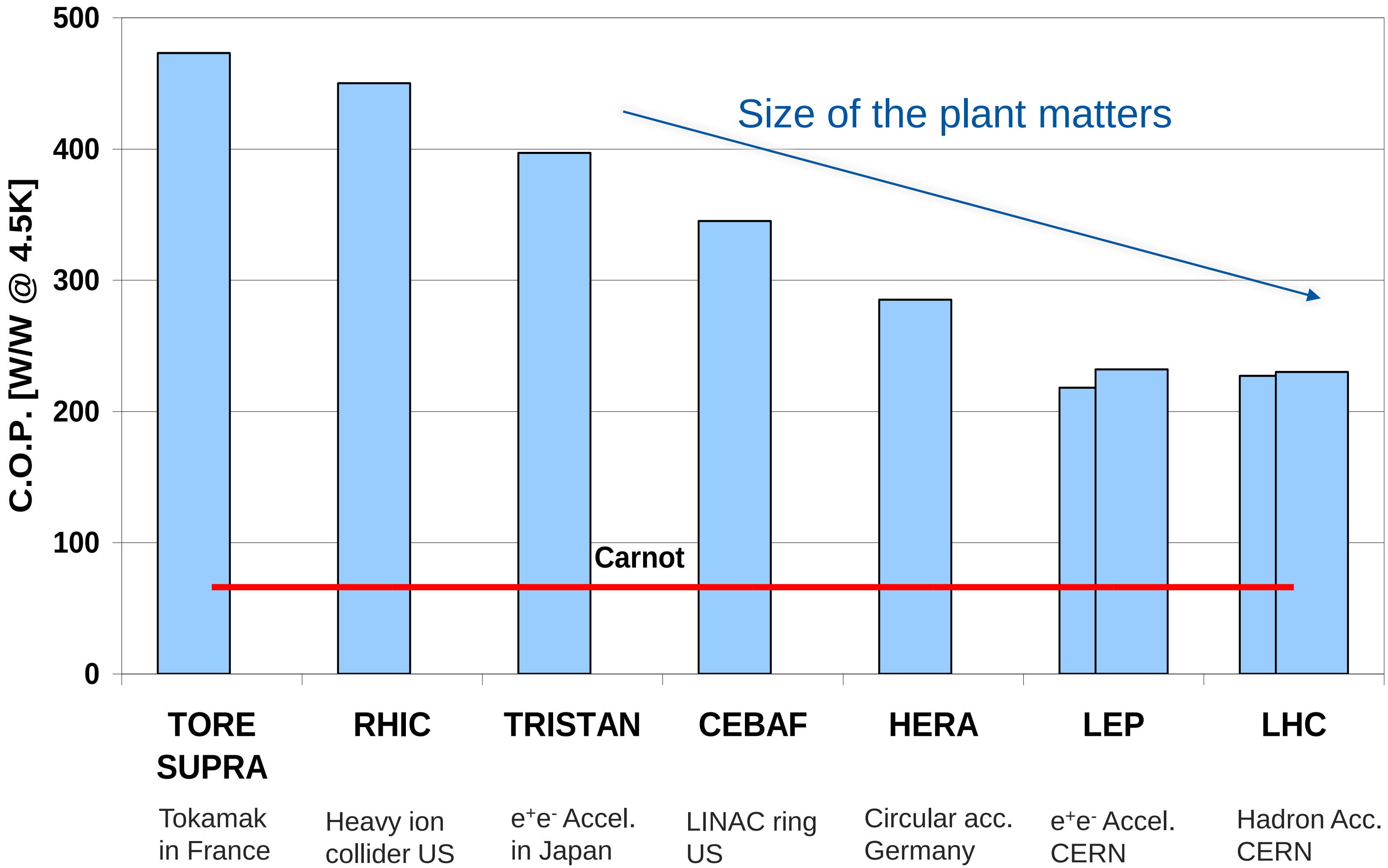


Source: Frey, Haefer, Tieftemperaturtechnologie, VDI Verlag 1981, ISBN 3-18-400503-8, adapted.

Process diagram, LHC refrigerator 18 kW @ 4.5 K



COP of large cryogenic helium refrigerators

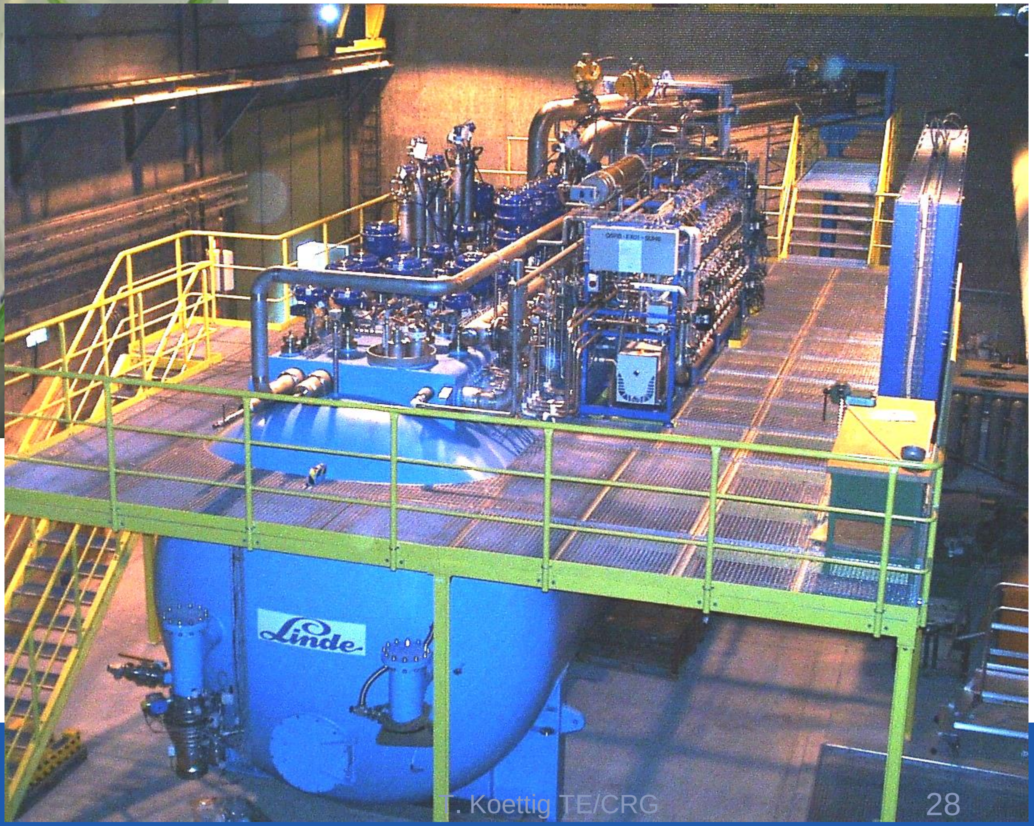


LHC 18 kW @ 4.5 K helium cryoplants

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

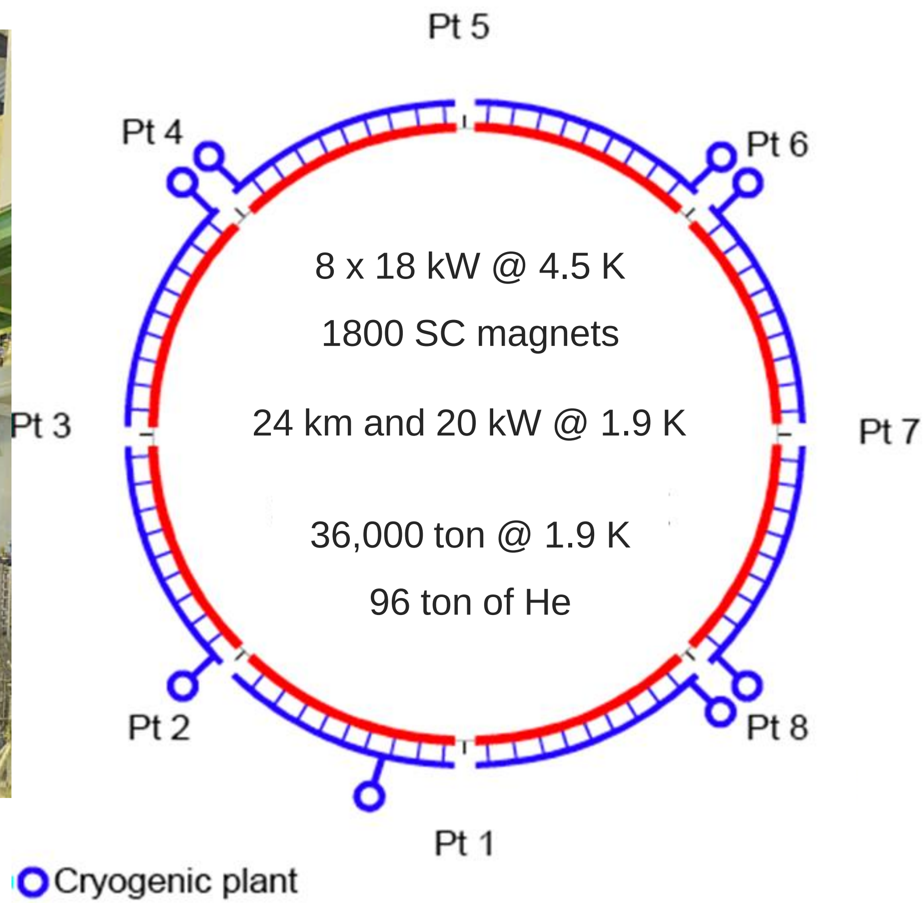
4 MW compressor power
COP 220-230 W_{el}/W @ 4.5 K

Air Liquide



Linde

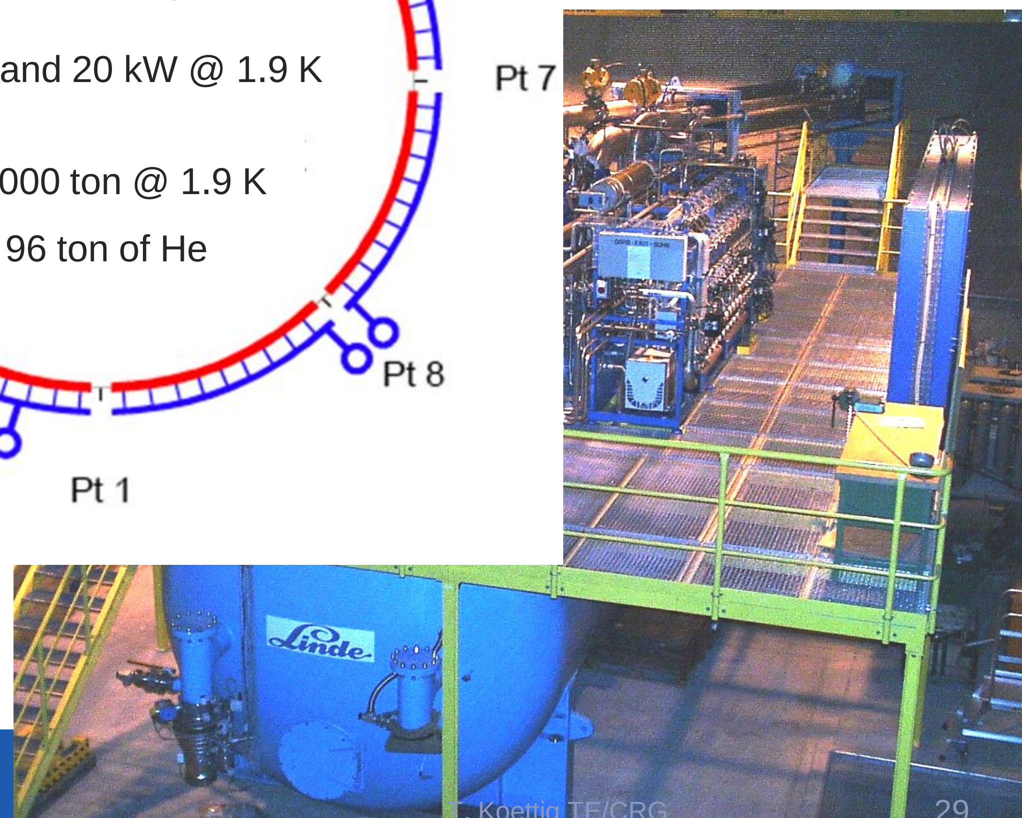
LHC 18 kW @ 4.5 K helium cryoplants



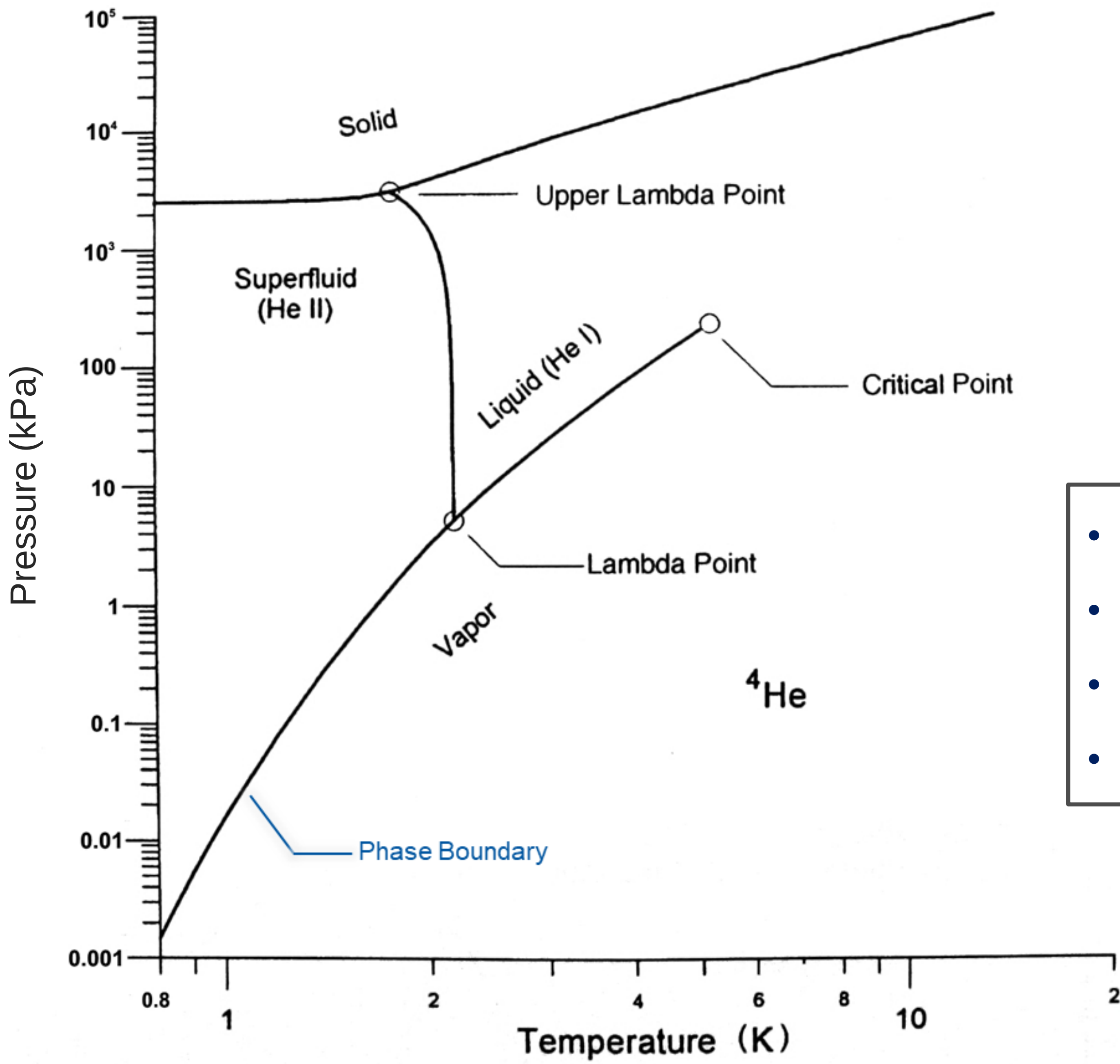
K to 75 K
5 K to 20 K
faction
ressor power
30 W/W @ 4.5 K

Air Liquide

Linde



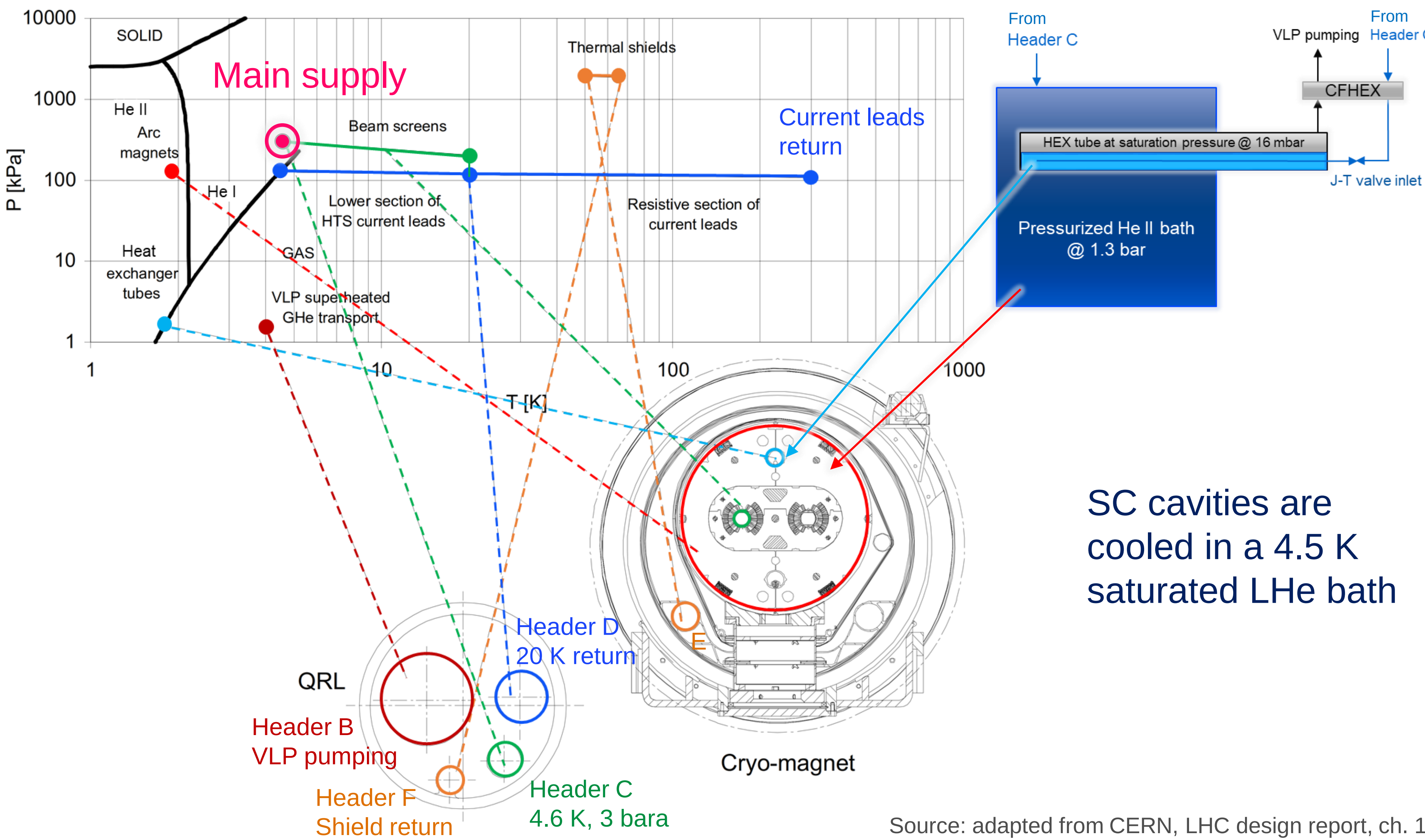
^{4}He phase diagram



- Helium has no triple point
- Solid He only above 25 bar
- Lambda line => He I / He II separ.
- He II with very special properties

From Weisend, Handbook of Cryogenic Engineering, 1984.

LHC Cooling scheme



SC cavities are cooled in a 4.5 K saturated LHe bath

Source: adapted from CERN, LHC design report, ch. 11

Cryogenic Fluid Properties

He I and He II

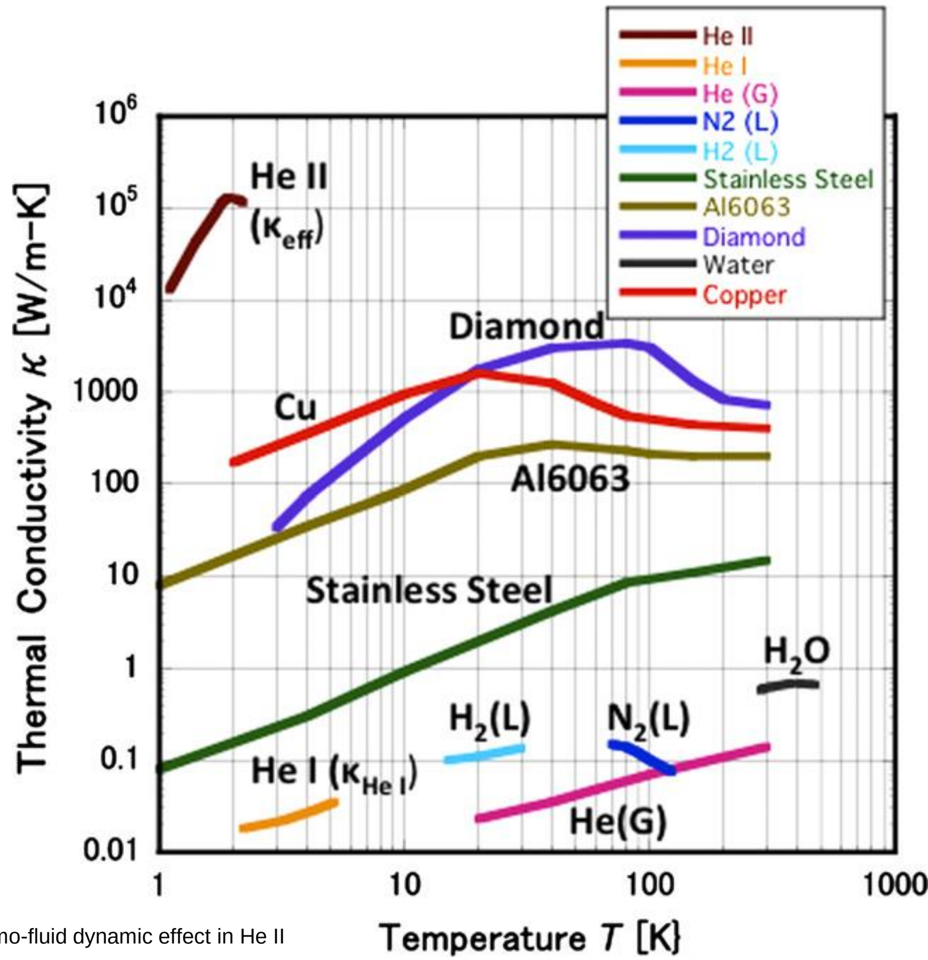
From He I to He II

Normal fluid helium => He I

- Like a standard fluid: viscosity etc.

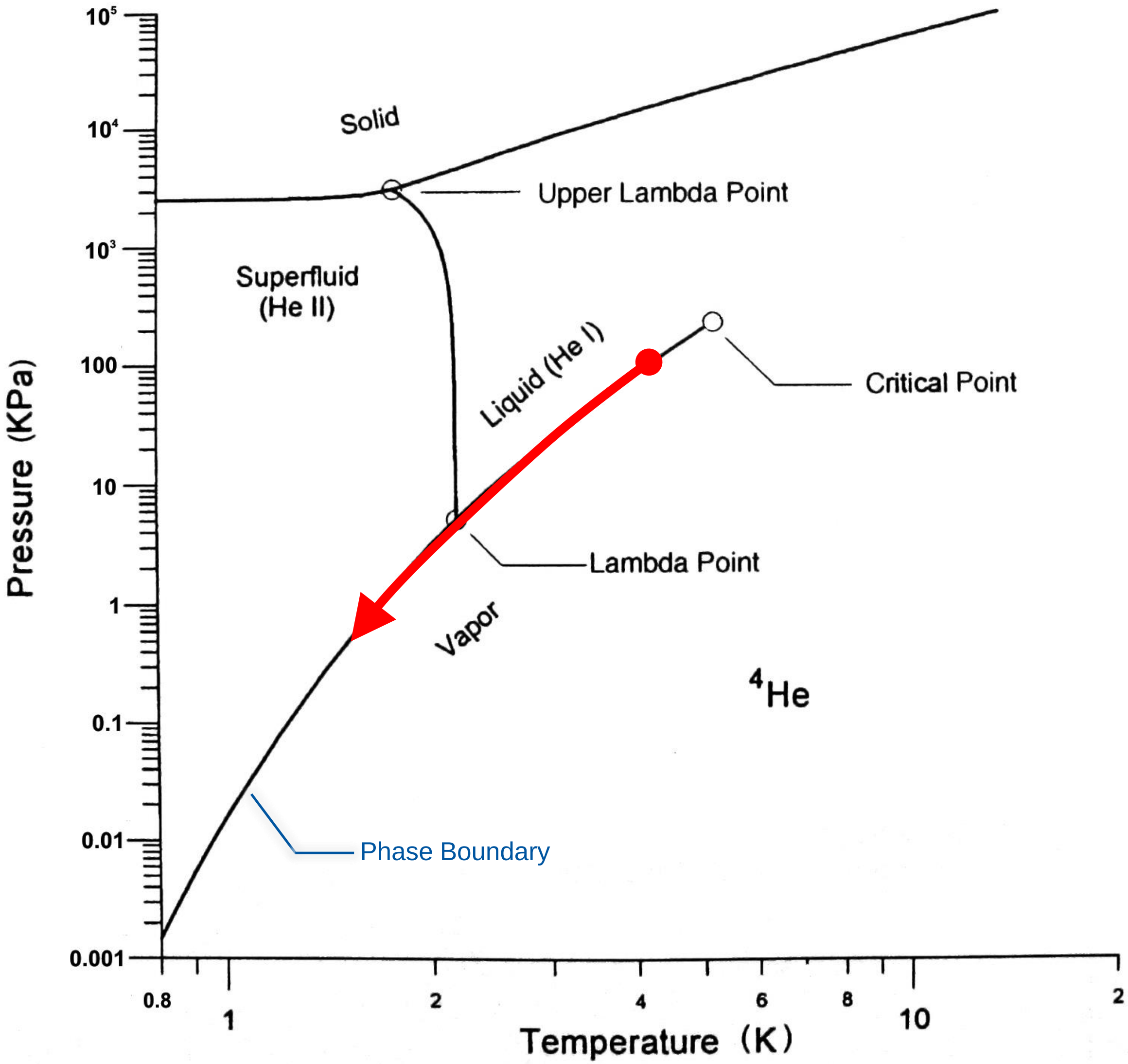
Superfluid helium => He II

- 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

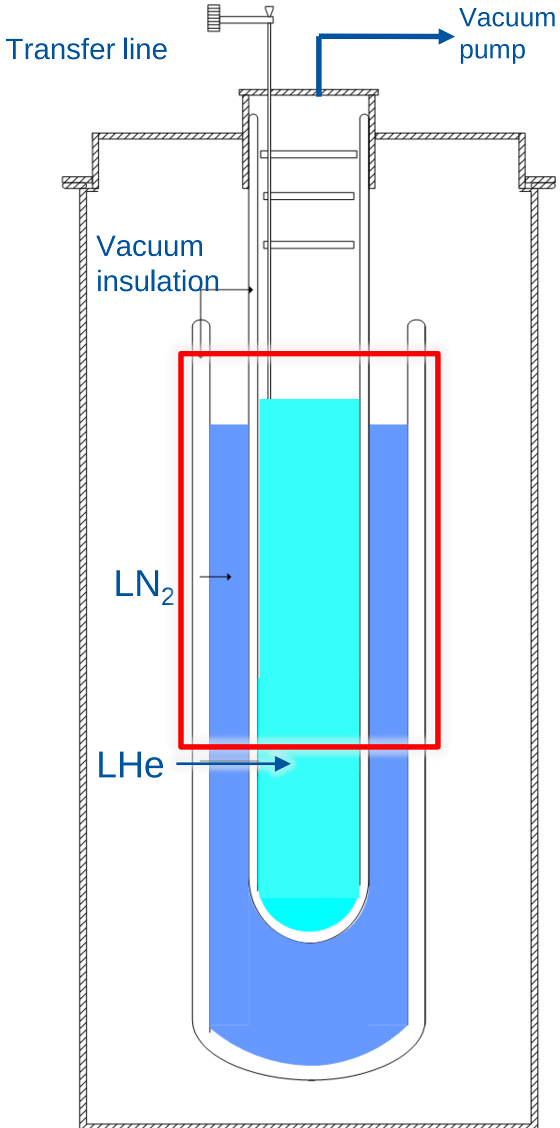


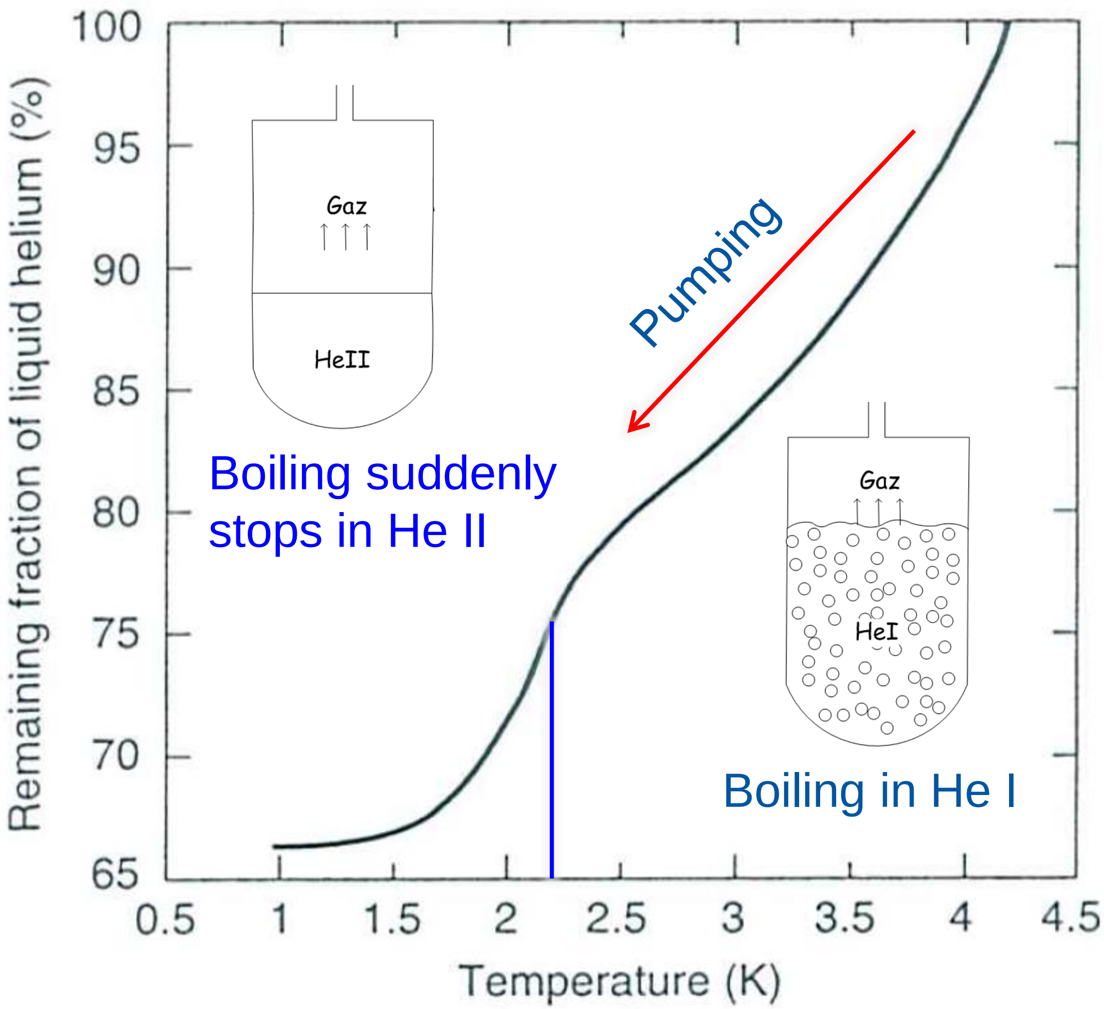
$T_\lambda \approx 2.1768$ K @

$p_\lambda \approx 50.41$ mbar

From Weisend, Handbook of Cryogenic Engineering, 1984.

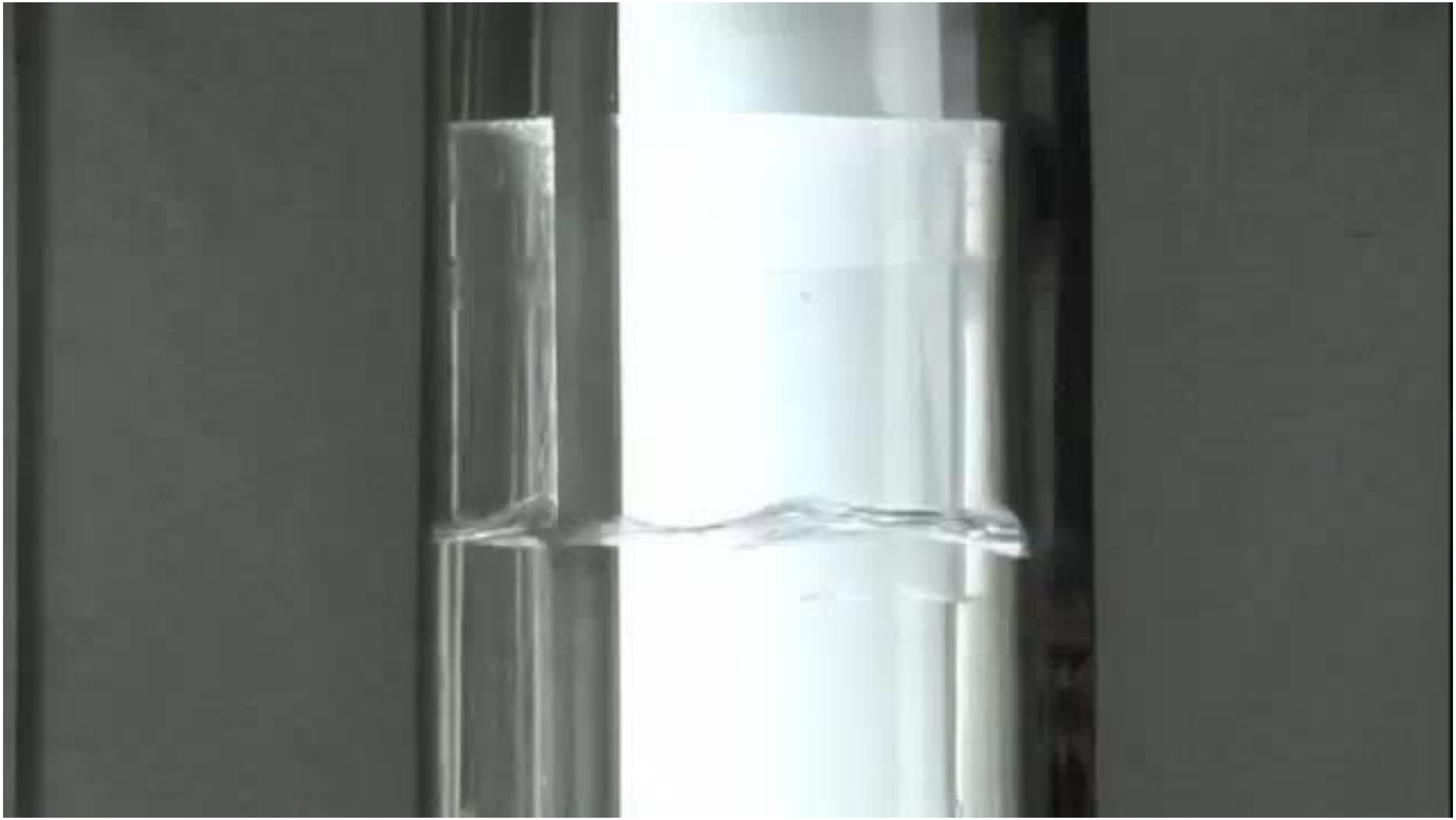
Glass cryostat set-up





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

Boiling effects during cooldown / Pumping on the He vapour



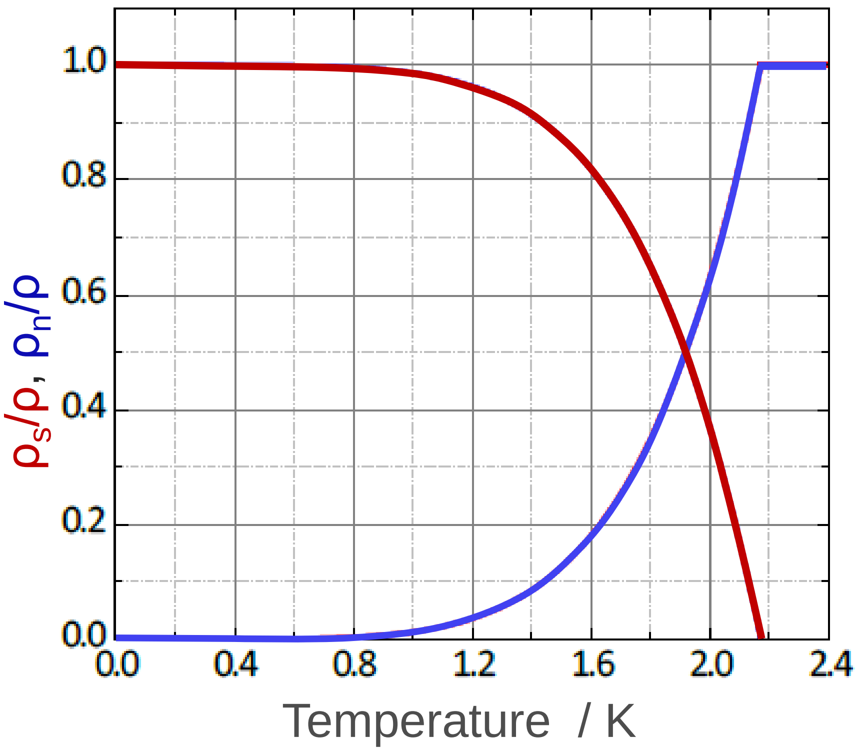
How to explain that unique behaviour ?

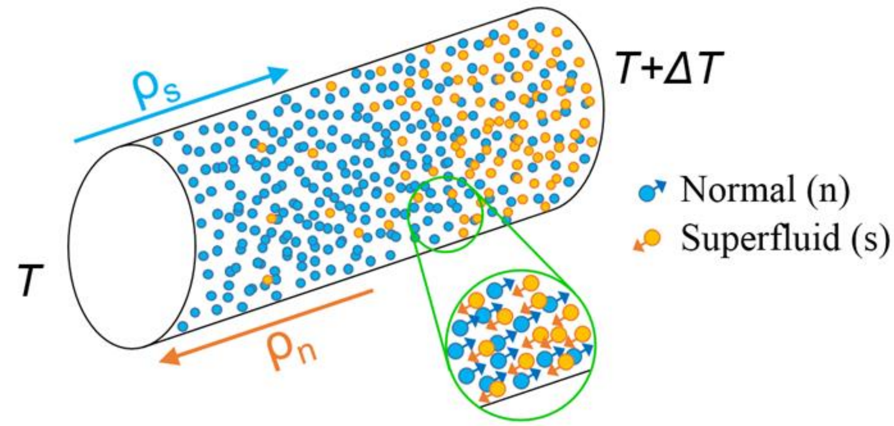
Two fluid model of L. Tisza:

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:

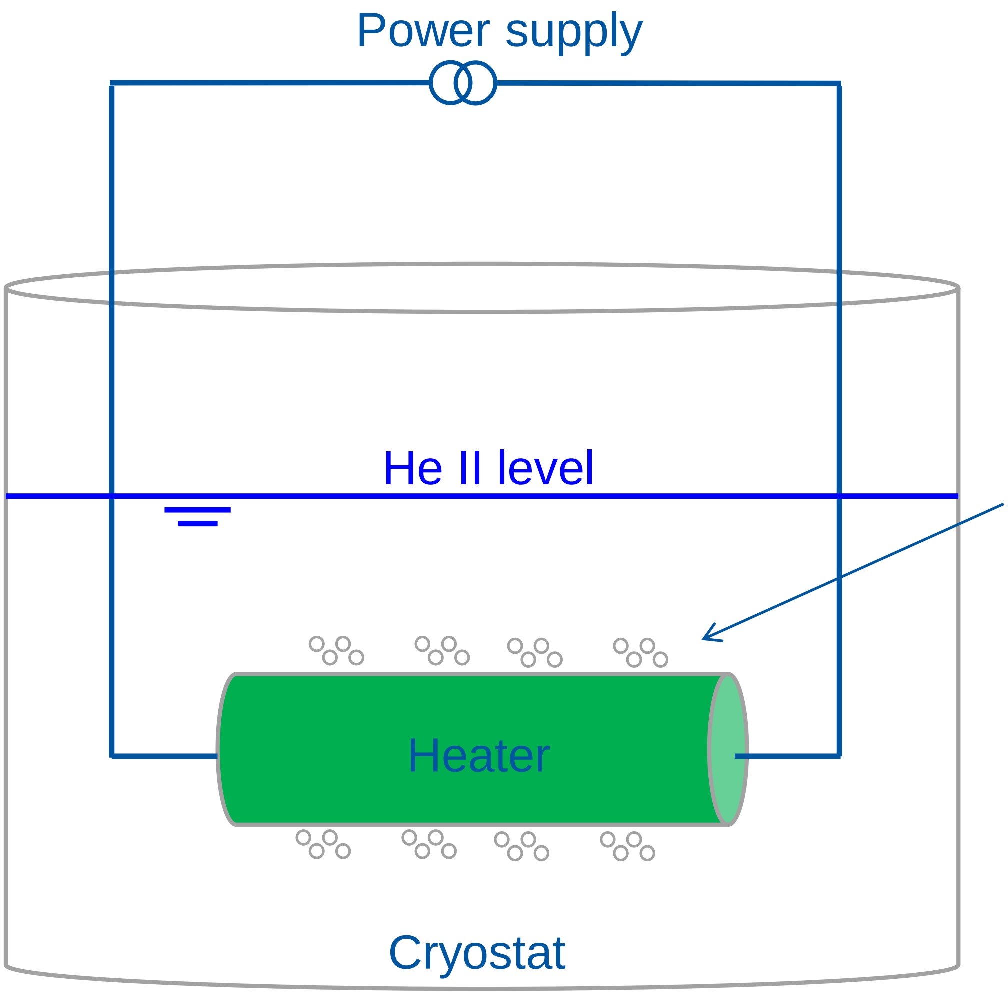
- carries total entropy: $S_n = S$
- finite viscosity: $\eta_n = \eta_n$

He II in practice

Superleak below T_λ

1963 movie 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)

$k \downarrow$ and $\eta \uparrow$

Formation of vapor bubbles at the surface of the heater

In He II re-condensation of the vapor

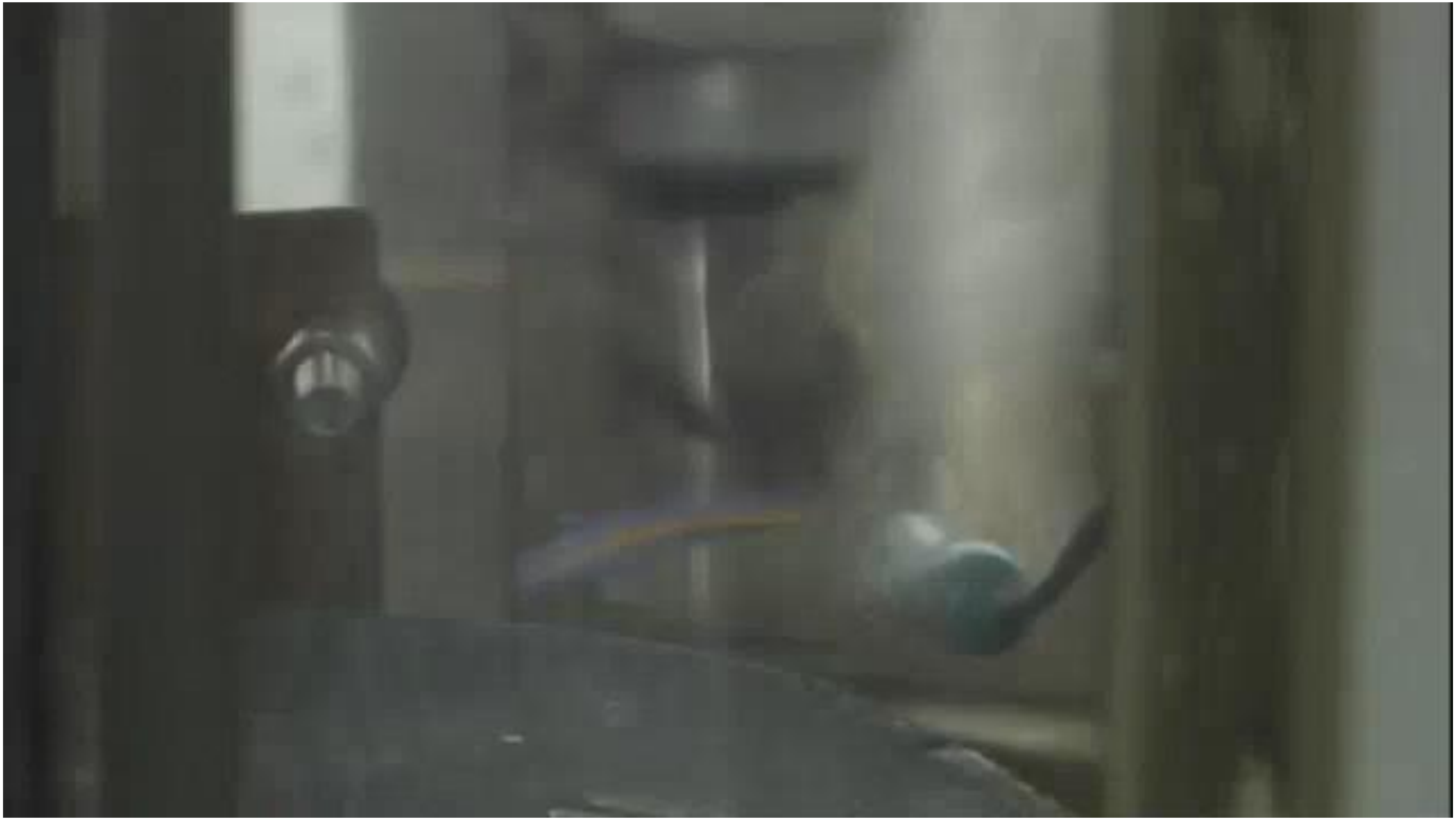
Surface tension let the bubbles implode

Implosion speed exceeds v_1

Shock wave => cavitation

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

LHe I cooling ($T>T_\lambda$)



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, project schedule …
- I could only recommend that demonstrated experience is evaluated and adapted to specific requirements you may have.

Some references

- K. Mendelssohn, *The quest for absolute zero*, McGraw Hill (1966)
- R.B. Scott, *Cryogenic engineering*, Van Nostrand, Princeton (1959)
- G.G. Haselden, *Cryogenic fundamentals*, Academic Press, London (1971)
- R.A. Barron, *Cryogenic systems*, Oxford University Press, New York (1985)
- B.A. Hands, *Cryogenic engineering*, Academic Press, London (1986)
- S.W. van Sciver, *Helium cryogenics*, Plenum Press, New York (1986)
- K.D. Timmerhaus & T.M. Flynn, *Cryogenic process engineering*, Plenum Press, New York (1989)
- Proceedings of *CAS School on Superconductivity and Cryogenics for Particle Accelerators and Detectors*, Erice (2002)
  - U. Wagner, *Refrigeration*
  - 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

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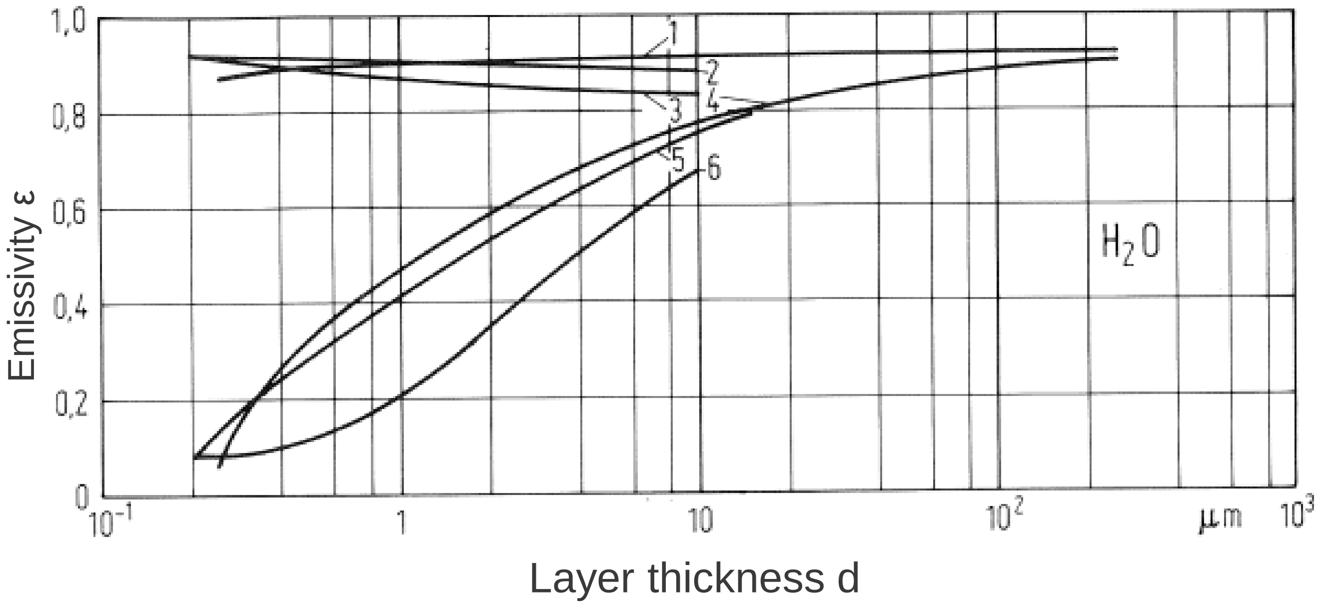
Spare slides

Emissivity of technical materials at low temperatures

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



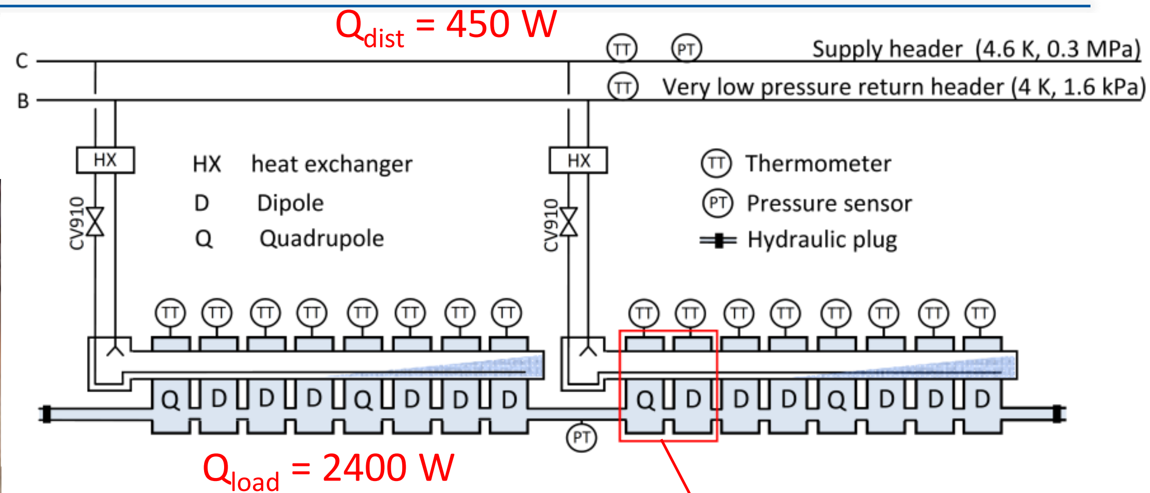
Source: Haefer, Kryovakuumtechnik, 1981

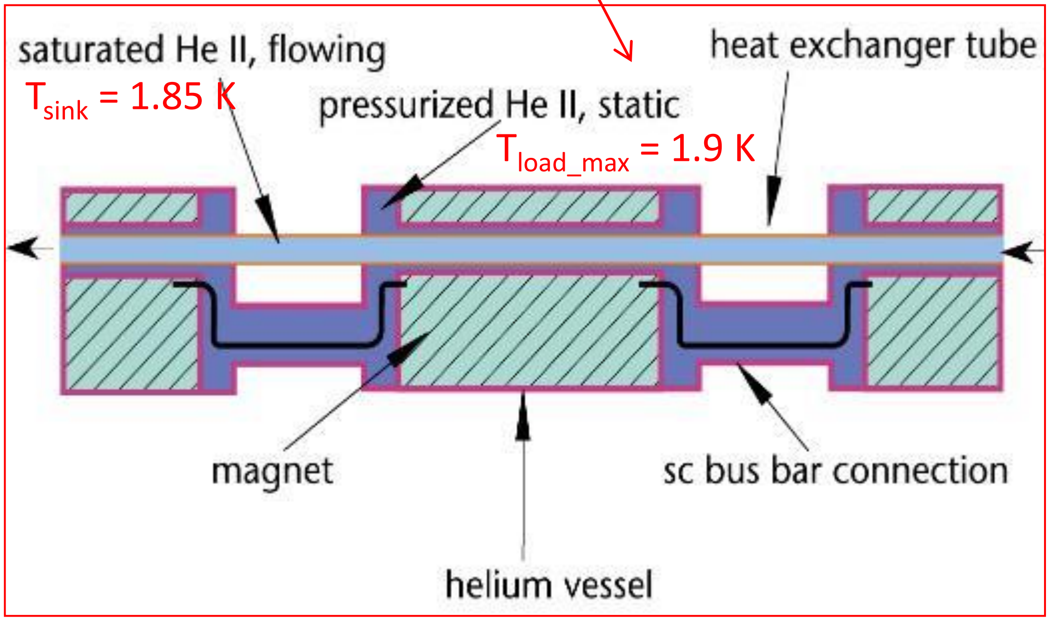
	Cold surface, 77 K	Gas inlet
1	Al + Cat-a-Lac	Uniform over time, 0.06 Pa
2	Ni + Black Velvet 101-C10/3M	Sporadic
3	Ni + Black Velvet 101-C10/3M	Uniform over time, 0.1 Pa
4	Al, polished, ε = 0.07	Uniform over time, 0.06 Pa
5	Ni, polished	Sporadic
6	Ni, polished	Uniform over time, 0.1 Pa

LHC cryogenic distribution scheme - QRL

Pressurized/saturated He II

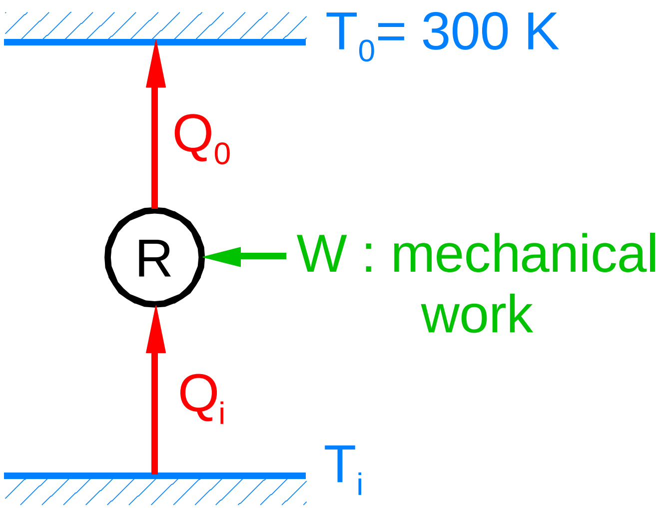
37’500 tons at 1.9 K





Source: Ph. Lebrun, Cooling with Superfluid Helium

Thermodynamics of cryogenic refrigeration



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

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

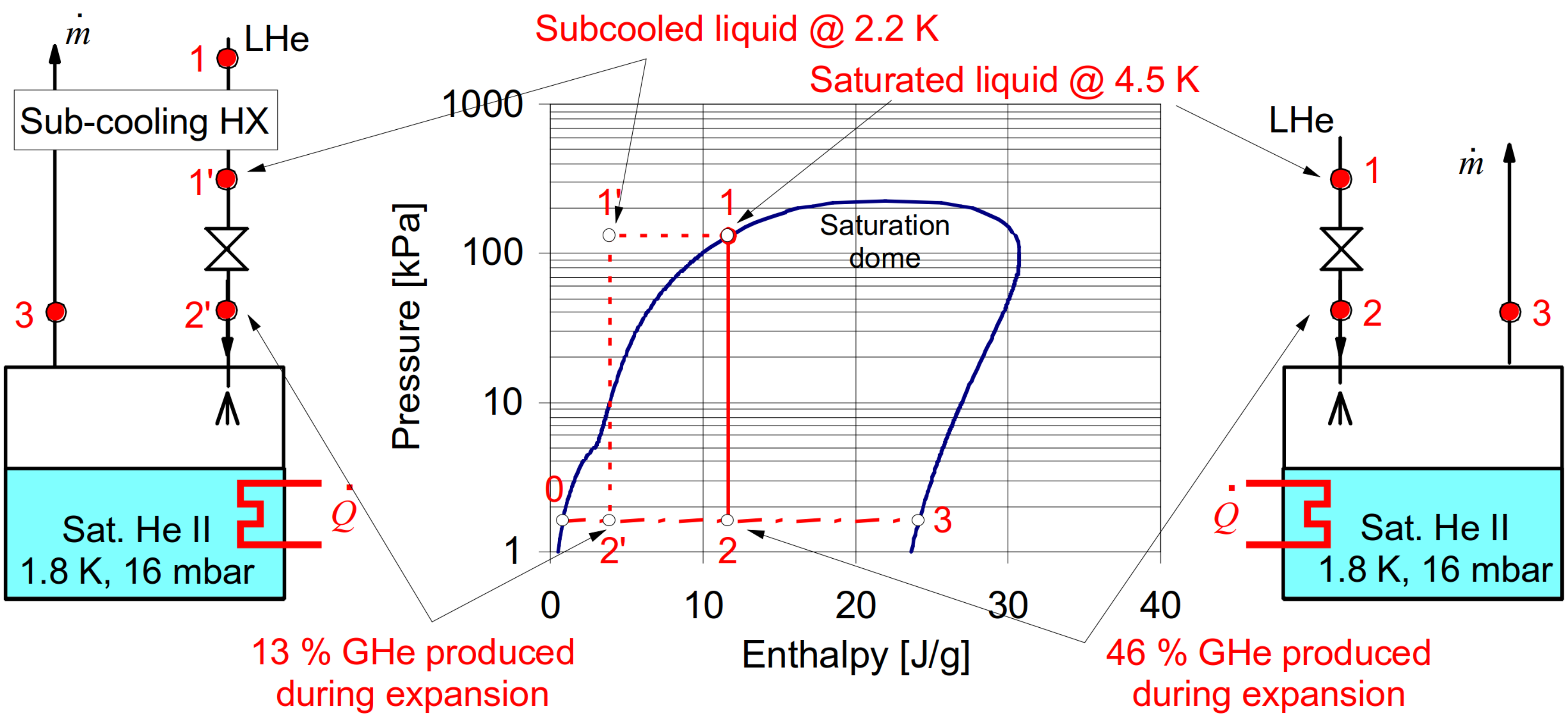
(= for reversible process)

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

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

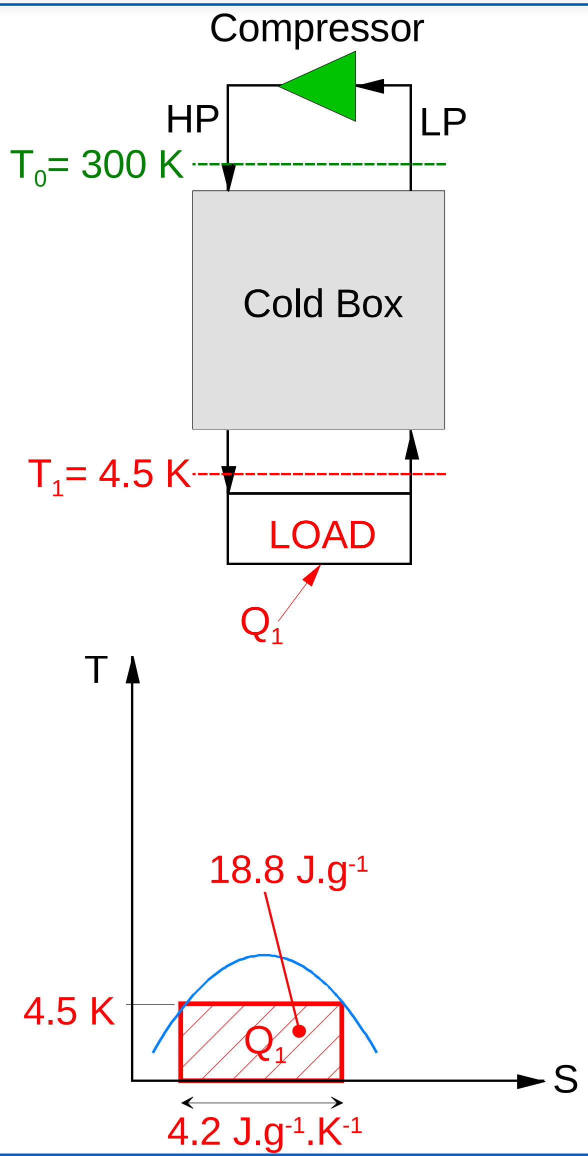
2 $W \geq Q_i \cdot \boxed{\left(\dfrac{T_0}{T_i} - 1 \right)}$ Carnot factor

The effectiveness of J-T expansion

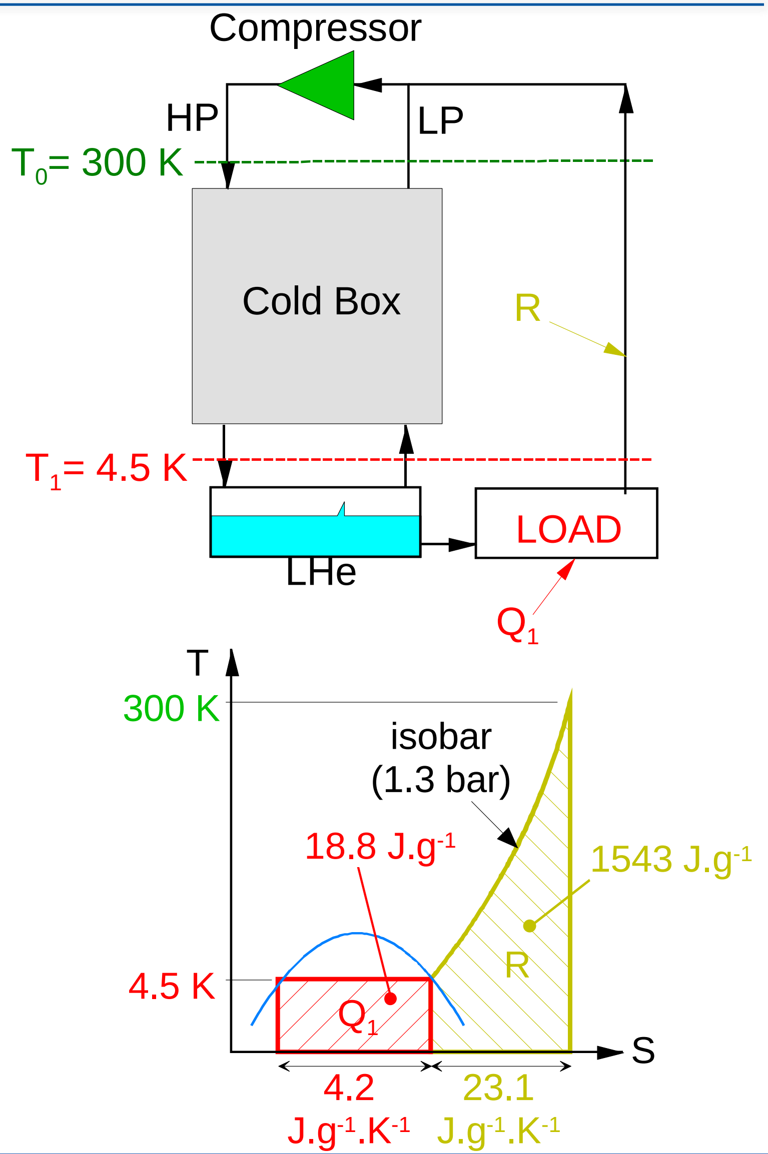


Source: Ph. Lebrun, Cooling with Superfluid Helium

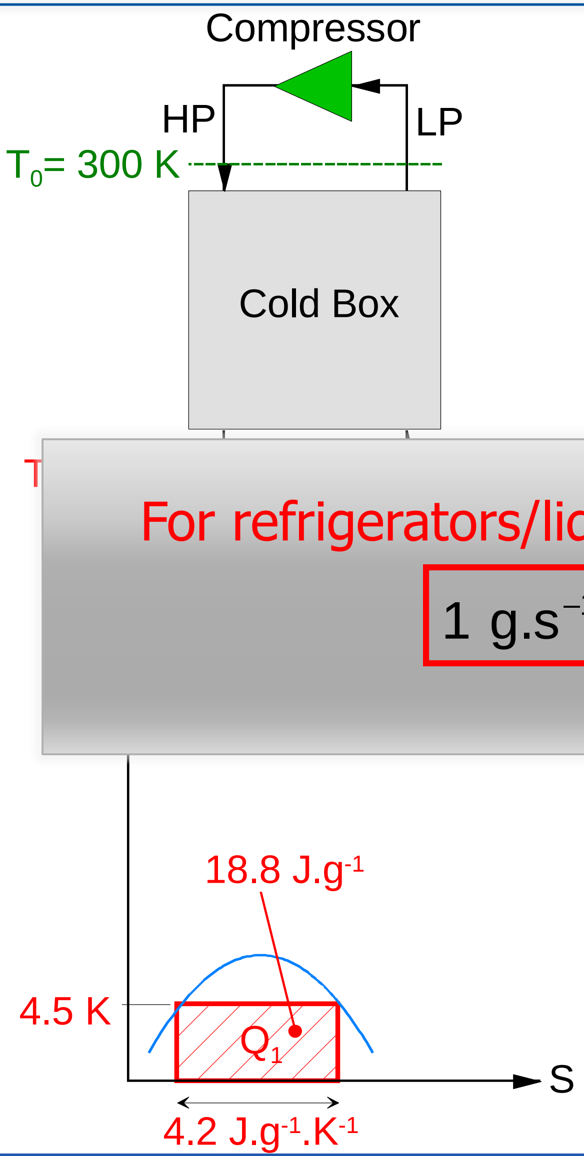
Refrigerator



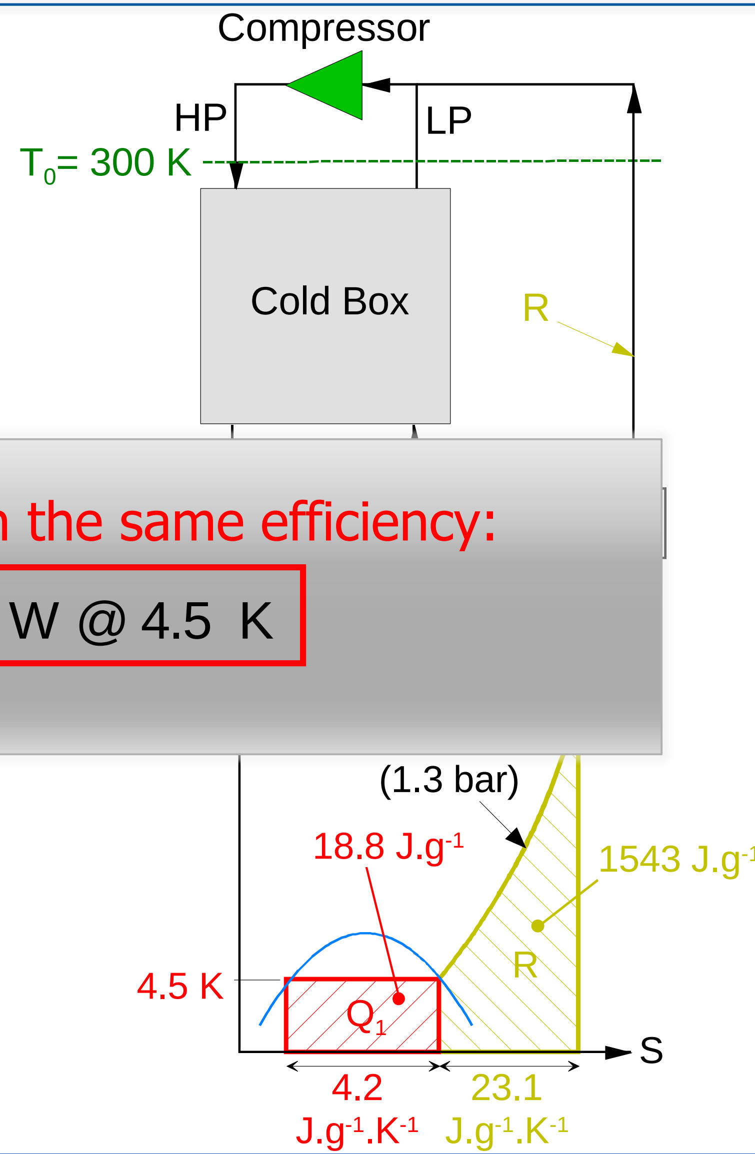
Liquefier



Refrigerator



Liquefier



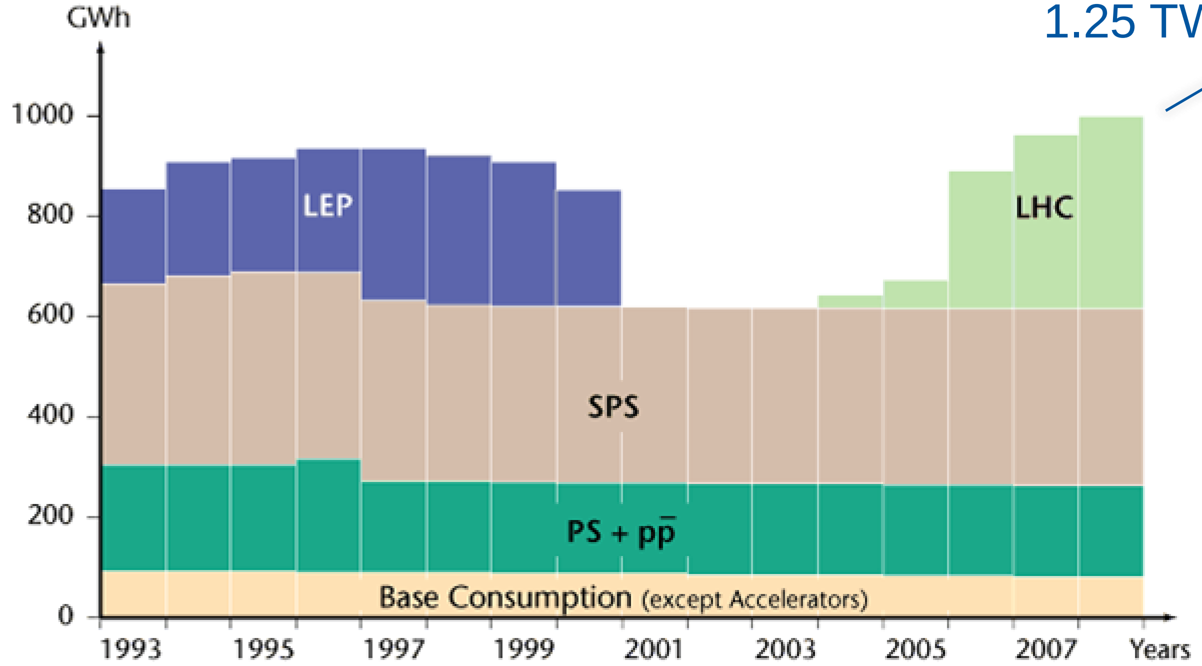
For refrigerators/liquefiers with the same efficiency:

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

Energy consumption CERN, LHC and Cryo

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

1.25 TWh in 2018



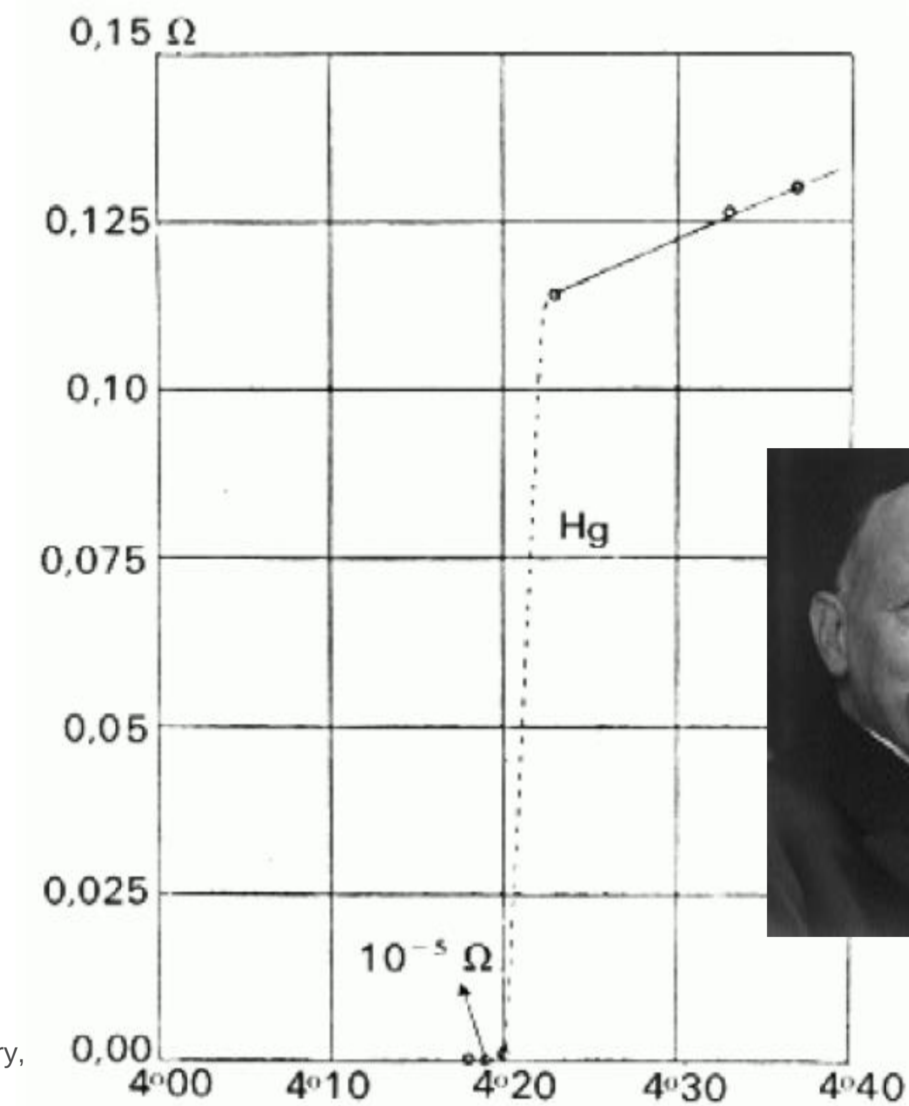
Source: https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.energy_consumption

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

Superconductivity

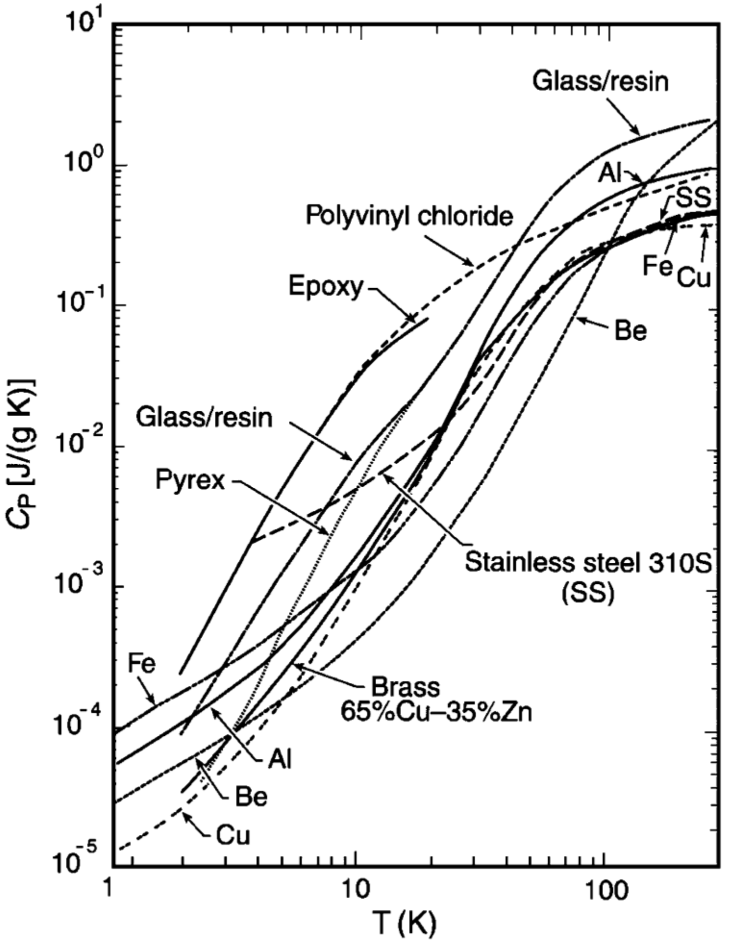
- H. Kamerlingh Onnes
- Liquefied helium in 1909 at 4.2 K with 60 g He inventory
- Observed in 1911 for the first time superconductivity of mercury
- Nobel prize 1913



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

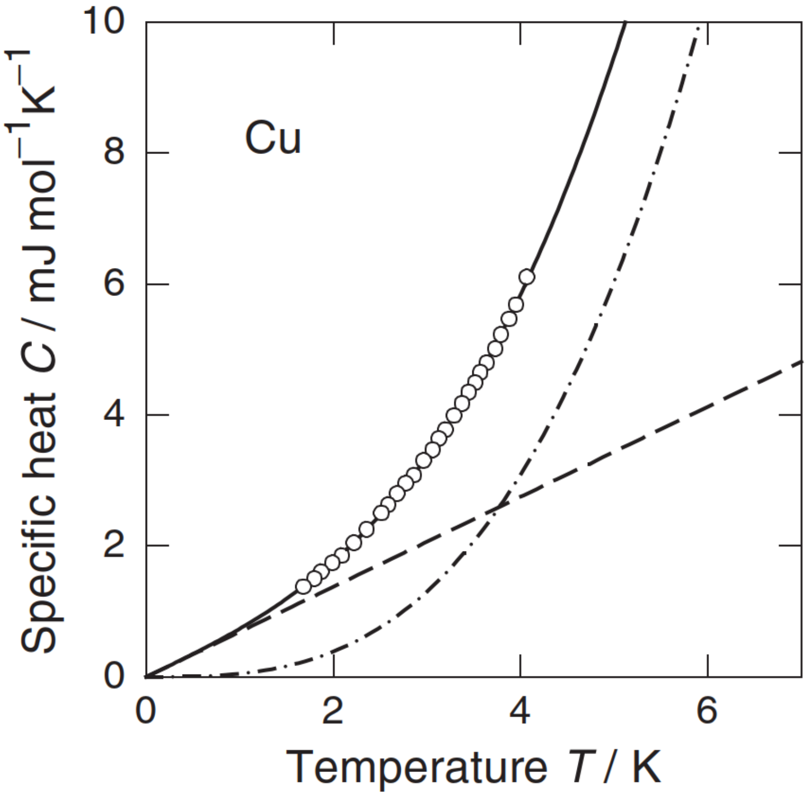
Heat capacity of materials – what to cool?

Discrete lattice vibrations => Phonons



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.