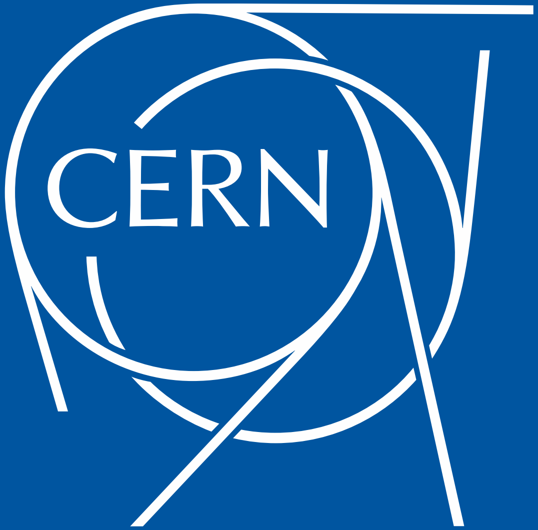
CERN

Introduction to Cryogenics

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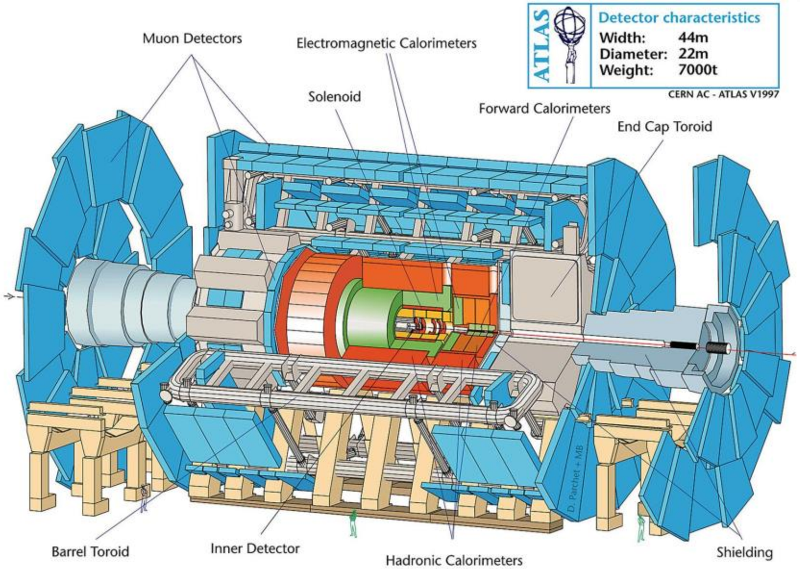
Contributions from S. Claudet and Ph. Lebrun

CAS@ESI: Basics of Accelerator Physics and Technology, 25-29 June 2018, Archamps

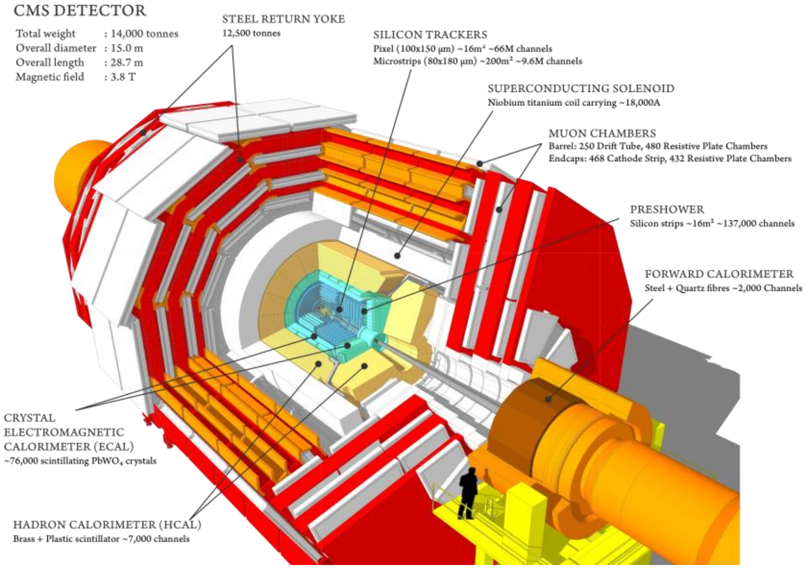
Content

- Introduction to cryogenic installations
- Safety aspects => handling cryogenic fluids
- Motivation => superconductivity needs cryogenics
- Heat transfer and thermal insulation
- Helium cryogenics, He I => He II
- Conclusion
- References

Overview of cryogenics at CERN - Detectors



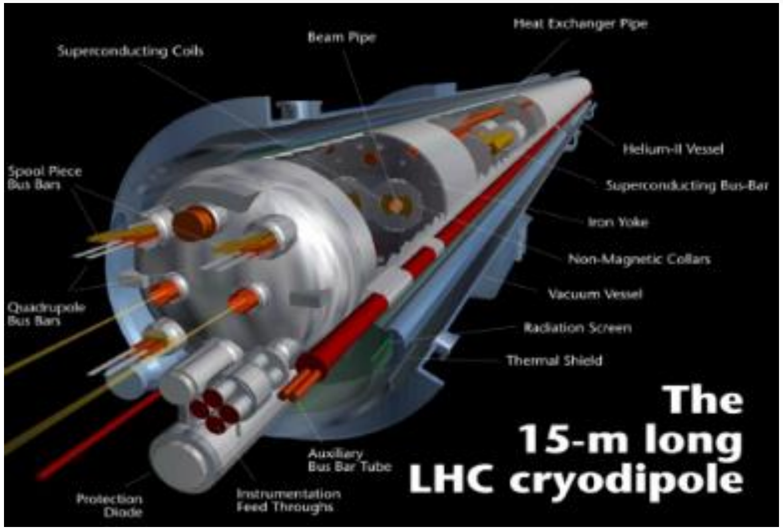
From: CERN-DI-9803026

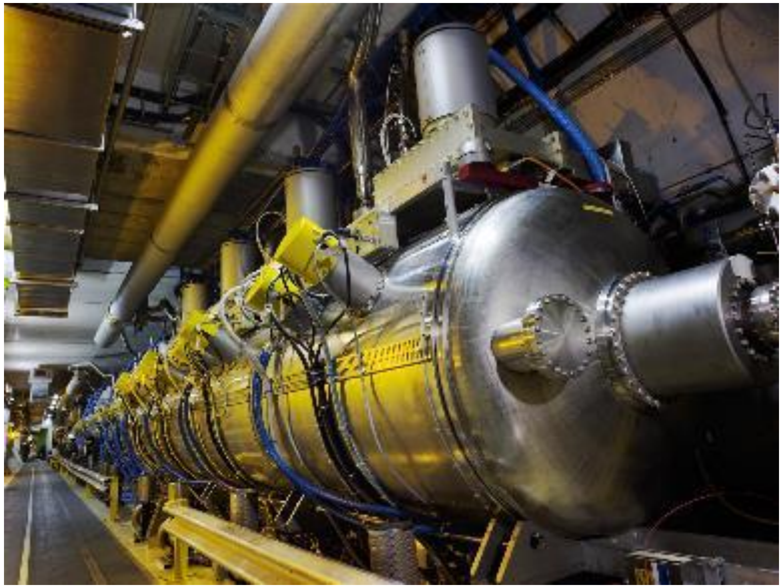


From: http://cms.web.cern.ch/news/cms-detector-design

- 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

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


GHe 20 bar


QRL


LN_2 at 80 K


LHe at 4.5 K

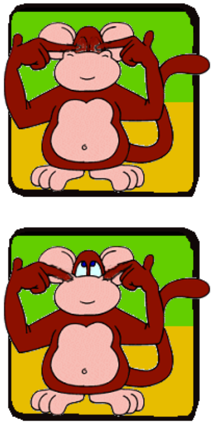
- Storage vessels: GHe or LHe
- Networks of distribution lines (warm and cryogenic)
- Q stands for Cryogenics

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	21	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 – 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:

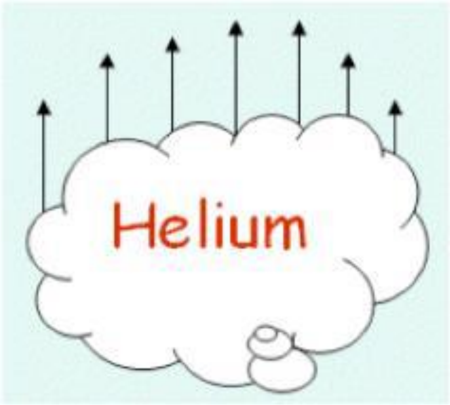
Ice, water, air condensation (!) → indicates cold surfaces

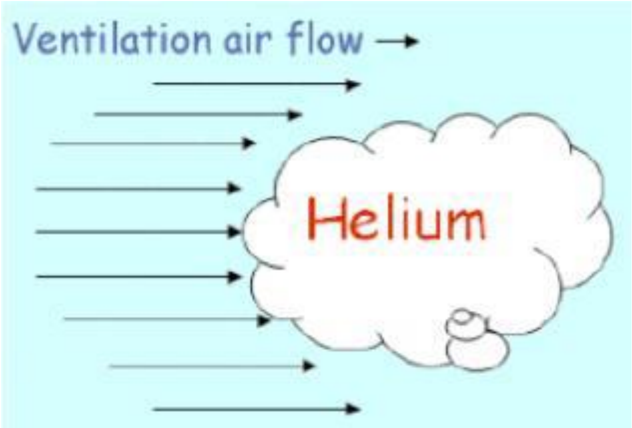
Fog → may indicate a leak of liquid or gazeous cryogens

Risk of cold burn / Frost bite

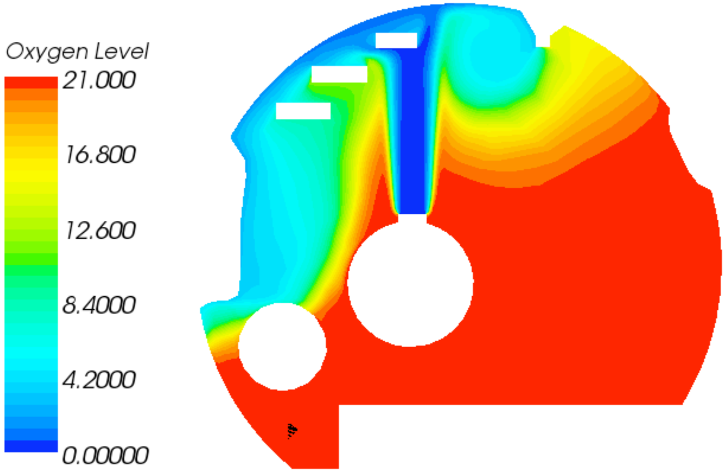
Source: Sever et al. (2010). Frostbite Injury of Hand Caused by Liquid Helium: A Case Report. Eplasty. 10. e35.

Cryogenic hazardous events – Discharge of helium





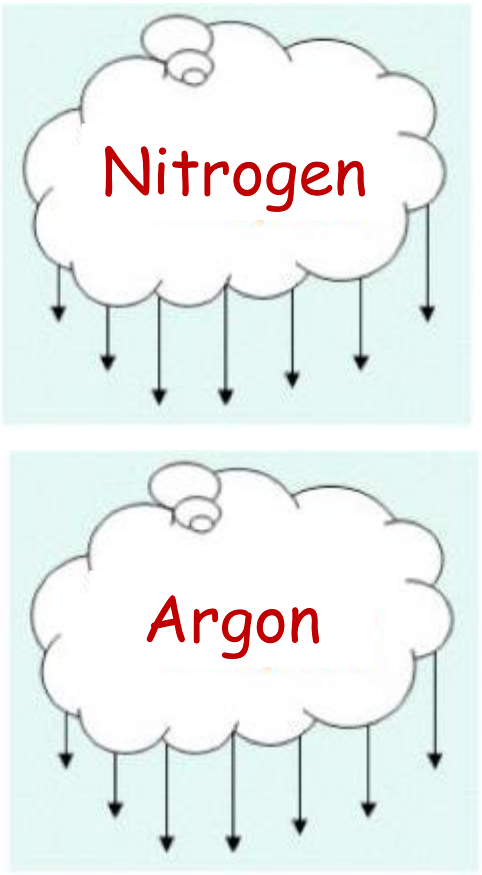
Safer location on the floor



Simulated blow out in the LHC tunnel cross section

- Helium forms clouds while evaporating that move up, mixing rapidly with air
- Helium gas accumulates on the top T>40 K
- Displacement of Oxygen => Asphyxiation risk

Cryogenic hazardous events - Discharge of N_2, Ar …




Safer location at the top

- Argon and nitrogen fall downwards when discharged, forming clouds
- Avoid confined spaces in pits underground channels etc.
- Displacement of Oxygen => Asphyxiation risk

Technical risks

Embrittlement

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

  (carbon steel, ceramics, plastics)

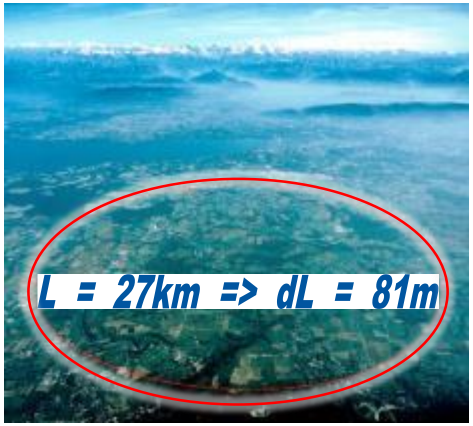
Thermal contraction (293 K to 80 K)

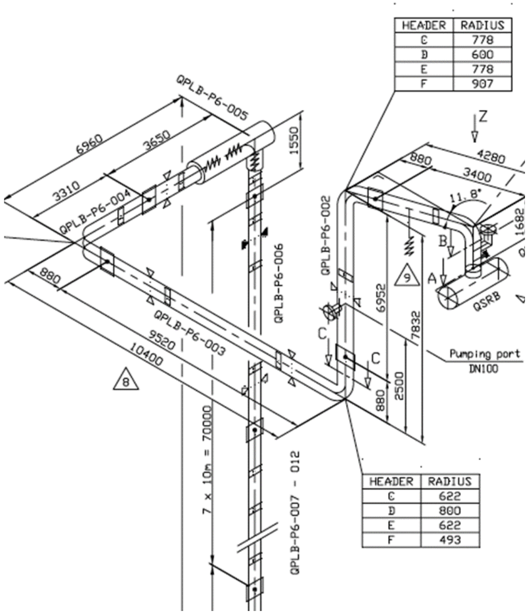
- Stainless steel: 3 mm/m
- Aluminum: 4 mm/m
- Polymers: 10 mm/m

- 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)





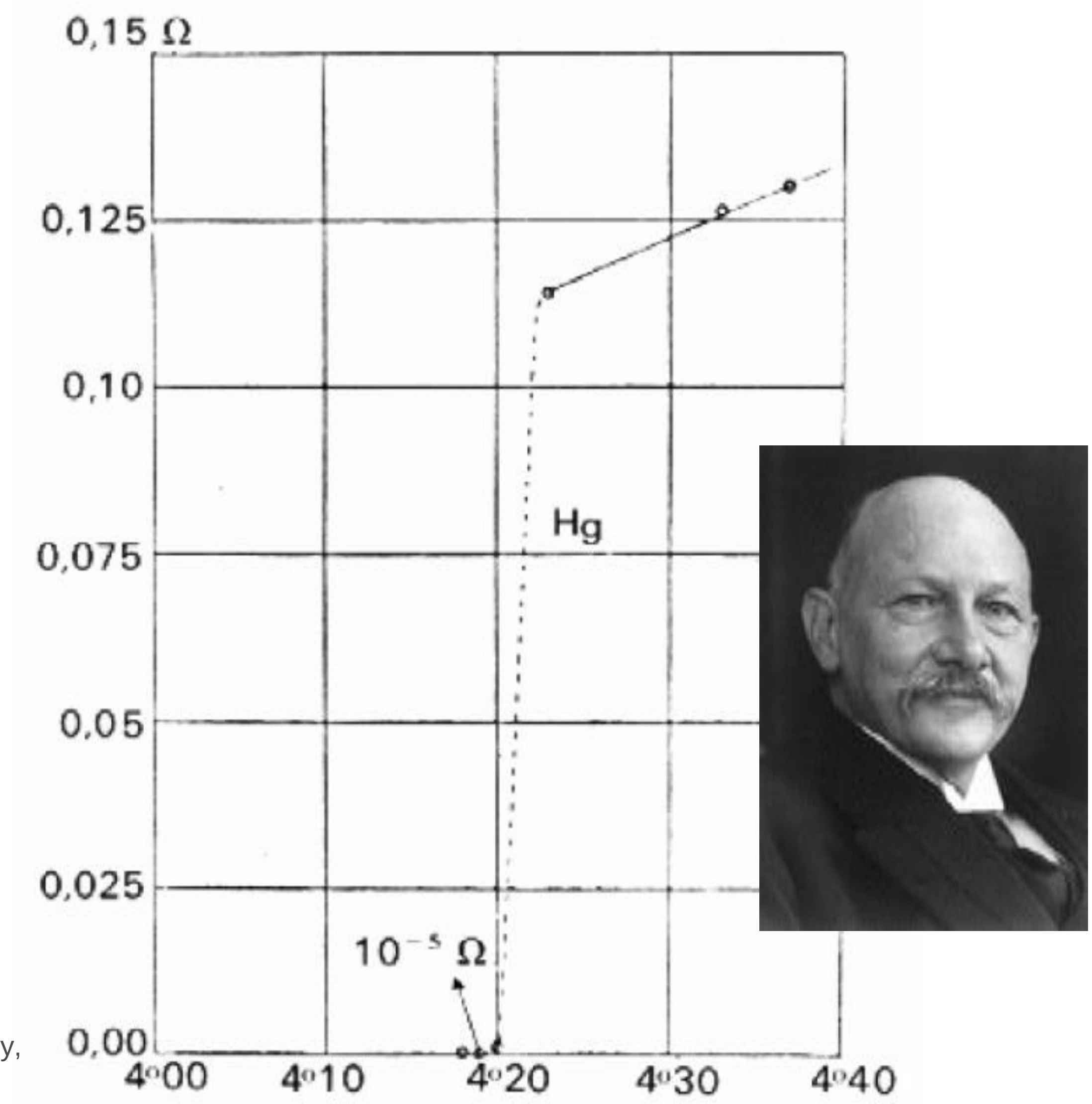
Cryogenics and Superconductivity

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 helium 4	2.17 K
Bolometers for cosmic radiation	< 1 K
Low-density atomic Bose-Einstein condensates	~ μK

Superconductivity

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



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

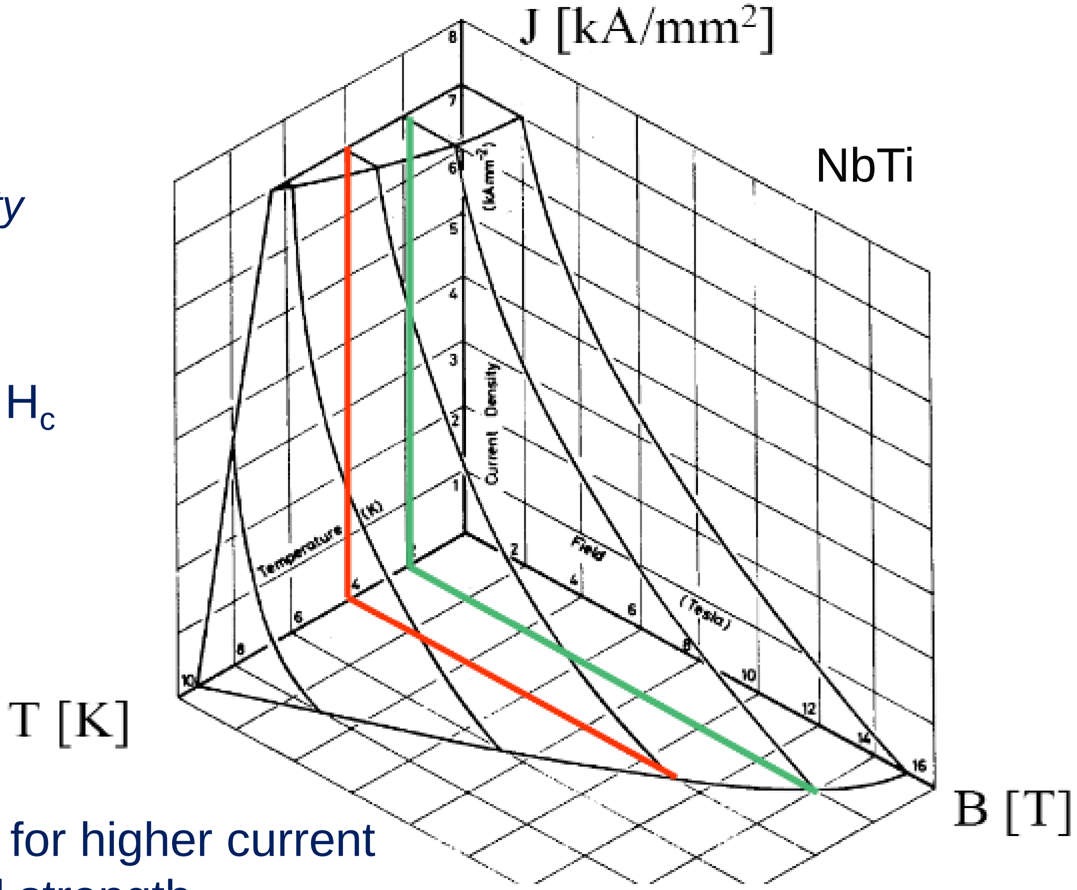
Superconductivity – Properties

Three essential parameters of SC :

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

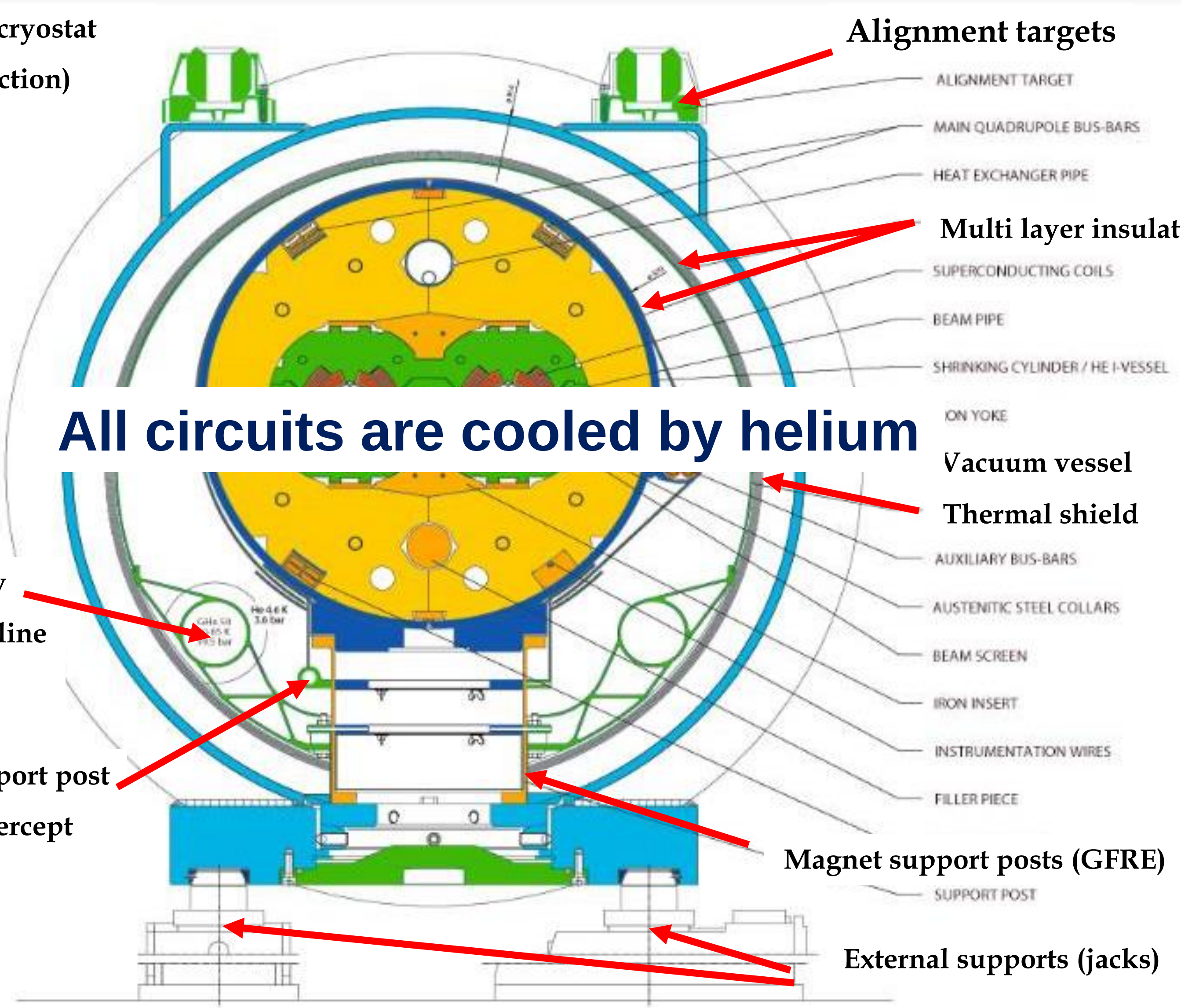
- Critical magnetic field strength: H_c

- Critical current density: j_c



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

Cryogenic application: Dipole magnets of the LHC



LHC main cryostat

(Cross-section)

Alignment targets

Multi layer insulation (MLI)

All circuits are cooled by helium

Vacuum vessel

Thermal shield

Bottom tray

(50-65 K feed line

~ 19.5 bar)

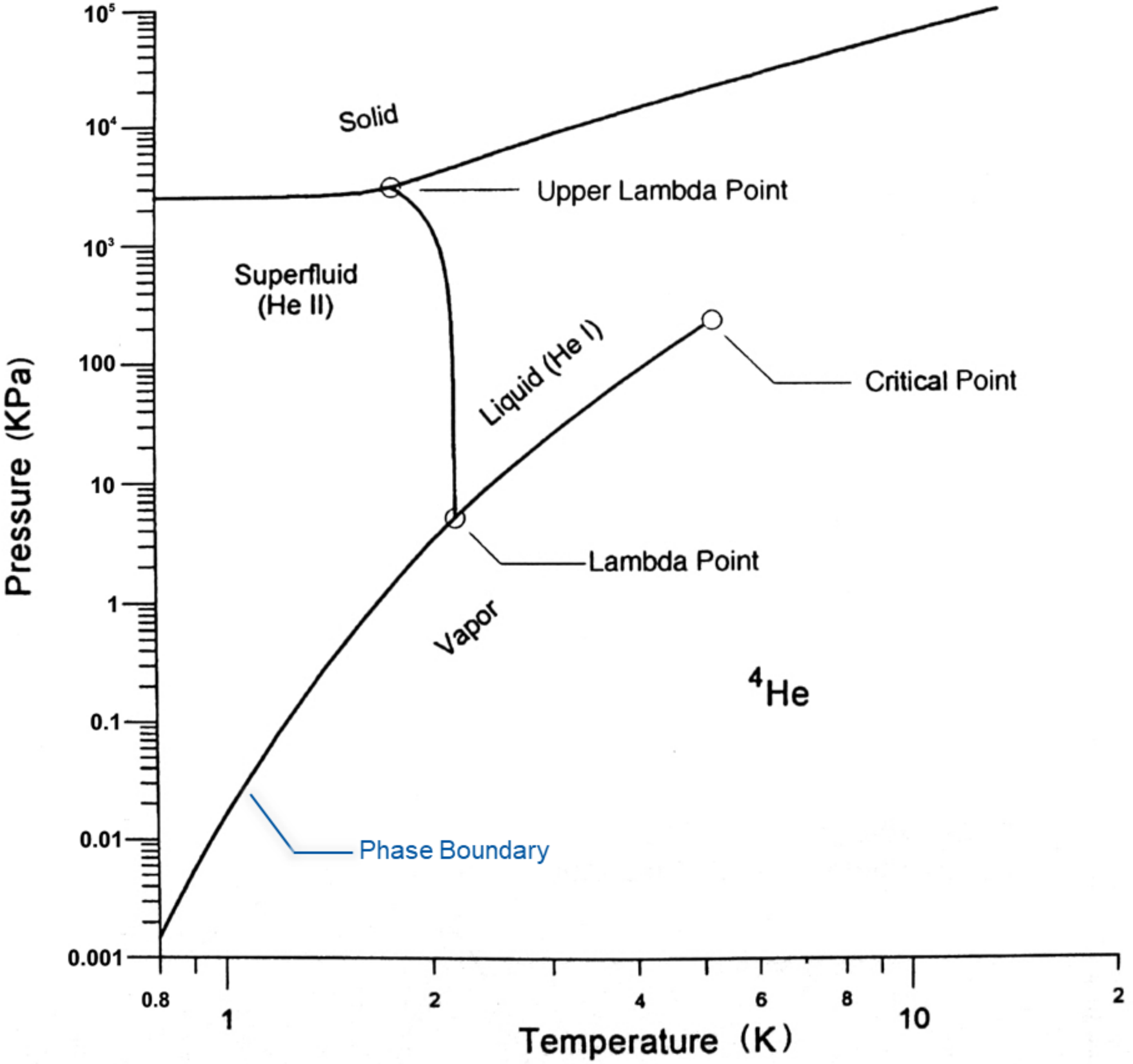
5-20 K support post

heat intercept

Magnet support posts (GFRE)

External supports (jacks)

^{4}He phase diagram

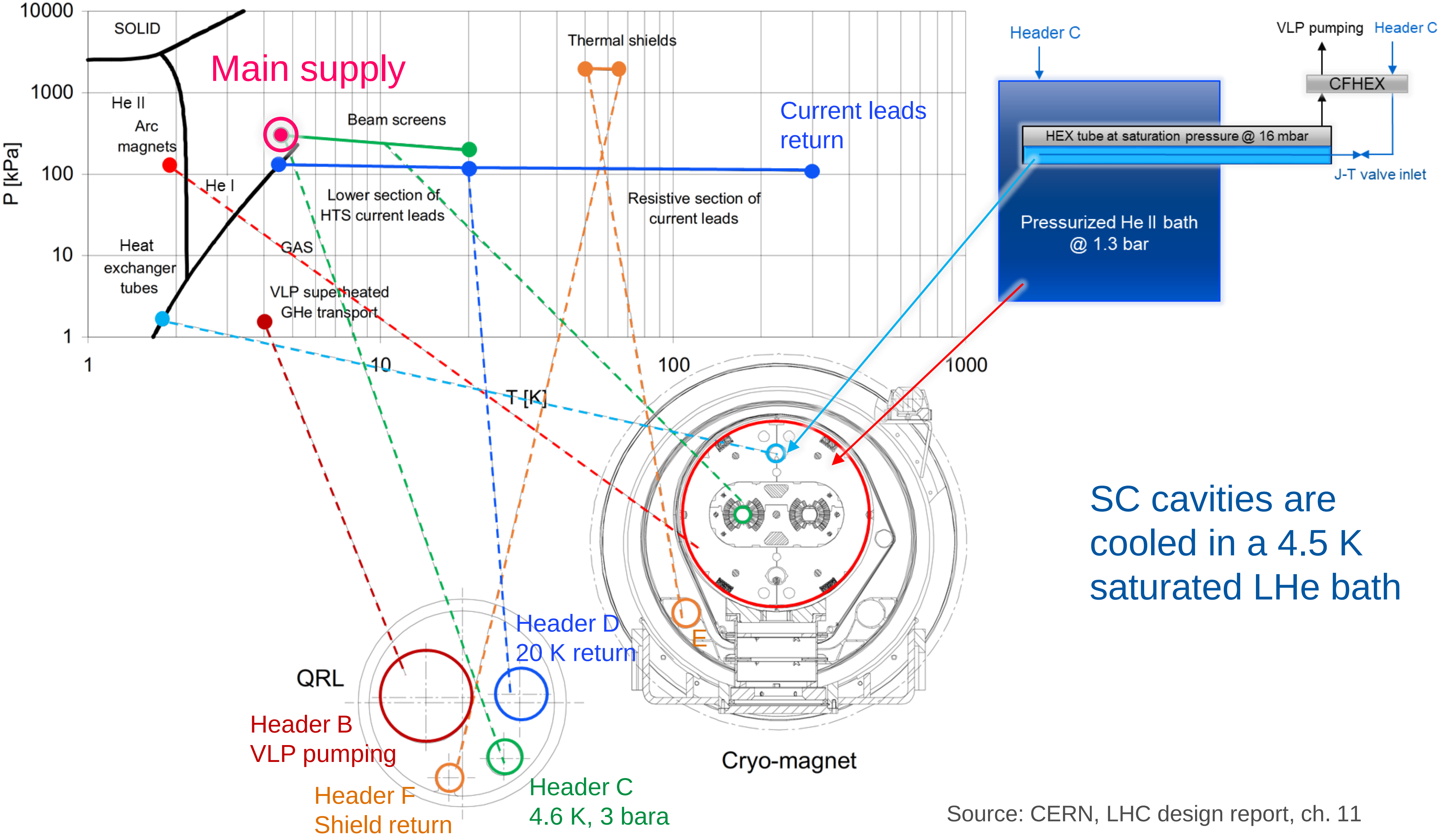


$T_\lambda \approx 2.1768$ K @

$p_\lambda \approx 50.41$ mbar

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

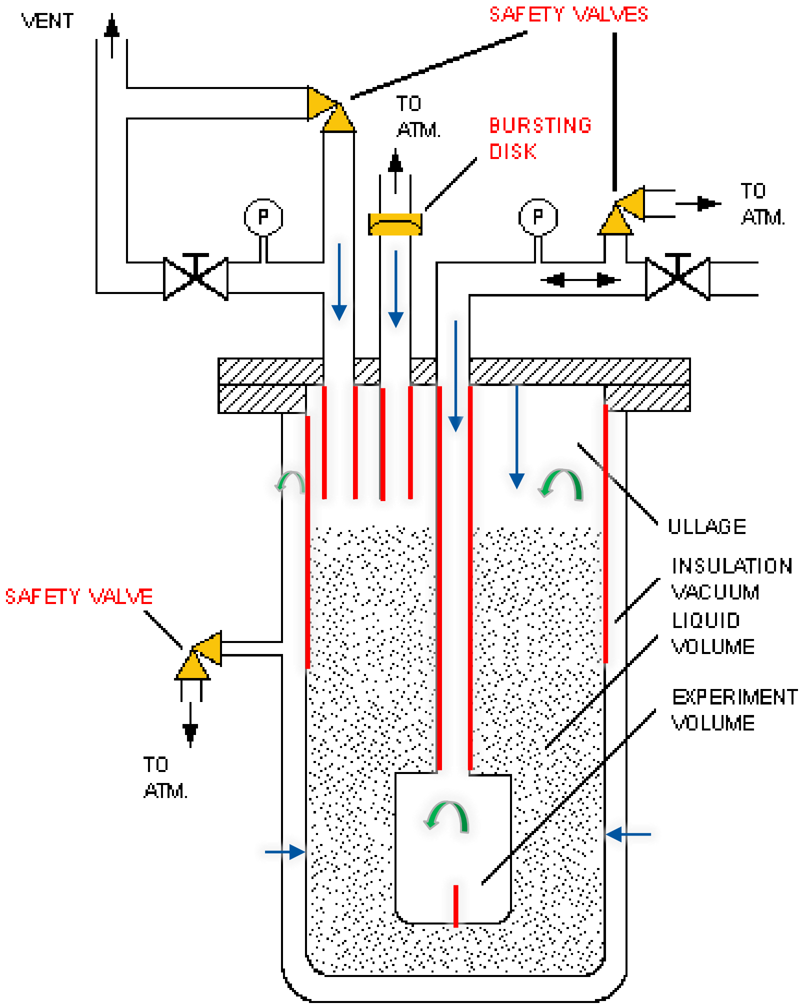
Heat Transfer and Thermal Insulation

Heat Transfer: General

- Solid conduction:

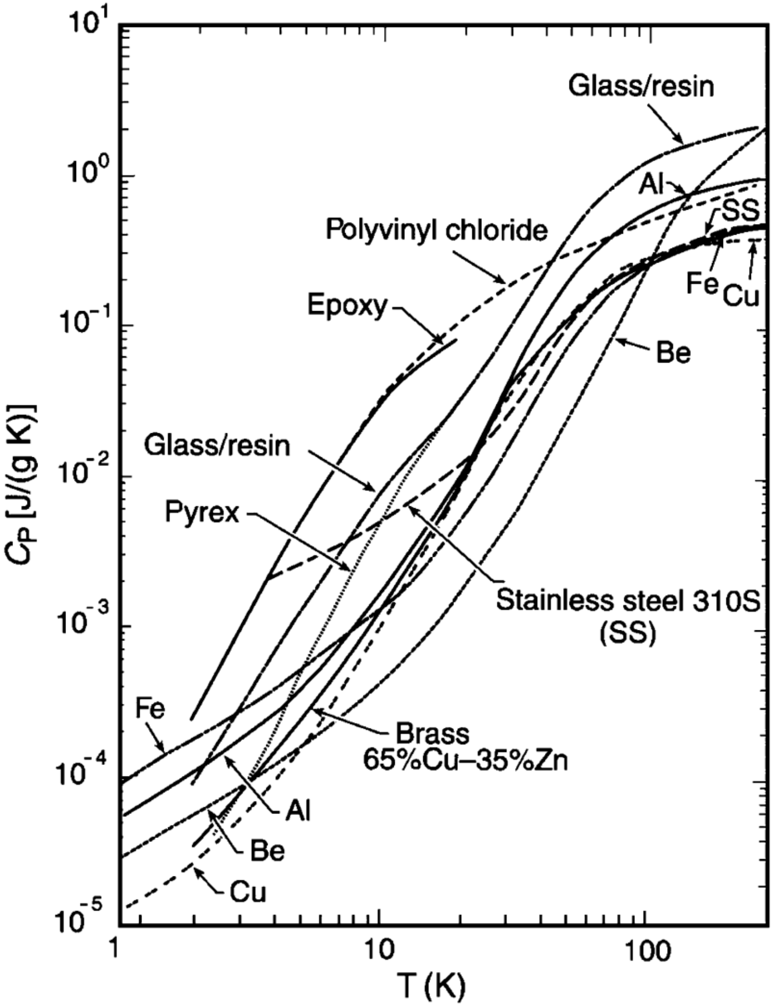
- Thermal radiation:
  (with and without MLI)

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

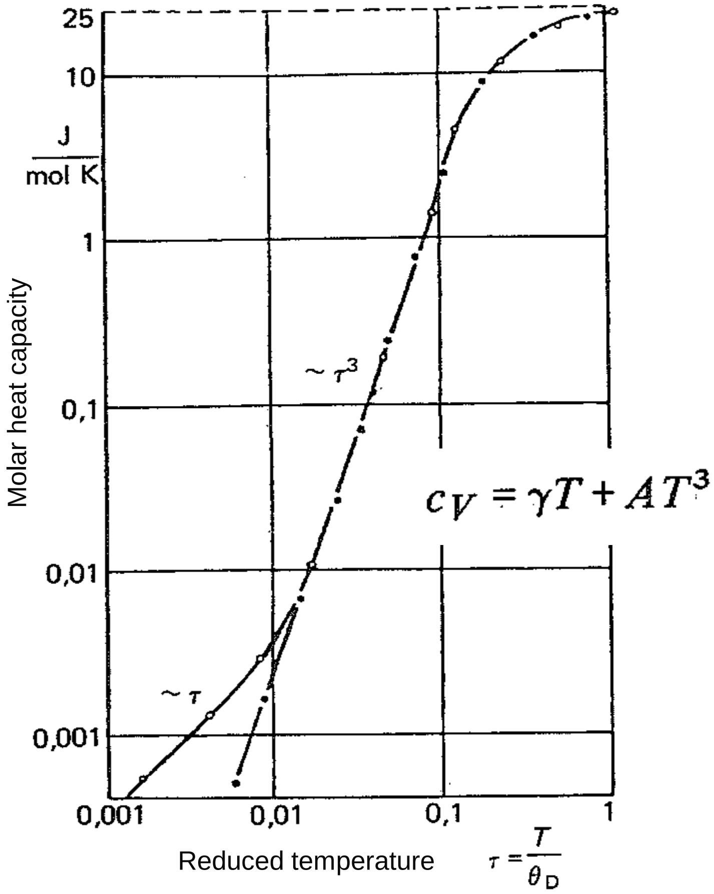


Source: Edeskuty, Safety in the Handling of Cryogenic Fluids

Heat capacity of materials



Source: Ekin, Experimental Techniques for Low-Temperature Measurements



Heat capacity of Cu Θ_D=343 K (circles) and diamond Θ_D=2200 K (dots), Source: Frey, Tieftemperaturtechnologie, 1981

Heat capacity of materials vs. cooldown

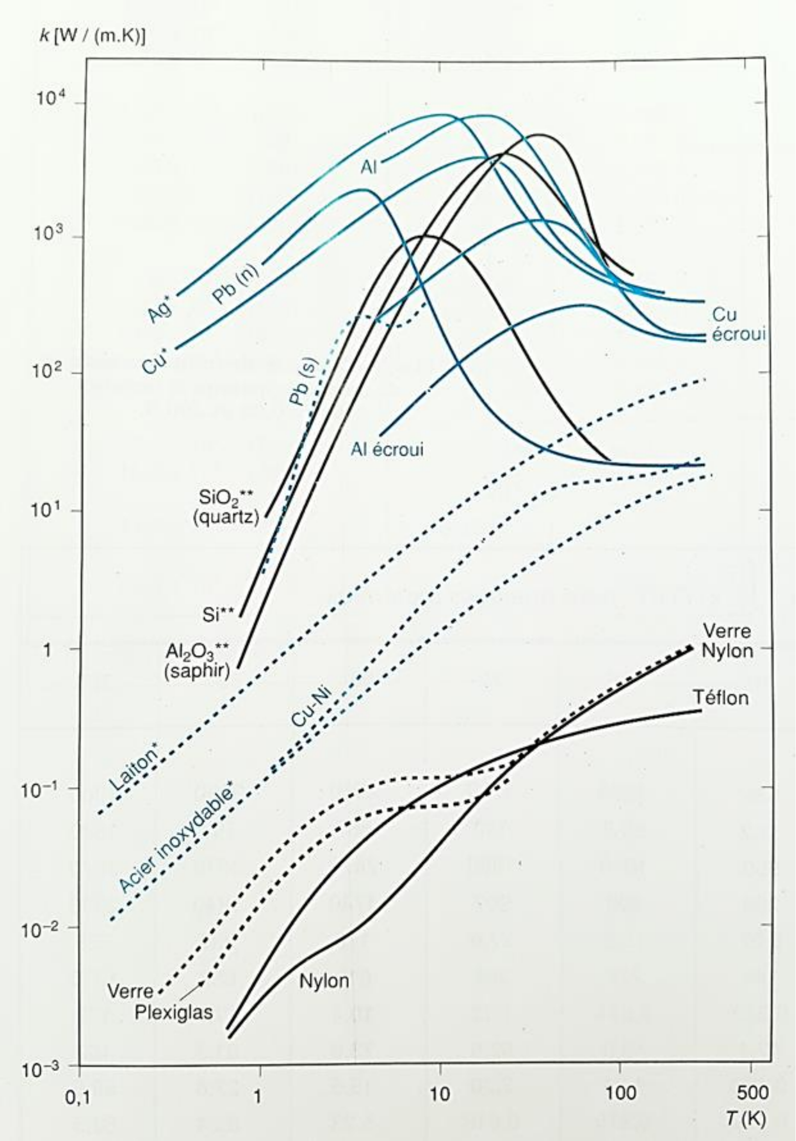
Amount of cryogen required to cool down 1 kg iron to sat. temperature

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

Thermal conductivity, solid conduction



From: Cryogenie, Institut International du Froid, Paris

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

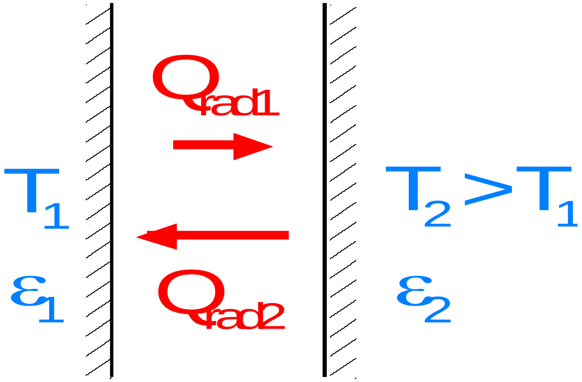
Alloyed metals: electrons and phonons

Radiative heat transfer

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

    $\lambda_{max}T$ = 2898 in µm K

    => 10 μm for 300 K



- Stefan-Boltzmann's law
  - Black body

    $\dot{Q}_{rad} = \sigma A T^4$

    σ = 5.67 x 10^{-8} W/(m^2 K^4)

    (Stefan-Boltzmann's constant)
  - "Gray" body

    $\dot{Q}_{rad} = \varepsilon \sigma A T^4$

    ε emissivity of surface
  - "Gray" surfaces at T_1 and T_2

    $\dot{Q}_{rad} = E \sigma A (T_1^4 - T_2^4)$

    E function of ε_1, ε_2, geometry

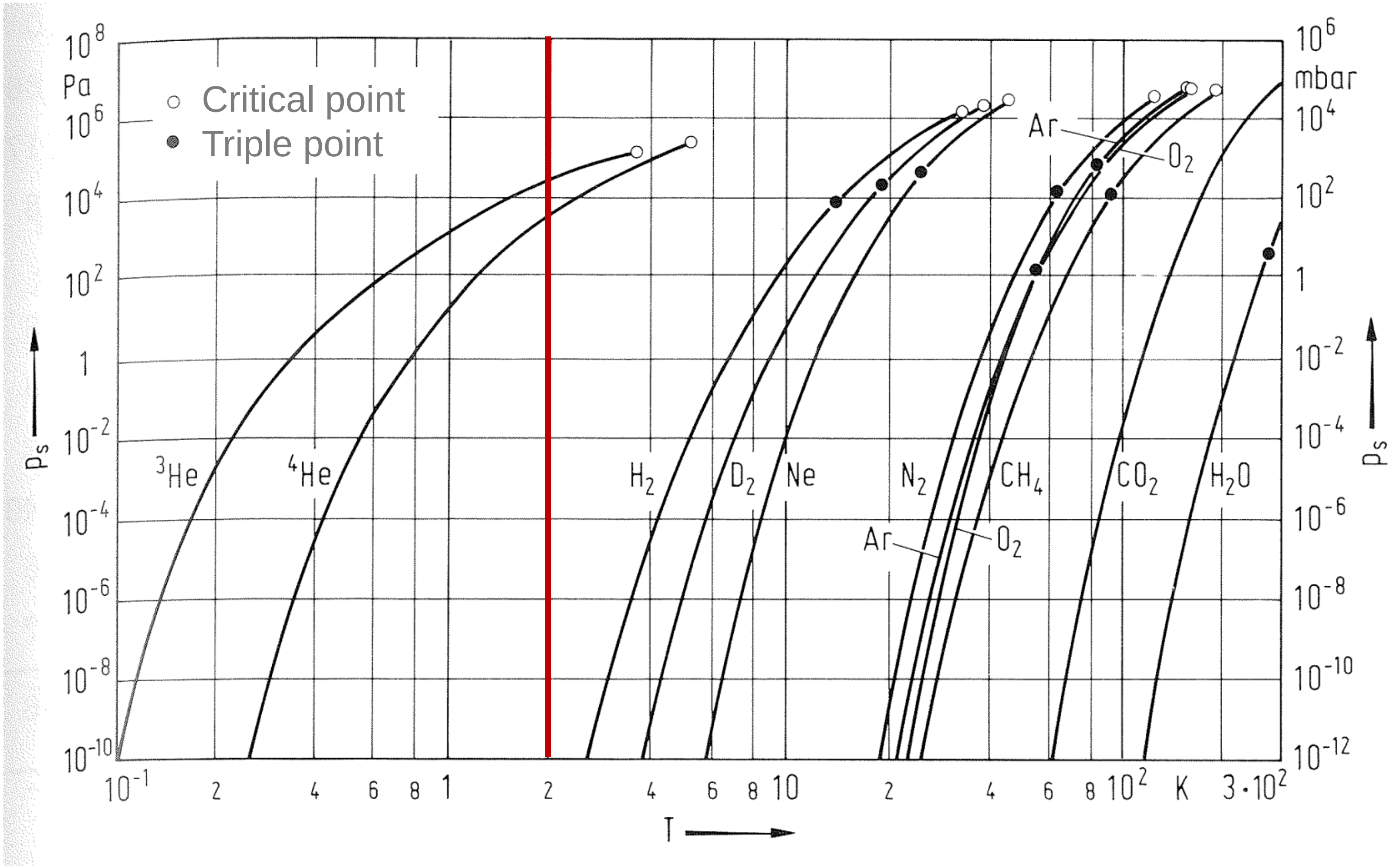
Emissivity of technical materials at low temperatures

	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	0.01
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

Condensed layers easily vary these values !

T_{warm}=293 K

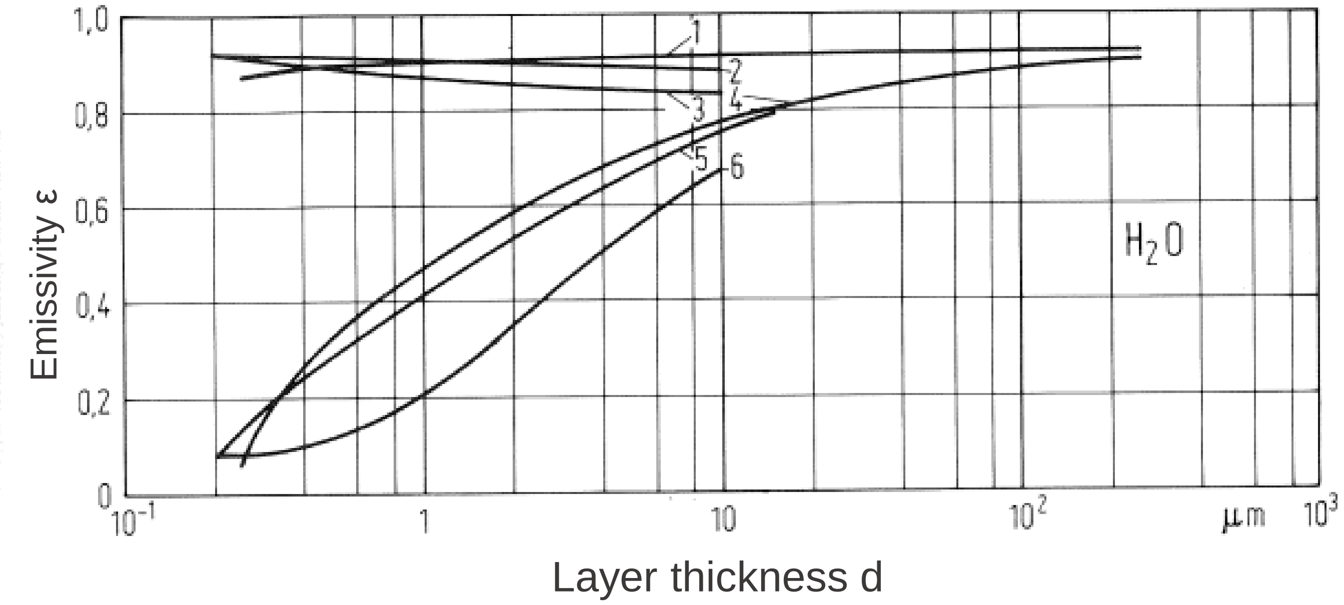
Vapor pressure curves of common gases



Source: Haefer; Kryovakuumtechnik, 1981

Emissivity of technical materials at low temperatures

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



	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

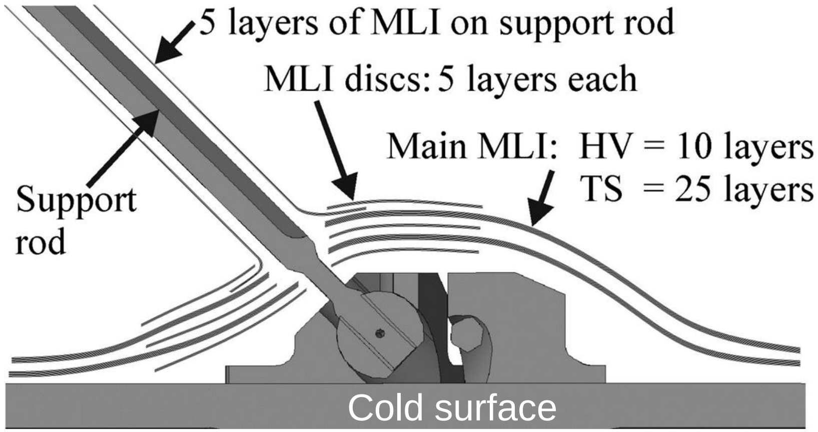
Source: Haefer, Kryovakuumtechnik, 1981

Multi-layer insulation (MLI)

Complex system involving three heat transfer processes

- $Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res}$
- With *n* reflective layers of equal emissivity, $Q_{rad} \sim 1/(n+1)$
- Parasitic contacts between layers, Q_{sol} increases with layer density
- Q_{res} 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



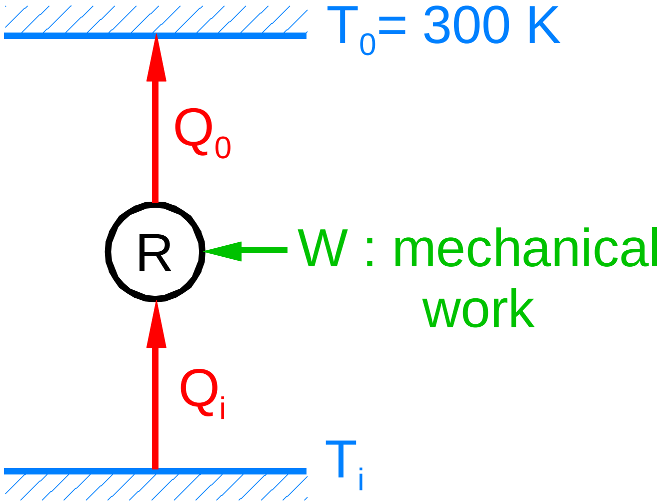
Solutions for penetrations and support structures

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
Gas conduction (100 mPa He) from 290 K (10^{-3} mbar)	19
Gas conduction (1 mPa He) from 290 K (10^{-5} mbar)	0.19
Gas conduction (100 mPa He) from 80 K	6.8
Gas conduction (1 mPa He) from 80 K	0.07
MLI (30 layers) from 290 K, pressure below 1 mPa	1-1.5
MLI (10 layers) from 80 K, pressure below 1 mPa	0.05
MLI (10 layers) from 80 K, pressure 100 mPa	1-2

Refrigeration and Liquefaction

Thermodynamics of cryogenic refrigeration



T_0= 300 K

Q_0

R

W : mechanical work

Q_i

T_i

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)

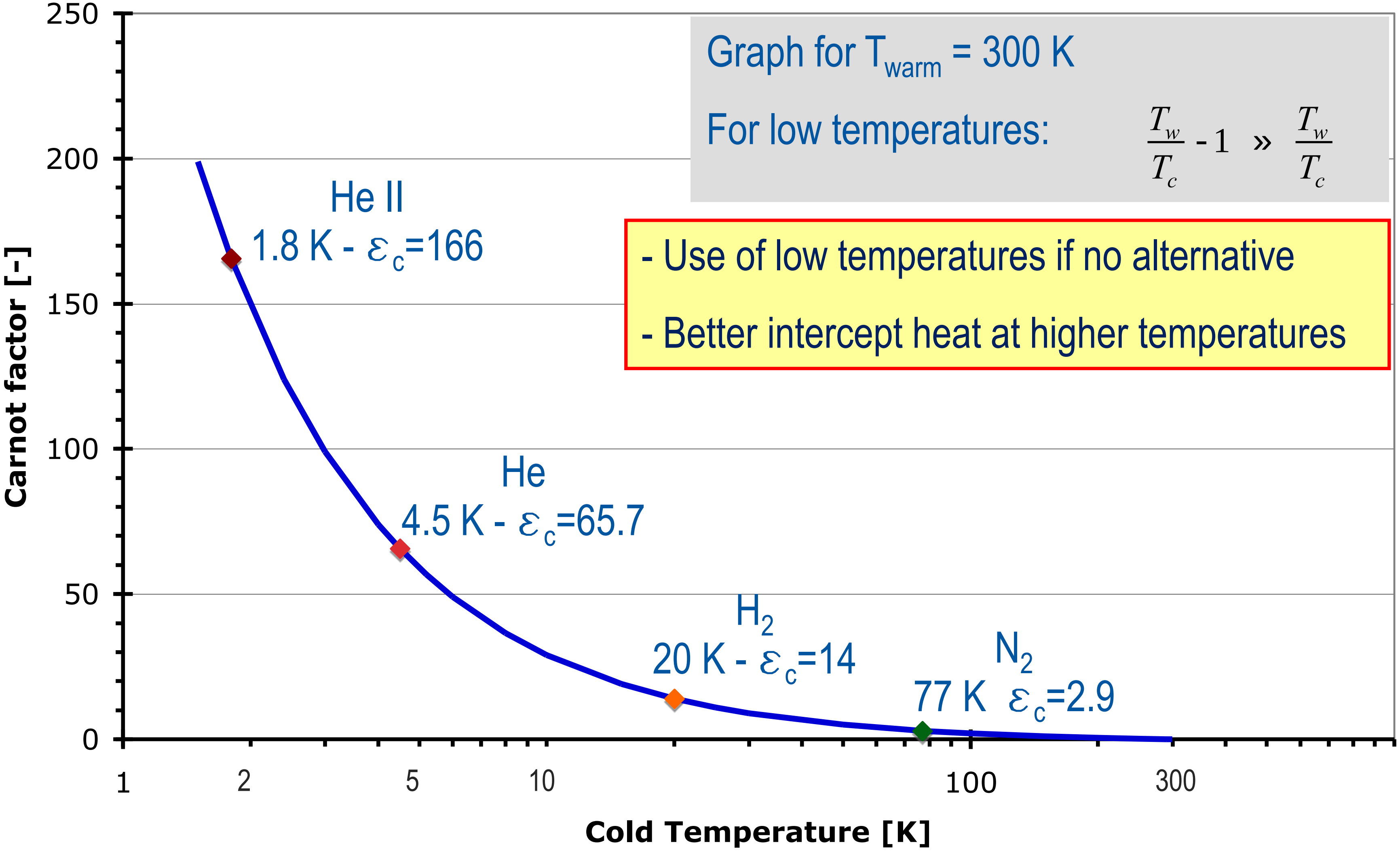
Hence, $W \geq T_0 \cdot \frac{Q_i}{T_i} - Q_i$ which can be written in different ways:

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

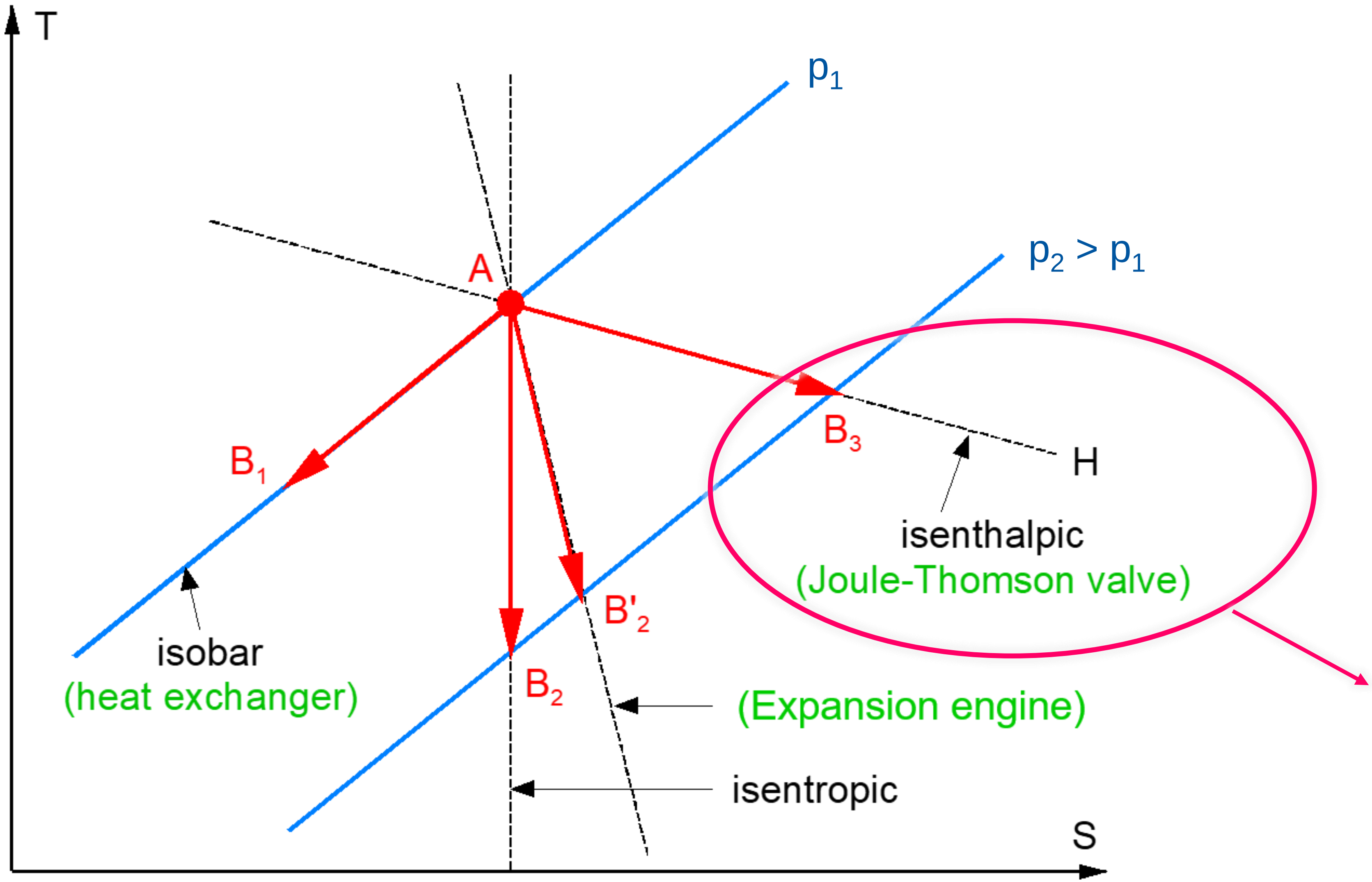


Graph for T_{warm} = 300 K

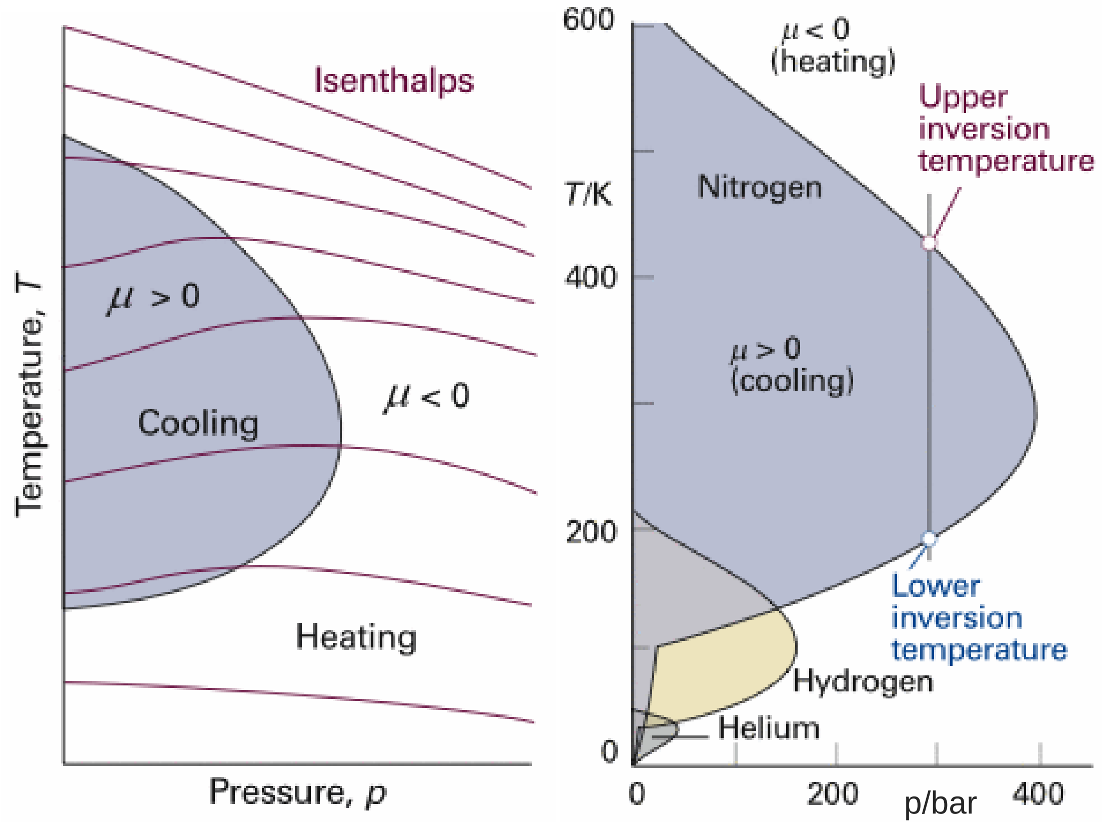
For low temperatures: $\frac{T_w}{T_c} - 1 \approx \frac{T_w}{T_c}$

- Use of low temperatures if no alternative
- Better intercept heat at higher temperatures

Elementary cooling processes in a T-s diagram



Maximum Joule-Thomson inversion temperatures



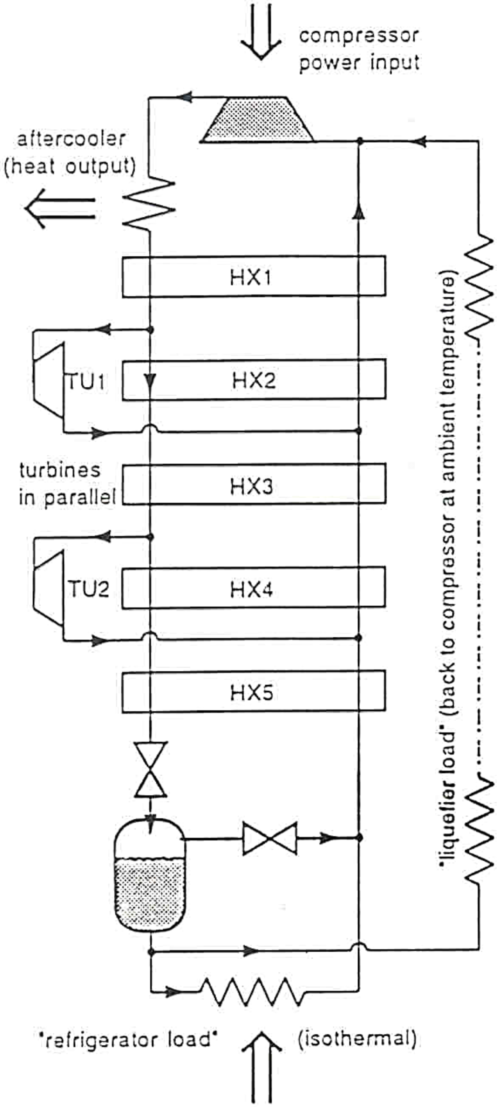
Source: http://faculty.chem.queensu.ca/people/faculty/mombourquette/Chem221/3_FirstLaw/ChangeFunctions.asp

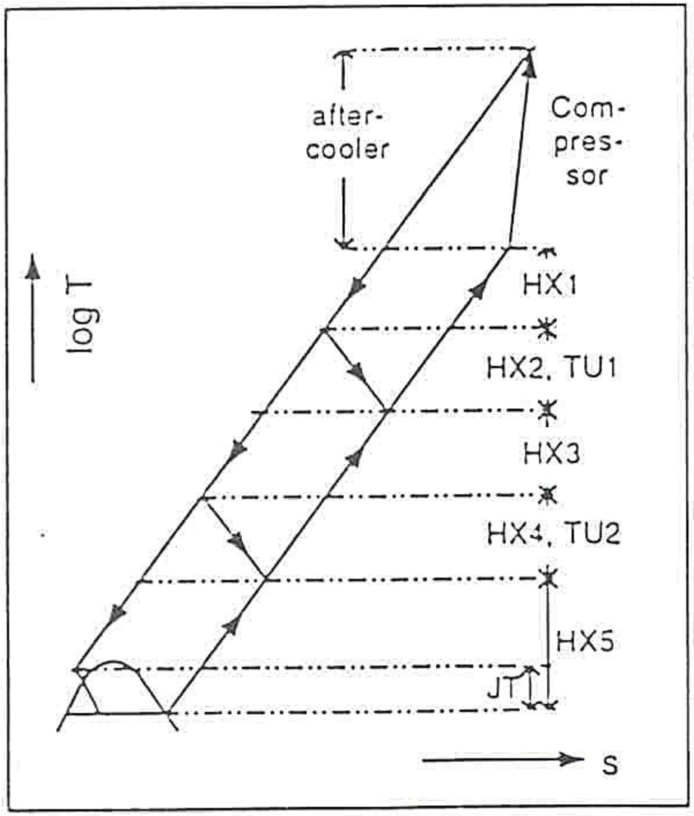
Cryogen	**Max. inversion temperature [K]**
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Argon	723

Source: Refprop®

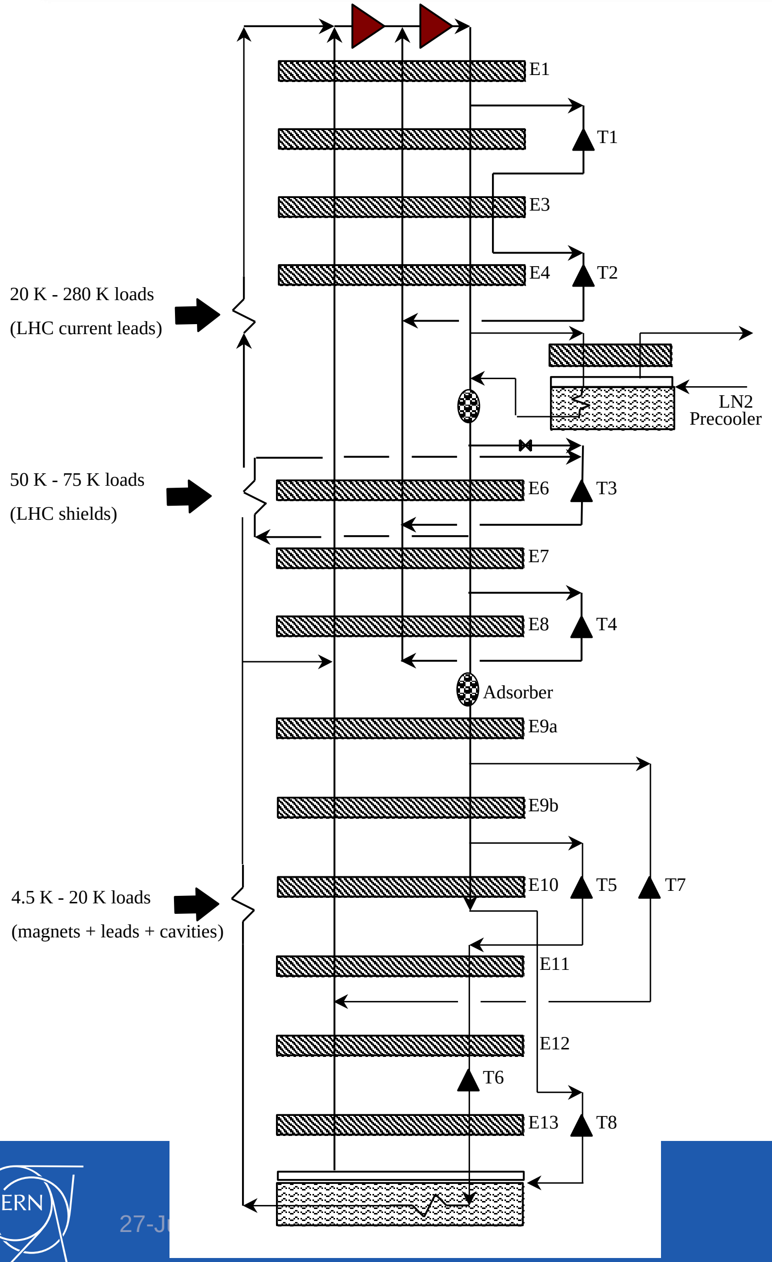
- Air can be cooled down and liquefied by J-T expansion from room temperature,
- Helium and hydrogen need precooling down to below the inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

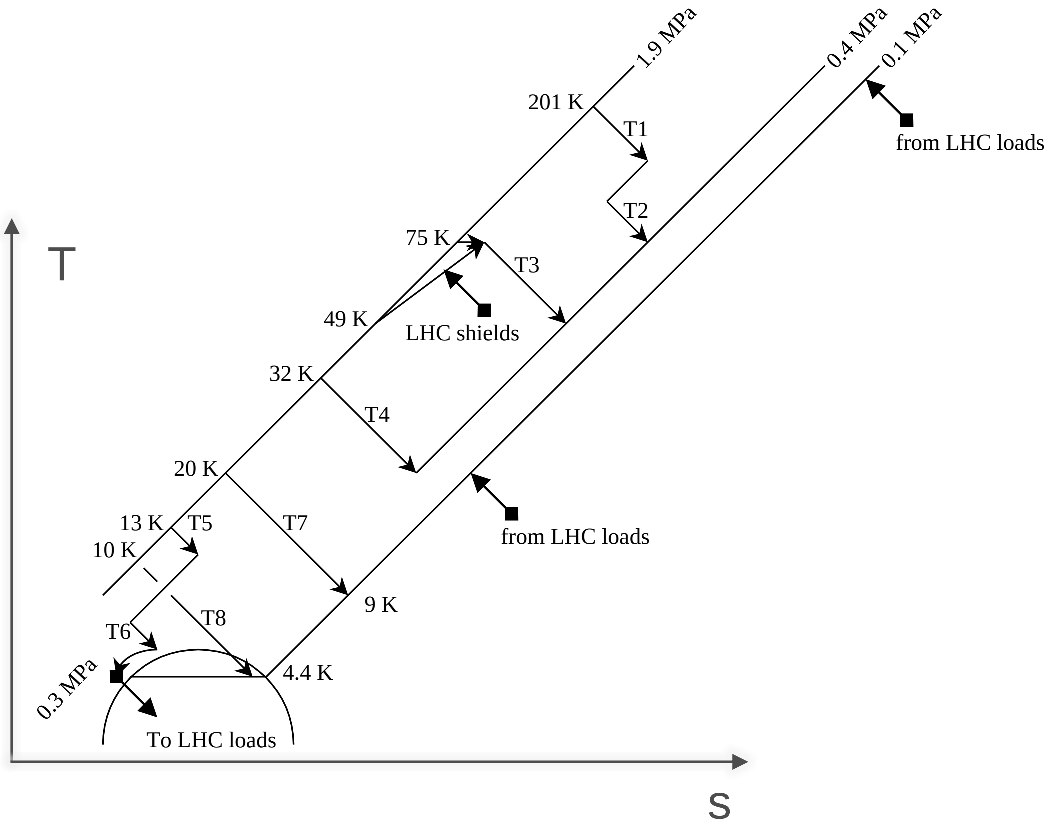
Two-stage Claude cycle



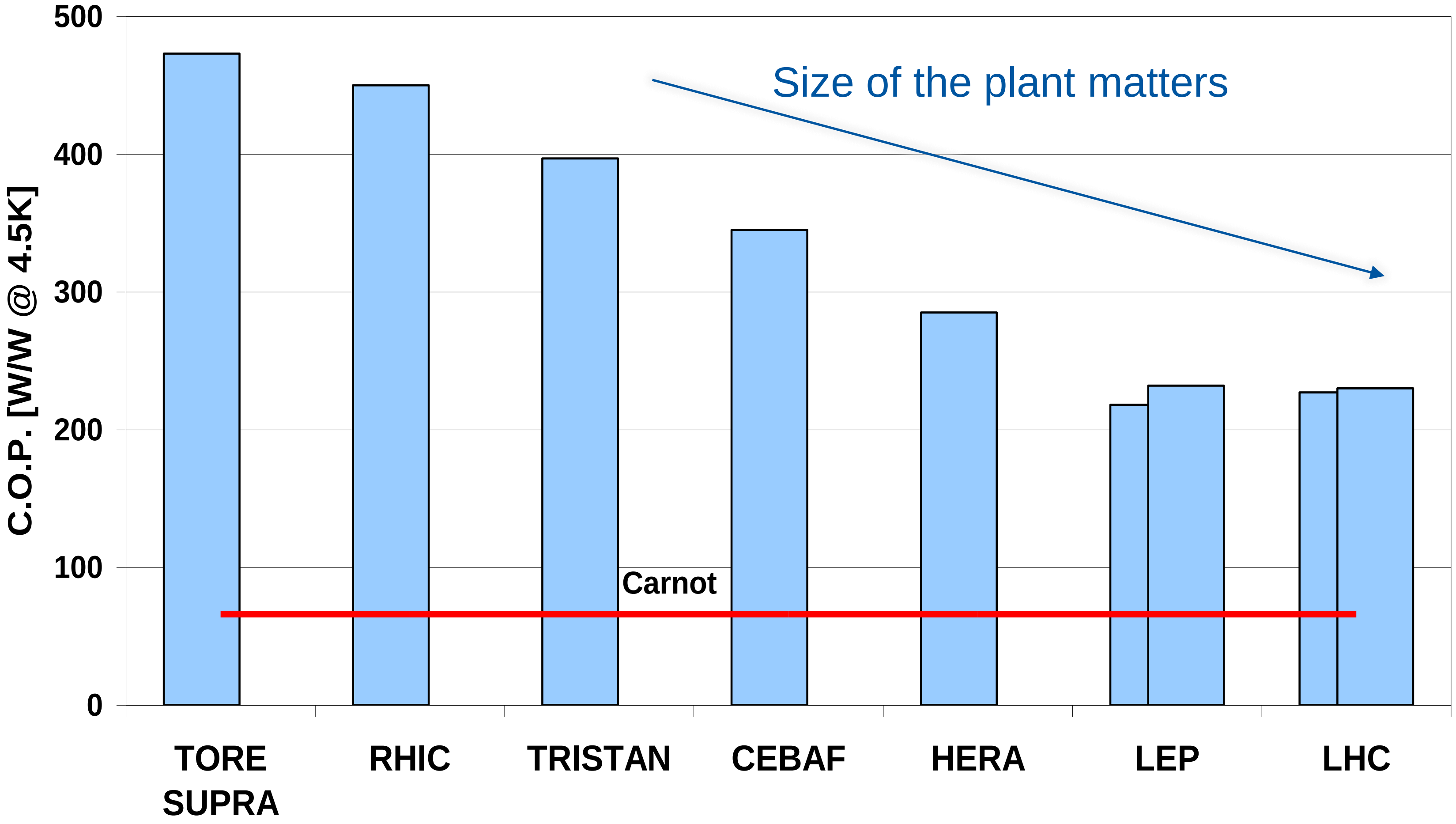


Process cycle & T-s diagram of LHC 18 kW @ 4.5 K cryoplant





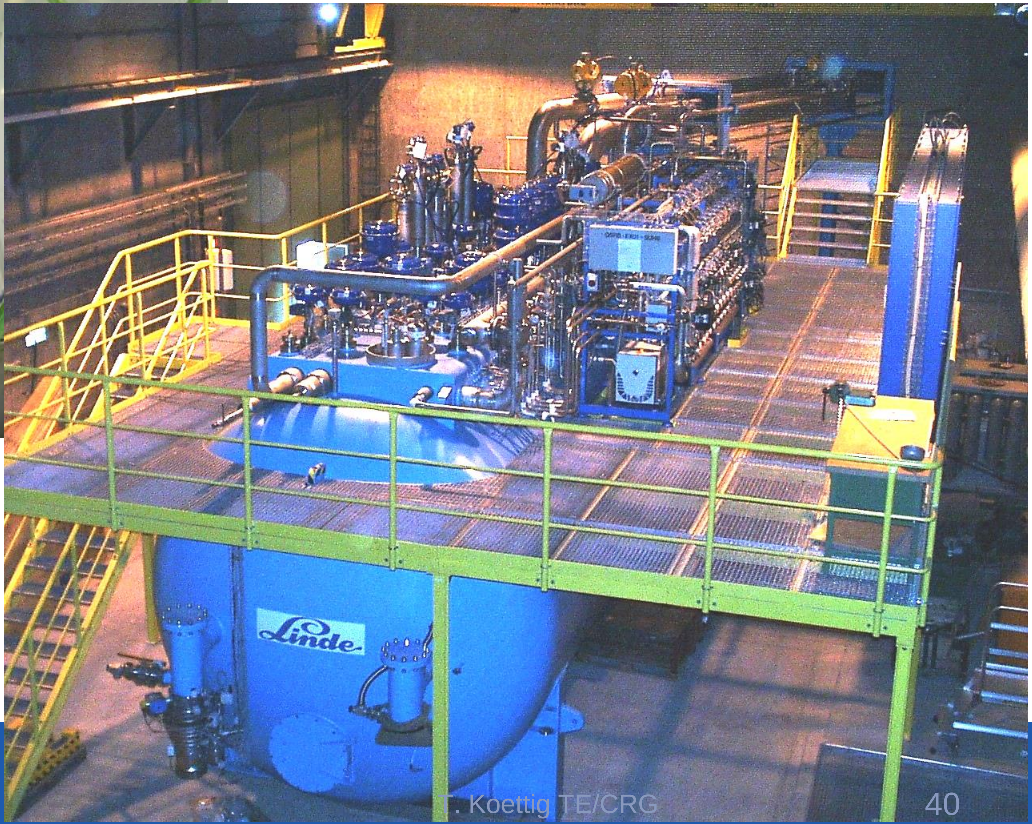
COP of large cryogenic helium refrigerators



LHC 18 kW @ 4.5 K helium cryoplants

33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction
4 MW compressor power
COP 220-230 W/W @ 4.5 K

Air Liquide



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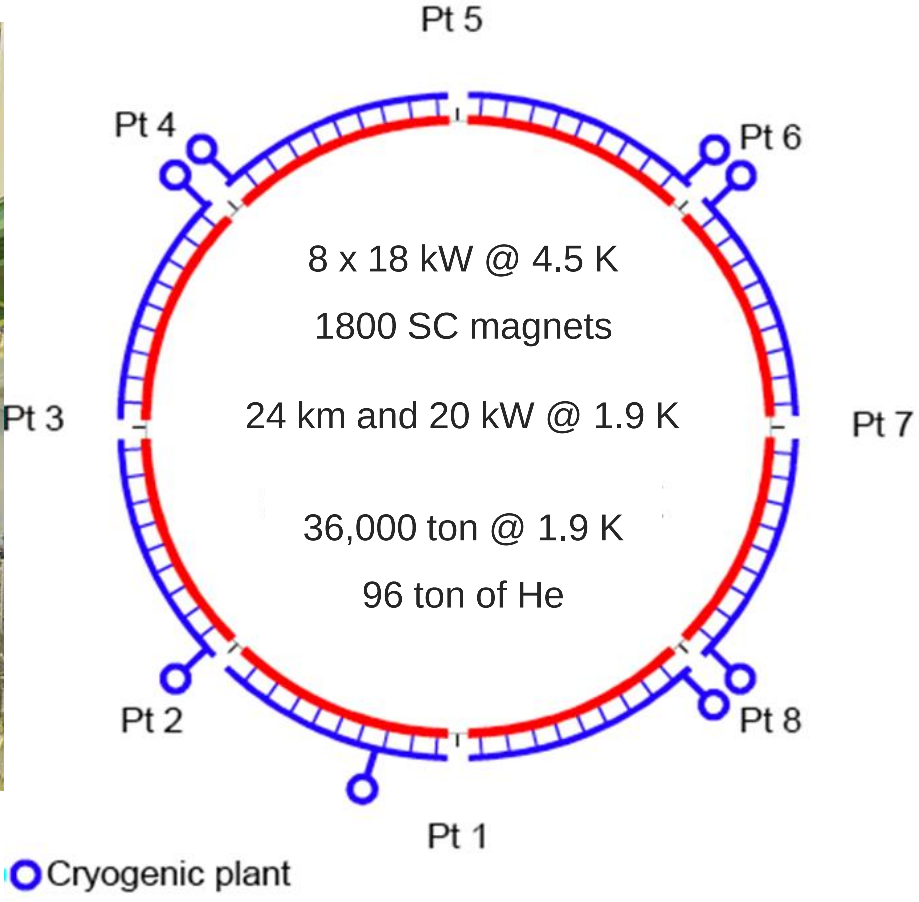
LHC 18 kW @ 4.5 K helium cryoplants

Air Liquide



8 x 18 kW @ 4.5 K

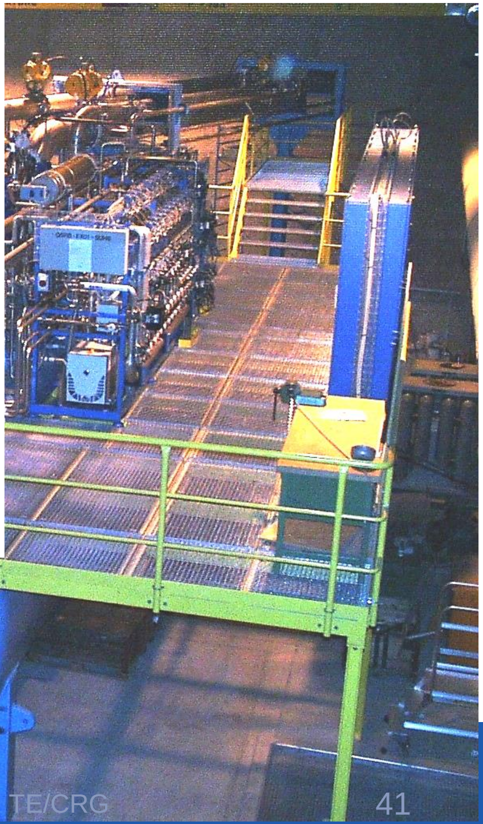
1800 SC magnets

24 km and 20 kW @ 1.9 K

36,000 ton @ 1.9 K

96 ton of He

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



Linde

Cryogenic Fluid Properties

He I and He II

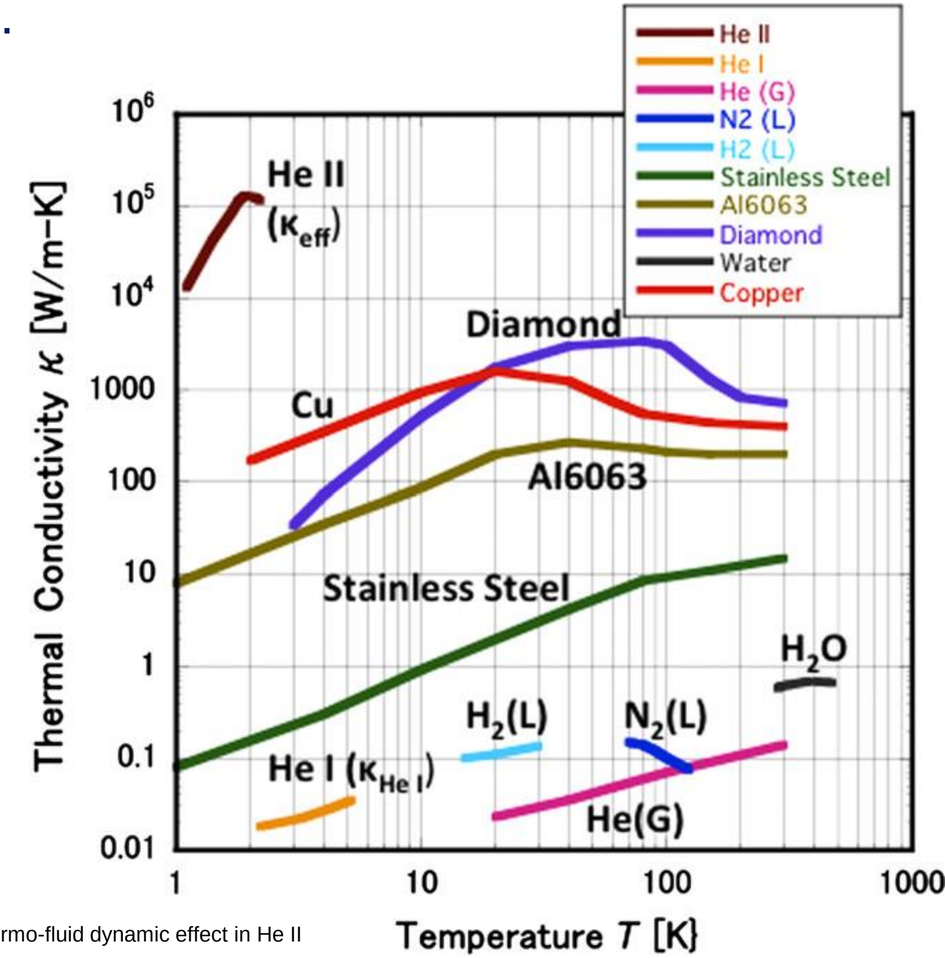
From He I to He II

Normal fluid helium => He I

- Like a standard fluid: viscosity etc.

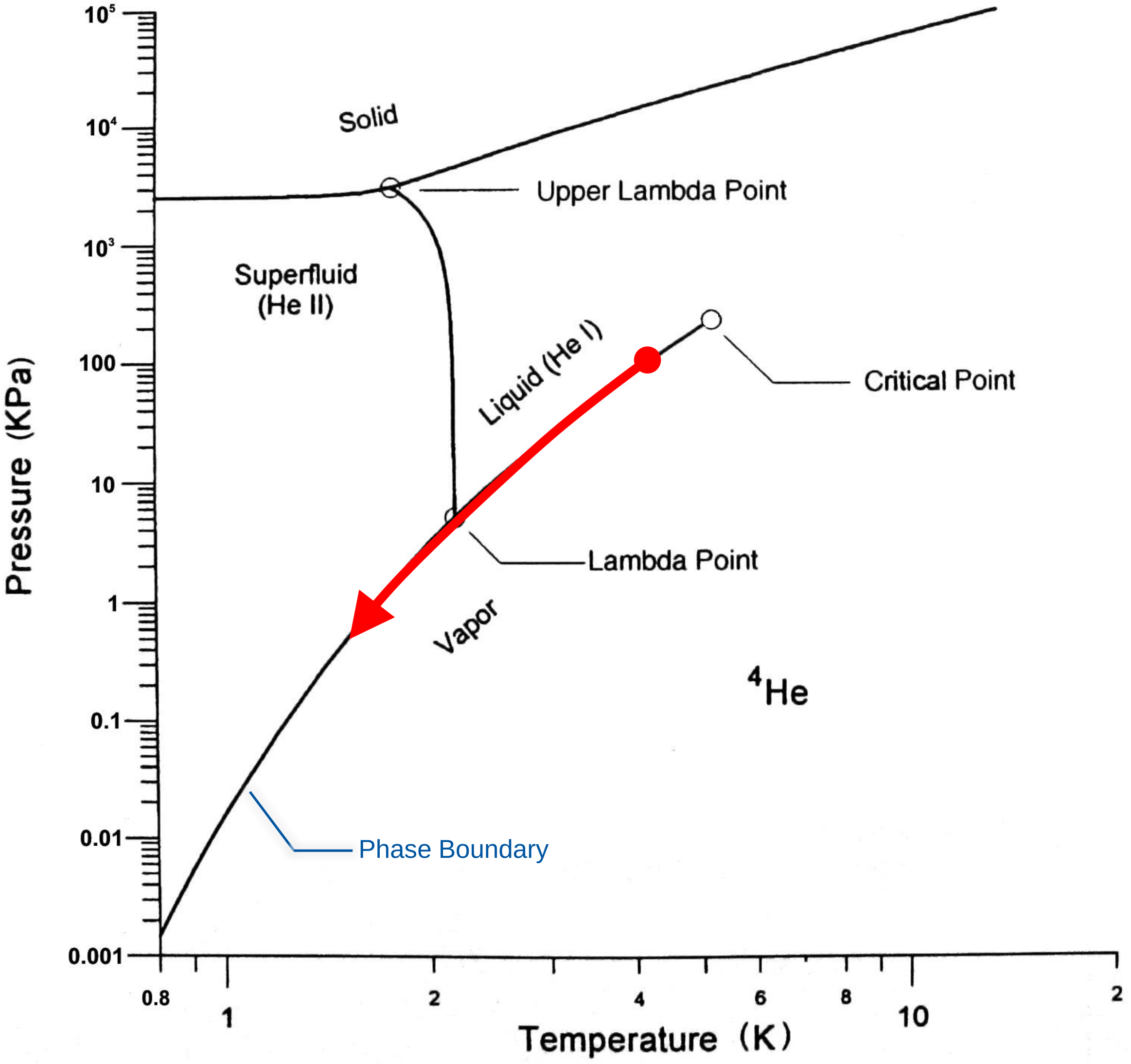
Superfluid helium => He II

- 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 ^{4}He

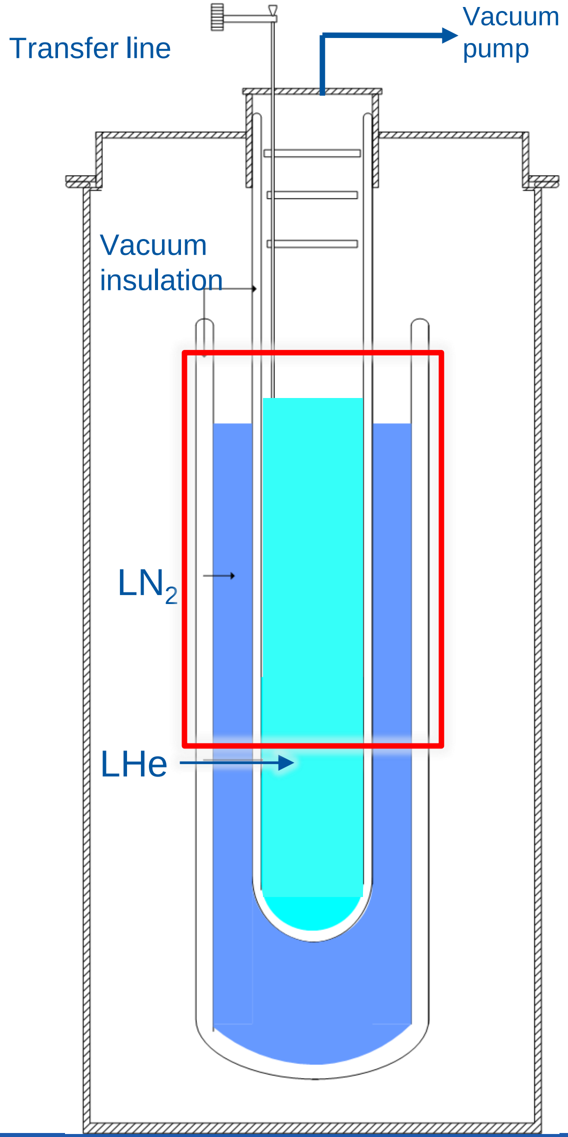


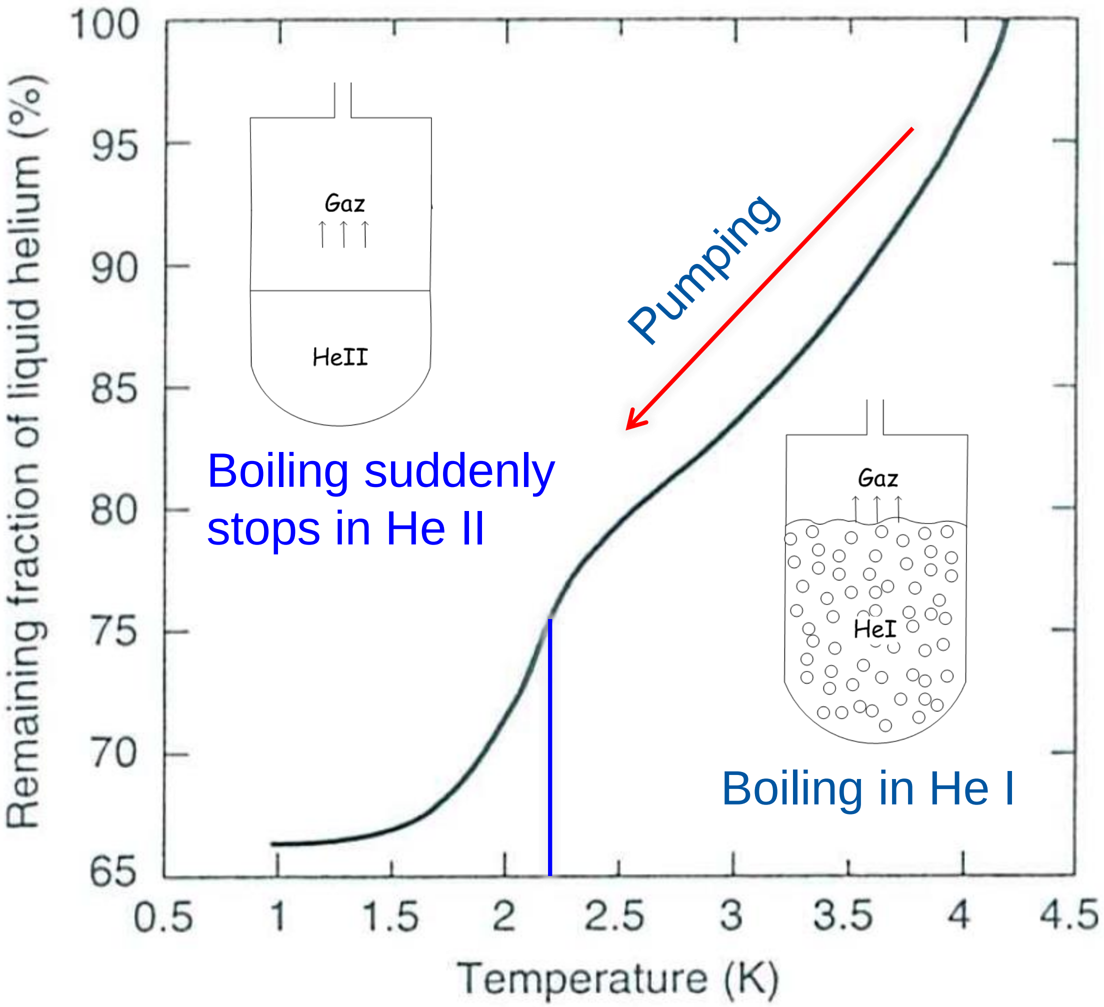
$T_\lambda \approx 2.1768$ K @

$p_\lambda \approx 50.41$ mbar

From Weisend, Handbook of Cryogenic Engineering, 1984.

Glass cryostat set-up





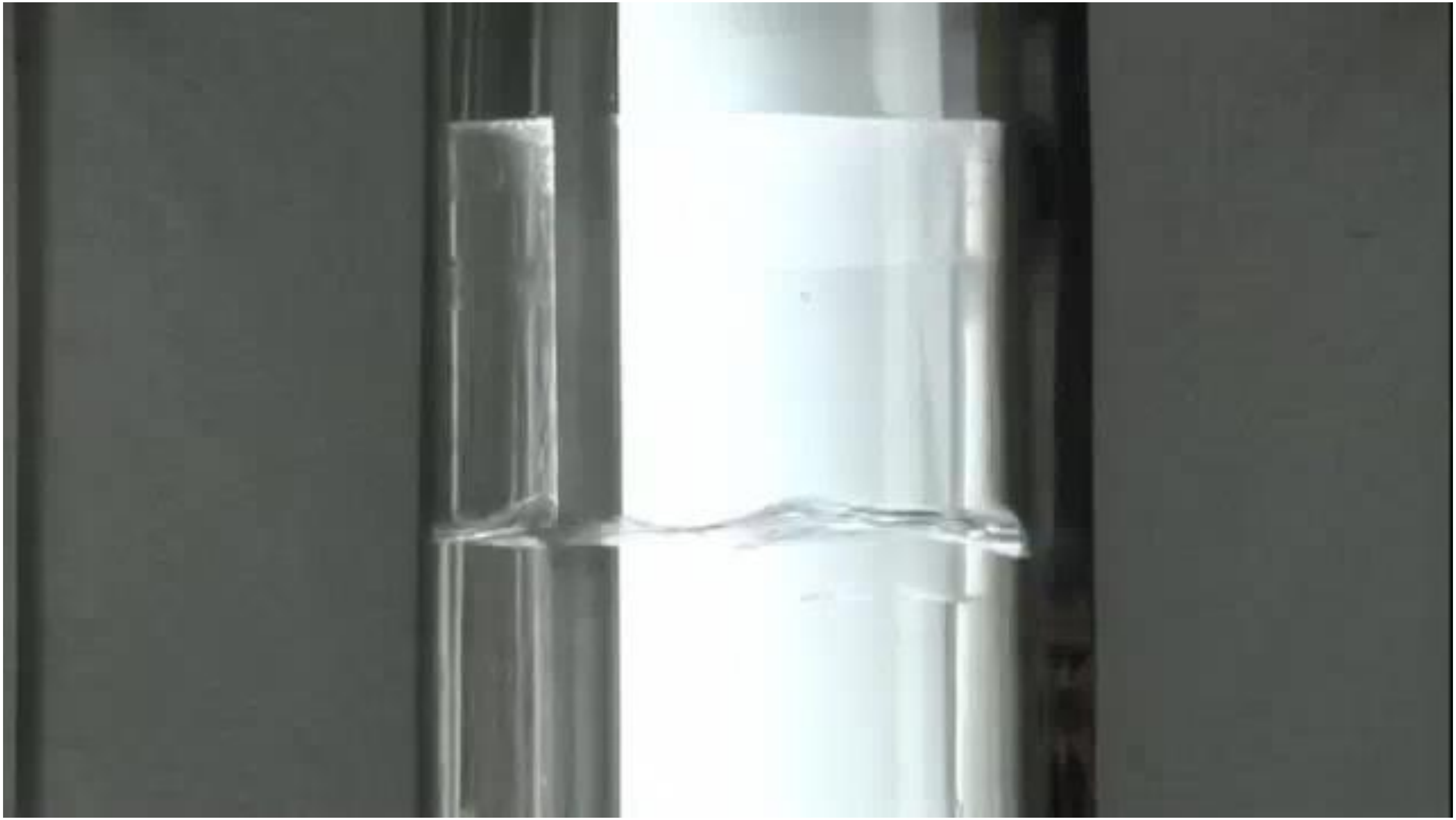
Pumping

Boiling suddenly stops in He II

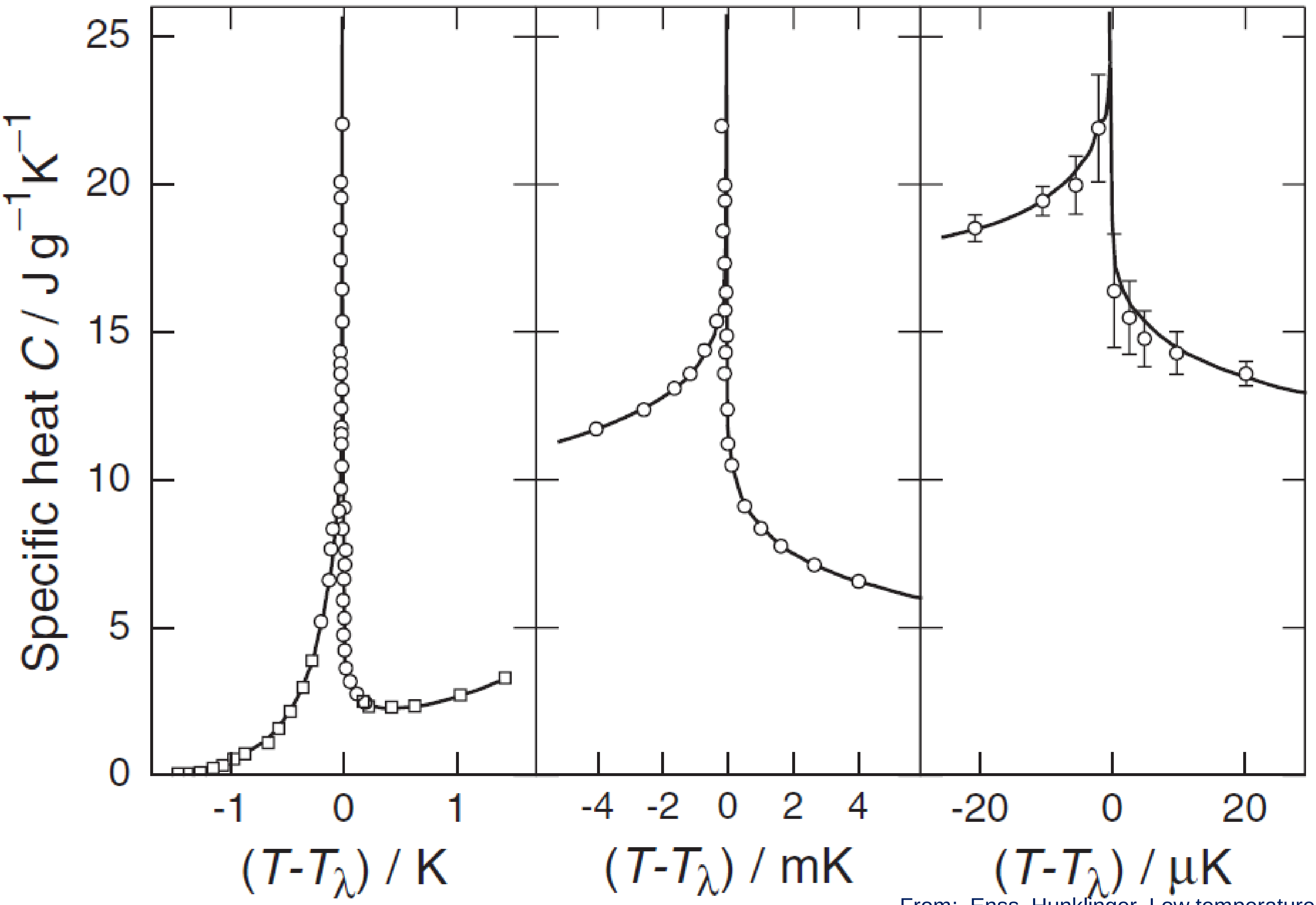
Boiling in He I

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

Boiling effects during cooldown / Pumping on the He vapour

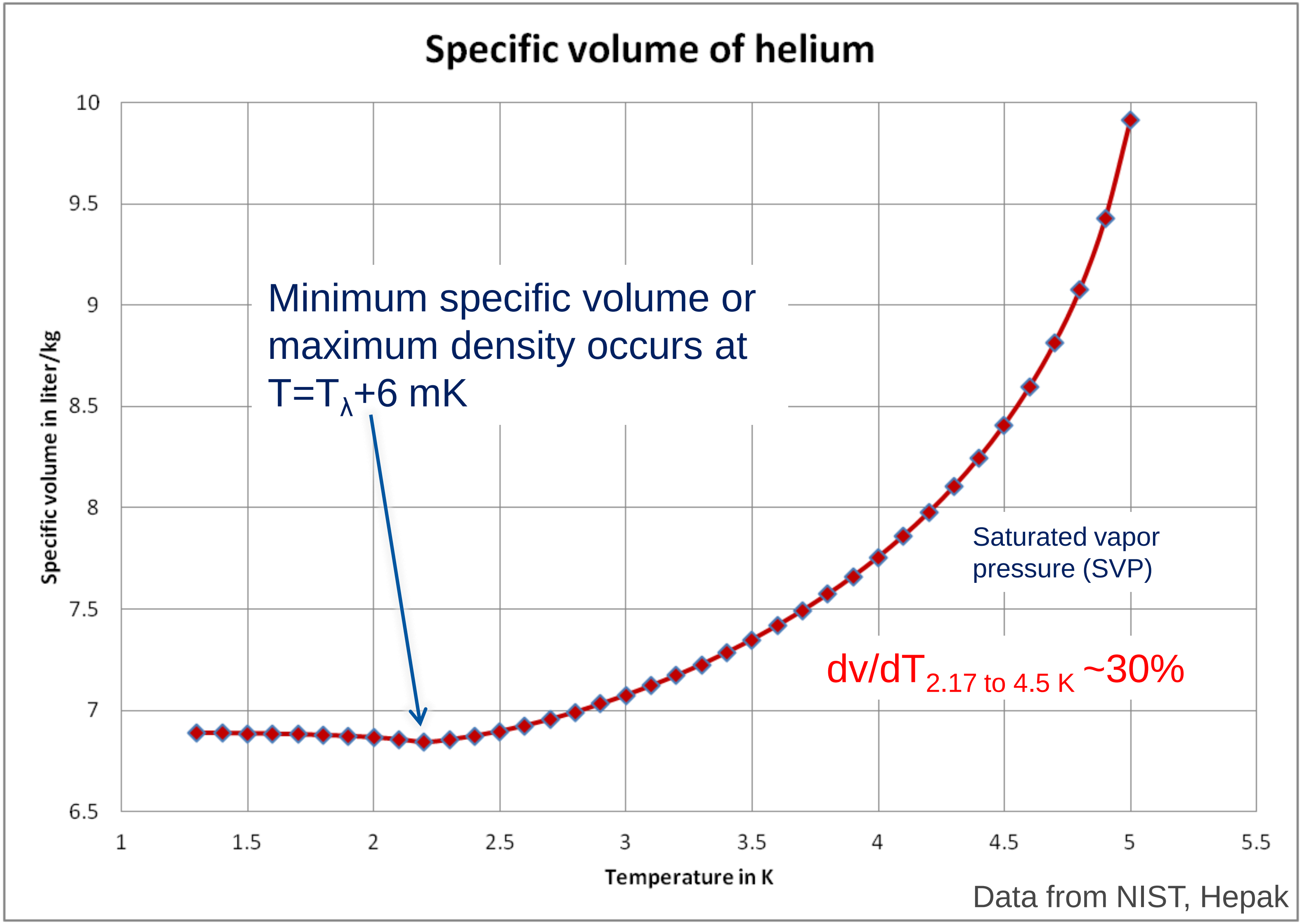


Heat capacity – Lambda point



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

Specific volume of ^{4}He



Minimum specific volume or maximum density occurs at $T=T_\lambda+6$ mK

Saturated vapor pressure (SVP)

$dv/dT_{2.17 \text{ to } 4.5 \text{ K}}$ ~30%

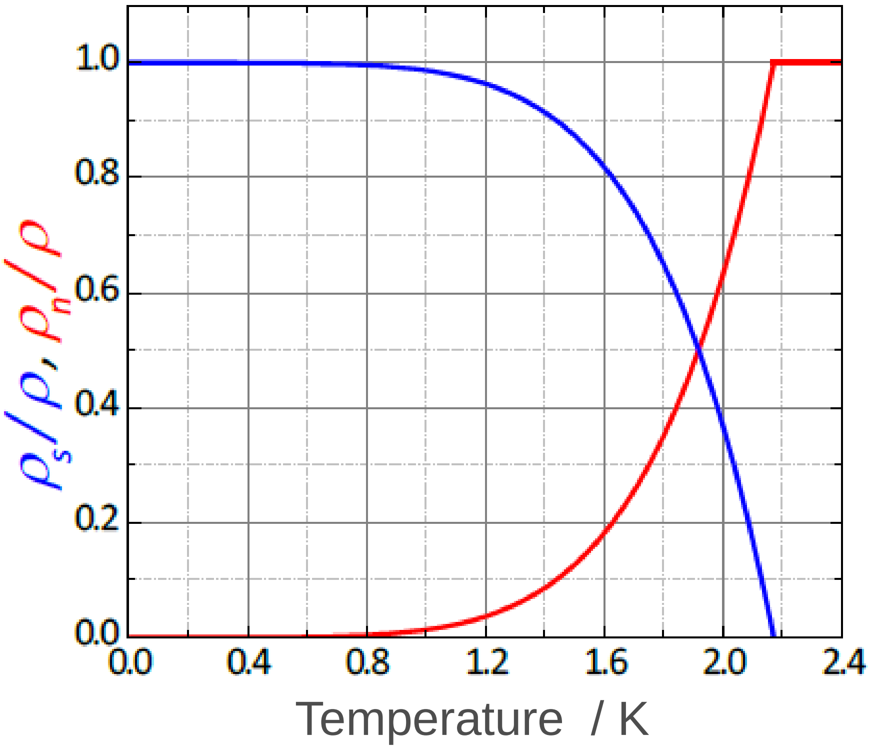
Data from NIST, Hepak

How to explain that unique behaviour ?

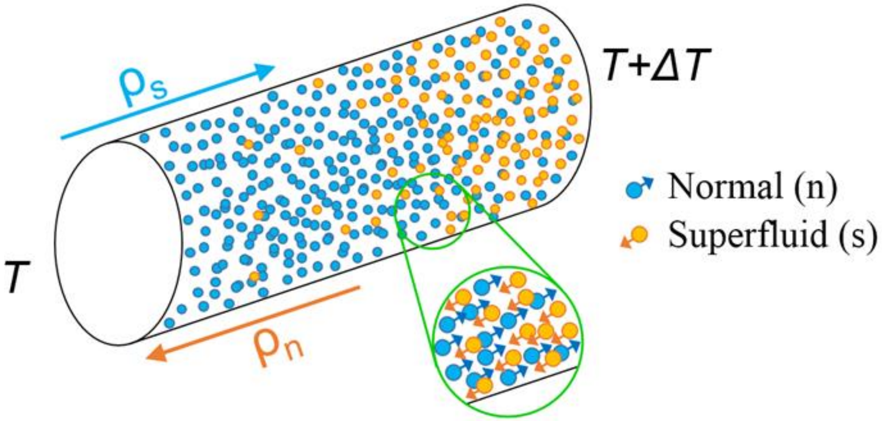
Two fluid model of L. Tisza:

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:

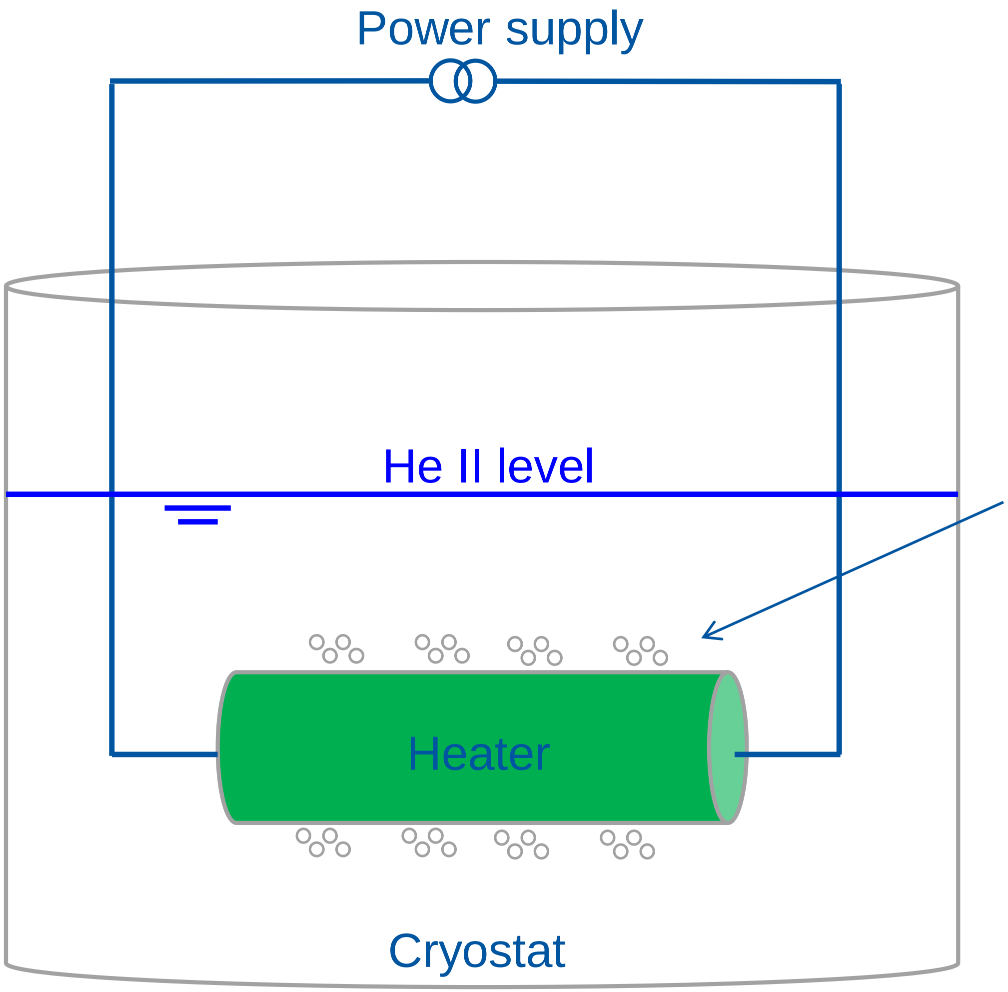
- carries total entropy: $S_n = S$
- finite viscosity: $\eta_n = \eta_n$

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)

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

Formation of vapor bubbles at the surface of the heater

In He II re-condensation of the vapor

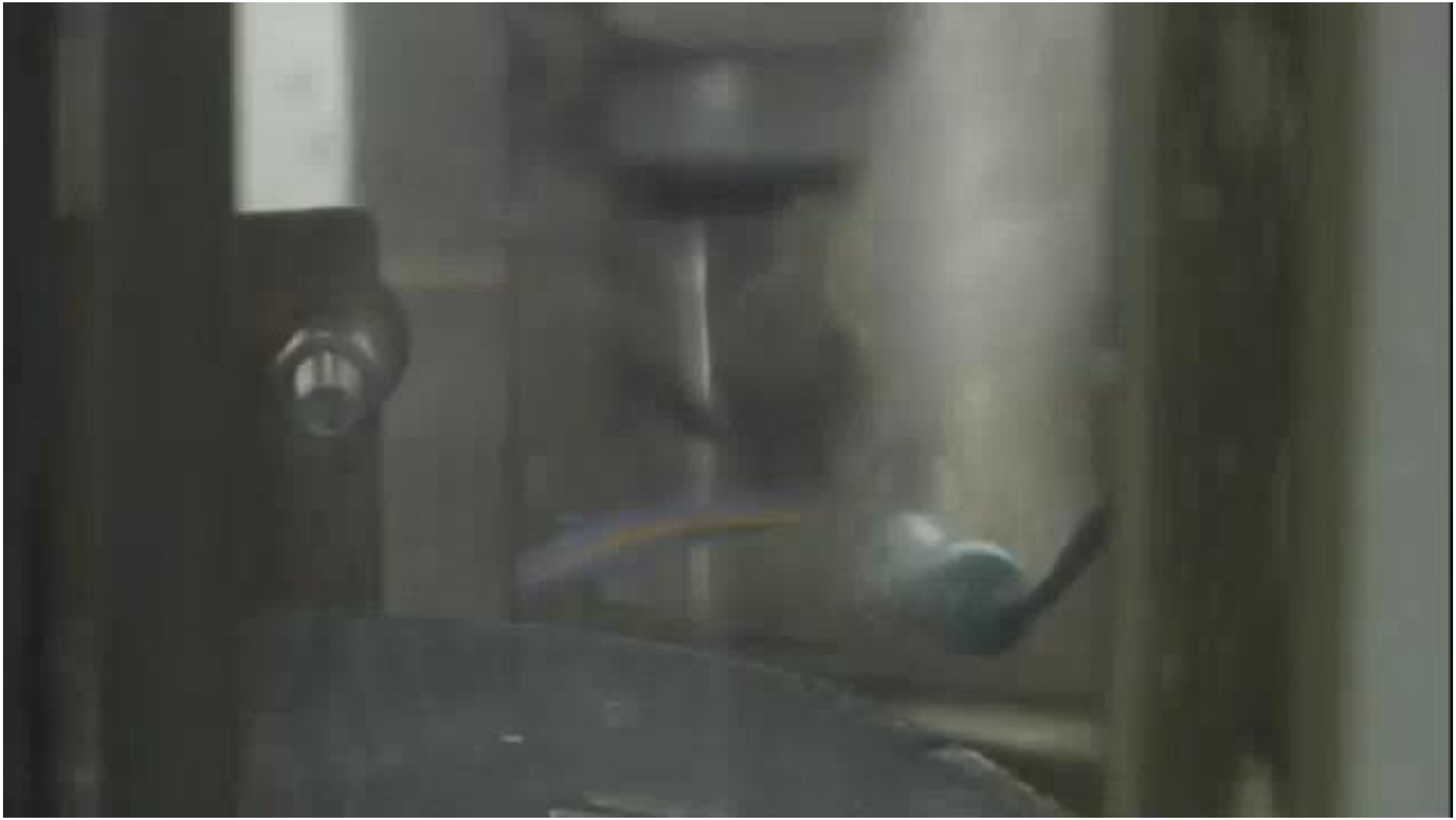
Surface tension let the bubbles implode

Implosion speed exceeds v_1

Shock wave => cavitation

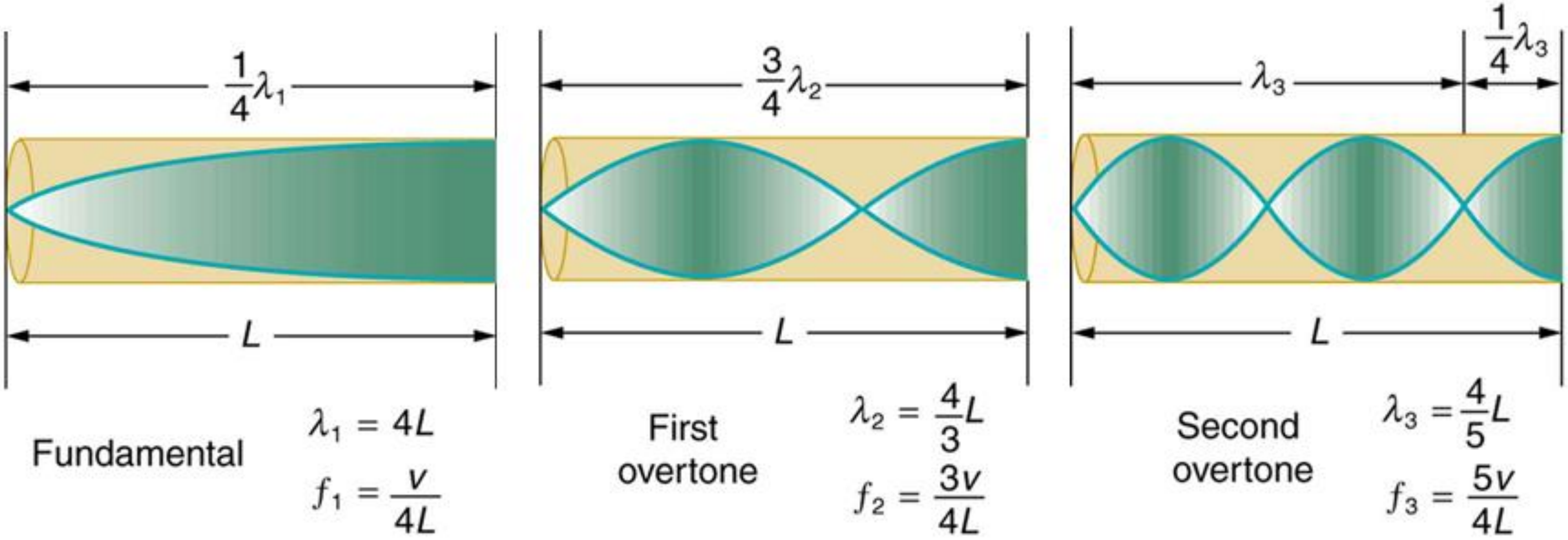
Critical heat flux in He II ($T<T_\lambda$)

Normal fluid cooling ($T>T_\lambda$)



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/.

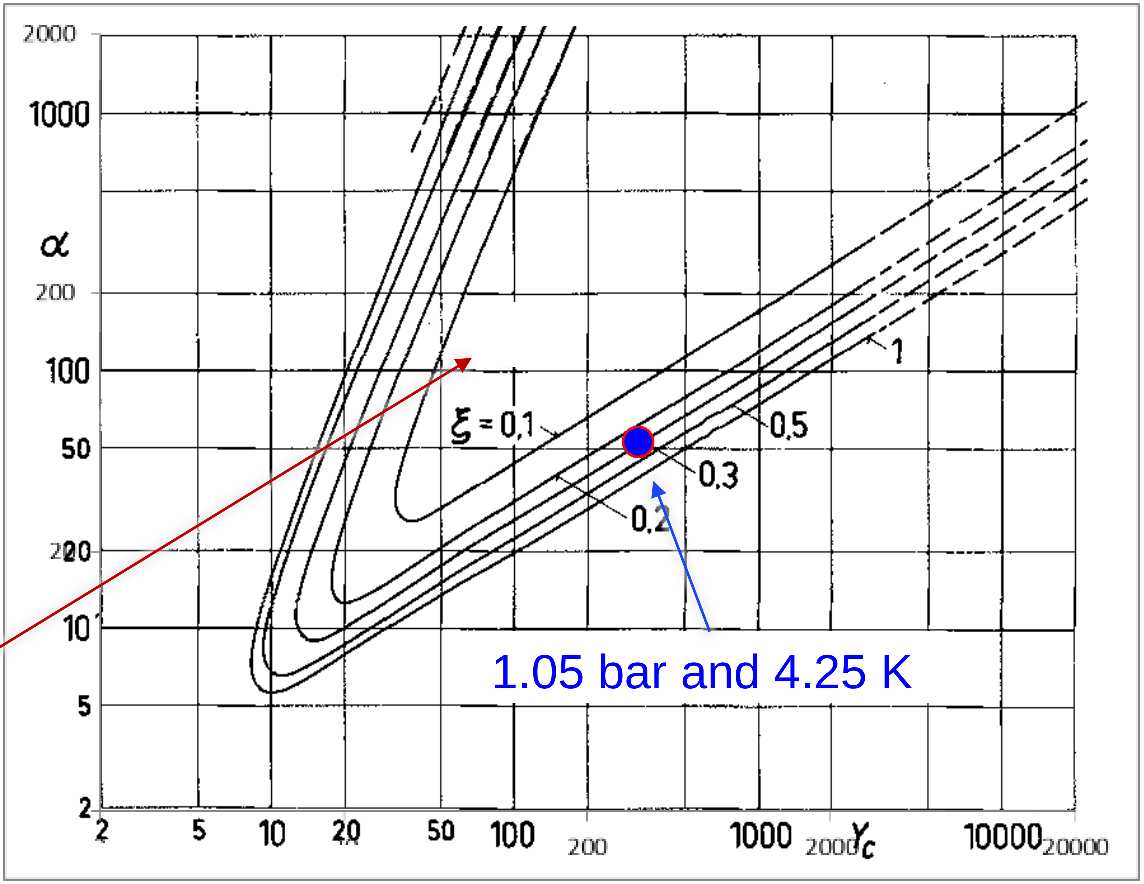
Thermo-acoustic oscillations (TAO or Taconis)

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



1.05 bar and 4.25 K

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

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

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

Concluding remarks

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

Some references

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- 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)
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- 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

Thank you for your attention.

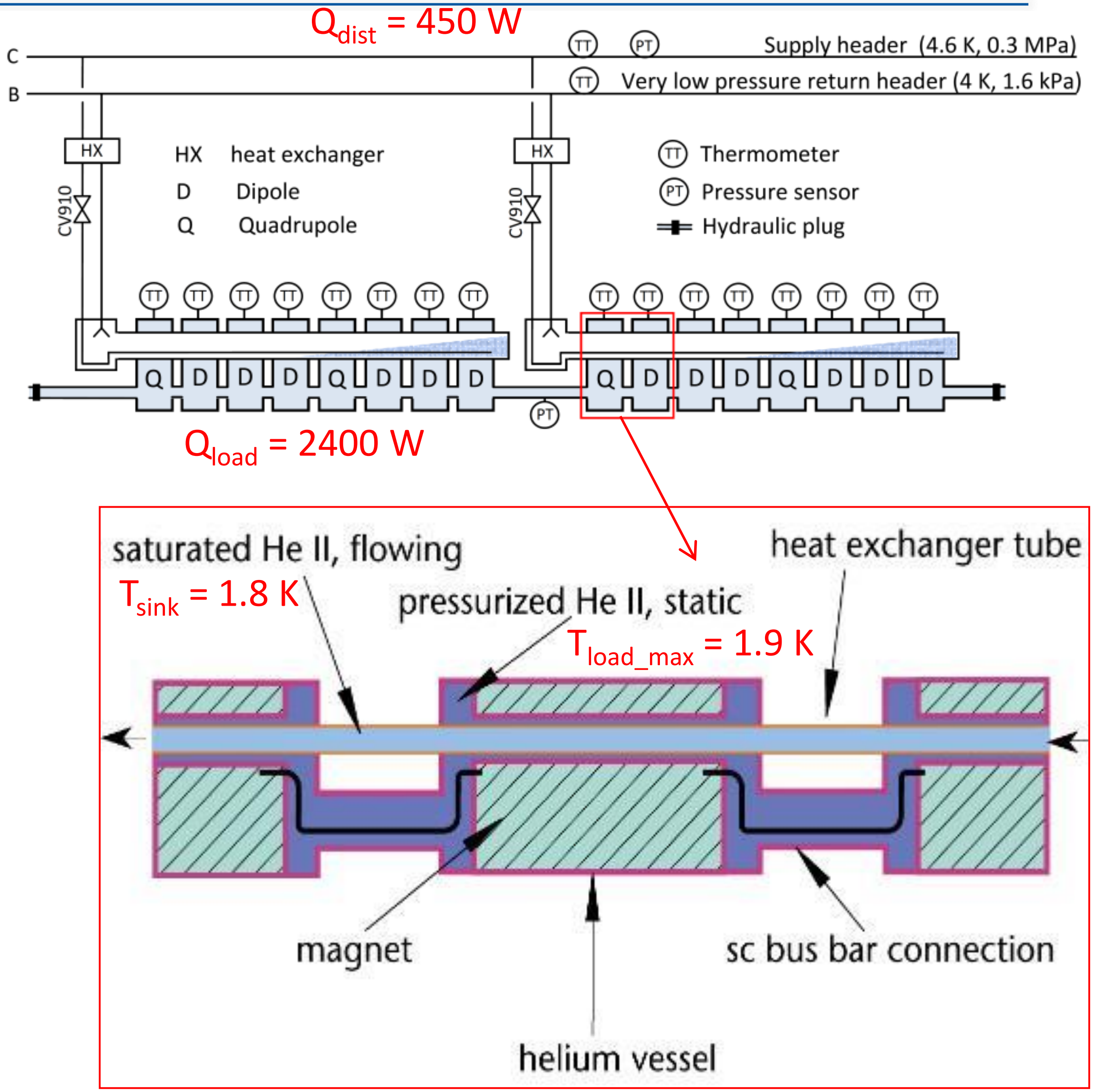
www.cern.ch

Spare slides

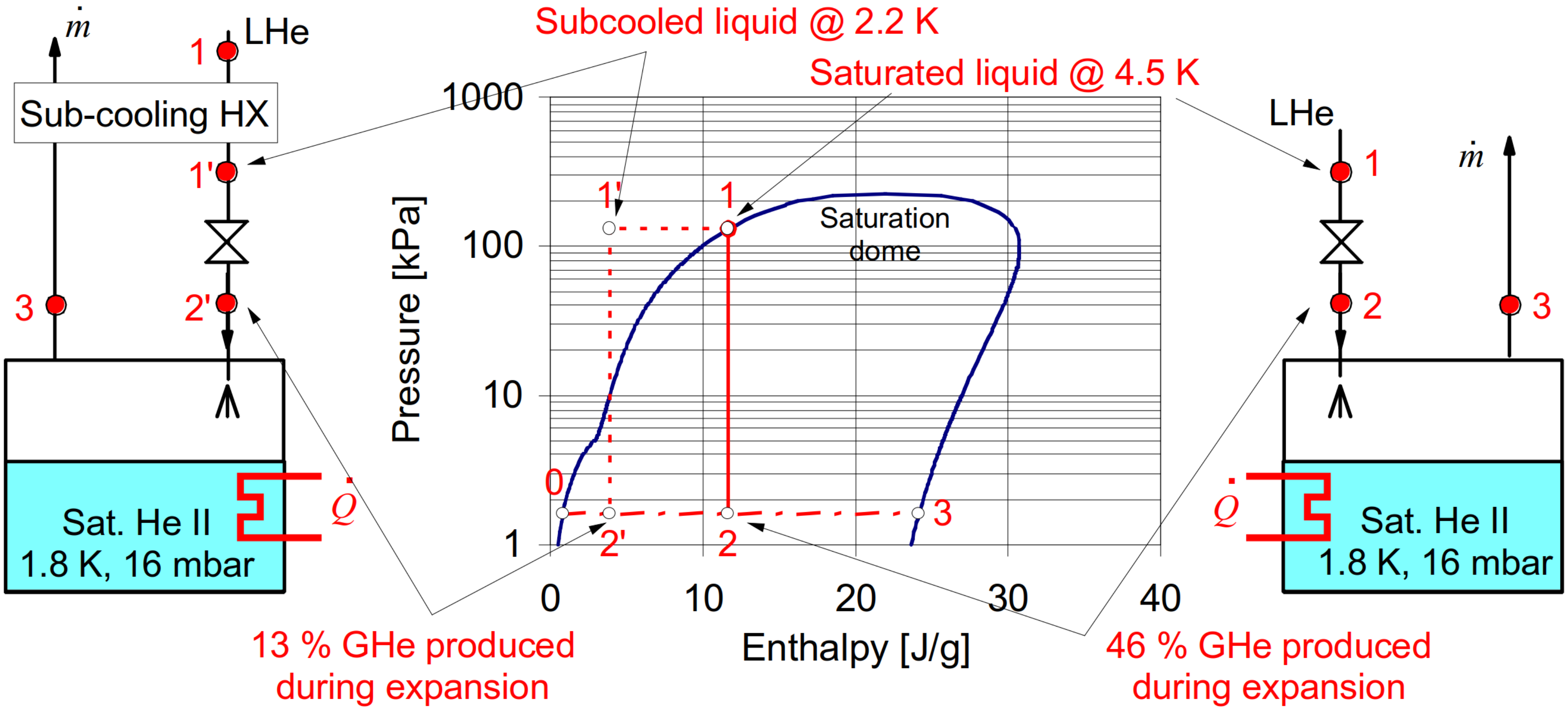
LHC cryogenic distribution scheme - QRL

Pressurized/saturated He II

37’500 tons at 1.9 K

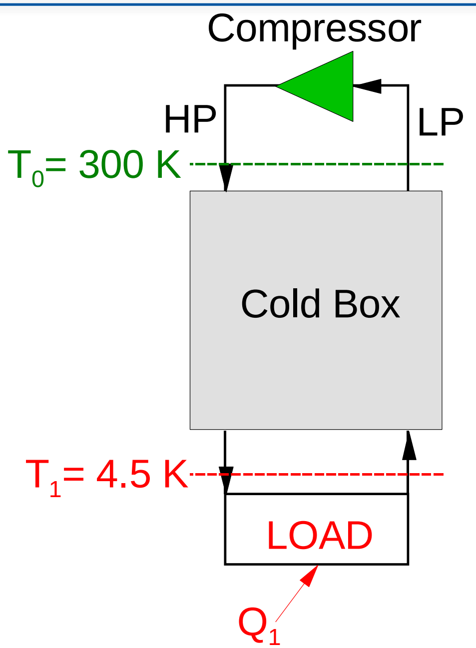


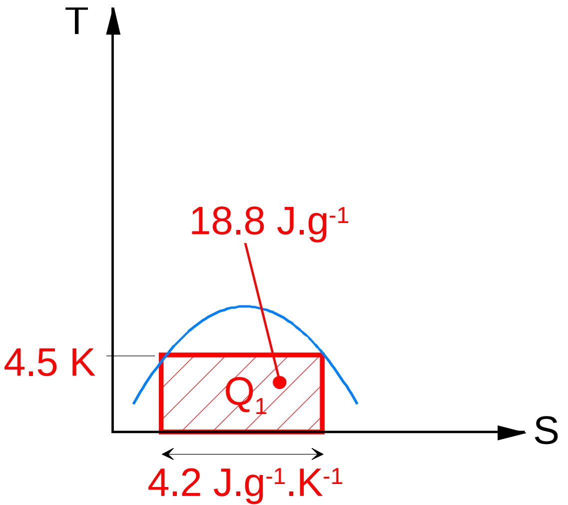
The effectiveness of J-T expansion



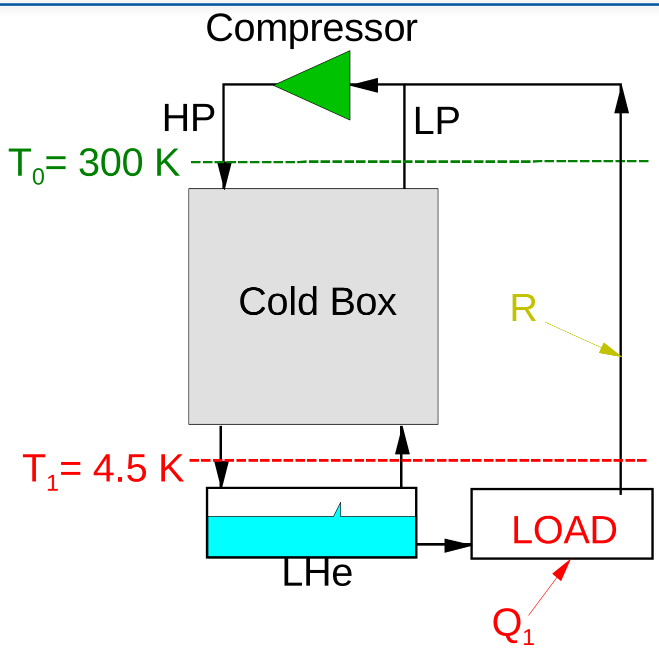
Source: Ph. Lebrun, Cooling with Superfluid Helium

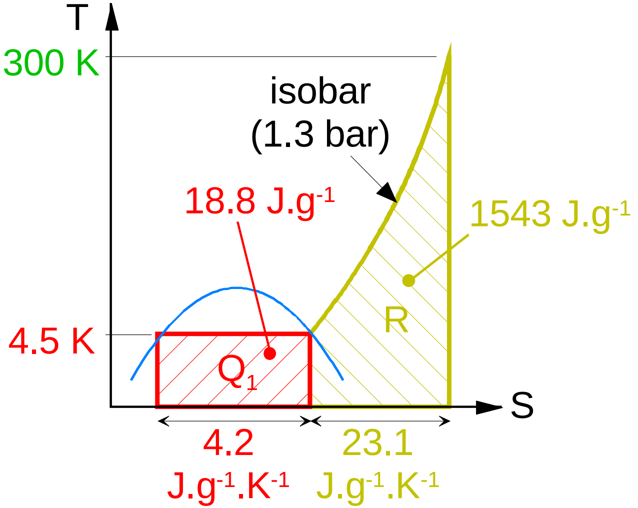
Refrigerator



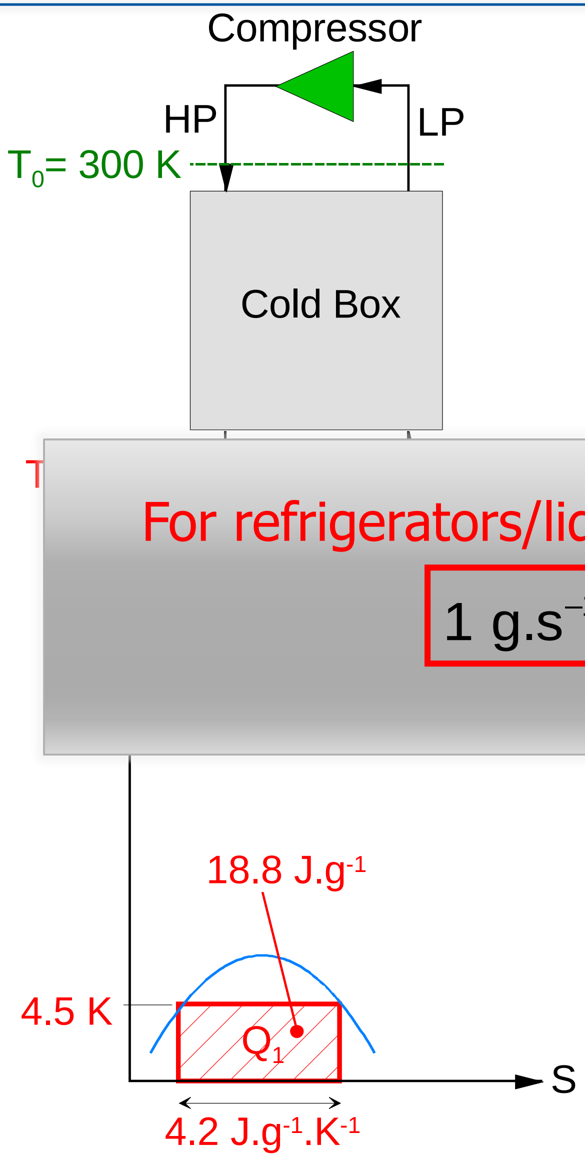


Liquefier

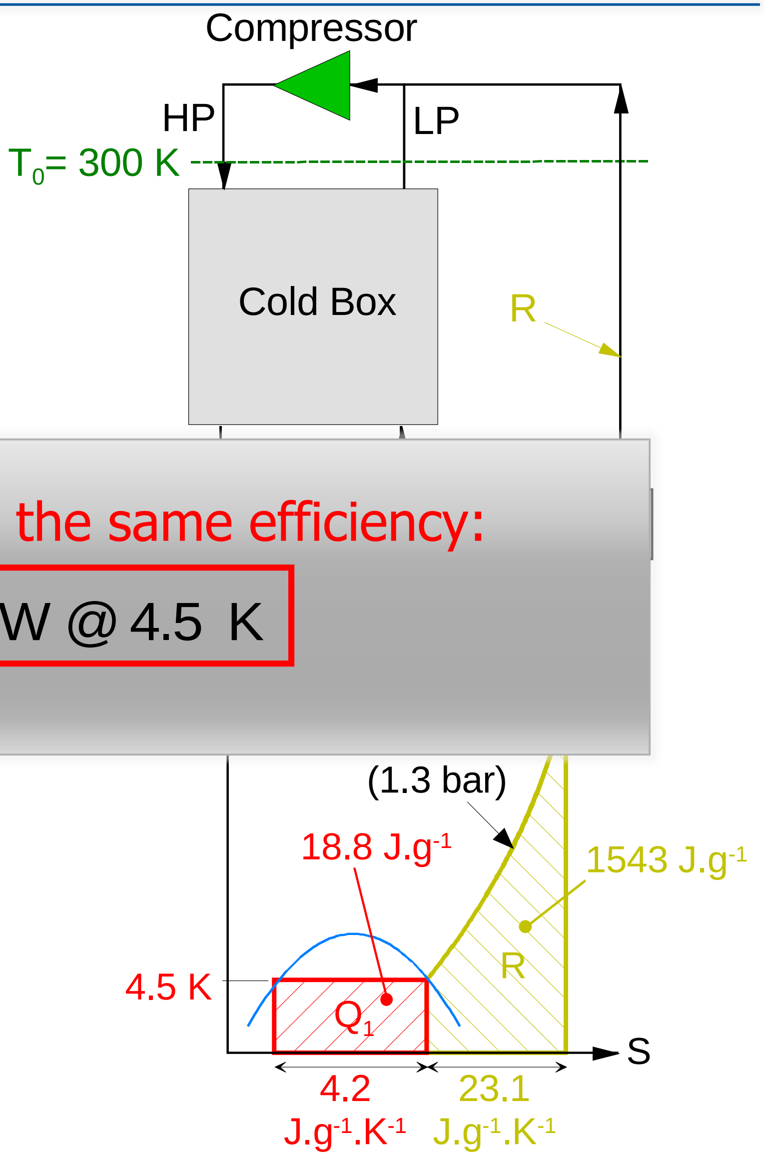




Refrigerator



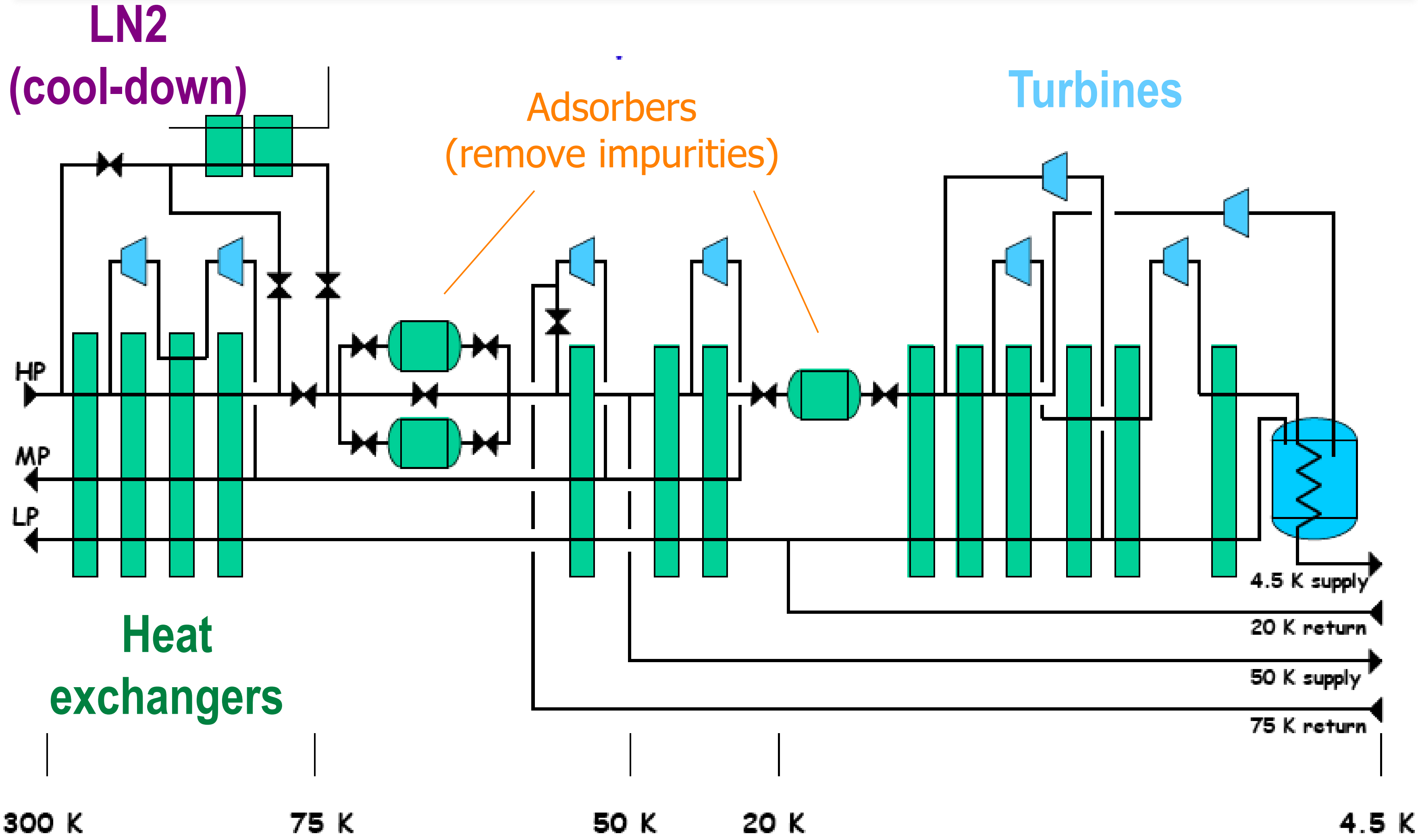
Liquefier



For refrigerators/liquefiers with the same efficiency:

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

Process diagram, LHC refrigerator 18 kW @ 4.5 K



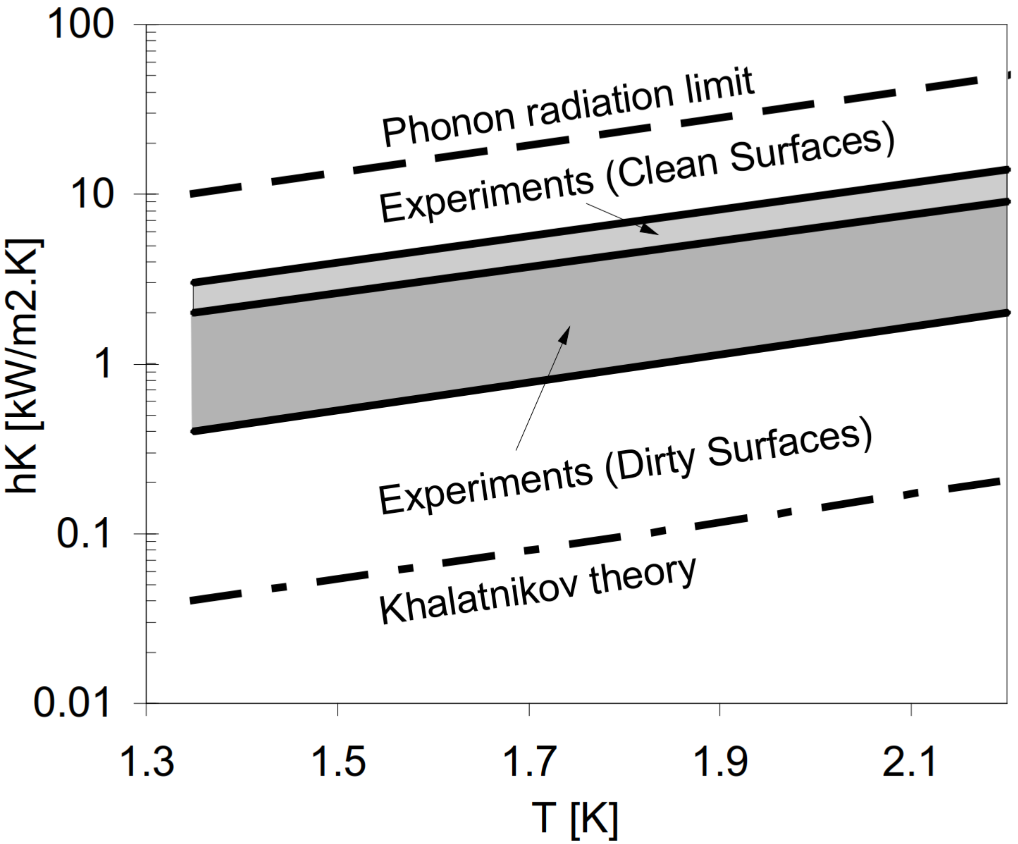
LN2 (cool-down)

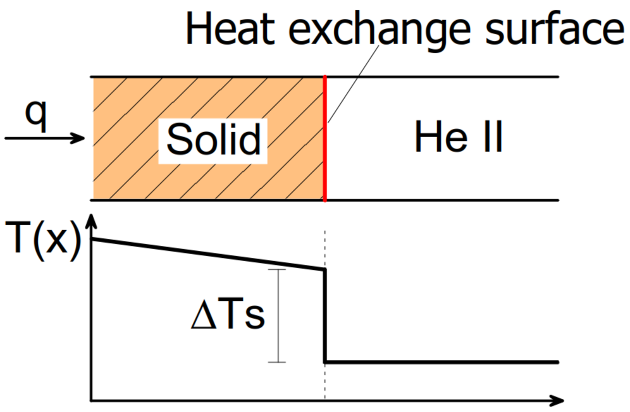
Adsorbers (remove impurities)

Turbines

Heat exchangers

Interface heat transfer at very low temperature





Valid for small heat flux

(when $\Delta T \ll T$)

Source: Ph. Lebrun, Cooling with Superfluid Helium