The technology of superfluid helium

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Cryostat Engineering for Helium Superconducting Devices
CERN, 7-9 November 2022

Contents

- Introduction to superfluid helium
- Superfluid helium as a technical coolant
- Practical cooling schemes
- Refrigeration below 2 K
- Specific technology for He II systems
- Applications

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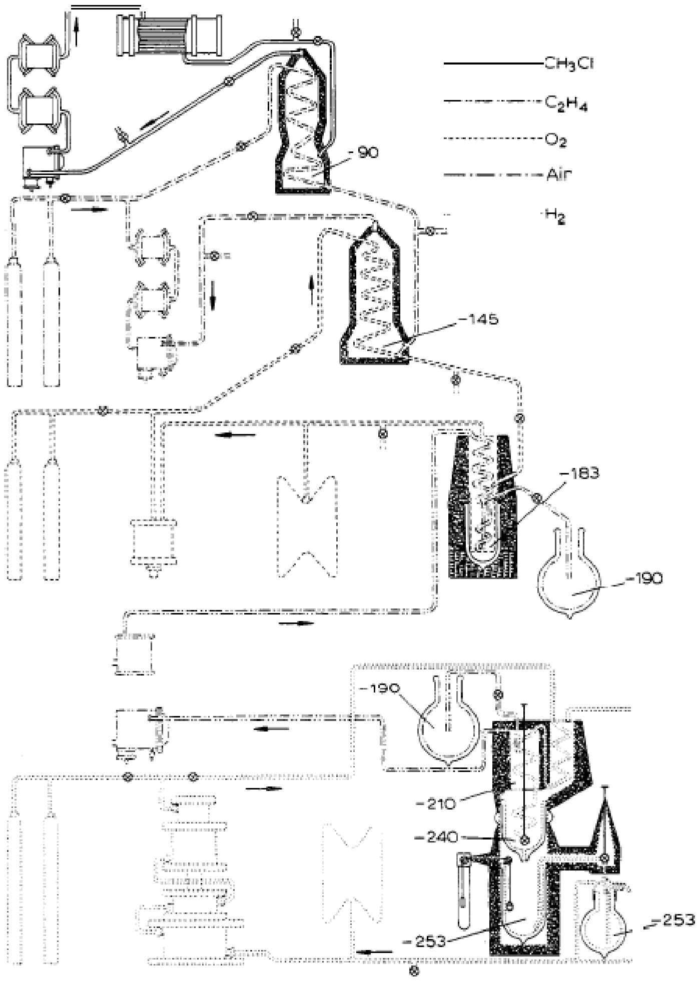
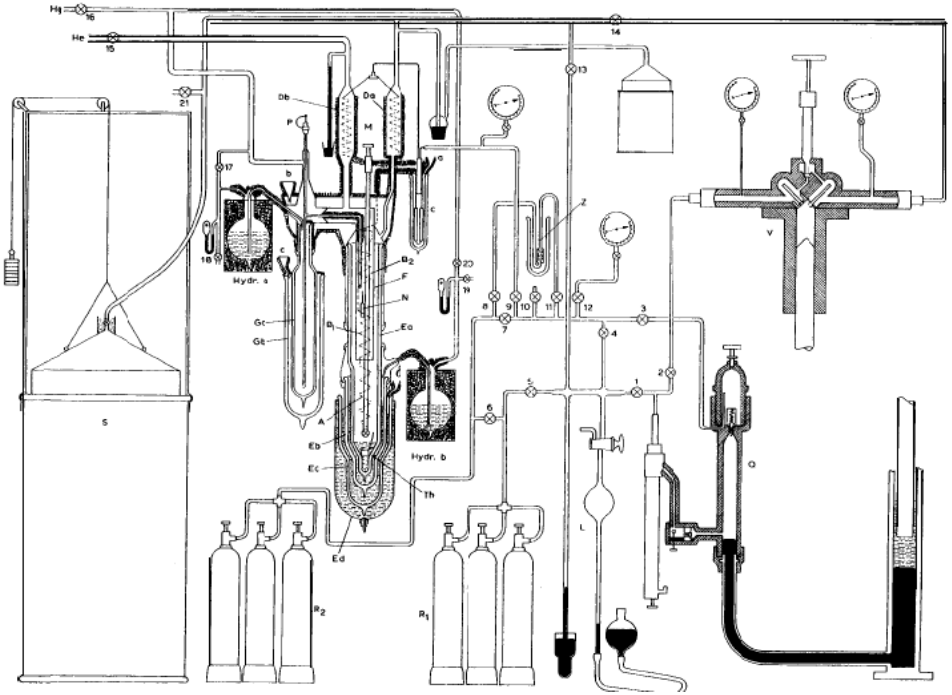
First liquefaction of helium (1908)



Leiden « cascade » to produce liquid hydrogen



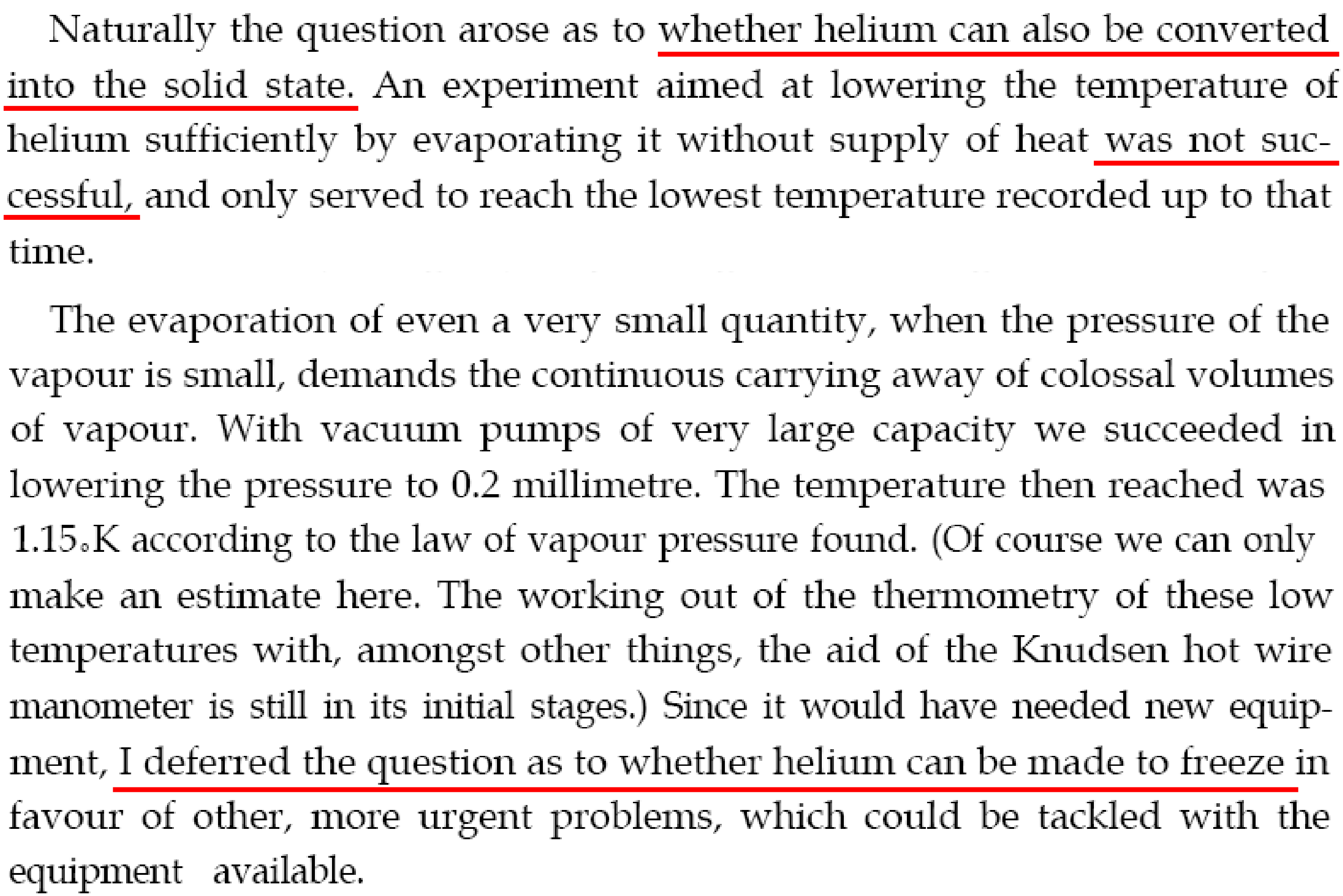
Helium liquefaction stage with liquid hydrogen precooling

HEIKE KAMERLINGH ONNES

Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium

Nobel Lecture, December 11, 1913

Unsuccessful attempt to solidify helium



Naturally the question arose as to whether helium can also be converted into the solid state. An experiment aimed at lowering the temperature of helium sufficiently by evaporating it without supply of heat was not successful, and only served to reach the lowest temperature recorded up to that time.

The evaporation of even a very small quantity, when the pressure of the vapour is small, demands the continuous carrying away of colossal volumes of vapour. With vacuum pumps of very large capacity we succeeded in lowering the pressure to 0.2 millimetre. The temperature then reached was 1.15°K according to the law of vapour pressure found. (Of course we can only make an estimate here. The working out of the thermometry of these low temperatures with, amongst other things, the aid of the Knudsen hot wire manometer is still in its initial stages.) Since it would have needed new equipment, I deferred the question as to whether helium can be made to freeze in favour of other, more urgent problems, which could be tackled with the equipment available.

Hint of a quantum effect…?

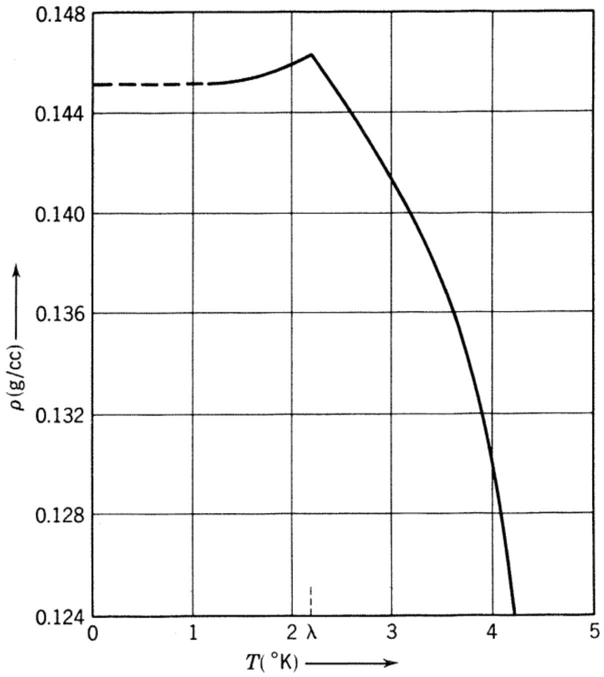


Fig. 1. Density of liquid helium as a function of temperature (after Kamerlingh Onnes and Boks[2]).

It is very noticeable that the experiments indicate that the density of the helium, which at first quickly drops with the temperature, reaches a maximum at 2.2°K approximately, and if one goes down further even drops again. Such an extreme could possibly be connected with the quantum theory.

Zero-point (quantum) energy prevents helium from solidifying

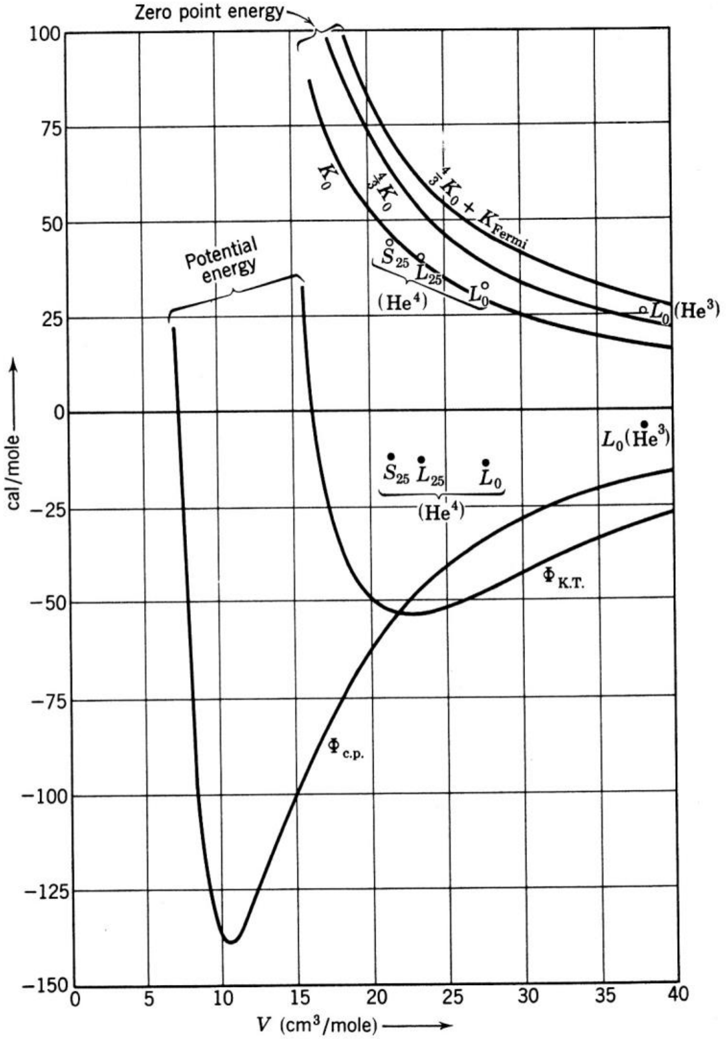
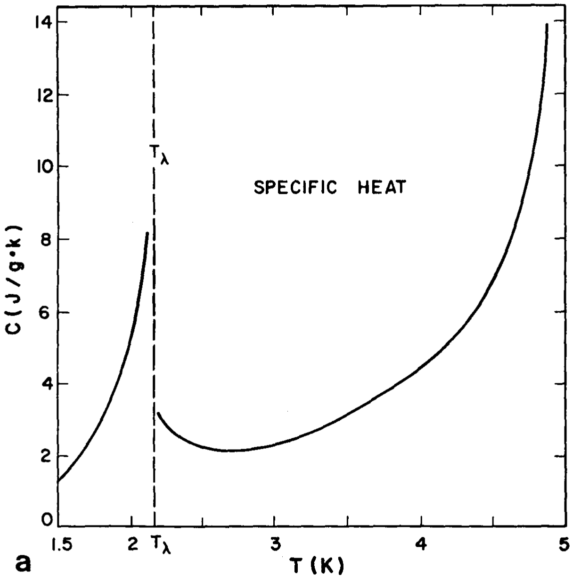


Fig. 15. The potential energy of the close-packed structure, $\Phi_{c.p.}$, and of the T_d^2 configuration suggested by Keesom and Taconis, $\Phi_{K.T.}$. The curve K_0 gives the zero point energy of eq. (6), §5. The solid circles refer to the experimental energy content of condensed He^4 and He^3 at 0°K. The open circles refer to the "experimental zero point energies," defined as the difference between the experimental total energies and the lowest potential energy.

F. London

Discovery of He II phase transition (1928)
Helium phase diagram (1933)



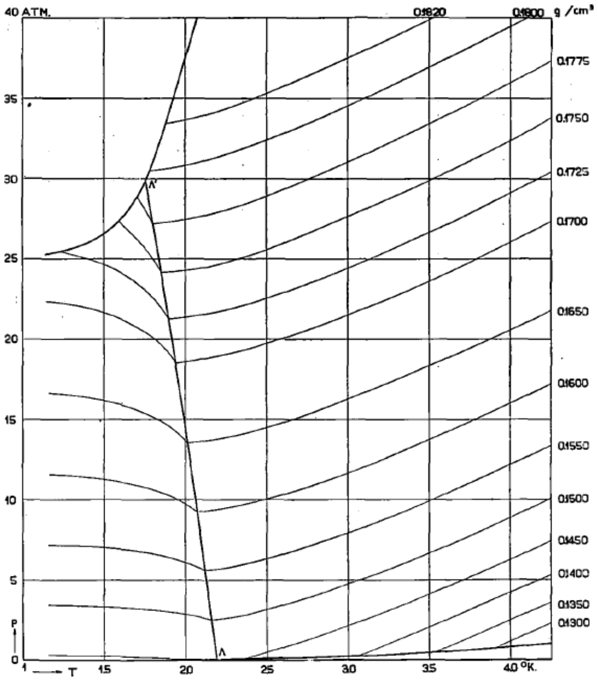


Fig. 1.

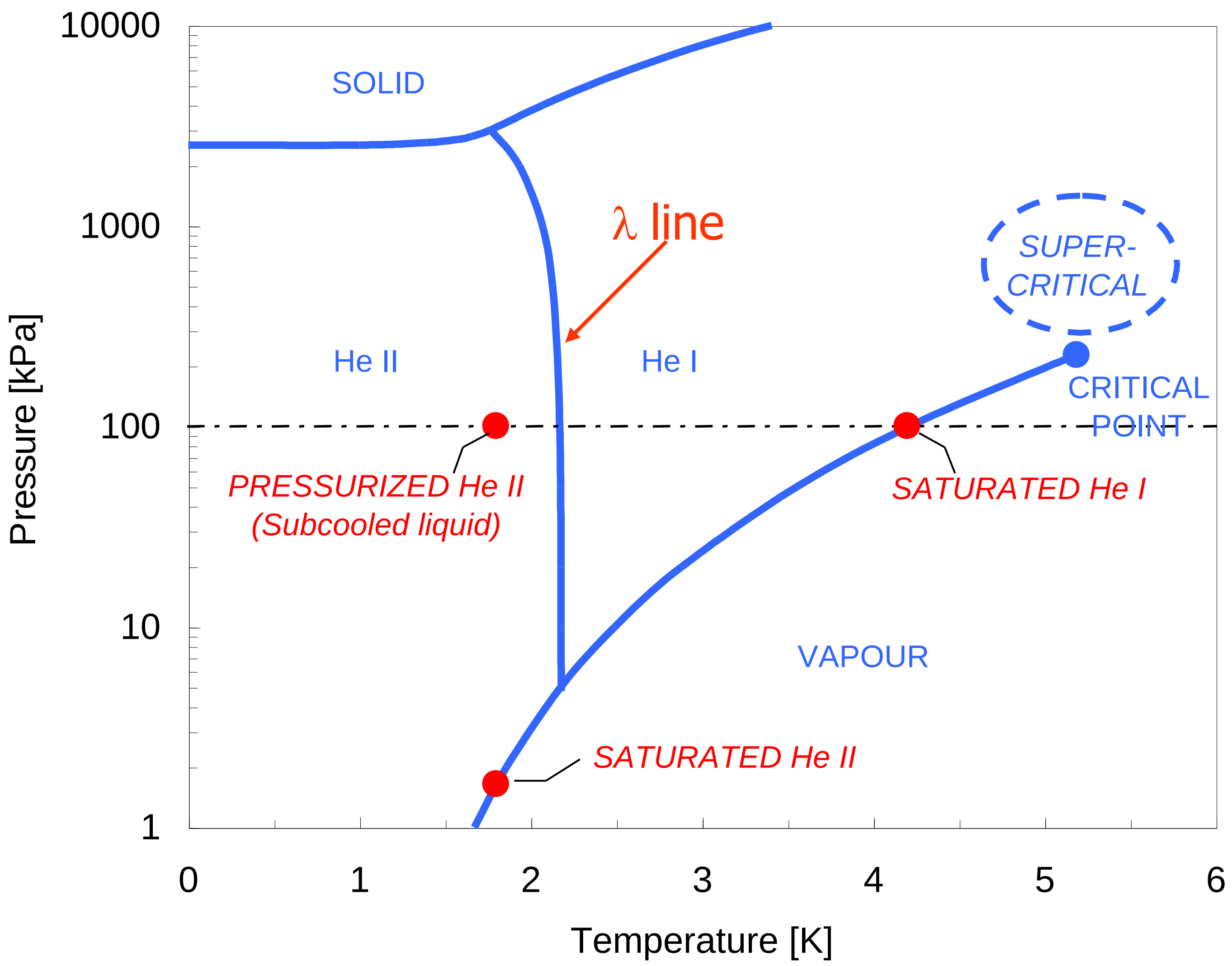
W.H. Keesom

THERMODYDAMIC DIAGRAMS OF LIQUID HELIUM

by W. H. KEESOM and Miss A. P. KEESOM

Supplement No. 76*b* to the Communications from the Kamerlingh Onnes Laboratory at Leiden

Phase diagram of helium

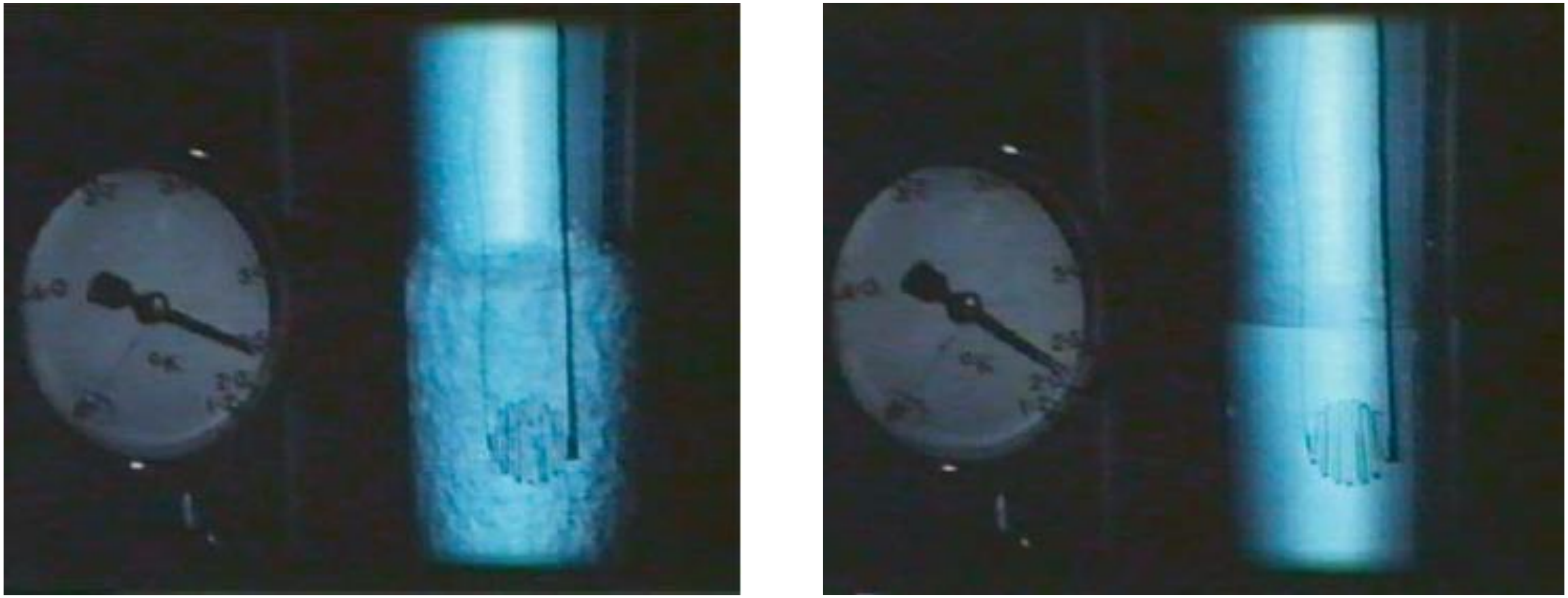


First signs of unusual thermal behaviour of He II (1935-1937)

J.O. Wilhem, A.D. Misener and A.R. Clark (Toronto)
W.H. Keesom and A. Keesom (Leiden)
J.F. Allen, R. Peierls and M.Z. Uddin (Cambridge)

- the viscosity of liquid He drops down below 2.2 K
- the thermal conductivity of liquid He increases below 2.2 K

Vaporization of liquid helium under applied heat load



He I (T=2.4 K)

He II (T=2.1 K)

Discovery of superfluidity in He II (1938)

P.L. Kapitsa (Moscow)

- *Viscosity of liquid helium below the lambda point*, Nature 141, 74 (Jan. 1938)
  - *through a 0.5 µm slit, liquid He does not flow above 2.2 K but flows very easily below 2.2 K*
  - *the viscosity of helium II is at least 1500 times less than that of helium I*
  - *by analogy with superconductors, ... the helium below the lambda-point enters a special state which might be called superfluid*

Discovery of superfluidity in He II (1938)

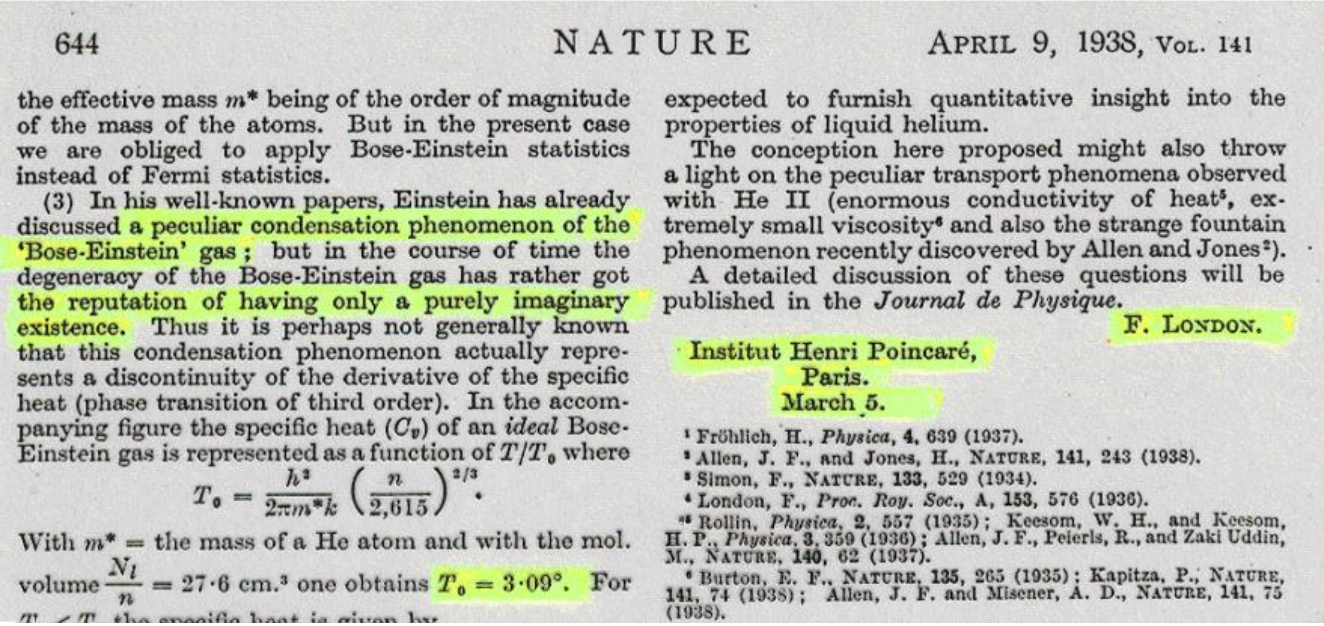
J.F. Allen & A.D. Misener (Cambridge)

- *Flow of liquid helium II*, Nature 141, 75 (Jan. 1938)
  - *through thin capillaries and below 2.2 K, the flow of liquid He is nearly independent of the pressure difference and of the capillary cross section*
  - *the observed type of flow ... in which the velocity becomes almost independent of pressure, most certainly cannot be treated as laminar or even as ordinary turbulent flow. Consequently, any known formula cannot, from our data, give a value of the viscosity which would have much meaning*

Theoretical approaches to superfluid helium [1/4]

Bose-Einstein condensation

Fritz London



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the effective mass m^* being of the order of magnitude of the mass of the atoms. But in the present case we are obliged to apply Bose-Einstein statistics instead of Fermi statistics.

(3) In his well-known papers, Einstein has already discussed a peculiar condensation phenomenon of the 'Bose-Einstein' gas; but in the course of time the degeneracy of the Bose-Einstein gas has rather got the reputation of having only a purely imaginary existence. Thus it is perhaps not generally known that this condensation phenomenon actually represents a discontinuity of the derivative of the specific heat (phase transition of third order). In the accompanying figure the specific heat (C_v) of an *ideal* Bose-Einstein gas is represented as a function of T/T_0 where

$$T_0 = \frac{h^2}{2\pi m^* k}\left(\frac{n}{2{,}615}\right)^{2/3}.$$

With m^* = the mass of a He atom and with the mol. volume $\frac{N_l}{n} = 27 \cdot 6$ cm.^{3} one obtains $T_0 = 3 \cdot 09°$. For

expected to furnish quantitative insight into the properties of liquid helium.

The conception here proposed might also throw a light on the peculiar transport phenomena observed with He II (enormous conductivity of heat[5], extremely small viscosity[6] and also the strange fountain phenomenon recently discovered by Allen and Jones[2]).

A detailed discussion of these questions will be published in the *Journal de Physique*.

F. LONDON.

Institut Henri Poincaré,
Paris.
March 5.

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[1] Fröhlich, H., *Physica*, **4**, 639 (1937).

[2] Allen, J. F., and Jones, H., NATURE, **141**, 243 (1938).

[3] Simon, F., NATURE, **133**, 529 (1934).

[4] London, F., *Proc. Roy. Soc.*, A, **153**, 576 (1936).

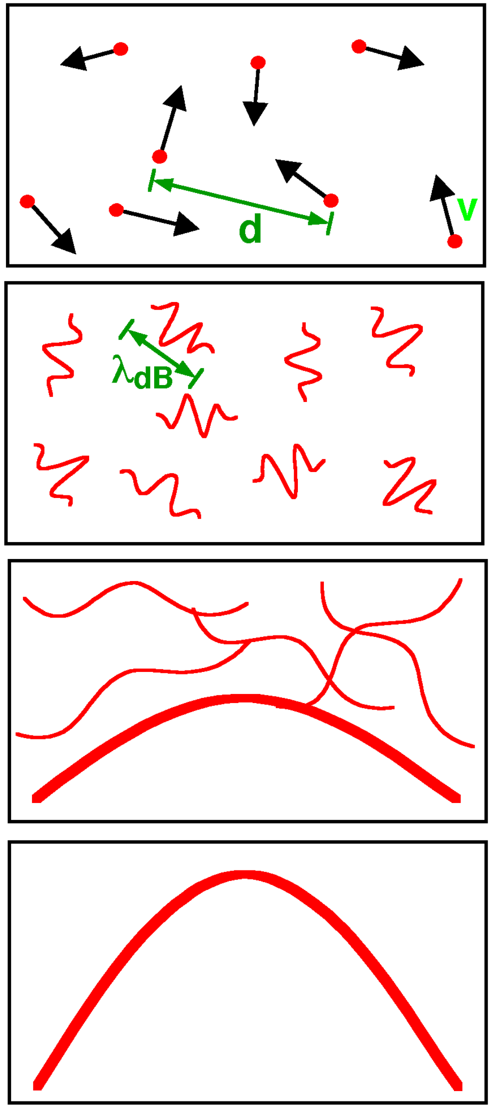
[5] Rollin, *Physica*, **2**, 557 (1935); Keesom, W. H., and Keesom, H. P., *Physica*, **3**, 359 (1936); Allen, J. F., Peierls, R., and Zaki Uddin, M., NATURE, **140**, 62 (1937).

[6] Burton, E. F., NATURE, **135**, 265 (1935); Kapitza, P., NATURE, **141**, 74 (1938); Allen, J. F. and Misener, A. D., NATURE, **141**, 75 (1938).

$$T_{\mathrm{BEC}} = \left(\frac{2\pi\hbar^2}{1.897 m k_B}\right) n^{2/3}$$

it seems difficult not to imagine a connexion with the condensation phenomenon of the Bose-Einstein statistics… On the other hand, it is obvious that a model which is so far away from reality that it simplifies liquid helium to an ideal gas…

Bose-Einstein condensation in gas of particles
(from W. Ketterle)



High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

"Wave packets"

$T=T_{crit}$:

Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0:

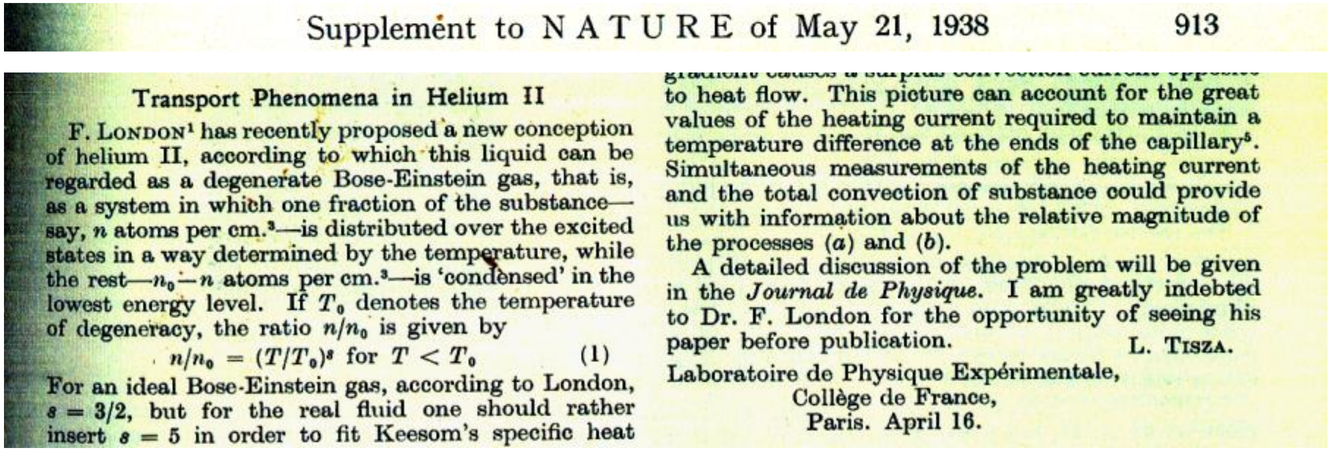
Pure Bose condensate

"Giant matter wave"

Theoretical approaches to superfluid helium [2/4]

Two-fluid model

Laszlo Tisza



Supplement to NATURE of May 21, 1938 913

Transport Phenomena in Helium II

F. London[1] has recently proposed a new conception of helium II, according to which this liquid can be regarded as a degenerate Bose-Einstein gas, that is, as a system in which one fraction of the substance—say, n atoms per cm.[3]—is distributed over the excited states in a way determined by the temperature, while the rest—$n_0 - n$ atoms per cm.[3]—is 'condensed' in the lowest energy level. If T_0 denotes the temperature of degeneracy, the ratio n/n_0 is given by

$$n/n_0 = (T/T_0)^s \text{ for } T < T_0 \qquad (1)$$

For an ideal Bose-Einstein gas, according to London, $s = 3/2$, but for the real fluid one should rather insert $s = 5$ in order to fit Keesom's specific heat

to heat flow. This picture can account for the great values of the heating current required to maintain a temperature difference at the ends of the capillary[5]. Simultaneous measurements of the heating current and the total convection of substance could provide us with information about the relative magnitude of the processes (*a*) and (*b*).

A detailed discussion of the problem will be given in the *Journal de Physique*. I am greatly indebted to Dr. F. London for the opportunity of seeing his paper before publication.

L. Tisza.

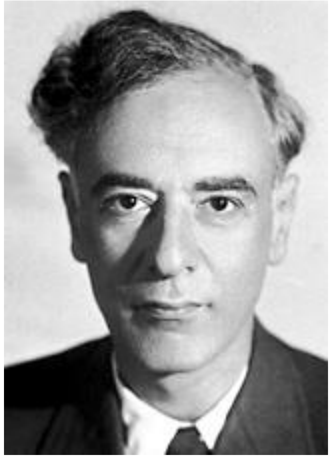
Laboratoire de Physique Expérimentale,
Collège de France,
Paris. April 16.

liquid He should have two components:

- *condensed atoms would be the superfluid component which has zero viscosity and carries no entropy*
- *non-condensed atoms would be a normal viscous component carrying all the entropy of the whole fluid*
- *the respective densities* ρ_s *and* ρ_n *would only depend on* T $(\rho_s + \rho_n = \rho)$

Theoretical approaches to superfluid helium [3/4]

Quasi-particle description



Lev Davidovich Landau

$$\epsilon = \hbar\omega = \Delta + \frac{(p-p_0)^2}{2\mu}$$

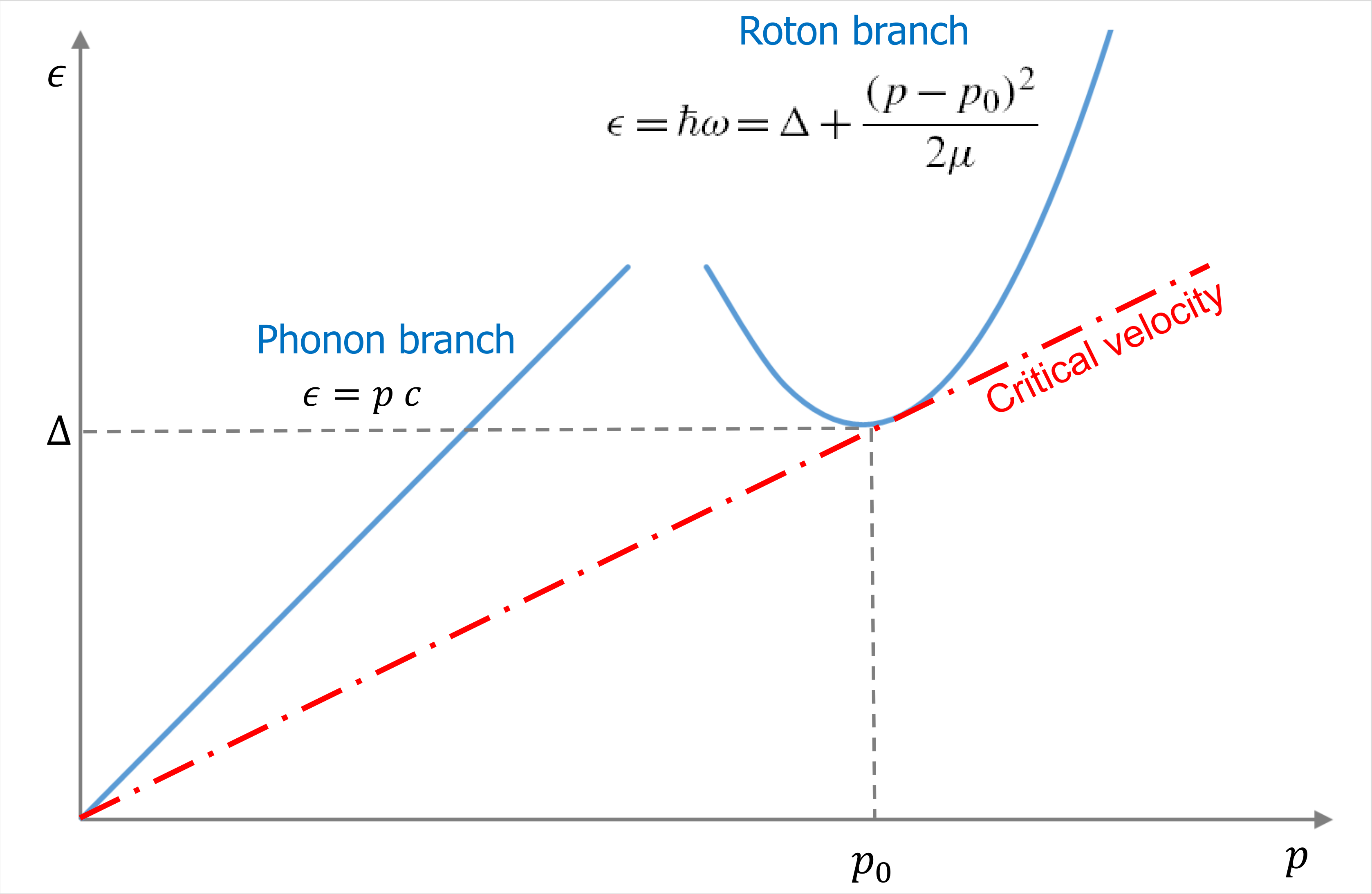
- *L. Tisza suggested that helium II should be considered as a degenerate ideal Bose gas... This point of view, however, cannot be considered as satisfactory... nothing would prevent atoms in a normal state from colliding with excited atoms, i.e. when moving through the liquid they would experience a friction and there would be no superfluidity at all*

- *every weakly excited state can be considered as an aggregate of single elementary excitations:*
  - *sound quanta (phonons)* $\varepsilon = cp$
  - *elementary vortices (rotons)* $\varepsilon = \Delta + (p-p_0)^2/2\mu$

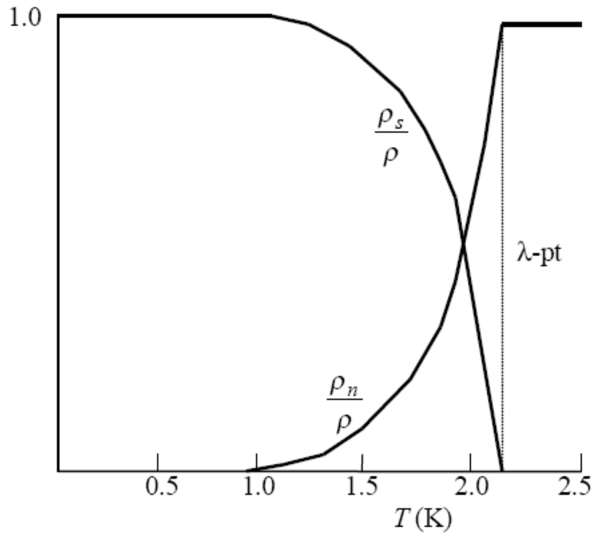
- *dissipation requires emission of either phonons or rotons, that is a minimum velocity*

Theoretical approaches to superfluid helium [4/4]

Quasi-particle description



Two-fluid model of He II



Phenomenological model

Two interpenetrating fluids

$\rho = \rho_s + \rho_n$

Normal & superfluid fractions varying with T

$\rho\, v = \rho_s\, v_s + \rho_n\, v_n$

$\rho\, s = \rho_n\, s_n$ since $s_s = 0$

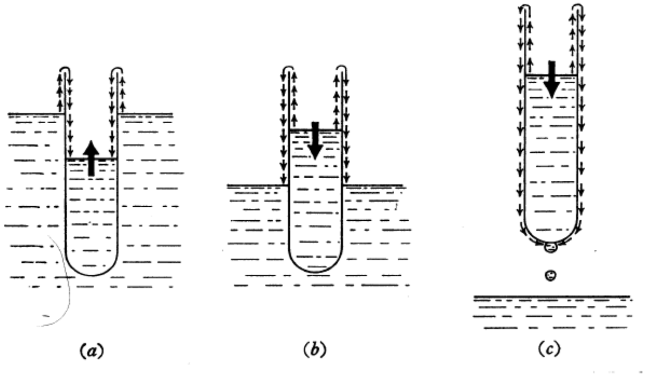
All entropy carried by normal component

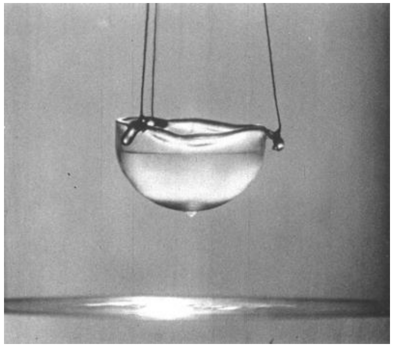
Physical basis of the two-fluid model

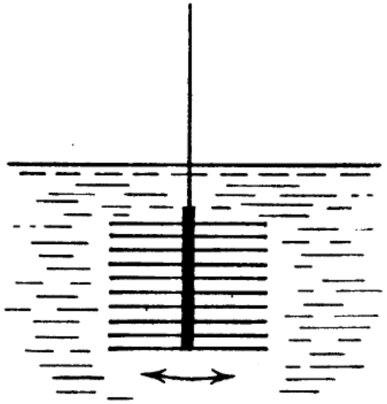
- *Collective excitations constitute the normal component (Landau)*
- *B-E condensate in liquid (Penrose & Onsager)*

He II behaviour explained by two-fluid model [1/2]

- Film flow
  - Frictionless flow of surface tension film
- Measured viscosity depends on the measurement method
  - Frictionless leakage through capillary channels
  - Finite viscosity by rotating cylinder method
- Andronikashvili experiment
  - Rotating cylinder replaced by stack of finely-spaced disks
  - Only normal component entrained by stack rotation
  - Effective moment of inertia depends on normal fluid density, varies with temperature

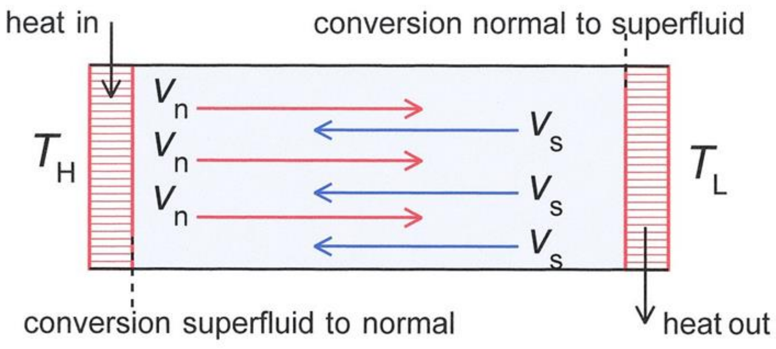


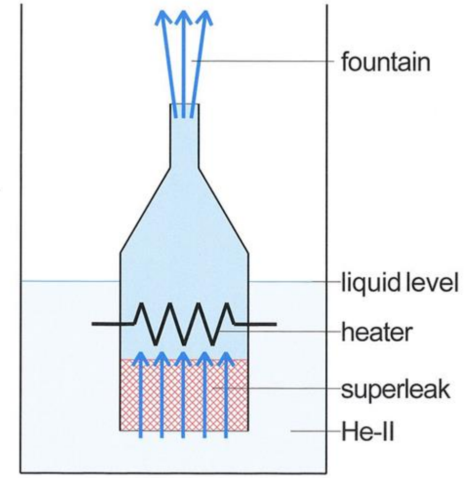


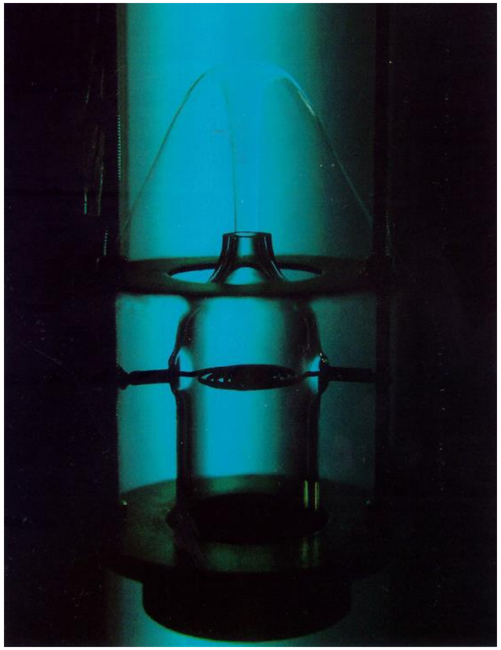


He II behaviour explained by two-fluid model [2/2]

- Thermal transport by counterflow
- Thermomechanical
  - Fountain effect
  - Superfluid pump
- Longitudinal wave propagation
  - Two fluids in phase: first sound (~240 m/s)
  - Two fluids in antiphase: second sound (~20 m/s)







Thermophysical properties of helium

- A convenient property software, used in the Cryogenics course, is REFPROP by NIST, which unfortunately does not cover the superfluid range.
- In this we use HEPAK by CRYODATA
  - Valid from 0.8 K (or the melting line) to 1500 K temperature
  - Valid up to 1000 bar pressure (20’000 bar between 80 and 300 K)
- Some HEPAK functions are available in EXCEL, in particular HeCalc which returns the calculated value of the thermodynamic property to the calling program

  HeCalc(Index, Phase, Input1, Value1, Input2, value2, Unit)

- Contact person: Rob van Weelderen, TE-CRG

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Benefits of He II cooling

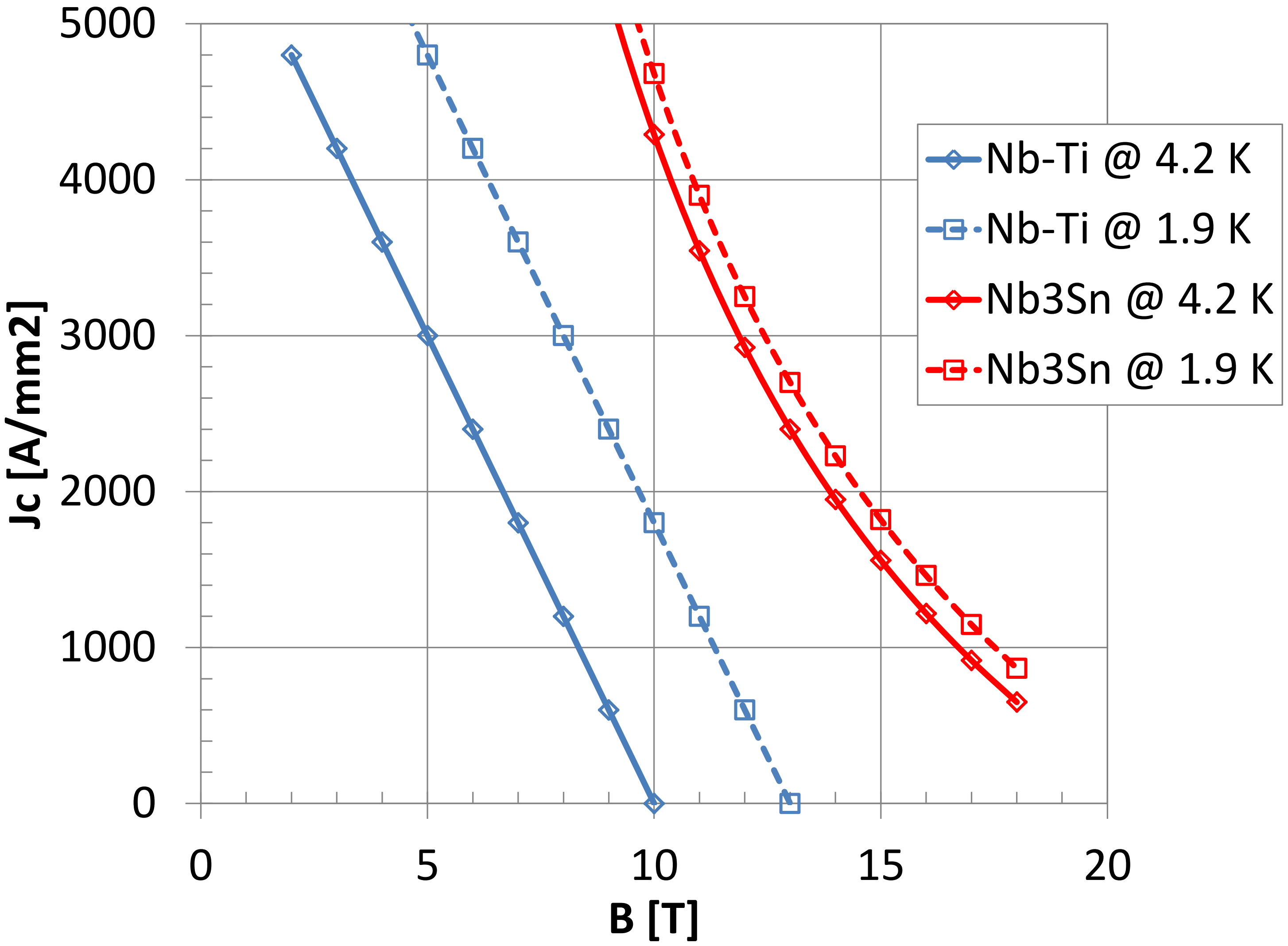
- Lower the operating temperature
  - Achieve higher magnetic field through increase of critical current density of superconductor
  - Minimize overall energy dissipation in RF cavities

- Enhance heat transfer
  - At solid-liquid interface ⇒ conductor cooling
  - In the bulk liquid

  ⇒ device/system cooling scheme

  ⇒ calorimetry in isothermal bath

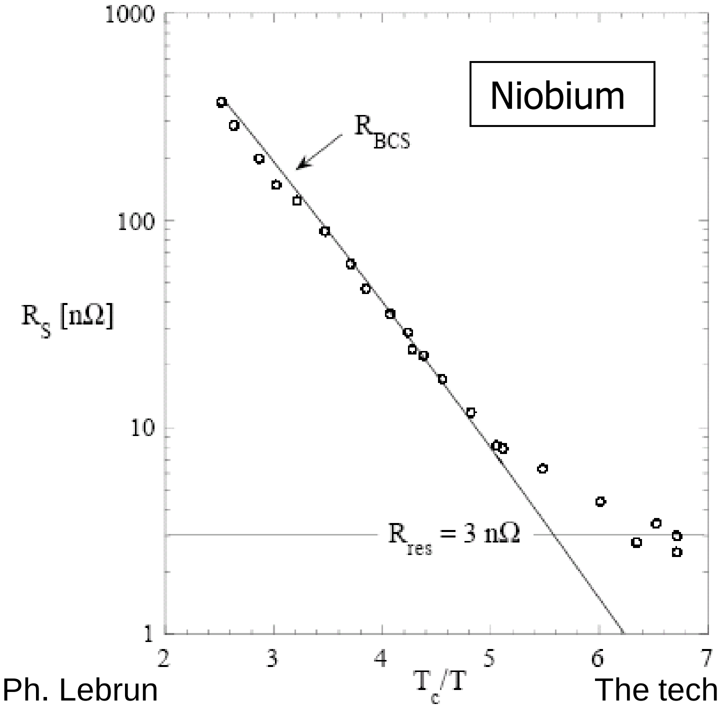
Critical current density of superconductors for high-field accelerator magnets

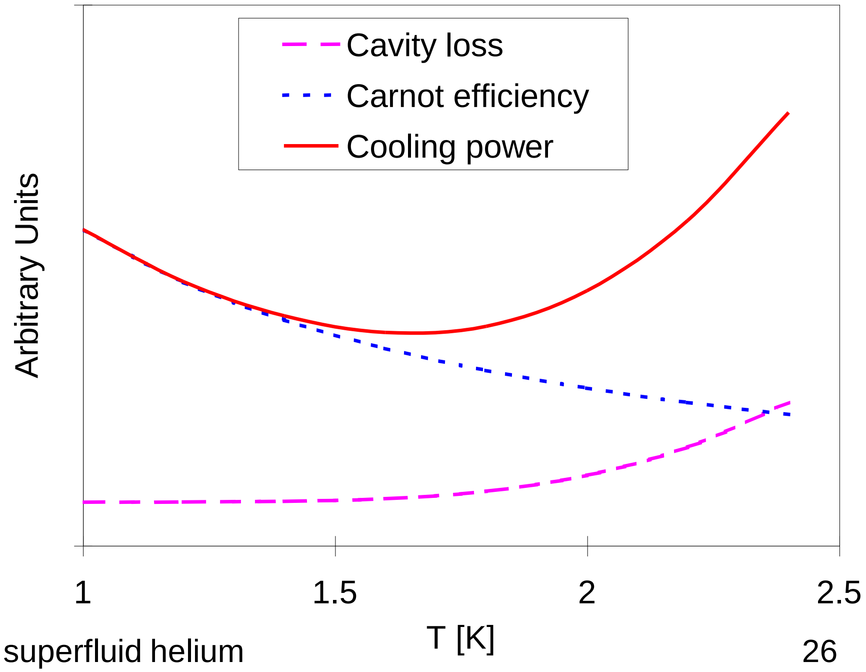


Optimization of operating temperature for superconducting RF cavities

- BCS theory $R_{BCS} = (A\ \omega^2 / T)\ \exp(-B\ T_c/T)$
- For practical materials $R_S = R_{BCS} + R_0$
- Refrigeration (Carnot) $P_a = P\ (T_a/T - 1)$

$\Rightarrow$ depending upon ω and R_0, optimum operating temperature for superconducting cavities



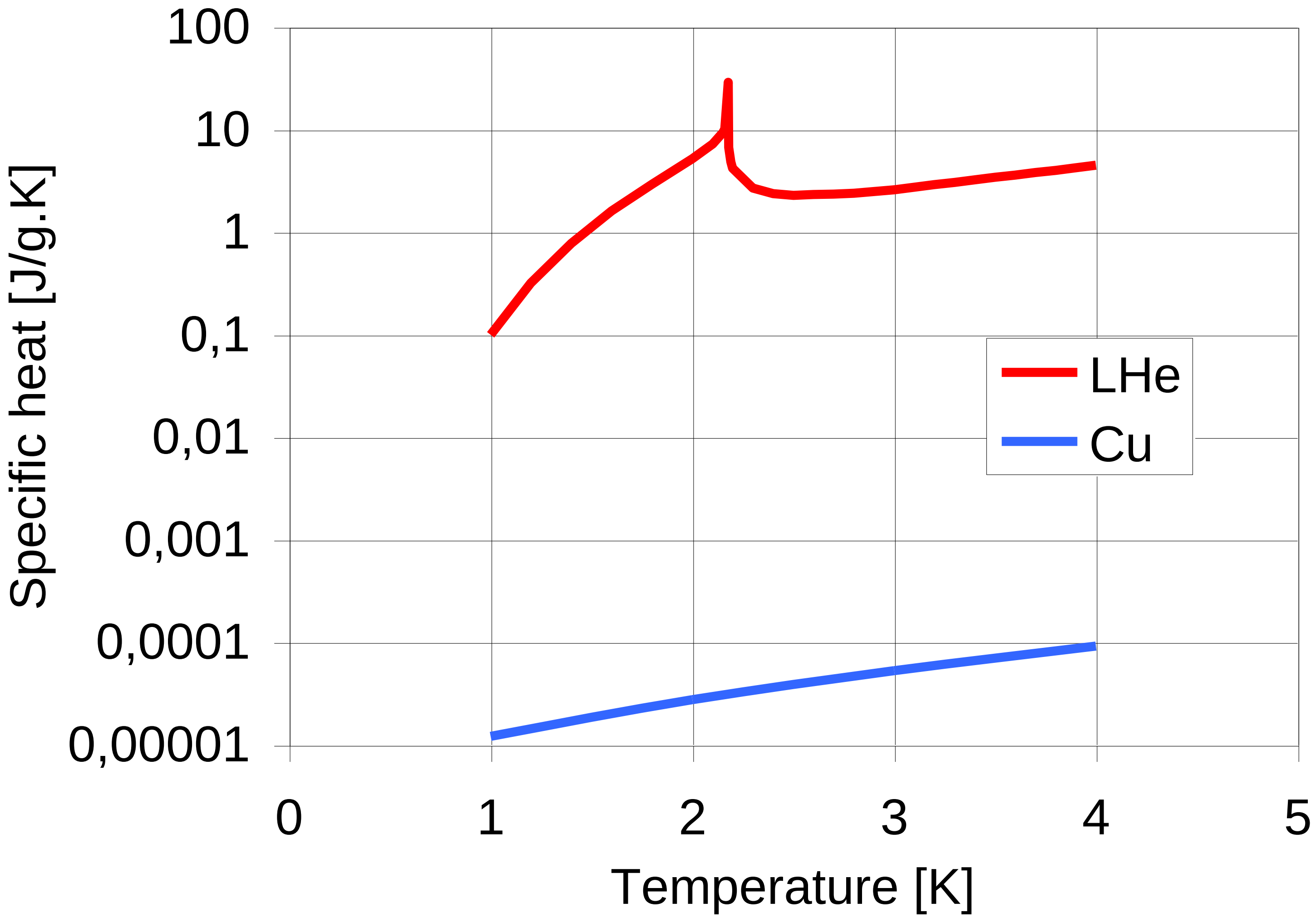


Enhancement of heat transfer

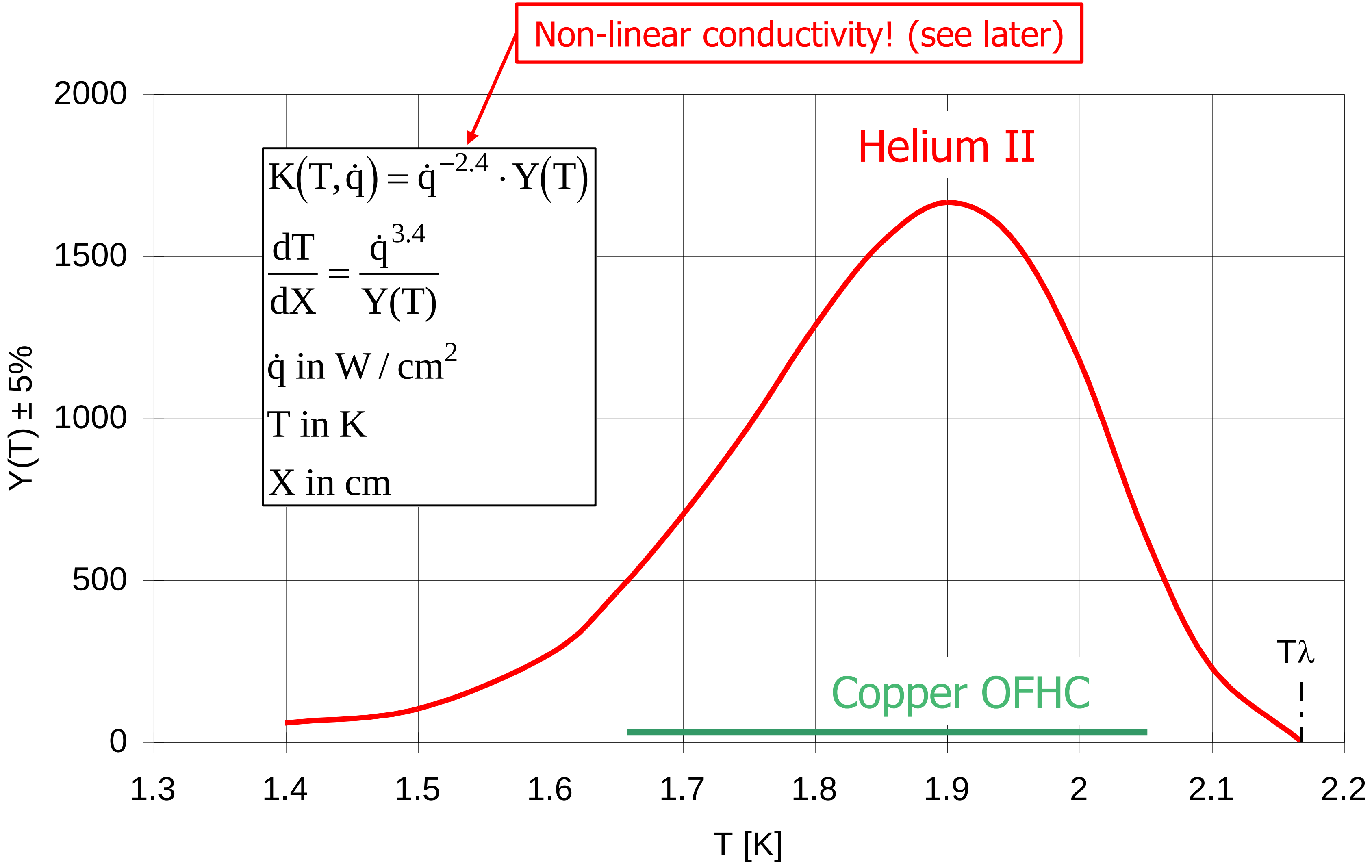
- Low viscosity ⇒ *permeation*
- Very high specific heat ⇒ *stabilization*
  - 10^5 times that of the conductor (Cu + SC) per unit mass
  - 2×10^3 times that of the conductor per unit volume
- Very high thermal conductivity ⇒ *heat transport*
  - 10^3 times that of cryogenic-grade OFHC copper
  - peaking at 1.9 K

Full benefit of these transport properties can only be reaped by appropriate design providing good wetting of the superconductors and percolation paths in the insulation, often in conflict with other technical requirements

Specific heat of liquid helium and copper



Equivalent thermal conductivity of He II p



Non-linear conductivity! (see later)

$$K(T,\dot{q}) = \dot{q}^{-2.4} \cdot Y(T)$$

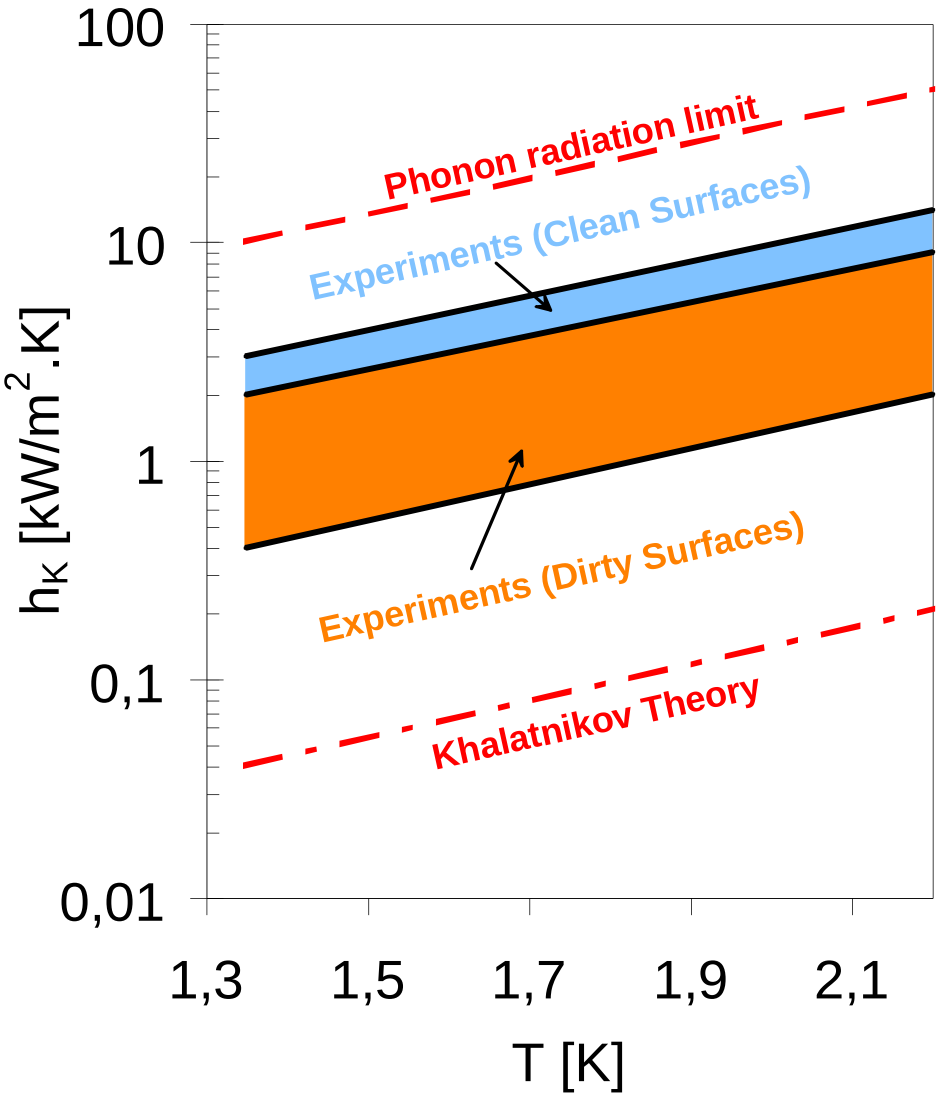
$$\frac{dT}{dX} = \frac{\dot{q}^{3.4}}{Y(T)}$$

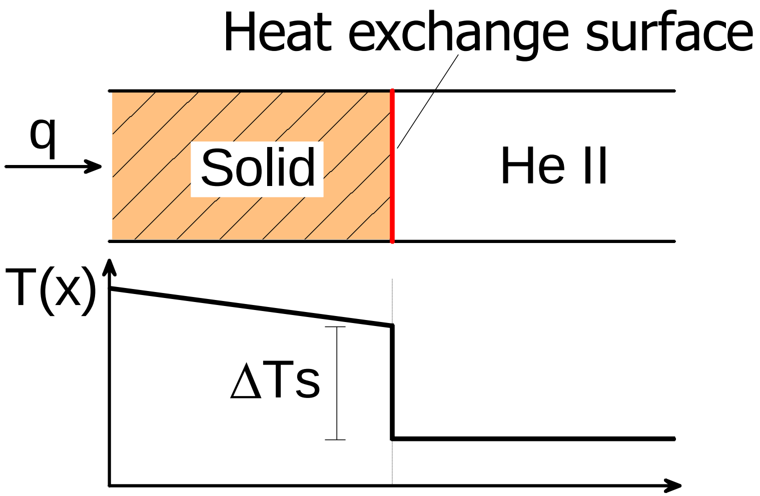
$\dot{q}$ in W/cm^2

T in K

X in cm

Solid-liquid interface: Kapitza conductance





Experimental data for Copper

(S. Van Sciver, "Helium Cryogenics")

$h_K \sim T^3$

Valid for small heat flux (when $\Delta T \ll T$)

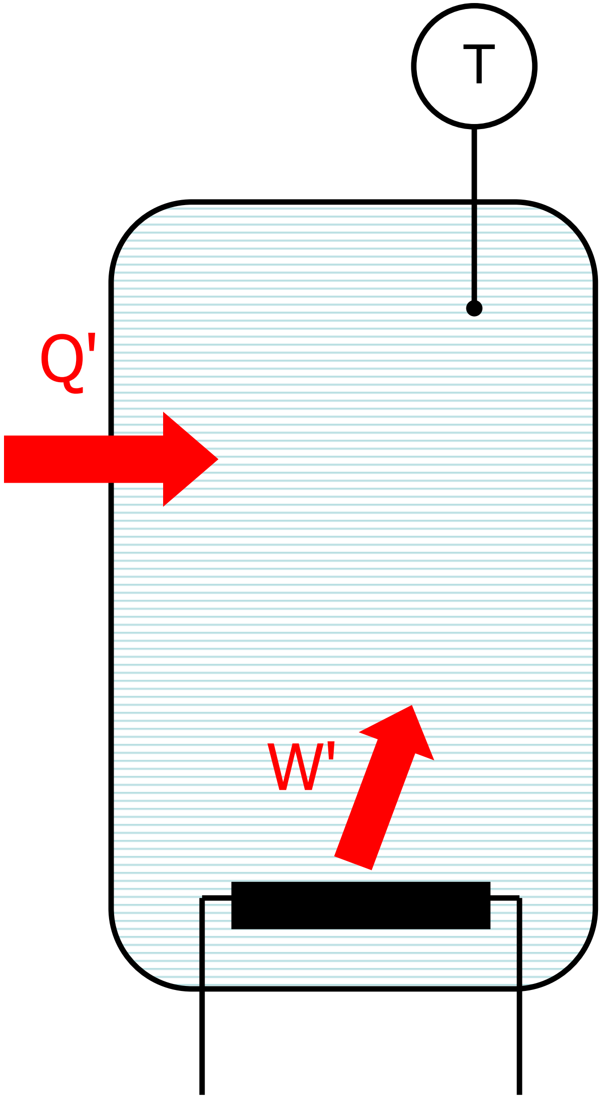
Application of high thermal conductivity
Calorimetry in isothermal He II bath

- For slow thermal transients, the He II bath is quasi-isothermal: a single temperature measurement allows to estimate heat deposition/generation Q'

  - at constant P $Q' = M_{bath}\, dH/dt|_1$
  - at constant V $Q' = M_{bath}\, dE/dt|_1$

- M_{bath} can be estimated by *in situ* calibration, using applied heating power W'

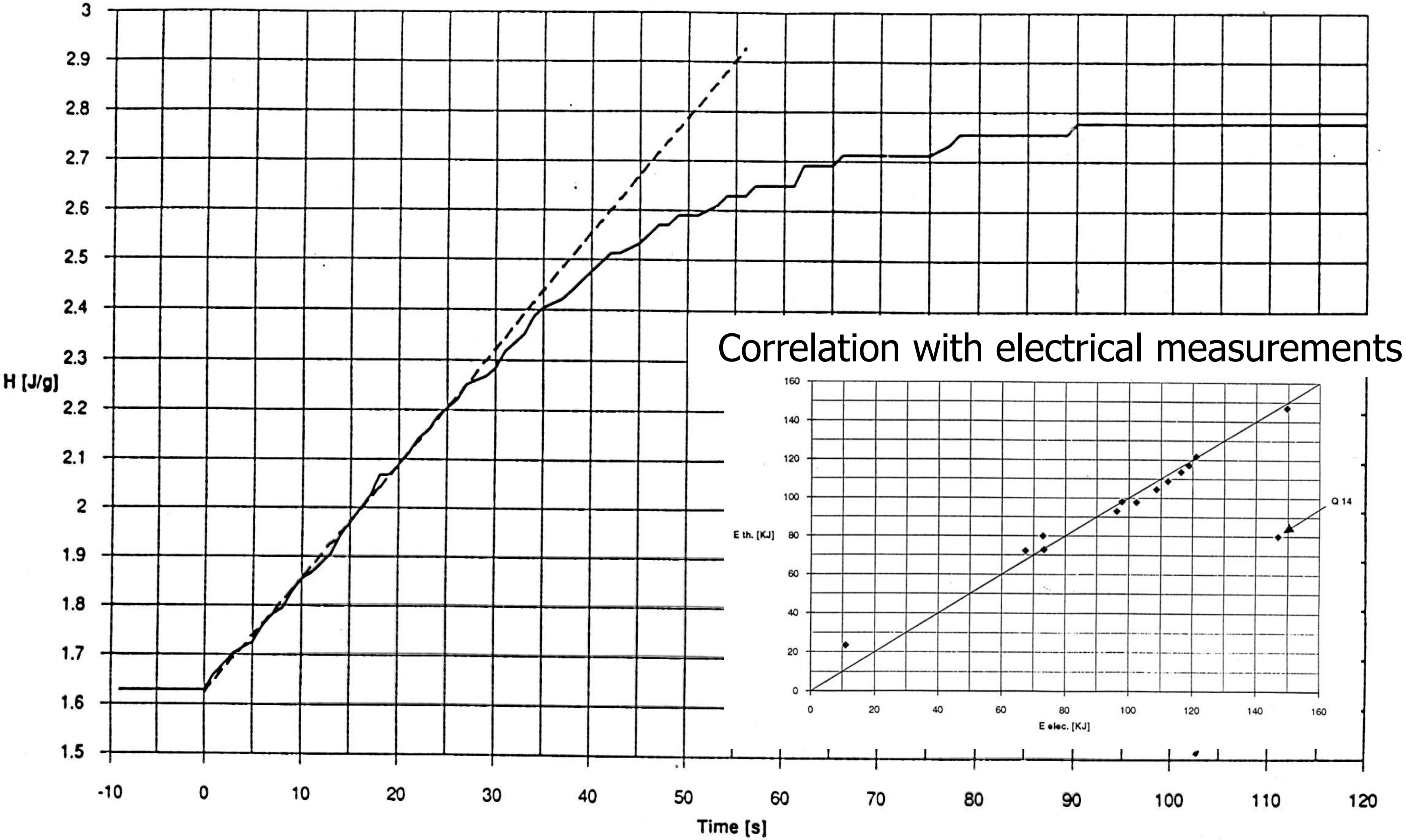
  - at constant P $W' = M_{bath}\, dH/dt|_2$
  - at constant V $W' = M_{bath}\, dE/dt|_2$



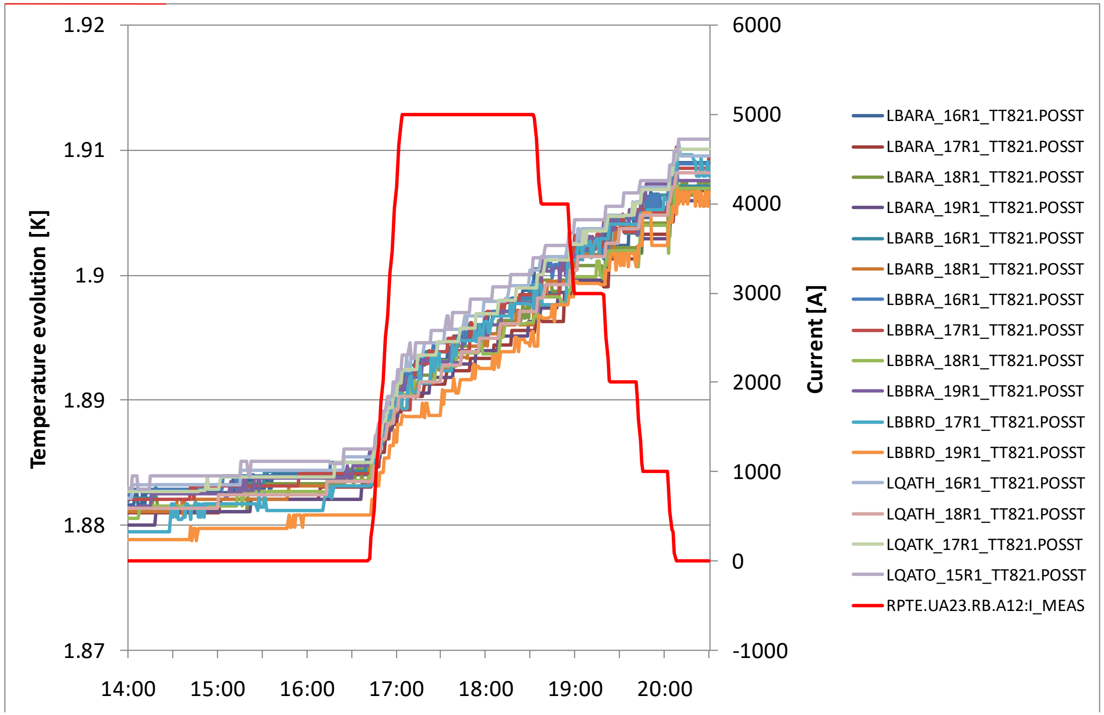
Calorimetry of magnet quench in He II bath

Time evolution of bath temperature

Correlation with electrical measurements



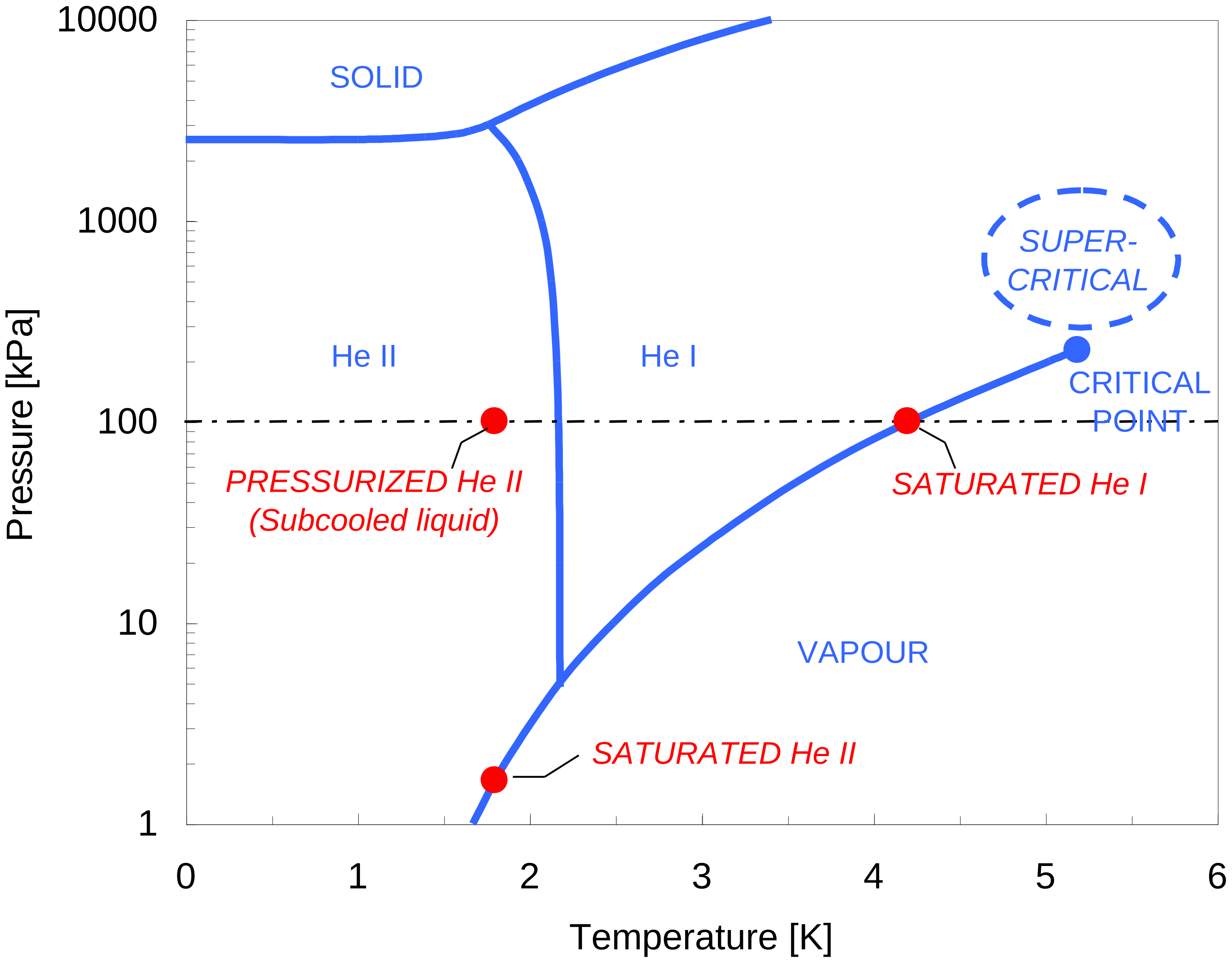
Precision thermometry allows calorimetric detection of faulty joints in LHC at safe powering level



Current	Total (measured)		Nominal Splices*	Add. local dissipation	Uncertainty
[A]	[mW/m]	[W]	[W]	[W]	[W]
3000	4.4	1.0	0.4	0.6	0.6
5000	14.9	3.2	1.1	2.1	0.6
7000	32.2	6.9	2.1	4.8	0.6

→ Local resistance: ~90 nΩ, confirmed by electrical measurement

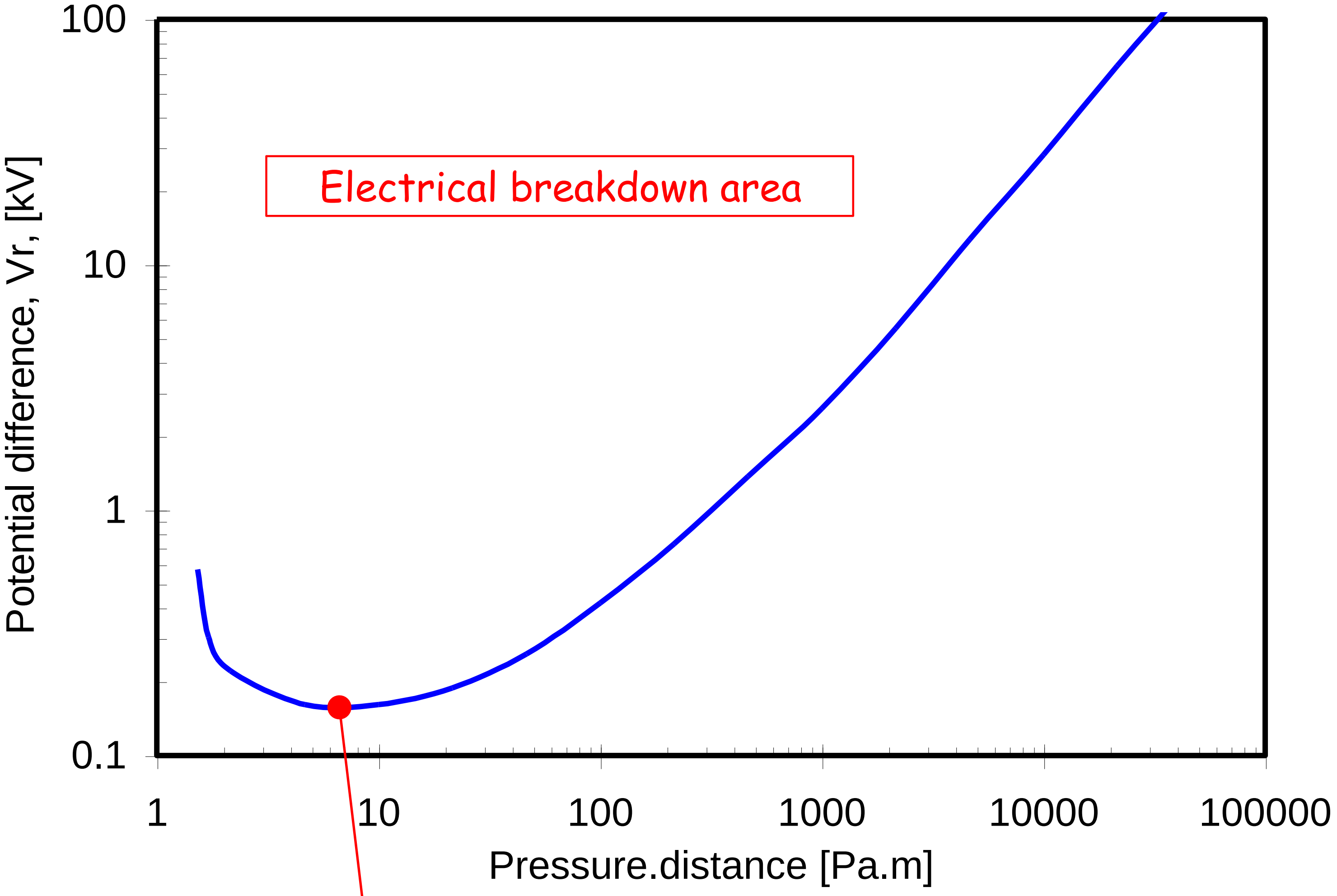
Pressurized vs saturated He II



Advantages & drawbacks of He II p

- Advantages
  - limits the risk of air inleaks and contamination in large and complex cryogenic systems
  - for electrical devices, limits the risk of electrical breakdown at fairly low voltage due to the bad dielectric characteristics of helium vapour (Paschen curve)
  - better stabilizer for heat buffering
- Drawbacks
  - one more level of heat transfer
  - additional process equipment (pressurized-to-saturated helium II heat exchanger)

Paschen curve for gaseous He at 20 °C



e.g., 1.6 kPa pressure and 6 mm gap

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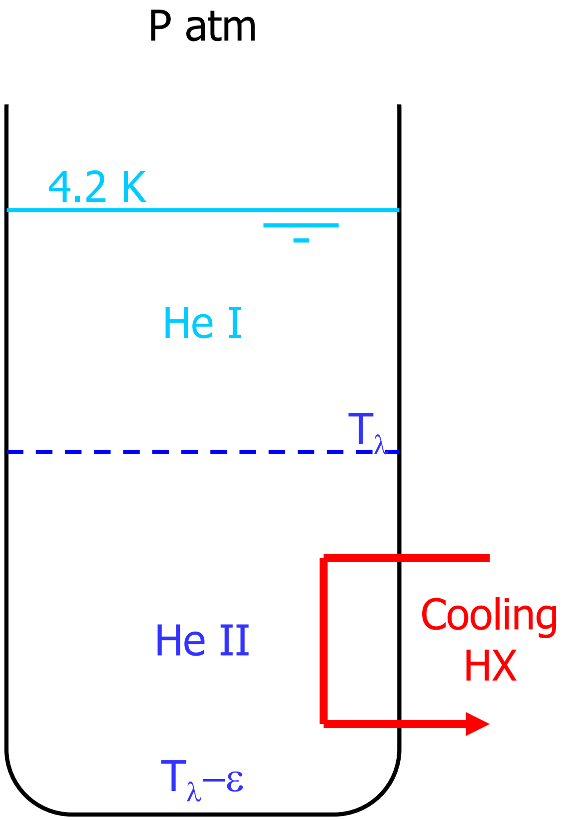
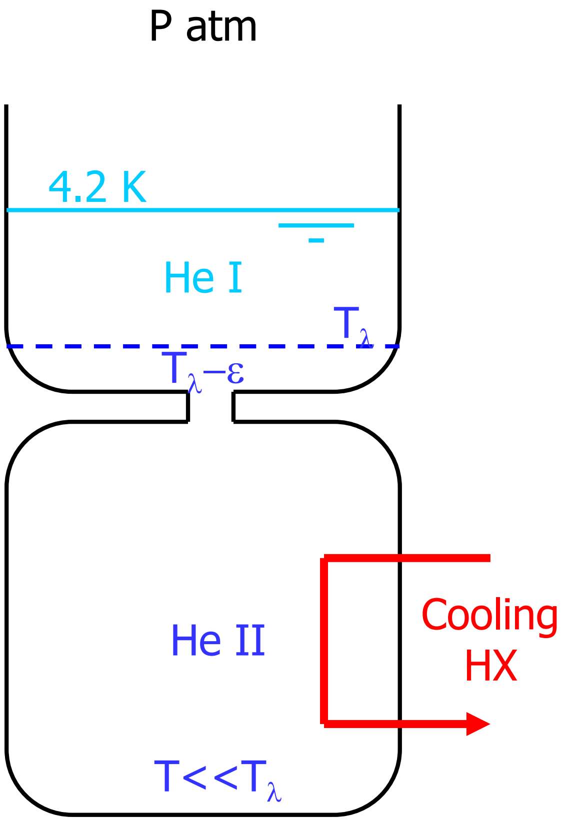
Working with superfluid helium at atmospheric pressure

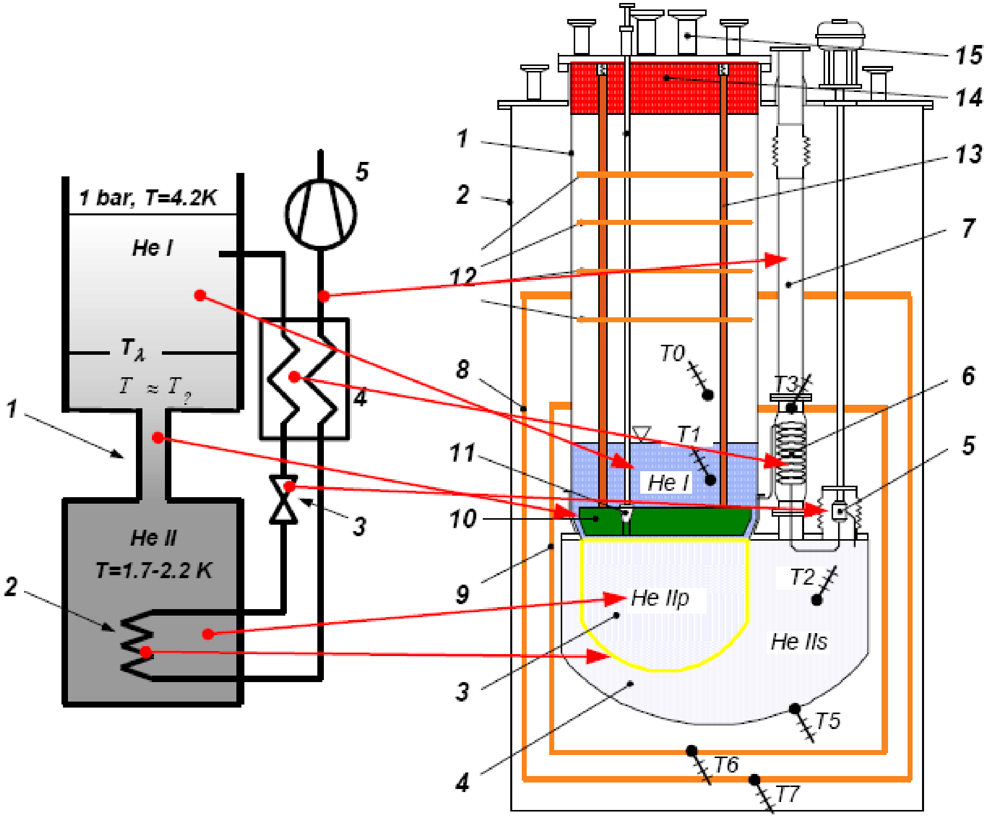


« Roubeau bath »: He II conduction prevents from lowering the bath temperature well below T_λ



« Claudet bath »: restriction in cryostat allows subooling He II bath to temperatures well below T_λ

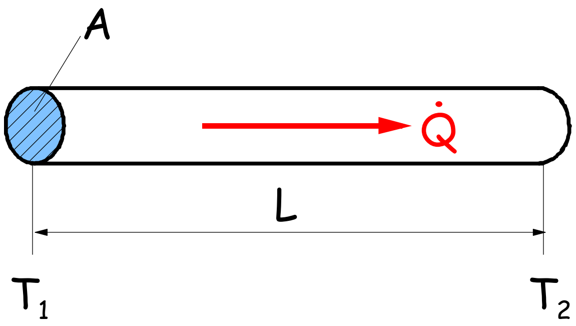
A practical Claudet bath



(a) (b)

Figure 1. a) Claudet bath principle: 1 – constriction, 2 – He IIs/He IIp heat exchanger, 3 – J-T valve, 4 – recuperative heat exchanger, 5 –vacuum pump; b) NED cryostat scheme: 1 – He I vessel, 2 – vacuum container, 3 – He IIp vessel, 4 – He IIs vessel, 5 – J-T valve, 6 – recuperative heat exchanger, 7 – heat exchanger pipe, 8/9 – external/internal radiation shield, 10 – λ-plate, 11 – λ-valve, 12 – insert radiation shields, 13 – λ-plate supports, 14 – foam insulation, 15 – instrumentation ports, T0 – T7 temperature measurement points

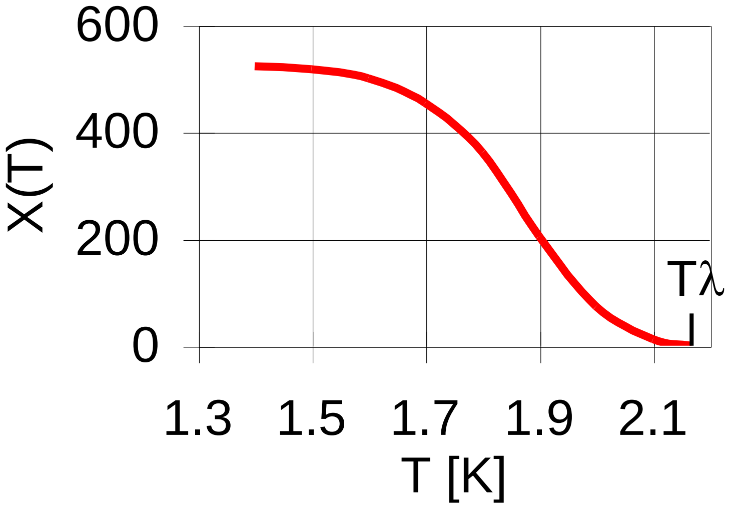
Conduction cooling in static He II p



Cross-section: A
Length: L
Power: $\dot{Q}$
Heat Flux: $\dot{q} = \frac{\dot{Q}}{A}$

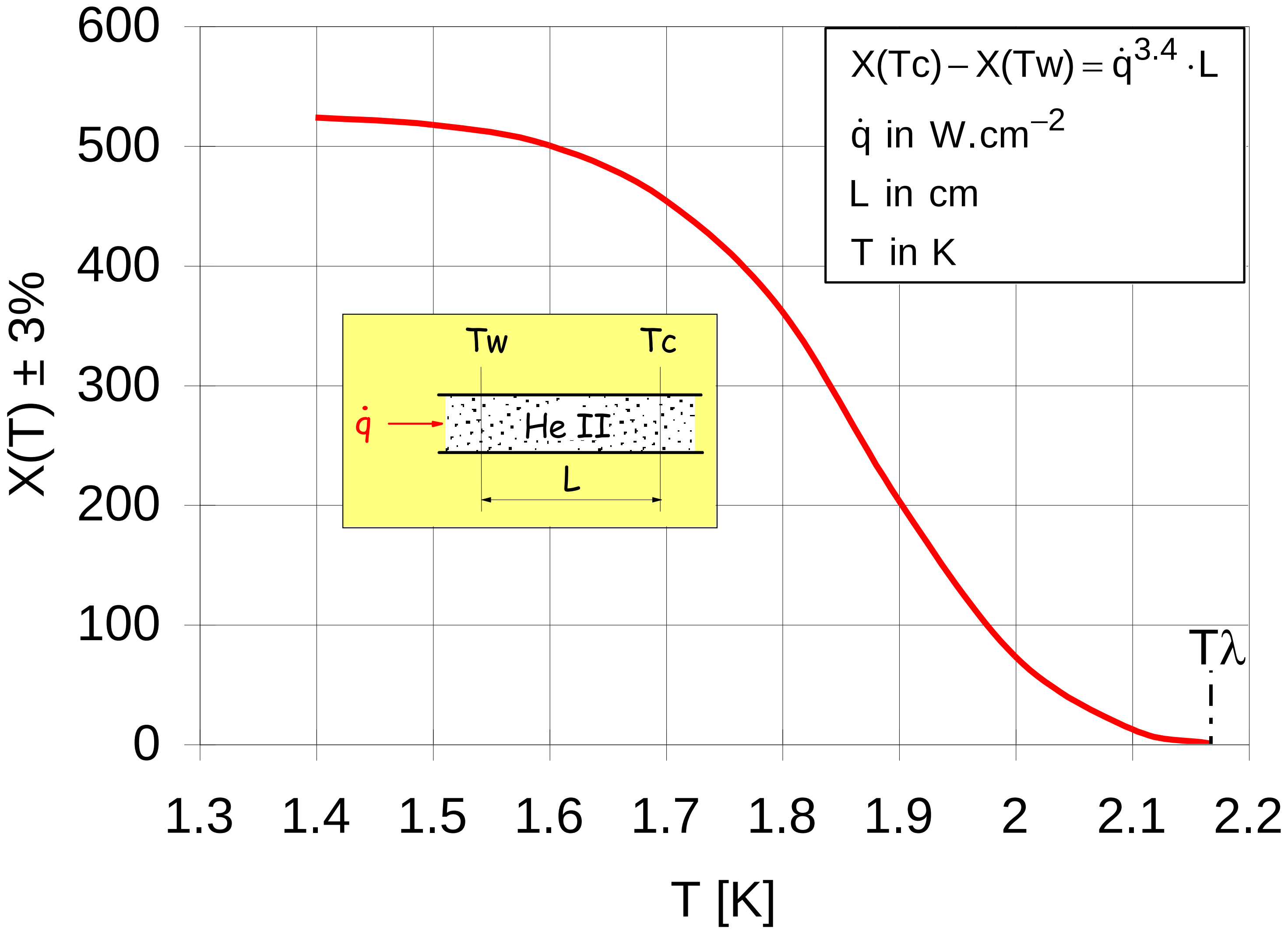
- Gorter-Mellink law: $\dot{q}^m \cdot L = X(T_2) - X(T_1)$

- Experimental work of Bon Mardion, Claudet & Seyfert:
    - m ≈ 3.4
    - tabulation of X(T)



Note 1: this is a non-linear formula for conduction ⇒ use proper units!
Note 2: m = 1 for classical solid conduction (Fourier’s law)

Thermal conduction integral function of He II p



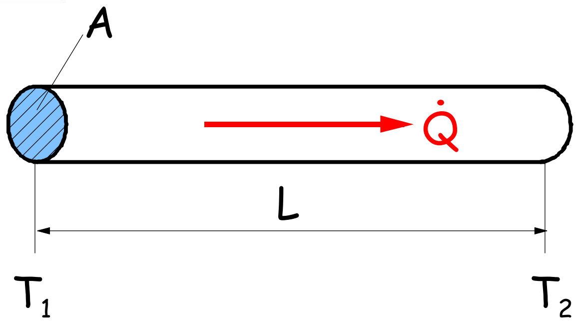
$$X(Tc) - X(Tw) = \dot{q}^{3.4} \cdot L$$

$\dot{q}$ in $W.cm^{-2}$

L in cm

T in K

Conduction cooling: a numerical example



$A = 1\ \mathrm{cm}^2$

$L = 1\ \mathrm{m} = 100\ \mathrm{cm}$ *(Units!)*

$T_1 = 1.9\ \mathrm{K}$ ➔ $X(T_1) = 200$

$T_2 = 1.8\ \mathrm{K}$ ➔ $X(T_2) = 360$

Then: $\dot{q}^{3.4}.L = 360 - 200$ ➔ $\dot{q}^{3.4} = 1.6$ ➔ $\dot{q} = 1.15\ \mathrm{W/cm}^2$

Comparison with "good solid conductor", e.g. **Copper**

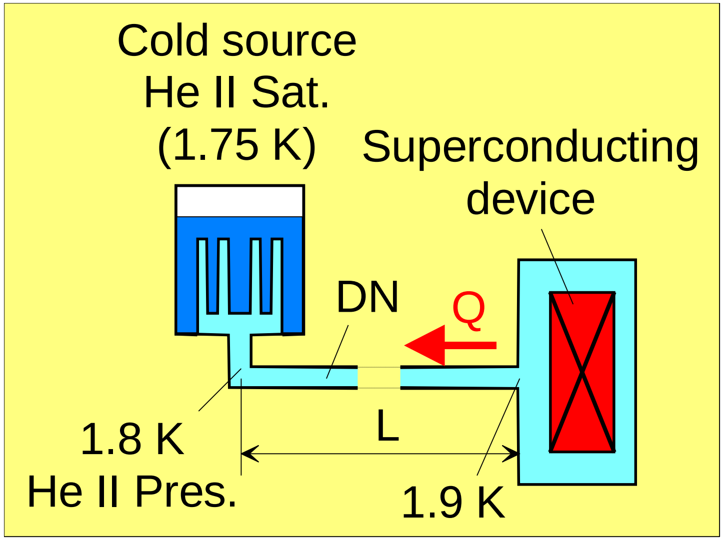
$$\dot{q} = k \cdot \frac{\Delta T}{L}$$ with k = thermal conductivity at 1.8 K

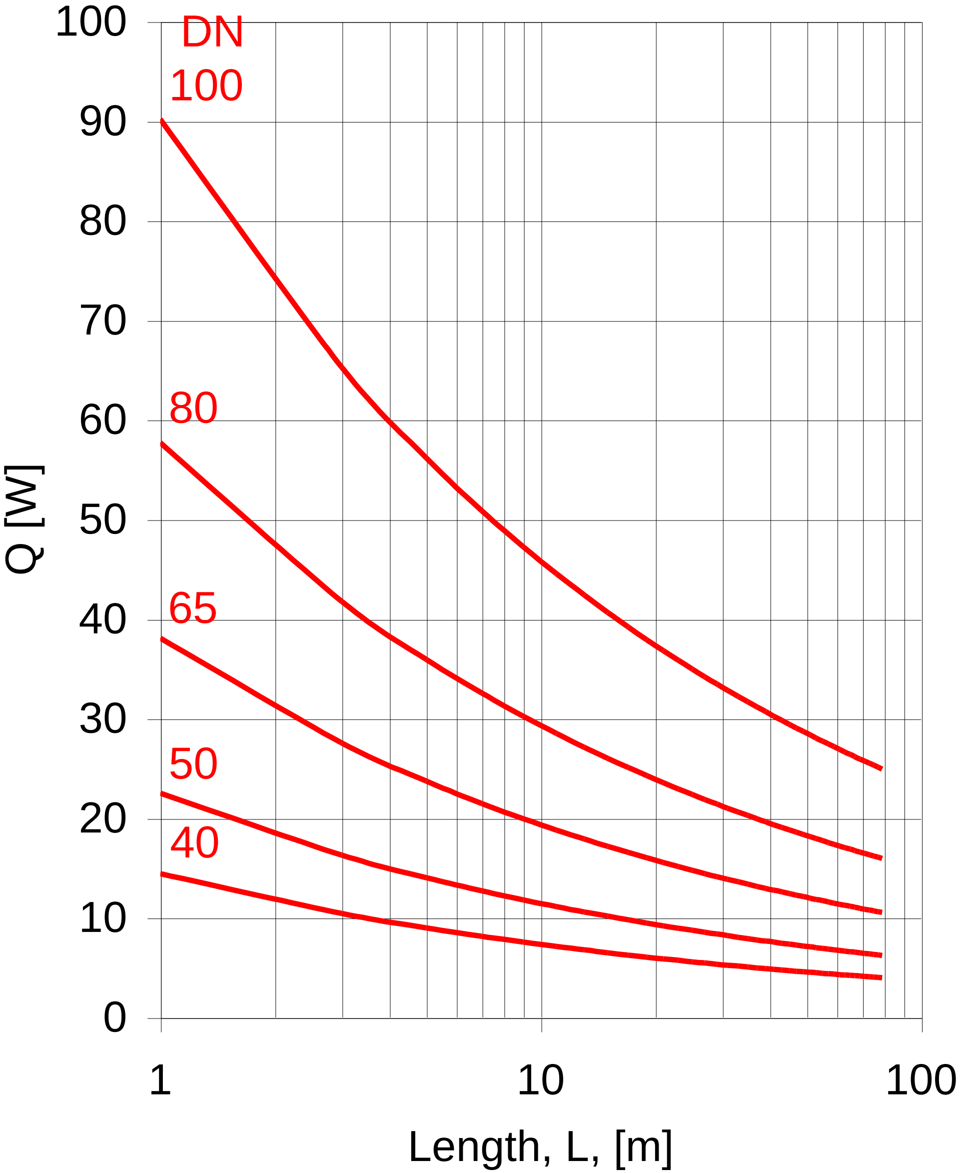
Cu type	k [W/m.K]	ΔT [K]	L [m]	q [mW/cm^2]
OFHC	120	0.1	1	**1.2**
DHP	3	0.1	1	**0.03**

He II conducts heat 1000 times better than OFHC Cu

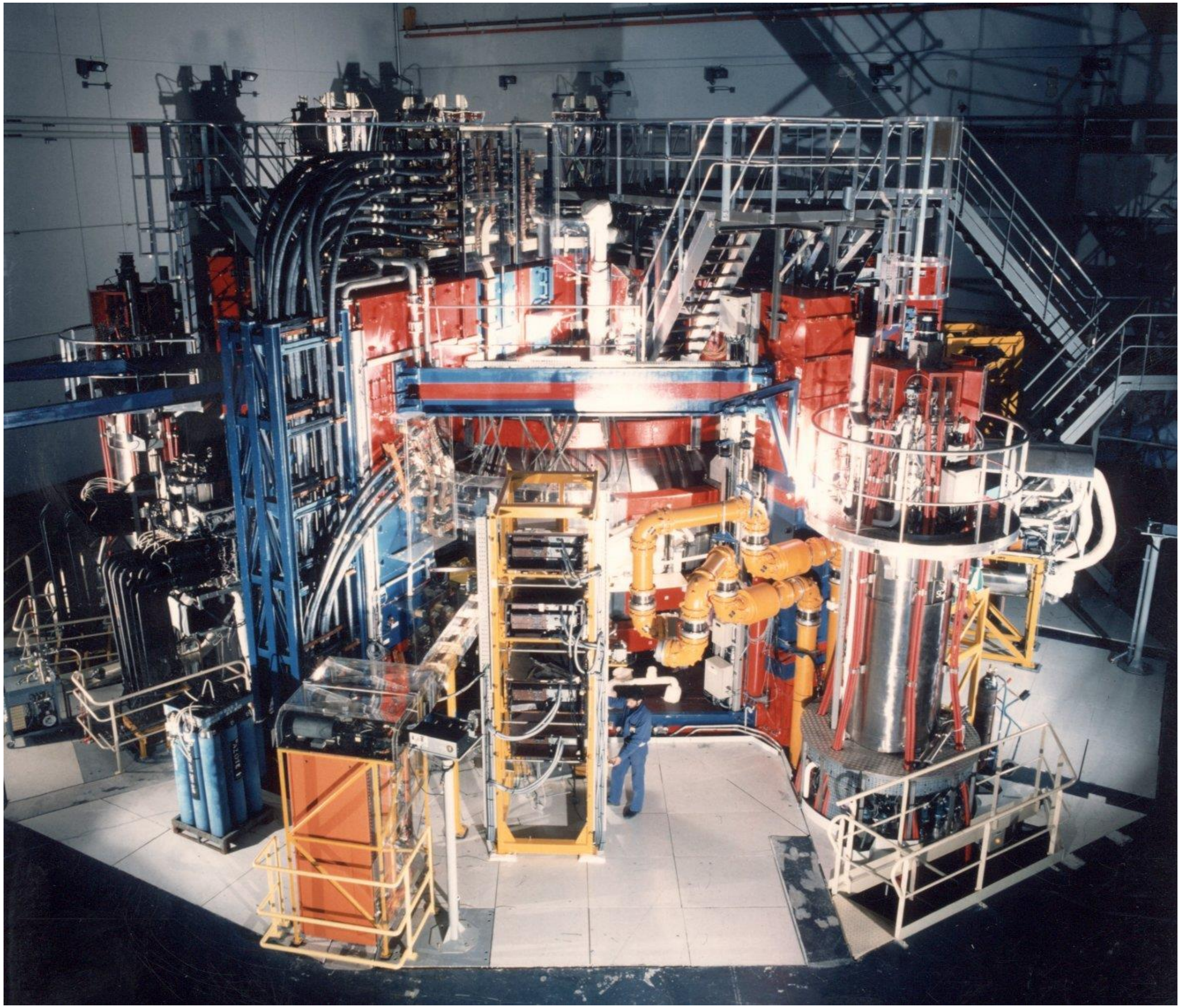
Steady-state conduction duct in He II

From 1.80 K to 1.90 K





Tore Supra (WEST) tokamak at CEA Cadarache, France



He IIp conduction cooling of Tore Supra coils

CEA Cadarache

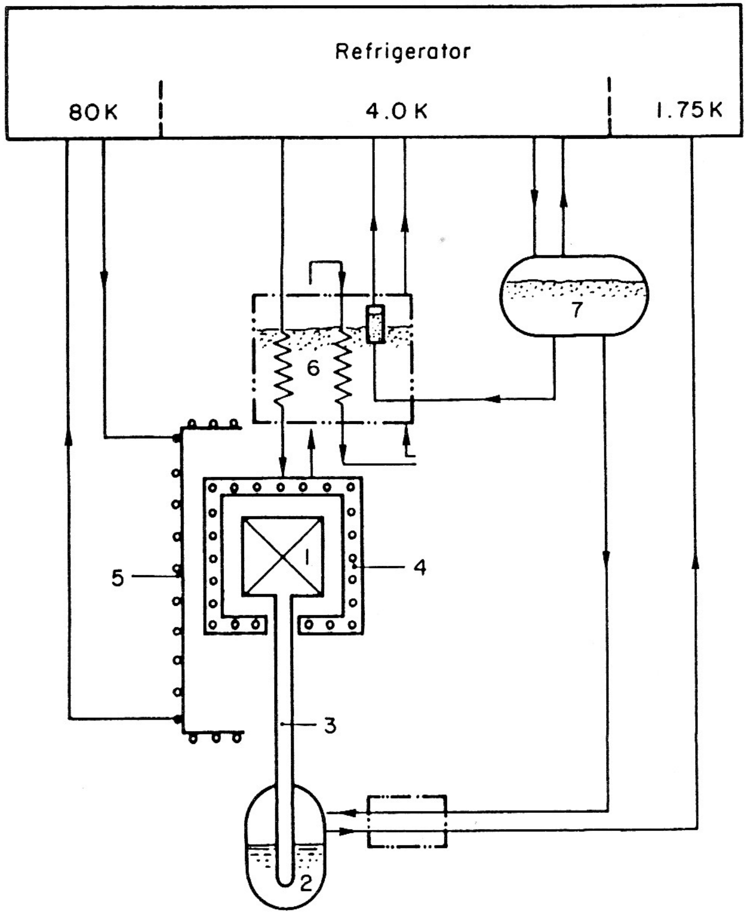


Figure 2 Schematic design of the cryogenic system. 1, 1.8 K coil; 2, 1.75 K cold box; 3, static pressurized superfluid helium; 4, thick casing total weight = 120 tonnes; 5, 80 K shield total weight = 22 tonnes; 6, thermal ballast; 7, 20 000 dm^3 He tank

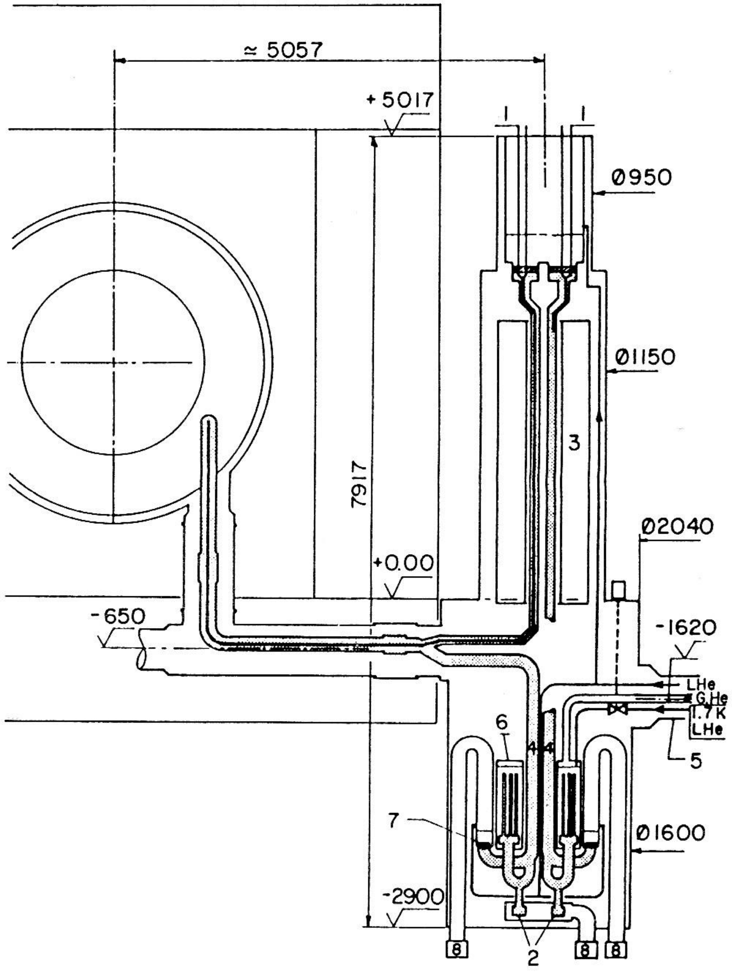
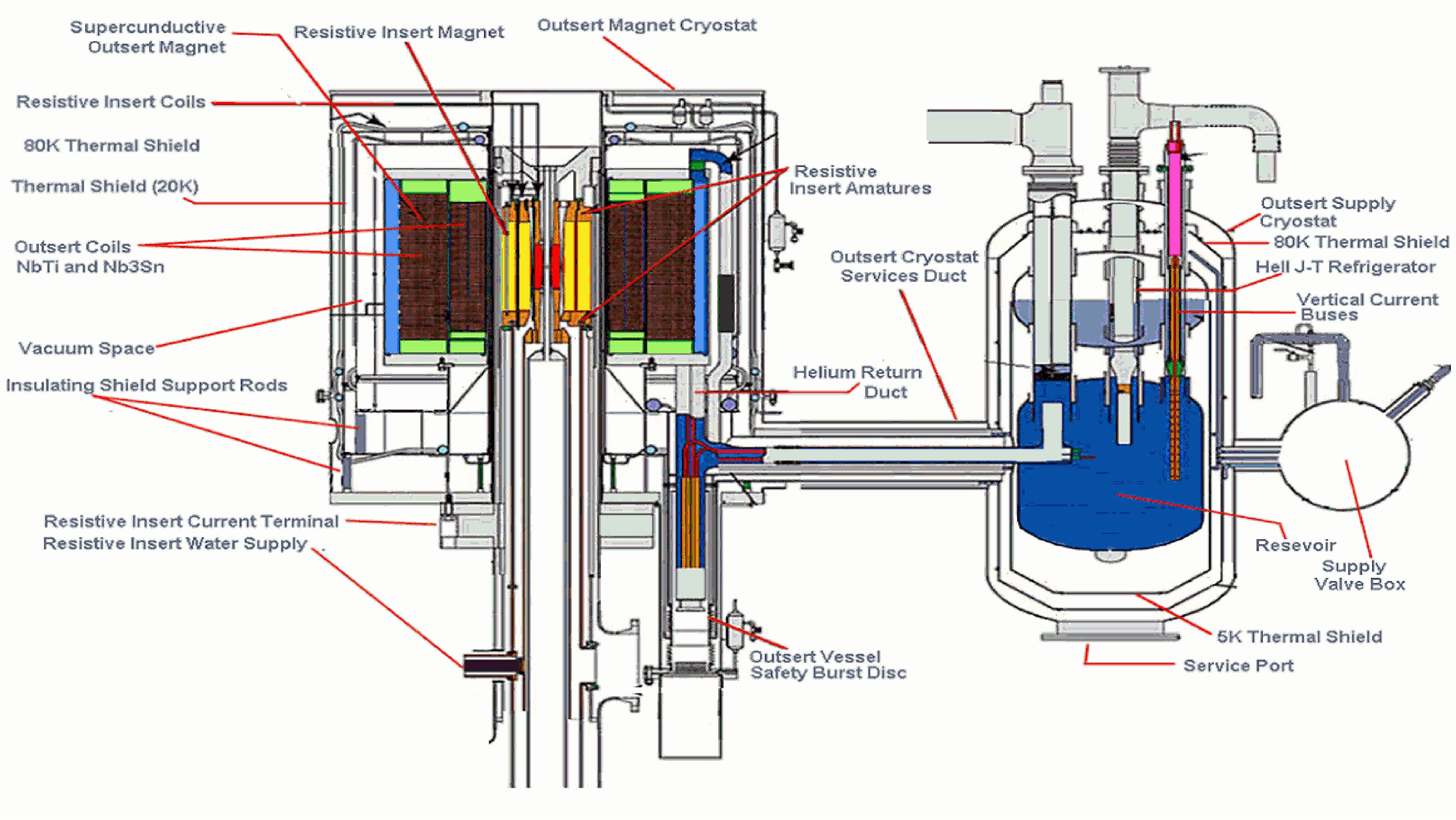


Figure 3 1 atm He II circuit. 1, 12 Current leads; 2, cold burst discs; 3, thermal ballast = 1500 dm^3; 4, six He II pipes; 5, cryogenic line; 6, 1.7 K cold source; 7, cold valves; 8, safety valves

He IIp conduction cooling of 45 T hybrid magnet
NHFML Tallahassee



Problem 1: Steady-state conduction in He II

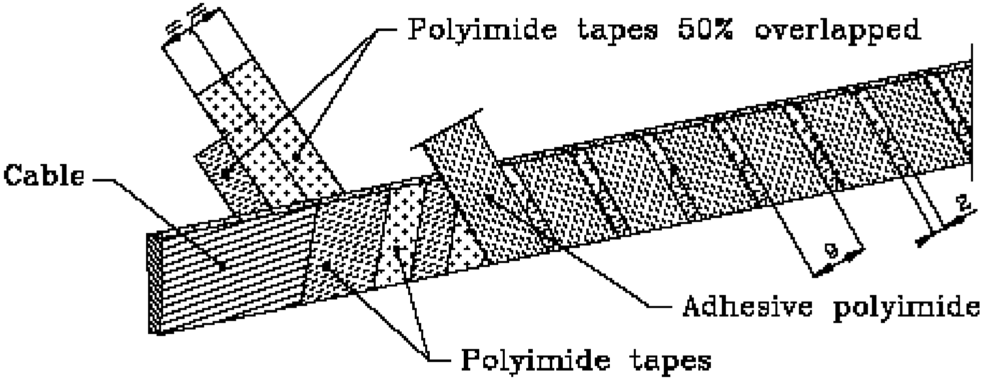
Consider a 8-m long duct cooling a superconducting magnet by conduction in pressurized superfluid helium at 1 bar, from a cold source at 1.8 K.

1. Calculate the diameter of the duct to maintain the magnet at 1.9 K if its total heat load is 20 W
2. Calculate the diameter of the duct if its length is doubled to 16 m, same magnet heat load and temperature conditions
3. With the duct length and diameter of question 1, what will be the magnet temperature if its heat load is increased to 25 W?
4. Is there a maximum heat flux that the duct of question 1 can conduct to the cold source? Calculate this maximum heat flux and the corresponding heat flow with the duct diameter and length of question 1.

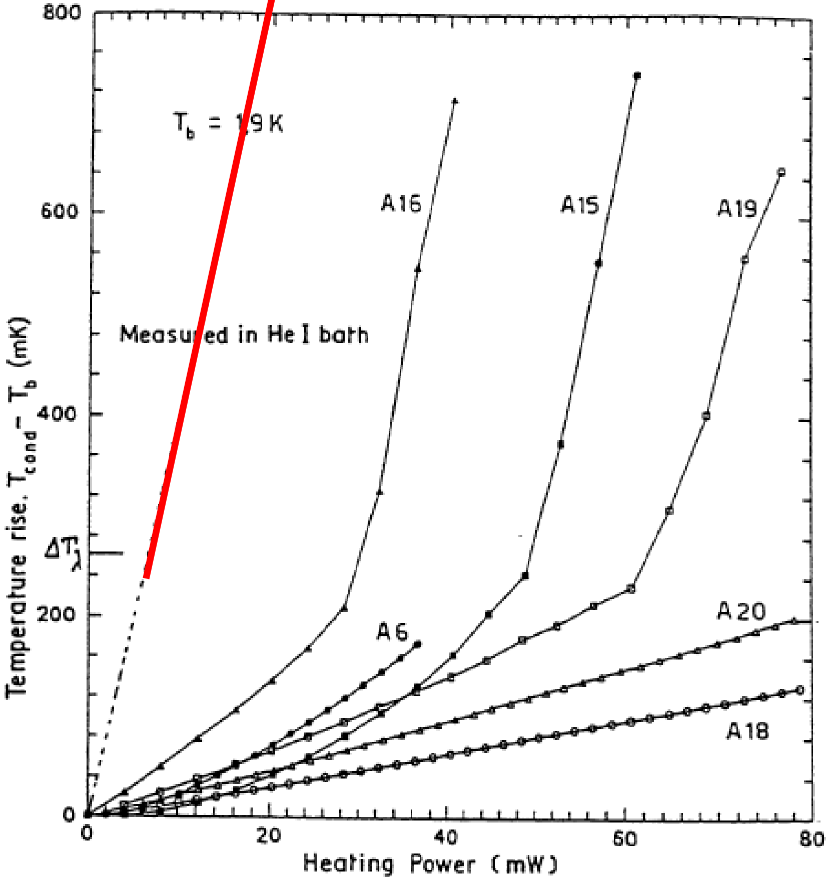
Problem 2: Cooldown of liquid helium duct to superfluid state

Consider a duct that cools a superconducting magnet by conduction in pressurized superfluid helium at 1 bar from a cold source at 1.8 K. The magnet and the duct are initially filled with saturated liquid helium at 4.2 K. At time zero, the end of the duct opposite the magnet is put in contact with the cold source.

1. Sketch the temperature profile along the duct and explain what happens
2. Calculate the velocity of the superfluid/normal fluid front (at T lambda) in the duct as a function of its distance x to the cold source
3. Calculate the time taken by the front at T lambda to reach the magnet, as a function of the distance L to the magnet. Calculate for L=8 m.



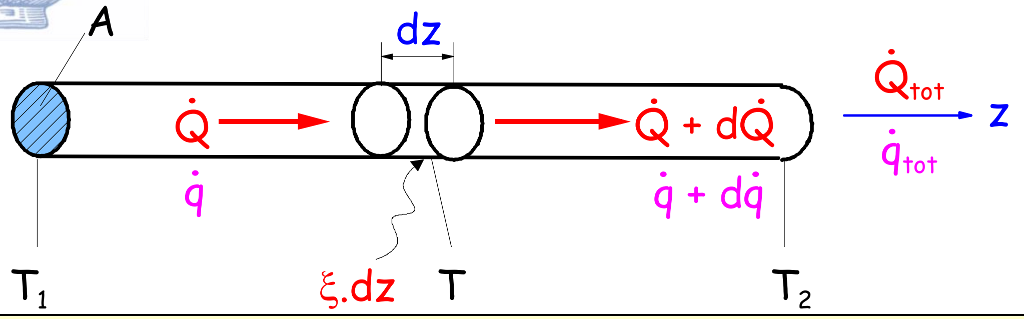
Conduction in polyimide



Heat transfer across electrical insulation of LHC superconducting cable

The LHC: 1716 main superconducting magnets cooled at 1.9 K in 3 km long strings: how to transport the heat over such distances?

Conduction cooling of accelerator string: the fin problem



Distance : z

Linear heat load: ξ

G-M law applied on dz: $\dot{q}^{3.4} \cdot dz = dX(T)$

Energy conservation: $d\dot{q} = \frac{\xi}{A} \cdot dz$

$\rightarrow \quad dz = \frac{A}{\xi} \cdot d\dot{q}$

then, $\dot{q}^{3.4} \cdot d\dot{q} = \frac{\xi}{A} \cdot dX(T) \quad \rightarrow \quad \dot{q}_{tot}{}^{4.4} = 4.4 \cdot \frac{\xi}{A} \cdot [X(T_2) - X(T_1)]$

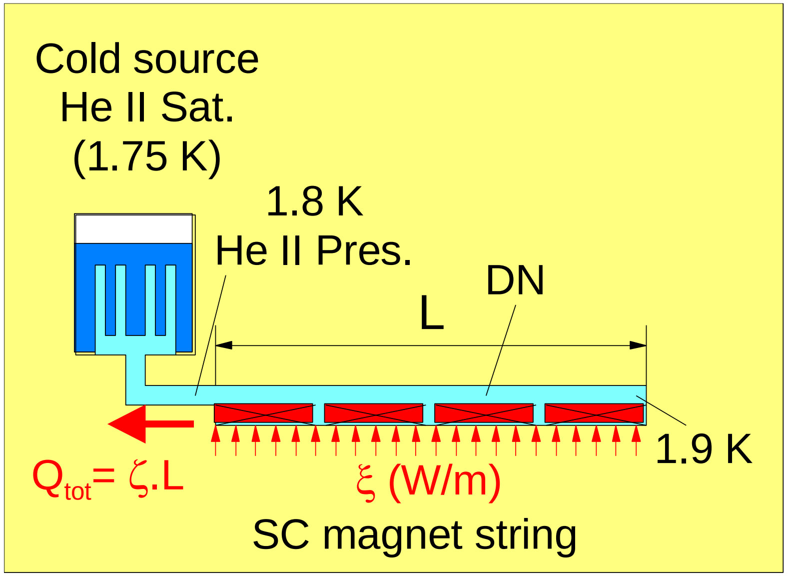
Calling Q_{tot} the total heat load on the string of length L:

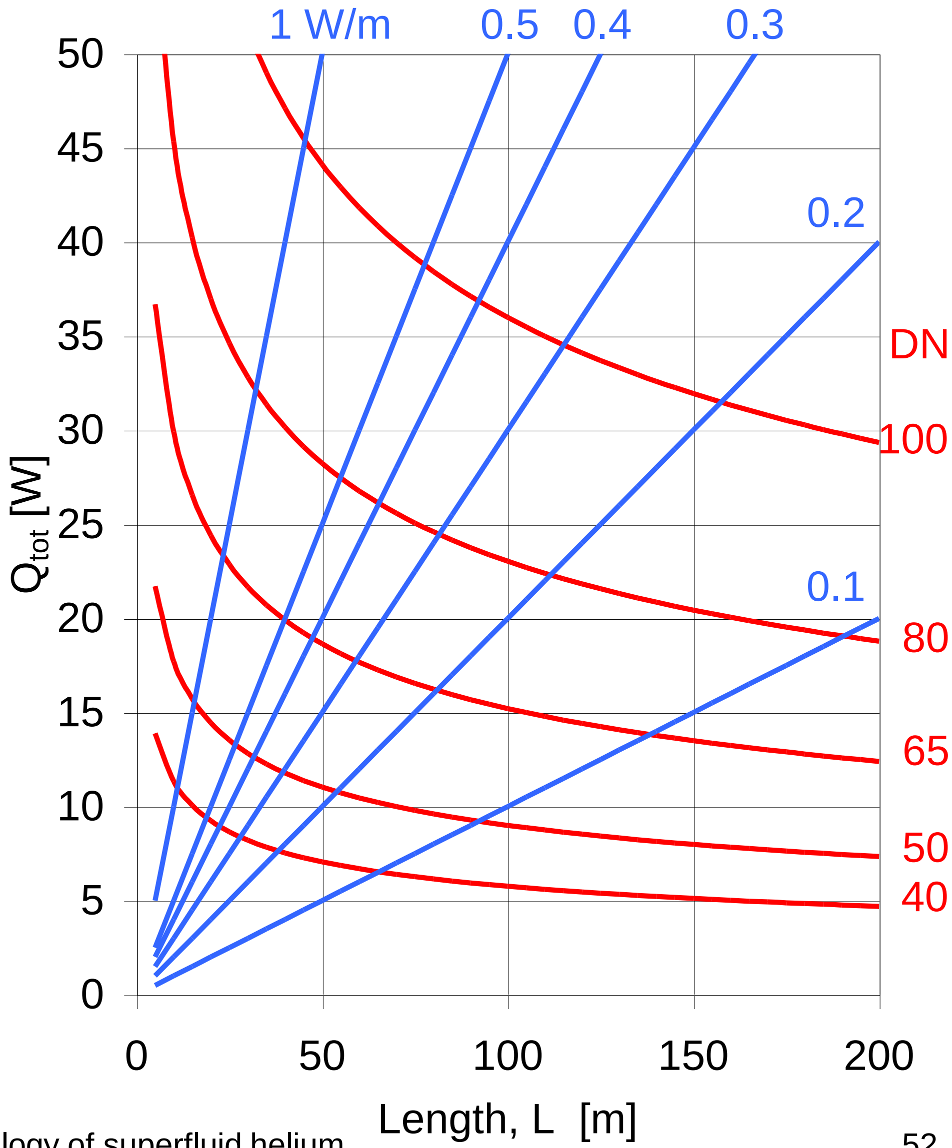
$$\dot{Q}_{tot} = L \cdot \xi = \dot{q}_{tot} \cdot A \quad \Rightarrow \quad \frac{\xi}{A} = \frac{\dot{q}_{tot}}{L}$$

Hence, $\boxed{\dot{q}_{tot}{}^{3.4} \cdot L = 4.4 \cdot [X(T_2) - X(T_1)]}$

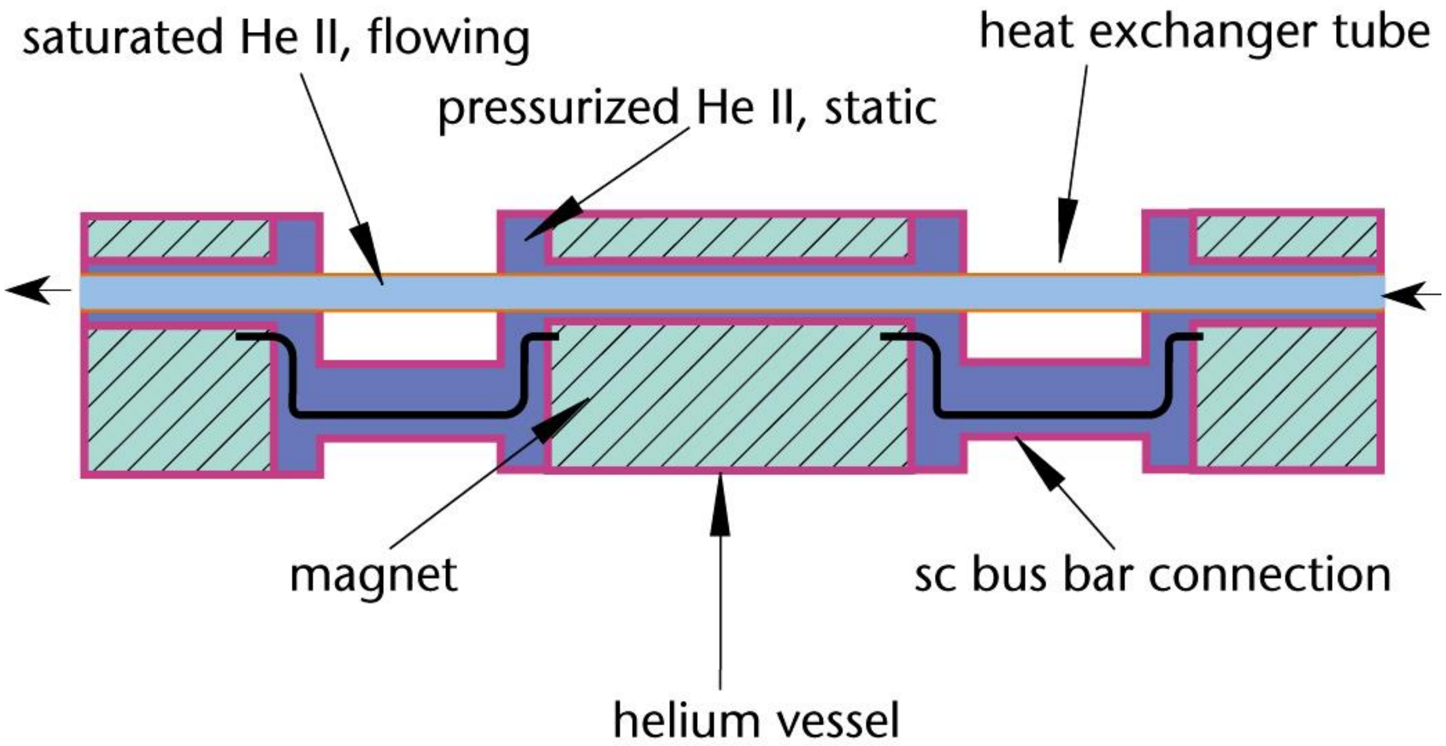
Conduction in He II with linear applied heat load

From 1.80 K to 1.90 K





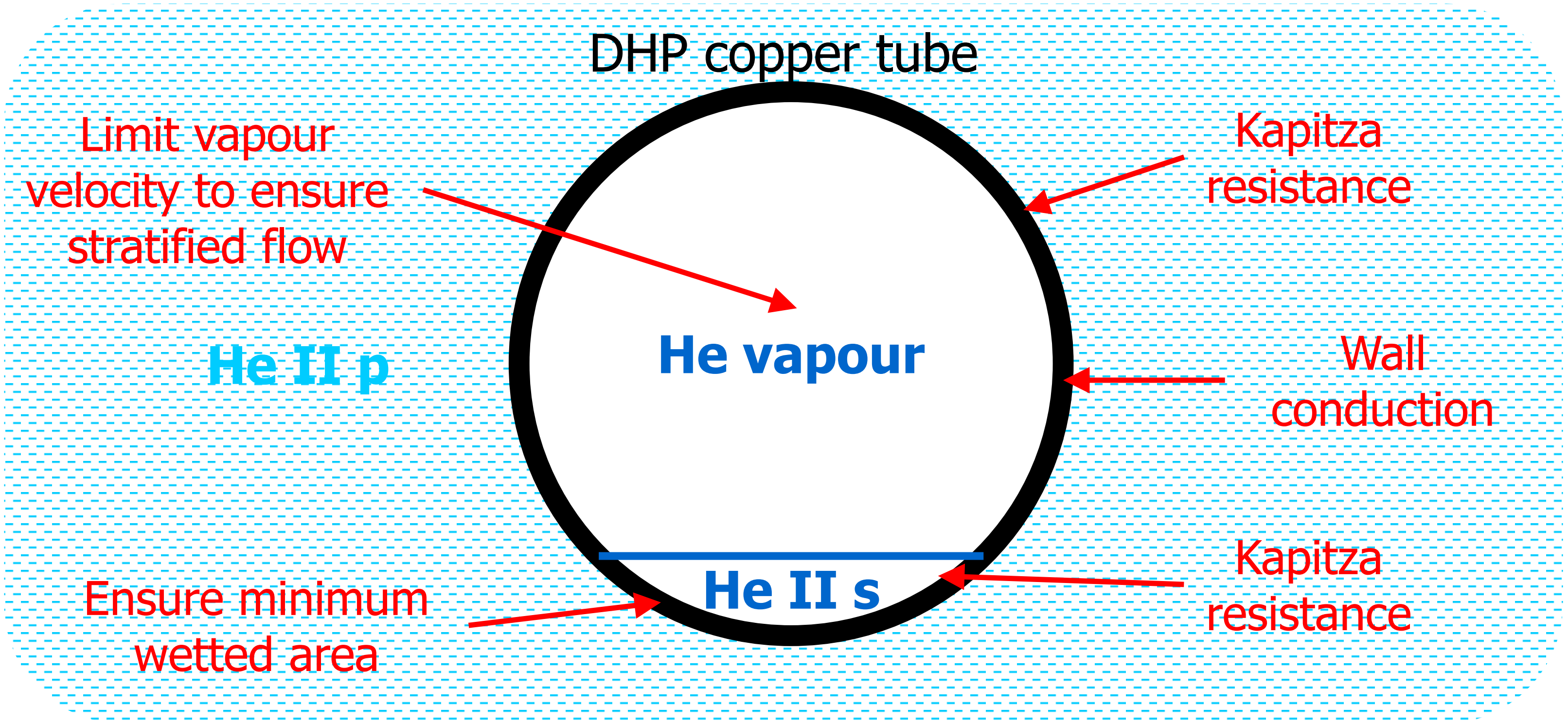
Cooling of the LHC magnet strings by two-phase flow of He IIs



- Heat exchanger tube in copper with a diameter DN50
- Overall thermal conductance: ~ 100 W/m.K

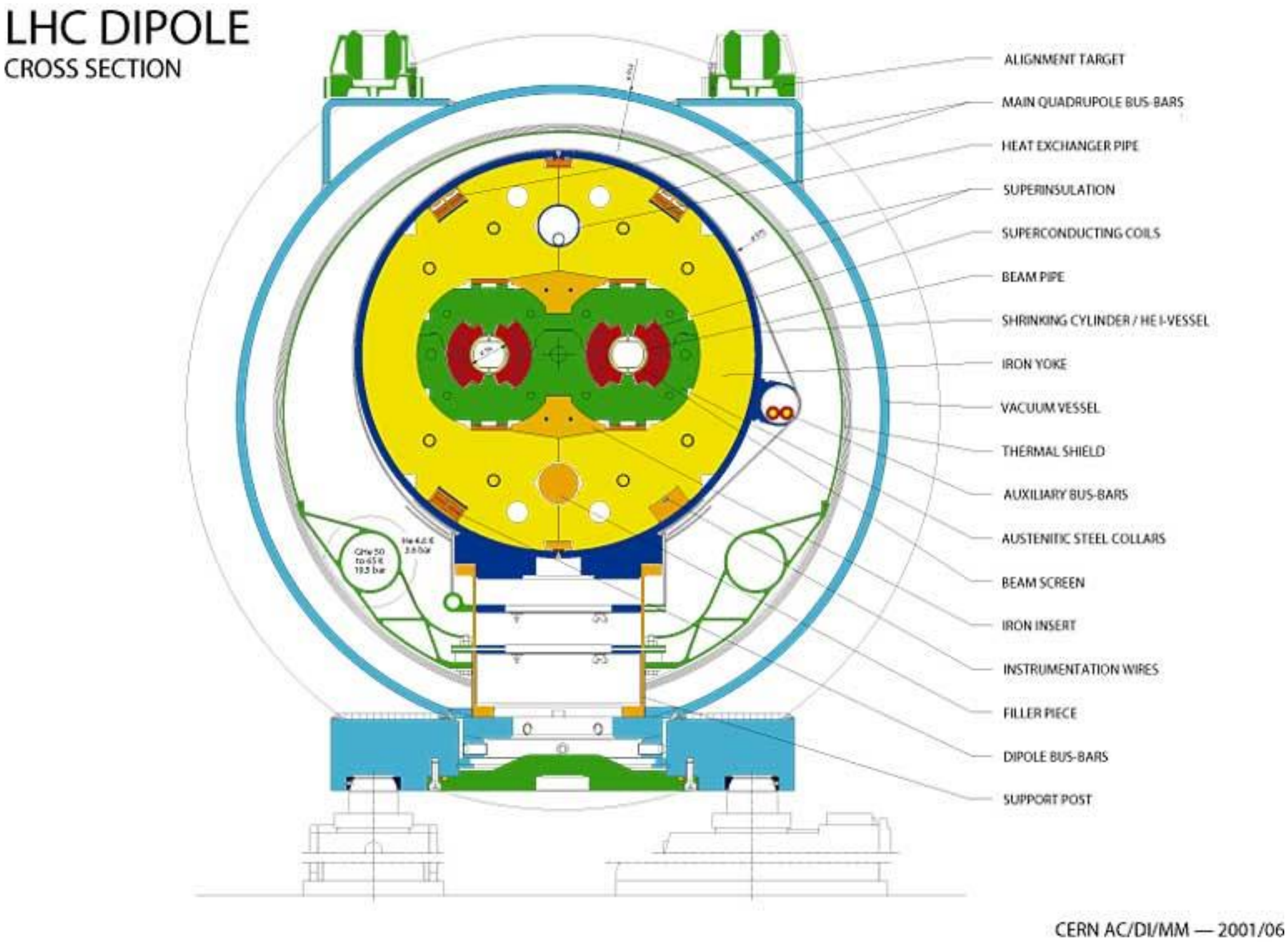
(i.e., for 1W/m, a temperature difference of 10 mK)

The He II bayonet heat exchanger tube

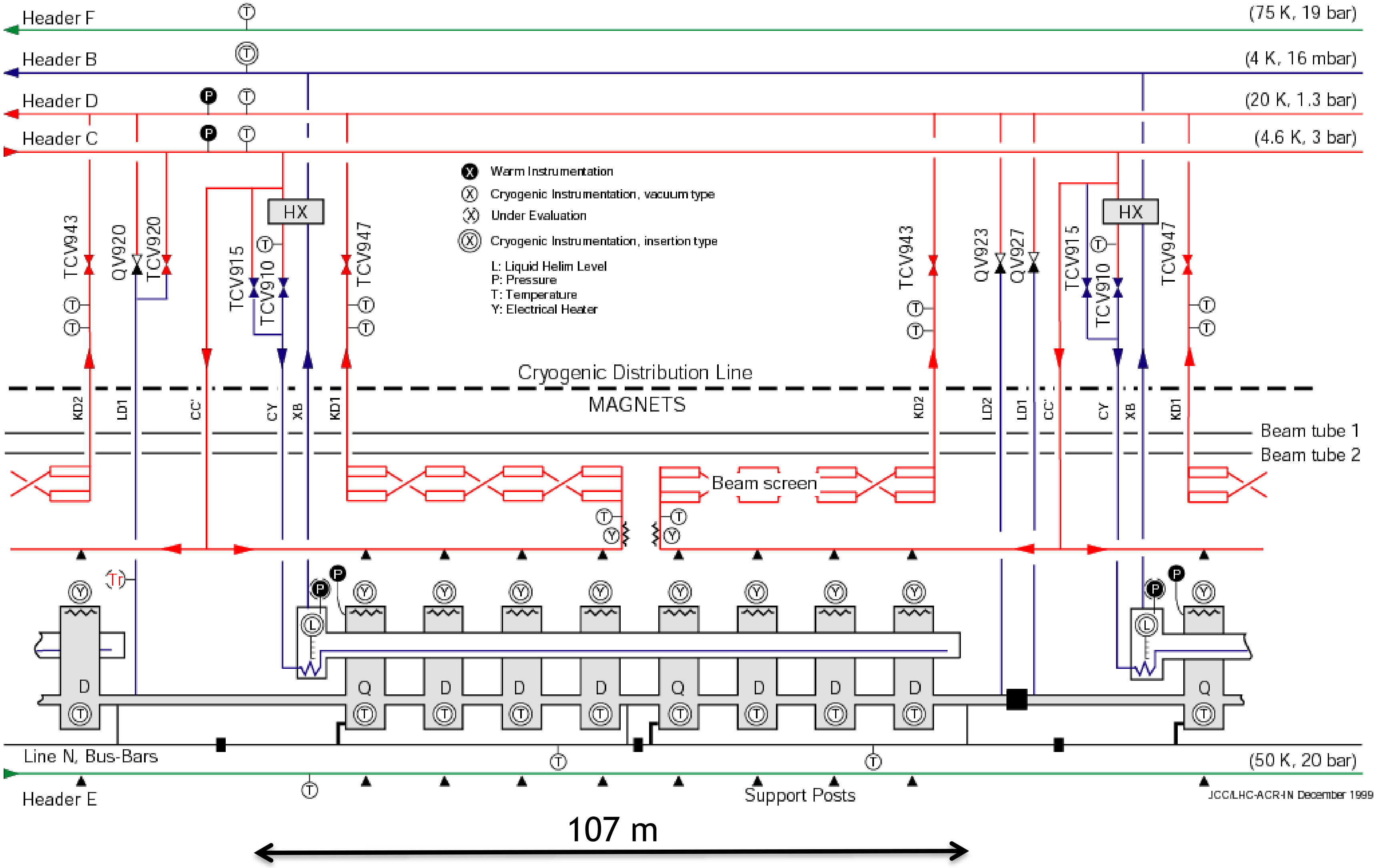


Measured overall heat transfer factor across DN50 tube: 100 W/m.K as long as some He II s liquid is present

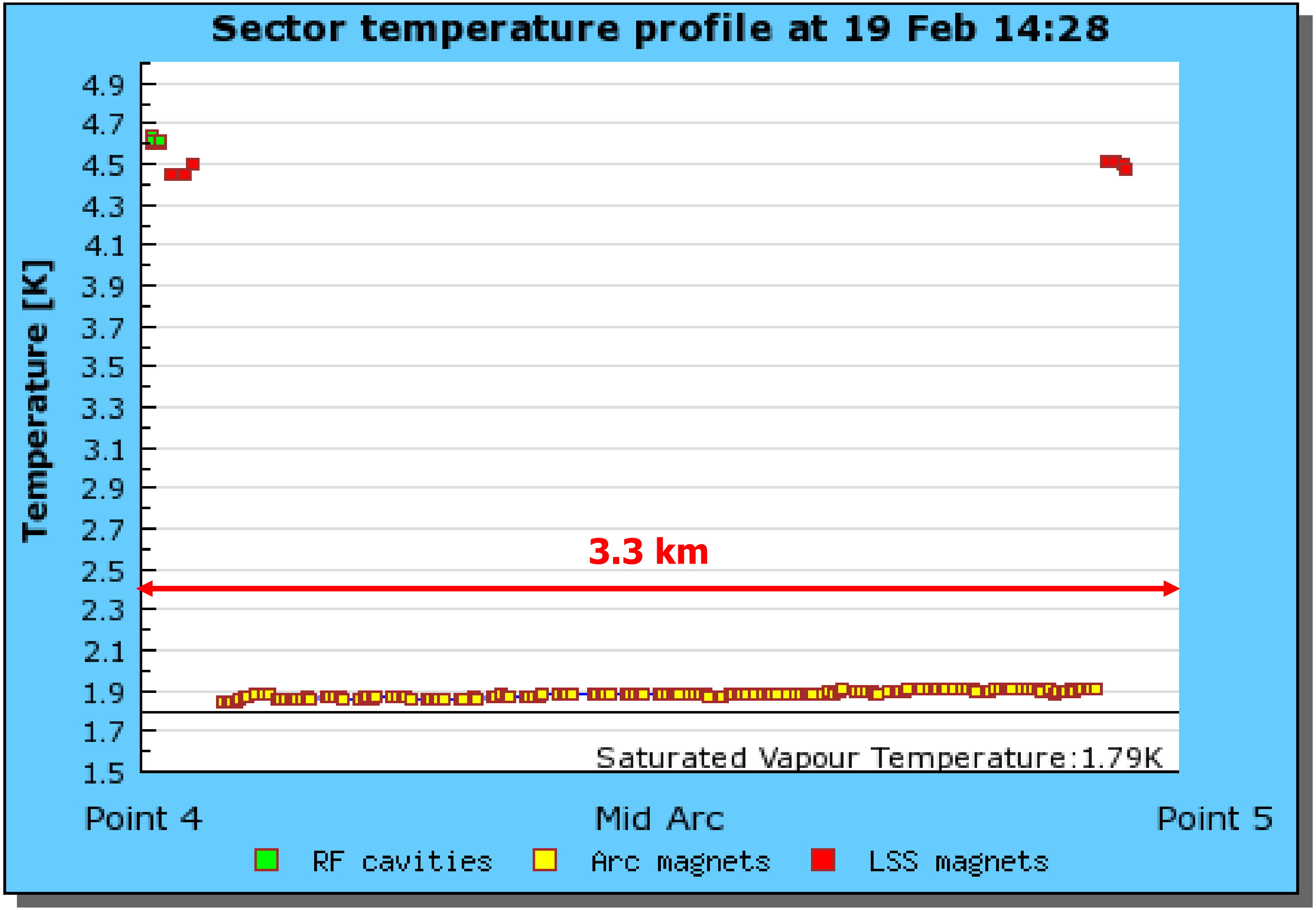
Cross-section of LHC magnet in cryostat



LHC magnet string cooling scheme

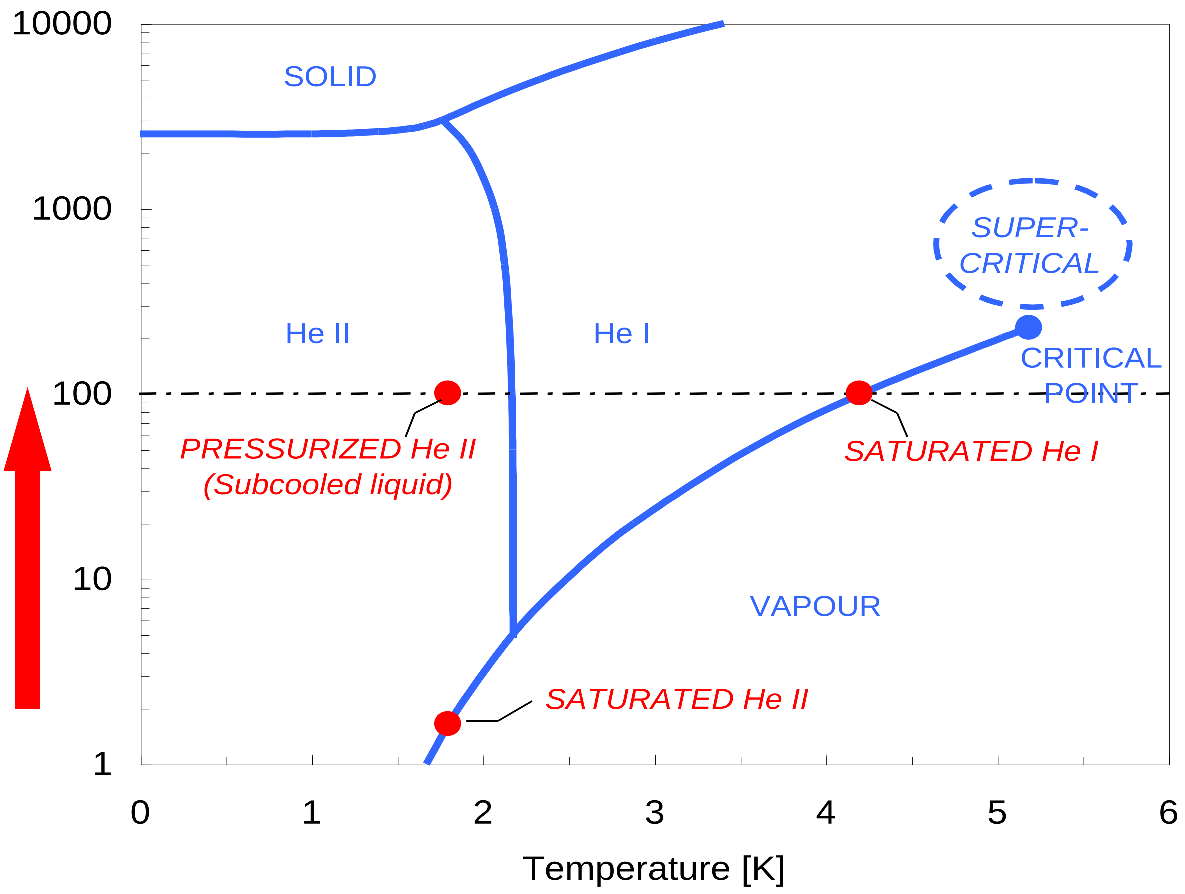


Temperature profile of LHC sector



Contents

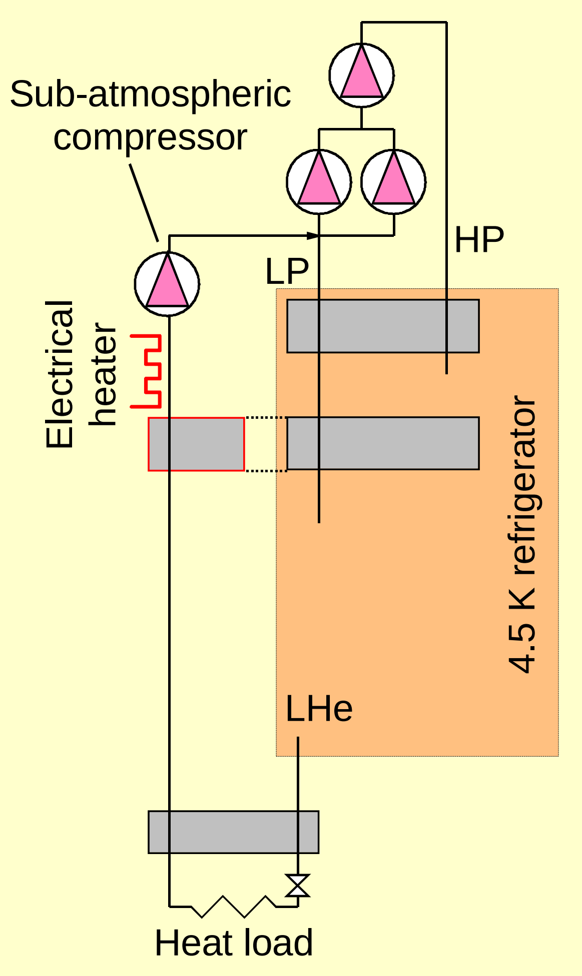
Challenges of power refrigeration at 1.8 K



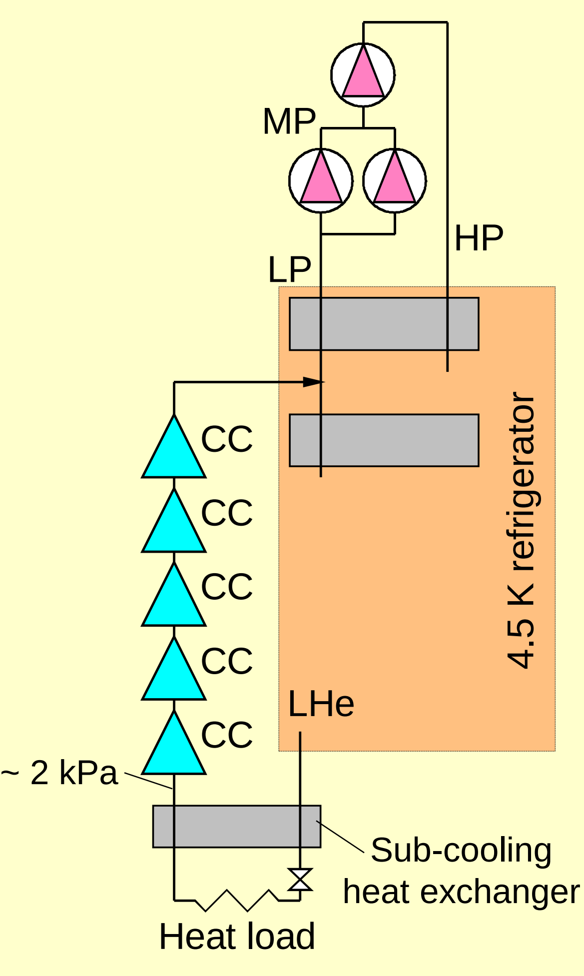
Compression > 80

Large mass flow-rate of low-density He vapor initially at low temperature must be compressed efficiently across high pressure ratio

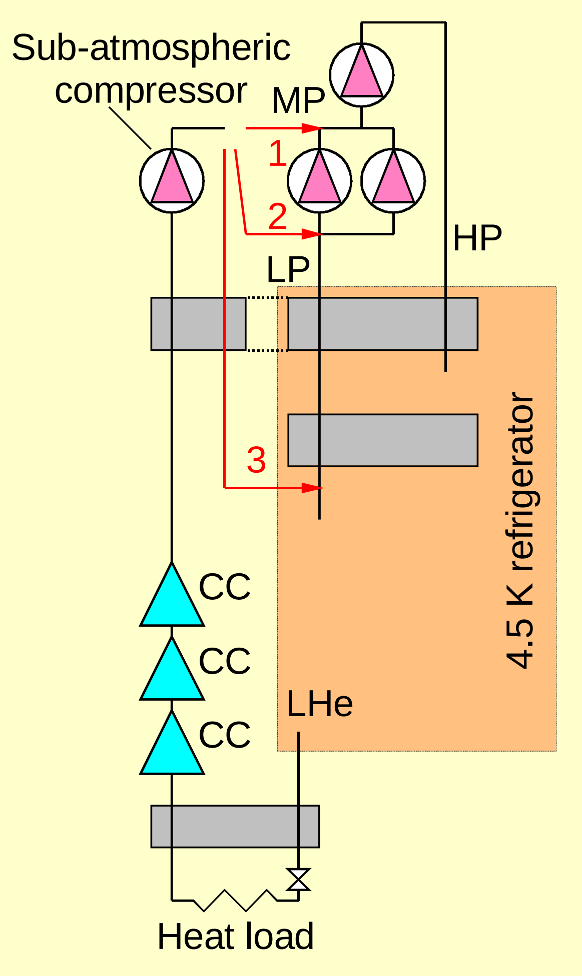
Cycles for refrigeration below 2 K



"Warm" Compression



"Integral Cold" Compression

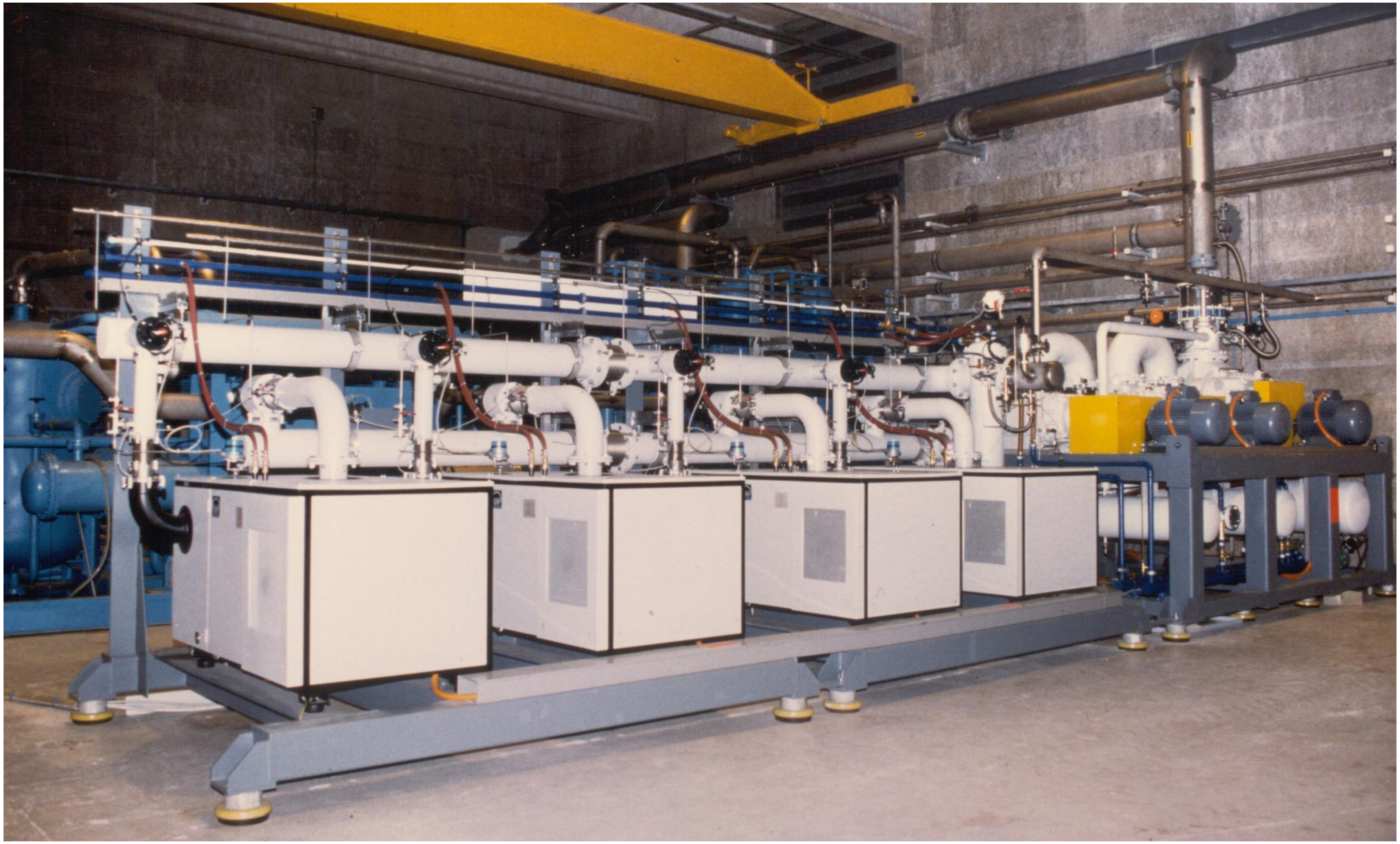


"Mixed" Compression

Warm pumping unit for LHC magnet tests

3 stages of Roots + 1 stage rotary-vane pumps

6 g/s @ 10 mbar *(1/160 of LHC!)*

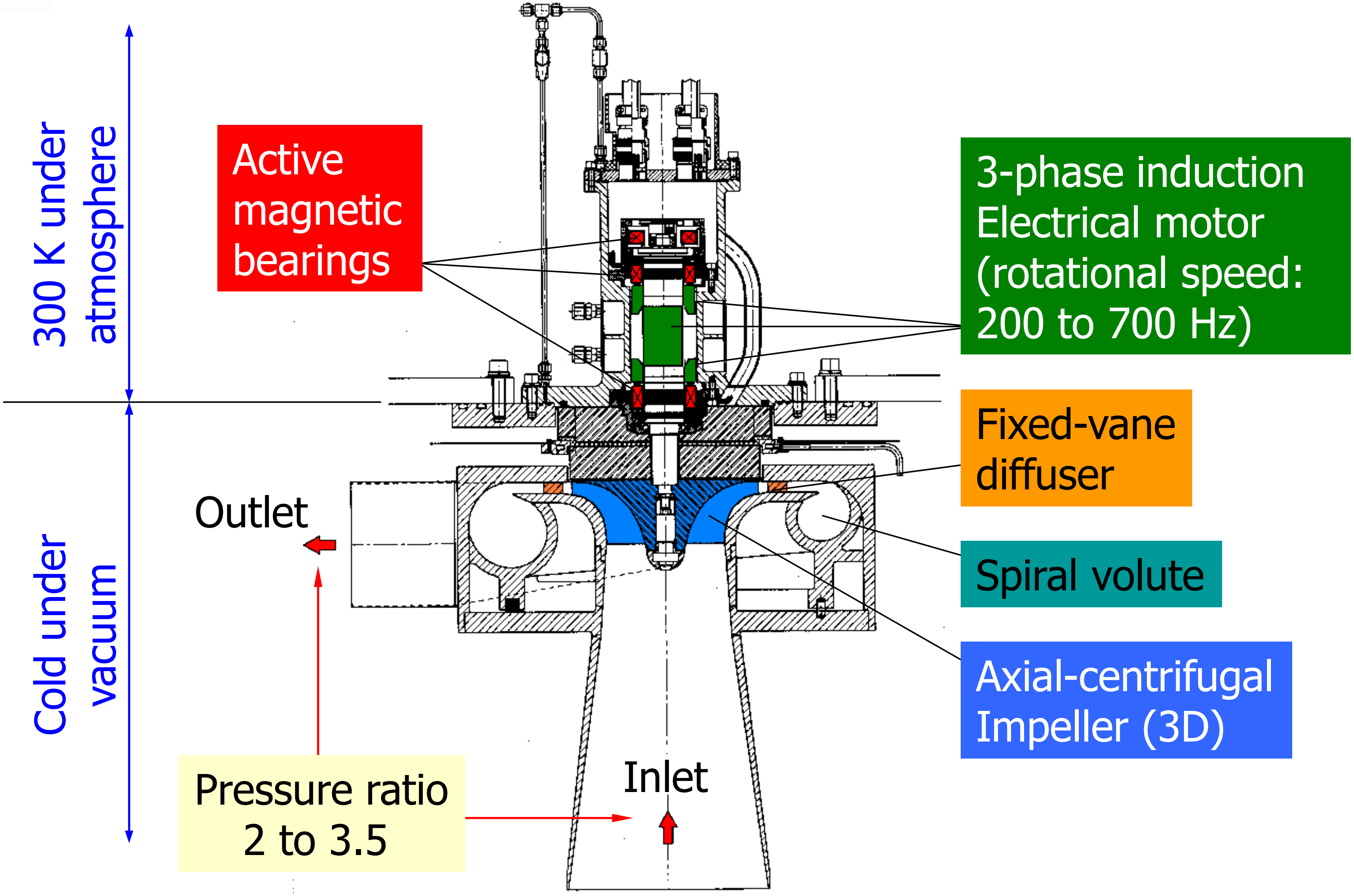


Cold hydrodynamic helium compressors

Air Liquide

IHI

Specific features of LHC cold compressors



300 K under atmosphere

Cold under vacuum

Active magnetic bearings

3-phase induction Electrical motor (rotational speed: 200 to 700 Hz)

Fixed-vane diffuser

Spiral volute

Axial-centrifugal Impeller (3D)

Outlet

Inlet

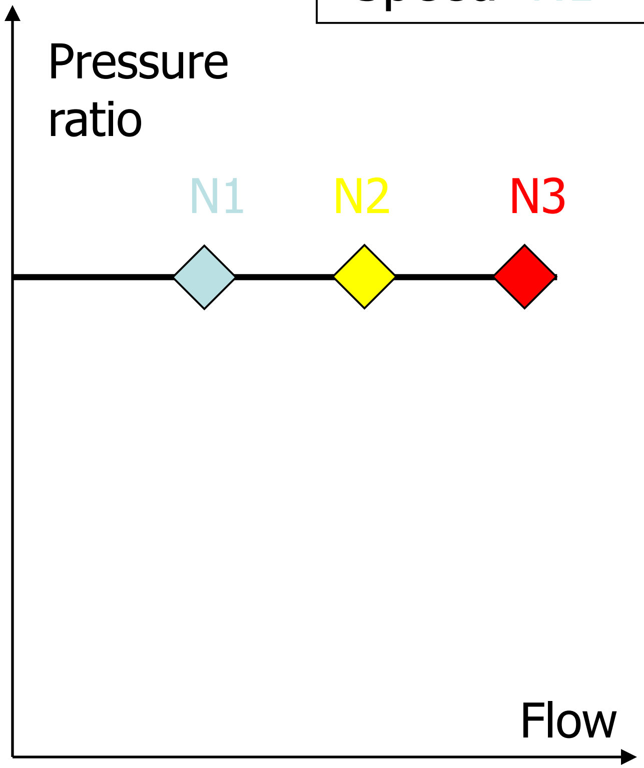
Pressure ratio 2 to 3.5

Cold versus «warm» (RT) compression

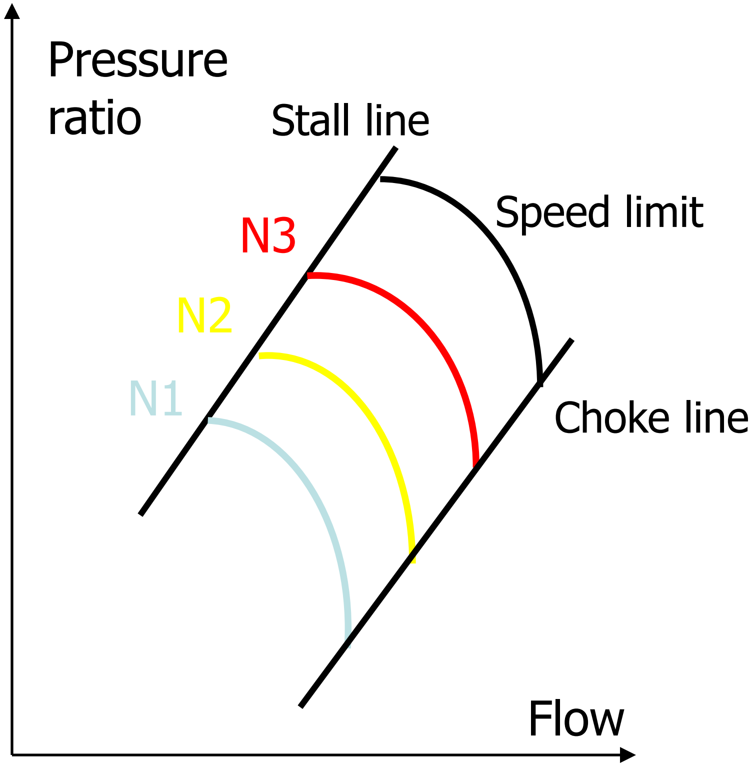
Criterion	Cold compression	«Warm» compression
Type of machine	Hydrodynamic	Volumetric
Examples of machines	Centrifugal, axial-centrifugal	Rotary vane pump, roots, liquid ring, screw
Rejection of heat of compression	-	+
Limitation of volume flow-rate (size of compressor)	+	-
Efficiency of heat exchange (size of HX)	+	-
Lubrication of compressor	-	+
Pressure ratio per stage of compressor	-	+
Compliance to variable flow & inlet conditions	-	+

Operating ranges
of volumetric & hydrodynamic compressors

Speed N1 < N2 < N3

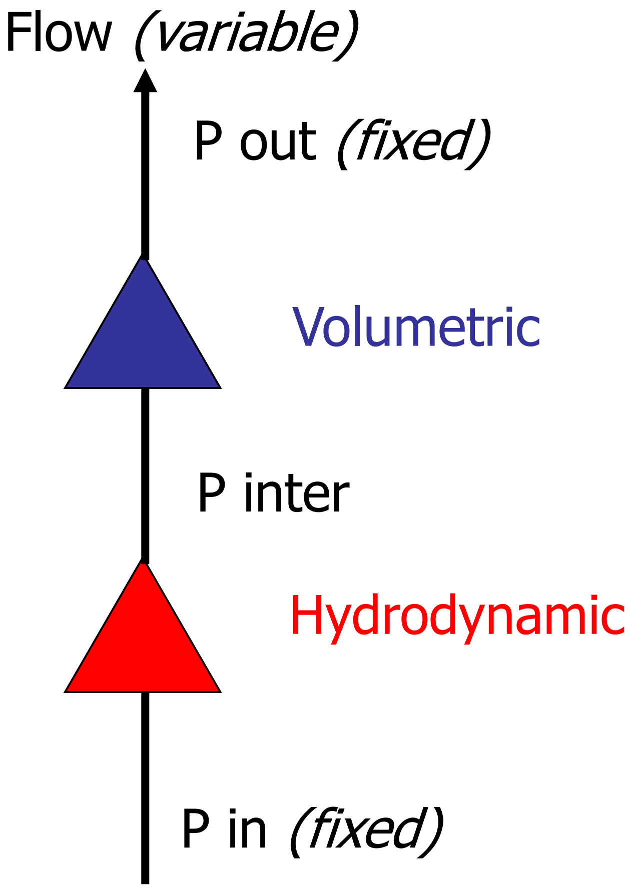


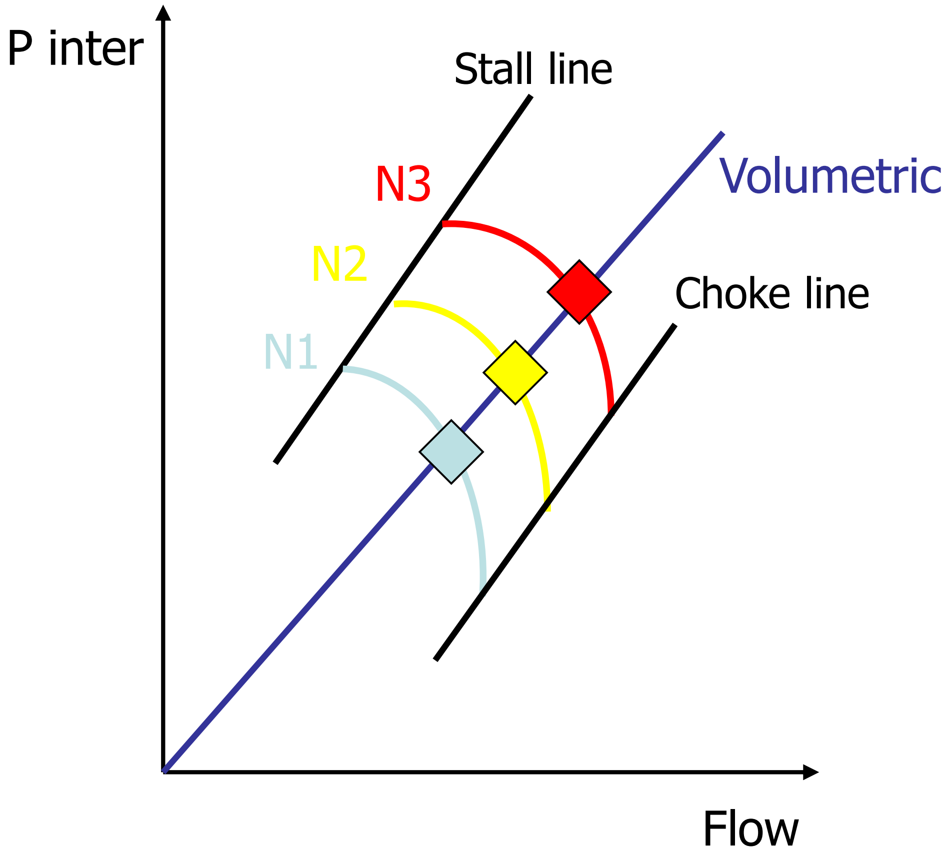
Volumetric (ideal)



Hydrodynamic

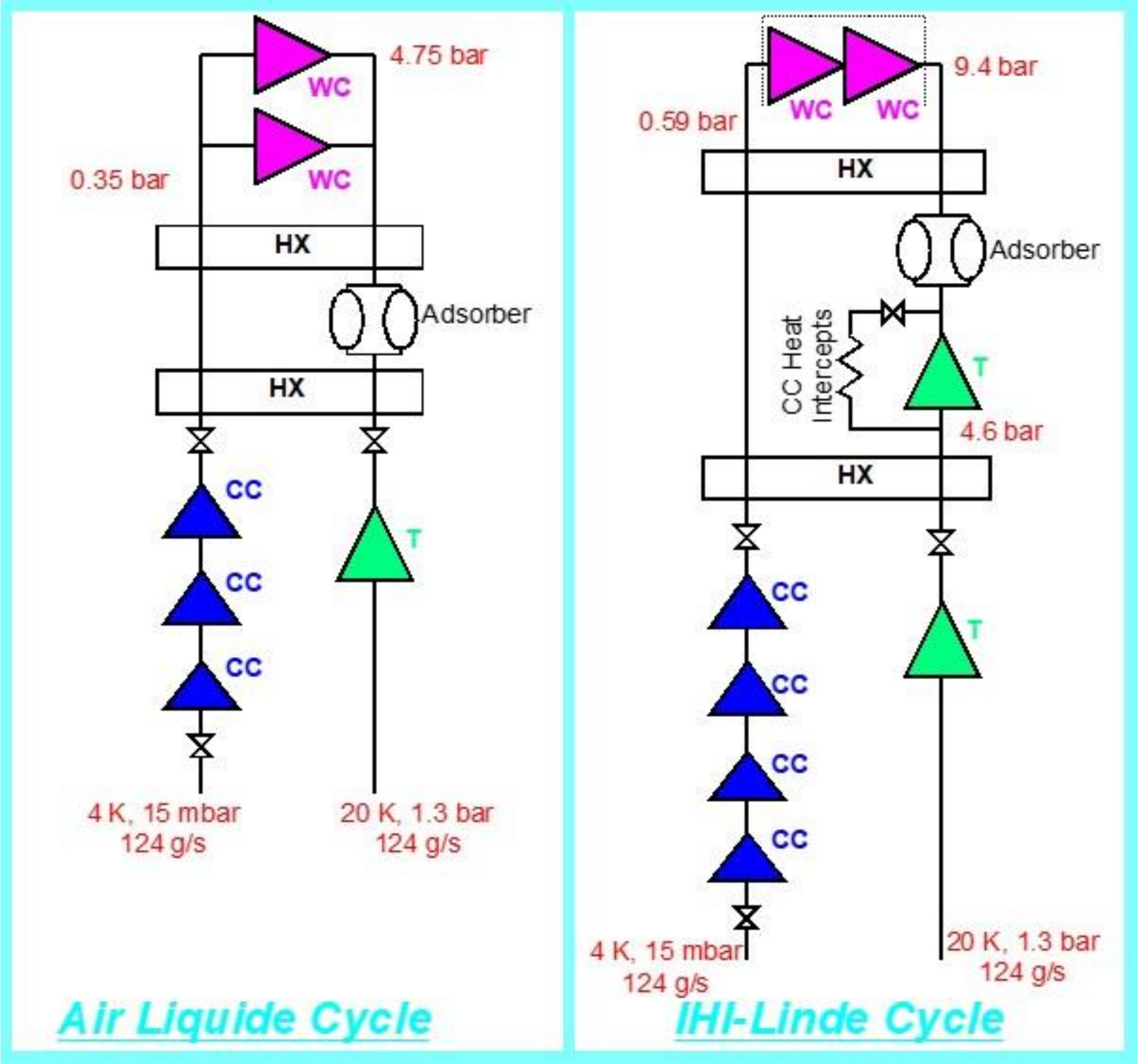
Flow compliance of “mixed” compression



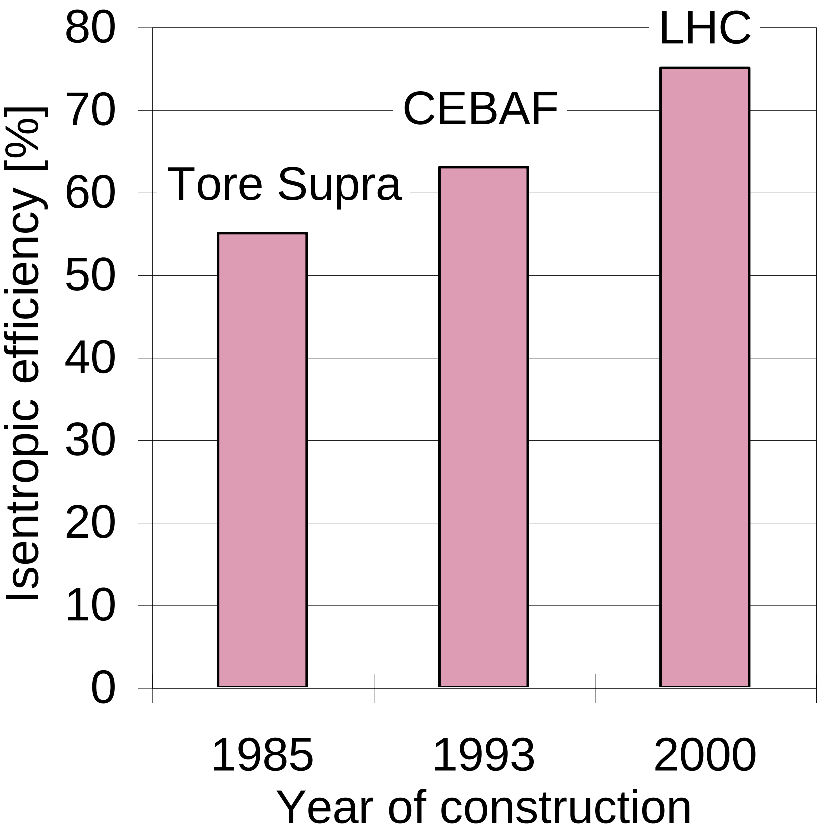


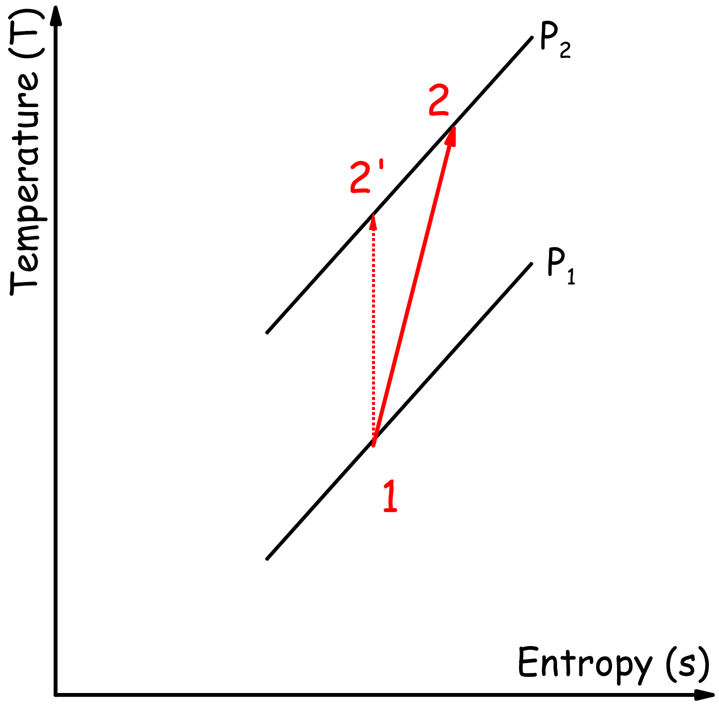
For fixed overall inlet & outlet conditions, coupling of the two machines *via* P inter maintains the operating point in the allowed range

Simplified flow-schemes of the 1.8 K refrigeration units of LHC



Performance of LHC cold compressors





$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$

Warm sub-atmospheric screw compressors

Compound two-stage screw compressor

Mycom

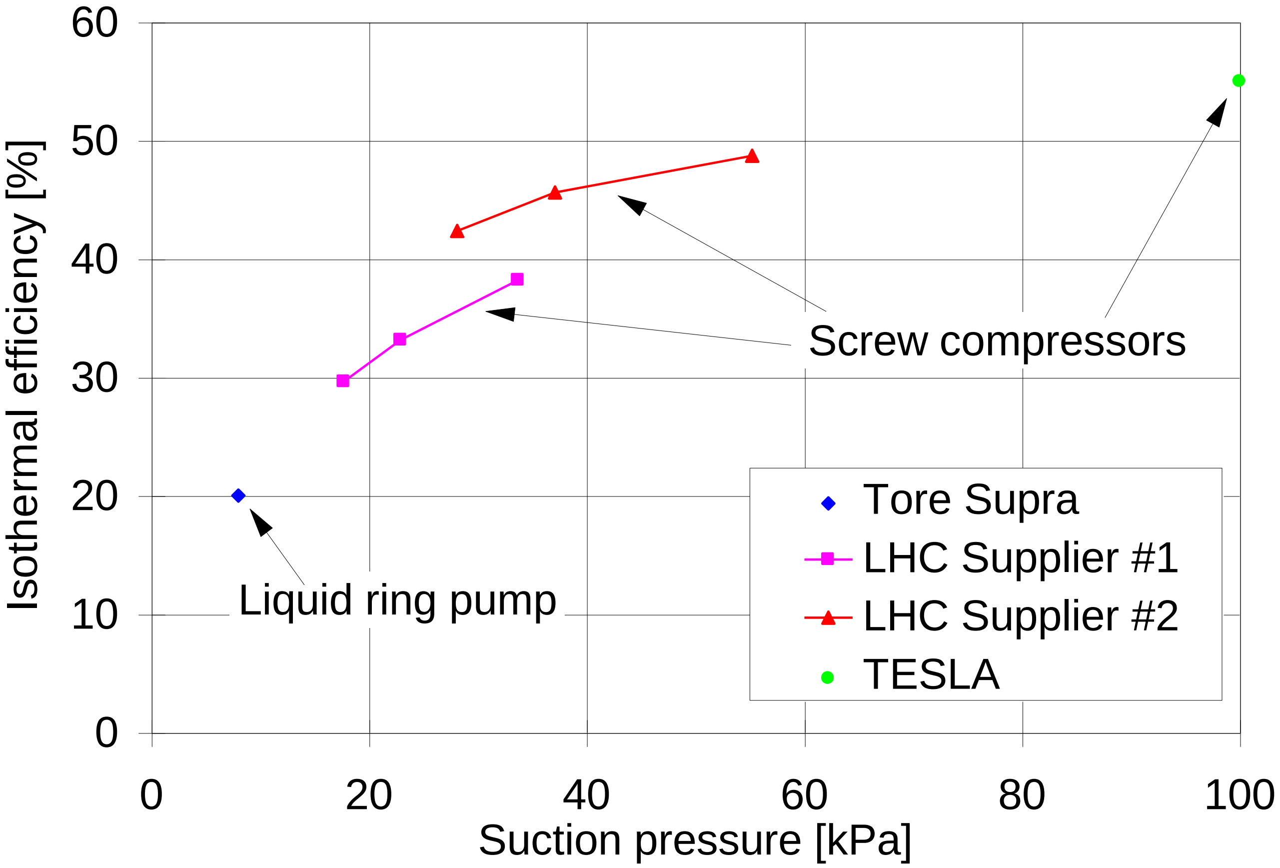
WCS at CERN:
125 g/s @ 0.6 bar
or
4600 m3/h @ 15 °C

Warm sub-atmospheric screw compressors

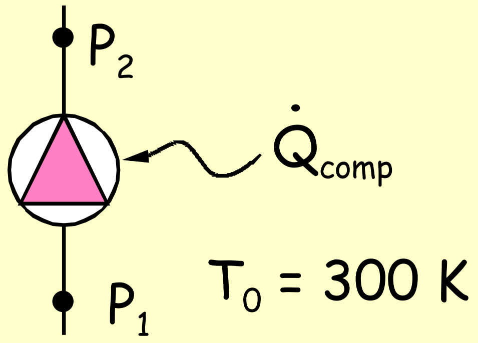
WCS at CERN:
125 g/s @ 0.35 bar
or
2 x 3900 m3/h @ 15 °C

Kaeser

Isothermal efficiency of warm subatmospheric compressors

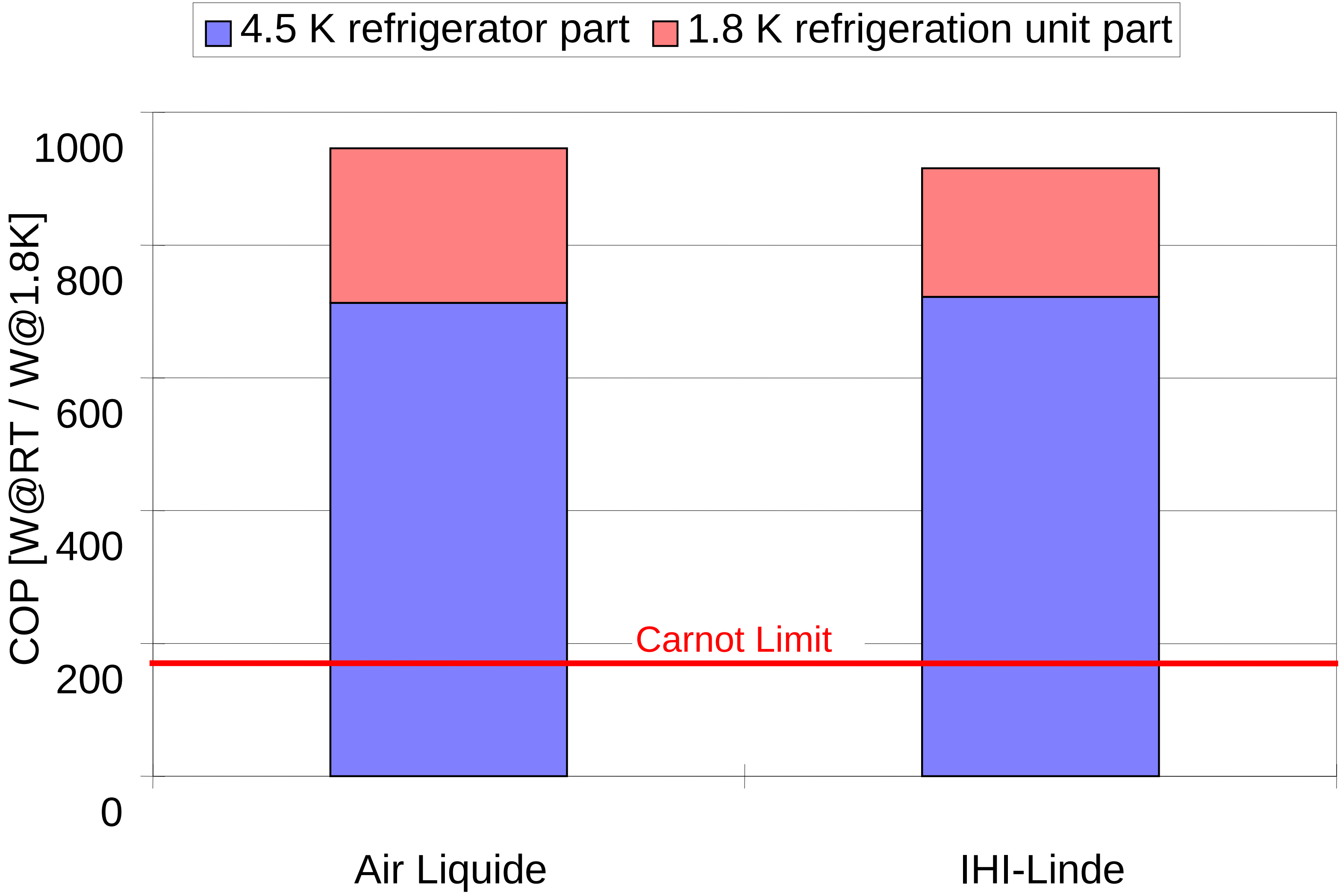


Isothermal efficiency

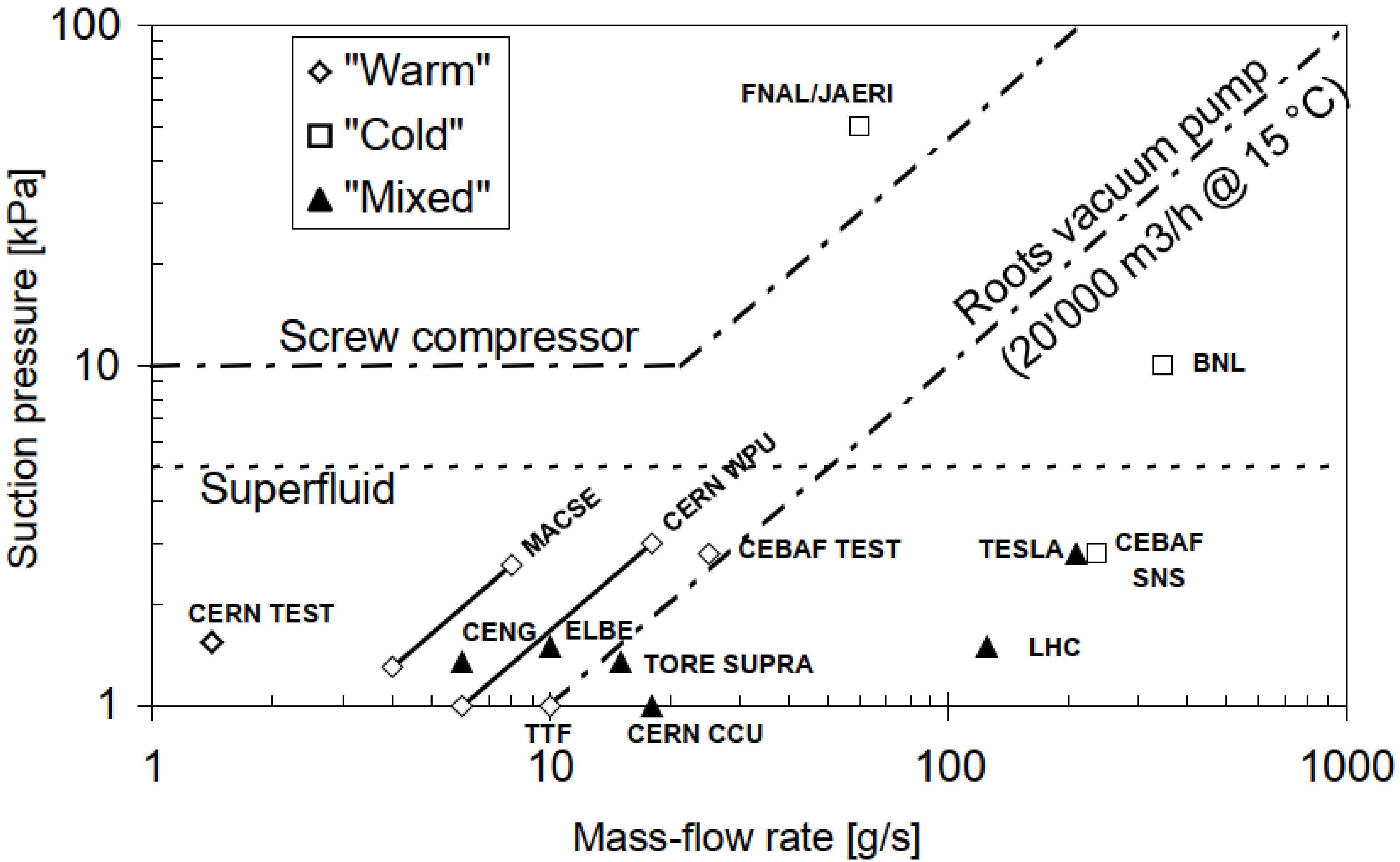


$$\eta_{th} = \frac{n \cdot R \cdot T_0 \cdot \ln\left(\frac{P_2}{P_1}\right)}{\dot{Q}_{comp}}$$

C.O.P. of LHC 1.8 K units



Range of application of low-pressure helium compression techniques



Problem 3: Adiabatic compression of low-pressure gaseous helium

One wishes to produce 120 W refrigeration at 1.8 K by compressing gaseous helium at the corresponding saturation pressure of 16.4 mbar, up to atmospheric pressure (1 bar), where it can then be recovered in a gas bag or enter the LP side of a helium liquefier.

1. Calculate the corresponding mass flow-rate.
2. Calculate the corresponding volume flow-rate:
    a) for a cold compressor handling the gas at 4 K, with a density 0.198 kg/m^3,
    b) for a conventional "warm" vacuum pump handling the gas at room temperature (290 K), with a density of 0.00272 kg/m^3.
3. Assuming reversible adiabatic compression and taking helium as an ideal gas, calculate the compression power in both cases.
4. Redo the calculations of compression power using real thermodynamic properties of helium. Was the ideal gas approximation justified?

Contents

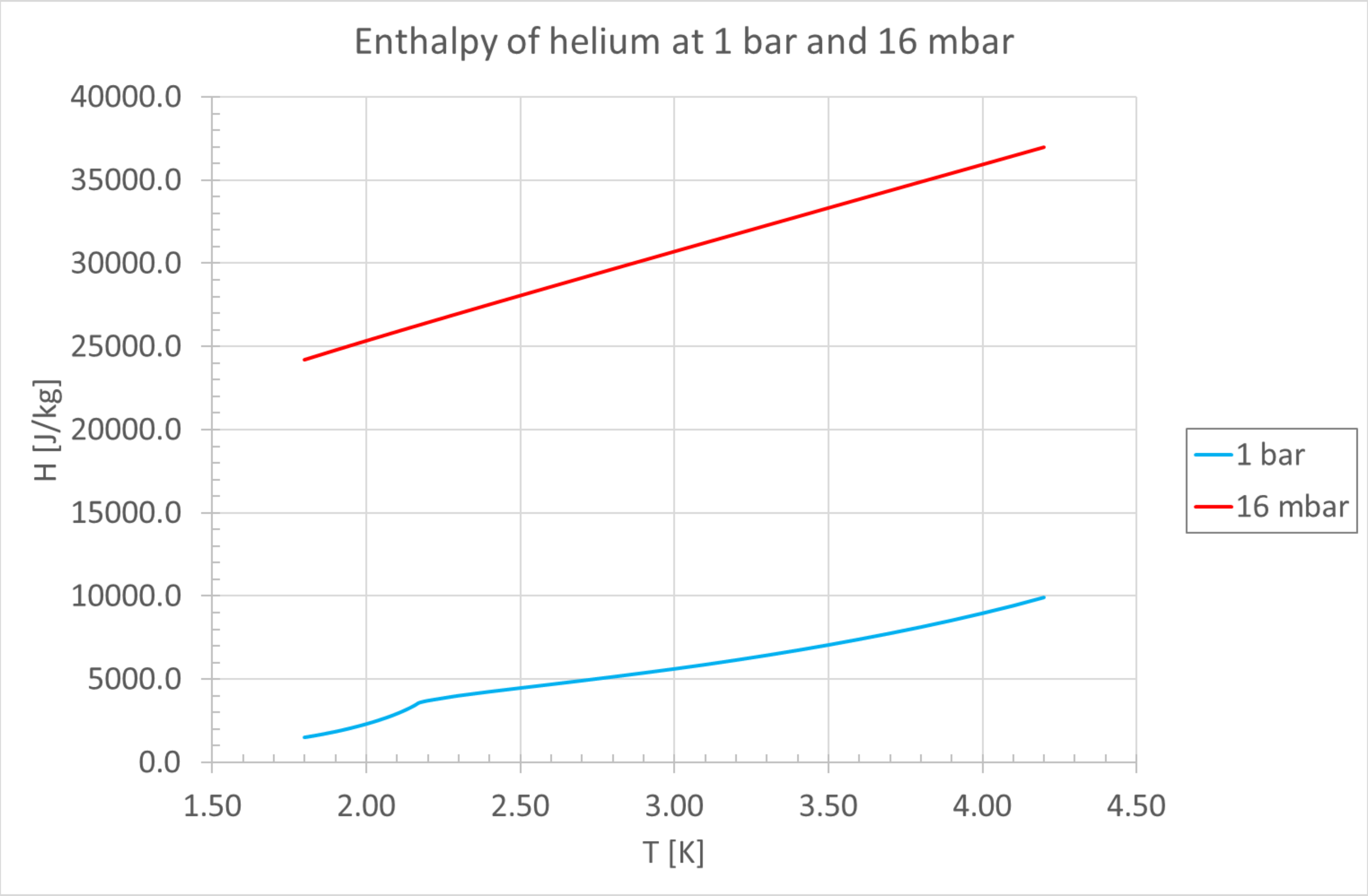
- Introduction to superfluid helium
- Superfluid helium as a technical coolant
- Practical cooling schemes
- Refrigeration below 2 K
- Specific technology for He II systems
- Applications

Problem 4: Production of saturated superfluid by J-T expansion

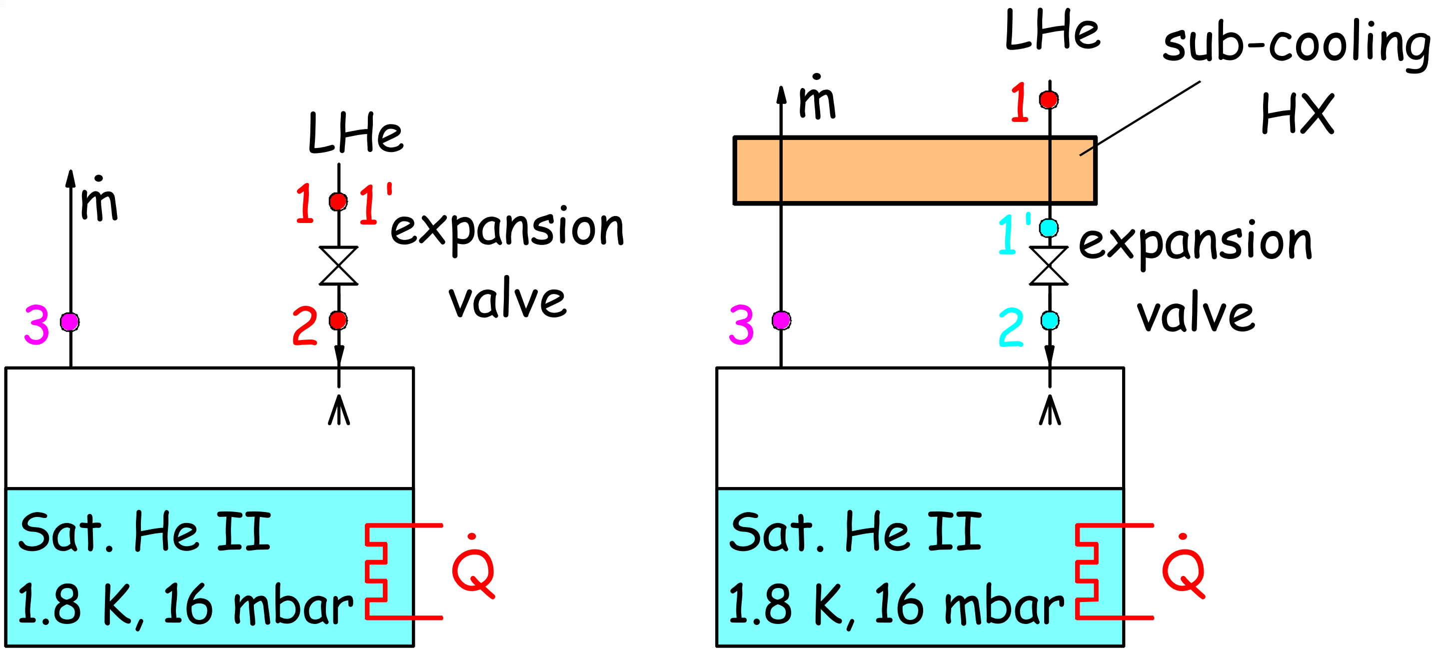
Consider Joule-Thomson expansion of saturated helium at 4.2 K through a valve, down to the pressure corresponding to a saturation temperature of 1.8 K.

1. What is the saturation pressure of helium at 1.8 K?
2. Which thermodynamic function of state remains constant in the expansion?
3. Calculate the fraction of vapour produced in the expansion, and the remaining fraction of liquid. What do you conclude about the efficiency of the process to produce saturated superfluid helium?
4. A heat exchanger is introduced before the expansion valve, to subcool the liquid by the returning cold vapour. What are the temperatures of the two streams at the cold end of the heat exchanger? What are the temperatures of the two streams at the warm end of the heat exchanger? Calculate the fraction of vapour produced in the expansion, and the remaining fraction of liquid, What do you conclude about the efficiency of the process?
5. What are the design and construction challenges of the heat exchanger?

Enthalpy of helium at 1 bar and 16 mbar



Efficiency of Joule-Thomson expansion



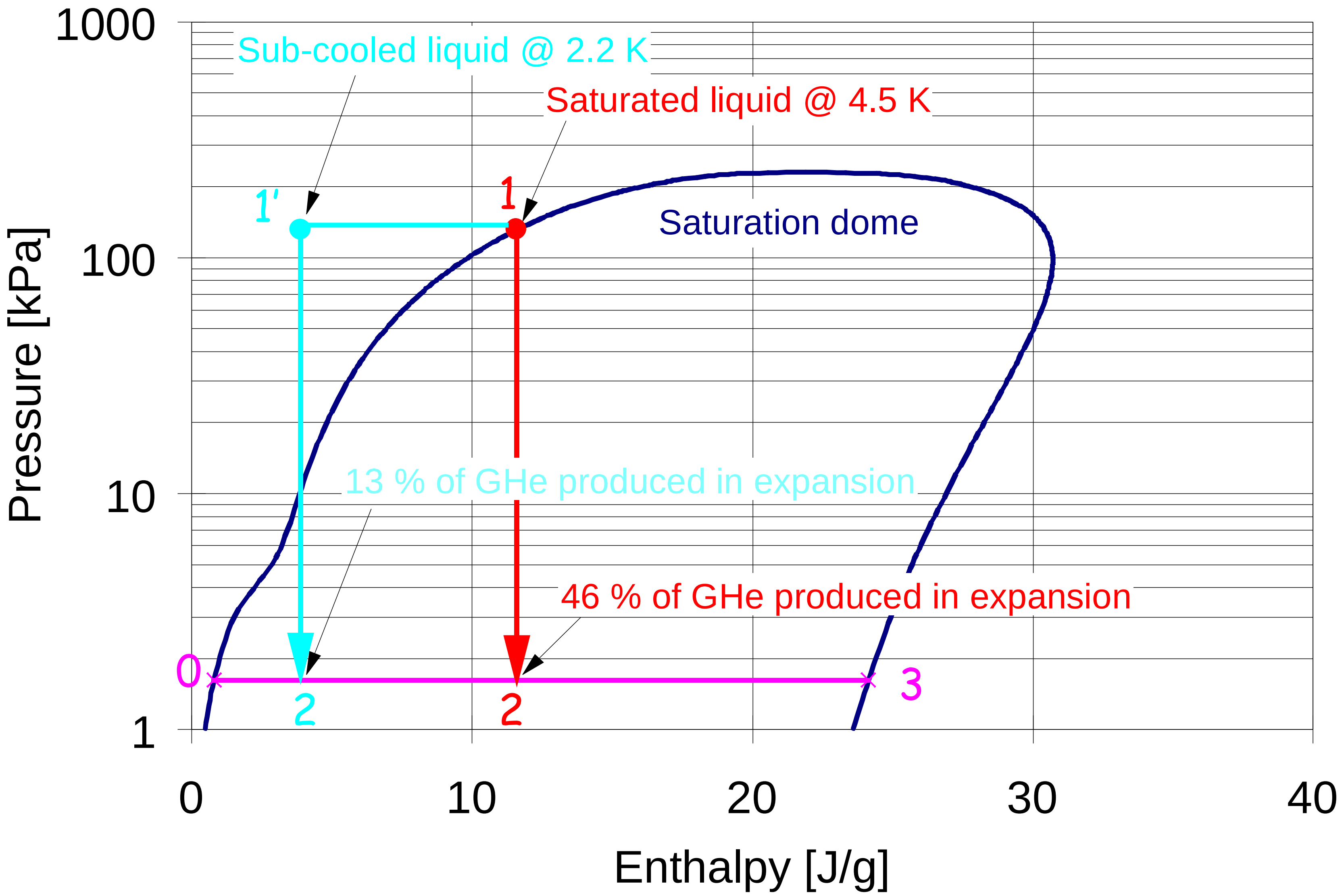
Sub-cooling efficiency :

$$\eta_{sc} = \frac{H_3 - H_2}{H_3 - H_0}$$

Enthalpy of pure liquid

Sub-cooling	$T_{1'}$ [K]	H_3-H_2 [J/g]	H_3-H_0 [J/g]	η_{sc} [%]
without	4.5	12.6	23.4	54
with	2.2	20.4	23.4	87

Benefit of subcooling before J-T expansion

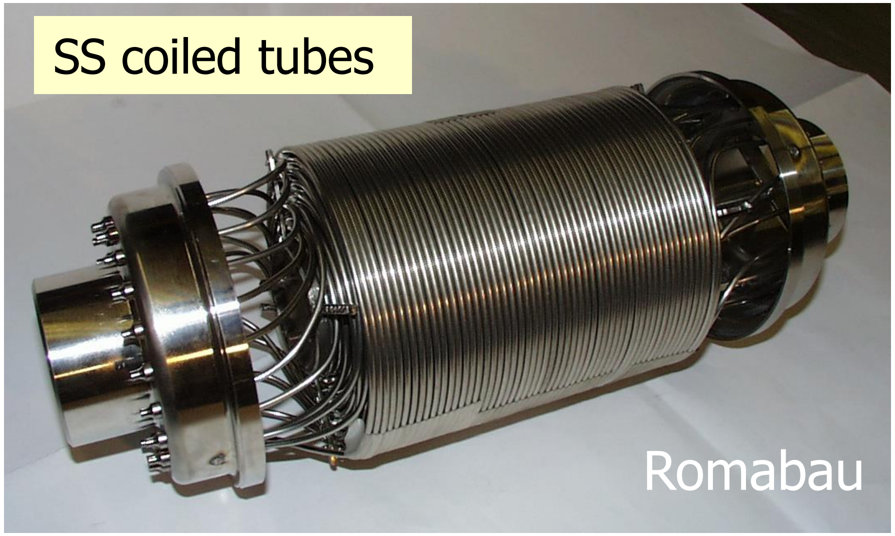


Subcooling HX technologies investigated for LHC

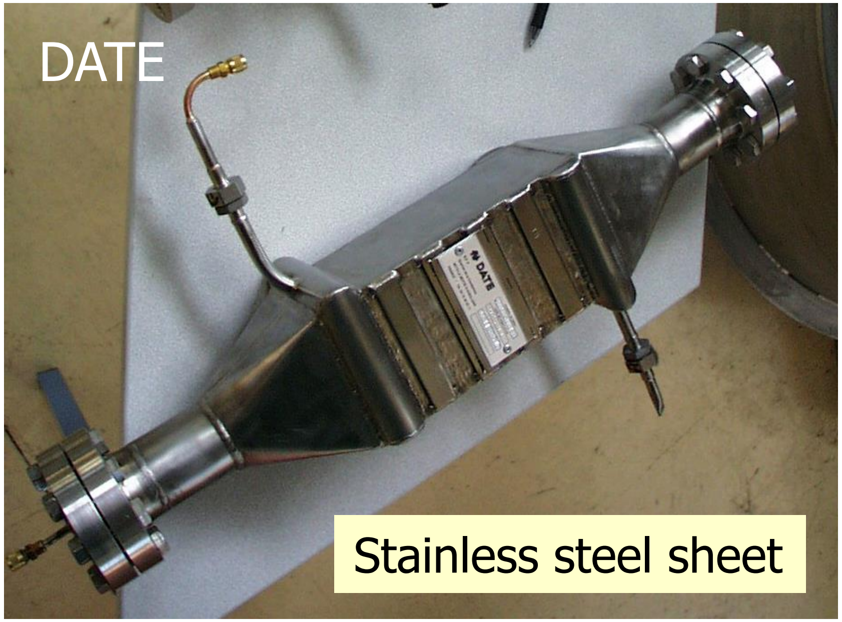
Mass-flow: 4.5 g/s
ΔP VLP stream: < 1 mbar
Sub-cooling T: < 2.2 K


SNLS

Perforated copper plates with SS Spacers


SS coiled tubes

Romabau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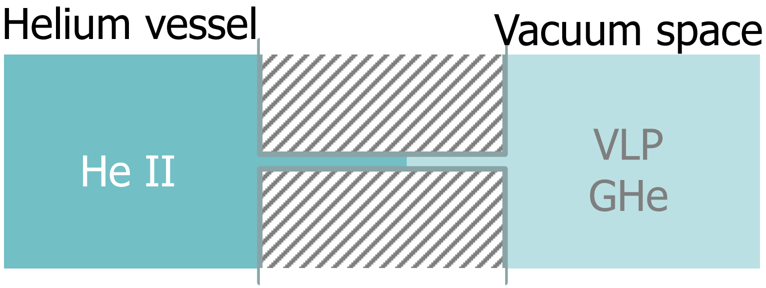
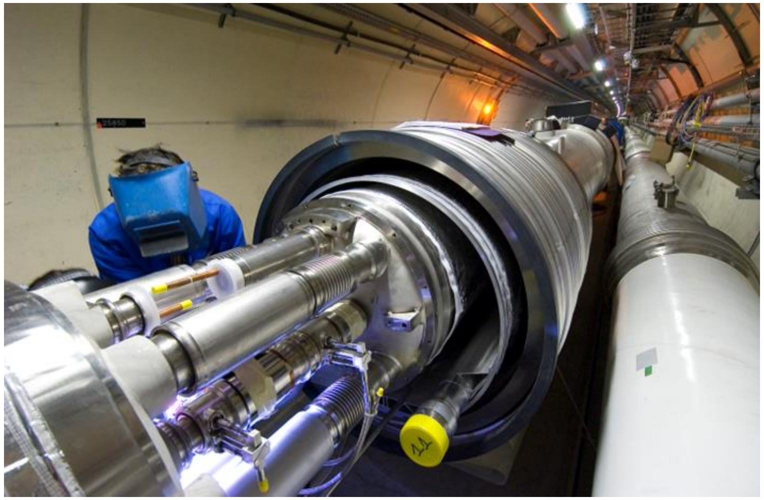
Stainless steel sheet

Helium II to vacuum leak-tightness

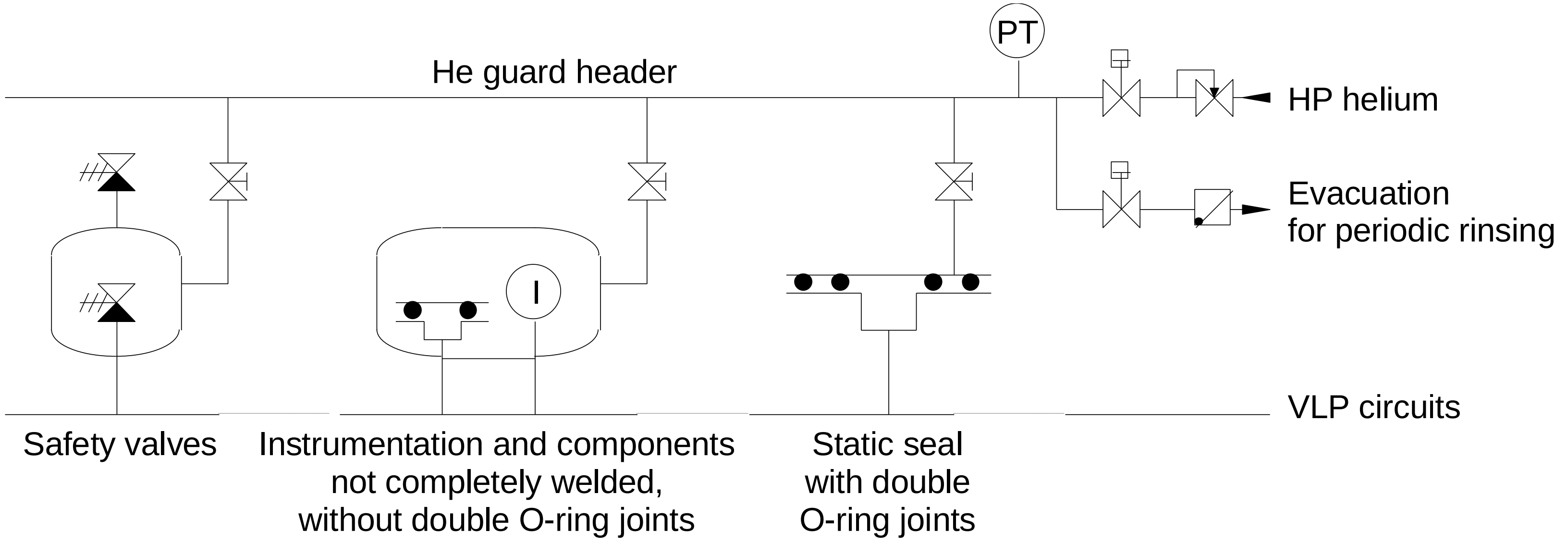
- Design and construction rules applicable for cryogenic equipment operating with normal liquid helium are sufficient to ensure helium II leak-tightness
  - In a crack in the wall of the helium II vessel of a cryostat, the leaking helium will vaporize when it reaches saturation pressure some way along the crack
  - The leakage rate will be controlled by the flow of vapour downstream – as for a normal helium leak
- Prefer all-welded austenitic stainless steel construction, using automatic welding to reduce human error
- Enforce systematic pressure- and leak-testing after cold shock





Protection against air inleaks

- Motor shaft of warm sub-atmospheric compressors placed at the discharge side to work above atmospheric pressure.
- For sub-atmospheric circuits which are not under guard vacuum or not completely welded, apply helium guard protection on dynamic seal of valves, on instrumentation ports, on safety relief valves and on critical static seals



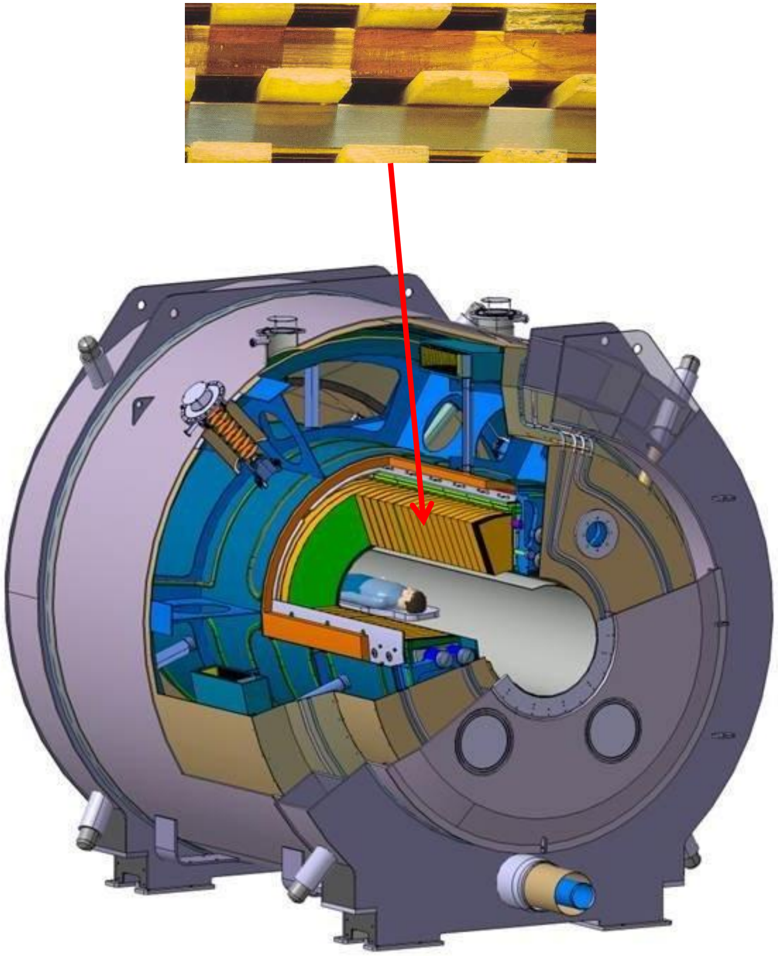
Contents

- Introduction to superfluid helium
- Superfluid helium as a technical coolant
- Practical cooling schemes
- Refrigeration below 2 K
- Specific technology for He II systems
- Applications

High-field magnets for high-frequency NMR

900 MHz ⇔ 21.2 T

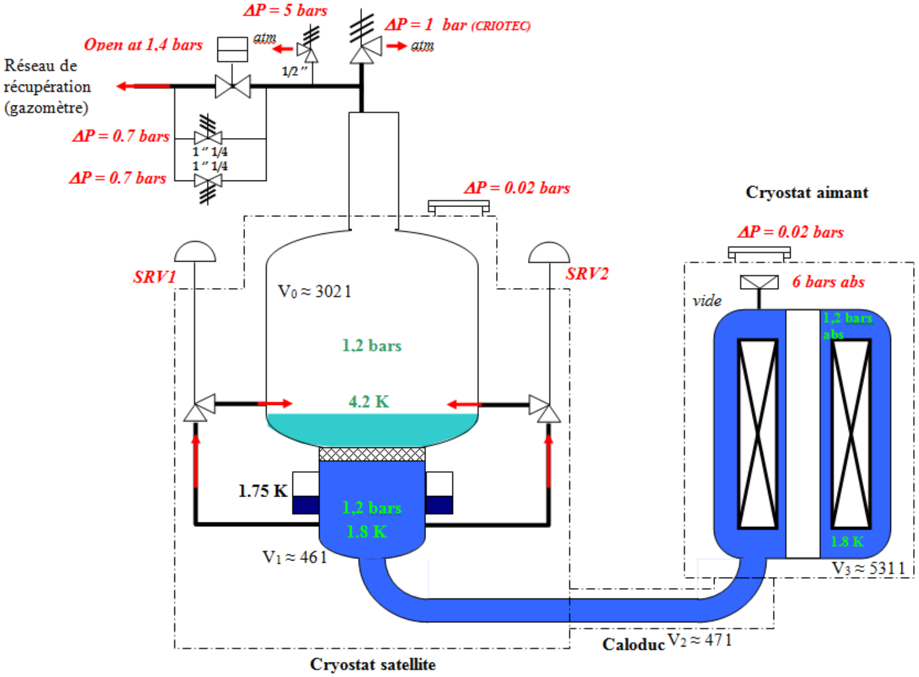
ISEULT 11.7 T whole-body MRI magnet
CEA Saclay (France)



Pressurized He II at 1.8 K at 1.2 bar

Insulator/separator of conductors creates cooling channels in magnet coil

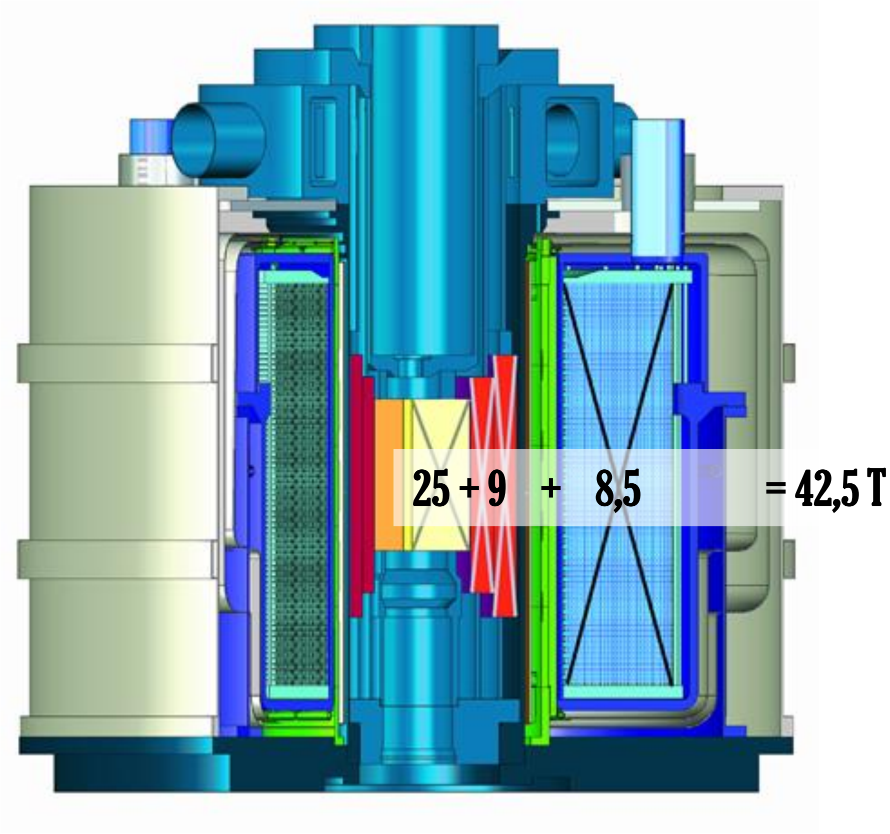
Magnet cooled by conduction from satellite cryostat

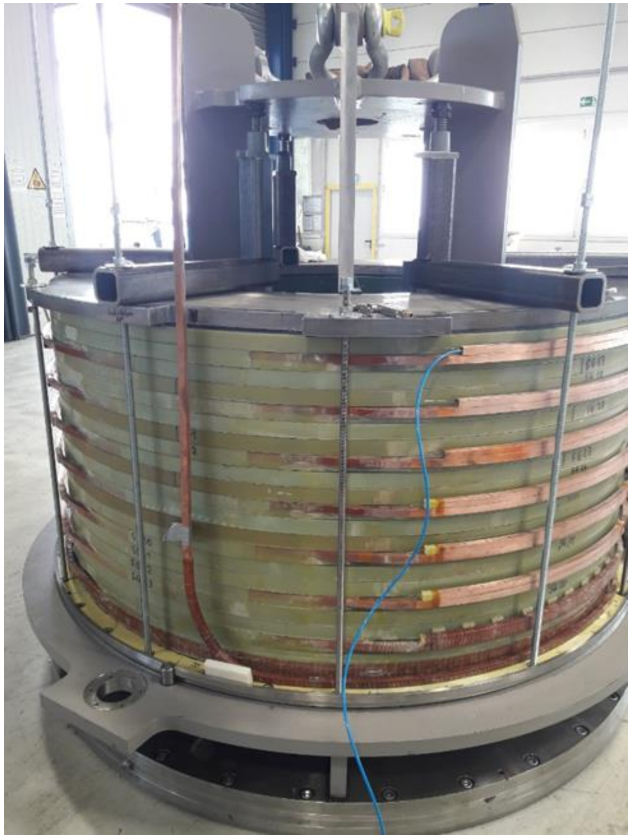


The ISEULT magnet in its cryostat

42.5 T hybrid magnet at LNCMI, Grenoble

NbTi superconducting solenoid in superfluid He + Bitter coil + Polyhelix coil



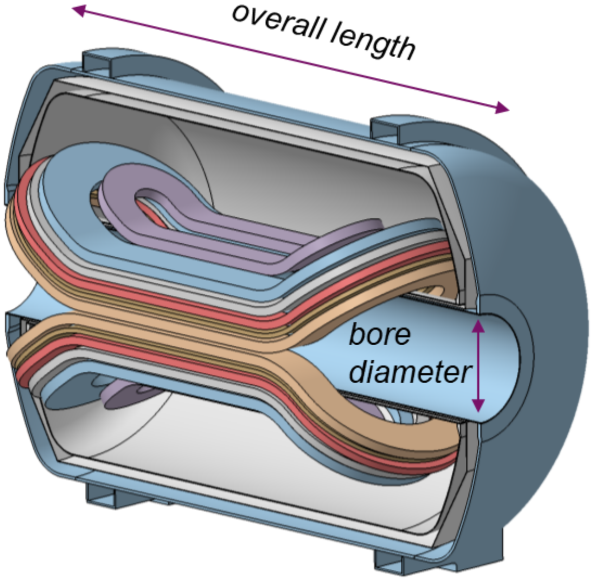


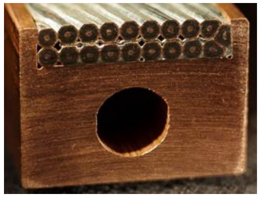
Axion detection by conversion to photons: MADMAX

Study for Max Planck Institute, based on large-bore, high-field superconducting NbTi dipole magnet (hollow conductor) cooled by superfluid helium

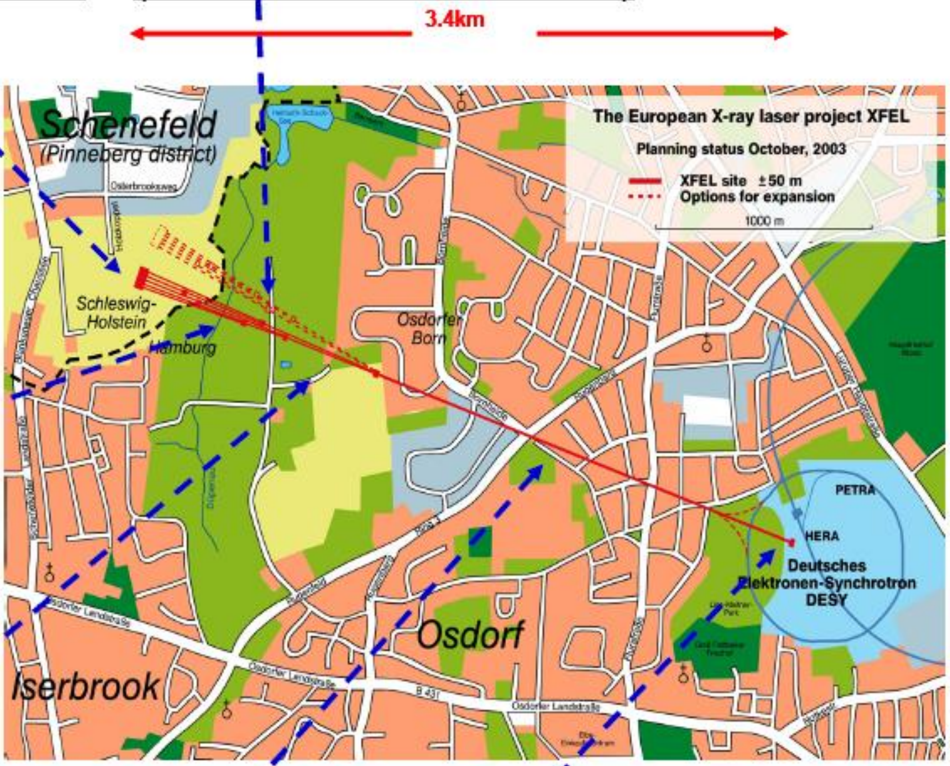
Design Constrains	
Bore Diameter	1250 mm
Overall Length	< 6900 mm
Magnet Length	< 5900 mm
Overall Mass	200 tons
B peak (10% LL @ 1.8 K)	< 12 T

Specification	
FoM (Z = 0 mm)	100 T^2m^2
FoM (Z = ±1000 mm)	> 90 T^2m^2
B Field Homogeneity (H)	± 5%





The European X-ray FEL
DESY, Hamburg (Germany)



Experimental Hall

(Possible future extension)

Undulators and Photon Beamlines,

1.2 km

Beam Distribution System

Linac Tunnel, 2 km

Injector

Very brilliant, ultra-short (100 fs) pulses of X-rays down to 0.1 nm

Based on s.c. e linac

Beam energy 17.5 GeV

Beam power 600 kW

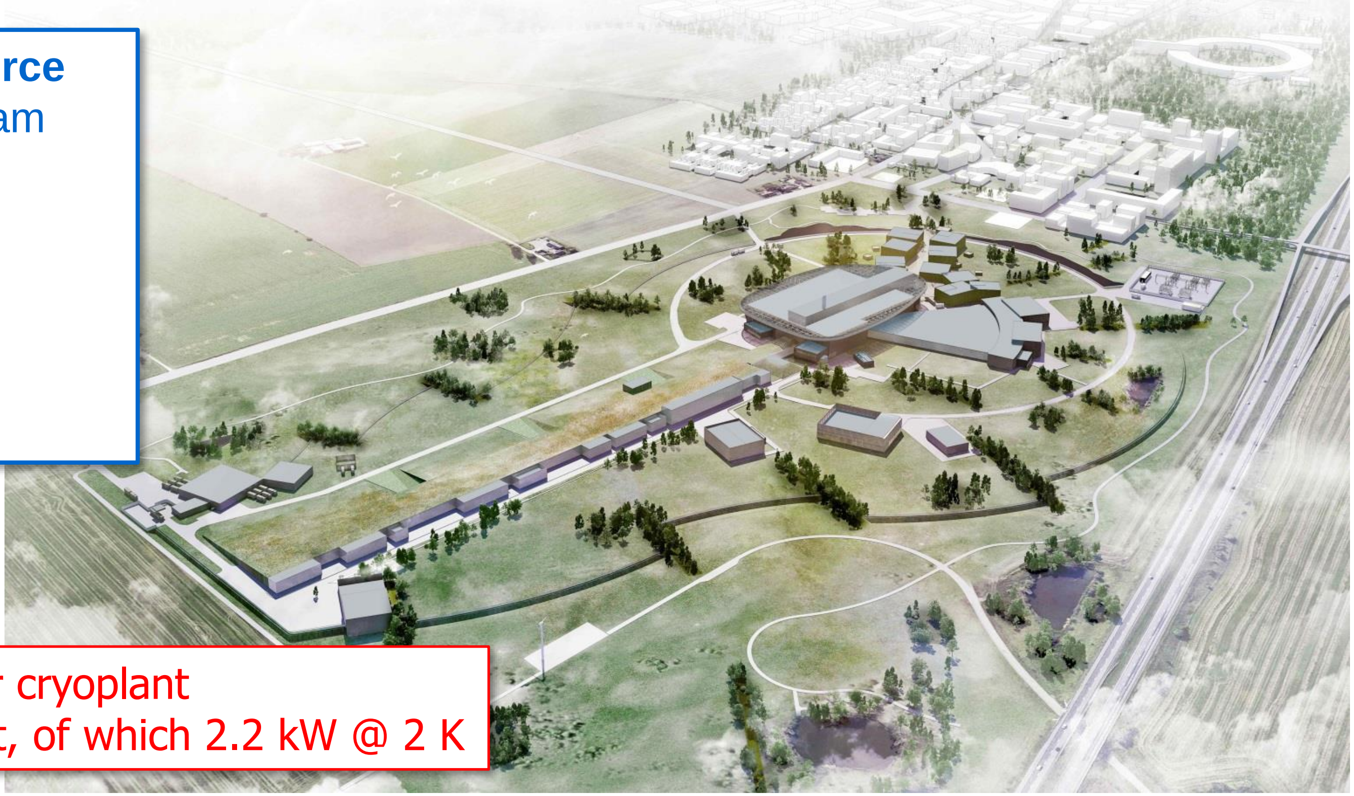
Linac length 1.7 km

928 superconducting RF cavities operated at 2 K

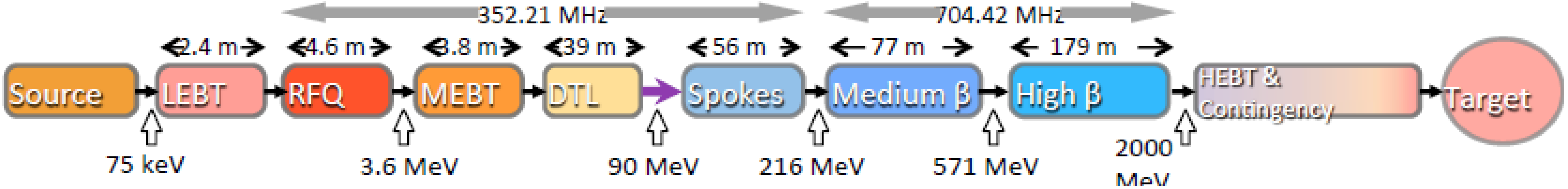
2.5 kW @ 2 K

European Spallation Source
Lund (Sweden)

Long-pulse neutron source
- 5 MW, 2 GeV proton beam
- 62.5 mA
- 2.86 ms pulse length
- 14 Hz
- Low losses
- High availability > 95 %
- High efficiency



Accelerator cryoplant
10 kW @ 4.5 K equivalent, of which 2.2 kW @ 2 K

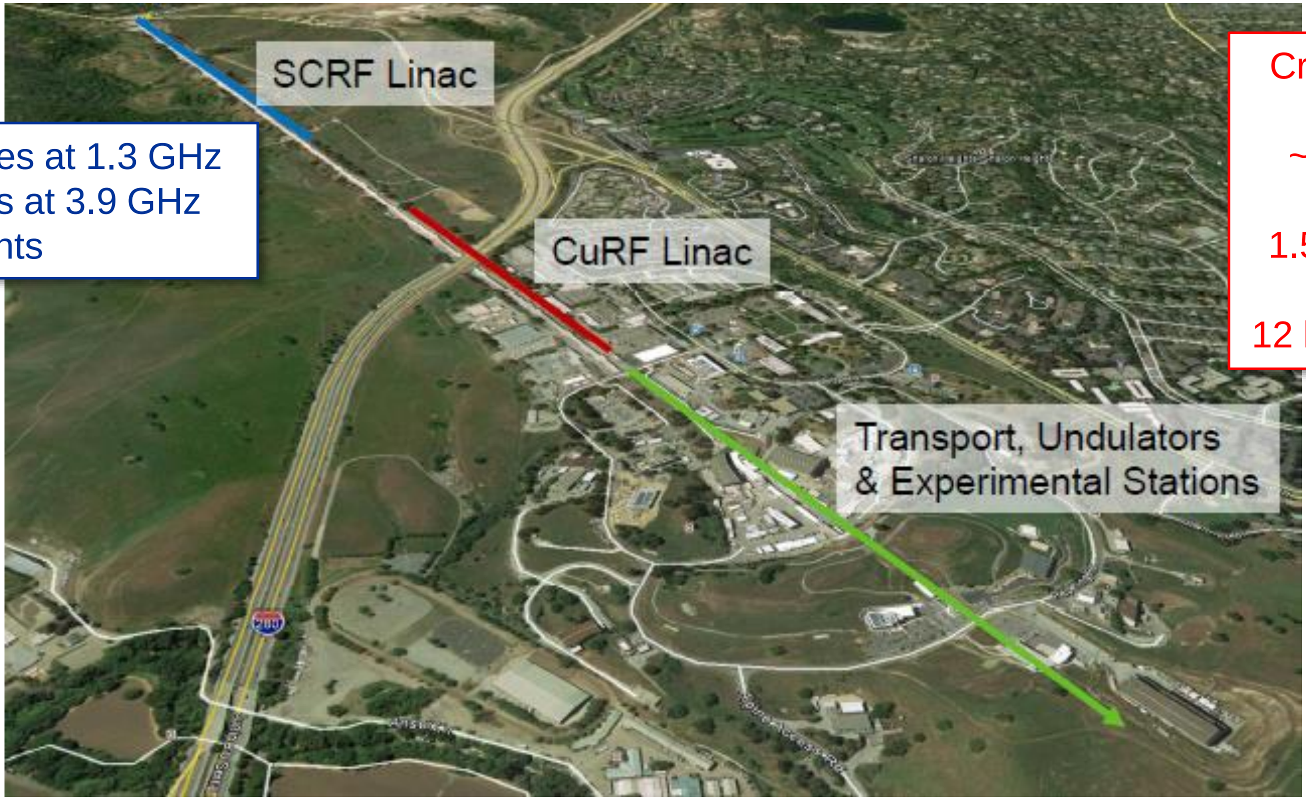


The Linear Coherent Light Source II (LCLS II)

SLAC, Stanford (USA)

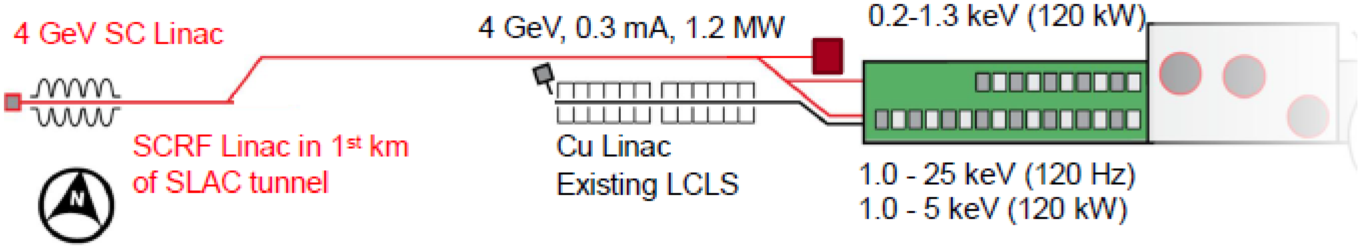
High-brightness, high repetition rate FEL for soft and hard X-rays

35 cryomodules at 1.3 GHz
2 cryomodules at 3.9 GHz
4 cold segments

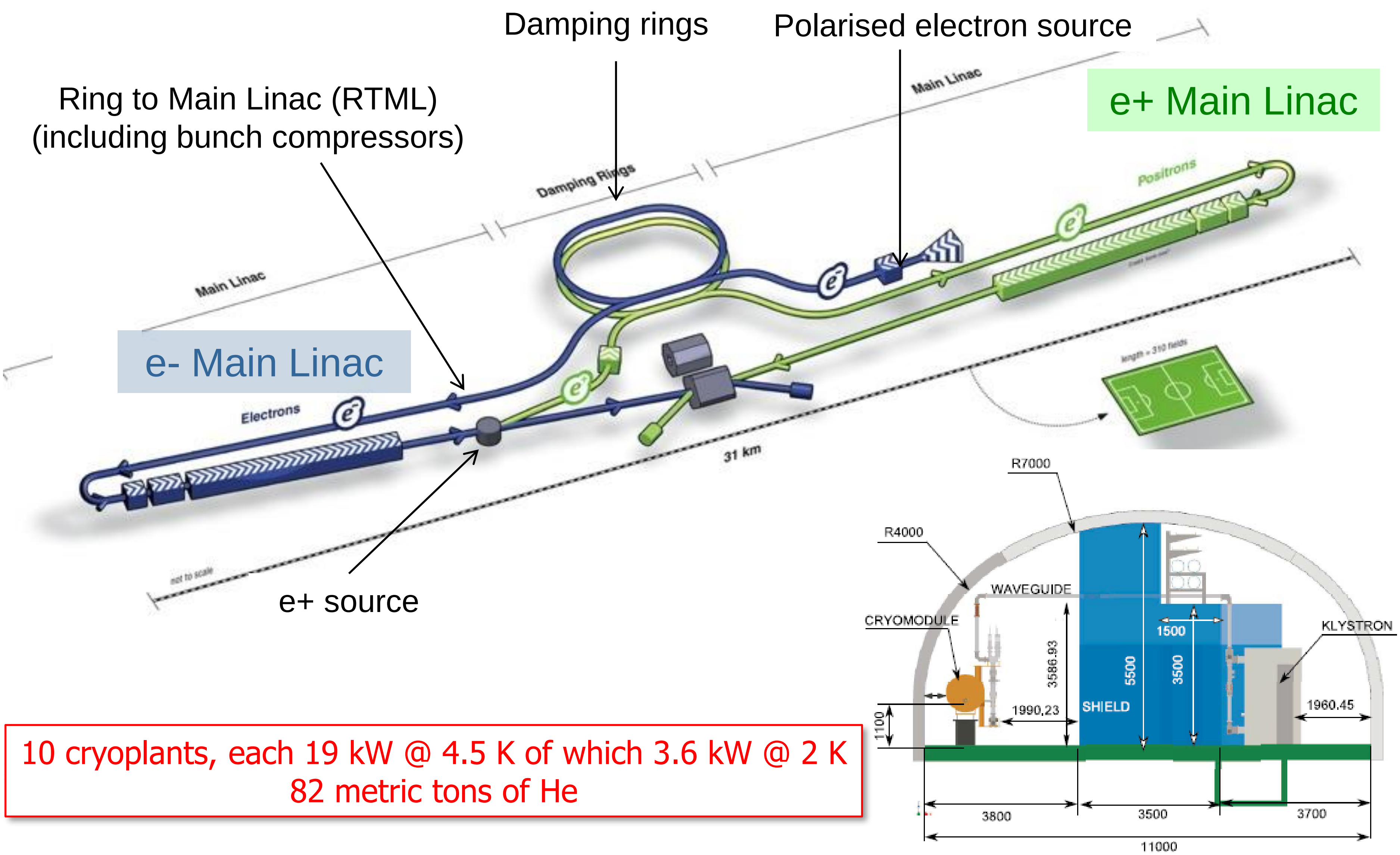


Cryogenic plant

~4 kW @ 2 K
+
1.5 kW @ 4.5 K
+
12 kW @ 40-50 K



The International Linear Collider (ILC) project



Damping rings

Polarised electron source

Ring to Main Linac (RTML)
(including bunch compressors)

e+ Main Linac

e- Main Linac

e+ source

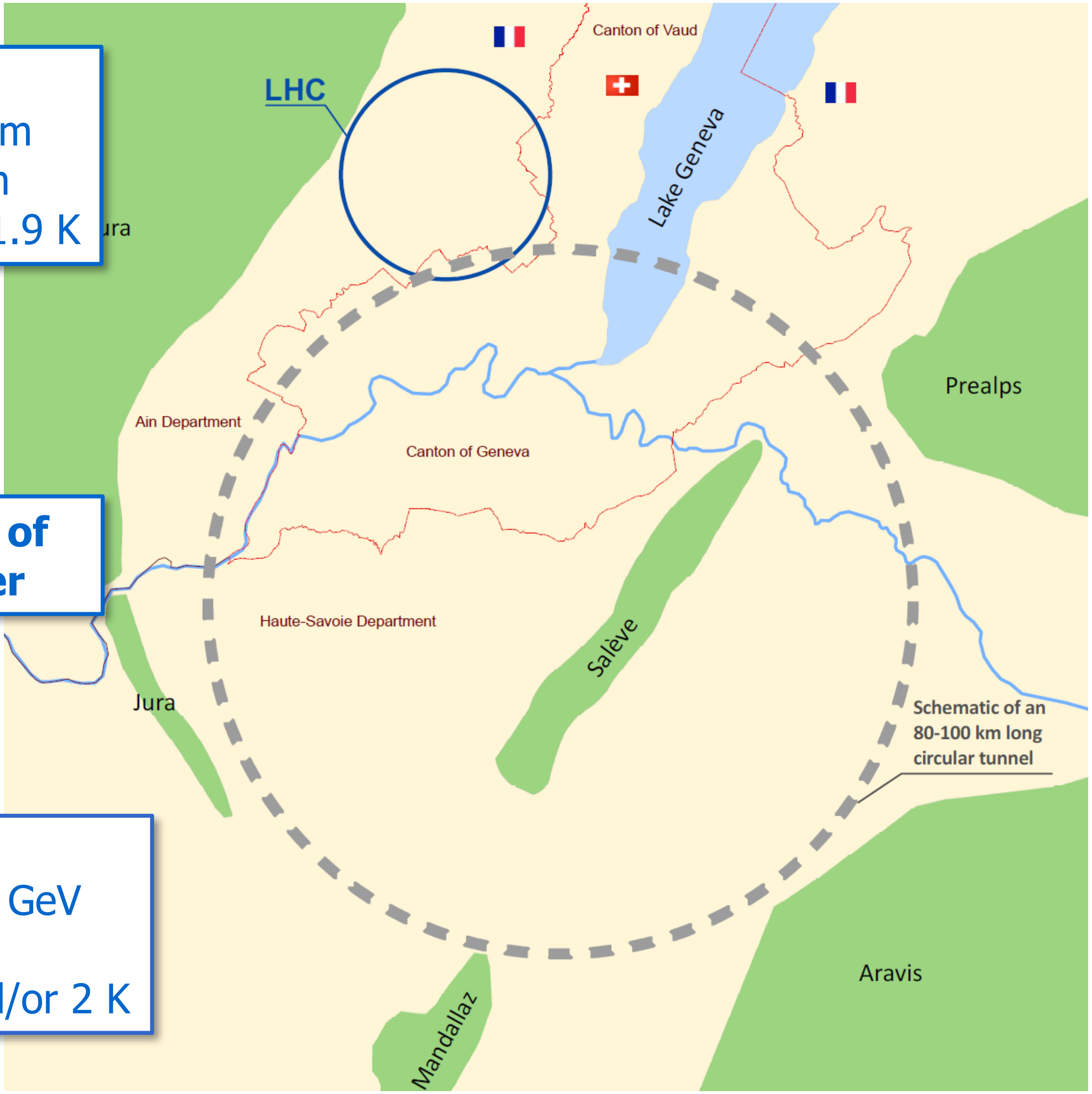
10 cryoplants, each 19 kW @ 4.5 K of which 3.6 kW @ 2 K
82 metric tons of He

Future Circular Collider (FCC) study at CERN

Hadron collider
16 T ⇒ 100 TeV for 100 km
20 T ⇒ 100 TeV for 80 km
High-field SC magnets at 1.9 K

Quasi-circular tunnel of 80-100 km perimeter

e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity
SC RF system at 4.5 K and/or 2 K



Conclusion and outlook

- From a laboratory curiosity and a hot research topic in condensed-matter physics, superfluid helium has become a state-of-the-art cryogen for cooling large superconducting devices such as high-energy accelerators, tokamaks and research magnets
- Projects such as TORE SUPRA, CEBAF, SNS and LHC have triggered vigorous development programmes in laboratories and industry concerning flow and heat transfer, refrigeration techniques, instrumentation and engineering
- Superfluid helium remains an enabling technology for NMR magnets and future large projects using high-field superconducting devices, e.g. the European X-FEL, ESS, ILC.
- The unique hydrodynamic properties of the fluid can also be used *per se*, e.g. in turbulence research

Reference

- Ph. Lebrun & L. Tavian, *Cooling with superfluid helium* in the Proceedings of the CAS-CERN Accelerator school: Superconductivity for Accelerators, Erice, Italy, 24 April-4 May 2013, CERN-2014-005 (2014) pp. 453-476

  This write-up is available on-line http://cds.cern.ch/record/1507630

  It contains a comprehensive list of references and bibliography on superfluid helium technology