Technology of superfluid helium

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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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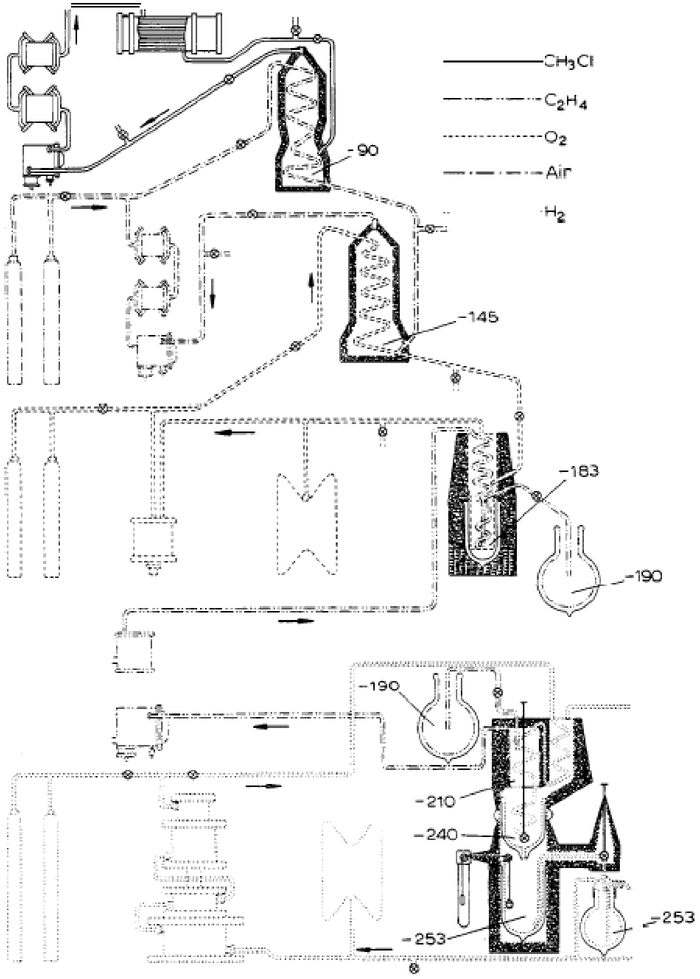
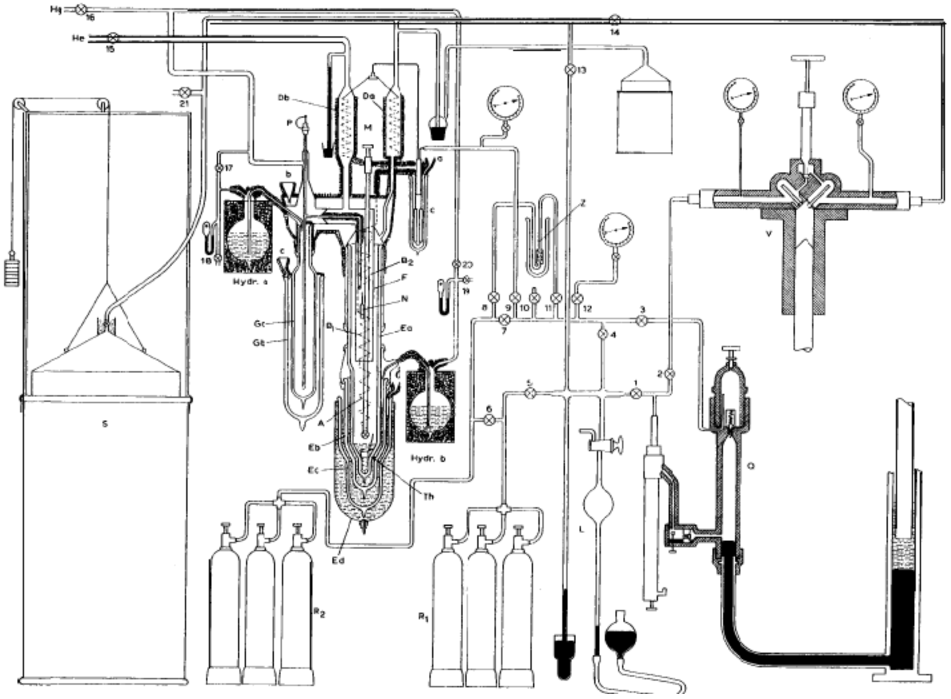
First liquefaction of helium (1908)



Leiden « cascade » to
produce liquid hydrogen



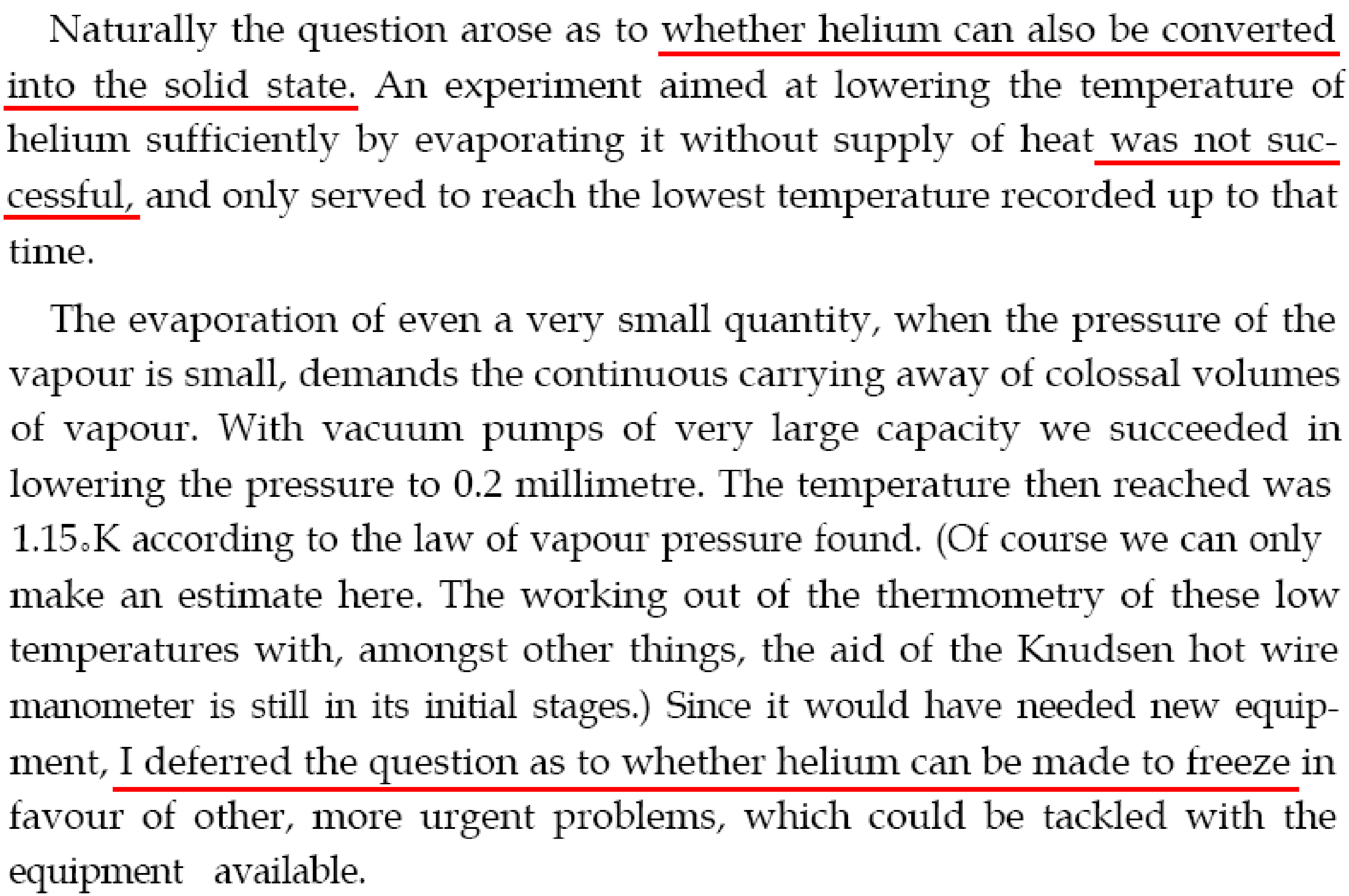
Helium liquefaction stage
precooled by liquid hydrogen

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

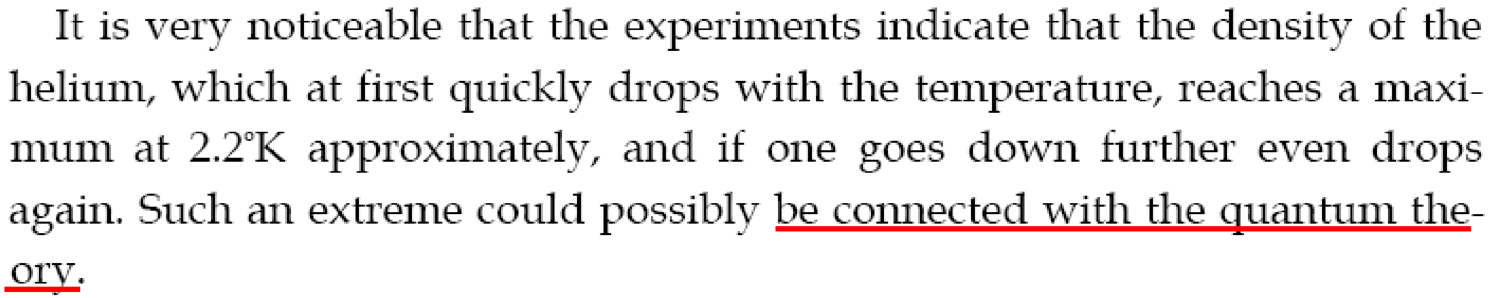
Unsuccessful attempt to solidify helium



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…?



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

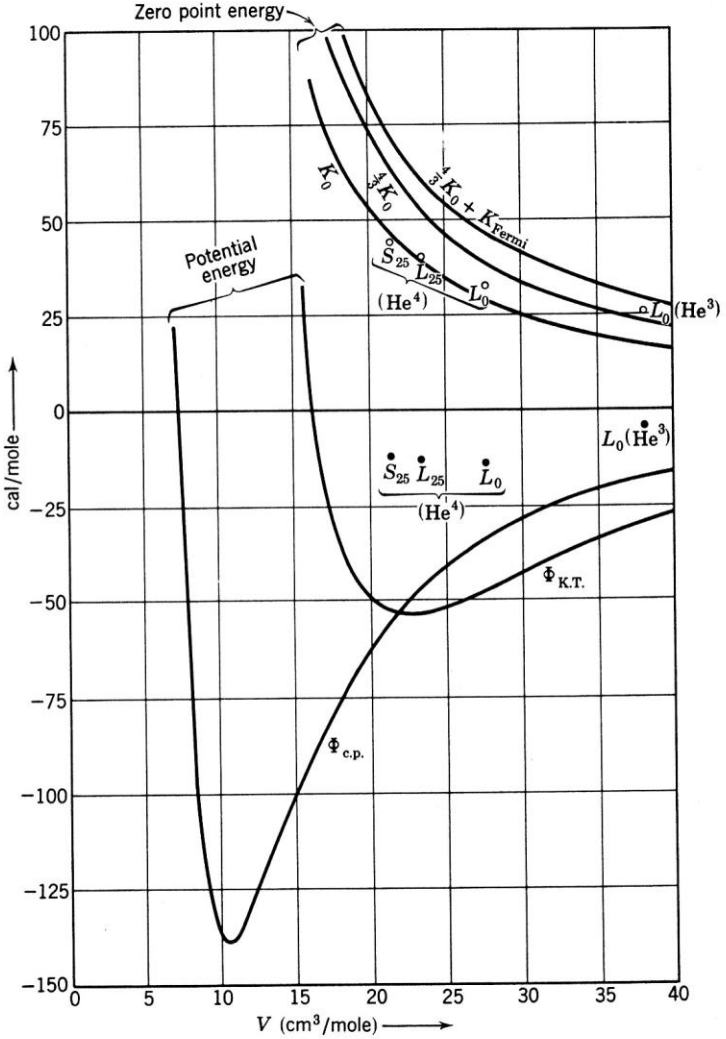
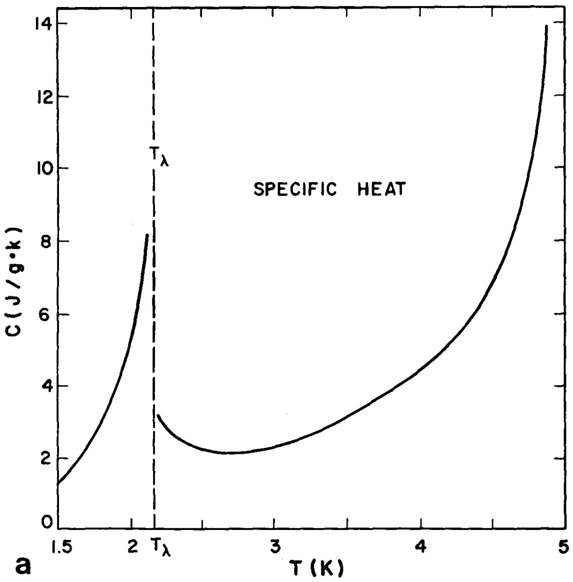


Fig. 15. The potential energy of the close-packed structure, $\Phi_{c.p.}$, and of the T_d^2 configuration suggested by Keesom and Taconis, $\Phi_{K.T.}$. The curve K_0 gives the zero point energy of eq. (6), §5. The solid circles refer to the experimental energy content of condensed He^4 and He^3 at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



W.H. Keesom

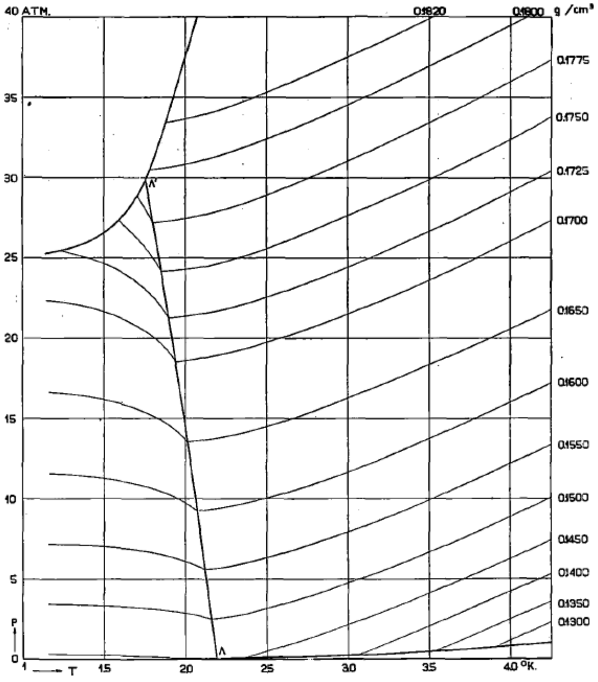


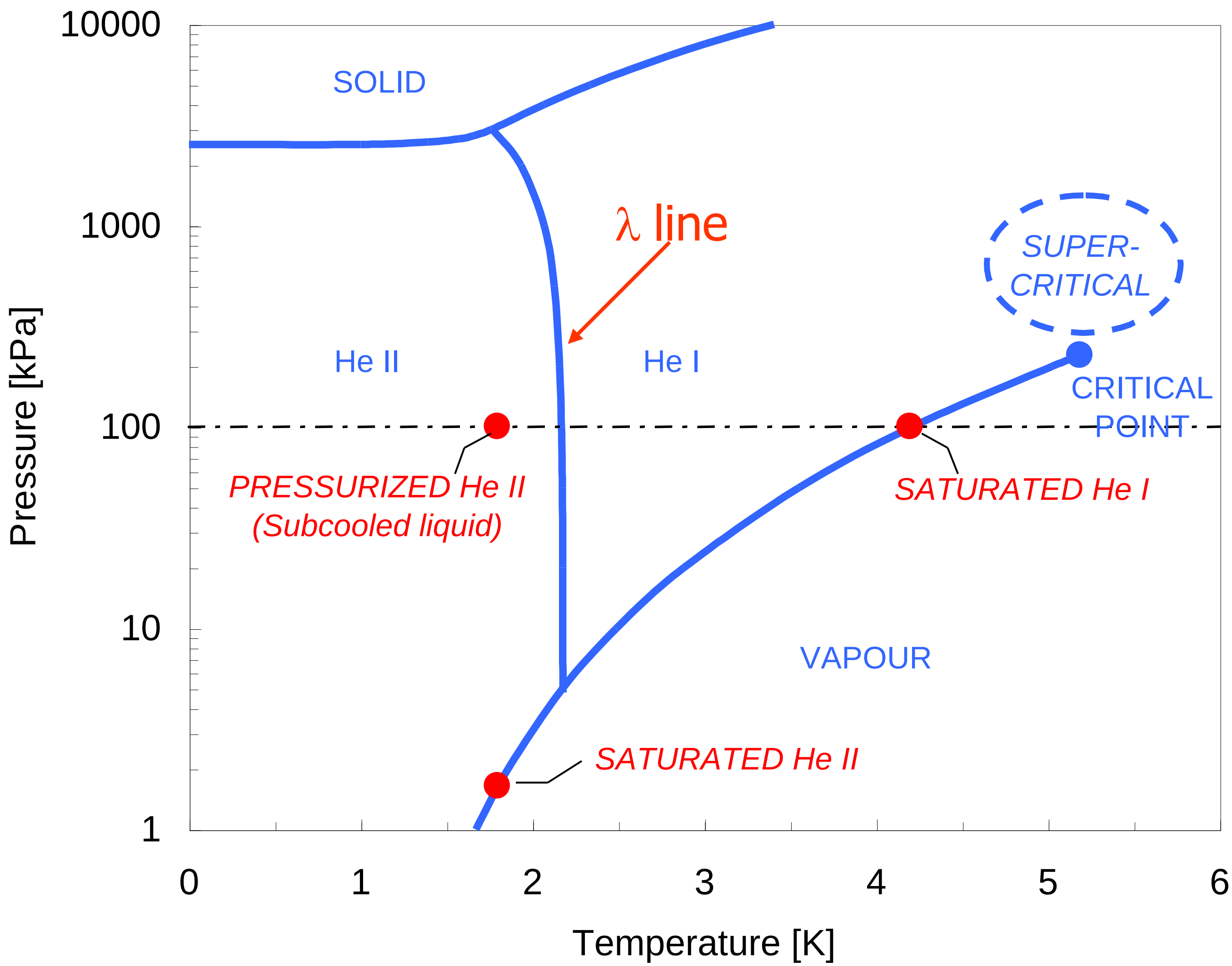
Fig. 1.

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

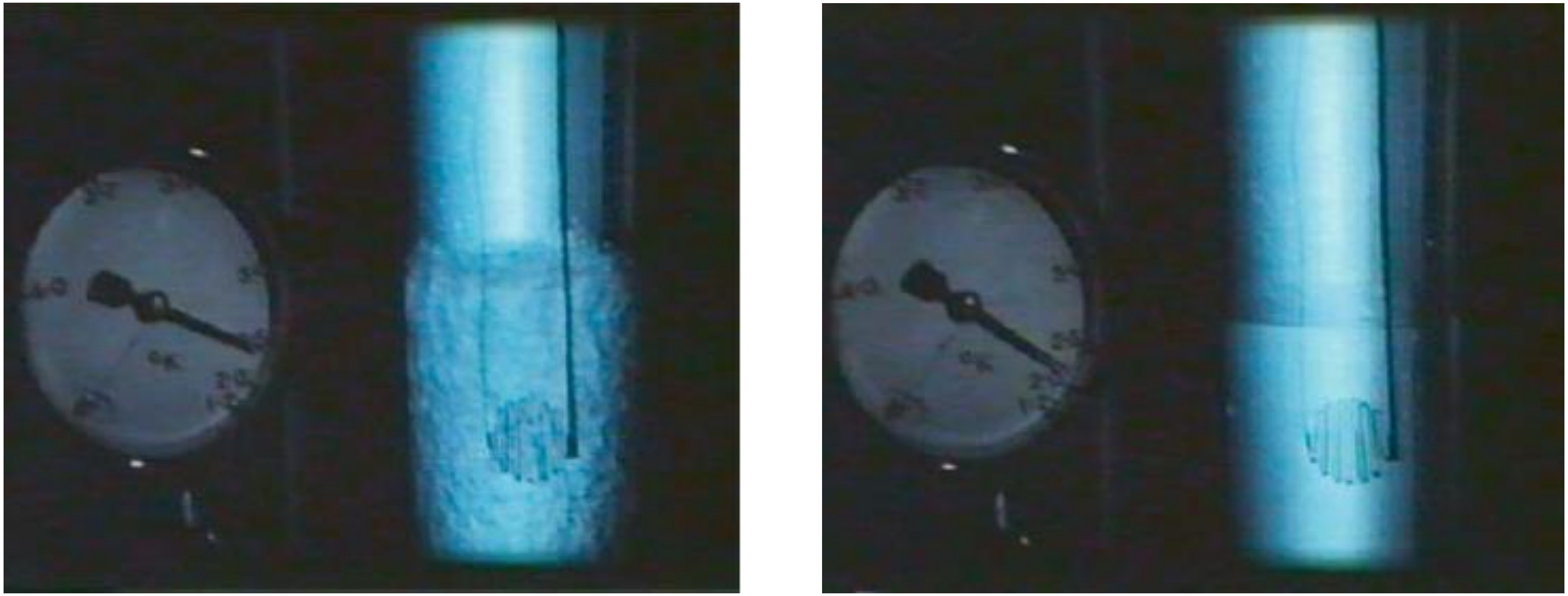
Phase diagram of helium



Discovery of superfluidity in He II (1938)

J.F. Allen & A.D. Misener (Cambridge)
P.L. Kapitsa (Moscow)

Vaporization of liquid helium under applied heat load



He I (T=2.4 K)

He II (T=2.1 K)

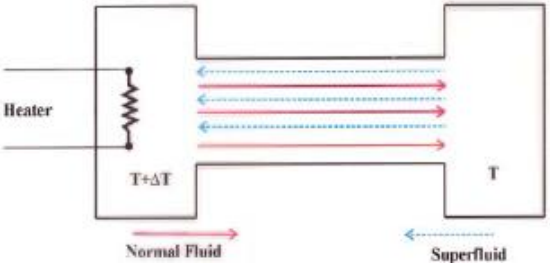
Theoretical approaches to superfluid helium

Fritz London

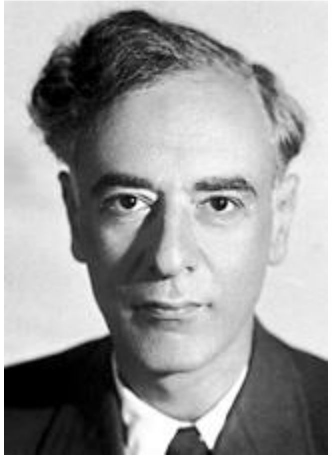
$$T_{\mathrm{BEC}} = \left(\frac{2\pi\hbar^2}{1.897 m k_B} \right) n^{2/3}$$

Bose-Einstein condensation

Laszlo Tisza



Two-fluid model

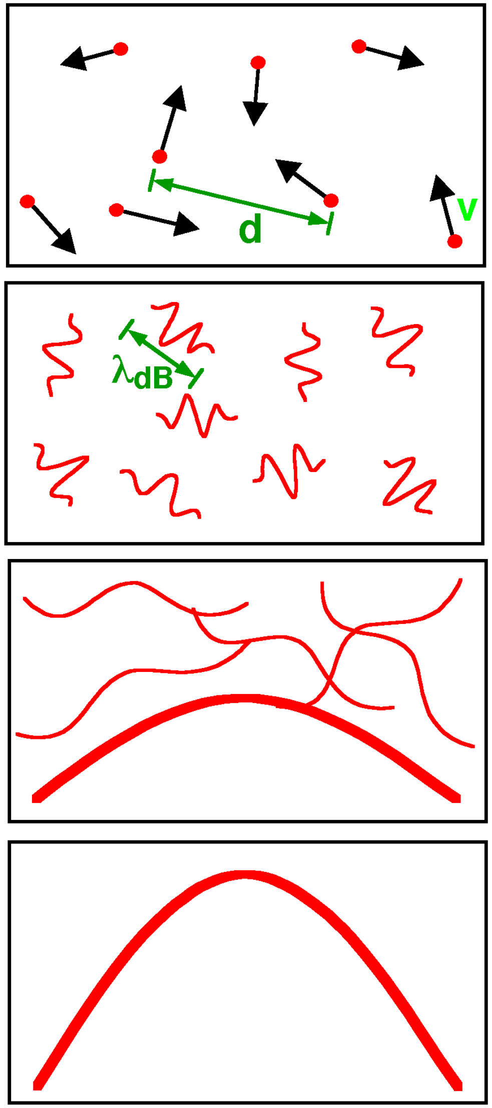


Lev Davidovich Landau

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

Quasi-particle description

Bose-Einstein condensation in gas of particles



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

$\lambda_{dB} \approx d$

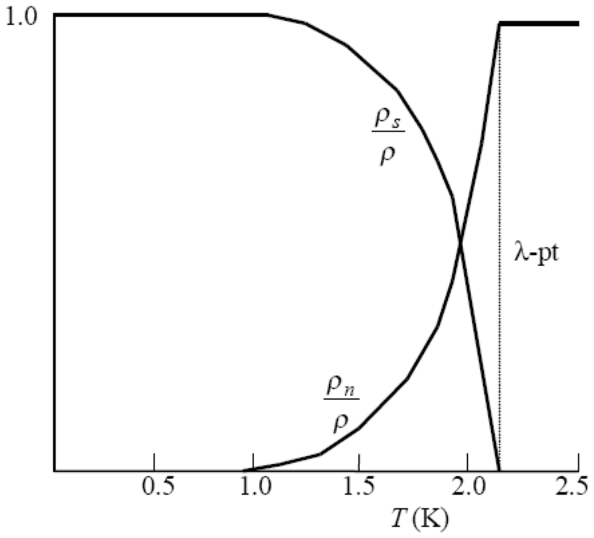
"Matter wave overlap"

T=0:

Pure Bose condensate

"Giant matter wave"

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 $s_s = 0$

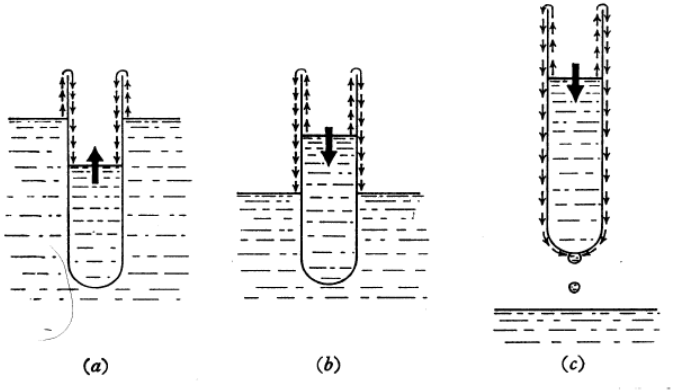
All entropy carried by normal component

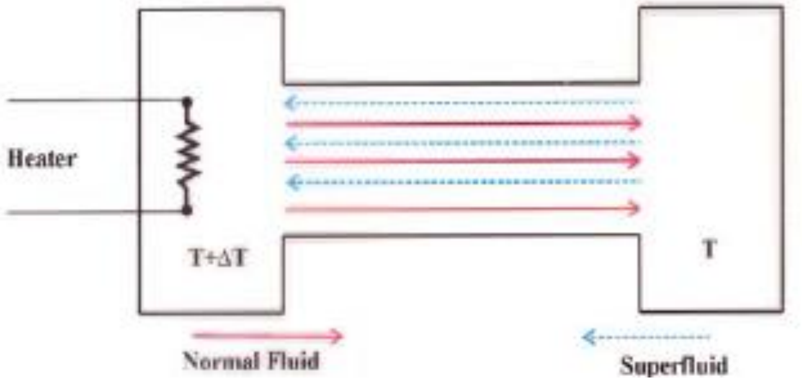
Physical basis of the two-fluid model

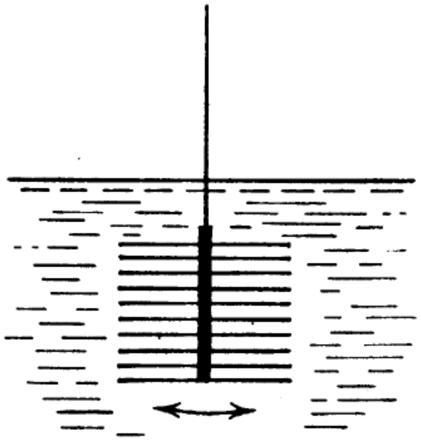
- *Collective excitations constitute the normal component (Landau)*
- *B-E condensate in liquid (Penrose & Onsager)*

He II behaviour explained by two-fluid model

- Frictionless flow through small channels
  - Film flow
  - Andronikashvilii experiment
- Thermal transport by counterflow
  - Laminar
  - Turbulent
- Thermomechanical effect
- Second sound







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Benefits of He II cooling

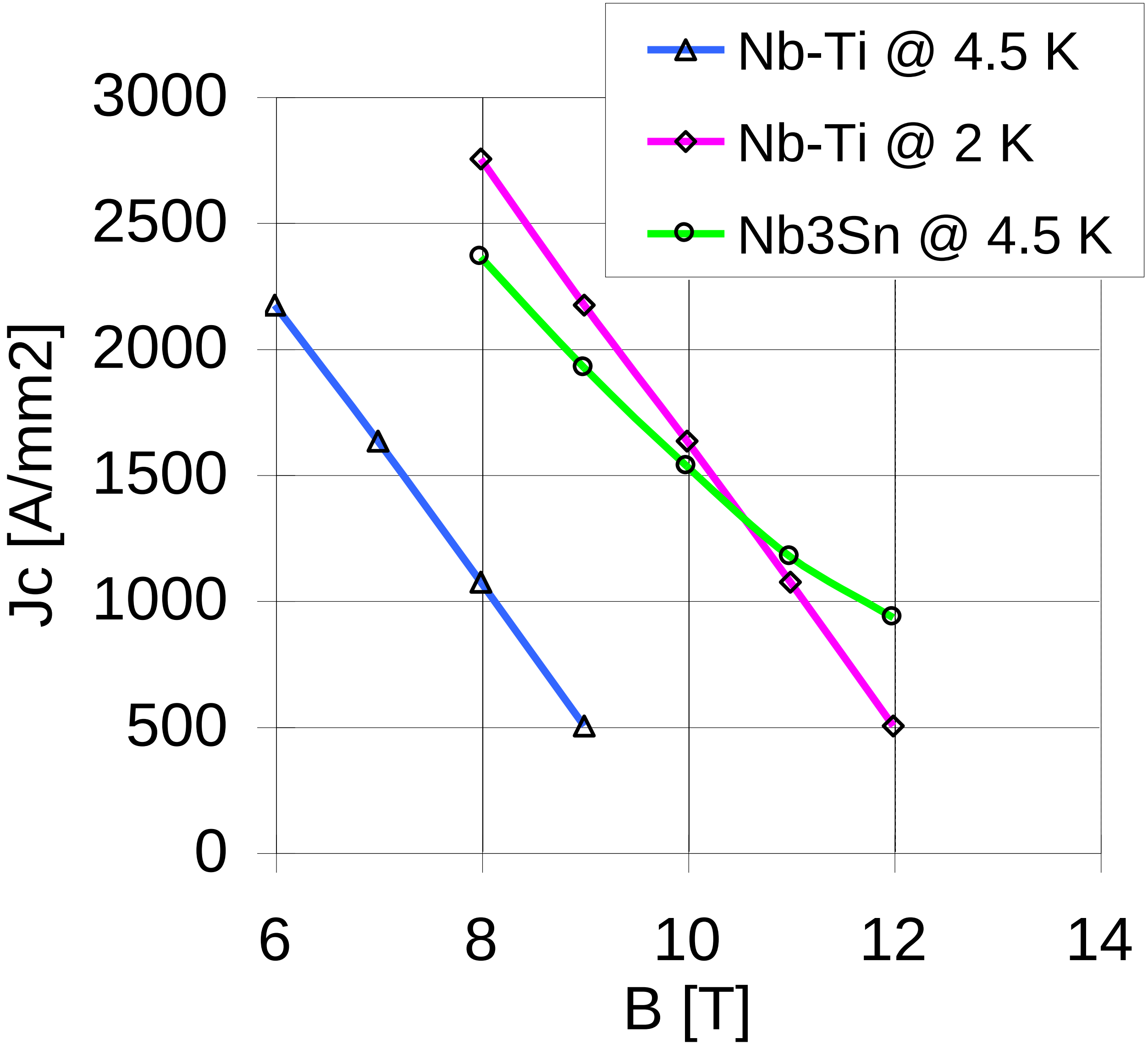
- Lower the operating temperature
  - Achieve higher magnetic field through increase of critical current density of superconductor
  - Minimize overall energy dissipation in RF cavities

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

  ⇒ device/system cooling scheme

  ⇒ calorimetry in isothermal bath

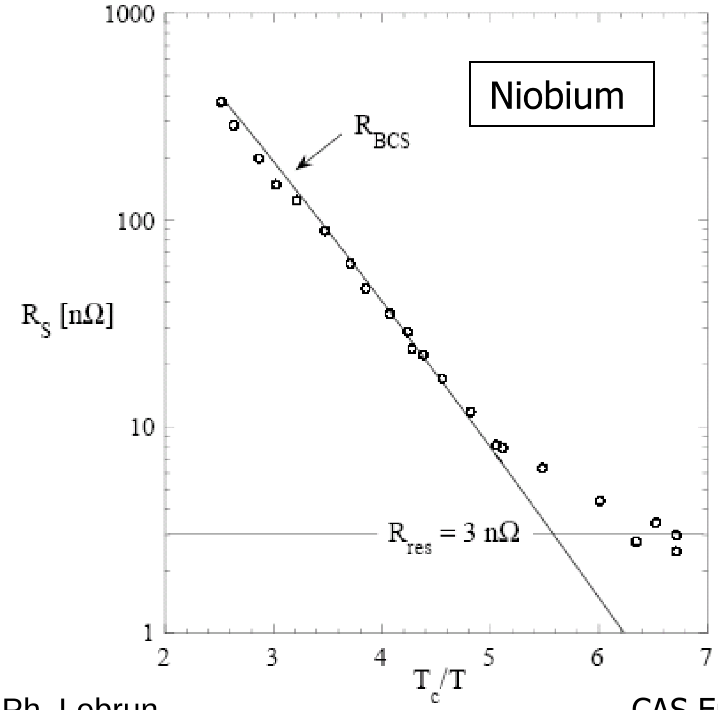
Critical current density of superconductors for high-field magnets

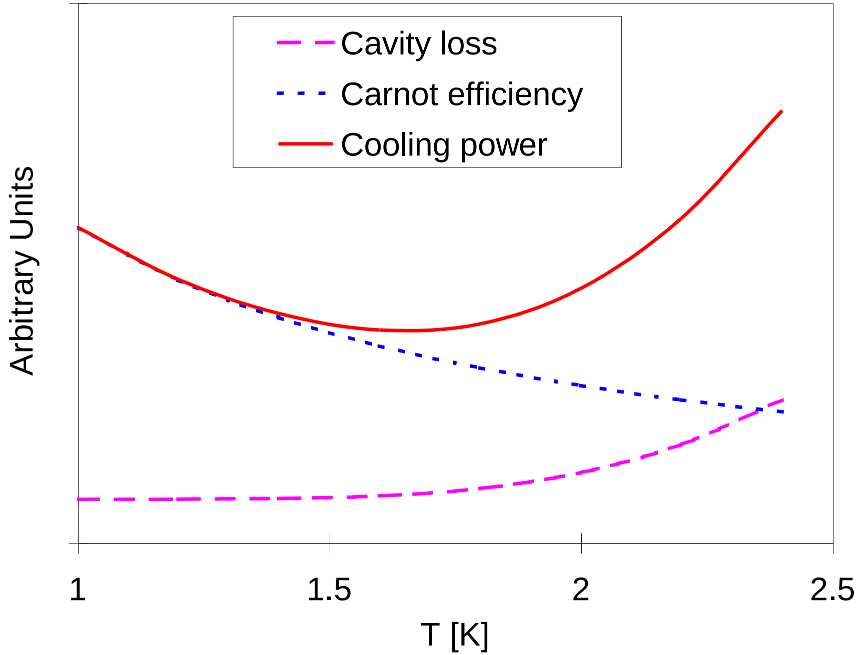


Optimization of operating temperature for superconducting RF cavities

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

⇒ depending upon ω and R_0, optimum operating temperature for superconducting cavities



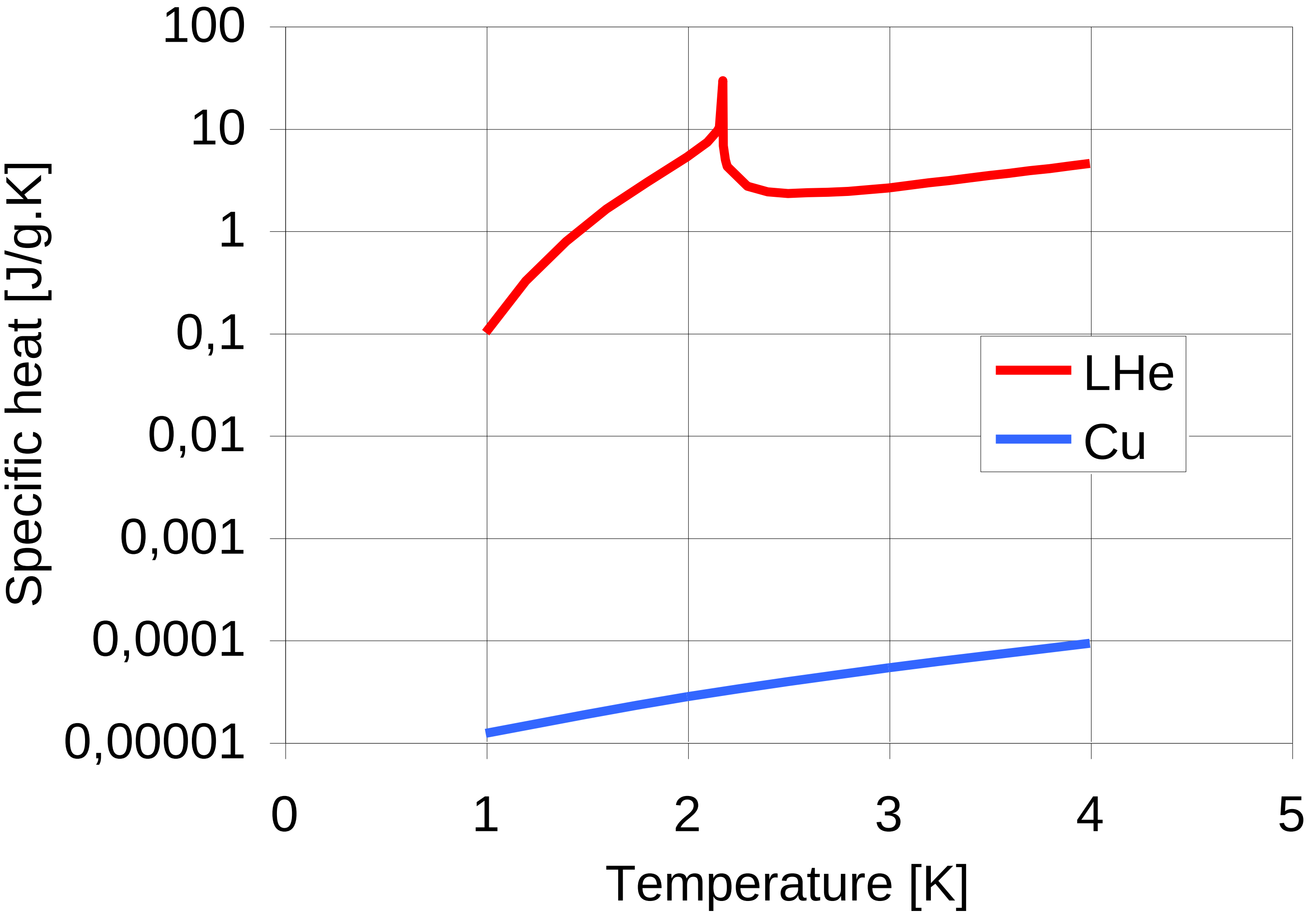


Enhancement of heat transfer

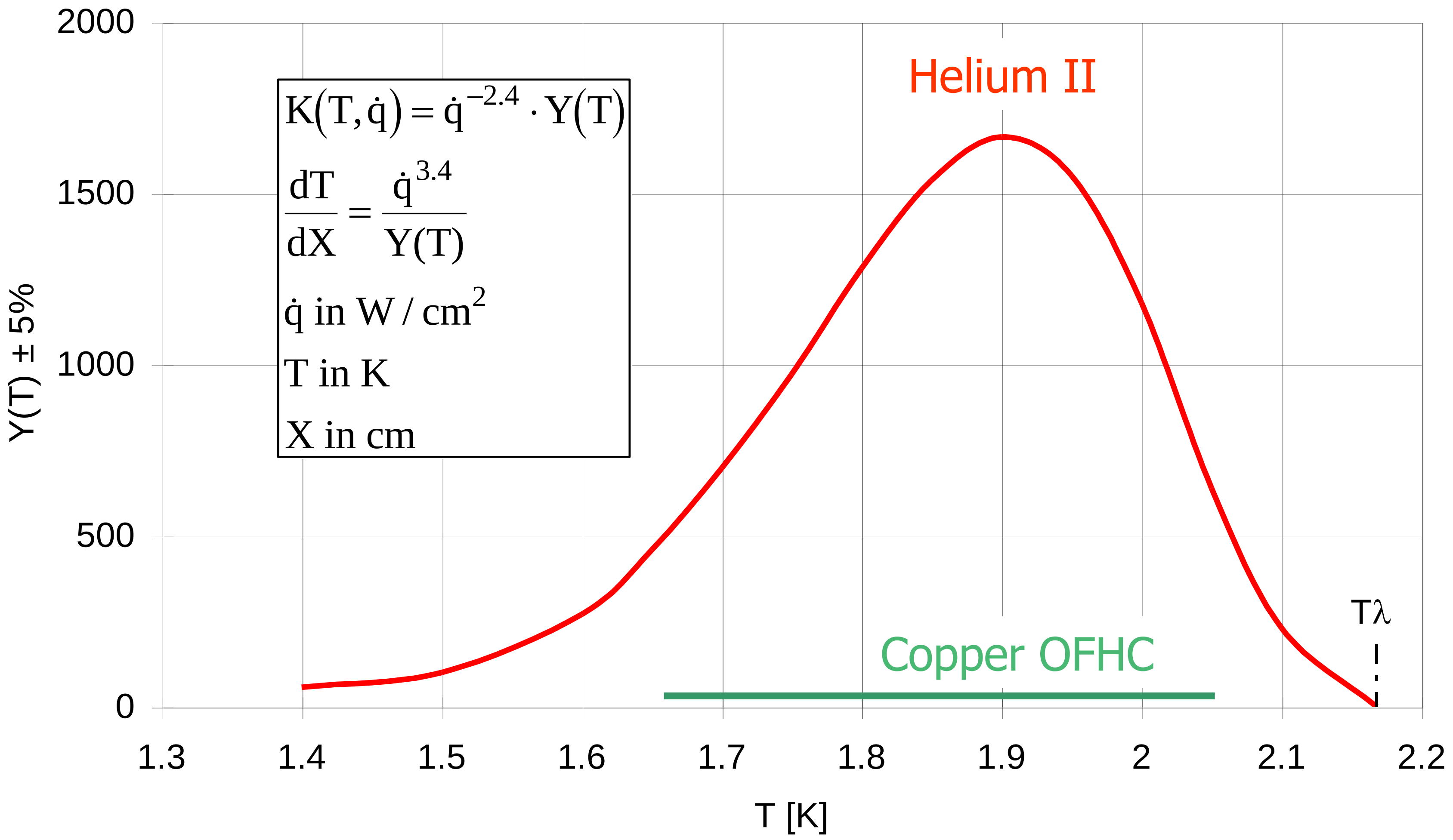
- Low viscosity ⇒ *permeation*
- Very high specific heat ⇒ *stabilization*
  - 10^5 times that of the conductor per unit mass
  - 2×10^3 times that of the conductor per unit volume
- Very high thermal conductivity ⇒ *heat transport*
  - 10^3 times that of cryogenic-grade OFHC copper
  - peaking at 1.9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



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

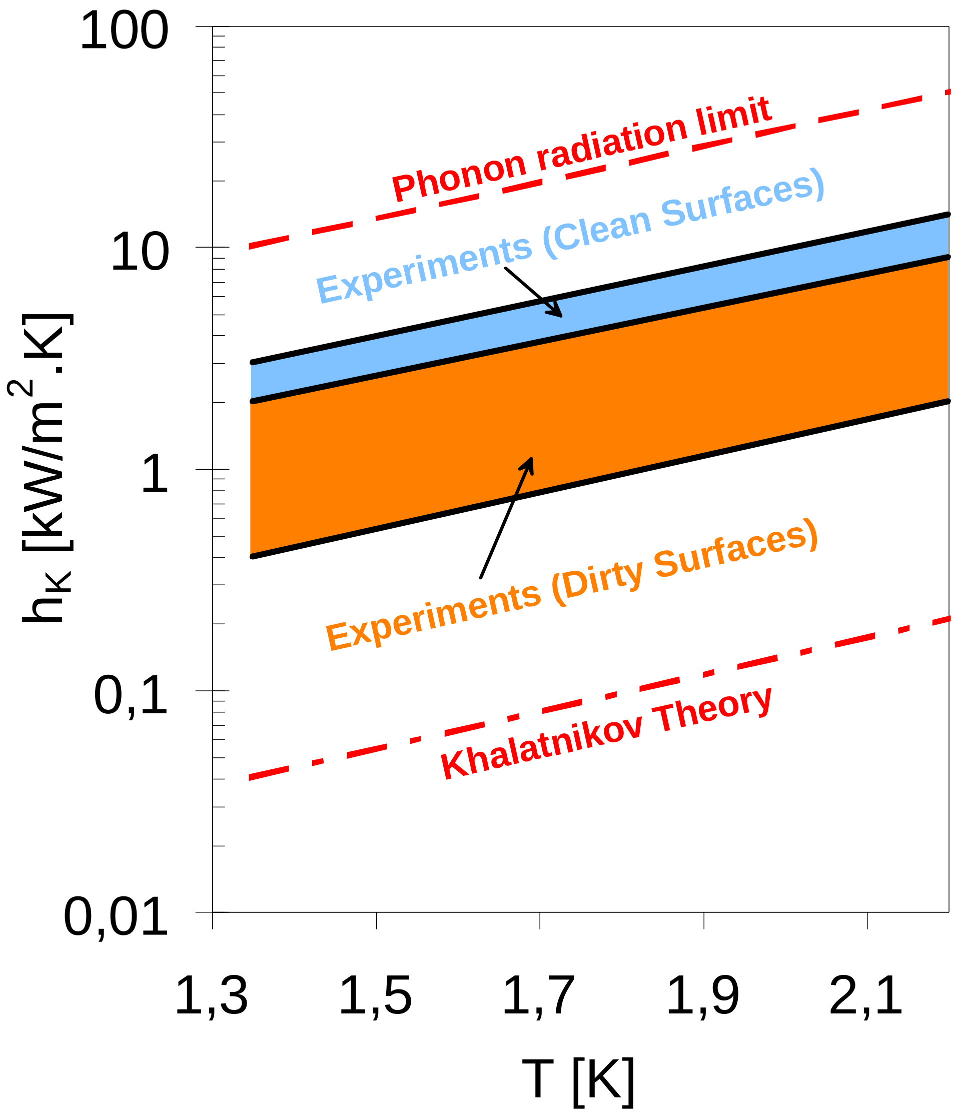
$$\frac{dT}{dX} = \frac{\dot{q}^{3.4}}{Y(T)}$$

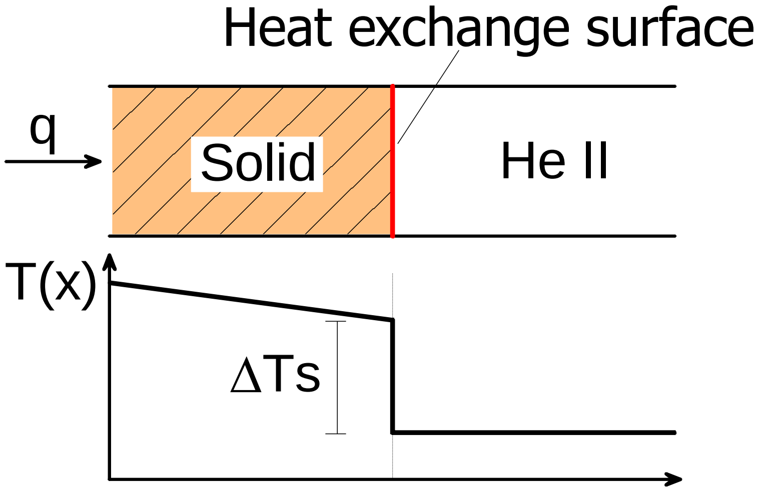
$\dot{q}$ in W / cm^2

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 $\Delta T << T$)

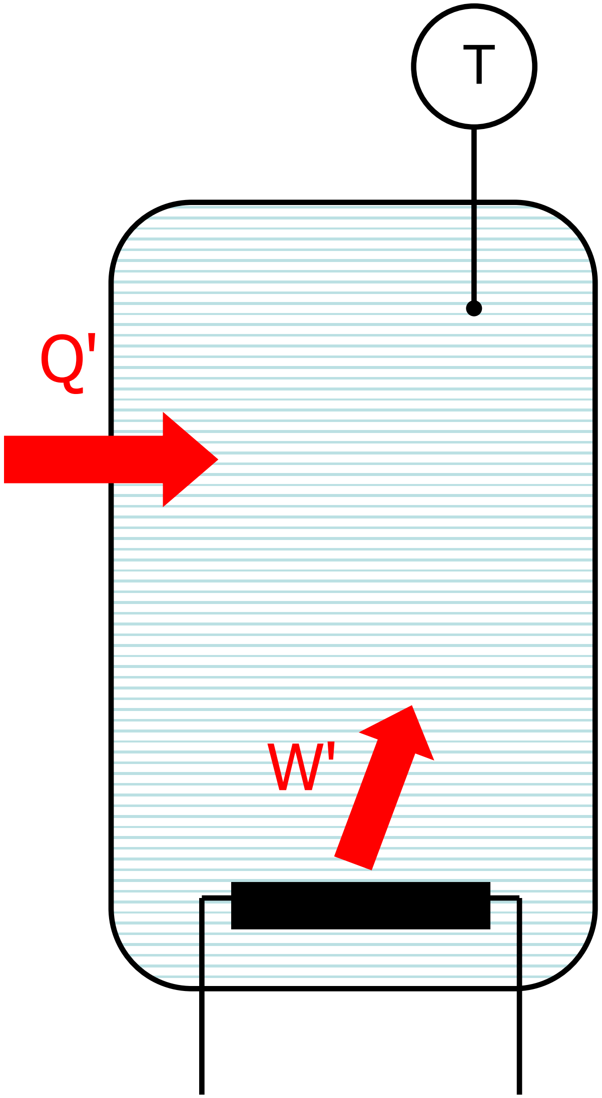
Application of high thermal conductivity Calorimetry in isothermal He II bath

- 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 $Q' = M_{bath}\, dE/dt|_1$

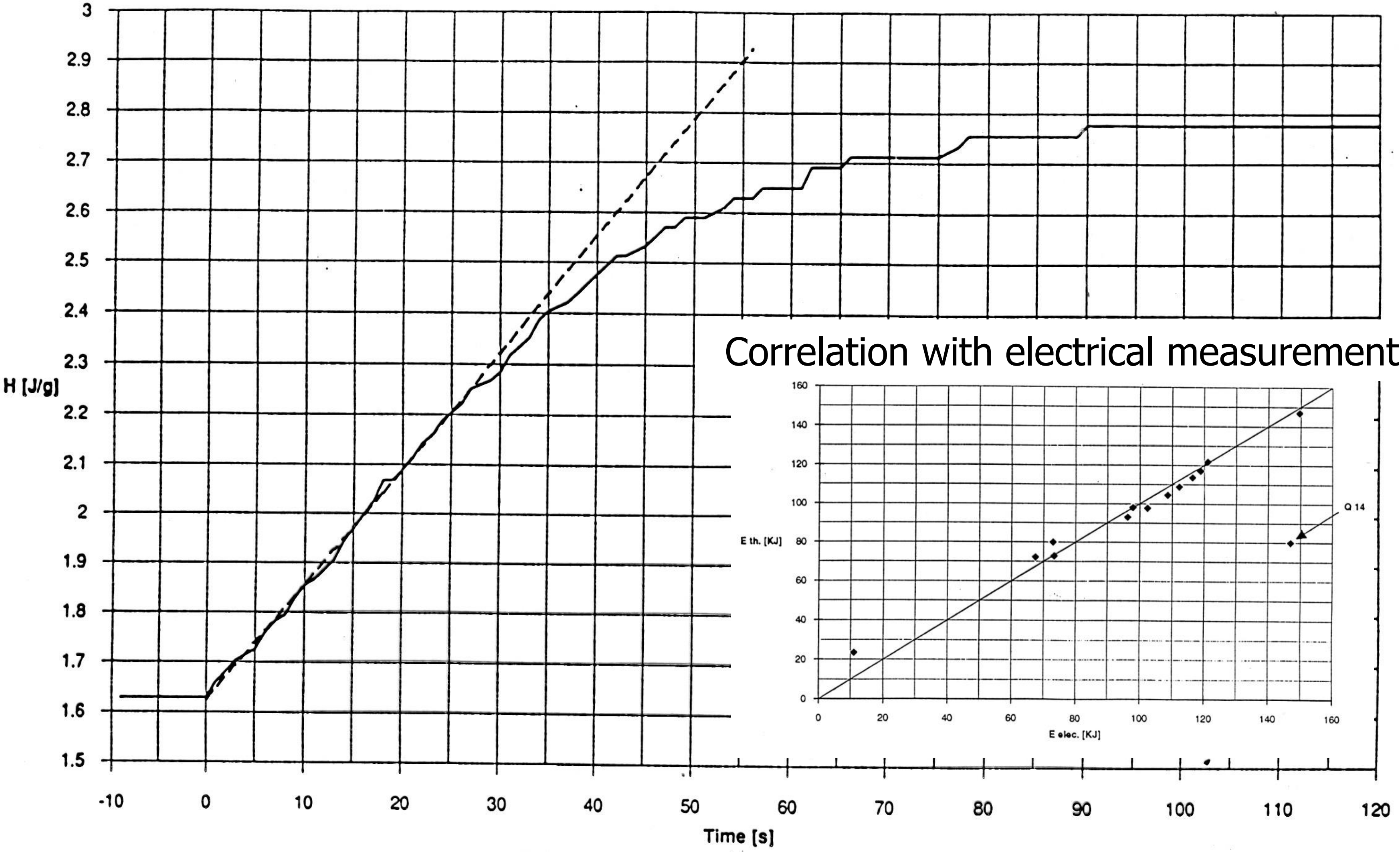
- M_{bath} can be estimated by *in situ* calibration, using applied heating power W'

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



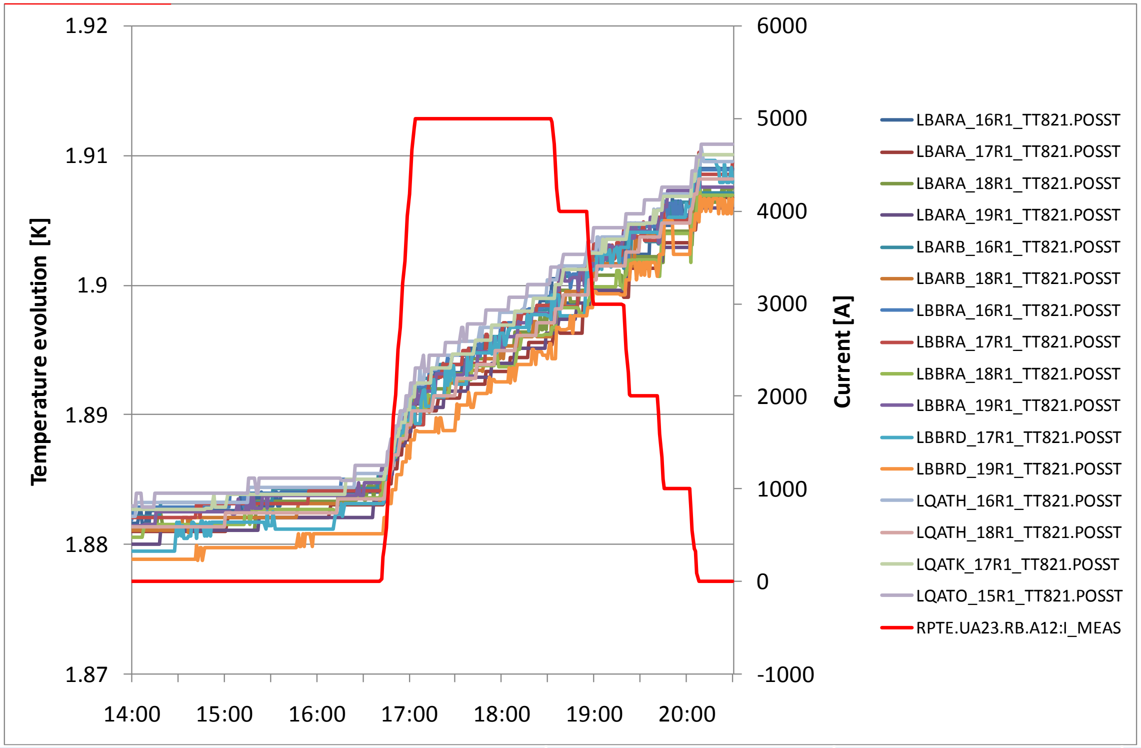
Calorimetry of magnet quench in He II bath

Time evolution of bath temperature



Correlation with electrical measurements

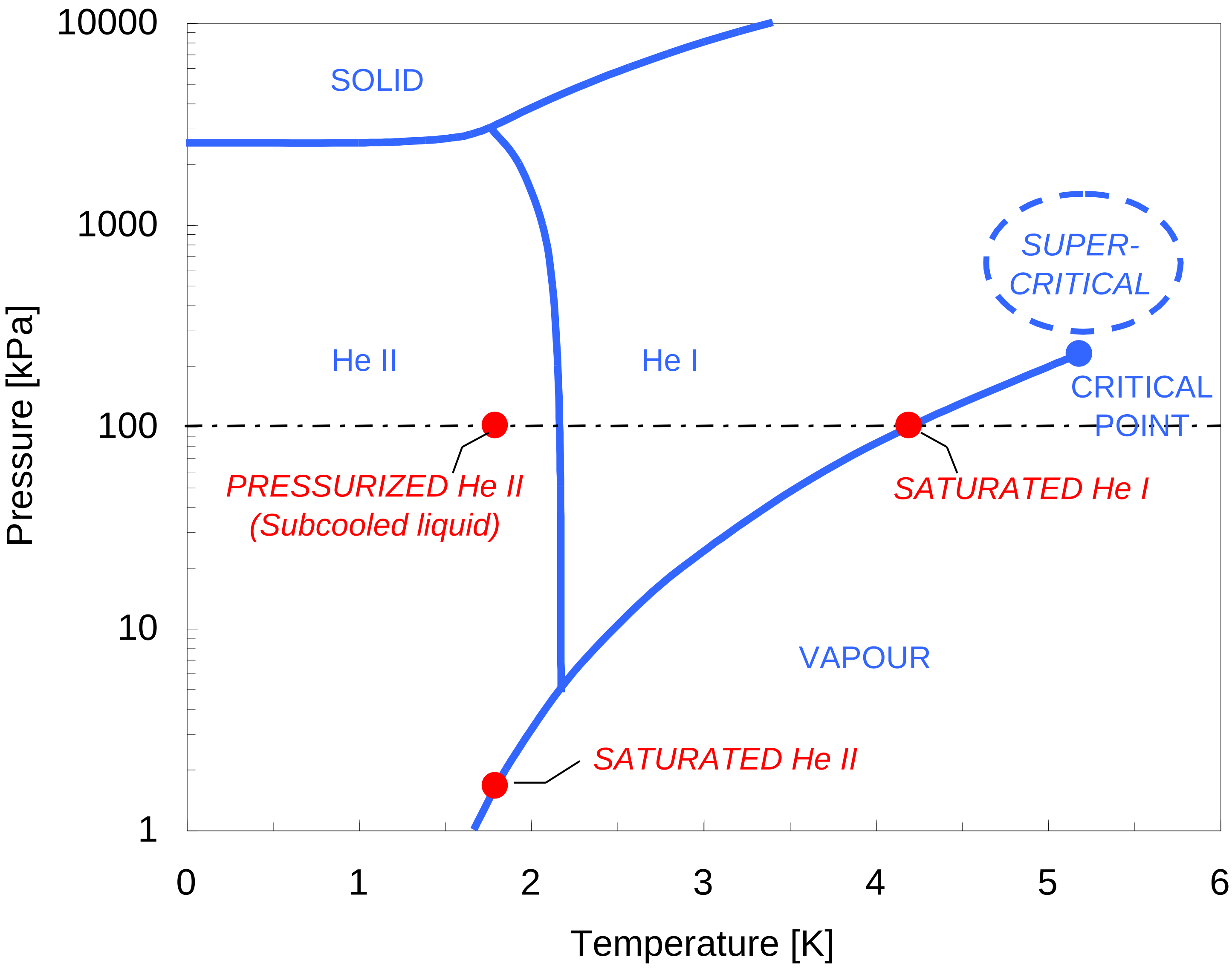
Precision thermometry allows calorimetric detection of faulty joints in LHC at safe powering level



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

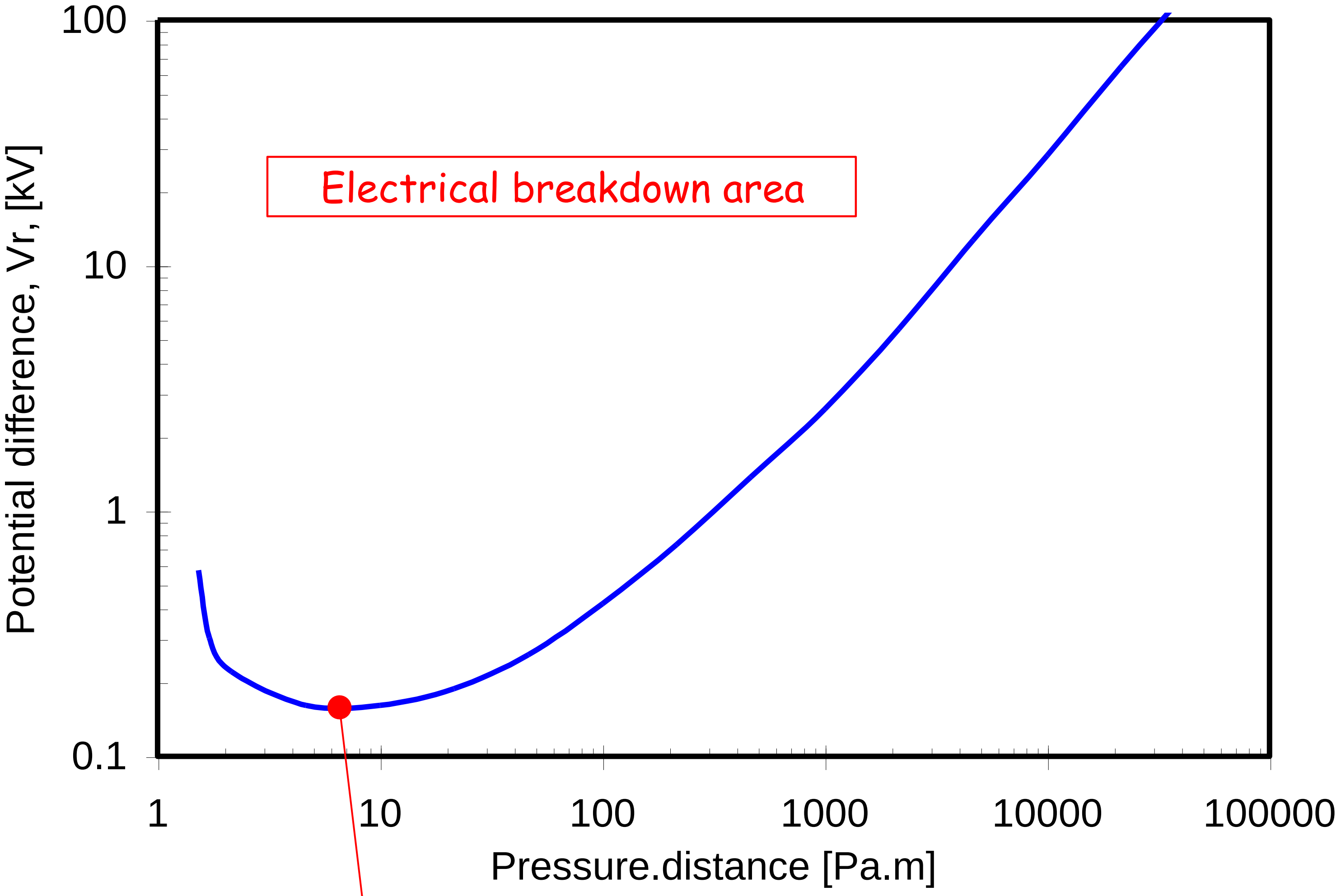
Pressurized vs saturated He II



Advantages & drawbacks of He II p

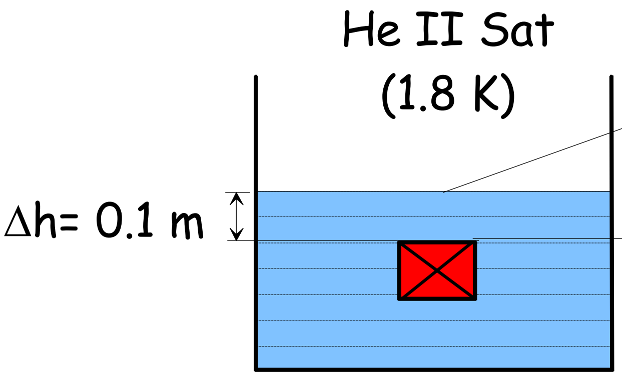
- Advantages
  - limits the risk of air inleaks and contamination in large and complex cryogenic systems
  - for electrical devices, limits the risk of electrical breakdown at fairly low voltage due to the bad dielectric characteristics of helium vapour (Paschen curve)
  - better stabilizer for heat 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

Thermal stabilisation in He II s



At the liquid surface:

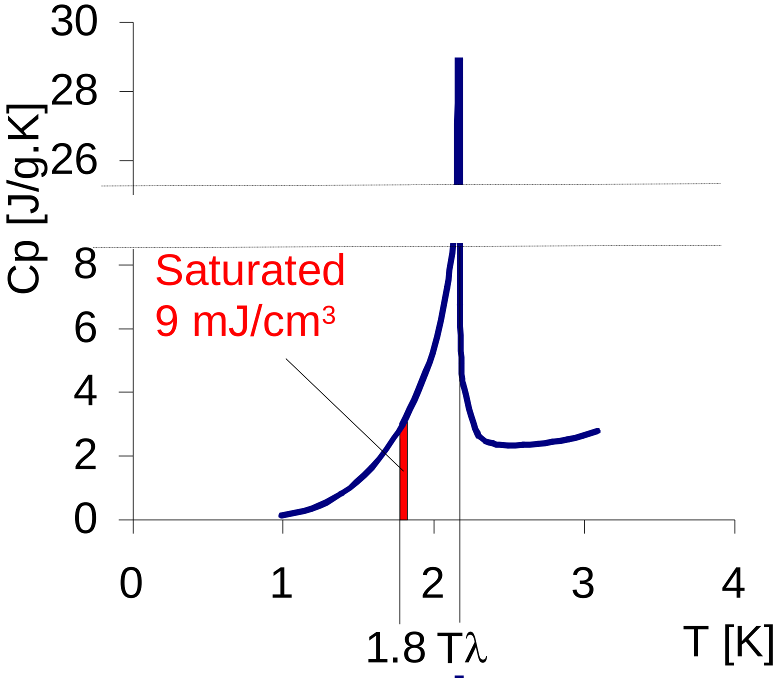
P= Psat = 16.4 mbar

At the device surface:

(adding hydrostatic head)

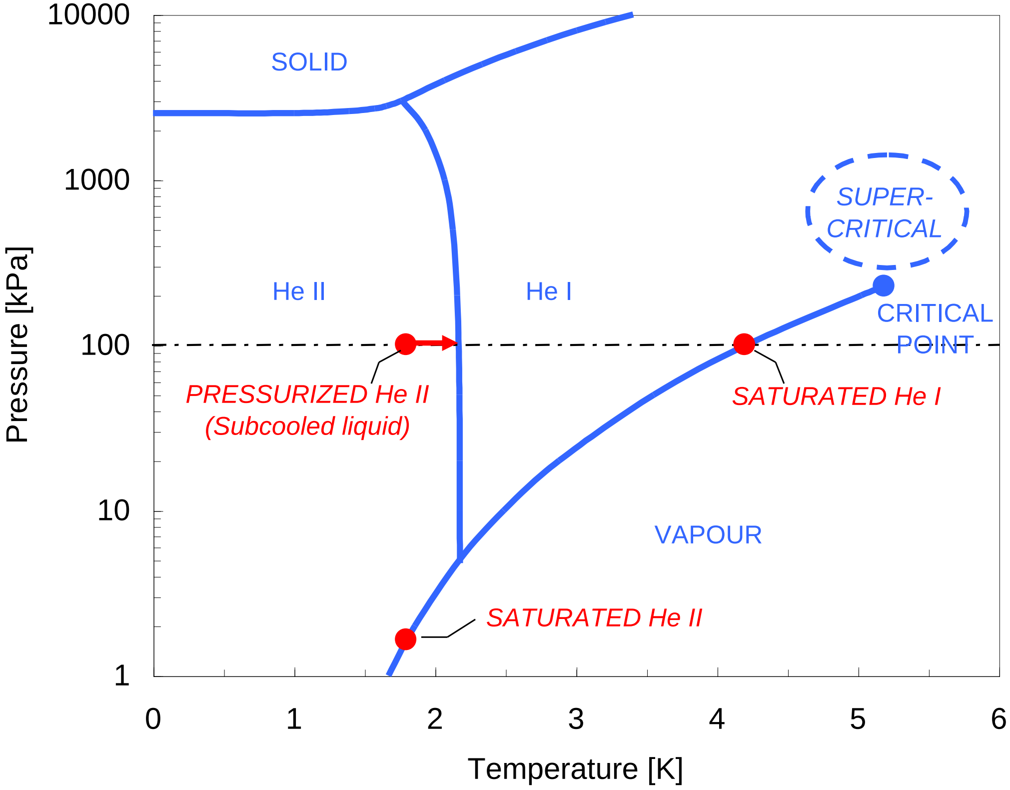
P*= P + ρ.g.Δh = 17.8 mbar

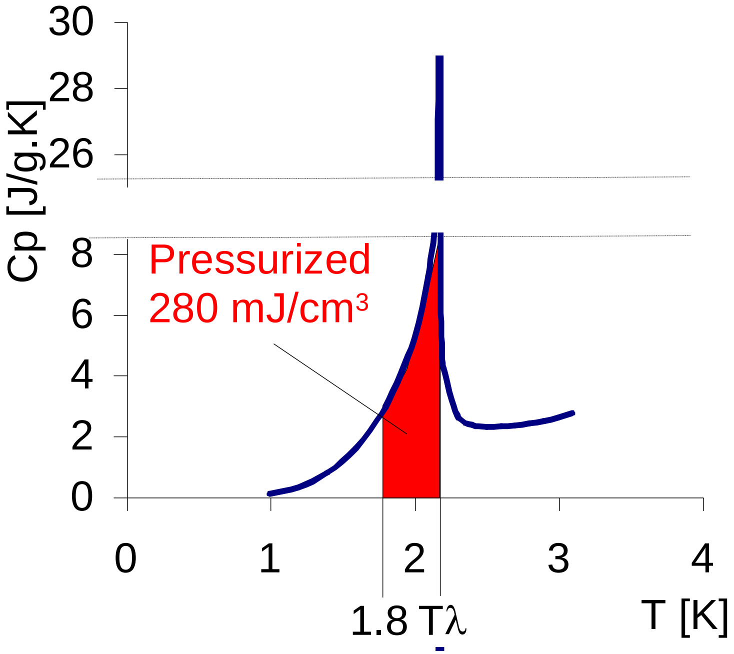
for which corresponds a temperature of saturation of T*= 1.82 K



The corresponding ΔH is 9 mJ/cm^3

Thermal stabilisation in He II p





The corresponding ΔH is 280 mJ/cm³
(30 times higher than in He II s)

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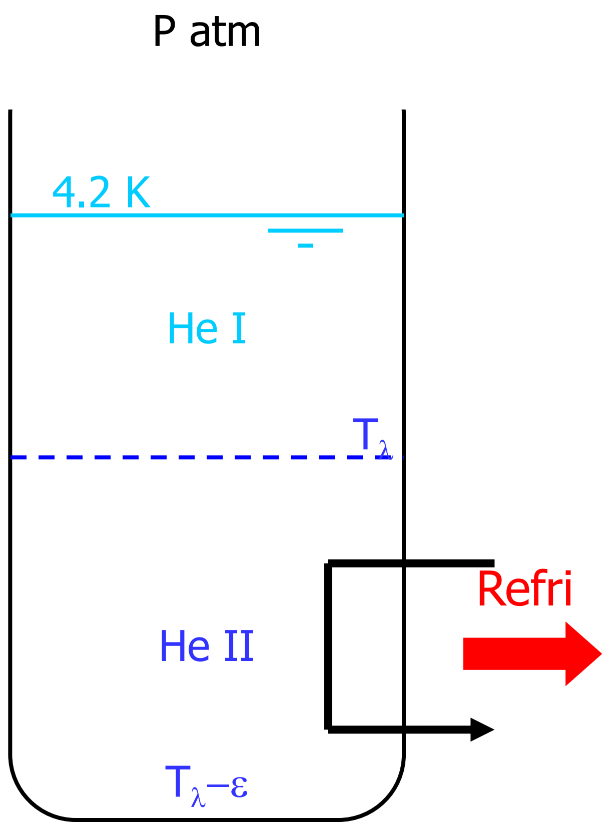
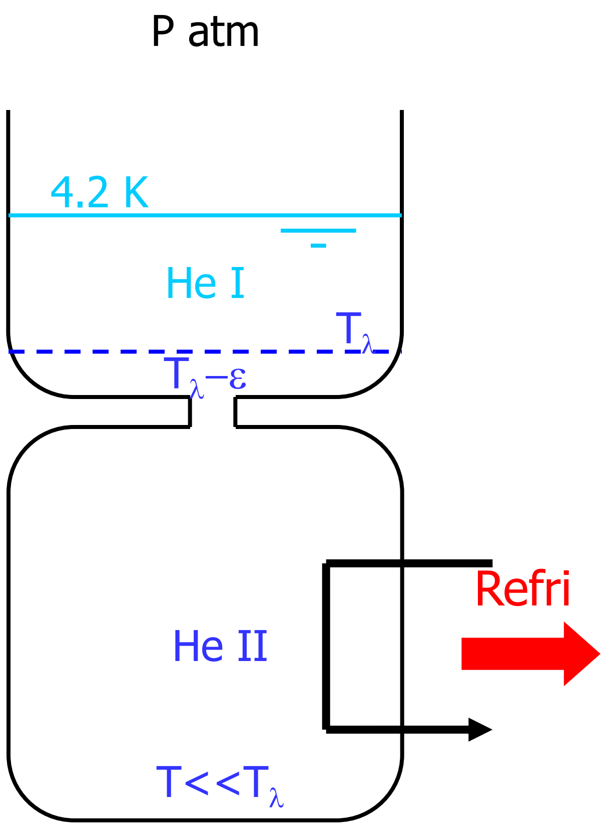
Working with superfluid helium at atmospheric pressure

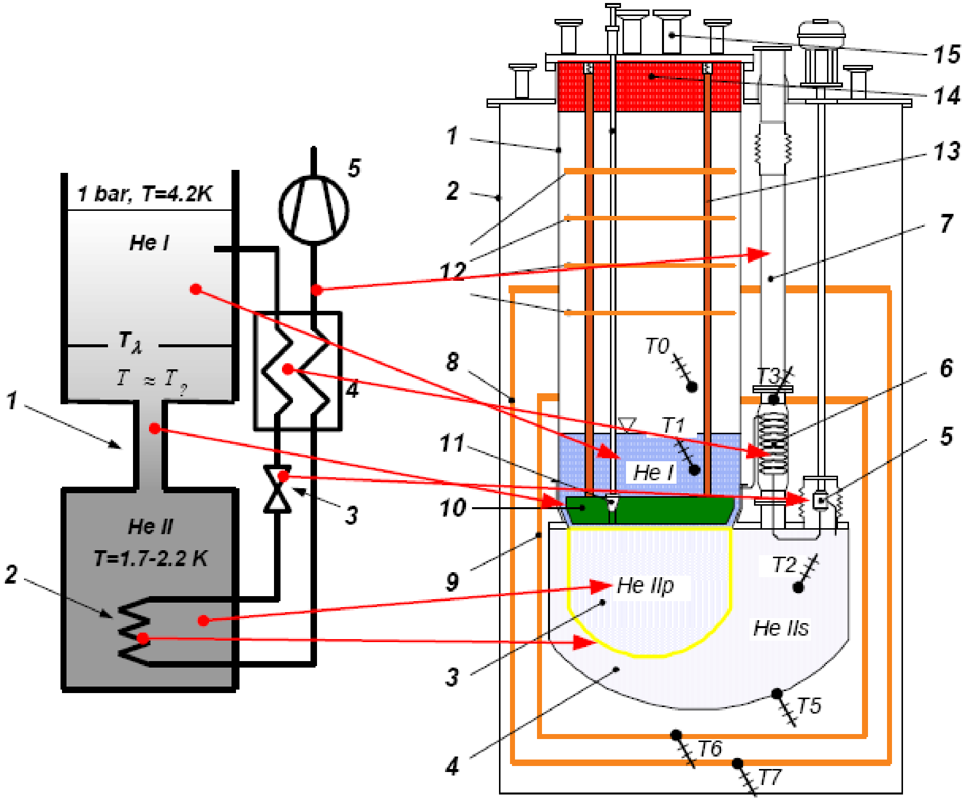


« Roubeau bath »: He II conduction prevents from lowering the bath temperature well below T_λ



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

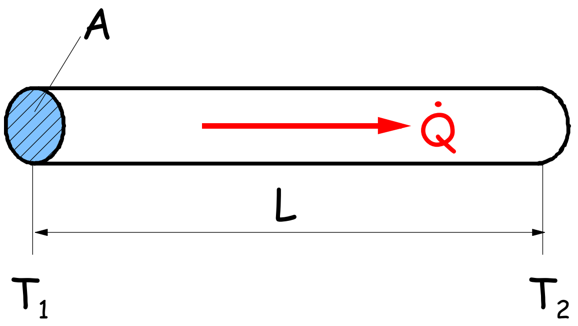
A practical Claudet bath



(a) (b)

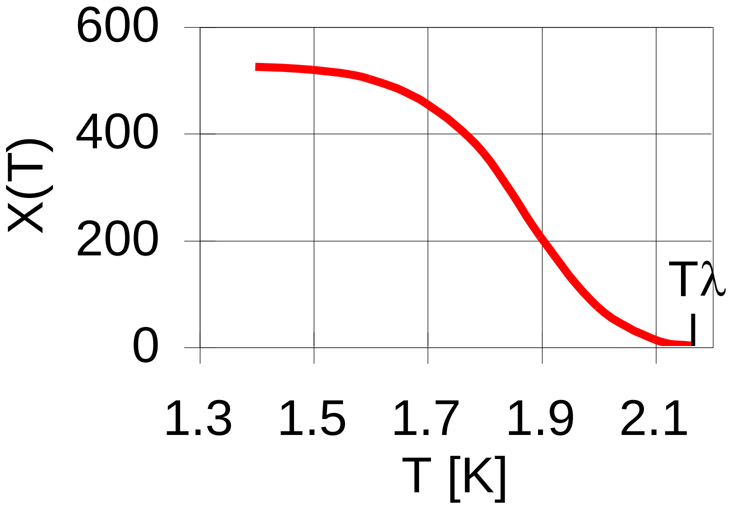
Figure 1. a) Claudet bath principle: 1 – constriction, 2 – He IIs/He IIp heat exchanger, 3 – J-T valve, 4 – recuperative heat exchanger, 5 –vacuum pump; b) NED cryostat scheme: 1 – He I vessel, 2 – vacuum container, 3 – He IIp vessel, 4 – He IIs vessel, 5 – J-T valve, 6 – recuperative heat exchanger, 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



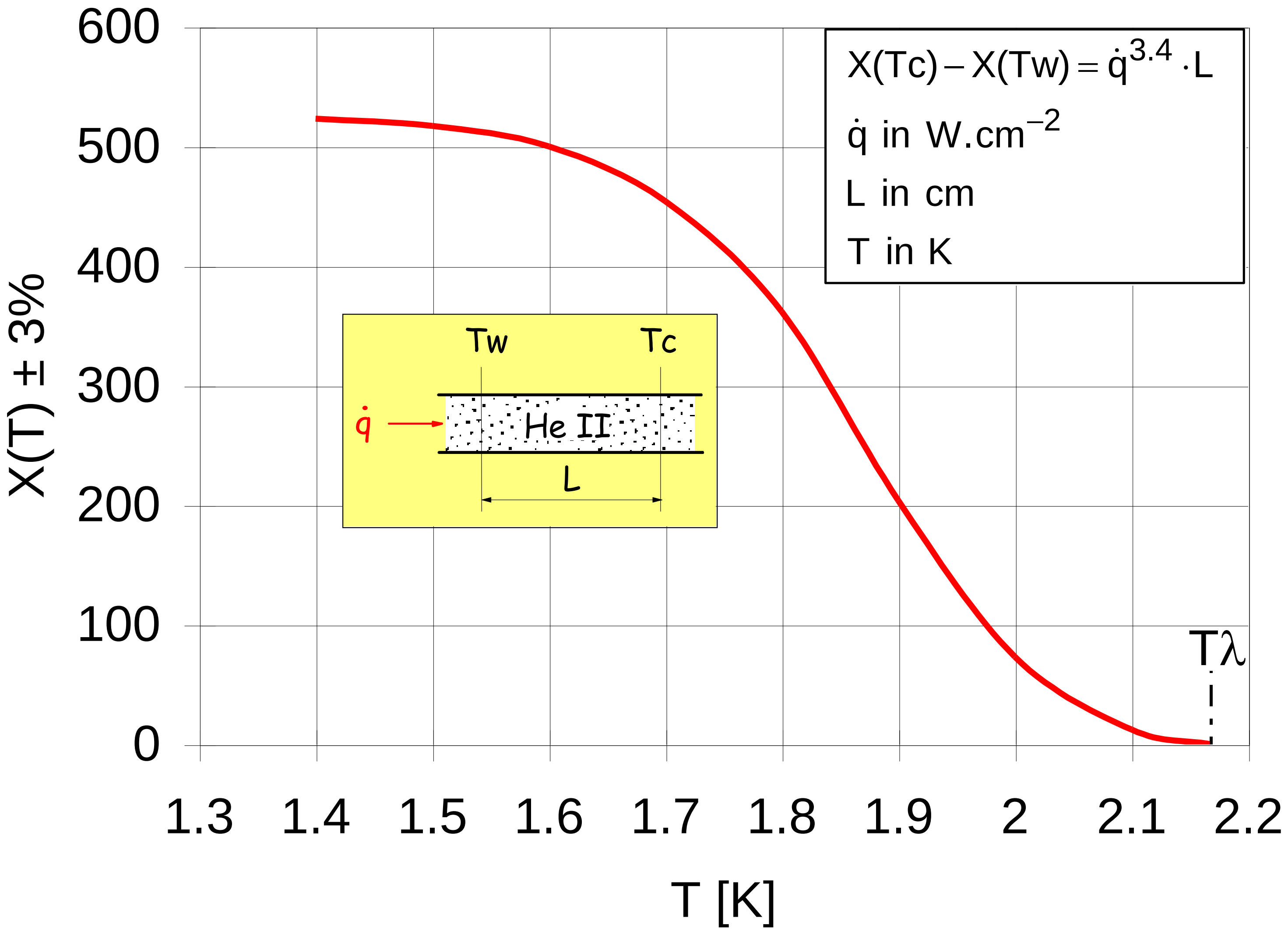
Cross-section: A
Length: L
Power: $\dot{Q}$
Heat Flux: $\dot{q} = \dfrac{\dot{Q}}{A}$

- 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



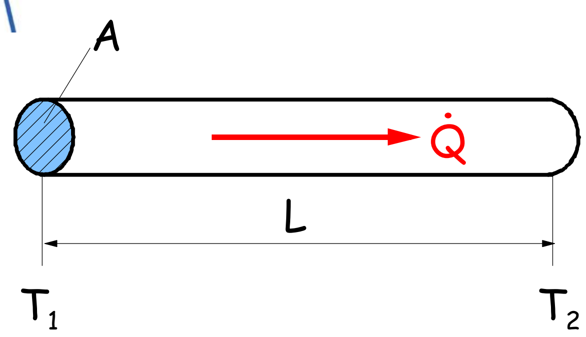
$$X(Tc) - X(Tw) = \dot{q}^{3.4} \cdot L$$

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

L in cm

T in K

Conduction cooling: a numerical example



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

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

$T_1 = 1.9\ \text{K} \rightarrow X(T_1) = 200$

$T_2 = 1.8\ \text{K} \rightarrow X(T_2) = 360$

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

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

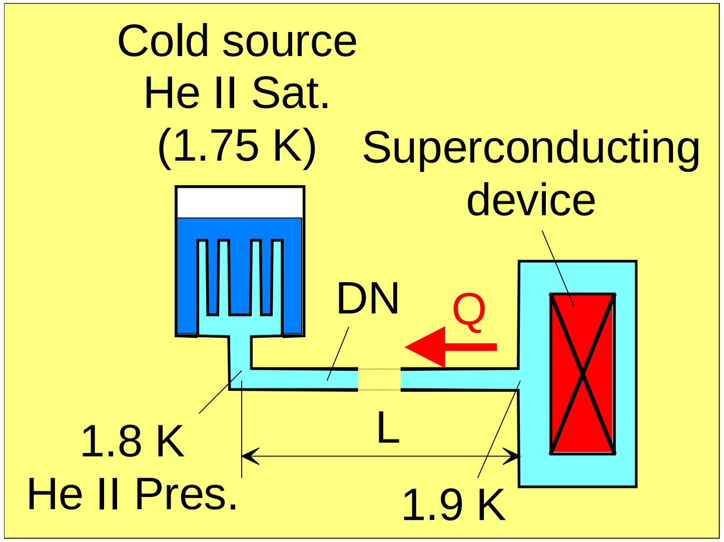
$$\dot{q} = k \cdot \frac{\Delta T}{L}$$ with k = thermal conductivity at 1.8 K

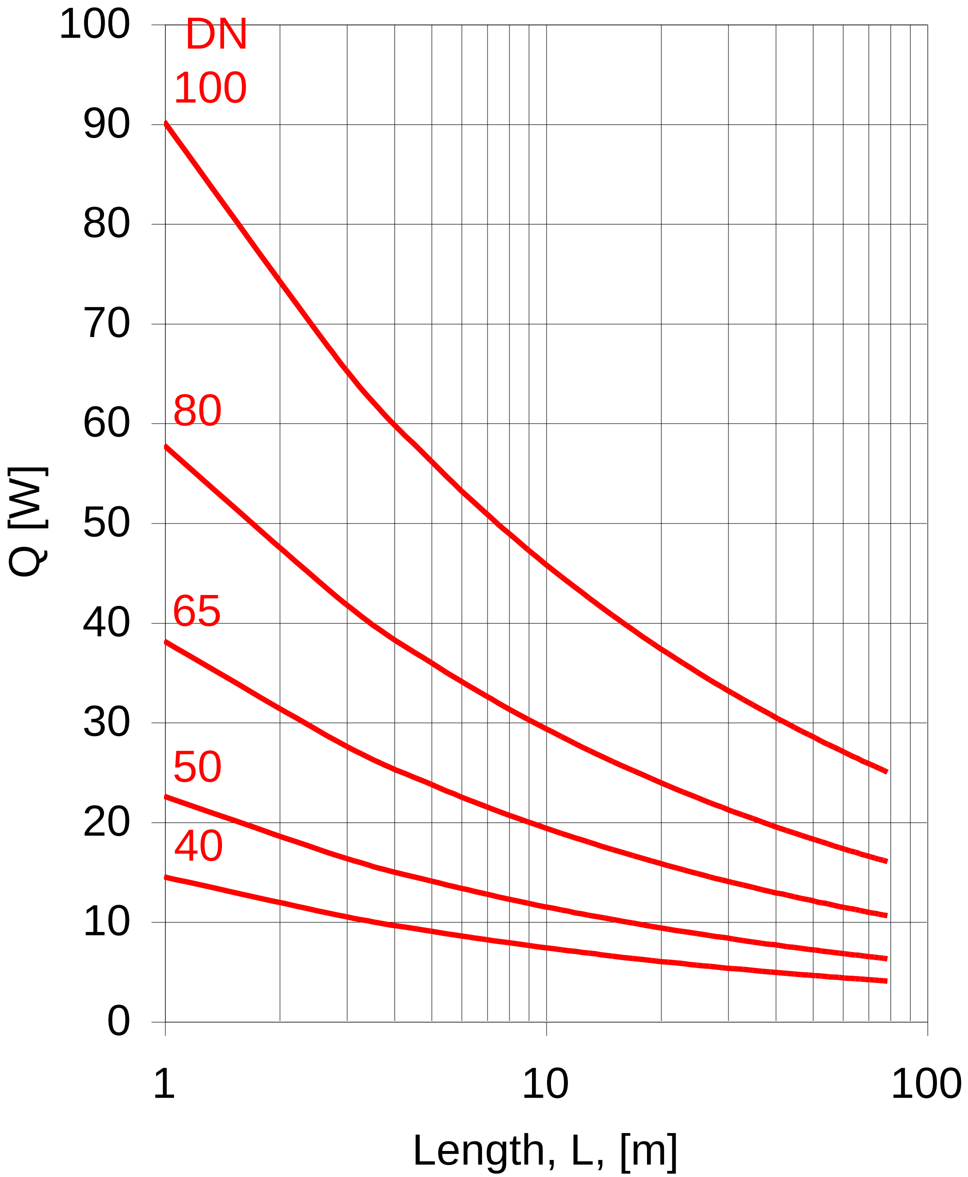
Cu type	**k [W/m.K]**	**ΔT [K]**	**L [m]**	**q [mW/cm^2]**
OFHC	120	0.1	1	**1.2**
DHP	3	0.1	1	**0.03**

He II conducts heat 1000 times better than OFHC Cu

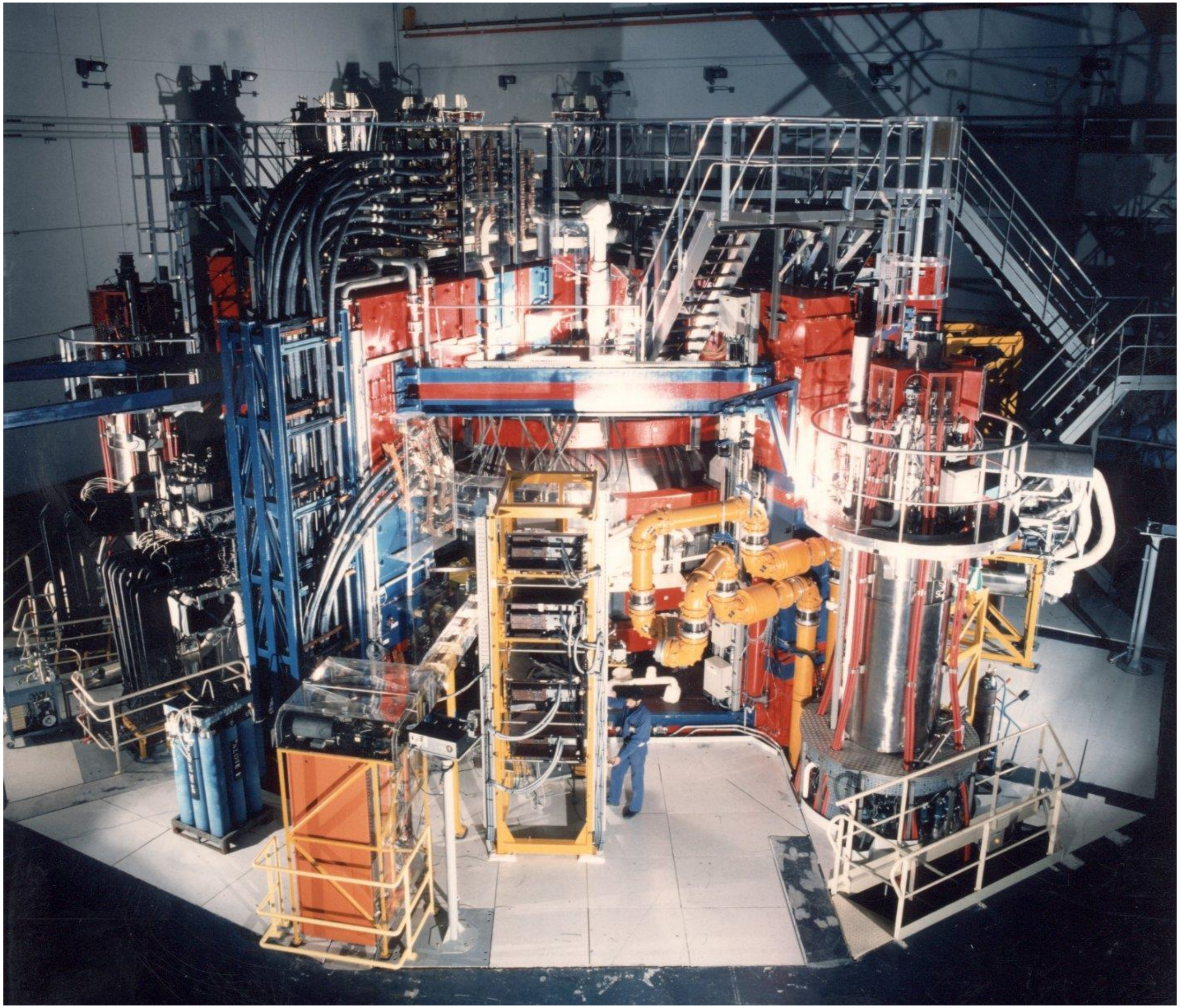
Steady-state conduction duct in He II

From 1.80 K to 1.90 K





Tore Supra tokamak at CEA Cadarache, France



He II p conduction cooling of Tore Supra coils

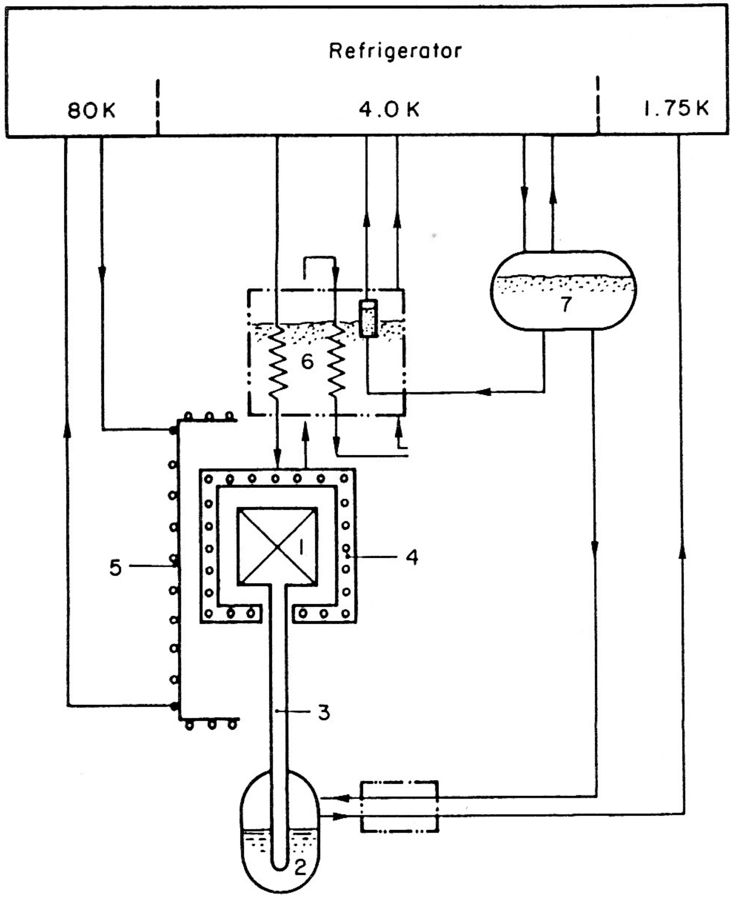


Figure 2 Schematic design of the cryogenic system. 1, 1.8 K coil; 2, 1.75 K cold box; 3, static pressurized superfluid helium; 4, thick casing total weight = 120 tonnes; 5, 80 K shield total weight = 22 tonnes; 6, thermal ballast; 7, 20 000 dm^3 He tank

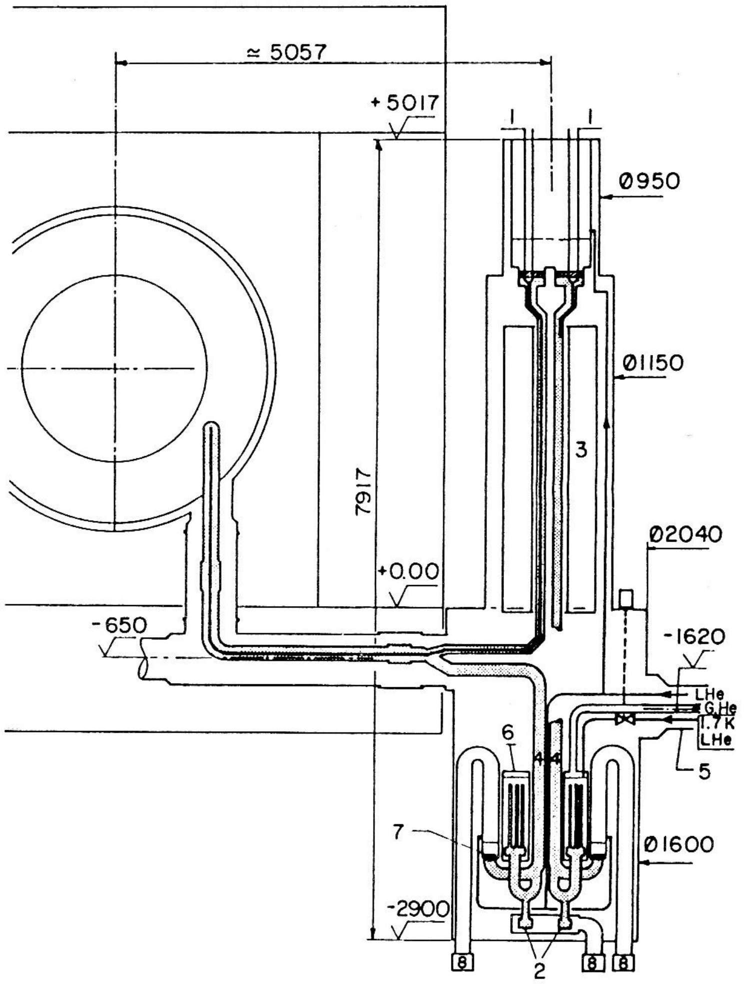
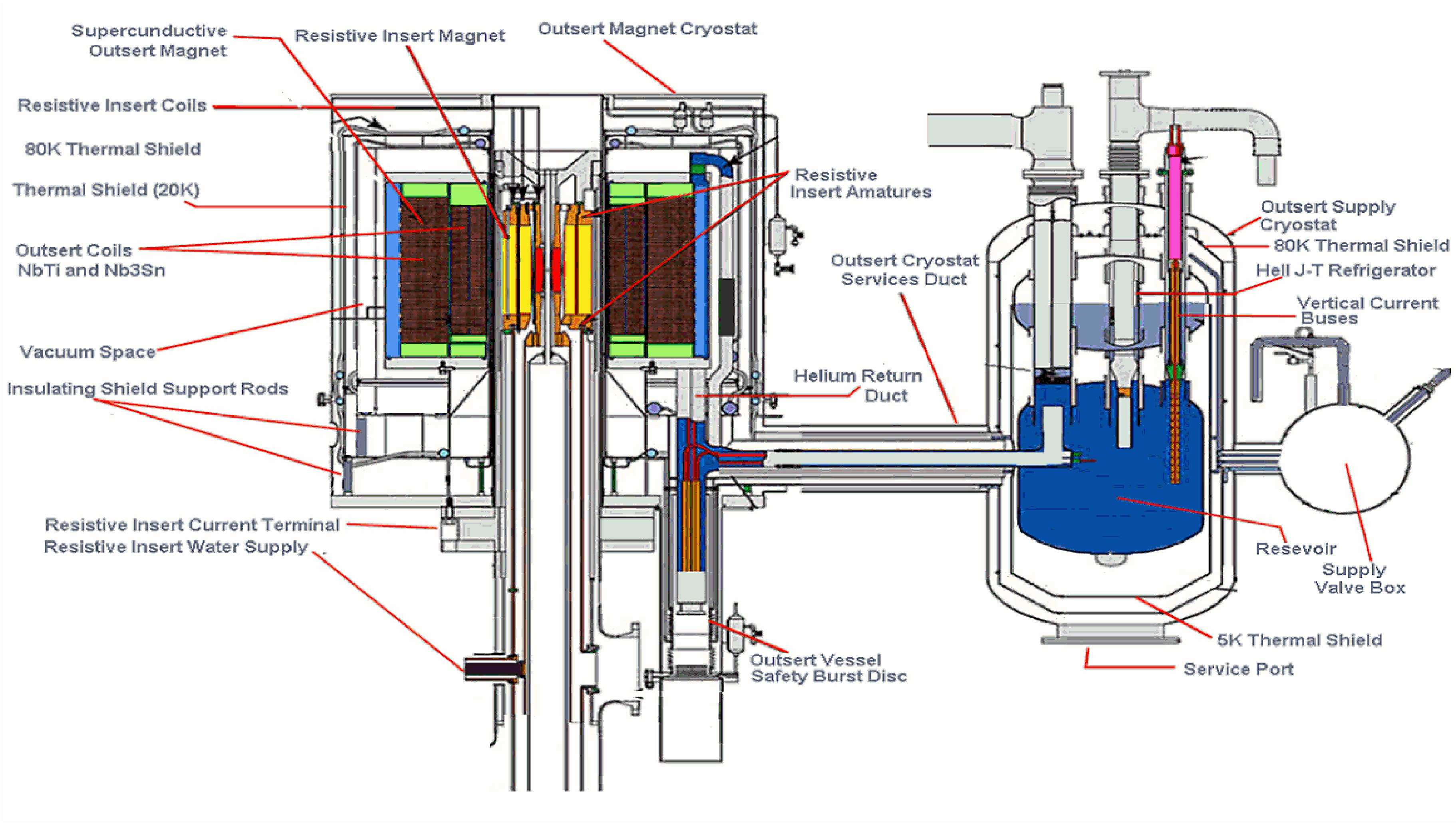
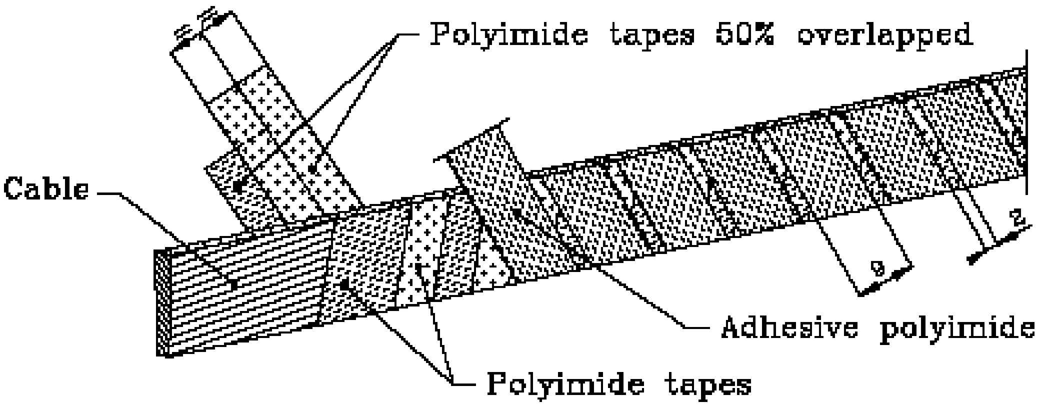


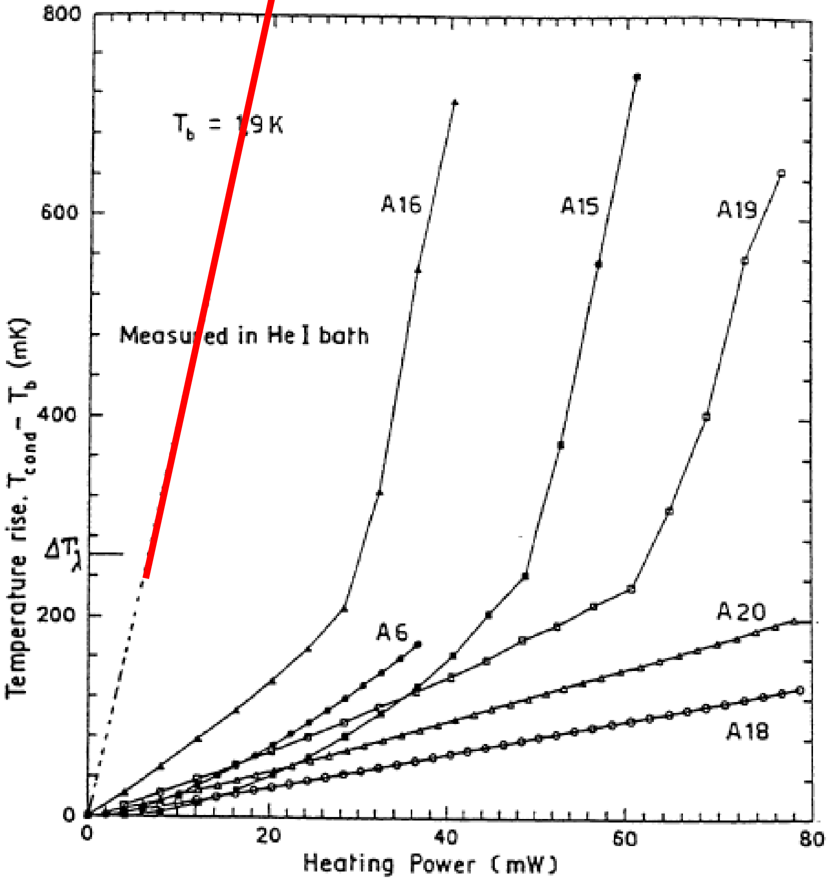
Figure 3 1 atm He II circuit. 1, 12 Current leads; 2, cold burst discs; 3, thermal ballast = 1500 dm^3; 4, six He II pipes; 5, cryogenic line; 6, 1.7 K cold source; 7, cold valves; 8, safety valves

He IIp conduction cooling of 45 T hybrid magnet
NHFML Tallahassee





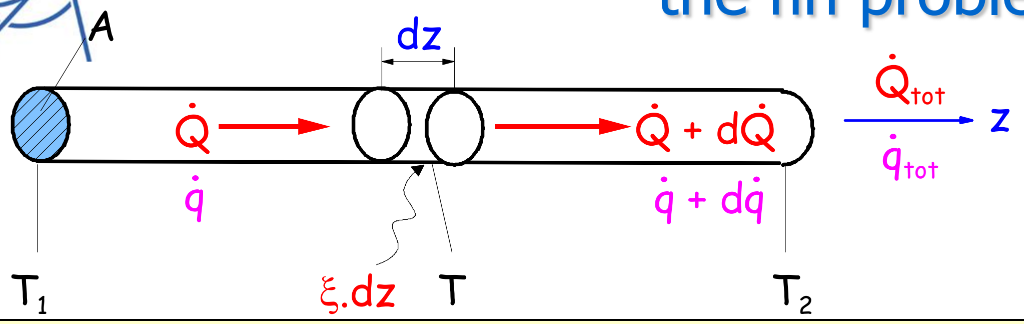
Conduction in polyimide



Heat transfer across electrical insulation of LHC superconducting cable

The LHC: 1716 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: $d\dot{q} = \frac{\xi}{A} \cdot dz$ ➔ $dz = \frac{A}{\xi} \cdot d\dot{q}$

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

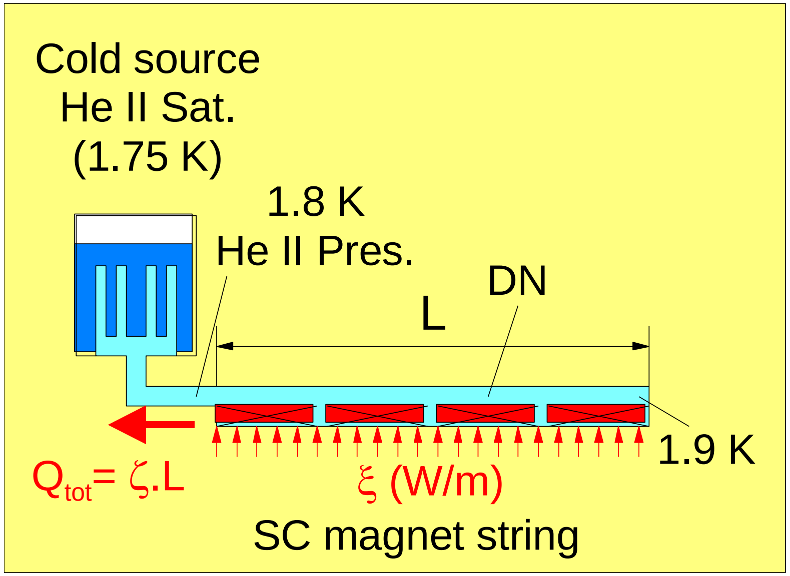
Calling Q_{tot} the total heat load on the string of length L:

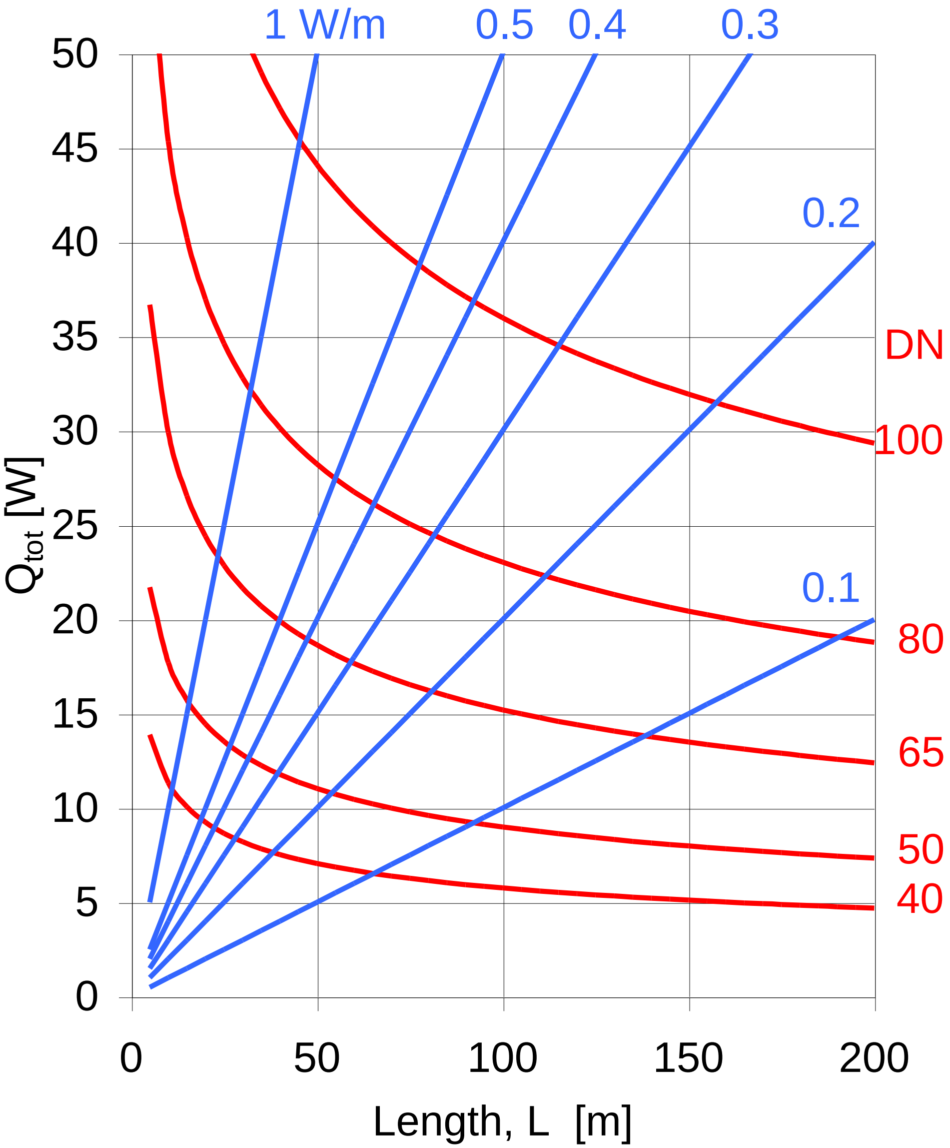
$$\dot{Q}_{tot} = L \cdot \xi = \dot{q}_{tot} \cdot A \Rightarrow \frac{\xi}{A} = \frac{\dot{q}_{tot}}{L}$$

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

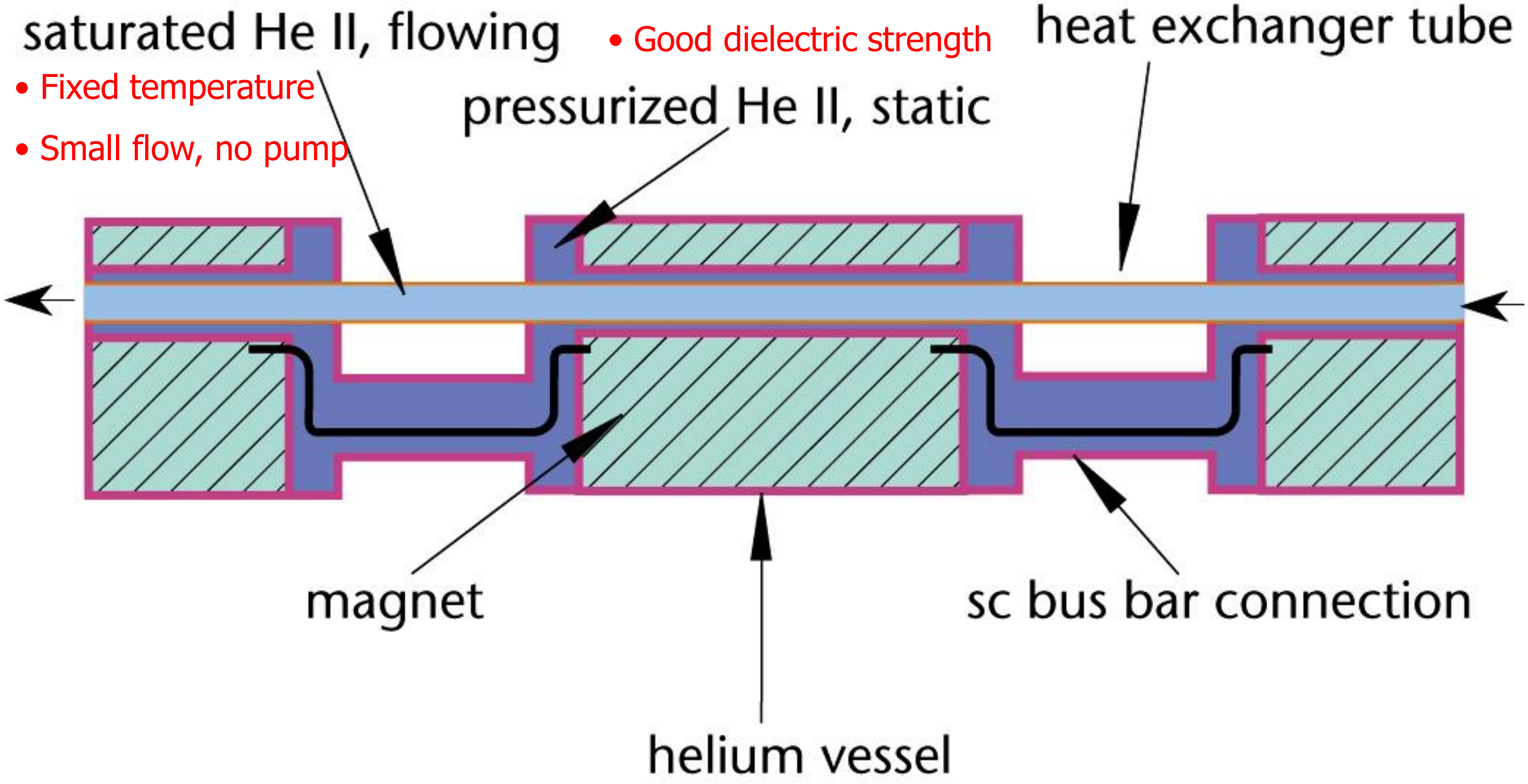
From 1.80 K to 1.90 K





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

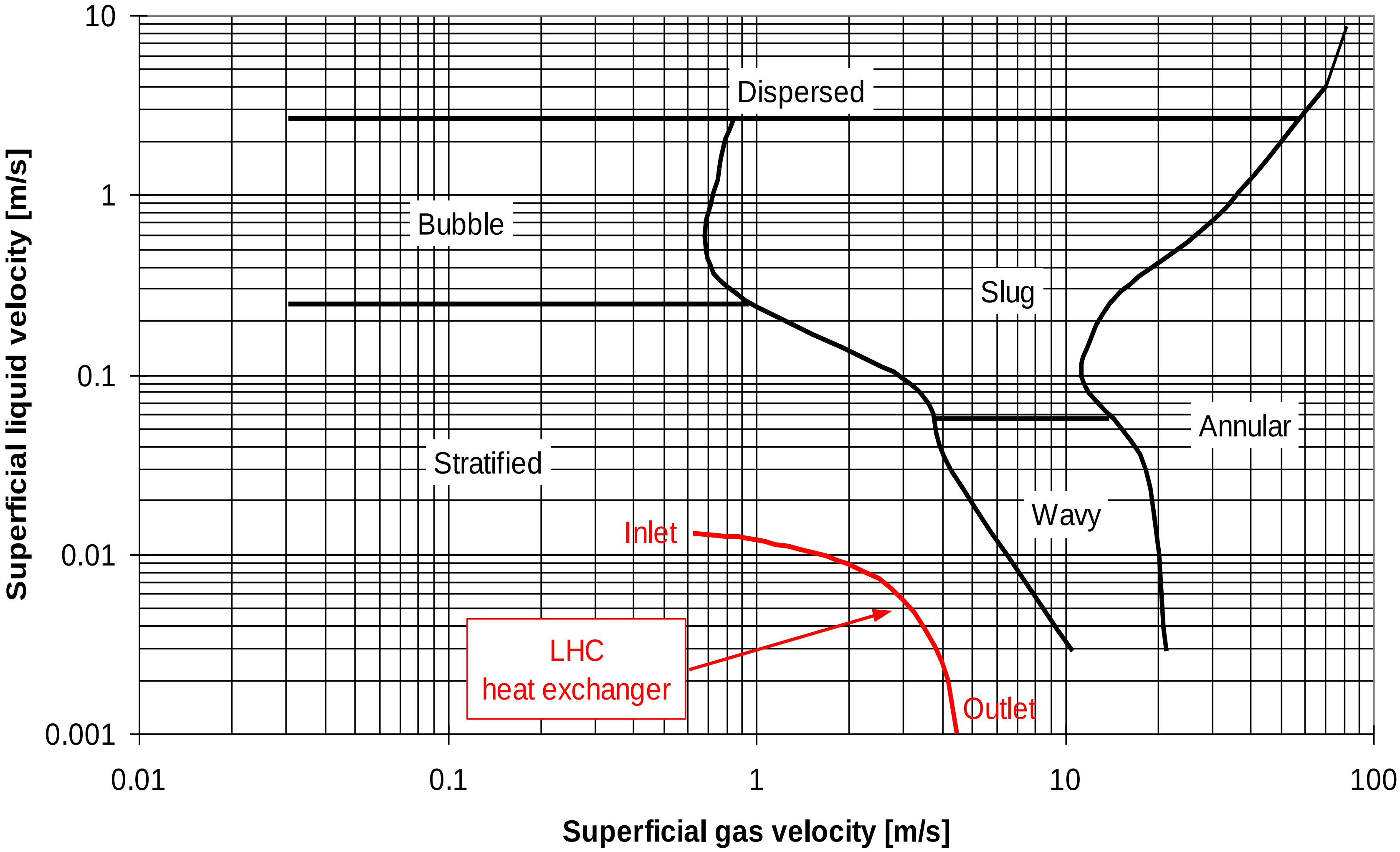
- Monophase
- Excellent thermal conductivity
- Good dielectric strength



- Fixed temperature
- Small flow, no pump

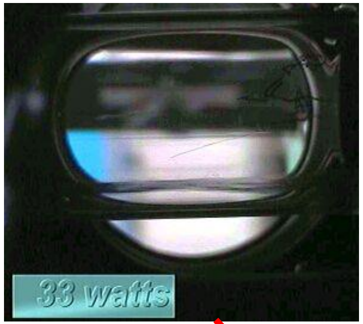
Two-phase Flow of Saturated He II

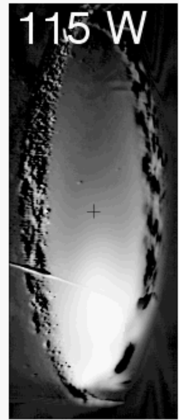
(Mandhane, Gregory & Aziz flow map)

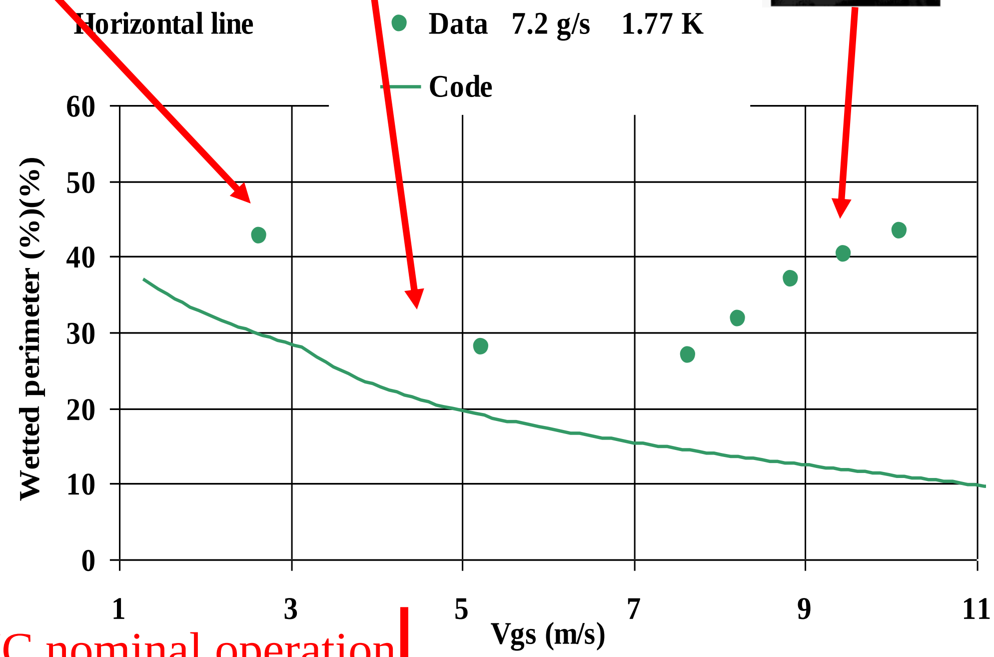


Investigation of two-phase He II s flow
(CEA Grenoble, France)

- Phenomenology
- Stability
- Pressure drop
- Heat transfer at wall

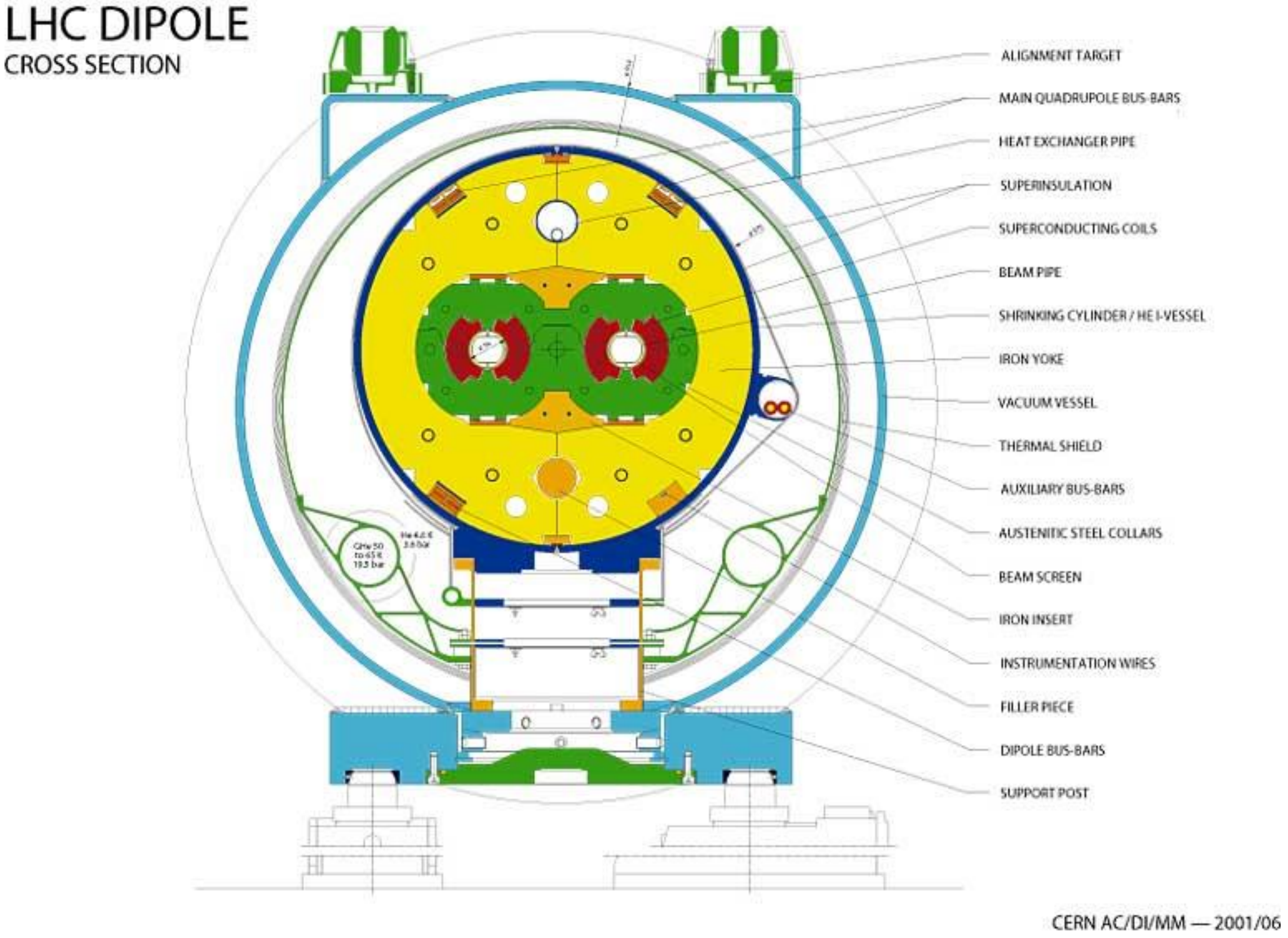




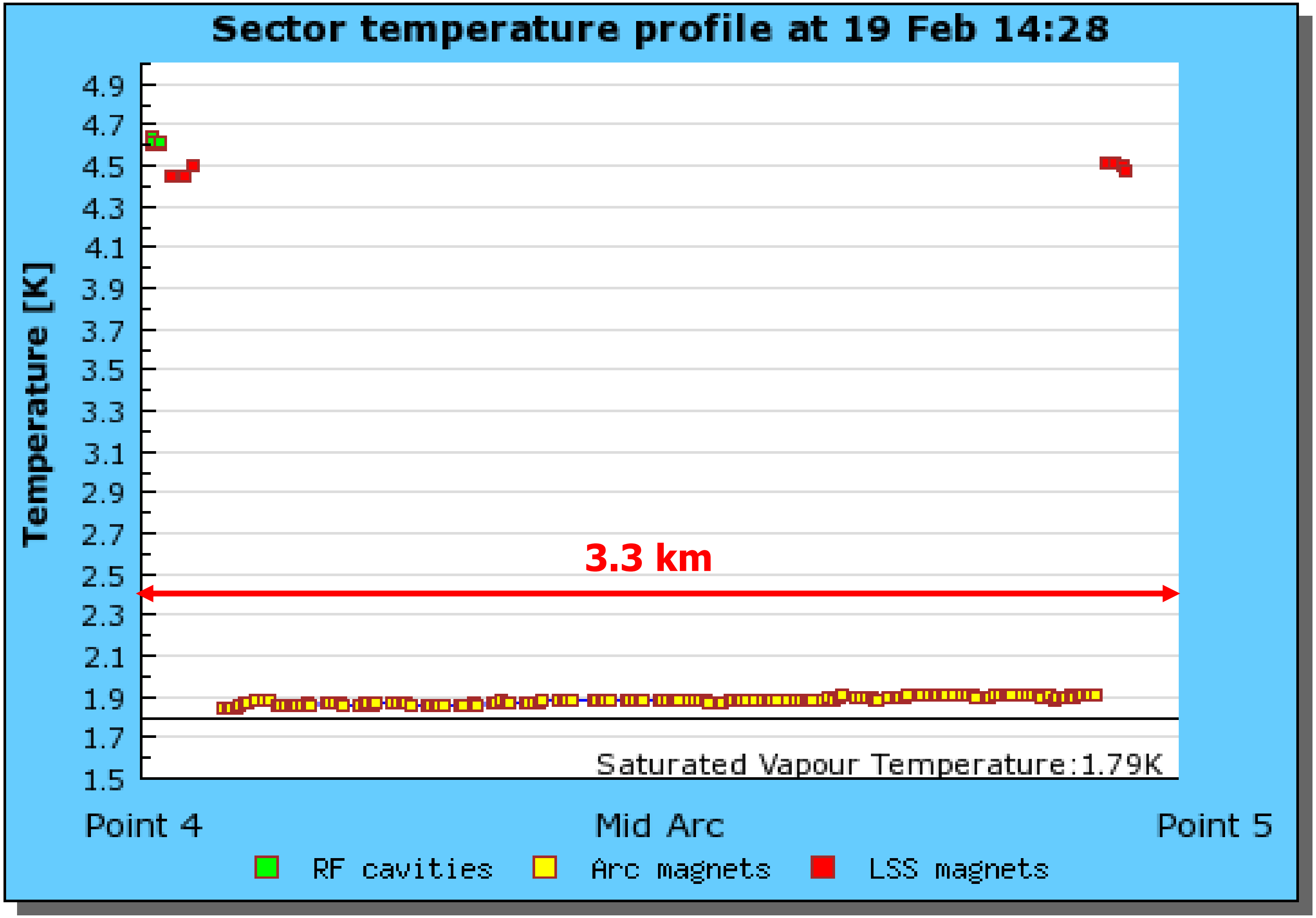


LHC nominal operation

LHC magnet cross-section



Temperature profile of LHC sector



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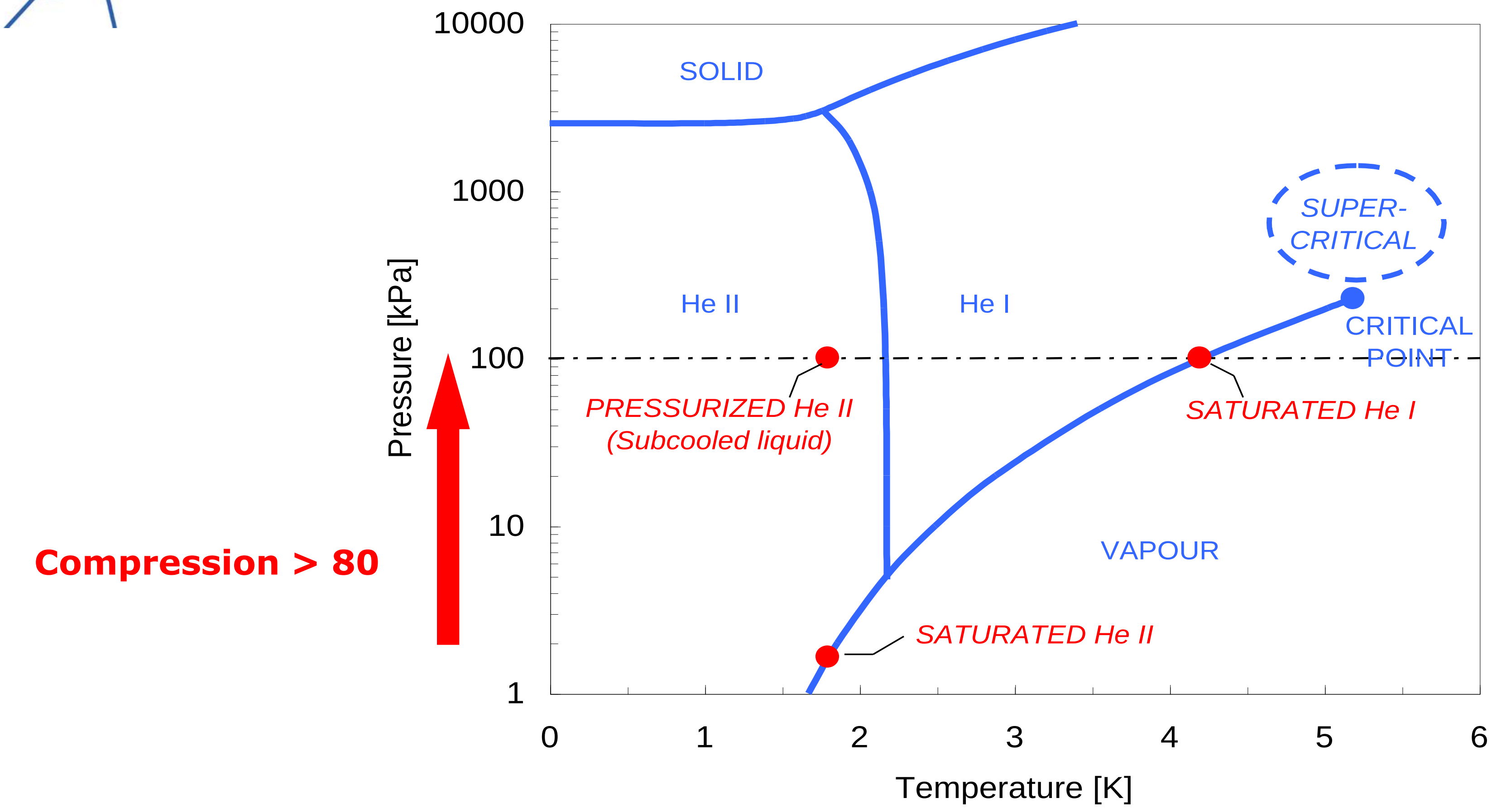
Challenges of power refrigeration at 1.8 K



- Compression of large mass flow-rate of He vapor across high pressure ratio

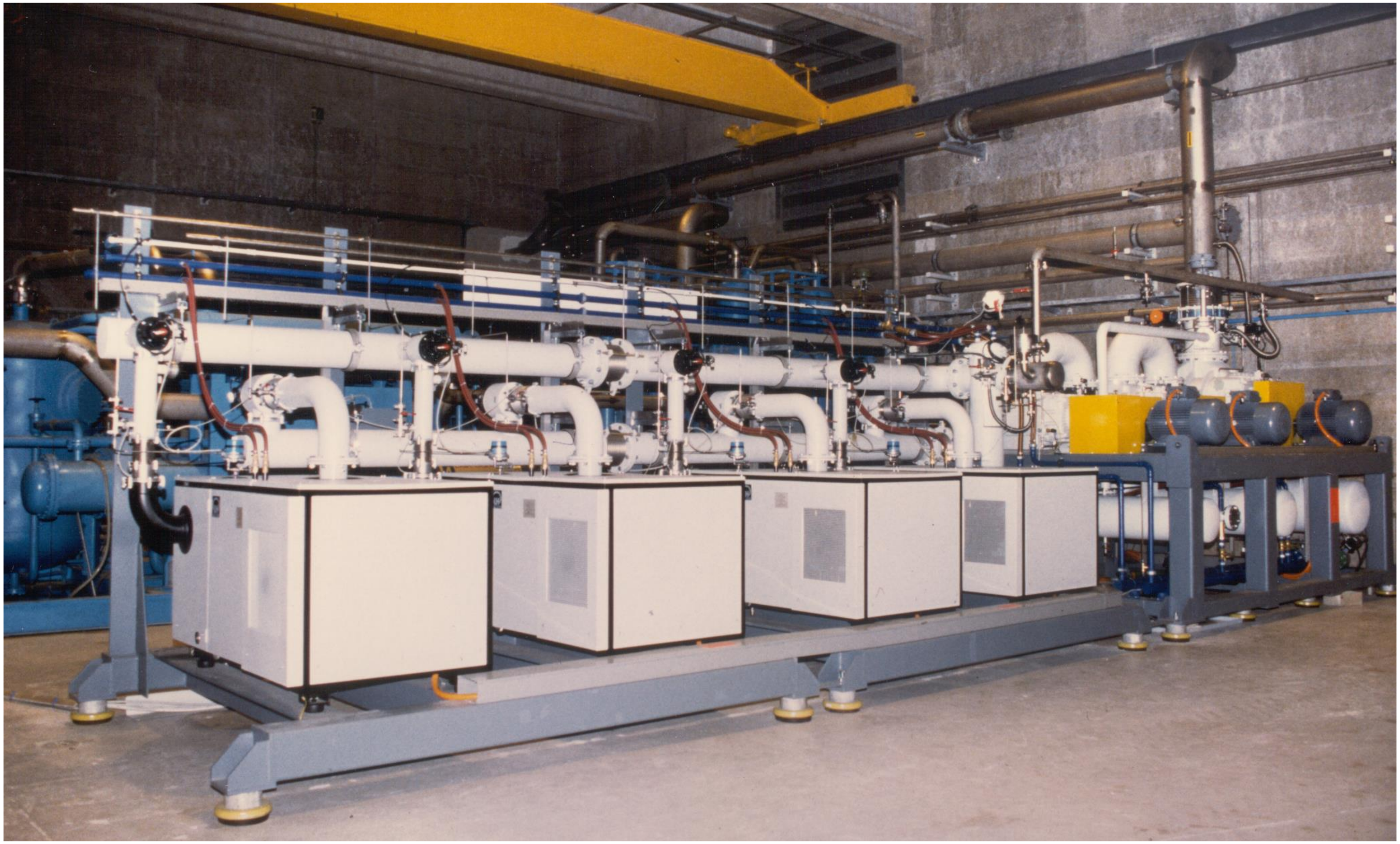
⇒ intake He at maximum density, i.e. cold

- Need contact-less, vane-less machine ⇒ hydrodynamic compressor
- Compression heat rejected at low temperature ⇒ thermodynamic efficiency

Warm pumping unit for LHC magnet tests

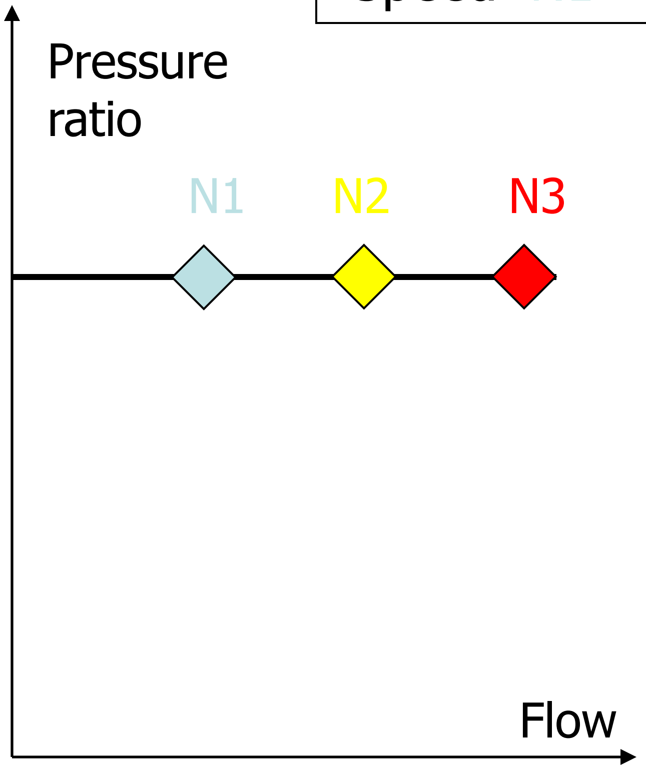
3 stages of Roots + 1 stage rotary-vane pumps

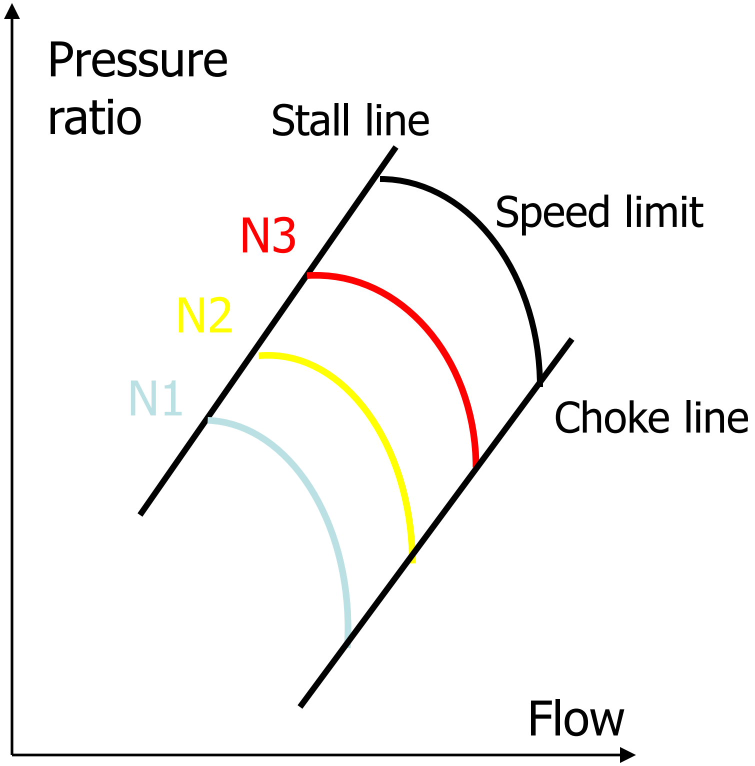
6 g/s @ 10 mbar *(1/160 of LHC!)*



Operating ranges of volumetric & hydrodynamic compressors

Speed N1 < N2 < N3

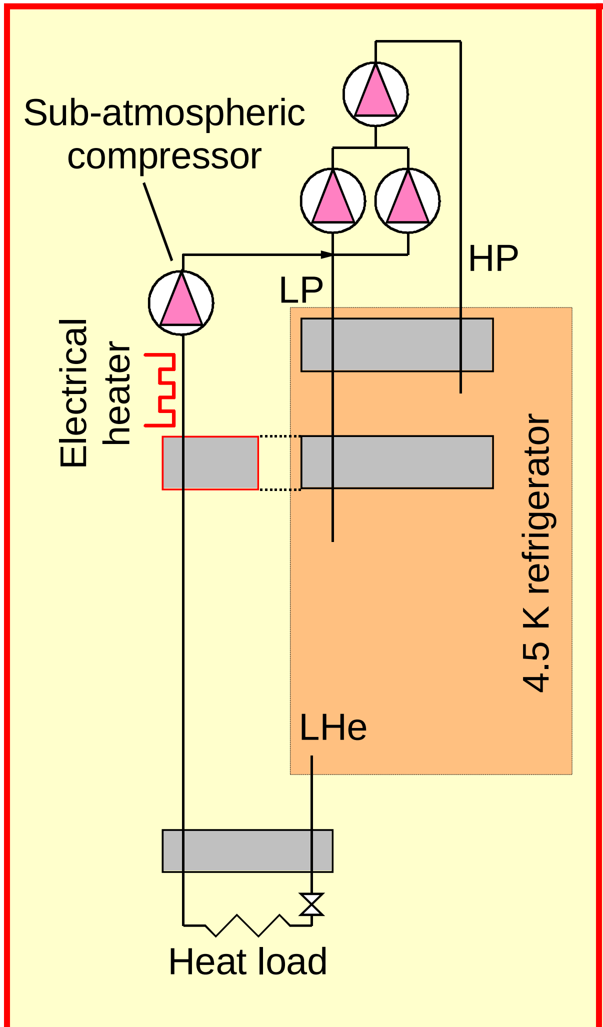




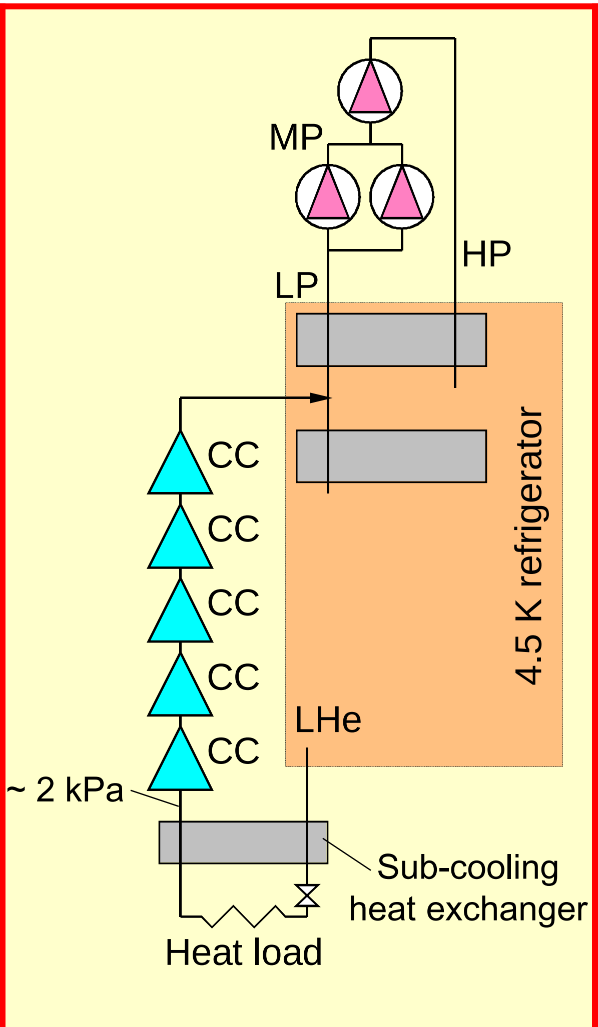
Volumetric (ideal)

Hydrodynamic

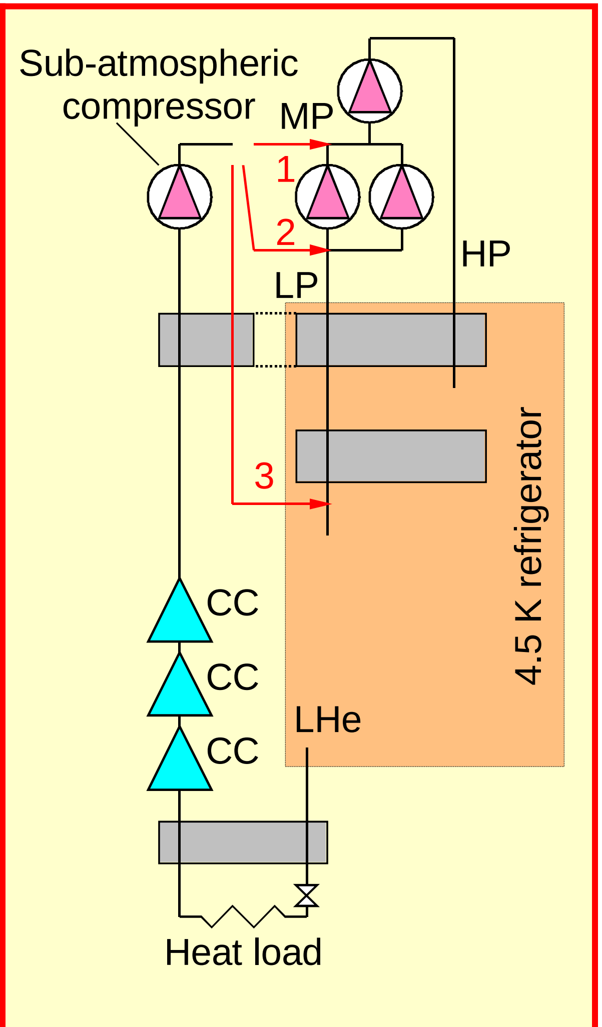
Cycles for refrigeration below 2 K



"Warm" Compression

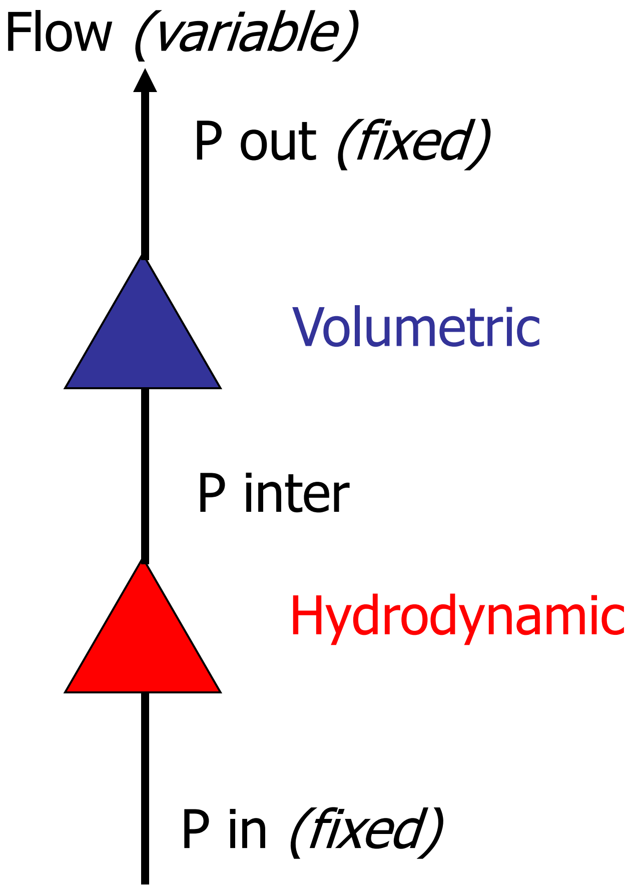


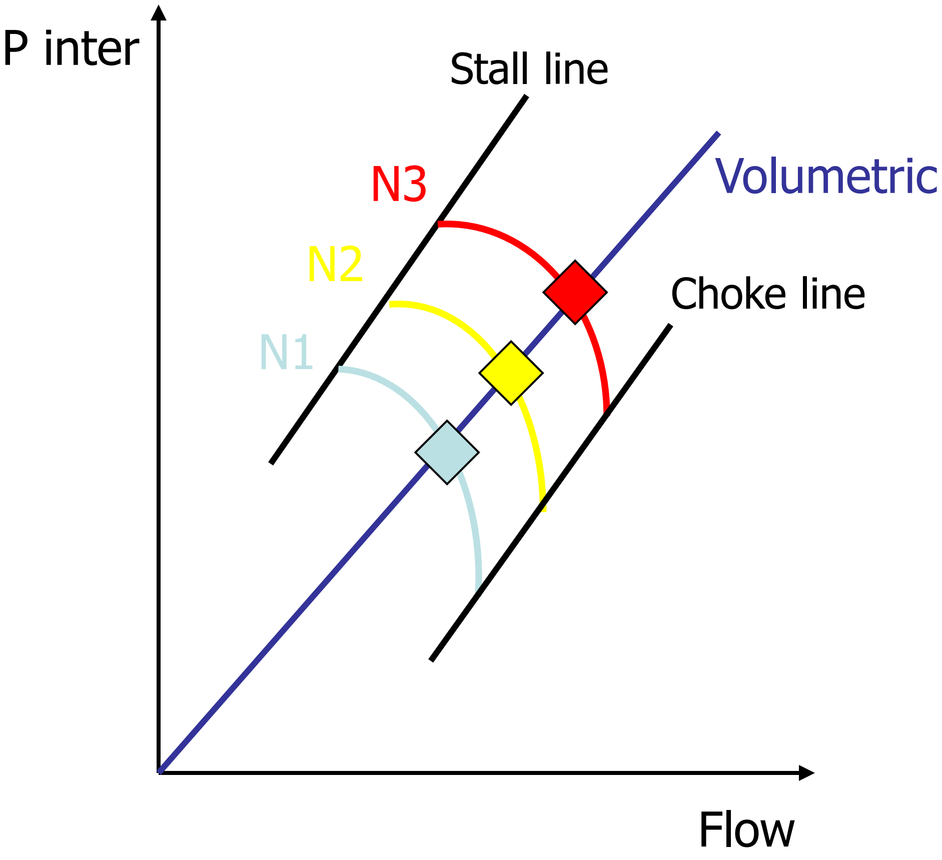
"Integral Cold" Compression



"Mixed" Compression

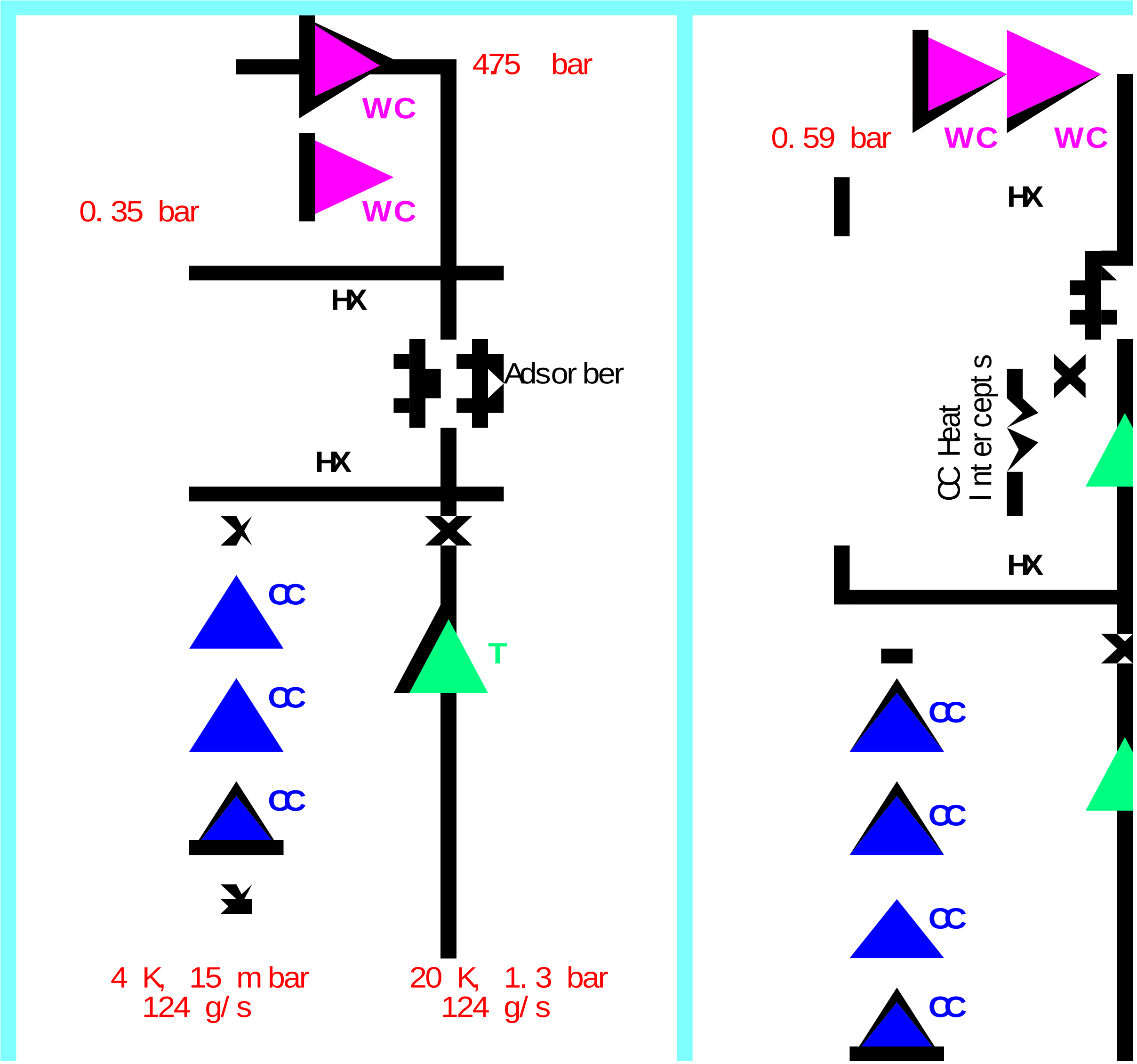
Flow compliance of “mixed” compression





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

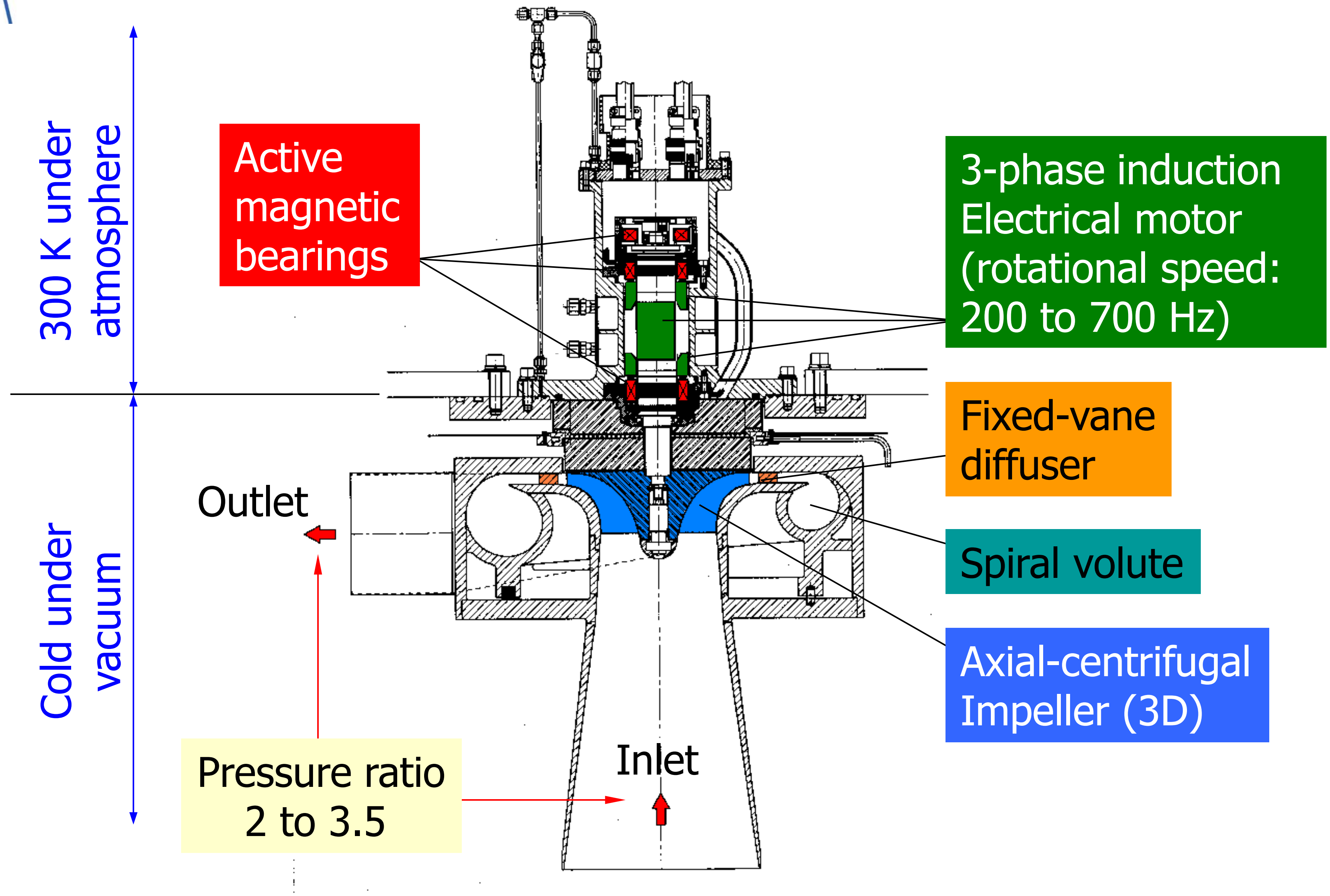


Cold hydrodynamic helium compressors

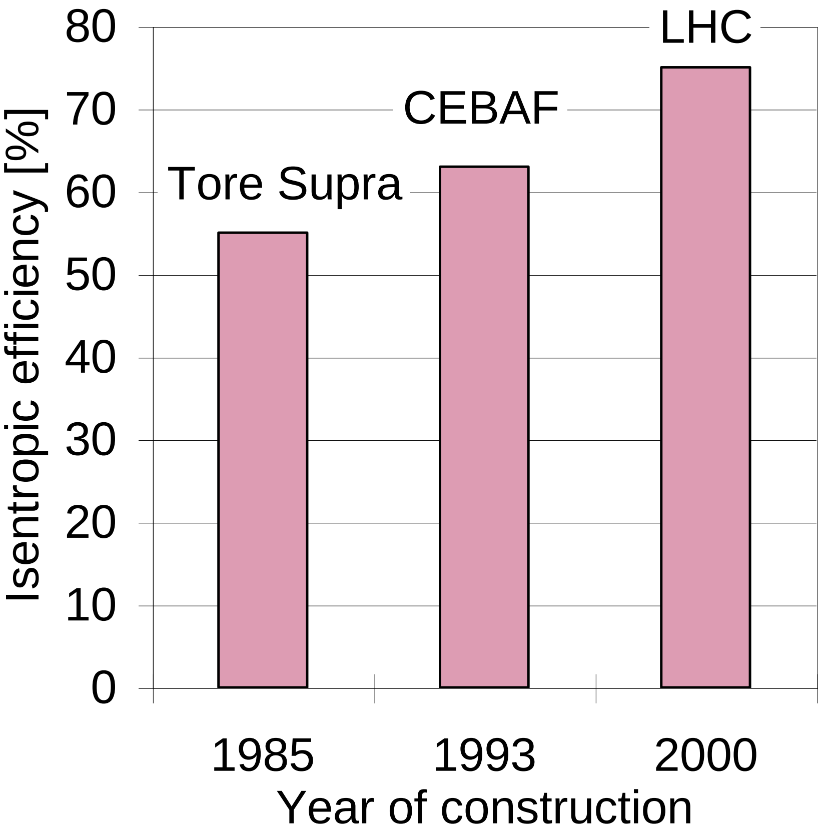
Air Liquide

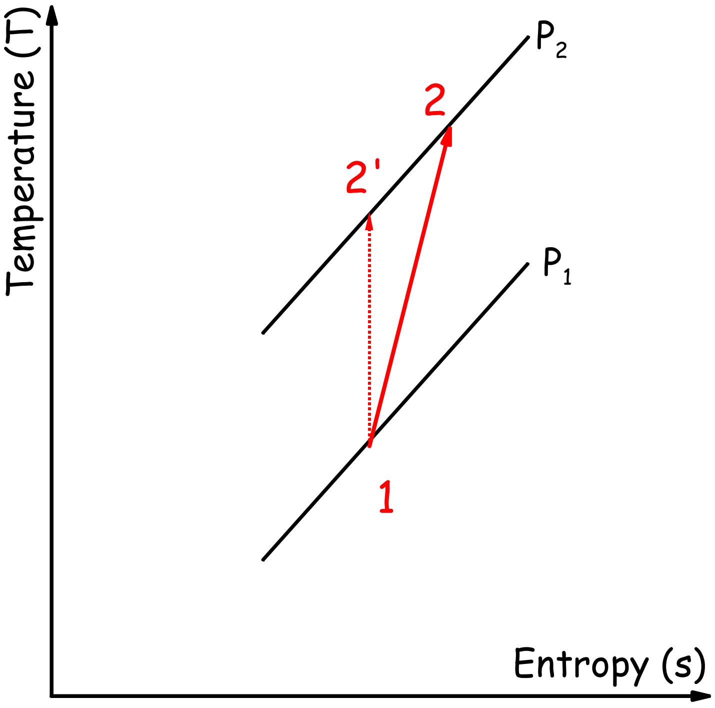
IHI

Specific features of LHC cold compressors



Performance of LHC cold compressors





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

Warm subatmospheric screw compressors

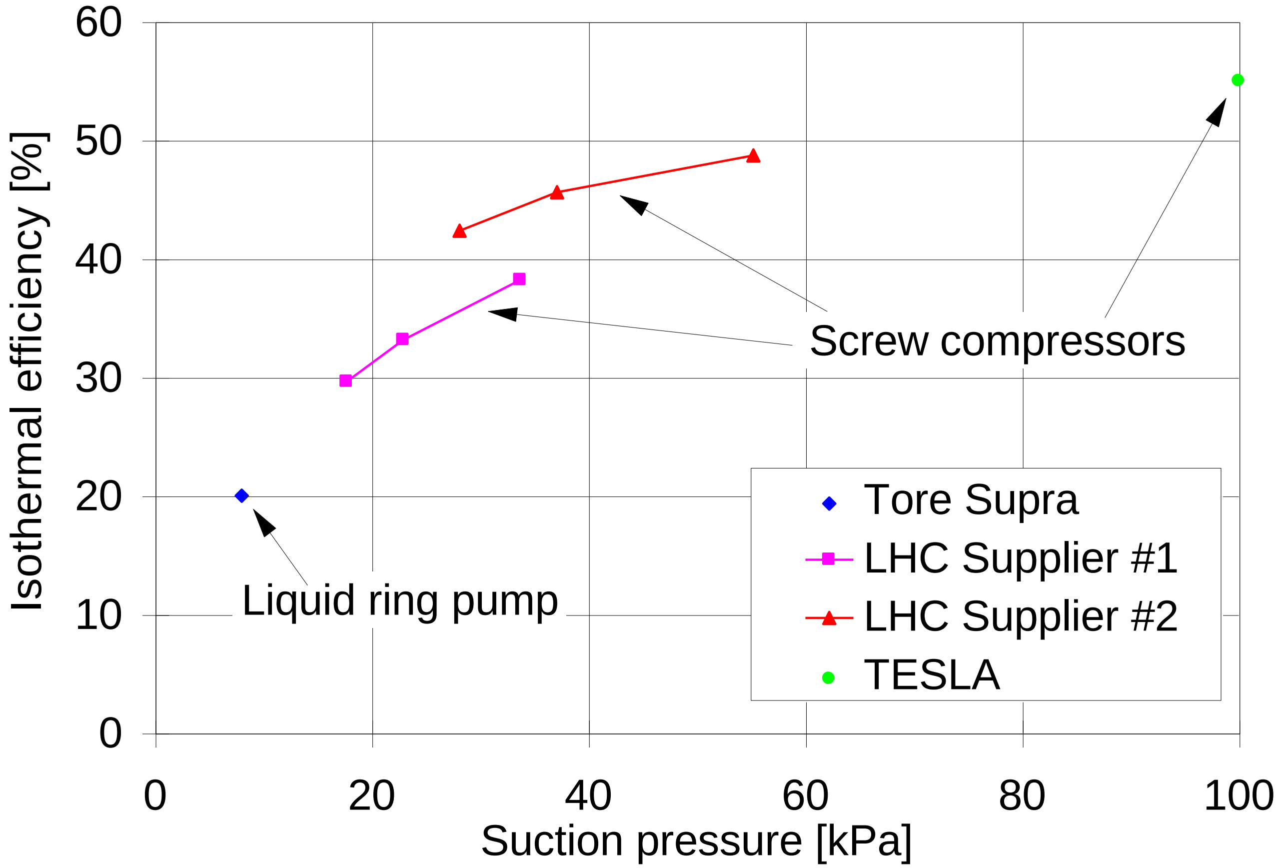
Mycom

125 g/s @ 0.6 bar
or
4600 m3/h @ 15 °C

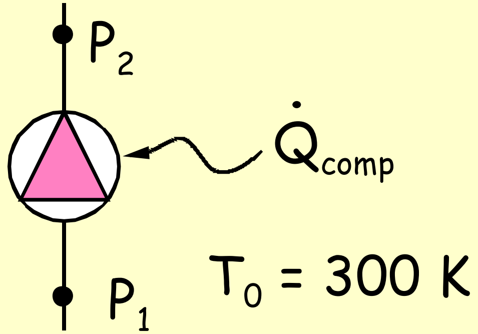
125 g/s @ 0.35 bar
or
2 x 3900 m3/h @ 15 °C

Kaeser

Isothermal efficiency of warm subatmospheric compressors



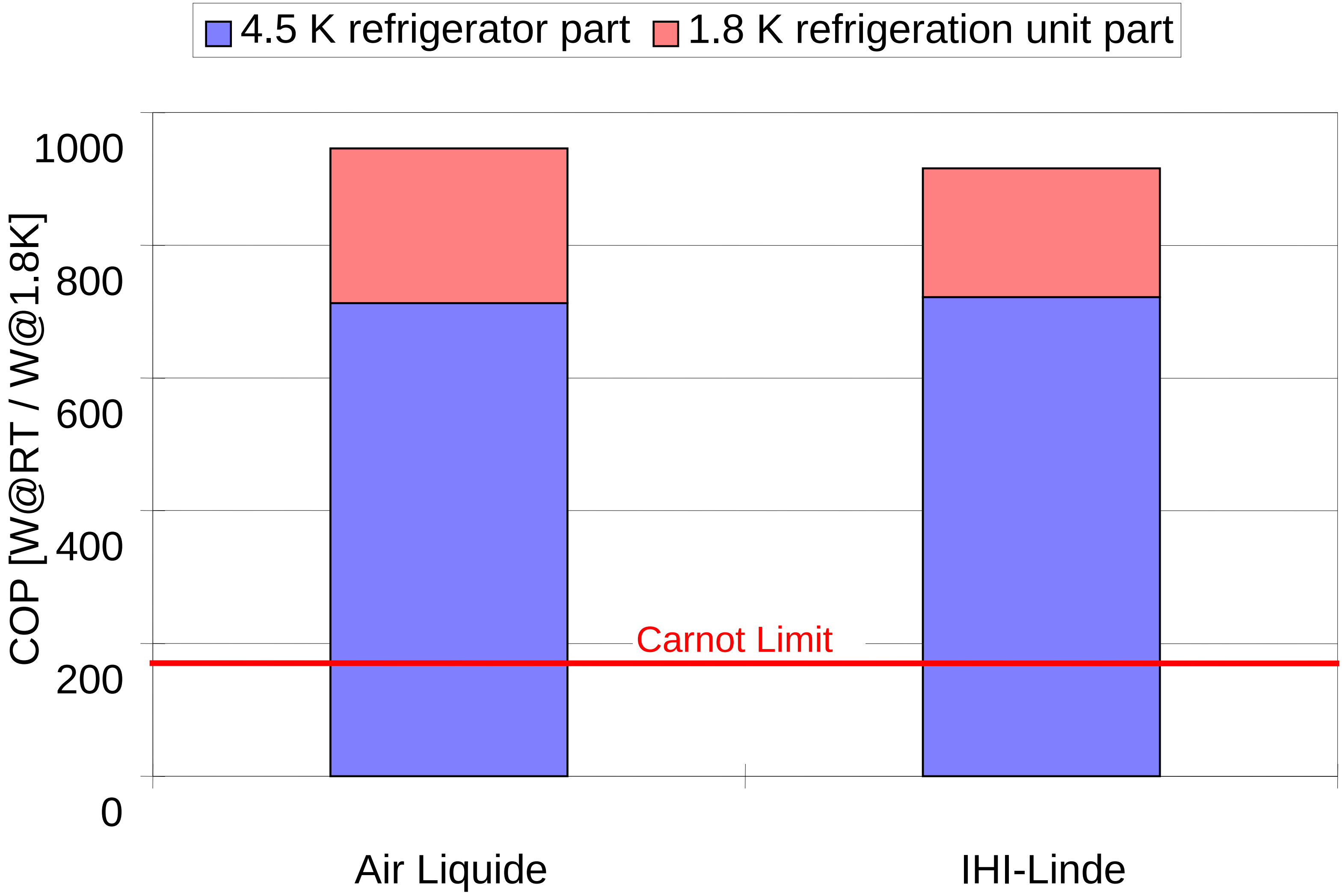
Isothermal efficiency



$T_0 = 300$ K

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

C.O.P. of LHC 1.8 K units



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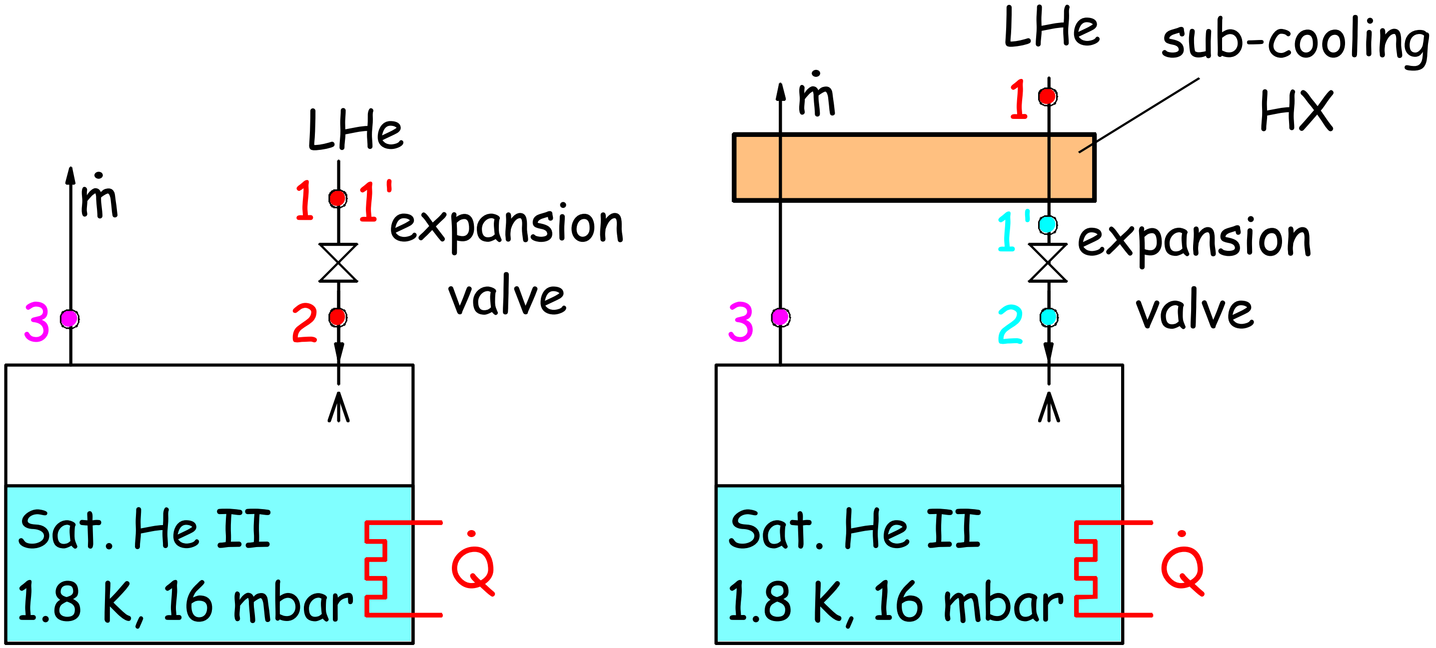
Efficiency of Joule-Thomson expansion



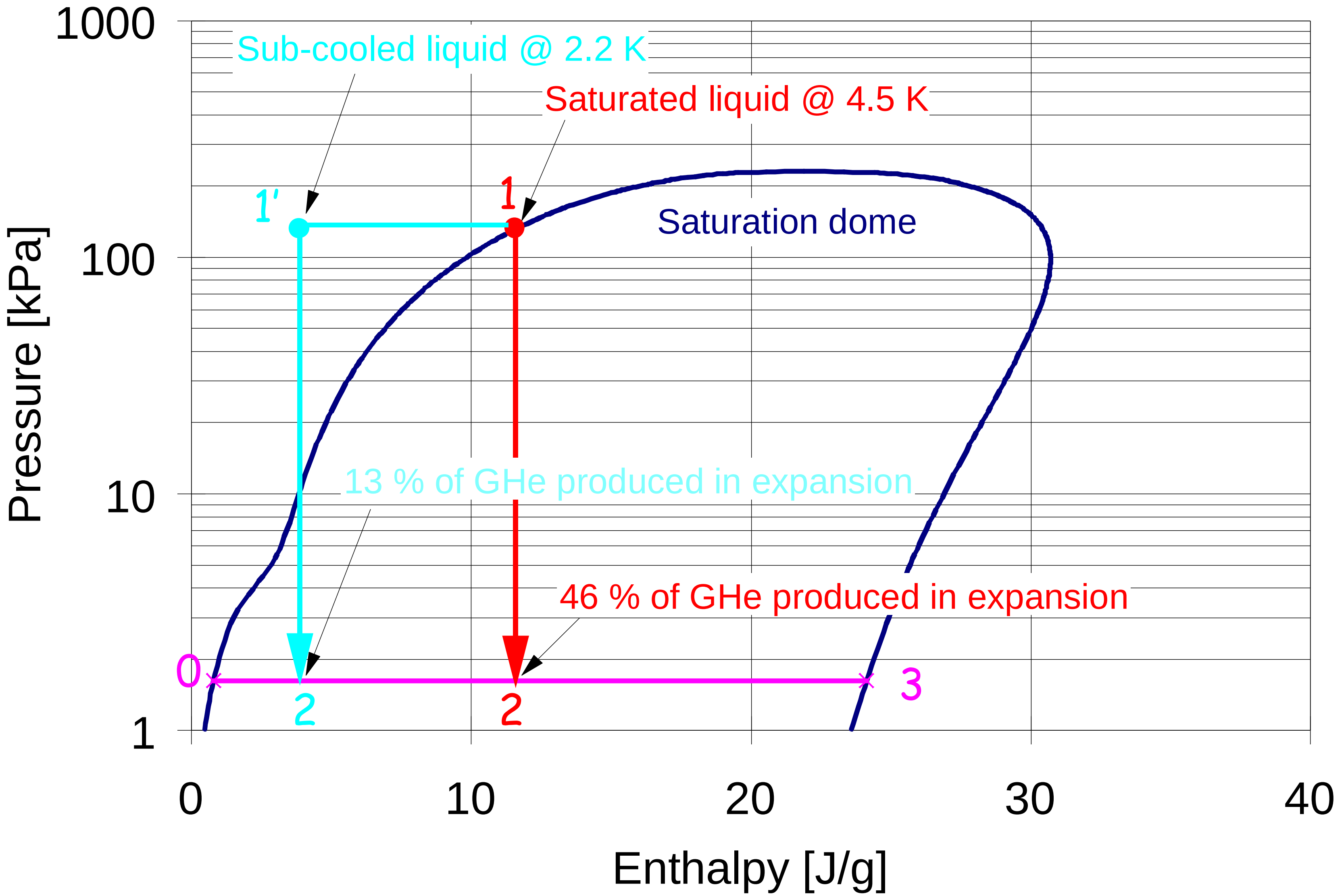
Sub-cooling efficiency :

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

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

Subcooling before J-T expansion

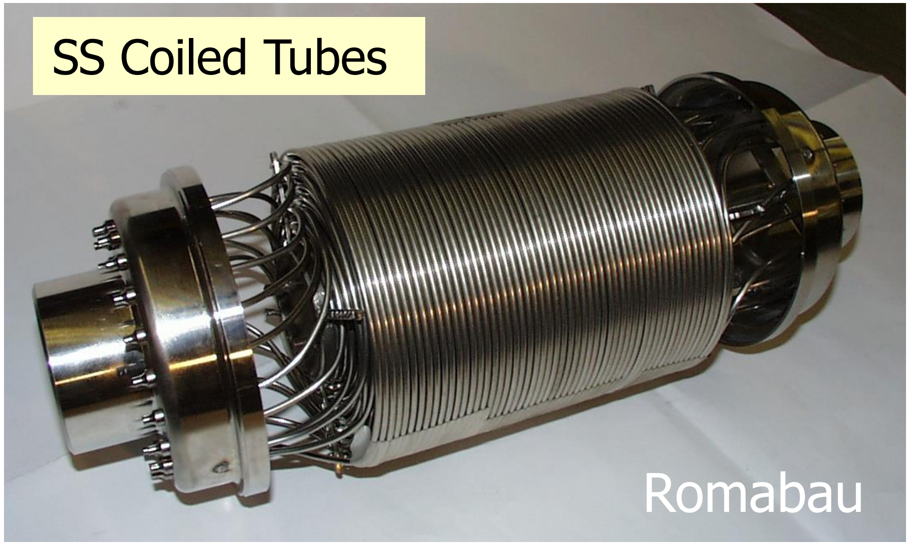


Prototypes of subcooling HX for LHC

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

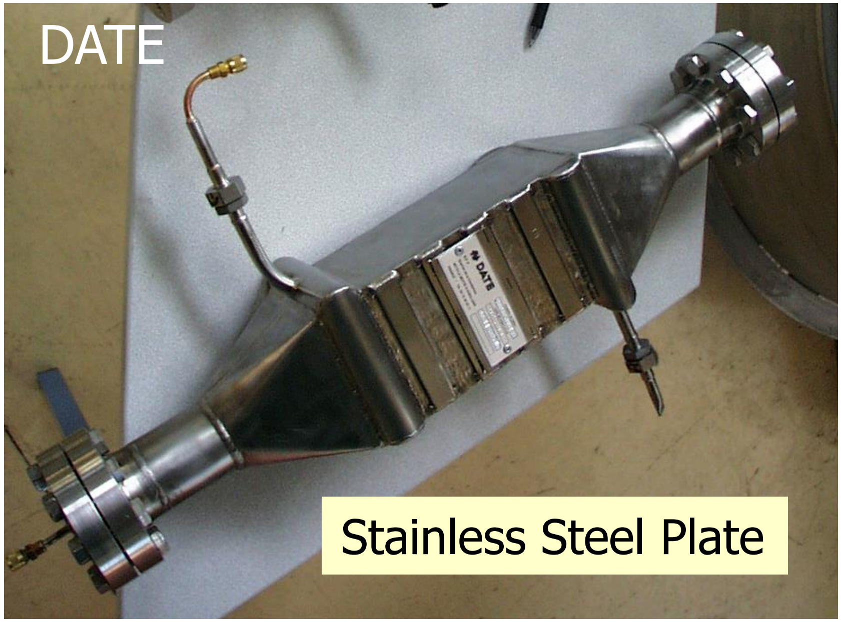
SNLS

Perforated
Copper Plates
with SS Spacers



SS Coiled Tubes

Romabau

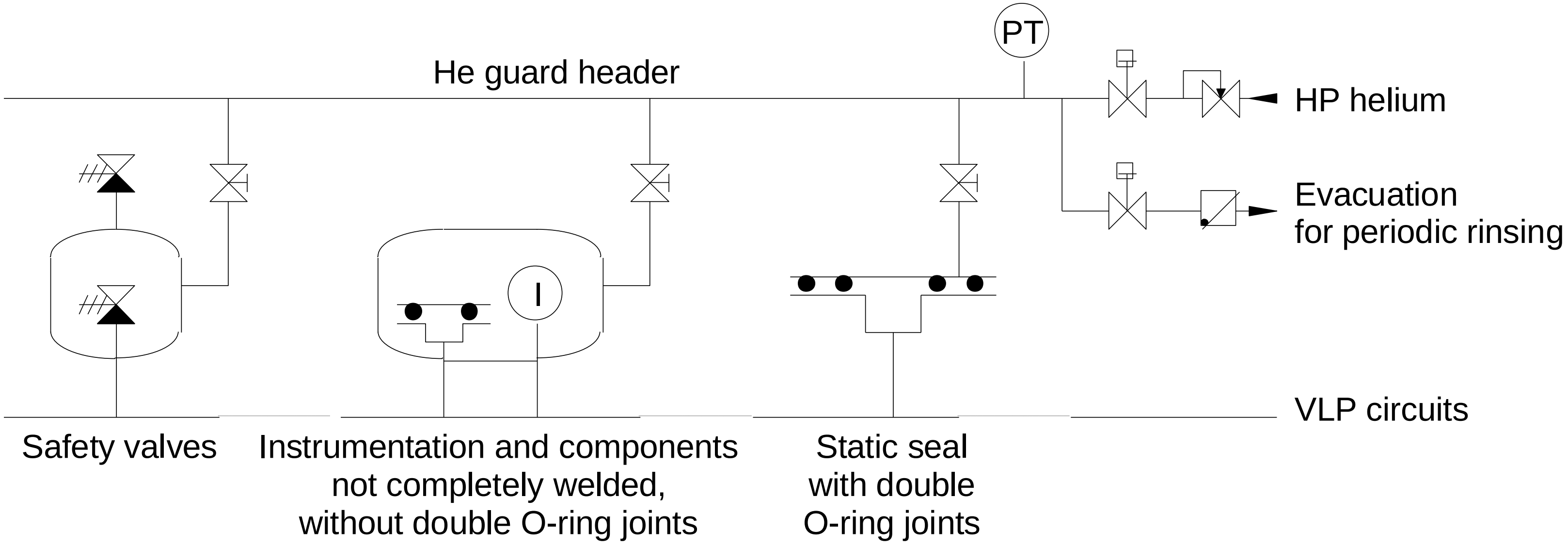


DATE

Stainless Steel Plate

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



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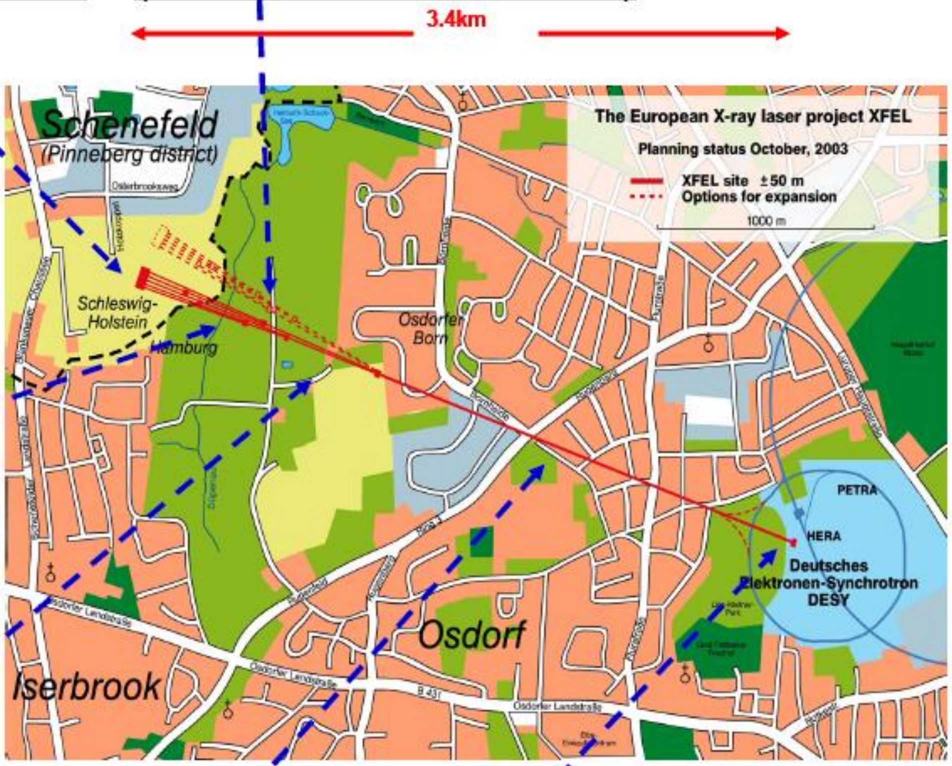
High-field magnets for high-frequency NMR

900 MHz ⇔ 21.2 T

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

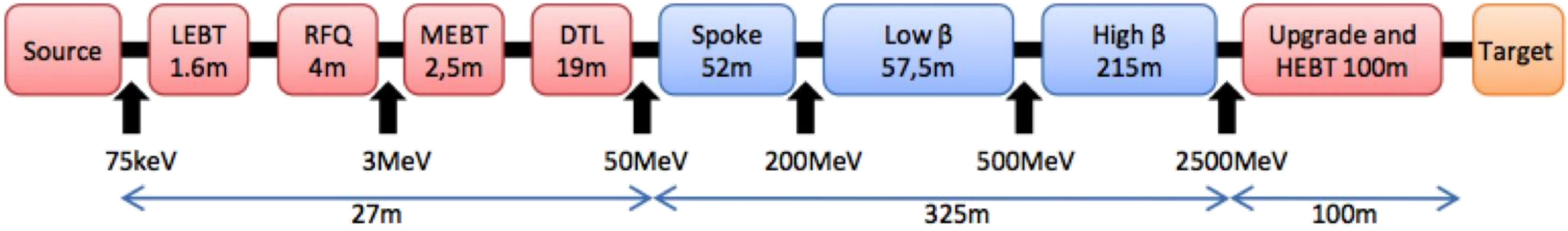
928 superconducting RF cavities operated at 2 K

Refrigeration 2.5 kW @ 2 K

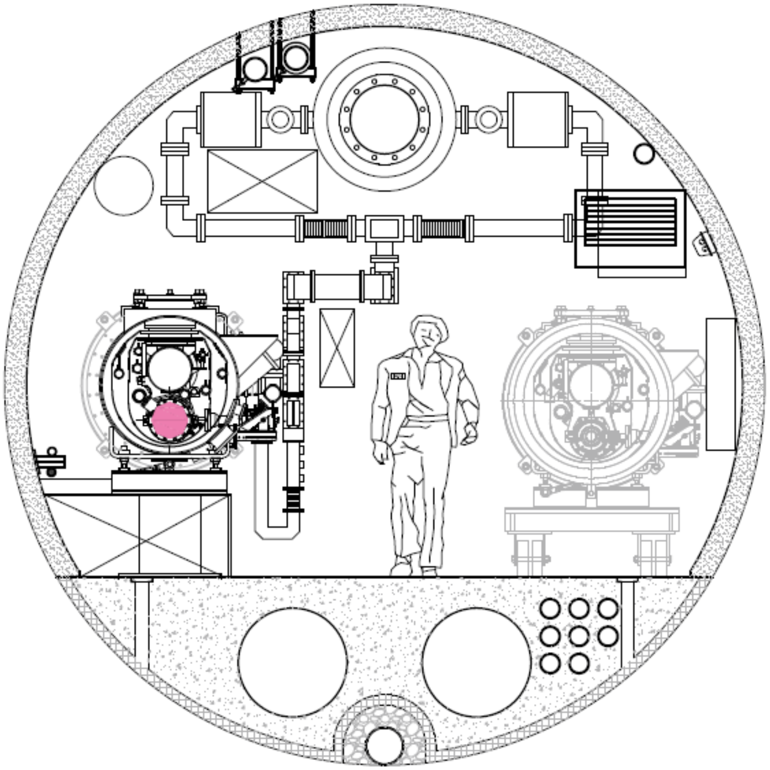
European Spallation Source, Lund (Sweden)

EUROPEAN
SPALLATION
SOURCE

5 MW long pulse source
- ≤2 ms pulses
- ≤20 Hz
- Protons (H+)
- Low losses
- High reliability, >95%
- 2.5 GeV



International Linear Collider (ILC)

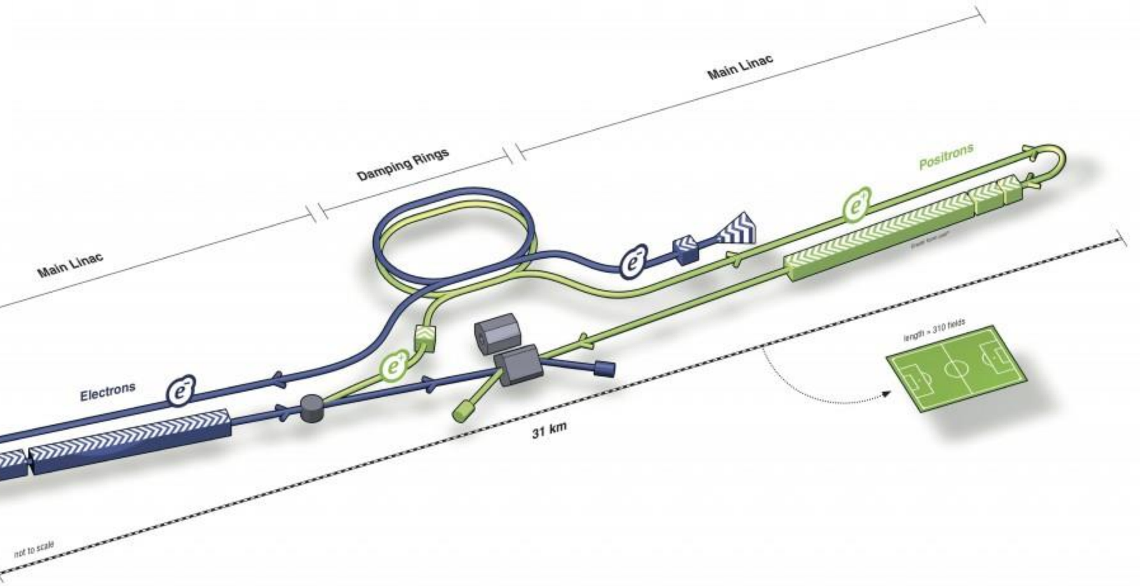


e+ e- linear collider

Collision energy 500 GeV c.m. initially, later upgrade to ~1 TeV c.m.

Overall length 31 km

Key technology: SC RF cavities



Global Design Effort

No central laboratory

World-wide collaboration

Site-specific studies conducted on sample sites

Conclusion

- 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