Cryogenics for superconducting devices

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Contents

- **κρυος, ους** (το) **1** deep cold [Arist. *Meteor.*]
  2 shiver of fear [Aeschyl. *Eumenid.*]

- **cryogenics,** that branch of physics which deals with the production of very low temperatures and their effects on matter

  Oxford English Dictionary

  2nd edition, Oxford University Press (1989)

- **cryogenics**, the science and technology of temperatures below 120 K

  New International Dictionary of Refrigeration

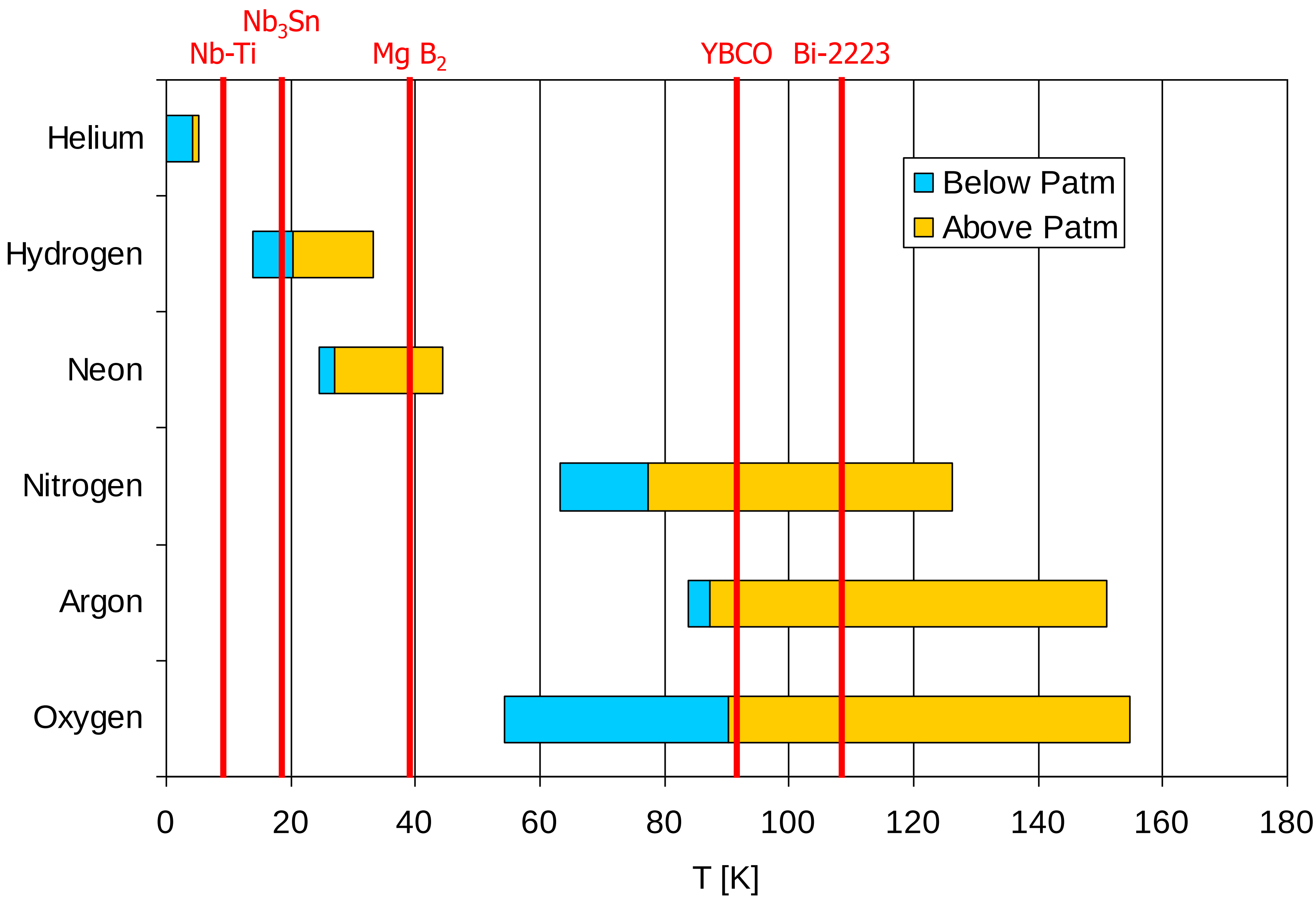
  4th edition, IIF-IIR Paris (2015)

Characteristic temperatures of cryogens

Cryogen	Triple point [K]	Normal boiling point [K]	Critical point [K]
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (*)	4.2	5.2

(*): λ Point

Useful range of liquid cryogens & critical temperature of superconductors



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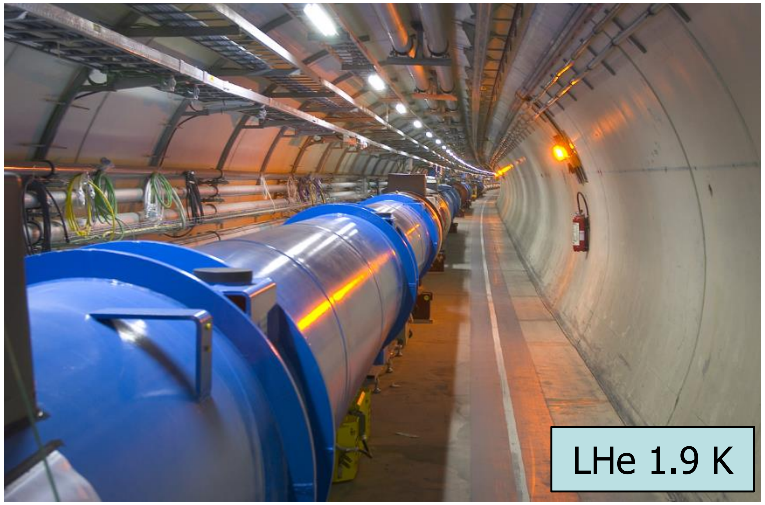
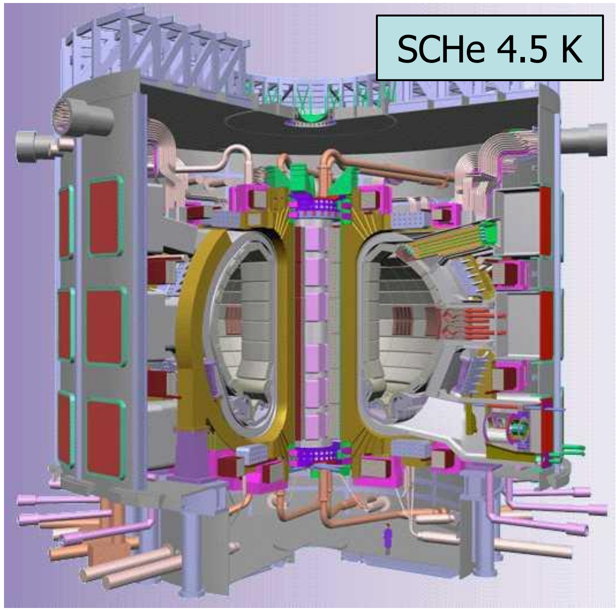
Cooling of superconducting devices





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- Cryogenic fluids
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- Thermal screening with cold vapour
- Refrigeration & liquefaction
- Thermometry

Properties of cryogens compared to water

Property		He	N_2	H_2O
Normal boiling point	[K]	4.2	77	373
Critical temperature	[K]	5.2	126	647
Critical pressure	[bar]	2.3	34	221
Liq./Vap. density (*)		7.4	175	1600
Heat of vaporization (*)	[$J.g^{-1}$]	20.4	199	2260
Liquid viscosity (*)	[μPl]	3.3	152	278

(*) at normal boiling point

Vaporization of normal boiling cryogens under 1 W applied heat load

Let h be the enthalpy of the fluid

At constant pressure $\dot{Q} = L_v \dot{m}$ with $L_v = h_{vap} - h_{liq}$

Cryogen	[mg.s^{-1}]	[l.h^{-1}] (liquid)	[l.min^{-1}] (gas NTP)
Helium	48	1.38	16.4
Nitrogen	5	0.02	0.24

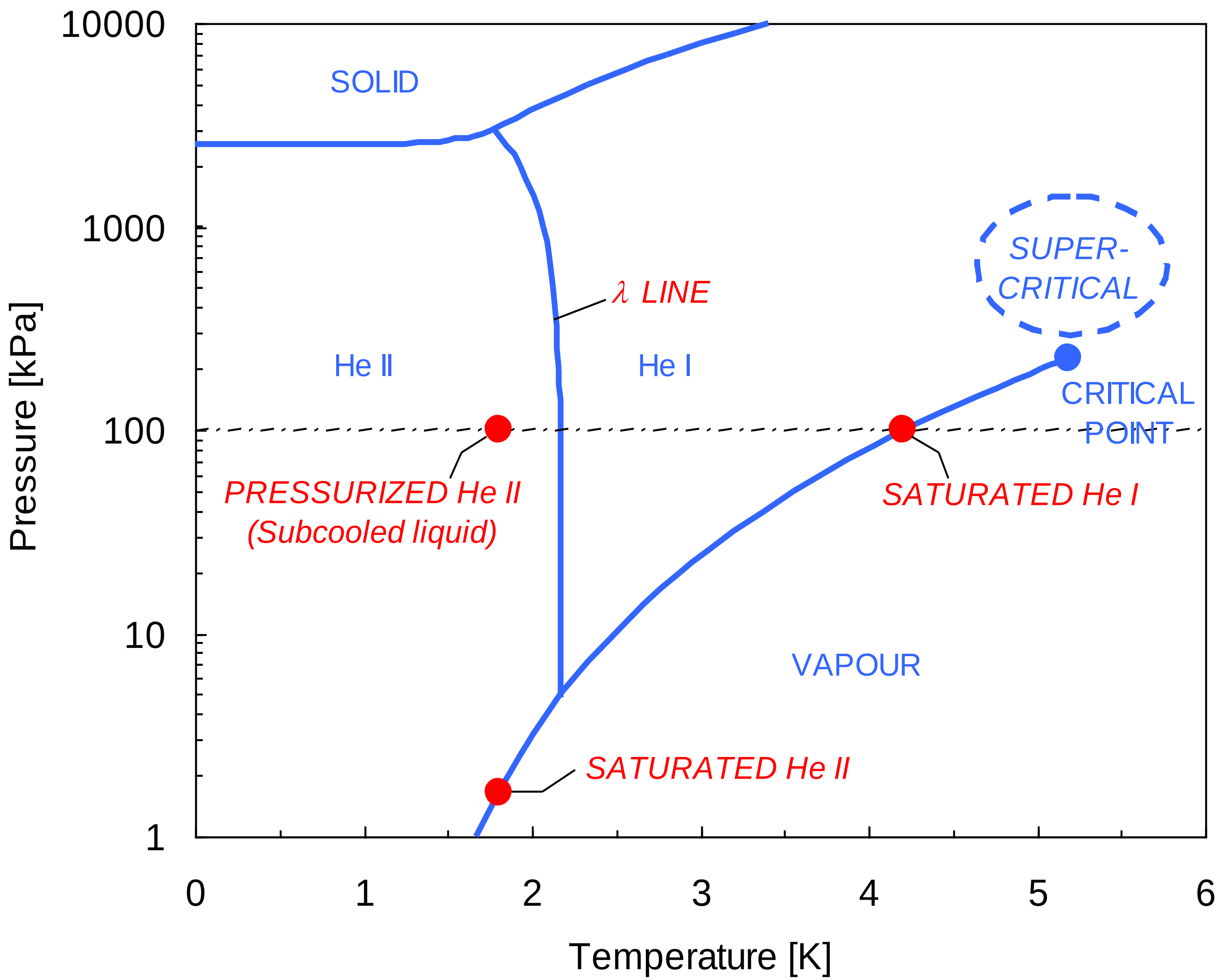
Amount of cryogens required to cool down 1 kg iron

Assuming perfect heat exchange between iron and the fluid

$$\int_{T_{final}}^{T_{initial}} M_{Fe} C_{Fe} dT = m\left[L_v + \left(h_{vap}^{final} - h_{vap}^{sat}\right)\right] \approx m\left[L_v + C_p\left(T_{final} - T_{sat}\right)\right]$$

Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 litre	0.75 litre
LHe from 77 to 4.2 K	1.46 litre	0.12 litre
LN2 from 290 to 77 K	0.45 litre	0.29 litre

Phase diagram of helium



Helium as a cooling fluid

Phase domain	Advantages	Drawbacks
Saturated He I	Fixed temperature High heat transfer	Two-phase flow Boiling crisis
Supercritical	Monophase Negative J-T effect	Non-isothermal Density wave instability
He II	Low temperature High conductivity Low viscosity	Second-law cost Subatmospheric

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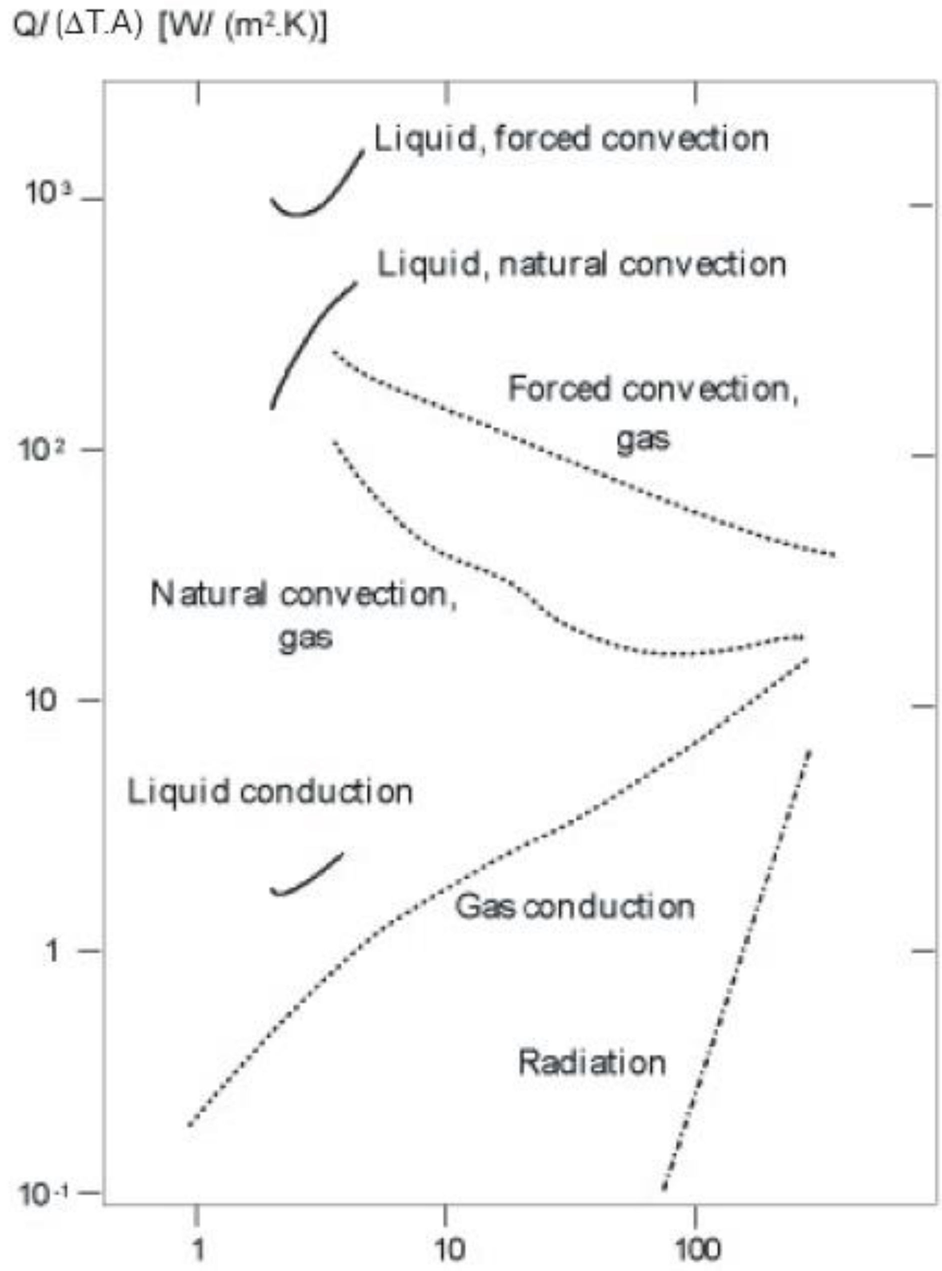
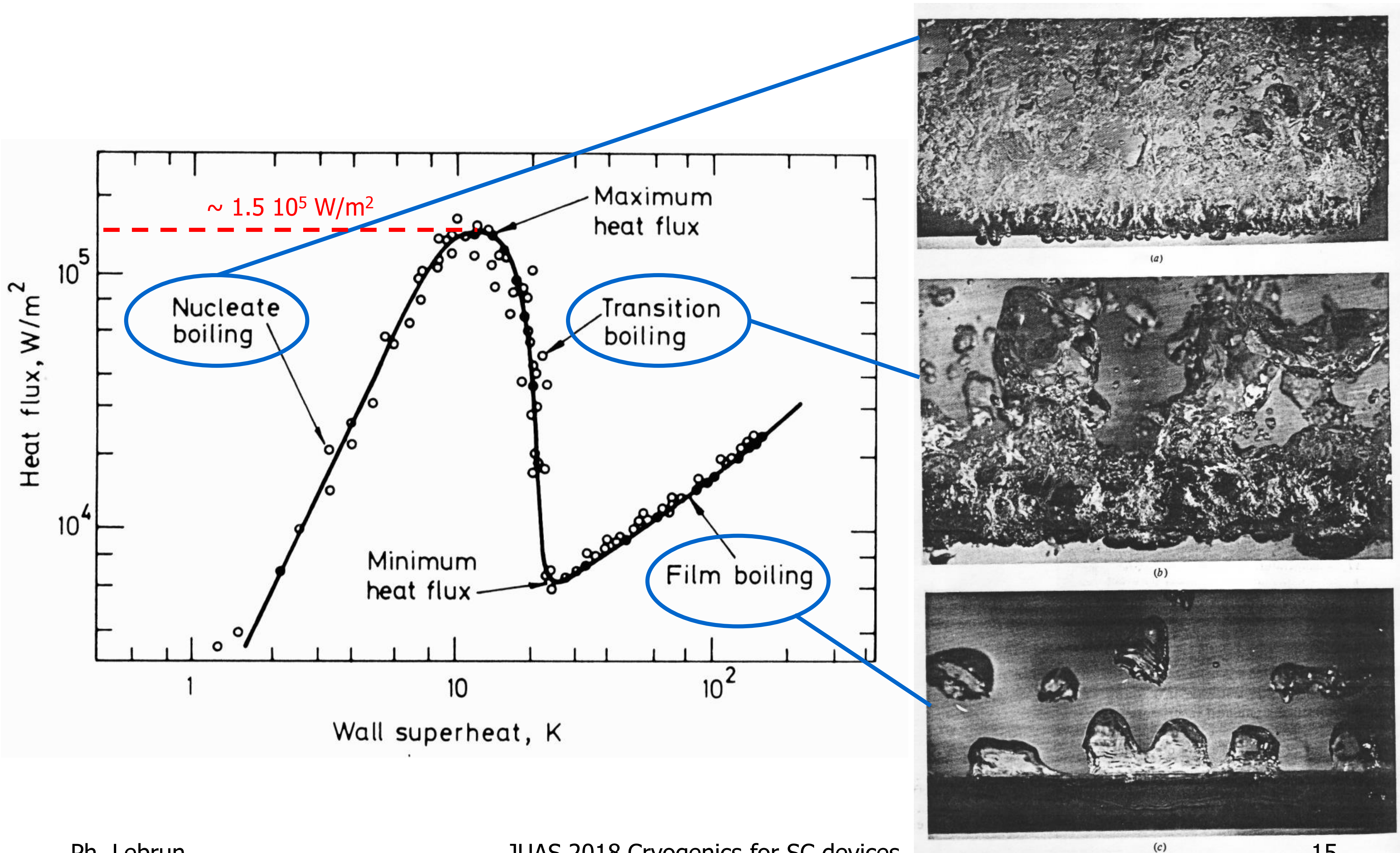
Typical heat transfer coefficients at cryogenic temperatures

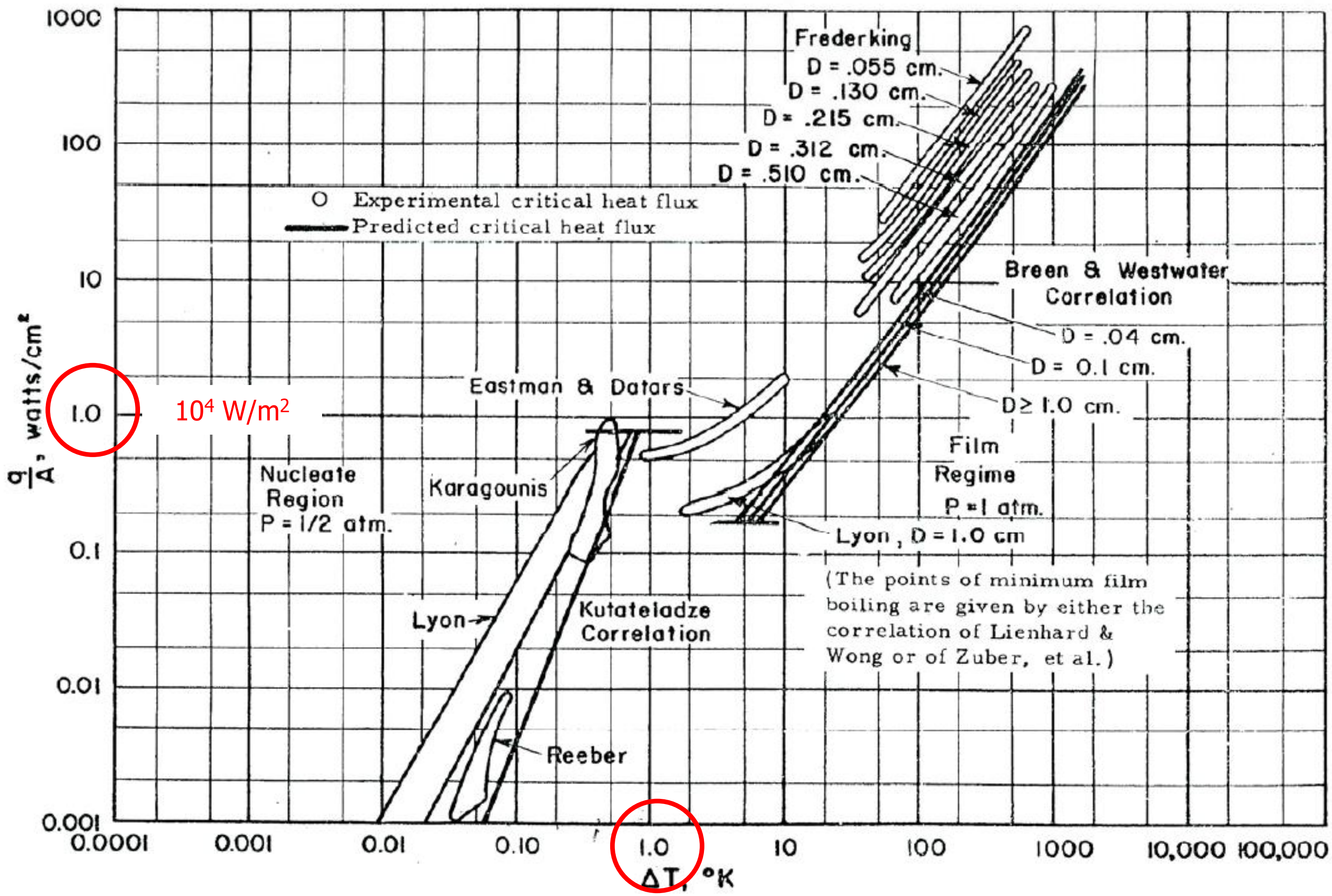
- Same basic processes as at temperatures above ambiant, but large variations in
  - absolute values
  - dependence on temperature
- These variations can be exploited for
  - cooling equipment
  - thermal insulation of cryostats
- Particular importance of two-phase heat transfer



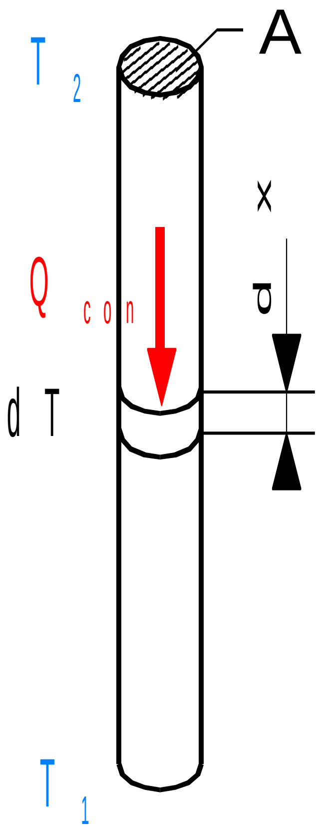
Non-linear heat transfer to liquid cryogens
Pool boiling nitrogen



Non-linear heat transfer to liquid cryogens
Pool boiling helium



Heat conduction in solids

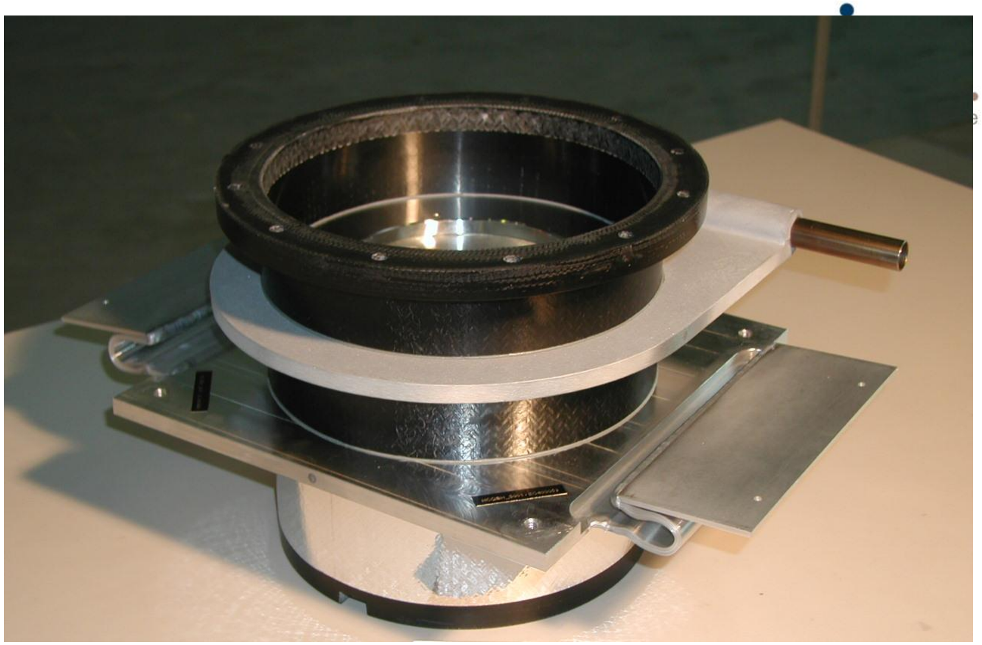


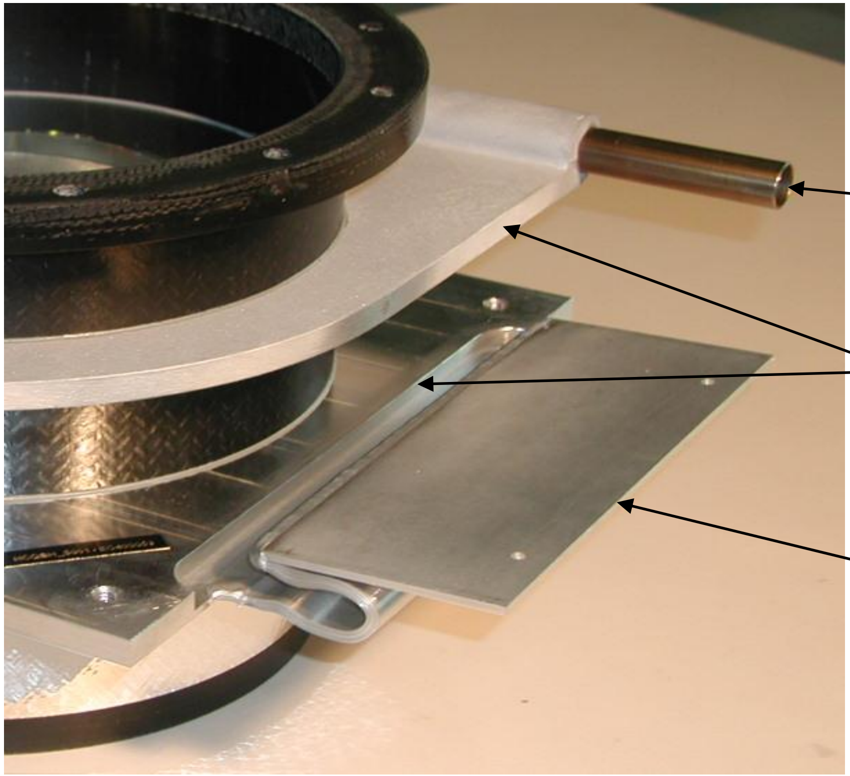
- Fourier's law $\dot{Q}_{cond} = k(T)A\frac{dT}{dx}$
- Thermal conductivity $k(T)$ [W/m.K]
- Integral form $\dot{Q}_{cond} = \frac{A}{L}\int_{T_1}^{T_2} k(T)dT$
- Thermal conductivity integral $\int_{T_1}^{T_2} k(T)dT$ [W/m]
- Thermal conductivity integrals for standard construction materials are tabulated

Thermal conductivity integrals of selected materials [W/m]

From vanishingly low temperature up to	20 K	80 K	290 K
OFHC copper	11000	60600	152000
DHP copper	395	5890	46100
1100 aluminium	2740	23300	72100
2024 aluminium alloy	160	2420	22900
AISI 304 stainless steel	16.3	349	3060
G-10 glass-epoxy composite	2	18	153

Non-metallic composite support post with heat intercepts



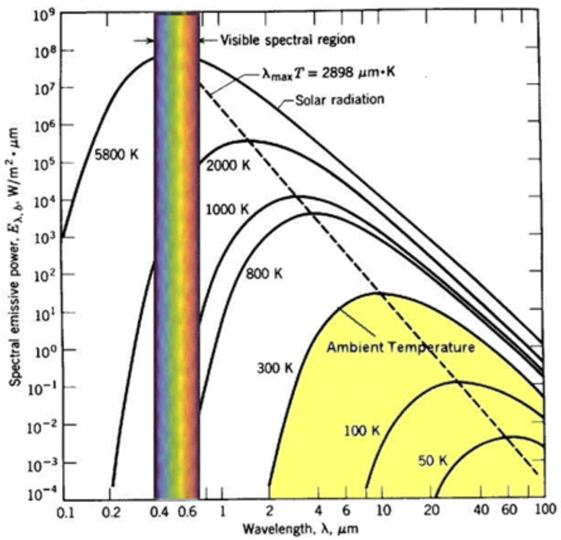


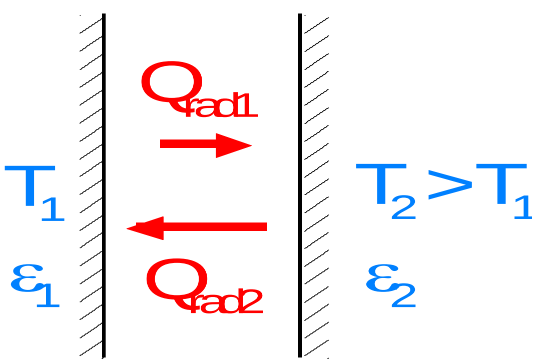
5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

Aluminium strips to thermal shield at 50-75 K

Thermal radiation





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

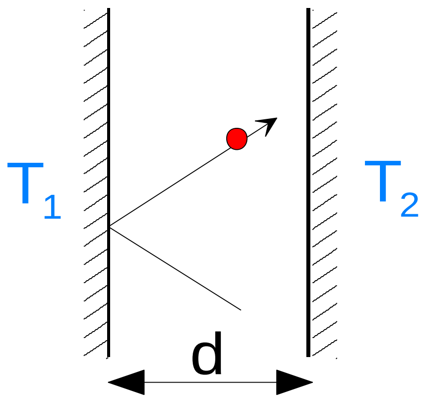
$$\lambda_{max}\, T = 2898\ [\mu m.K]$$

- Stefan-Boltzmann's law
  - Black body $\dot{Q}_{rad} = \sigma\, A\, T^4$
    with $\sigma = 5.67\ 10^{-12}\ W/m^2K^4$
  - «Gray» body $\dot{Q}_{rad} = \varepsilon\, \sigma\, A\, T^4$
    with ε surface emissivity
  - Between «gray» surfaces at temperatures T_1 and T_2
    $\dot{Q}_{rad} = E\, \sigma\, A\, (T_2^4 - T_1^4)$
    with E function of $\varepsilon_1, \varepsilon_2$ and geometry of facing surfaces

Emissivity of technical materials at low temperatures

	Radiation from 290 K Surface at 77 K	Radiation from 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

Residual gas conduction



- Two different regimes, depending upon the relative values of heat transfer distance d and mean free path of gas molecules $\lambda_{molecule}$
- Viscous regime
  - At higher pressure $\lambda_{molecule} \ll d$
  - Classical conduction $\dot{Q}_{residual} = A\, k(T) \frac{dT}{dx}$
  - Thermal conductivity $k(T)$ independant of pressure
- Molecular regime
  - At lower pressure $\lambda_{molecule} \gg d$
  - Kennard's law $\dot{Q}_{residual} = A\, \alpha(T)\, \Omega\, P\, (T_2 - T_1)$
  - Heat transfer proportional to pressure, independant of spacing between surfaces
  - Ω depends on gas species
  - Accommodation coefficient $\alpha(T)$ depends on gas species, T_1, T_2 and geometry of facing surfaces

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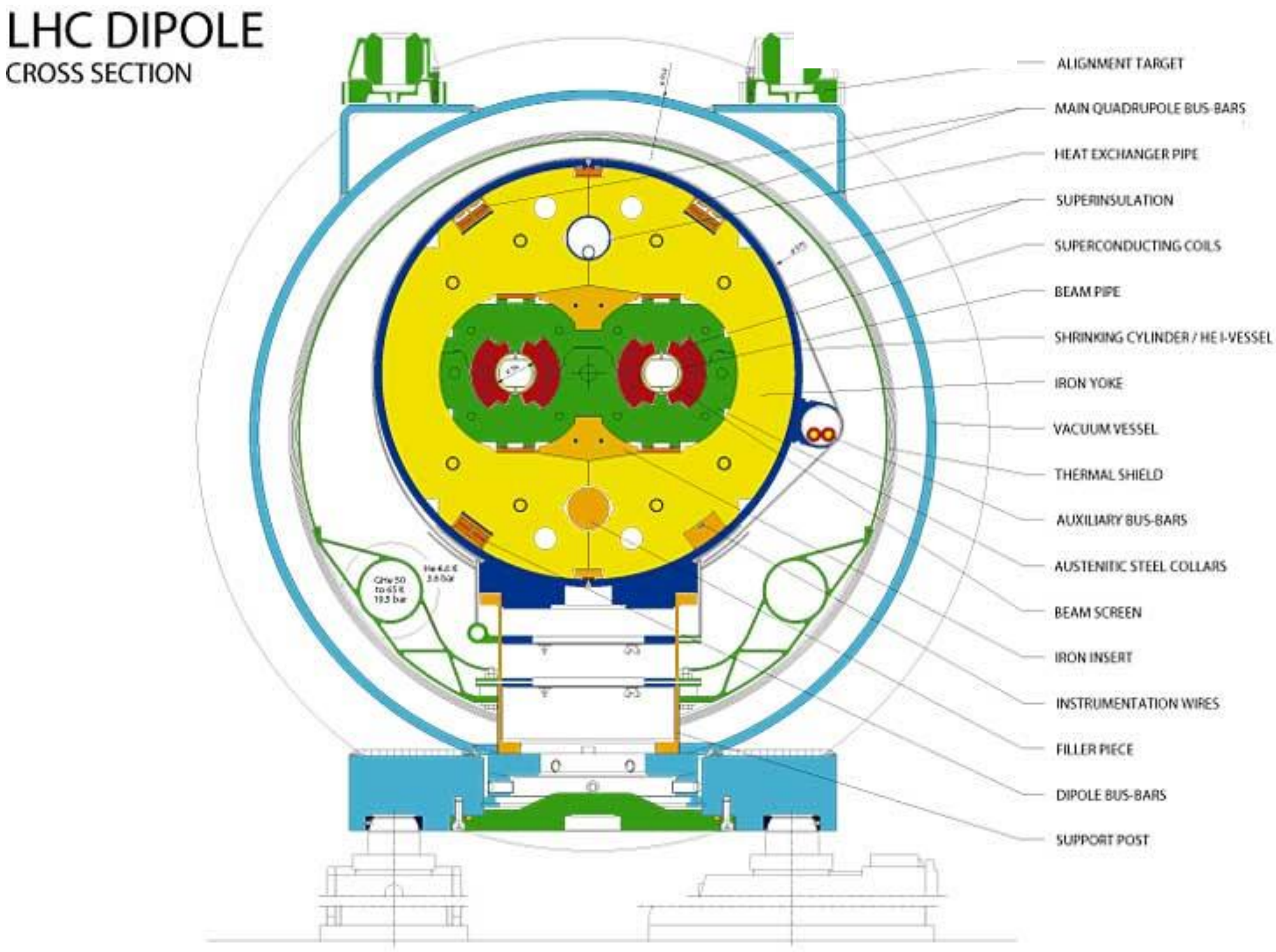
Multi-layer insulation (MLI)

- Complex system involving three heat transfer processes
  - $\dot{Q}_{MLI} = \dot{Q}_{rad} + \dot{Q}_{contact} + \dot{Q}_{residual}$
  - With n reflective layers of equal emissivity, $\dot{Q}_{rad} \sim 1/(n+1)$
  - Due to parasitic contacts between layers, $\dot{Q}_{contact}$ increases with layer density
  - $\dot{Q}_{residual}$ due to residual gas trapped between layers, scales as $1/n$ in molecular regime
  - Non-linear behaviour requires layer-to-layer modeling
- In practice
  - Typical data available from (abundant) literature
  - Measure performance on test samples

Typical heat fluxes at vanishingly low temperature between flat plates [W/m^2]

Black-body radiation from 290 K	401
Black-body radiation from 80 K	2.3
Gas conduction (100 mPa He) from 290 K	19
Gas conduction (1 mPa He) from 290 K	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

Cross-section of LHC dipole cryostat

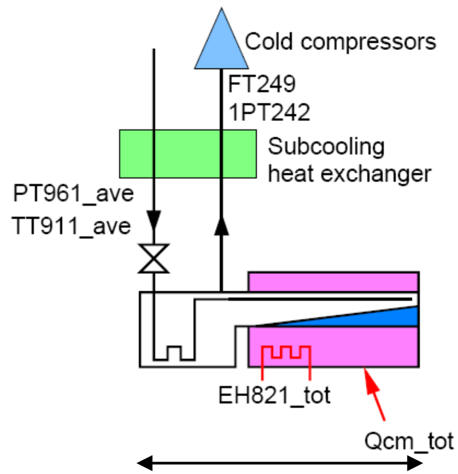


LHC cryostat heat inleaks at 1.9 K

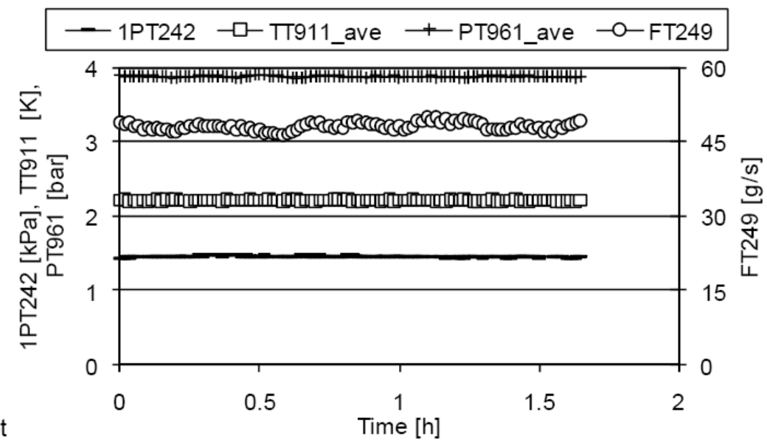
Measured

$$\dot{Q} = \dot{m}\,\Delta h(P,T)$$

He property tables

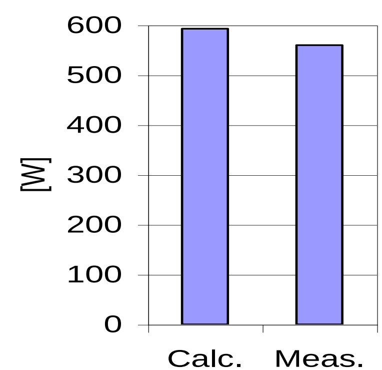


LHC sector (2.8 km)



On full LHC cold sector (2.8 km)

- Measured 560 W, i.e. 0.2 W/m
- Calculated 590 W, i.e 0.21 W/m



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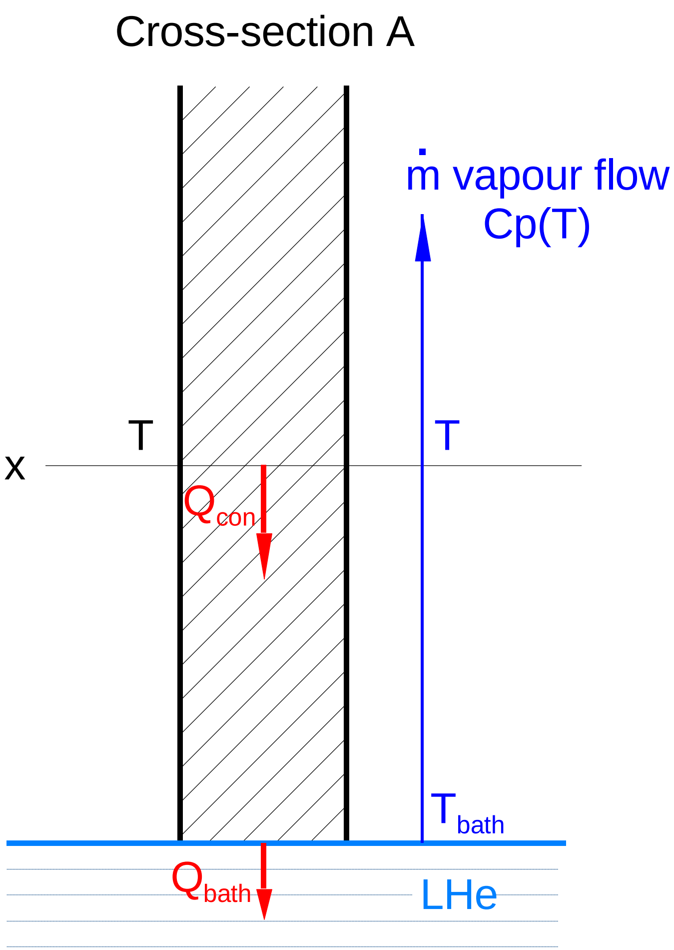
Vapour cooling of cryostat necks and supports with perfect heat transfer



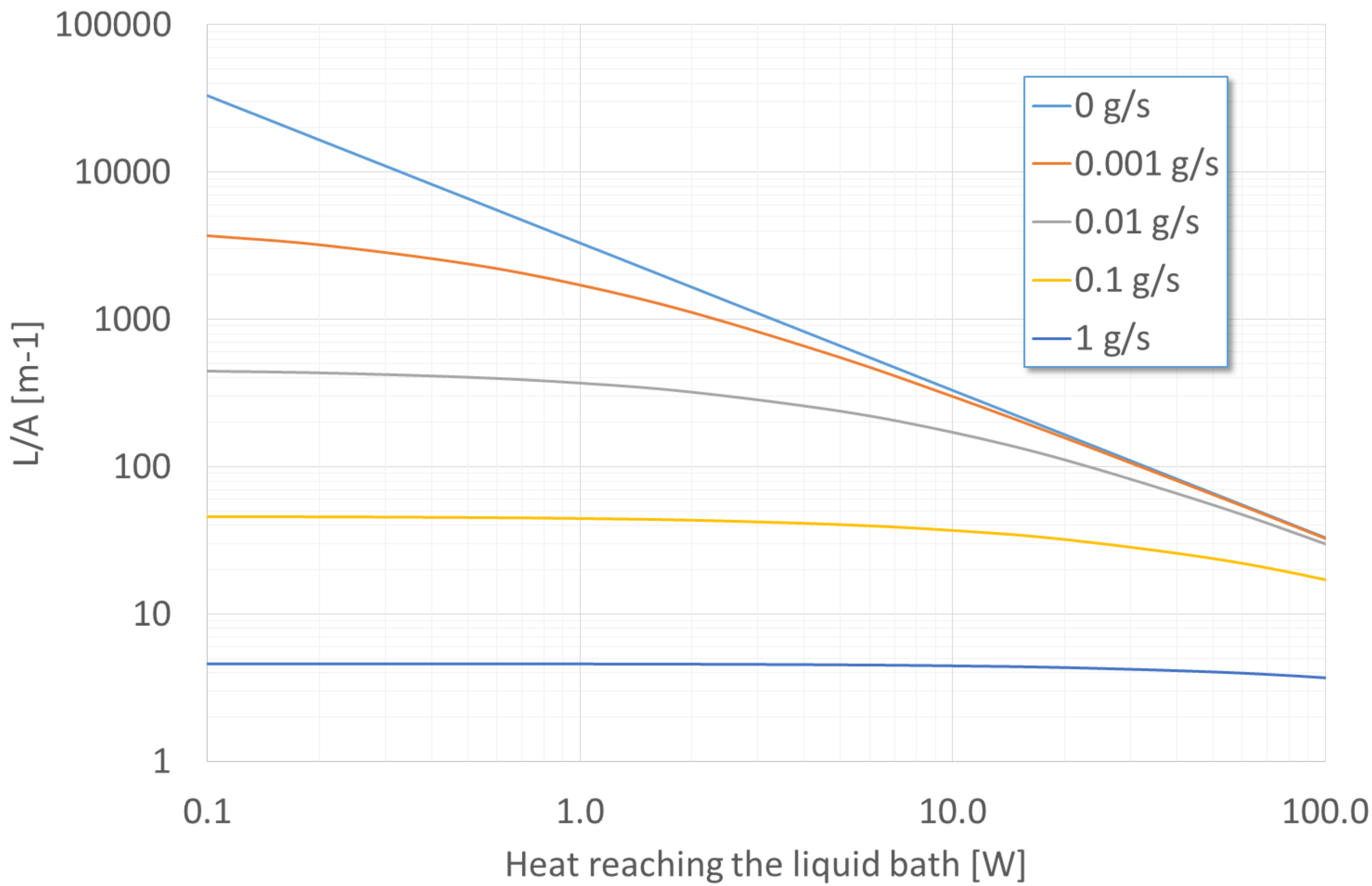
- Assuming perfect heat transfer between solid and vapour, i.e. $T_{solid}(x) = T_{vapor}(x) = T(x)$

$$\dot{Q}_{cond} = \dot{Q}_{bath} + \dot{m}C_p(T)(T - T_{bath})$$

$$A\,k(T)\frac{dT}{dx} = \dot{Q}_{bath} + \dot{m}C_p(T)(T - T_{bath})$$

- $C_p(T)$ specific heat of vapour
- $k(T)$ thermal conductivity of support
- $\dot{Q}_{bath}$ can be calculated by numerical integration for
  - different cryogens
  - different values of aspect ratio L/A
  - different values of vapour flow

He vapour screening of stainless steel neck between 300 K and 4 K



Vapour cooling of cryostat necks and supports in self-sustained mode

- A particular case of gas cooling is the self-sustained mode, i.e. the vapour flow is generated only by the residual heat $\dot{Q}_{bath}$ reaching the bath
- Then $\dot{Q}_{bath} = L_v \dot{m}$
  with L_v latent heat of vaporization
- Given the general equation $A\,k(T)\frac{dT}{dx} = \dot{Q}_{bath} + \dot{m}C_p(T)(T - T_{bath})$
- The variables can be separated and integration yields

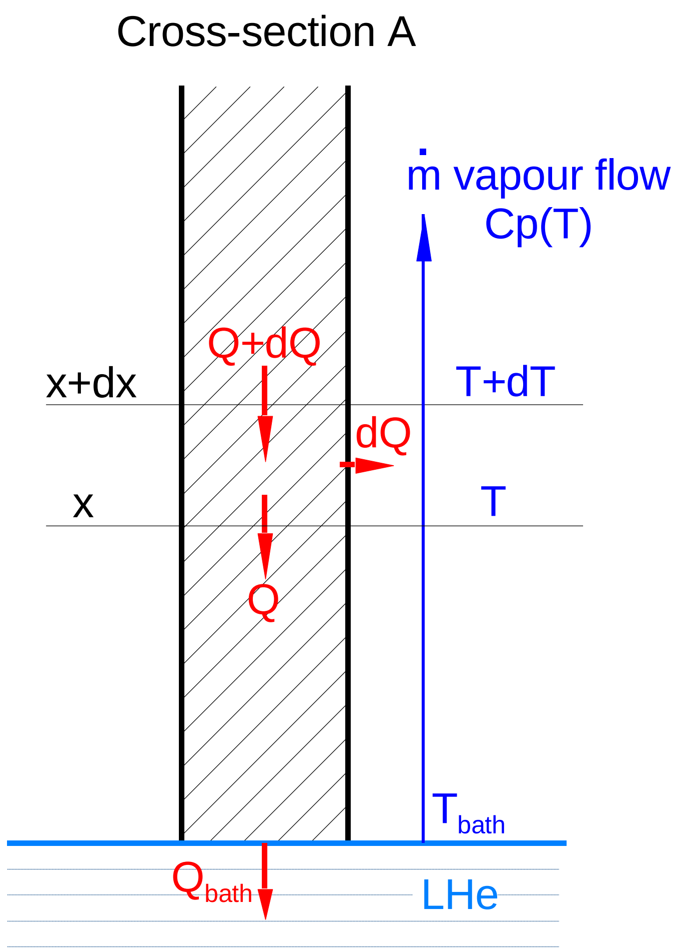
$$\dot{Q}_{bath} = \frac{A}{L}\int_{T_{bath}}^{T} \frac{k(T)}{1+\frac{C_p(T)}{L_v}(T-T_{bath})} dT$$

- The denominator of the integrand $1 + \frac{C_p(T)}{L_v}(T - T_{bath})$ acts as an attenuation factor of the thermal conductivity $k(T)$

Reduction of heat conduction by self-sustained helium vapour cooling

Effective thermal conductivity integral from 4 to 300 K	Purely conductive regime [W.cm^{-1}]	Self-sustained vapour-cooling [W.cm^{-1}]
ETP copper	1620	128
OFHC copper	1520	110
Aluminium 1100	728	39.9
Nickel 99% pure	213	8.65
Constantan	51.6	1.94
AISI 300 stainless steel	30.6	0.92

Vapour cooling of cryostat necks and supports with imperfect heat transfer



- Introducing efficiency of heat transfer f between solid and vapour $(0 \leq f \leq 1)$

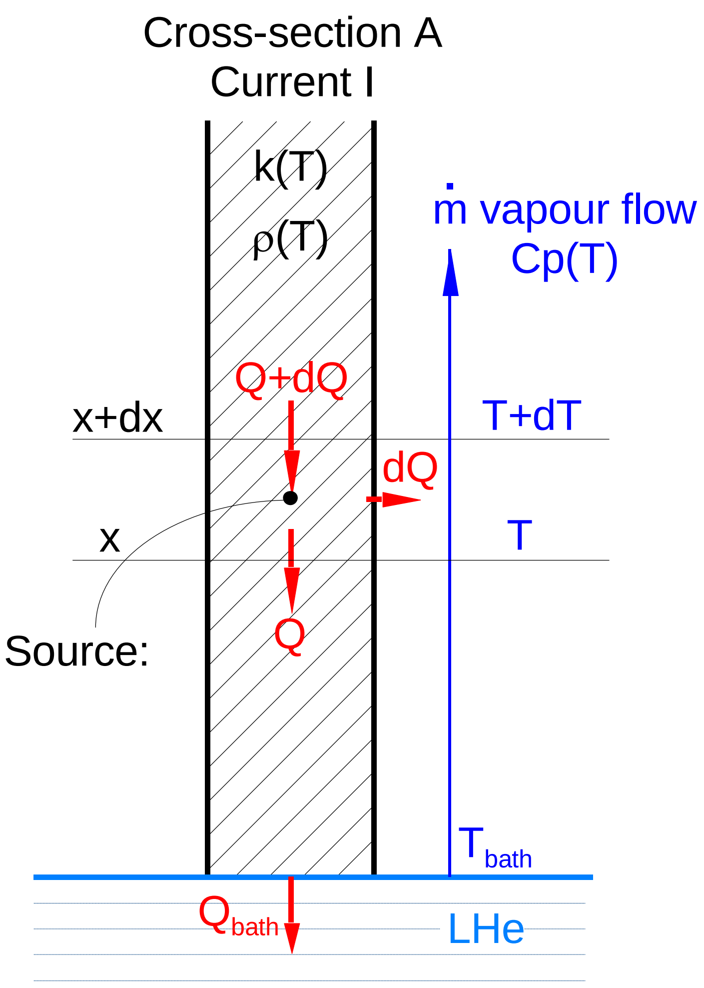
$$dQ = f\,\dot{m}\,C_p(T)\,dT$$

- The steady-state heat balance equation becomes

$$\frac{d}{dx}\left[A\,k(T)\,\frac{dT}{dx}\right] = f\,\dot{m}\,C_p(T)\,\frac{dT}{dx}$$

- This non-linear equation needs to be solved by numerical integration

Vapor-cooled current leads



- The (imperfect) heat transfer between solid and vapour can be written

$$dQ = f\,\dot{m}\,C_p(T)\,dT$$

- Introducing electrical resisitivity $\rho(T)$, the steady-state heat balance equation reads

$$\frac{d}{dx}\left[A\,k(T)\,\frac{dT}{dx}\right] - f\,\dot{m}\,C_p(T)\,\frac{dT}{dx} + \frac{\rho(T)\,I^2}{A} = 0$$

- Assuming the material follows the Wiedemann-Franz-Lorenz (WFL) law

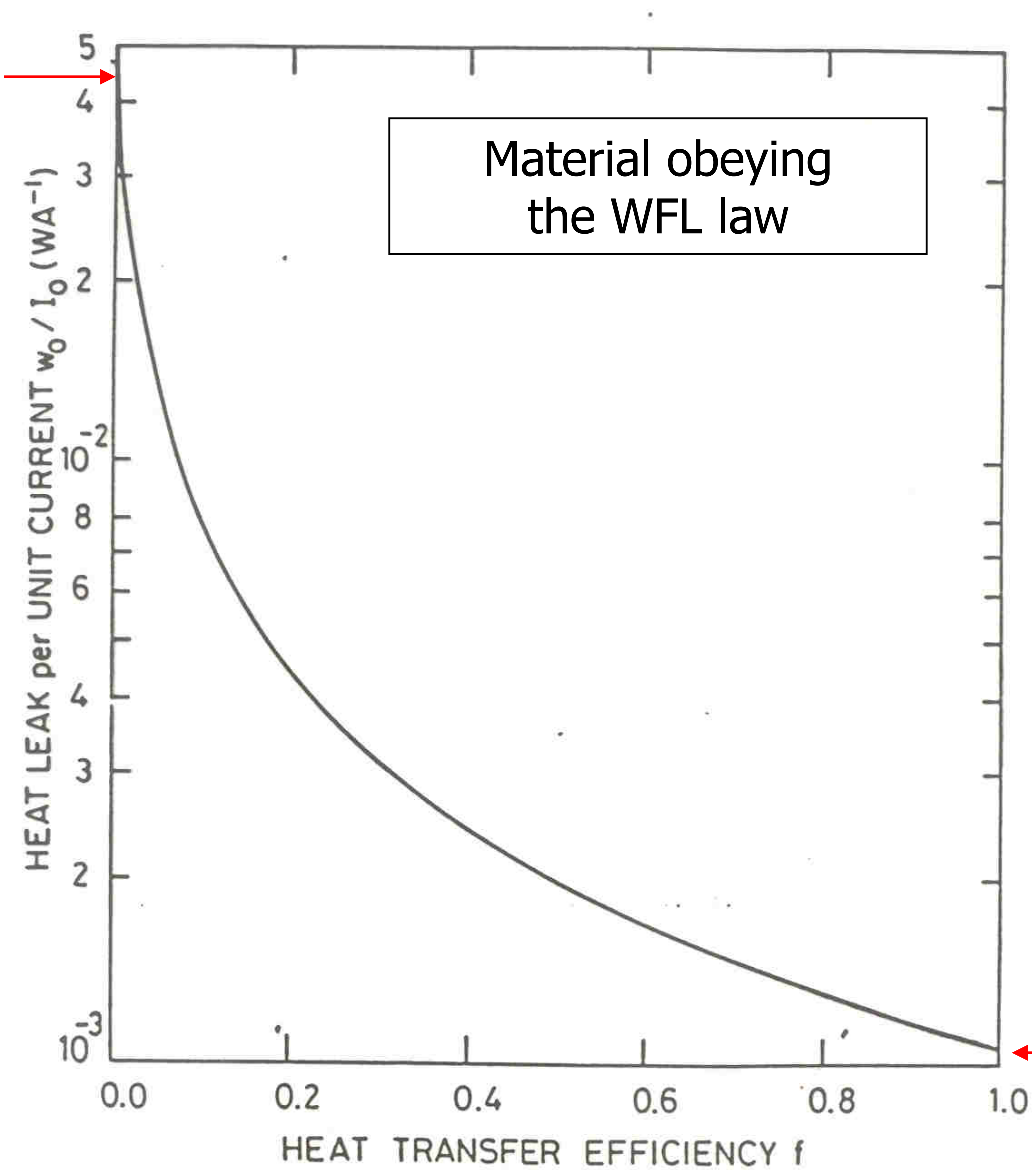
$$k(T)\,\rho(T) = \mathcal{L}_0\,T$$

with $\mathcal{L}_0 = 2.45\;10^{-8}\;\mathrm{W.\Omega.K^{-2}}$

The aspect ratio L/A can be chosen for minimum heat inleak $\dot{Q}_{bath}$, and the minimum heat inleak does not depend on the material

Heat load of optimized current lead

Uncooled
47 W/kA

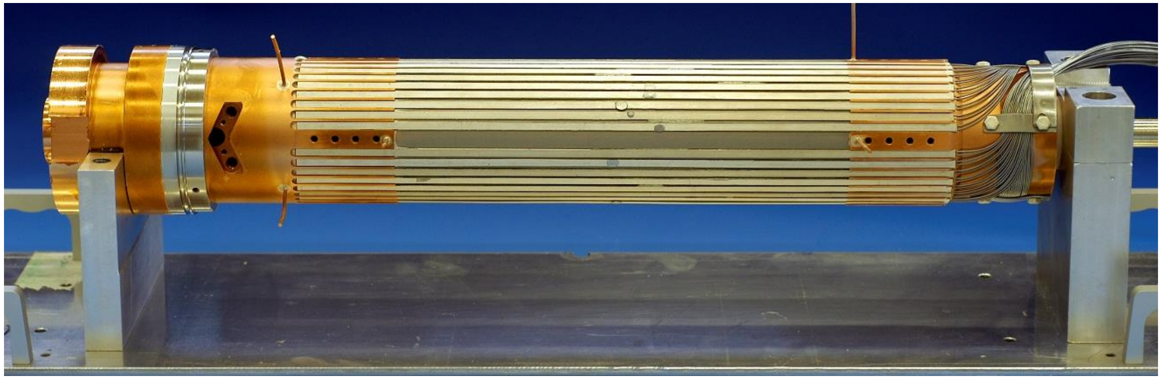


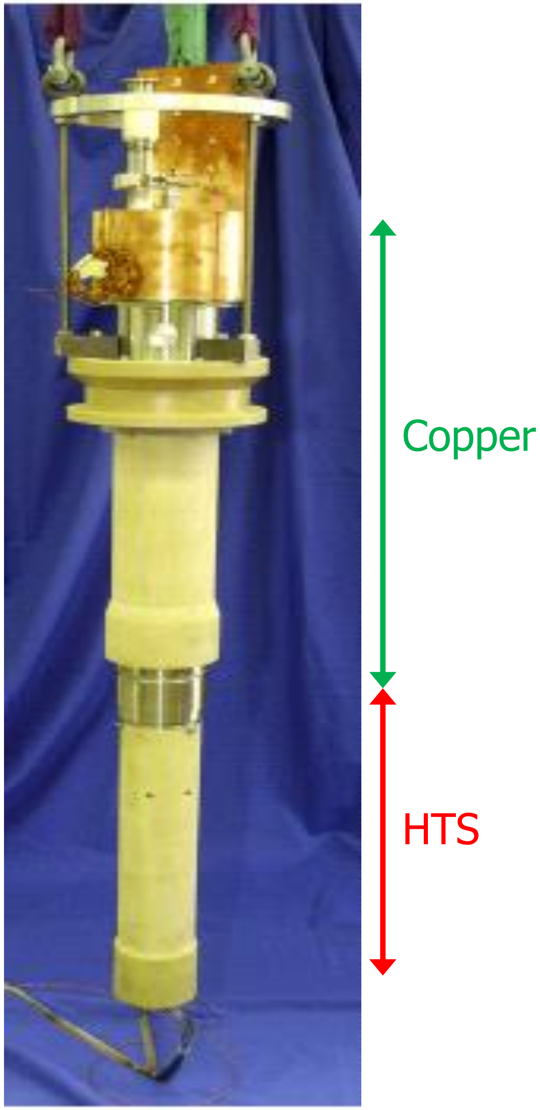
Minimum residual
heat load
1.04 W/kA

Beating the WFL law: HTS current leads

- The WFL law essentially states that good electrical conductors are also good thermal conductors
- Efficient current leads need good electrical conductors with low thermal conductivity
- Superconductors are bad thermal conductors with zero resisitivity

⇒ Build current lead with superconductor up to temperature as high as possible, i.e. use HTS





HTS vs. normal conducting current leads

Type		Resistive	HTS (4 to 50 K) Resistive (above)
Heat into LHe	[W/kA]	1.1	0.1
Total exergy consumption	[W/kA]	430	150
Electrical power from grid	[W/kA]	1430	500

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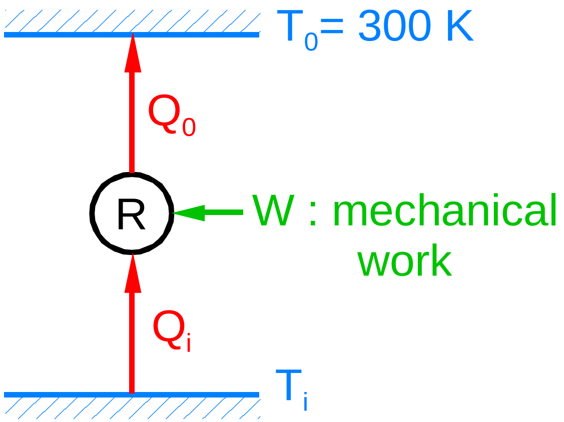
Basic thermodynamics of refrigeration



- First principle (Joule) $$Q_0 = Q_i + W$$
- Second principle (Clausius) $$\frac{Q_0}{T_0} \geq \frac{Q_i}{T_i}$$
  (= for reversible process)
- Hence $$W \geq T_0 \frac{Q_i}{T_i} - Q_i$$

- This equation can be written in three different ways
  - $W \geq T_0 \, \Delta S_i - Q_i$ introducing entropy S defined by $\Delta S_i = \frac{Q_i}{T_i}$
  - $W \geq Q_i \left(\frac{T_0}{T_i} - 1\right)$ where $\left(\frac{T_0}{T_i} - 1\right)$ is called the Carnot factor
  - $W \geq \Delta E_i$ introducing exergy E defined by $\Delta E_i = Q_i \left(\frac{T_0}{T_i} - 1\right)$

Minimum refrigeration work

- Consider the extraction of 1 W at liquid helium temperature 4.5 K, rejected at room temperature 300 K

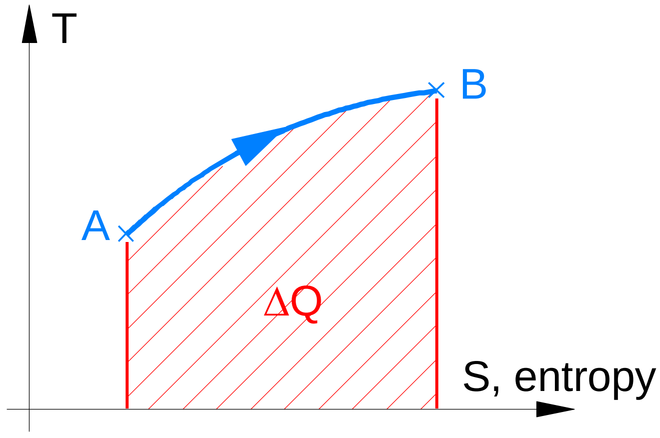
- The minimum refrigeration work is

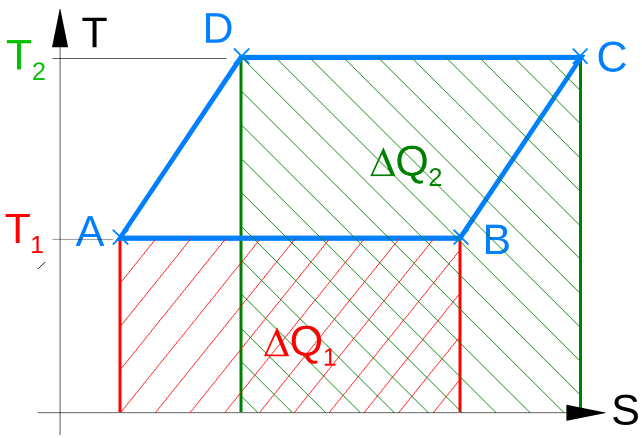
$$W_{min} = Q_i \left(\frac{T_0}{T_i} - 1\right) = 1\left(\frac{300}{4.5} - 1\right) \cong 65.7 \text{ W/W}$$

- In practice, the most efficient helium refrigerators have an efficiency η of about 30% with respect to the Carnot limit

$$W_{real} = \frac{W_{min}}{\eta} = \frac{65.7}{0.3} \cong 220 \text{ W/W}$$

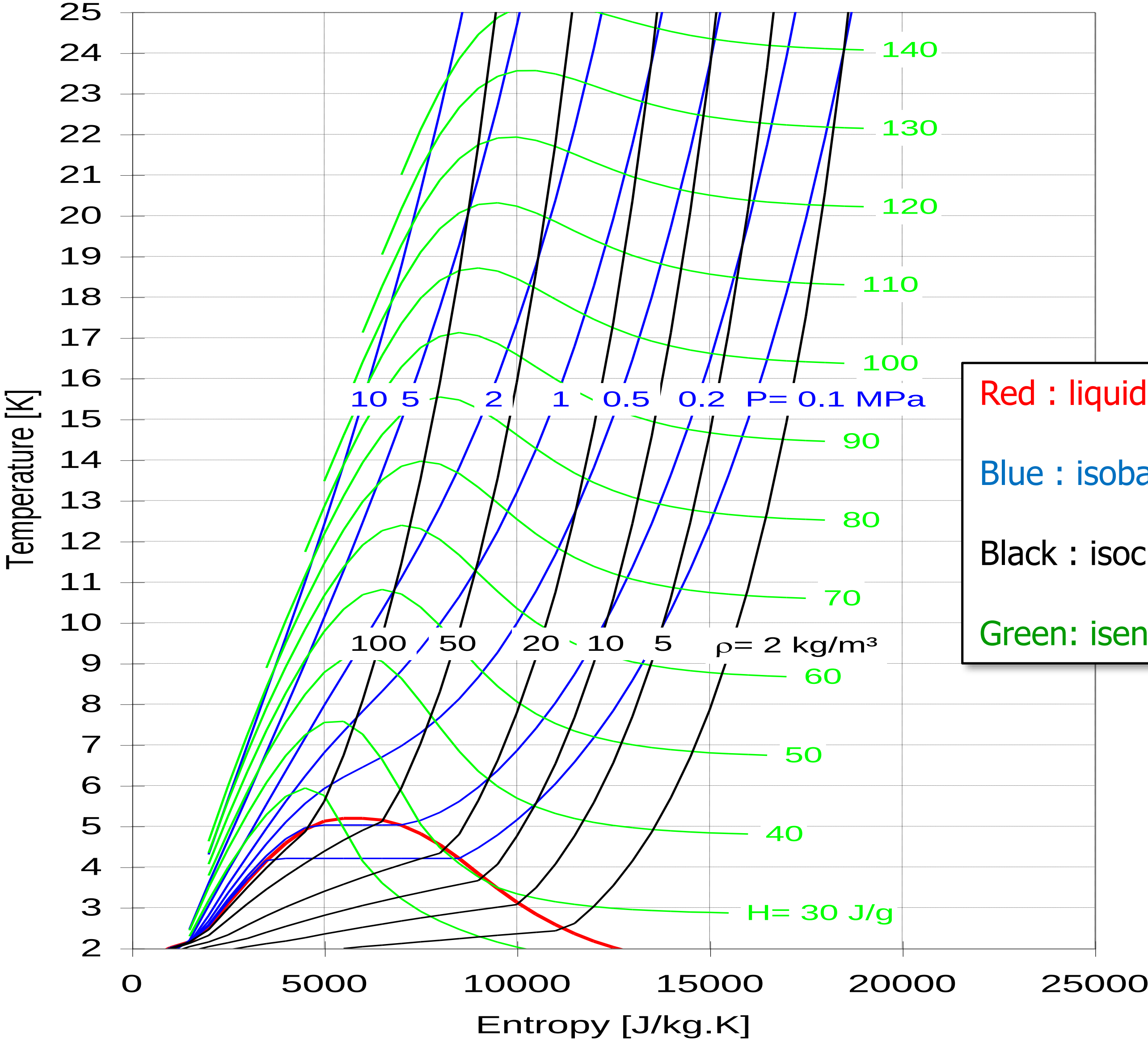
Refrigeration cycles





- Introducing the temperature-entropy diagram
  - Consider the thermodynamic transform from A to B, involving heat transfer ΔQ
  - If it is reversible $\Delta Q = \int_A^B T\, dS$
  - ΔQ is proportional to the area under the curve in the temperature-entropy diagram
- To make a refrigeration cycle, one needs a substance, the entropy of which depends on some other physical variable than temperature, e.g.
  - Pressure of gas or vapor (compression/expansion)
  - Magnetization of solid (magnetic refrigeration)
- Refrigeration cycle ABCD
  - ΔQ_1 heat absorbed at T_1
  - ΔQ_2 heat rejected at T_2

T-S diagram for helium



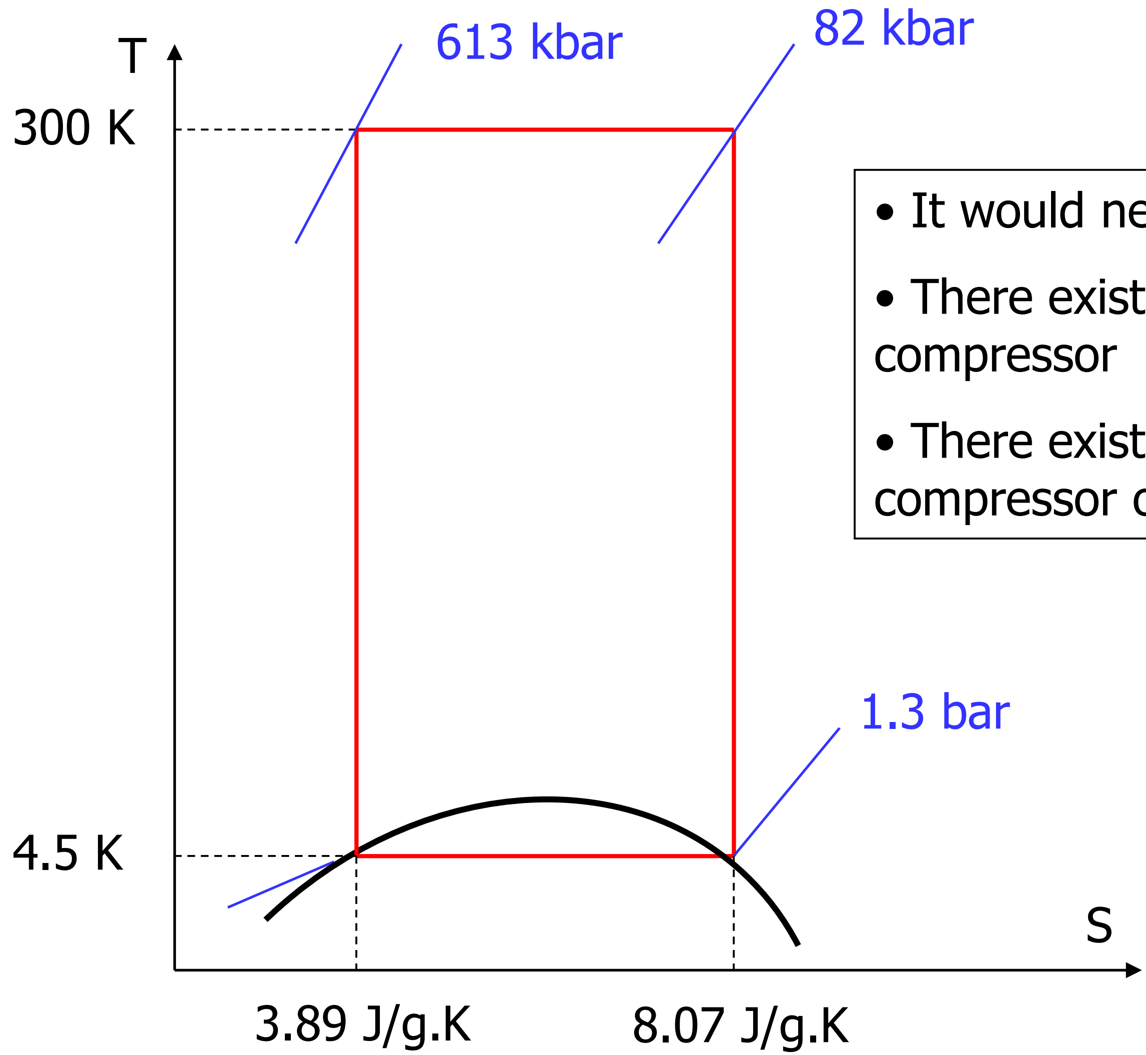
Red : liquid-vapour dome

Blue : isobars

Black : isochores

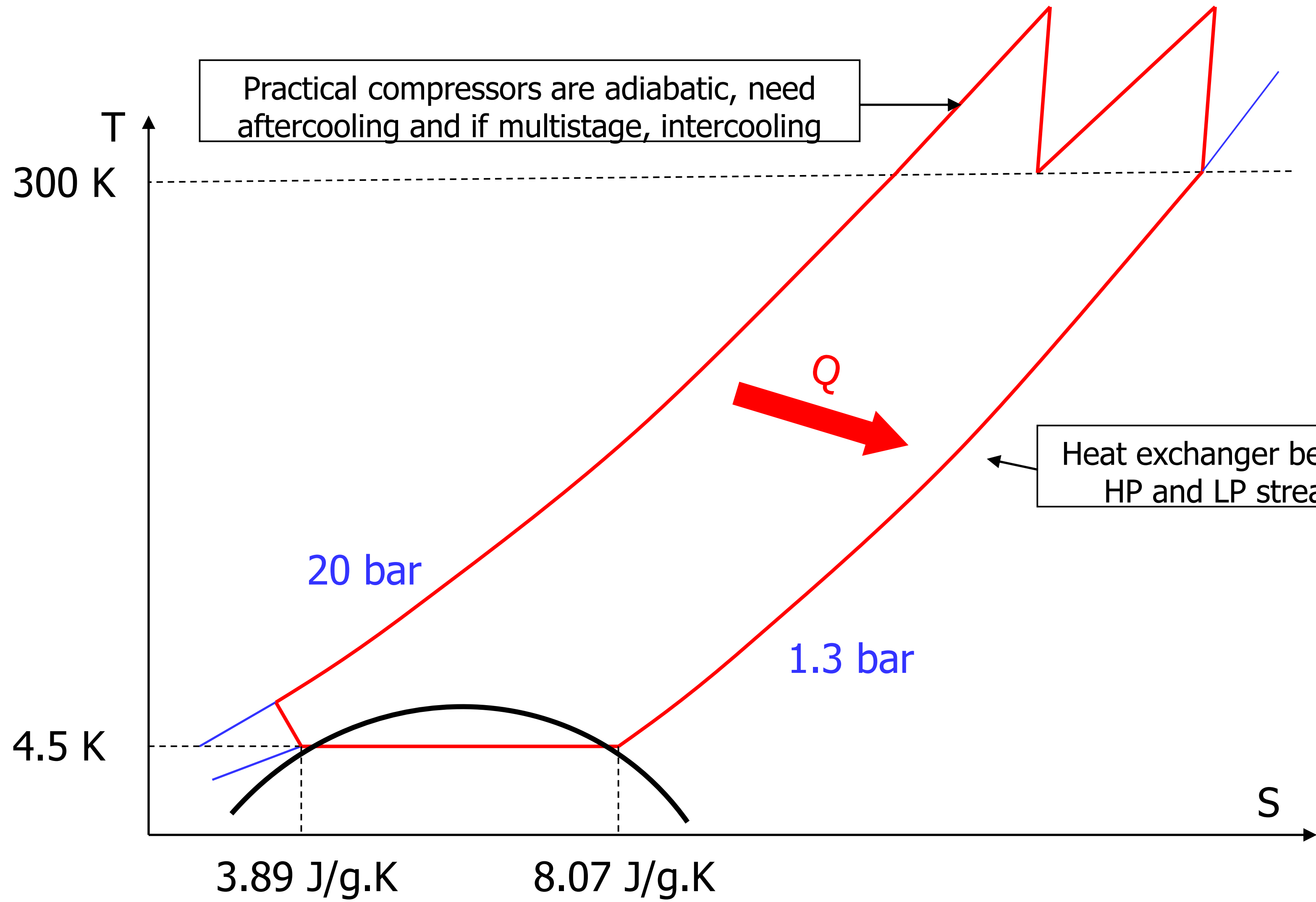
Green: isenthalps

A Carnot cycle is not feasible for helium liquefaction

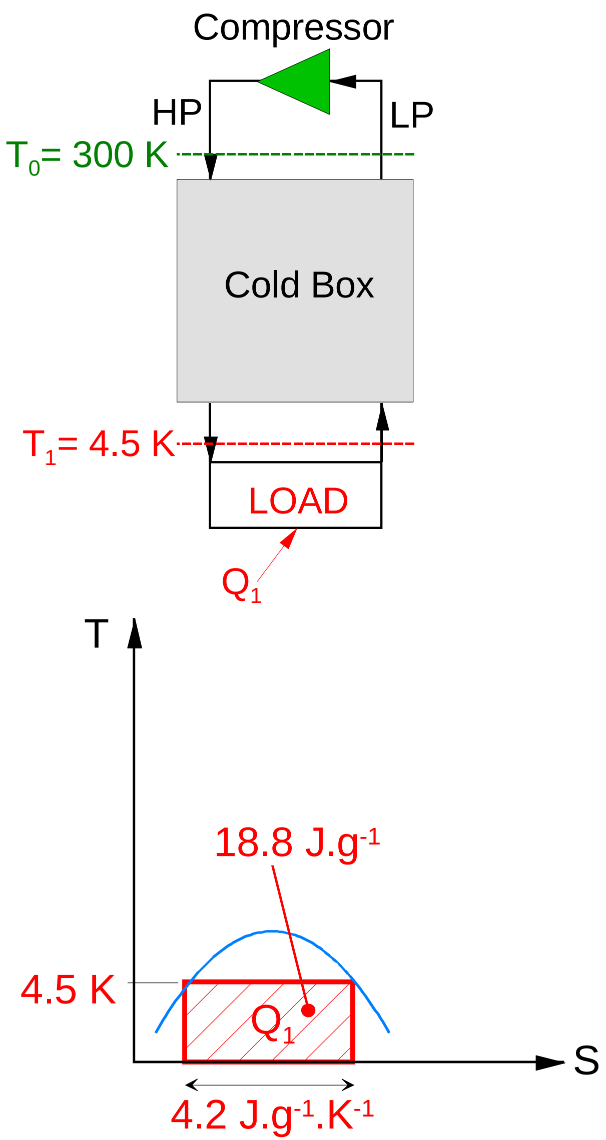


- It would need a HP of 613 kbar!
- There exists no true isothermal compressor
- There exists no true isentropic compressor or expander

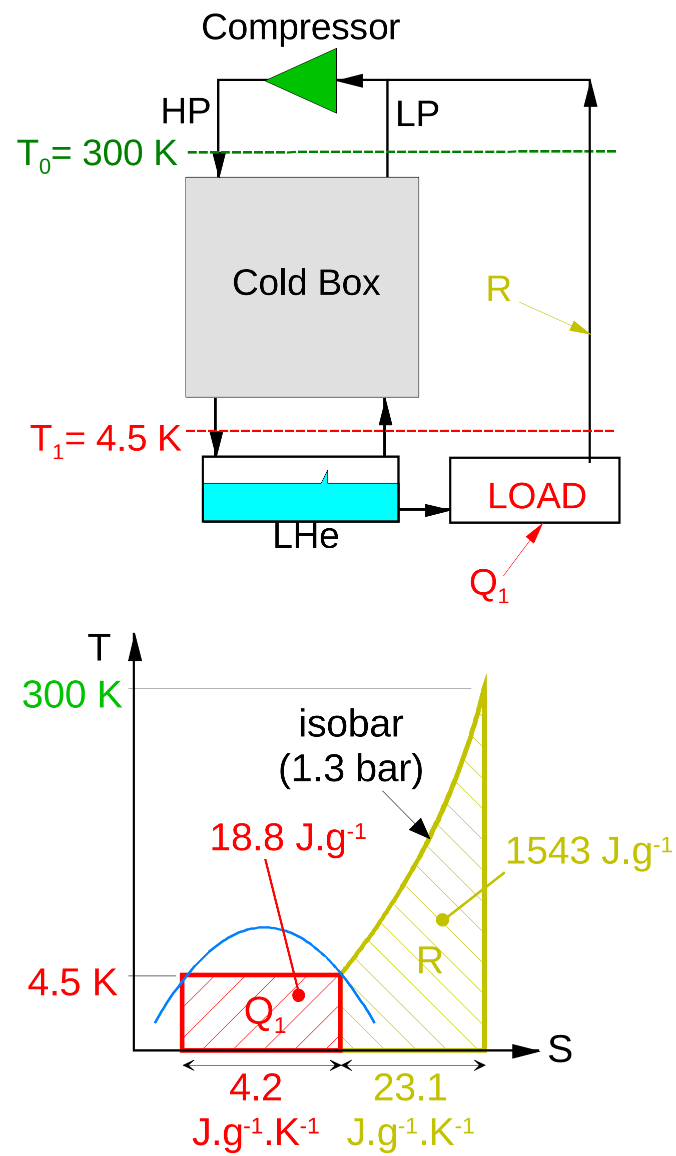
A real cycle needs internal heat exchange and para-isothermal compression



Refrigerator



Liquefier



Thermodynamic equivalence between refrigeration and liquefaction

- What is the equivalent to 1 g helium liquefaction in terms of isothermal refrigeration at liquid helium temperature $T_1 = 4.5\ \mathrm{K}$?

$$W_{liq} = m_{liq}(T_0\ \Delta S - Q_1 - R)$$

with $T_0 = 300\ \mathrm{K}$

$\Delta S = 27.3\ \mathrm{J/g.K}$

$Q_1 = 18.8\ \mathrm{J/g}$

$R = 1543\ \mathrm{J/g}$

hence $W_{liq} = 6628\ \mathrm{J}$

- Write that the same work is used to produce isothermal refrigeration at 4.5 K

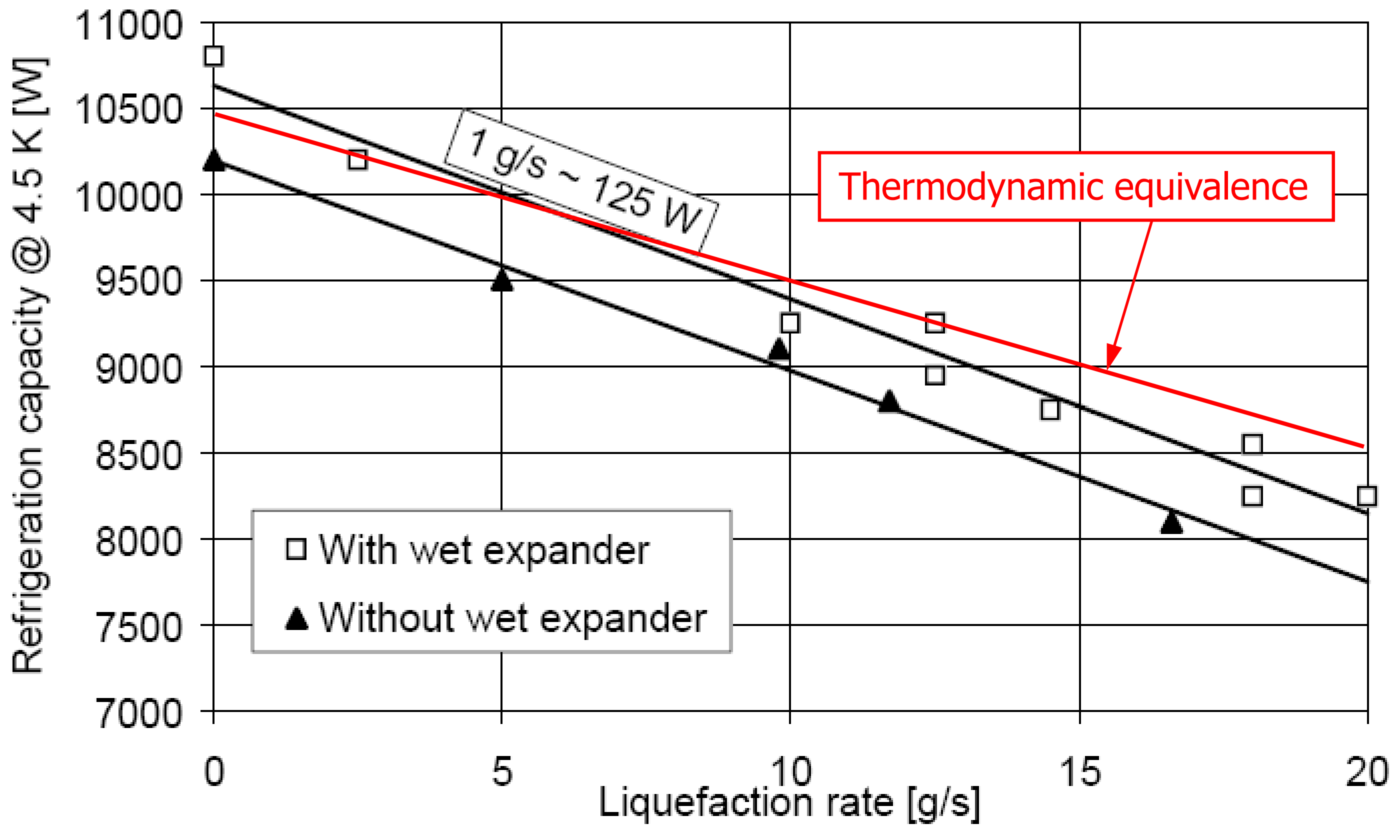
$$W_{ref} = Q_1\left(\frac{T_0}{T_1} - 1\right) = 6628\ \mathrm{J}$$

hence $Q_1 \cong 100\ \mathrm{J}$

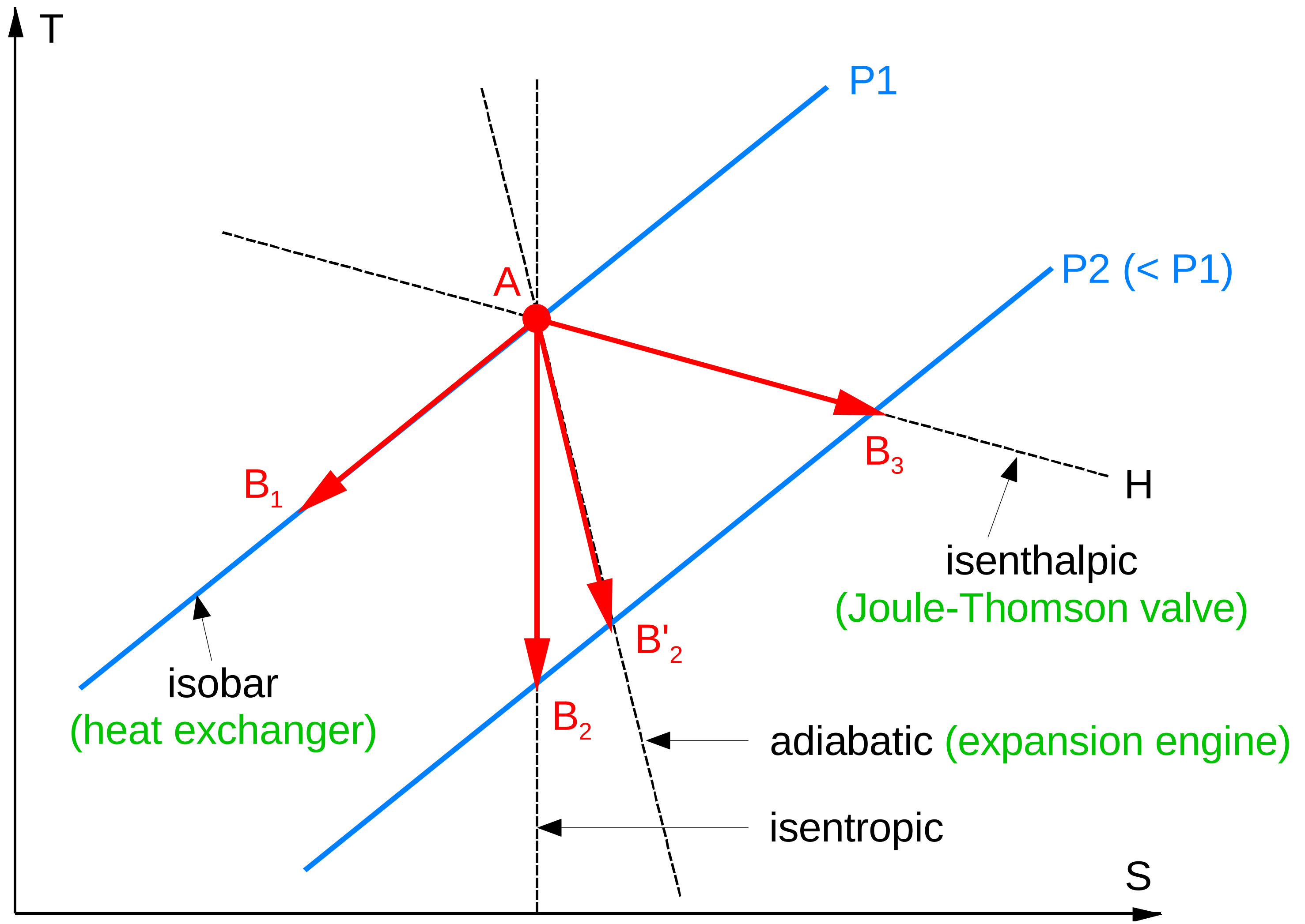
- For refrigerators and liquefiers of the same efficiency

1 g/s liquefaction ≈ 100 W refrigeration at 4.5 K

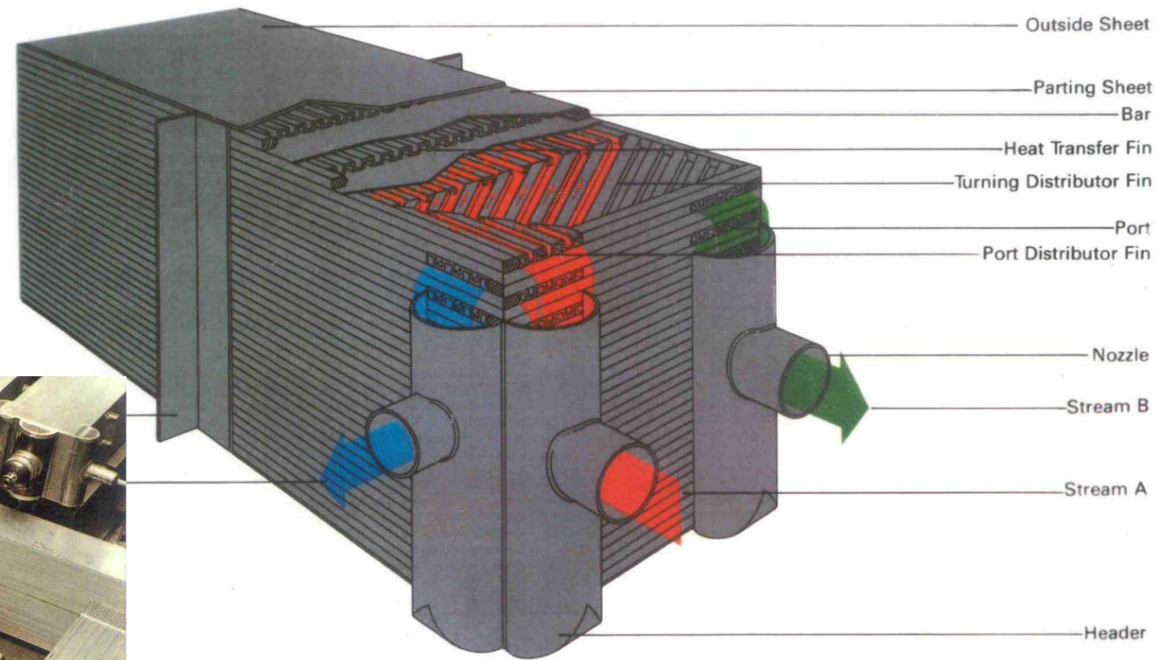
Measured refrigeration/liquefaction equivalence
12 kW @ 4.5 K helium refrigerators for LEP 2

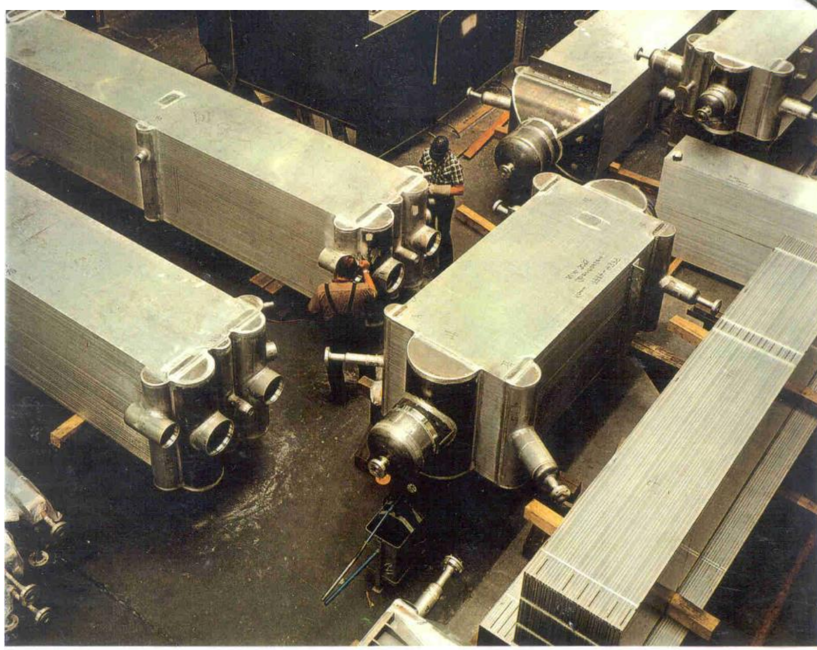


Elementary cooling processes on T-S diagram

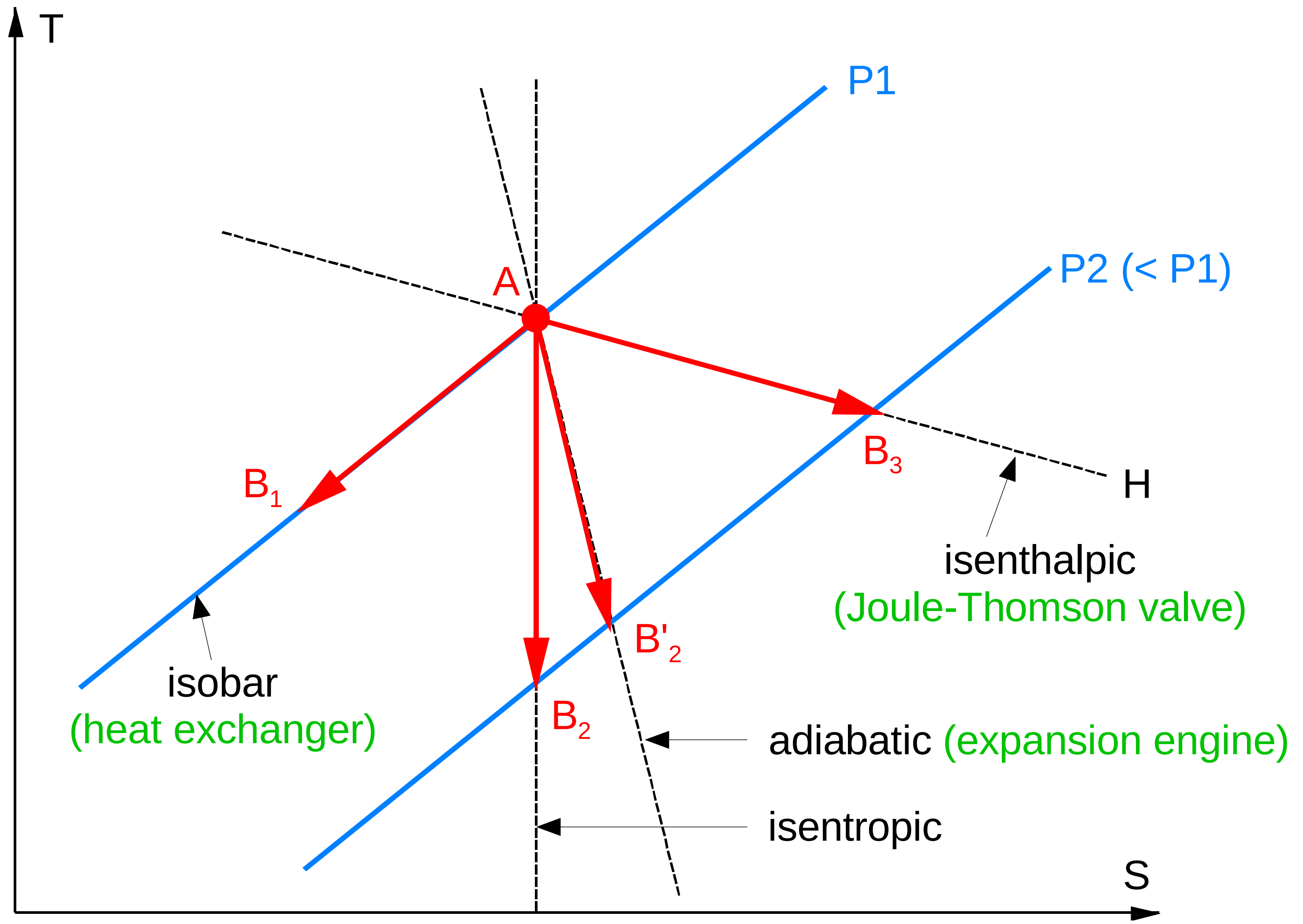


Brazed aluminium plate heat exchanger



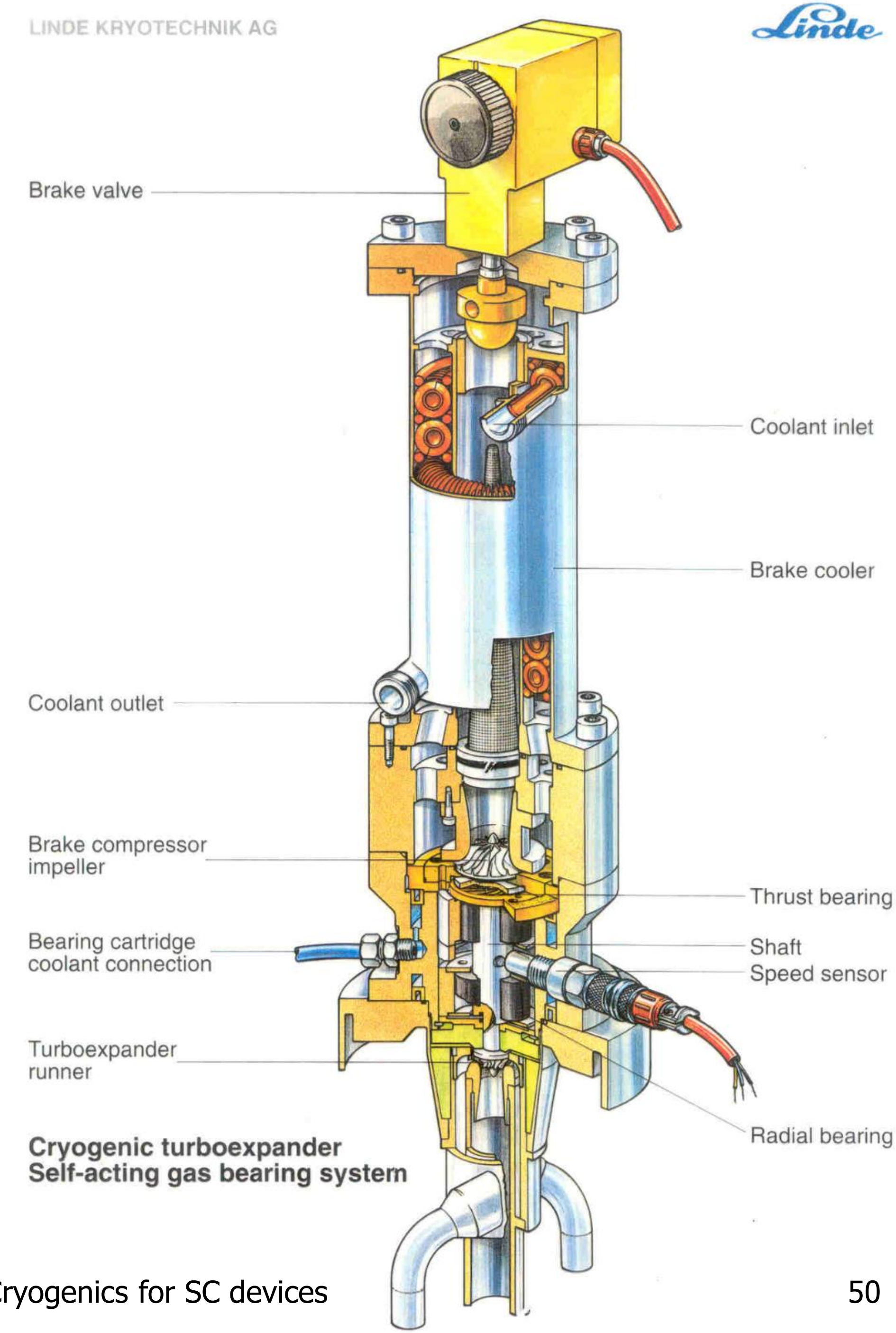


Elementary cooling processes on T-S diagram

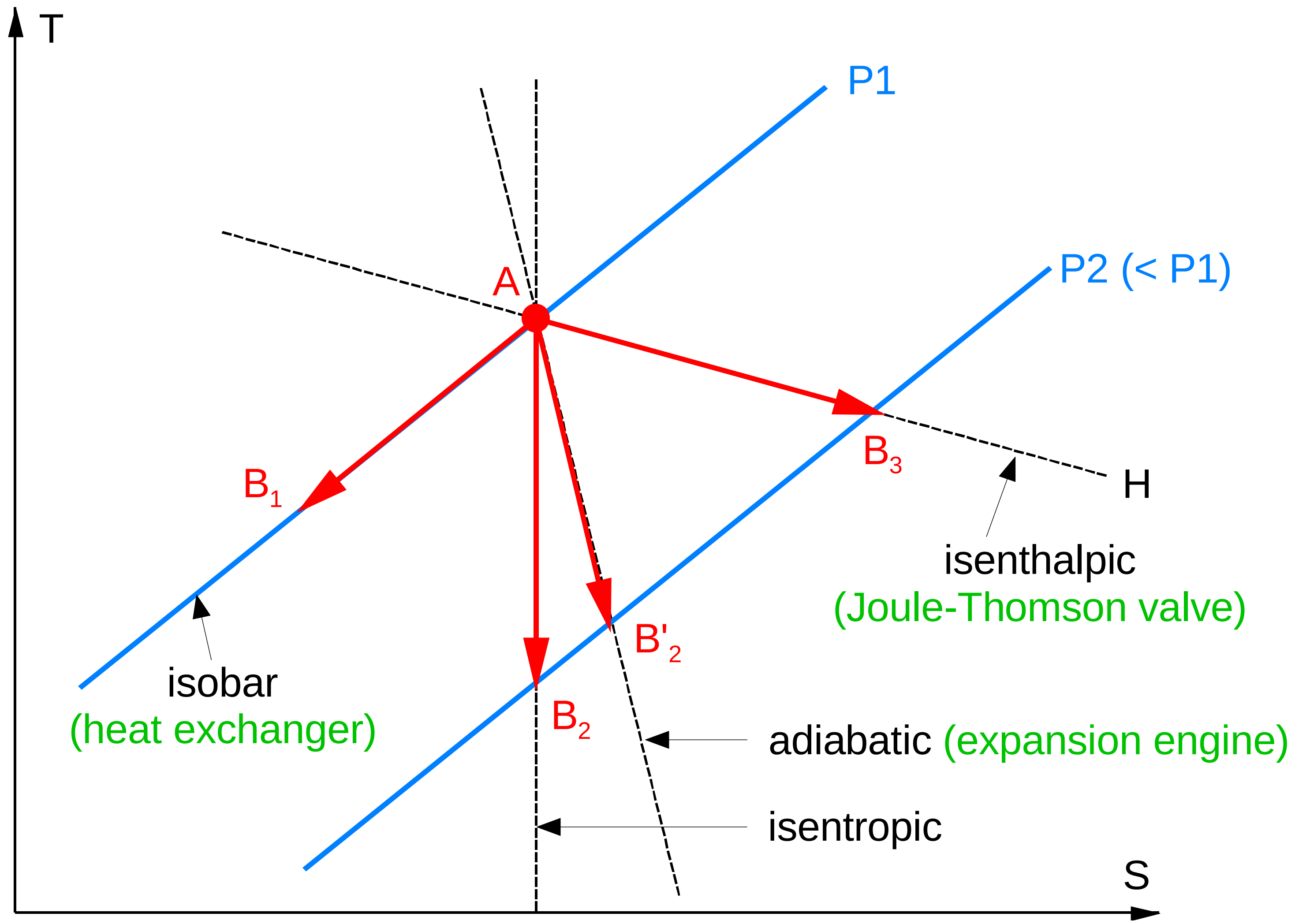


Joint Universities Accelerator School

Cryogenic turbo-expander



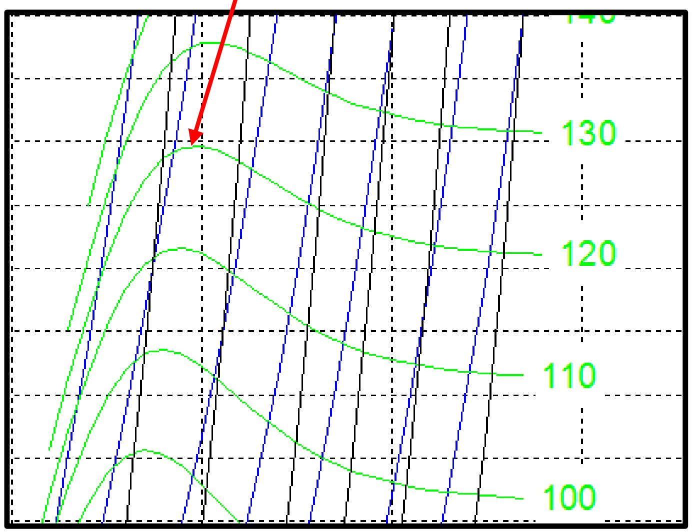
Elementary cooling processes on T-S diagram



Joule-Thomson inversion temperatures

Isenthalps in T-S diagram can have positive or negative slope, i.e. isenthalpic expansion can produce warming or cooling

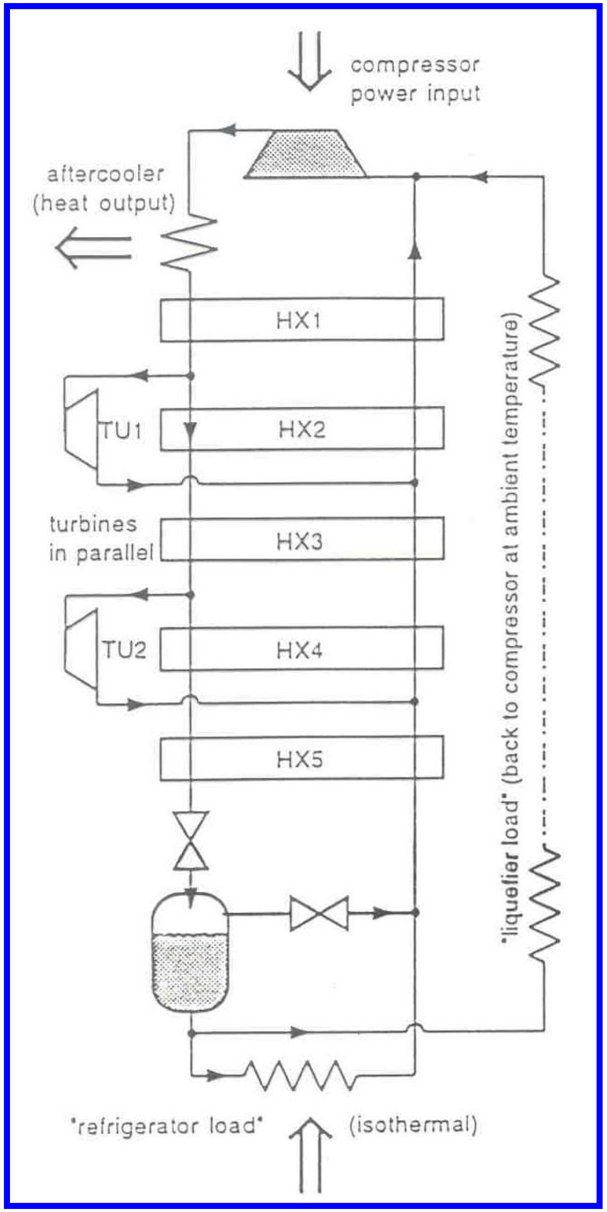
⇒ **inversion temperature**

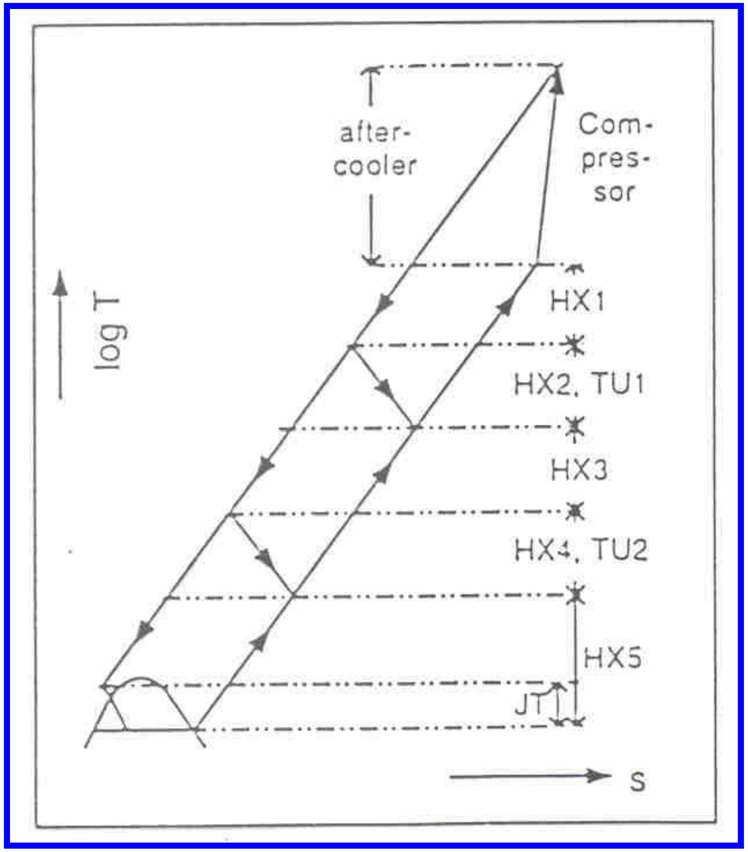


Cryogen	Maximum inversion temperature [K]
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Oxygen	761

While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

Two-stage Claude cycle

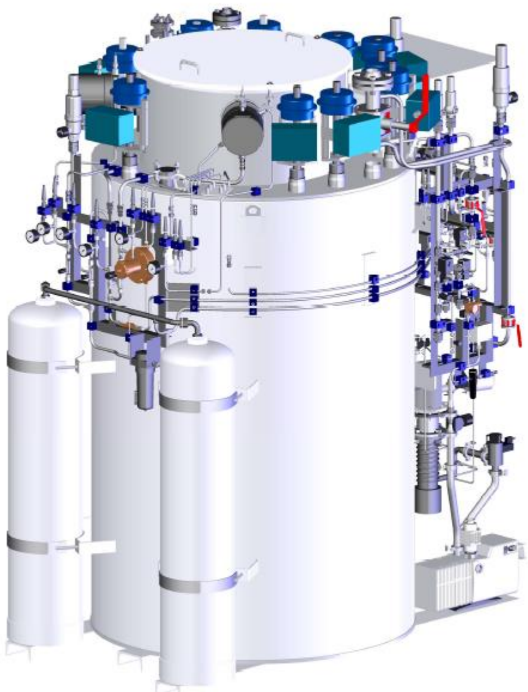




Claude-cycle helium refrigerators/liquefiers

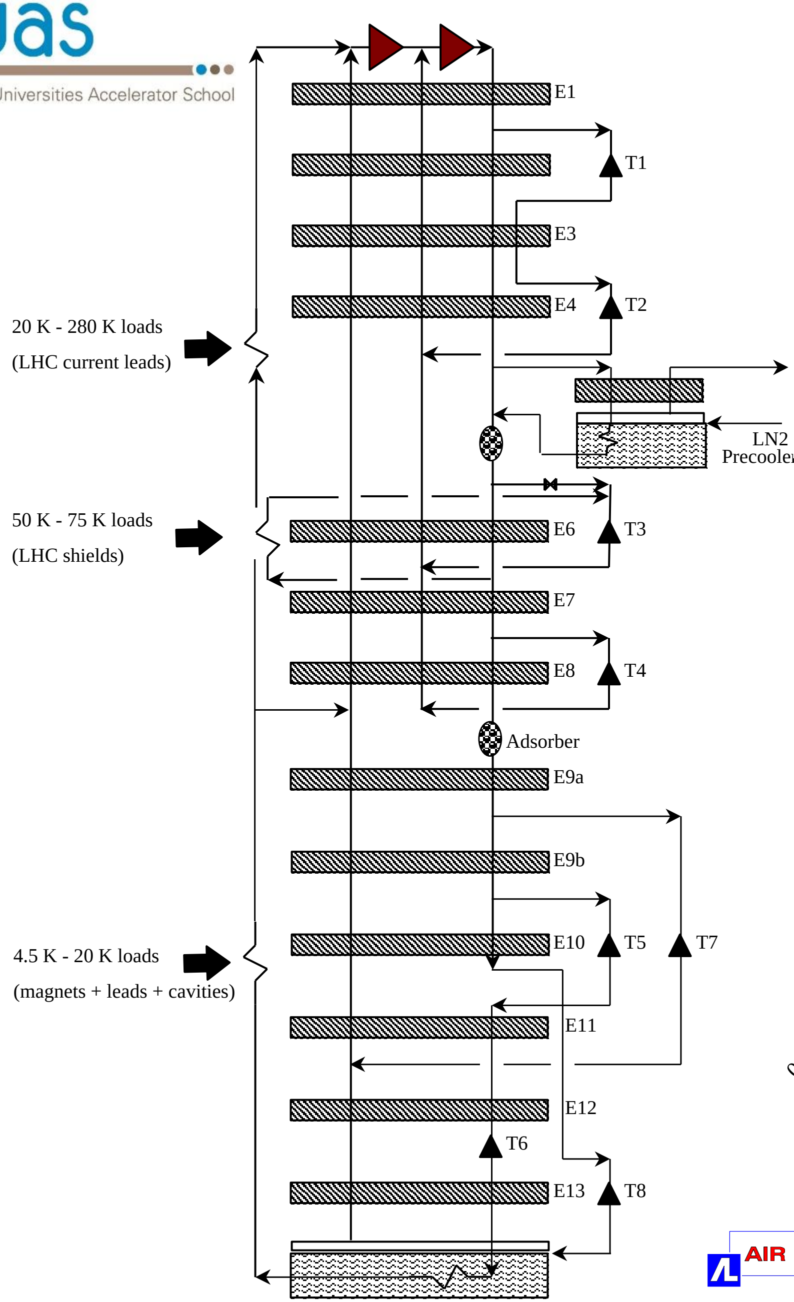
Air Liquide & Linde

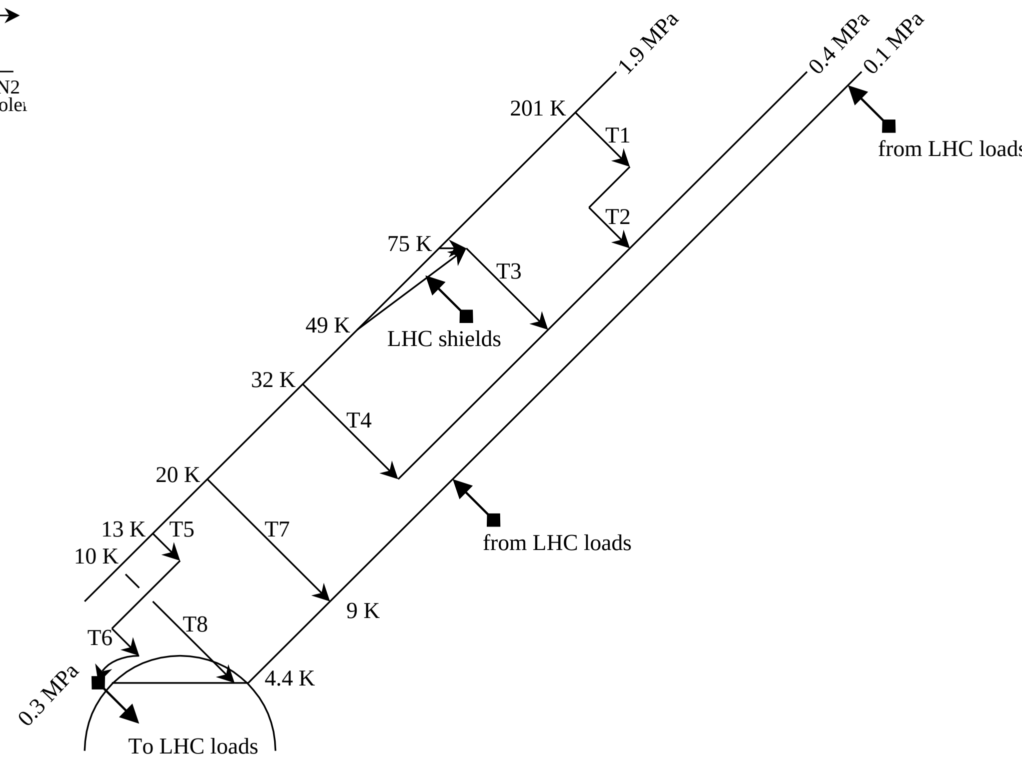
	HELIAL SL	HELIAL ML	HELIAL LL
Max. Liquefaction capacity without LN2	25 L/h	70 L/h	145 L/h
Max. Liquefaction capacity with LN2	50 L/h	150 L/h	330 L/h
Compressor electrical motor	55 kW	132 kW	250 kW
Specific consumption for liquefaction w/o LN2	645 W/W	552 W/W	505 W/W
% Carnot	**10%**	**12%**	**13%**



	Without LN_2 precooling	With LN_2 precooling
L70	20 – 35 l/h	40 – 70 l/h
L140	45 – 70 l/h	90 – 140 l/h
L280	100 – 145 l/h	200 – 290 l/h
LR70	100 – 145 Watt	130 – 190 Watt
LR140	210 – 290 Watt	255 – 400 Watt
LR280	445 – 640 Watt	560 – 900 Watt

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





AIR LIQUIDE

LHC 18 kW @ 4.5 K helium cryoplants

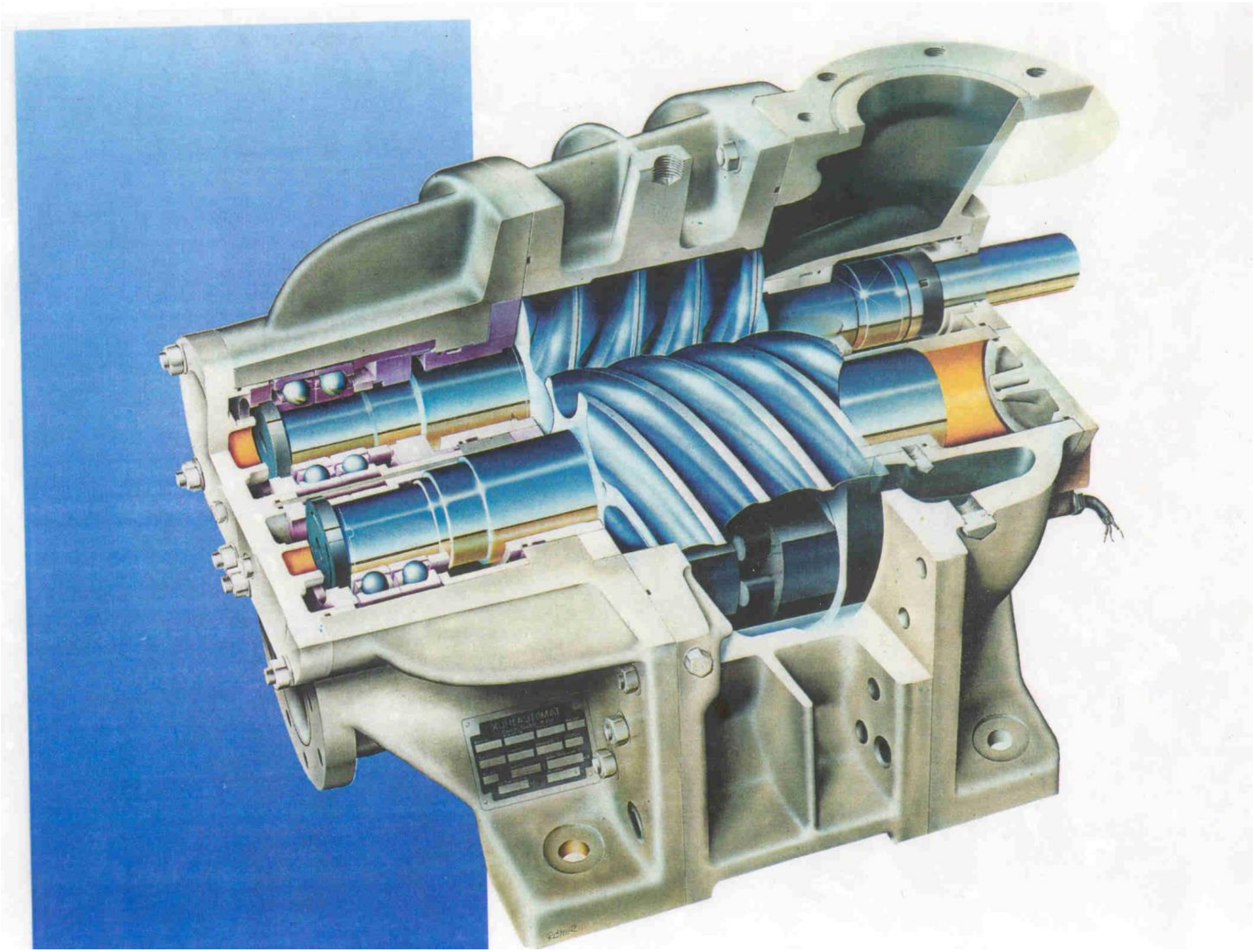
33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction
4 MW compressor power
C.O.P. 220-230 W/W @ 4.5 K

Air Liquide

Linde

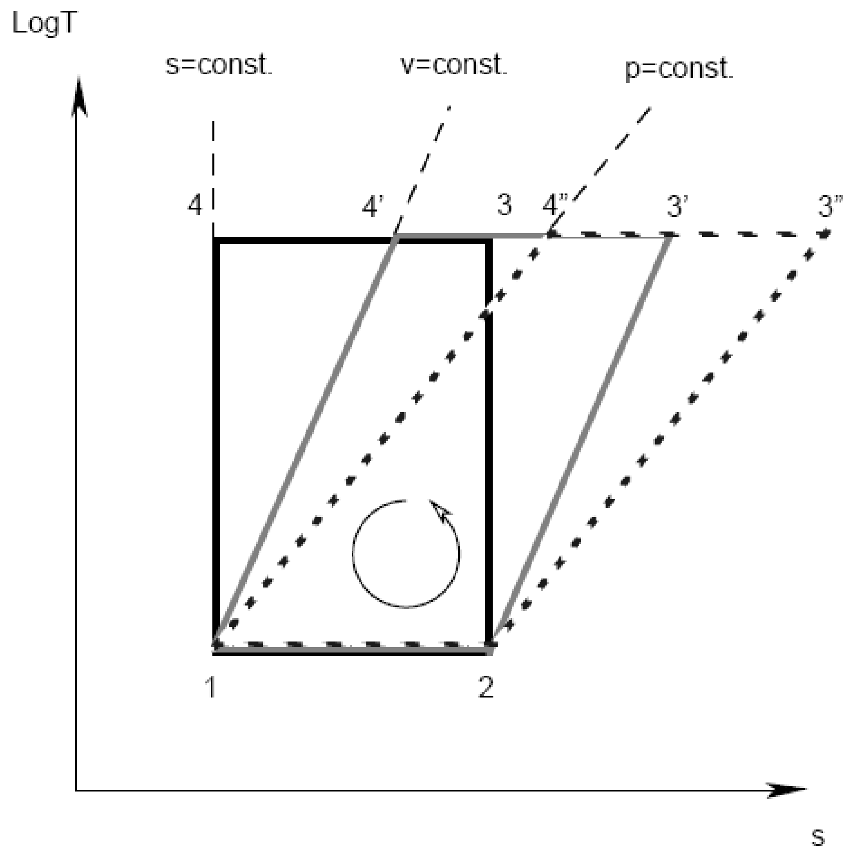
ITER 25 kW @ 4.5 K helium refrigerator

Oil-injected screw compressor



Compressor station of LHC 18 kW@ 4.5 K helium refrigerator

Carnot, Stirling and Ericsson cycles



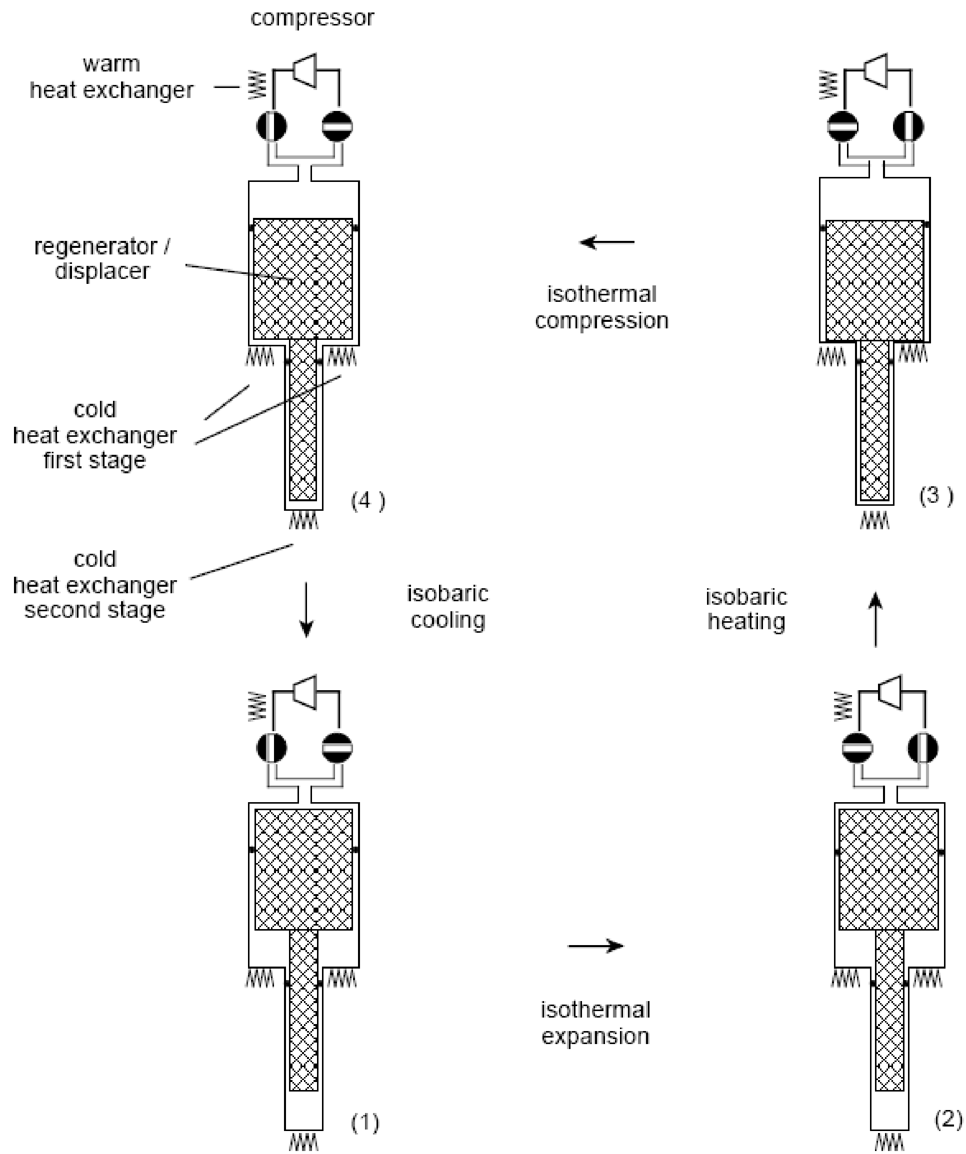
All «sloping» cycles need internal heat exchange

For small machines, this is done by regenerative, rather than recuperative heat exchangers

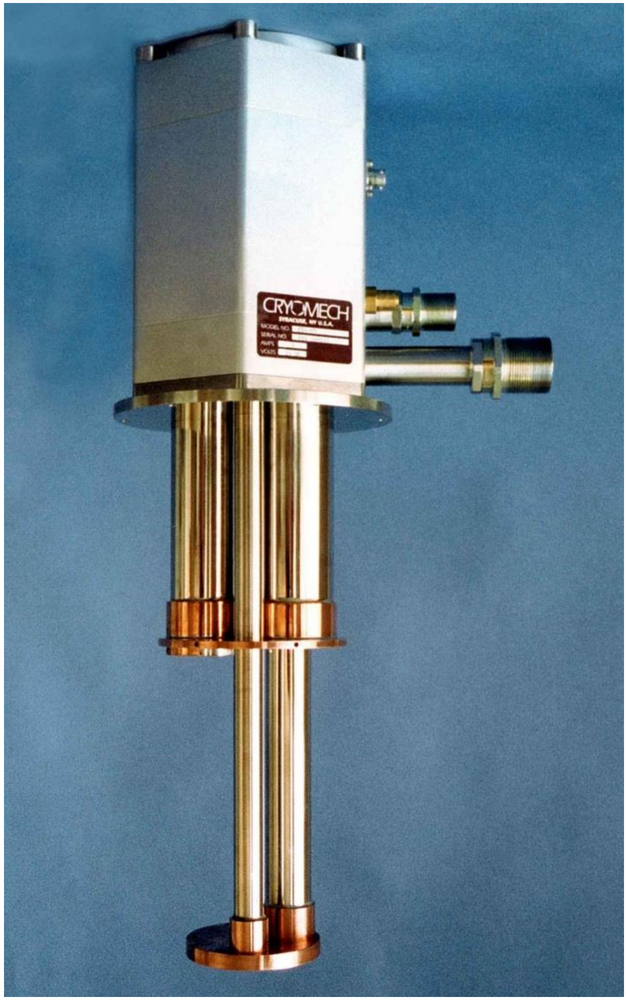
⇒ alternating rather than continuous operation

Carnot cycle (1,2,3,4), Stirling cycle (1,2,3',4') and Ericsson cycle (1,2,3",4")

Operation of a Gifford-McMahon cryocooler (Ericsson cycle)



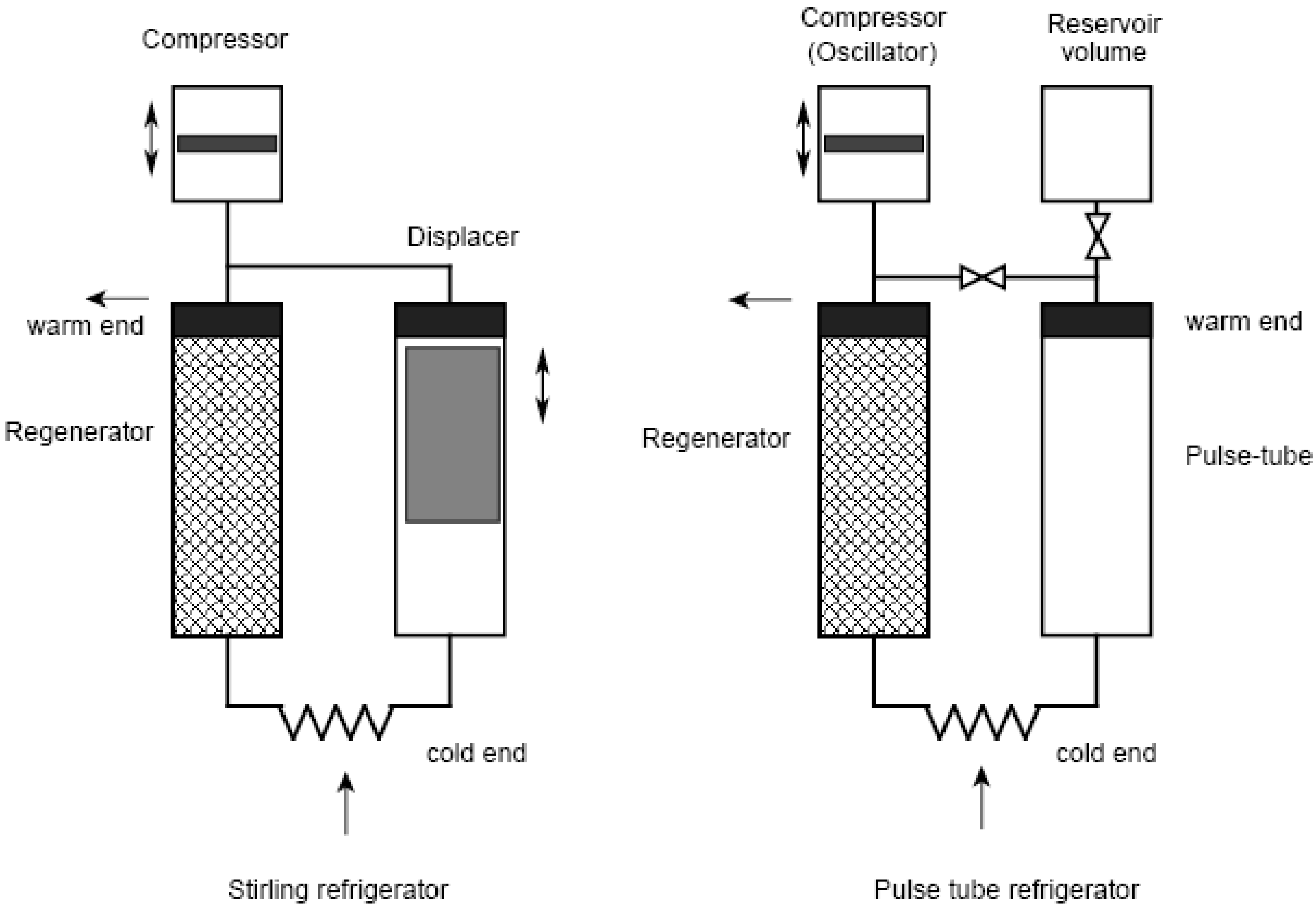
Two-stage Gifford-McMahon cryocooler



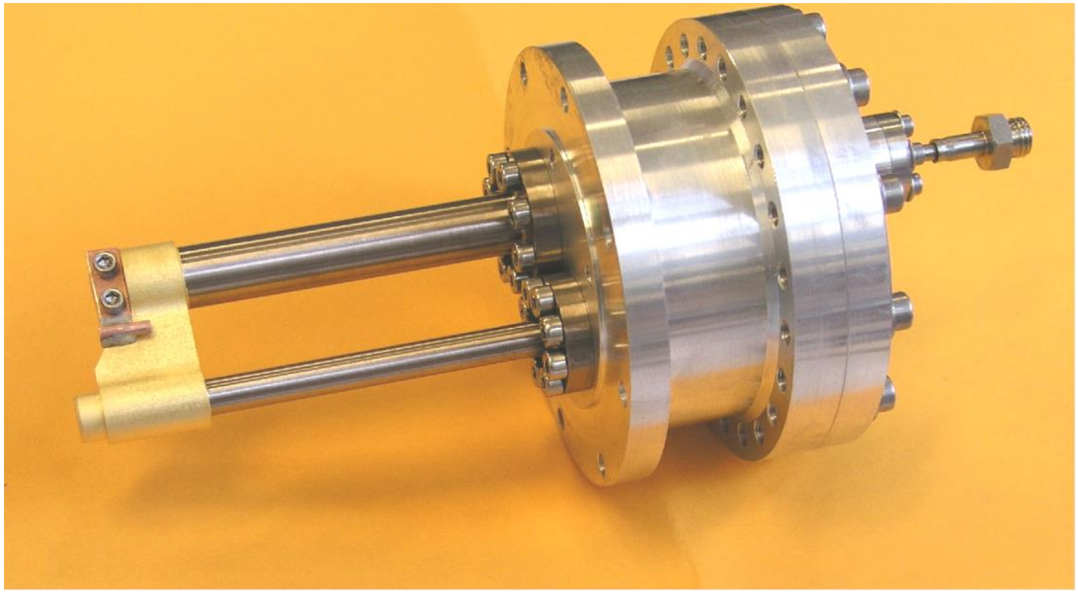
CRYOMECH PT407 & CP970 compressor

~ 0.7 W @ 4.2 K & 25 W @ 55 K

Stirling and pulse-tube cryocoolers



Mini pulse-tube cryocoolers

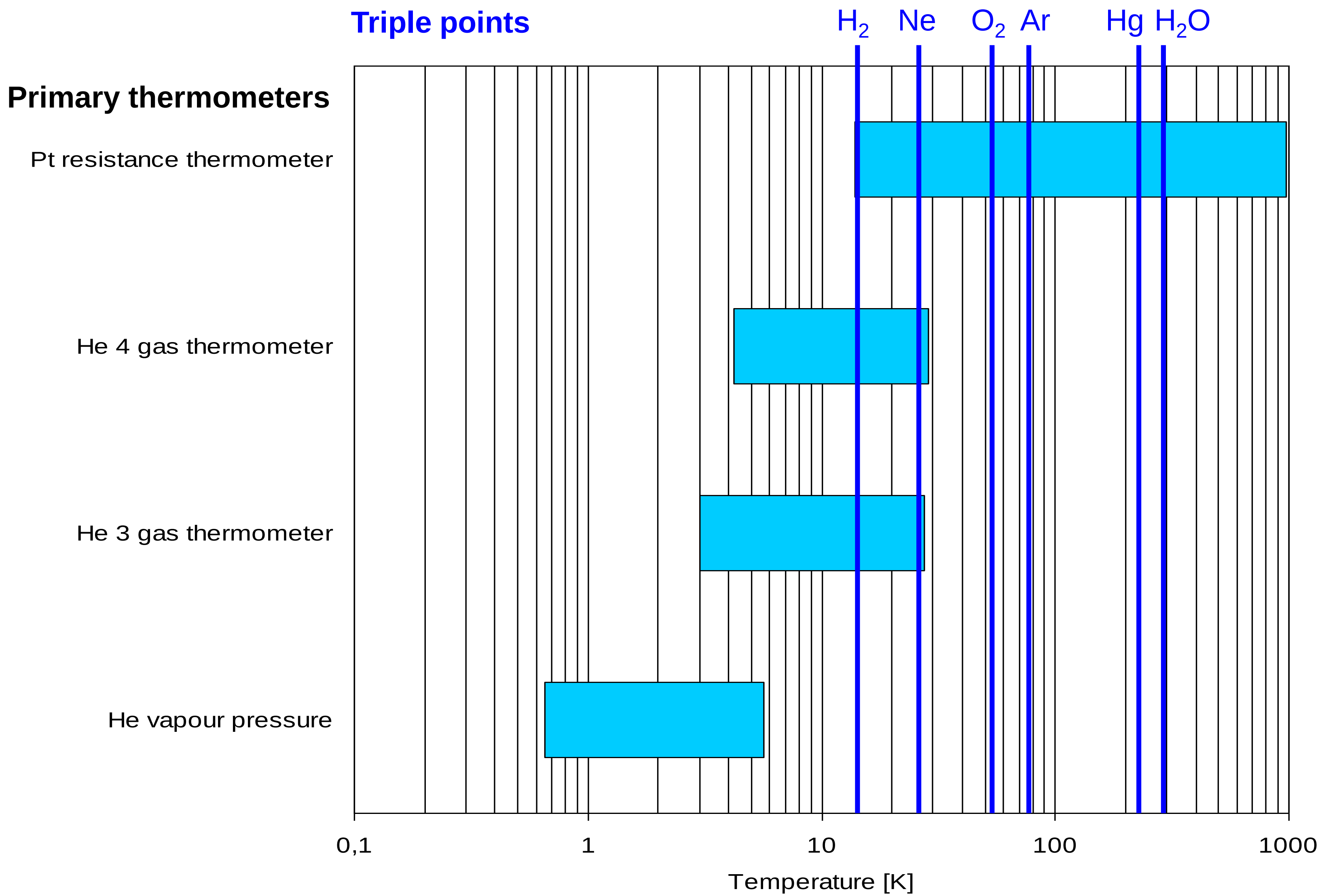


ESA MPTC development model – 1W @ 77K

CEA/SBT coaxial PTC– 6W @ 80K

Contents

Definition of ITS90 in cryogenic range

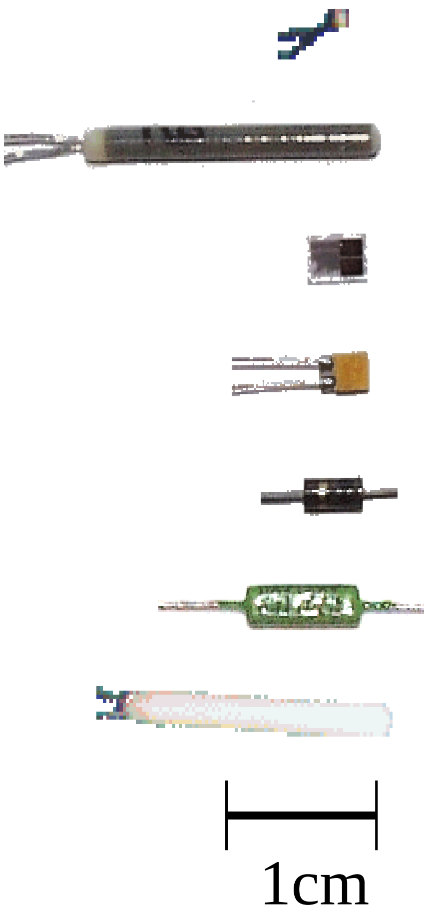


Primary fixed points of ITS90 in cryogenic range

Fixed point	Temperature [K]
H_2 triple point	13.8033
Ne triple point	24.5561
O_2 triple point	54.3584
Ar triple point	83.8058
Hg triple point	234.3156
H_2O triple point	273.16 (*)

(*) *exact by definition*

From temperature sensor to practical thermometer



Ge

RhFe wire

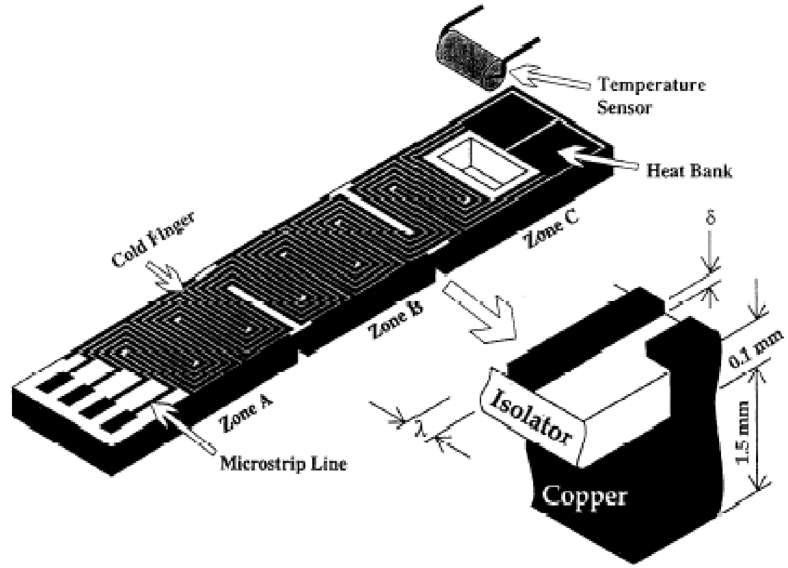
RhFe thin film

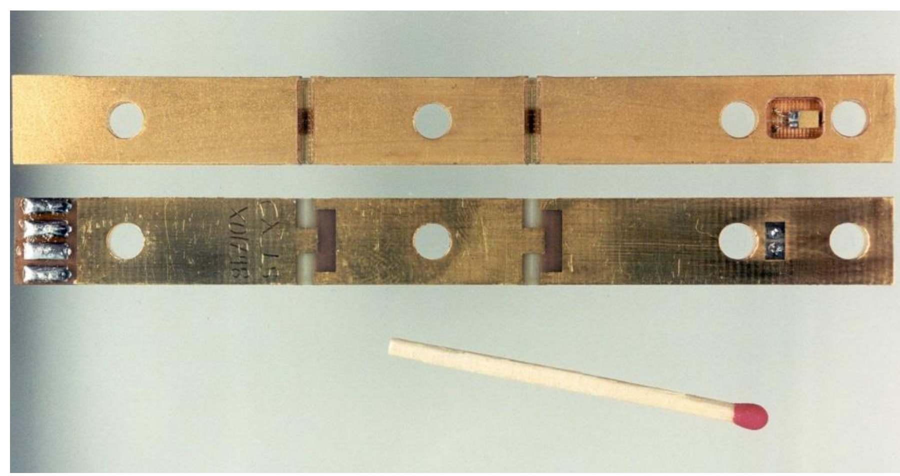
Cernox

Carbon A-B

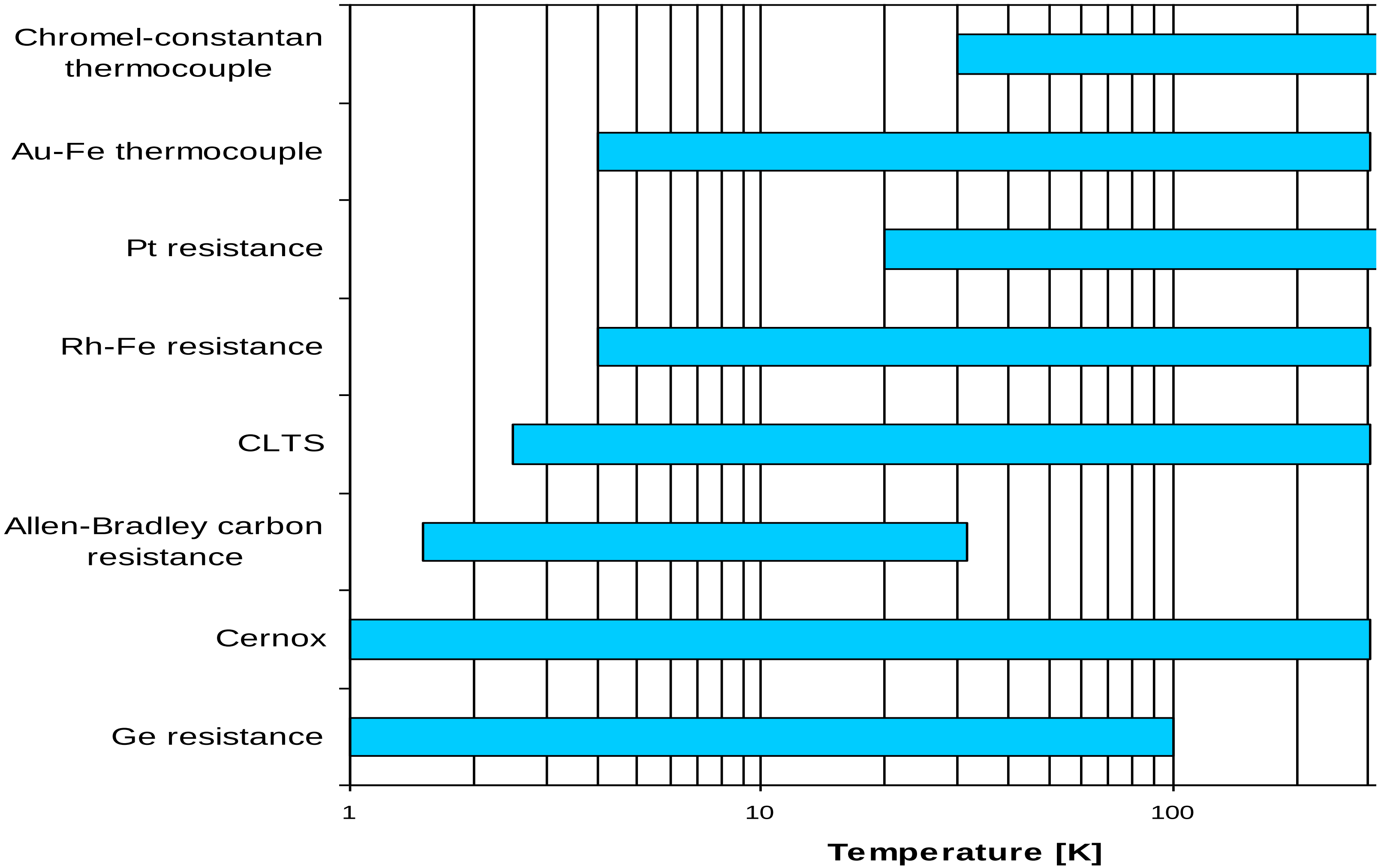
Carbon TVO

CBT





Practical temperature range covered by cryogenic thermometers



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