Cryogenics for particle accelerators

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Contents

- Low temperatures and liquefied gases
- Cryogenics in accelerators
- Properties of fluids
- Design of cryogenic equipement
- Refrigeration & liquefaction

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- **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

3rd edition, IIF-IIR Paris (1975)

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

Industrial cryogenics: densification, liquefaction & separation of gases

LNG

130 000 m^3 LNG carrier with double hull

LIN & LOX

Air separation by cryogenic distillation

Up to 4500 t/day LOX

Rocket fuels

Ariane 5

25 t LHY, 130 t LOX

What is a low temperature?

- The entropy of a thermodynamical system in a macrostate corresponding to a multiplicity W of microstates is

$$S = k_B \ln W$$

- Adding reversibly heat dQ to the system results in a change of its entropy dS with a proportionality factor T

$$T = dQ/dS$$

⇒ *high temperature: heating produces small entropy change*

⇒ *low temperature: heating produces large entropy change*

L. Boltzmann's grave in the Zentralfriedhof, Vienna, bearing the entropy formula

Temperature and energy

- The average thermal energy of a particle in a system in thermodynamic equilibrium at temperature T is

$$E \sim k_B T$$

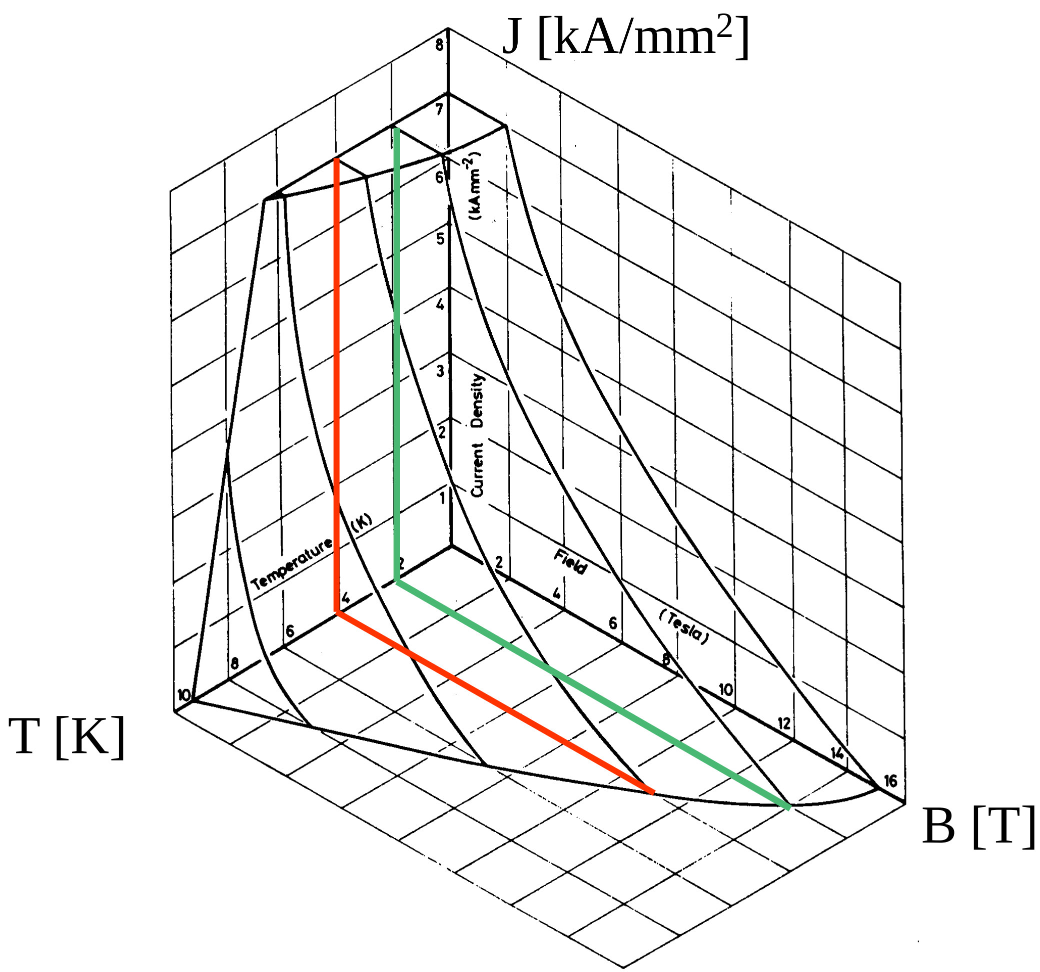
$$k_B = 1.3806 \times 10^{-23}\ J.K^{-1}$$

- 1 K is equivalent to 10^{-4} eV or 10^{-23} J thermal energy
  - a temperature is « low » for a given physical process when $k_B T$ is small compared with the characteristic energy of the process considered
  - cryogenic temperatures reveal phenomena with low characteristic energy and enable their application

Characteristic temperatures of low-energy phenomena

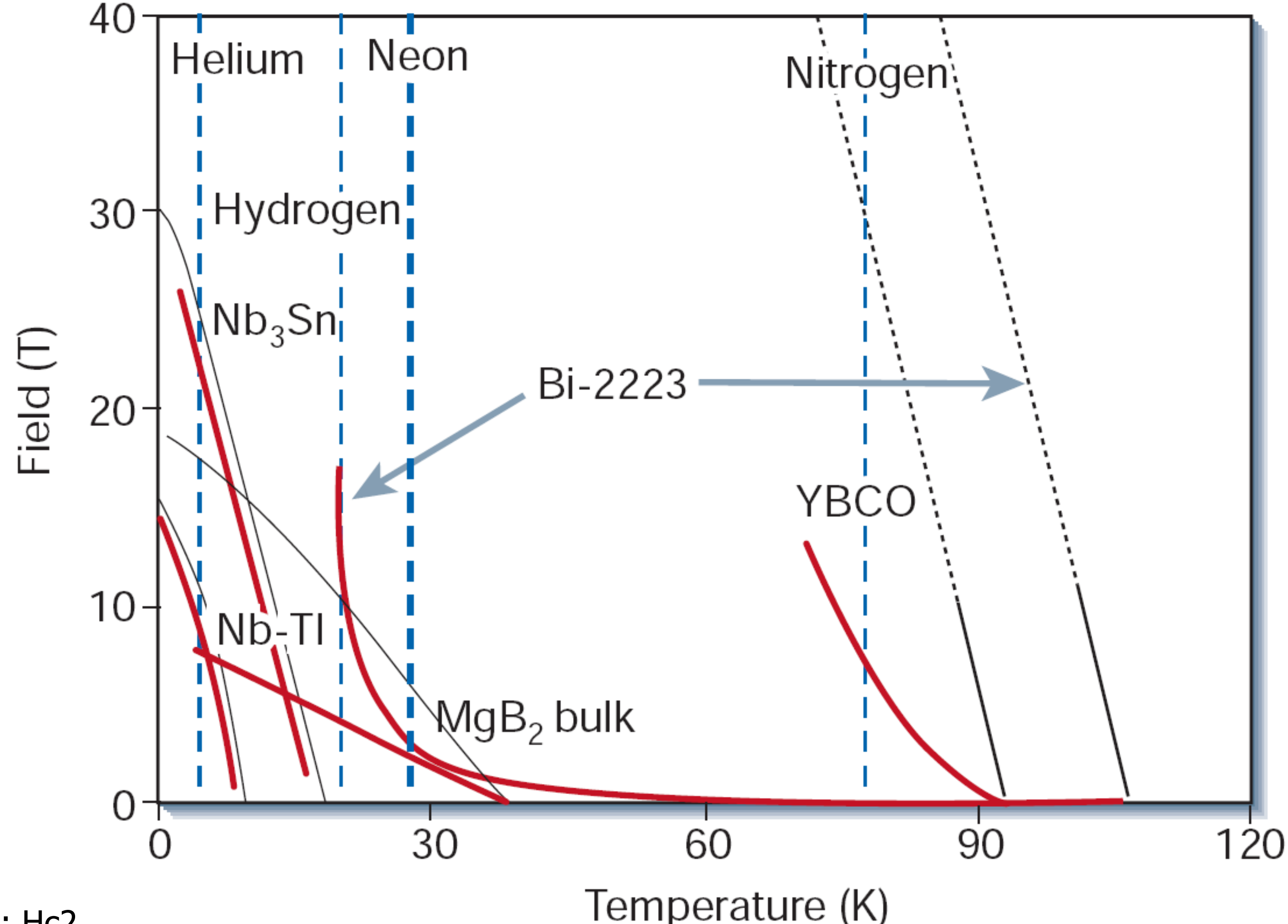
Phenomenon	Temperature
Debye temperature of metals	few 100 K
High-temperature superconductors	~ 100 K
Low-temperature superconductors	~ 10 K
Intrinsic transport properties of metals	< 10 K
Cryopumping	few K
Cosmic microwave background	2.7 K
Superfluid helium 4	2.2 K
Bolometers for cosmic radiation	< 1 K
Low-density atomic Bose-Einstein condensates	~ μK

Operating temperature
& DC performance of superconductors



- Superconductivity only exists in a limited domain of temperature, magnetic field and current density
- Electrotechnical applications require transport current and magnetic field
- Operating temperature of the device must therefore be significantly lower than the critical temperature of the superconductor

Critical field vs. temperature of LTS and HTS superconductors



Black: Hc2

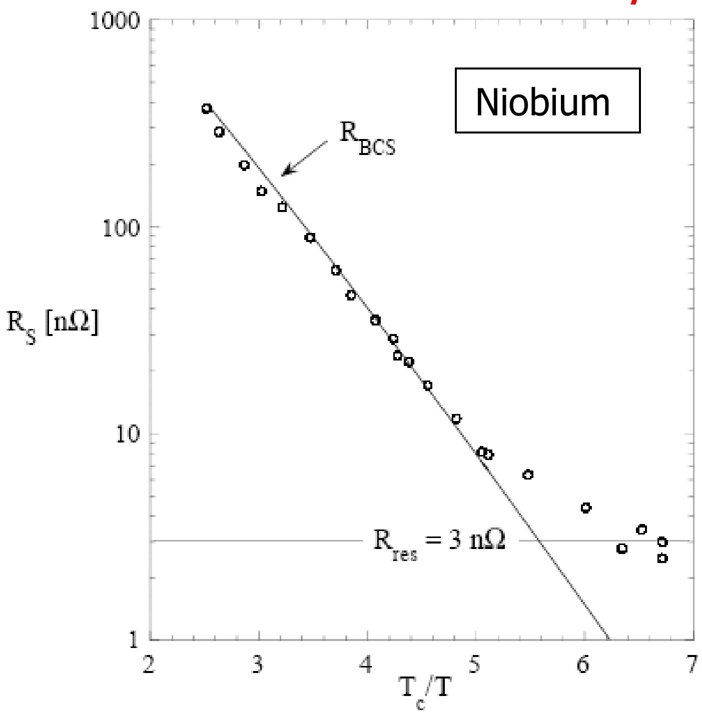
Red: irreversibility field (jc = 0)

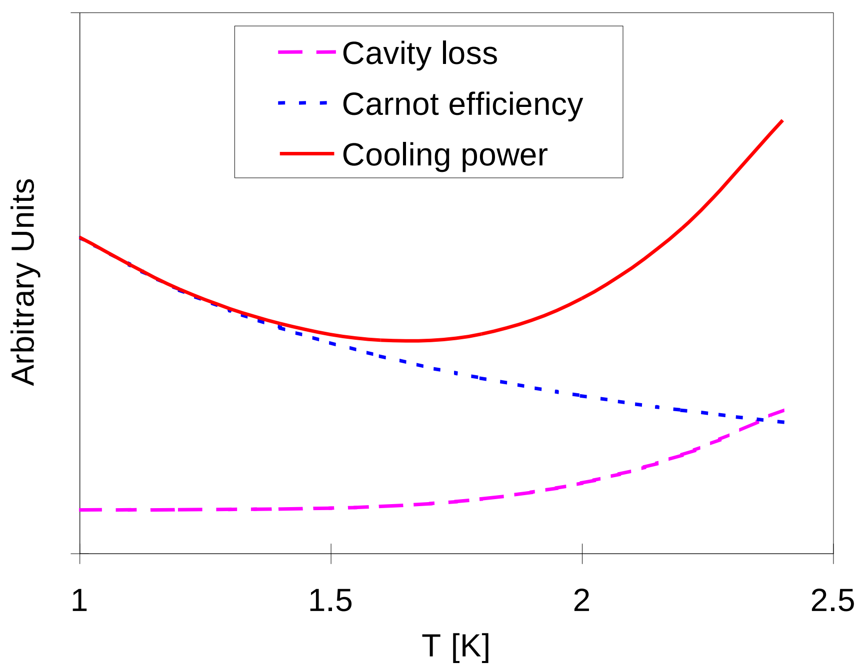
D. Larbalestier *et al.*

Optimization of operating temperature for superconducting RF cavity

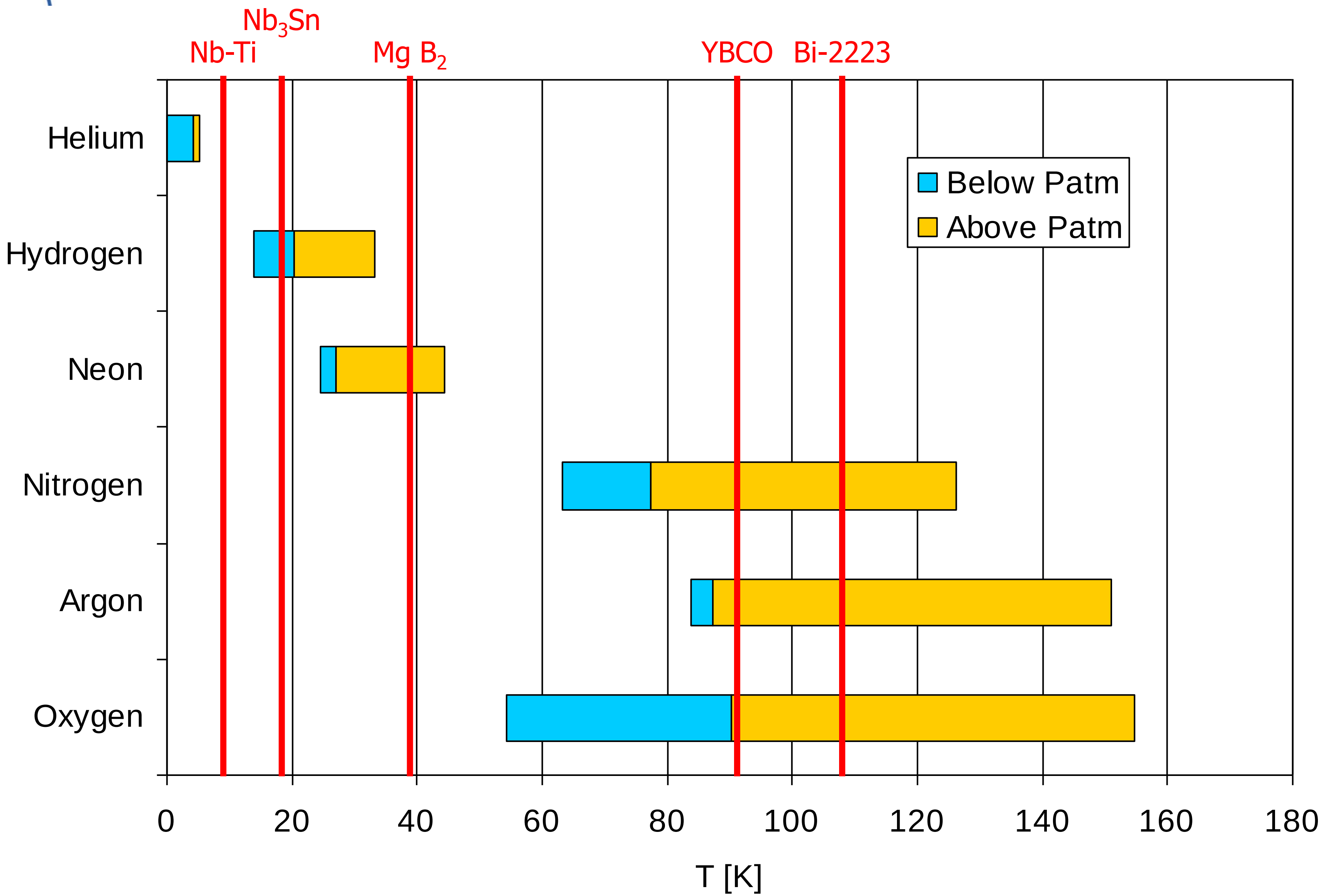
- Power per unit length $P/L \sim R_S \, \boldsymbol{E}^2 / \omega$
- BCS theory $R_{BCS} = (A\,\omega^2/T)\ \exp(-B\,T_c/T)$
- For practical materials $R_S = R_{BCS} + R_{res}$
- Refrigeration (Carnot) $P_a = P\,(T_a/T - 1)$

⇒ optimum operating temperature for superconducting cavities is well below critical temperature of superconductor





Useful range of cryogens & critical temperature of superconductors



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Superconductivity and circular accelerators

- Beam energy, field in bending magnets and machine radius are related by:

$$E_{beam} = 0.3 \; \boldsymbol{B} \; r$$

[GeV] [T] [m]

At the LHC (r = 2.8 km), ***B*** = 8.33 T to reach E_{beam}= 7 TeV

- Superconductivity permits to produce high field and thus to limit size and electrical consumption of the accelerators

	Normal conducting	**Superconducting (LHC)**
Magnetic field	1.8 T (iron saturation)	8.3 T (NbTi critical surface)
Field geometry	Defined by magnetic circuit	Defined by coils
Current density in windings	10 A/mm^2	400 A/mm^2
Electromagnetic forces	20 kN/m	3400 kN/m
Electrical consumption	10 kW/m	2 kW/m

Limiting energy stored in beam

- Energy W stored in the beams of circular accelerators and colliders

  W [kJ] = 3.34 E_{beam} [GeV] I_{beam} [A] C [km]

  C circumference of accelerator/collider

  ⇒ *building compact machines, i.e. producing higher bending field B limits beam stored energy*

- Example: the LHC

  E_{beam} = 7000 GeV

  I_{beam} = 0.56 A ⇒ W = 350 MJ*!*

  C = 26.7 km

Low impedance for beam stability

- Transverse impedance

  $Z_T(\omega) \sim \rho\ r\ /\ \omega\ b^3$

  ρ wall electrical resistivity

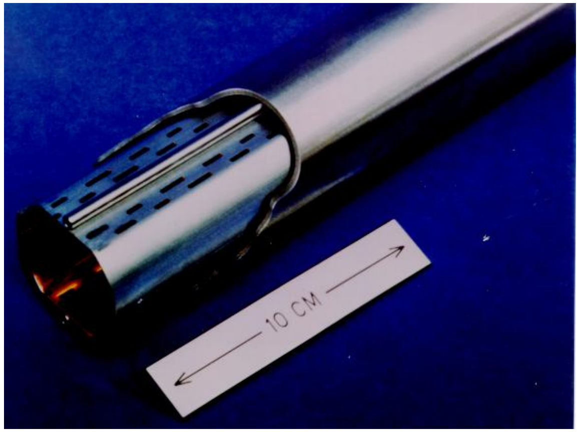
  r average machine radius

  b half-aperture of beam pipe

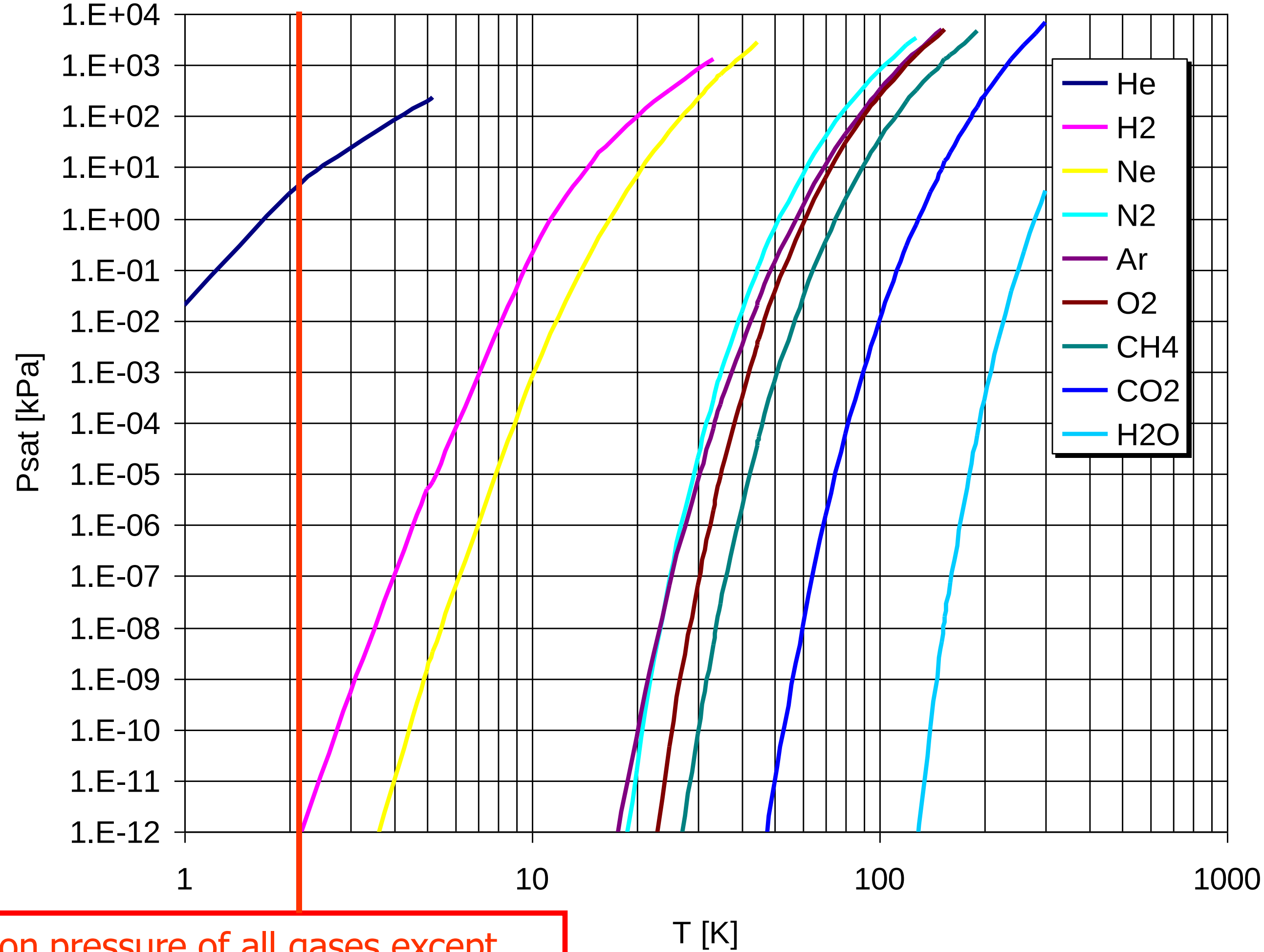
- Transverse resistive-wall instability
  - dominant in large machines
  - must be compensated by beam feedback, provided growth of instability is slow enough
  - maximize growth time $\tau \sim 1/\ Z_T(\omega)$ i.e. reduce $Z_T(\omega)$

$\Rightarrow$ *for a large machine with small aperture, low transverse impedance is achieved through low ρ, i.e. low-temperature wall*

LHC beam pipe

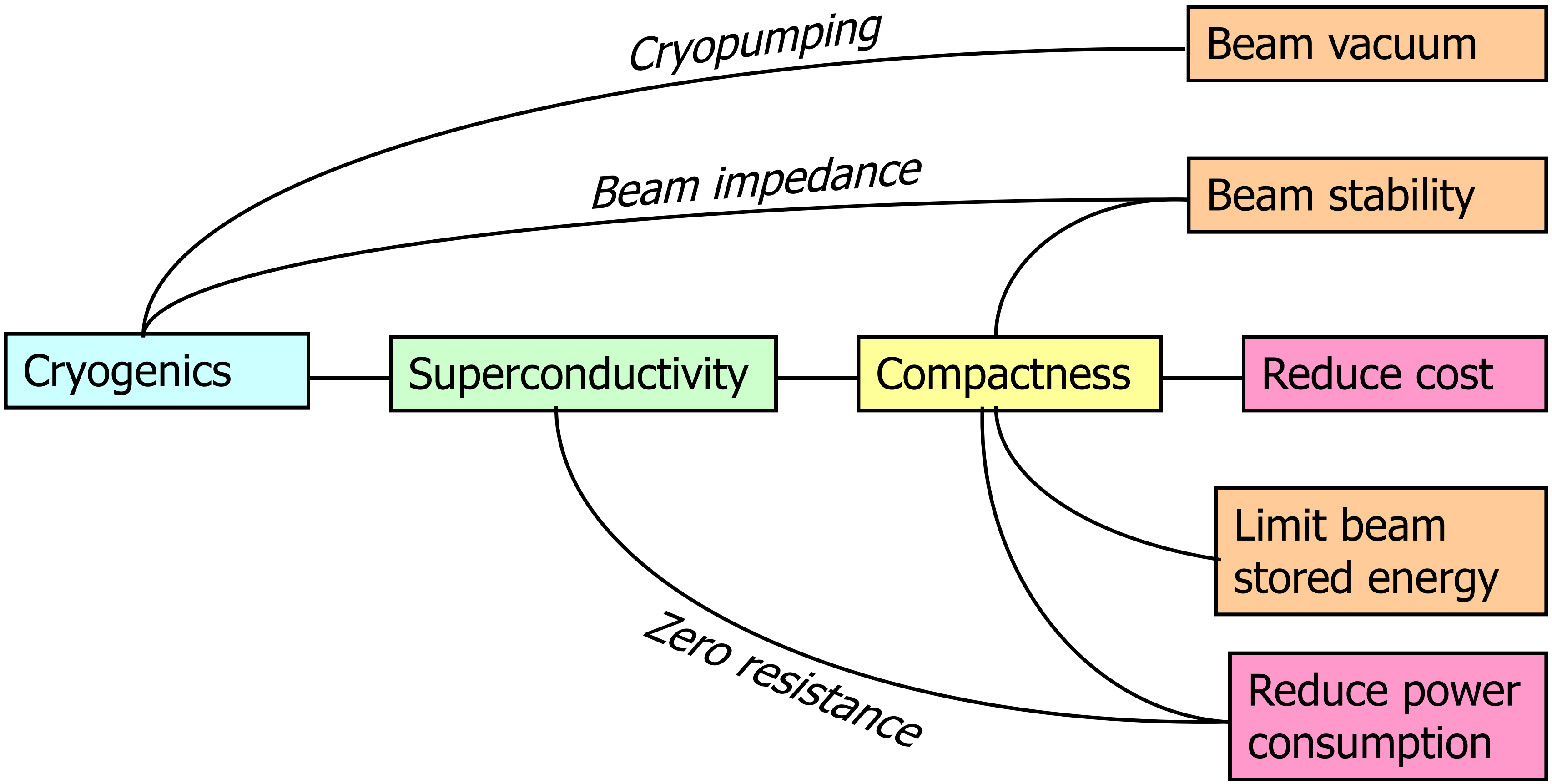


Cryopumping maintains good vacuum



Saturation pressure of all gases except helium vanish at cryogenic temperature

Rationale for superconductivity & cryogenics in particle accelerators



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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

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

These numbers may be used for measuring heat load to a cryogen bath from boil-off flow measurements at constant liquid level

At decreasing level, the escaping flow is lower than the vaporization rate and a correction must be applied

$$\dot{m}_{out} = \dot{m}_{vap}\left(1 - \frac{\rho_v}{\rho_l}\right) < \dot{m}_{vap}$$

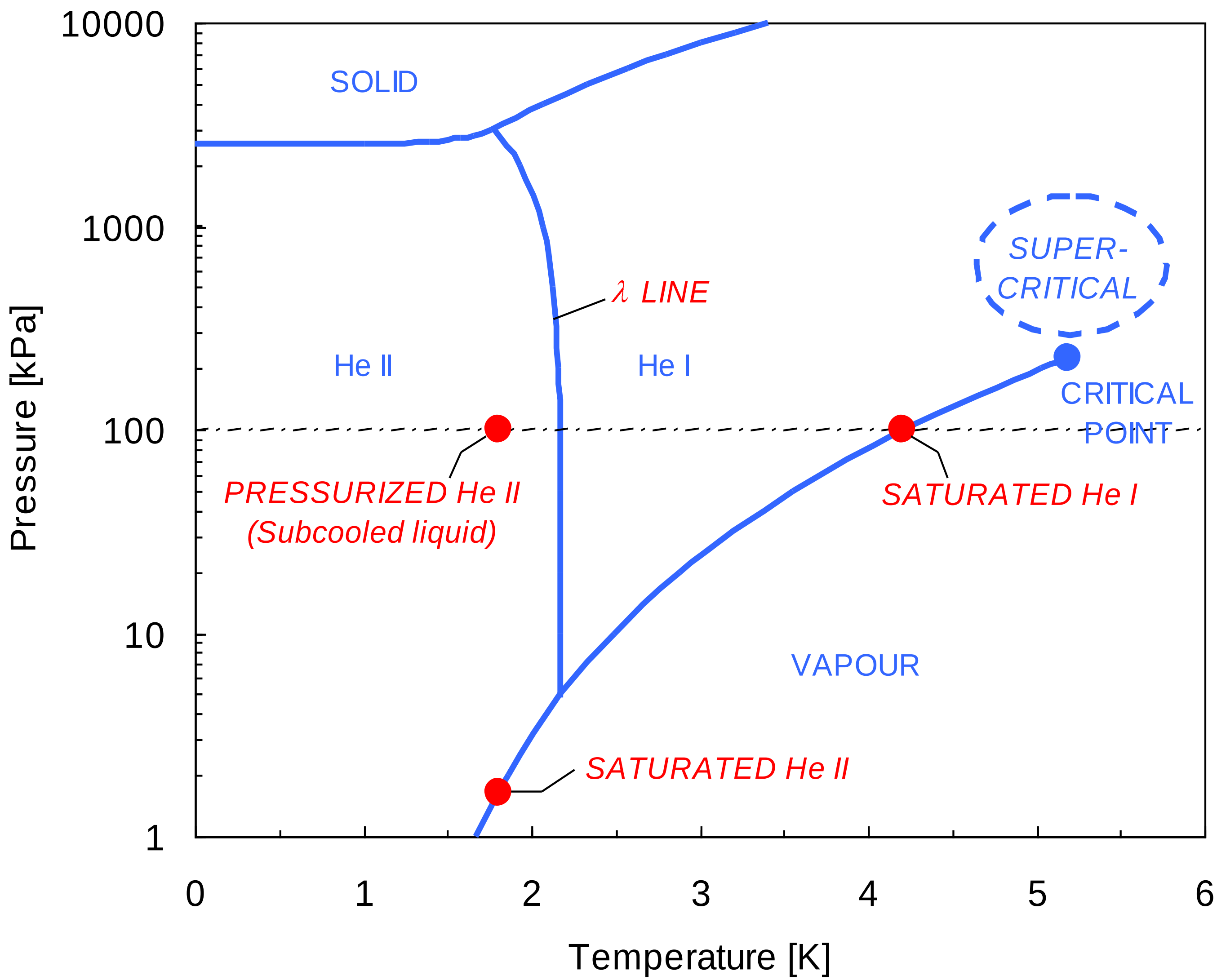
Amount of cryogens required to cool down 1 kg iron

Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 litre	0.75 liter
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

⇒ *recover enthalpy from cold gas (i.e. moderate flow of cryogen)*

⇒ *pre-cool with liquid nitrogen to save liquid helium*

Phase diagram of helium

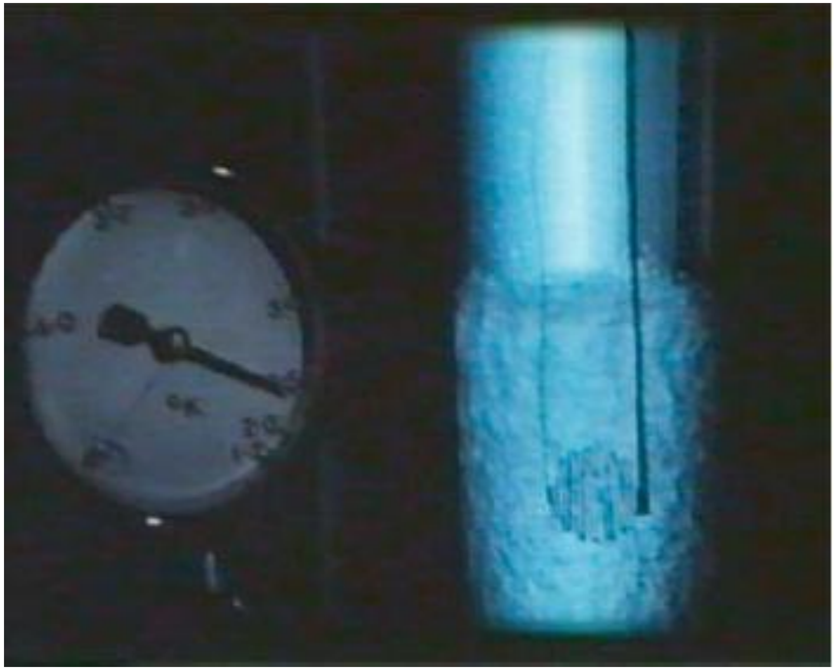


Helium as a cooling fluid

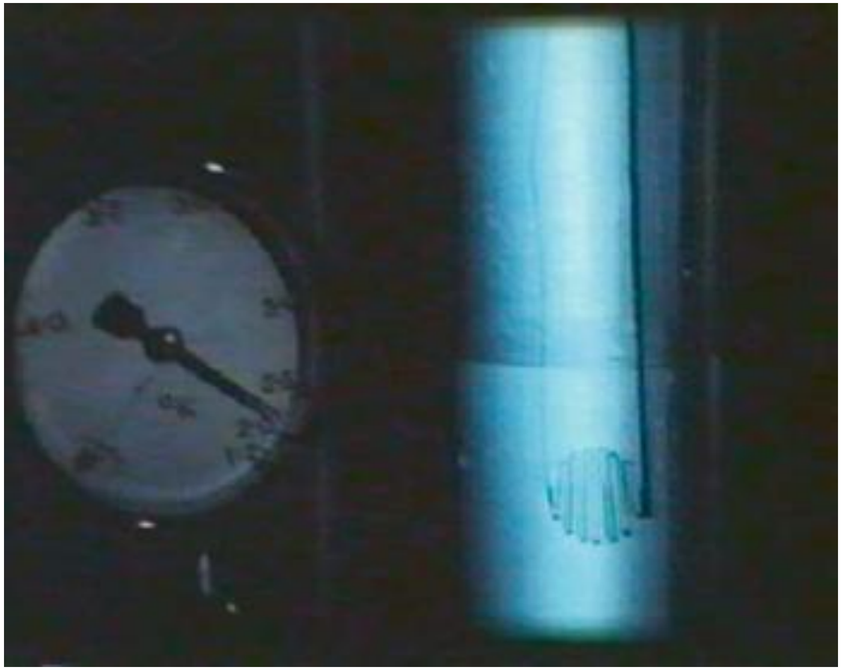
Phase domain	Advantages	Drawbacks
Saturated He I	Fixed temperature High heat transfer	Two-phase flow Boiling crisis
Supercritical	Monophase Negative J-T effect	Non-isothermal Density wave instability
He II	Low temperature High conductivity Low viscosity	Second-law cost Subatmospheric

High thermal conductivity of helium II suppresses boiling

Electrical heater in saturated liquid helium



He I (T=2.4 K)



He II (T=2.1 K)

Contents

Basic thermodynamics at low temperature

- Minimum refrigeration work W_{min} to extract heat Q at temperature T and reject it at ambient temperature T_a

$$W_{min} = Q\,(T_a/T - 1) = T_a\,\Delta S - Q$$

[Carnot] [Clausius]

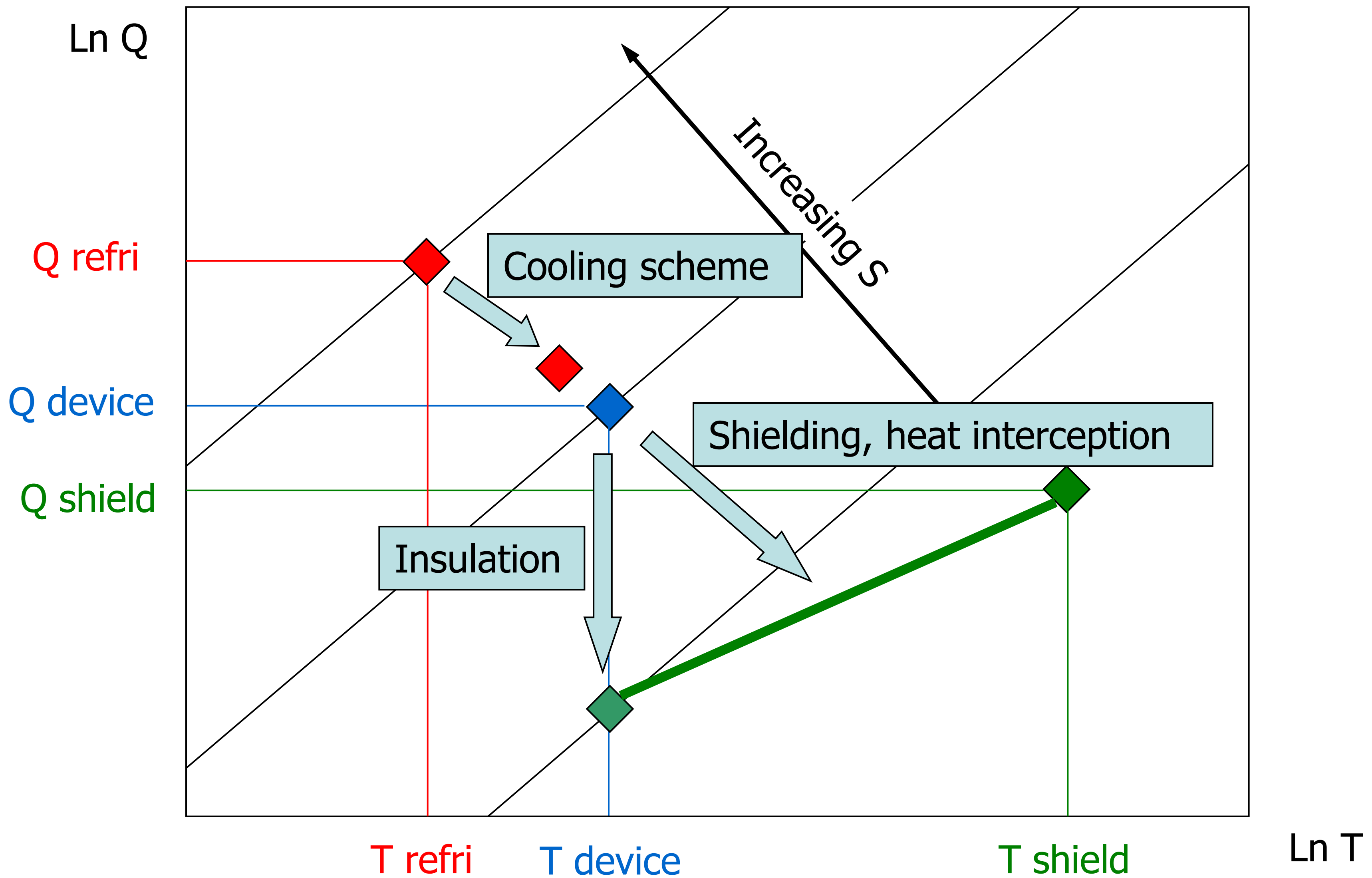
- At cryogenic temperature $T \ll T_a$

$$W_{min} \simeq Q\,T_a/T \simeq T_a\,\Delta S$$

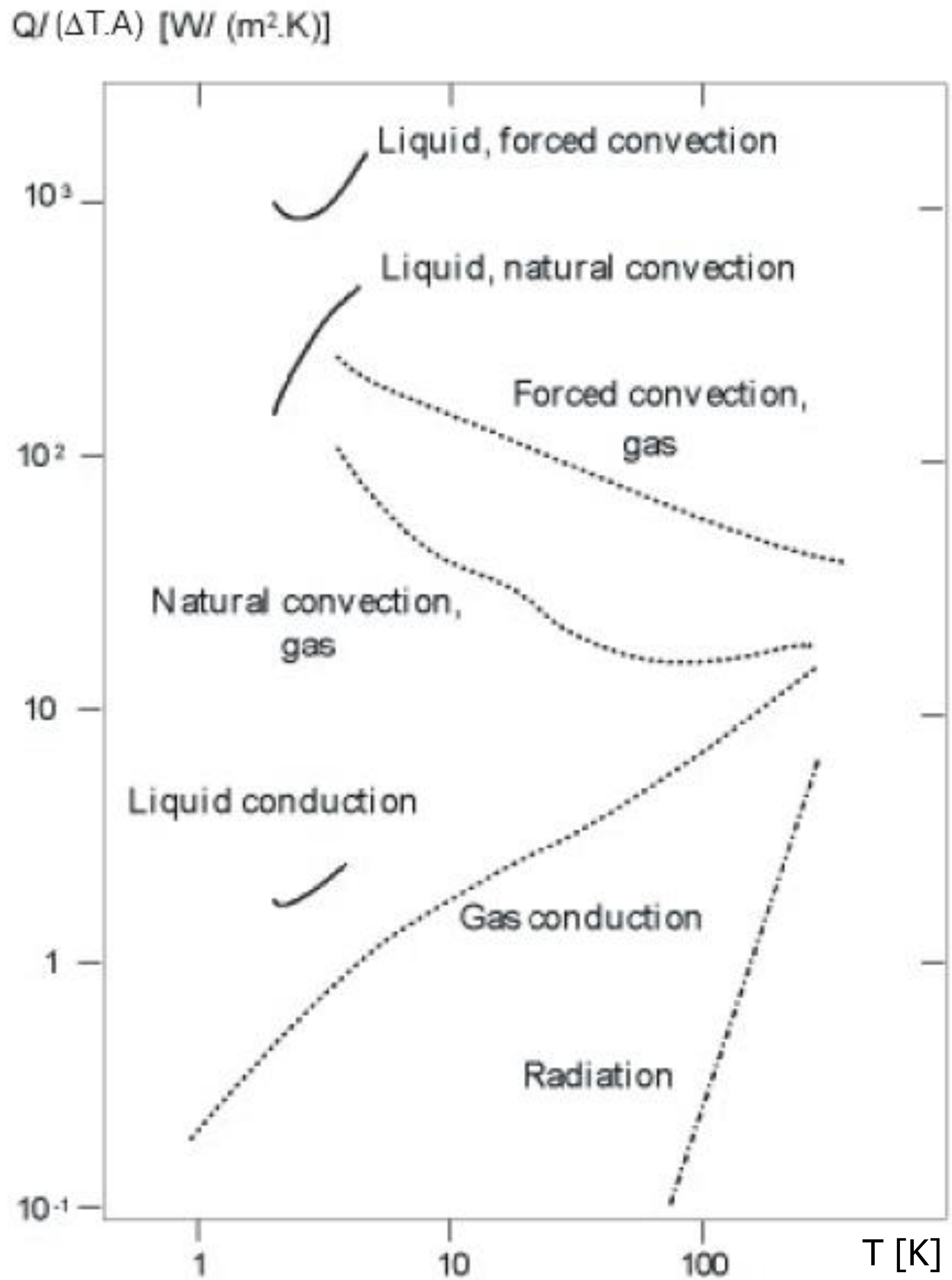
⇒ *entropy is a good measure of the cost of cryogenic refrigeration*

⇒ *strategies minimizing ΔS improve cryogenic design*

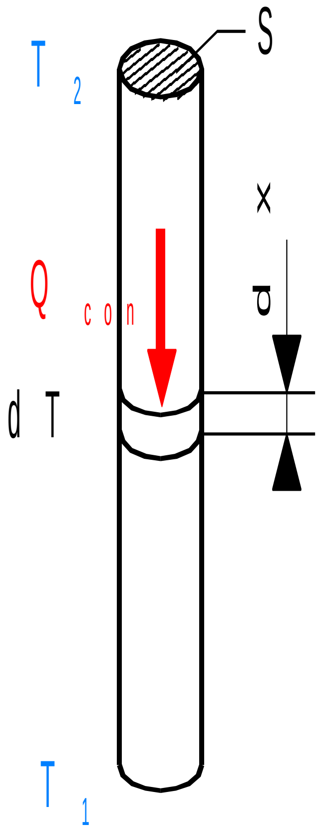
Cryogenic design strategies



Typical heat transfer coefficients at cryogenic temperatures



Heat conduction in solids



Fourier's law:

$$Q_{con} = k(T) \cdot S \cdot \frac{dT}{dx}$$

k(T): thermal conductivity [W/m.K]

Integral form:

$$Q_{con} = \frac{S}{L} \cdot \int_{T1}^{T2} k(T) \cdot dT$$

$\int k(T) \cdot dT$: thermal conductivity integral [W/m]

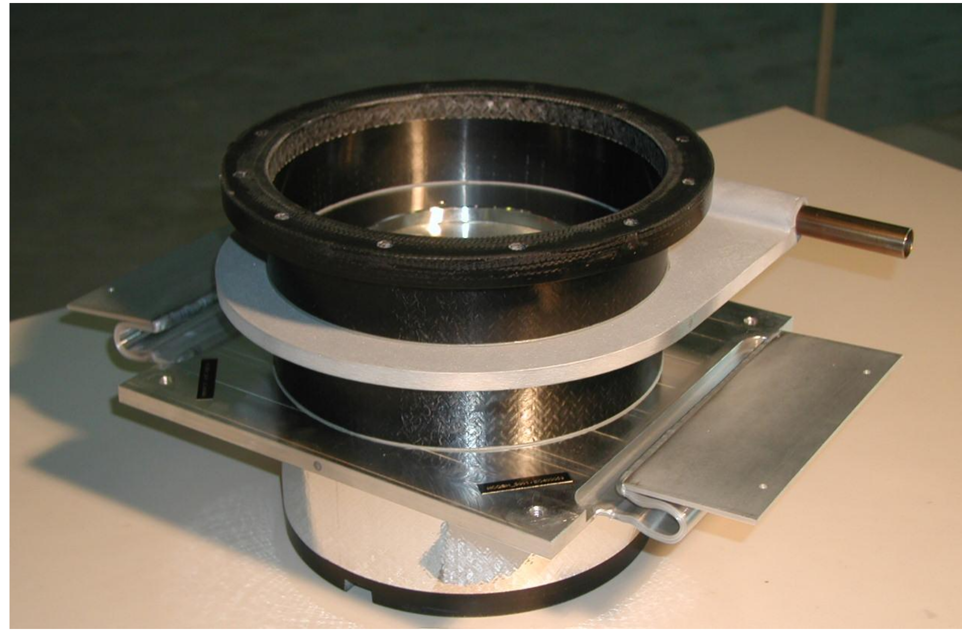
Thermal conductivity integrals for standard construction materials are tabulated

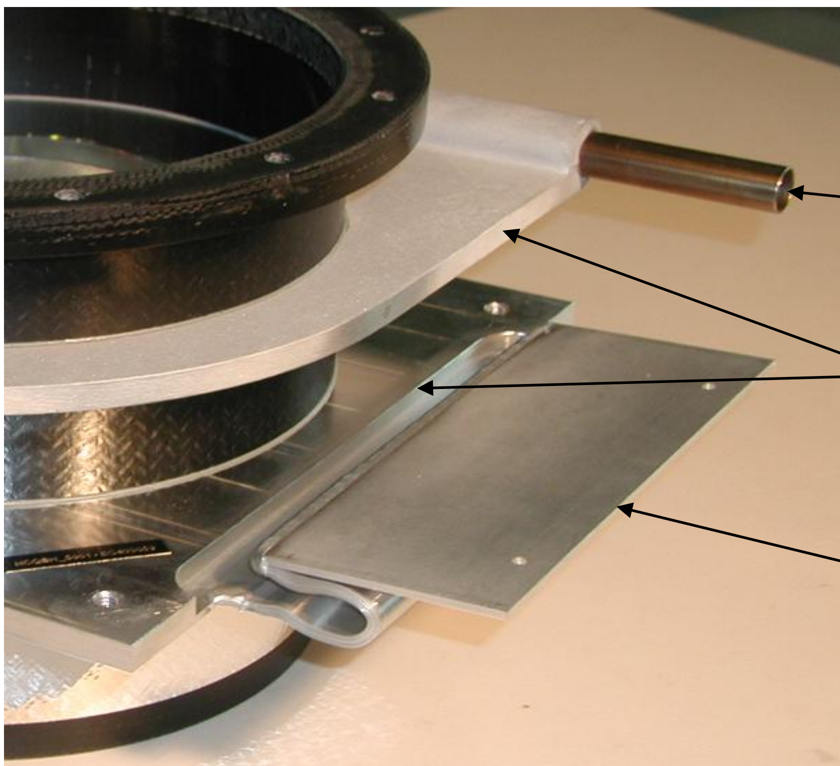
Thermal conductivity integrals of selected materials [W/m]

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

CERN

Non-metallic composite support post with heat intercepts



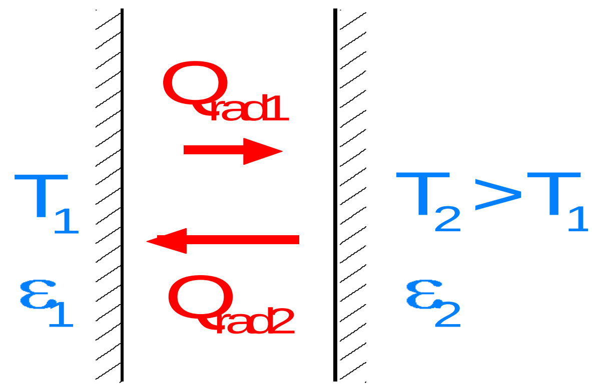


5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

Aluminium strips to thermal shield at 50-75 K

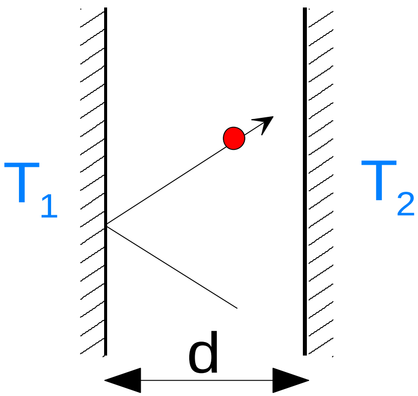
Thermal radiation



- Wien's law
  - Maximum of black body power spectrum
    $\lambda_{max}.T$ = 2898 [μm.K]
- Stefan-Boltzmann's law
  - Black body — $Q_{rad} = \sigma A T^4$
    σ = 5.67 x 10^{-8} $W/m^2.K^4$
    (Stefan Boltzmann's constant)
  - "Gray"body — $Q_{rad} = \varepsilon \sigma A T^4$
    ε emissivity of surface
  - "Gray" surfaces at T_1 and T_2 — $Q_{rad} = E \sigma A (T_1^4 - T_2^4)$
    E function of ε_1, ε_2, geometry

Emissivity of technical materials at low temperatures

	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

$\lambda_{molecule}$: mean free path of gas molecules

- <u>Viscous regime</u>
  - At high gas pressure $\lambda_{molecule} << d$
  - Classical conduction $Q_{res} = k(T)\, A\, dT/dx$
  - Thermal conductivity $k(T)$ independant of pressure
- <u>Molecular regime</u>
  - At low gas pressure $\lambda_{molecule} >> d$
  - Kennard's law $Q_{res} = A\, \alpha(T)\, \Omega\, P\, (T_2 - T_1)$
  - Conduction 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

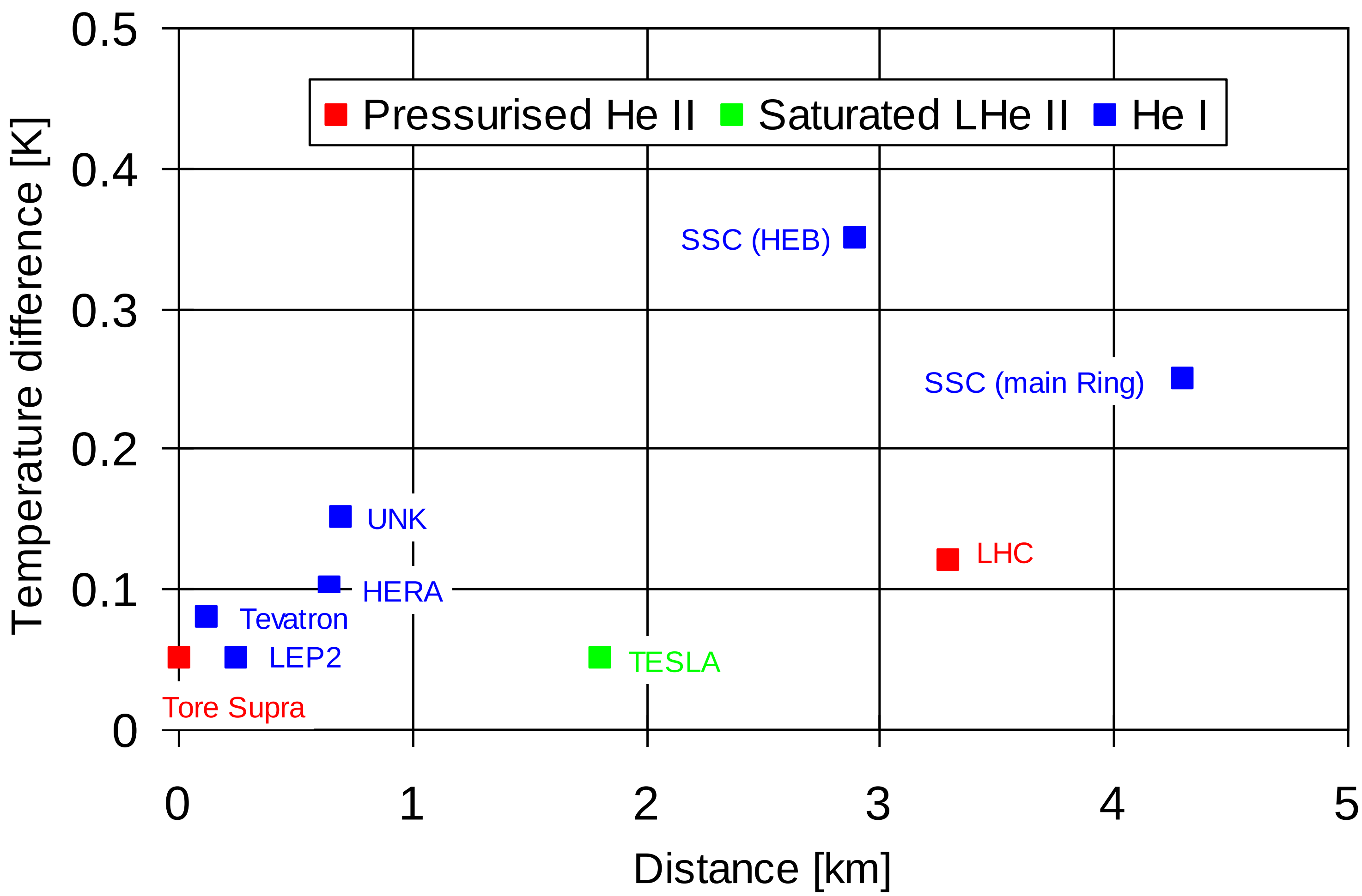
Multi-layer insulation (MLI)

- Complex system involving three heat transfer processes
  - $Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res}$
  - With n reflective layers of equal emissivity, $Q_{rad} \sim 1/(n+1)$
  - Due to parasitic contacts between layers, Q_{sol} increases with layer density
  - Q_{res} due to residual gas trapped between layers, scales as 1/n in molecular regime
  - Non-linear 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

Transport of refrigeration in large distributed cryogenic systems



Cryogenic distribution scheme: design issues

- Monophase vs. two-phase
  - temperature control
  - hydrostatic head & flow instabilities
- Pumps vs. no pumps
  - efficiency & cost
  - reliability & safety
- Use of liquid nitrogen
  - cooldown and/or normal operation
  - capital & operating costs of additional fluid
  - safety in underground areas (ODH)
- Lumped vs. distributed cryoplants
- Separate cryoline vs. integrated piping
- Number of active components (valves, actuators)
- Redundancy of configuration

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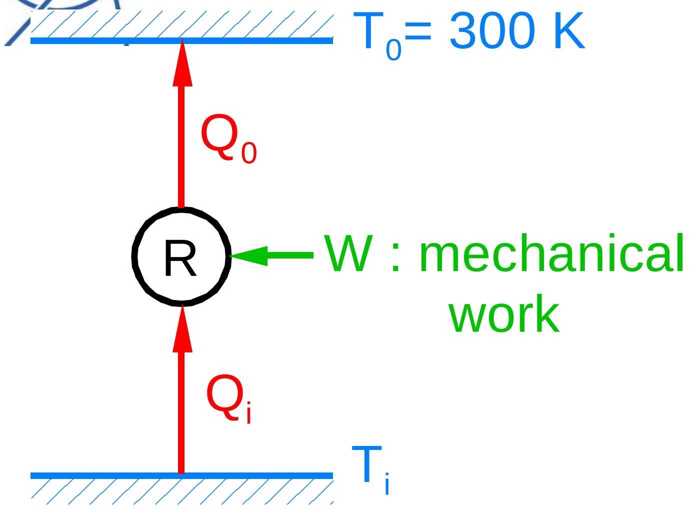
Thermodynamics of cryogenic refrigeration



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

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

2. $W \geq Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right)$ ← Carnot factor: $\left(\frac{T_0}{T_i} - 1 \right)$

3. $W \geq \Delta E_i$ introducing exergy E as $\Delta E_i = Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right)$

Minimum refrigeration work

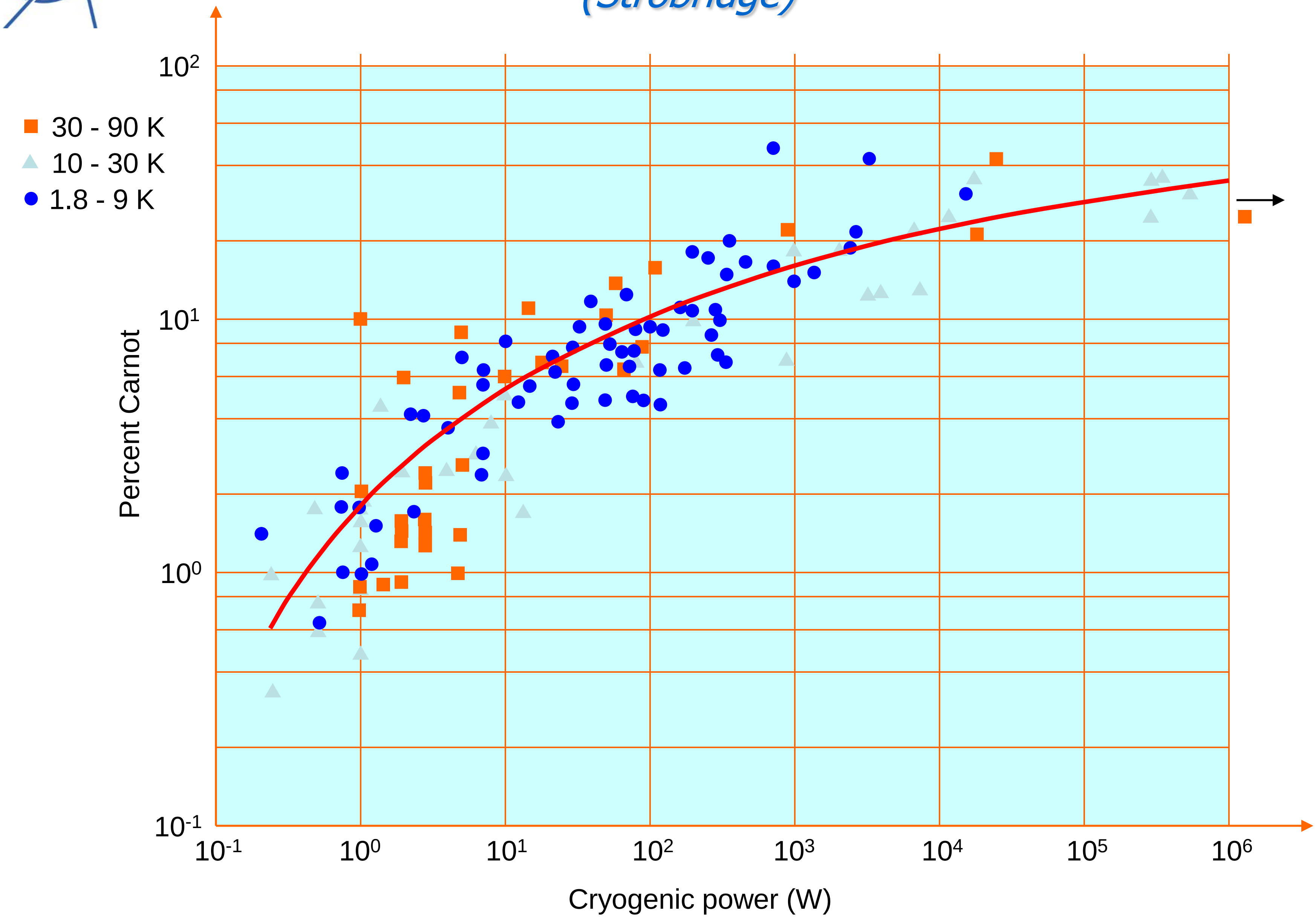
Consider the extraction of 1 W at 4.5 K, rejected at 300 K
The minimum refrigeration work (equation 2) is:

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

In practice, the most efficient helium refrigerators have an efficiency of about 30% w.r. to the Carnot limit

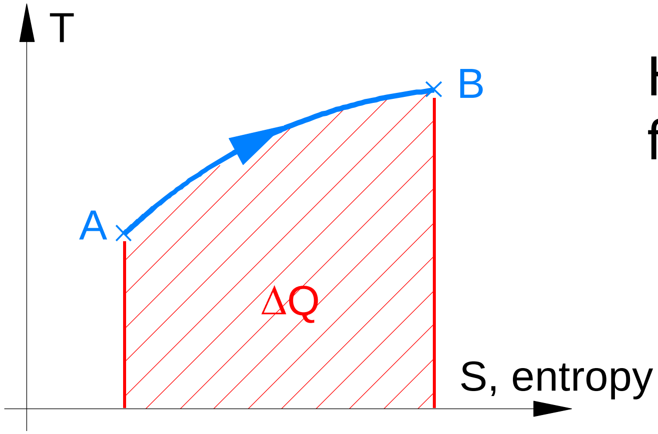
$$\Rightarrow \ W_{real} = \frac{W_{min}}{\eta} = \frac{65.7}{0.3} = 220 \ \ W$$

Efficiency of cryogenic refrigerators
(Strobridge)



Refrigeration cycles and duties

Introduction to the T-S diagram

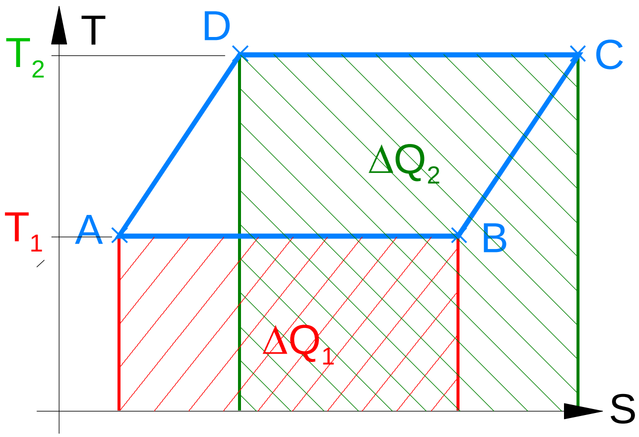


Heat involved in thermodynamic transformation from A to B, if reversible:

$$\Delta Q = \int_A^B T \cdot dS$$

To make a refrigeration cycle, need a substance, the entropy of which depends on some other variable than temperature

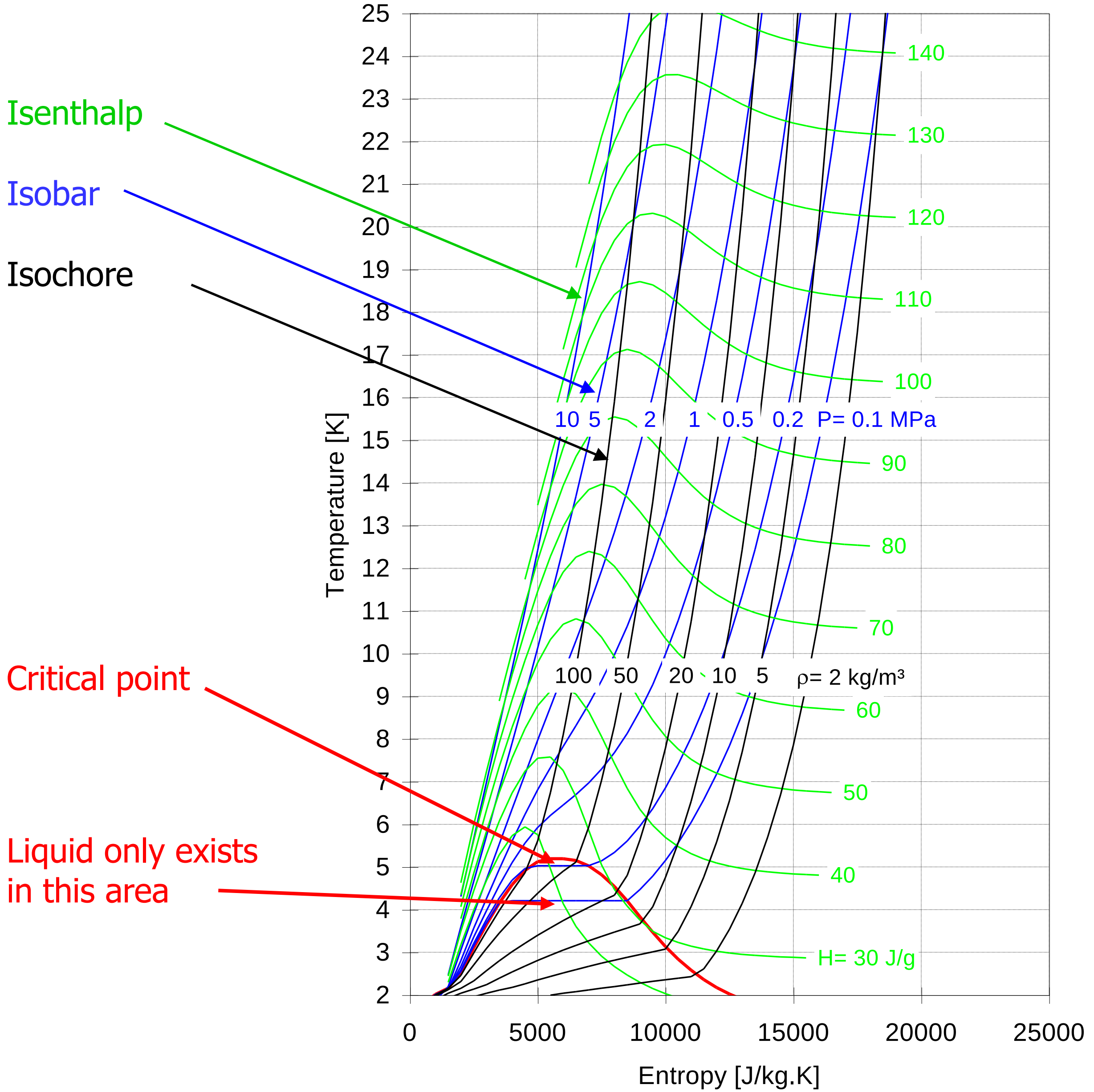
Pressure of gas: Compression/expansion cycle
Magnetization of solid: magnetic refr. cycle



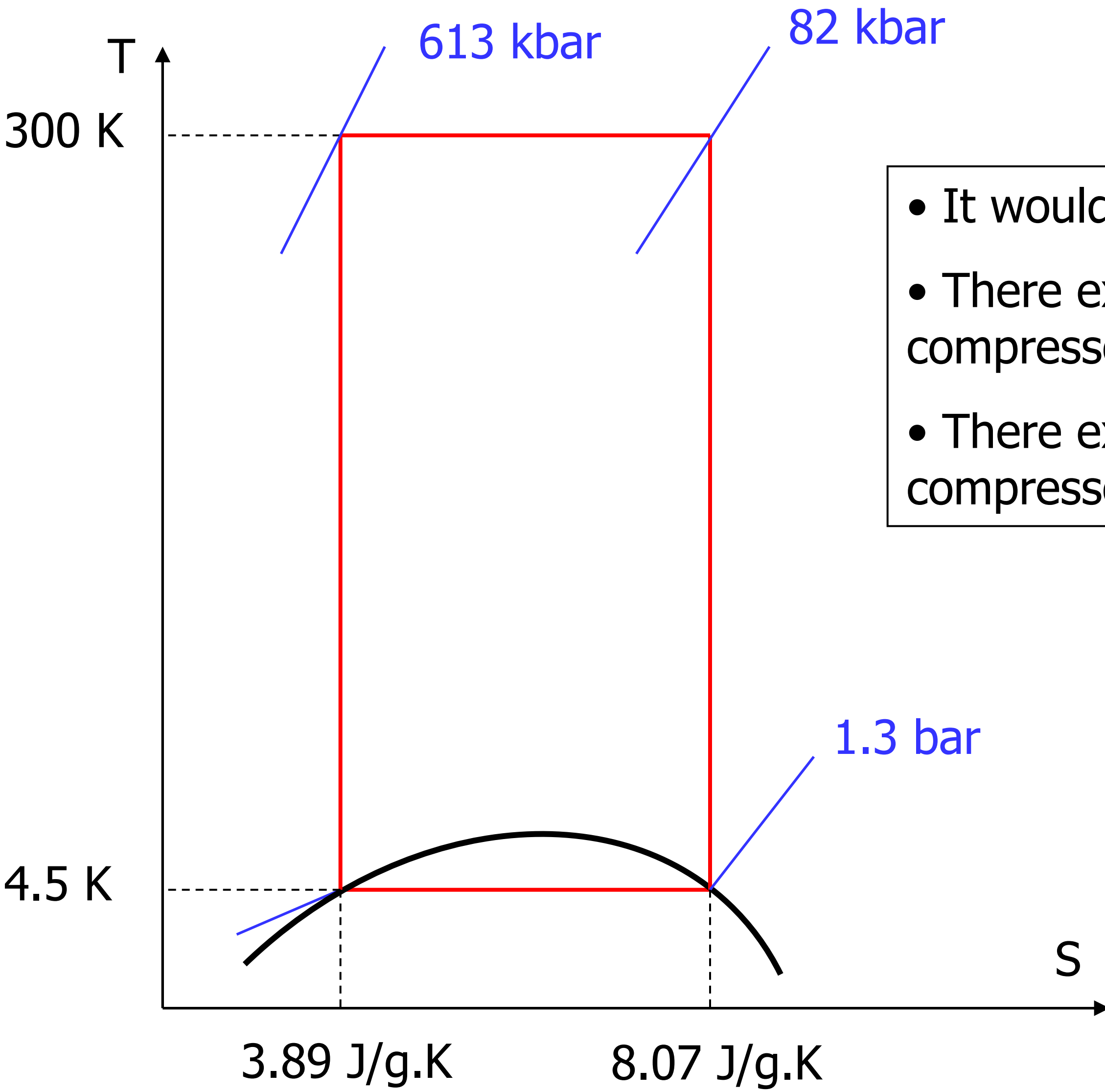
ΔQ_1: heat absorbed at T_1
ΔQ_2: heat rejected at T_2

→ Refrigeration cycle A B C D

T-S diagram for helium

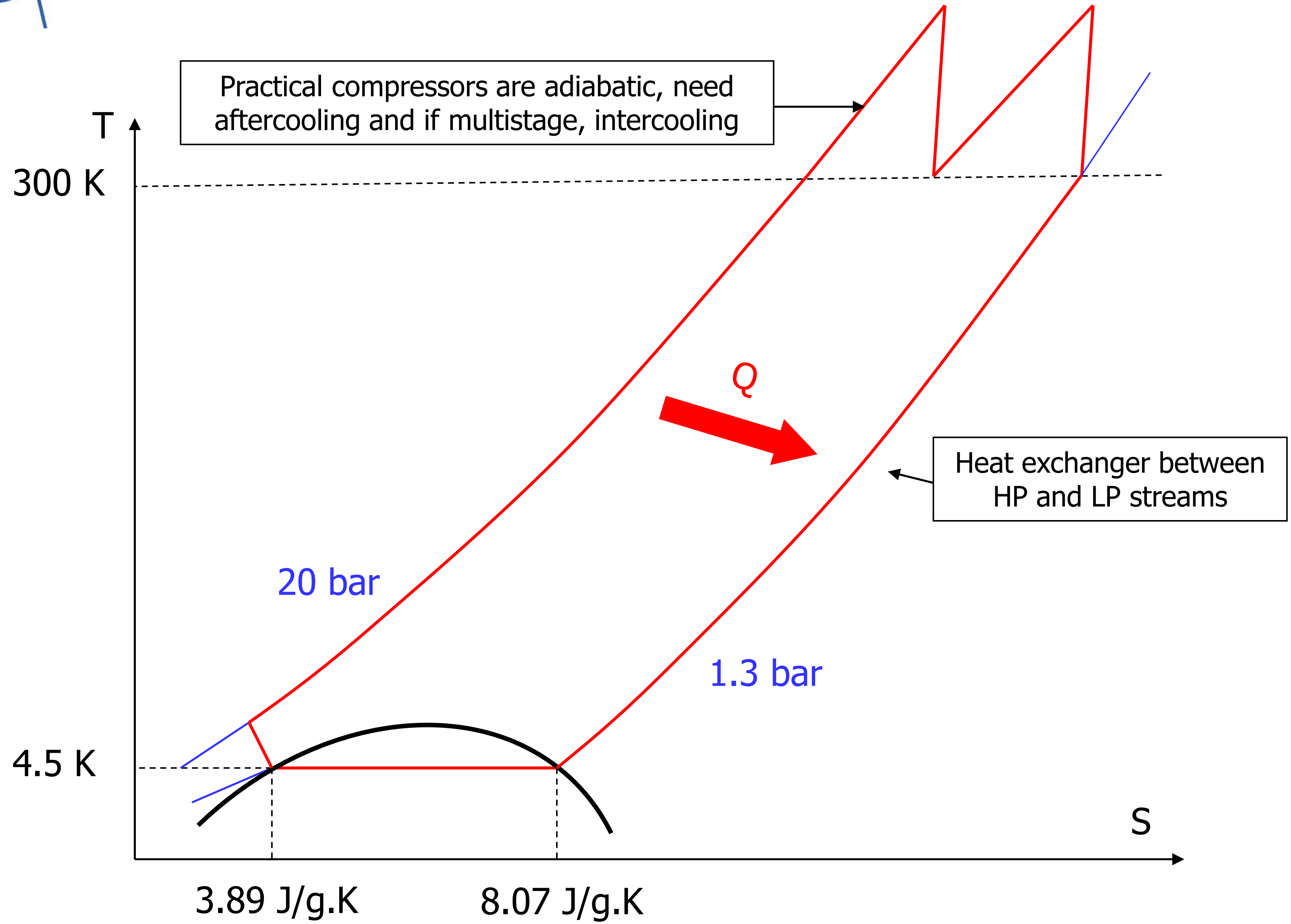


A Carnot cycle is not feasible for helium liquefaction

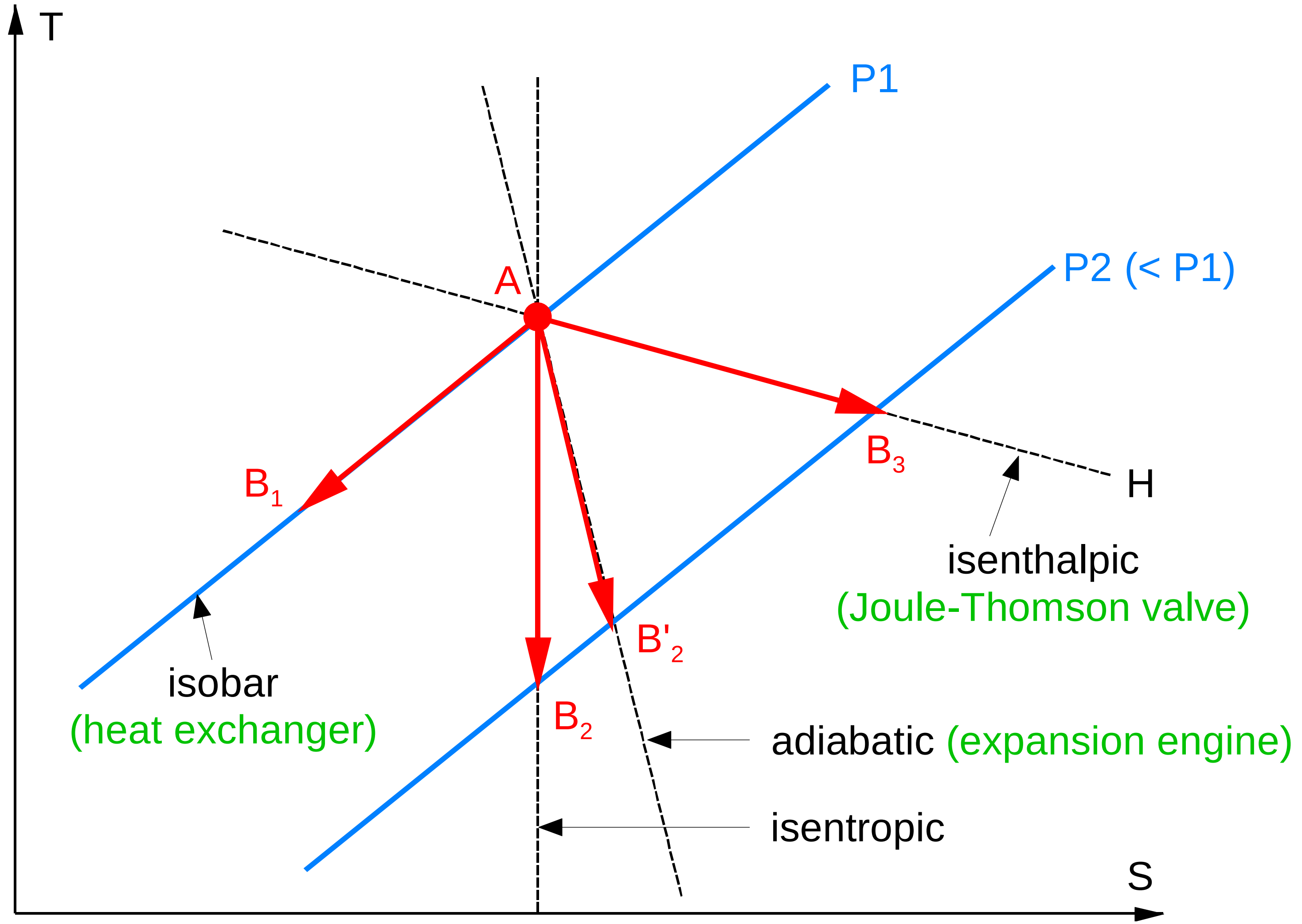


- It would need a HP of 613 kbar!
- There exists no true isothermal compressor
- There exists no true isentropic compressor or expander

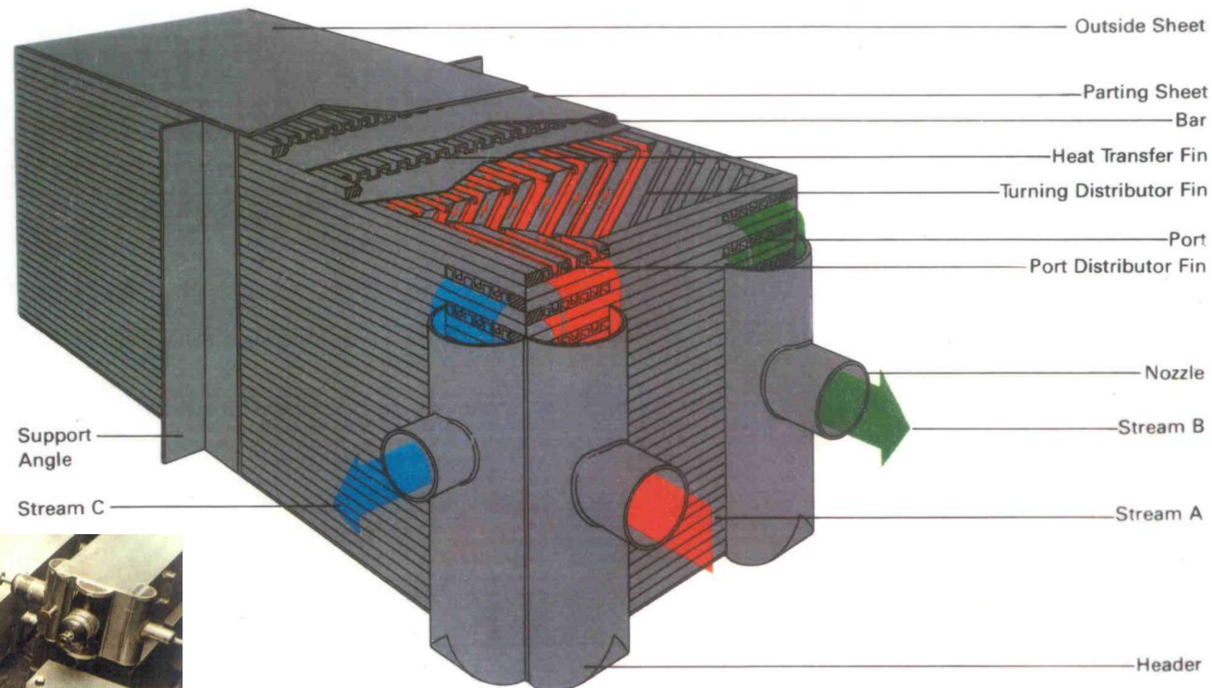
A real cycle for helium liquefaction
internal heat exchange and para-isothermal compression

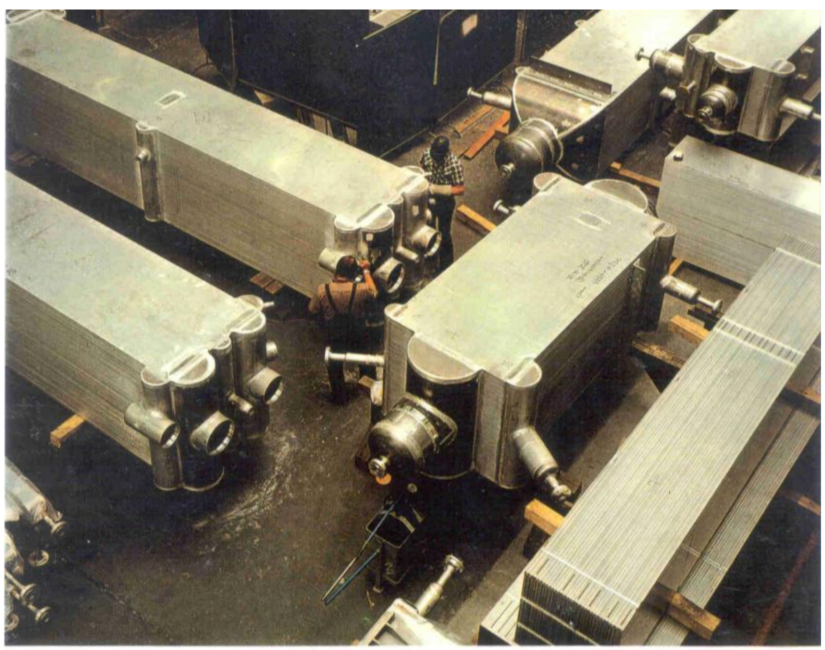


Elementary cooling processes on T-S diagram

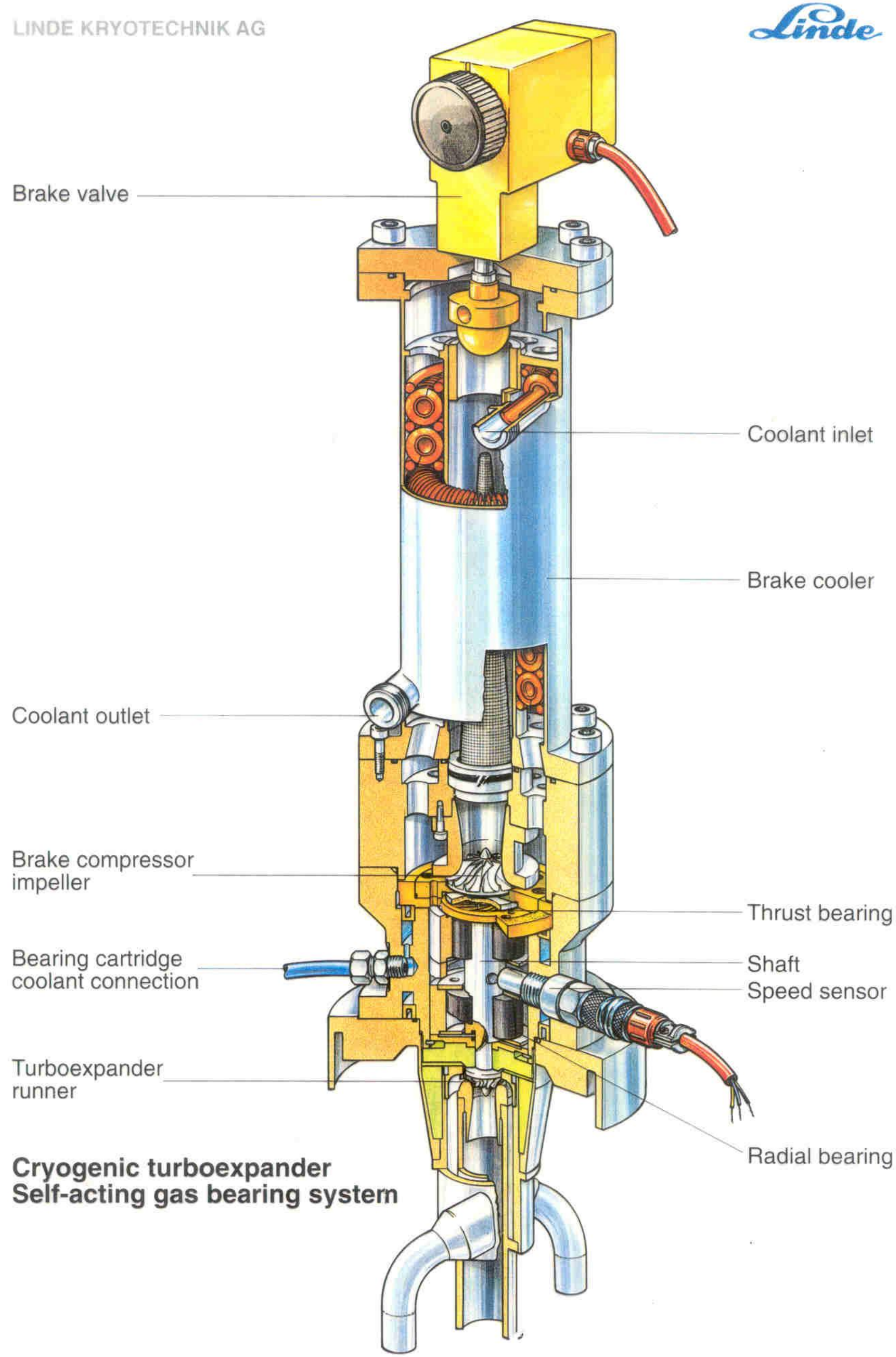


Brazed aluminium plate heat exchanger





Cryogenic turbo-expander

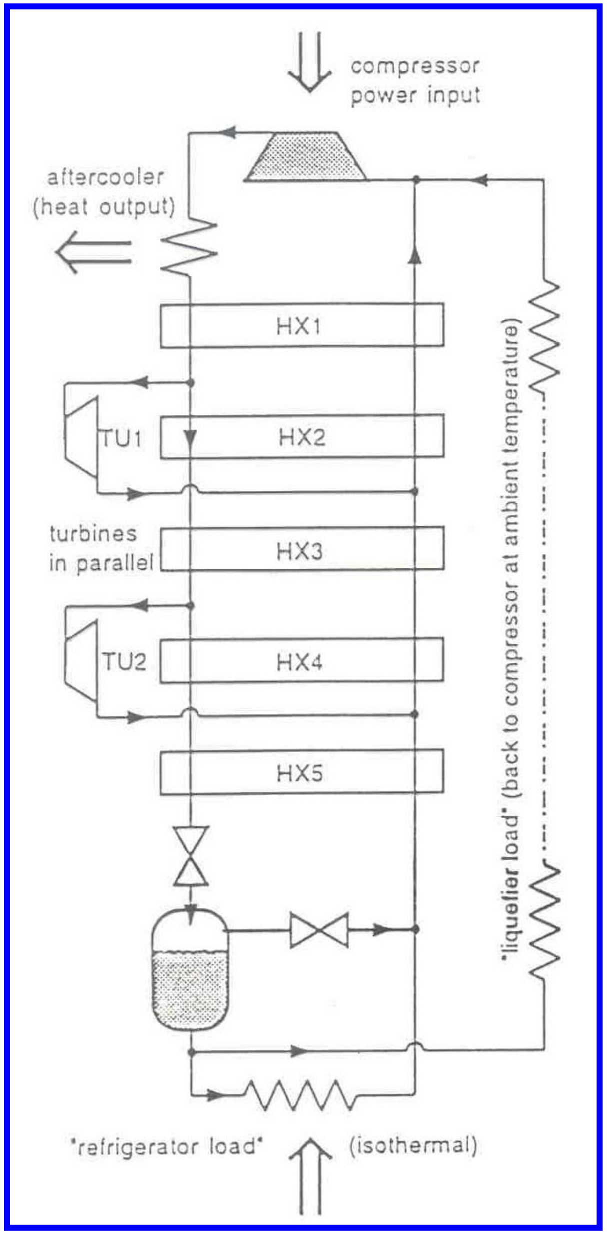


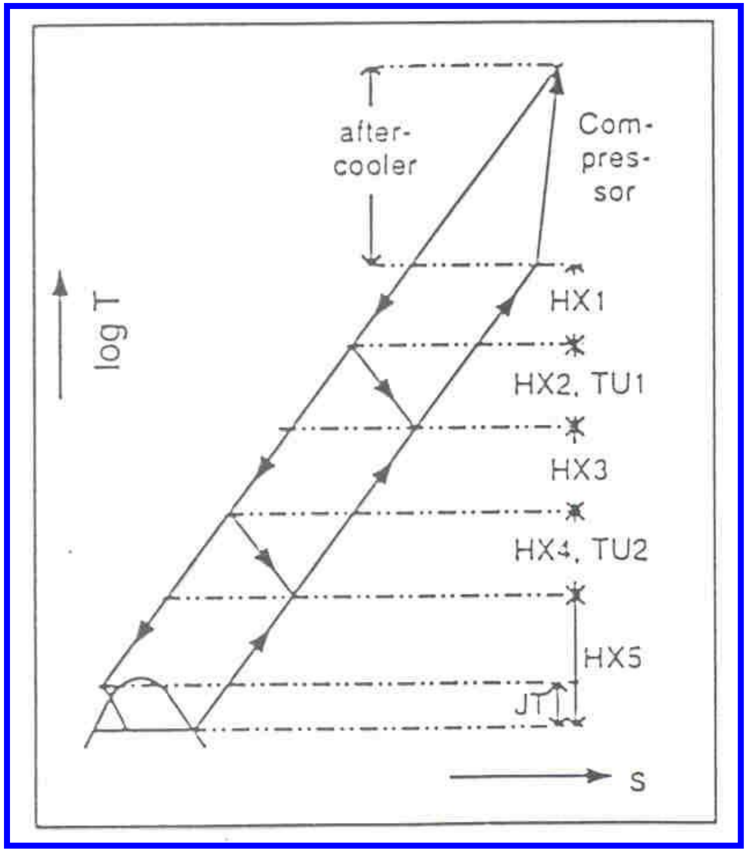
Maximum Joule-Thomson inversion temperatures

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

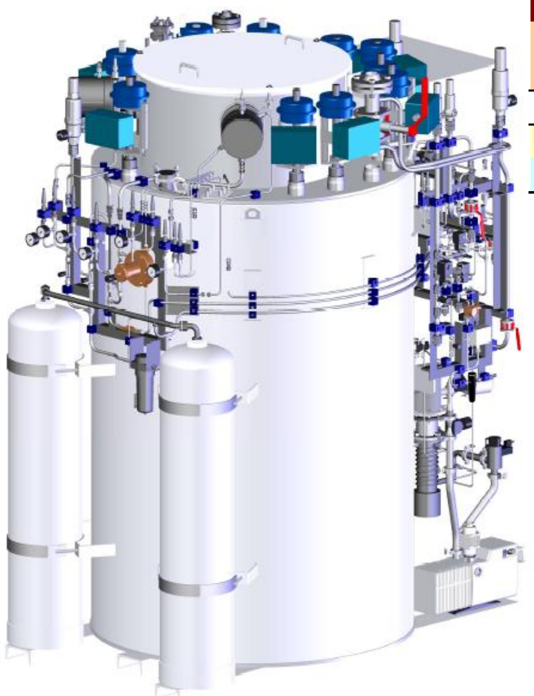
While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

Two-stage Claude cycle





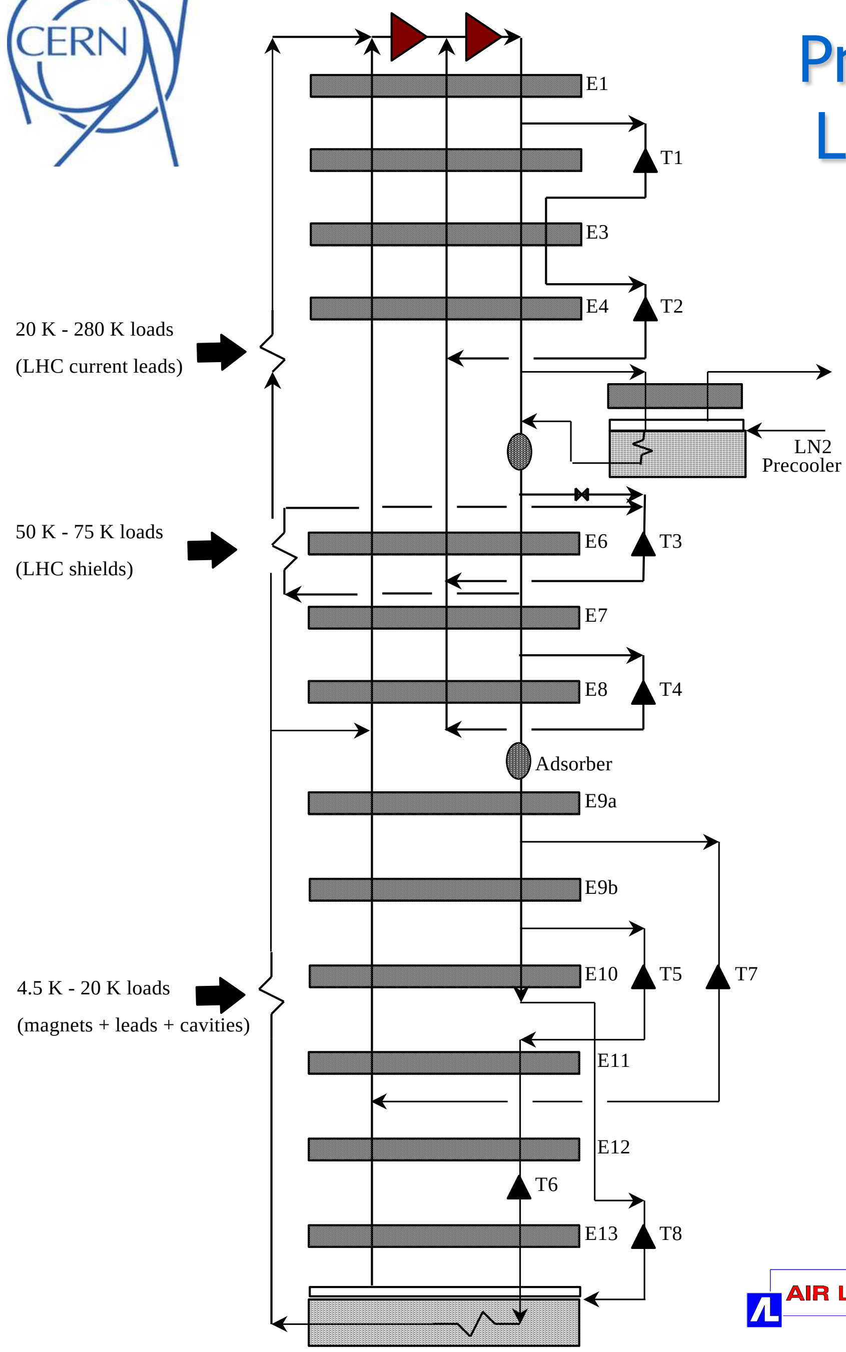
Commercial Claude-cycle helium refrigerators/liquefiers (Air Liquide & Linde)

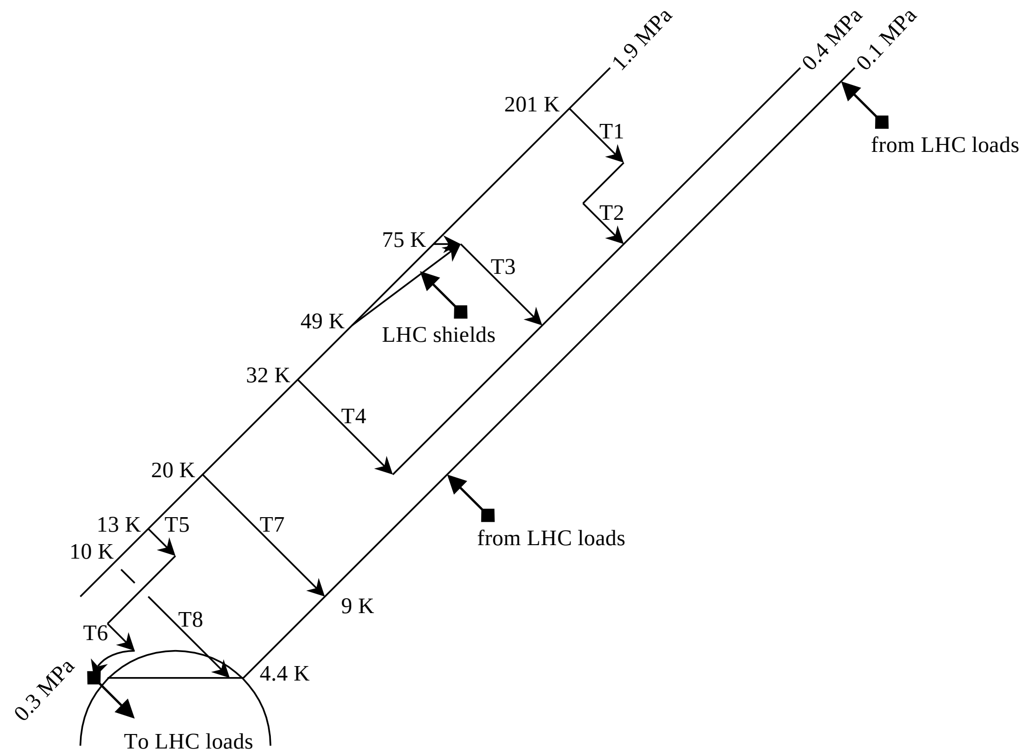


	HELIAL SL	HELIAL ML	HELIAL LL
Max. Liquefaction capacity without LN2	25 L/h	70 L/h	145 L/h
Max. Liquefaction capacity with LN2	50 L/h	150 L/h	330 L/h
Compressor electrical motor	55 kW	132 kW	250 kW
Specific consumption for liquefaction w/o LN2	645 W/W	552 W/W	505 W/W
% Carnot	**10%**	**12%**	**13%**

	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

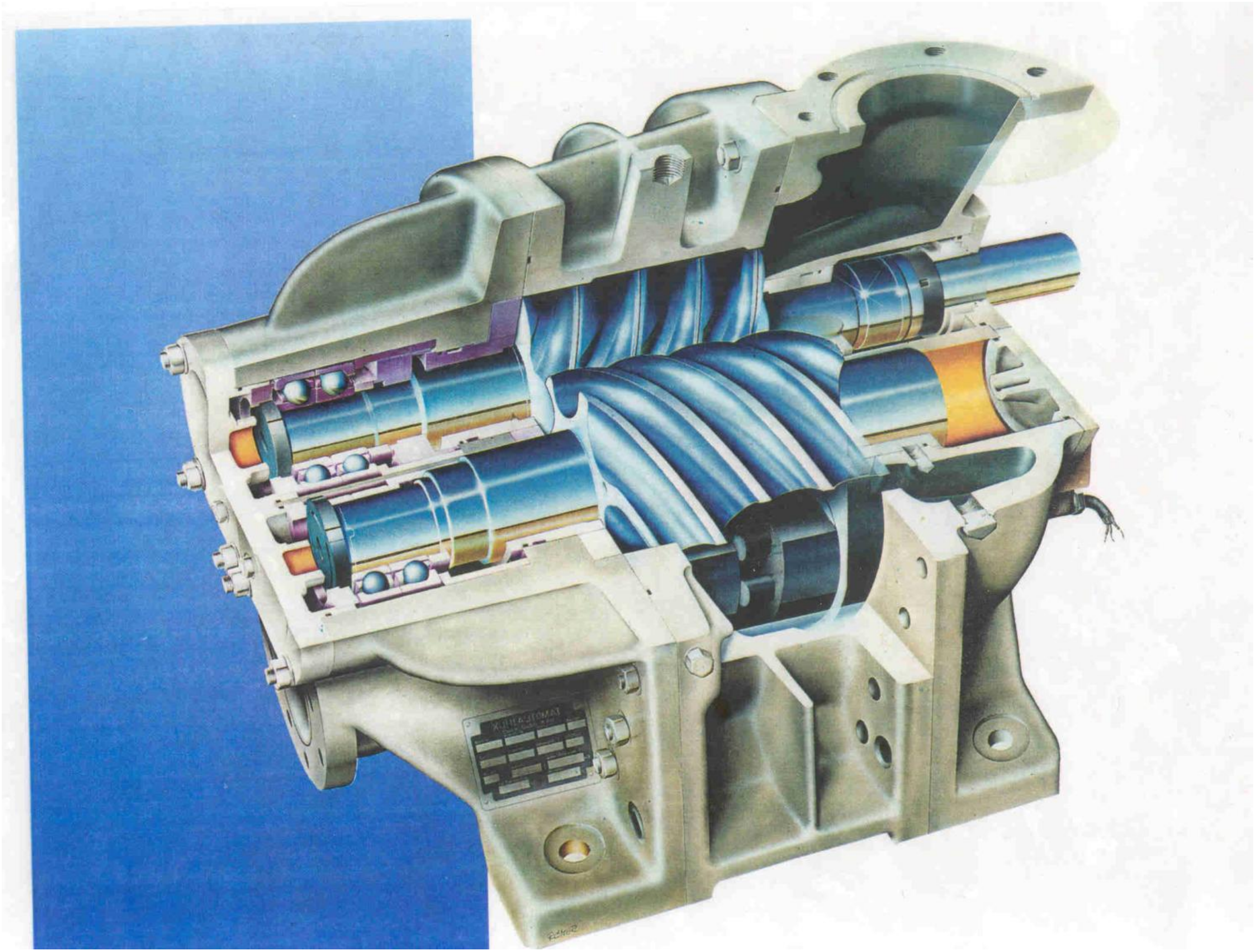




LHC 18 kW @ 4.5 K helium cryoplants

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

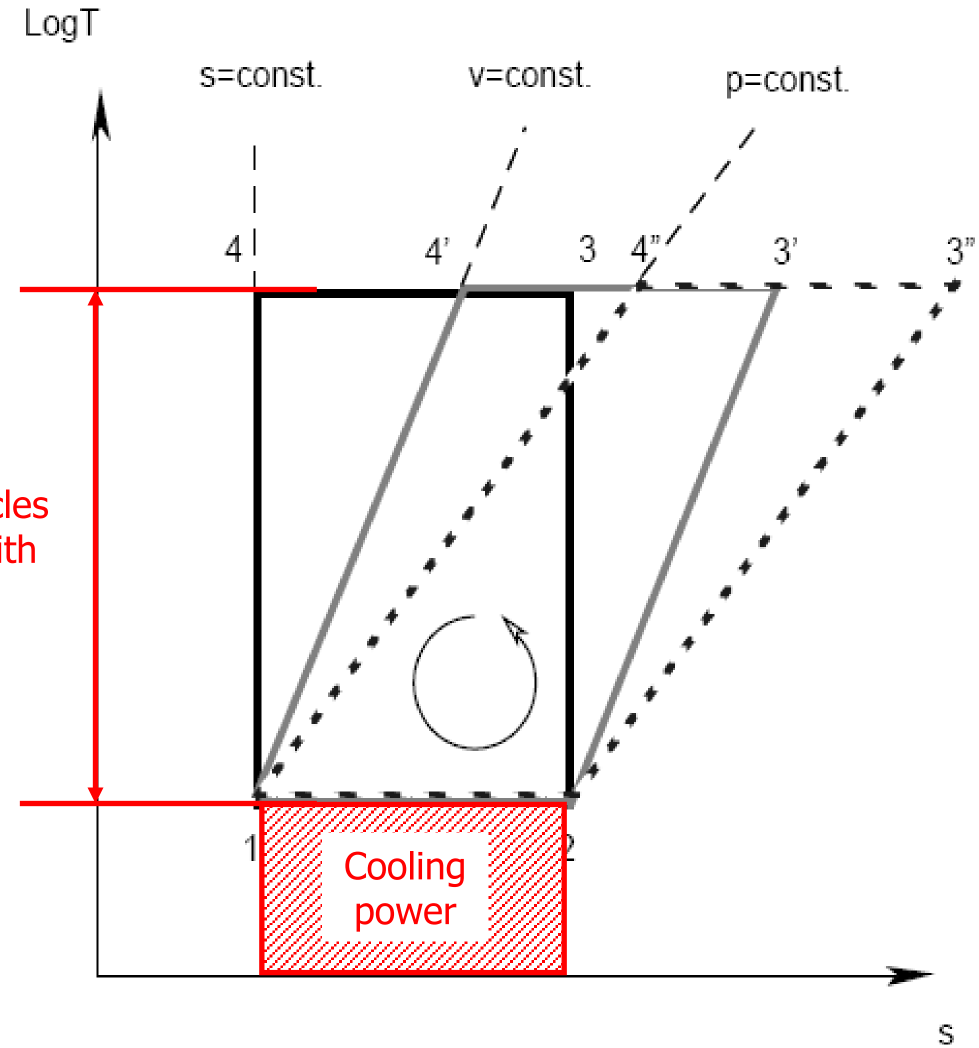
Oil-injected screw compressor



Compressor station of LHC 18 kW@ 4.5 K helium refrigerator

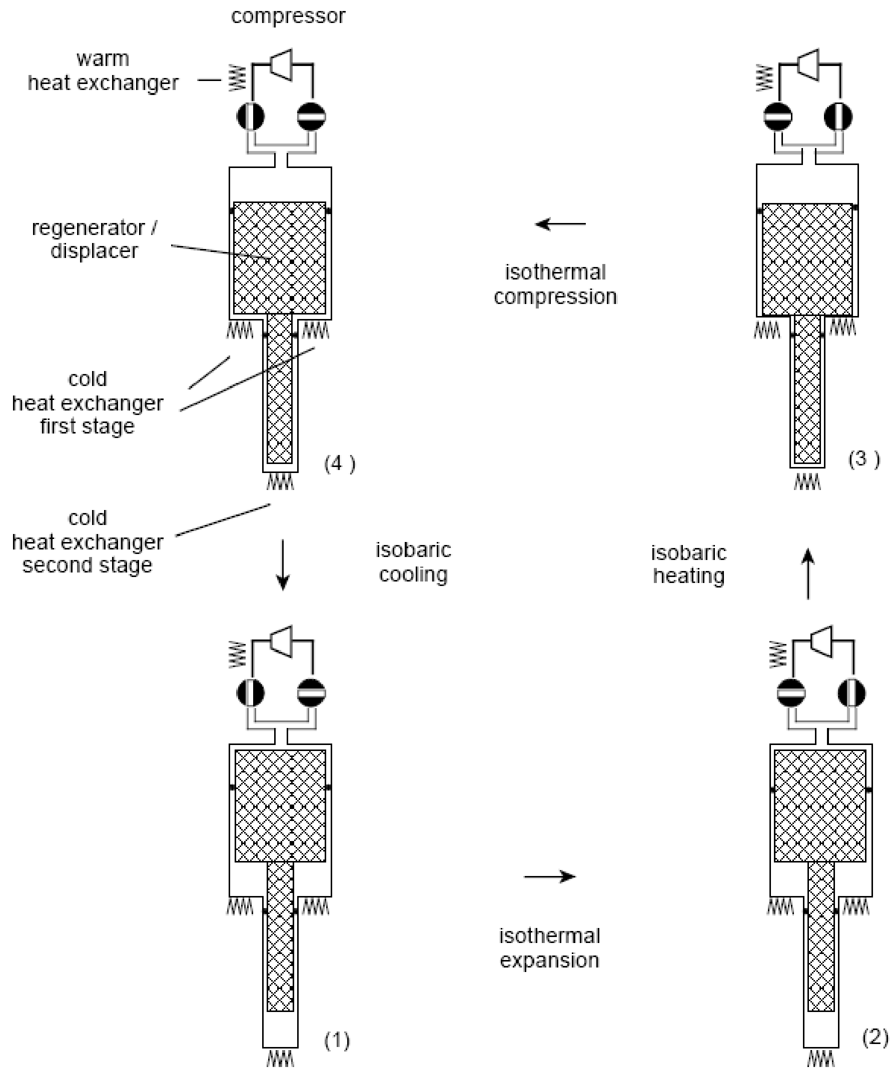
Carnot, Stirling and Ericsson cycles

In practice, many small cycles thermally in series, each with limited temperature span



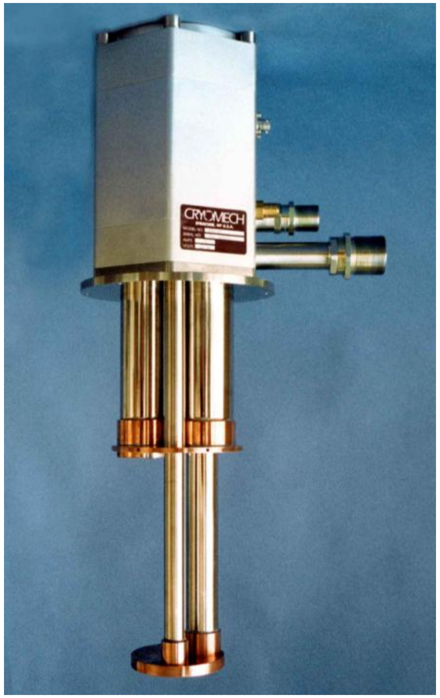
Carnot cycle (1,2,3,4), Stirling cycle (1,2,3',4') and Ericsson cycle (1,2,3",4")

Gifford-McMahon cryocooler (Ericsson cycle)

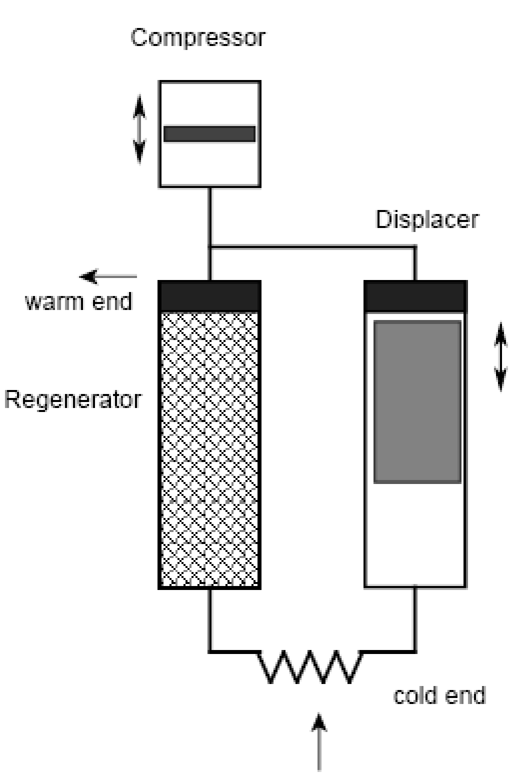


CRYOMECH PT407 & CP970 compressor

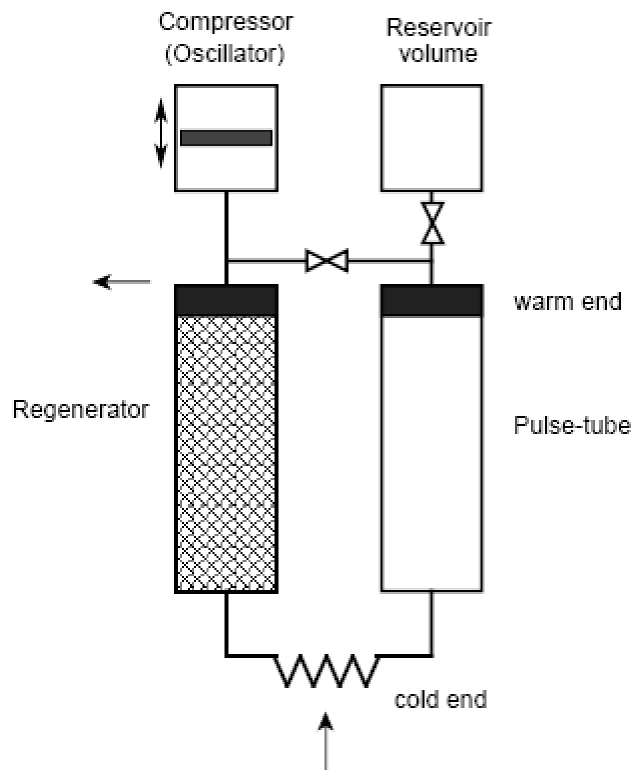
~ 0.7 W @ 4.2 K & 25 W @ 55 K



Stirling and pulse-tube cryocoolers



Stirling refrigerator



Pulse tube refrigerator

ESA MPTC development model

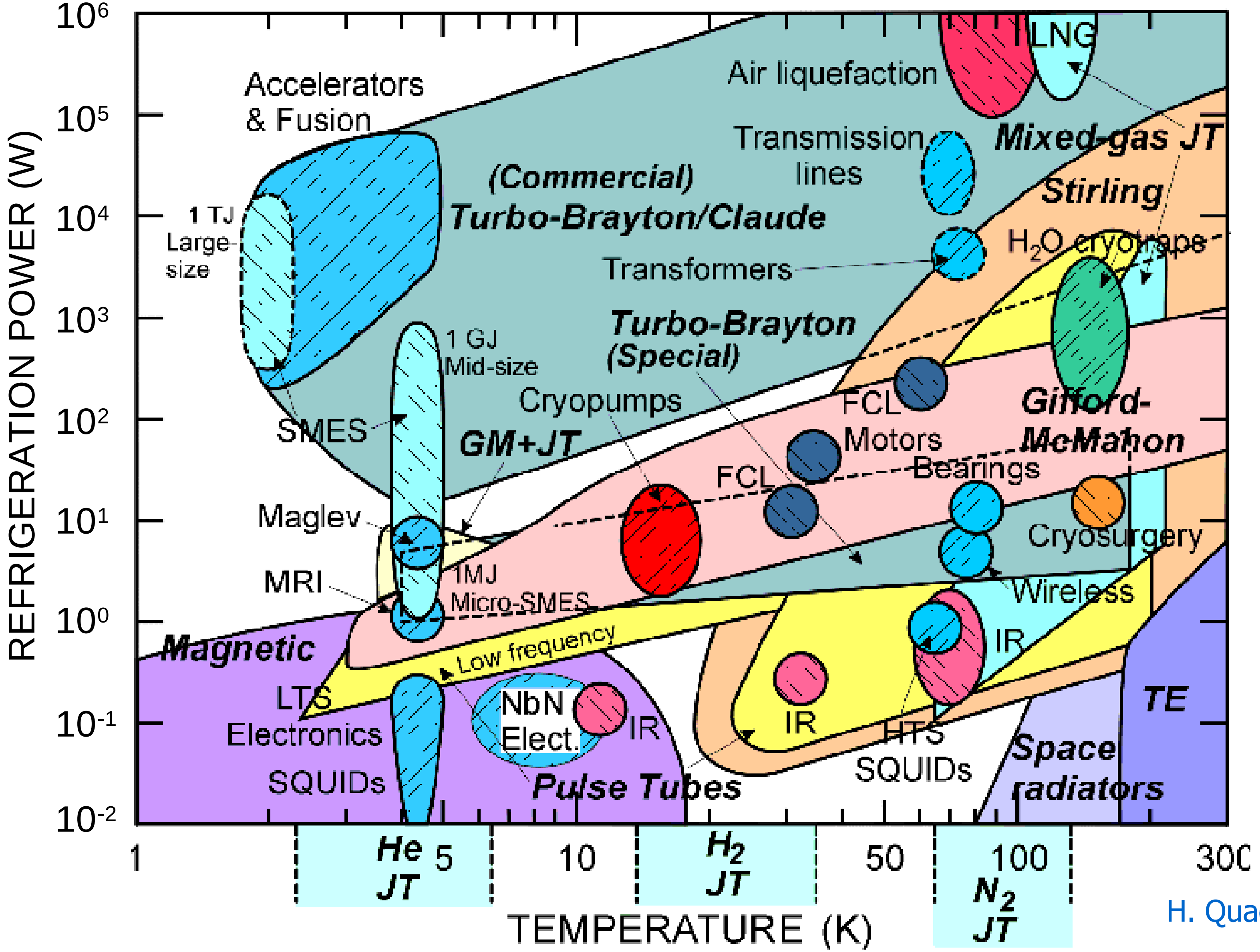
1W @ 77K

« Cryogen-free » superconducting magnets

4 T magnet (Accel) cooled by Gifford-McMahon cooler

MRI magnet (Bruker) with active shielding and recondensation of helium vapor by pulse-tube cooler

Selecting the right cryogenic refrigerator



H. Quack

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