TECHNISCHE UNIVERSITÄT DRESDEN

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Cryogenic Refrigeration Efficiency Over a Large Range of Temperature

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ESSRI Madrid,
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History of (cryogenic) cooling

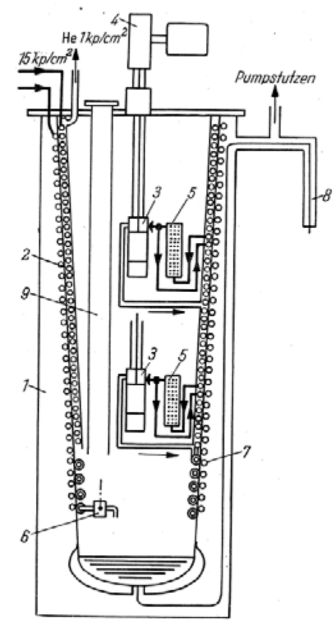
Ice harvest in winter / delivery / „cold box“

USA, NH_3 based
costs (1922): $ 714
car (Ford Model T): $ 450
average salery: $ 2000 / yr

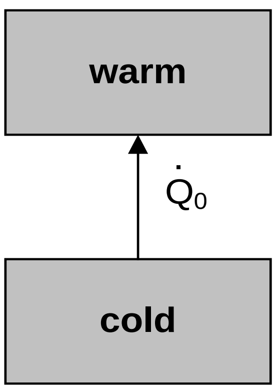
Household fridge becoming widely available in Europe?
→ after WW II !

First Commercial Helium Liquefier

Prof. Sam Collins,
MIT/Boston → ADL comp.
1946



Theory of (Cryogenic) Cooling

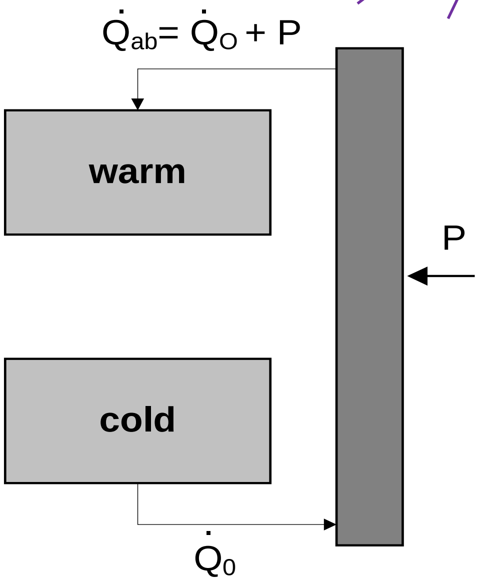


Not allowed !

OK for energy conservation;

not OK for laws of thermodynamics

extra $\Delta T \approx 3 \ldots 5$ K needed for heat transfer !



any kind of **Cooling Machine**

- working fluid/material
- „ heat lift“ effect
- apparatus

Demands:

- acceptance of entropy load
- transport (without further entropy production!)
- entropy transfer to ambient
  - a) continous (circulation)
  - b) single shot (batch process)

Possible physical effect:

- **gas compression / expansion**
- **fluid evaporation / condensation**
- thermoelectric (Peltier)
- magnetocaloric (Gd, …)
- thermoacoustic
- optic (Anti-Stokes)
- …

Second law of thermodynamics ("Carnot")

Refrigeration:

Minimum input power for respective cooling power

$$P_{\min} = \dot{Q}_0 * \frac{T_U - T_0}{T_0}$$

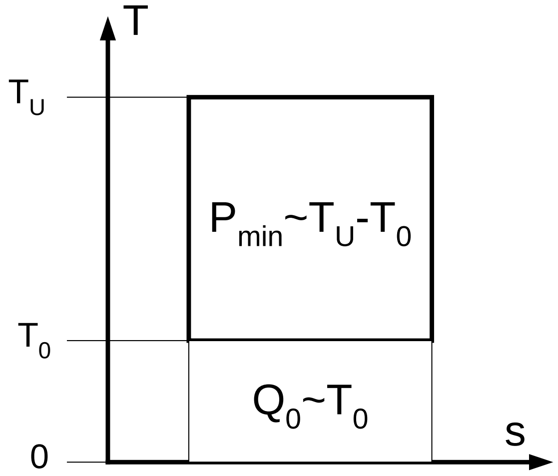
T_U Ambient temp.

T_0 Low temp.

T, s diagram:

P_{min} vs. Q_o

graphically visible ⇨



first headache: **Carnot Limit**

$$COP_{carnot} = \varepsilon_{carnot} =$$

$$Q_o / W = T_o / (T_u - T_o)$$

for T_{amb} = 288 K:

T_o = 280 K ➪ min 0.03 W / W

T_o = 77 K ➪ min 3 W / W

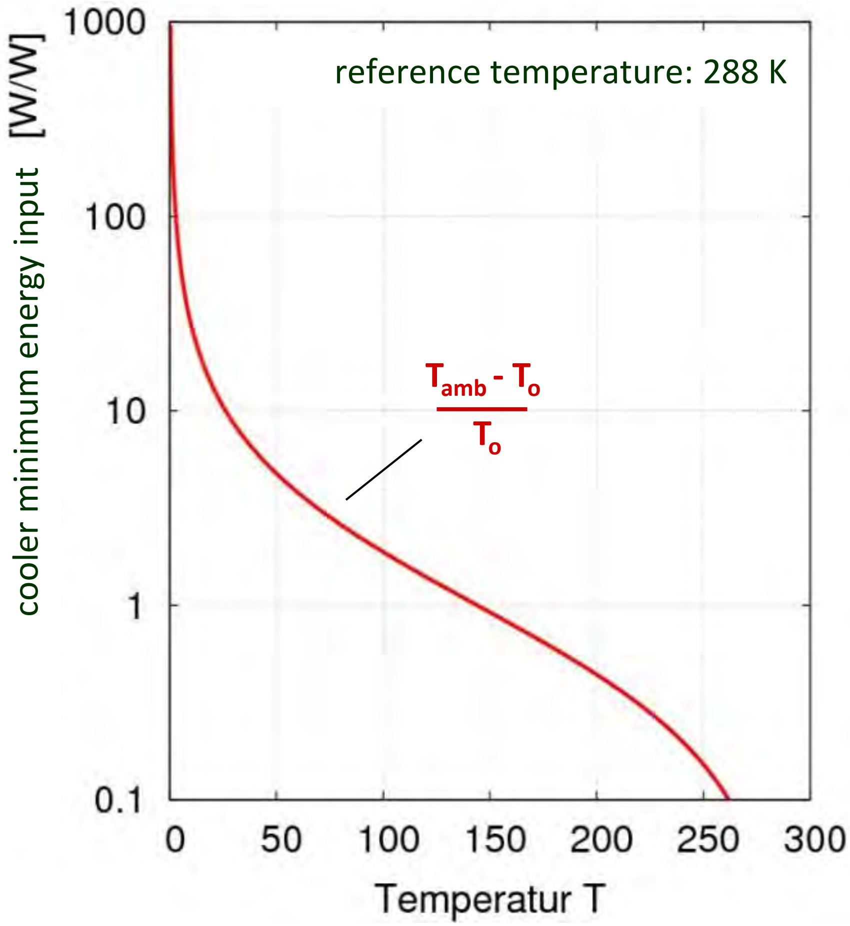
T_o = 20 K ➪ min 13 W / W

T_o = 4 K ➪ min 70 W / W

T_o = 2 K ➪ min 144 W / W

T_o = 1 mK ➪ min 288 **k**W / W

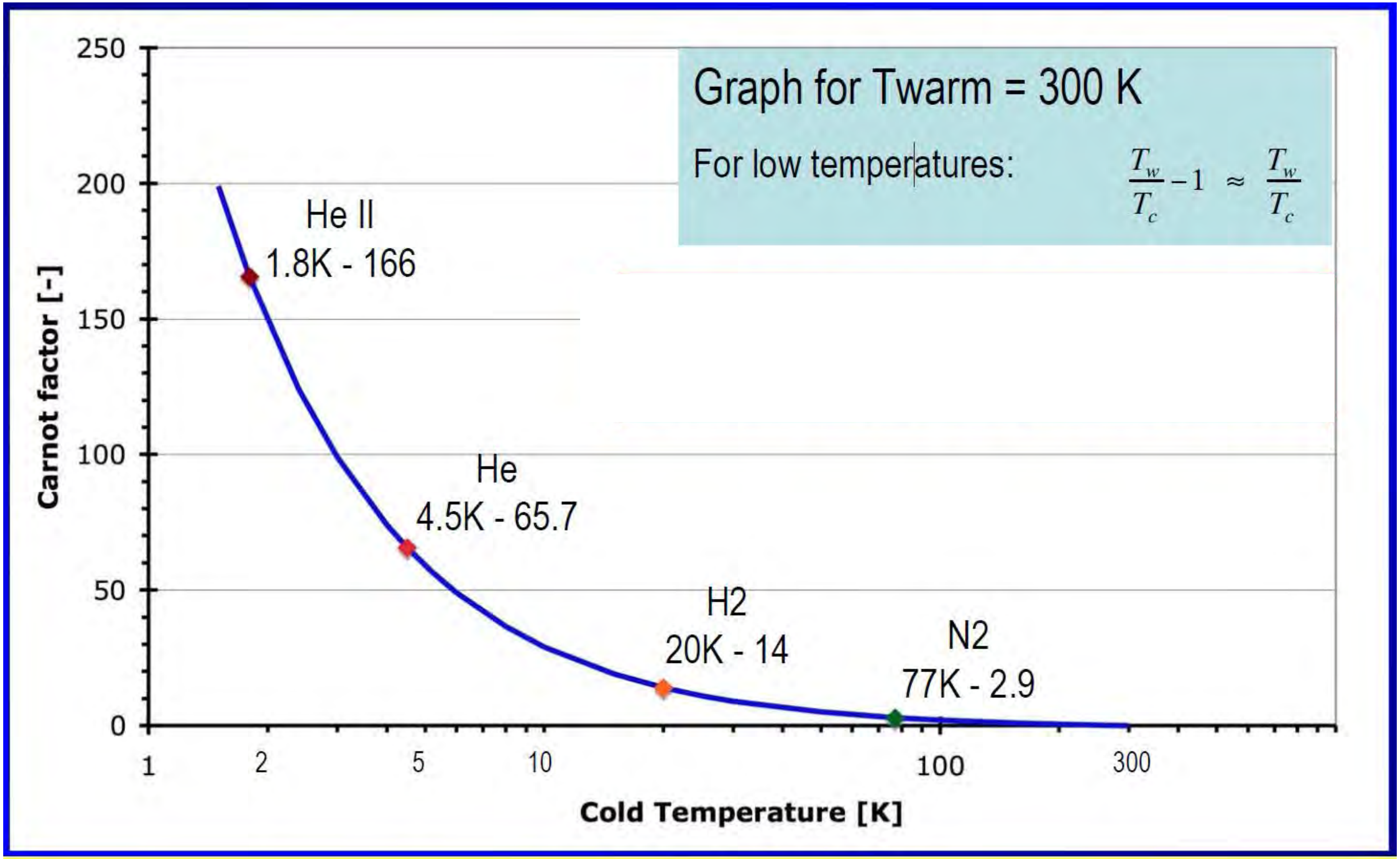
valid for ideal, reversible process
without any losses only !



beware! Extra losses at cold and hot heat exchanger
($\Delta T \approx 3 \dots 5$ K) ← unless e.g. bath cooling at low end temperature

first headache: **Carnot Limit**

Courtesy: Serge Claudet



Lesson learned from „Carnot"

- ⇨ The colder, the more energy expensive
- ⇨ Do not operate at temperatures lower than necessary
- ⇨ Minimize the heat load at very low temperatures

don't:

full heat load at
e.g. 4 K only

better:

thermal shields, intercepts
@ 80 K ⇦ by cheap LN_2
@ 20 K e.g.
minimum heat load at 4 K

⬆

trade-off: more complicated cooling plant / coldbox;
CAPEX vs. OPEX

second headache: **Carnot Fraction**

Carnot **Fraction**:

Efficiency $\eta = \varepsilon_{real} / \varepsilon_{Carnot}$

household refrigerator:

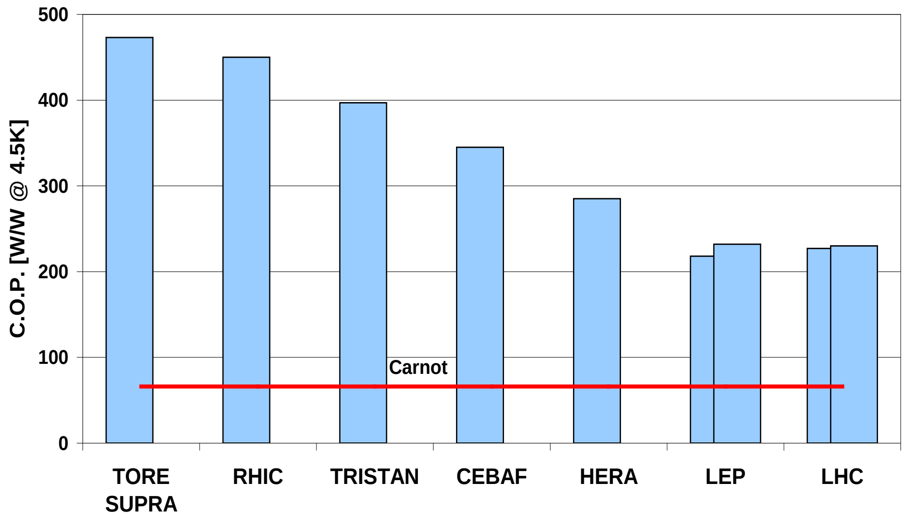
typ. 1 W/W ⇨ $\eta \approx$ 5 %

in cryogenics:

η = 35 % …. < 1 %

e.g.: input power P_{el} ≈ 0.5 MW

cooling power @ 1.8 K: 200 W

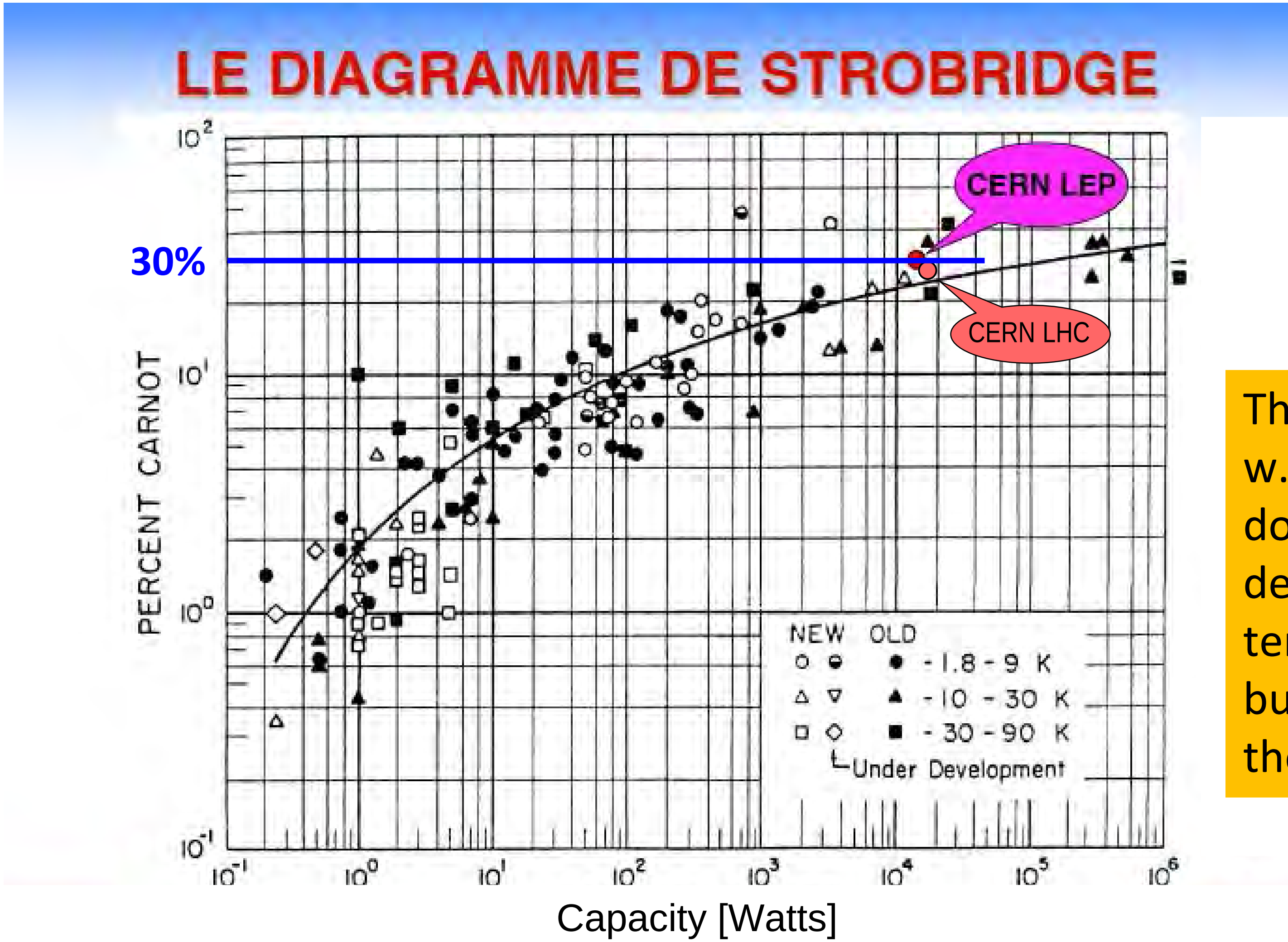


COP – coefficient of performance

improvements achieved
for large cryogenic helium plants

Ph. Lebrun, CERN

second headache: **Carnot Fraction**



Courtesy:
Guy Gisteau;
Serge Claudet

The efficiency w.r.t Carnot does not depend on the temperature, but rather on the size

Lesson learned from Strobridge:

⇨ A real cooling plant needs much more input power then a Carnot cycle (unavoidable)

⇨ The larger the cooling plant, the more efficient

⇨ better one large central cooling plant then several distributed small local plants

⇨ Avoid „multiple“ safety factors

e.g. $\dot{Q}_o = 1.5 \times 1.5 \times 1.5$

- safety factor assigned by physicist
- safety factor assigned by plant specification
- safety factor assigned by plant manufacturer

all cryogenic cooling plants suffer a poor part load efficiency

Why do we need such low temperatures after all?

a) condensation and liquefaction of gases

air separation; **more easy transport and storage** of N_2, O_2, H_2, Ar, natural gas →

⇨ no interest in low temperatures, uneasy additional complication

Bonus: high purity gases

b) reduction of thermal noise and excitation

- undisturbed measurements in solid state physics, nuclear physics
- noise-reduced amplifiers
- all superconductive application

thermal excitation:

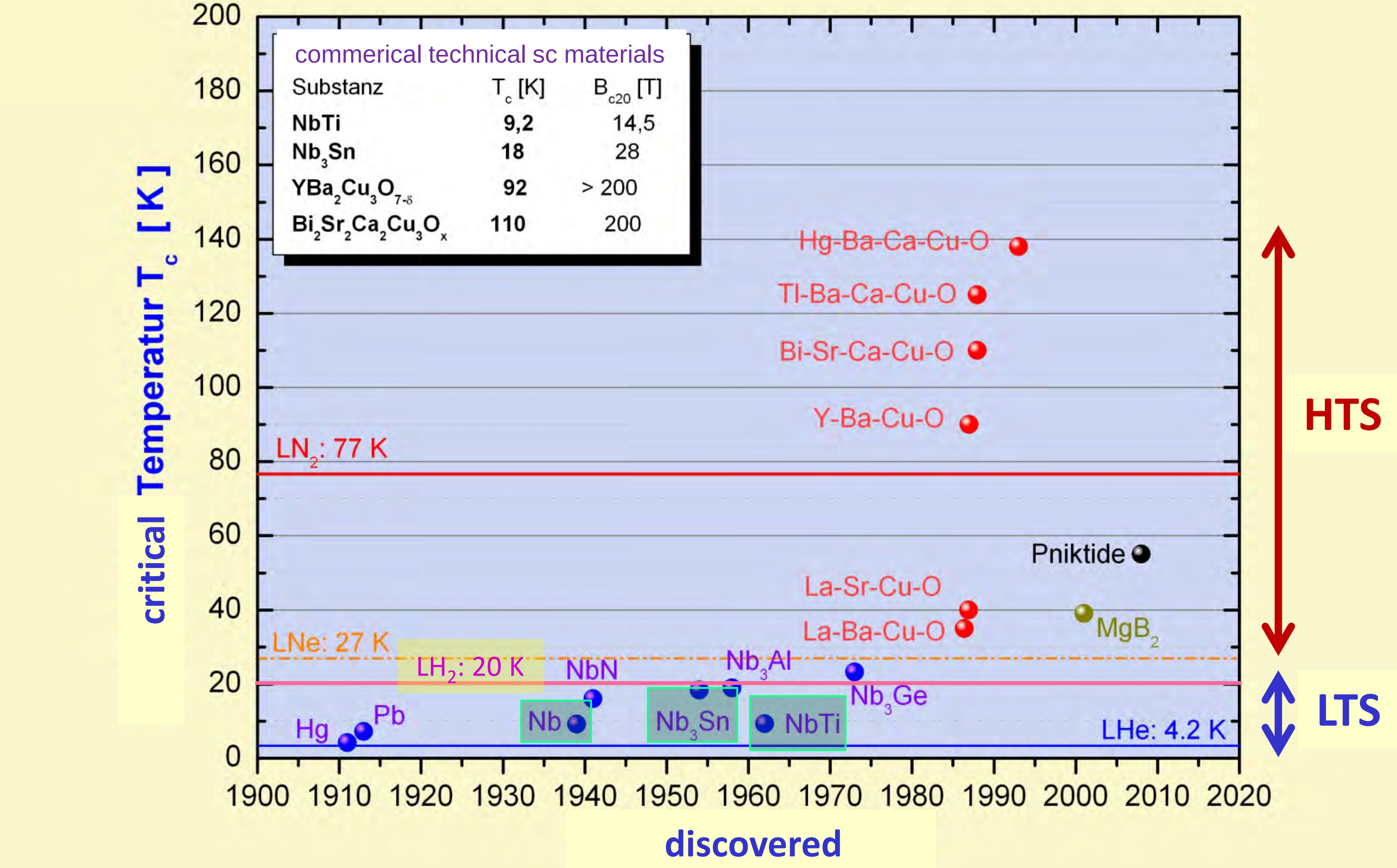
E = k·T

288 K: k·T = 25 meV ← close to binding energies in semi-conductors etc.

4 K: k·T = 0.3 meV

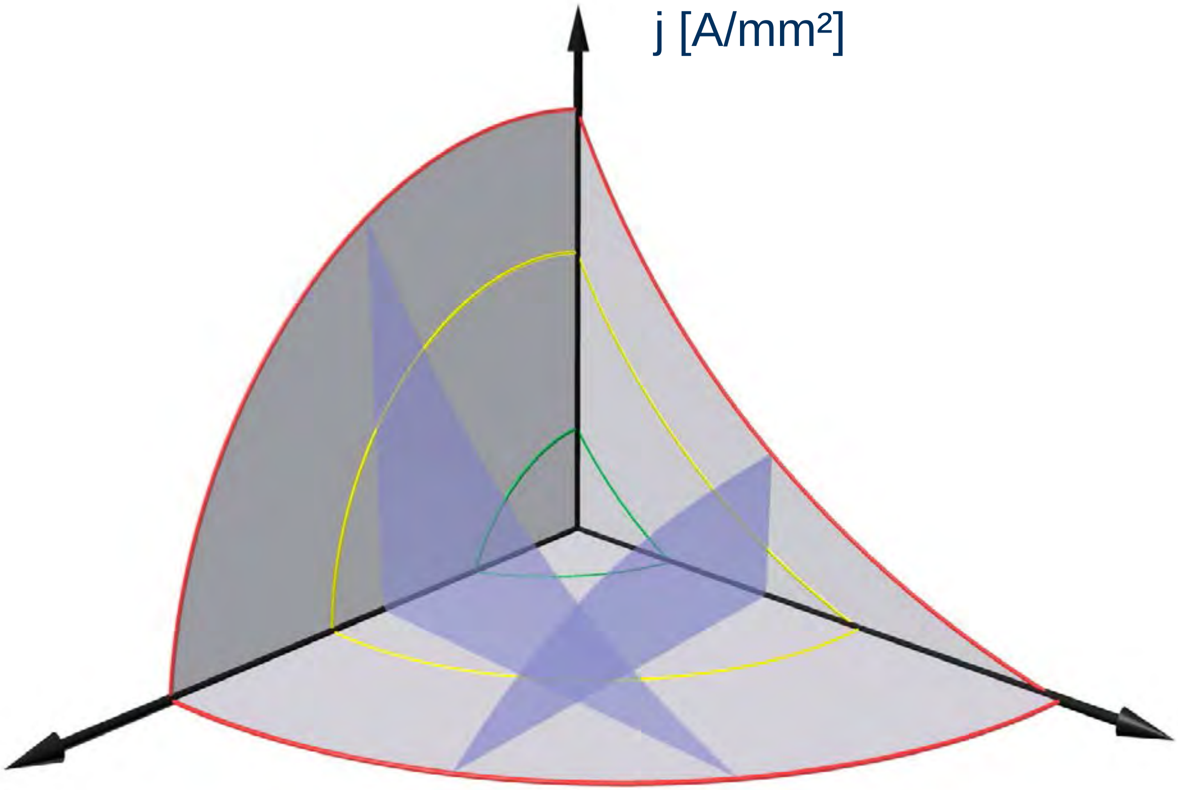
Superconducting materials

Courtesy:
Theo Schneider, KIT



nearly exclusively used

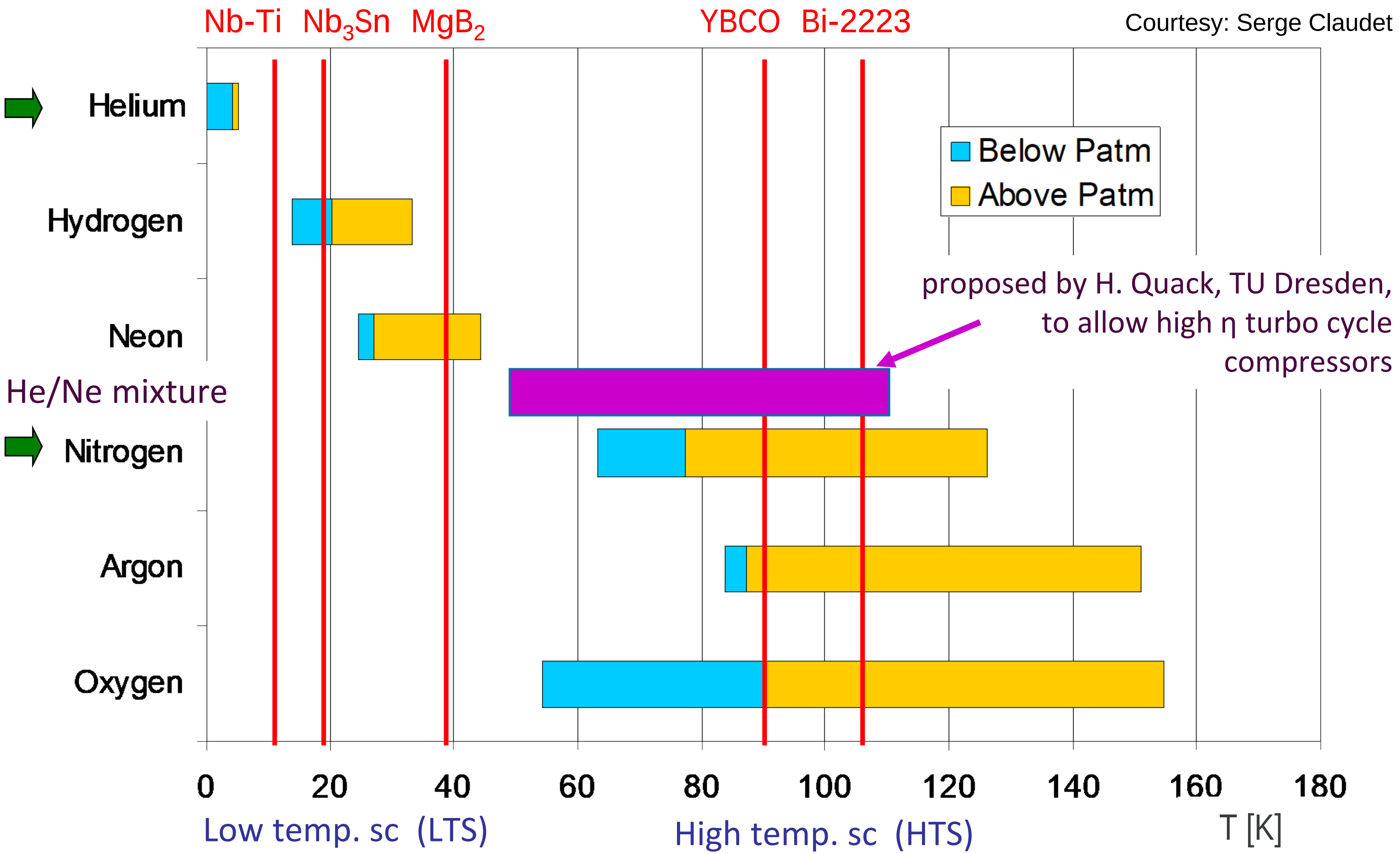
Technical Superconductors: Operational Limits



better j, B values when operated well below T_c

trade-off between sc performance and cooling effort

Cryogenic Fluids for Superconductor Cooling

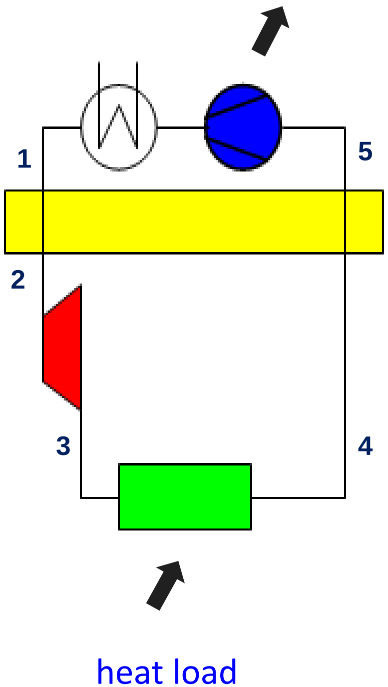


Cooling cycles with work extracting expansion

isentropic (work extracting) expansion: $\Delta S_{ideal} = 0$ (reversible)

$\dot{m}$ small: volumetric expander (e.g. piston)
$\dot{m}$ large: turbines

Brayton Process



idealized:

isothermal compression
and heat release

isobaric
cool-down / warm-up

isentropic expansion

isothermal heat transfer

+ works always (ideal gas property)
+ much higher cooling effect
– mechanically demanding

real: isentropic efficiency η_s

$$\eta_s = \frac{h_2 - h_3}{h_2 - h_{3s}}$$

Cooling cycles with work extracting expansion

Expansion Turbines

axial + radial gas bearing; speed typ. 4500 s^{-1}

picture: Linde

recent optimization:

- geometry rotor / stator blades
- clearance losses
- material heat flow

isentropic efficiency

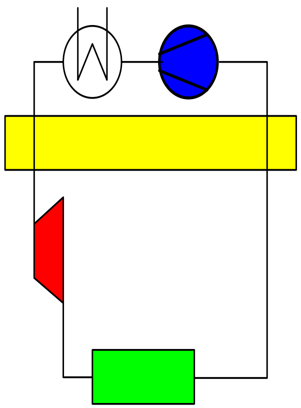
80th: $\eta_s \approx$ 65 %

today: **$\eta_s \approx$ 75 … 86 %**

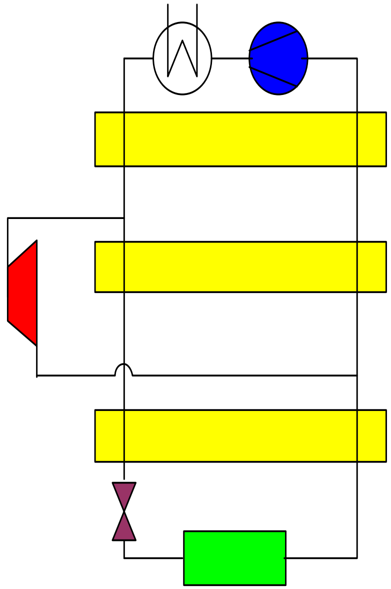
⇨ increase in cooling power by 1.5 … 2

Basic Cryogenic Cycles

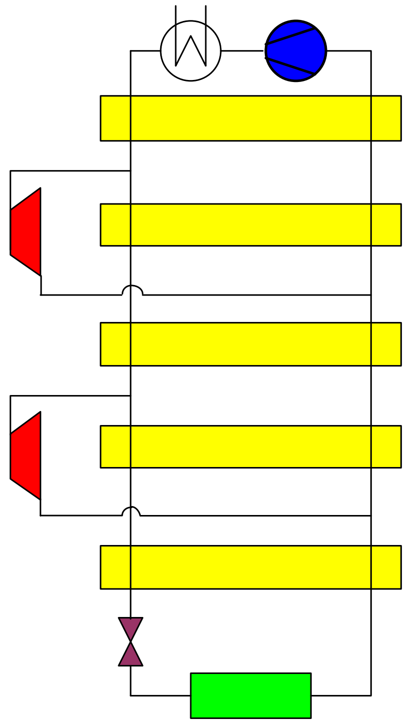
volumentric compressors
(oil lubricated screws); poor η
future: turbo machinery?



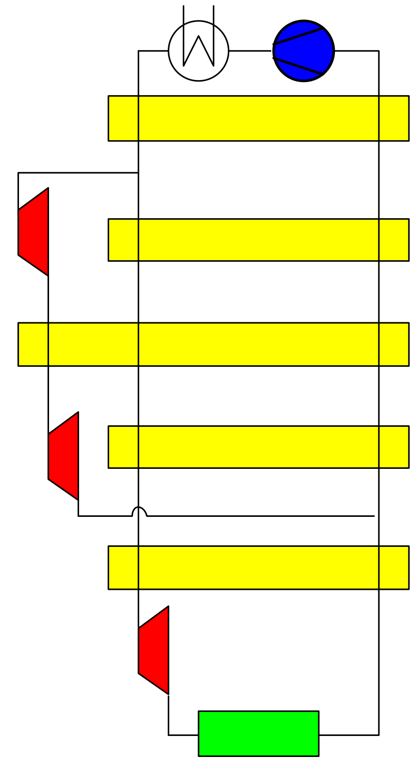
Brayton



Claude

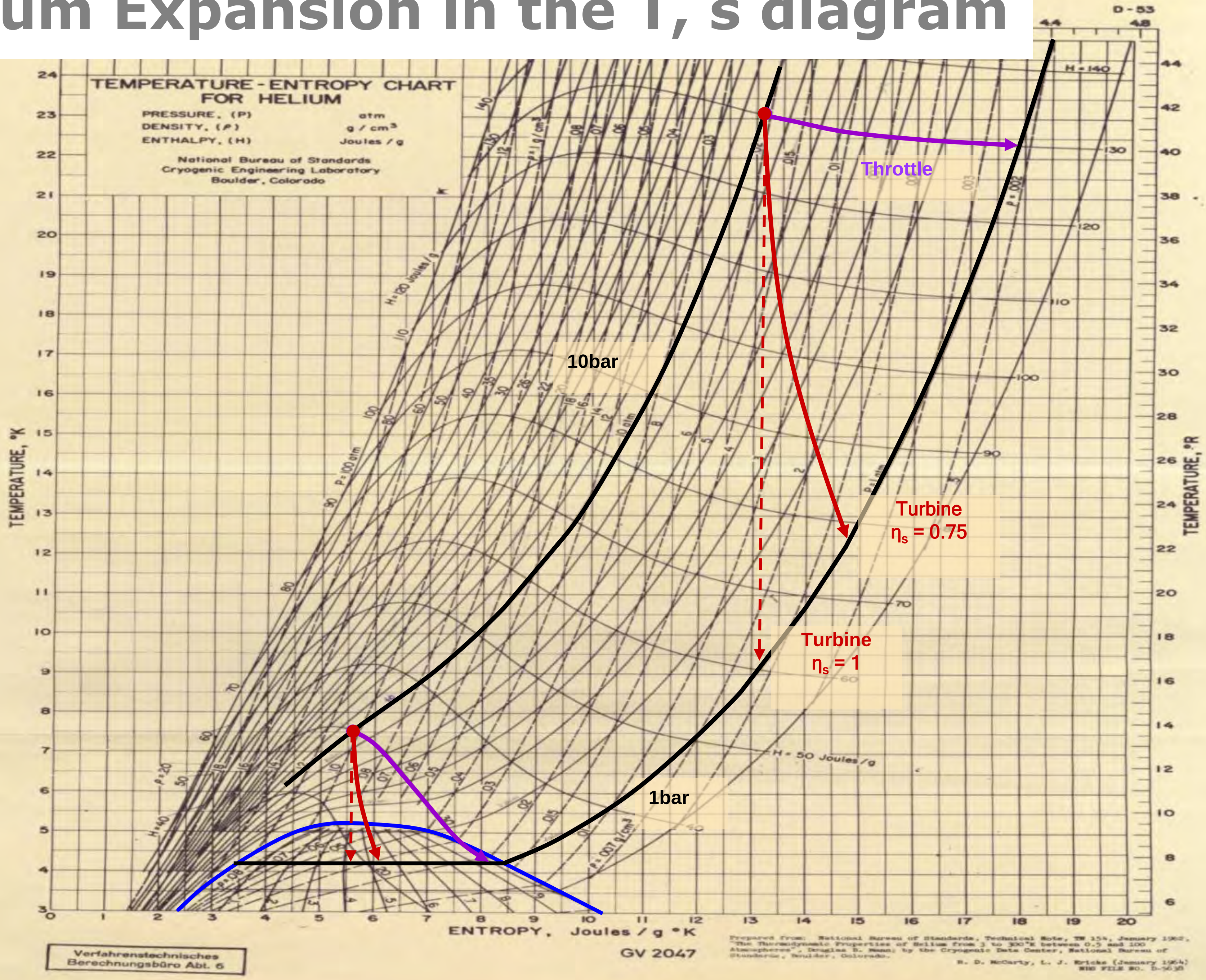


Expanders in parallel
(Collins)

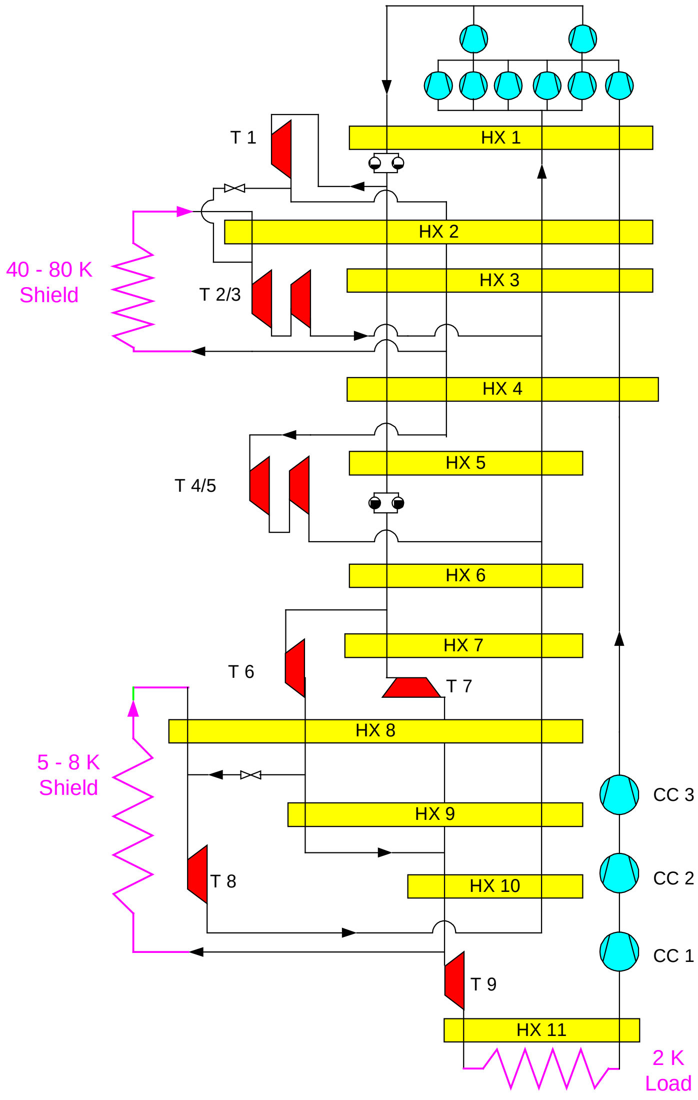


Expanders in series
plus wet expander

Helium Expansion in the T, s diagram



Cooling cycles with work extracting expansion



"High-end" Helium Plant

Conceptual design for DESY, TESLA:

- 8 cycle compressors in two stages
- 9 expansion turbines
- 3 cold compressors
- heat loads at three temperatur levels

to be operated 24/7
cool-down / warm up: days…weeks
shut-down once per year typically only

trade-off between
CAPEX – Capital Expenditure
and plant efficiency

Cryocooler as possible solution?

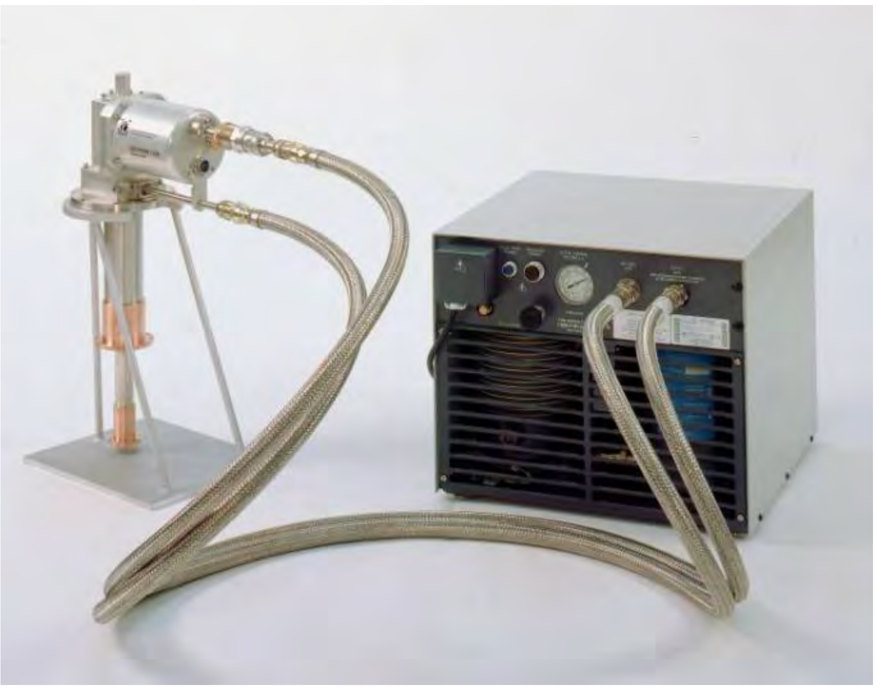
range, typically: „some Watt" @ 3 ... 100 K

- Stirling Cryocooler
- Gifford-McMahon Cooler
- Pulse Tube Cooler

well available

convenient, closed system

costs ~ 3000 .... 45000 €



e.g.: 18 W @ 20 K + 110 W @ 80 K; P_{in} = 8 kW

Cryomech

PT450

5.0 W @ 4.2 K + 65 W @ 45 K

P_{in} = 27 kW

Cryocooler as possible solution?

Cryocooler placed in a dewar's neck tube

ca. 100 000 …. 300 000 € + yearly service

alternative Helium Liquefaction:

Cryocooler + Dewar

Chao WANG, **www.cryomech.com**

HeRL15: > 15 l/day 1.5 W @ 4.2 K, P_{el} = 9.2 kW

ca. 14 kWh / l $_{LHe}$

compare:

turbine liquefier

2 kWh / l $_{LHe}$

at least: can be switched on/off on a few hours basis

Thank you for your attention!