TECHNISCHE UNIVERSITÄT DRESDEN
Fakultät Maschinenwesen
Institut für Energietechnik
Lehrstuhl für Kälte- und Kryotechnik

Helium Refrigeration for sc Accelerators

SRF 2009 Tutorial Rossendorf

Ch. Haberstroh
Sept. 19th, 2009

Outline

- introduction
- fluid properties of He
- liquefaction history
- theory of refrigeration cycles
- plant components
- 2 K systems
- efficiencies
- He resources

Professorship for Refrigeration and Cryogenics at TU Dresden:

1993 – 2008: Prof. Dr. H. Quack (before: Sulzer Cryogenics, Swiss)

actually (provisional): Dr. rer. nat. et Ing. habil. Ch. Haberstroh

ca. 12 permanent members, mostly Ph.D. students

Teaching:
- **Refrigeration**
- **Compressor Technology**
- **Kryo Technology**

Research:
- **...**
- **...**
- **Helium, Hydrogen Technology; Conceptual design for large Helium Plants**

He / H2 Liquefiers, Dewar optimization, Neon cooling, ...

responsible for the central Helium Plant TU Dresden

co-operation with DESY, CERN, Rossendorf, GSI, BESSY, SLAC, FNAL, ...

sc Accelerator Cooling Task

Demand: Refrigeration at ~ 5 K .... 1.7 K
+ thermal shield @ ~ 20 K … 100 K
heat load: 10 W … kW range

plus:
high efficiency, high reliability,
low noise level,
low invest costs,
8000 h continuous operation, …

way to go: helium refrigeration cycles

cryogenic fluids:

	normal boiling point	price (m³ gas)	
LN_2	77 K	0.15 €	⇦ pre-cooling only
LNe	27 K	150 €	
LH_2	20 K	0.50 €	
L^4He	4.2 K	10 € (rising)	⇦ standard working fluid
L^3He	3.2 K	250 000 €	⇦ extremely expensive, for closed mK coolers only

Helium (^4He)

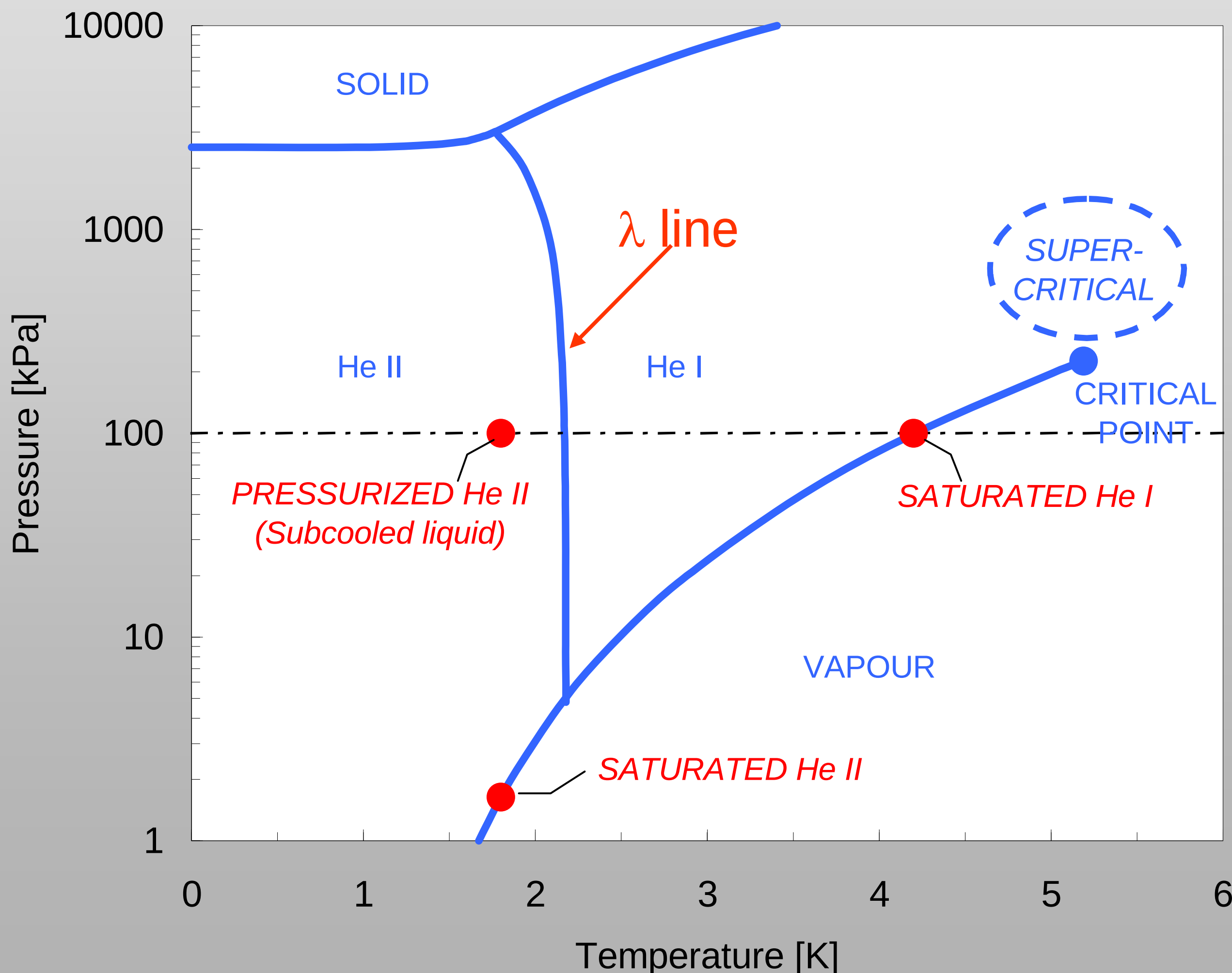
ideal cooling fluid:

+ chemically inert, nontoxic, odorless
+ high heat conductivity
+ radiological inert
+ high ionization energy
+ low solubility
+ extrem low boiling point

as well a few drawbacks:

- price, shortages ⇦ helium recovery, closed refrigeration cycles
- low evaporation enthalpy ⇦ nearly perfect thermal isolation
- low molecular mass ⇦ hard for turbo pumps or expanders
- high diffusion rates ⇦ special materials, sealings

^{4}He Phase Diagramm



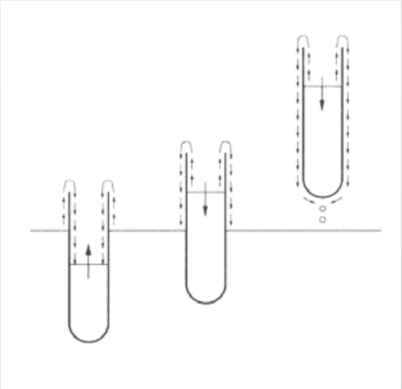
Ph. Lebrun, 2009

Superfluid Helium

LHe I:
„normal“ liquid

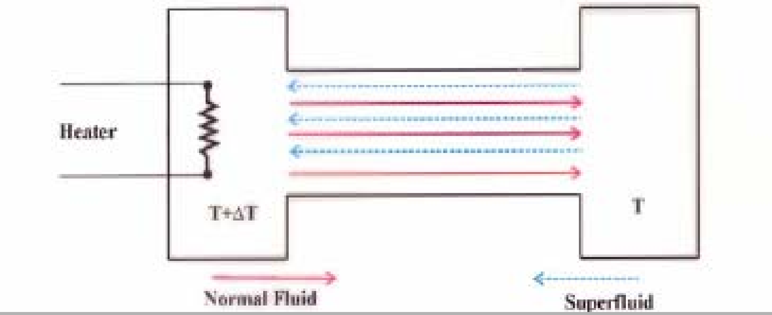
nucleate boiling
at saturation line

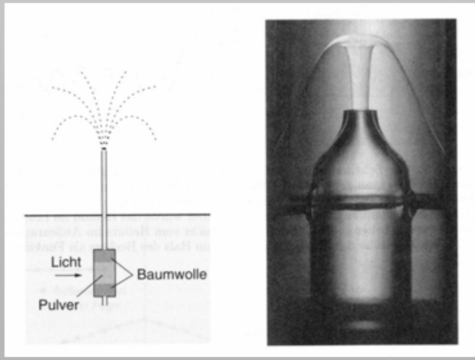
LHe II:
superfluid helium
strange behavior
$\lambda_{He\ II} \approx 10^6 \cdot \lambda_{He\ I}$
apparently no viscosity
quietly boiling from the surface only



film creeping

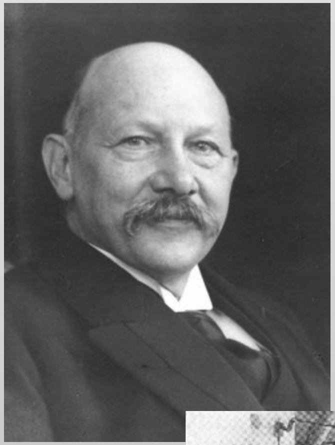
explained by „two-fluid“ model
below λ line: normal + superfluid phase
two interpenetrating fluids, no friction





thermocaloric (fountain) effect

Helium Liquefaction

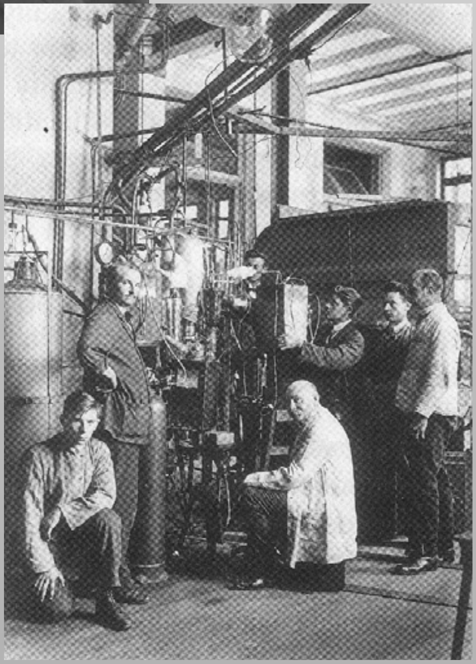


first time by Heike Kamerlingh Onnes,

Leiden University,

July 10th, 1908

Helium from monazite sand



next 15 years: exclusive LHe laboratory

discovery of supraconductivity,

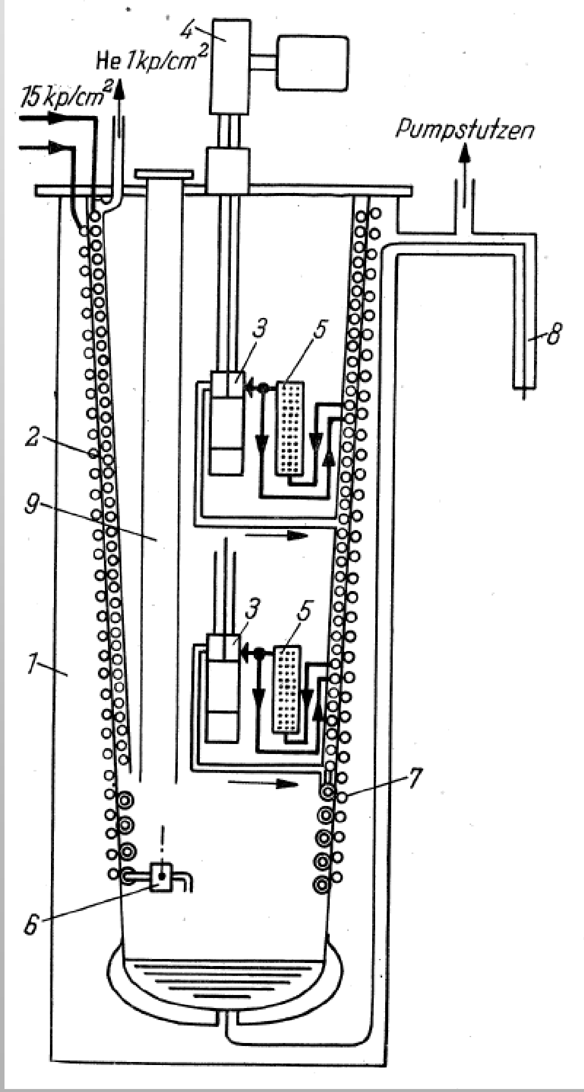
superfluidity, …

Commercial Liquefier Breakthrough

Prof. Samual Collins,
MIT/Boston
1946

use of piston expanders

capacity: 10 l/h



Collins Liquefier

1946 – 1964 about 250 units sold

“revolution” in cryogenic research

Manufacturer:

A.D. Little Company ➾ 500 Inc. ➾ CTi

➾ HPS ➾ KPS ➾ PSI ➾ CPS/Linde

nevertheless basically unchanged

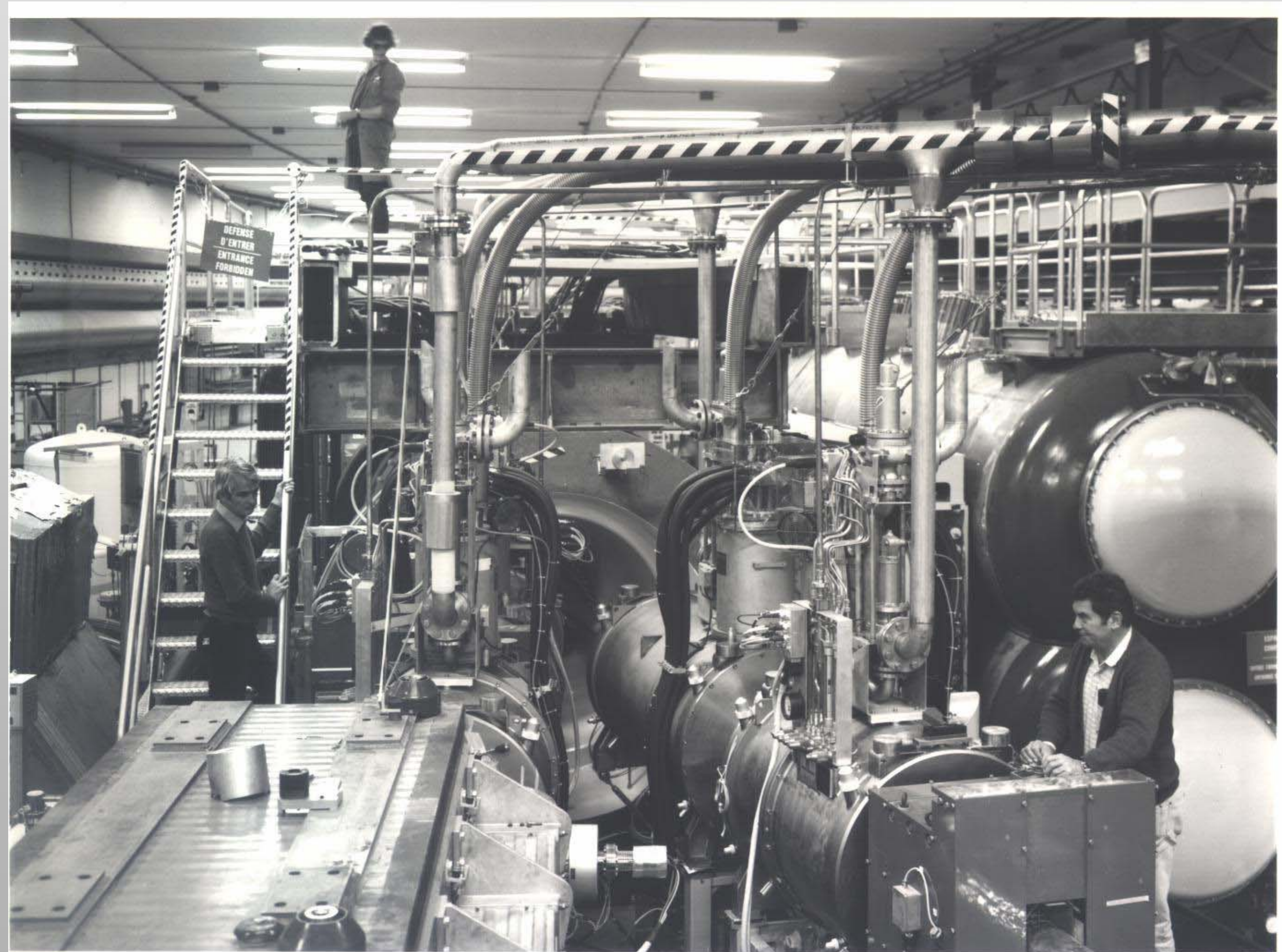
capacity: 12 … 70 l/h

First sc Accelerator Magnets

implemented

in the 70th

(CERN, Fermilab)

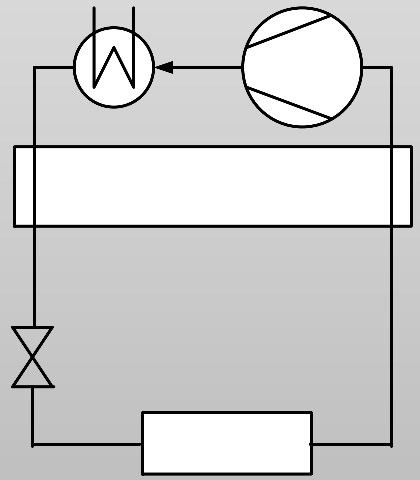


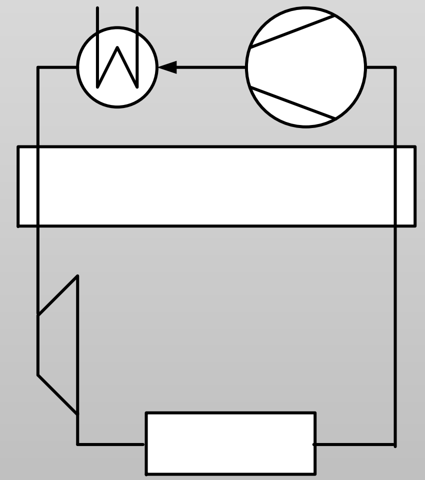
Helium Plants Today

LHC Cold Box
18 kW @ 4.5 K

33 kW @ 50 K …75 K
+
23 kW @ 4.6 K … 20 K
+
41 g/s liquefaction

Theory: how to get a gas cold?





a) Joule-Thomson-Effect
simple throttle valve, isenthalpic expansion (without work extraction)

$$\Delta H = 0$$

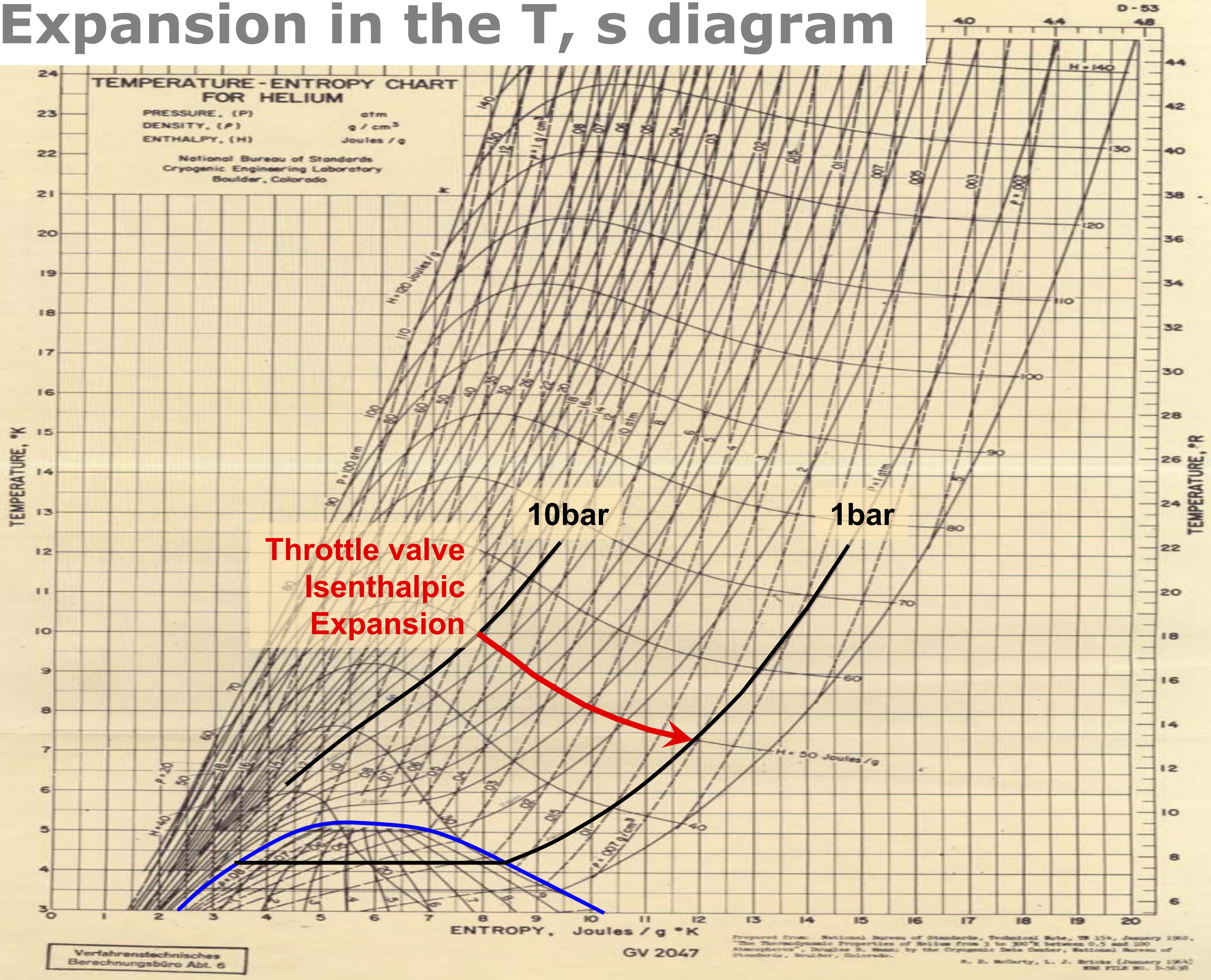
⇔ small effect (real gas property), below inversion curve only

b) Expansion machine
isentropic change of state
work is extracted from the fluid

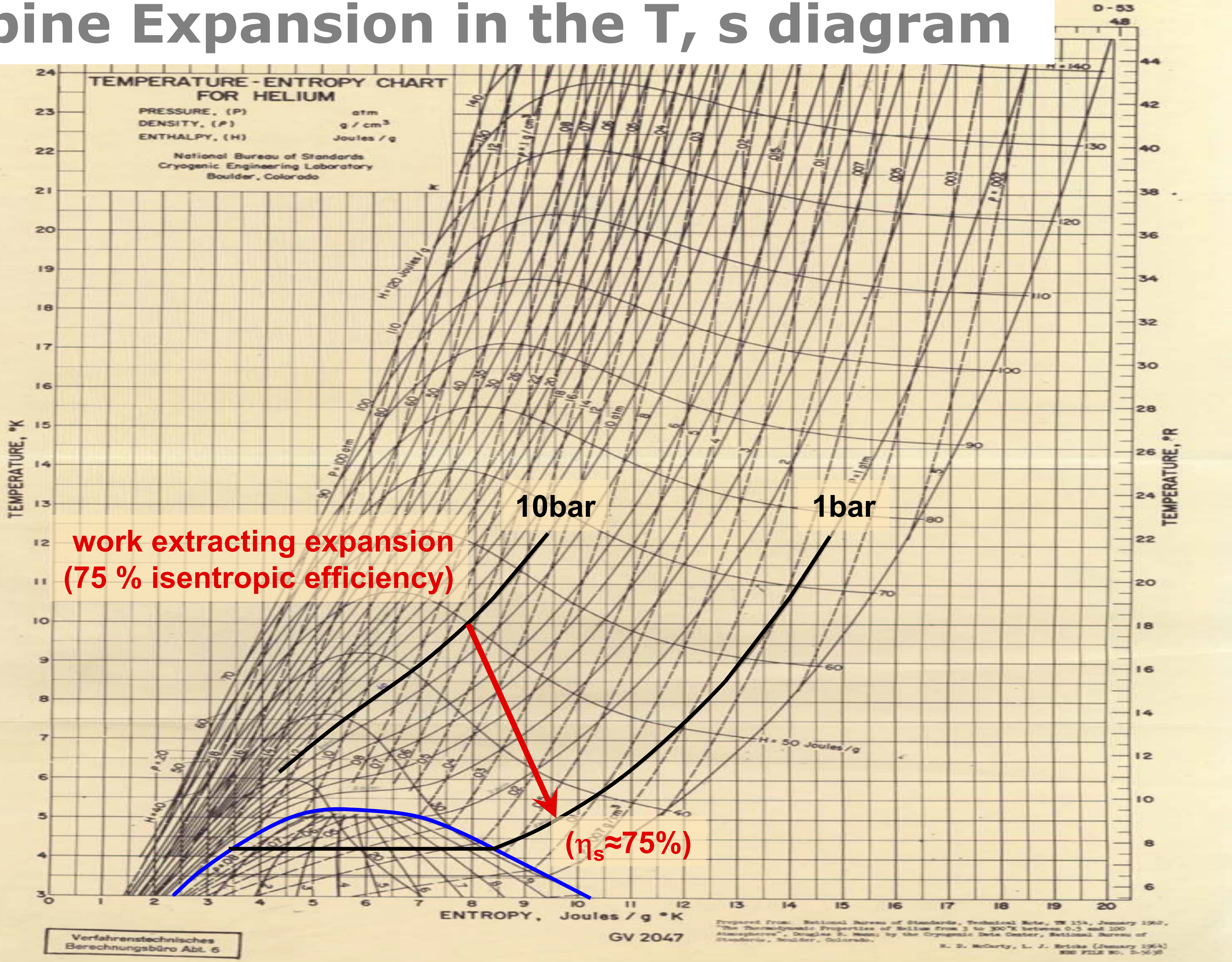
$$\Delta S_{ideal} = 0$$

⇔ big effect at any starting temperture (ideal gas property)

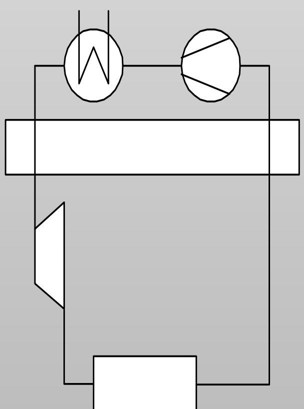
J-T Expansion in the T, s diagram



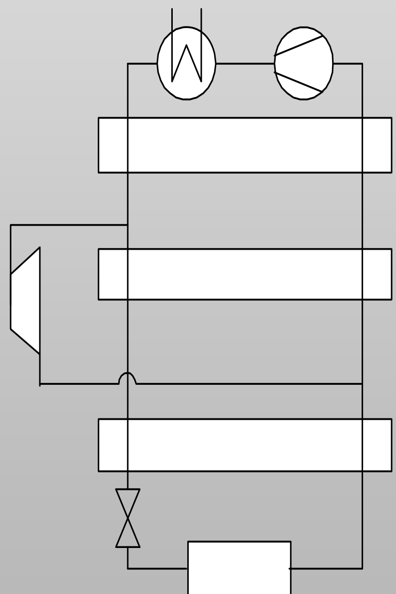
Turbine Expansion in the T, s diagram



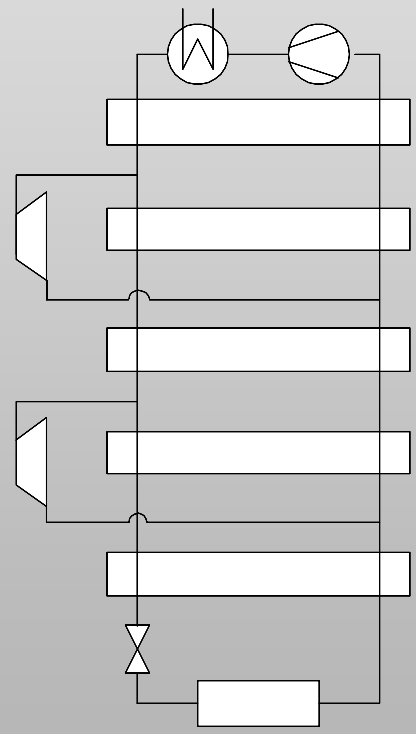
Basic Refrigerator Cycles



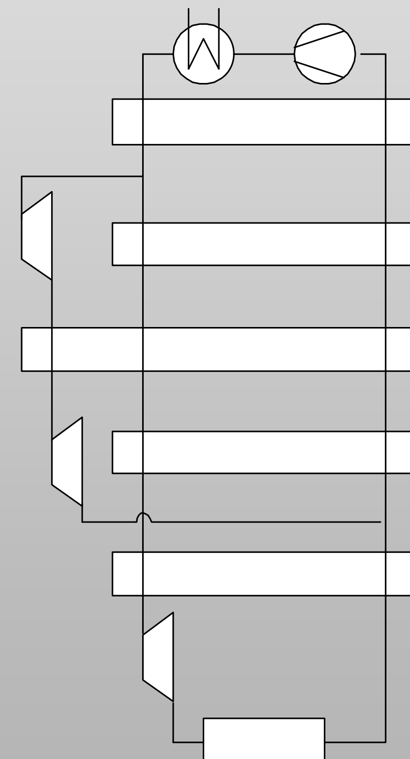
Brayton



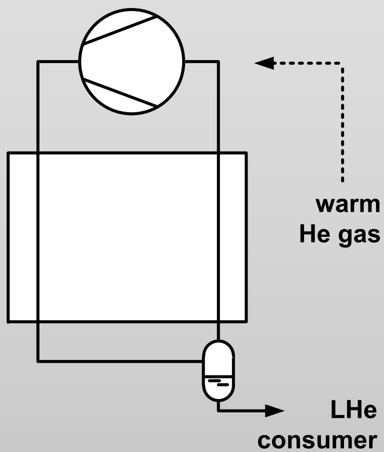
Claude



Expanders in parallel (Collins)



Expanders in series plus wet expander



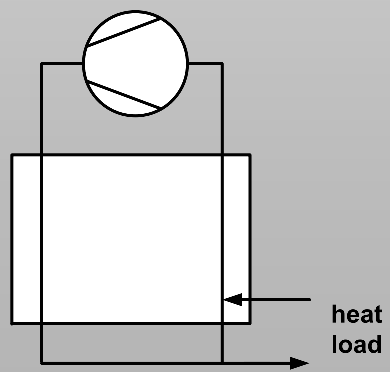
Liquefier

often only evaporation enthalpy used (20.4 kJ/kg)

(cold gas warm-up: 1500 kJ/kg)

standard liquefier: 10 … 200 l/h

bulk liquefier: ~ 1000 … 4000 l/h



Refrigerator

heat load (e.g. cavity cryostat)

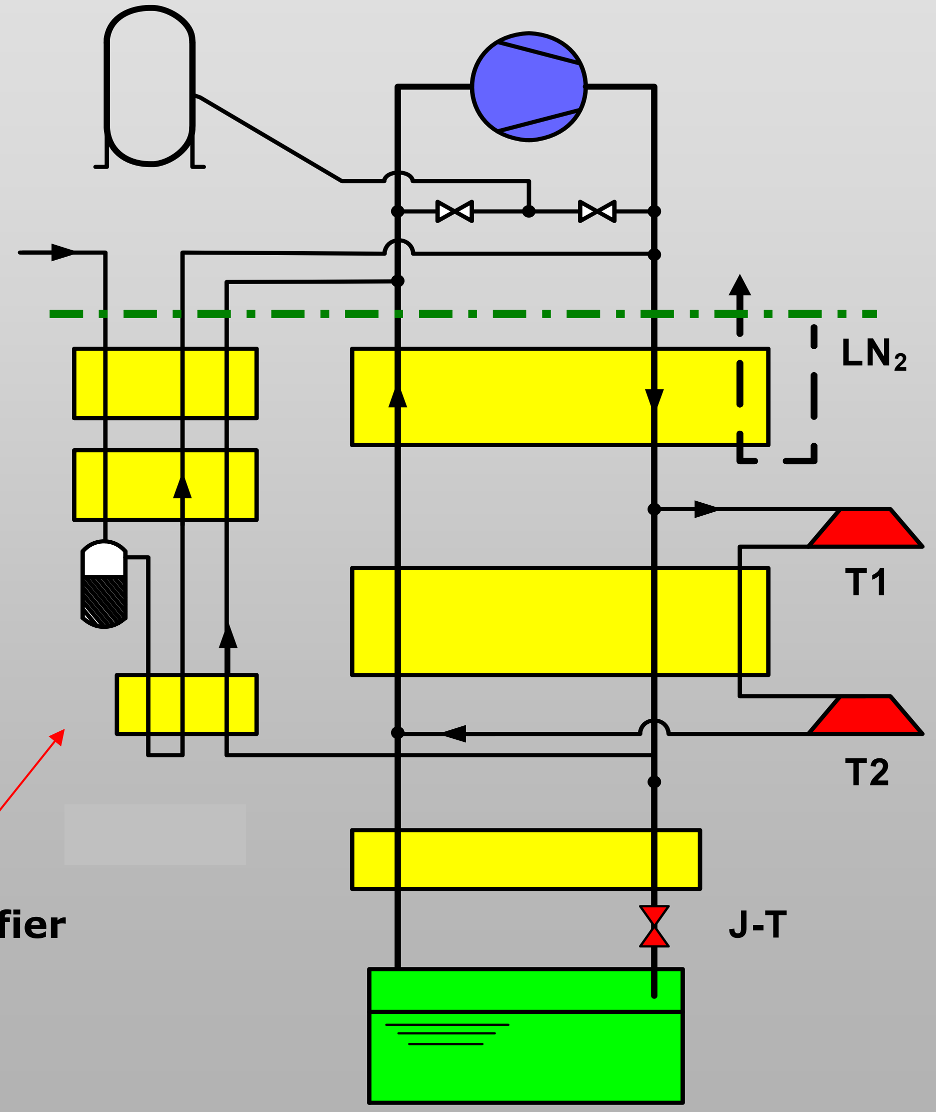
directly connected via transfer line + cold gas return

0.1 … 20 kW @ 1.8 …. 5 K

Components needed

typ. helium liquefier:

- (warm) cycle compressor
- buffer tank
- counter flow heat exchangers
- (optional) LN_2 precooling
- expansion Turbines
- J-T throttle valve
- Cold box



integrated freeze-out purifier

(for impure helium feed)

Helium Expansion Turbines

Motivation:

isentropic Expansion

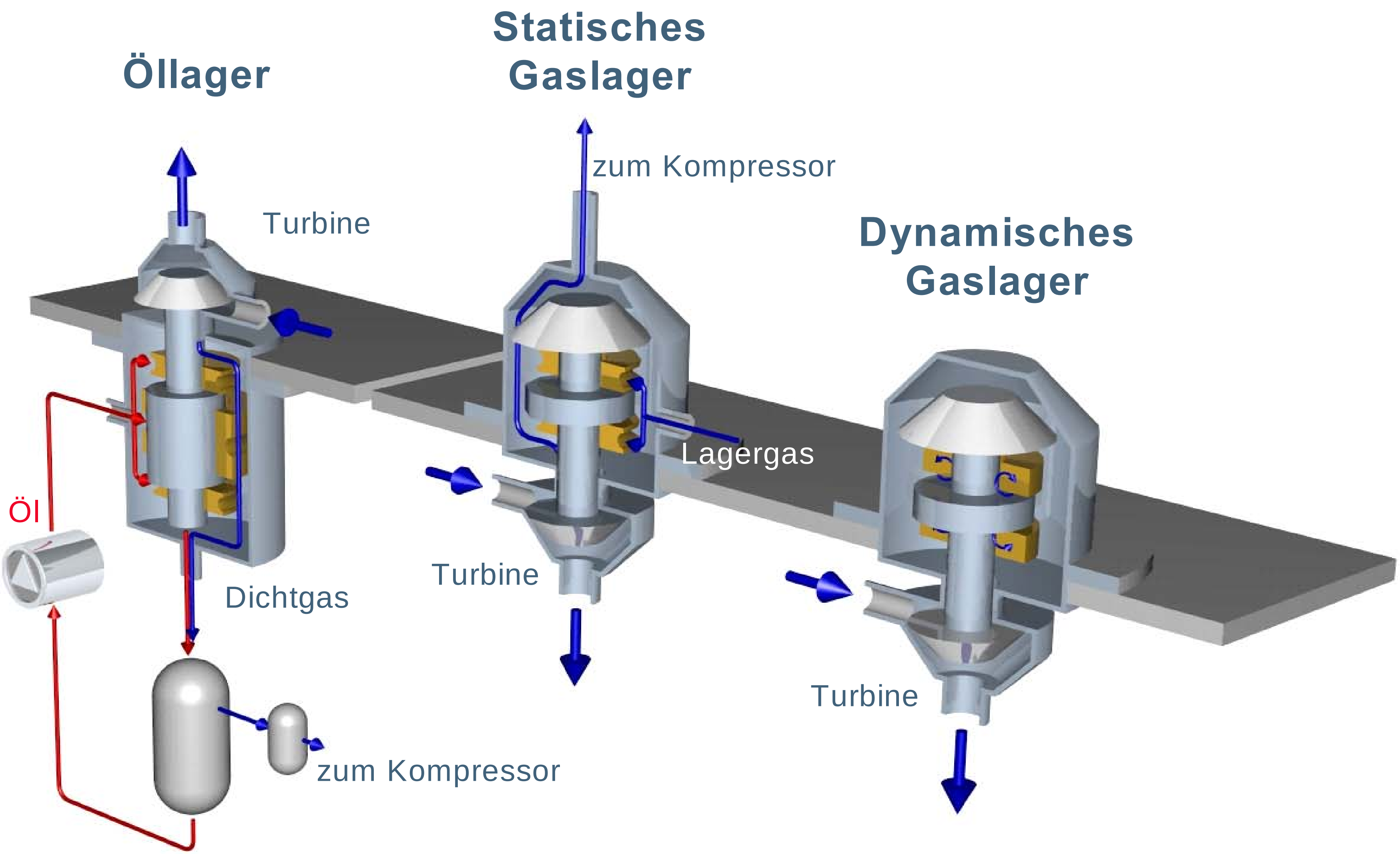
without cold piston maschine

Problems:

- small mass flow
- high circumferencial speed
- need for high isentropic efficiency

rotational speed up to 5400 s^{-1}

↳ oil- or gas bearing exclusively


Öllager
Statisches Gaslager
Dynamisches Gaslager
Turbine
zum Kompressor
Lagergas
Öl
Dichtgas
Turbine
Turbine
zum Kompressor

Helium Expansion Turbines

axial and radial gas bearing; operational speed 4500 s^{-1} typically

recently optimized:

- **blades geometry**
- **clearances**
- **heat fluxes**

isentropic efficiency

90th: $\eta_s \approx$ 65 %

today: $\eta_s \approx$ 75 … 80 %

➩ **50 % more cooling power !**

Cycle Compressors

today: oil-lubricated screw compressors

(followed by oil removal system down to ppb level !)

one-stage 1,05 bar → ca. 14 bar

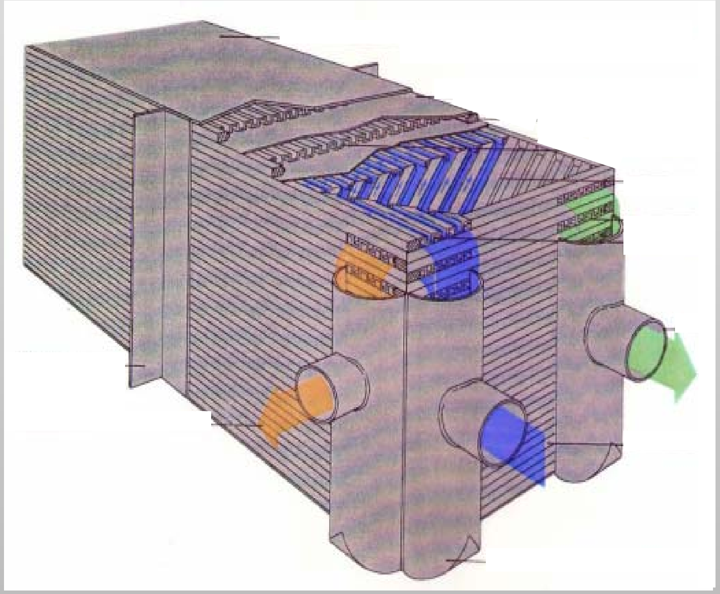
input power 50 kW … MW

- expensive
- efficiency ~ 50 %

Heat Exchangers

Aluminium plate-fin
counterflow heat exchangers

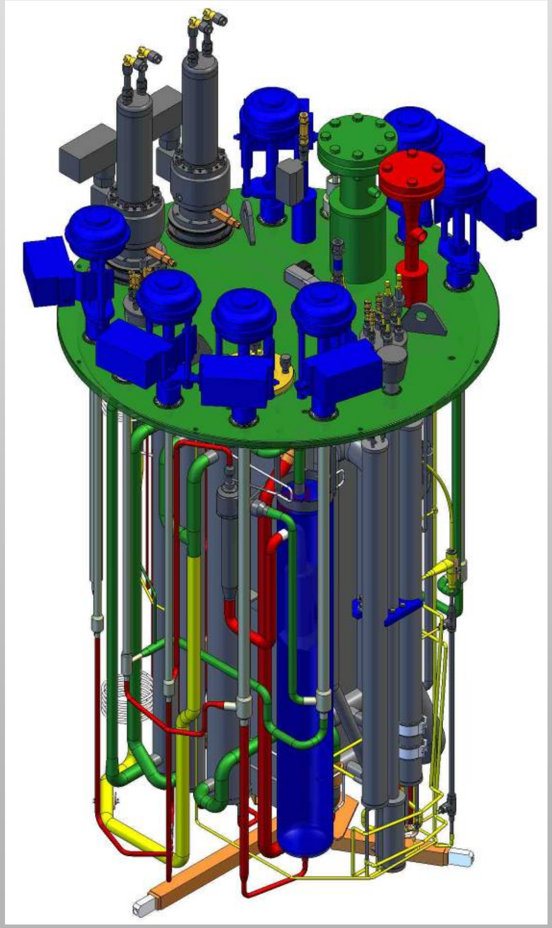
vacuum-brazed



- very reliable

- excellent efficiency ($\Delta T_{in/out} \approx 3$ K)

Coldbox



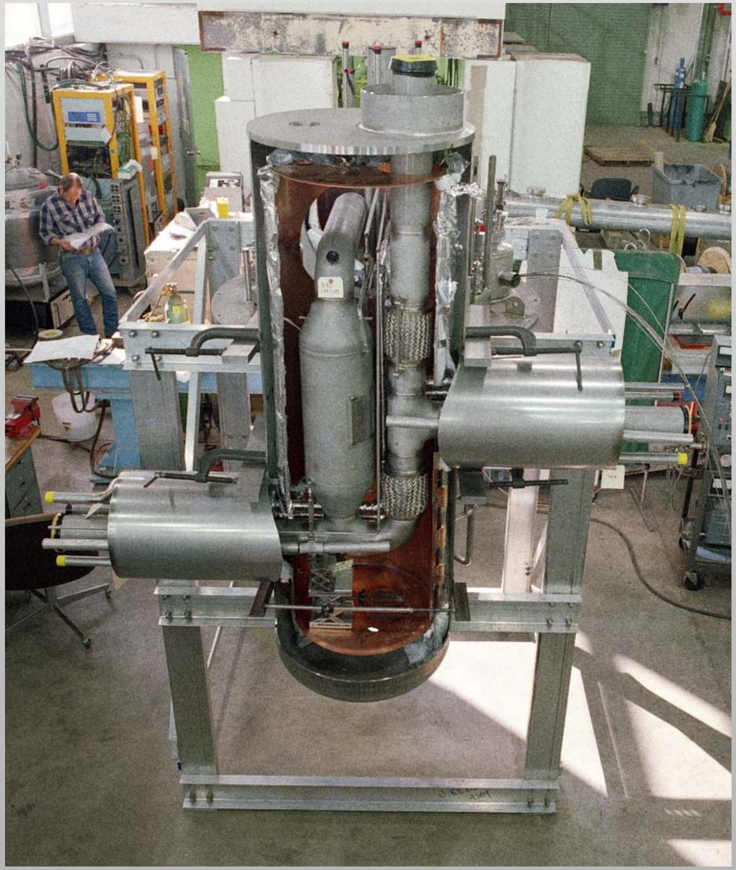
- vacuum isolated
- vertical arrangement: all components mounted at top flange

Transfer Lines

vacuum isolated

+ thermal shield

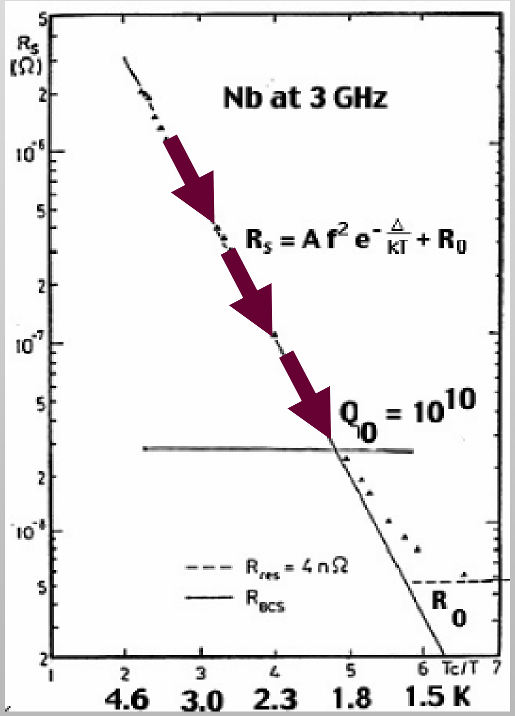
Transfer Lines

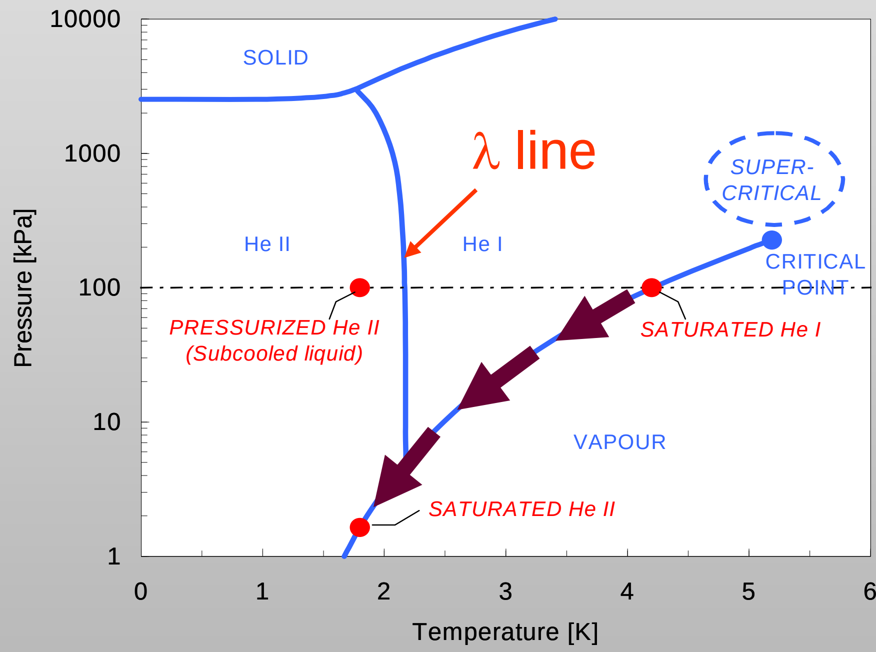


distribution box with heat exchanger

ELBE transfer line + valve box

Quest for lower working temperatures





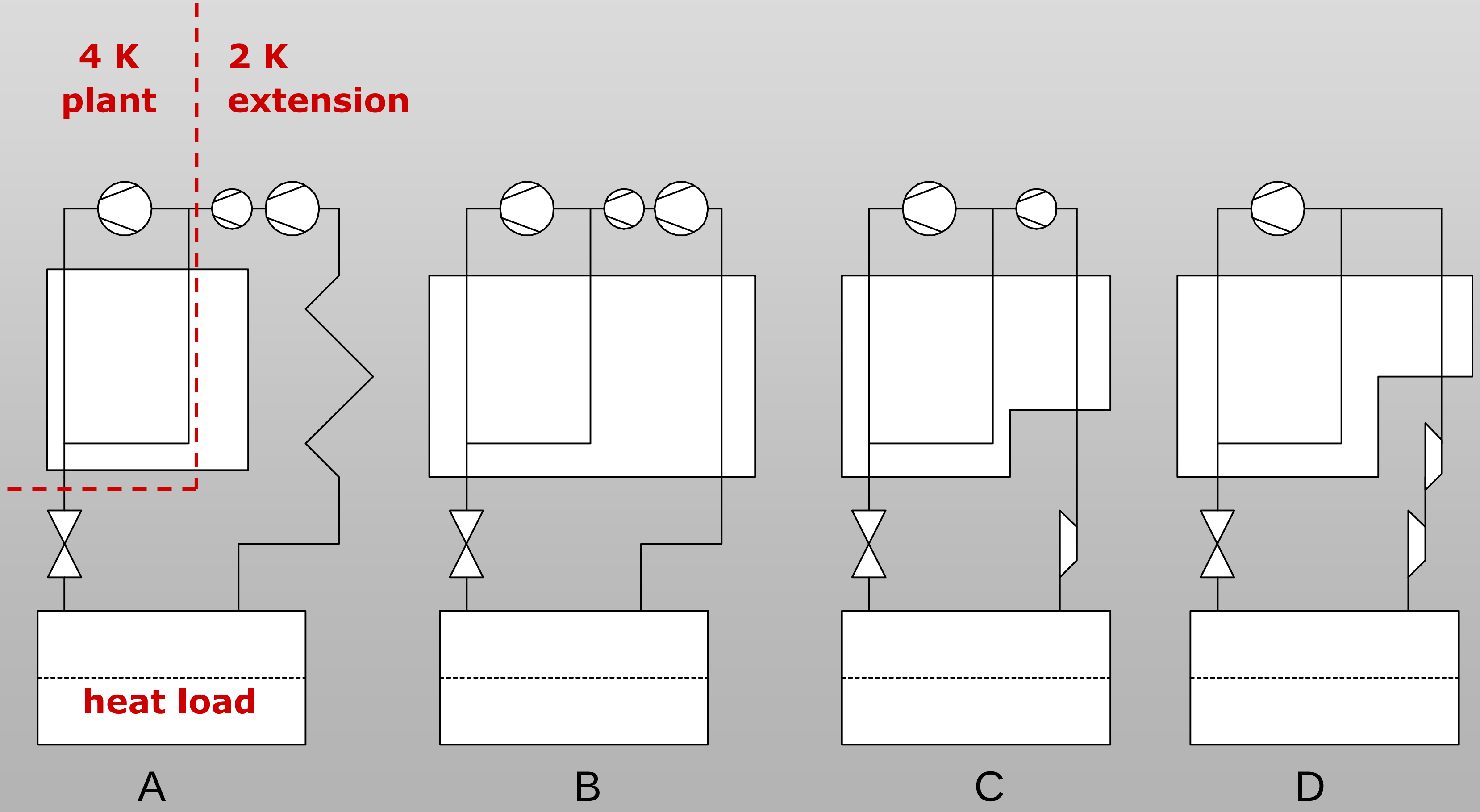
+ much less power dissipation in rf cavities

+ I_c, B_c gain for sc magnets

- pumped LHe bath (subatmosperic system)

- increase in power consumption (Carnot)

Subatmospheric (LHe II) helium plants



Subatmospheric (LHe II) helium plants

A: heating of helium return gas to ambient + warm vacuum pumps

DESY VUV-FEL Linac;

DESY TTF supply:

4 rotary vane pumps

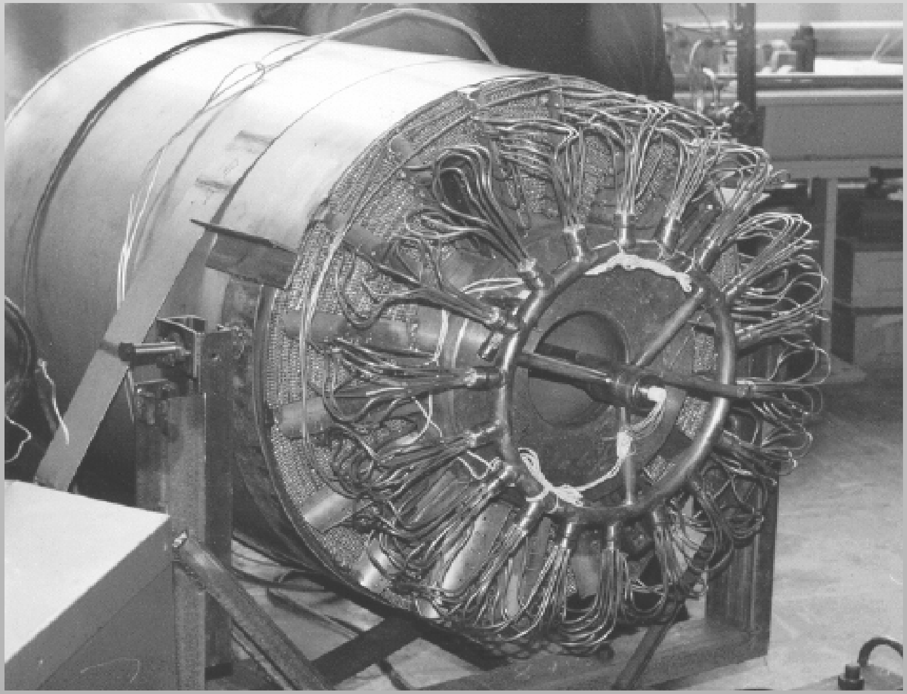
+ 3 stages of roots blowers

10 g/s He;

10 mbar ⇨ 1.05 bar

Subatmospheric (LHe II) helium plants

B: **demanding, large heat exchanger necessary**
(low density helium return gas)



DESY :

3.5 K 31 mbar	⇨	280 K 29 mbar
7.5 K 12 bar	⇦	300 K 12 bar

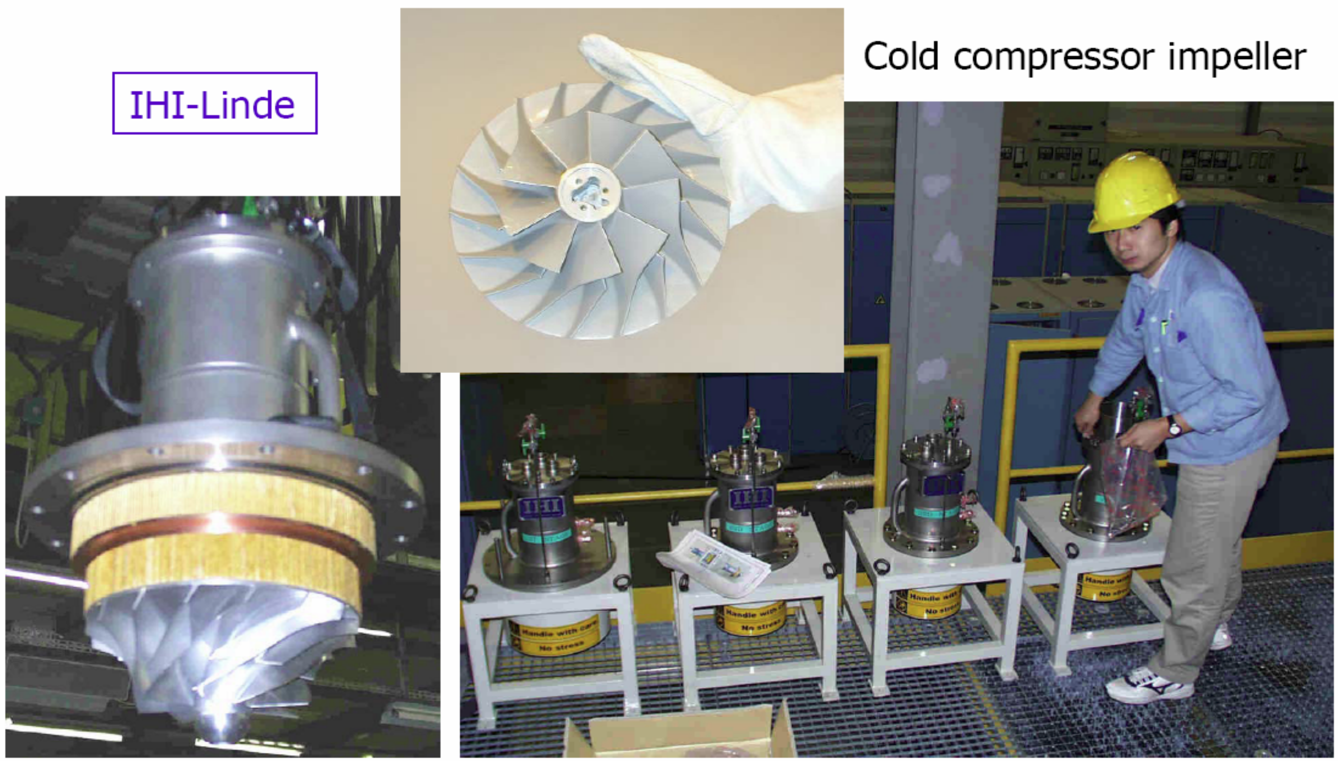
Subatmospheric (LHe II) helium plants

C: cold compressor(s) necessary

Cold Compressor Cartridges of 2.4 kW @ 1.8 K Refrigeration Units

IHI-Linde

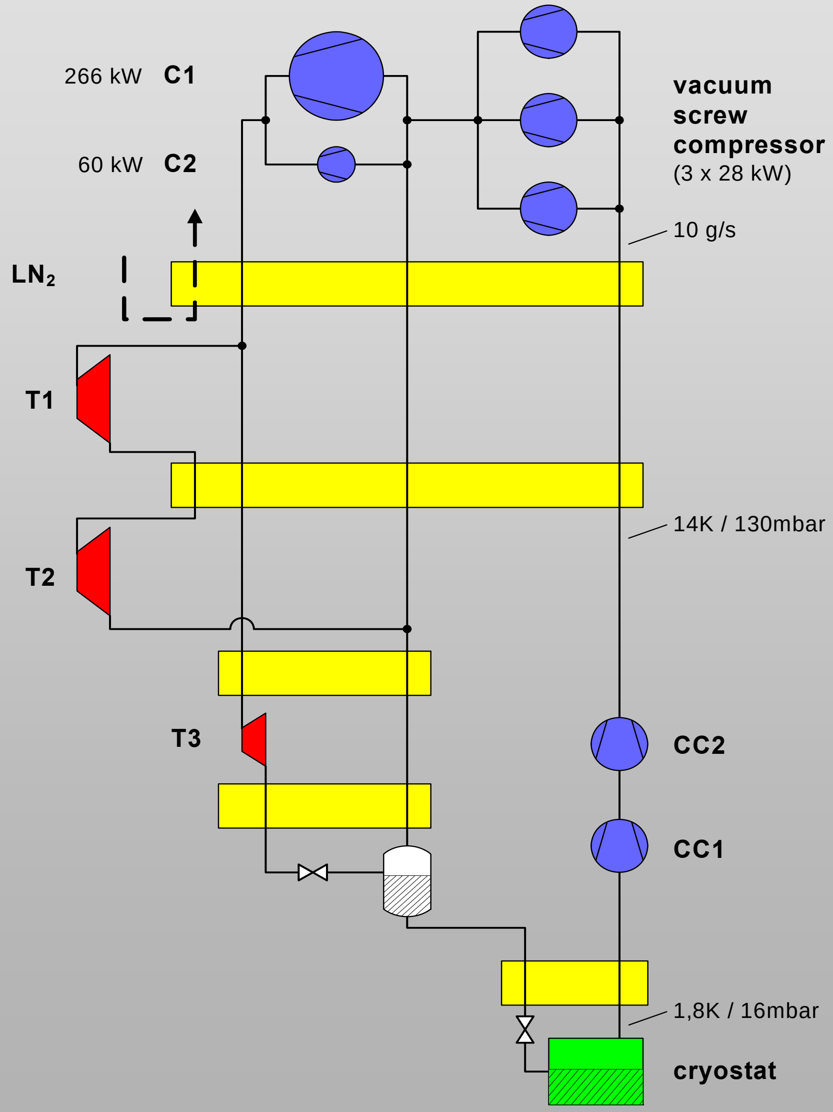
Cold compressor impeller

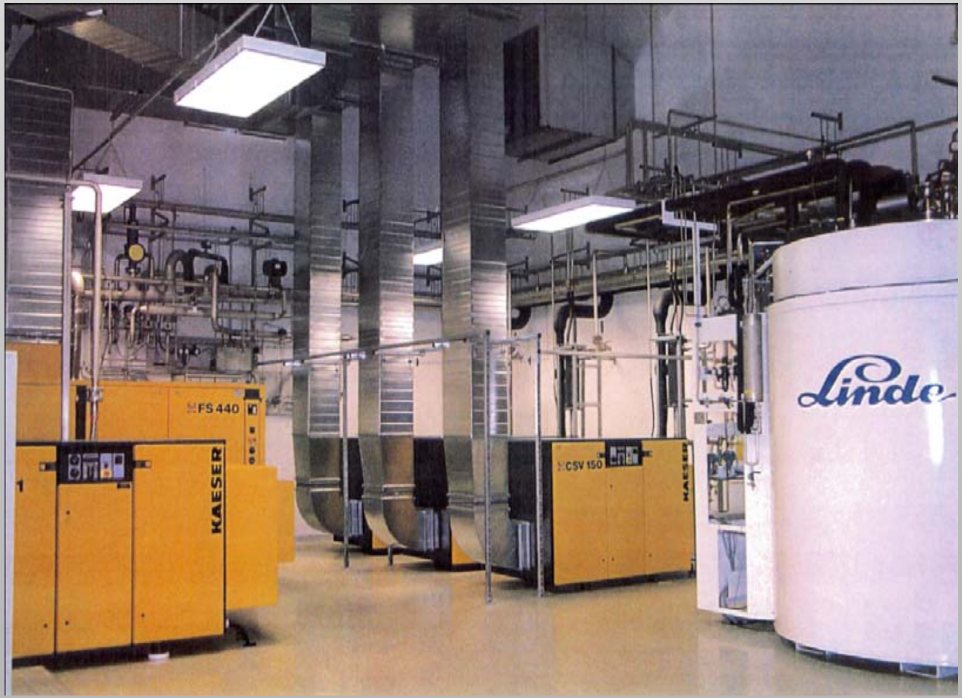


1st stage

The four-stage LHC cold compressors

FZ Rossendorf, ELBE accelerator

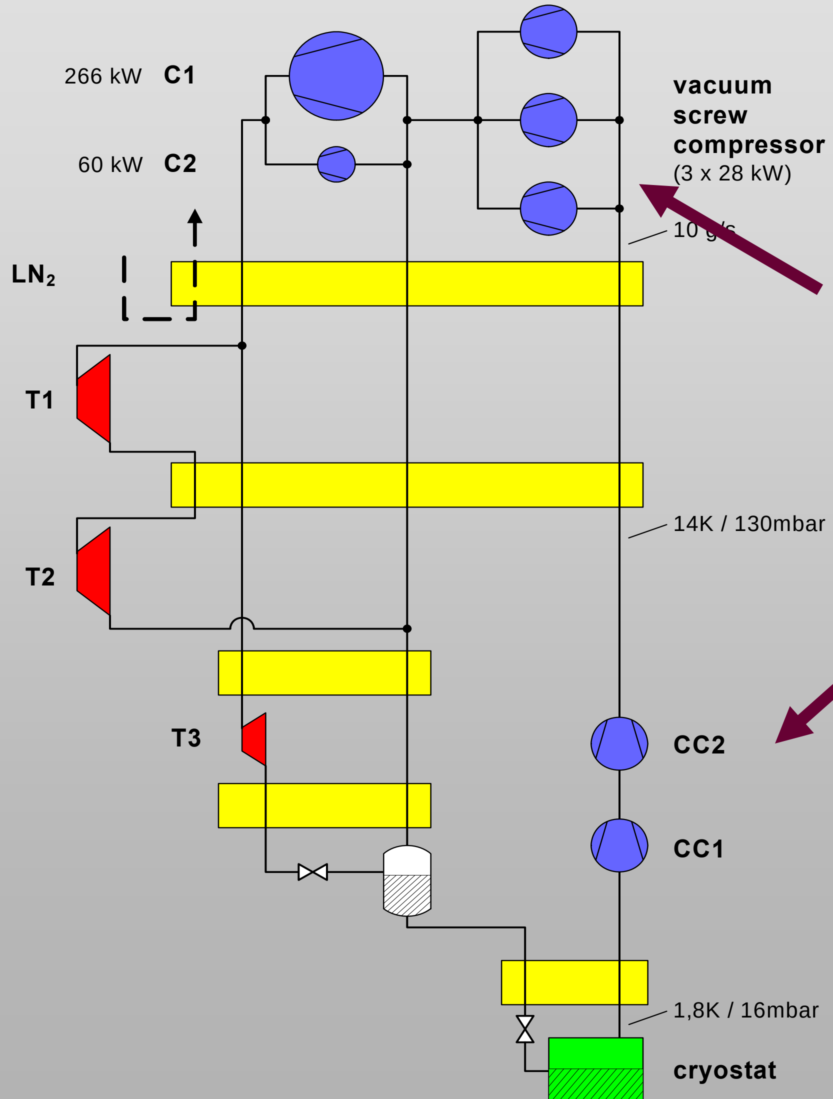




Helium Refrigerator 220 W @ 1.8 K

(fourth in size allover Germany!)

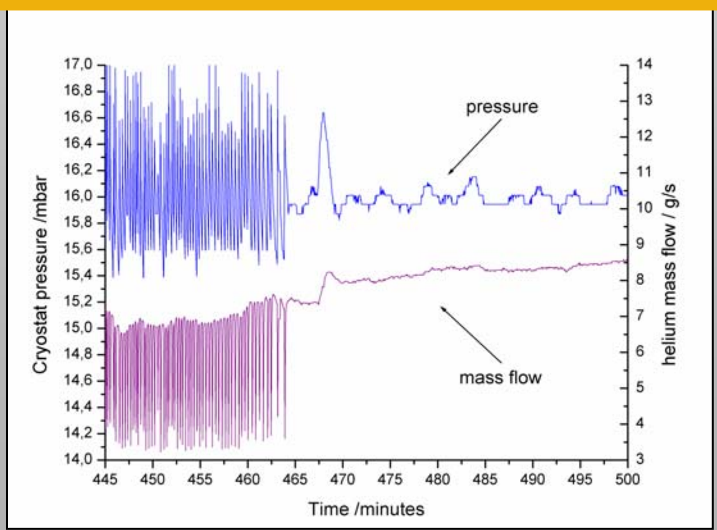
ELBE Helium Plant



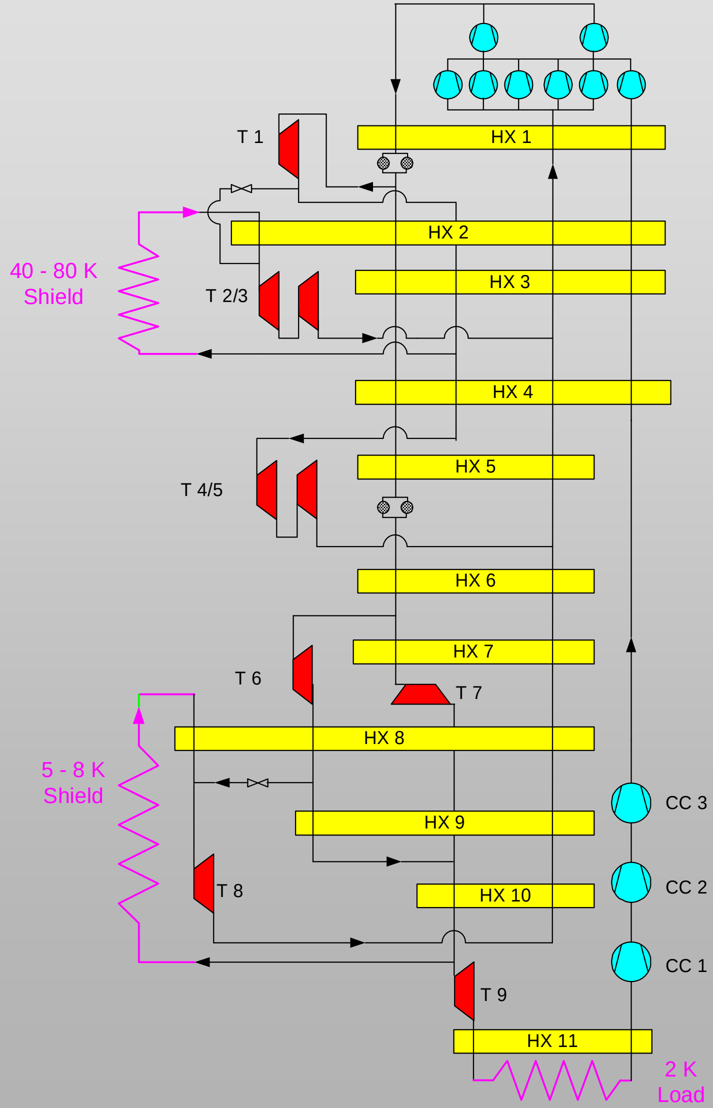
Complications with the subatmospheric part:

local overheating ⇨ oil cracking ⇨ para-formaldehyd formation + deposition

„1 Hz" phenomenon: wrong cold compressor operating map in the beginning ⇨ oscillations due to stall regime at part load conditions



"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

Maximum Efficiency

Carnot limit:

$$COP_{ideal} = Q/W = T_o/T_{amb} - T_o$$

for full reversible process,

perfect components, ...

77 K: $COP_{ideal} \approx 0.25$ (3 W/W)

4.2 K: $COP_{ideal} \approx 0.014$ (70 W/W)

1.8 K: $COP_{ideal} \approx 0.006$ (166 W/W)

Carnot fraction: $\eta := COP_{real} / COP_{ideal}$

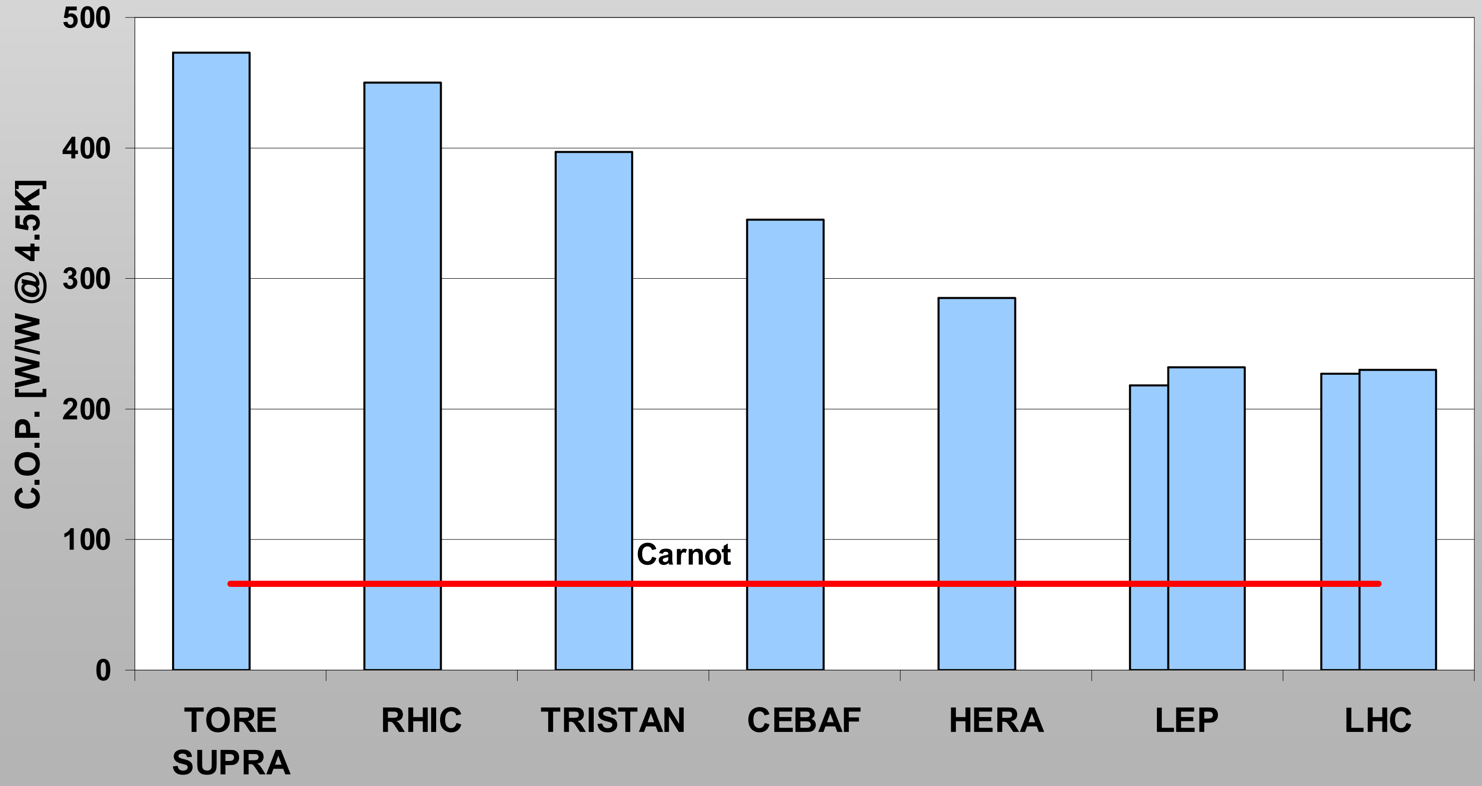
He Plants: $\eta \approx 0.01 \dots 0.35$

e.g.: input power $P_{el} \approx 0.5$ MW

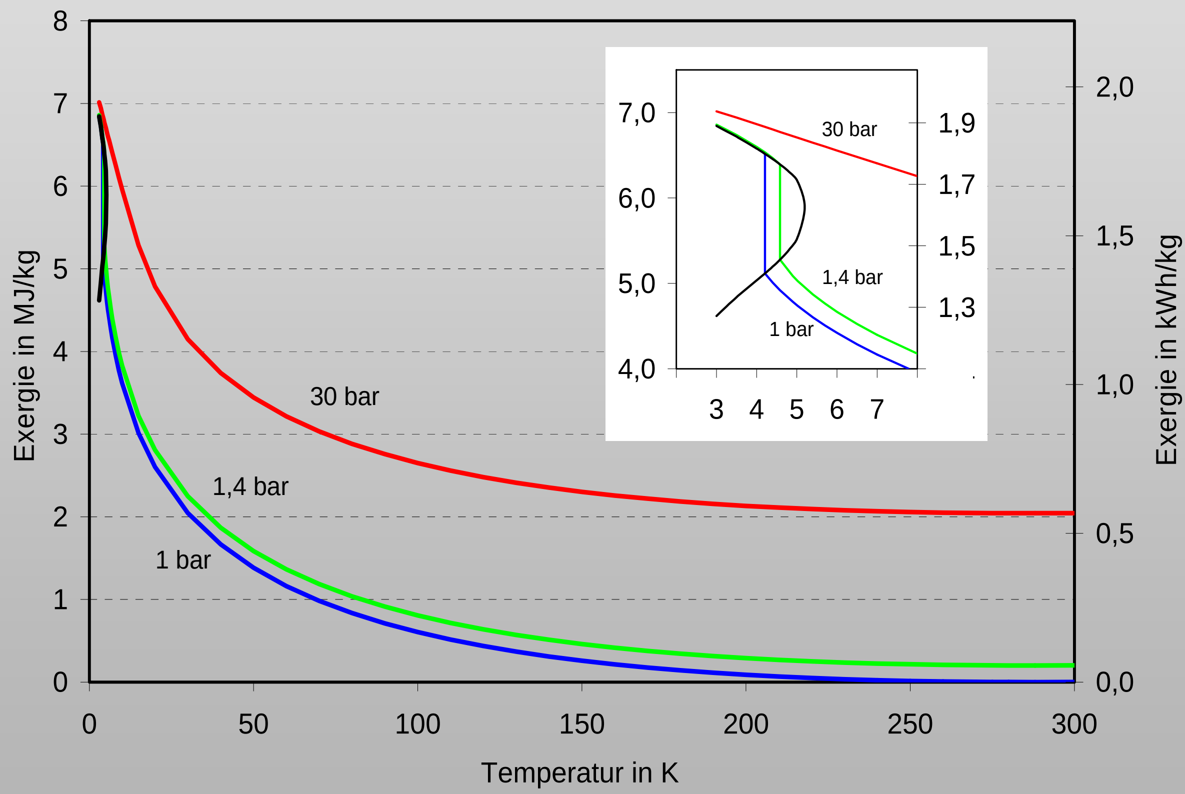
↕

cooling power @ 1.8 K: 200 W

COP of Large Helium Refrigerators



Liquefier Efficiency: Exergy Analysis



Mimimum energy input for complete liquefaction from 288 K at 1 bar:

6.52 MJ/kg

= 0.23 kWh/l $_{LHe}$

state-of-the-art:

2 kWh/l $_{LHe}$

10^5 l $_{LHe}$ /year
0,12 €/kWh

} 24 000 €/year operational costs

$$E_{min} = m\cdot[h_o - h_u - T_u\cdot(s_o - s_u)] = m\cdot(e_o - e_u)$$

Central Helium Liquefier TU Dresden (standard plant of the 80th):

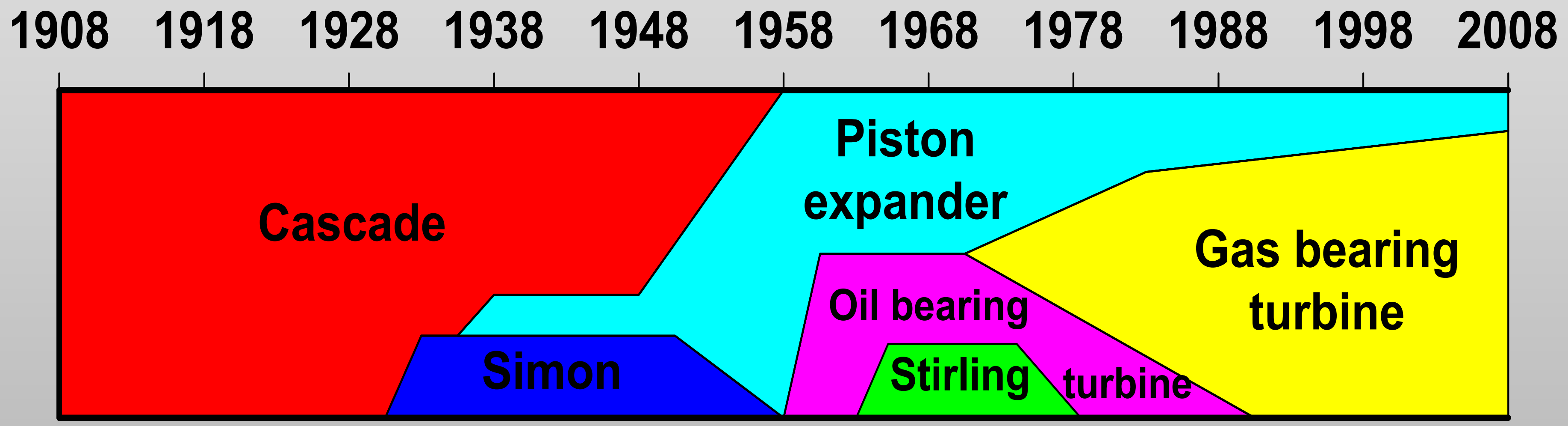
4.5 kWh / l $_{LHe}$ ⇨ $\eta \approx 0.05$

State-of-the-art helium liquefier

capacity 30 … 120 l LHe/h

2 kWh / l_{LHe} ⇨ η ≈ 0.012

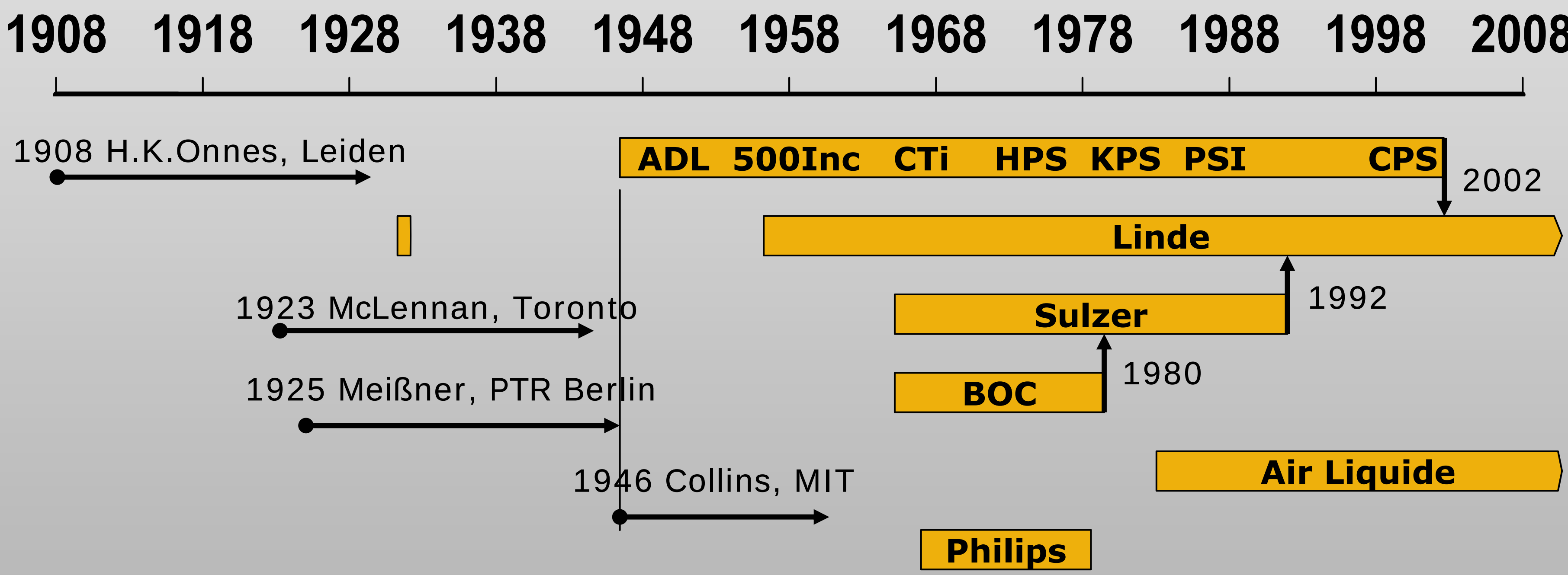
"Evolution" of Helium Plant Technology



⇨ 1. clear trend towards turbine plants with gas bearing

2. concentration on suppliers with own turbine development

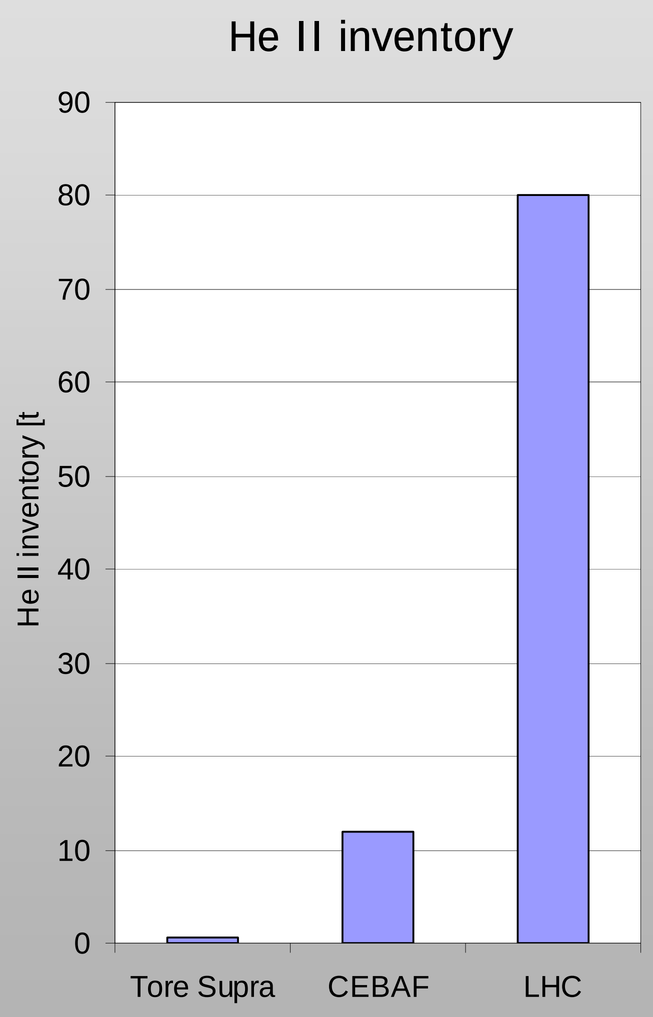
“Evolution” of Suppliers

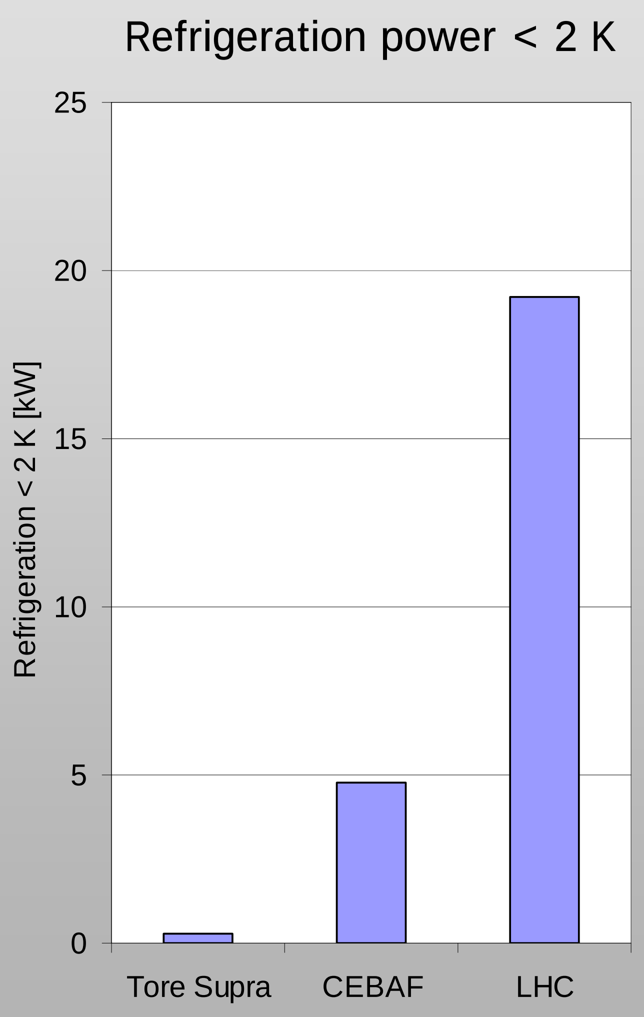


From the very beginning up to the present day:

always excellent co-operation between academic research and industry;

Innovations triggered by demanding customers /particle accelerators


He II inventory
He II inventory [t
90
80
70
60
50
40
30
20
10
0
Tore Supra
CEBAF
LHC


Refrigeration power < 2 K
Refrigeration < 2 K [kW]
25
20
15
10
5
0
Tore Supra
CEBAF
LHC

Helium Inventory

250 m³ @ 2 MPa Gaseous Helium Tanks

Helium Sources

Helium extracted as by-product from natural gas

helium concentration:

traces … 0.1 % … 6 %

worldwide demand:

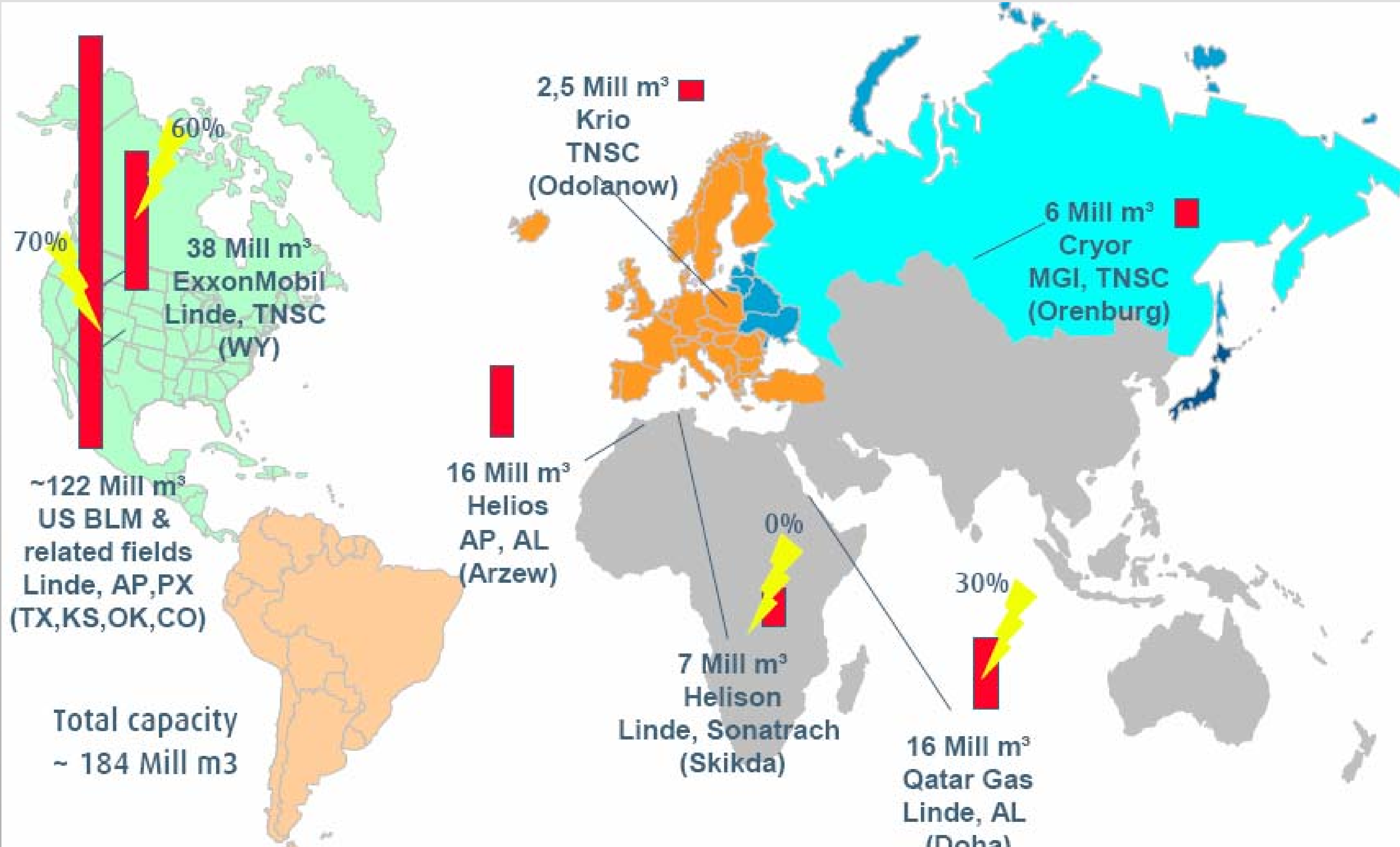
75 tons/day actually

(¼ of that for cryogenics)

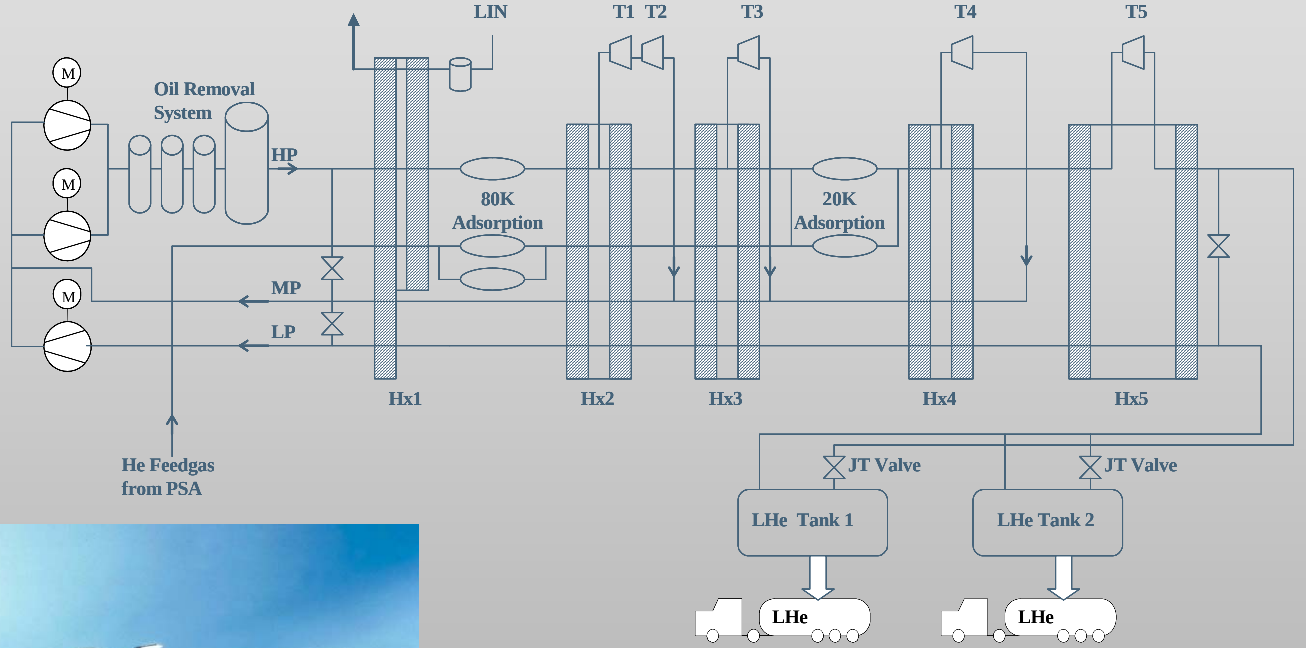
	helium resources (in 10^6 m³), figures from 2000	helium resources / -sales (in 10^6 m³), figures from 2007
USA	11 100 [a]	8 200 [a] / 138 [b]
Qatar	(among „others“)	10 000 / 5,5
Algeria	2 100	8 300 / 20
Russia	6 700	6 700 / 6,4
Canada	2 100	2 000 / -
China	1 100	1 100 / -
Poland	280	280 / 3
others	2 800	2 800 / -
total	26 180	39 000 / 173

[a] incl. Cliffside storage field (national helium reserve)

[b] 80 · 10^6 m³ production + 58 · 10^6 m³ withdrawal from Cliffside


2,5 Mill m³
Krio
TNSC
(Odolanow)
6 Mill m³
Cryor
MGI, TNSC
(Orenburg)
60%
70%
38 Mill m³
ExxonMobil
Linde, TNSC
(WY)
~122 Mill m³
US BLM &
related fields
Linde, AP,PX
(TX,KS,OK,CO)
16 Mill m³
Helios
AP, AL
(Arzew)
0%
7 Mill m³
Helison
Linde, Sonatrach
(Skikda)
30%
16 Mill m³
Qatar Gas
Linde, AL
(Doha)
Total capacity
~ 184 Mill m3

Helium Facility Skikda /Algeria



In operation since 2006;

natural gas / He separation and liquefaction (3000 l_{LHe}/h);

11 000 gal LHe oversesas transport container

Helium Resources

- worldwide helium demand permanently rising over the last decades
- new extraction facilities built or planned
- acutally cheap helium sold from the USA (liquidation of the Cliffside National Helium Reserve)
- some prominent rich sources are fading out

⇨ helium price strongly increased

⇨ worldwide bottlenecks with helium supply ⬅

sommer 2000
autumn 2001
autumn 2005
autumn 2006
autumn 2007
spring 2008
....

Lesson to learn:

- Helium is a noble and a rare gas
- it will become quite expensive in future
- effective use + gas recovery are essential

Thank you for your attention !

Questions ?