Karlsruhe Institute of Technology

Lecture Superconducting Power Systems
Winter term 2022/2023
Basics of Cryogenics

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Institute for Technical Physics (ITEP)

Contents

Motivation

What effort is required to cool back a heat output of 1 W at low temperatures?

Carnot efficiency of refrigerators

$$\eta_{c,77\,K} = \frac{T_k}{T_w - T_K} = \frac{77\,K}{300\,K - 77\,K} = \frac{77\,K}{223\,K} = 0.3453$$

2.9 W

$$\eta_{c,4.5\,K} = \frac{T_k}{T_w - T_K} = \frac{4{,}5\,K}{300\,K - 4{,}5\,K} = \frac{4{,}5\,K}{295{,}5\,K} = 0.01523$$

65.7 W

Motivation

What effort is required to cool back a heat output of 1 W at low temperatures?

Real efficiency of refrigerators

$$\eta_{real} = \eta_c \cdot COP$$

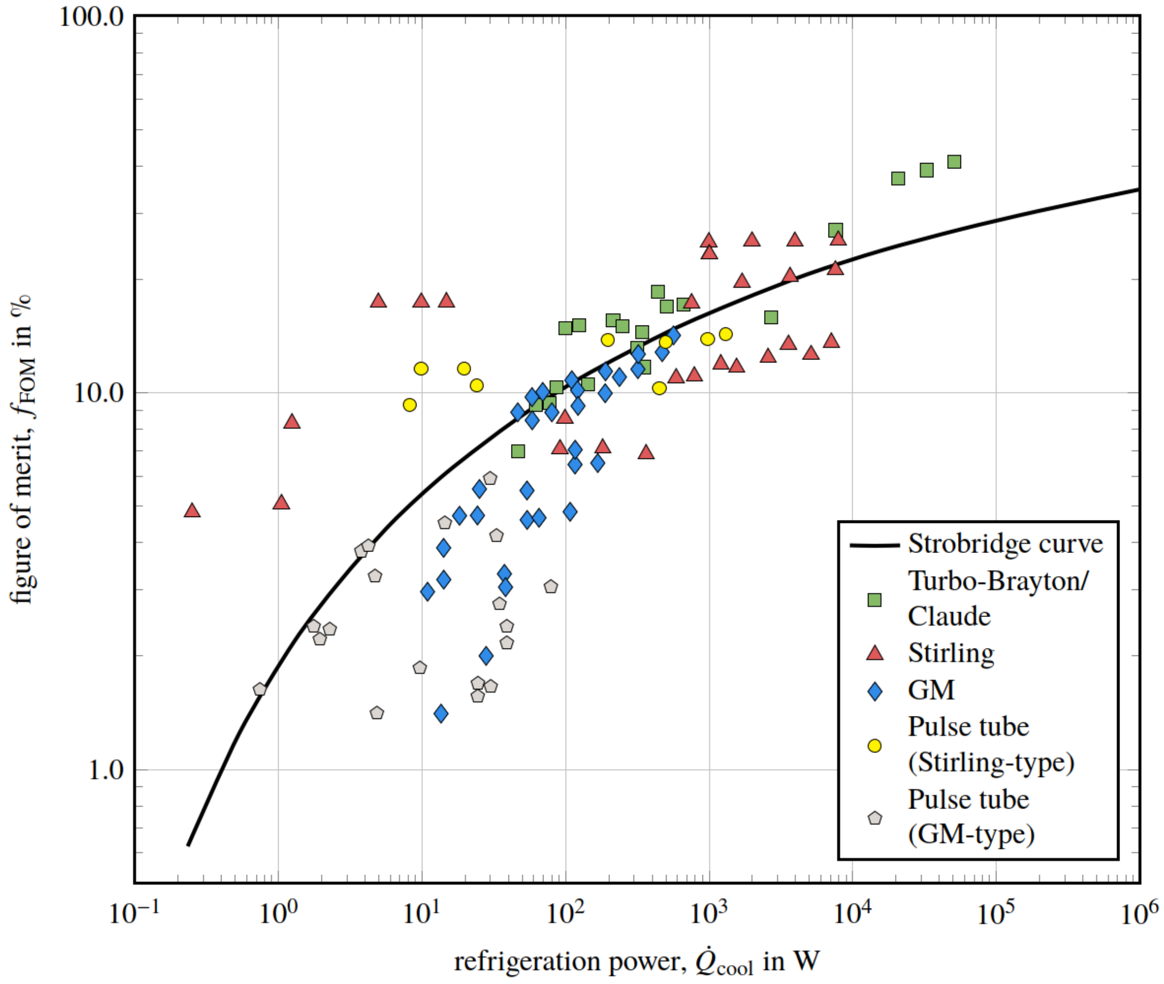
COP: Coefficient of Performance

Motivation

What effort is required to cool back a heat output of 1 W at low temperatures?

Real efficiency of refrigerators

$$\eta_{real} = \eta_c \cdot COP$$



Motivation

What effort is required to cool back a heat output of 1 W at low temperatures?

At 77 K

- 1 W heat load costs approx. 100 €/W for the purchase of the refrigeration plant
- 15-20 W electric power consumption per 1 W heat
- 1 Liter liquid nitrogen costs 10 ct to 1 € depending on purchase quantitiy

At 4,5 K

- 1 W heat load costs >1000 €/W for the purchase of the refrigeration plant
- 700-1000 W electric power consumption per 1 W heat
- 1 Liter liquid helium costs 10,6 € at KIT

Motivation

What types of losses occur at low temperatures?

AC losses

Heat radiation

Conduction

Current leads

Motivation

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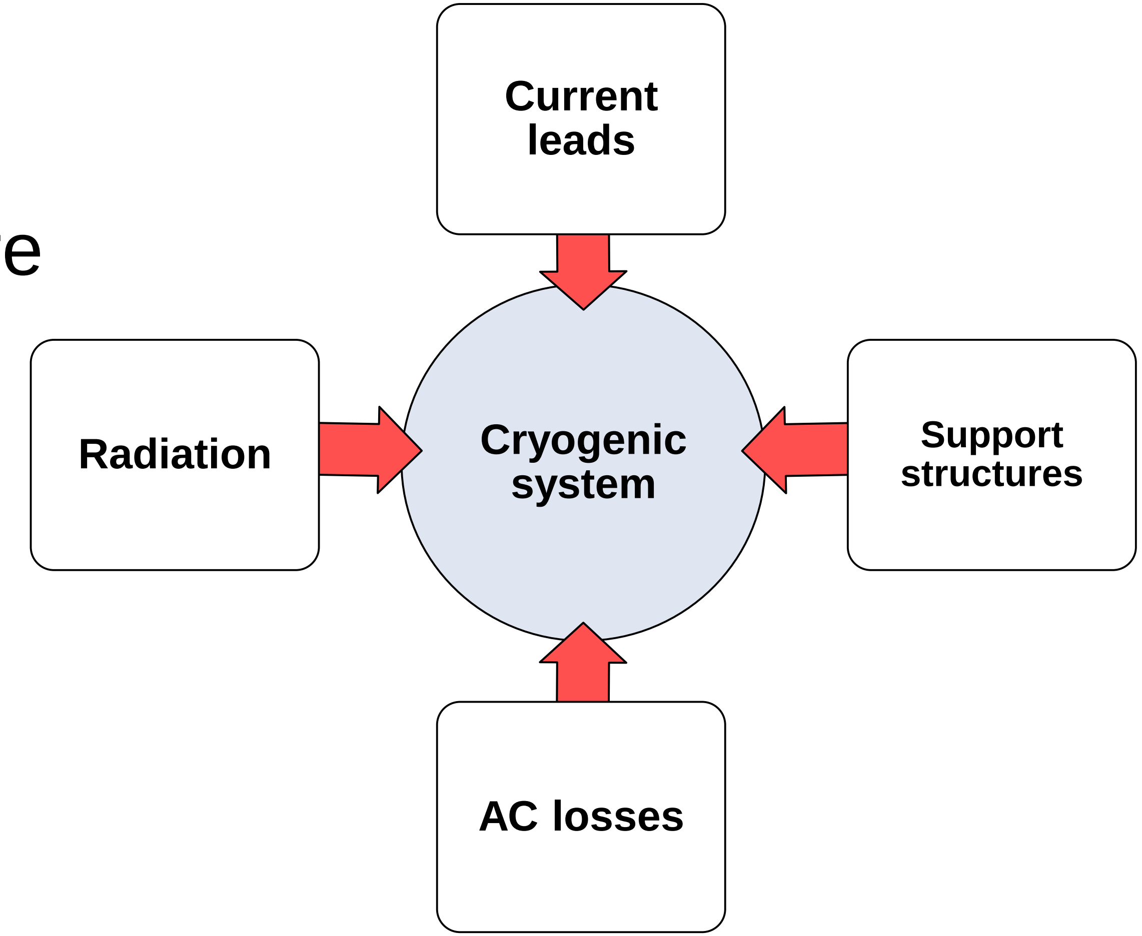
What types of losses occur at low temperatures?

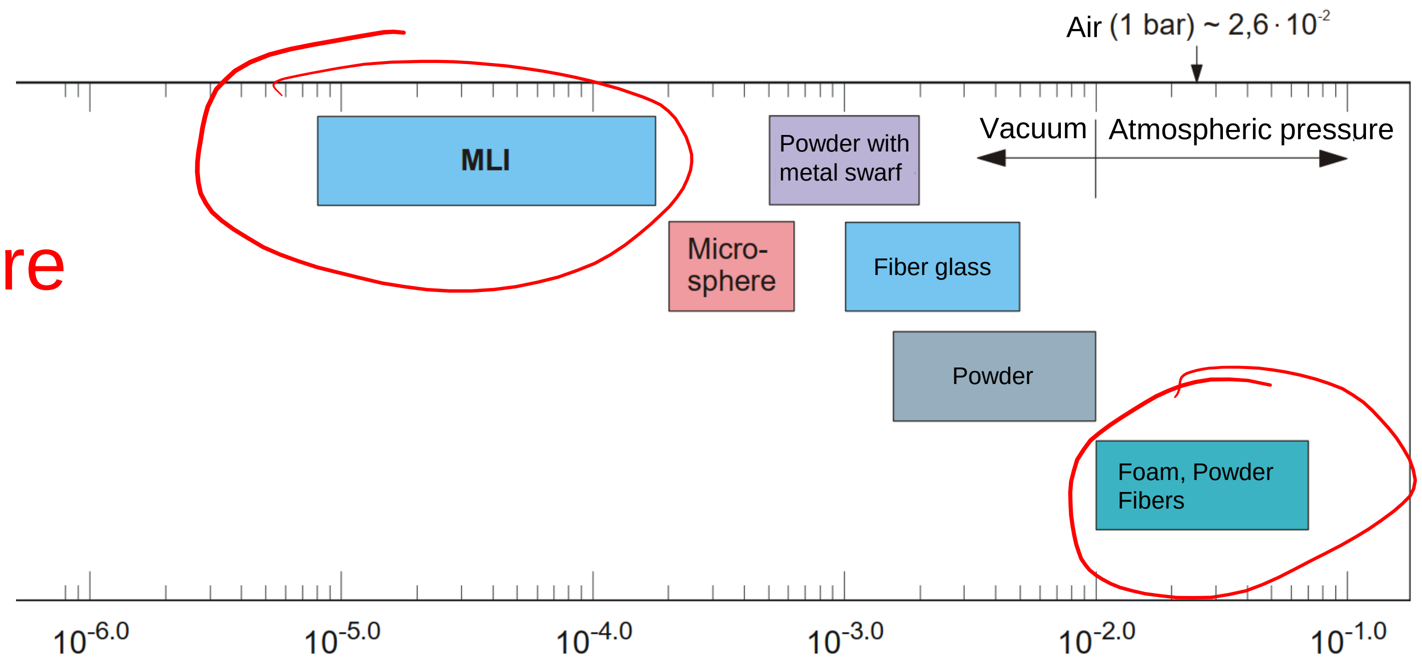
- Current leads
- Heat radiation
- Mechanical support structure
- AC Losses
- Other



Motivation

What types of losses occur at low temperatures?

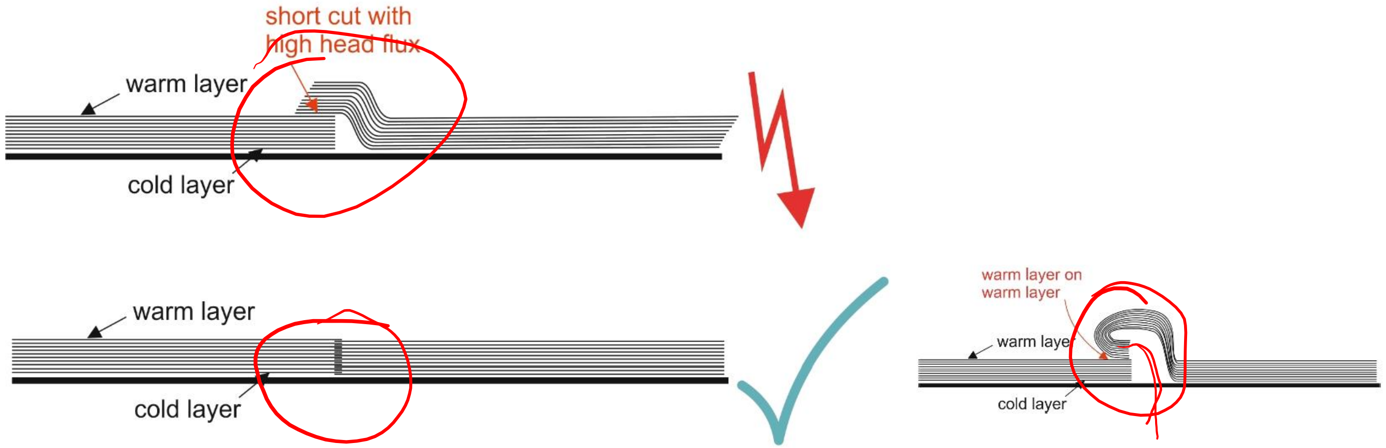
- Current leads
- Heat radiation
- Mechanical support structure
- AC Losses
- Other



Thermal conductivity λ in W/(m*K) between 77 K – 300 K

Superinsulation - MLI

- Currently the most effective insulation method
- MLI consists of:
  - Reflective foils, coated polymer sheets
    - Reduction of heat radiation
  - Spacer between layers with minimal contact points
    - Reduction of heat conduction
  - High vacuum (10^{-3} - 10^{-6} mbar)
    - Reduction of convection
    - Reduction of residual gas conduction

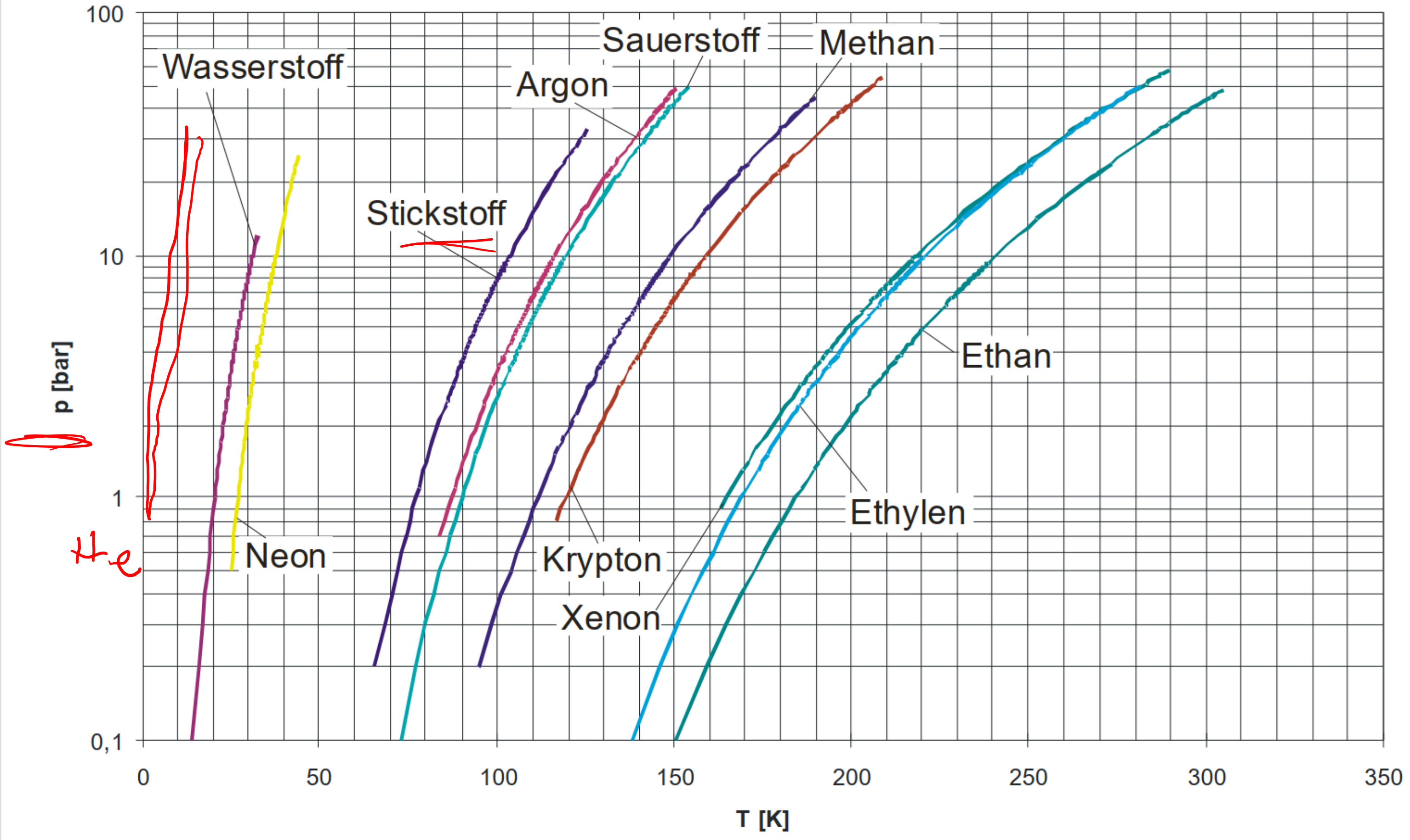


- Requirements:
  - High quality of materials
  - Know-How
  - Careful processing

Contents

Pool boiling

Vapor pressure curves of cooling fluids



Pro

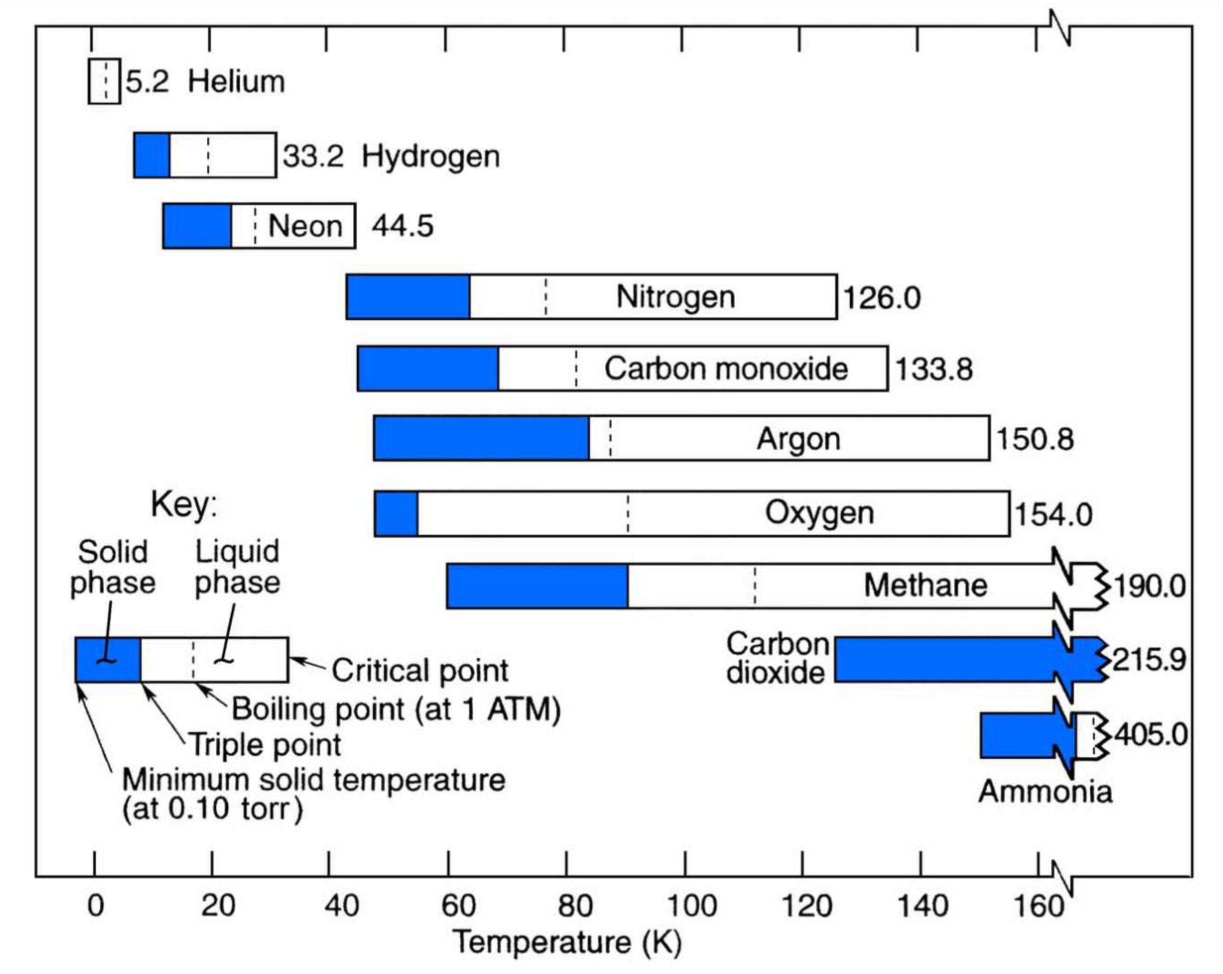
easy
const. temperature

Con

temperature not freely
gap between 30 K – 60 K
refilling required

Pool boiling

Vapor pressure curves of cooling fluids



Pro

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temperature not freely
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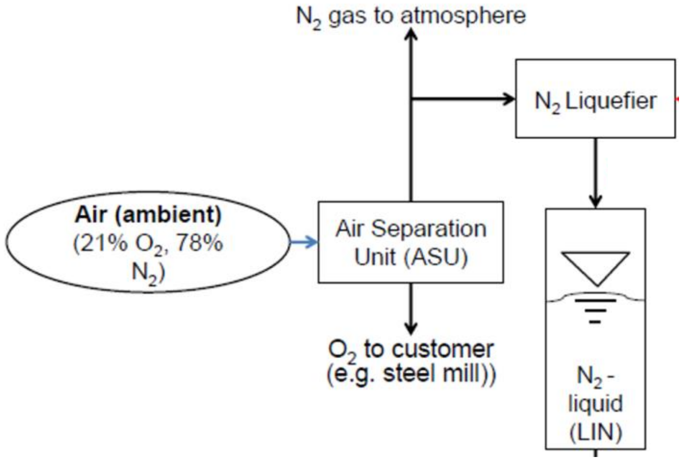
Nitrogen liquefication

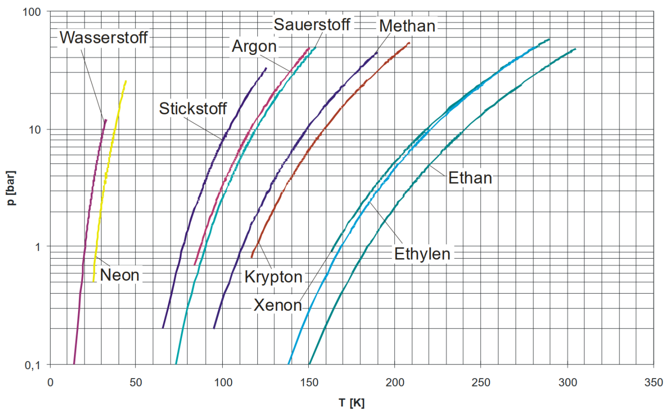
- Usually, liquid nitrogen is produced in large air separation plants.



- For a liquefaction capacity of 68 kg/h, 33 kWh of energy are required. (Data and pictures Friedhelm Herzog, Messer)

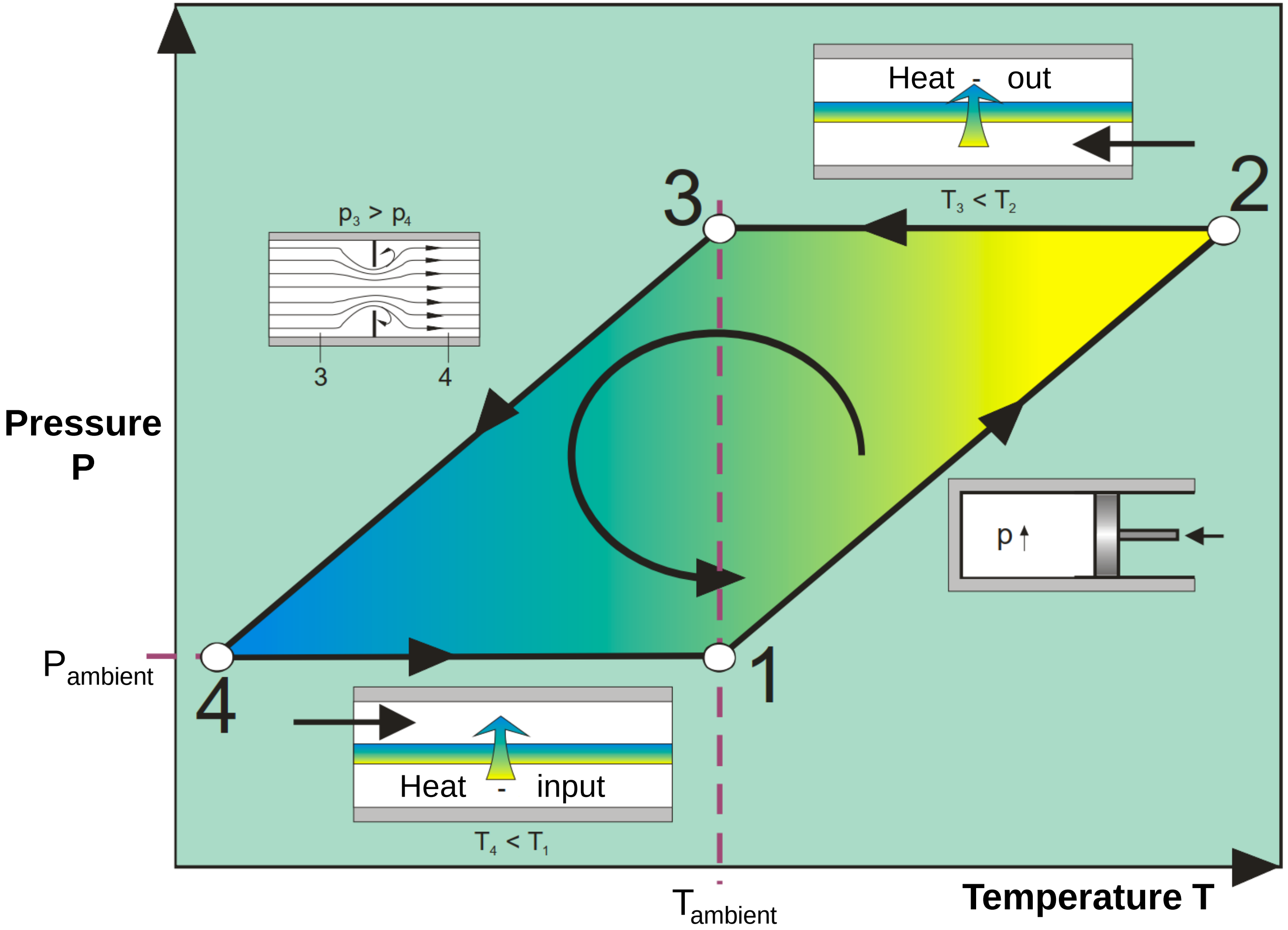
Pool boiling

For which applications pool boiling under normal pressure can be used?



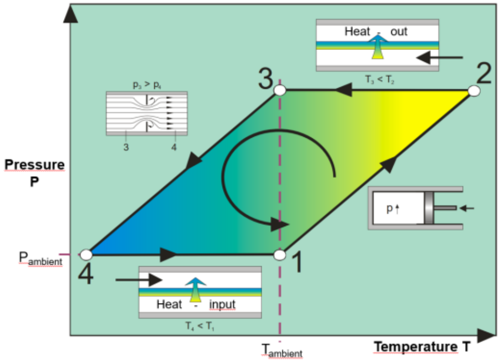
Cable	No, pressure difference needed
Current limiter	Yes, up to medium voltage (insulation)
Rotating machine	Yes, nearly normal pressure
Transformer	Yes, up to medium voltage (insulation)
SMES	Yes

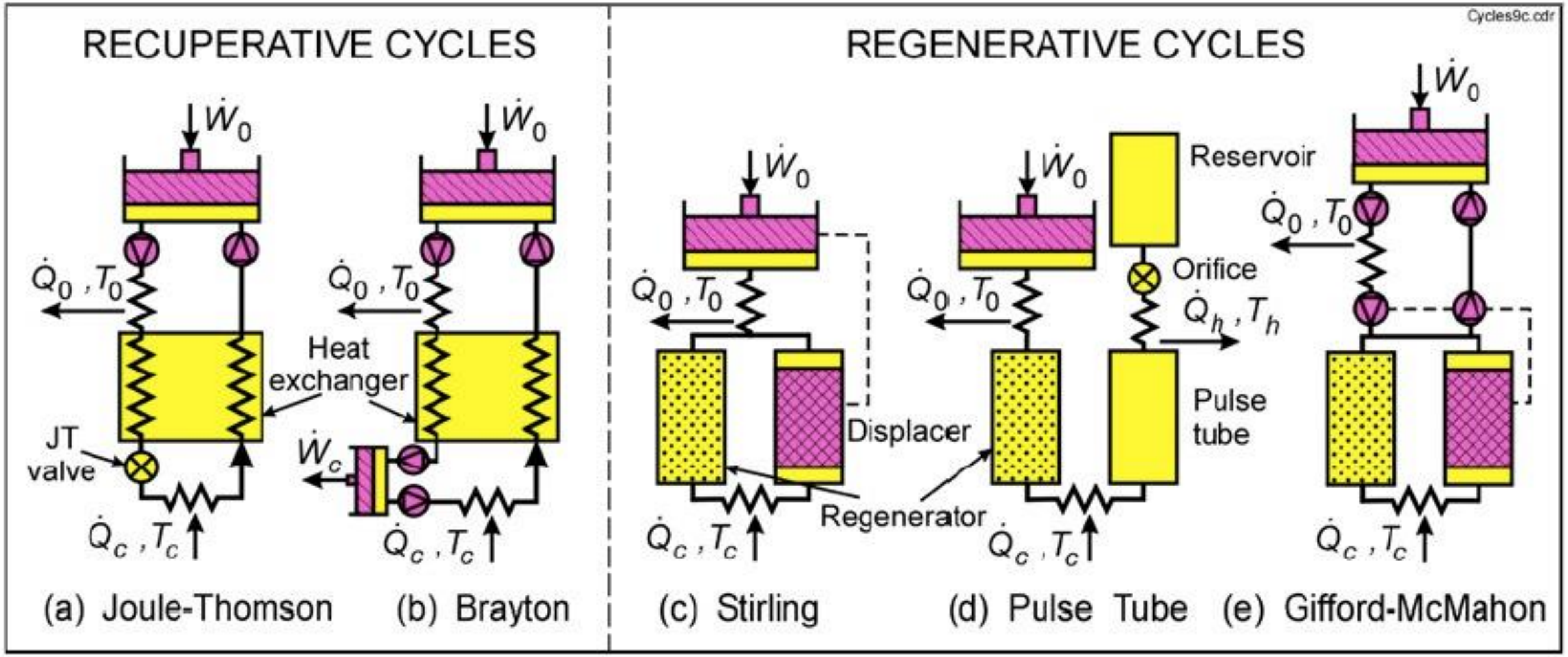
Basic principle of refrigeration



Refrigerators

- Cryocooler types





Quelle: Radebough, J. Phys. Cond. Matter 21 (2009), 164219

Cryocooler

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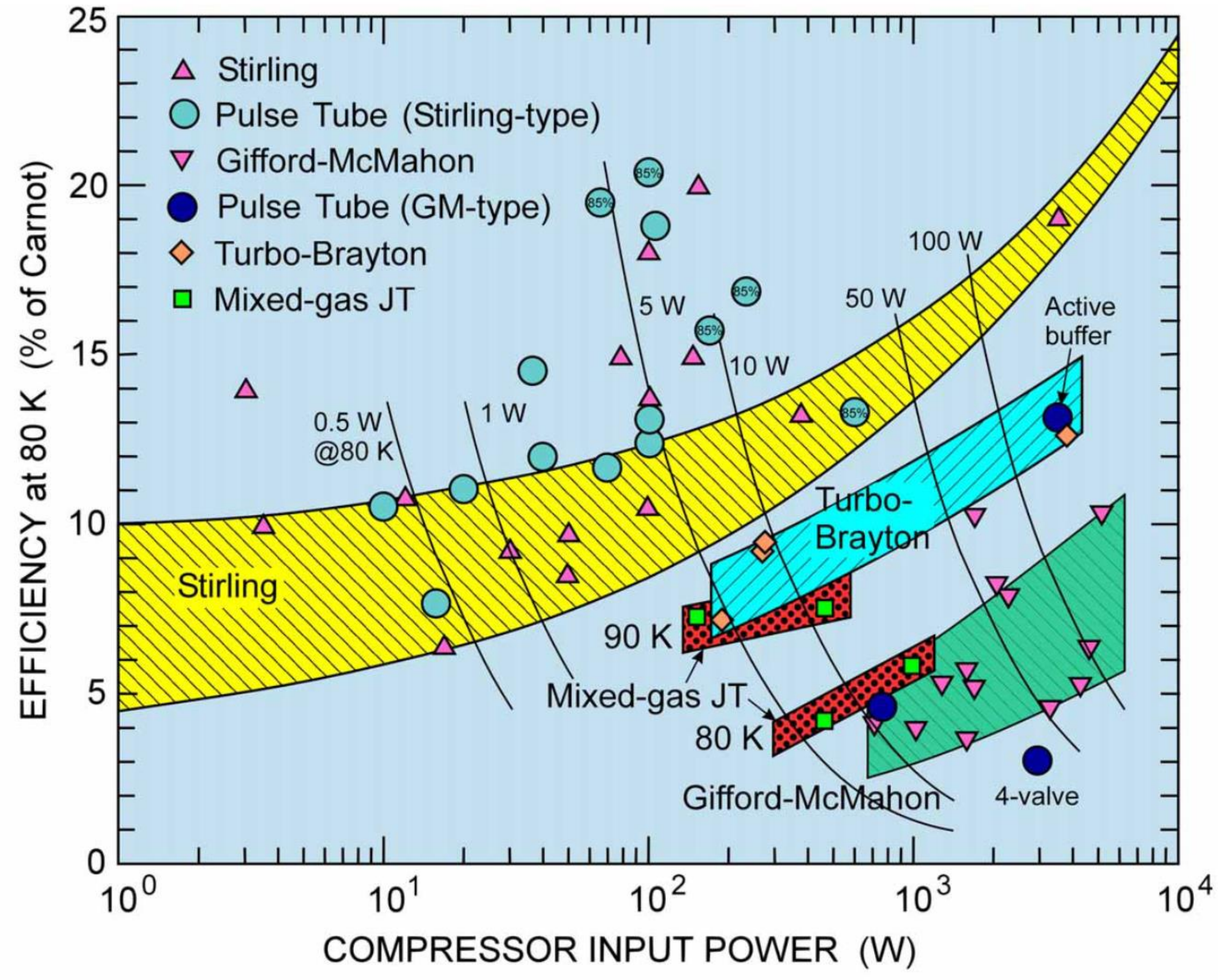
- Principles

Type	Explanation
Brayton	Turbines are used to compress a working gas, which is then expanded by either a turbine (Brayton) or a throttle (Joule-Thompson). The technology is particularly suitable for high outputs, e.g. in air condensers. For small Brayton systems, high speeds are required in the expander turbine, which make the technology more expensive.
Gifford-McMahon	This is a simplified variant of the Stirling process. Compressed gas is supplied via a compressor and the expansion volume is pressurized with high or low pressure via a rotary valve.
Pulse Tube	Pulse tube cooler is a refrigerating machine based on the principle of the Stirling engine. The advantage over the Stirling engine is that no mechanical moving parts are necessary near the cold heat exchange point. This makes very compact cooling heads possible and the achievable minimum temperature is not limited by the mechanical frictional heat of these parts.

Cryocooler

COP



Overview Cryocooler

- Overview of available cryocoolers > 100 W at 77 K

Company	Cooling Type	Type	Cooling Power	at Temp	Input Power
Sumitomo Heavy Industries	GM	CH 110	175 W	77 K	
Air Liquide	Turbo Brayton	TBF-80	7800 W	77 K	
Air Liquide	Turbo Brayton	TBF-175	16500 W	77 K	
Mayekawa	Turbo Brayton	Neo	5000 W	77 K	62,8 kW
Leybold	GM	Coolpower 250 MD	175 W	80 K	
Leybold	GM	Coolpower 140 T	140 W	80 K	
Fabrum Solutions	Pulse Tube	PTC 1000	1450W	77 K	25,0 kW
Fabrum Solutions	Pulse Tube	PTC 330	480 W	77 K	11,0 kW
Cryomech	Pulse Tube	PT90	90 W	80 K	4,3 kW
Cryomech	GM	AL300	320 W	80 K	7,5 kW
Cryomech	GM	AL600	600 W	80 K	11,5 kW
Stirling	Reversed Stirling Cycle	SPC-1	1000 W	80 K	11,2 kW
Stirling	Reversed Stirling Cycle	SPC-4	4200 W	80 K	

Overview Cryocooler

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Air Liquide	Turbo Brayton	TBF-175	16500 W	77 K	
Mayekawa	**Turbo Brayton**	**Brayton Neo**	**5000 W**	**77 K**	**62,80 kW**
Leybold	GM	Coolpower 250 MD	175 W	80 K	
Leybold	GM	Coolpower 140 T	140 W	80 K	
Fabrum Solutions	**Pulse Tube**	**PTC 1000**	**1450 W**	**77 K**	**25,00 kW**
Fabrum Solutions	Pulse Tube	PTC 330	480 W	77 K	11,00 kW
Cryomech	Pulse Tube	PT90	90 W	80 K	4,30 kW
Cryomech	GM	AL300	320 W	80 K	7,50 kW
Cryomech	**GM**	**AL600**	**600 W**	**80 K**	**11,50 kW**
Stirling	Reversed Stirling Cycle	SPC-1	1000 W	80 K	11,20 kW
Stirling	Reversed Stirling Cycle	SPC-4	4200 W	80 K	

Examples Cryocooler

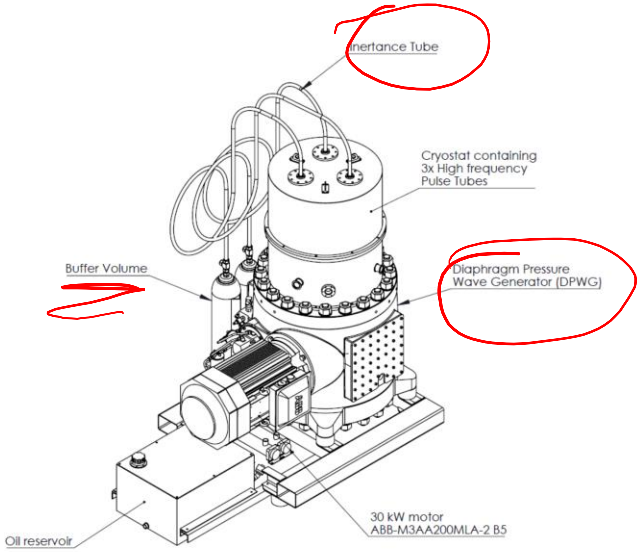
- Cryomech AL 600 (GM)

Cooling capacity	600W @ 80K, 500 W@ 70 K
Cooling time	15 Min to 80K
Weight	41.8kg
Compressor Package:	CPA1114
Water Cooled Weight:	470lb (213kg)
Water Cooled Dimensions:	61 X 61 X 79cm
Input Power:	380/415 VAC 3 PH / 11.5kW
Cooling:	Water (11,4 l/min) or air
Temperature range:	7 to 38°C

Examples Cryocooler

- Fabrum PTC 1000 (PT Stirling)

Cooling capacity	1450 W @ 77 K
Input power	25 kW
Weight	1300 kg
Cooling	Water (40 l/min) or air
Dimensions	1.8 (L) x 1.2 (W) x 2.1(H) m
Temperature range:	0 to 35°C



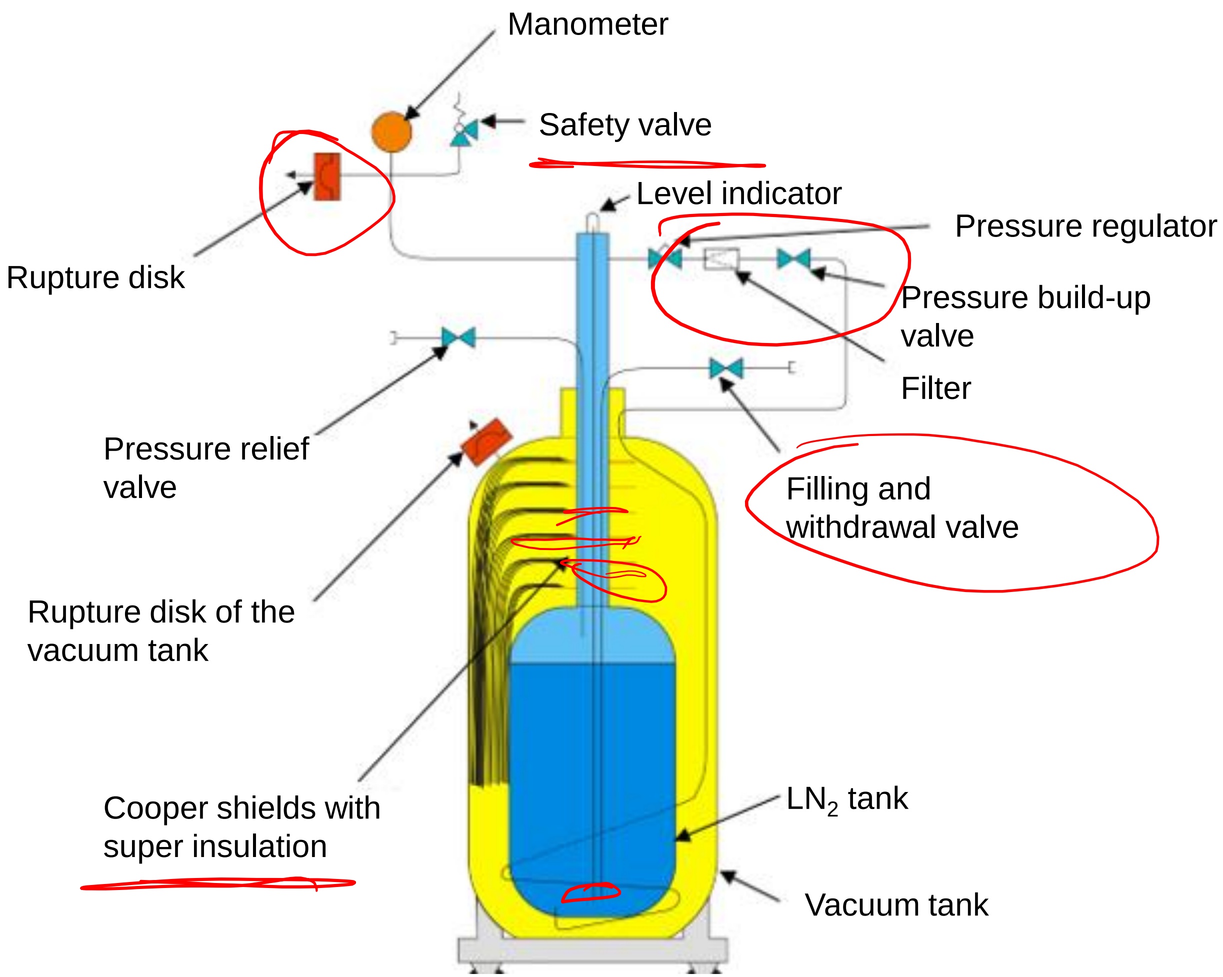
Examples Cryocooler

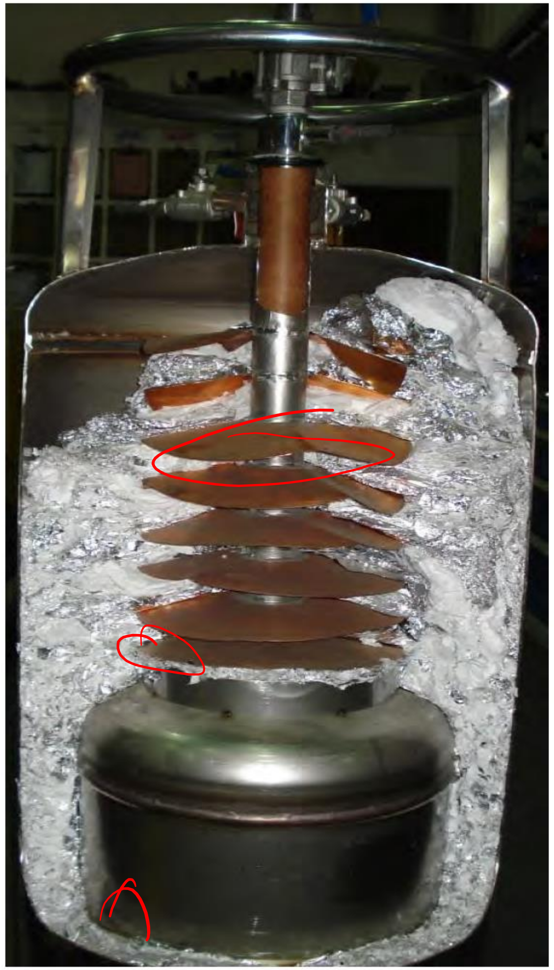
- Mayekawa Brayton NeO

Cooling capacity	5000 W at 77 K
Input power	75 kW
Weight	5.500 kg
Cooling	Water 200 l/min
Dimensions	2,2x3,6x2,2 m
COP	0.08 @ 77 K

Contents

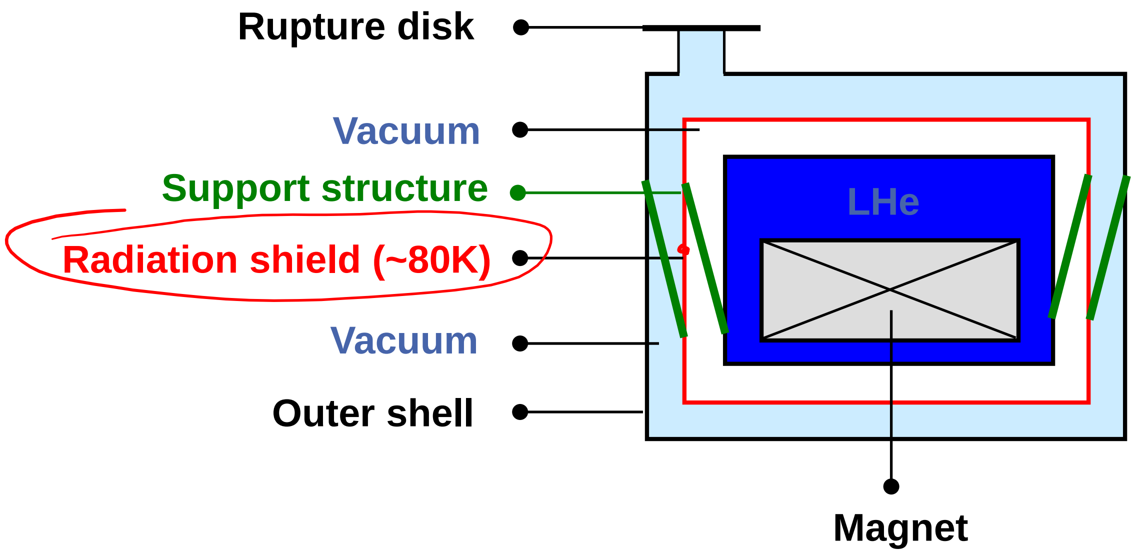
Schematic sketch of a LN_2 cryostat





Schematic sketch LHe cooled magnet

- Cryostat with liquid helium

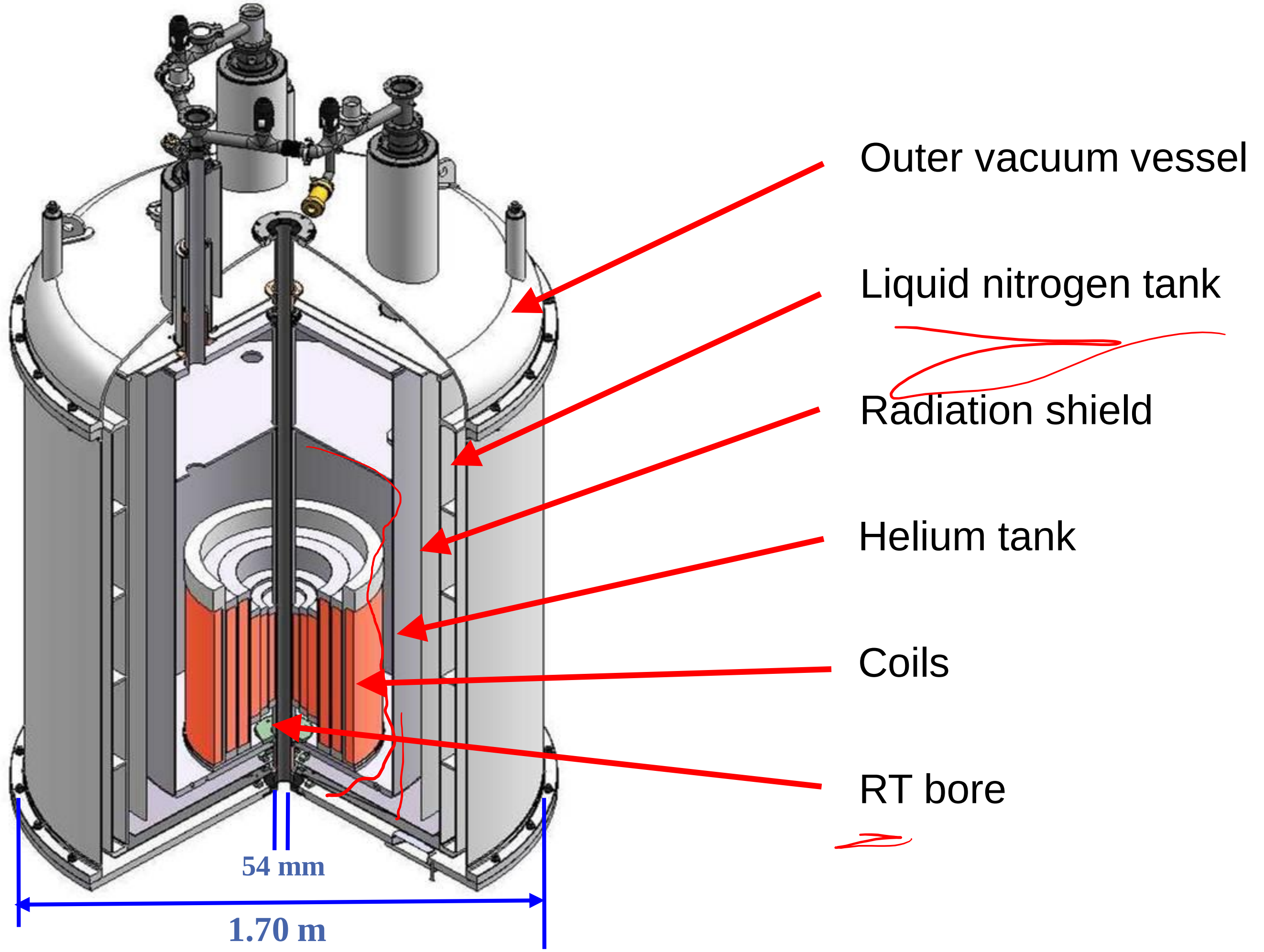


Thermal cryostat losses

- Thermal conduction through support structure
- Thermal radiation from warm to cold surfaces
- Residual gas thermal conduction
- Current lead losses and sensor lines

Application example

- Cryostat of a NMR magnet



Source: Bruker Biospin

Application example

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- Cryostat of a NMR magnet

Picture: Bruker Biospin

Coil

Helium tank

40 K – radiation shield

LN_2 tank with
super insulation

Vacuum vessel

Contents

Project data

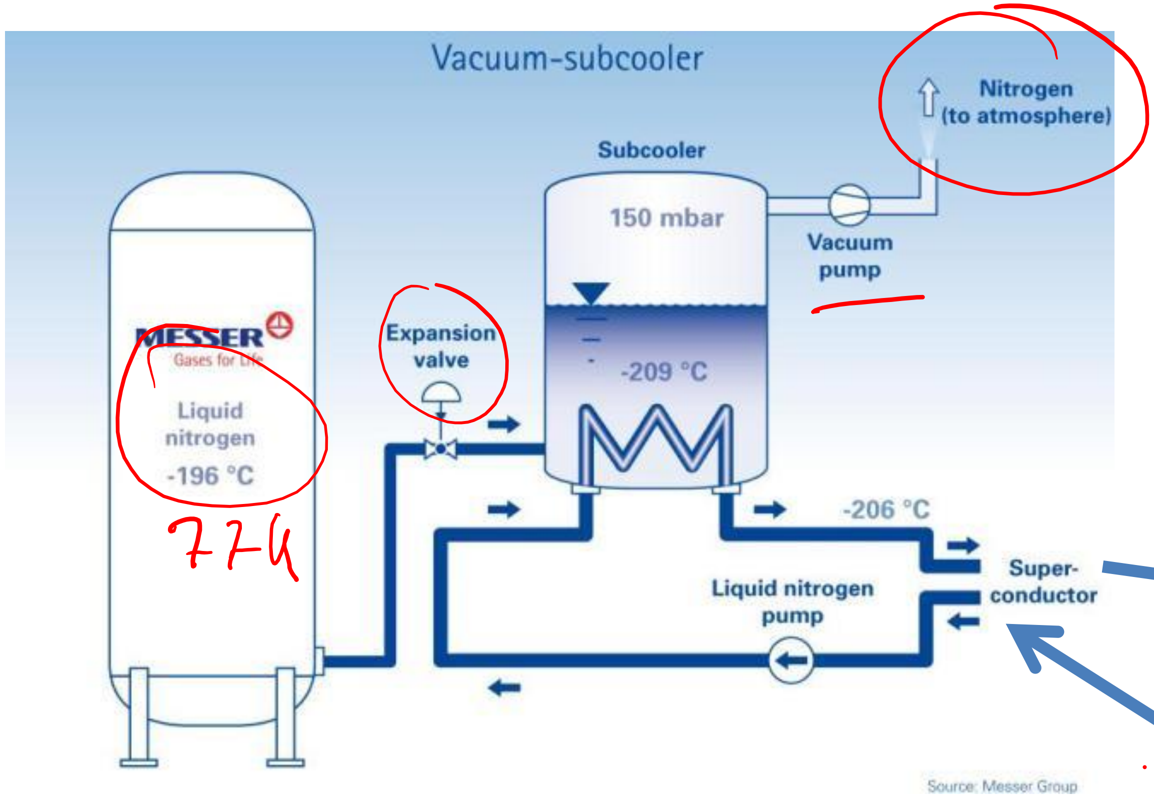
Place: Essen, Germany

- Cable length: 1,000 m
- Voltage: 10,000 V
- Electrical capacity: 40,000 kW

- Cooling capacity (cable): 4 kW
- Cooling temperature: - 206°C (67 K)

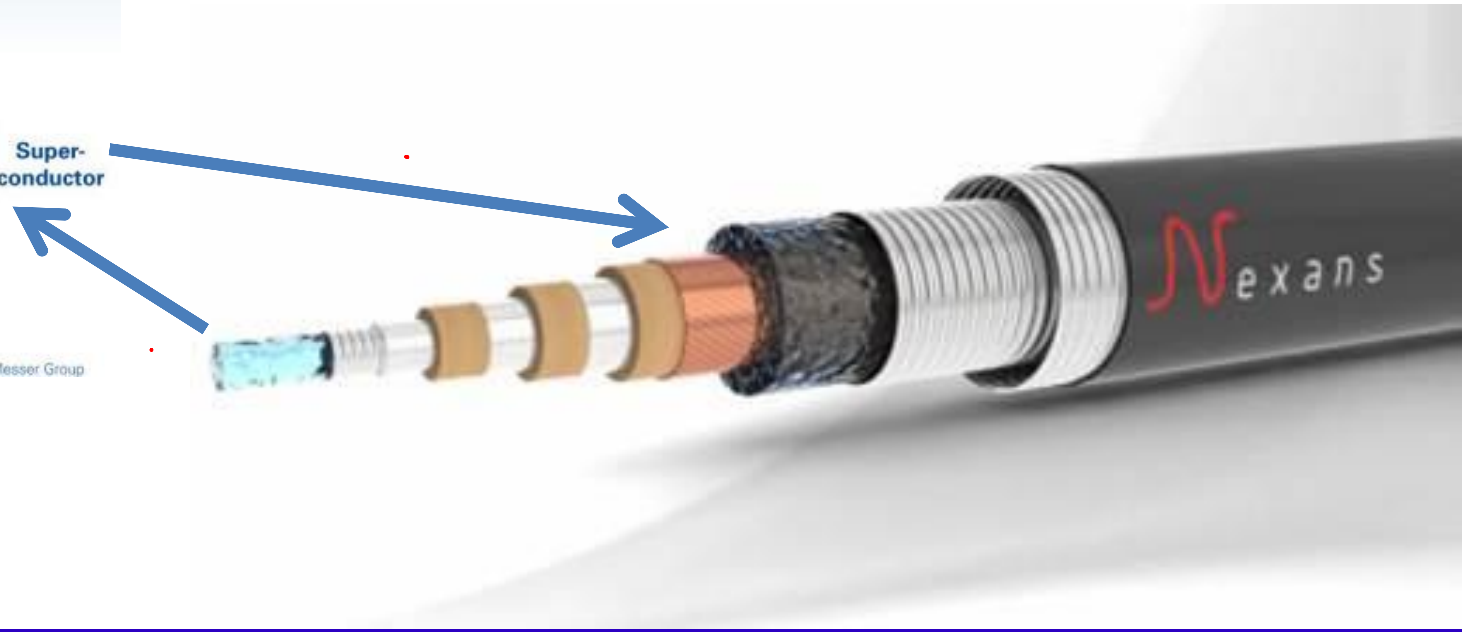
MESSER Gases for Life

The most important components



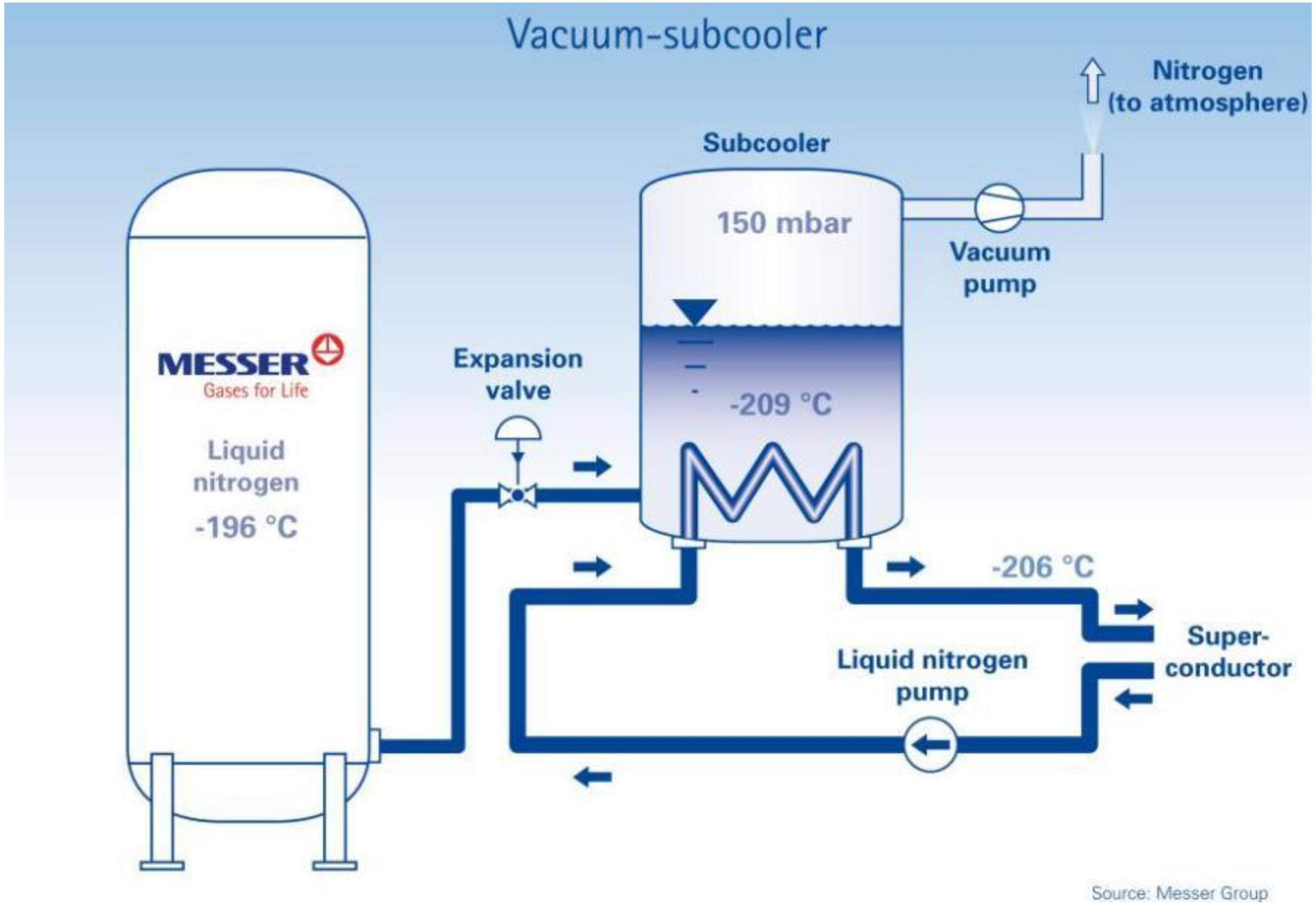
Messer cooling unit

Nexans cable



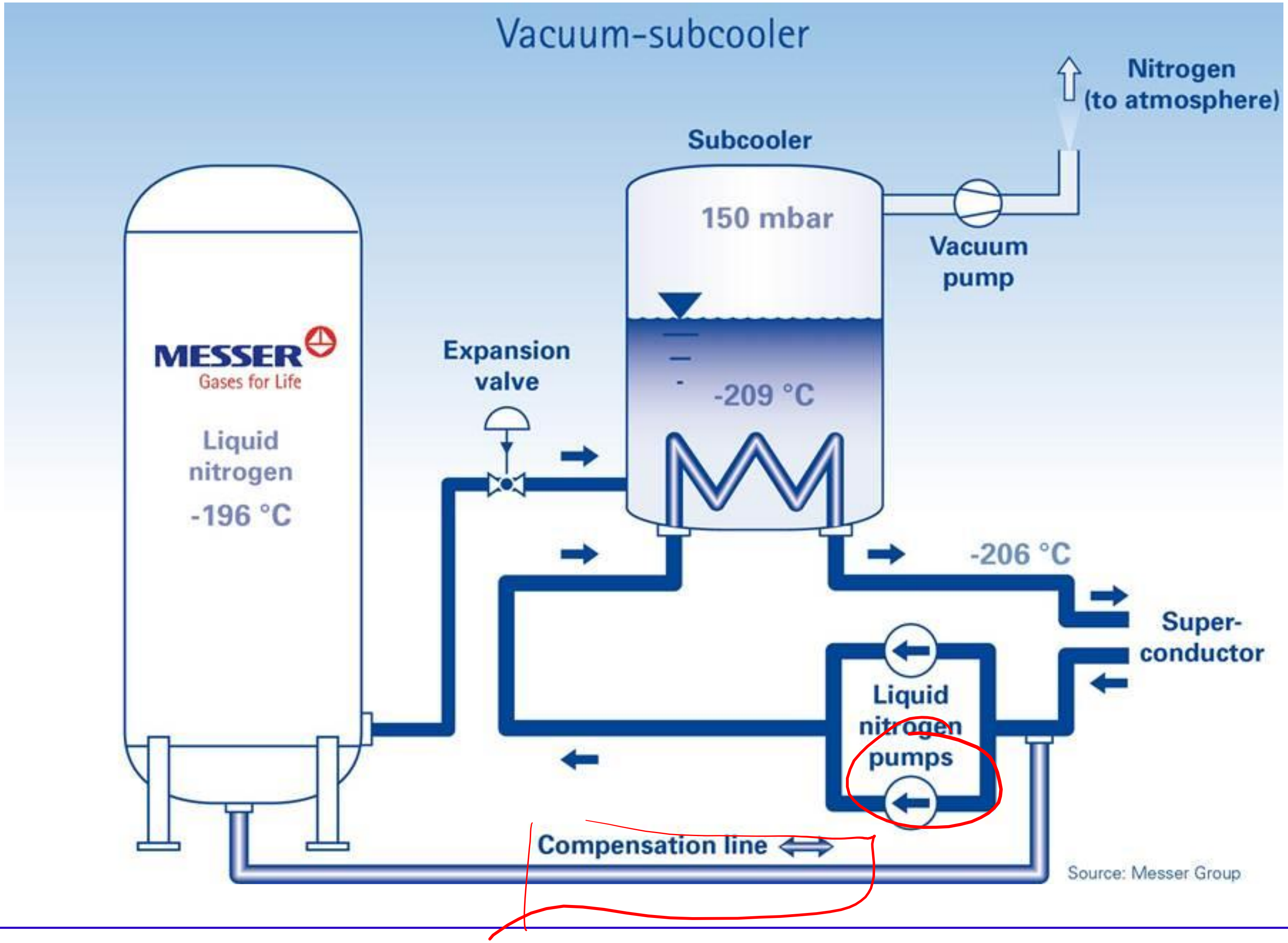
Basic diagram

- Liquid nitrogen is used
  - as heat transfer medium
  - as cooling agent
- LIN is pumped through the superconducting cable
- LIN is recooled in the subcooler (to -206°C)
- LIN vaporizes at 150 mbar(a) (forced by vacuum pumps)
- LIN temperature decreases to -209°C (expansion through the regulation valve)



Redundancy (circulation)

- There are installed 2 liquid nitrogen circulation pumps.
- 1 pump is in operation, the other one is in standby.
- Pump maintanance is done without stopping the circuit.
- In case of malfunction there is automatic switchover to the standby pump.
- Full redundancy for the circulation is achived with quite low additional investment (app. 3%).



Redundancy (vacuum pumps)

- For operation at full capacity (4 kW @ 67 K) 2 vacuum pumps are in operation.
- In case of failure the duty of the malfunctioning item is automatically taken over by the 3rd vacuum pump.
  (app. 1% add. investment)
- For operation at actual capacity (1.8 kW @ 67 K) only 1 vacuum pump is necessary.
- Actual 2 vacuum pumps are in reserve.

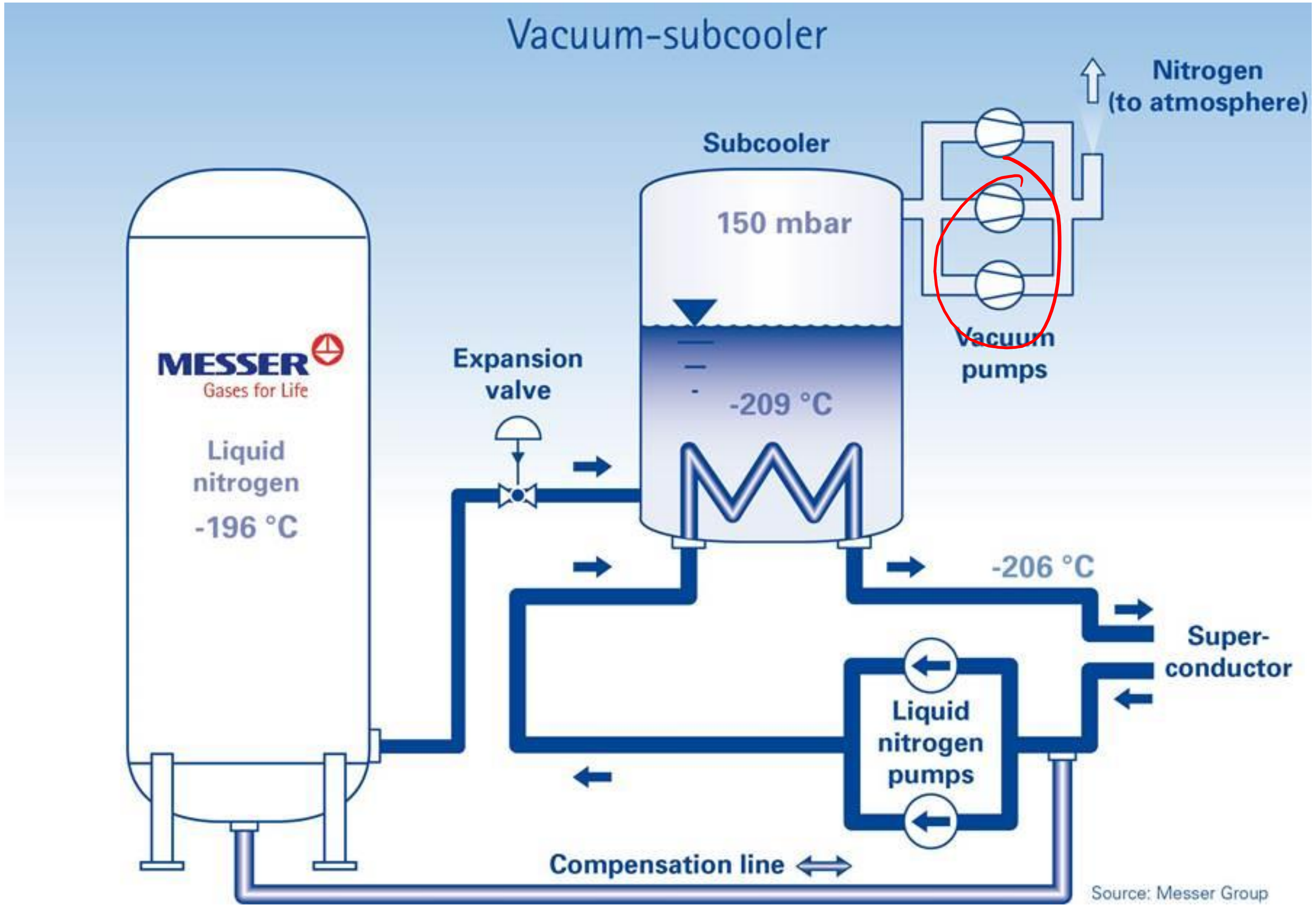


Photo of the cooling unit during FAT - 09.10.2013 - (factory acceptance test)

- Left: control cabinet
- Bottom (blue): LIN pumps
- Right: vacuum pump skid

Tank Installation

- 19.09.2013
- Transport
- Installation and piping

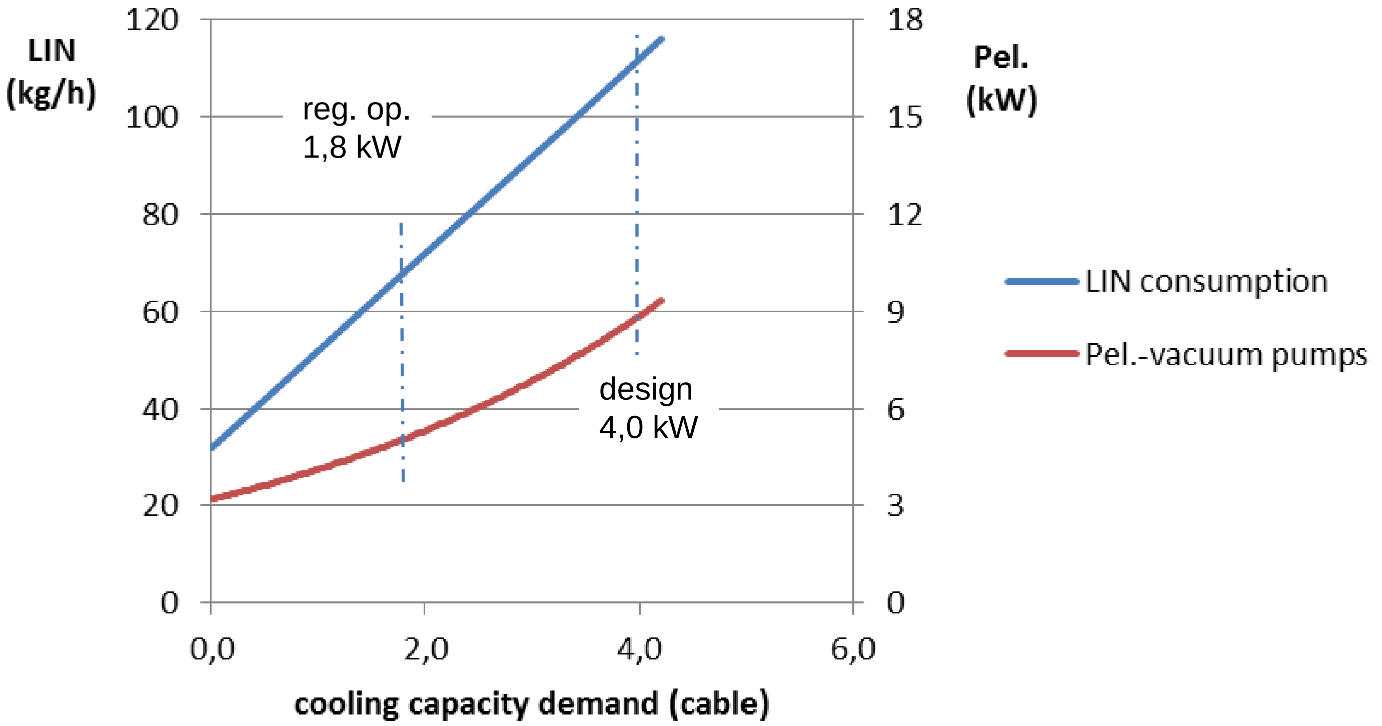
liquid nitrogen and electricity consumption

	cooling-demand (cable)	liquid nitrogen consumption	$P_{el.}$ vacuum pumps	$P_{el.}$ other components	$P_{el.}$ total
design	4.0 kW	110 kg/h	9 kW	4 kW	13 kW
regular operation	1.8 kW	68 kg/h	5 kW		9 kW
cable-bypassed	0.0 kW	32 kg/h	3 kW		7 kW

liquid nitrogen and electricity consumption

Cable-cooling demand:

- design 4.0 kW
- regular operation 1.8 kW
- cable-bypass 0.0 kW



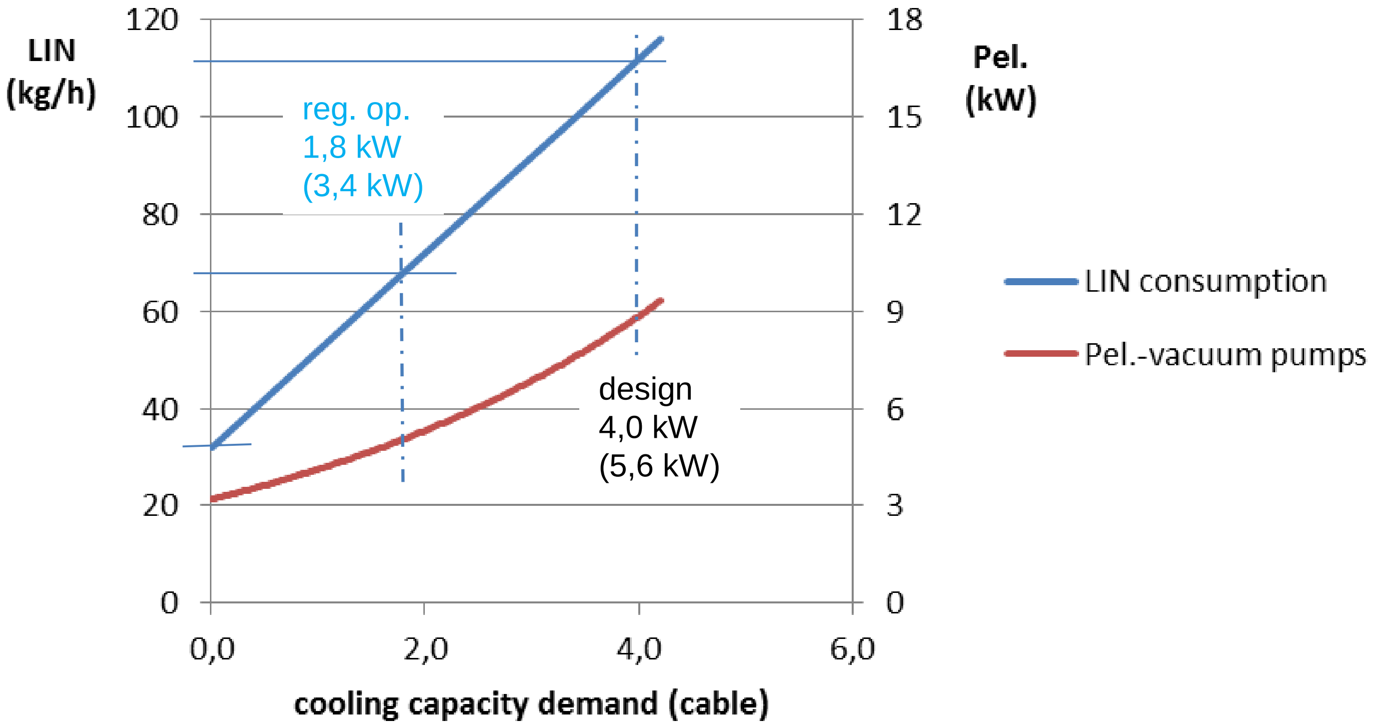
liquid nitrogen and electricity consumption

Cable-cooling demand:

- design 4.0 kW
- regular operation 1.8 kW
- cable-bypass 0.0 kW

total-required cooling capacity:

- design (5.6 kW)
- regular operation (3.4 kW)
- cable-bypass (1.6 kW)



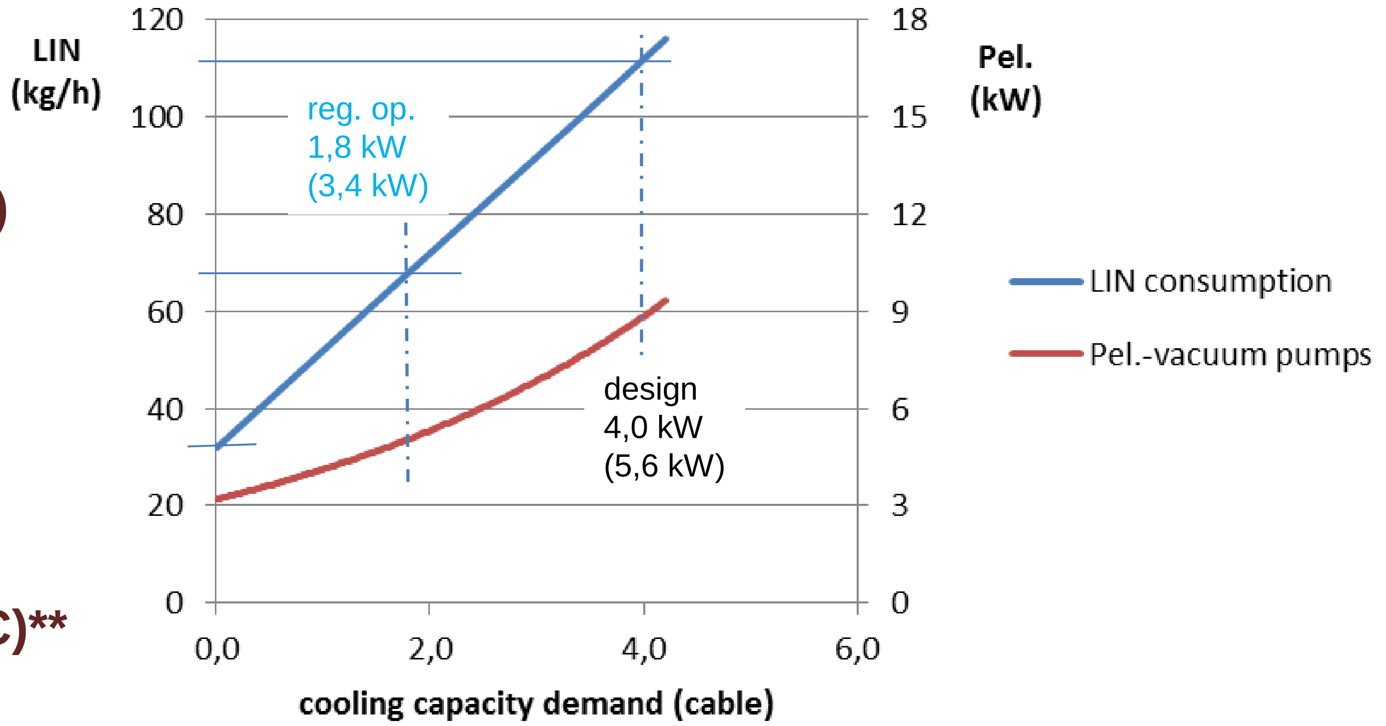
liquid nitrogen and electricity consumption

Cable-cooling demand:

- design 4.0 kW @ 67 K
- regular operation 1.8 kW (-206°C)
- cable-bypass 0.0 kW

total-required cooling capacity:

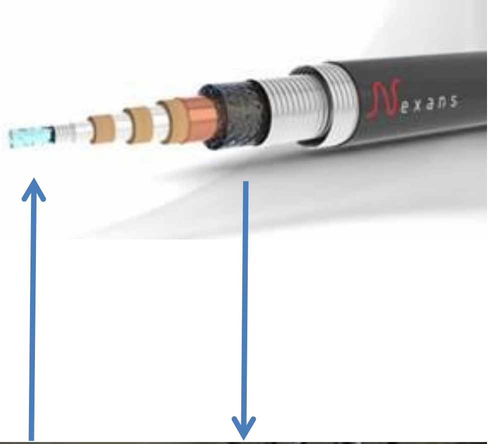
- design (5.6 kW) @ 64 K
- regular operation (3.4 kW) (- 209°C)**
- cable-bypass (1.6 kW)



** N2 becomes solid at 63 K (-210°C)

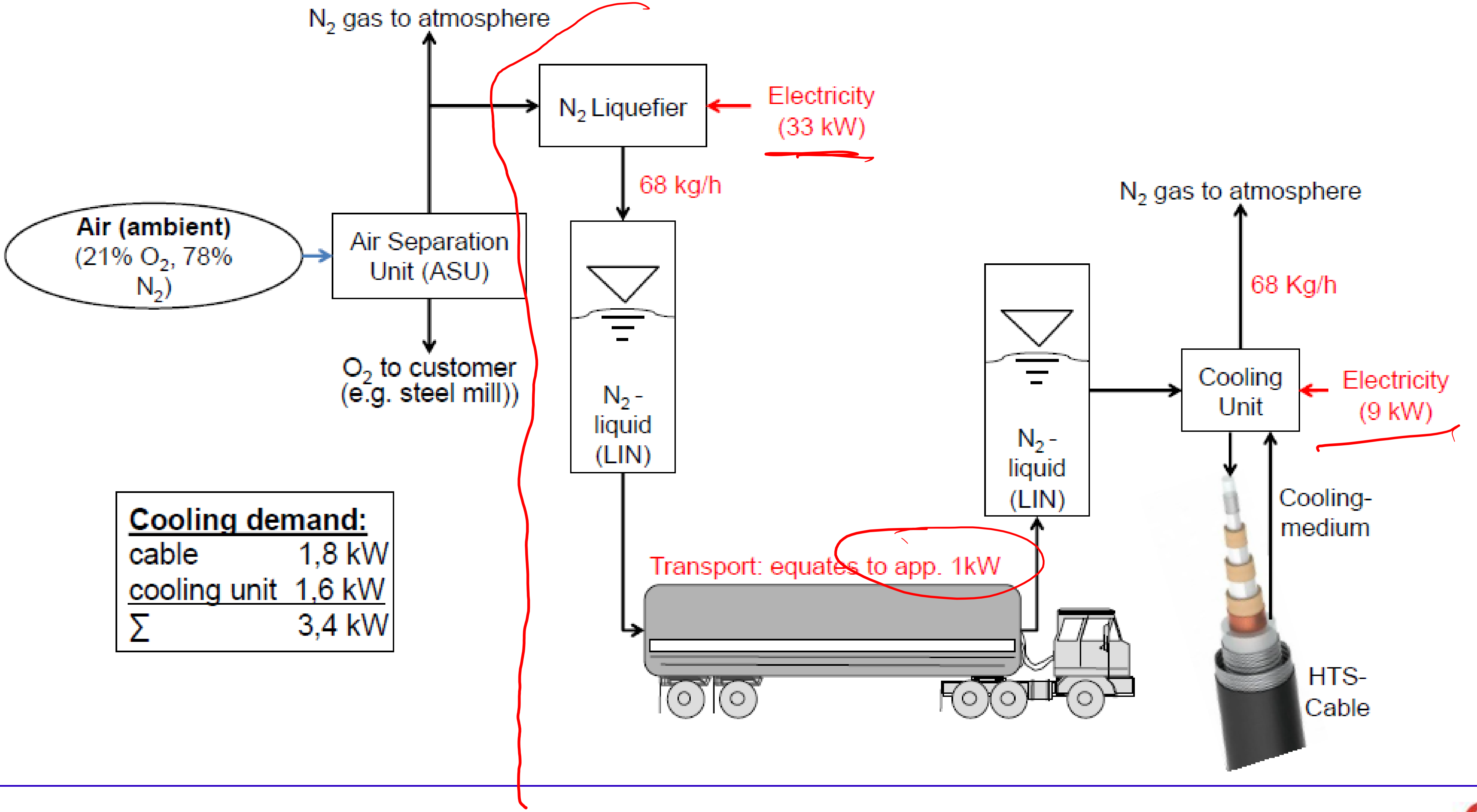
Energy-data comparison (regular operation point)

- **Cable-cooling demand:** **1.8 kW (@ 67 K)**
- **Total required cooling capacity:** **3.4 kW (@ 64 K)**
- **Liquid nitrogen consumption:** **68 kg/h**



air separation unit (ASU) → transport → tank → cooling unit

HTS – cooling unit: nitrogen and energy balance



Cooling demand:

cable	1,8 kW
cooling unit	1,6 kW
Σ	3,4 kW

Energy-data comparison (regular operation point)

- Cable-cooling demand: 1.8 kW (@ 67 K)
- Total required cooling capacity: 3.4 kW (@ 64 K)

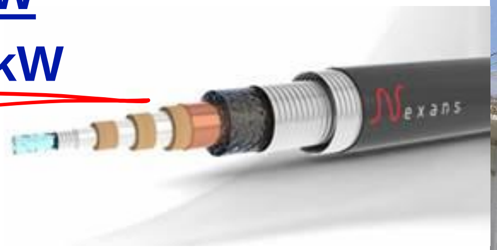
- Liquid nitrogen consumption: 68 kg/h

- Required electricity for N_2-liquefying: 33 kW
- Exergetic effect LIN transport (130 km): 1 kW
- Pel. (vacuum pumps): 5 kW
- Pel. (other equipment): 4 kW

total: 43 kW

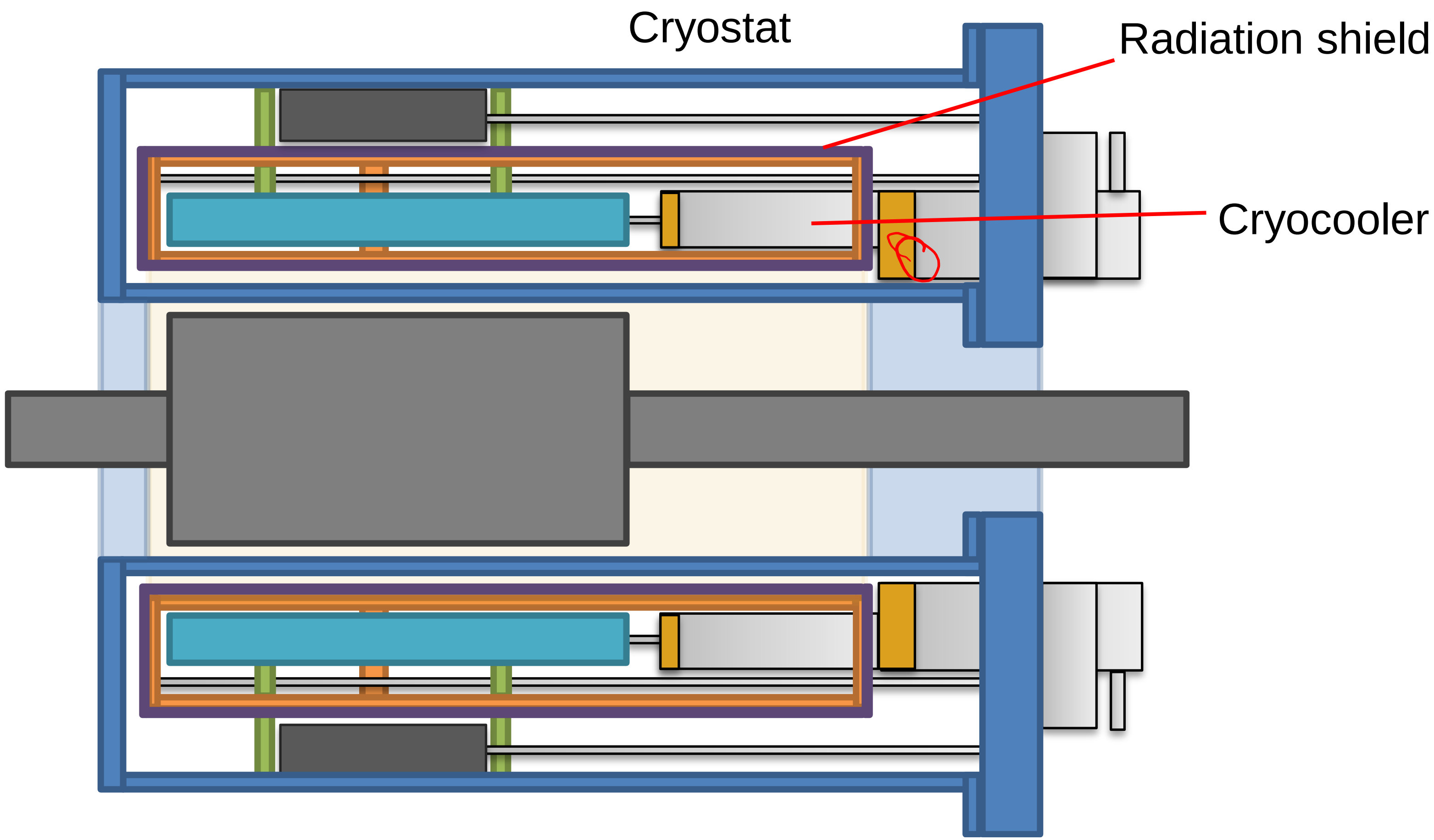
- for comparison:

Pel. for mechanical cooling: 75 to 100 kW
(dependant on the availability of cooling water)



Calculation for a HTS DC Wind generator demonstrator

- PhD thesis Fabian Schreiner



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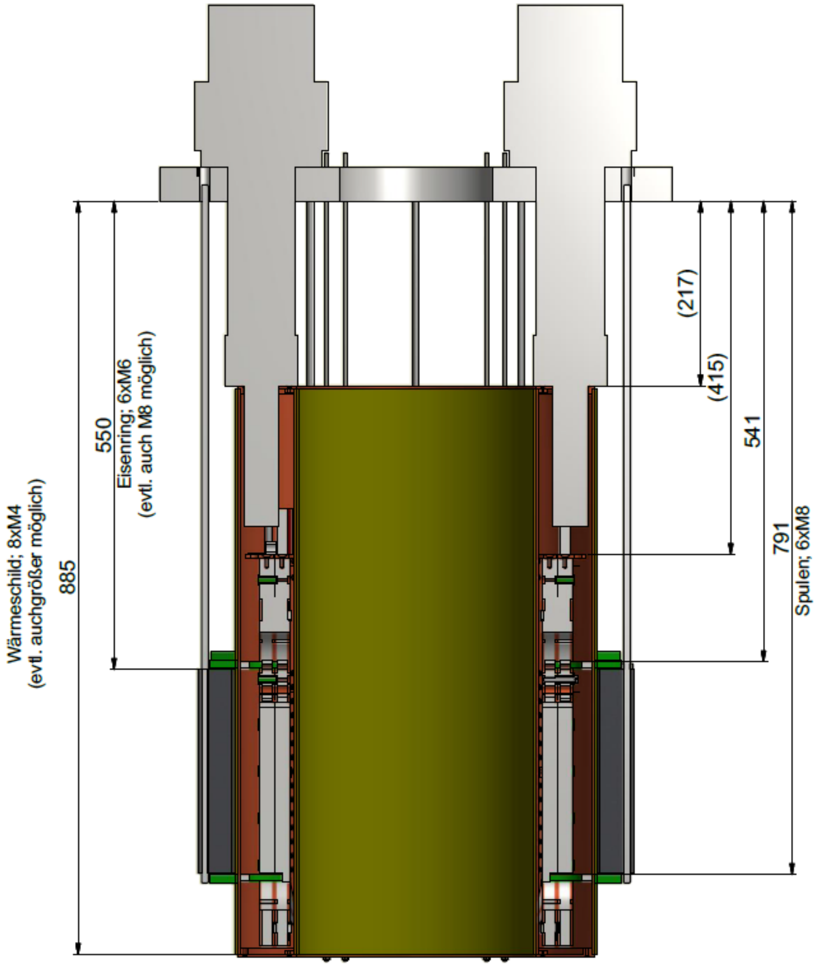

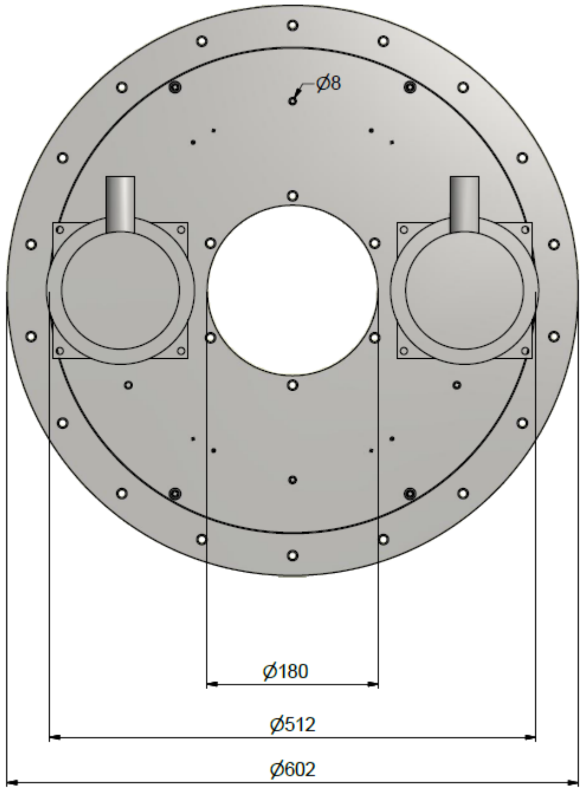

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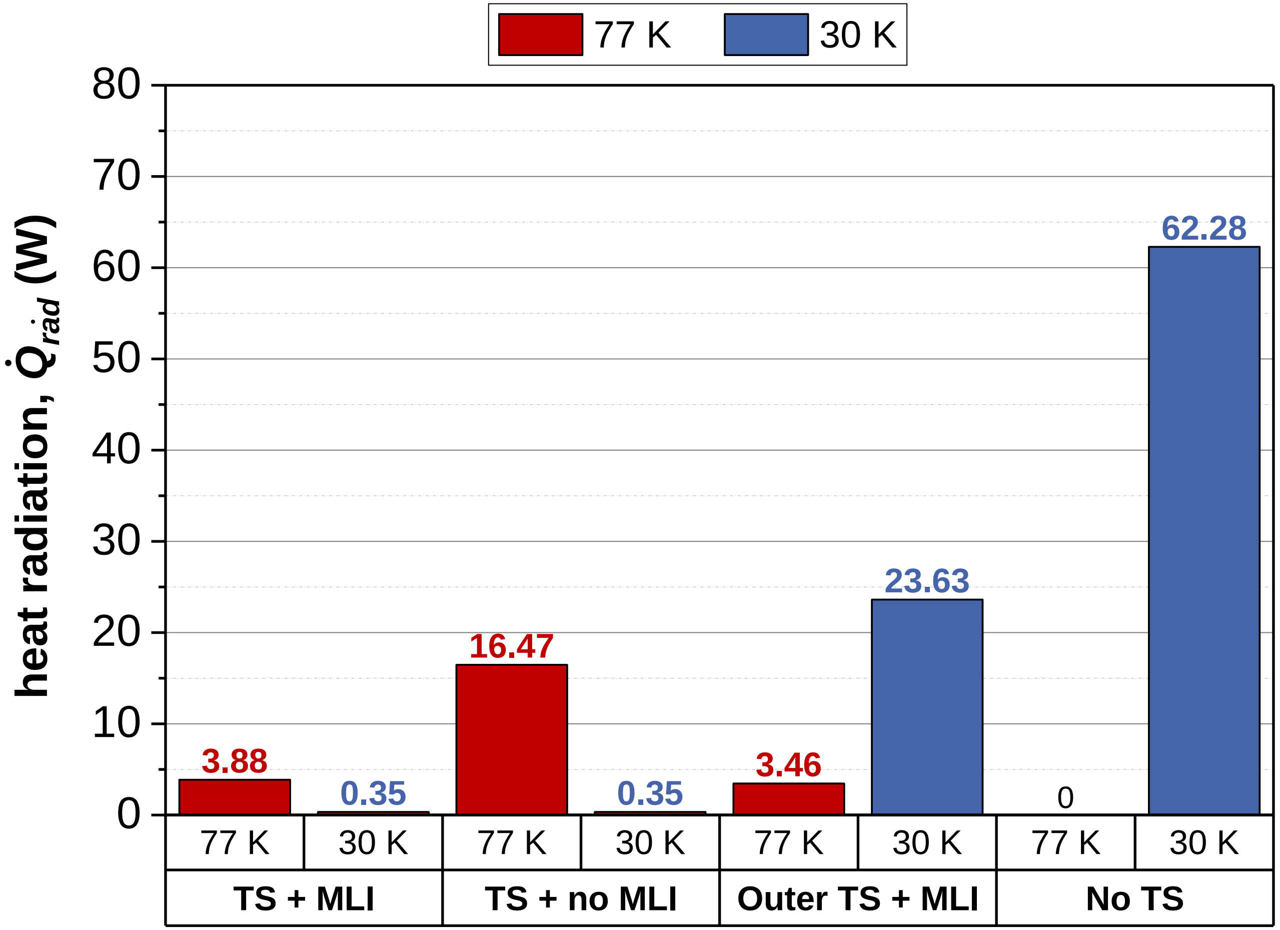
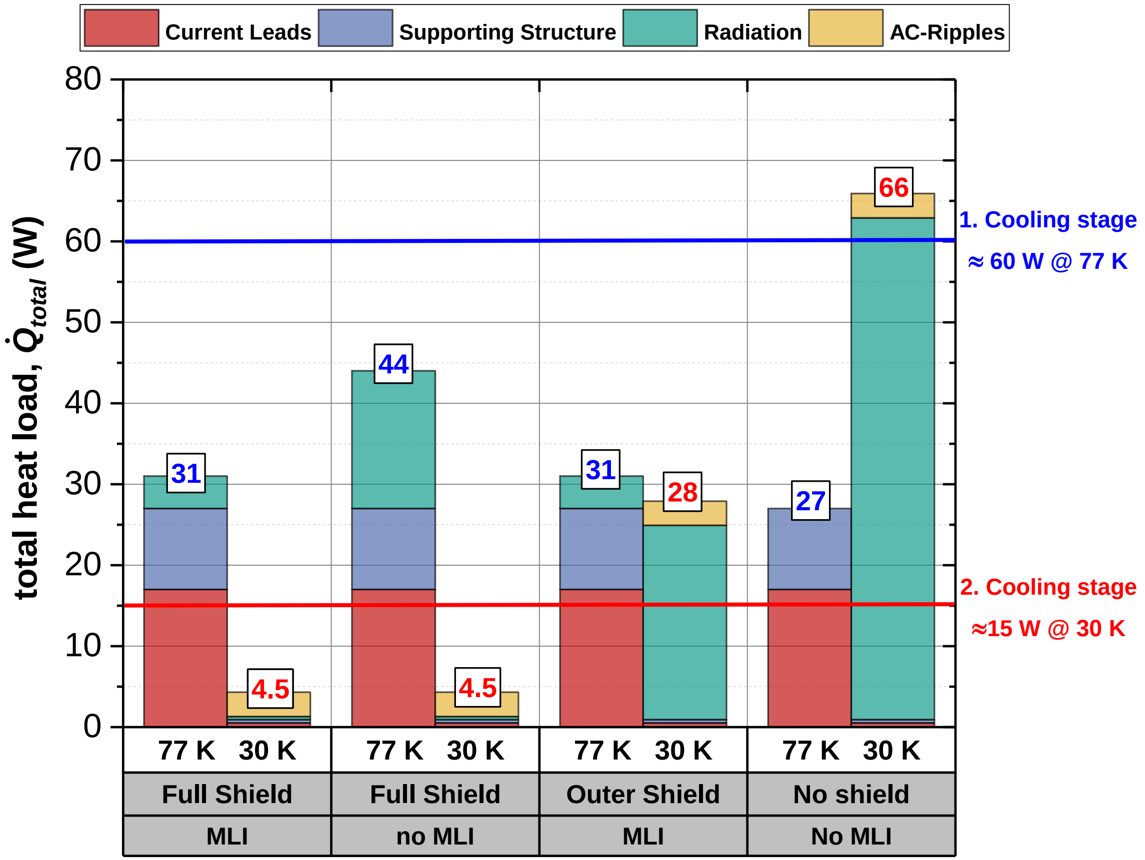


Calculation for a HTS DC Wind generator demonstrator

- Comparison of total heat input with 4 mm Theva tape



Calculation for a HTS DC Wind generator demonstrator

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- Comparison of total heat input with 12 mm Theva tape