Cryogenic refrigeration system at DESY

Thermodynamic principles and its components

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Hamburg, 29.10.2025

Outline

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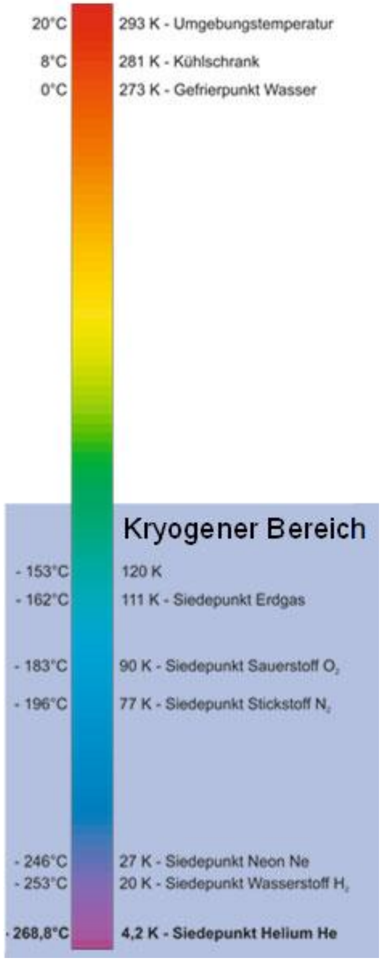
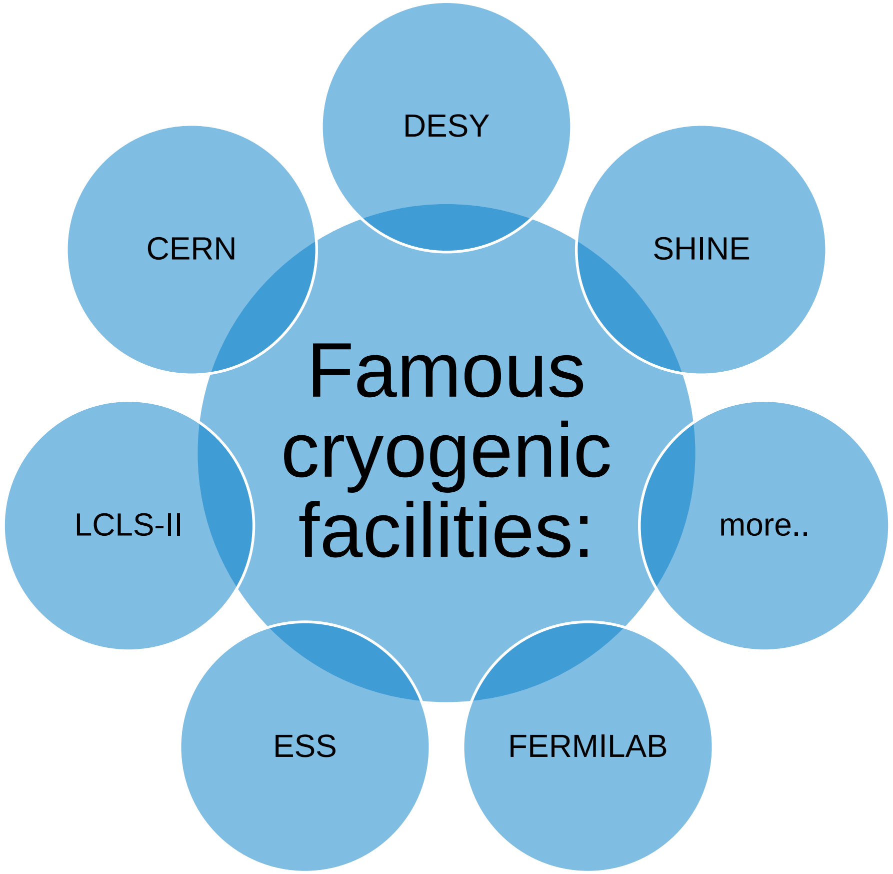
Introduction

Cryogenic refrigerators (cryoplant)

- Purpose: to generate cold helium (liquid and gaseous) at cryogenic temperatures.





Applications

Superconducting accelerators

Quantum computing

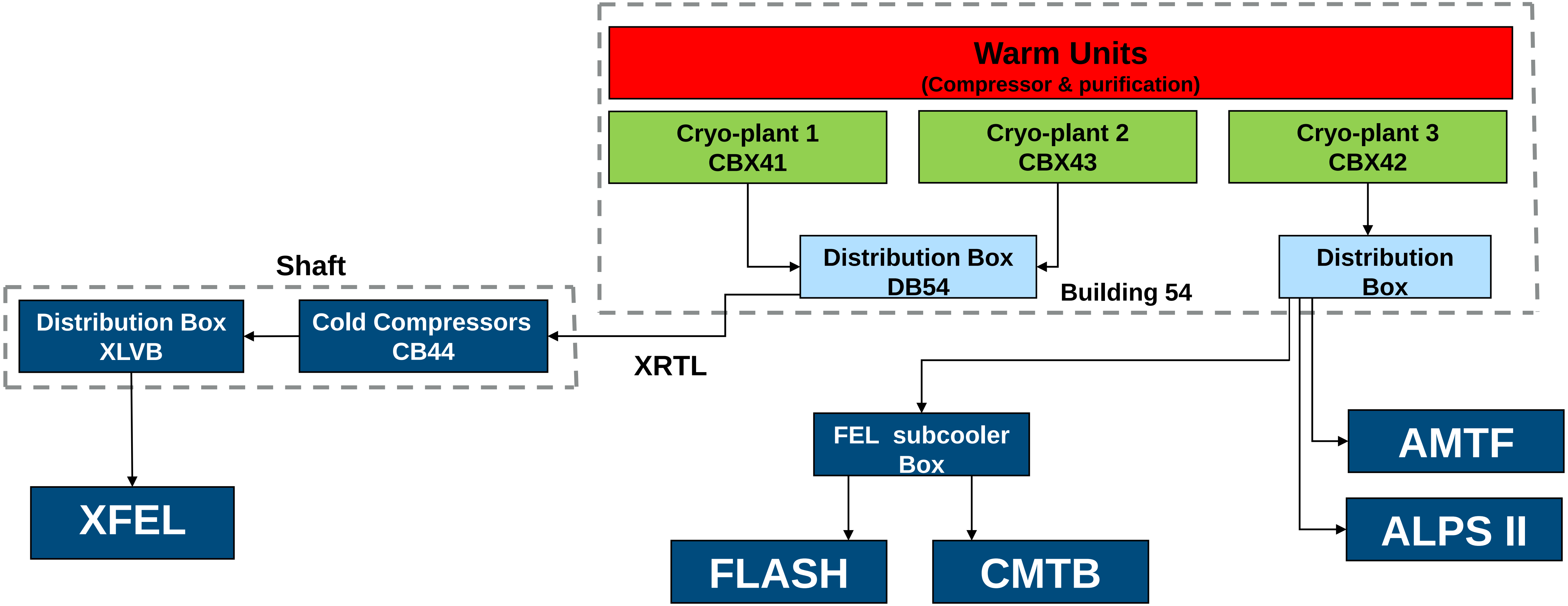
MRI

Nuclear fusion

Introduction

DESY cryoplant

- The cryoplant is used to supply cold helium to DESY and XFEL facilities



Helium as refrigerant

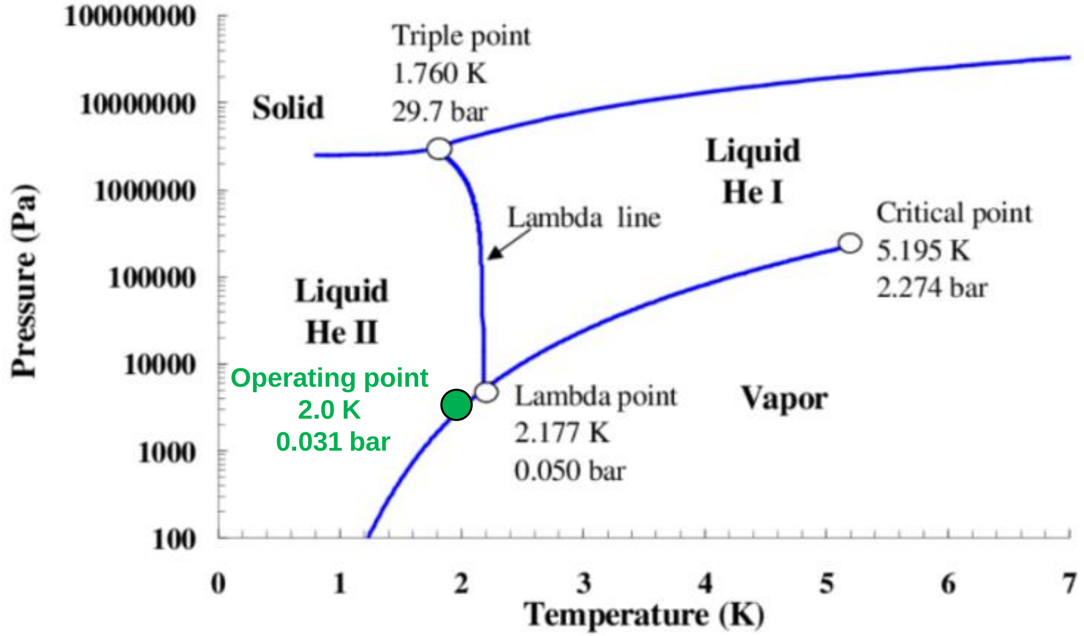
What makes helium interesting for cooling DESY and XFEL facilities?

Refrigerant	Liquefaction temperature at 1 bar (K)
Nitrogen	77
Hydrogen	20
Neon	27
Helium	4,2

- Only helium can reach 2K temperature without solidifying.

Superfluid state below lambda point

- Very high heat transfer
  - Prevents hot spots on cavities
- Zero viscosity
  - Negligeable turbulances



Working principle of the cryoplant

Claude process for helium liquefaction

The functioning of the cryoplant relies on a sequence of thermodynamic processes to cool helium from 300 K down to the application temperature.

Step 1: Helium compression (9 – 1)

Step 2: High pressure warm gas suuply flow precooled with heat exchanger (1- 2)

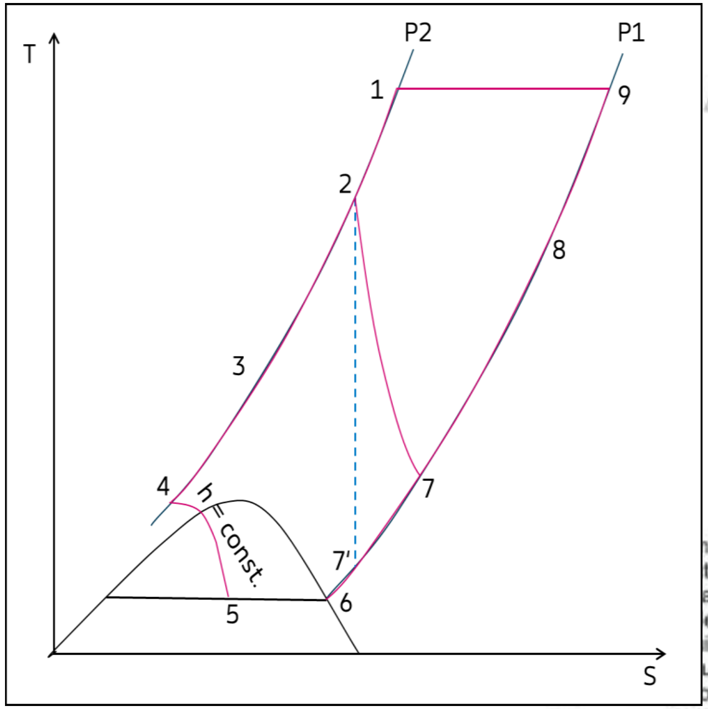
A part of the forward flow is precooled using turbine expansion. (2 – 7)

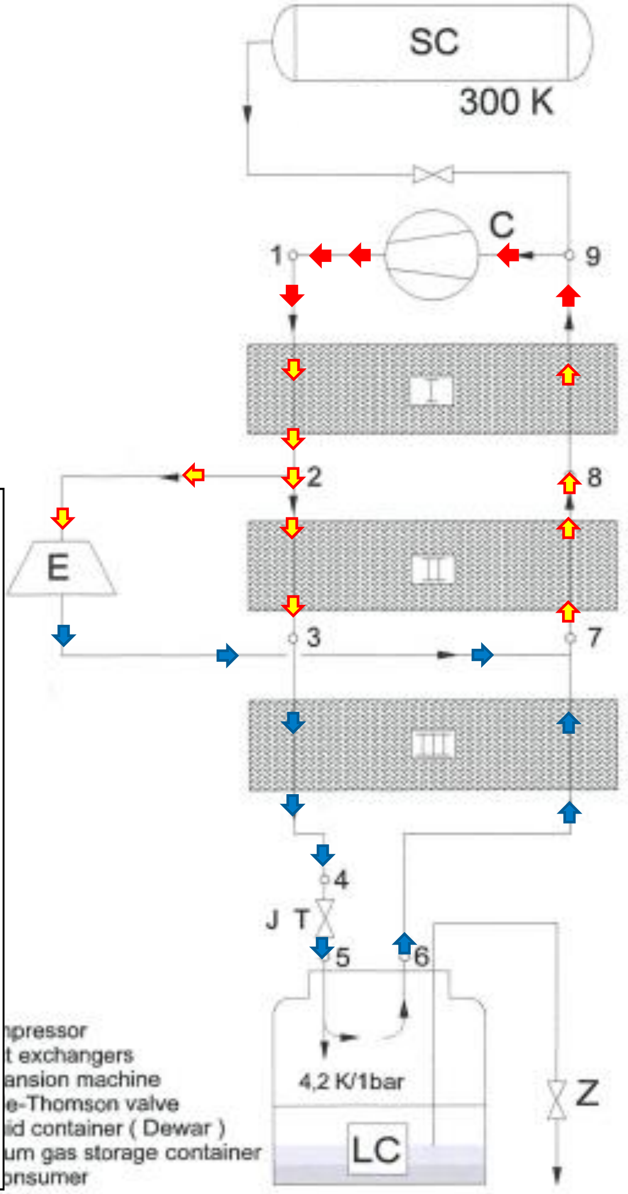
It is injected in the return flow to further cool the main stream. (7 - 9)

Step 3: If the temperature after the heat exchanger is low enough helium is expanded with a JT valve. (4 – 5)

JT valve produces a liquid and gas fraction (5)

Step 4: The gas fraction is used to precool the main stream. (6 – 7)





Compressors system

Helium screw compressors

- 2 rotating parts (screws)

Working principle:

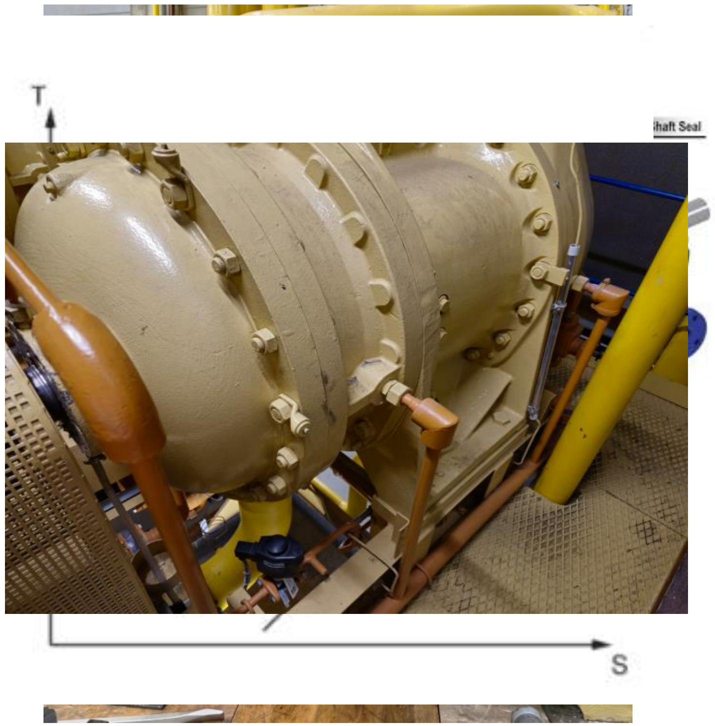
- Mechanical energy (rotation of screws) is converted into pressure energy.

Helium (monoatomic gas) compression generates very high temperature increase:

- Multi stage compression needed
- Aftercooler after each compression stage (He/Water heat exchanger)
- Oil injection during compression

Role of lubricating oil

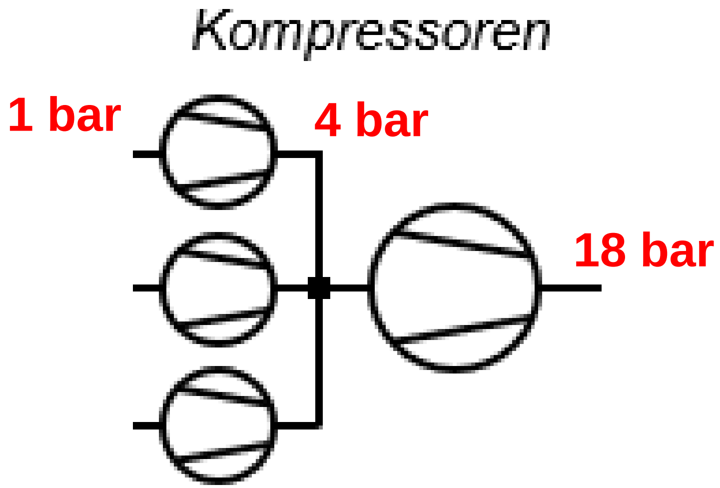
- Lubricating the rotors
- Cooling of helium and rotors during compression
- Tighting to prevent backflow



Compressors system

Helium screw compressors

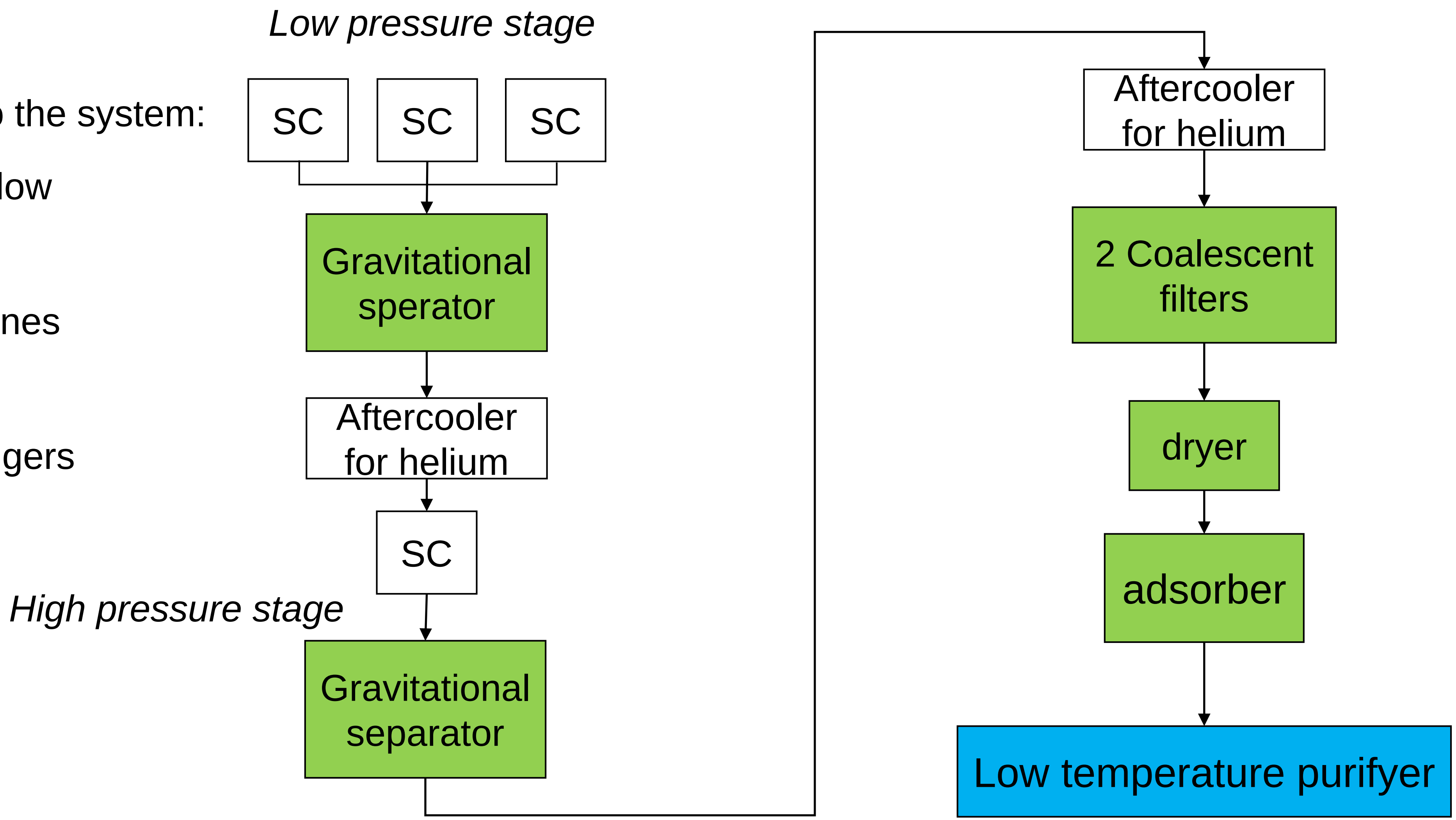
- **Each cold box has a screw compressors station:**
  - 2 compression stages:
    - **Low pressure stage:** 1 bar ⟶ 4 bars
      - 3 compressors + 1 redundancy
    - **High pressure stage:** 4 bars ⟶ up to 18 bars
      - 1 compressor + 1 redundancy



Purification systems

Oil and air removal

- Impurities enter into the system:
  - Become solid at low temperature
  - damage the turbines
  - clog pipings
  - clog heat exchangers

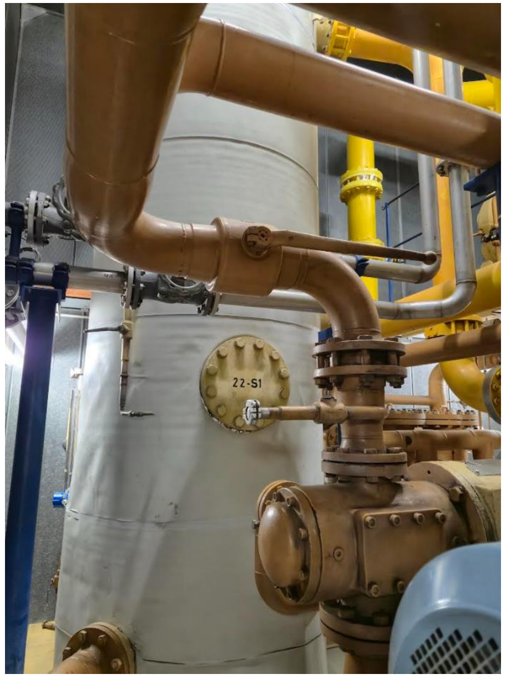


High temperature purification systems

Oil seperators: rough oil separation

- **Low pressure separator**
  - 3 Oil separators (1 per compressor station)

- **High pressure separator**
  - 4 Oil separators (1 per compressor stage)



- Two big vessels
- Separation of large oil particles with gravity

High temperature purification systems

Coalescent filters

2 separation steps in series.

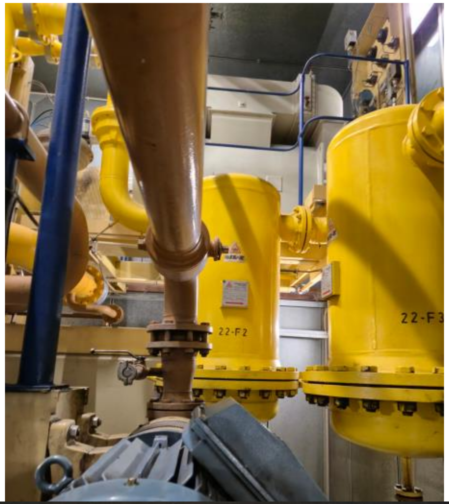
Role

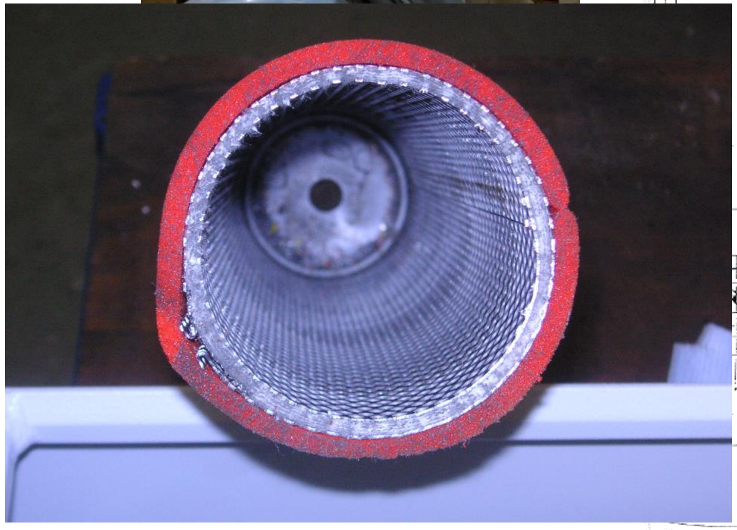
- Fine separation with Dominick Hunter filter

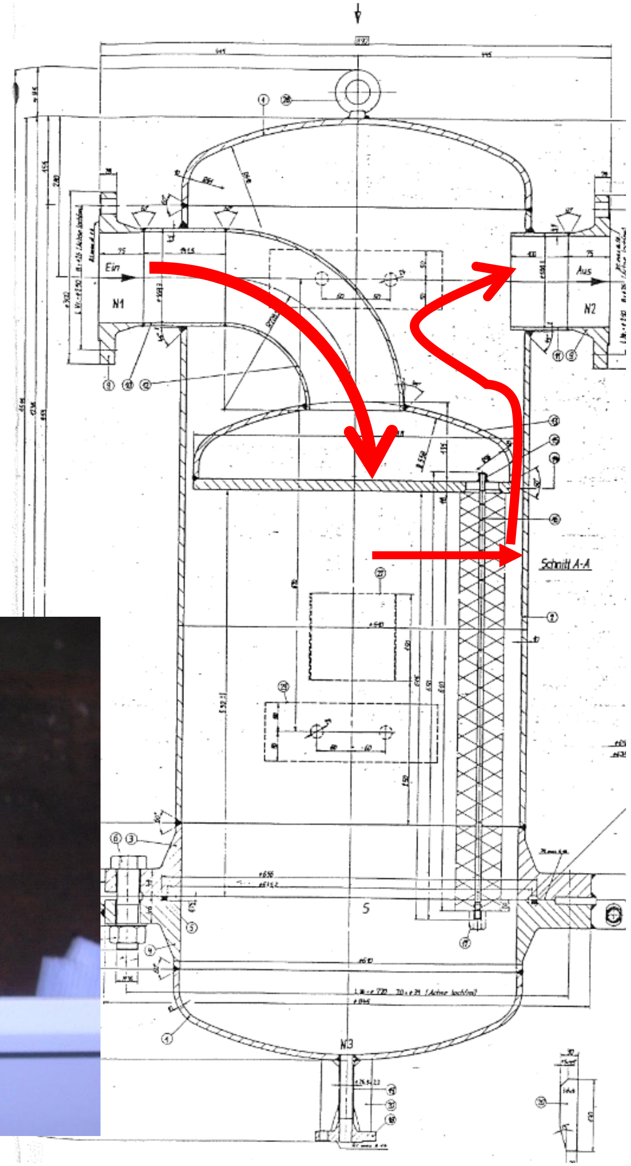
Working principle:

Filters material: metal /Borosilicate microfiber

- Flow comes inside the filters
- It flows radially to shell.
- Oil particles collect on the filter fibers.
- they combine to form larger and heavier droplets (coalescence).
- Large droplets fall to the bottom of the filters where they are collected and drained.







High temperature purification systems

Dryers

4 dryers

Role:

Remove humidity before entering adsorbers.

Working principle:

- Physical adsorption of water particles with molecular sieve.
- The mixture of oil/He will flow through the particles bed.
- Water is trapped withing the pores of the molecular sieve. Helium is excluded.

Regeneration: Moisture is removed at 240-300°C in a dry air stream

High temperature purification systems

Oil adsorbers

4 adsorbers

Role:

- Oil adsorbers help remove the rest of oil remaining after compression.

Working principle:

- Oil vapours and mist are adsorbed with active charcoal.

Regeneration:

- no regeneration. It will be changed only if it is saturated.

Low temperature purification system

Temperature swing system

- There are 2 low temperature purifiers:
  - TTR35 for CBX42 and XLTP for XFEL operation

Role:

remove air particles from Helium

- 1 ppm (weight) purity reached

Working principle:

- Air is separated with adsorption.
- **Adsorbent material:**
  - Molecular sieve for XLTP and Linde Perlgel Typ N silica gel for TTR35
- Helium stream is cooled before TTR with nitrogen heat exchanger at 80K.
- Air particles have higher affinity to stick to the adsorbent material surfaces at low temperature.

Regeneration:

- gases are removed with helium gas stream at 300°C.

Helium cooling process

Cold box components

- **7 Turbines**
  - To cool down the helium using isentropic expansion.
- **A set of 4 Heat exchangers**
  - Provide necessary precooling of the high pressure helium coming from the compressors.
- **3 Adsorbers**
  - To remove impurities
  - Two 80K adsorbers of large size impurities (N_2, O_2..)
    - Each adsorber contains a set of two adsorption columns (1 in operation + 1 in regeneration mode)
  - One 20K adsorber for small size impurities (Neon, H_2)

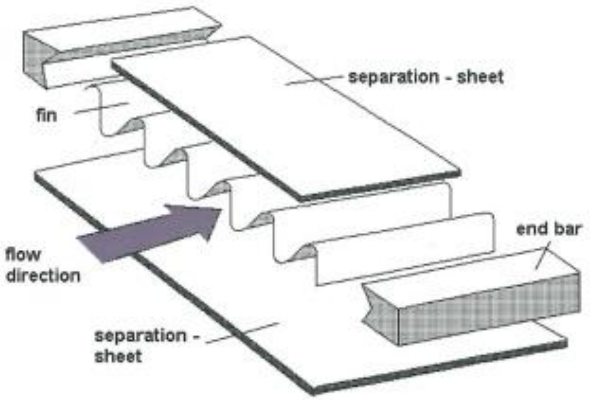
Helium cooling process

Heat exchangers

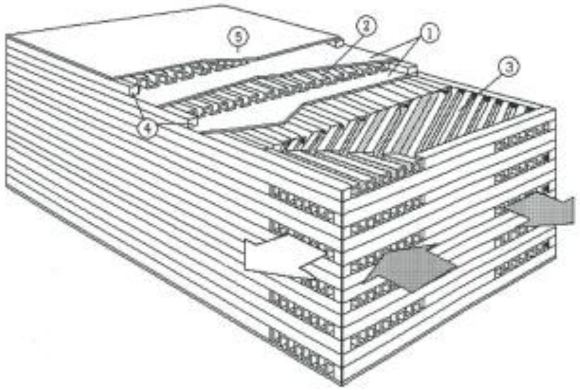
- Brazed aluminium plate-fin heat exchangers
- They come with different dimensions.
  - The largest HX is 7m long.

Working principle:

- Cold helium resulting from the turbines expansion absorbs the heat from the warm helium stream.



Principle of cryogenic heat exchanger



Schematic structure of aluminium plate fin heat exchanger

1 - Separator sheet
2 - Fins
3 - Distributing fins
4 - End bars
5 - Endplate

Helium cooling process

Expansion Turbines

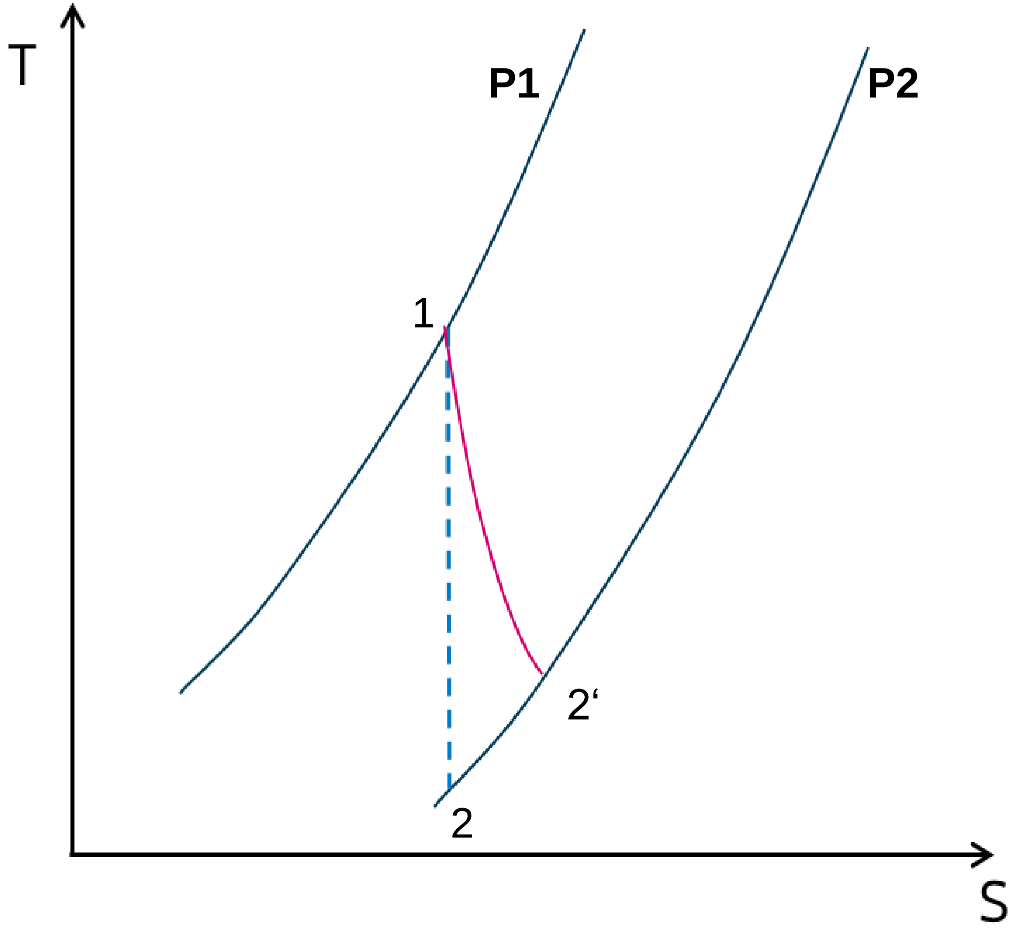
Role:

- To provide cold helium using isentropic expansion.

Isentropic expansion:

- For a **ideal** process:
  - **reversible:** $dS = \frac{dQ}{T}$
  - **No heat input (adiabatic**) (1-2) $\rightarrow$ $dS = 0$
  - **Ideal gas:**
    - $T_2 = T_1 . \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$
      - with $\gamma = \frac{c_p}{c_v}$ is the adiabatic index, For helium $\gamma = 1{,}66$
  - For an actual process: Not adiabatic + irreversible
    - The temperature after expansion is higher than the ideal case (1-2‘)

$\rightarrow$ This is how the cooling effect is obtained



Helium cooling process

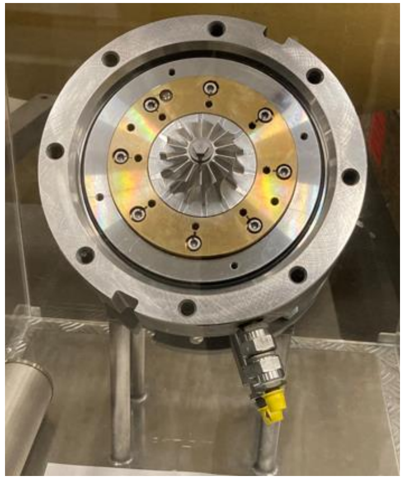
Expansion Turbines

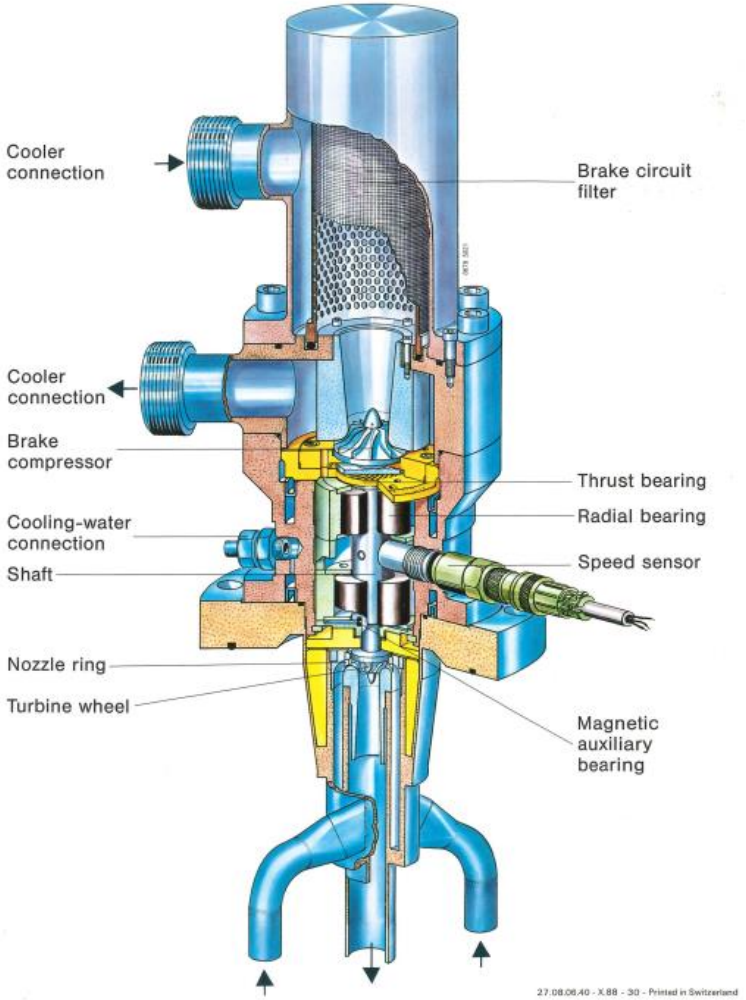
Working Principle:

- Change of fluid cross section within the wheel blades:
- Cross section increases ⇨ The pressure decreases.
- The energy of pressure is converted into mechanical energy.
- Mechanical energy is used to rotate the turbine wheel.

Brake compressor:

- to control the rotational speed of the turbine.
  - A regulation valve helps to adjust flow in the brake circuit.
- It absorbs work released by the turbine after expansion.
- Helium flowing through brake compressor warms up. It is cooled with a water heat exchanger.





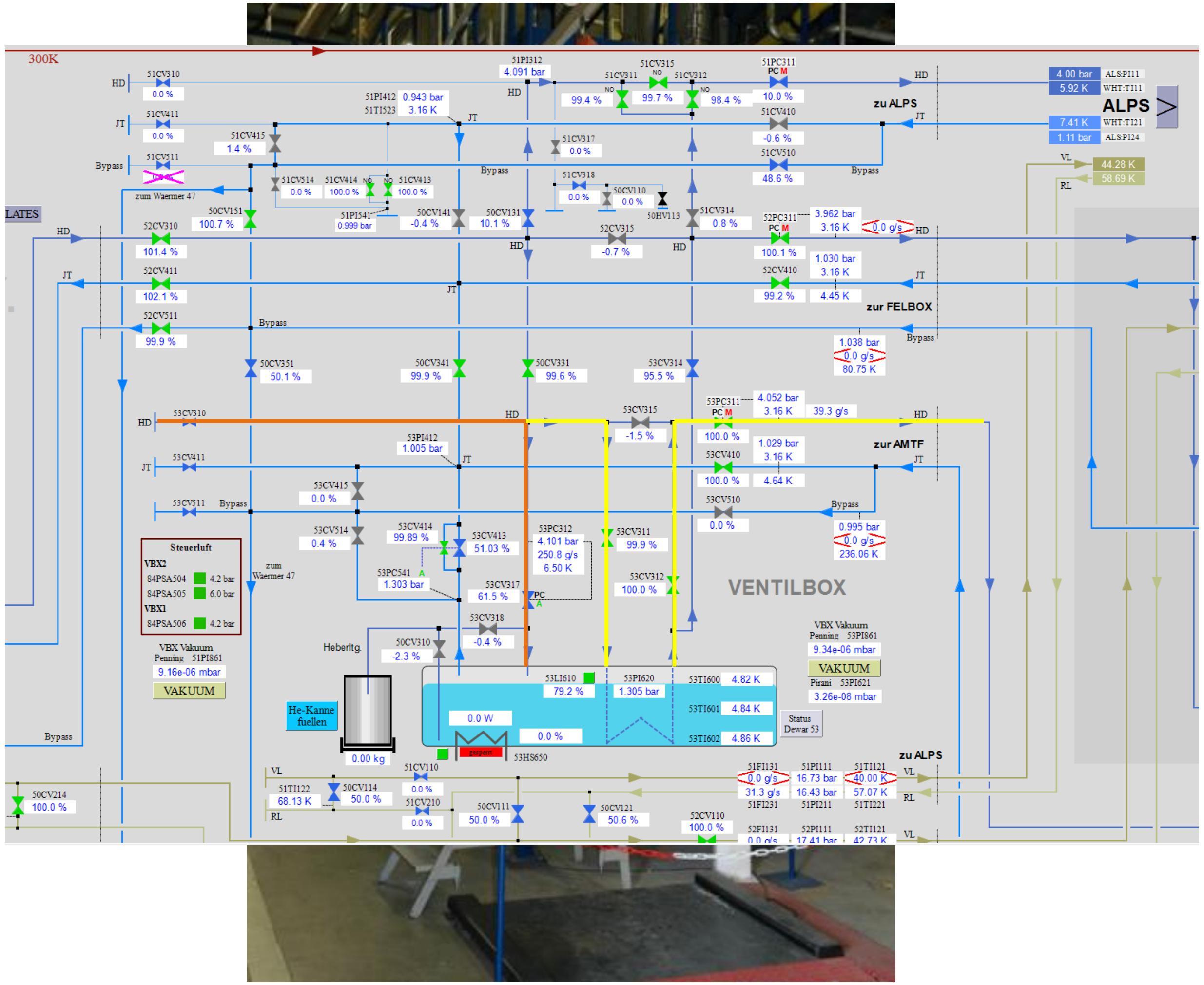
Helium cooling process

Dewars

Role: Dewars act as energy buffer

- Subcooler:
  - The dewar is equiped with a heat echanger to subcool the high pressure helium.

- A surplus of cold capacity
  - Helium is liquified using a JT valve and stored in a dewar.
  - Liquid helium is recuperated from the dewar when needed. (liquid is evaporated using a heater).

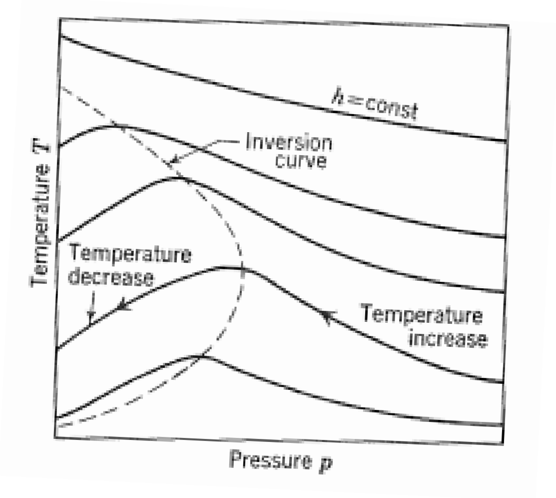


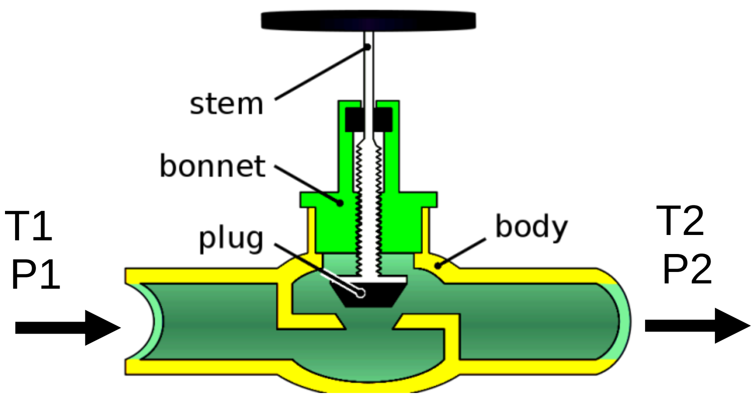
Helium cooling process

Joule-Thomson expansion

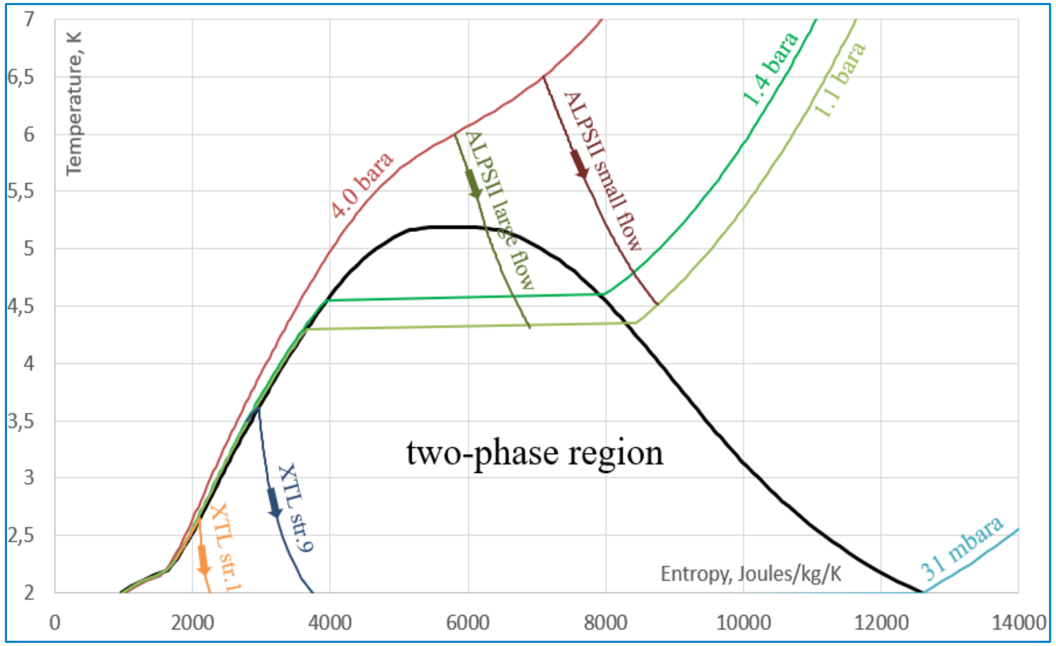
- **Working principle:**
  - When the valve opens, high pressure gas expands in a low pressure regime.
  - This gas expansion creates a temperature change at a constant enthalpy (isenthalpic expansion).
  - Cooling effect : $T_{He} < 40\ K$ before expansion.

  - In dewar: 4bar, 6K ⟶ 1 bar, 4.2K
  - In cryomodules: 1.5 bar, 2.5K ⟶ 31 mbar, 2K





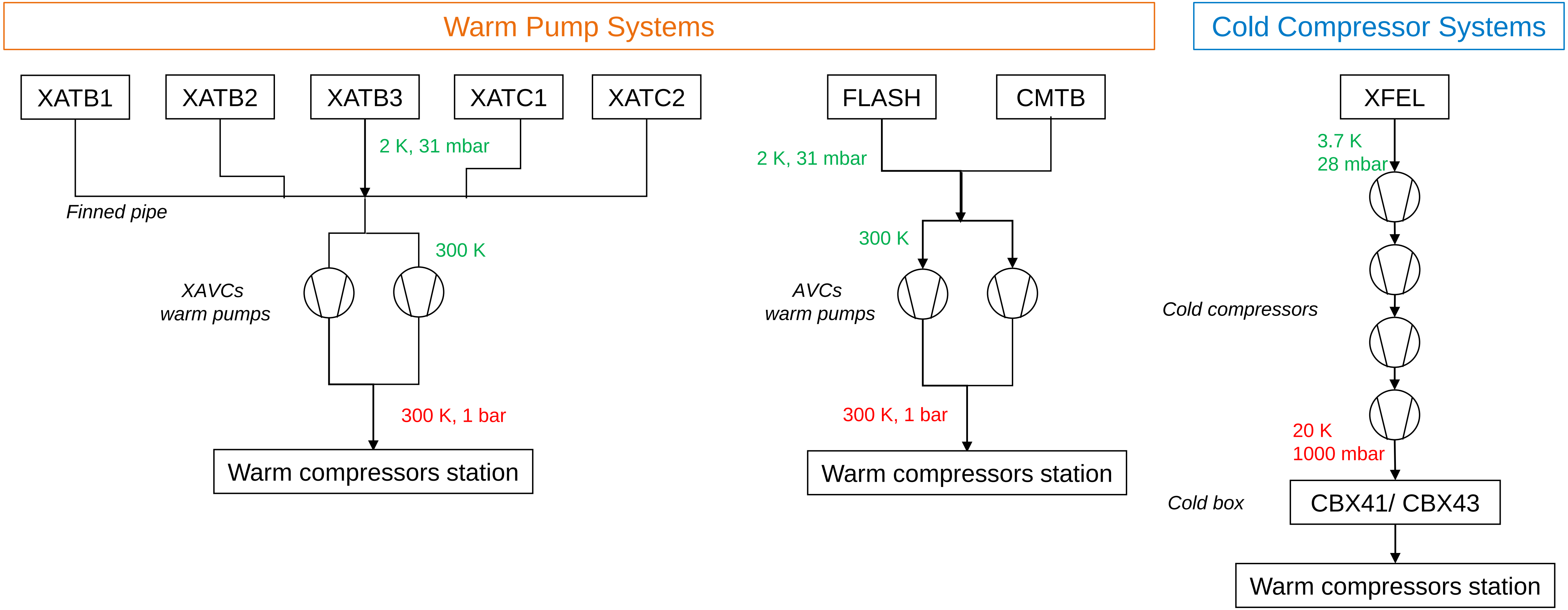
P1 > P2



Helium cooling process

2 KR flow pumping system

- Cold gas resulting from cavities heat loads + flash gas are forwarded back to the cryoplant



Helium cooling process

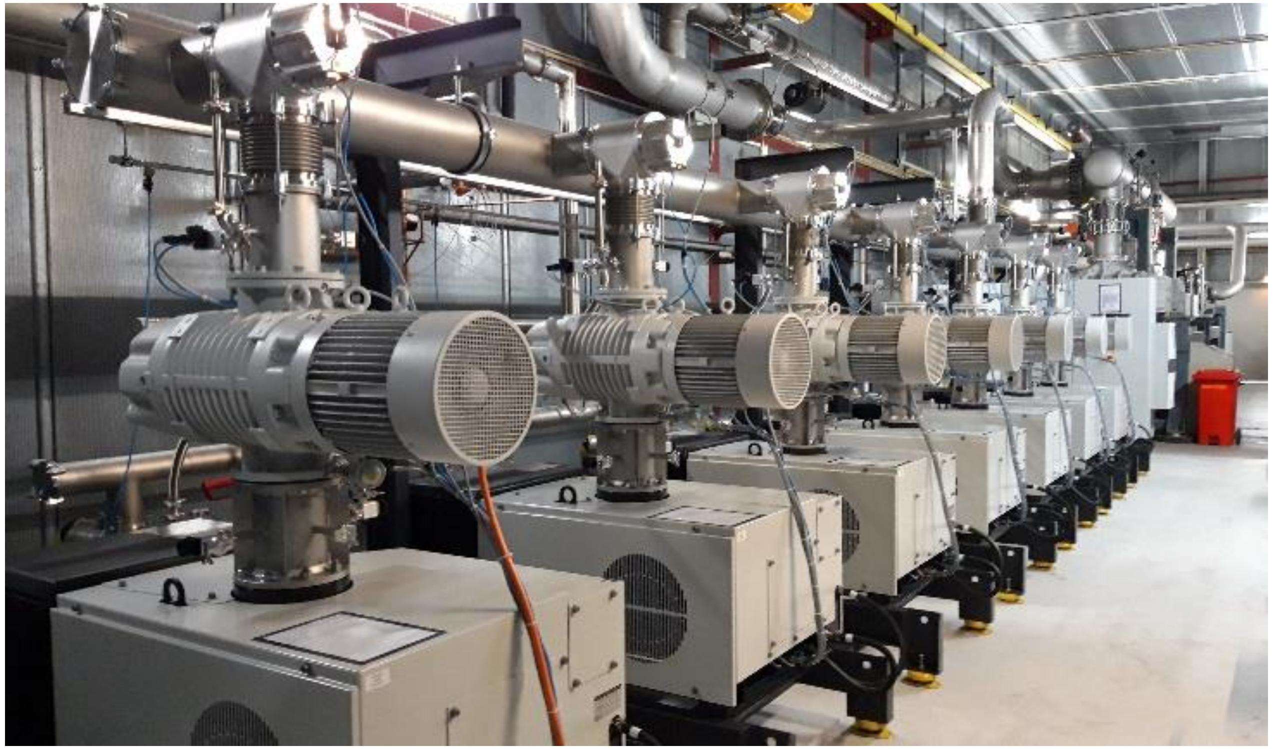
2K return pumping flow: What differences between warm pumps and cold compressors?

Warm pumps	***Cold compressors***
Volumetric machines	Hydrodynamic machines
Robust system (wide operating range)	sensitive to mass flow, pressure and temperature conditions
High operating costs	Optimized operating costs (ca. 5M Euros energy savings per year and more..)

Helium cooling process

Warm pump systems (Volumetric Machine)

- Finned pipe (160 m)
  - To transport subatmospheric helium to warm pumps
  - To increase the temperature from 2 K to 300 K.
- Number of pump systems
  - 13 pumps in XAVC1
  - 12 pumps in XAVC2.
- Total flow: 20g/s at 20mbar for XAVC1/XAVC2
- Discharge pressure : 1 bar to the suction line of screw compressors.
- Each pump has 2 pumping stages:
  - Roots pumps. (discharge pressure)
  - Rotary vane vacuum pumps.



Helium cooling process

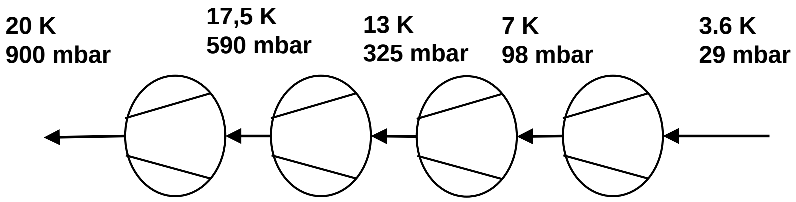
Cold compressors system (Hydrodynamic machine)

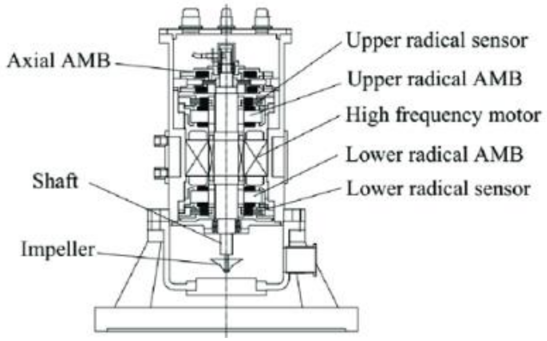
Centrifugal compressors

- 4 compression stages

Role:

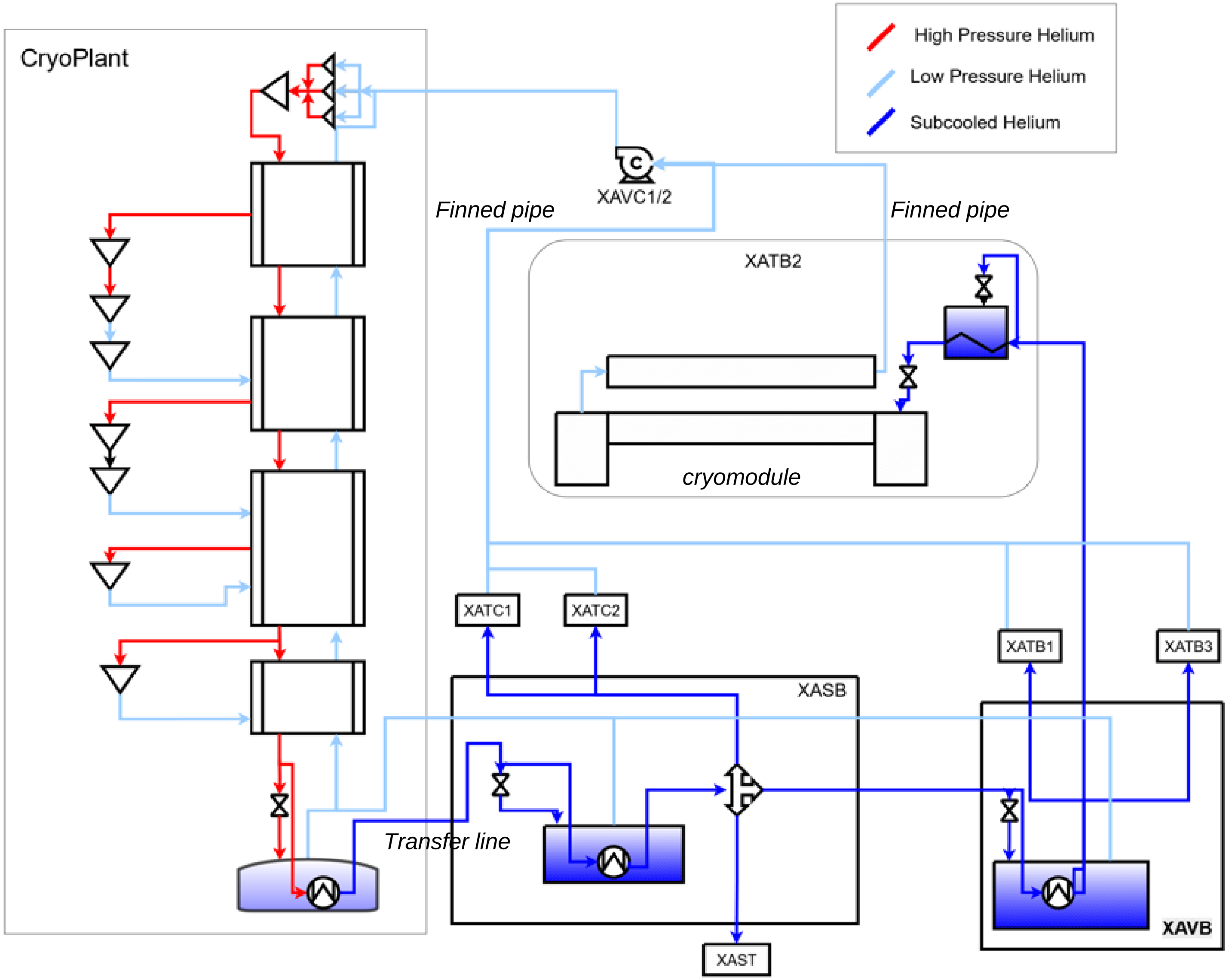
- To create 31mbar corresponding to 2K liquid temperature in cryomodules.
- Outlet flow (20K) is used to cool the cold box which increases its efficiency.





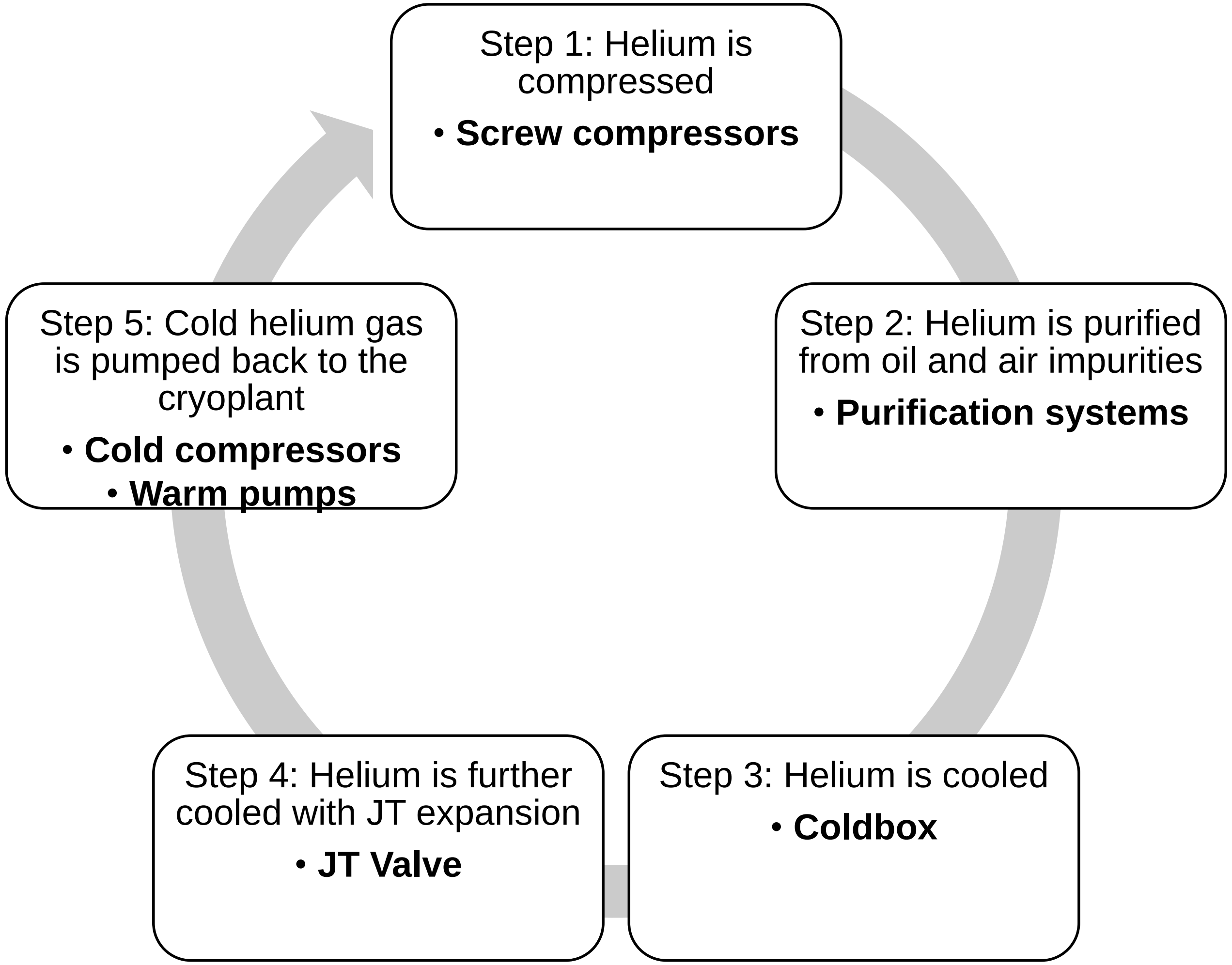
Helium cooling process

2K system in AMTF



Summary

- DESY and XFEL facilities are cooled with superfluid helium.



Thank you for your attention

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A special thank to my collegues for their support and advice: A. Dhillon, Y. Bozhko, T.Schnautz, J. Zajac

Backup slide

Definitions of key thermodynamic properties

- Enthalpy:
    - A thermodynamic property that measures the energy content of a system:

$$H = U + PV$$

U is the internal energy, P is the pressure and V is the volume of the system

- Entropy:
    - A thermodynamic is a state function that measures how energy is distributed within a system.
    - It is a measure of disorder, randomness of a system.
        - $\Delta S > 0$ if the process is irreversible
        - $\Delta S = 0$ if the process is reversible