Thermalisation of HTS-based current leads using a single-stage GM cryocooler

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Introduction to cryocooler-based cooling technology

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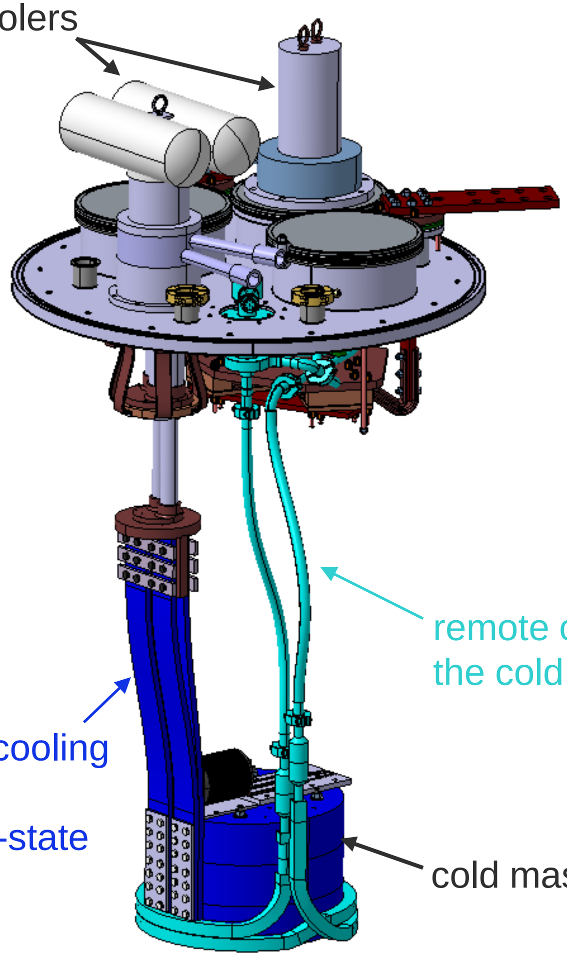
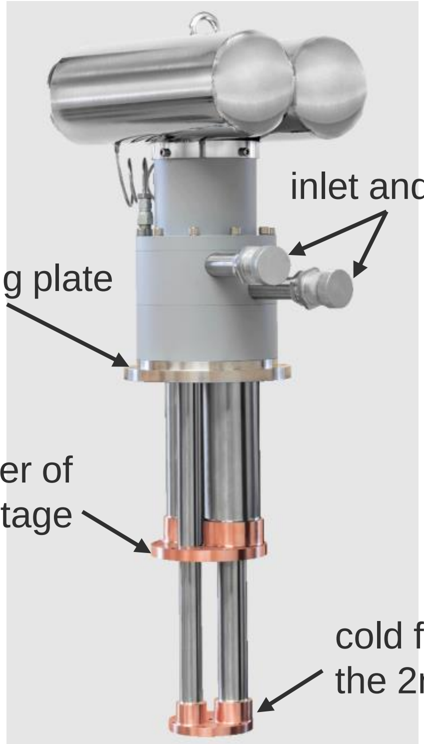
Cryocooler-based cooling methods:
→ **conduction-based cooling**
→ **remote cooling**



Examples of commercial cryocoolers

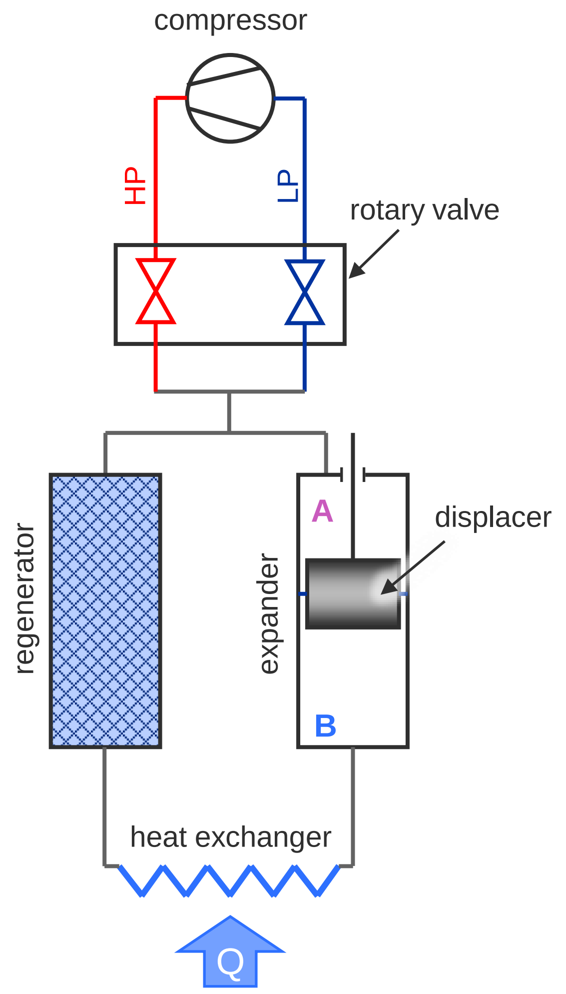
Gifford-McMahon cryocooler AL600:
- single-stage cryocooler
- 340 W of available cooling power @50K

Pulse tube cryocooler PT420:
- two-stage cryocooler
- max. 55 W on the first stage @44 K
- max. 2 W on the second stage at 4.5 K

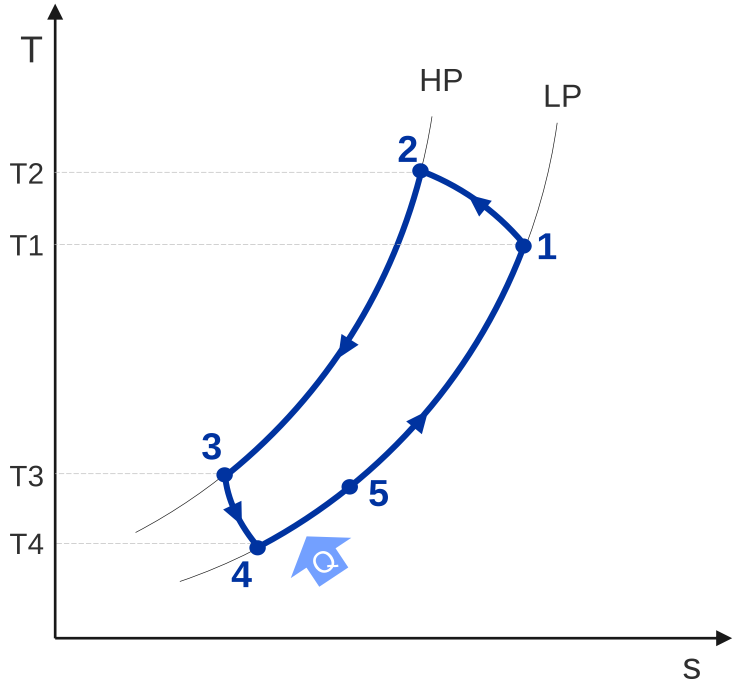


Sources:
[1] scikro-instru.com [2] https://bluefors.com/

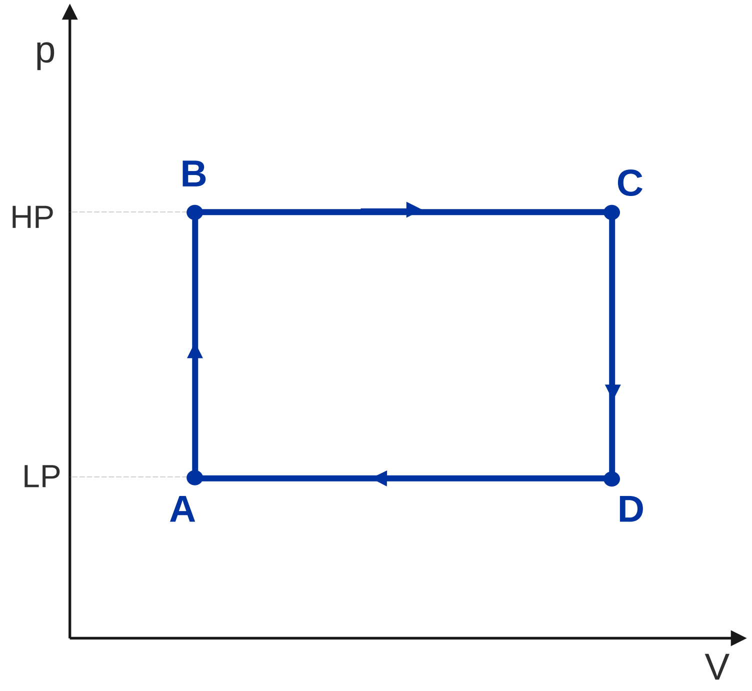
Operating principle of the Gifford-McMahon cryocooler



Thermodynamic processes of the GM cryocooler
on the T-s diagram



p-V transitions in the cold chamber (B)



1 → 2 **pressure increase:** HP valve open, displacer in the bottom, A max volume

2 → 3 **gas pumping:** HP valve open, displacer is moving up, B volume increases

3 → 5 **free exhaust:** LP valve open, displacer is in the top, B volume max

5 → 1 **forced exhaust from B:** LP valve open, displacer is moving down, A volume increases

HP – high-pressure side
LP – low-pressure side

A – warm volume
B – cold volume

Sources:
[1] Maciej Chorowski, *Kriogenika - podstawy i zastosowania*, I.P.P.U. MASTA Sp. z o.o., 2007
[2] Milind D. Atrey, *Cryocoolers. Theory and Applications*, Springer, 2020

Operating principle of the Pulse Tube cryocooler

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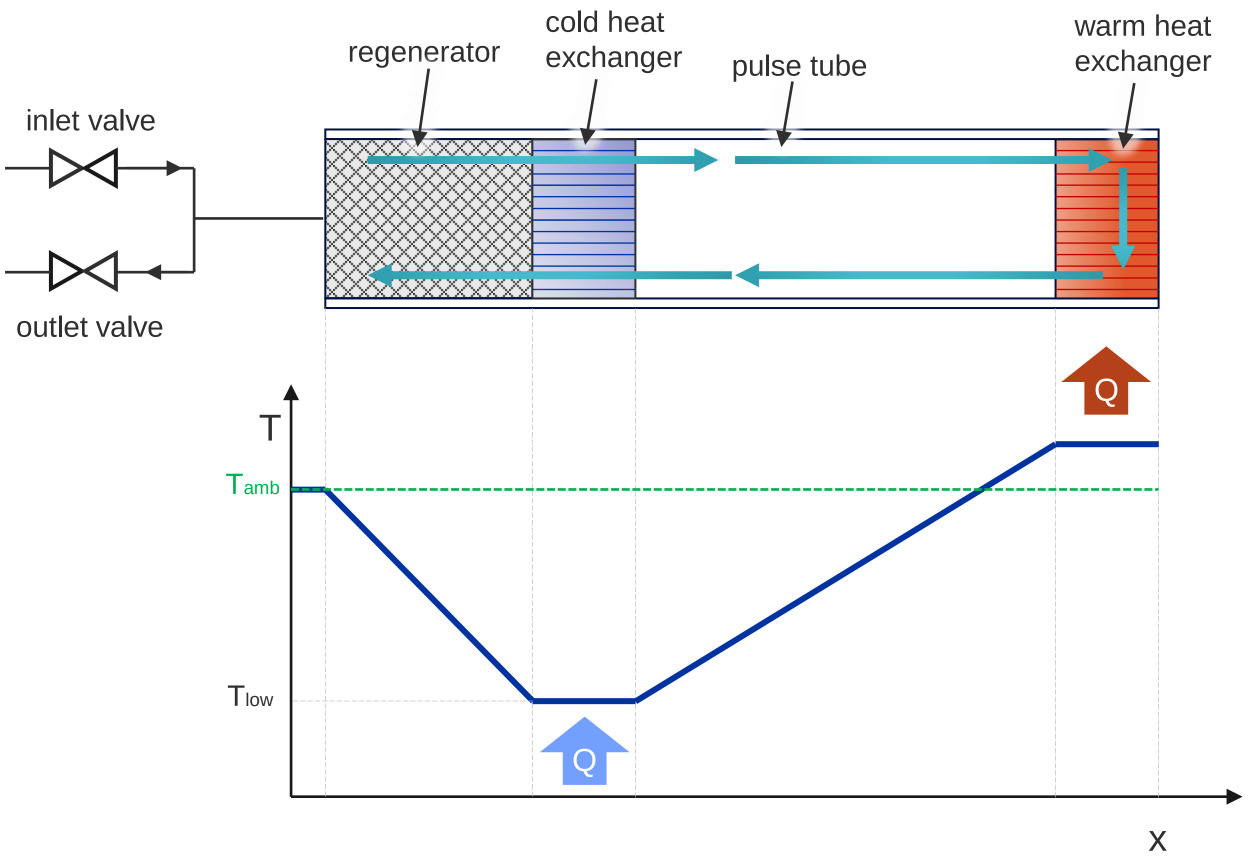
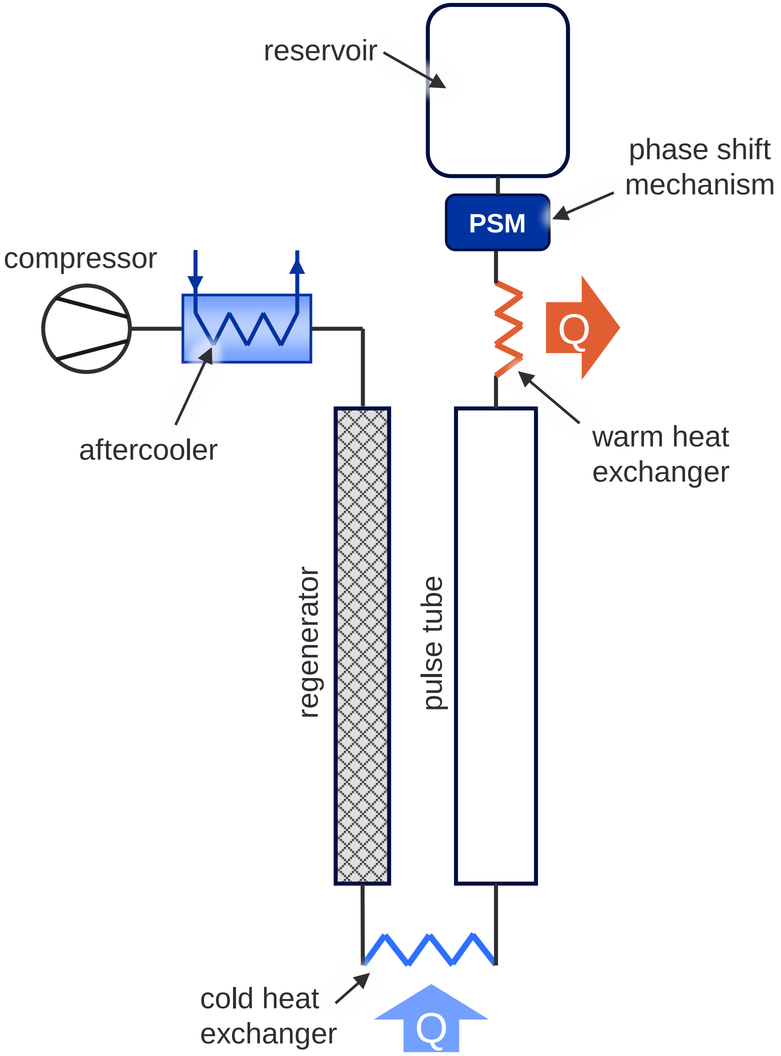
The cooling concept of a pulse tube



Stirling-type pulse tube

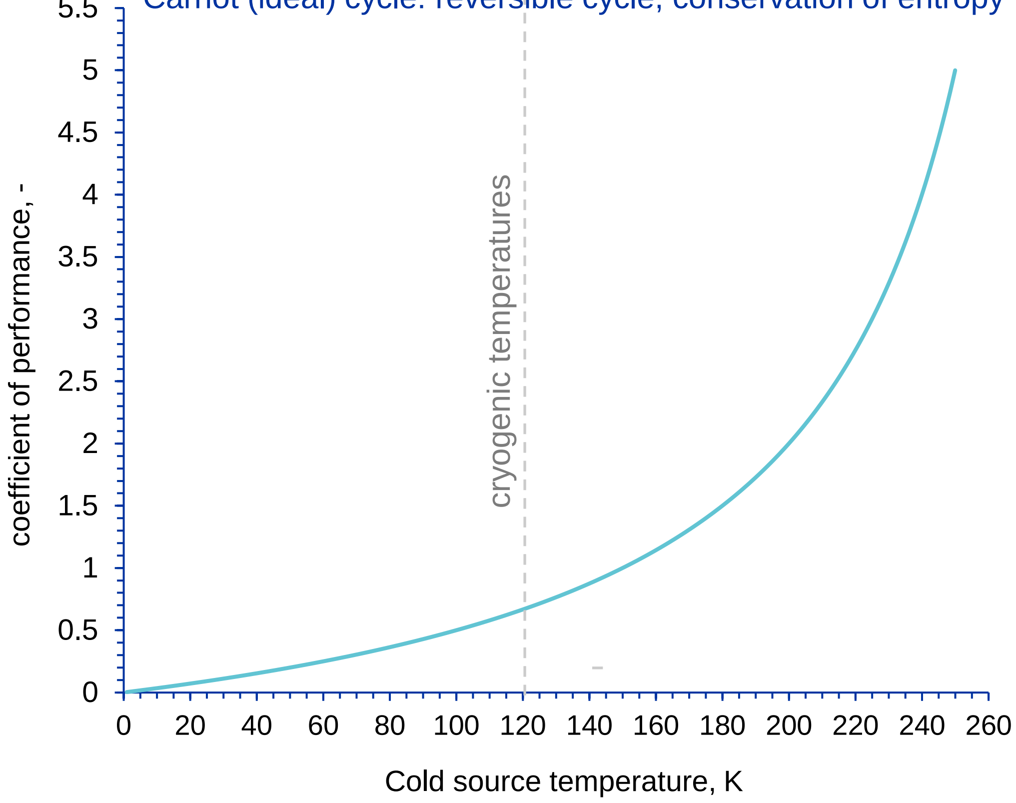


Sources:
[1] Maciej Chorowski, *Kriogenika - podstawy i zastosowania*, I.P.P.U. MASTA Sp. z o.o., 2007
[2] Milind D. Atrey, *Cryocoolers. Theory and Applications*, Springer, 2020

Cooling efficiency at cryogenic temperatures

Cooling efficiency of the Carnot cycle

Carnot (ideal) cycle: reversible cycle, conservation of entropy



Carnot's efficiency

$$COP_{Carnot} = \frac{\dot{Q}_o}{P} = \frac{T_c}{T_w - T_c}$$

where:

$\dot{Q}_o$ – cooling power, W

P – power imput to the system, W

T_c – temperature of a cold source, K

T_w – temperature of a warm source, K

COP(Tw = 300K and Tc = 4.2K) = 1/70

Assuming P = 11.4kW → Q_o = 159.6 W

COP(Tw = 300K and Tc = 50K) = 1/5

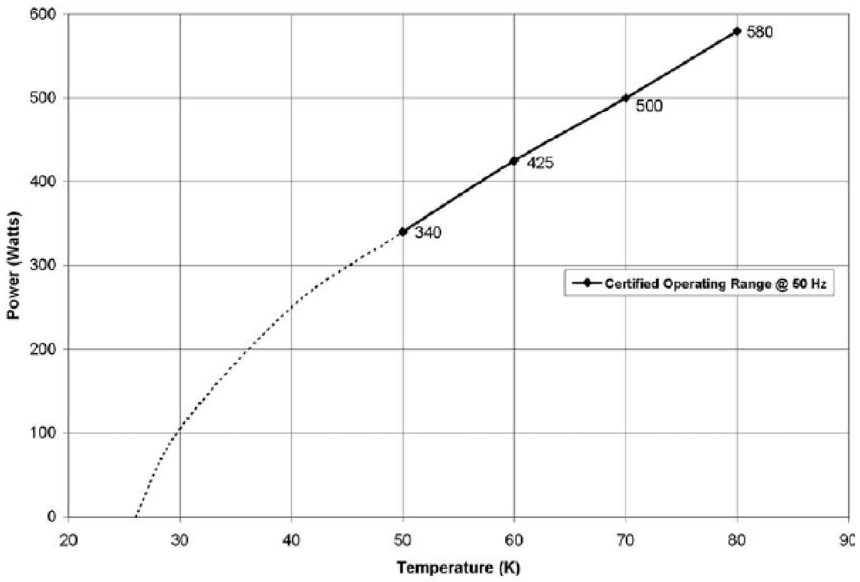
Assuming P = 11.4kW → Q_o = 2.3 kW

Conclusions:

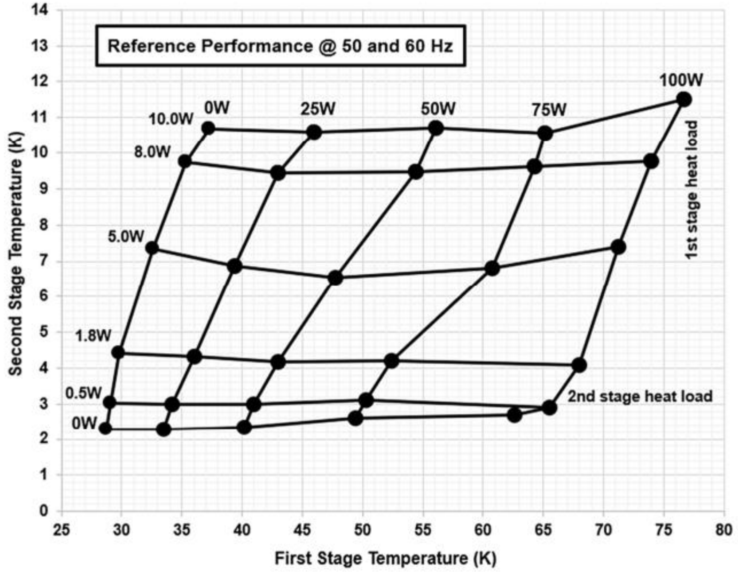
1) COPs of real cryocoolers are significantly lower than the Carnot's one at the same temperature levels

2) Heat interception at higher temperatures it is higly recommended for crocooler-based systems

Capacity curve of the AL600 [1]



Capacity curve of the PT420 [1]



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Sources:
[1] https://bluefors.com/

Advantages and challenges

Compared to traditional cryogenic plants

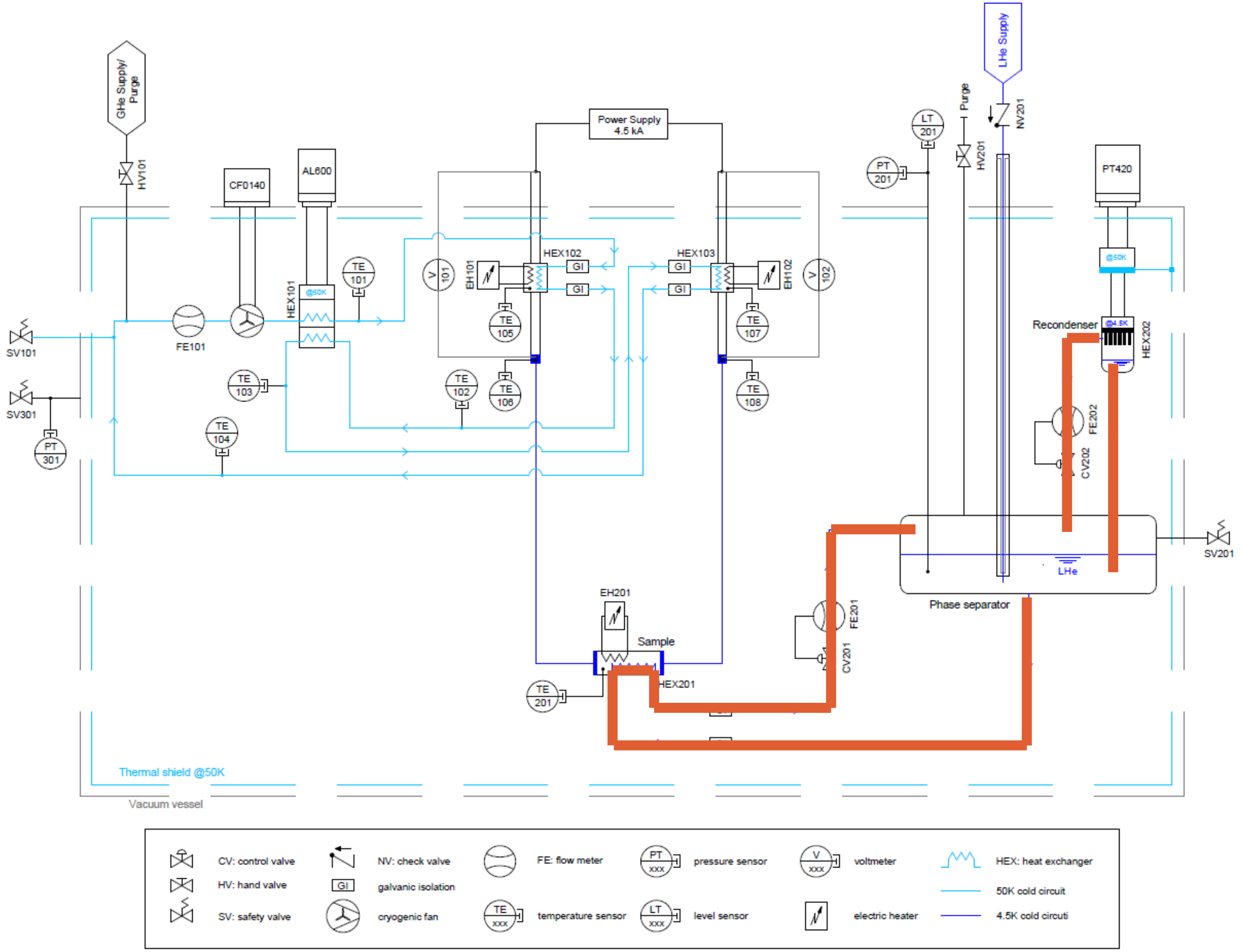
CRYOCOOLER-BASED COOLING APPLIED TO SUPERCONDUCTING DETECTOR MAGNETS

Advantages:
- MODULARITY
- COMPACTNESS
- LONG TRANSFER LINES AVOIDED
- LIMITED HELIUM LOSSES
- COST EFFECTIVENESS

Challenges:
- LIMITED COOLING CAPACITY
- EFFICIENCY <<1% at 4K
- MAGNETIC STRAY FIELD SENSITIVITY
- ELONGATED THERMAL LENGTH

How to get the cooling power from the cryocooler to where it is needed?

Concept of the thermosiphon & ZBO cooling



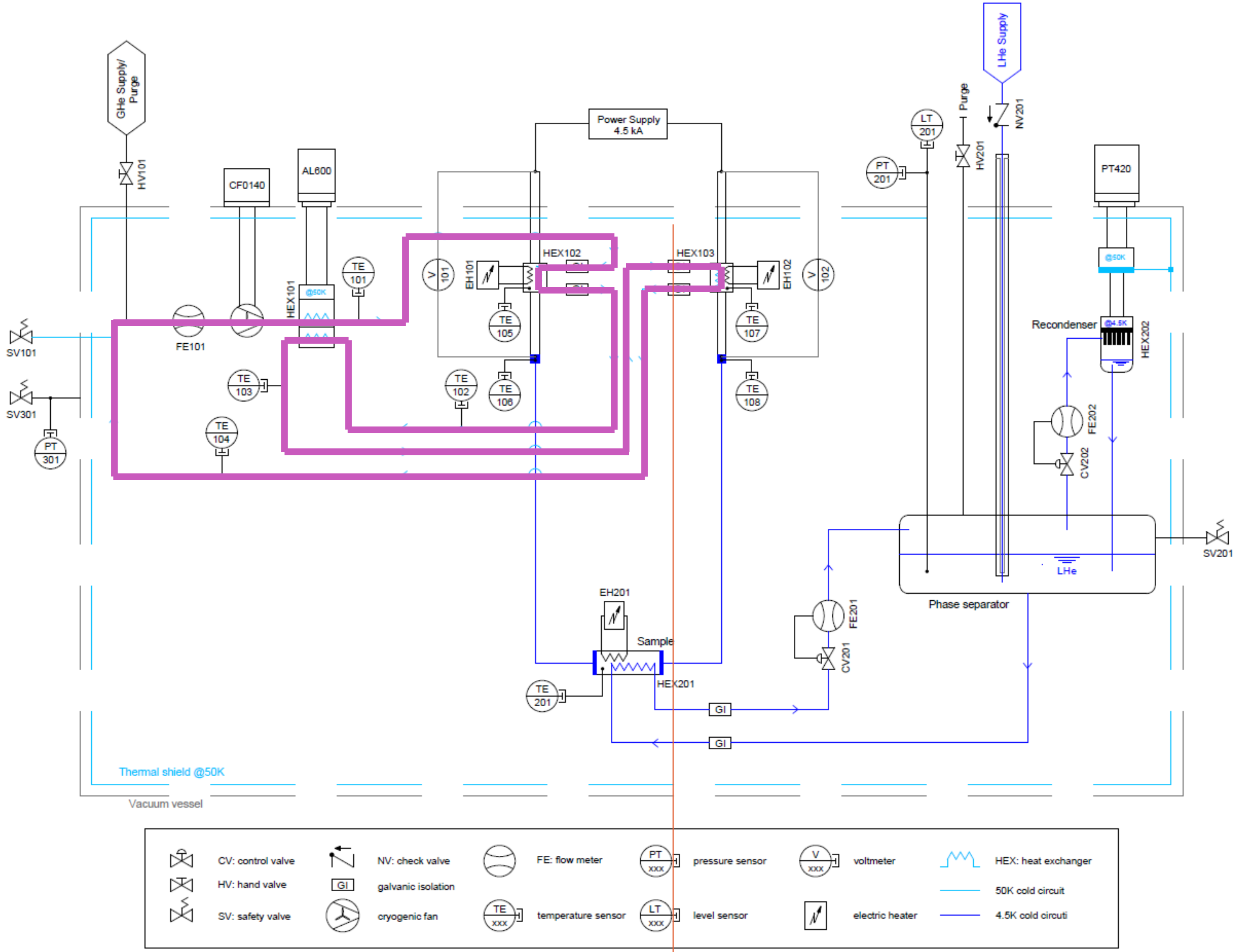
The installation consists of:

- **Low-temperature loop**
  - Cold mass
  - Two-phase helium @ 4.2 K
  - Thermosiphon in Zero-Boil-Off configuration
  - Recondensing heat exchanger
  - Two-stage cryocooler PT420 with the capacity of 2W @4.2K
  - Measuring and safety apparatus

Intermediate loop

- Gas helium @50K
- Cold circulator Bohmwind
- Single-stage cryocooler AL600 with the capacity of 170W @50K
- Cryocooler-to-helium-gas heat exchanger
- HTS-based current leads with the heat exchangers integrated
- Measuring and safety apparatus

Concept of the thermosiphon & ZBO cooling



The installation consists of:

- **Low-temperature loop**
  - ➢ Cold mass
  - ➢ Two-phase helium @ 4.2 K
  - ➢ Thermosiphon in Zero-Boil-Off configuration
  - ➢ Recondensing heat exchanger
  - ➢ Two-stage cryocooler PT420 with the capacity of 2W @4.2K
  - ➢ Measuring and safety apparatus

Intermediate loop

- ➢ Gas helium @50K
- ➢ Cold circulator Bohmwind
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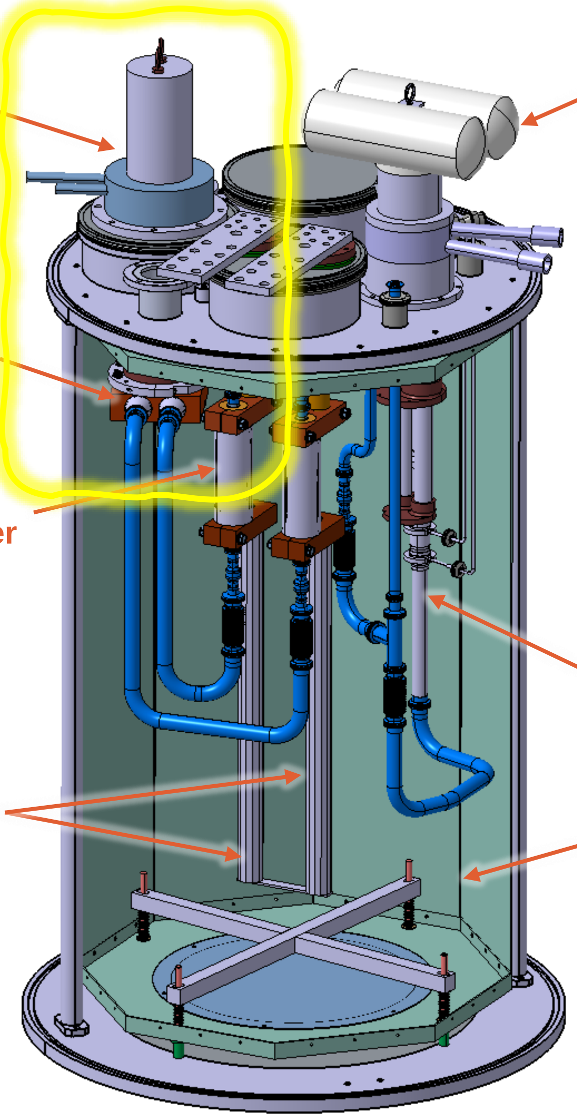
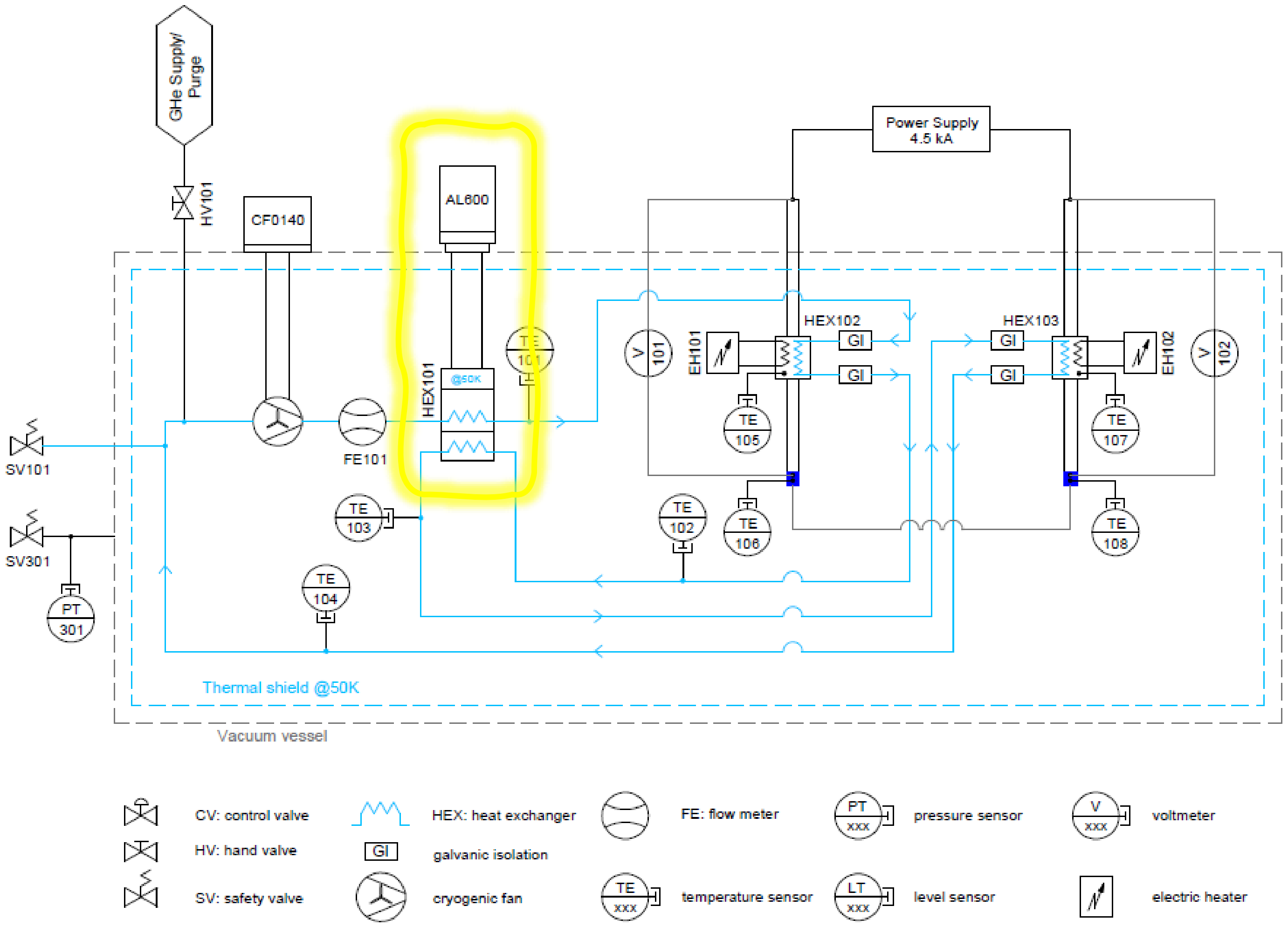
- ➢ Cryocooler-to-helium-gas heat exchanger
- ➢ HTS-based current leads with the heat exchangers integrated
- ➢ Measuring and safety apparatus

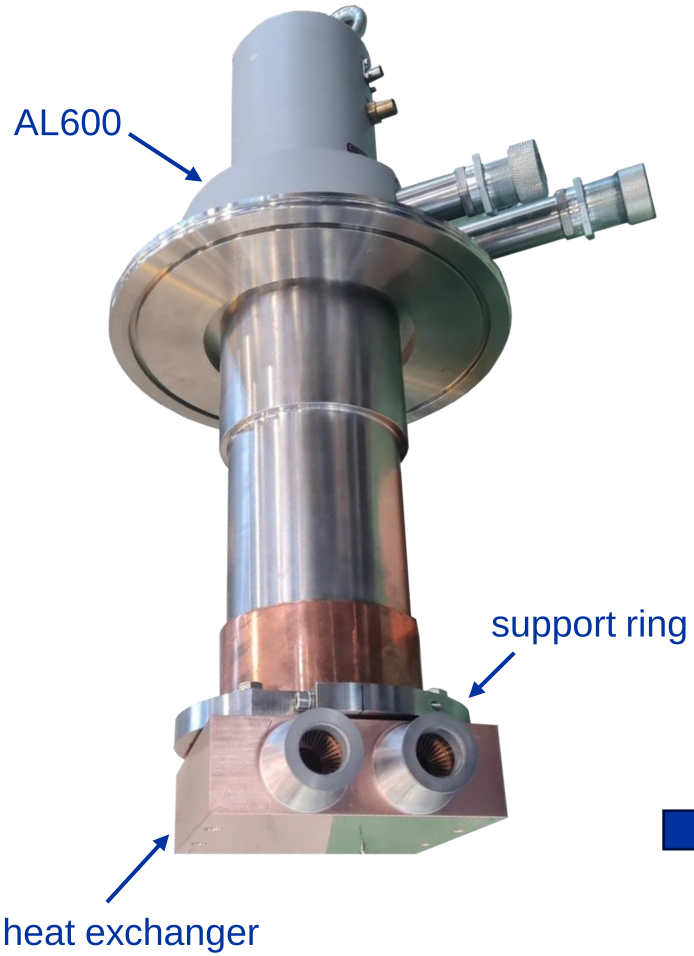
Demonstrator of the HTS current lead cooling



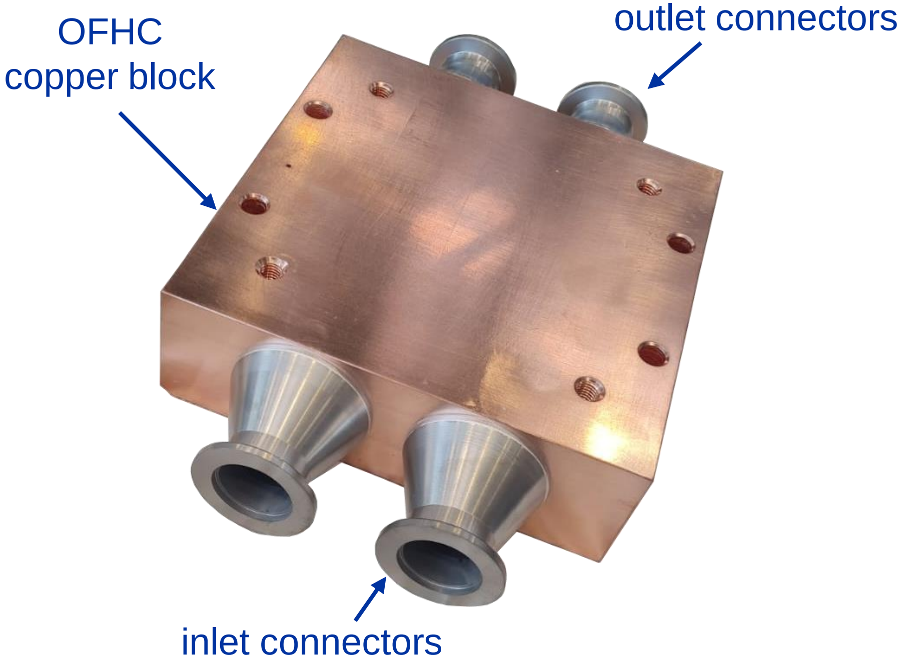


Thermal interface between cryocooler & helium gas

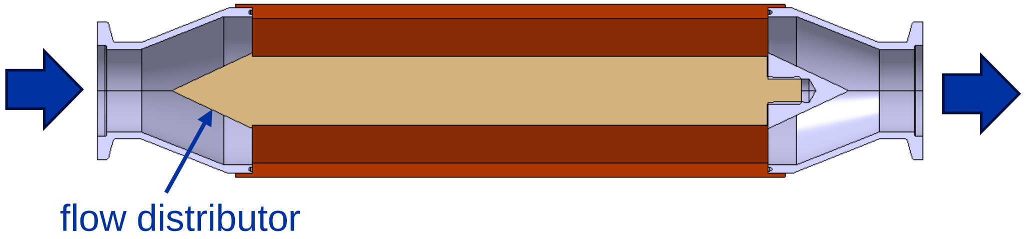
Assembly of the AL600 with the HEX101



Assembly of the HEX101

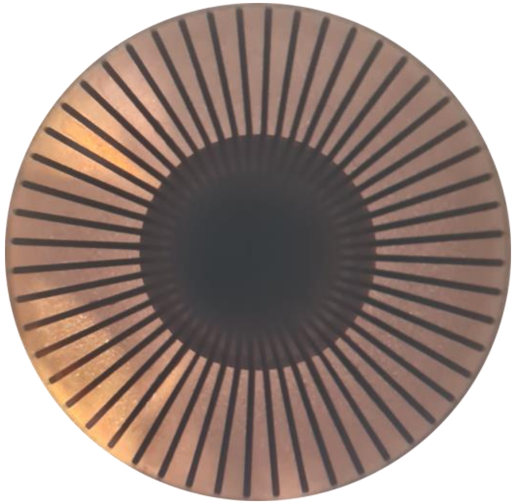


Section view of the HEX101



GEOMETRY OF THE HEX101	
Manufacturing technology:	EDM
Number of cooling channels:	104
Width of the cooling channel:	0.6 mm
Length of the cooling channel:	11 mm

Section view of the cooling channels



Thermal interface between cryocooler & helium gas

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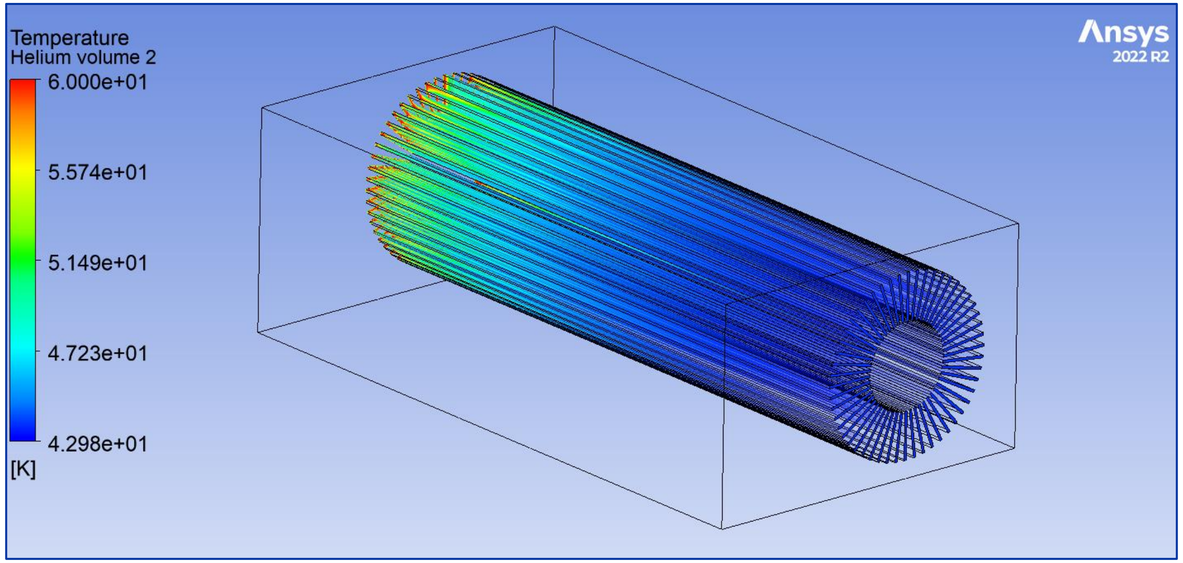
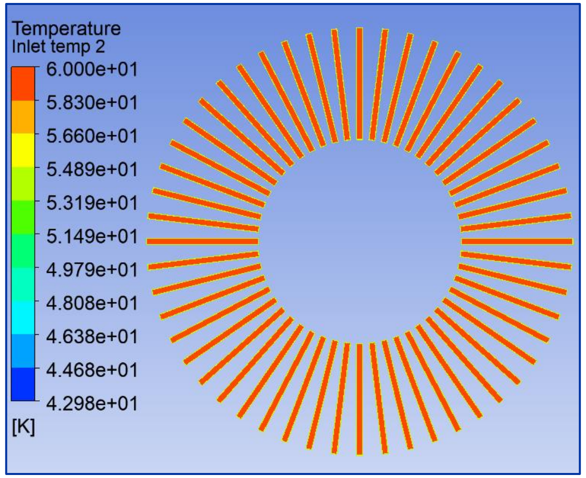
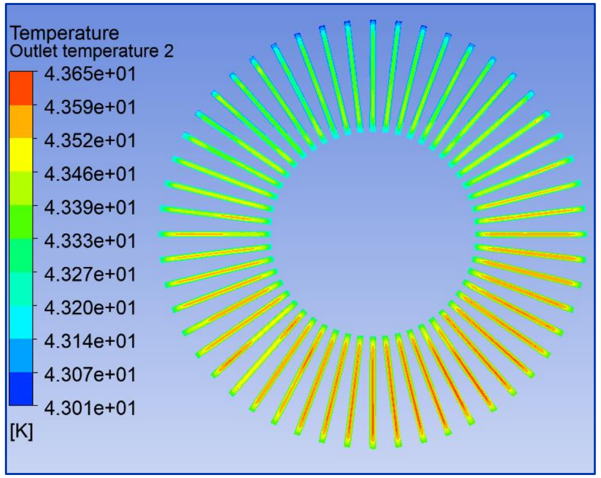
Heat transfer considerations

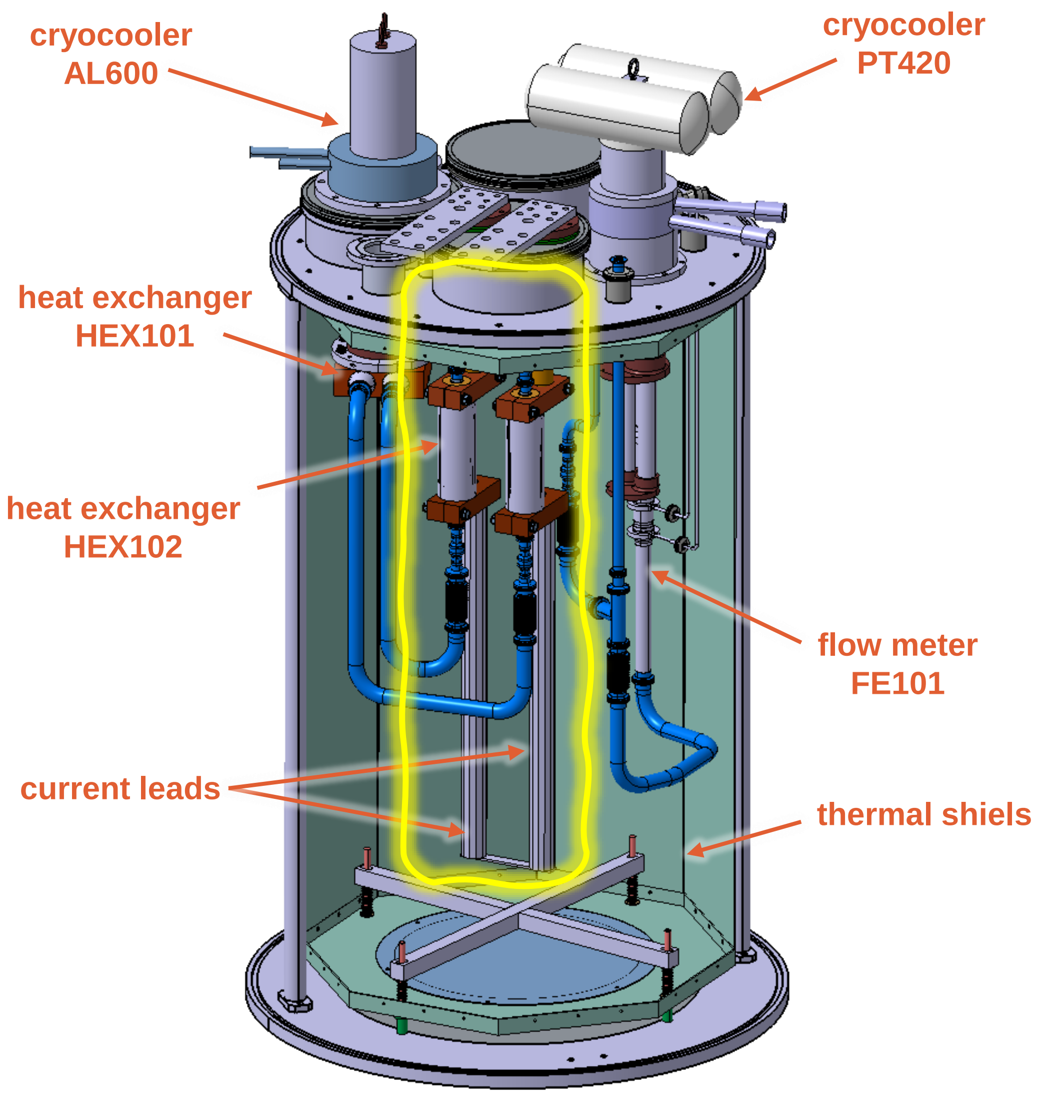
- Steady state is considered
- Cooling power applied as a function of temperature at the top of the block
- Mass flow of 2 g/s
- Operating static pressure of 5 bara
- Flow velocity of 1.22 m/s
- Laminar flow, Re= 1030
- Linear pressure drop of 0.43 mbar
- Inlet temperature of 60 K
- Outlet temperature of 43 K

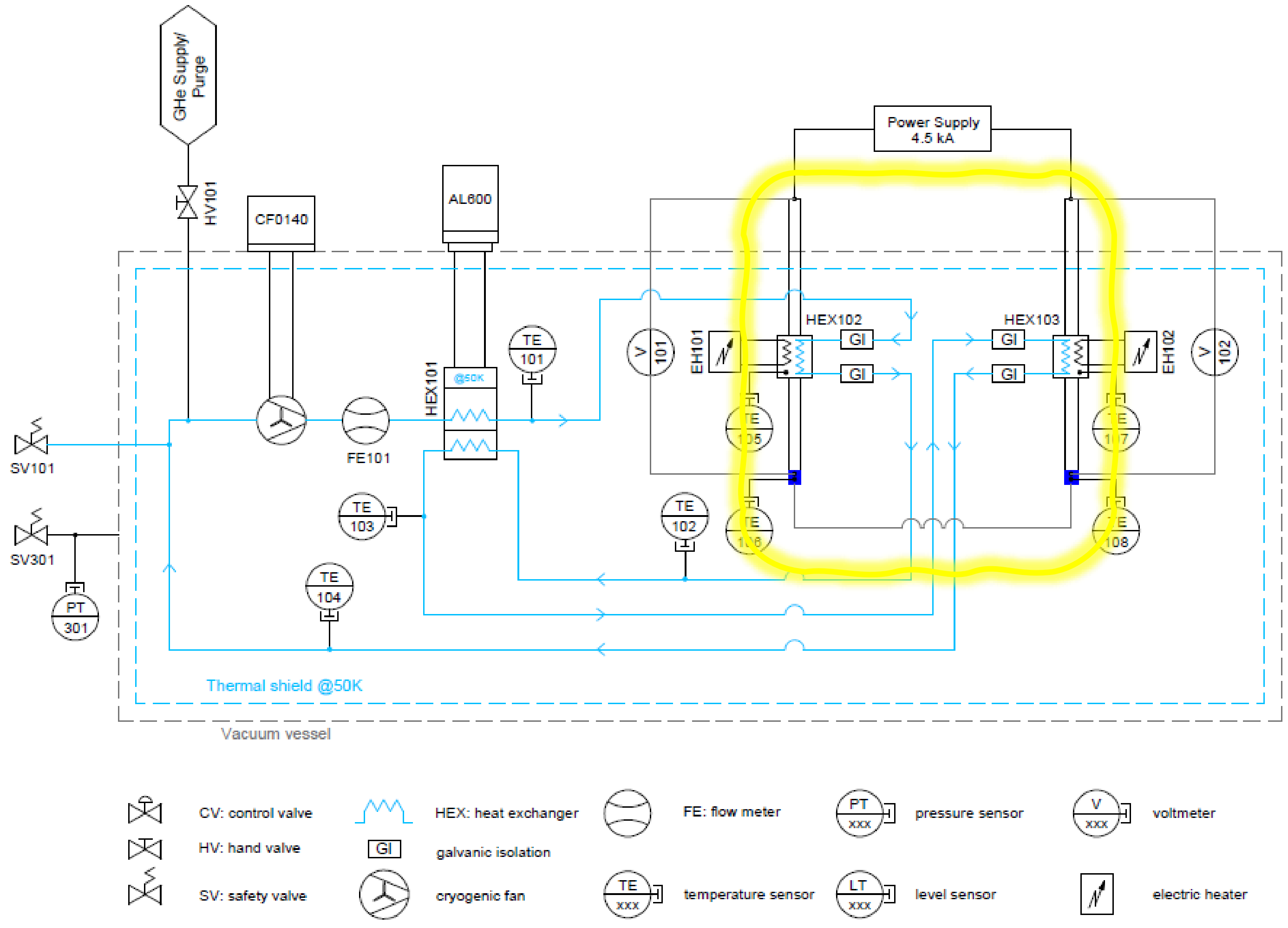






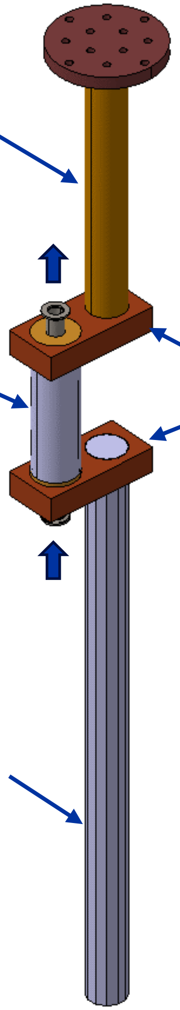
Demonstrator of the HTS current lead cooling



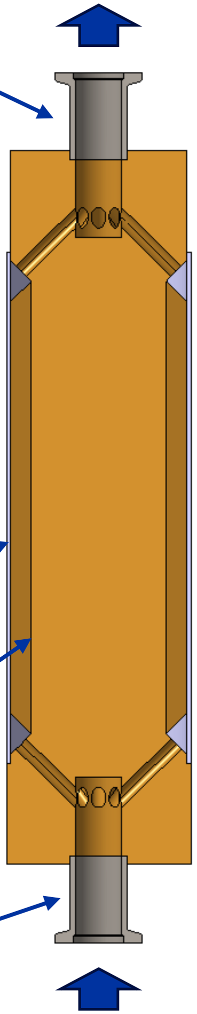


Thermal interface between helium gas & current lead

Assembly of the HTS-based current leads



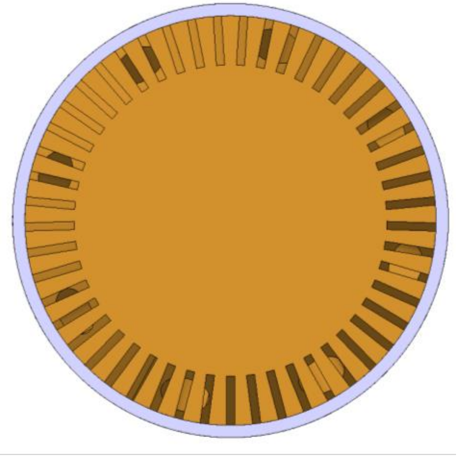
Cross-section of the heat exchanger HEX102



Brass heat sink

GEOMETRY OF THE HEX102	
Overall length of the lead	1.2 m
Length of the cooling channels	147 mm
Manifold inlet diameter	16 mm
Manifold number of holes	9
Manifold single hole diameter	5 mm
Single cut height	8 mm
Cut width	1 mm
Number of cuts	60

Front view of the cooling channels

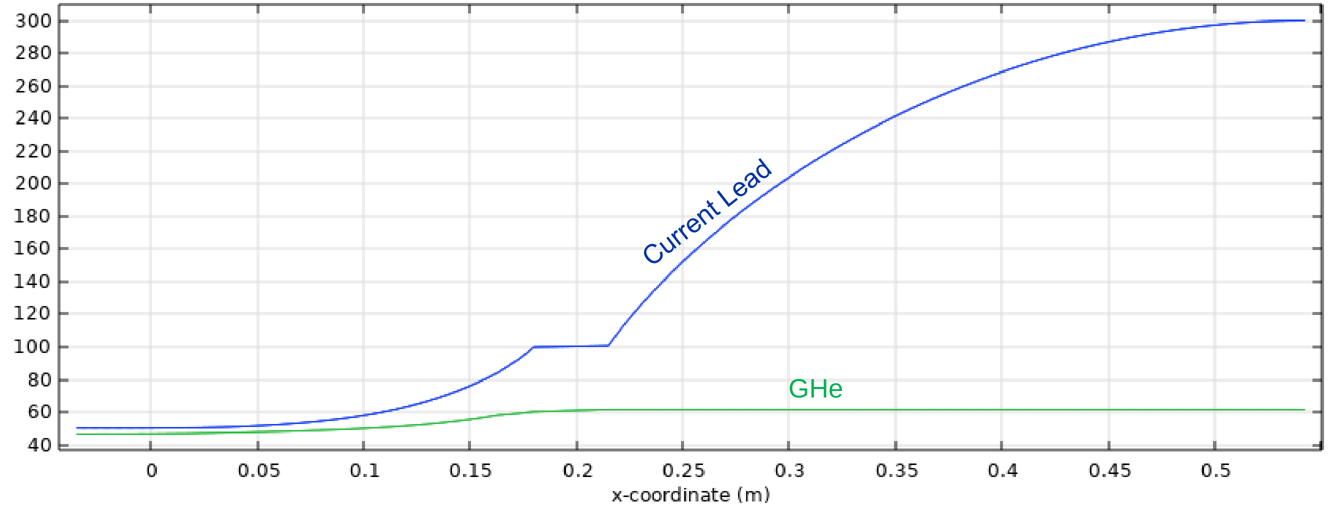


Design of the 3kA current leads: calculations

1D geometry optimization in COMSOL

$$\frac{d}{dx}\left(k(T)A\frac{dT}{dx}\right)+\rho(T)\frac{I^2}{A}-\dot{m}_{He}C_p(T_G)\frac{dT_G}{dx}=0$$

Current lead temperature vs. length

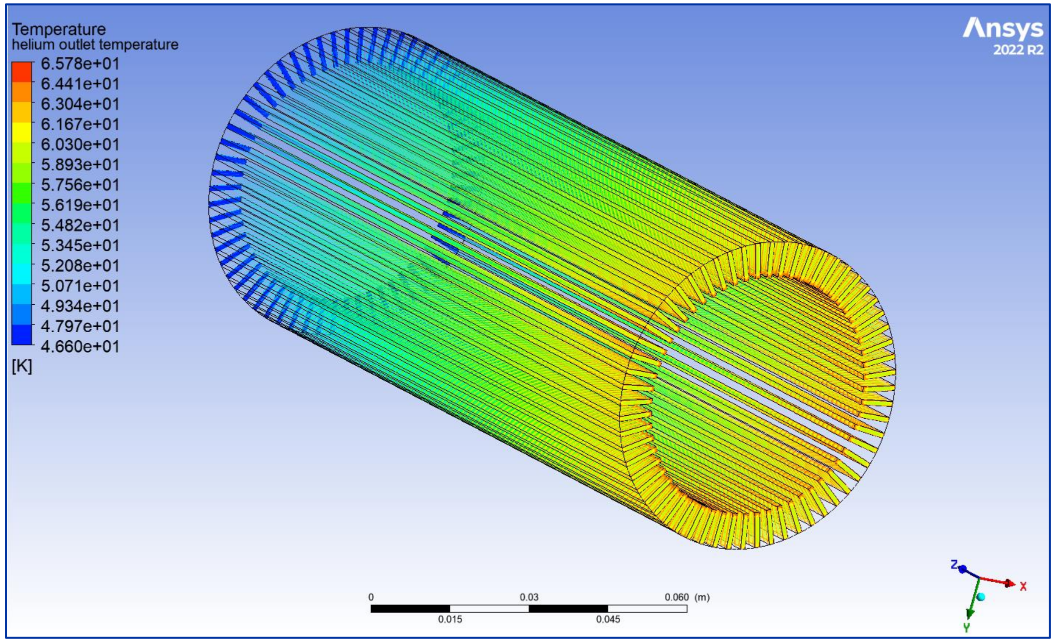


Characteristics of the current leads	
Material:	Brass
Current:	3 kA
Dissipation:	151 W
Outer diameter:	51/65

Heat Exchanger HEX102	
Operating temperatures (GHe)	46.6 → 61.6 K
Low temp. of the lead	50 K
Operating Pressure	5 bara
Mass flow	2 g/s

Verification in Ansys Fluent

View of the cooling channels



Input

Inlet gas temperature: 46.6 K

Power dissipation:151 W

Mass flow: 2 g/s

Static pressure: 5bara

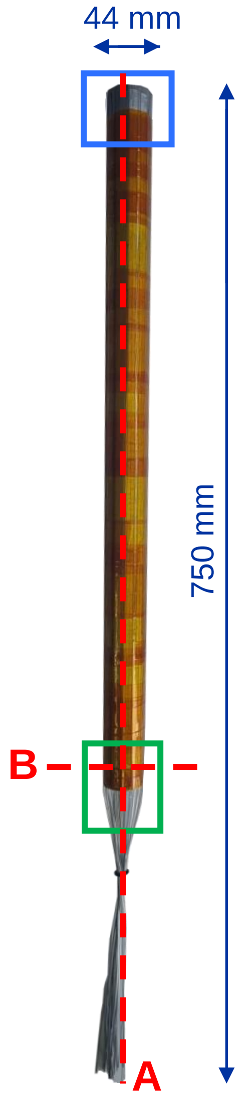
Output

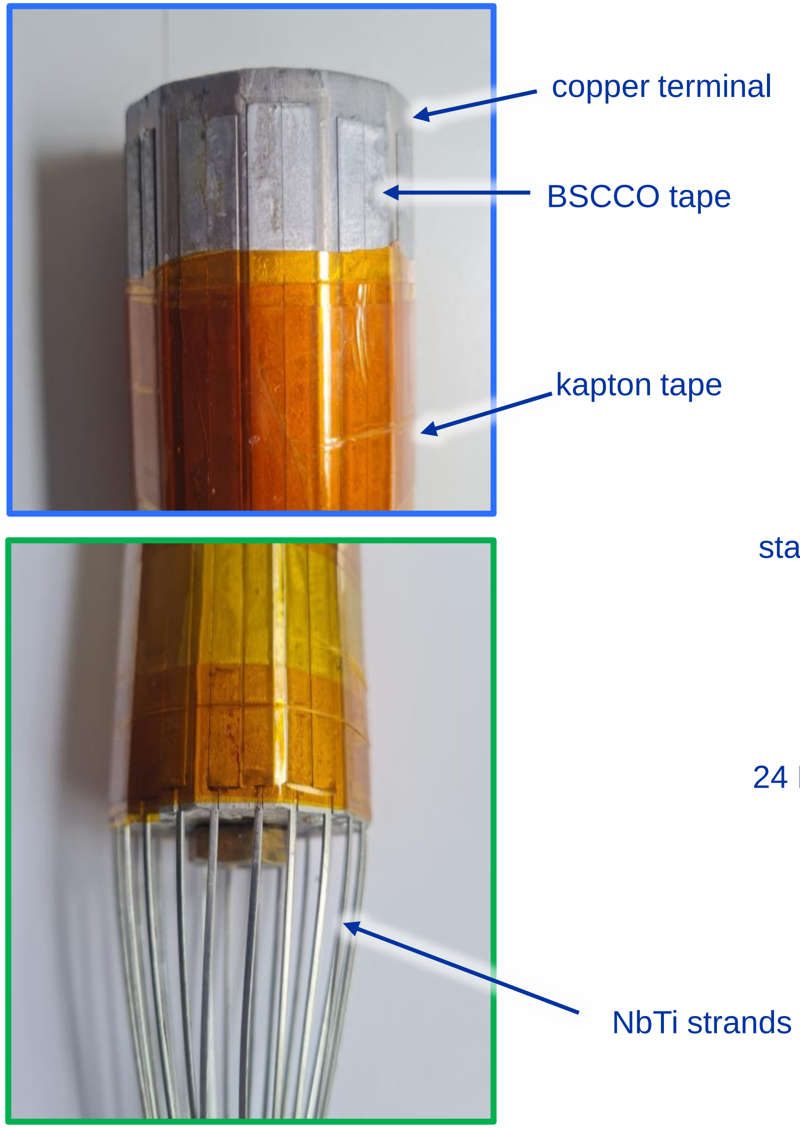
Gas temperature distribution

Av. outlet helium temperature: 61.1 K

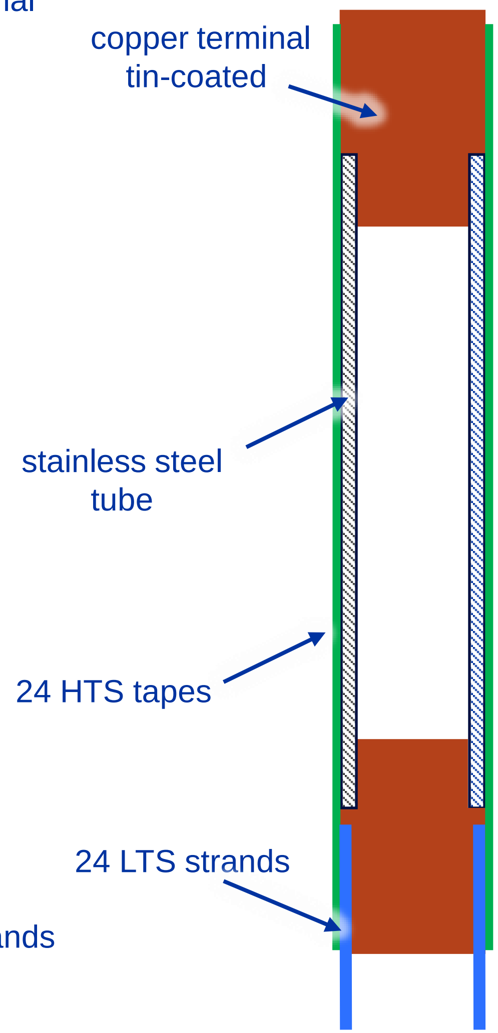
Design of the 3kA current leads: HTS part

HTS part

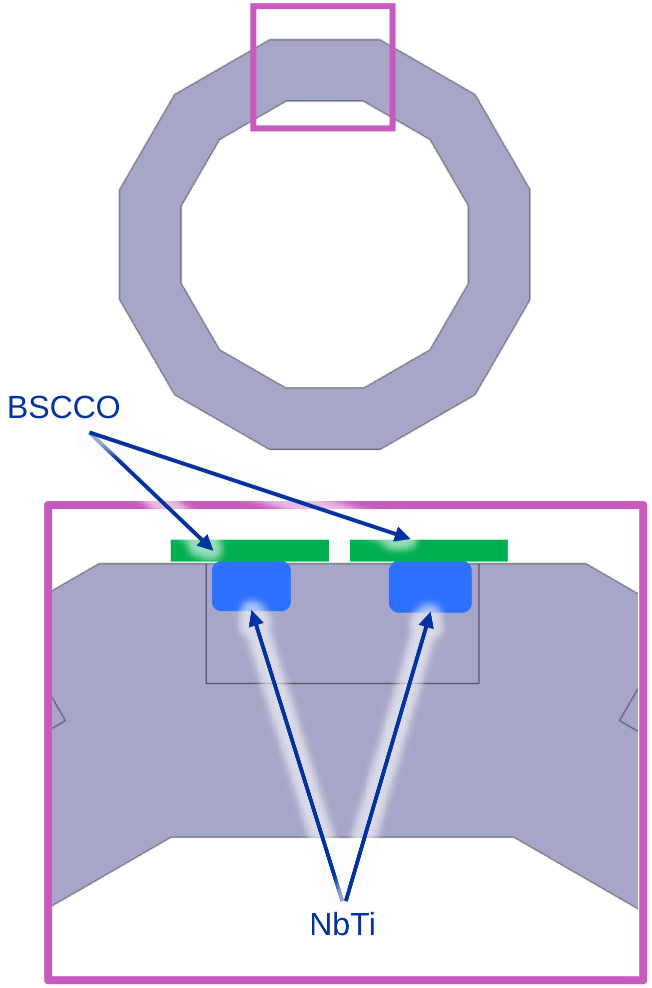




Diagonal cross section A



Normal cross section B



Planned activities

Within EP R&D: Ongoing effort to test an efficient cryocooler-to-helium-coolant thermal interface and HTS-based current leads cooled with cryocoolers.

Foreseen activities in the near future time

1) Testing of the heat exchangers HEX101 and HEX102:
   - → thermal performance
   - → pressure drop
2) Assembling the demonstrator of the HTS current lead cooling
   - → performance of the current leads
3) Theoretical considerations of the thermosiphon in ZBO configuration
   - → design of a recondenser
   - → design of a passive cooling loop
4) Building the demonstrator of the thermosiphon in Zero-Boil-Off configuration @4.2 K

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Thank you for your attention