Development of a remote cooling system for detector magnet current leads using a single-stage cryocooler

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Special thanks to Tomasz Banaszkiewicz, Philippe Benoit, Thibaut Coiffet, Philippe Frichot, Marco Garlasche,, Torsten Koettig, Allan Saillet, Michał Sajdak, Patricia Tavares Coutinho Borges De Sousa, Anton Titenkov, Igor Titenkov, Jasper van der Werf

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Content

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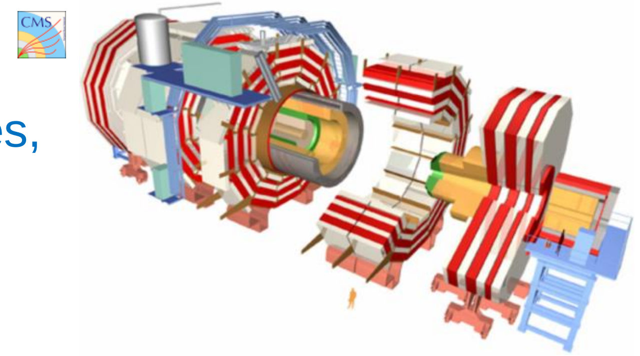
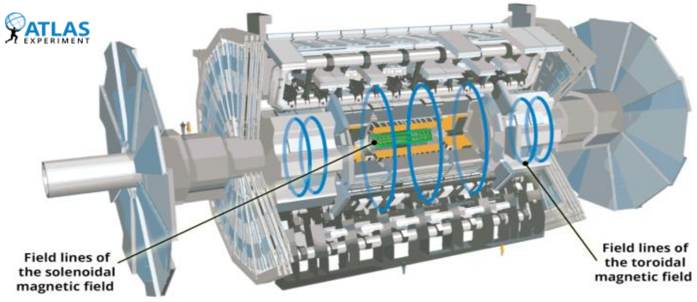
Introduction: High Energy Physics needs

Particle detectors have (very) large bore and strong magnetic fields:

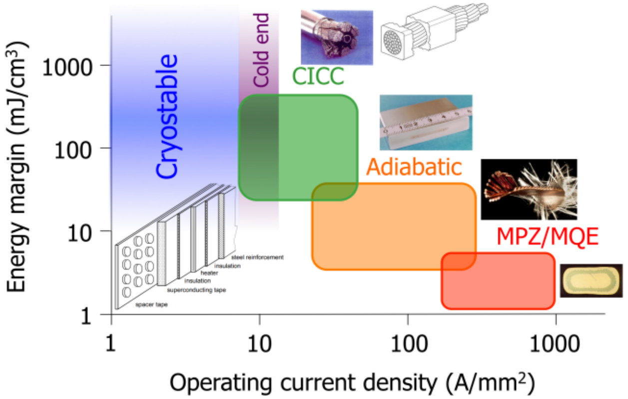
- **Typical field range 2 T ~ 4 T,**
- **High DC currents** (several tens kA),
- High stored energy (**up to GJ**) and magnetic forces,
- Transparent to particles,
- **Large bore** (several meters) **and lengths,**





- Magnets are dipoles, solenoids, toroids, etc.
- Mostly made with Nb-Ti/Cu (and Nb3Sn) superconducting cables.

- Cooling methods applied with success over decades:
  - ✓ Direct cooling in liquid helium bath at 4 K,
  - ✓ Cable in conduit conductors,
  - ✓ Indirect cooling (enthalpy stabilization, pure copper of aluminium).



Source: L. Bottura, CERN Accelerator School, 2013

Future of HEP:

More than 15 projects in the world (collider and non-collider projects) either under construction or design phase over the next years and decades.

Motivation

Superconducting detector magnets:

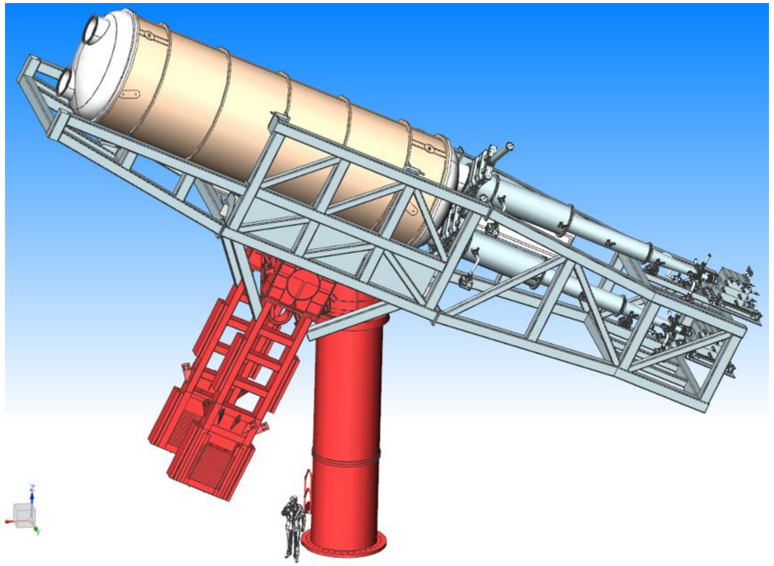
- Typically relying on the work-horse superconducting conductor: Nb-Ti, requiring $T_{Op} < 5$ K
- Historical cryogenic solution: Stand-alone cryogenic plant
- Stray field

Cryo-cooler technology:

- Continuous advances in commercially available cryocoolers in recent years
- Minimal amount of non-renewable helium needed, modular, modest maintenance expected, compact
- But: Modest cryogenic efficiency, modest cooling power at 5 K, and sensitive to magnetic fields

Research questions:

- PhD research: Are large Nb-Ti-based superconducting detector magnets compatible with cryocooler technology?
- This presentation: Can current leads for superconducting detector magnets be combined with cryocooler technology?



Example: The BabyIAXO detector concept, combining cryo-cooler technology with a large Nb-Ti-based superconducting dipole [1]

[1] The IAXO collaboration, *Conceptual design of BabyIAXO, the intermediate stage towards the International Axion Observatory*, May 17, 2021

Introduction: Main heat sources to the cold mass

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→Heat radiation from the ambient environment

→Heat conduction through the supports

→ **Heat conduction through the current leads**

→ **Joule heating of the current leads**

Introduction: Different types of magnet current leads

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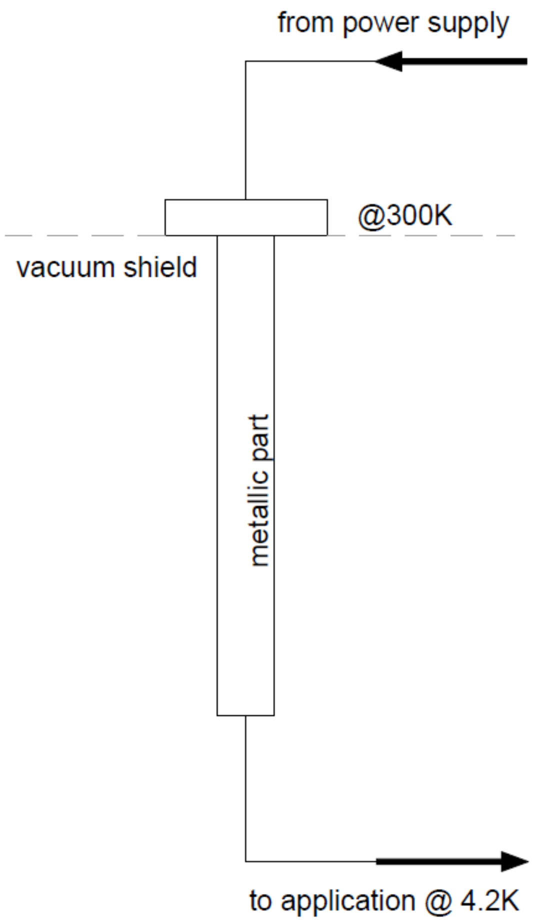
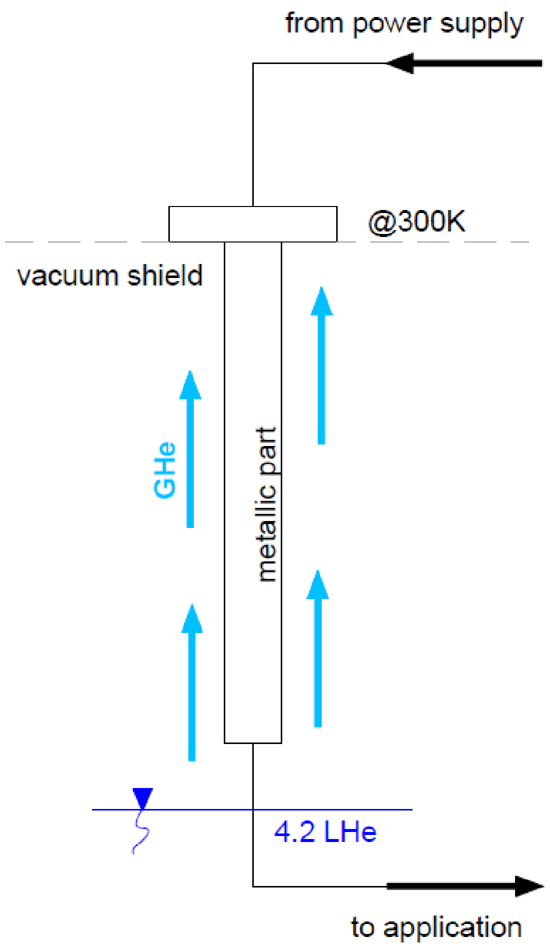
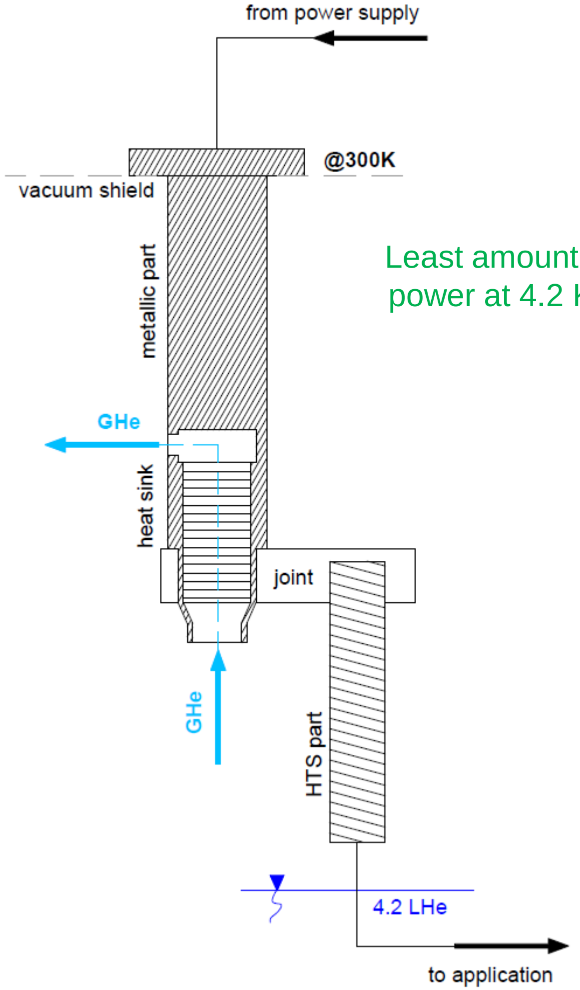
Conduction-cooled current leads



Gas-cooled current leads



Hybrid current leads



Least amount of cooling power at 4.2 K required

[1]J.G. Weisend, *Handbook of cryogenic engineering*, Taylor & Francis, 1998

Concept of the thermosiphon & ZBO cooling

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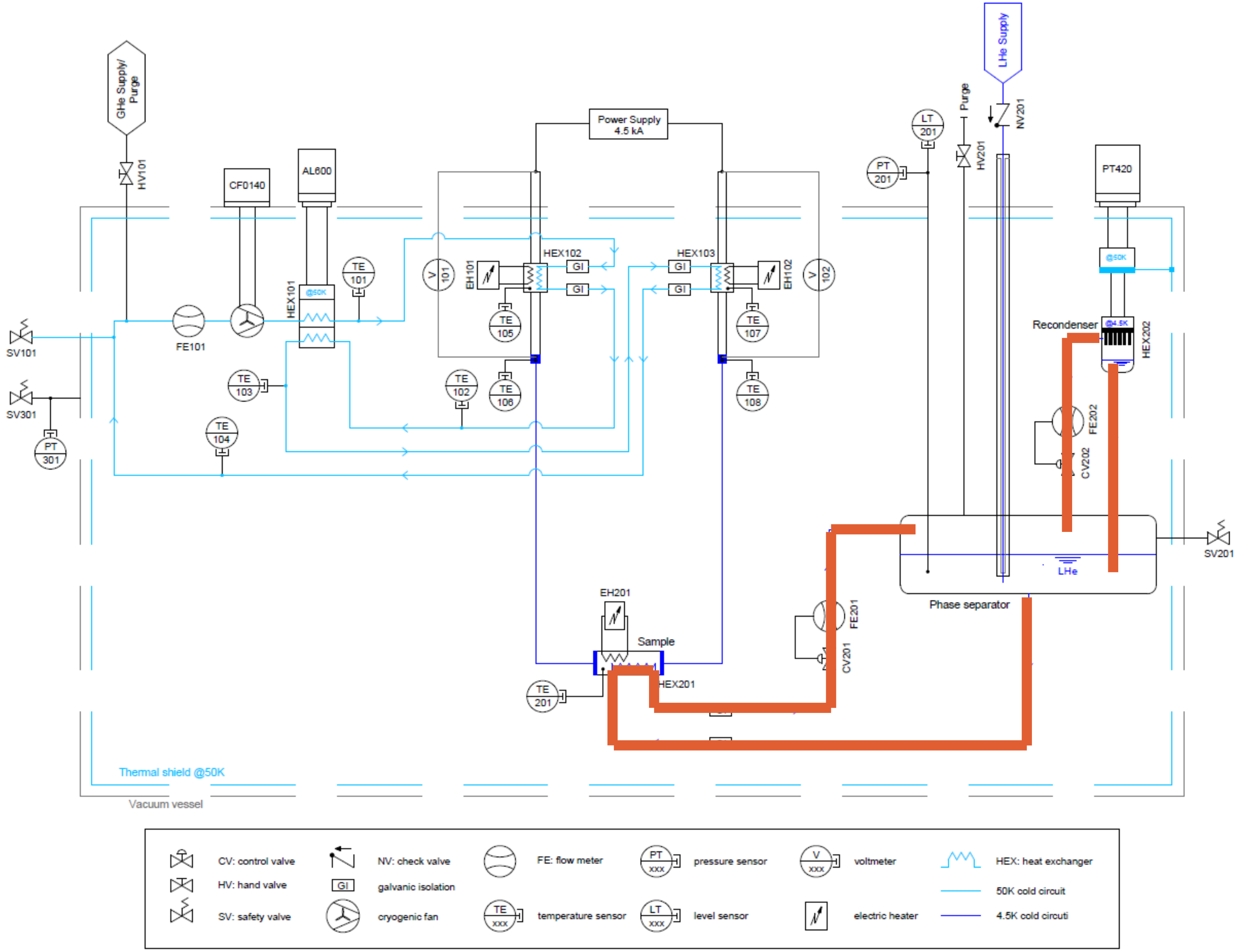

The installation consists of:

- **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

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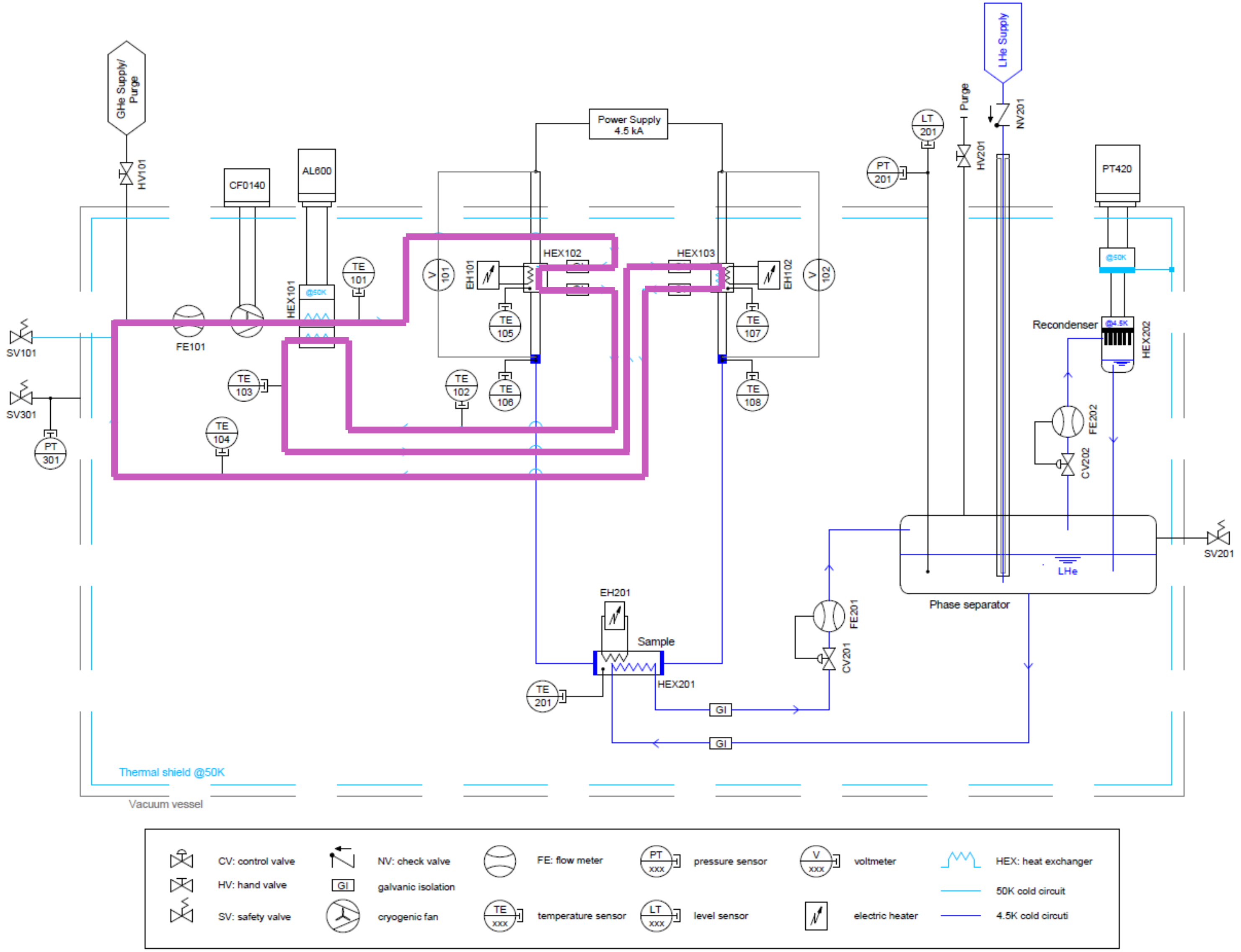

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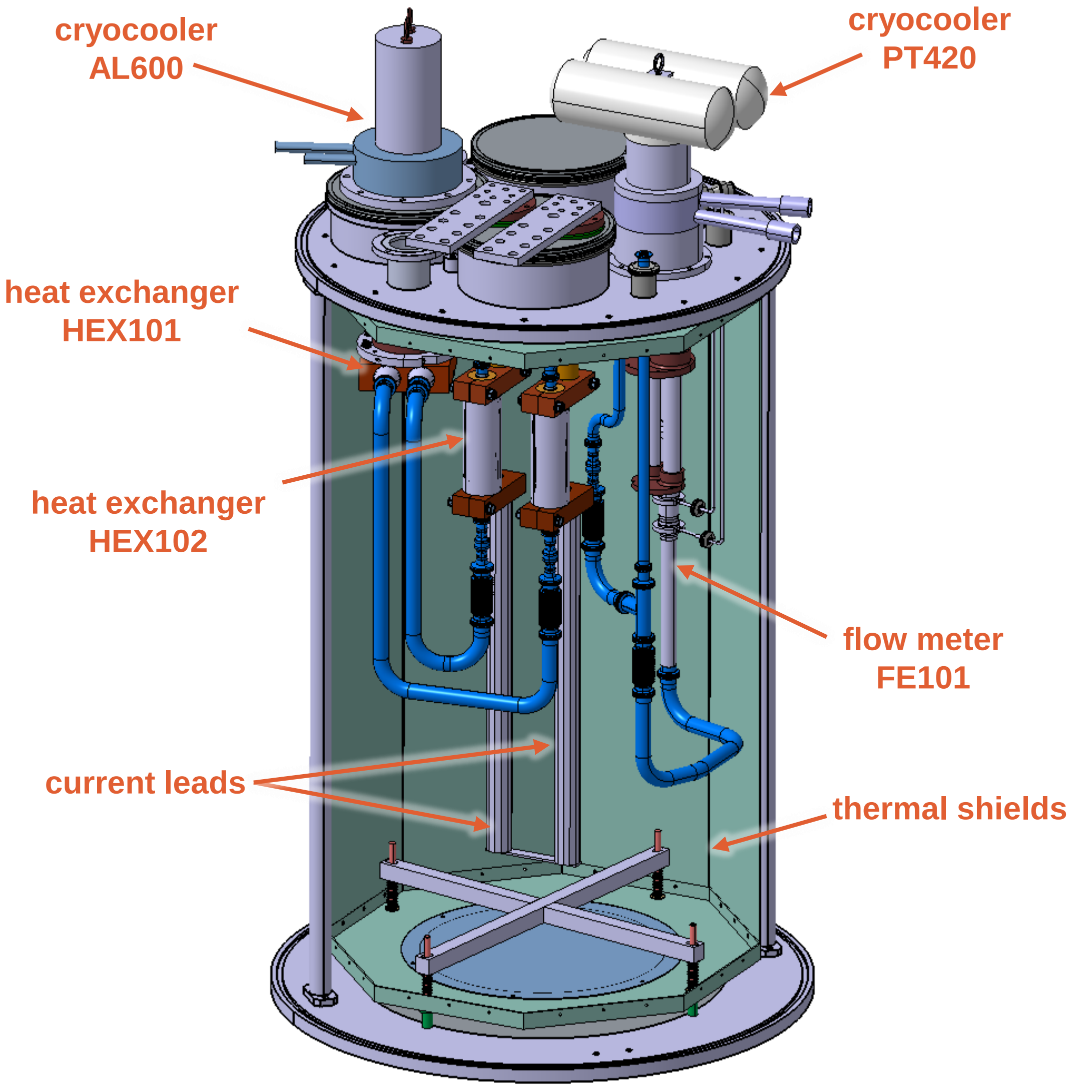
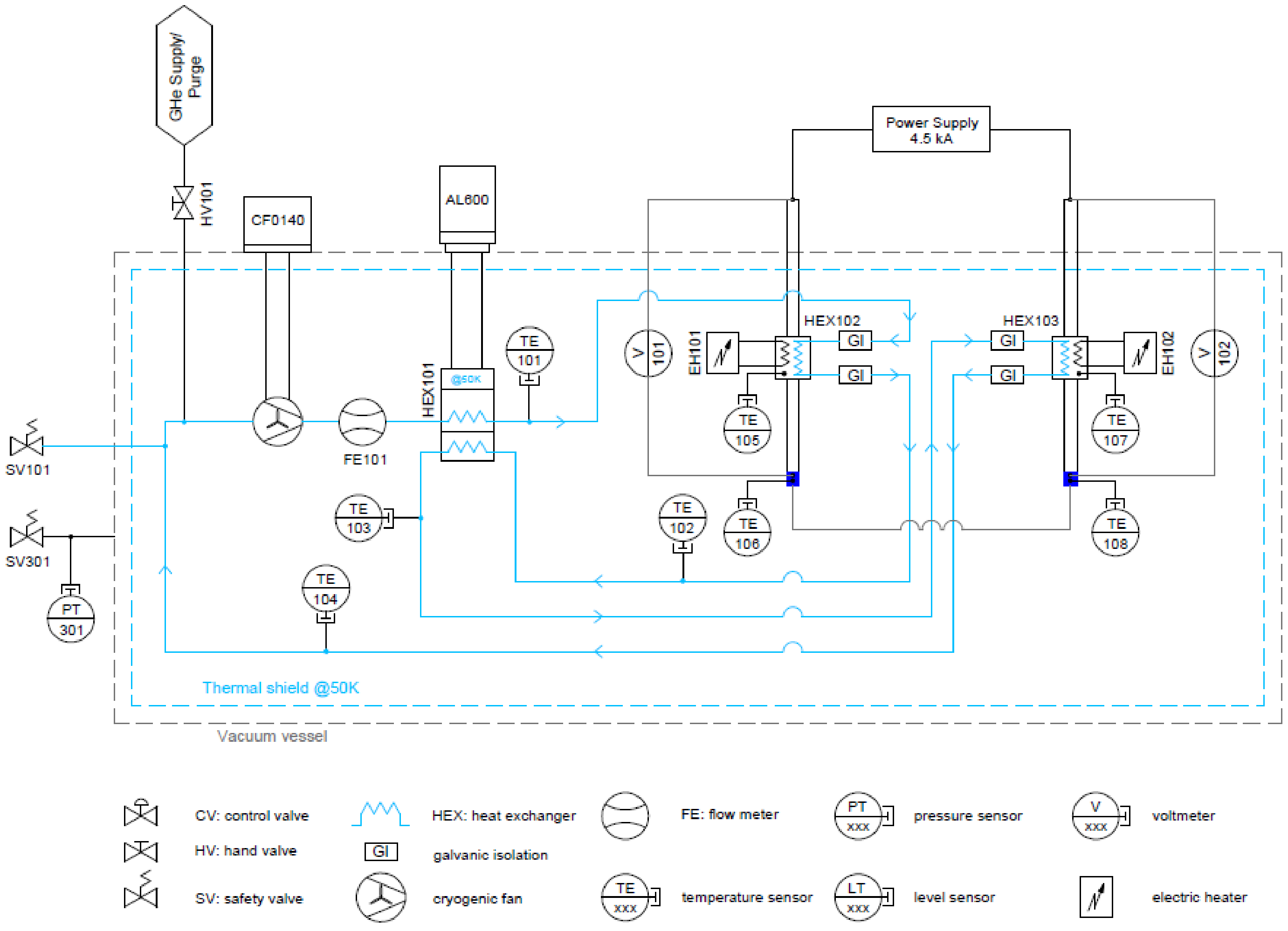
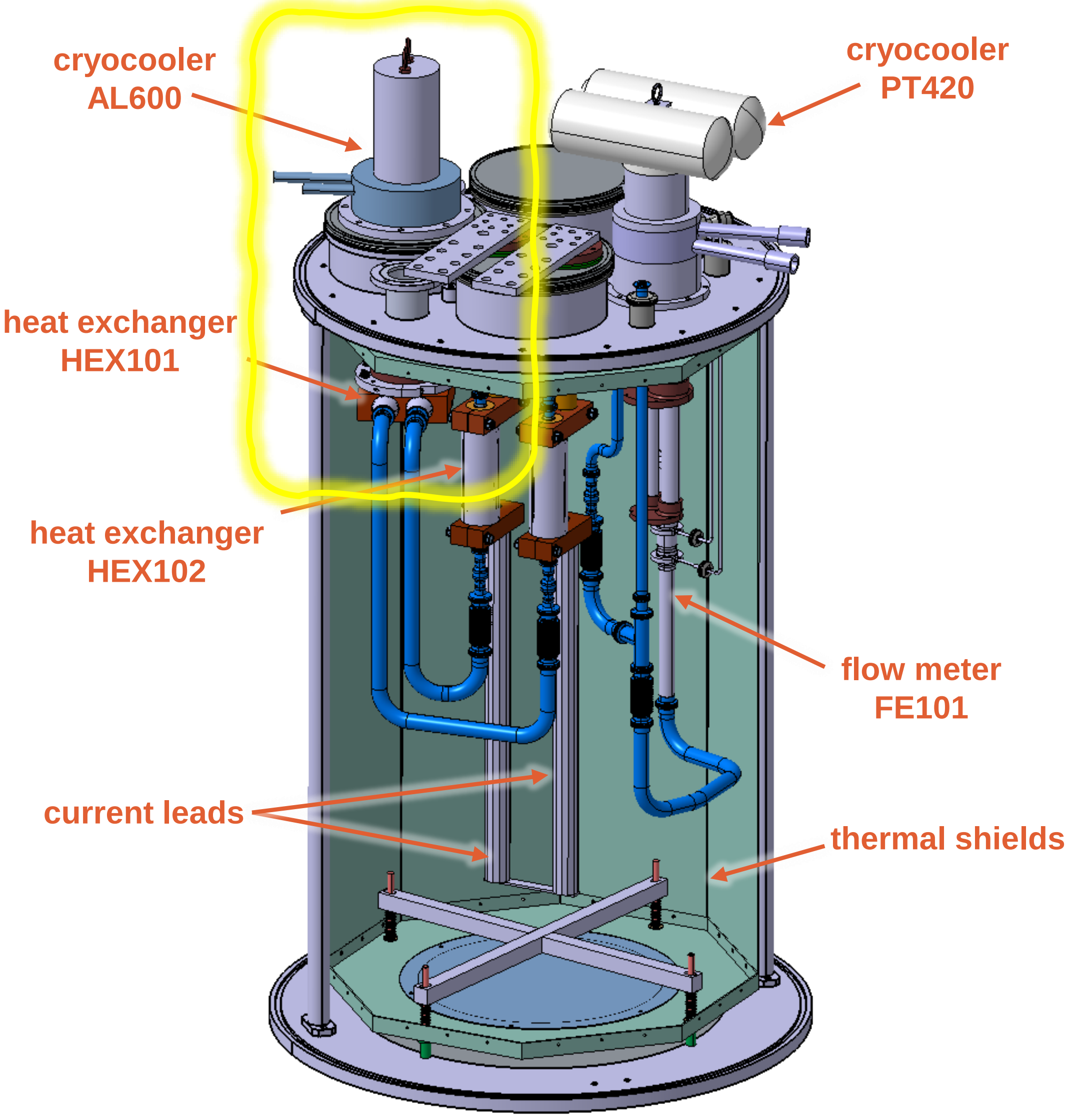
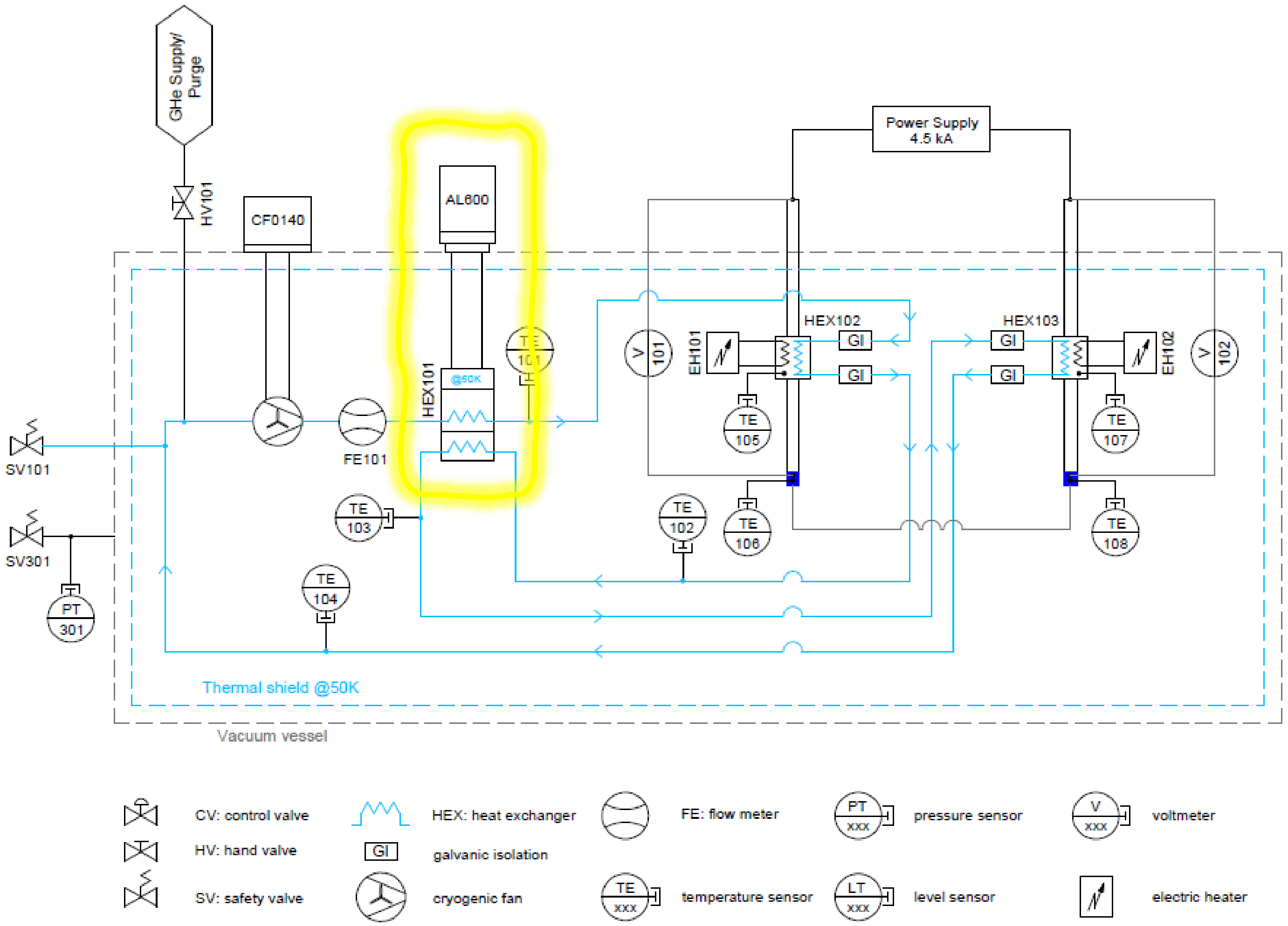
Demonstrator of the HTS current lead cooling





Demonstrator of the HTS current lead cooling





Thermal interface between cryocooler & helium gas

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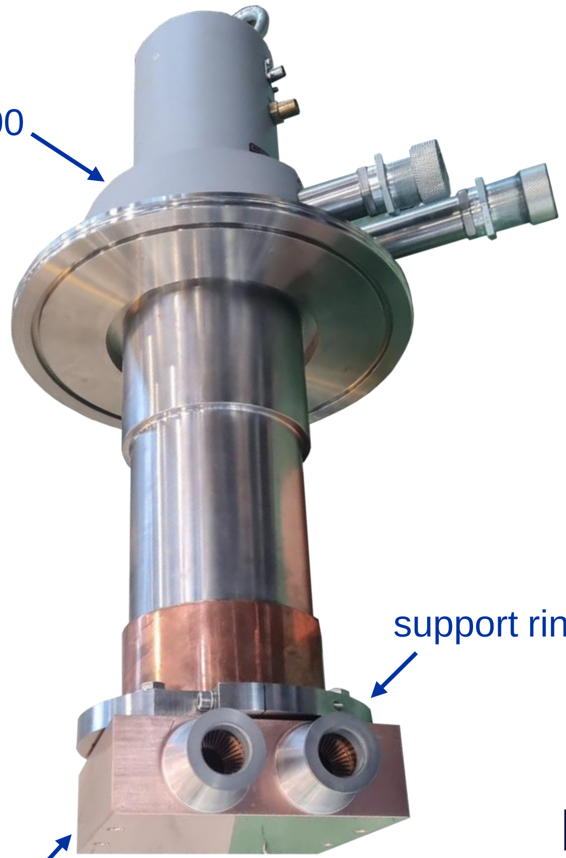
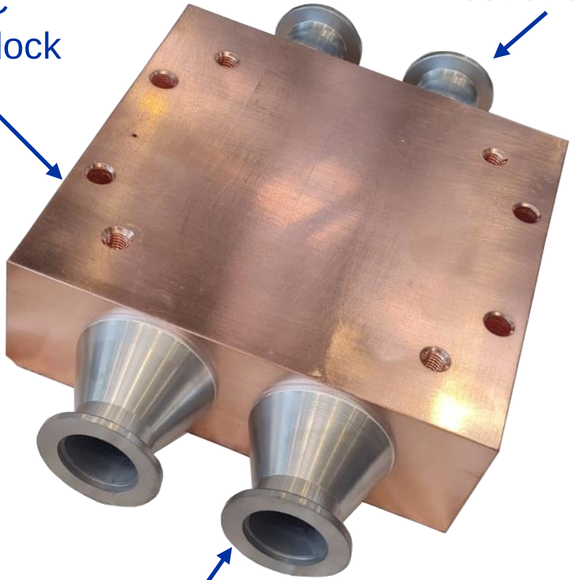
Assembly of the AL600 with the HEX101

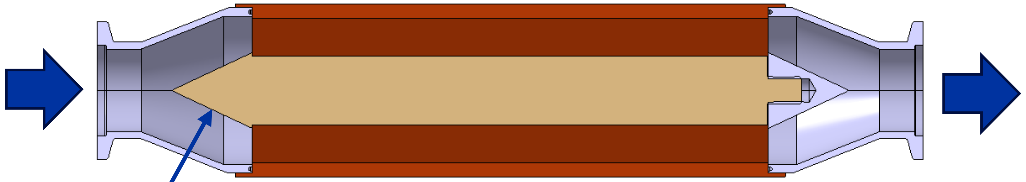


Assembly of the HEX101

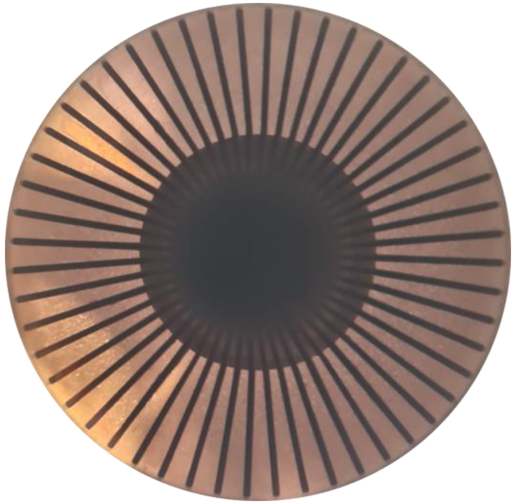


GEOMETRY OF THE HEX101	
Manufacturing technology:	EDM
Number of cooling channels:	104
Width of the cooling channel:	0.6 mm
Length of the cooling channel:	11 mm

Section view of the HEX101



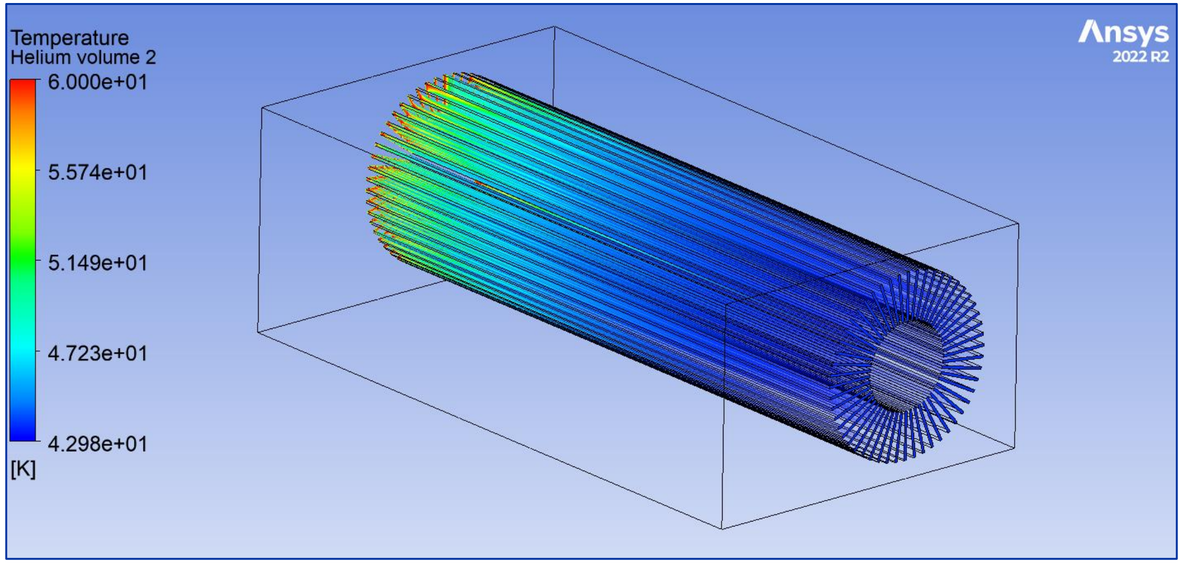
Section view of the cooling channels

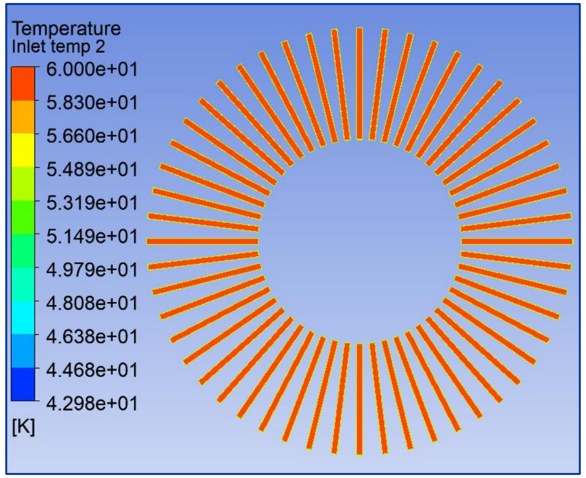


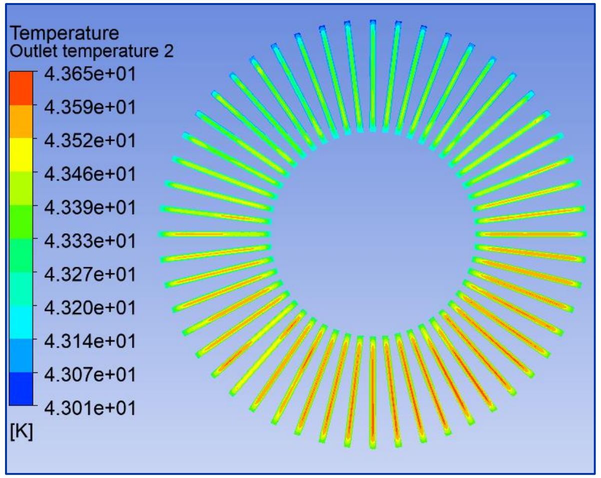
Thermal interface between cryocooler & helium gas

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

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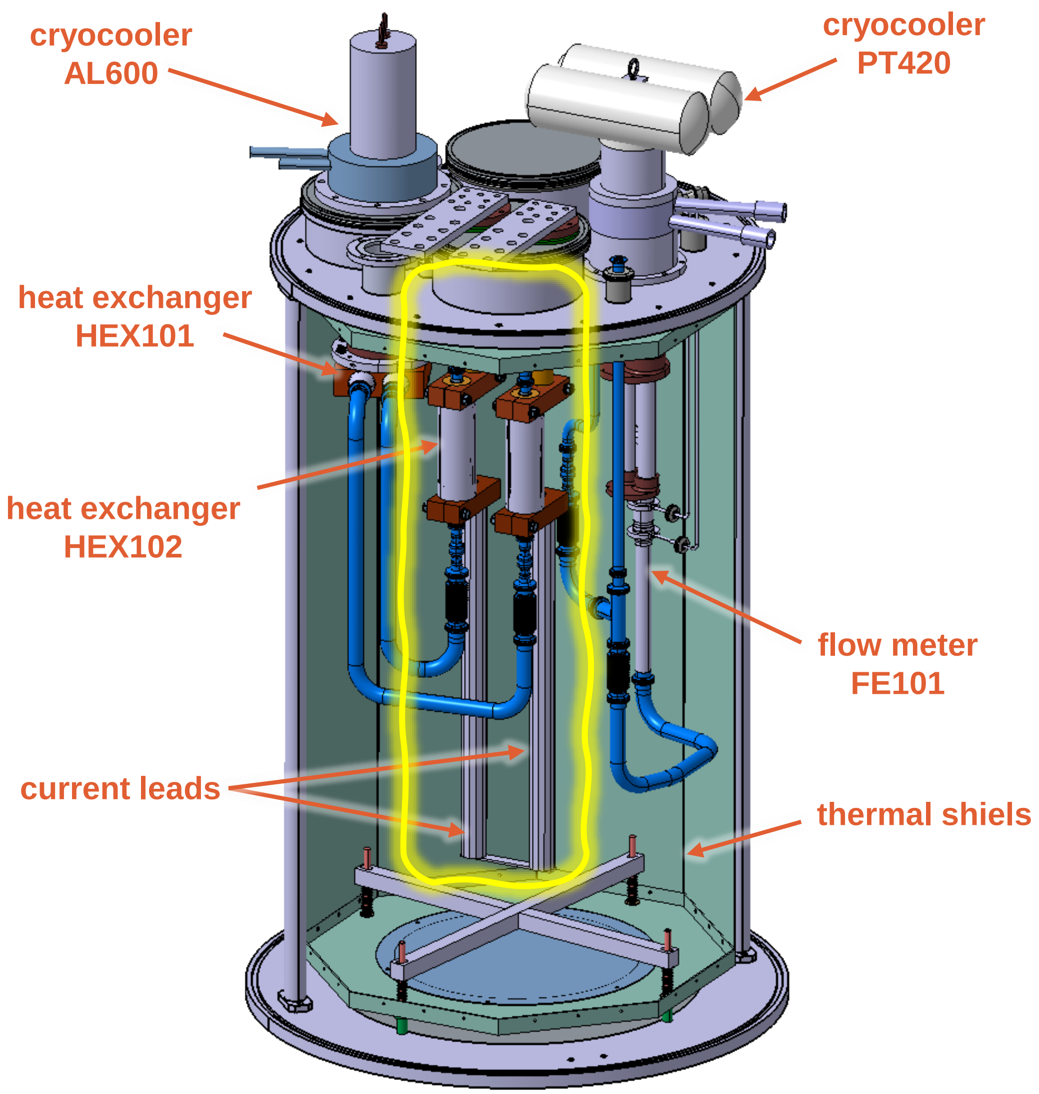
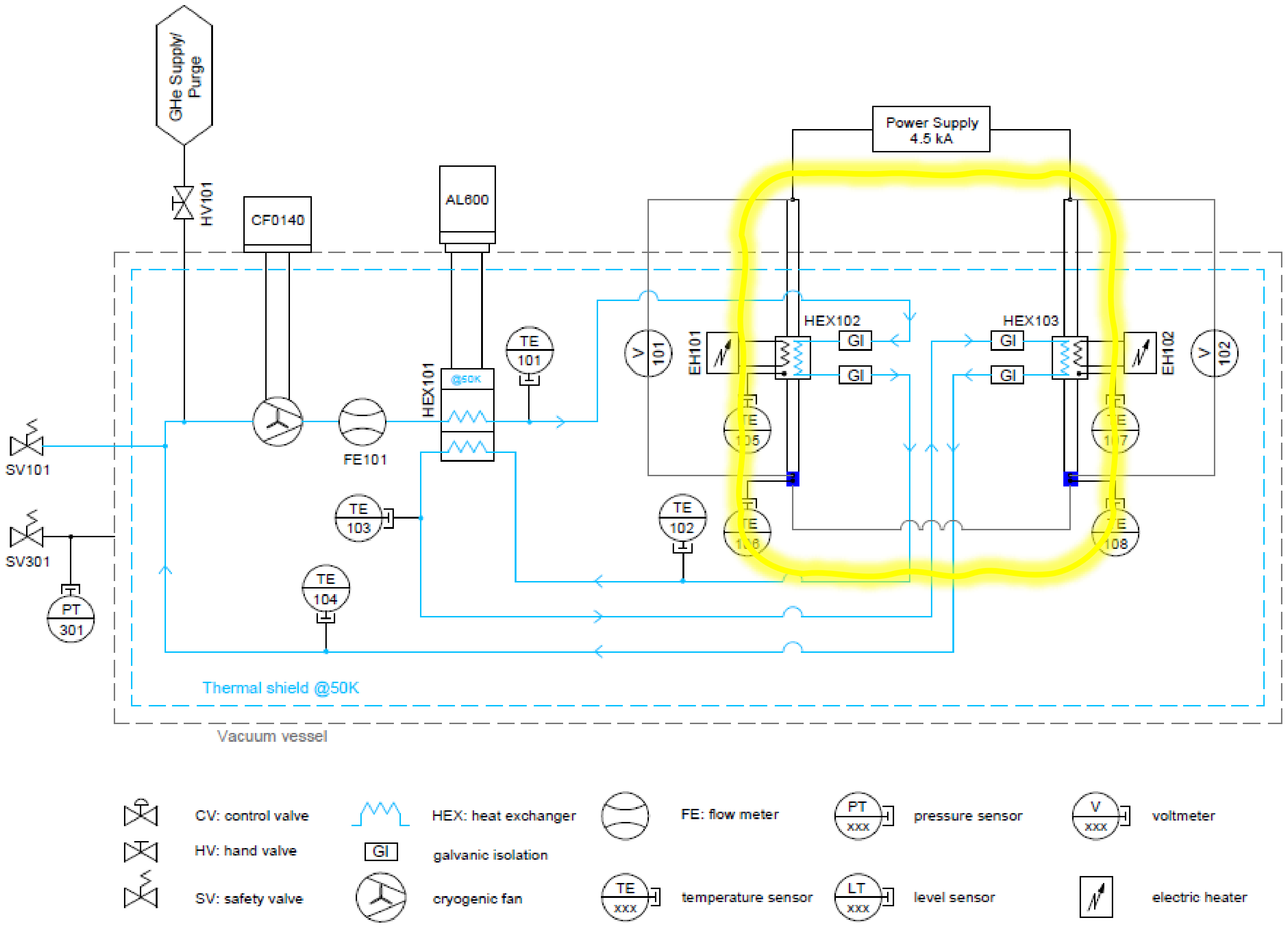
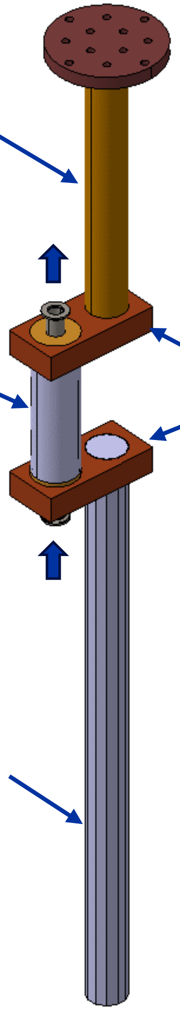


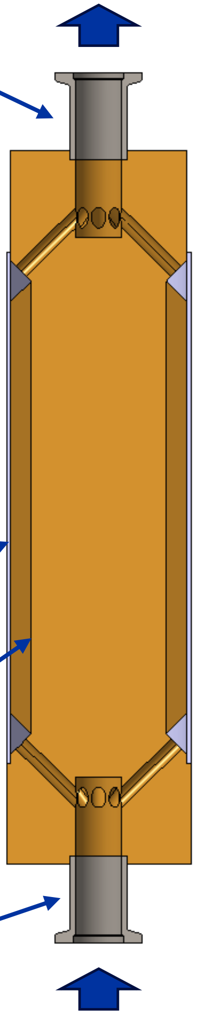


Thermal interface between helium gas & current lead

Assembly of the HTS-based current leads



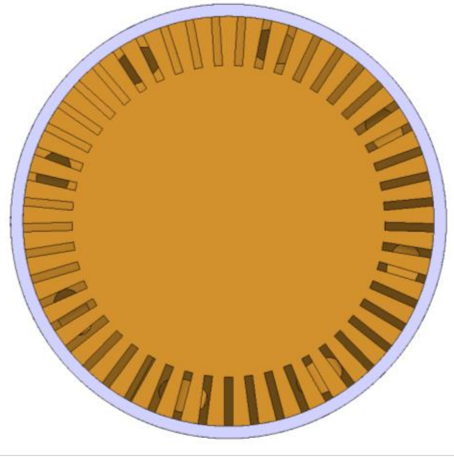
Cross-section of the heat exchanger HEX102



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

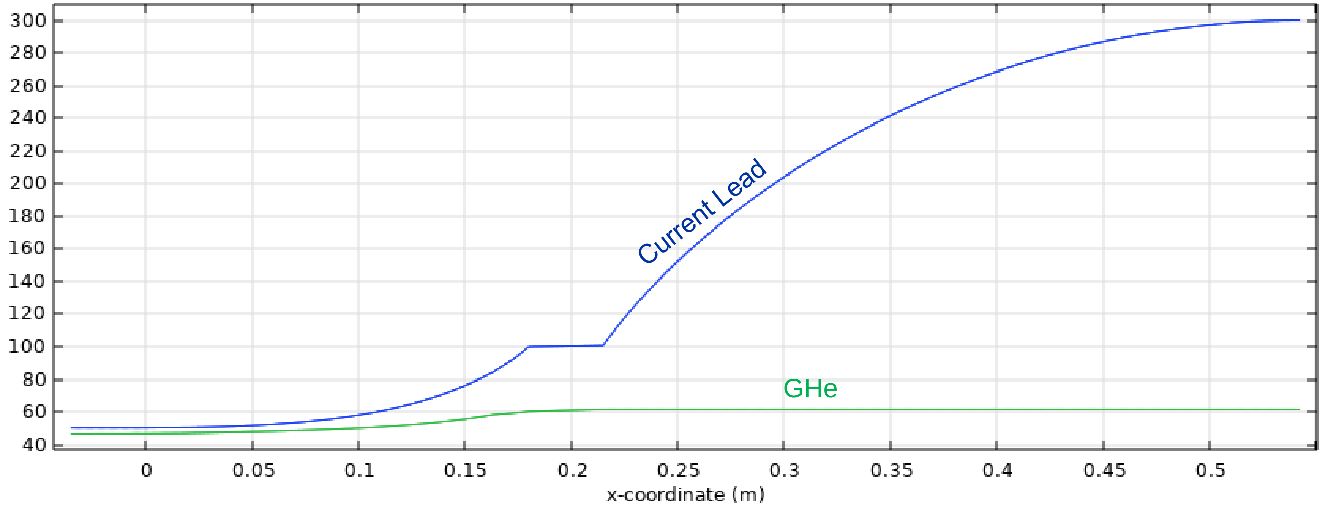


Design of the 3kA current leads: calculations

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

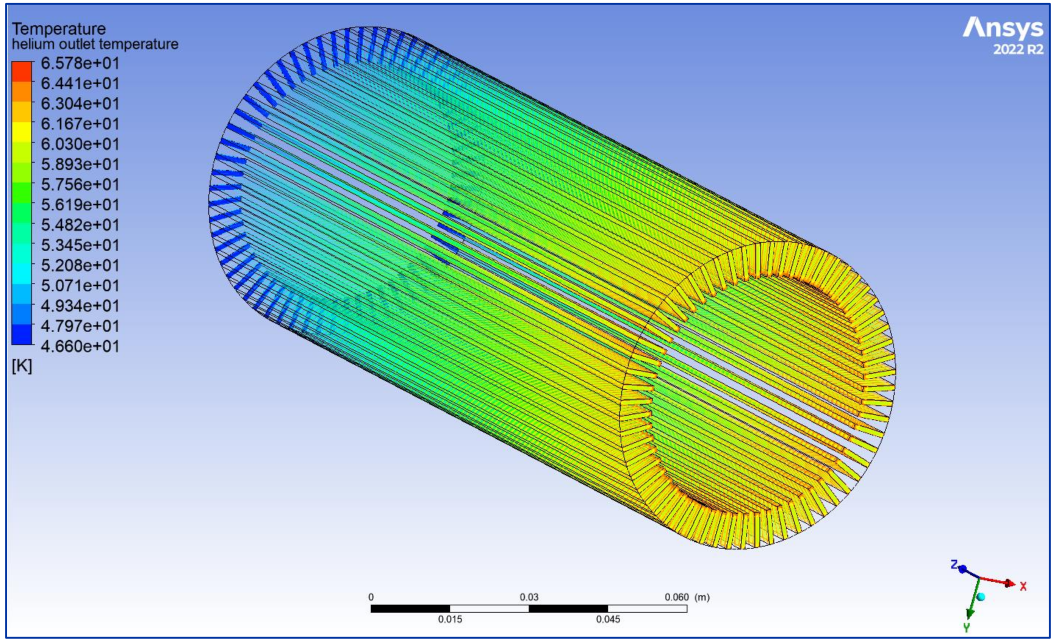


Characteristics of the current leads	
Material:	Brass
Current:	3 kA
Dissipation:	151 W
Outer diameter:	51/65

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

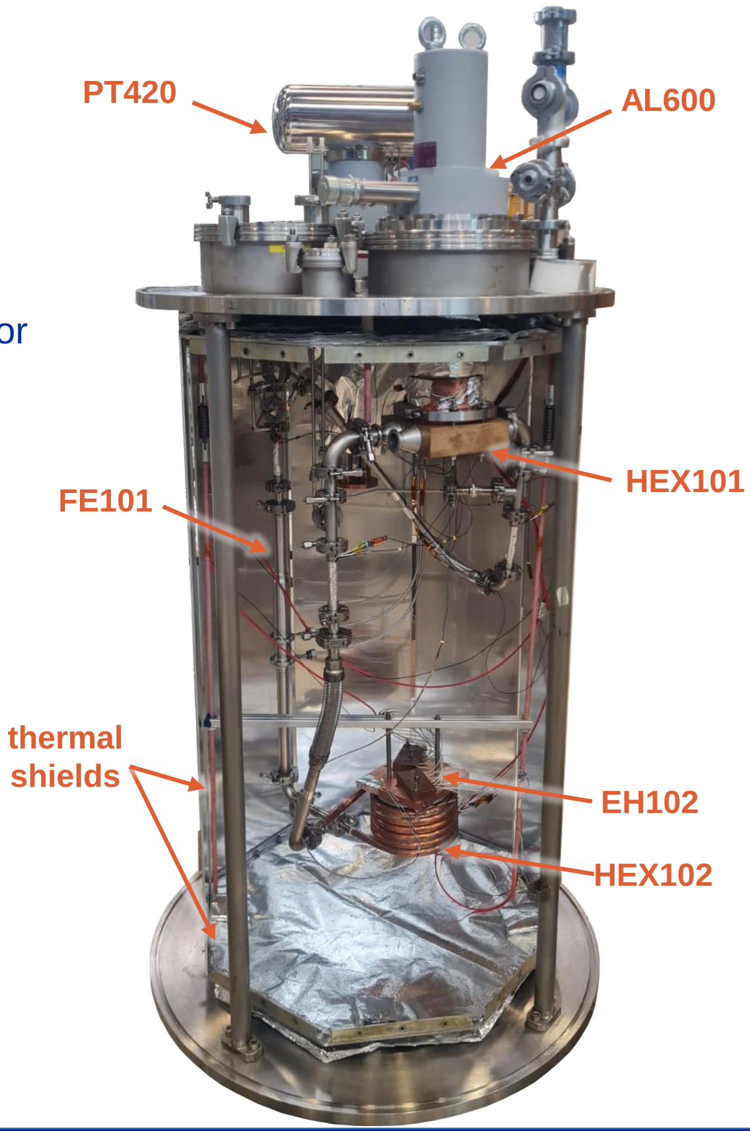
Av. outlet helium temperature: 61.1 K

Current ongoing: Experimental verification of the 50K loop subcomponents

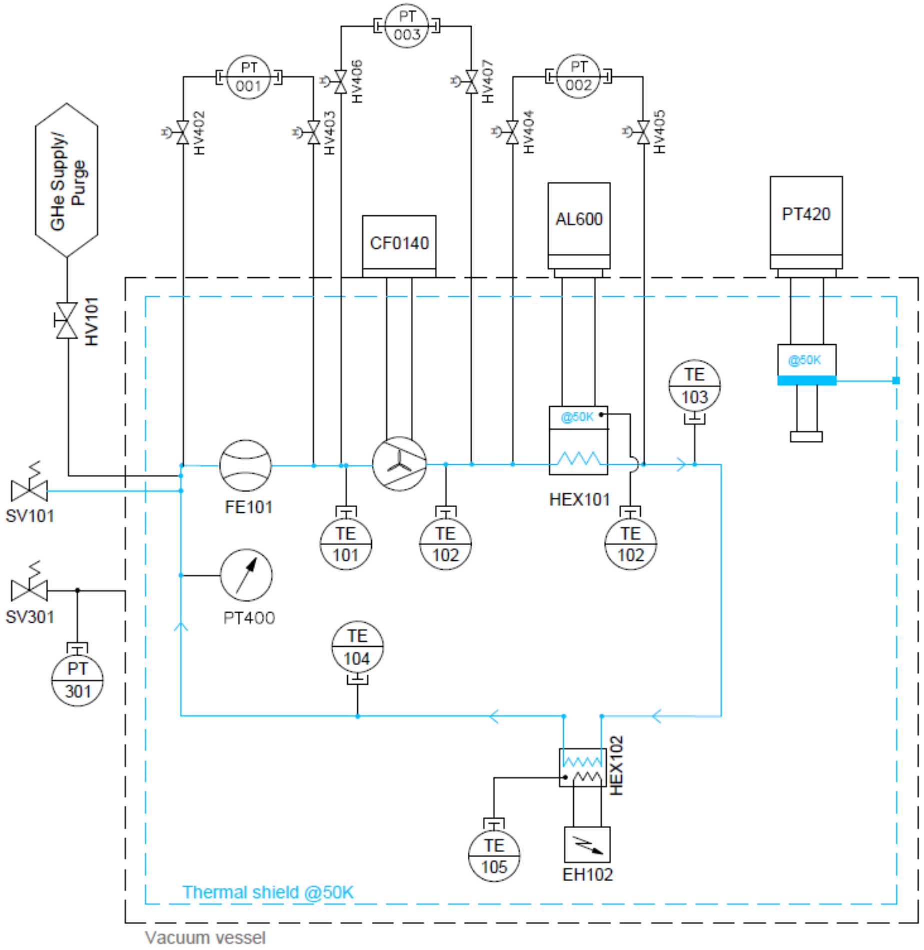
Integration of the experimental installation

The objective of the test:

- experimental verification of the heat exchangers' performance
- experimental verification of cold circulator performance: isentropic efficiency to be determined
- experimental verification of the AL600 performance
- experimental verification of the process calculations
- acquiring practical experience in integrating and operating a remote cooling loop



P&ID of the experimental installation



Conclusions

Within CERN EP R&D programme: Ongoing effort to develop novel cooling concepts for HEP detector magnets: HTS-based current leads thermalised through a remote cooling loop using a single-stage GM cryocooler, Zero-Boil-Off concept with passive circulation to provide cooling power for an LTS detector magnet. **Cryocoolers constitute a promising alternative for cooling of superconducting magnets in HEP experiments.**

Current status

- ✓ The design of the experimental installation accomplished
- ✓ Process calculations for the intermediate loop @50 K done
- ✓ Optimization studies of the thermal interfaces @50K through simulation with Comsol and Ansys Fluent performed
- ✓ Cryocooler-to-helium-gas heat exchanger designed, manufactured, to be tested in the following months
- ✓ Optimized design of the 2 x 3 kA current lead cooled with the use of a single-stage cryocooler
- ✓ The assembly of the demonstrator for the thermalisation of the HTS current lead is ongoing

Foreseen activities in the near future time

- Tests of the heat exchangers HEX101 and HEX102
- Tests of the demonstrator for the current leads thermalisation @50 K
- Thermosiphon in Zero-Boil-Off configuration @4.2 K

Thank you for your attention

Introduction: Cooling methods for HEP superconducting magnets

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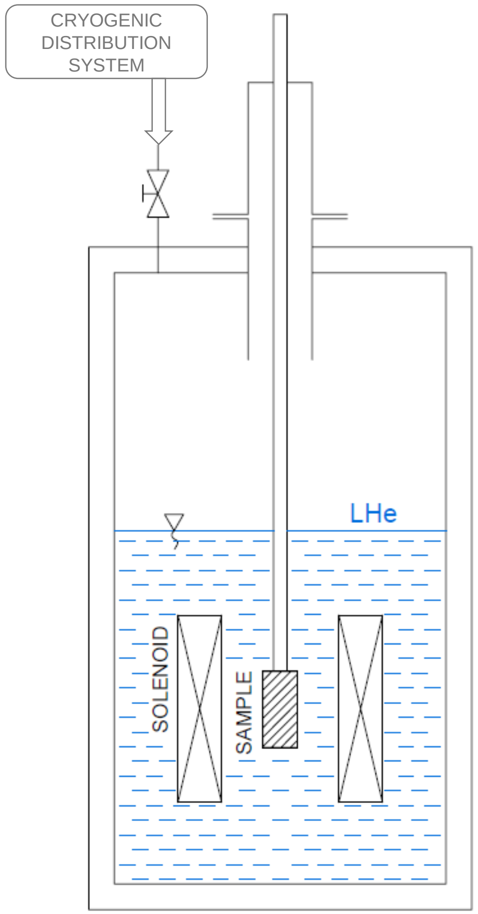
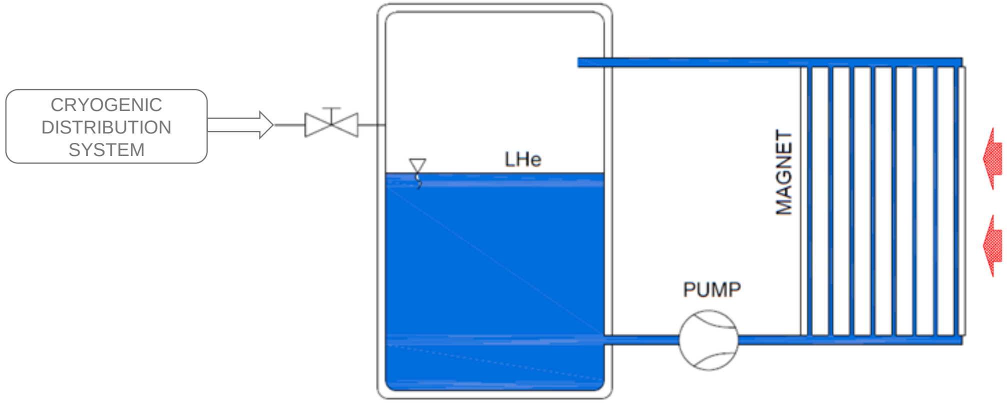
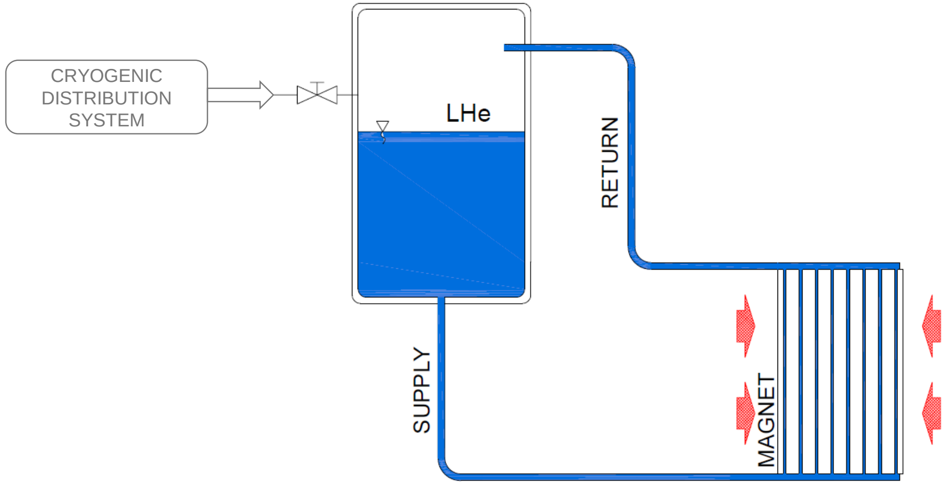
Bath cooling



Closed cooling loop with a forced circulation



Closed cooling loop with a passive circulation



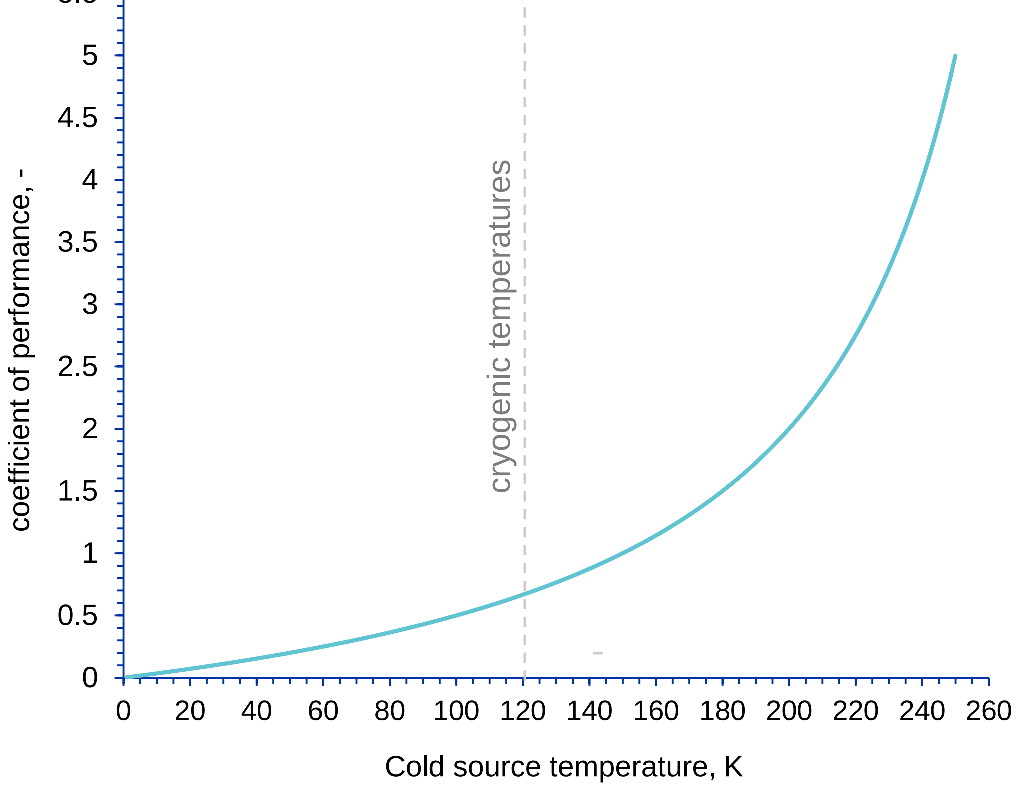
Cryocooler-based cooling

EFFORTS ARE BEING MADE TO FIND AND TEST A SUITABLE SOLUTION FOR HIGH ENERGY PHYSICS (HEP) SUPERCONDUCTING MAGNETS

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 → Qo = 159.6 W

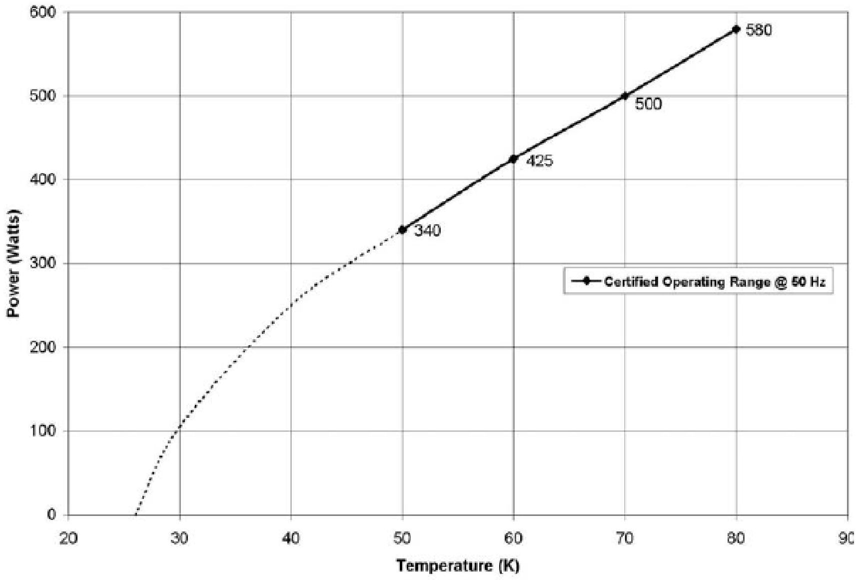
COP(Tw = 300K and Tc = 50K) = 1/5
Assuming P = 11.4kW → Qo = 2.3 kW

Conclusions:

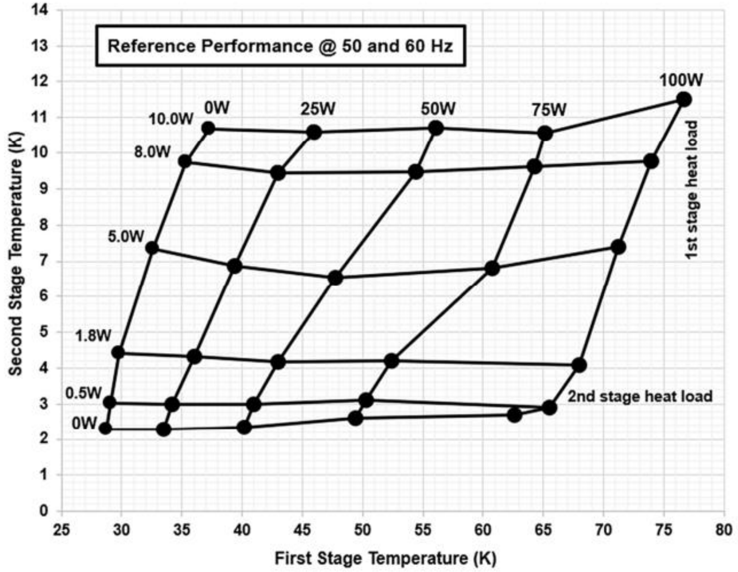
1) COPs of real cryocoolers are significantly lower than the Carnot's one at the same temperature levels

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]



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

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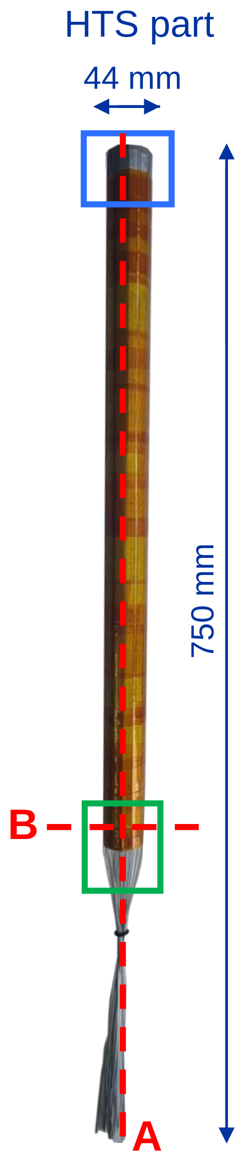
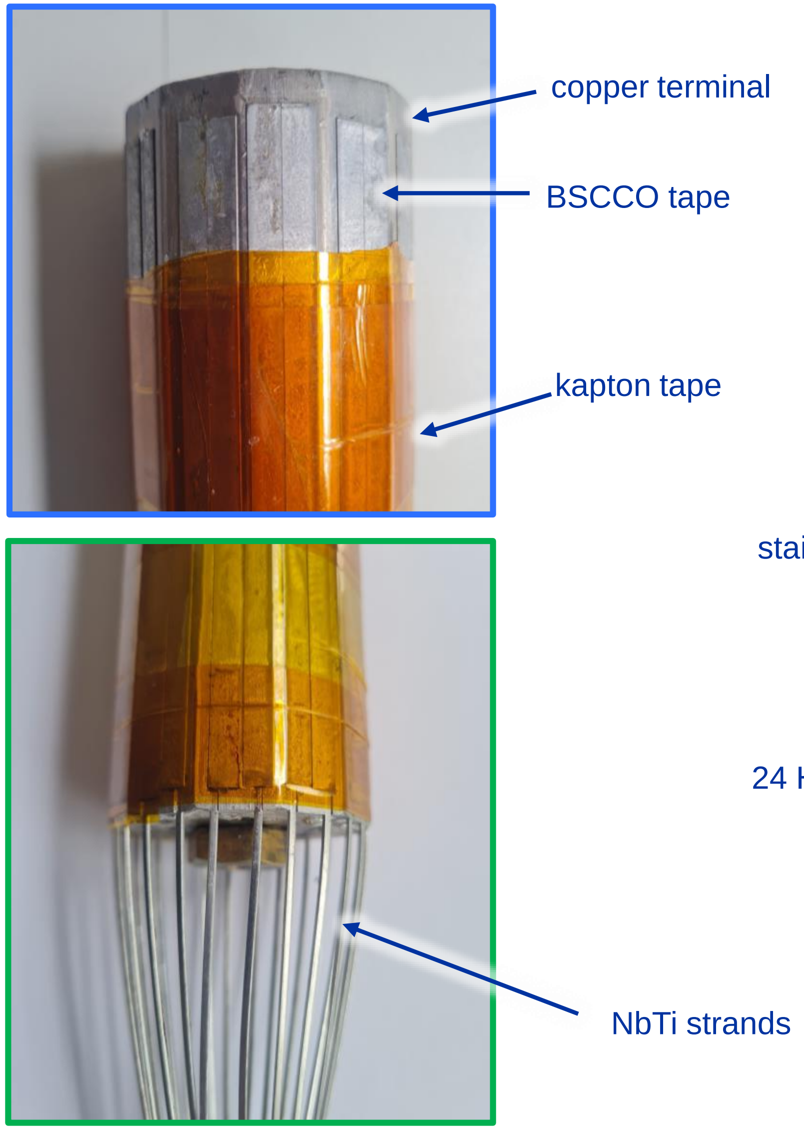
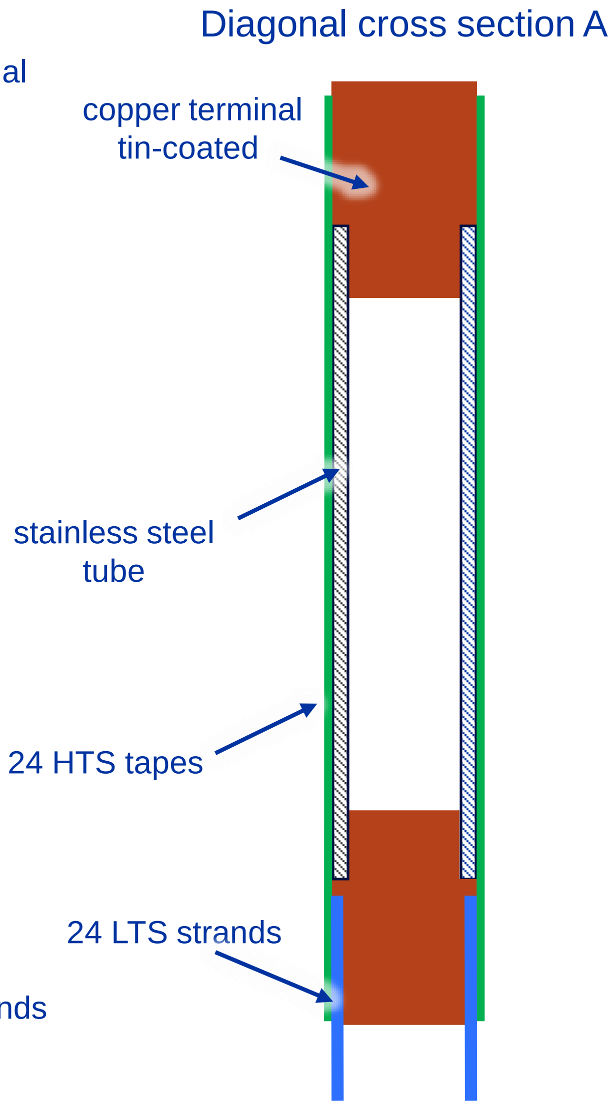
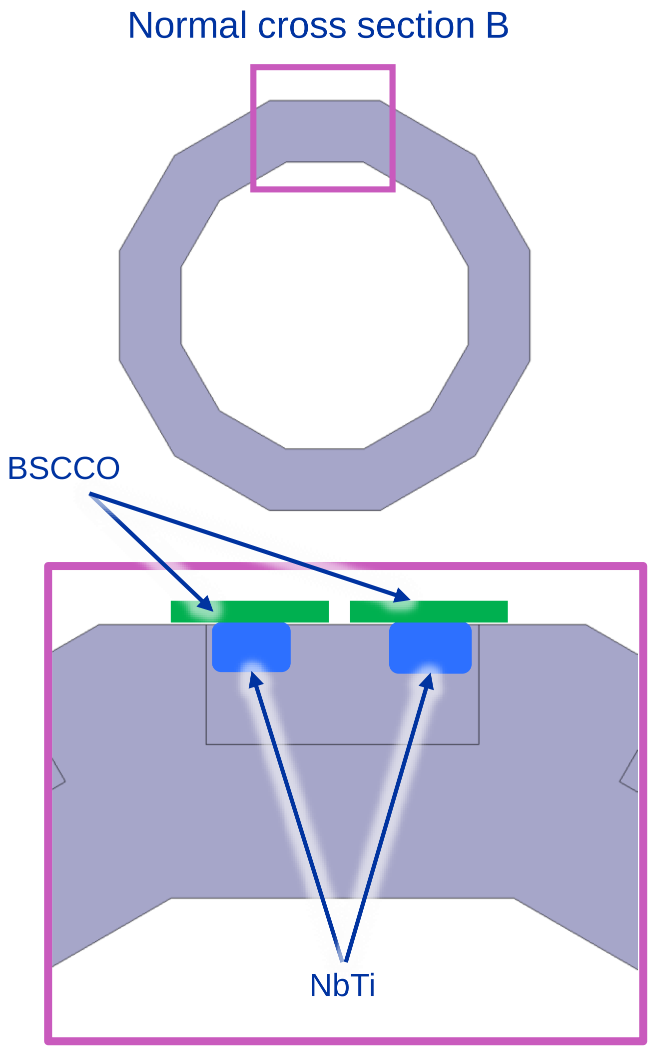
Design of the 3kA current leads: HTS part









Introduction: Advantages and challenges

Compared to traditional cryogenic plants

CRYOCOOLER-BASED COOLING APPLIED TO SUPERCONDUCTING DETECTOR MAGNETS

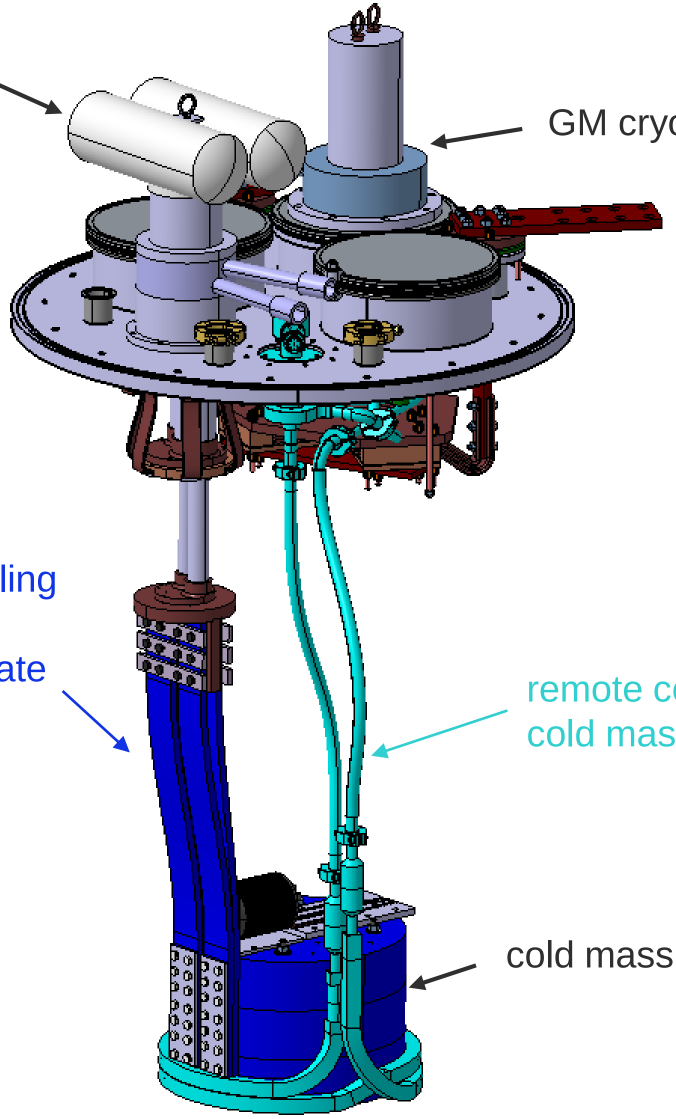
Advantages:

- 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

Introduction: heat exchange between the cryocooler & cooled object



Courtesy: Patricia Tavares Coutinho Borges De Sousa

Conduction-based cooling:

- heat transfer obtained by conduction through a solid object that constitutes a thermal bridges between the cold finger and the cold mass
- length of the thermal bridge affects the thermal efficiency of the system

Remote cooling:

- gas enthalpy is used to obtain a heat transfer between the cold finger and the cold mass, i.e. Convection between a gas and a solid
- cooling power can be „transported" over elongated distances, the limitation comes from the pressure drop