Cryogenic and thermal management studies for HFM magnets

Status of activities – WP4.6 at CERN

P. Borges de Sousa on behalf of WP4.6

HFM Annual Meeting, 1st November 2023

Scope of the Work Package

Studies of novel cryogenic cooling modes for future high-field magnets including:

- **Innovative options towards reduced helium content or dry magnet cooling** modes based on remote cooling circuits and their **integration into large scale cryogenic infrastructures**
- **Thermal management of LTS and HTS magnets** with associated R&D programmes during the global process of magnet design and development.
- **Thermohydraulic calculations and numerical simulations** of cryogenic refrigeration processes
- **Investigation into associated material properties** at cryogenic temperatures.
- **Upgrade of Cryogenic Laboratory test stands for testing and experimental validation** of thermal characterization on novel cryogenic cooling modes.

Cryogenic and thermal management studies

- **T1** Innovative large scale cryogenic infrastructure options towards reduced accelerator & magnets' helium-content cooling-modes and minimal total energy consumption
- **T2** Thermal properties of magnet components at cryogenic temperatures
- **T3** Thermal design, modelling and validation of coils towards reduced magnets' helium-content including conduction-cooling
- **T4** Modelling of full cold mass designs' thermal performance
- **T5** Small scale, variable temperature-range HTS-coils and splice characterisation
- **T6** Thermal aspects of quench protection with WP4.5
- **T7** Test stands for HFM measurements

T1: Cryogenic options towards reduced He content cooling

- Studies on **reduced He cooling options for future high-field accelerator magnets**
- Definition of possible **cryogenic layouts at various temperature levels ≥ 4.5 K**, in an effort to move away from 1.9 K bath cooling
- This starts with an **overall evaluation of efficient cryogenic processes**, combined with evaluation of effectiveness of **heat extraction at local (coil) level**
- The **design of the coils and cold masses needs to be carried out in close collaboration with magnet designers**, and requires a shift of paradigm to move away from 1.9 K operation towards higher temperatures, and from bath cooling to confined, reduced-He content configurations
- This has an impact not only on the coil and cold mass design but also on the **magnet stability and quench protection** as one can no longer rely on the available enthalpy of the bath

T1: Cryogenic options towards reduced He content cooling

- There are several reasons to try and move away from the **habit** of **He II bath cooling**:
  - He II cooling relies on cold compressors, **thermodynamically costly**
  - This makes an intrinsically low **COP** (energy efficiency) even lower
  - Due to the sheer amount of He, **quench management and safety** are rather complex
  - Operational downtime after a quench is significant, due to large enthalpy difference of He I → He II transition, **reducing availability**
  - **He is a limited, expensive, and volatile (geological) resource**

Main cryogenics drivers for future accelerators

Energy consumption
- Establish a target for electrical consumption
- Target ≥ 4.5 K coil T

Cryo availability
- Availability increases with lower # of cryoplants

Local heat extraction
- Coil design complexity increases with heat load

Choice of conductor
- Determines temperature level and allowed ΔT

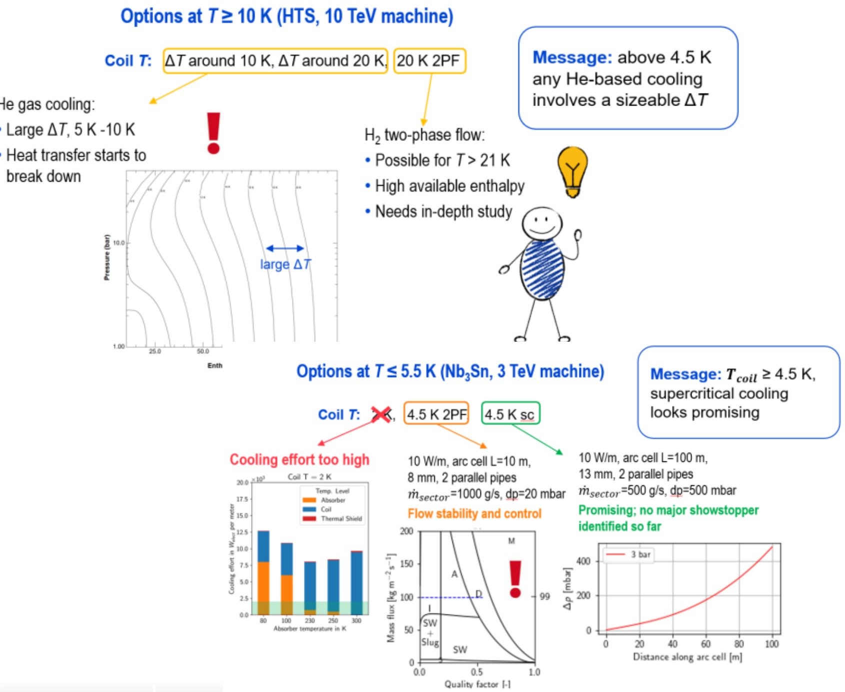
Distribution losses
- Optimisation of flow conditions and distribution scheme

Reduced complexity
- Minimise # jumpers (*i.e.* long arc cells)
- Reduce # of temperature levels provided
- Function of the nature and T range of the fluid
- Reduced fluid content in cryostats

T1: Cryogenic options towards reduced He content cooling

- Cooling options for LTS (around 5 K):
  Need R&D to explore the **limits of two-phase flow and sc cooling in confined geometries**

- Cooling options for HTS (if 10K+):
  Need in-depth study → He gas cooling does not provide efficient heat transfer; H2 cooling needs demonstration and change of mindset, safety assessment



Muon collider study currently being generalised to other accelerators/colliders as well as individual magnets
→ purpose of WP4.6-T1

Outcome should have an impact on the Nb_3Sn studies targeted in WP4.6-T2

Presented at the annual IMCC meeting, June 2023 (link)

Cryogenic and thermal management studies

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T2: Thermal properties of magnet components

Polyimide samples for thermal conductivity measurements

Thermal conductivity:

- Measured DISCUP C3/30 coil wedges down to 6 K (shown)
- Measured thermal conductivity of Mix 61 (below 10 K)
- Measurements of modified polyimide materials ongoing: APICAL AV, APICAL N-P, PIT 050, report in preparation for PIT 050
- Samples to come from RD2 (tbc)

Thermal contraction:

- Measured thermal contraction (at 77 K and 4.2 K) of 3 samples of resins for coil impregnation: MSUT, MY750, Mix 61, report in preparation

RRR:

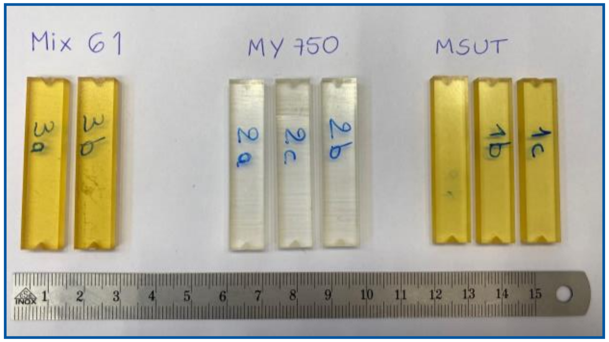
- Measured RRR of copper samples for WP4.5

SC splices:

- Nb_3Sn-Nb_3Sn splice in the context of the 12 T magnet R&D (tbc)

IRRAD test facility:

- Cryogenic operation support for IRRAD test facility



Resin samples as prepared for thermal contraction test stand

Cryogenic and thermal management studies

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T3: Thermal design, modelling and validation of coils using reduced He content incl. conduction cooling

- All tasks within T3 to be started in 2023 are delayed, as they require direct input from RD2 and RD3
- Studies at coil (magnet) level must be combined with cryo-infrastructure energy optimisation
- Discussion with both RD lines has started

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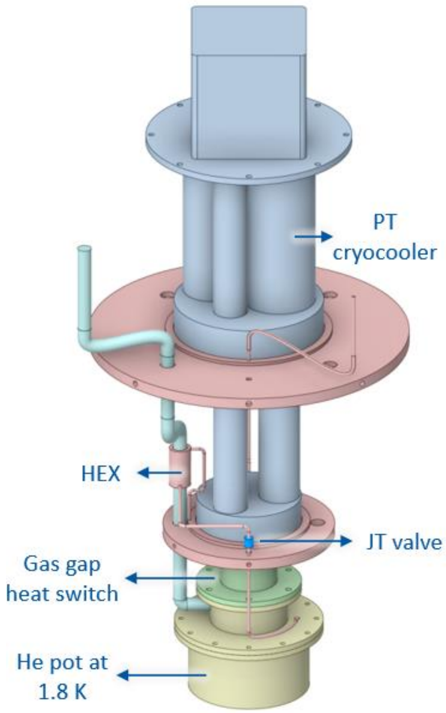
T7: Test stands for HFM measurements

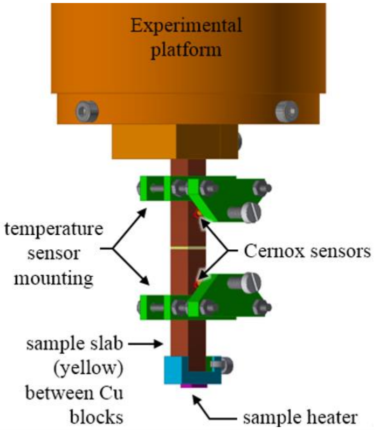
Thermal conductivity & diffusivity	**Operational / Construction**
Thermal contraction	**Operational**
Electrical resistivity and RRR	**Operational**
Splice resistance measurements	**Operational**
He II permeability	**On hold**
Heat extraction of coil packs	**Operational**
Variable *T* range test stand for small HTS coils/splices	**On hold**
Test of small components in variable *T* in magnetic field	**Operational***
Demonstrator of reduced He content cooling variants	**Procurement**

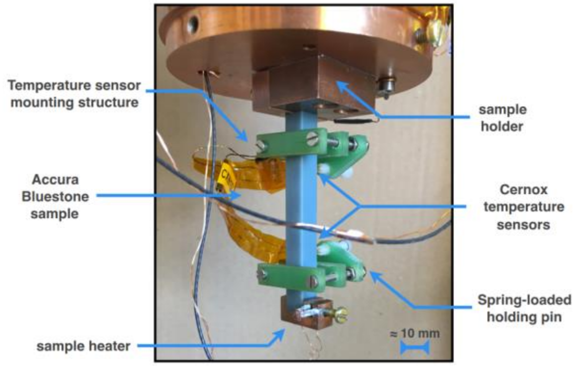
Thermal conductivity & diffusivity

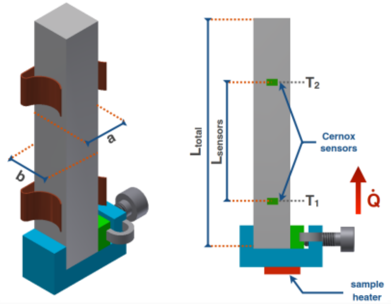
Capabilities	Thermal conductivity, diffusivity, specific heat capacity (inferred)
Temp. range	1.8 – 50 K / 4.5 K – 100 K
Sample dimensions	typically 8 x 8 x 100 mm^3 envelope ≈ Ø90 mm, L = 150 mm
Environment	Vacuum, radiation shield at T_{sample}



Thermal conductivity test stand, temperatures down to 1.8 K



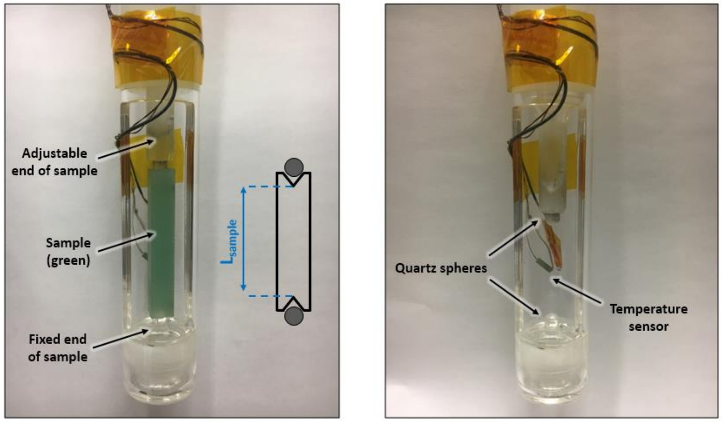




Thermal contraction

Capabilities	Length change measurement by inductive displacement sensor in quartz sample holder
Temp. range	Points at 77 K (LN_2) and 4.2 K (LHe)
Sample dimensions	strictly 8 x 8 x 50 mm^3
Environment	In LN_2/LHe vapours

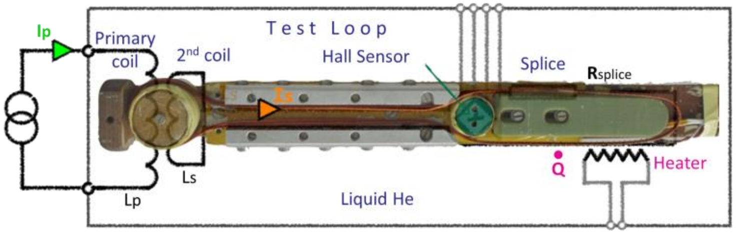
Thermal contraction test stand, sample detail

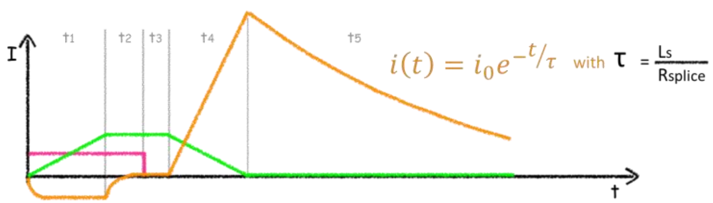


SC splice resistance

Capabilities	Splice resistance calculated using the time constant and the inductance of the splice (magnetic field decay measured via a Hall probe)
Temp. range	4.2 K
Sample dimensions	Specific loop geometry; LHC-type cables and larger (e.g. MQXF) fit
Environment	In liquid Helium

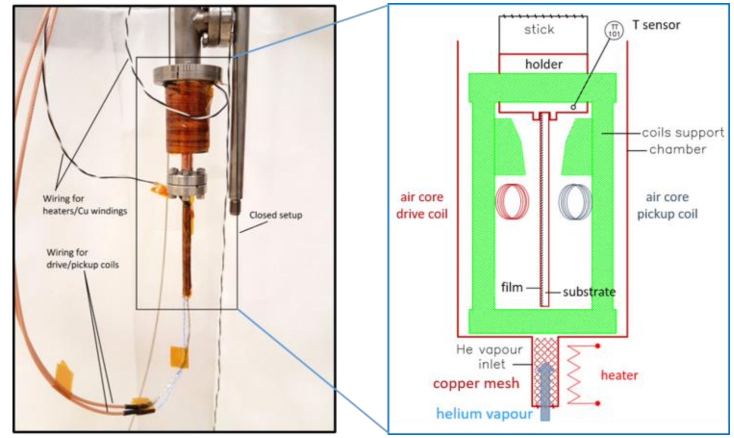
SC splice test stand





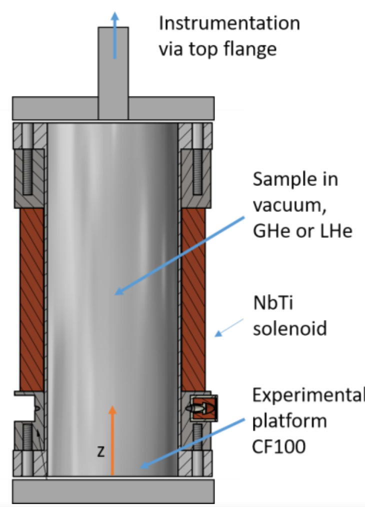
T_C of SC thin films on substrate

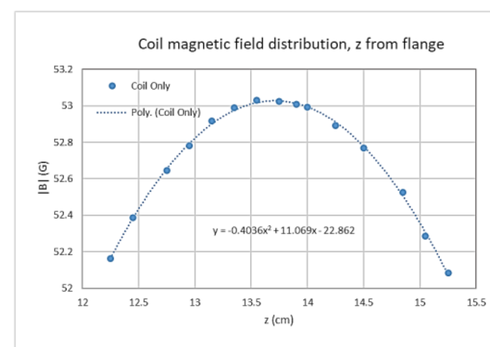
Capabilities	AC contactless method, drive and pick-up coil separated by sample, temperature sweep scanning sample response – T_C is max. slope of transition
Temp. range	4.2 K – 30 K
Sample dimensions	35 x 13 x 1.5 mm^3 flat plates
Environment	In He vapours



Test of small components in variable *T* in field

Capabilities	Solenoid with 100 mm bore and max. 5 T background field Current leads up to 4 kA exist for sample
Temp. range	4.2 K – 30 K
Sample dimensions	Ø 90 mm, max. length ≈ 200 mm
Environment	In vacuum, He exchange gas, or LHe



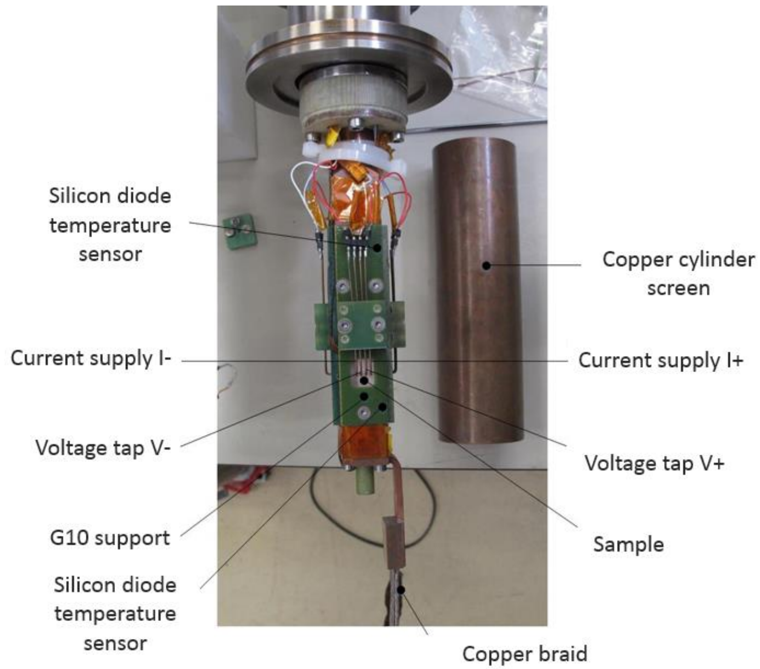


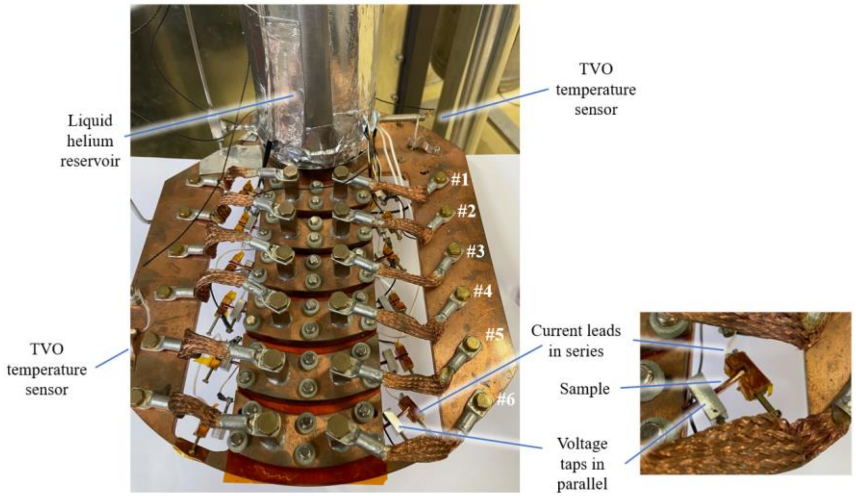
Coil magnetic field distribution measured along z axis at room temperature with 100 mA.

RRR measurements

Capabilities	Thin films on substrate RRR as ratio between 4.2 K and 293 K Possibility to log resistance throughout cooldown
Temp. range	4.2 K and 293 K
Sample dimensions	50 x 10 mm^2 flat plates
Environment	Liquid He

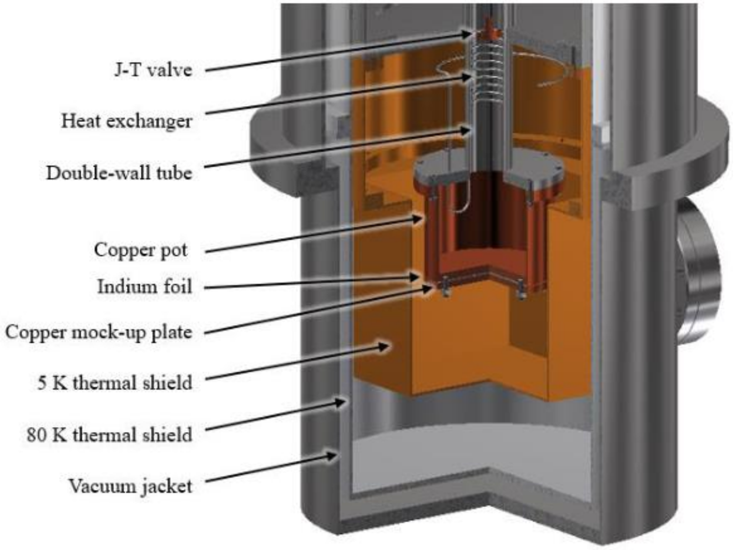
Capabilities	Bulk samples RRR as ratio between ≈7 K and 293 K Possibility to log resistance throughout cooldown
Temp. range	7 K and 293 K
Sample dimensions	120 x 2 x 2 mm^3
Environment	In vacuum

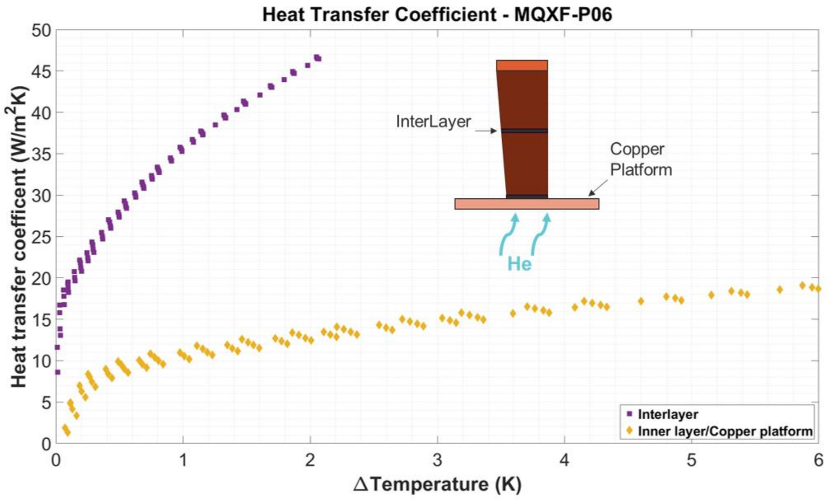


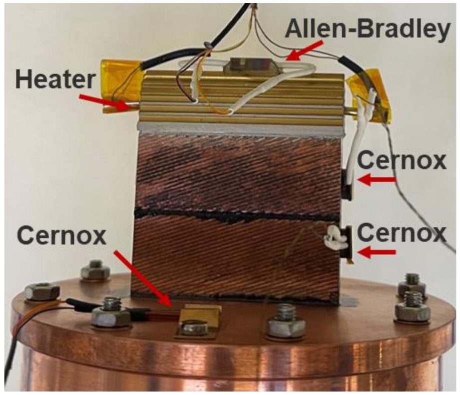


Heat extraction of coil packs

Capabilities	Measurement of effective thermal conductivity of coil stacks, and heat transfer coefficient of bonded contacts
Temp. range	1.7 K – 4.2 K base *T*, ≈10 K on heated side
Sample dimensions	Coil samples or stacks, max. ≈ 70 mm long
Environment	In vacuum







MQXF – P06

Demonstrator of reduced He content cooling (I)

- The aim of the test stand is the **demonstration of reduced He content cooling schemes, at temperatures ≥ 4.5 K**, applied to accelerator-type magnet structures

- For early stages the ‘magnet’ can be a dummy load, but:

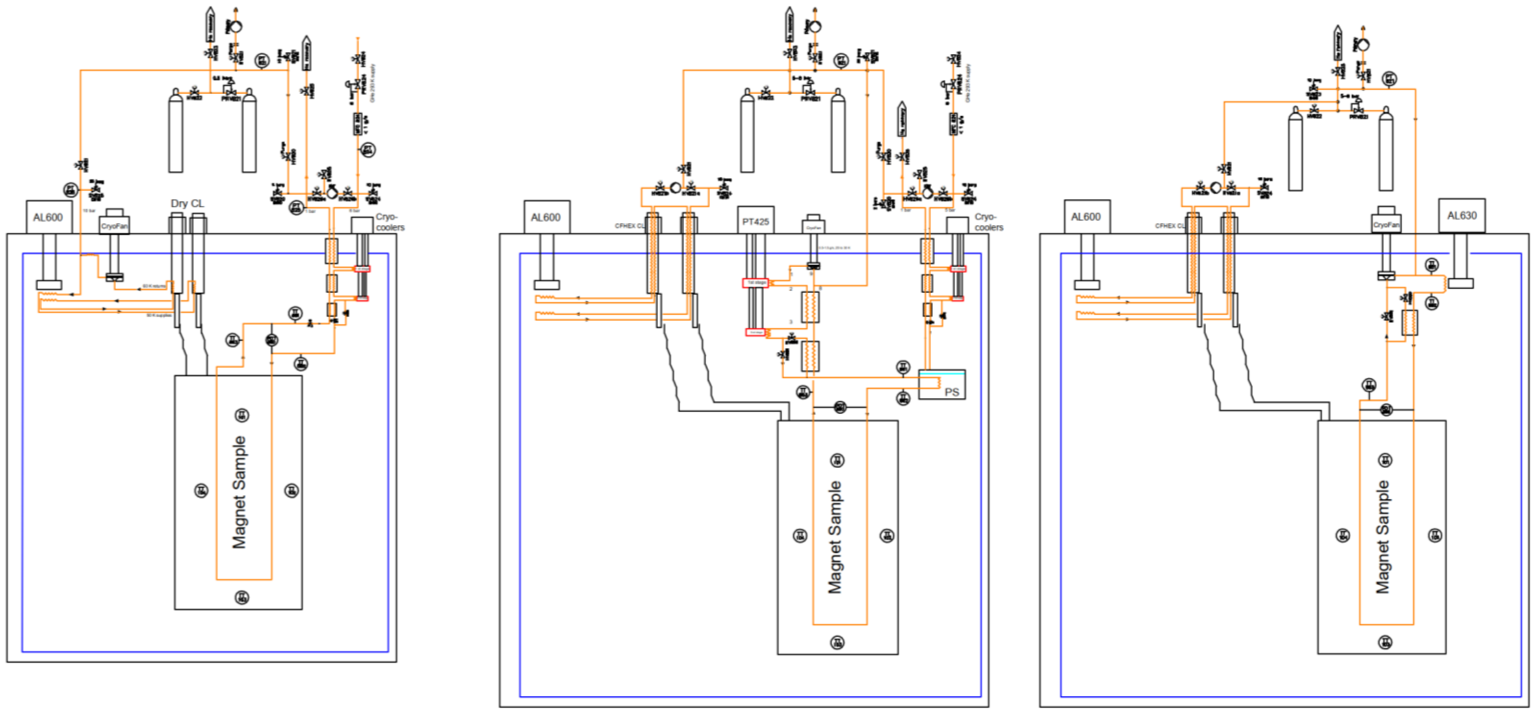
- For full validation of the concept, **testing the cooling concept(s) with a real (small) magnet should be considered**, before the chosen solution is adopted for series testing of magnets (e.g. at the SM18 test facilities)
  - This approach would allow to test the performance of a full (albeit small) cold mass, which includes the thermal/mechanical interfaces, integration, cooldown, powering…

- **Similar work on ‘dry’ cooling using sc He has started for RF cavities** (see T. Koettig’s talk at EUCAS 2023), but there are challenges exclusive to implementation in accelerator magnets that need to be tackled in a dedicated test stand

Demonstrator of reduced He content cooling (II)

Demonstrator test stand designed to be upgradable:

- **Stage 1:** 4.25 K two-phase flow ($\dot{m}$ < 1 g/s) - 3 stages JT circulation loop
- **Stage 2:** sc forced flow 4.5 K < T < 10 K ($\dot{m}$ < 1.5 g/s), 2 circulation loops, one for cooling power, other for high pressure supply
- **Stage 3:** He circulation at T > 18 K, high pressure high $\dot{m}$

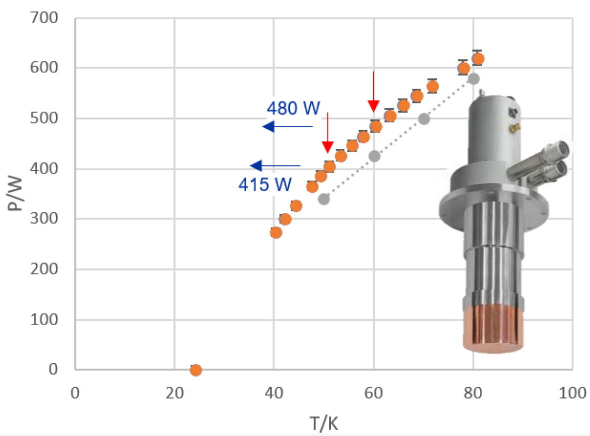


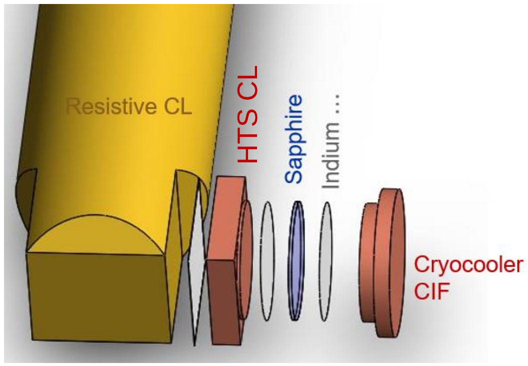
Demonstrator of reduced He content cooling (III)

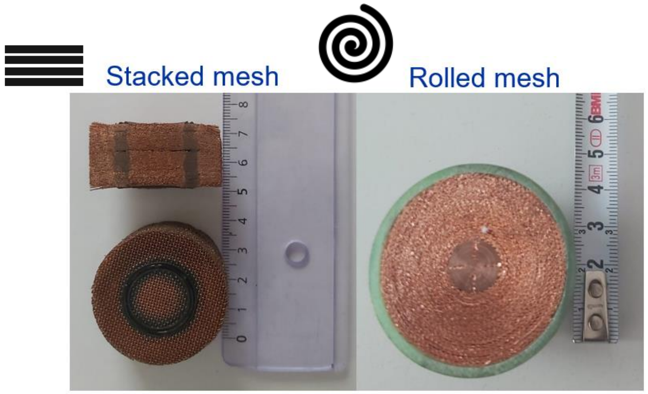
Status of the cooling demonstrator test stand:

- **Cooling sources** (cryocoolers) identified, **procurement** of major components **completed**
- **High-effectiveness CFHEXs** developed at the Cryolab (A. Onufrena) **enable these cooling options at a laboratory scale**
- Thermodynamic studies of CFHEX applied to current lead heat intercepts, namely:
  - Investigation of **high thermal conductivity electrical insulators**
  - He-cooled (not vapour cooled!) current leads: investigation of options for circulators (cold/warm), design **of built-in HEX** in the current lead

Performance of cryocooler 1







Conclusions

- **Work is progressing on all activities**, with special emphasis on the **construction of test stands** for conduction-cooled/reduced He content magnets
- **Studies for optimized cooling options for future accelerators** to be generalized to future accelerators and to include distribution considerations
- **Measurements of thermal properties ongoing**, dedicated conductivity test stand will help speed up measurement lead times
- **Need input** on developments from **RD2 (HTS)** and **RD3 (14+ T Nb_3Sn magnets)** to advance on the **thermal design of reduced He content/conduction-cooled magnets** (WP4.6-T3)

Thank you for your attention.

Spare slides / administration

TASK	Description	Assigned to	Progress	Start	End
WP4.6-T1	**Innovative large scale cryogenic infrastructure options towards reduced accelerator & magnets' helium-content cooling-modes and minimal total energy consumption**			**Jan 2023**	**Dec 2025**
WP4.6-T1-D1	Case studies for future accelerators under consideration		ongoing	Jan 2023	Dec 2025
WP4.6-T1-D2	Review of sustainable cooling options using superfluid, saturated and supercritical helium for accelerator magnets		ongoing	Jan 2023	Dec 2025
WP4.6-T1-D3	Review of alternative cooling schemes at temperatures above 20 K			Jan 2024	Dec 2025
WP4.6-T2	**Thermal properties of magnet components at cryogenic temperatures**			**Sep 2022**	**Dec 2027**
WP4.6-T2-D1	Thermal conductivity, thermal diffusivity and specific heat of pure epoxy resins (WP4.4)			Sep 2022	Dec 2027
WP4.6-T2-D2	Thermal expansion/contraction of pure epoxy resins (WP4.3)		ongoing	Jan 2023	Dec 2027
WP4.6-T2-D3	Superfluid He permeability of pure epoxy resins (WP4.3)			Jan 2023	Dec 2025
WP4.6-T2-D4	Thermal conductivity, thermal diffusivity and specific heat of magnet and cold-mass materials (WP4.3)			Jan 2023	Dec 2027
WP4.6-T2-D5	Thermal conductivity, thermal diffusivity and specific heat of coil mock-ups (RD2 & RD3)		ongoing	Jan 2024	Mar 2027
WP4.6-T2-D6	Yellow Report on low temperature thermal properties of magnet components			Jan 2027	Dec 2027

TASK	Description	Assigned to	Progress	Start	End
WP4.6-T3	**Thermal design, modelling and validation of coils towards reduced magnets' helium-content including conduction-cooling**			**Jan 2023**	**Dec 2027**
WP4.6-T3-D1	Study on Nb_3Sn-coils at 1.9 K (RD3)		not started	Jan 2023	Dec 2025
WP4.6-T3-D2	Study on Nb_3Sn-coils at 4.5 K (RD3)		not started	Jan 2023	Dec 2025
WP4.6-T3-D3	Study on Nb_3Sn-coils at 5.0 K (RD3)		not started	Jan 2023	Dec 2025
WP4.6-T3-D4	Summary review report on thermal design options for Nb_3Sn-coils (RD3)			Sep 2025	Dec 2025
WP4.6-T3-D5	Study on Alternative wires (HTS, iron-based…)-coils at 1.9 K (RD2)		RD2-dependent	Sep 2023	Sep 2026
WP4.6-T3-D6	Study on Alternative wires (HTS, iron-based…)-coils at 4.5 K (RD2)		RD2-dependent	Sep 2023	Sep 2026
WP4.6-T3-D7	Study on Alternative wires (HTS, iron-based…)-coils at > 5.0 K (RD2)		RD2-dependent	Sep 2023	Sep 2026
WP4.6-T3-D8	Study on Hybrid coils (RD2 & RD3)		RD2 & RD3-dependent	Sep 2023	Sep 2026
WP4.6-T3-D9	Summary review report on thermal design options for Alternative (HTS, iron-based…)-coils (RD2)		RD2-dependent	Sep 2023	Sep 2026
WP4.6-T3-D10	Demonstrator of reduced helium content cooling variants for Nb_3Sn		RD3-dependent	Sep 2024	Dec 2027
WP4.6-T3-D11	Demonstrator of reduced helium content cooling variants for HTS, iron-based, MgB_2,… (non-Nb_3Sn)		RD2-dependent	Sep 2024	Dec 2027
WP4.6-T3-D12	Heat extraction measurement of coil-packs (RD2 & RD3)		RD2 & RD3-dependent	Sep 2023	Dec 2026

TASK	Description	Assigned to	Progress	Start	End
WP4.6-T4	**Modelling of full cold mass designs' thermal performance**			**Jan 2024**	**Dec 2026**
WP4.6-T4-D1	Robust performance Nb_3Sn 12T-dipole (WP3.3)			Jan 2024	Dec 2024
WP4.6-T4-D2	Ultimate performance Nb_3Sn dipole (WP3.5)			Jan 2025	Dec 2025
WP4.6-T4-D3	HTS, iron-based, MgB_2,… (non-Nb_3Sn) magnets (RD2)			Jan 2025	Dec 2026
WP4.6-T5	**Small scale, variable temperature-range HTS-coils and splice characterisation**			**Sep 2023**	**Dec 2027**
WP4.6-T5-D1	HTS splice tests in 5T background field		in discussion	Sep 2023	Dec 2027
WP4.6-T5-D2	Small HTS coils tests 4 K - 70 K		In discussion	Sep 2023	Dec 2027
WP4.6-T6	**Thermal aspects of quench protection with WP4.5**			**Jan 2023**	**Dec 2027**
WP4.6-T6-D1	Experimental demonstration of External-CLIQ concepts in a cryogenic environment			Jan 2024	Dec 2027
WP4.6-T6-D2	Studies of energy extraction and energy recuperation for magnet chain: impact on cryogenic requirements, efficiency and power consumption.			Jan 2024	Dec 2027
WP4.6-T6-D3	Quantifying the impact of new, reduced He content cooling schemes on magnet protection, including temperature gradients on the magnet and induced currents and forces in the cooling structures.			Jan 2024	Dec 2027

TASK	Description	Assigned to	Progress	Start	End
WP4.6-T7	**Test stands for HFM measurements**			**Sep 2022**	**Dec 2025**
WP4.6-T7-D1	Dedicated thermal conductivity, diffusivity and specific heat test stand		**building**	Sep 2022	Dec 2023
WP4.6-T7-D2	Upgrade of thermal expansion/contraction test stand		**ready**	Sep 2022	Dec 2022
WP4.6-T7-D3	Upgrade of Superfluid He permeability test stand		**ready**	Jan 2023	Dec 2023
WP4.6-T7-D4	Upgrade of test stand for heat extraction measurement of coil packs		**ready**	Jan 2023	Dec 2023
WP4.6-T7-D5	Upgrade of variable temperature range test stand for HTS coils and splices			Sep 2023	Dec 2023
WP4.6-T7-D6	Test stand for demonstrator of reduced helium content cooling variants including conduction-cooling		**procurement**	Jan 2024	May 2025