HFM

High Field Magnets

Introduction to the activities of WP4.6 at CERN

Cryogenic and thermal management studies for HFM magnets

R. van Weelderen, P. Borges de Sousa

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Comments/Foreword:

- The milestones and deliverables for WP4.6 were presented during the **HFM workshop in November 2022**.
- The intense **ramp-up of Muon Collider activities** at CERN has had **an impact on the HFM activities of WP4.6**:
  - It kick-started the activities of WP4.6-T1, and prompted them to **all start in parallel in January 2023**
  - It highlighted the need to bring forward in the schedule the **combined approach to the overall optimization of cryogenic infrastructures** (WP4.6-T1), considering both sustainable magnet design and optimization of cryogenic infrastructures accounting for all other temperature levels
  - This provides essential **input for magnet & accelerator designers on where to orient their development efforts**, focusing not only on the coil but also on the magnet cold mass as part of a sustainable cryo-layout.

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 its **integration into large scale cryogenic infrastructures**
- **Thermal management of LTS and HTS magnets** with associated R&D program during the global process of magnet design and development.
- **Thermohydraulic calculations and numerical simulations** of cryogenic refrigeration processes
- **Investigation of associated material properties** at cryogenic temperatures.
- **Upgrade of Cryogenic Laboratory facilities for testing and experimental validation** of thermal characteristics on novel cryogenic cooling modes.

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	Report on main accelerator at 1.9 K			Jan 2023	Dec 2023
WP4.6-T1-D2	Report on main accelerator at 4.5 K			Jan 2023	Dec 2024
WP4.6-T1-D3	Report on main accelerator at 5.0 K			Jan 2023	Dec 2024
WP4.6-T1-D4	Review report for superfluid, saturated to supercritical scenarios			Jan 2024	Dec 2024
WP4.6-T1-D5	Report on main accelerator at >10 K			Jan 2024	Dec 2025
WP4.6-T1-D6	Report on main accelerator with hybrid coils			Jan 2024	Dec 2025
WP4.6-T1-D7	Summary review report			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 (WP4.4)			Jan 2023	Dec 2027
WP4.6-T2-D3	Superfluid He permeability of pure epoxy resins (WP4.4)			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)			Jan 2024	Mar 2027
WP4.6-T2-D6	Yellow Report on low temperature thermal properties of magnet components			Jan 2027	Dec 2027

Work triggered by Muon Coll. studies highlighted the need to regroup the deliverables differently

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)			Jan 2023	Dec 2025
WP4.6-T3-D2	Study on Nb_3Sn-coils at 4.5 K (RD3)			Jan 2023	Dec 2025
WP4.6-T3-D3	Study on Nb_3Sn-coils at 5.0 K (RD3)			Jan 2023	Dec 2025
WP4.6-T3-D4	Summary review report on thermal design options for Nb_3Sn-coils (RD2)			Sep 2025	Dec 2025
WP4.6-T3-D5	Study on Alternative wires (HTS, iron-based…)-coils at 1.9 K (RD2)			Sep 2023	Sep 2026
WP4.6-T3-D6	Study on Alternative wires (HTS, iron-based…)-coils at 4.5 K (RD2)			Sep 2023	Sep 2026
WP4.6-T3-D7	Study on Alternative wires (HTS, iron-based…)-coils at > 5.0 K (RD2)			Sep 2023	Sep 2026
WP4.6-T3-D8	Study on Hybrid coils (RD2 & RD3)			Sep 2023	Sep 2026
WP4.6-T3-D9	Summary review report on thermal design options for Alternative (HTS, iron-based…)-coils (RD2)			Sep 2023	Sep 2026
WP4.6-T3-D10	Demonstrator of reduced helium content cooling variants for Nb_3Sn			Sep 2024	Dec 2027
WP4.6-T3-D11	Demonstrator of reduced helium content cooling variants for HTS, iron-based, MgB_2,… (non-Nb_3Sn)			Sep 2024	Dec 2027
WP4.6-T3-D12	Heat extraction measurement of coil-packs (RD2 & RD3)			Sep 2023	Dec 2026

Nb_3Sn-related studies must be strongly connected to RD3 needs, in combination with overall cryo-infrastructure energy optimisation

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	Utlimate 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			Sep 2023	Dec 2027
WP4.6-T5-D2	Small HTS coils tests 4 K - 70 K			Sep 2023	Dec 2027
WP4.6-T6	**Thermal aspects of quench protection with WP4.5**			**Jan 2023**	**Dec 2027**
WP4.6-T6-D1	To be discussed with M. Wozniak			Jan 2023	Dec 2027
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			Sep 2022	Dec 2023
WP4.6-T7-D2	Upgrade of thermal expansion/contraction test stand			Sep 2022	Dec 2022
WP4.6-T7-D3	Upgrade of Superfluid He permeability test stand			Jan 2023	Dec 2023
WP4.6-T7-D4	Upgrade of test stand for heat extraction measurement of coil packs			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			Jan 2024	May 2025

Summary of planned activities for 2023

- WP4.6-T1: Cryogenic options towards reduced He content cooling
  - Report on studies for reduced He cooling options for collider-type magnets for different temperature configurations, definition of possible cryogenic layouts
- WP4.6-T2: Thermal properties of magnet components at cryogenic temperatures
  - Measurements of thermal contraction of pure epoxy resins – test stand ready
  - Measurements of thermal conductivity and specific heat of pure epoxy resins
- WP4.6-T3: Thermal design, modelling and validation of coils with reduced He content
  - Cooling scheme design of conduction-cooled magnet demonstrator at 4.5 K
- WP4.6-T5: Small-scale, variable temperature range HTS-coils and splice characterisation
  - Splice characterisation in background 5 T field
- WP4.6-T7: Test stands for HFM measurements
  - Completion and commissioning of thermal conductivity test stand (< 2 K)
  - Commissioning of test stand for heat extraction measurements of coil packs
  - Start of construction of test stand for demonstrator magnet (conduction-cooled/reduced He content) – activity ahead of scheduled start date

Activities in 2022/2023 (1/4)

- WP4.6-T1: Cryogenic options towards reduced He content cooling
  - Overview of cooling options for collider-type magnets considering optimisation of overall cryogenic infrastructure (*i.e.* considering all temperature levels), triggered by magnet designers for Muon Collider studies

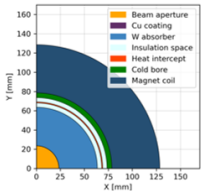
This type of study needs to be generalised to other accelerators/colliders → purpose of WP4.6-T1

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

Energy consumption	≤ 2.5 kW/m	$T_{absorber}$ ≥ 230 K
Absorber circuit	Operating T + distribution losses	$T_{absorber}$: 100 K or 250 K
Coil circuit	Total heat load + Required $\dot{m}$	T_{coil}: 4.5 K to 20 K
Coil design	$\dot{Q}$ to coil ≤ 10 W/m	Heat intercept between coil and absorber needed

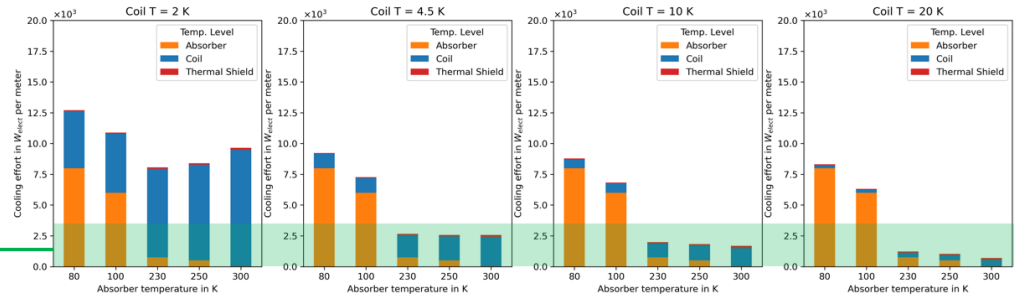
Power consumption at refrigerator I/F

w/ heat intercept



Blue: electrical power required to provide cooling power at cold mass temp. level
Orange: electrical power required to provide cooling power at absorber temp. level
Red: electrical power required to provide cooling power at thermal shield temp. level

Cooling effort at refrigerator I/F, w/o distribution, vs. absorber T, absorber thickness = 0.04 m, th. shield = 80 K, w/ thermal intercept between absorber and coil at T = 80 K



W/ heat intercept between coil and absorber!

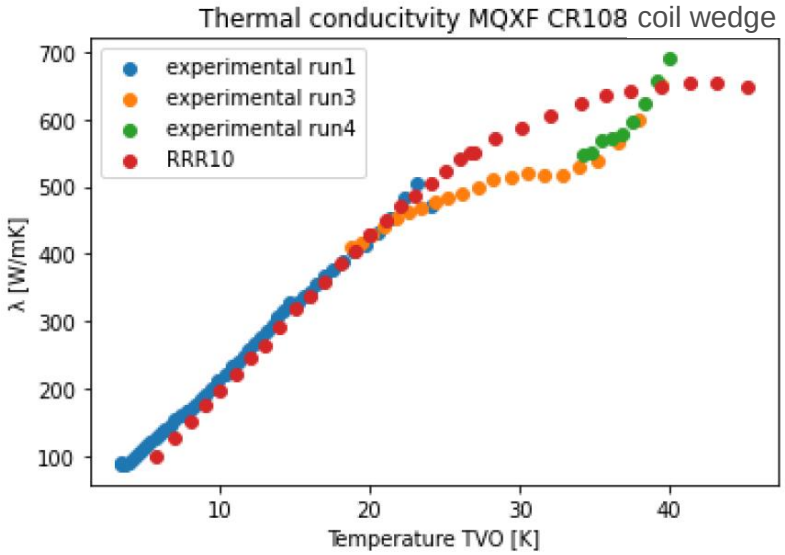
Target for 25 MW for Cryo in collider

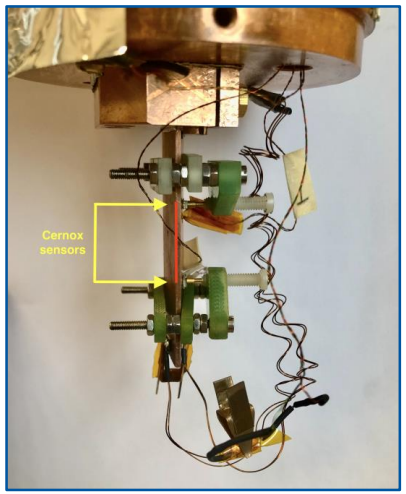
The larger the **blue** component → the more difficult the coil design

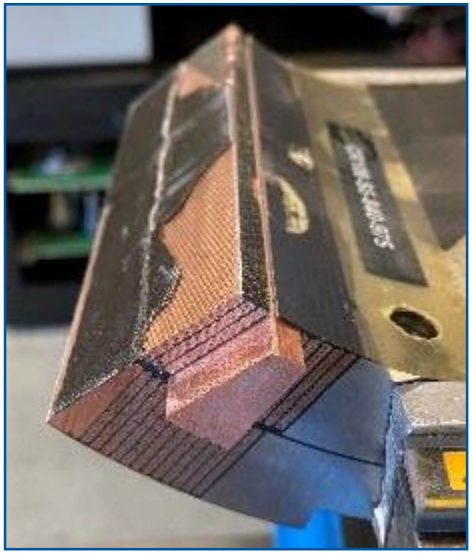
N.B. I: the cost to extract heat at 300 K is nearly zero, reflecting the fact that the distribution effort (circulation) is not yet included
N.B. II: although COP^{-1} based on cryoplants using certain fluids, so far, we're talking only about temp. level, *i.e.*, no fluid-dependent costs considered (as distribution, special handling, etc…)

Activities in 2022/2023 (2/4)

- WP4.6-T2: Thermal properties of magnet components at cryogenic temperatures
  - Measured thermal conductivity of DISCUP C3/30 (coil wedges) down to 6 K (shown)
  - Measured thermal conductivity of Mix 61 (below 10 K)





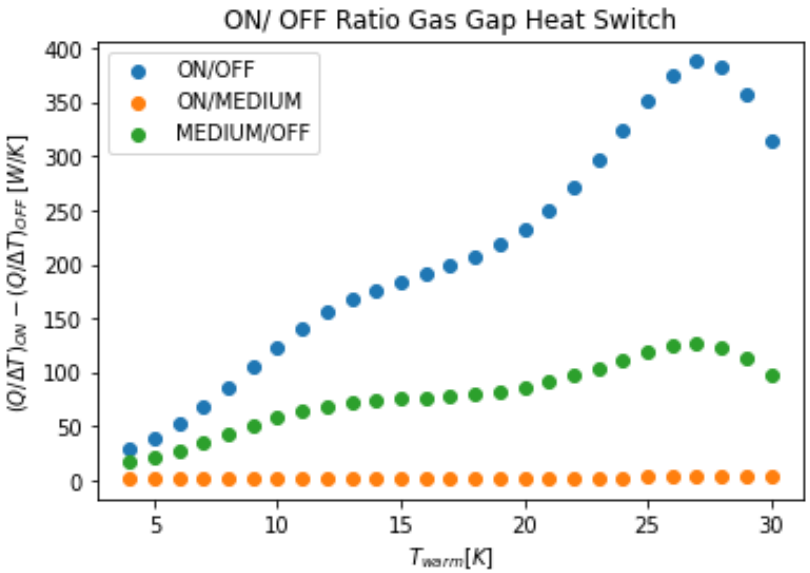


Extraction of sample from bulk coil CR108-S5

- Anomaly seen in values between 25 K – 38 K → interaction of phonons with the fine alumina powder
- Cold data show RRR10 Cu equivalent thermal conductivity
- Good candidate for future cooling tubes (limited quench interaction)

Activities in 2022/2023 (3/4)

- WP4.6-T7: Test stands for HFM measurements
  - Design of a test stand to measure thermal conductivity and diffusivity of materials down to 1.8 K (GGHS and He loop)
  - Set-up in construction
  - Components being individually tested



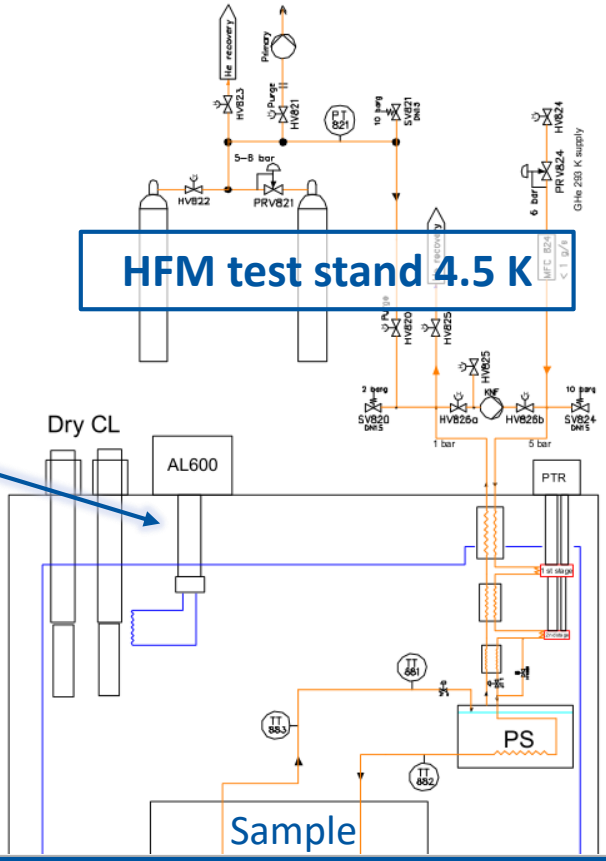
Gas-gap heat switch

Activities in 2022/2023 (4/4)

- WP4.6-T7: Test stands for HFM measurements
  - Design of a test stand for conduction-cooled/reduced He content demonstrator magnet (ahead of schedule)
  - Testing of individual components ongoing

Single-stage cold heads in a cryostat

EH mock-up & PID controlled



- Performance check of two AL600 GM cryocoolers,
- Use it for “dry” current lead cooling at 60 K Cu to HTS transition

Conclusions

- **Work is progressing on all tasks**, with special emphasis on the **construction of test stands** for conduction-cooled/reduced He content magnets and on the **studies for optimized cooling options for future accelerators**
- Cross-WP and cross-RD **exchange of information needs to intensify**
- Nb_3Sn-related tasks must be **adapted according to RD3 needs**

- **Open points:**
  - Discussion on **thermal aspects of quench protection** (WP4.6-T6)
  - **Need input** on developments from **RD2 (HTS)** and **RD3 (Nb_3Sn magnets)** to advance on the **thermal design of reduced He content/conduction-cooled magnets** (WP4.6-T2)