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FCC-hh CRYOGENICS

R&D AND COOLING SCHEMES FOR SC MAGNETS

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Introduction

Following the decision to speed up the delivery of the FCC mid-term report (CDR$^+$) in May 2025, the **compatibility of a future FCC-hh machine with the infrastructure outlined for FCC-ee needs to be evaluated**.

This requires us to assess the compatibility of **several FCC-hh scenarios** (baseline using Nb_3Sn at 1.9 K, 4.5 K using Nb_3Sn and 20 K using HTS) **with the tunnel cross-section and space reservation at the surface for the baseline FCC-ee machine.**

Roadmap for 2024 towards a CDR^{+}

Need to answer if **a 1.9 K, a 4.5 K or a 20 K version of FCC-hh would fit in the baseline FCC-ee tunnel, incl. cryogenic distribution line** (QRL)

To answer this, we'll need to address:

- Estimated **heat loads** for each case, need input/scaling
- How to **buffer transient heat loads** (ramping)
- **Cooling layout** inside magnets, and **length of cooling cell** (≠ arc cell?)
- Size of **distribution line**

Heat load estimation and scaling

Heat load deposited on or generated by the magnets can be divided into (in increasing order of magnitude):

Static heat in-leaks

- Cold mass supp. system
- Radiative insulation
- Thermal shield
- Feedthrough + vacuum barrier
- Beam screen
- Distribution

✓ Calculated for 1.9 K, can be scaled for a cold mass at 4.5 K and 20 K

Dynamic heat loads

- Synchrotron radiation
- Image currents
- Resistive heating in splices
- Beam-gas scattering

✓ Almost no change with respect to 1.9 K

✓ Contribution of splices will maybe change

Transient loads

- Magnetic field ramping losses

✓ Scale Nb_3Sn losses for 4.5 K design

✓ HTS losses unknown, potentially 10x higher than Nb_3Sn

Heat load estimation and scaling

Heat load deposited on or generated by the magnets can be divided into (in increasing order of magnitude):

- **Transient loads** of Nb_3Sn due to magnet ramping **are 2x the steady-state** (static+dynamic) **heat loads at 1.9 K [1]**
- A design using HTS technology might **amplify this issue by potentially a factor 10**
- In the absence of the c_p of He II, one needs to turn to the $\boldsymbol{c_p}$ **of the cold mass** (yoke) or foresee (liquid) **reservoirs to buffer the additional load**

→ **Transient loads will shape/affect the cooling layout and size of QRL**

Transient loads

- Magnetic field ramping losses

✓ Scale Nb_3Sn losses for 4.5 K design
✓ HTS losses unknown, potentially 10x higher than Nb_3Sn

Cooling layout inside magnets

- The **cooling layout and QRL sizing exist for cooling at 1.9 K**; these **have been reassessed** to reflect the 8 surface points update (see B. Naydenov's talk)

- For **4.5 K** and **20 K**, only **a preliminary assessment** can be achieved in time for the CDR$^+$:
  - Size of the QRL can be estimated for both
  - Cooling layout will depend on various factors (esp. for 20 K, see next slides), level of detail will partly depend on input given by magnet design

Cooling schemes at 4.5 K

- Any **cooling scheme at 4.5 K will be based on He**, either in **saturated** or **supercritical** conditions in confined geometries (cooling pipes):
    - In the case of **two-phase (saturated) He circulating inside pipes**, there is a negligible temperature gradient along **magnet** and **arc cell,** but prone to **instabilities** and large friction losses
    - For the **supercritical He** option, there is a **moderate temperature gradient** along magnet/arc cell, but can provide good heat transfer and low frictional losses
- In either case, **ramping losses cannot be managed only by using the c_p of the cold mass**; options such as LHe reservoirs at end of sector + extra channels will need to be studied

Cooling schemes at 20 K

- Any **He-based cooling** scheme at **20 K** will involve a **sizeable temperature gradient** both radially and along a **magnet** and an **arc cell**:
    - This has a direct impact on magnet design as the **ΔT affects field quality** along the cell
    - **Whether a compromise exists** that can achieve both feasible magnet design & feasible He cooling **remains to be addressed**
    - High pressure required – might affect magnet design

- Any **H_2-based cooling** scheme would require a **complete change of mindset**, but:
    - Ability to provide **cooling at a constant temperature** throughout an arc cell;
    - Lower mass flow rate required (*i.e.*, **smaller QRL**) as latent heat is 20x that of He at 4.5 K
    - Coupled to high c_p of the cold mass itself (at 20 K), could cope with ramping losses
    - Safety concerns

Main drivers for FCC-hh compatibility

Option	Cryogen content	Power consumption	Able to handle transient loads?	ΔT along arc cell?	Size of QRL
FCC at 1.9 K (Nb_3Sn) Baseline	≈ 10^6 kg He	262 MW [2]	Yes (via c_p of He II)	Extremely low gradient with He II operation (≈ mK)	≈ Ø1.1 m (8 points)
FCC at 4.5 K (Nb_3Sn)	↓↓ Intrinsically lower, no liquid bath	↓↓ Carnot + no cold compressors	In principle yes (might need liquid reservoirs at end of sector)	↑ Will require moderate ΔT (≈ K)	↓↓↑ No VLP line required but could have large $\dot{m}$; lower ΔT means larger QRL (but still < Ø1.1 m)
FCC at 20 K (HTS)	↓↓ Only gas if He; two-phase flow confined in pipes if H_2	↓↑ Carnot + no cold compressors; could be still high if transients are also high	Unclear if using He (c_p of cold mass insufficient)	↑↑ Will require sizeable ΔT (≈ 5+ K)	↓↓↑ No VLP line required but could have large $\dot{m}$; lower ΔT means larger QRL (but still < Ø1.1 m)

As an output we'd like to have a 3D plot of QRL size as a function of heat loads to magnets (steady-state + transient) and allowed temperature gradient along an arc cell

What we won’t be able to deliver

In time for the CDR$^+$

- **Detailed cooling layouts** for the options at 4.5 K and 20 K, incl. studies on **local heat extraction** at coil/cold mass level
- **Surface area needed for FCC-hh scenario at 20 K** needs to be studied (surface area for 1.9 K and 4.5 K scenarios is in the baseline)
- Cryogenic design for **detectors and MDI** (partially done for detector infrastructure at 4.5 K)

Open points

- With a cold mass at 4.5 K or 20 K, does the beam screen remain at 40 K – 60 K? Do vacuum “windows” change?
- Effect of temperature gradients on magnet design and performance: what is the acceptable temperature gradient along a magnet and arc cell? What is the required temperature stability?
- Transient heat loads (ramping losses) on HTS option need consolidated figures

HFM activities related to FCC-hh

Thermal design of coils w/ reduced He content (incl. conduction cooling)

- No activities started in the context of HFM, as they rely on input from the relevant RD lines

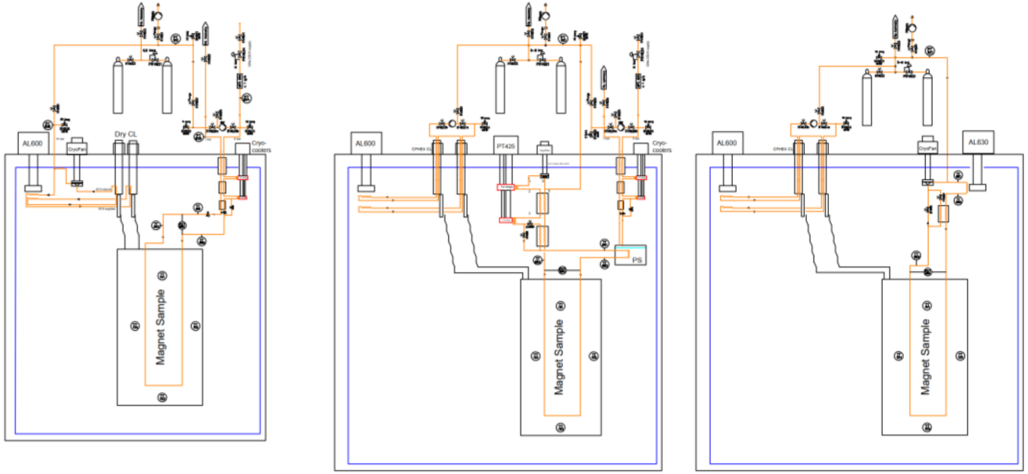
BUT

- Involvement in other CERN projects such as **EESD** (towards SHiP) and **euroSIG** has allowed us to **start designing cooling layouts for local heat extraction of (one-of-a-kind) magnet coils** and cold masses

HFM activities related to FCC-hh

Reduced He cooling demonstrator

- Goal is the **demonstration of reduced He content cooling schemes, at temperatures ≥ 4.5 K**, applied to accelerator-type magnet structures
- **Testing the cooling concept(s) with a real magnet should be considered**, before the chosen solution is adopted for series testing of magnets (*e.g.* at the SM18 test facilities). This would allow to test the performance of a full (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), but there are challenges exclusive to implementation in accelerator magnets that need to be tackled in a dedicated test stand

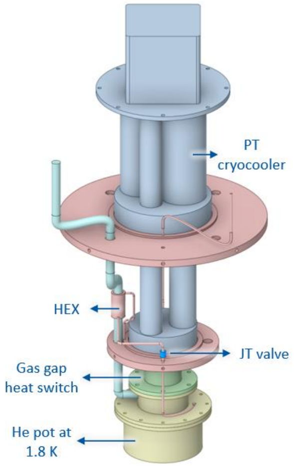


Demonstrator test stand designed to be upgradable:

- **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 $\dot{m}$

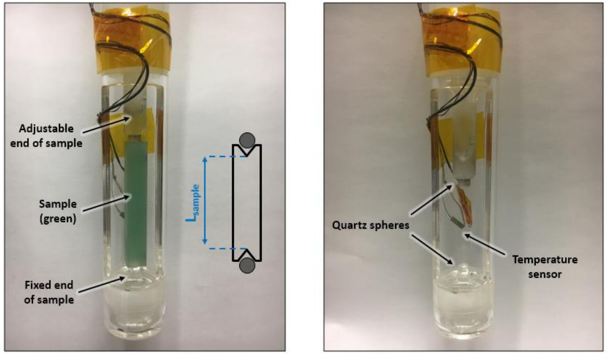
Measurement capabilities at the Cryolab

Thermal conductivity and 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 contraction

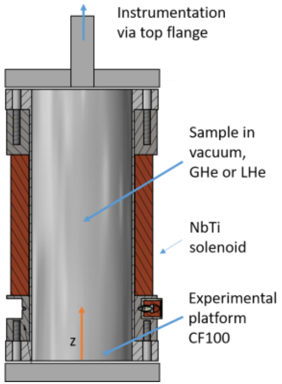


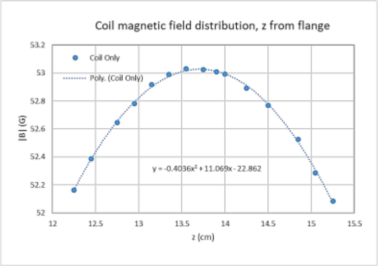
Thermal contraction test stand, sample detail

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

Measurement capabilities at the Cryolab

Test of small components in variable *T* field

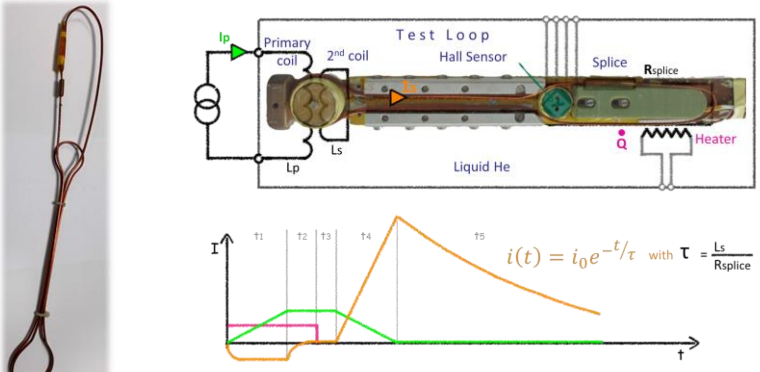




Coil magnetic field distribution measured along z axis at room temperature with 100 mA.

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

SC splice resistance



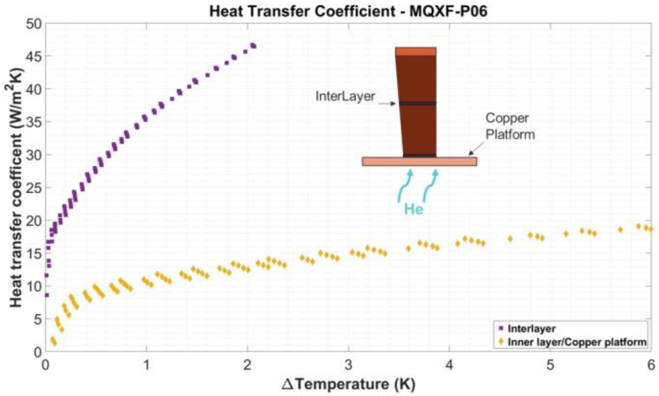
SC splice sample (left) and test stand (right)

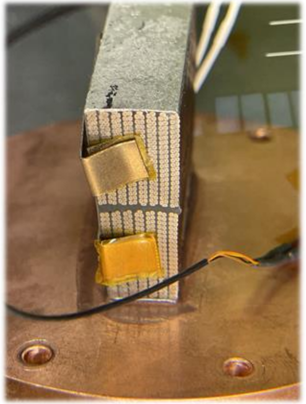
Capabilities	Splice resistance calculated using the time constant and the inductance of the splice (magnetic field decay measured via a Hall probe)
Temp. range	4.2 K
Sample dimensions	Specific loop geometry; LHC-type cables and larger (e.g. MQXF) fit
Environment	In liquid Helium

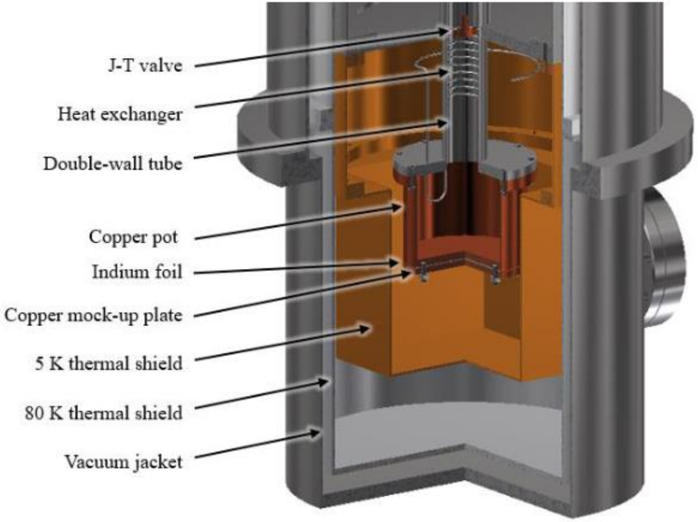
Measurement capabilities at the Cryolab

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







Detail of sample preparation (origin: MQXF P06 coil)

Summary

- In time for the CDR+, we’ll evaluate whether each of **the three cooling scenarios for FCC-hh** magnets (1.9 K, 4.5 K and 20 K) **is compatible with underground tunnel space (QRL size)**.
- **We will need input from magnet designers**, namely with respect to conductor losses and allowable temperature gradients.
- **We won’t be able to address** the cooling layouts of each option in detail, nor tackle MDI and detector cryogenics design.
- We have **started studies on cooling using He at 4.5 K and 20 K** for standalone magnets, can profit from synergies.
- **Cryolab is equipped with several test stations** (some existing, some under development) to support the High Field Magnet programme.

THANK YOU FOR YOUR ATTENTION

References

[1] *Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report,* preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058, Geneva, December 2018. Published in Eur. Phys. J. ST. (link)

[2] FC*C-hh cryo interfaces summary*, B. Naydenov, EDMS 2820789 (link)