This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

FCC-hh CRYOGENICS

R&D AND COOLING SCHEMES FOR SC MAGNETS AT 4.5 K

– PRELIMINARY CONCEPT–

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on behalf of HFM WP4.6
17th of October 2024

Disclaimer

- **The calculations included in this talk are preliminary**, as the study is at an early stage and many parameters are yet to be defined or fully understood.
- This talk is intended to show what the proposed strategy is, and **to share it with magnet designers in a timely manner**, so we can work together towards the most effective magnet/cryogenic system design.
- Please keep in mind that **the numbers shown here are likely to change** as the design matures.

Introduction

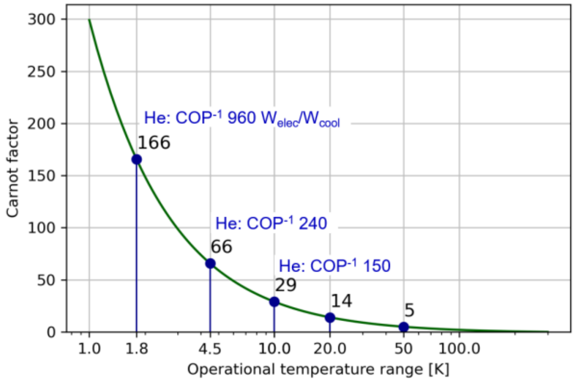
Following the decision to speed up the delivery of the FCC mid-term report (CDR^{+}) in May 2025, the **compatibility of a future FCC-hh machine with the infrastructure outlined for FCC-ee needs to be evaluated**.

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.**

The **main drivers** are to reduce operational **energy consumption**, capital costs, **reduce He inventory**, and ensure **compatibility with tunnel** and surface while providing a **viable solution for the magnets.**

This talk describes the efforts made towards a solution for 14 T magnets using Nb_3Sn at around 4.5 K.

Why 4.5 K?

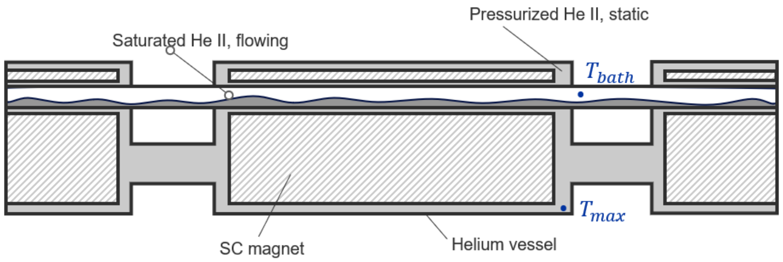


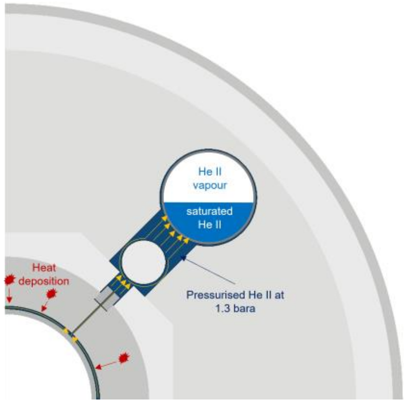
- Simpler cryogenic system/cryoplant
- Can **avoid cold compressors** that are a necessity for He II cooling
- Heat extraction at higher temperatures → lower COP^{-1}, **more energy efficient**
- Operational downtime after a quench is significant with He II (due to large enthalpy difference of He I → He II transition), reducing availability. **The operational downtime is reduced when working at 4.5 K.**

Why cooling channels ("dry-cooling")?

- Forced flow of supercritical He enables heat extraction with **high heat transfer coefficients**
- Confining the He to channels eliminates the need for a cold mass outer shell to be leak tight → **simpler design, Q&A, shorter interconnects**
- By circulating He in confined channels instead of using immersion cooling, one **reduces the He inventory significantly** → this has an important impact on He management (logistics, procurement, management in case of release into tunnel, surface space requirements...)

Cooling at 1.9 K *vs.* 4.5 K





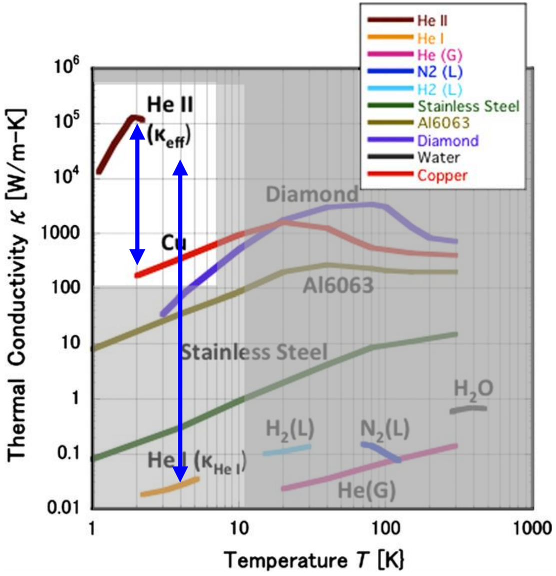
https://edms.cern.ch/document/2864235/1

- Heat **extraction** occurs in the saturated He II part
- Static He II bath (pressurized) acts as a very effective conduction medium to **transport** the heat from the coils to the HEX
- Effective **heat conductivity of He II is 1000x that of Cu** at same *T*
- In the LHC we relied on He II to be able to generate 8.3 T using NbTi

Need change of paradigm!

Forced flow in closed channels?

- **Conductivity of bulk liquid at 4.5 K is 5-6 orders of magnitude lower** than that of He II
- This means that **He I performs worse than metals** as a conduction medium (to transport heat away from the coils to the heat sink)
- LHC-like scheme at 4.5 K using saturated/pressurised He I **makes no sense**

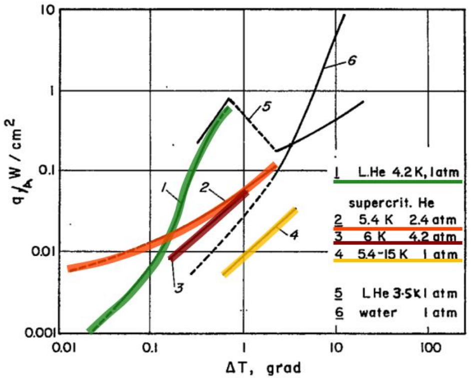


Murakami, Experimental study of thermo-fluid dynamic effect in He II cavitating flow, Cryogenics, 2012.

Cooling at 4.5 K – **how?**

Pool boiling

- 👍 Near isothermal along arc/sector
- 👎 Large He inventory in contact with cold mass
- 👎 (some) penetration of He close to coils if immersed
- 👎 Bubbles can form and be trapped
- 👎 Heat transfer of He I



Free convection!

Smith, Review of heat transfer to helium I (link)

Two-phase forced flow

- 👍 Near isothermal along arc/sector
- 👎 Flow instabilities, heavily dependent on local flow pattern (in turn dependent on local heat load)
- 👎 Challenging control, slope-dependent
- 👎 Circuit pressure limited to 1.3 bar
- 👎 High $\Delta p/p$
- 👎 Need to accept non-negligible ΔT radially in cold mass

Supercritical forced flow

- 👍 At 4.5 K, heat transfer comparable (or better) than 2-phase
- 👍 Circuit pressure can be 3-4 bar
- 👍 Low $\Delta p/p$
- 👍 Slope-independent cooling mode
- 👎 Larger temperature gradient along magnet/arc/cell w.r.t. 2-phase
- 👎 Need to accept non-negligible ΔT radially in cold mass

How to implement a cooling scheme using forced flow for a 90 km accelerator?

Heat loads to cold mass

We are assuming the same **steady-state heat loads (static + dynamic)** as stated in CDR for 1.9 K **(1.4 W/m)** but at around 4 K

Total heat load

$$\dot{Q}_{CM} = \dot{Q}_{static} + \dot{Q}_{dynamic} + \dot{Q}_{transient}$$

Steady-state loads (from CDR table)

Magnet ramp down/up cycle 10 kJ/m over 3200 s (tbc)

Table 5.11. Distributed steady-state heat loads (nominal conditions).

Temperature level		**40–60 K**	**1.9 K**	**4 K VLP**
Static heat in-leaks (W/m)	Cold mass supporting system	2.4	0.13	
	Radiative insulation		0.13	
	Thermal shield	3.1		
	Feedthrough and vacuum barrier	0.2	0.1	
	Beamscreen		0.12	
	Distribution	3.6	0.1	0.24
	Total static	**9.3**	**0.58**	**0.24**
Dynamic heat loads (W/m)	Synchrotron radiation	57	0.08	
	Image current	3.4		
	Resistive heating in splices		0.3	
	Beam-gas scattering		0.45	
	Total dynamic	**60**	**0.83**	
Total		**70**	**1.4**	**0.24**
Dynamic range		8	2.5	1

From original 2019 FCC-hh CDR

- **Transient loads** (hysteresis losses from ramping) are assumed to be **10 kJ/m** for a full ramp-up/down cycle for a double-aperture coil (E. Todesco)
- This means an **added 3.1 W/m** to the steady-state loads if considering powering schedule of CDR (3200 s for full cycle)

The Superconducting Super Collider (SSC)

Accelerator magnet cooling at around 4 K

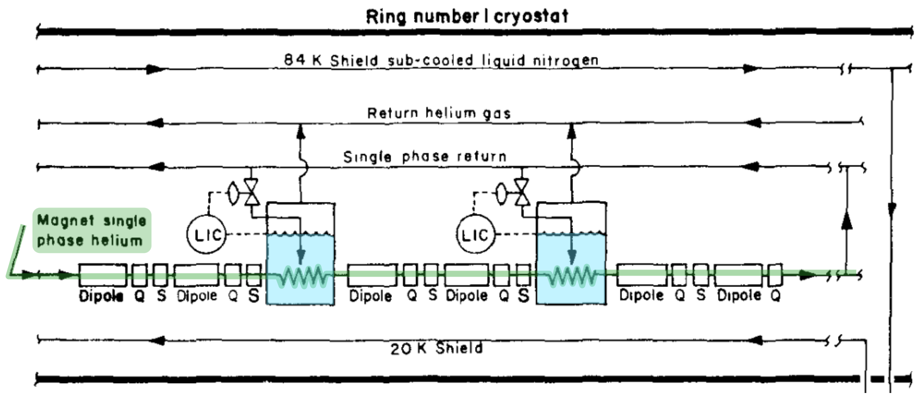


Figure 5.3-1. A conceptual representation of the SSC collider rings cryogenics system. In each of the two rings the collider magnets are cooled in series by a flow of single-phase helium. This stream is recooled at cell intervals by heat exchange with boiling helium. The cryostat of each ring contains cooled shields at 84 K and 20 K.

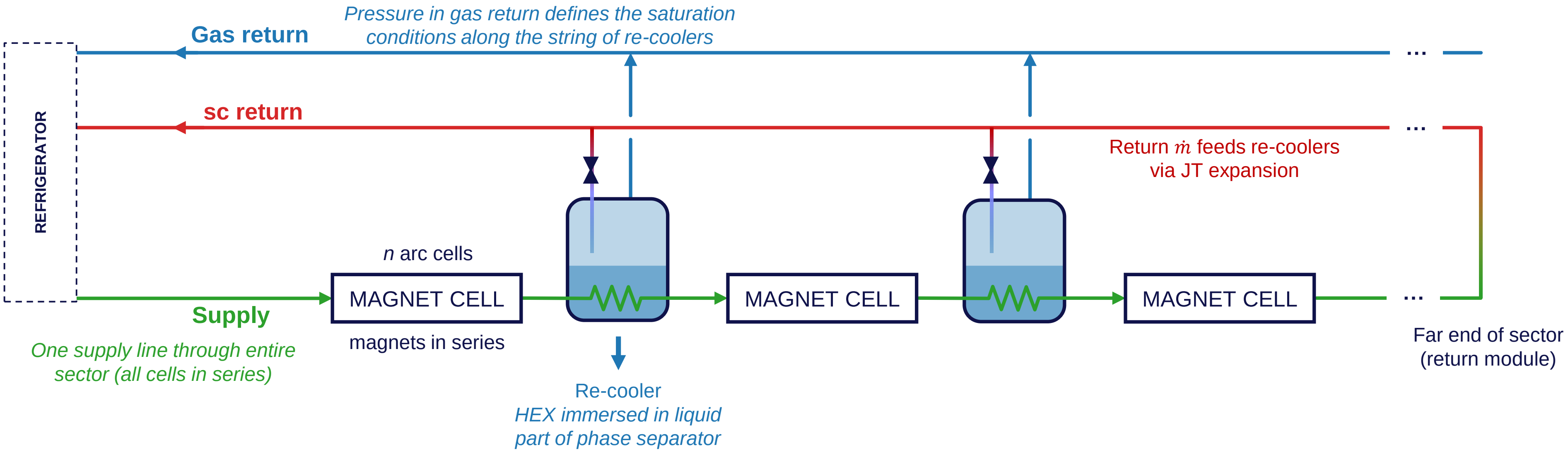
The basic concept of magnet cooling and refrigeration distribution is illustrated in Fig. 5.3-1. In this figure a refrigeration plant is on the left, providing and accepting flow. Single-phase helium at 4.15 K and 4 atmospheres is forced out into the magnet string of each ring upstream and downstream from the refrigerator for a distance of 4 km. It flows through the magnets in series and is recooled periodically to maintain the superconducting windings at or below the specified 4.35 K. At the end of the 4 km string, the flow is returned toward the refrigerator. This fluid is flowing at a pressure above its critical pressure, so in all parts of the circuit only a single phase is possible. Along this line small flows are withdrawn and expanded into pool-boiling recoolers spaced at intervals of one cell, 192 meters. The saturated gas from the recoolers is collected and returned to the refrigerator in a third line.

Tevatron → SSC → … FCC ?

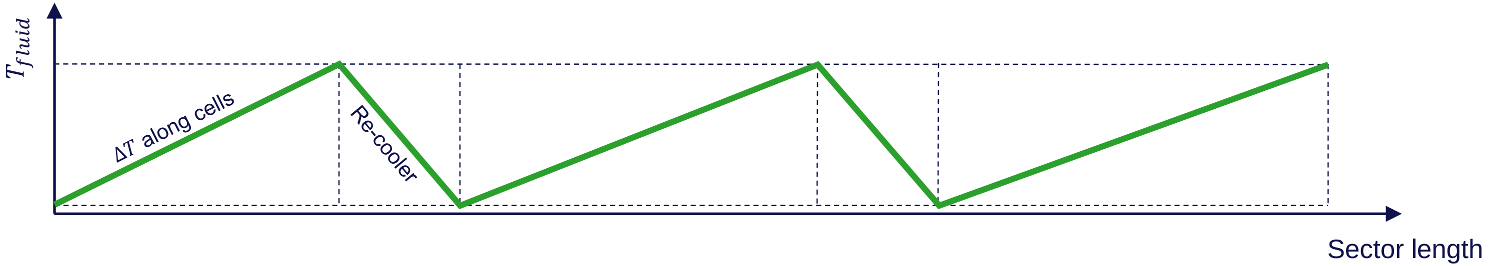
The ancestor of the SSC is, of course, the Tevatron, and this heredity is reflected in the cryogenic system requirements. The Tevatron has produced a body of successful superconducting magnet operating experience with beam and beam-loss heating. The Tevatron magnets are cooled by immersion in supercritical helium, the so-called single-phase flow, that is cooled in turn by heat exchange with boiling helium. Although other systems are possible and may have attractive features, any fundamental change in the single-phase cooling concept requires development and demonstration under realistic operating conditions. This is a complex and expensive task; unless some very strong reasons can be adduced for the superiority of some alternative system, the Tevatron model must be used for the SSC.

Conceptual Design of the Superconducting Super Collider, 1986

Proposed cooling scheme

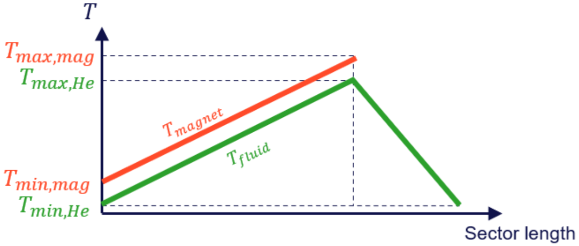


- T_{min}?
- T_{max}?
- $\Delta T_{coil \rightarrow He}$?

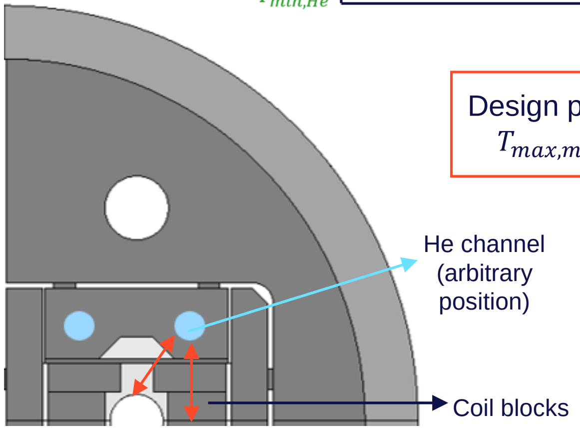


Let's talk about temperature gradients

Unlike the baseline cooling scheme at 1.9 K, where there are virtually no temperature differences along an entire sector, **cooling at around 4.5 K intrinsically involves both radial and longitudinal temperature gradients**



14 T block coil design, courtesy Ariel Haziot



Design parameter:
$T_{max,mag}$= 5 K

Radial gradient:
- Between the heat sink (e.g. He inside cooling channel) and the magnet coil/cold mass
- Depends on the solid materials between the coil and the heat sink, contact forces and thermal contact resistance
- **Heavily dependent on the magnet design**

Longitudinal gradient:
- Temperature increase along the length of a magnet and along the string of magnets (arc cell)
- **Depends on the characteristics of the cooling circuit** (circulating $\dot{m}$, base temperature, heat loads, etc.)
- (almost) independent of magnet design

Radial ΔT: estimates based on x-section

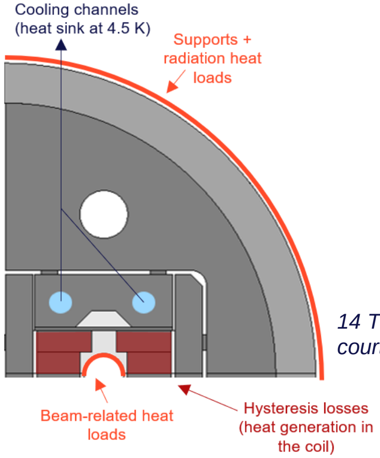
Courtesy X. Gallud Cidoncha

Using the magnet cross-section provided by A. Haziot, we estimated the **radial temperature gradient during steady-state operation and during the ramp down/up cycle**

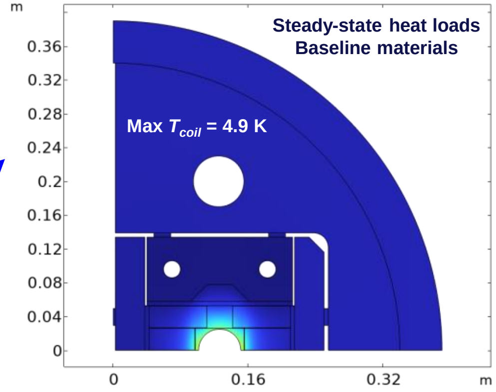
Reminder:
- Steady-state – 1.4 W/m
- Ramping – 3 W/m

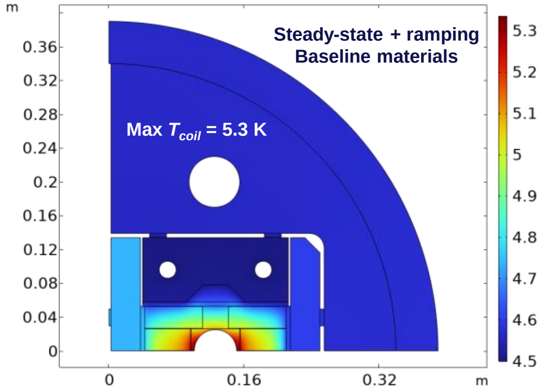
*Calculated for He T = 4.5 K

	Pole material	Insulation scheme	Heat load case	Max. T in coil [K]	ΔT from He [K]
First design	Titanium alloy	G10	Steady state	4.92	0.42
			Steady-state + ramp	5.28	0.78



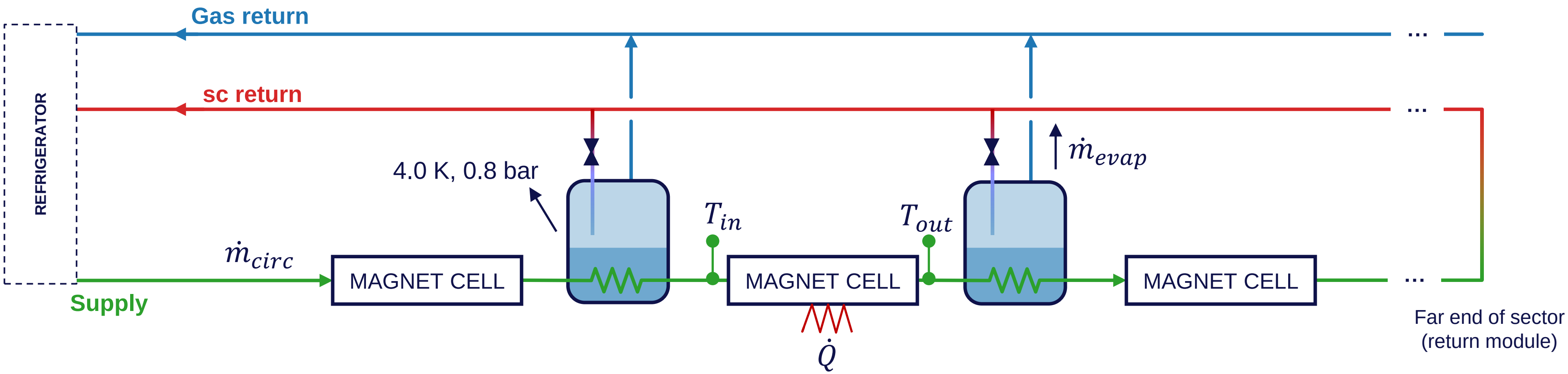
14 T block coil design, courtesy Ariel Haziot





NB: Effective thermal conductivity used for the coil blocks is taken from 11T experimental data, incl. impregnation and interlayer insulation where applicable (see EDMS 1871957)
NB II: Thermal properties of other solids from NIST data, no thermal contact resistance added

Longitudinal ΔT: sizing the cryogenic system



Considering a 200 m cell:

Longitudinal gradient in fluid → for magnet T add radial ΔT

*includes circulation effort

Heat load case	$\dot{Q}$ [W/m]	$\dot{Q}$ [W]	p [bar]	T_{in} [K]	T_{out} [K]	ΔT [K]	$\dot{m}_{circ}$ [g/s]	$\dot{m}_{evap}$ [g/s]
Steady-state	1.41	282	3	**4.1**	**4.5**	**0.4**	~225	~18

Steady-state loads only!

How to buffer the hysteresis losses?

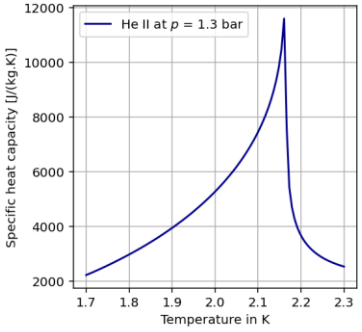
Using He II at 1.9 K

- Take advantage of the **high c_p of the press. He II bath** and absorb the extra heat load by allowing the bath's temperature to rise

  Example:
  To buffer **10 kJ/m** (ramp up/down cycle for a dual aperture magnet) and keep the temperature below T_λ (2.17 K) from its nominal 1.9 K, **40 litres/m** are necessary (5.8 kg/m)

Over 6.5x LHC inventory!

(incl. QRL)



Using He I at ~4.5 K

- **c_p of solid materials is insufficient** to absorb the extra heat load due to ramping

  Example: cold mass 55 tons/15.8 m dipole = 3.5 ton/m (CDR), c_p(Fe) at 4.5 K = 0.5 J/(kg.K) → 1.75 kJ/K per meter

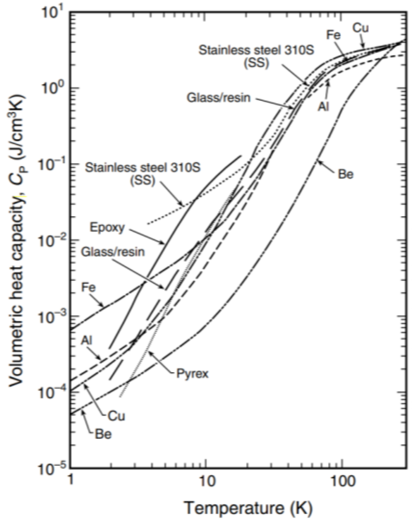
- Add He to the cold mass to buffer heat load

  Example: To buffer **10 kJ/m** and keep the temp. between 4.5 K and 5 K, using the c_p of supercritical He at 3 bar, **30 litres/m** are needed (4.2 kg/m)

- <u>**Increase circulating $\dot{m}$ of He in the magnets**</u>

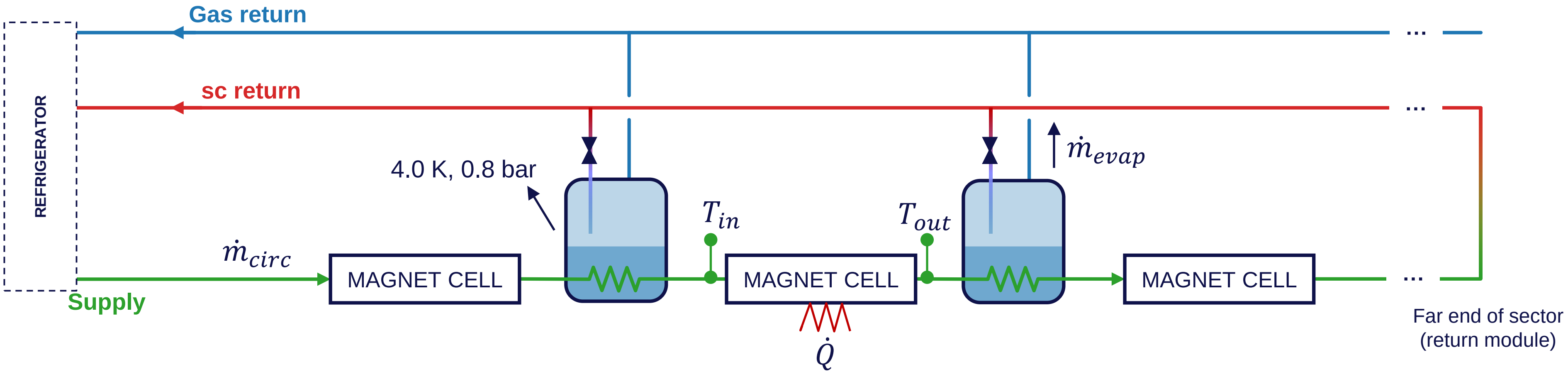
Estimated 2-3x LHC inventory
(incl. QRL)

(see next slide)



J.W. Ekin, *Experimental Techniques for Low-Temperature Measurements*

Cryo system: higher $\dot{m}$ to tackle ramping losses



Considering a 200 m cell:

Longitudinal gradient in fluid → for magnet *T* add radial *ΔT*

*includes circulation effort

Heat load case	$\dot{Q}$ [W/m]	$\dot{Q}$ [W]	p [bar]	T_{in} [K]	T_{out} [K]	Max. T in coil [K]	$\dot{m}_{circ}$ [g/s]	$\dot{m}_{evap}$ [g/s]
Steady-state	1.41	282	3	**4.1**	**4.5**	**4.92**	~225	~37
Steady-state + ramping	4.51	902	3	**4.1**	**4.5**	**5.28**	~590	~46

*for first design of x-section

Status/conclusions

From an overall system perspective:

- **Proposed cooling scheme seems technically feasible**, respecting drivers for lower energy consumption and He management
- Move from 1.9 K to 4.5 K may **reduce the power consumption** by at least estimated 30% (preliminary!)
- Overall, **He inventory ~400 tons** (~3x LHC) **is lower** than baseline at 1.9 K (~6.5x LHC) → positive implications on quench management, He availability, storage, access restrictions in the tunnel
- **Simpler interconnects:** cold mass does not need to be leak tight + less space required for jumper, can increase filling factor
- Details, optimization, and study of transient modes (cooldown, quench recovery) will follow

From a magnet cooling point of view:

- Proposed cooling scheme can provide a reasonable environment for operating 14 T Nb_3Sn magnets at around 4 K – 5 K
- Reasonable temperature gradients along a 200 m magnet cell (~0.4 K), radial gradients can be optimized
- Opportunity to **gain significantly on available temperature margin by carefully designing the cold mass** for conduction-cooled scheme (as most of the gradient is radial and not longitudinal) → results shown are for a non-optimized cross-section!
- System can be sized to directly absorb the heat loads from ramping, not relying on liquid buffering

Thank you for your attention!

Many thanks to B. Bradu, L. Delprat, T. Koettig, R. van Weelderen, A. Haziot, E. Todesco, X. Gallud Cidoncha, B. Naydenov for very fruitful discussions!

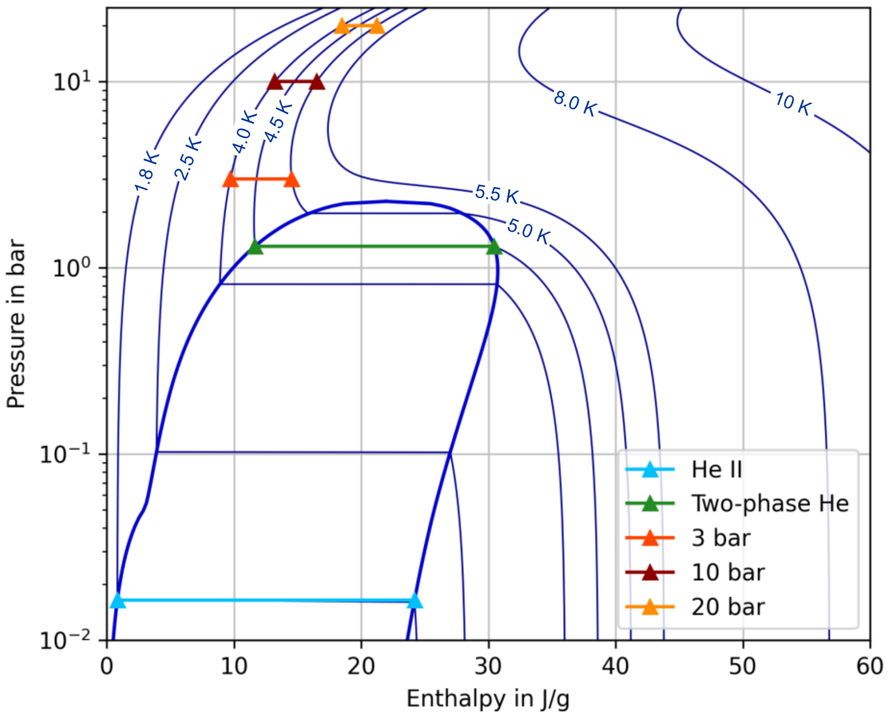
Spare slides

FCC-hh parameter table evolution

Original 2019 FCC-hh CDR *FCC Week 2024 update (L. Delprat)*

	Original CDR (2019)	Updated baseline (2024)	This talk (2024)
Dipole field strength	16 T	16 T	12-14 T
Cold mass temperature	1.9 K	1.9 K	~ 4.5 K
Cooling method	He II sat./press.	He II sat./press.	supercritical He ~3-4 bar
Heat load by SR	57 W/m per dual aperture	57 W/m per dual aperture	14-27 W/m per dual aperture
Beam screen temperature	40-60 K	40-60 K	60-80 K (tbc)
Heat loads	• 1.4 W/m @ 1.9 K • 70 W/m @ 40-60 K	• 1.4 W/m @ 1.9 K • 70 W/m @ 40-60 K	• O(1.4 W/m) @ 4.5 K • O(20-40 W/m) @ 60-80 K
QRL diameter	1350 mm	1100 mm	???
Cryo cooling length	8.4 km	5 km per side	5 km per side
Header B diameter	630 mm	470 mm	???
He inventory	~ 880 ton	~ 820 ton	???

p-H diagram for helium



Synchrotron radiation in FCC-hh

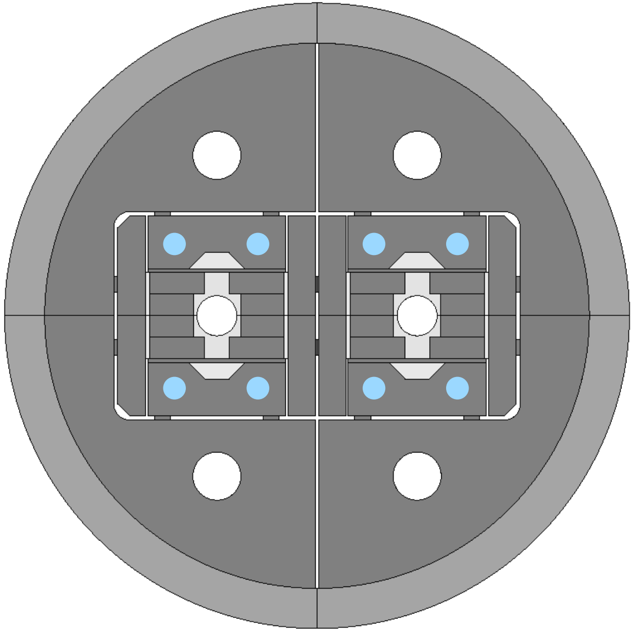
- We're dealing with **half of the SR** w.r.t. CDR (or even less)

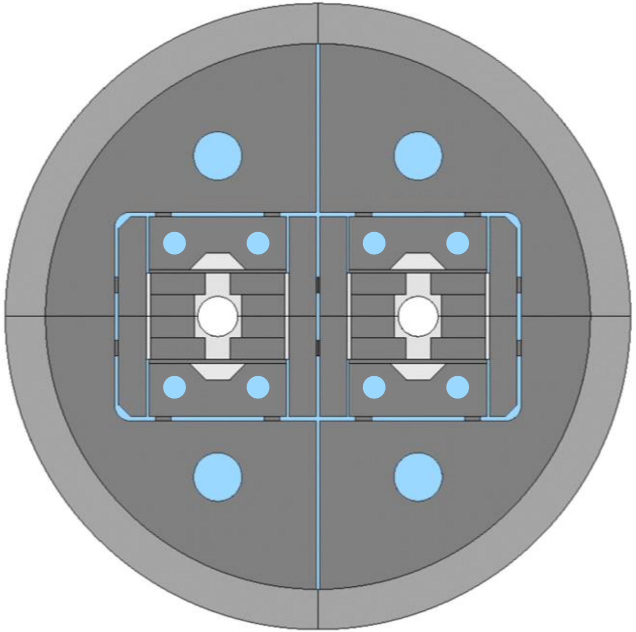
parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10[11]]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

M. Benedikt, FCC Week 2024

Configuration	C [km] *ring circumference	L [km] *straight sections	B [T]	η [%] *straight sections	E_{CM} [TeV]	Total SR [kW] *both apertures	SR [W/m] *for both apertures	Source/comments
FCC as per CDR	97.75	14	16		102	4800	58	FCC-hh CDR pp. 801
FCC, 2024 update	90.7	13.8	20	80	117	8490	110	FCC week 2024
			16		94	3480	45	calculated
			14		82	2040	27	FCC week 2024
			13		76	1520	20	calculated
			12		70	1100	14	calculated
FCC, 2024 HFM	90.7	13.8	14	87	89	2850	37	calculated

Cooling channels *vs.* cross-flow





Cooling channels
- He is confined to cooling pipes places close to the coil
- Rest of cold mass (white spaces) is in vacuum; no need for thick He vessel withstanding 20 bar

Cross-flow
- The same He circuit is allowed to flow through the openings of the cold mass (+ additional cooling pipes)
- Entire cold mass needs to be leak tight, and withstand pressure rise in case of quench

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)