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FCC-hh CRYOGENICS

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

PRELIMINARY CONCEPT

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on behalf of CERN TE/CRG and HFM WP4.6

FCC Week, 19-23 May 2025, Vienna, Austria

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.
- **Work is actively ongoing**; 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) **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 the F14 Scenario, i.e., an accelerator using 14 T Nb_3Sn-based magnets operating at around 4.5 K.

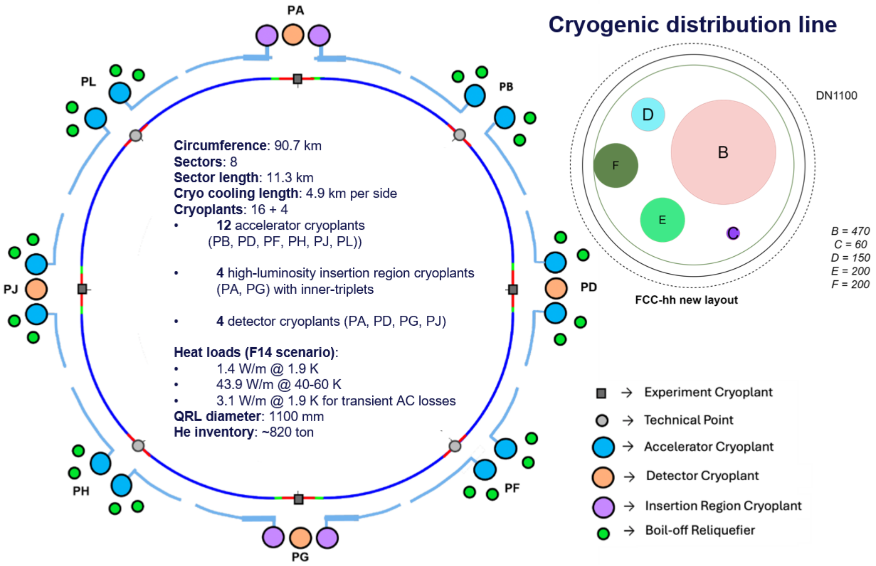
FCC-hh in numbers: F14 scenario

FCC-hh Parameters	F14 scenario at 1.9 K [2024]	F14 scenario at 4.5 K [2024]
Circumference [km]	90.7	90.7
Dipole field [T]	14	14
Centre of mass energy [TeV]	854	84
Sync. Rad. for 2 beams [MW]	2.4	2.4
Magnet temperature [K] Beam screen temperatures [K]	1.9 [40 – 60]	4.5 [40 – 60]
Helium Cryogenic Capacity @ 4.5 K equivalent [kW]	1040	698
Number of cryo islands [-]	8	8
Number of cryoplants in total [-]	16	16
Arc cooling length [km]	16 x 4.9 = 78.4 km	16 x 4.9 = 78.4 km
Electrical consumption [MW]	206	139
Helium inventory [tons]	820	390

See L. Delprat's talk on Tuesday 11h30 on TI: RF and Cryogenics session!

F14 scenario @ 1.9 K

- **Baseline cryogenic configuration** of FCC-hh
- **Cooling scheme** similar to LHC:
  - Heat transport by static **pressurized He II**
  - Heat extraction by **saturated He II** in bayonet HEX
- **Ramping losses** buffered by >30 L/m He II static bath (T allowed to increase up to T_{λ})



Circumference: 90.7 km
Sectors: 8
Sector length: 11.3 km
Cryo cooling length: 4.9 km per side
Cryoplants: 16 + 4

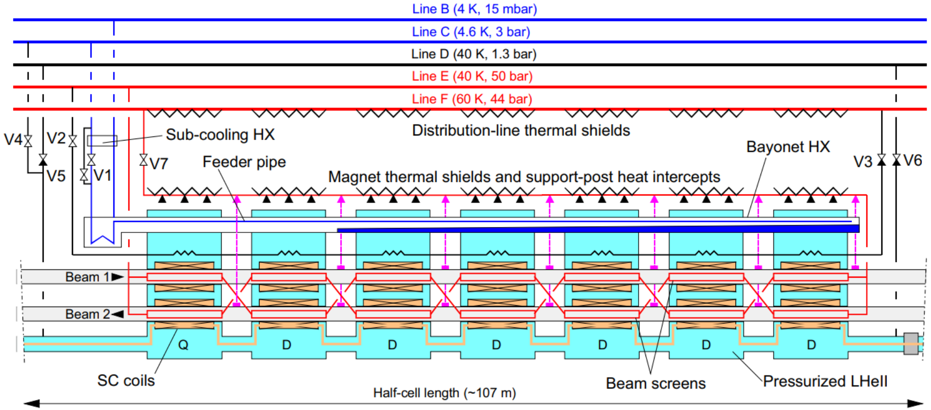
- **12** accelerator cryoplants (PB, PD, PF, PH, PJ, PL))
- **4** high-luminosity insertion region cryoplants (PA, PG) with inner-triplets
- **4** detector cryoplants (PA, PD, PG, PJ)

Heat loads (F14 scenario):

- 1.4 W/m @ 1.9 K
- 43.9 W/m @ 40-60 K
- 3.1 W/m @ 1.9 K for transient AC losses

QRL diameter: 1100 mm
He inventory: ~820 ton

■ → Experiment Cryoplant
● → Technical Point
● → Accelerator Cryoplant
● → Detector Cryoplant
● → Insertion Region Cryoplant
● → Boil-off Reliquefier



Adapted from 2019 CDR (link)

Key numbers on **cooling capacity, electrical consumption and He inventory in L. Delprat's talk on Tuesday** 11h30 on TI: RF and Cryogenics session

Why look beyond baseline @ 1.9 K?

See L. Delprat's talk on Tuesday 11h30 on TI: RF and Cryogenics session!

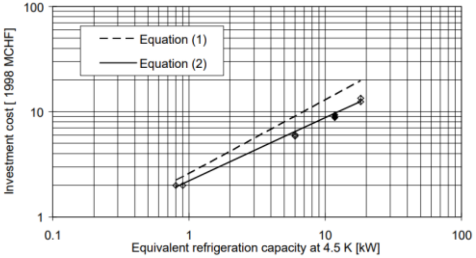
Make FCC-hh more sustainable, by reducing:

Capital cost

Reduce installed cryogenic cooling capacity (↓ kW, ↓ CHF)

Reduce complexity of cryoplant

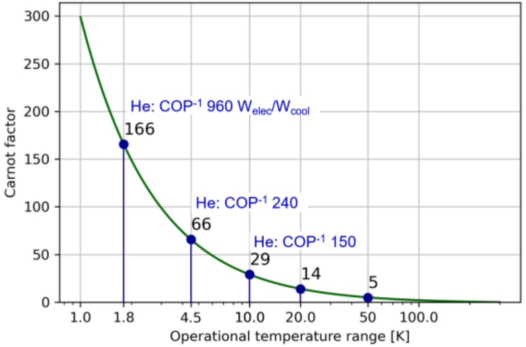
(no He II)



S. Claudet et al., Economics of Large Helium Cryogenic Systems [link]

Operational cost

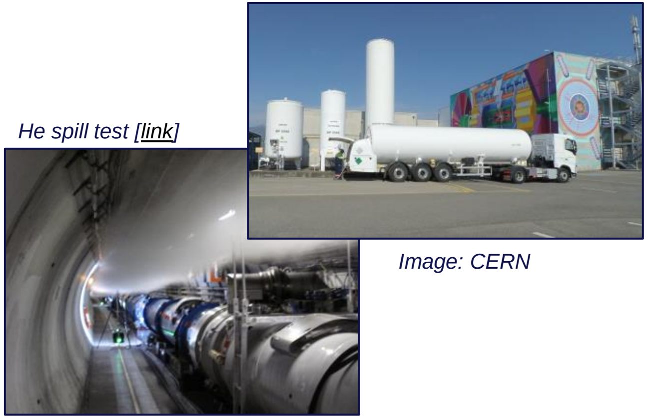
Reduce electrical power consumption (↑ T, ↓ W_{el}/W)



Cryogen inventory

Reduce He inventory overall if opting for conduction cooling (↓ He, ↓ CHF)

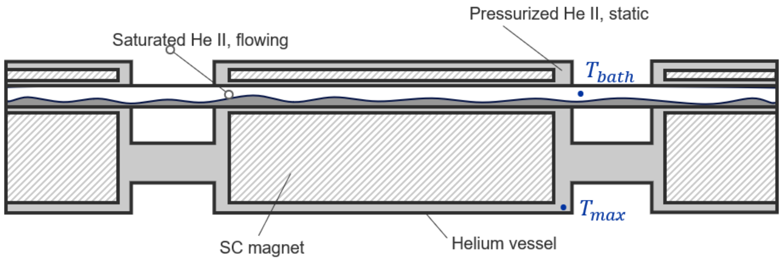
Impact on infrastructure, availability, He delivery logistics, safety risks

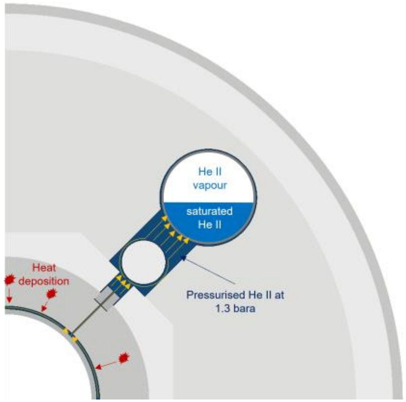


He spill test [link]

Image: CERN

Cooling at 1.9 K *vs.* 4.5 K





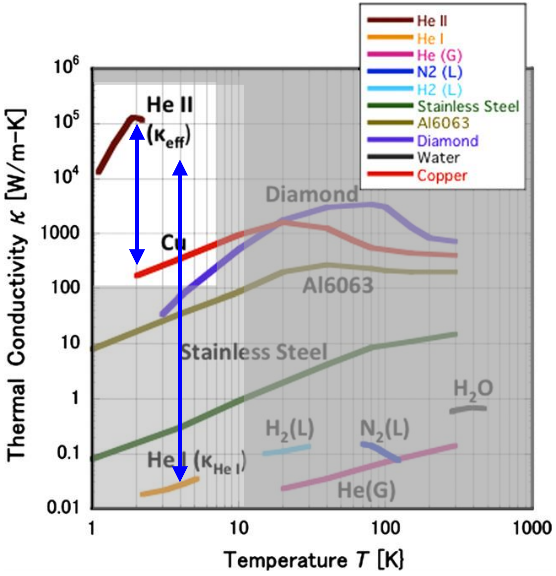
https://edms.cern.ch/document/2864235/1

- 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

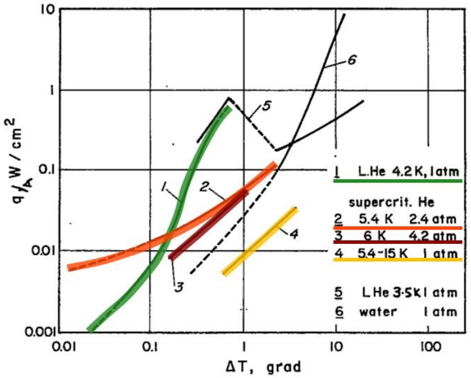
- 👍 Near isothermal along arc/sector
- 👎 Large He inventory in contact with cold mass
- 👎 (some) penetration of He close to coils if immersed
- 👎 Bubbles can form and be trapped
- 👎 Heat transfer of He I

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
- 👎 Non-negligible ΔT radially in cold mass

Single-phase forced flow

- 👍 At 4.5 K, heat transfer comparable (or better) than two-phase
- 👍 Circuit pressure can be 3-4 bar
- 👍 Slope-independent cooling mode
- 👎 Larger temperature gradient along magnet/arc/cell w.r.t. two-phase
- 👎 Non-negligible ΔT radially in cold mass



Free convection!

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

+ if confined to cooling channels:

- Forced flow of supercritical He enables **high heat transfer coefficients**
- Confining He to channels eliminates the need for a cold mass outer shell to be leak tight → **simpler design, Q&A, shorter interconnects**
- By using channels instead of using immersion cooling, one **reduces the He inventory significantly** → impact on He management, logistics, quench, release to tunnel, surface space requirements...

Summary so far:

Develop a cryogenic scheme for FCC-hh at around **4.5 K** by means of **forced flow in cooling channels** using **He in single-phase** (above 3 bar) to extract **steady-state** (static+dynamic) as well as **transient** (ramping) **heat loads** while keeping the warmest spot on the **coil below 5 – 5.5 K**

Heat loads to cryogenic system

We assume the **same static heat loads as CDR** but have **updated the dynamic loads to reflect the F14 scenario**

Updated from 2019 CDR to reflect F14 scenario

Temperature level		$\dot{Q}$ @ 40-60 K [W/m]	$\dot{Q}$ @ 4.5 K [W/m]	$\dot{Q}$ @ 4 K LP [W/m]
Static	Supports	2.4	0.13	
	Radiative insulation		0.13	
	Thermal shield	3.1		
	Feedthrough/vacuum barrier	0.2	0.10	
	Beam screen		0.12	
	Distribution	3.6	0.10	0.24
Total Static		**9.3**	**0.58**	**0.24**
Dynamic	Synchrotron radiation	31.2	0.04	
	Image currents	3.4		
	Resistive heating		0.30	
	Beam-gas scattering		0.45	
Total Dynamic		**34.6**	**0.79**	
Ramping	Magnetization losses		3.13	
Total without magnetization losses		**43.9**	**1.37**	**0.24**
Total with magnetization losses		**43.9**	**4.5**	**0.24**

Total heat load

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

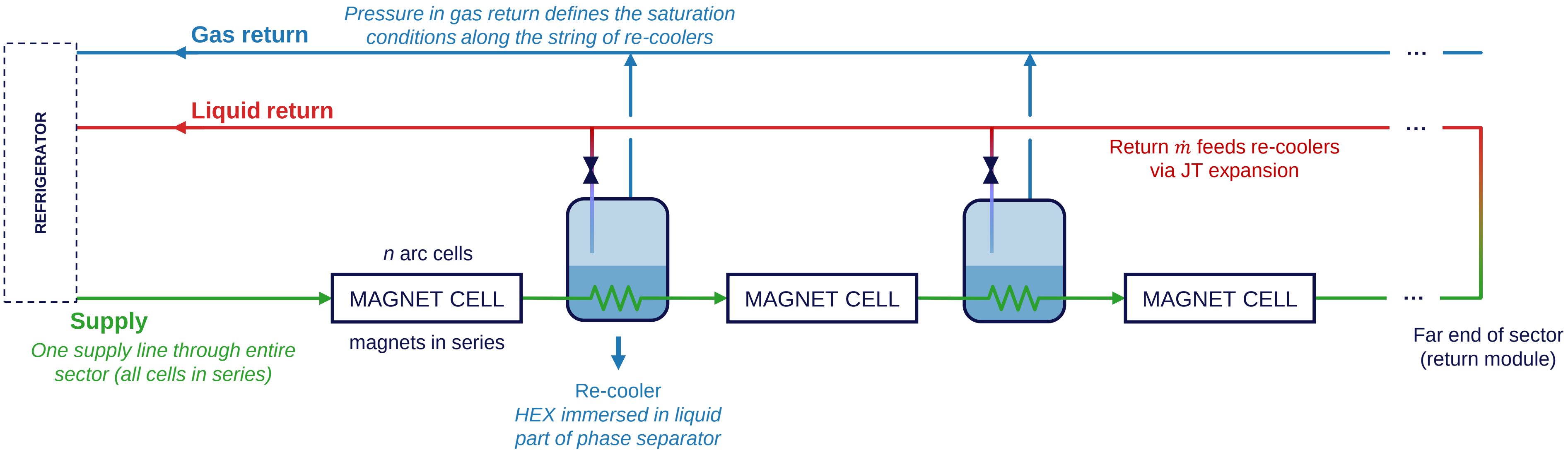
Steady-state loads
(from CDR table, updated to F14)

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

- **Transient loads** (AC losses from ramping) are assumed to be **10 kJ/m** for a full ramp-down/up 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 the CDR (3200 s for full cycle)

* State-of-the-art conductor has losses that result in 20 kJ//m per cycle per double aperture magnet

Proposed cooling scheme



Gas return

Pressure in gas return defines the saturation conditions along the string of re-coolers

Liquid return

Return $\dot{m}$ feeds re-coolers via JT expansion

REFRIGERATOR

n arc cells

MAGNET CELL

MAGNET CELL

MAGNET CELL

…

magnets in series

Supply

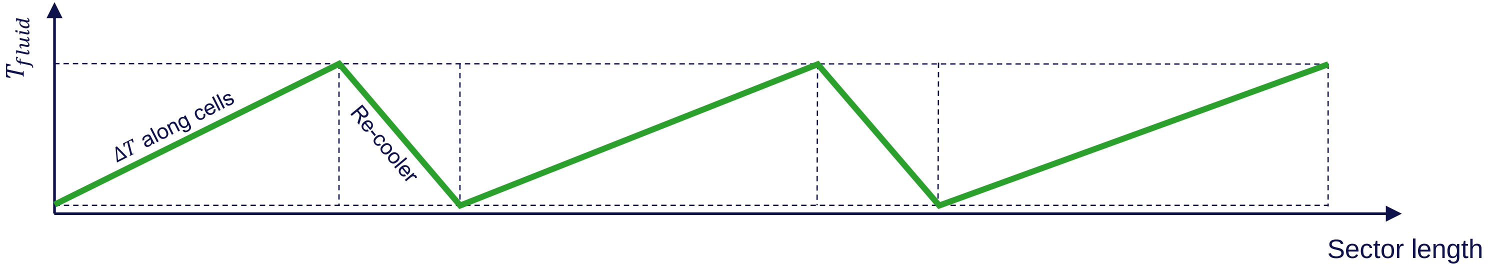
One supply line through entire sector (all cells in series)

Re-cooler

HEX immersed in liquid part of phase separator

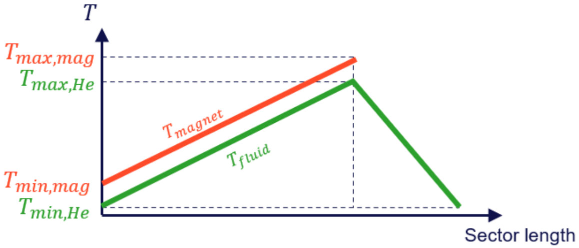
Far end of sector
(return module)

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



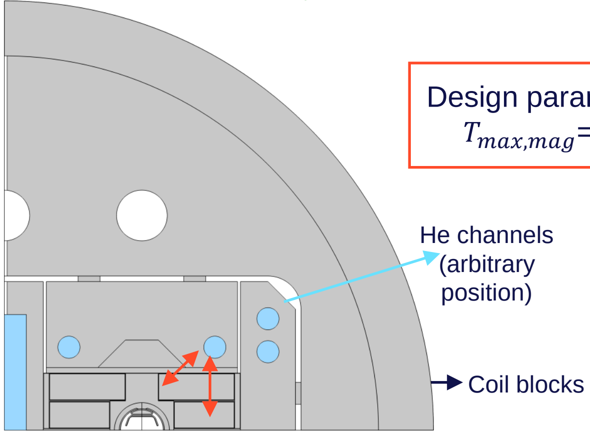
Let’s talk about temperature gradients

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**



Design parameter [HFM]:
$T_{max,mag}$ = 5 – 5.5 K

BOND 14 T block coil design, courtesy TE/MSC-SMT

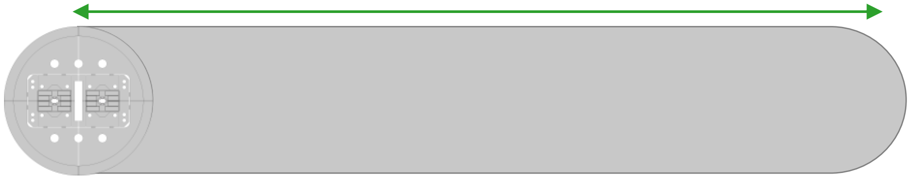


Radial gradient:

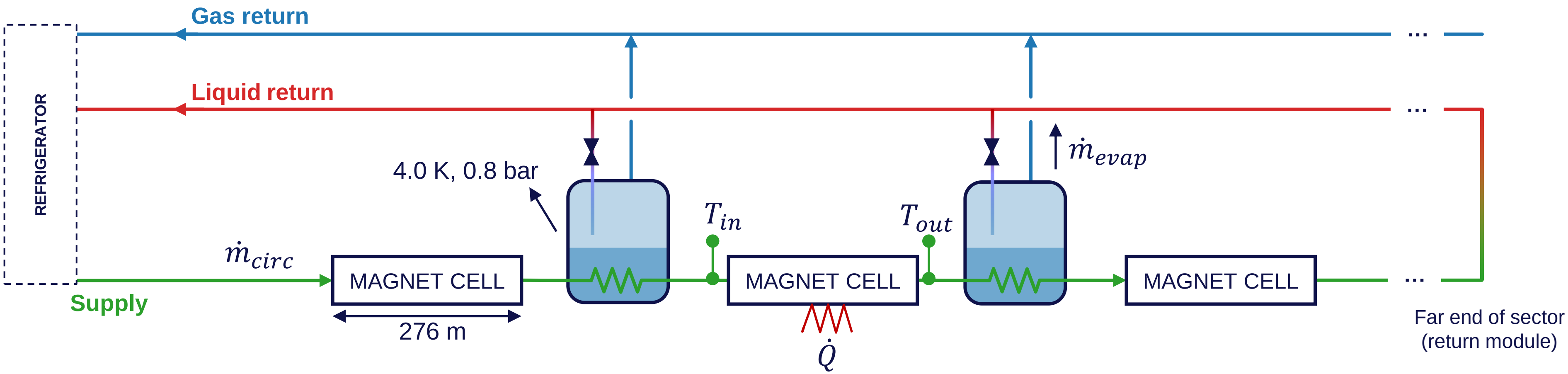
- Between the heat sink (e.g. He inside cooling channel) and the magnet coil/cold mass
- Depends on the solid materials between the coil and the heat sink, contact forces and thermal contact resistance
- **Heavily dependent on the magnet design**

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



Longitudinal ΔT: sizing the cryogenic system



Considering a 276 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	1.37	379	4	**4.1**	**4.5**	**0.4**	~306	~22

It would be easy if only steady-state heat loads!

How to buffer the hysteresis losses?

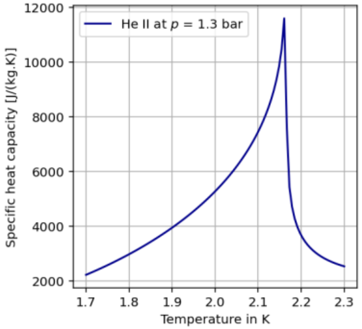
Using He II at 1.9 K

- 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

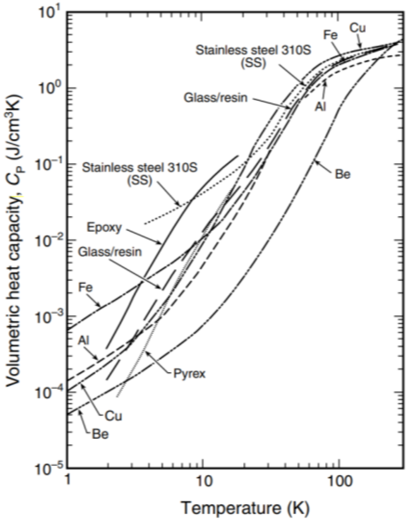
- **c_p of solid materials is insufficient** to absorb the extra heat load due to ramping

  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

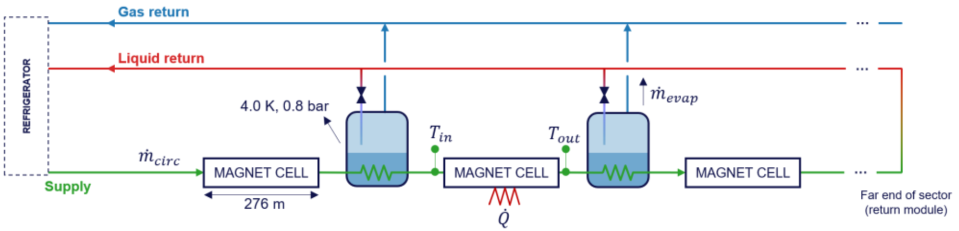
  Example: To buffer **10 kJ/m** and keep the temp. between 4.5 K and 5 K, using the c_p of He at 3 bar, **30 litres/m** are needed (4.2 kg/m)

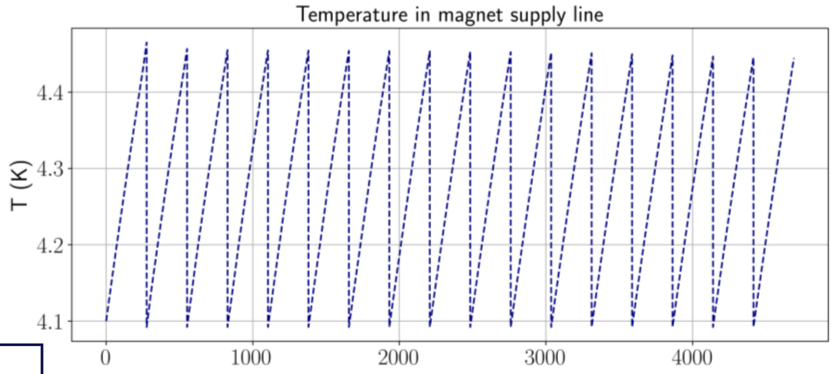
- **Increase circulating $\dot{m}$** of He in the magnets to extract full steady-state + ramping heat load, **increase installed cooling capacity** depending on allowed recovery time



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

Longitudinal ΔT: accounting for ramping losses





- **Large circulating $\dot{m}$** to extract the steady-state + ramping heat loads
- Re-coolers maintain constant level → **installed cryo capacity is 3x what is required in steady-state** !!
- If upper limit on **coil *T* increases to 5.5 K**, cold compressors can be suppressed!

Considering a 276 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 + ramping (constant re-cooler level)	4.5	1242	4	**4.1**	**4.5**	**0.4**	~857	~62

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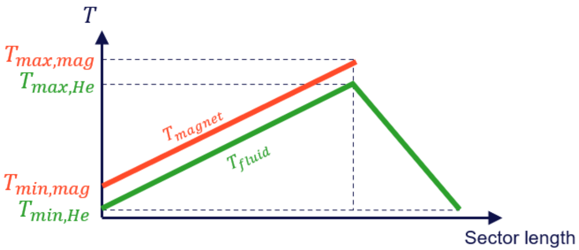
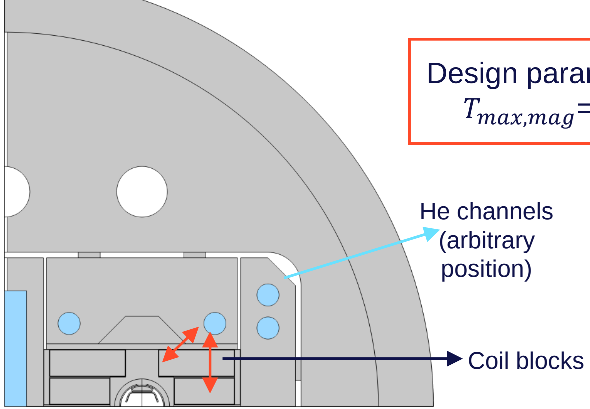


BOND 14 T block coil design, courtesy TE/MSC-SMT



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Longitudinal gradient:

- Temperature increase along the length of a magnet and along the string of magnets (arc cell)
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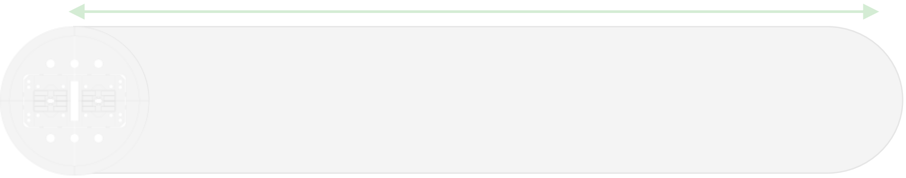
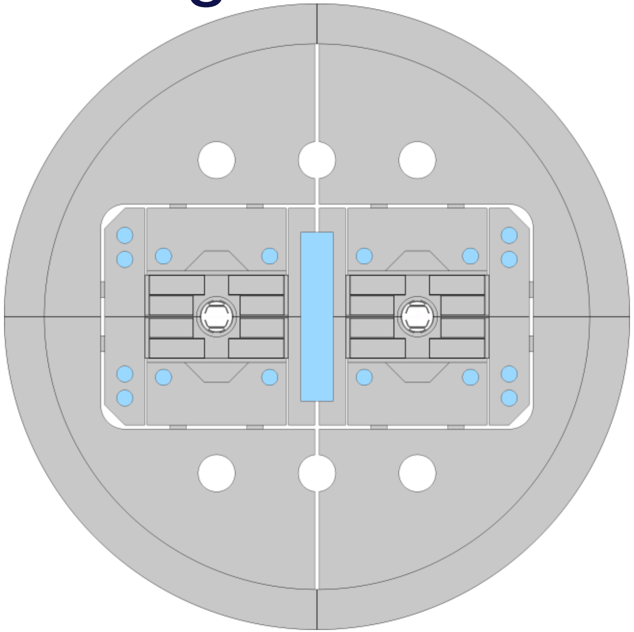
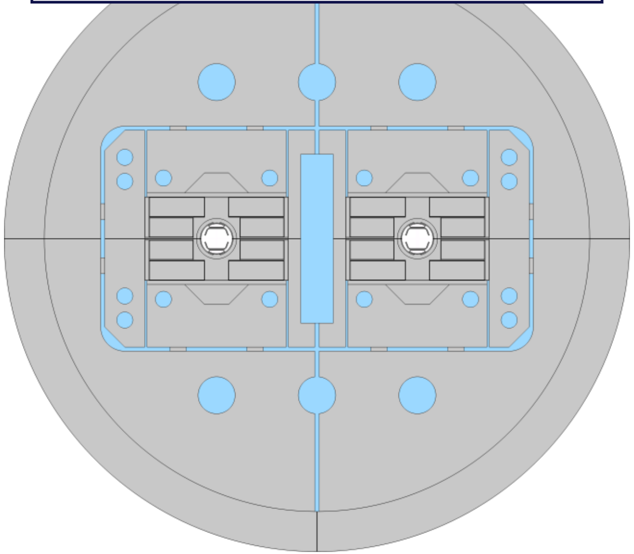


Cooling channels *vs.* “wet” flow





This configuration means **2x the He inventory** w.r.t. cooling channel option!

Cooling channels

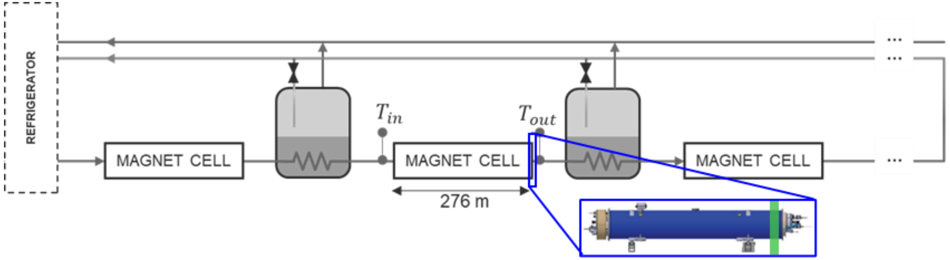
- He is confined to **cooling pipes** places close to the coil
- Rest of cold mass (white spaces) **is in vacuum**; no need for thick He vessel withstanding ~20 bar

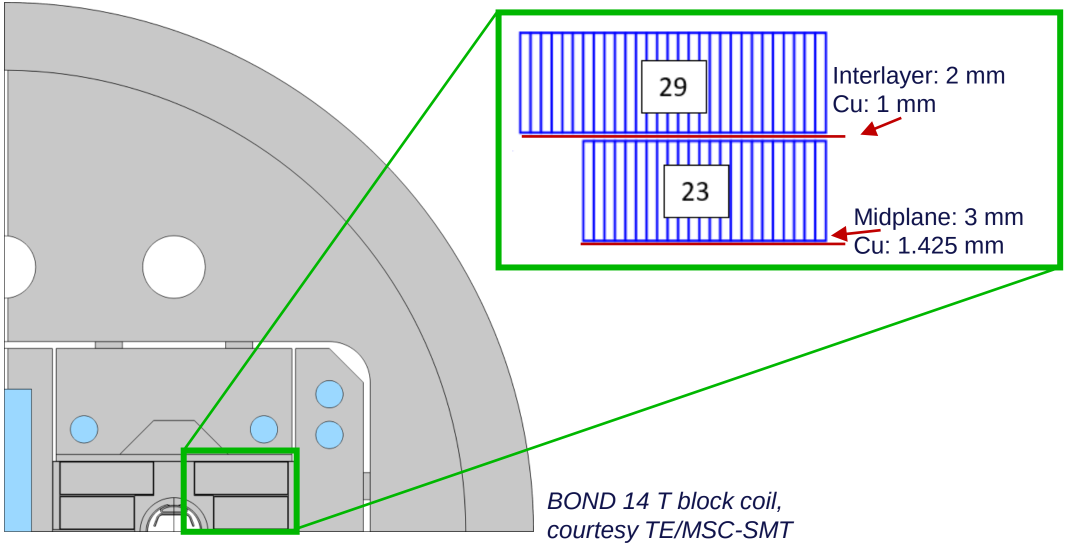
“wet” flow design

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

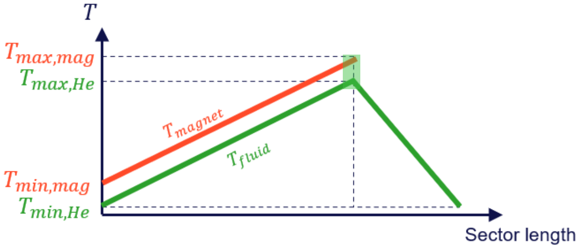
Thermal modelling of radial ΔT

- Studies based on latest BOND coil configuration using 40 strands cable
- Added Cu (RRR10) **heat sinks** to both midplane and interlayer – insulation ≥ 150 μm to coil
- Upgraded thermal contact geometry: **Helium thermal contact** (He at 4.5 K, α ~ 900 W/m^2.K)



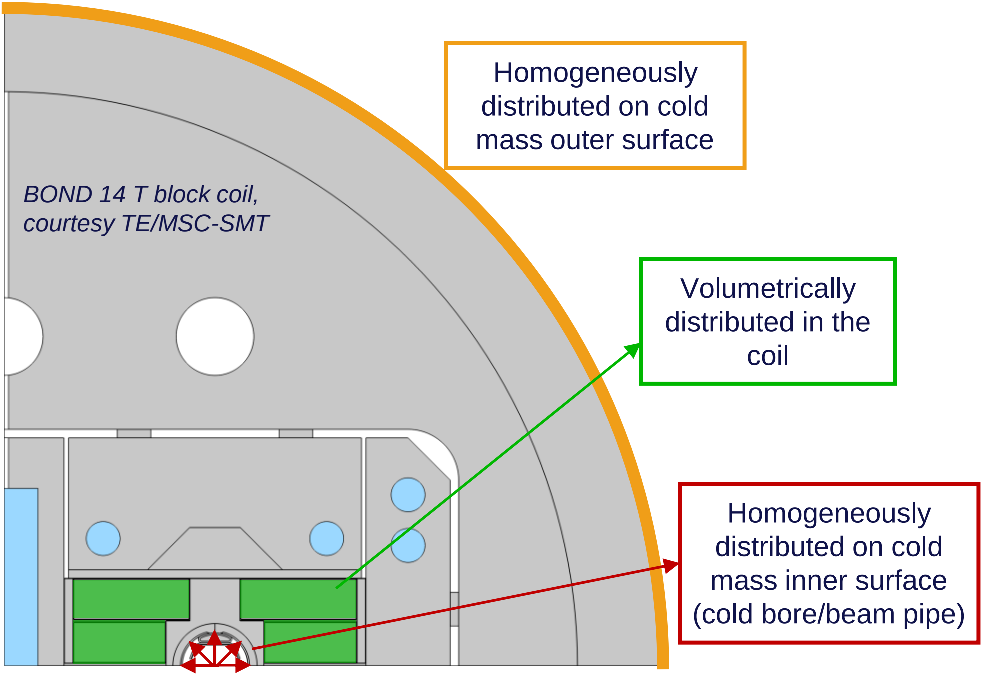


BOND 14 T block coil, courtesy TE/MSC-SMT



Thermal modelling of radial ΔT

- Heat loads on the cold mass applied to the cross-section model:



BOND 14 T block coil, courtesy TE/MSC-SMT

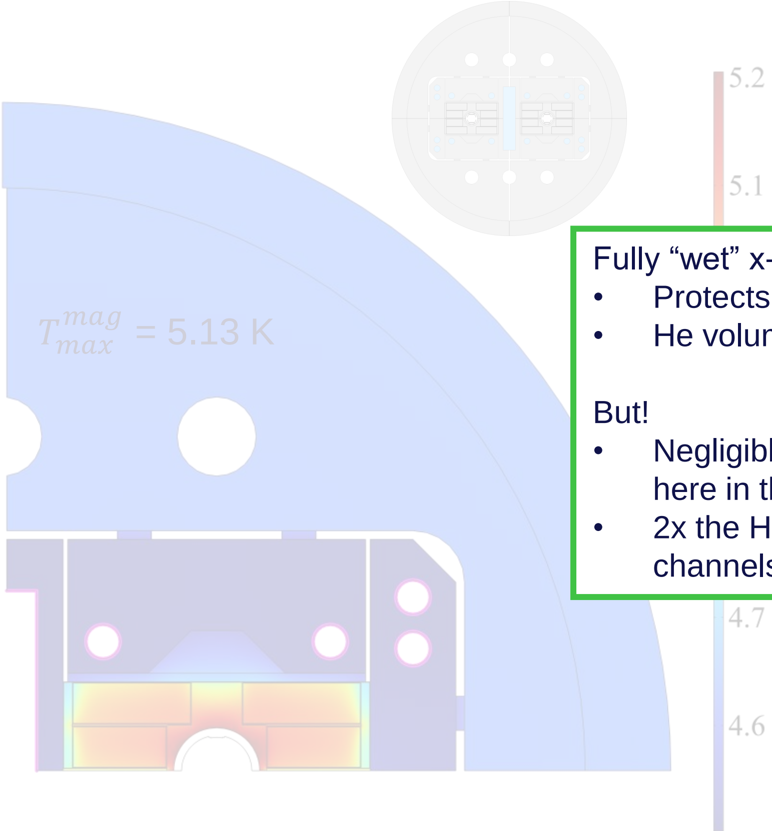
Homogeneously distributed on cold mass outer surface

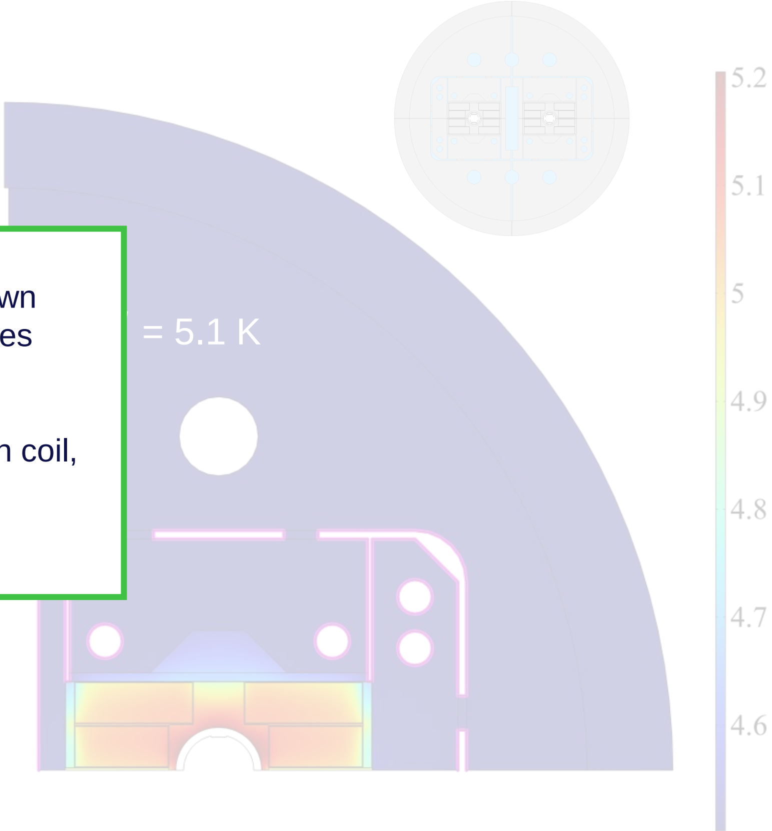
Volumetrically distributed in the coil

Homogeneously distributed on cold mass inner surface (cold bore/beam pipe)

F14 scenario heat loads to cold mass		**$\dot{Q}$ @ 4.5 K [W/m]**
Static	Supports	0.13
	Radiative insulation	0.13
	Feedthrough/vacuum barrier	0.10
	Beam screen	0.12
	Distribution	0.10
Dynamic	Synchrotron radiation	0.04
	Resistive heating	0.30
	Beam-gas scattering	0.45
Ramping	Magnetization losses	3.13
Total without magnetization losses		1.37
Total with magnetization losses		4.5

Radial ΔT: Cooling channels *vs.* “wet” x-section





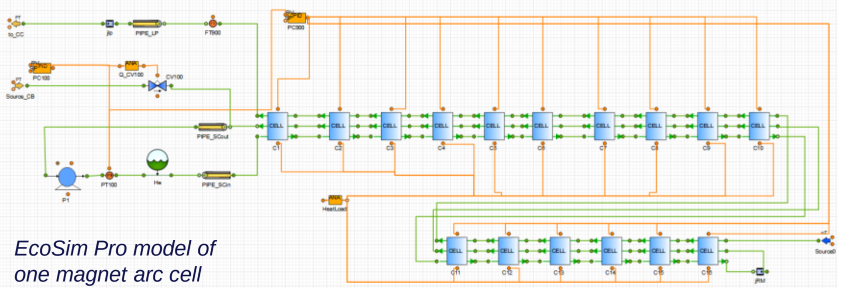
Fully “wet” x-section has advantages:

- Protects against voltage breakdown
- He volume to buffer ramping losses

But!

- Negligible reduction in radial ΔT in coil, here in the order of ~30 mK
- 2x the He inventory w.r.t. cooling channels

Simulation workflow



EcoSim Pro model of one magnet arc cell

Global inputs:

Parameter	Value	Units
Cell length	276	m
Hydraulic diameter	30.4	mm
He-filled cross section area	65.4	cm^2
Inlet pressure	**4.1**	**bar**
Initial pressure	4.1 - 4.07	bar
Initial T	4.1 – 4.16	K
Mass flow rate	**0.79**	**kg/s**
Roughness	15	μm

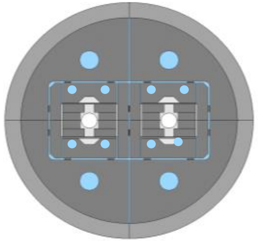
1D-transient single-phase flow model

- Solves compressible flow equations (mass, momentum, energy conservation, gas state equations)

$T_{He}(t), \alpha(t)$ at magnet cell end

2-D
Cross section
Geometry

Material data



2D-transient solid heat transport model

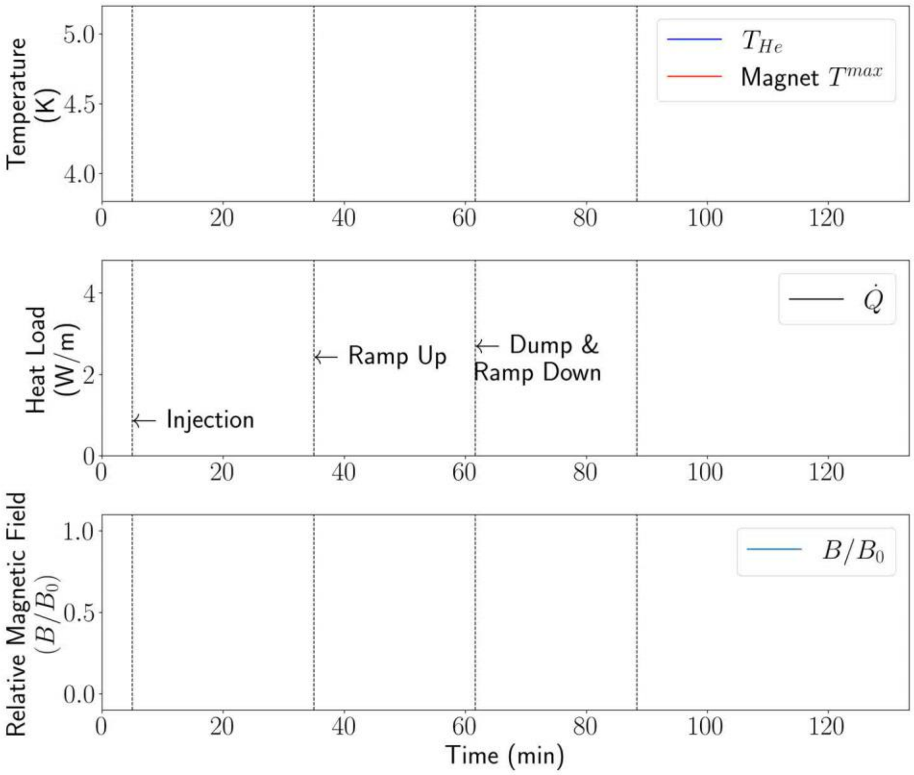
- Solves energy conservation with flow equations (mass, momentum, energy conservation, gas state equations).
- Convective heat transfer boundary condition at cooling channel:

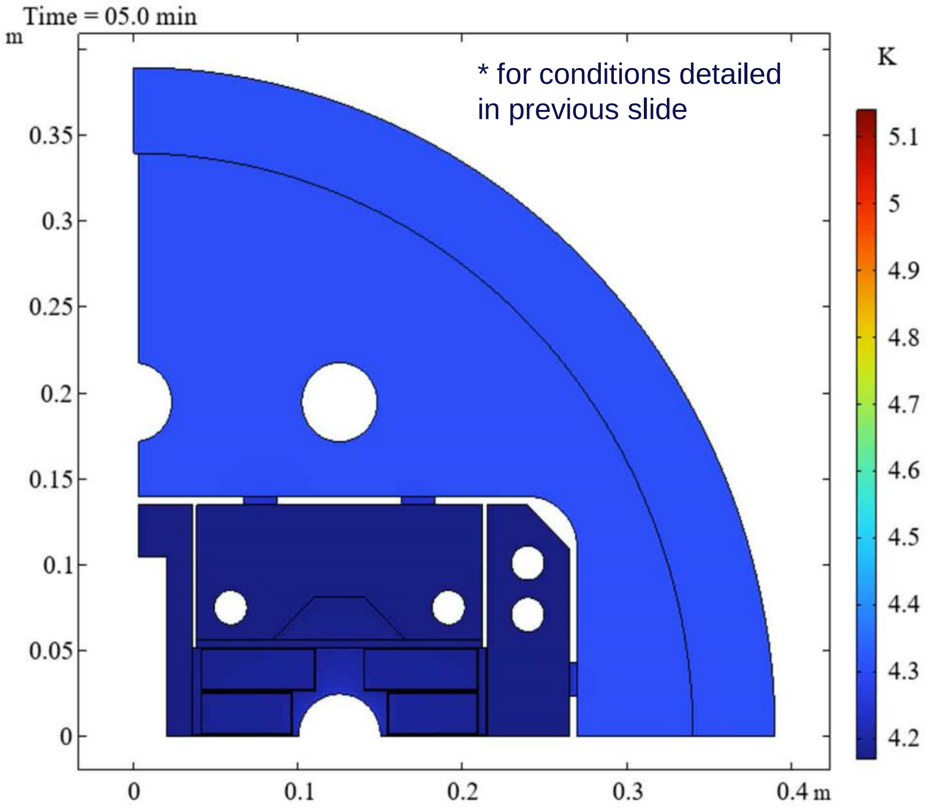
$$-\kappa(T)\nabla T \cdot n = \alpha\big(T - T_{He}(t)\big)$$

Global useful outputs:

- Maximum T_{Magnet}
- Radial T gradient

T evolution of cold mass during emergency cycle




* for conditions detailed in previous slide

Consequences of change of cooling paradigm

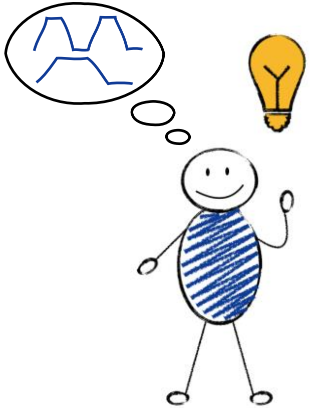
- 👍 Forced flow in confined channels means **the cold mass no longer needs to be a pressure vessel**; simplification of geometry and requirements
- 👍 Working point at 4.5 K instead of 1.9 K allows for intrinsic (Carnot) and technological (cold compressors) **improvement in the cryogenic COP**
- 👍 Proposed cooling scheme allows for a **reduction of ~40% in energy consumption and ~50% in He inventory**
- 👍 By limiting the contact between He and coil to the cooling channels, **impact of quench energy on cooling circuit limited**
- 👍 By avoiding the He I ↔ He II transition, **recovery time after a quench event potentially reduced**

- 👎 Intrinsic **longitudinal temperature gradient** along the length of the magnet/sector
- 👎 **Enthalpy reservoir** provided by large mass of LHe **is no longer available if keeping minimal He amount in channels**
- 👎 **Radial temperature gradient** inside the cold mass is more significant than when using He II

To do list:

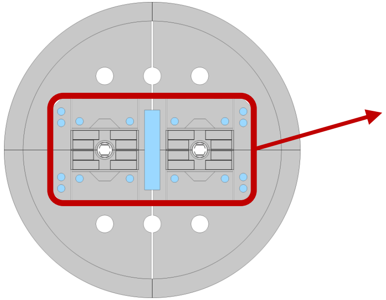
- **Refine cryogenic cooling scheme:** looking into optimization of the installed cooling capacity, operating pressure, He content, etc.
- **Study transients** such as **cooldown** from room temperature and **recovery after a quench** event
- **Analyze pressure rise** in the cooling channels/cold mass **during a quench** and identify hotspot temperature

- The **main challenge** for this low He inventory cooling scheme is the **magnet ramp up/down losses** – how much can we negotiate the duration of the cycle or waiting times between ramping?
- Can we negotiate the **maximum allowed temperature on the coil from 5 K up to 5.5 K**?



- Concerns over **dielectric breakdown** in a vacuum insulated magnet coil: determine if truly dry coil is a dealbreaker, compromise could be “local” Helium chamber (only in pads area as shown for example)? Impact on mechanical structure?

- Influence of **beam tube at 4.5 K instead of 1.9 K**: questions raised concerning effective pumping of H_2 from beam vacuum space



Leak tight He vessel around the immediate structure around coil?

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 390 tons** (~3x LHC) **is lower** than baseline at 1.9 K (820 tonnes, **~**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 276 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 half of the gradient is radial) → results shown are for a non-optimized cross-section!

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THANK YOU FOR YOUR ATTENTION!

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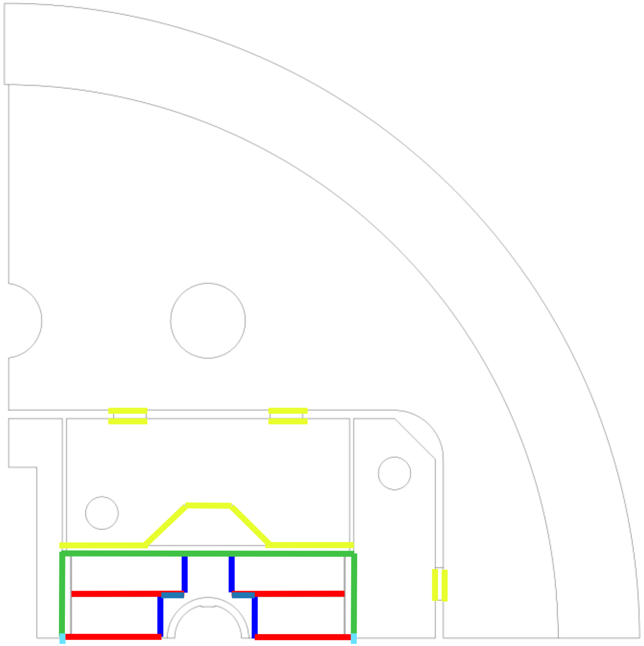
Spare slides

Thermal modelling of radial ΔT in BOND magnet

- Preliminary evaluation adding **thermal contact resistance** to the model
- Thermal contact resistance data spans wide range and **appropriate combination of materials is often missing**.

Thermal contact materials		Value (W/m^2K)	Remarks
Ti	G-10	**50**	**Extrapolated to 4.5 K from [30-300 K] data. [1]**
Cu	G-10/dielectric/kapton	**500**	**Interp. to 4.5 K from Cu/Epoxy data. [2]**
Stainless Steel	G-10/dielectric/kapton	**15**	**Interp. to 4.5 K from SS/SS data. [2]**
Al	Fe	**200**	**Interp. 4.5 K from Al/Al data. [2]**
SS	Fe	**40**	**Similar order of magnitude. From SS/SS data at 20 K [2]**
Ti	Cu	**200**	**Extrapolated to 4.5 K from Cu/C data at 20 K [2]**
Cu	Fe	**200**	**Extrapolated to 4.5 K from Cu/C data at 20 K [2]**



[1] De Bellis, L., Phelan, P.E., Drake, P., Kroebig, W. (2000). *Measurement of The Thermal Properties of Epoxied Titanium Contacts at Cryogenic Temperatures.*

[2] E Gmelin *et al.* (1999) *J. Phys. D: Appl. Phys.* **32** R19

The Superconducting Super Collider (SSC)

Accelerator magnet cooling at around 4 K

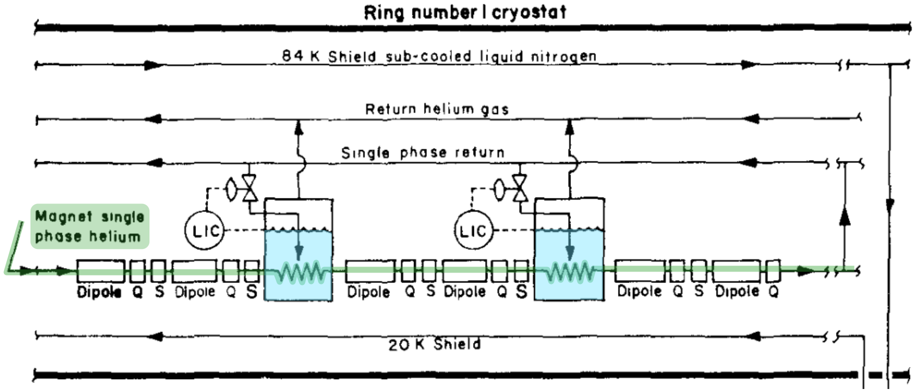
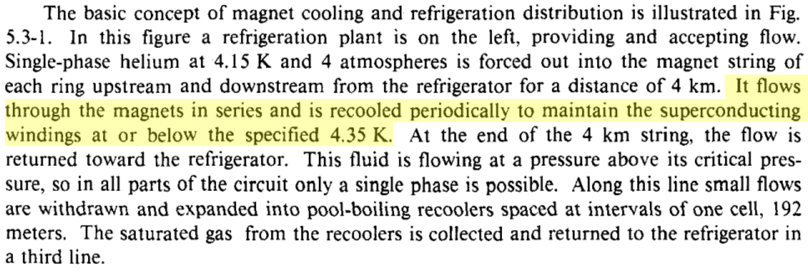
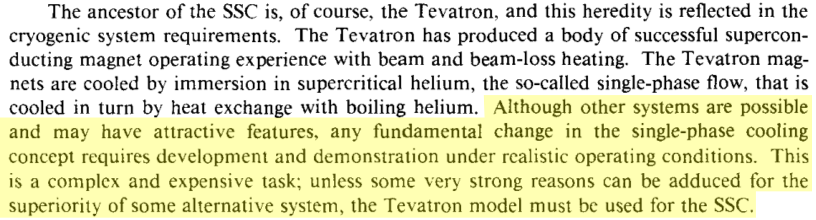


Figure 5.3-1. A conceptual representation of the SSC collider rings cryogenics system. In each of the two rings the collider magnets are cooled in series by a flow of single-phase helium. This stream is recooled at cell intervals by heat exchange with boiling helium. The cryostat of each ring contains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

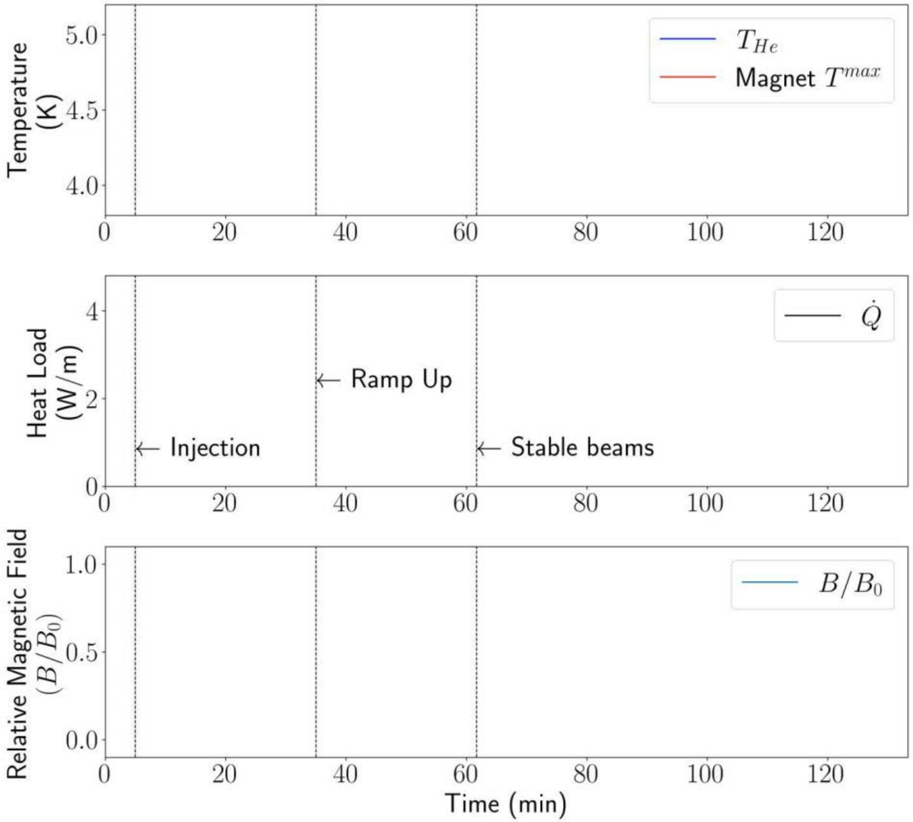

The basic concept of magnet cooling and refrigeration distribution is illustrated in Fig. 5.3-1. In this figure a refrigeration plant is on the left, providing and accepting flow. Single-phase helium at 4.15 K and 4 atmospheres is forced out into the magnet string of each ring upstream and downstream 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.

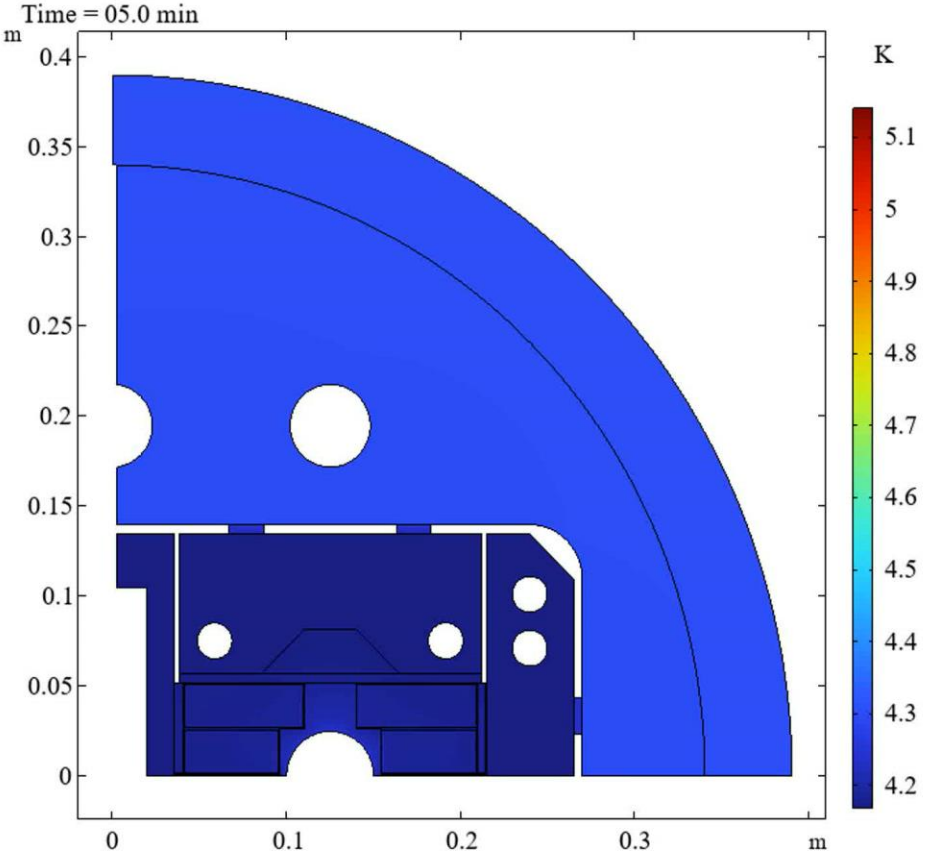
Tevatron → SSC → … FCC ?


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.

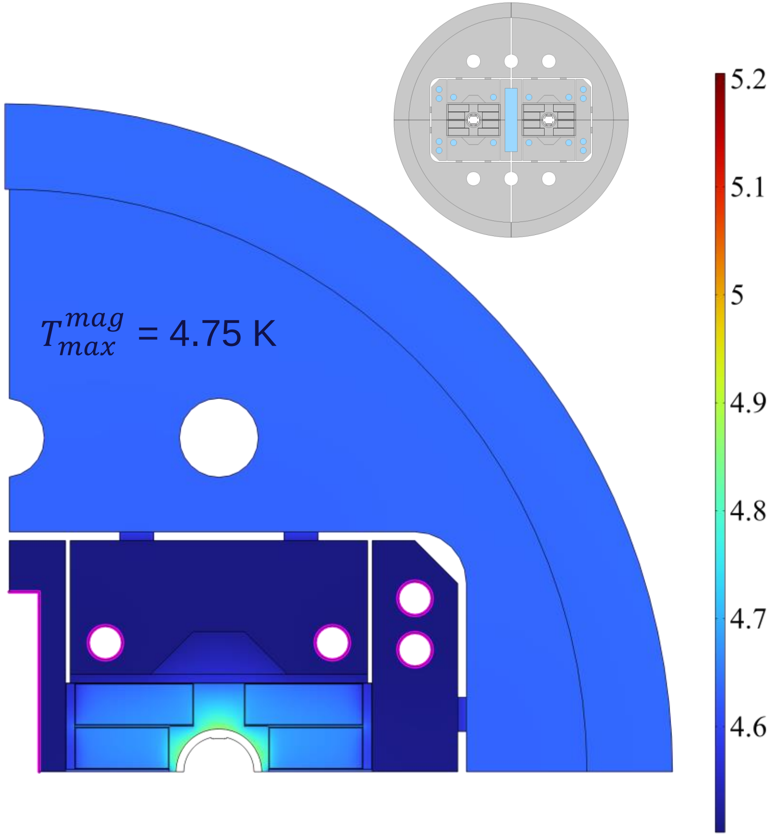
Conceptual Design of the Superconducting Super Collider, 1986

T evolution of cold mass during nominal cycle



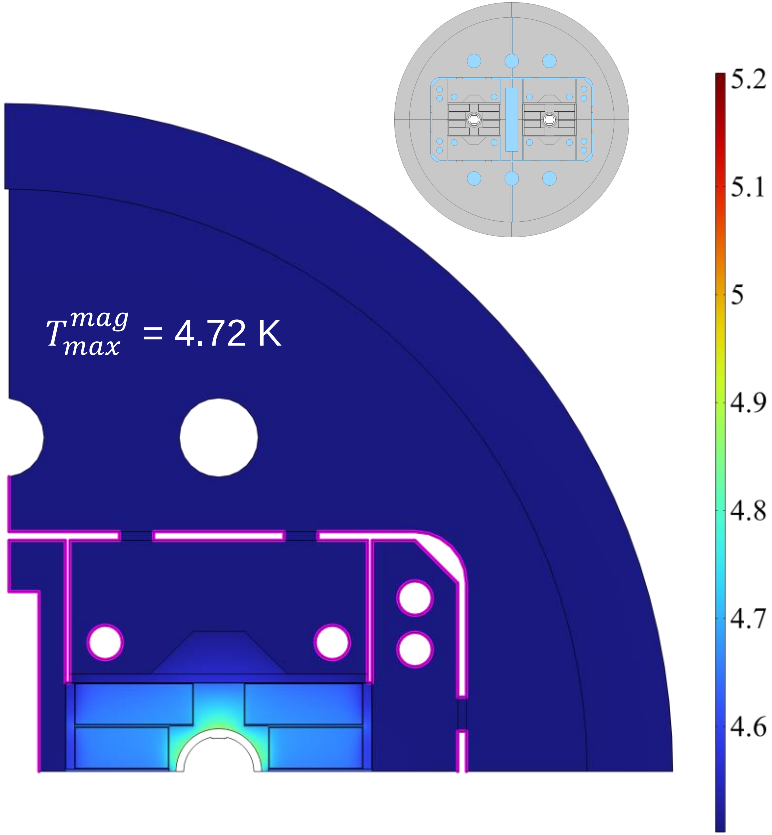


Radial ΔT: Cooling channels *vs.* “wet” x-section



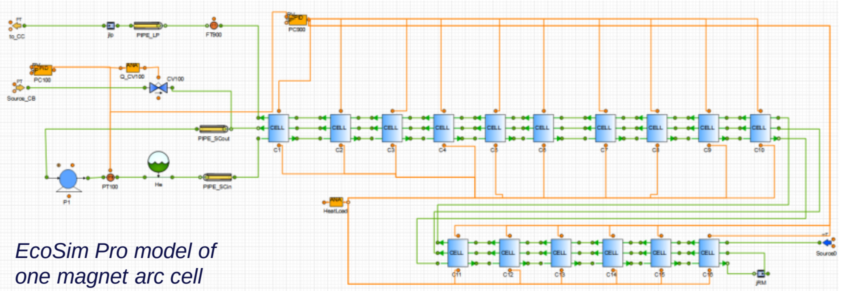
T_{max}^{mag} = 4.75 K

T profiles simulated for a **steady-state heat load of 1.4 W/m** distributed as detailed in previous slides, with T_{He}= 4.5 K



T_{max}^{mag} = 4.72 K

Further assumptions for 1- and 2-D simulations



EcoSim Pro model of one magnet arc cell

1D-Transient Supercritical Flow Model

- Pipe wall receives homogeneously distributed heat load.
- Conduction heat transfer in helium and wall neglected (only convective).
- Pressure drop scheme modeled as an equivalent pipe sytem with cross – section informed hydraulic diameter and He-wetted area.

2D-Transient Solid Heat Transport Model

- No heat transport in axial direction (Infinite cross section)
- Uncertainty on thermal contact resistance.