Ramblings on superconducting magnet cooling for accelerators
(based on CAS-course Austria-2023)

TE-MSC seminar – CERN 15-02-2024

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- Introduction
    1. Intent
    2. Main cooling-option drivers
- Temperature levels
    1. Introduction
    2. Cryogenic fluids
- Helium as a cold-source
    1. Phase diagram
    2. Intermezzo HeII - conduction through superfluid helium (HeII)
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- Intermezzo: Magnet-examples
- Temperature levels
    1. "Why do we need to talk about it"
    2. "That's why we need to talk about it"
- Fully immersed in HeII:
- LHC dipoles and HL-LHC cable-stacks
- Bayonet HX cooling scheme
- Numerical tool & application to HL-LHC Nb3Sn quadrupoles
- Helium availability and typical LHC reliance (fully immersed magnets)
- Food for thought of operating fully helium immersed accelerator magnets
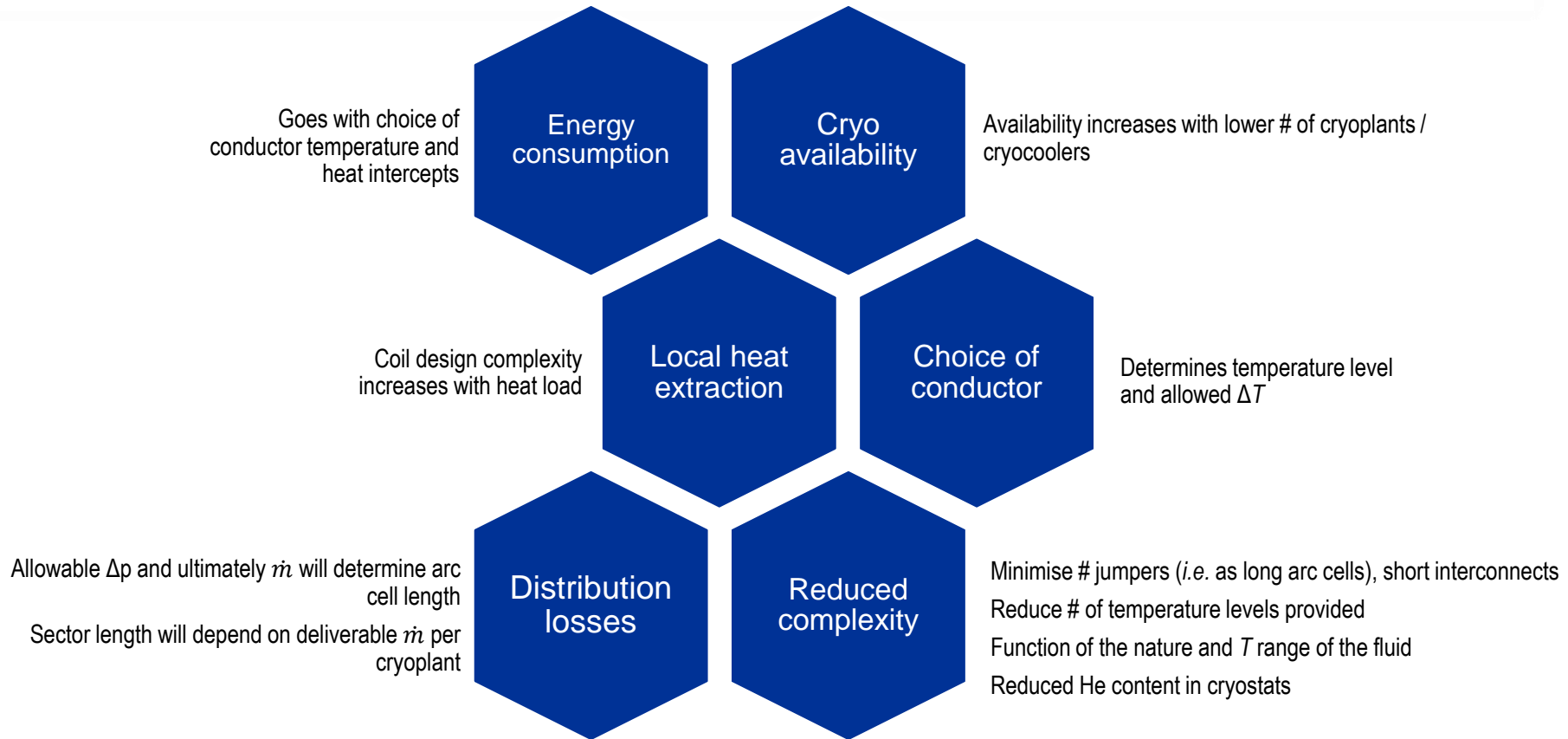- Some points to remember
- References

Introduction: Intent

The intent is to introduce *aspects of cryogenics* that enter the reflection of choosing a development direction when tasked with a superconducting magnet design.

We'll *familiarize* you with the major elements involved that arise in a coherent/optimized design *satisfying the magnet performance requirements on the one hand and on the other hand the cryogenic drivers of sustainability* (i.e. minimizing operational cost, infrastructure, complexity), safety constraints,…

The talk reflects my personal opinion

Introduction: main cooling-option drivers

Goes with choice of conductor temperature and heat intercepts

Energy consumption

Cryo availability

Availability increases with lower # of cryoplants / cryocoolers

Coil design complexity increases with heat load

Local heat extraction

Choice of conductor

Determines temperature level and allowed ΔT

Allowable Δp and ultimately $\dot{m}$ will determine arc cell length

Sector length will depend on deliverable $\dot{m}$ per cryoplant

Distribution losses

Reduced complexity

Minimise # jumpers (*i.e.* as long arc cells), short interconnects

Reduce # of temperature levels provided

Function of the nature and T range of the fluid

Reduced He content in cryostats

All "drivers" are interlinked, even if not shown adjacent

We'll mainly focus on Energy consumption & Local heat extraction

Temperature levels: introduction

Superconducting magnets come in *many variants and applications* ranging from small medical devices, motors, wind-power generators, huge particle detectors and plasma containing structures to km-long particle accelerators,…

The most common superconductors, NbTi, Nb_3Sn, MgB_2, HTS making up the magnet coils *generally operate at temperatures from 1.9 K – 4.5 K – 20 K < 77 K*

Temperature levels: Cryogenic fluids

THERMOPHYSICAL PROPERTIES

The choice of cryogenic fluid in the cooling system is principally driven by:

1. T_b: boiling temperature at atmospheric pressure of 1.013 bar
   - The boiling temperature provides a fixed *"base reference temperature"* for the cooling system. It will be the lowest temperature available. All cooled devices, will function at *slightly higher temperatures* depending on implementation specifics.

Coil @ T_{coil}

$\Delta T = T_{coil} - T_b$

cold-source @ T_b

Power
Q (W)
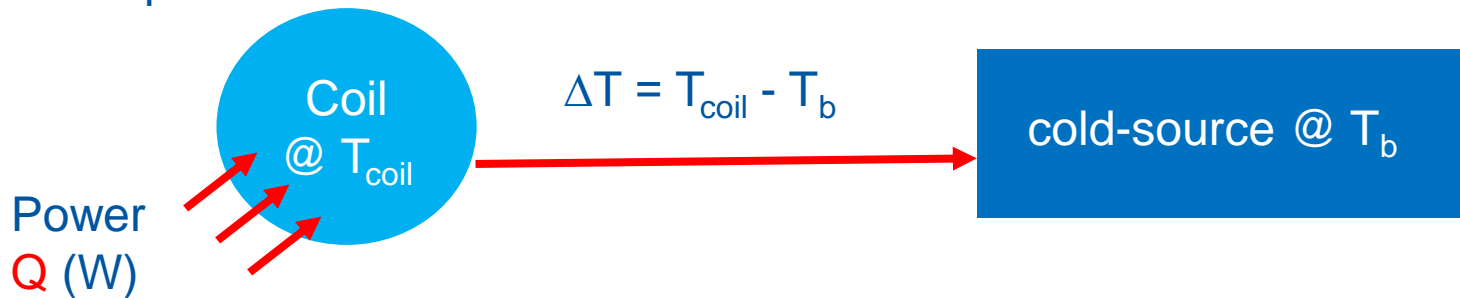
The ΔT originates from an accumulation of: conduction through solid material, solid-fluid interface resistances, conduction though cooling fluids, pressure drops in the cooling fluid system

Temperature levels: Cryogenic fluids

THERMOPHYSICAL PROPERTIES

The choice of cryogenic fluid in the cooling system, is principally driven by *(not counting distribution losses)*:

2. The latent heat "L_h" of evaporation at T_b (kJ/kg)
   - The latent heat determines the rate of liquid to evaporate per power at cold

   21 W for 1 g/s of helium   @   4.2 K
   199 W for 1 g/s of nitrogen @ 77   K

$$\frac{dm}{dt} = \frac{Q}{L_h}$$

Temperature levels: Cryogenic fluids

THERMOPHYSICAL PROPERTIES

Fluid	⁴He	N$_2$	Ar	H$_2$	O$_2$	Kr	Ne	Xe	Air	Water
Boiling temperature 1.013 bar (K)	4.2	77.3	87.3	20.3	90.2	119.8	27.1	165.1	78.8	373
Latent heat (evaporation a Tb) kJ/kg	21	199.1	163.2	448	213.1	107.7	87.2	95.6	205.2	2260
Ratio volume gas (273 K) /liquid	709	652	795	798	808	653	1356	527	685	-----
Specific mass of liquid (at Tb) – kg/m^3	125	804	1400	71	1140	2413	1204	2942	874	960

Given the present use of superconductors for accelerators (NbTi, Nb$_3$Sn) helium is applied as main cooling fluid, with sometimes nitrogen for thermal shields.
Future HTS use might open-up the use of liquid hydrogen (but has many issues to be solved).

Temperature levels: Cryogenic fluids

Comparison:

1L LHe: ≈ 12 - 50 € and *rising/fluctuating*

1L LN_2: ≈ 0.1 €

Quantity to cooldown 1 kg of stainless steel

Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 litre	0.75 liter
LHe from 77 to 4.2 K	1.46 litre	0.12 litre
LN2 from 290 to 77 K	0.45 litre	0.29 litre

Helium as a cold-source: phase-diagram

Phase diagram of helium

CERN AC - CR106 - 13/03/96

Helium behaves as any "normal-fluid in the domain indicated by HeI ("normal helium")

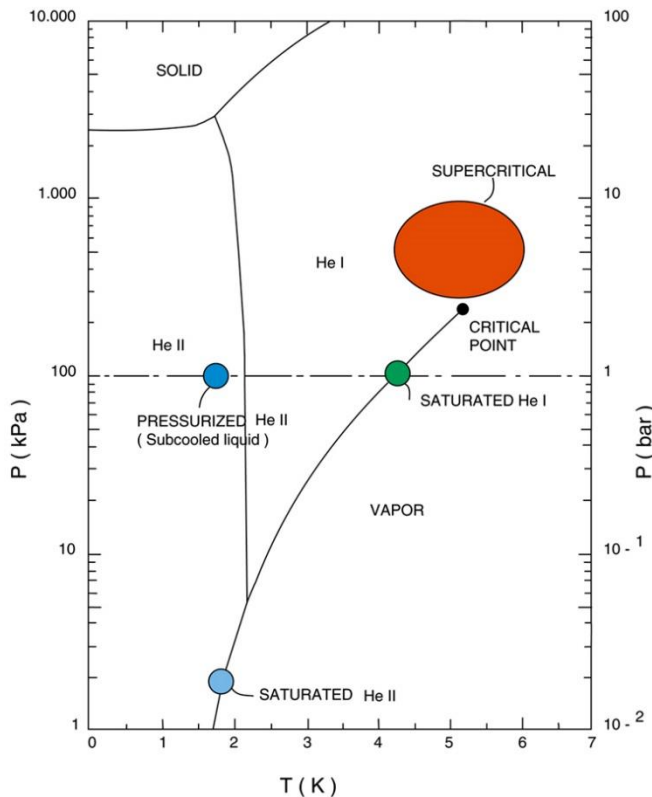Helium behaves as a "super-fluid" in the domain indicated by HeII ("superfluid helium")

Working domain of saturated helium II is along the saturation line from (starting from 5.0 kPa & 2.17 K, to typically 1.6 kPa & 1.8 K)

Working domain of pressurised helium II, by subcooling liquid at any pressure above saturation, typically near atmospheric pressure (100 kPa).

Additional advantage of functioning in pressurized superfluid helium is that subatmospheric pressures are avoided, thus minimizing the impact of air-inleaks, and the good electrically isolating properties (compared with low pressure helium).

Helium as a cold-source: phase-diagram

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Helium as a

Phase diagram of helium showing SOLID, He I, He II, SUPERCRITICAL, VAPOR regions with CRITICAL POINT, SATURATED He I, PRESSURIZED He II (Subcooled liquid), SATURATED He II labeled. Axes: P (kPa) / P (bar) versus T (K). CERN AC - CR106 - 13/03/96

Advantages of functioning in pressurized superfluid helium w.r.t. saturated helium

• pressurised helium II can absorb heat, up to the temperature at which the lambda-line is crossed. saturated helium II, which is slightly subcooled due to the hydrostatic head below the surface of the liquid bath, absorbs heat up to the point at which the saturation line is crossed.

--> The enthalpy difference from the working point to the transition line is usually much smaller in the saturated helium bath. One typically could get an order of magnitude better performance in pressurised helium II (see ref).

• sub-atmospheric pressures are avoided, thus minimizing the impact of air-inleaks.

• both liquids have good electrically isolating properties but low vapour areas, possible when using saturated helium, are prone to electrical breakthrough ("Paschen-curve").

ref: B. Rousset & F. Viargues, An alternative cooling scheme for the TeV superconducting linear accelerator project, Cryogenics 34 ICEC Supplement (1994) 91-94

Helium as a cold-source: phase-diagram
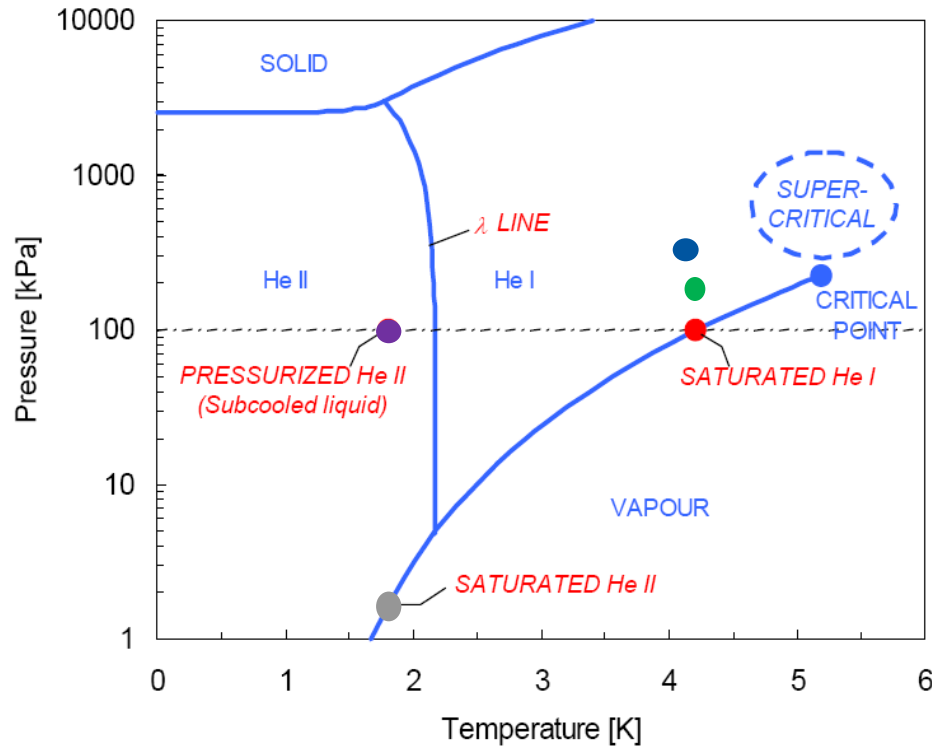
● SRF -- HERA, LEP, KEKB, CESR

● Magnets -- HERA, Tevatron

● Magnets – SSC

● Magnets -- Tore Supra, LHC

● SRF -- CEBAF, TTF, SNS, ILC

Listing courtesy Tom Peterson

Accelerator magnets are (up to now) often cooled with subcooled liquid
– Typically working near the limit of the superconductor with large stored energy
– Ensure complete liquid coverage and penetration

Superconducting RF cavities are generally (up to now) cooled with a saturated bath

"up to now": but there's a drive for several reasons to move most of the liquid out of the system

Intermezzo HeII: Specific heat

R. van Weelderen, 01.02.2016
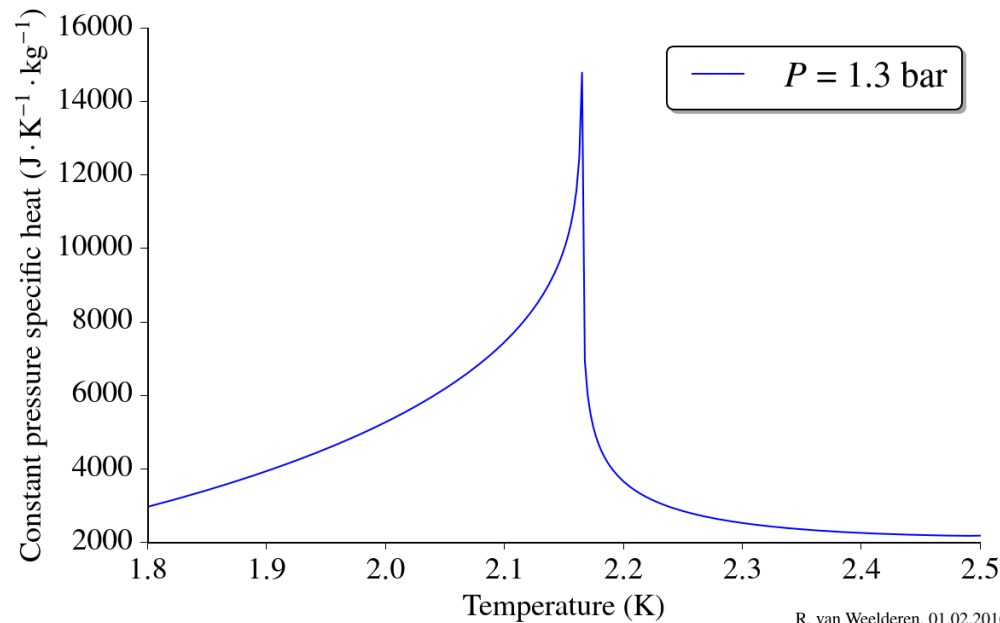
Cp of helium
showing the characteristic shape when crossing the superfluid to normal helium transition which gave the transition its name "λ − point"
At these low temperatures, the Cp of helium is roughly at least 4 to 5 orders of magnitude higher than values for coil-pack and collar & yoke materials!

This high thermal capacity of the superfluid helium contributes to coil stability in fully immersed coil magnet designs only at T < 2.17 K

Intermezzo HeII Conduction through helium II

Conduction cooling via (pressurized -) superfluid helium can for the majority of heat fluxes and geometries involved in the magnet design $\approx 100\,\mathrm{mW/cm^3}$ be described by the equations for the "turbulent" regime with full mutual friction between the components of the two-fluid model description of superfluid helium.

One uses a simplified superfluid model which is based on a non-linear heat diffusion equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot K_{eff} \nabla T + q_{vol}$$

where ρ is the density q_{vol} is the volumetric heat source and K_{eff} is the non-linear, effective thermal conductivity.

effective thermal conductivity in the turbulent regime (prevalent in the great majority of cases):

$$K_{effT} = \left(\frac{1}{f(T,p)|\nabla T|^2} \right)^{1/3} \tag{1}$$

with

$$\frac{1}{f(T,p)} = g(T_\lambda) \left[t^{5.7} \left(1 - t^{5.7} \right) \right]^3 \tag{2}$$

where $t = \frac{T}{T_\lambda}$ and $g(T_\lambda) = \frac{\rho^2 S_\lambda^4 T_\lambda^3}{A_\lambda}$.

S_λ is the reference entropy at the lambda point,
A_λ is the Gorter-Mellink mutual friction parameter and
T_λ is the transition temperature from superfluidity at a given pressure.

Intermezzo HeII Conduction through helium II
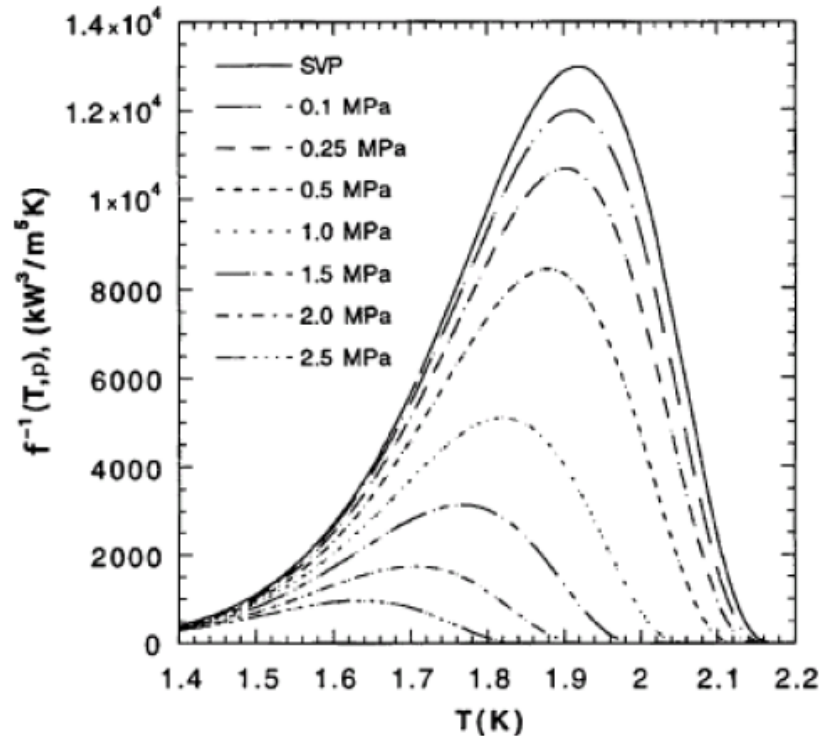
courtesy van Sciver

Conductivity function

- peaks around 1.9 K
- goes to zero at the lambda-point and for low temperatures

Intermezzo HeII Conduction through helium II

Inserting $q = -K_{effT} \frac{dT}{dx}$ in equation (1) we see that the conductivity, although very high, collapses for high heat fluxes

$$K_{effT} = \frac{1}{f(T,p)q^2}$$

and that the maximum heat flux q^* is limited by channel length L (see excercises)

$$q^* = Z(T_{bath})L^{-1/3}$$

Nevertheless, since $f^{-1}(T,p)$ has values around $1000 \, \text{W}^3/\text{cm}^5$, we get for $q = 1 \, \text{W}/\text{cm}^3$ an effective conductivity of about $100 \, \text{kW}/\text{mK}$. Two orders of magnitude above pure metals at low temperatures.

Intermezzo HeII Conduction through helium II

What makes superfluid helium as a coolant stand-out?
- **high heat capacity**
largely dominates all other cold-mass materials at low temperatures --> increases stability
- **extremely low viscosity**
even within very dense structures, just very low porosity is enough to bring the coolant near the hottest places
- **very good, but functionally special, effective thermal conductivity**
orders of magnitude better than any other cold-mass material

Helium as…: conduction comparative

Normal helium (HeI):
- Temperature > 2.17 K
  - Bad thermal conductivity
  - Viscous

Superfluid helium (HeII):
- Temperature < 2.17 K
- Peak in heat capacity c_p at T_λ
- High thermal conductivity
- Low / vanishing viscosity

→ If the *substantially higher refrigeration cost* (see later) can be justified, then HeII is used as a conductive medium

→ If not, *then highly conductive materials must be incorporated* in the magnet/coil design to efficiently connect to the cold source

But: HeII conductivity is q^{-3} heat flux dependent and can easily break down!

Legend:
- He II
- He I
- He (G)
- N2 (L)
- H2 (L)
- Stainless Steel
- Al6063
- Diamond
- Water
- Copper
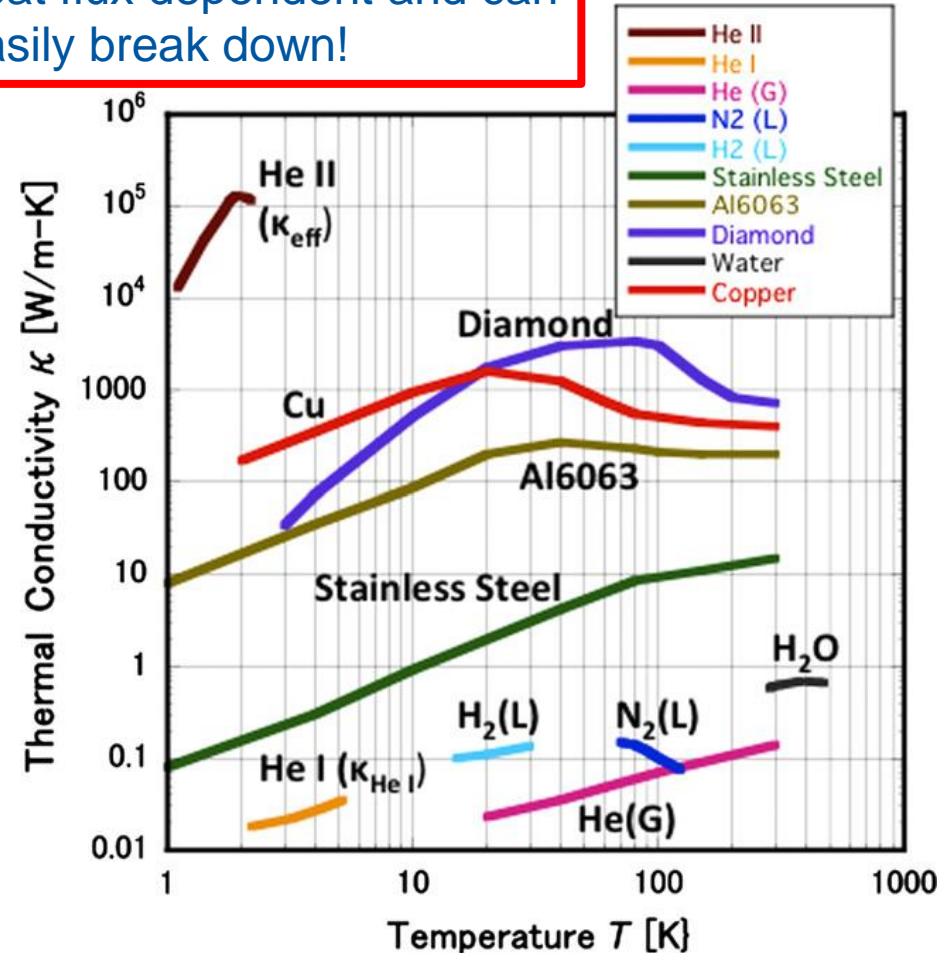
Intermezzo: Magnet-examples

Superconducting magnets come in *many variants and applications* ranging from small medical devices, motors, wind-power generators, huge particle detectors and plasma containing structures to km-long particle accelerators,…

The most common superconductors, NbTi, Nb_3Sn, MgB_2, HTS making up the magnet coils *generally operate at temperatures from 1.9 K – 4.5 K – 20 K < 77 K*

Limiting the heating power from the room temperature environment to reach the low-temperature environment of the coils requires *heat intercepts at intermediate temperatures* (will be quantified later on)

1. The superconducting magnet cryostats typically exhibit a "layered onion – shape": High temperatures on one side and layers at decreasing temperature levels until the layer that incorporates the superconducting coil.
2. Temperature layers are separated by vacuum spaces to limit heat exchange by gas molecules
3. Mechanical support structures and visible "thermal radiation windows" between these layers are optimized for low heat conduction

Magnet examples: LHC-particle (proton) accelerator

23 km superconducting magnets operating @ 1.9 K, NbTi-cables (HL-LHC upgrade quadrupole → Nb_3Sn)

1232 dipoles, 474 quadrupoles, 7612 corrector magnets
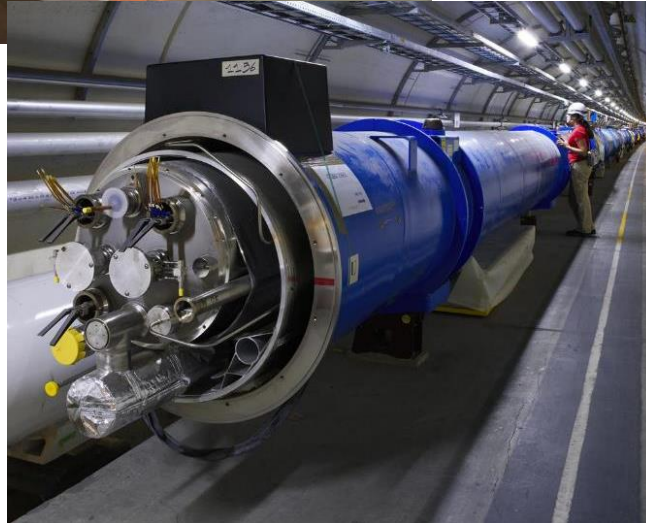
LHC DIPOLE
CROSS SECTION

ALIGNMENT TARGET
MAIN QUADRUPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
SHRINKING CYLINDER / HE I-VESSEL
IRON YOKE
VACUUM VESSEL
THERMAL SHIELD
AUXILIARY BUS-BARS
AUSTENITIC STEEL COLLARS
BEAM SCREEN
IRON INSERT
INSTRUMENTATION WIRES
FILLER PIECE
DIPOLE BUS-BARS
SUPPORT POST
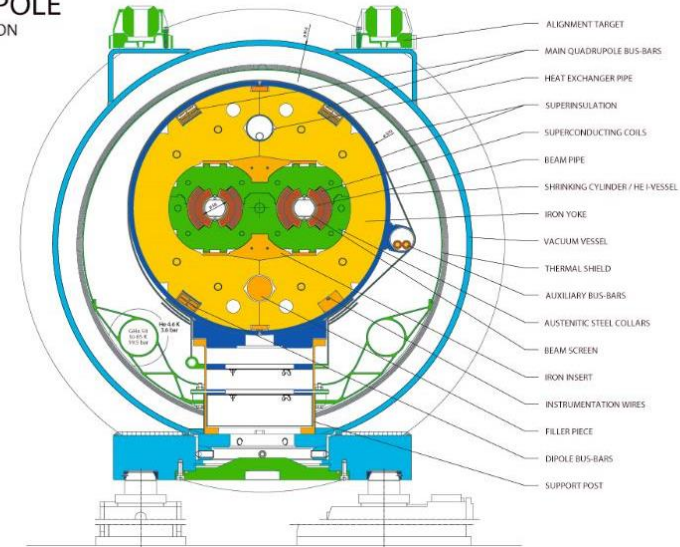
Fully helium- immersed magnet: coil, collars & yoke all @ 1.9 K (superfluid helium)

Magnet examples: LHC-dipole
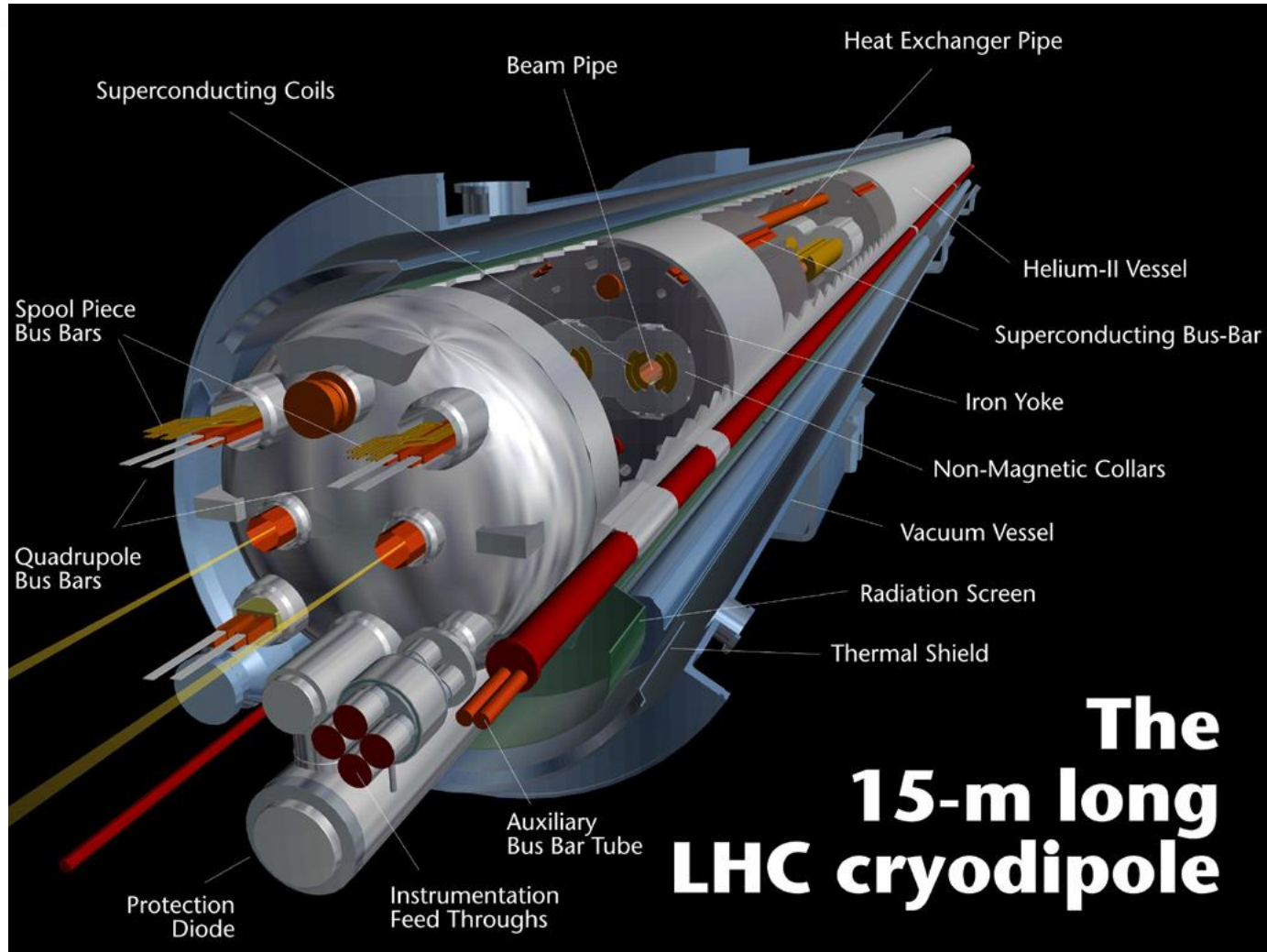
Typical thermal environment & terminology

Magnet examples: LHC-dipole

LHC DIPOLE : STANDARD CROSS-SECTION

ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST

CERN AC/DI/MM - HE107 - 30 04 1999

Vacuum spaces
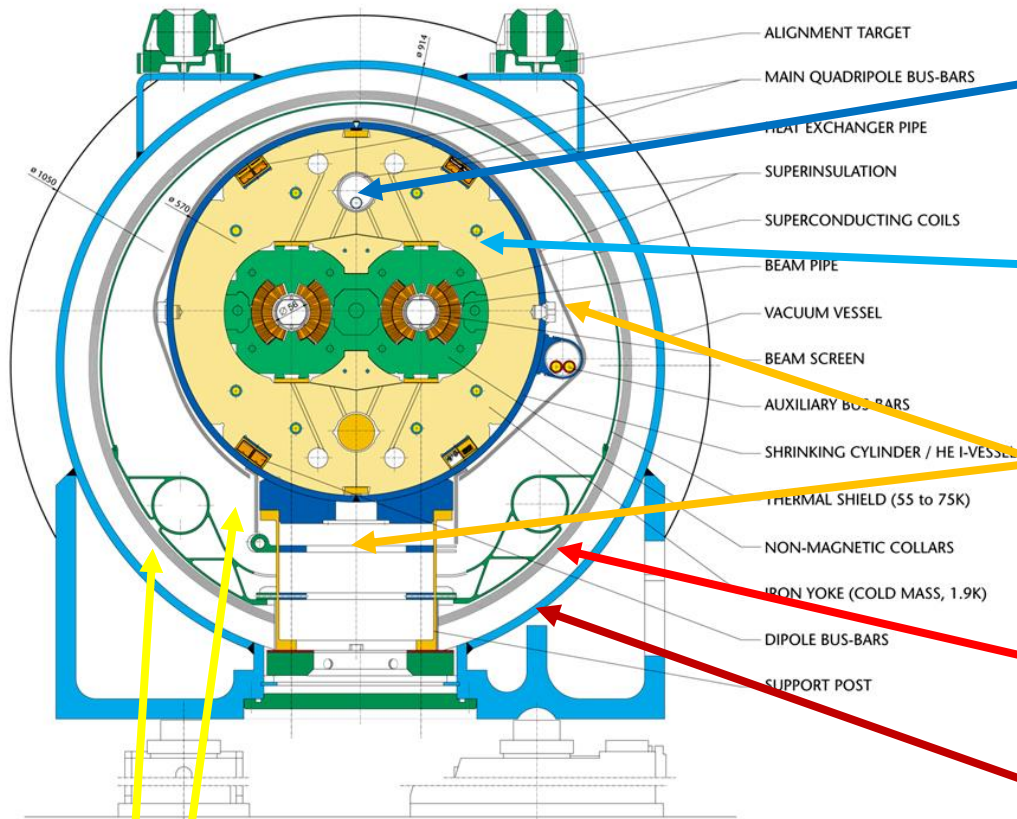
T – level (K)	Comment
1.8-2.1	Heat-sink (two-phase superfluid helium)
≤ 2.17	cold -mass (pressurized superfluid helium)
5	Thermal radiation/conduction intercepts
55 - 75	main thermal radiation intercept
RT	outer cryostat shell

Typical thermal environment & terminology (example of T-layers)

Magnet examples: Tevatron-particle accelerator

6.5 km of superconducting magnets operating @ 3.6 Kelvin, NbTi-cables & warm yoke

+777 dipoles, +216 quads, +204 correction elements

SINGLE-PHASE HELIUM OUTER
SINGLE-PHASE HELIUM INNER — COIL
SINGLE-PHASE PORT ELEVATION
TWO-PHASE HELIUM
LIQUID NITROGEN
COLLARS
TWO-PHASE PORT ELEVATION
WARM IRON
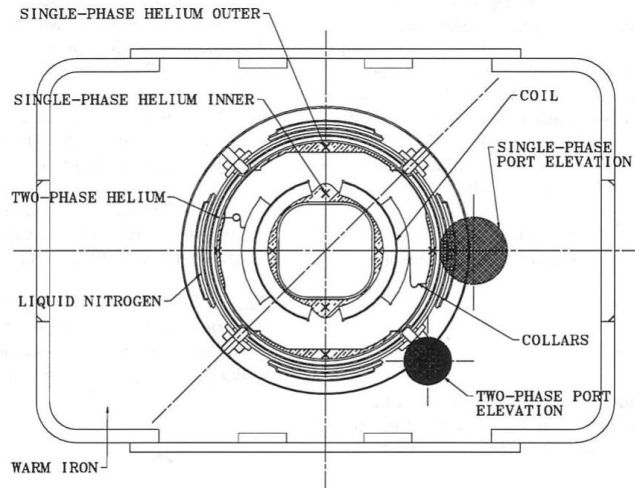
X = SINGLE-PHASE TEMPERATURE SENSOR LOCATION

TEVATRON CROSS-SECTION at SUSPENSION
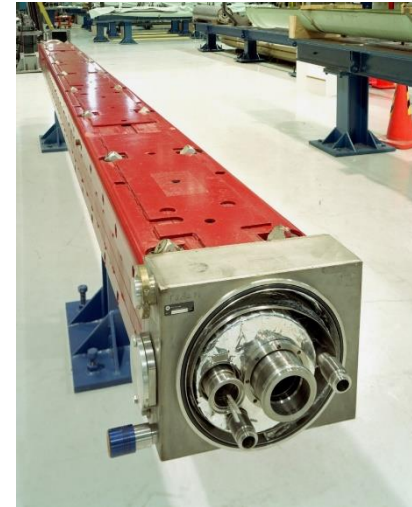
Warm Yoke

Coil @ 3.6 K
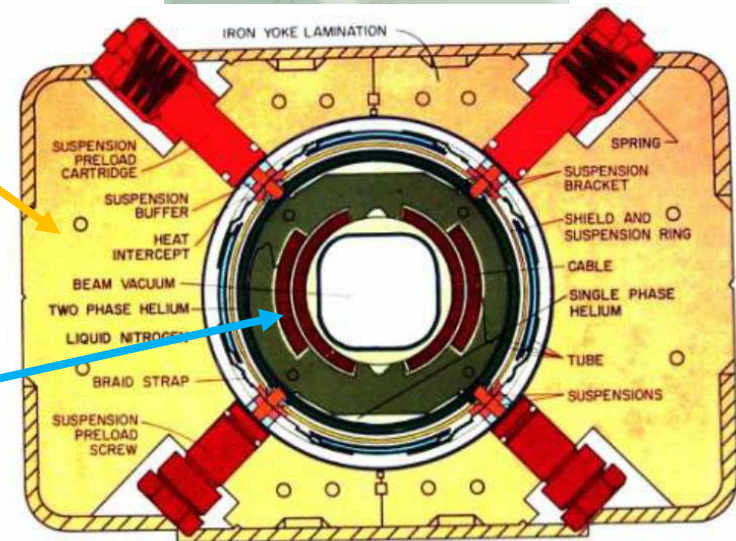
Magnet examples: ITER – fusion

Toroidal Field (TF) operating @ 4–6 K force flow cooled K, Nb3Sn-cables
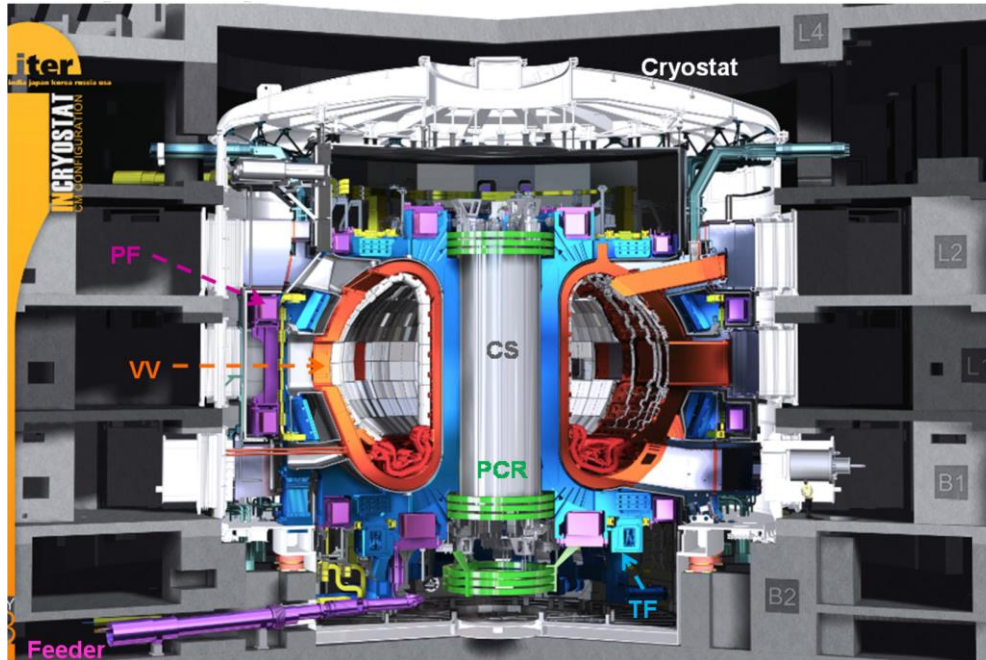
Nb$_3$Sn, operating at 4-6 K, force flow cooled

https://www.iter.org/mach/Magnets

Magnet examples: MRI
CEA/Irfu for NeuroSpin (900mm bore 11.74T 500MHz) magnet
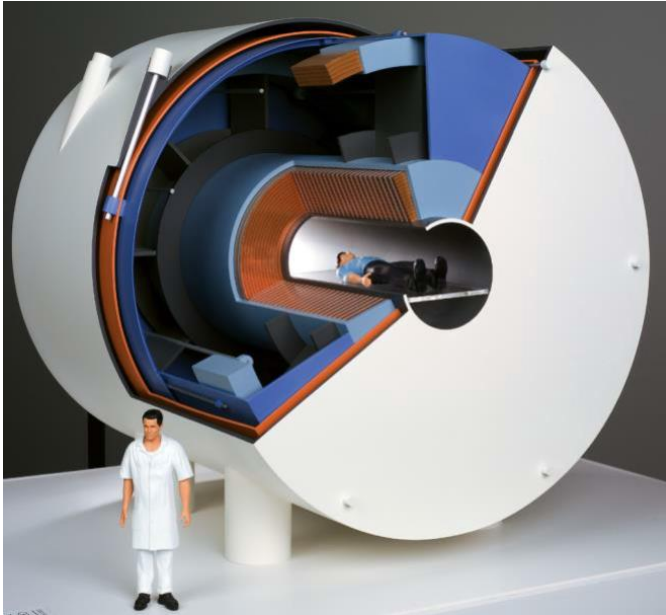
180 km of niobium-titanium superconducting wire wound in double pancake coils and carrying a current of 1,483 A. These superconducting coils are maintained at very low temperatures (1.8 K or -271 °C) using a bath of 5,000 liters of superfluid helium

https://joliot.cea.fr/drf/joliot/en/Pages/research_entities/NeuroSpin.aspx
https://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3377

Temperature levels
(and "Why do we need to talk about it?")

The superconducting magnet cryostats typically exhibit a "layered onion – shape":
High temperatures on one side and layers at decreasing temperature levels until
the layer that incorporates the superconducting coil.

Temperature level	Cost?	heat transmission	equipment
room temperature	300 K		Outer cryostat shell
		• Thermal radiation (T^4 dependence!) • Conduction	Supports, Shields, Insulation vacuum, Multilayer Insulation, Cold-warm transitions…
liquid nitrogen	77 K		Thermal shield
		• Conduction • Thermal radiation	Supports, (Shields), Insulation vacuum, (Multilayer Insulation), (Cold-warm transitions)…
liquid helium (HeI)	4.5 K		
		• Conduction • Thermal radiation	Coil level(s)
Superfluid helium (HeII)	< 2.17 K		
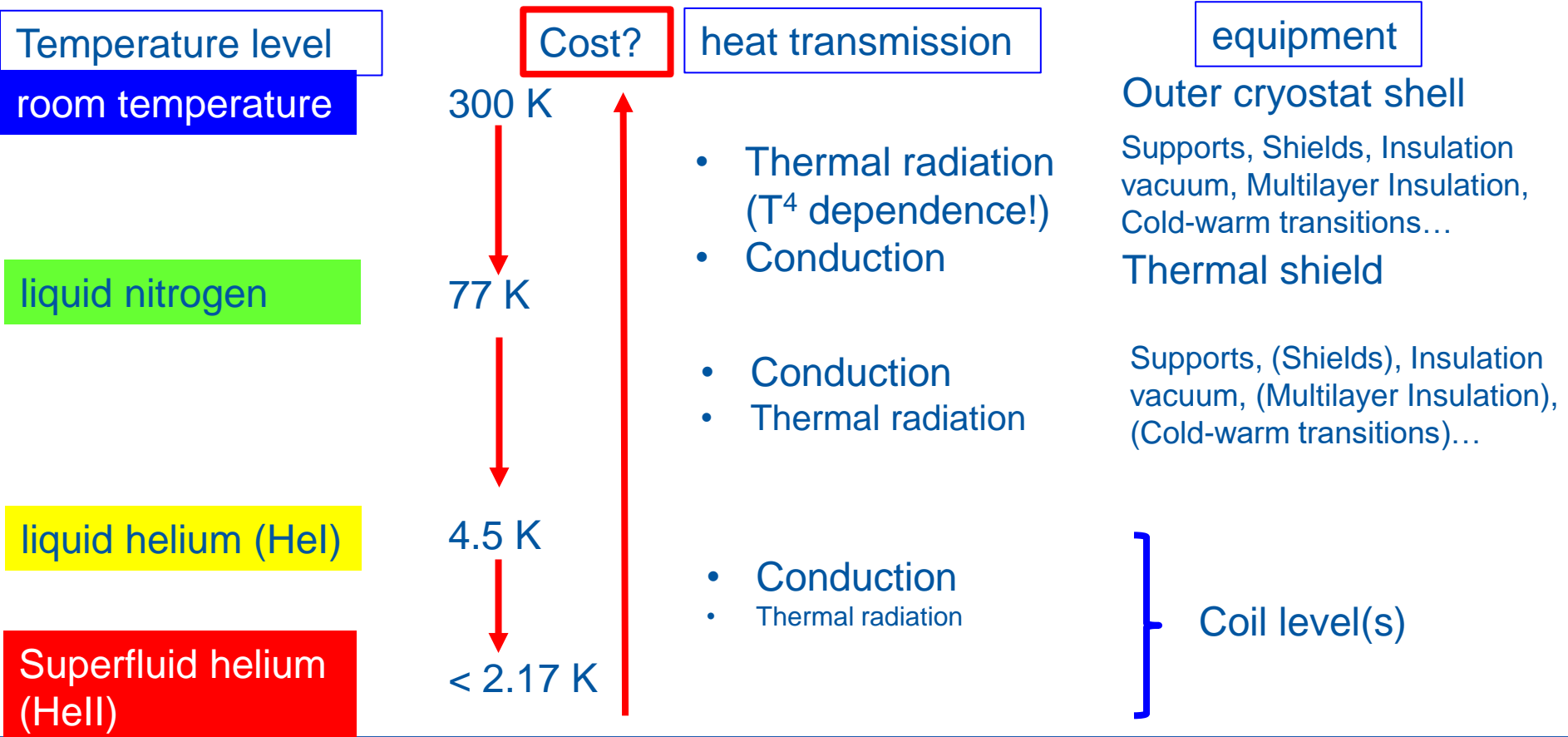
Temperature levels
(and "Why do we need to talk about it?")

In general, cooling is done by using a working fluid, helium in our case (I'll refrain from H_2) and making it undergo a closed thermodynamic cycle that *removes heat at low temperature (T_{cold})* and rejects the heat at *room temperature (T_{room})*.

This process requires work

Coefficient of Performance COP: the heat absorbed from the cold sink divided by the net work required to remove this heat

Ideally (i.e. thermodynamically reversible process) the "Carnot cycle coefficient":

$$COP_{ideal} = \frac{1}{(\frac{Troom}{Tcold} - 1)}$$

Temperature levels
(and "Why do we need to talk about it?")

In practice, the inverse (COP $^{-1}$) is often stated, as this shows the number of watts of work required to provide 1 Watt of cooling at a given temperature:

T_{cold} (K)	COP_{ideal}	COP^{-1}_{ideal} (W/W)
77	0.35	3
4.5	0.015	66
1.9	0.0064	157

!Take with care "Ideal" values" (see next slides)

→ it is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures!

Temperature levels
("These values are why we need to talk about it")

Power consumption at refrigerator I/F

The (*warning!*) "ideal" inverse coefficient of performance (COP^{-1}) power consumption electric power needed per power at cold (W/W).
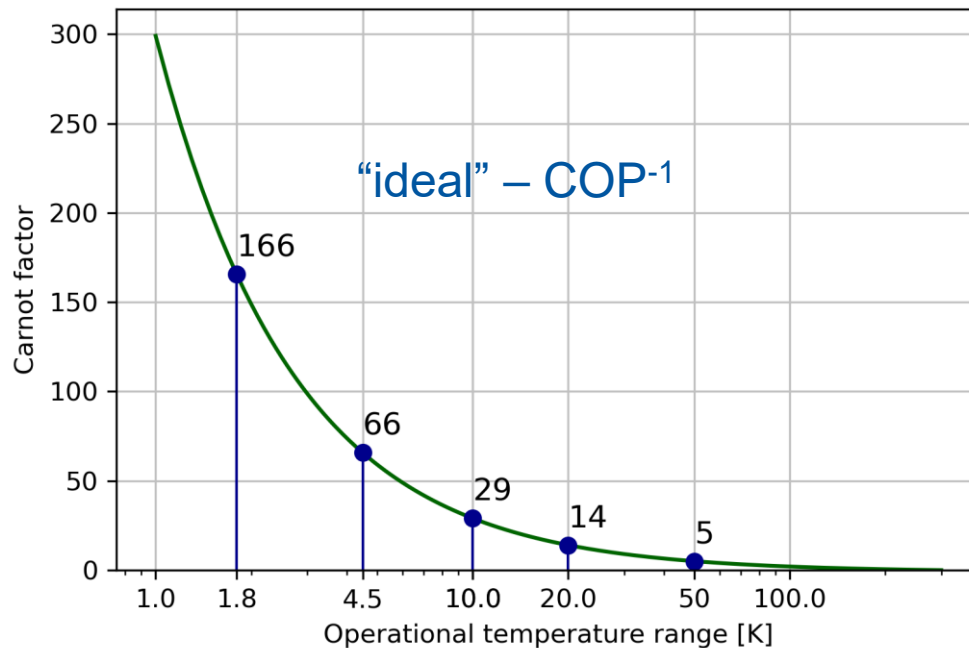
"ideal" – COP^{-1}

→ it is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures!

Temperature levels
(and "Why do we need to talk about it?")

In the real world we do not manage to have a cryoplant that operates a fully reversible (ideal) process.

A measure of how good a cryoplant operates is the Figure of Merit (FOM) :

$$FOM = \frac{COP_{real}}{COP_{ideal}}$$

Even the latest LHC cryoplants do not exceed a FOM ≈ 30 %

In addition to the non-ideal COP-value one has to add-in a non-negligible power loss to account for the distribution of the coolants (think of pumping losses p.e.). These distribution costs depend heavily on the cooling implementation and are not examined here.

Temperature levels
("These values are why we need to talk about it")

> Power consumption at refrigerator I/F
> *From heat loads to power consumption based on actual machine data*
>
> The inverse coefficient of performance (COP^{-1}) at refrigerator interface was estimated to give a <u>semi-realistic</u> power consumption.
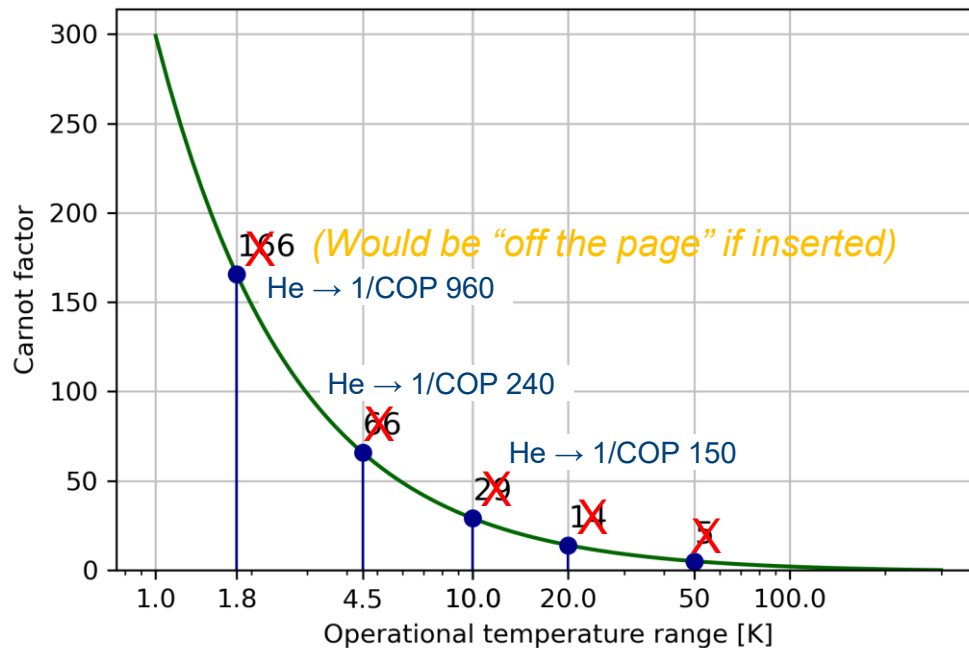
- Carnot efficiency gives a **potential** reduction in operational costs
  - e.g. from 4.5 K to 10 K there is a **potential** factor 2.3 improvement in efficiency
- But **reality** (process inefficiencies) need to be considered
  - Actual COP at refrigerator interface for 10 K is 150 *vs.* 240 at 4.5 K → factor 1.6 improvement in efficiency (W/W)
- Losses on distribution and heat extraction systems **still need to be added (up to 30%-50%!)**

Temperature levels
("These values are why we need to talk about it")

Power consumption at refrigerator I/F
From heat loads to power consumption based on actual machine data

The inverse coefficient of performance (COP^{-1}) at refrigerator interface was estimated to give a semi-realistic power consumption.

Temperature level	COP^{-1} in W_{elect}/W_{cool}	FOM (%)	Source
250 K	1		CO_2 plant ATLAS ITk
100 K	12		LN_2 plant ATLAS
80 K	16	17	LN_2 plant ATLAS
20 K	50		20 K/50 kW plot Frey
10 K	150		LHC cryoplant data
4.5 K	240	28	LHC cryoplant data
2.0 K	960	16	LHC cryoplant data

The efficiency of 2.0 K cryoplant wrt 4.5 K goes down much more than you'd estimate from the "ideal" Carnot: from 28 % down to 16 %!

→ Be careful not to fully rely power consumption-scaling, when changing temperatures, on ideal Carnot coefficient ratios!

≈ 1   kW/W @ 2.0 K !
≈ 0.24 kW/W @ 4.5 K

Temperature levels

("These values are why we need to talk about it?")

Temperature level	Electrical power consumption		equipment
room temperature	300 K	0 W/W	Outer cryostat shell
			Supports, Shields, Insulation vacuum, Multilayer Insulation, Cold-warm transitions…
liquid nitrogen	77 K	≈ 16 W/W	Thermal shield
			Supports, (Shields), Insulation vacuum, (Multilayer Insulation), (Cold-warm transitions)…
liquid helium (HeI)	4.5 K	≈ 0.24 kW/W	
			Coil level(s)
Superfluid helium (HeII)	< 2.17 K	≈ 1 kW/W	
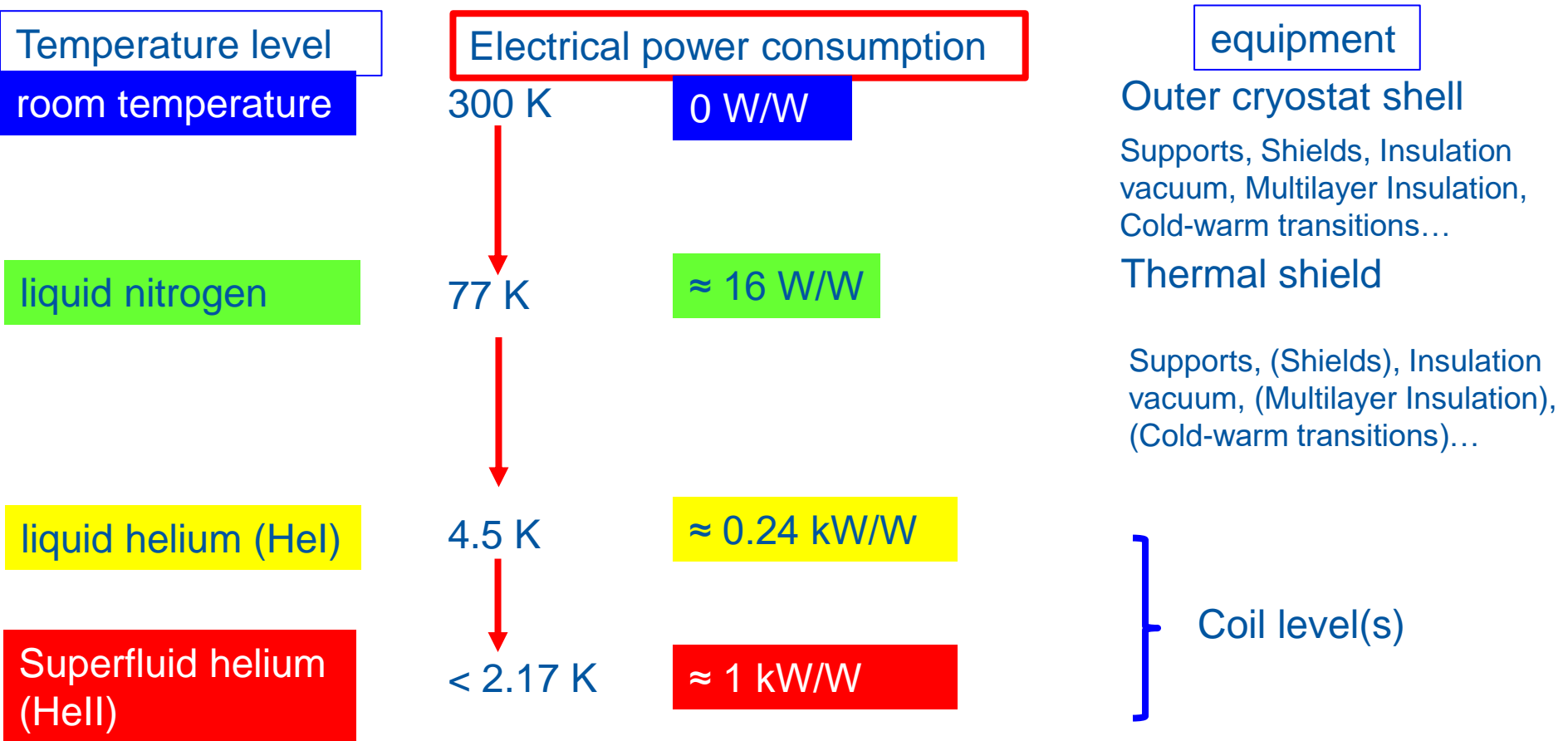
Take away: try to incorporate in the magnet design, whenever possible, features to intercept heat at as high T as possible!

Fully immersed in HeII: LHC-dipoles
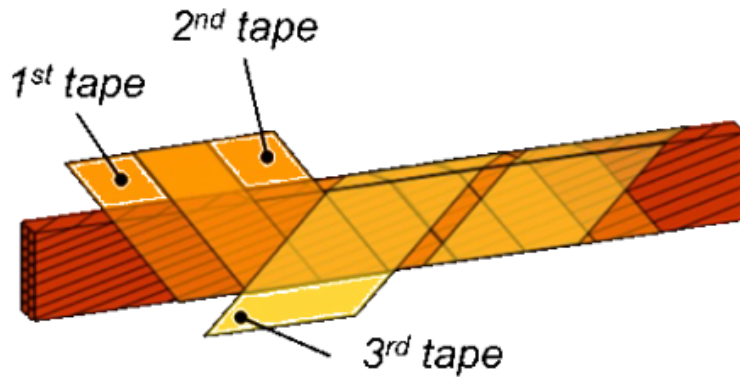
NbTi - cable is:

- non-impregnated

- Electrically insulated by partially overlapping layers of Kapton

--> porous to helium

Fully immersed in HeII: LHC-dipoles
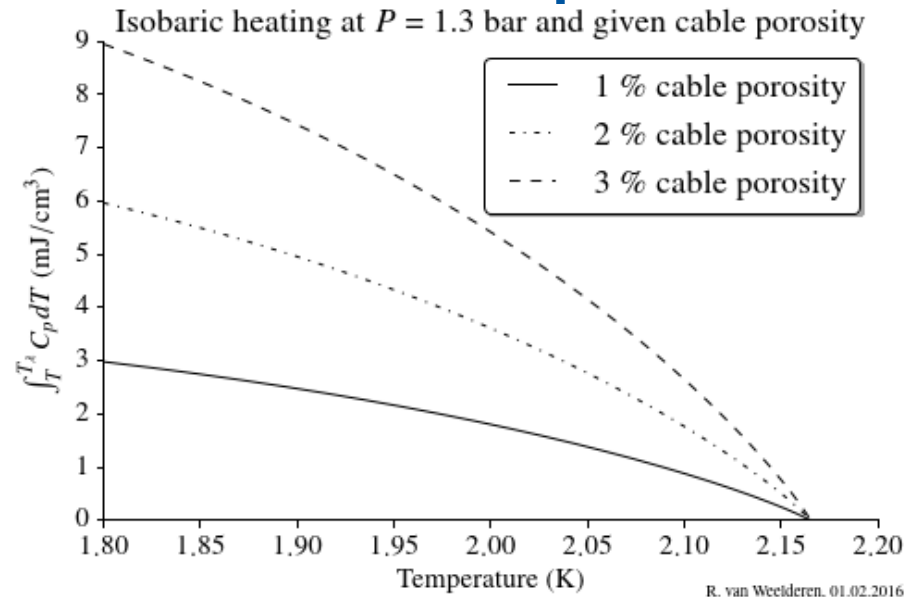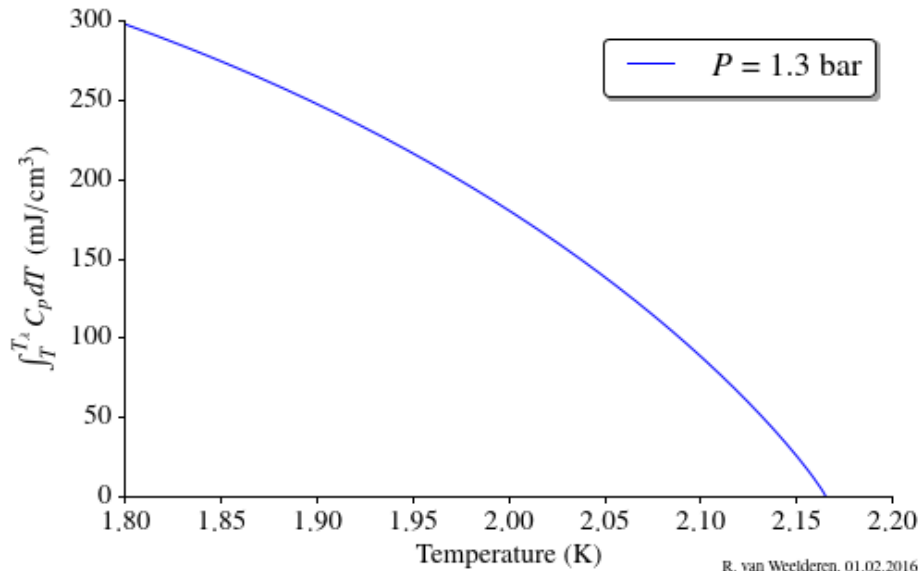
The high thermal capacity of the helium inside the porous NbTi - cable contributes to the stability

The order of magnitude is ~2 mJ/cm³ per % of He volume

To be compared with typical assumed quench stability margin of NbTi at T < 2.17 K of ~ 5-10 mJ/cm³

Heat sources and heat-sinks

(aka "cold-sources")

Cold-source

In *fully immersed* magnets the heat generated in the coil-pack must find its way out to the cold-source via helium path-ways kept clear in the cold-mass construct

In the example top left, of the LHC main dipole, heat flows from the coil pack into the annular space between beam-pipe and coil-pack and out via space between the collar laminations

Cold-source

In the example bottom left, of the HL-LHC MQXF quadrupole, heat flows from the coil pack into the annular space between beam-pipe and coil- pack and out via dedicated passages (8 mm diameter holes every 50 mm along the length of the magnet)
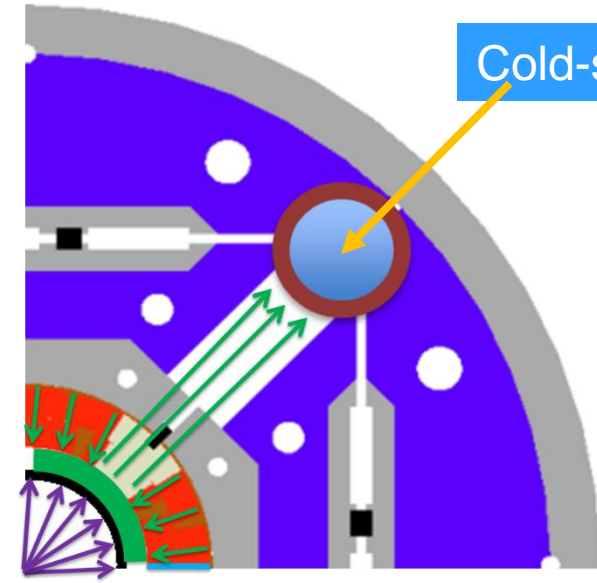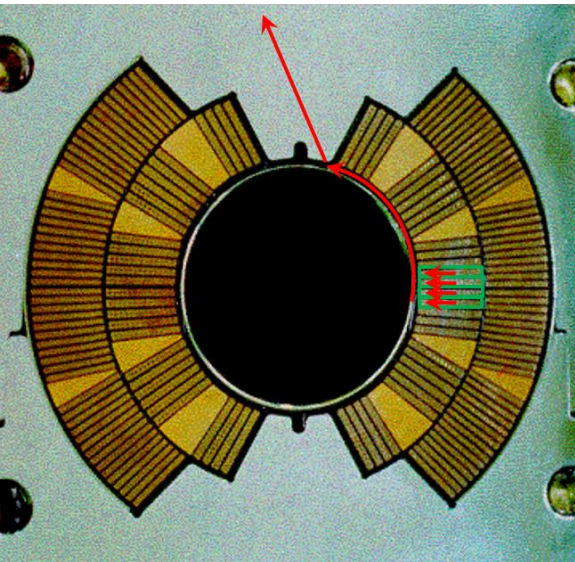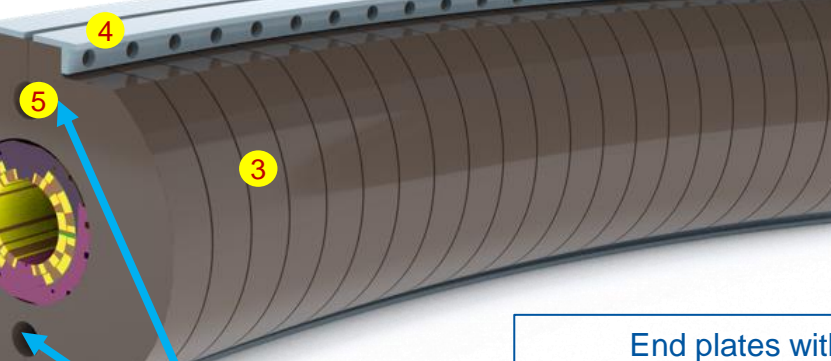
Heat sources and heat-sinks
(aka "cold-sources")

In a *"dry"* magnets the heat generated in the coil-pack must find its way out to the cold-source via solid conduction and solid-liquid interface

Mechanical Concept CERN, CNAO, INFN and MedAUSTRON on novel ion gantry concepts: "dry" conduction cooled magnet

1 Epoxy-impregnated 2-layer coils with inter-layer splice, wound with 34-strand 8.75 mm Nb-Ti cable with braided glass insulation

2 Stiff austenitic steel collars with 0.15..0.2 mm thick spacers on one side to follow the coil curvature

3 Horizontally split laminated iron yoke made of 1-mm-thick Si-steel with b-staged resin coating. Yoke sectors machined out of cured lamination stacks.

4 Yoke assembly clamps mounted under yoking press

5 Thermalisation at 4.5 K

End plates with axial loading of coil ends (not shown)

Heat sink(s)

Courtesy M. Karpinnen & Ch. Kokkinos

Fully immersed in HeII

Cable T excursions w.r.t. helium bath measured as function of power deposit
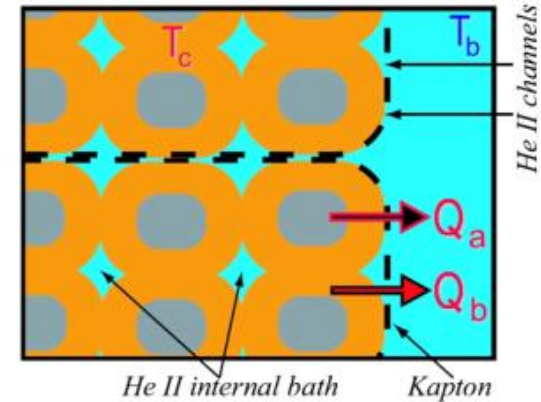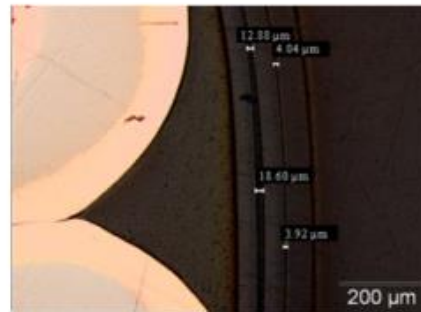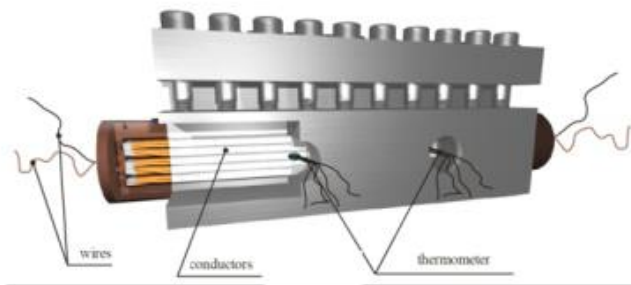
NbTi cables showing the porousity w.r.t. helium
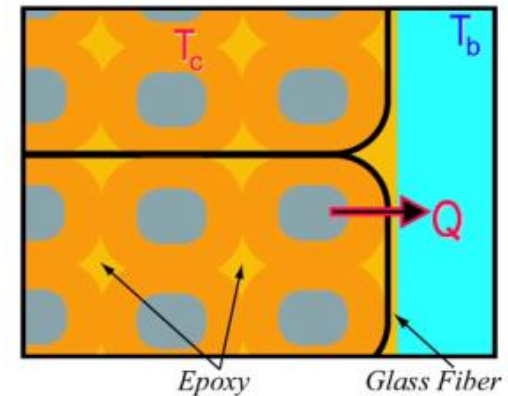
Nb3Sn cables, fully impregnated, only conduction through solids

courtesy H. R. Correia Rodrigues

Fully immersed in HeII
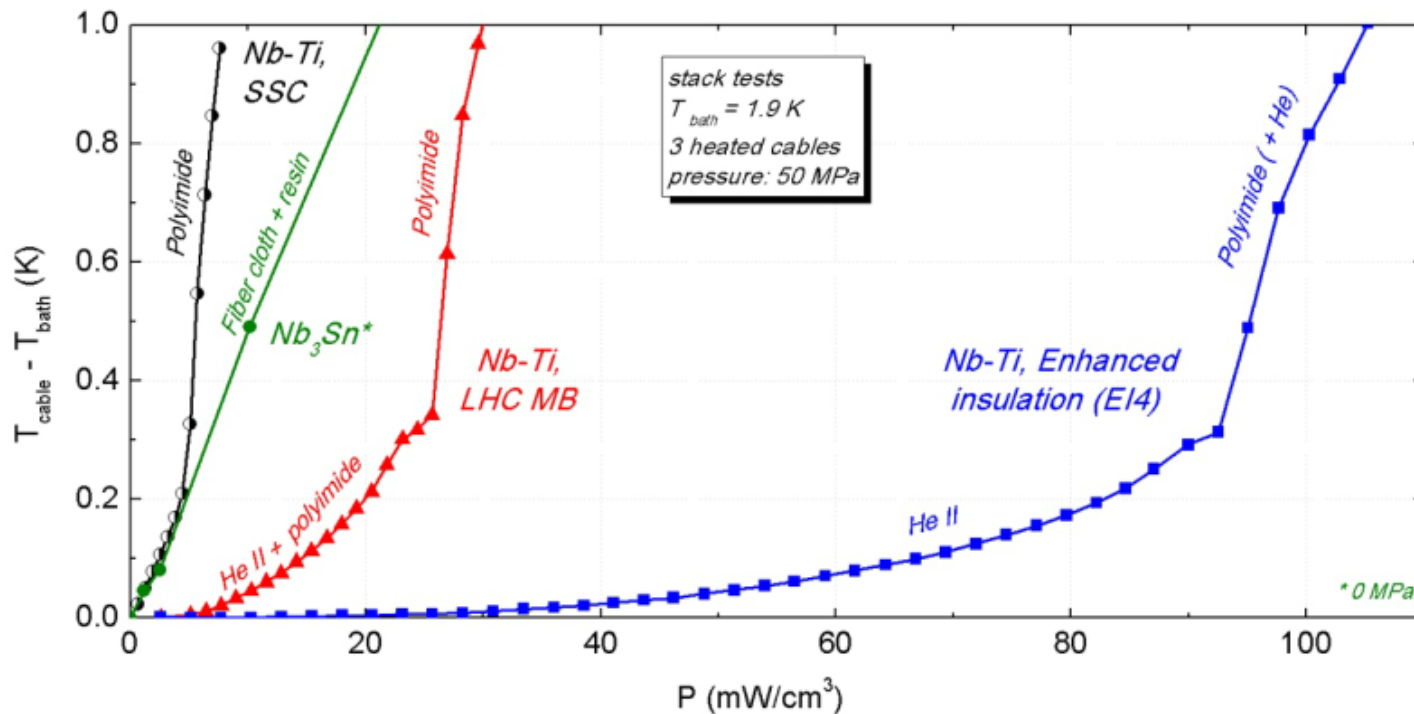
Stack measurement results, all faces open, showing the stark difference between porous and fully impregnated cables

Nb$_3$Sn measurements have since, the last 5 years, been addressed in more detail (see [3])

Fully immersed in HeII: LHC-dipoles
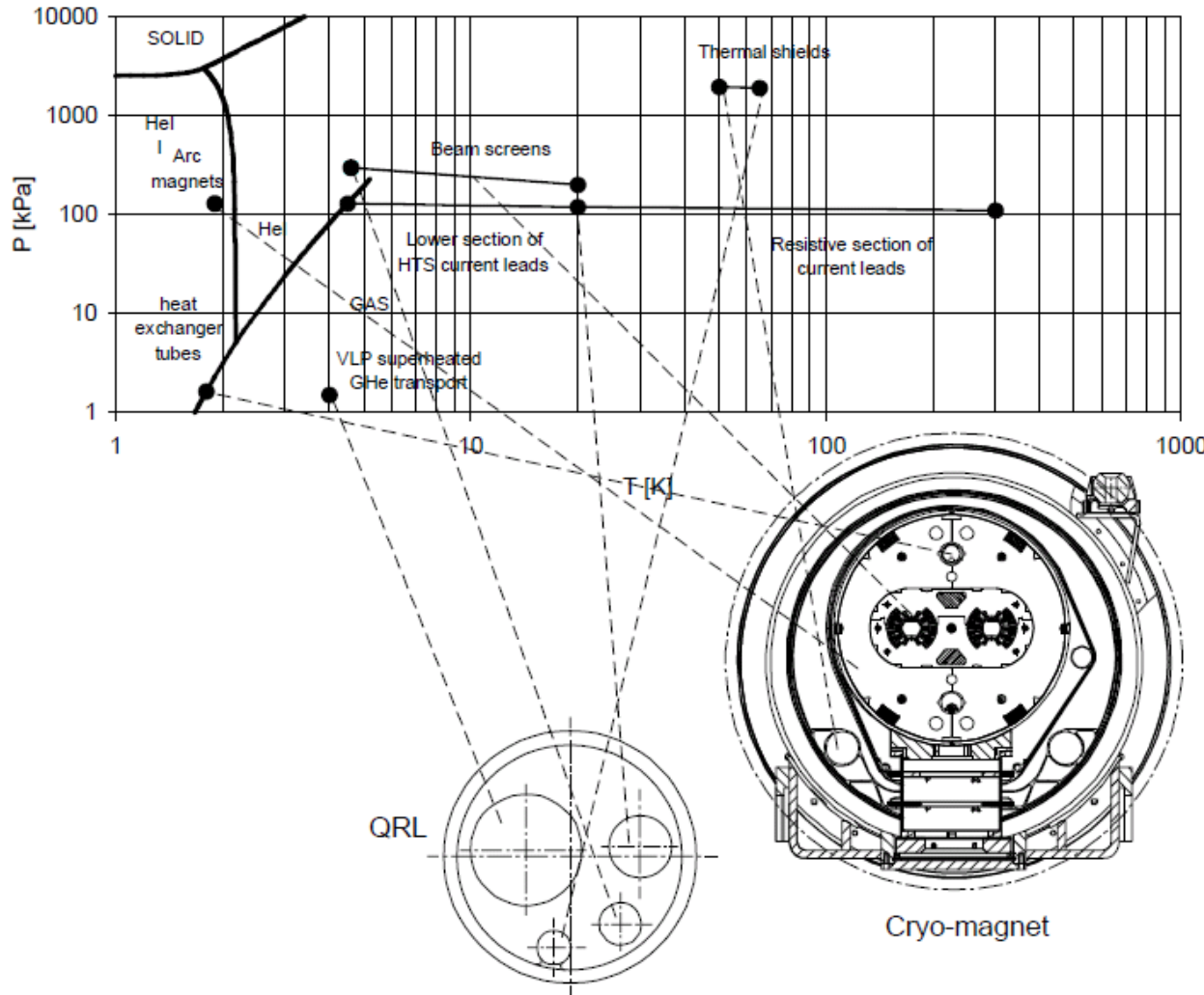
Addressing yesterday's question:

Even if the coil, collar and yoke are in pressurized HeII at 1.3 bar and ~ 1.9 K

The heat-sink (upper hole), where the heat is taken up by vapourizing liquid helium (~1.85 K, ~15 mbar) is in a copper-pipe protruding over the length of several magnets (107 m)

Fully immersed in HeII: LHC-dipoles
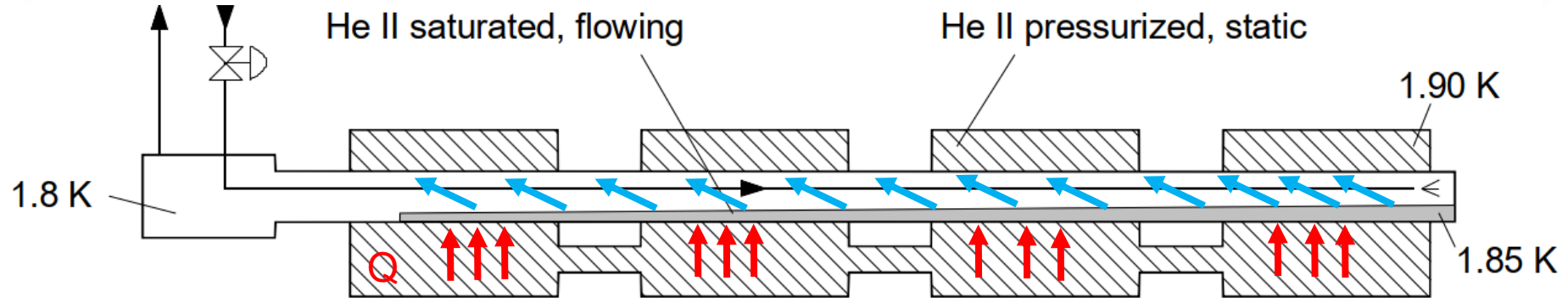
All the extracted heat has eventually to flow across the tube wall, where it encounters three thermal impedances in series:

- the limited solid conduction across the metal constitutive of the wall,
- the Kapitza resistances produced by the refraction of thermal phonons at the metal-to-helium interfaces.

The overall transverse impedance was measured on fully wetted test samples at varying temperature, so that the different temperature dependence of the solid conduction and Kapitza terms enabled to resolve them. For tubes with a wall thickness up to about 1 mm, the Kapitza resistance largely dominates below 2 K, and the use of high-purity, cryogenic-grade copper is not required.

See ref[1, 2]

Evaporation of two-phase, very low pressure, helium flow

Fully immersed in HeII: MQXF
(HL-LHC Nb$_3$Sn quadrupoles)

- In the context of HL-LHC at CERN, **a robust multi-region CFD numerical framework** for the modelling of **heat transfer in complex cryogenic system geometries involving He II** has been developed

- Numerical tool allowed to **provide thermal design requirements early enough in the magnets' design phase**

- Now, **a fully upgraded and consolidated tool** is used to reassess previous results, and for systematic analysis of heat extraction pathways in complex He II – composite solid geometries
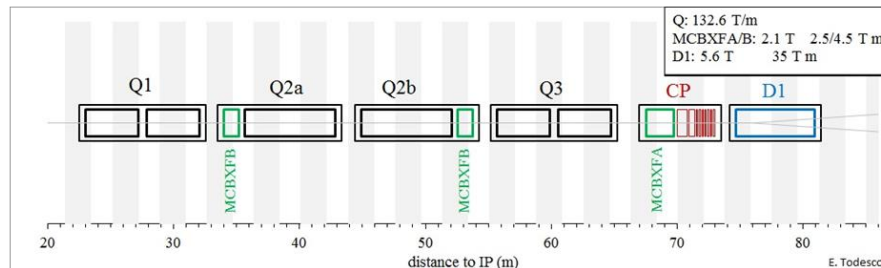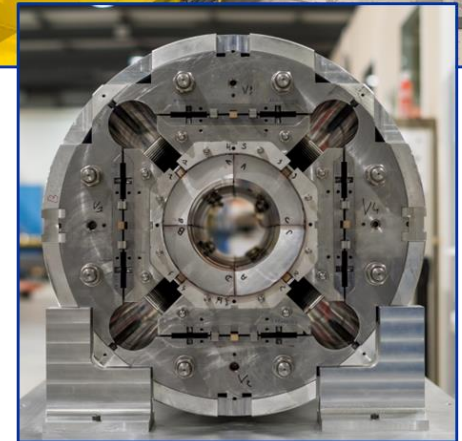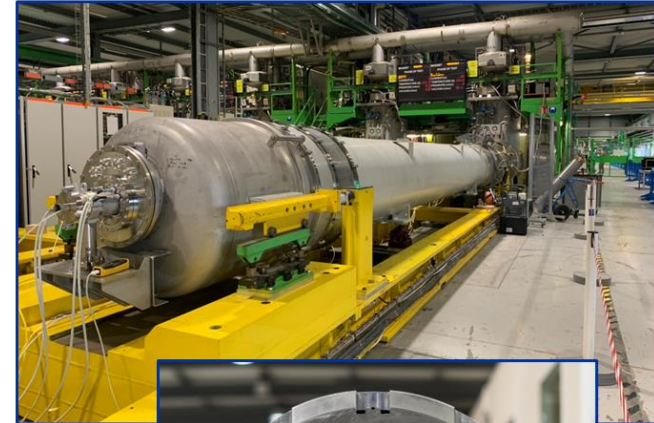
Following slides: courtesy P. Borges de Sousa | Revised estimates of temperature margins in MQXF, see also ref[x]

Numerical code applied to full-scale cold masses

- **Libraries and solver** implemented in OpenFOAM v7, **geometry** created via Python API for Salome, easily adjustable for **parametric studies**

- Currently handles **2D geometries** and **static He II conditions** (no flow) and **He II → He I transition**

- **Power deposition data** can be mapped directly onto the geometry, or **direct heat input** to any part

- **Coil described in detail;** mesh composed of 3.5M cells, **special refinement on thin layers**
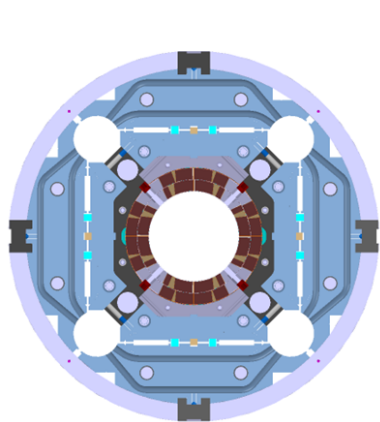
MQXF v7 + cold mass
(ST0703448)
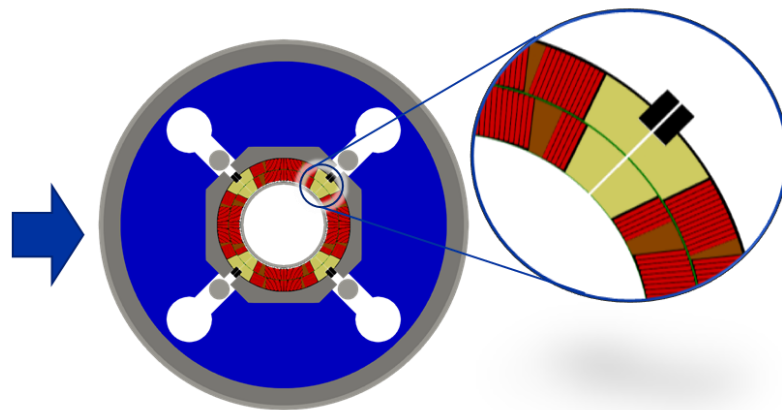
Simplified geometry for simulation
(coded in Python and Salome)
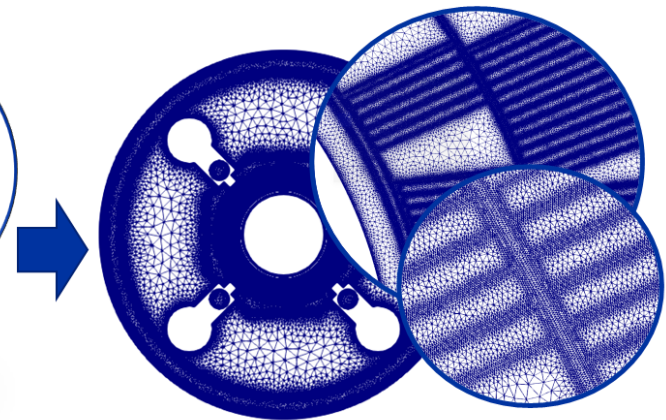
Resulting 2D meshed geometry
(coded in Python and Salome)

MQXF cold mass geometry – composite solid

Al collar

Outer vessel

Al shell

G10 keys

Cold bore

Iron yoke

Axial rods

Outer + ground insulation

Titanium pole (w/ He slit shown)

Inter-cable insulation

Coil wedge

Interlayer insulation

Inner insulation

Nb_3Sn cables
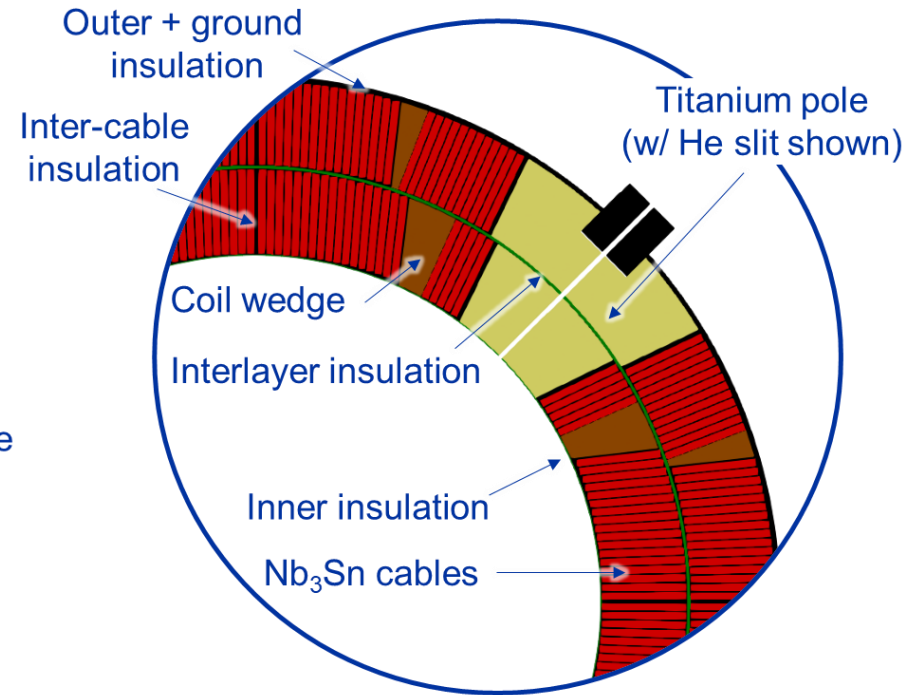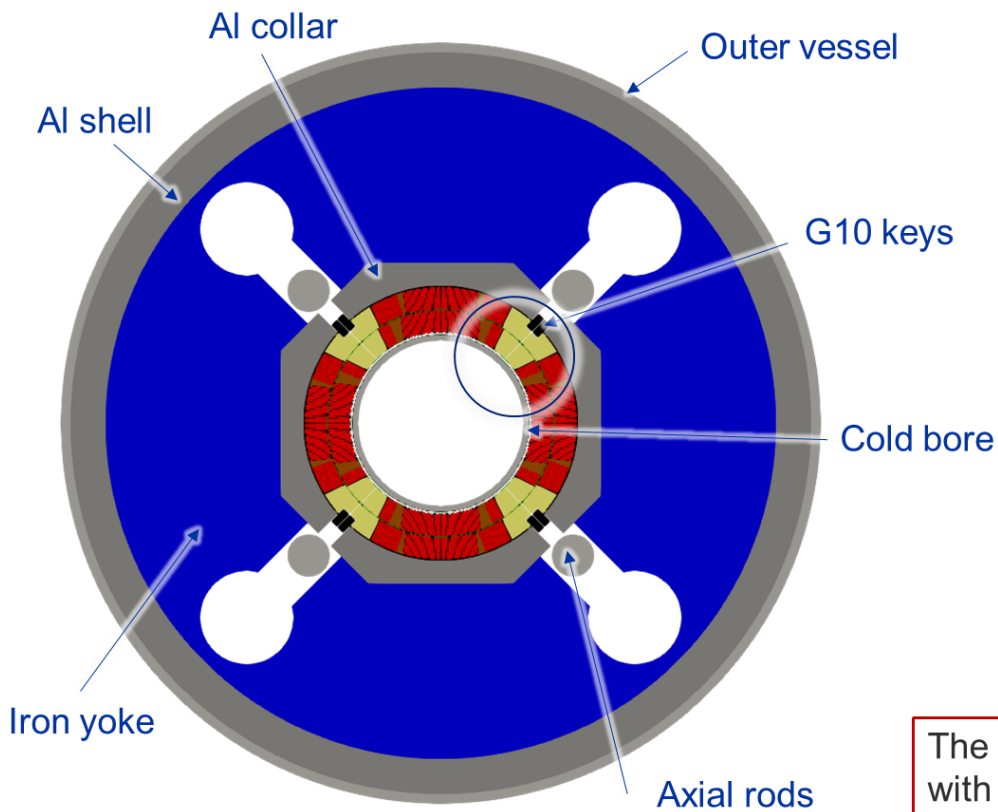
The **solid region** is composed of 17 different zones, each with their own temperature-dependent material properties

MQXF cold mass geometry – He II region

NB3:
saturated He II
HEX

NB4: 8 mm holes every
50 mm converted to
1 mm continuous slit in
2D

NB1: annular space 1.2 mm

(current baseline 1.5 mm,
see EDMS 2110647)

NB2: cold bore
insulation thickness of
510 µm
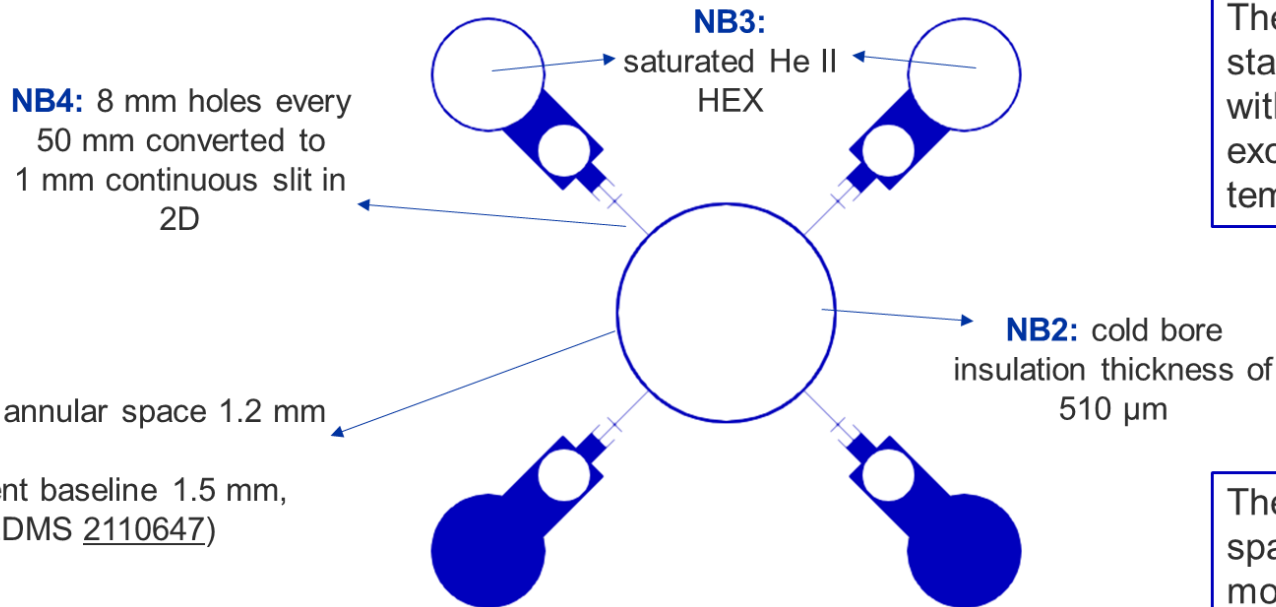
The **He II region** is modelled as a
static pressurised bath in contact
with the saturated He II heat
exchangers at a constant
temperature

The connection between annular
space and HEX passages is
modelled as a continuous 1 mm
slit over the cold mass' length

Input for heat deposition from dose calculations (I)

Peak power density profile in the inner coils ($L = 7.5 \times 10^{34}$ cm^{-2} s^{-1})
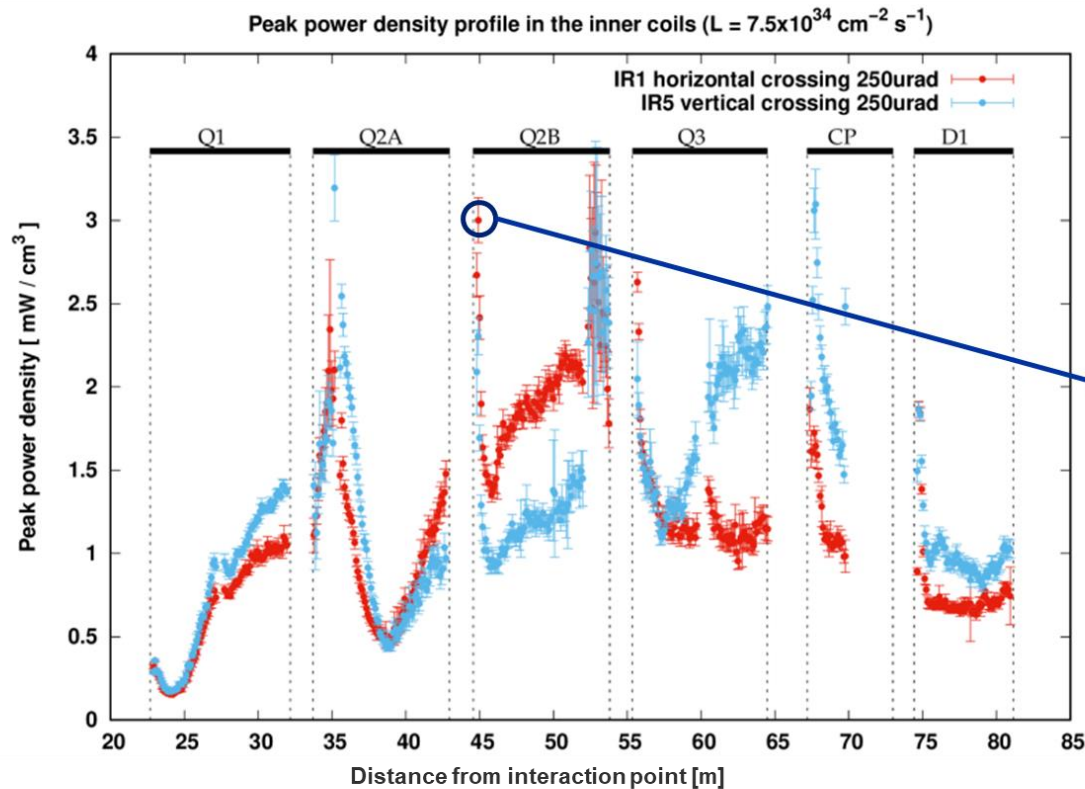
- For each magnet/cold mass, **the cross-section that corresponds to the highest dose** (and consequently heat load) is selected

- **12 cross-sections selected** (Q1/2/3 A and B, vertical and horizontal crossings)

power density at highest heat load in Q2B
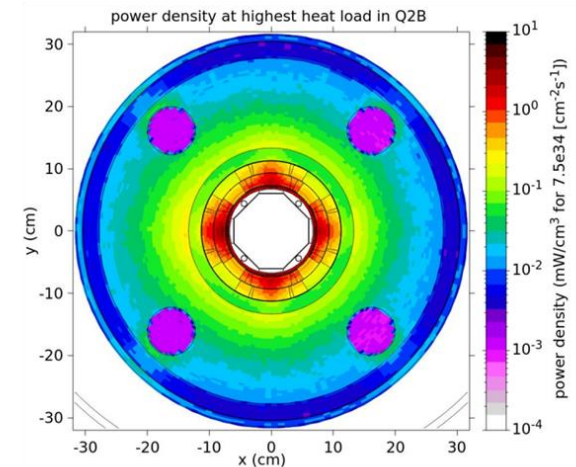
Source: Review of estimates of energy deposition, M. Sabate-Gilarte

Input for heat deposition from dose calculations (II)

- For each cold mass, the 2D **power density** (mW/cm^3) **at the peak** (maximum) **location** for nominal luminosity (7 TeV, 5.0x10^{34} cm^{-2}s^{-1}) is mapped onto the mesh

- Mesh is split into two regions, a **He II region** and a **solid region**

- Set of **boundary conditions** is chosen; power density map changes for every analysed cross-section

Q2B IR1-HC – power dep. @ peak loc.

Luminosity 5.0x10^{34} cm^{-2}s^{-1} Cold bore included

He II region (connected passages via poles)

Solid region (17 parts)

cold source 1.9 K

Power density map

adiabatic

Solid-to-He II Kapitza resistance
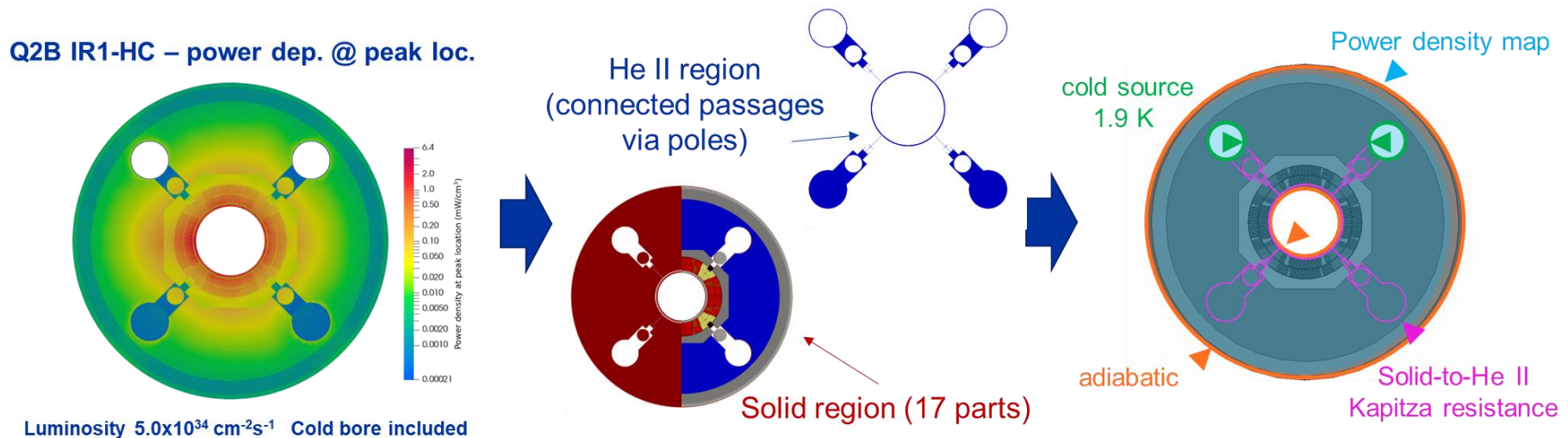
Results: example Q2B IR1-HC @ nominal luminosity

Temperature distribution at peak location

Temp. distribution at peak location (coil detail)

Max T in **cold bore**

Maximum coil temperature **2.2 K**
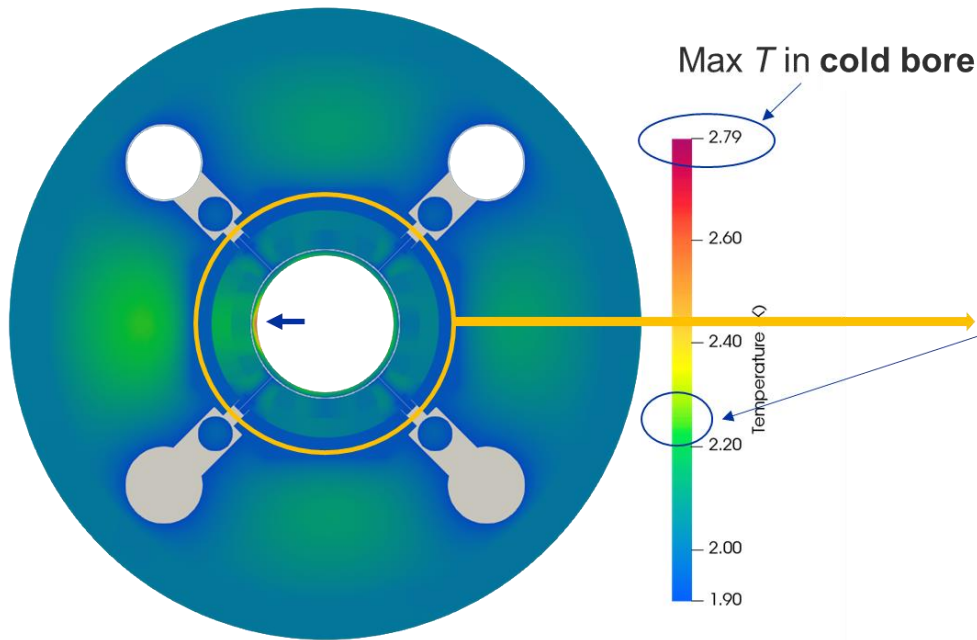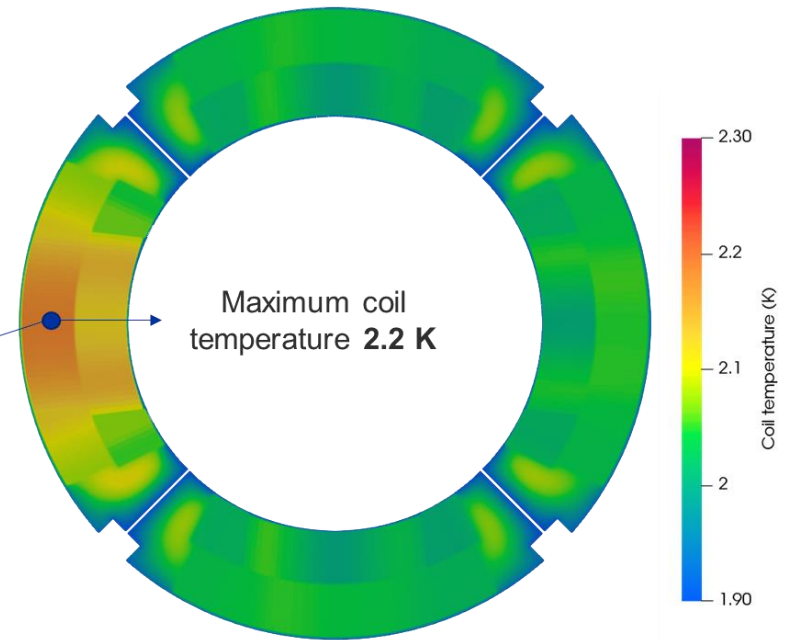
NB: Cold bore included, luminosity = 5.0×10^{34} cm^{-2}s^{-1}

Results: example Q2B IR1-HC @ nominal luminosity

Q2B-IR1/HC temp. distribution over line
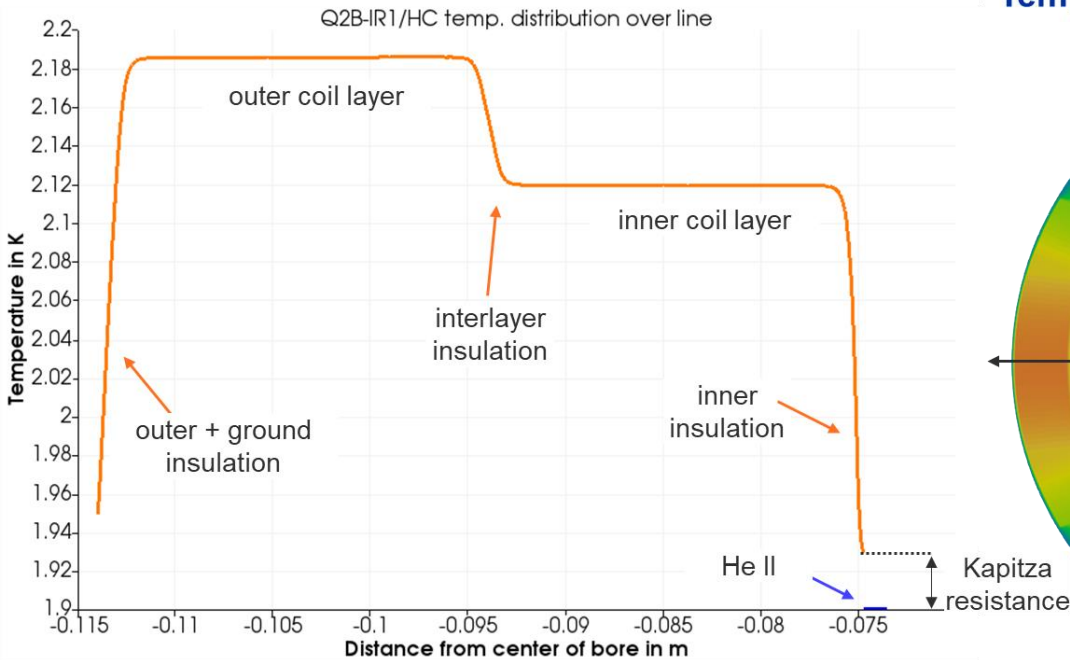
Temp. distribution at peak location (coil detail)
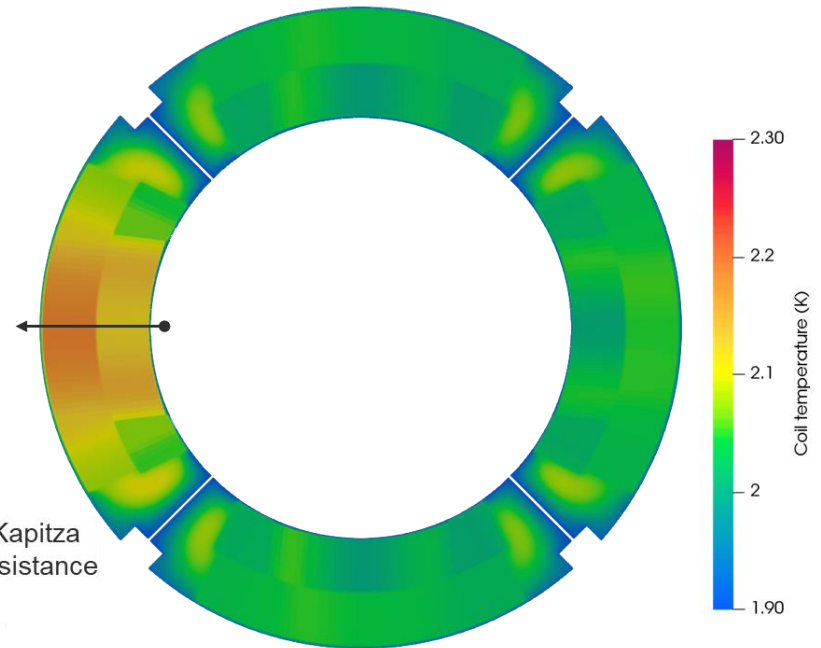
With fully impregnated cables, the thermal gradients are mainly determined by the interfaces (in contrast with NbTi-helium permeable cables)

With fully impregnated cables, the thermal gradients *are mainly determined by the interfaces* (in contrast with NbTi-helium permeable cables)

→ Going from fully helium-immersed coils to "dry" conduction-cooled coils is for fully impregnated cables, apart from an additional DT, a similar situation.

For future magnet development based on fully impregnated coils the temperature gradient ΔT across the coil must be kept as low as possible:

- Control the interfaces
    - Electrical insulation (Kapton foils p.e.)
    - Quench heaters (external, CLIQ, inductive…)
    - New impregnation materials (can we enhance the conductivity & Cp?)
- New conductors
    - Anisotropy of HTS tapes
    - Electrically insulated or non-insulated HTS tapes
    - …
- Conductivity & Cp data of new magnet designs to be measured
    - Accurate data greatly detailed thermal analysis

Key takeaways

- A **robust, easily adaptable numerical framework** has been consolidated to evaluate heat extraction mechanisms in **complex cryogenic system geometries involving He II**

- We are now able to produce results in a timeframe that allows for **parametric investigation of geometry, operational T, and power deposition** on magnet systems cooled by static, pressurised He II → this enables a **systematic approach**, and **can be used as a tool in magnet design** w.r.t. heat extraction

- Numerical simulations **directly benefit from the material data obtained from the experimental test campaign**, allowing for **more realistic, accurate calculations**

- The **heat extraction pathways for the HL-LHC inner triplet magnets have been validated** for the latest geometry, considering a steady-state power deposition at peak location for nominal operating conditions (5.0×10^{34} $cm^{-2}s^{-1}$, 7 TeV), at 1.9 K cold source

ASC 2022 paper submitted to *IEEE Transactions on Applied Superconductivity (TAS)*

Helium availability and typical LHC reliance
(fully immersed magnets)

- Presentation based on available public information only

- Not an economist nor a seller, only interest is to supply necessary molecules for the laboratory in the coming years

- Helium market is currently (2022-data) evolving really fast and situation may be significantly different in a few months

Carte 1 : production, échanges et consommation d'hélium dans le monde en 2018
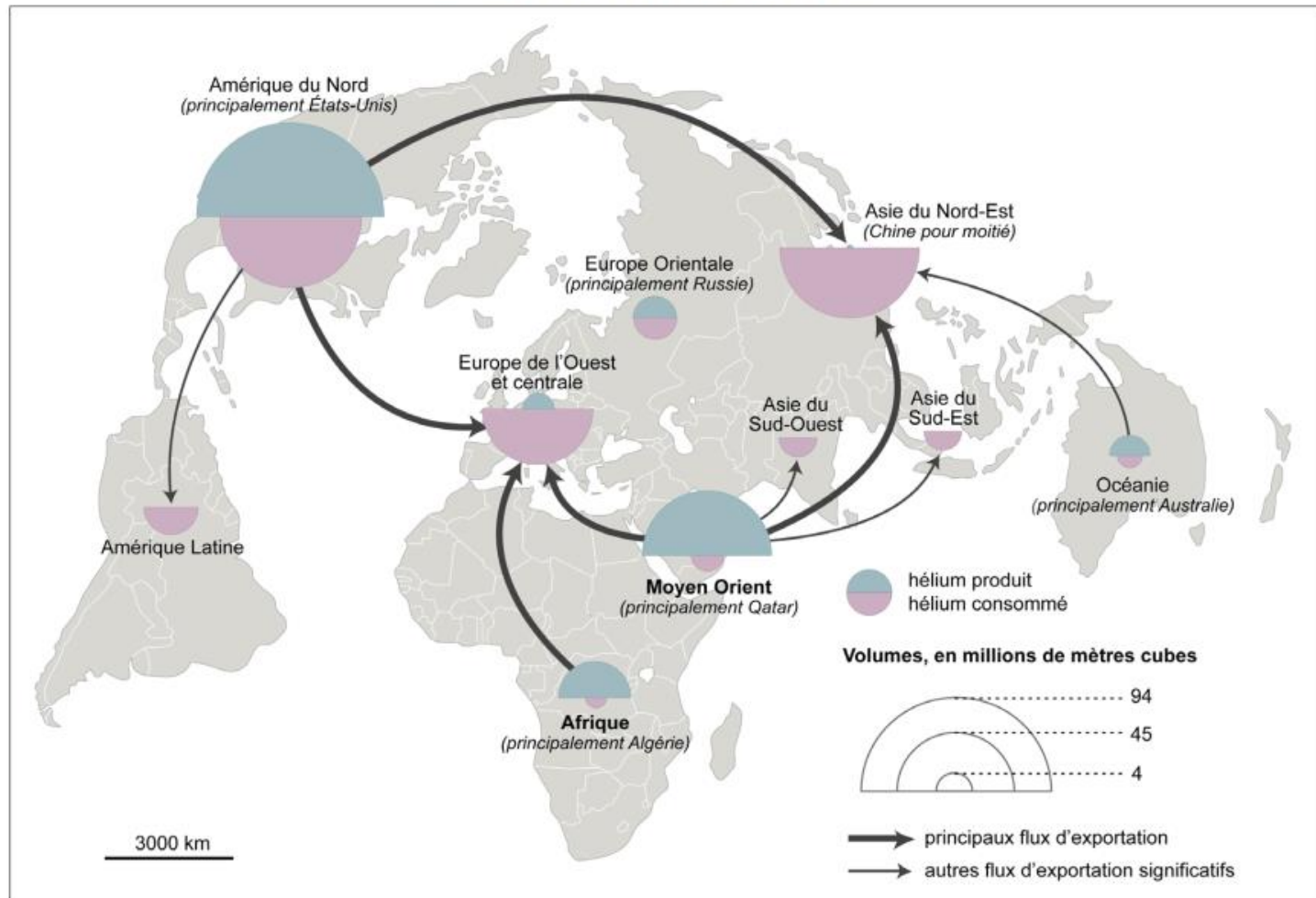
Source : Gubler et al. (2019).

Europe (and CERN) are outside supplier dependent

Ref: https://www.ifri.org/fr/publications/briefings-de-lifri/helium-nouvelles-geographies-dune-ressource-critique

Use of helium cryogenics at CERN

LHC & Experiments
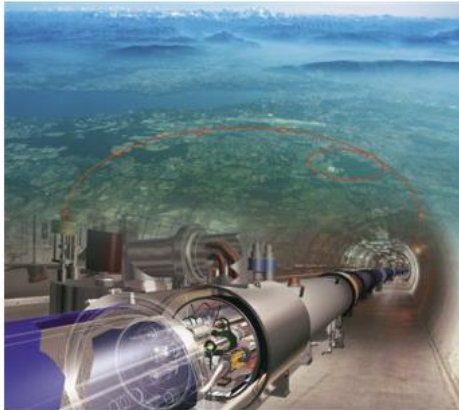
LHC 36'000 tonnes of cold mass distributed over the 26.7 km underground accelerator
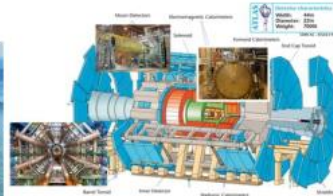
ATLAS 1'275 tonnes of cold mass
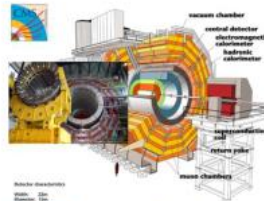
CMS 225 tonnes of cold mass

LHC accelerator cooling of the superconducting magnets at 1.9 K
ATLAS cooling at 4.5 K of the superconducting magnetic system
CMS cooling at 4.5 K of the superconducting solenoid

non-LHC & Test Facilities

SM18 test Facility

West Area test Facility

HIE Isolde Cryo Modules

SPS BA4 COLDEX

SPS BA6 Crab Cavities

Central Liquefier

North Area

Test Benches for accelerator magnets, wires, RF cavities
non-LHC facilities and **fixed target physics experiments**
Central Helium liquefier and **Cryogenics laboratory**

Courtesy Frederic Ferrand

LHC infrastructure

Surface storage & distribution
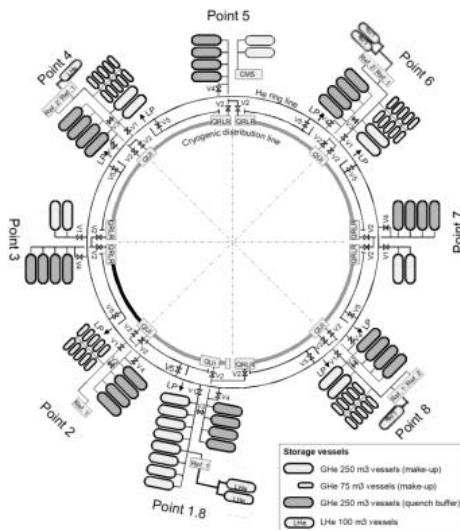
Gaseous helium storage 250m³

Liquid helium storage 250m³

Underground distribution & use
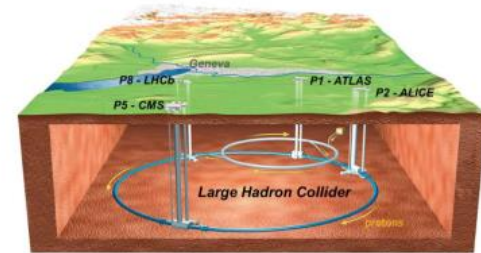
4.5K & 1.8K Cold Boxes   Distribution Valve Boxes   Distribution System

- Total inventory at CERN **175 tonnes** including **130 tonnes minimum for LHC**

- Distribution through the LHC Helium Ring Line, inter-sites High Pressure helium distribution line for non LHC and trailers

Courtesy Frederic Ferrand

Scope of supply for helium contracts 2022-2026

Liquid helium supply

200 tonnes

to compensate helium losses

Mainly for **testing and experiments**

For **LHC machine** constant effort to reduce losses showed results over the past 15 years
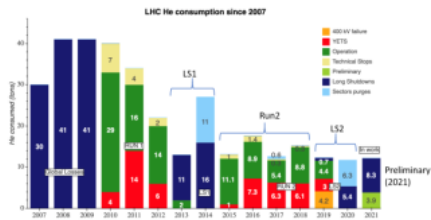
Helium quantities included:

- LHC needs for **Run 3** and refilling of the machine at the end of **Long Shutdown 3**
- Requirement for new **HL LHC cryogenic infrastructure** are also included

Helium management

140 tonnes

temporary sent out from CERN to contractual suppliers and returned on demand

This is a **necessary extension of CERN storage** capacity when LHC machine is partially or completely warm

During **Run year end closure up to 20 tonnes** are sent out for about 2 months

During **Long Shutdowns up to 80 tonnes** are sent out for about 18 months

Gaseous helium supply

6 tonnes

for LHC machine pressure tests

High Pressure helium trailers are used to pressurized sectors for safety pressure test

These deliveries are foreseen at the end of **Long Shutdown 3**

Courtesy Frederic Ferrand

Helium market long term evolution driven by US strategic decisions

Helium act 1925

- Significant increase of the production in the 60's
- Cliffside infrastructure and underground storage of the federal strategic reserve
- Almost monopoly of the US on the worldwide helium market
- Rapid decrease of production in the 70's, reaching peak in 1980
- Managed by the state BLM with significant associated costs
- Confort zone, low prospecting and investment elsewhere

Helium privatization act in 1996

- Federal government expenses pay back by selling 1bcm till 2015
- Large industrial investment in Algeria 1997 and Qatar since 2008
- Production capacity developments in the private sector was too low

Stewardship Act of 2013

- Regulation of the of the market by selling of the strategic reserve through yearly auctions to the private sector
- Make the bridge with new international extraction capacity development
- Regulation of the US domestic market, but reduction of exports over the years
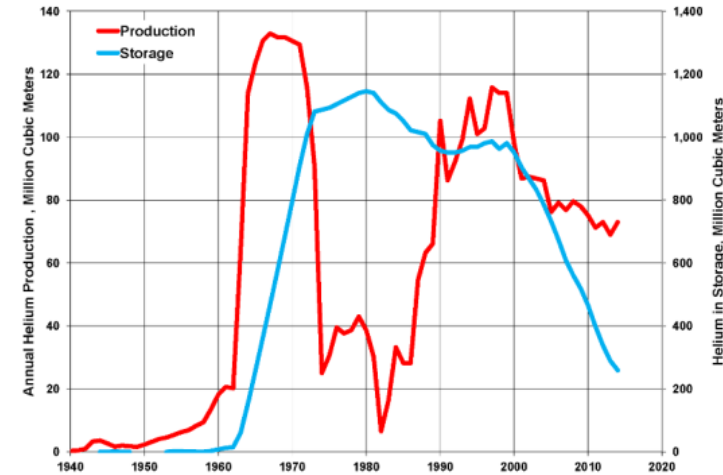
Wikipedia, based on US geological survey data

Good Read (in French): IFRI Briefing

Courtesy Frederic Ferrand

Known parameters affecting helium availability

- **Unbalanced supply and demand,** helium shortage 2006 & 2013

- **Geopolitical stability** in the country of extraction, Qatar 2017

- **Logistics complexity** blockage of Suez Canal in 2020

- **Maintenance shutdown or technical event** on LNG feed and helium liquefaction plants can impact market

Courtesy Frederic Ferrand

What's happening in 2022 ?

- **BLM closure** in January
  - Temporarily closed procedures for safe handling of chemical materials (Gasworld)
  - Outsource of BLM operations to private contractor

- **Explosion at AMUR** site in Russia production site in January
  - Several events leading to stop of the commissioning (Gasworld) ;
  - Expecting ramp up of the production postponed

- **Commercial limitation with Russia** due to conflict in Ukraine
  - Impact on the AMUR project repair and recommissioning of the helium plant
  - Takeover of the engineering from European by a Chinese company

- **Planned maintenance** during spring period

- **Restart of industrial activities** after Covid period

Courtesy Frederic Ferrand

Consequences

Current situation

- Market shortage is affecting industrial and scientific customers
- Manufacturing industry contracts are impacted with volume limitations
- Large scientific instrument cannot do so & rely on established industrial partnership

Helium market still at risk in 2023 and for the coming years

- Uncertainty on the effective Russian production capacity and market access
- Algerian gas production transferred using pipeline instead of LNG
- No more back-up from the US federal authorities, Cliffside for sale ! (C&en News)

Courtesy Frederic Ferrand

Perspective of new helium production capacities

- **LNG related**

  - Algeria debottlenecking of existing production sites

  - South Africa → 900Mm3 (lower estimate)

  - Qatar IV ?

- **Nitrogen-based helium production** (Physicsworld article)

  - Canada (Gasworld article 1 & article 2) → Announced production objectives 10% ww capacipty by 2030

  - Tanzania (The Citizen) 54bcf of primary helium at Lake Rukwa → Production announced in 2025

Courtesy Frederic Ferrand

Food for thought of operating fully helium immersed accelerator magnets

Disclaimer: the LHC has been an immense success and functions marvelously. A 27 km long accelerator of which about 23 km at 1.9 K!

A cryogenic success, on both magnet cooling as well as the whole cryogenic infrastructure which functions with very high availability!

However, there are a few points which are food for thought on whether we can do better for the next machine…
(whichever one that might be)

Safety: avoiding trapped volumes

What happens if one neglects (or even forgets) radial passages!

Relief valve   Winding   Annular space around beam tube   End reservoir
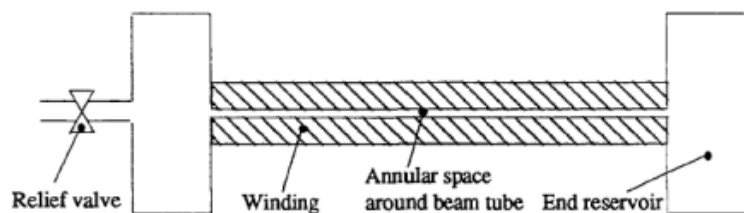
Figure 1.1 Dipole magnet

Inner winding layer
Outer winding layer
Upper pole
Beam tube
Lower pole
Annular space Helium

Pressure [bar] vs Time [s]
Annular space at magnet midlength
End reservoir
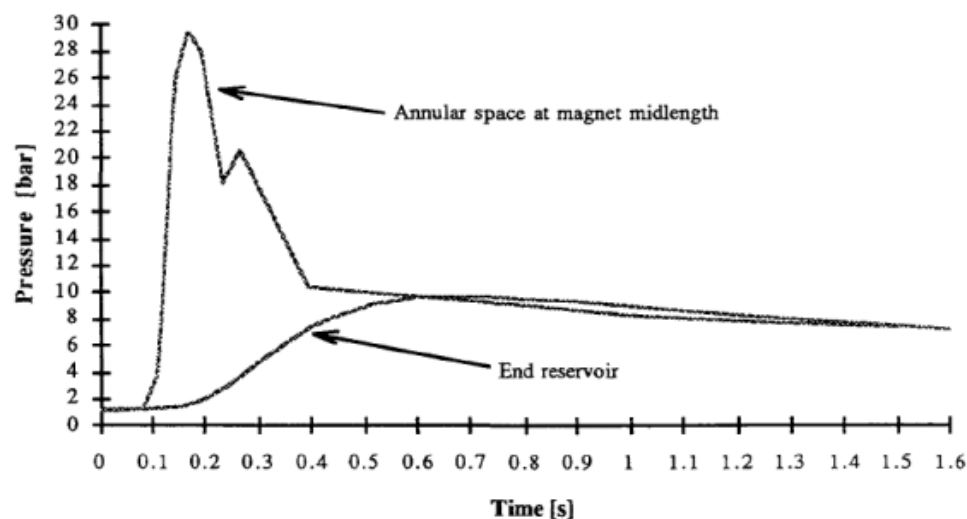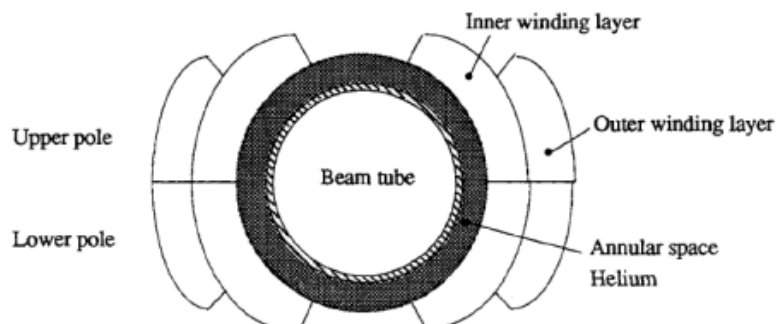
In a LHC-type cold-mass structure foreseen for a future 10 T coil, a low field (< 5 T) coil was placed, but to ease assembly a teflon sheet was mistakenly inserted between collar and yoke!

All radial escapes were closed, and even with the magnet energy of 5 T field, annular space pressures reached 30 bar.

A higher field coil of 10 T would have squeezed/distroyed the beam-pipe.

Safety: avoiding trapped volumes

- Since the experience with this very early stage LHC-cold mass test the explicit control of radial and longitudinal helium escape paths has become an integral part of the fully helium immersed magnet cold-mass designs and has never been an issue anymore

Safety: cold-mass pressure vessel

- A quench of a magnet-coil transfers about 25 % or more of the stored energy directly to the helium in which it is immersed
  - → pressure built up would be of the order of > 200 bar if not managed by safety relief devices
  - → The rate of pressure rise is coil-specific (porous or not p.e.) but initial adiabatic shock waves of several bar to about 10 bar cannot be avoided.
  - → The pressure rating of the cold-mass due to the helium pressure rise phenomena may be higher than desired because of this (think of machine-detector-interface magnets p.e.)

Safety: containing helium spill consequences

The shear amount of helium inside accelerator magnets has a heavy impact on personnel safety, especially in underground areas, and the infrastructure to deal with this:

- Helium release must be captured in dedicated cryogenic transfer lines
- Access restrictions for machine maintenance become dependent on the amount of helium in the cold-masses and their powering status
- Should accidents break the cold-mass to insulation vacuum helium will instead of being captured by the cryogenic transfer line spill into the ambient environment → Asphyxiation hazard

Inventory handling and supplier dependence

Some points to remember

Energy efficiency: Incorporate in the magnet design, whenever possible, features to intercept heat at as high T as possible!

Energy efficiency: If possible, use conductors that have a high Tc

Facilitating robust thermal design: Incorporate temperature margin to deal with heat extraction (no magnet operates at an ideal homogeneous temperature)

Inventory handling, supplier dependence, general & personnel safety: Aim for reduced helium content, preferably conduction cooled magnets

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