Heat transfer, cryostat, (conduction-)cooling (I of II)

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R. van Weelderen (CERN)

With contributions from P. Borges de Sousa (CERN), T. Kottig (CERN), F. Ferrand (CERN)

Outline Monday 27/11

- Introduction
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  2. Main cooling-option drivers
- Temperature levels
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  2. Cryogenic fluids
- Helium as a cold-source
  1. Phase diagram
  2. Intermezzo HeII - conduction through superfluid helium (HeII)
  3. Conduction comparative
- Intermezzo: Magnet-examples
- Temperature levels
  1. “Why do we need to talk about it”
  2. “That’s why we need to talk about it”

Introduction: Intent

The intent of these two lectures is to introduce you the *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,…

Introduction: main cooling-option drivers

Goes with choice of conductor temperature and heat intercepts

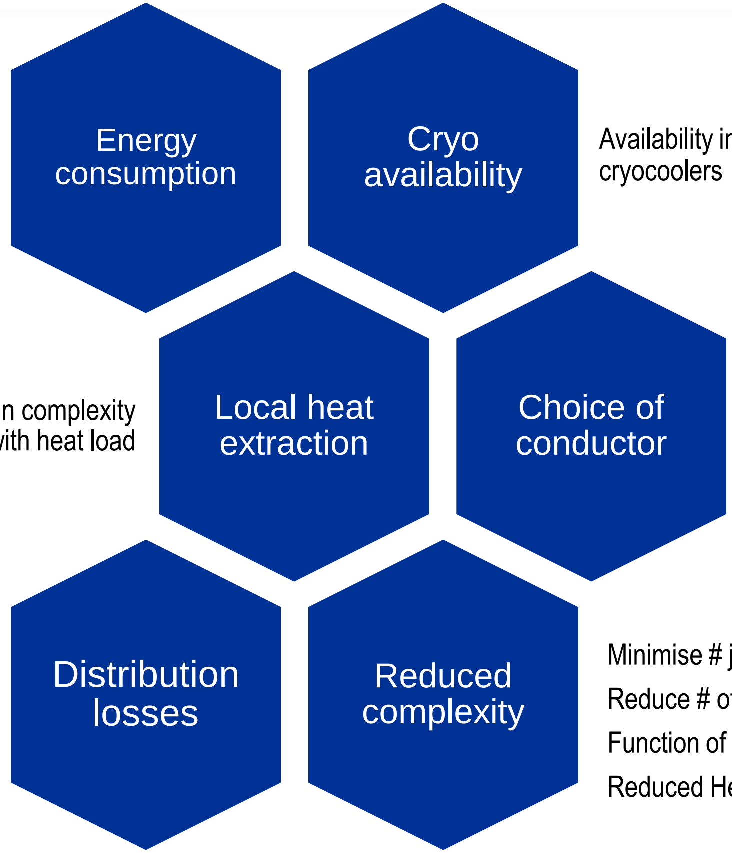
Availability increases with lower # of cryoplants / cryocoolers

Coil design complexity increases with heat load

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



- 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,…

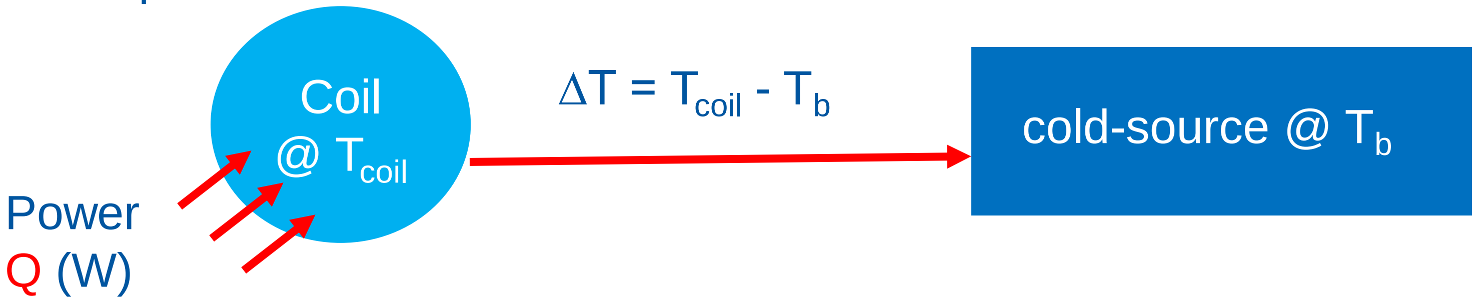
The most common superconductors, NbTi, Nb_3Sn, MgB_2, HTS making up the magnet coils *generally operate at temperatures from 1.9 K – 4.5 K – 20 K < 77 K*

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.



The ΔT originates from an accumulation off: 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:

2. The latent heat "L" 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

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

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, Nb3Sn) 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*

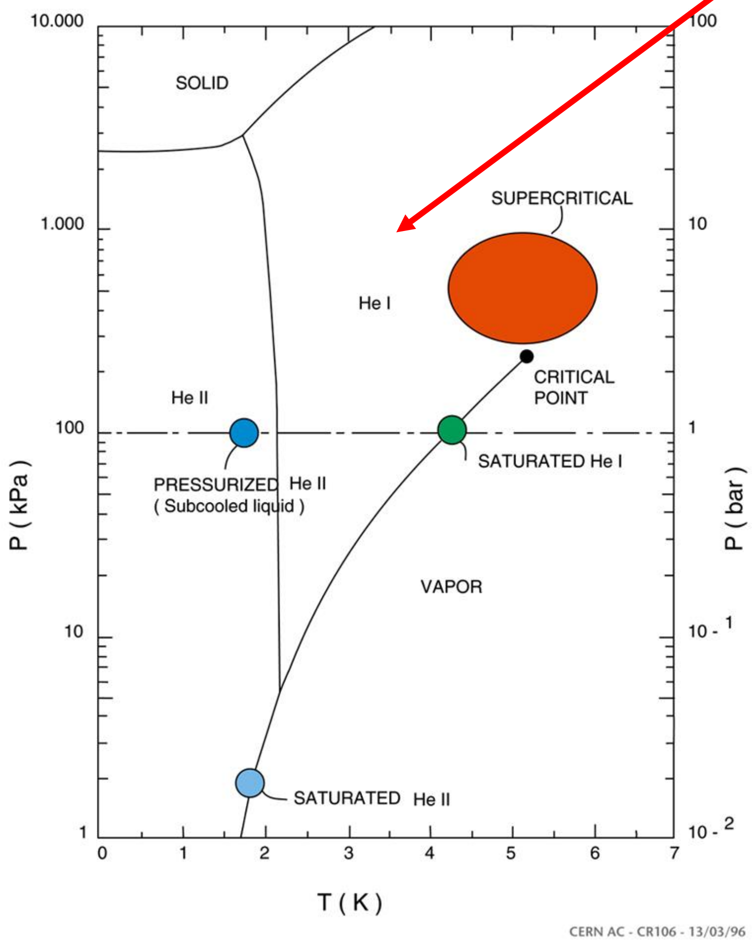
1L LN_2: ≈ 0.1 €

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



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")

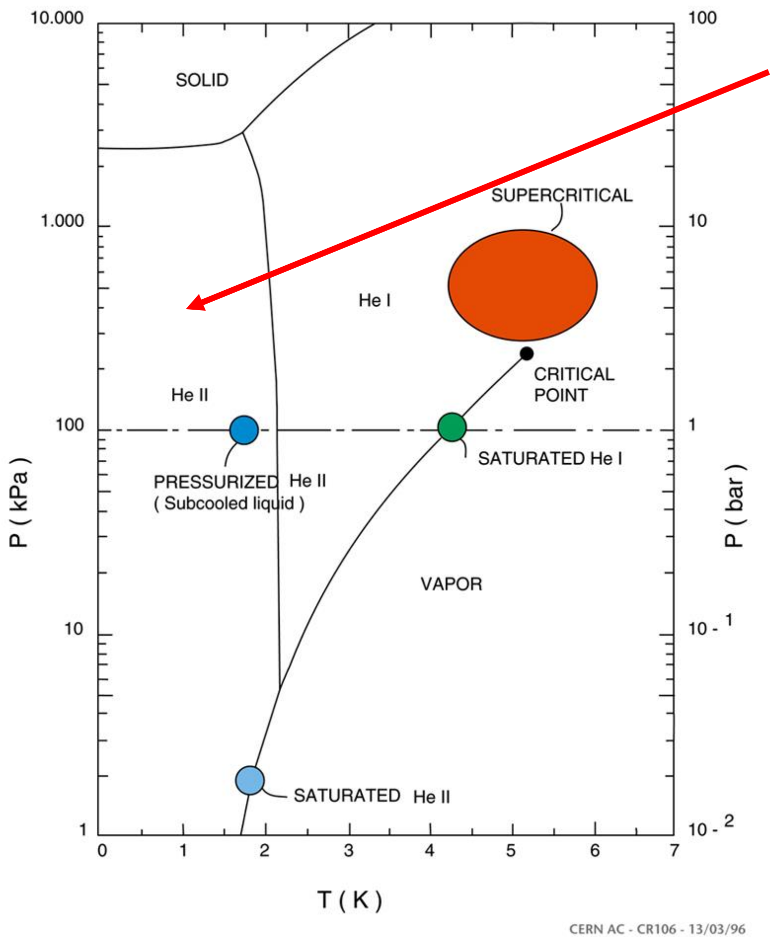
Working domain of saturated helium II is along the saturation line from (starting from 5.0 kPa & 2.17 K, to typically 1.6 kPa & 1.8 K)

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

Phase diagram of helium



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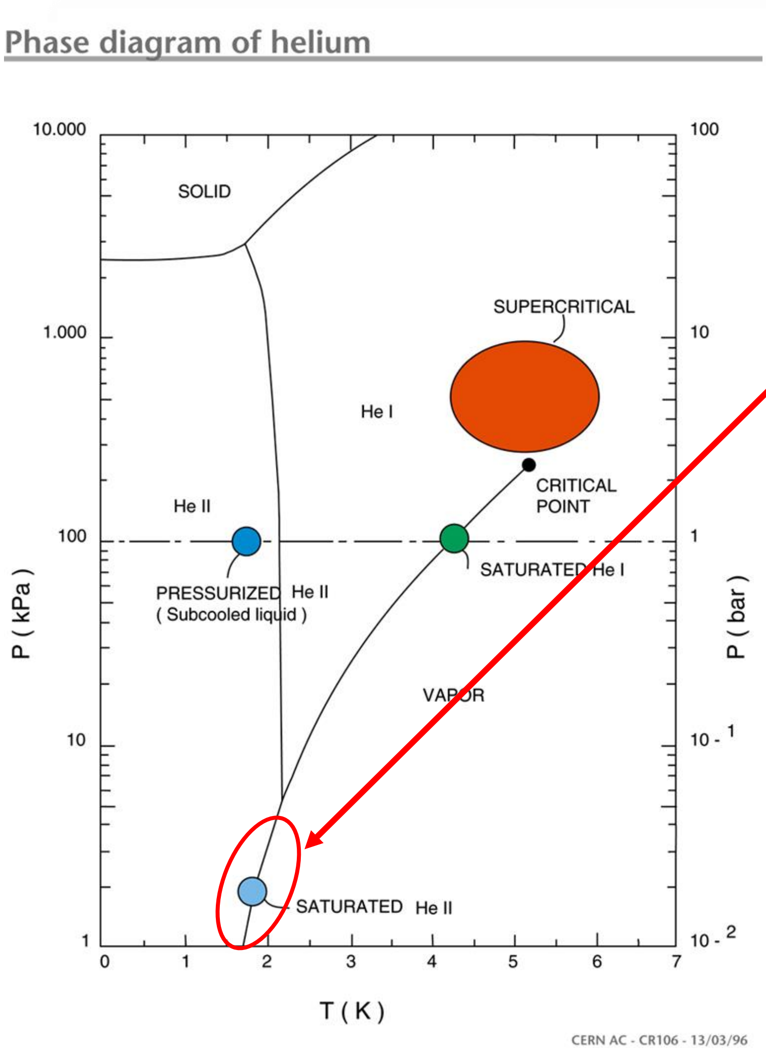

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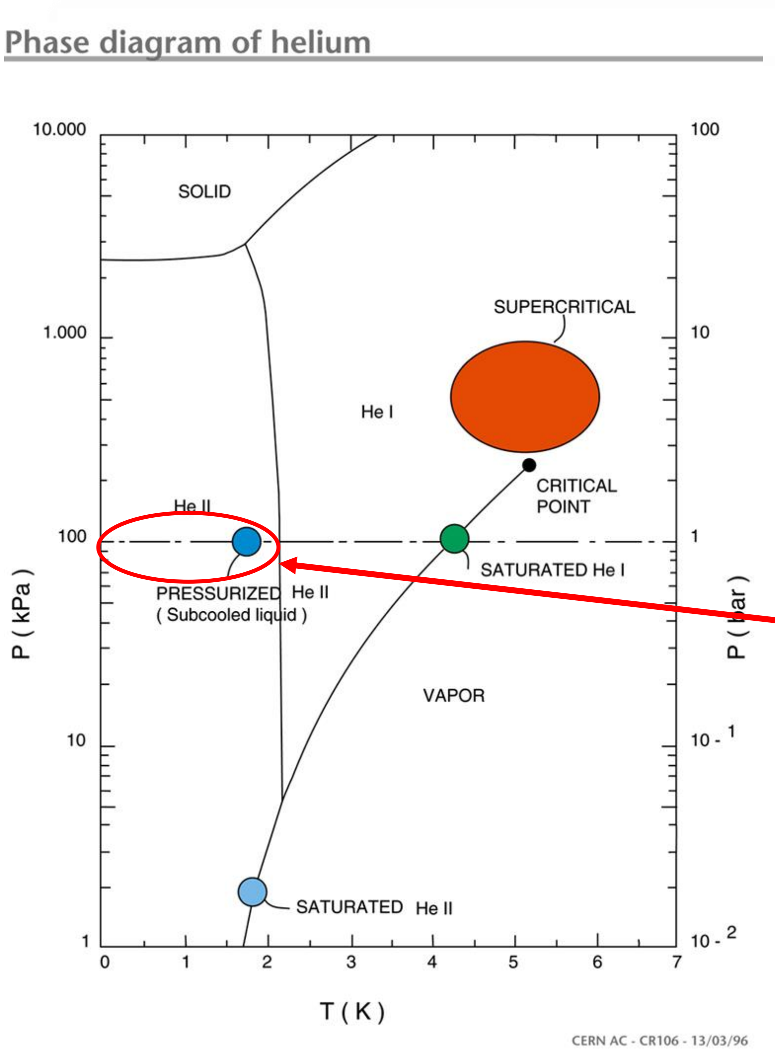

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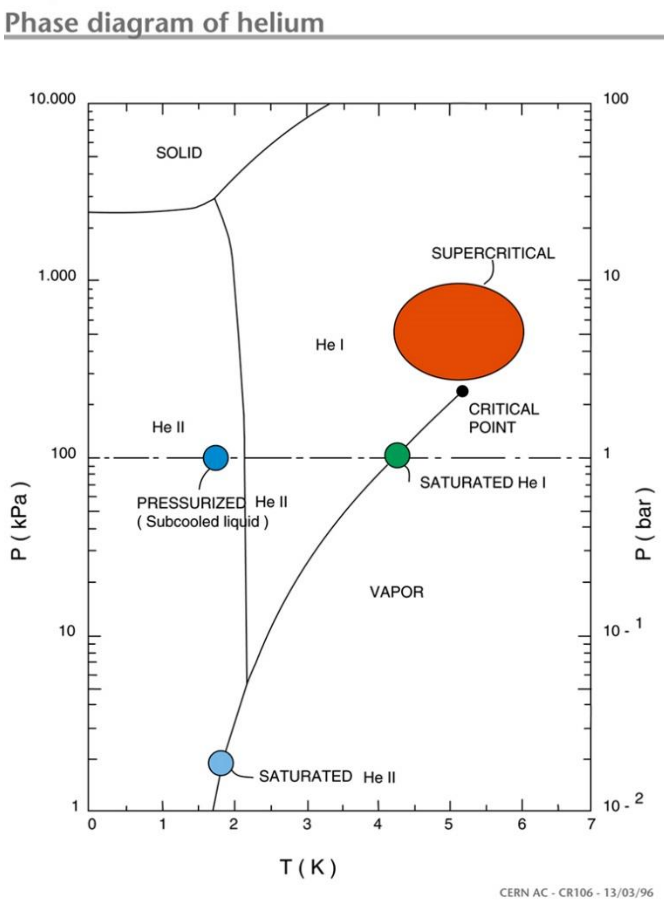
Helium as a



<u>Advantages of functioning in pressurized superfluid helium w.r.t. saturated helium</u>

• 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.

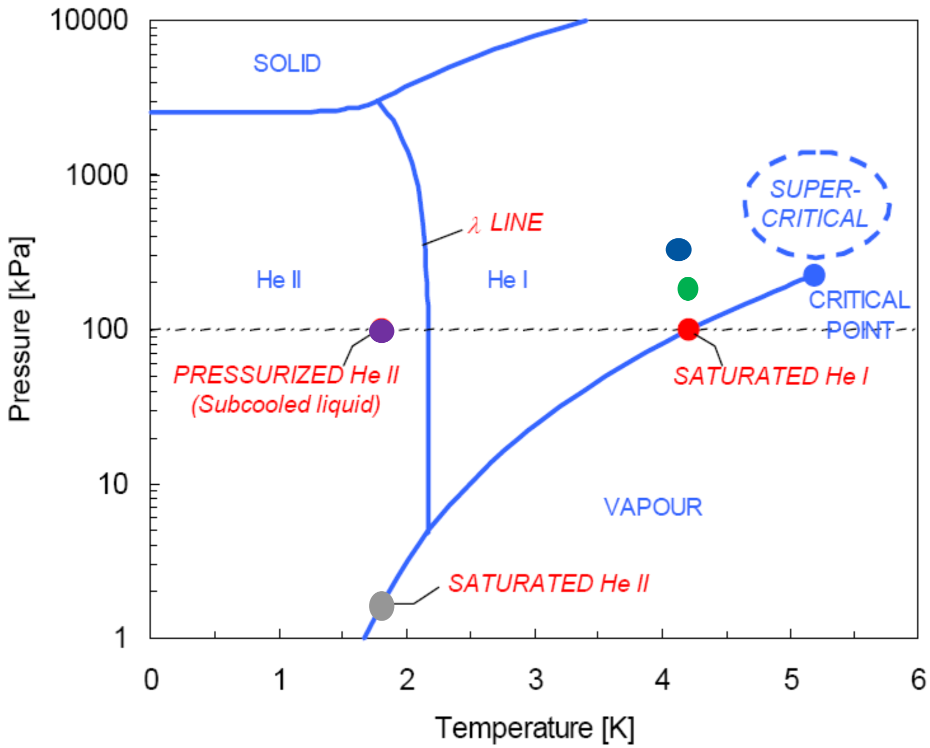
--> The enthalpy difference from the working point to the transition line is usually much smaller in the saturated helium bath. One typically could get an order of magnitude better performance in pressurised helium II (see ref).

• subatmospheric 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 breaktrough ("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

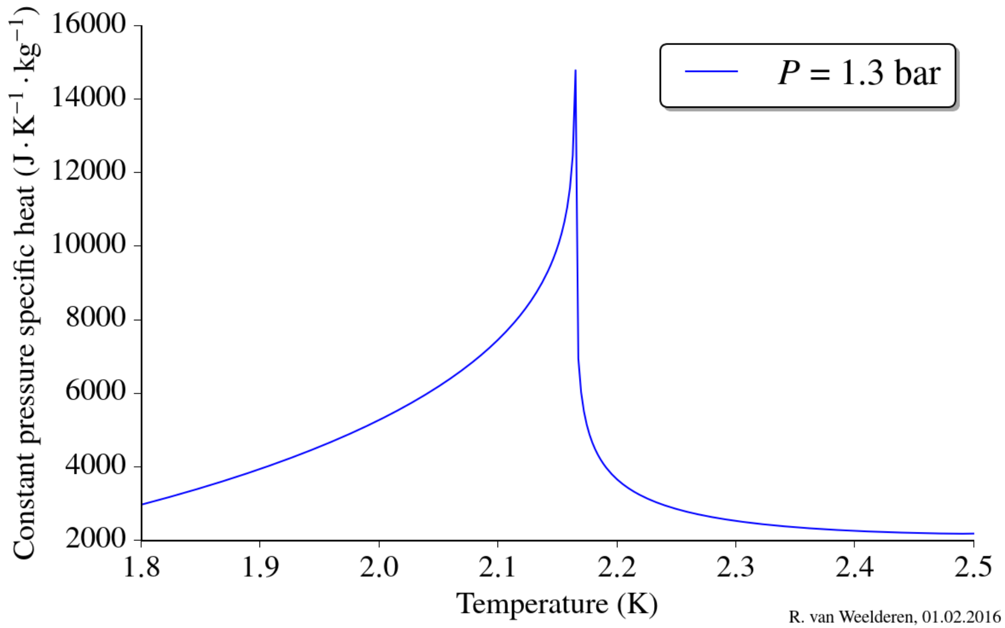
Listing courtesy Tom Peterson

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 Hell: Specific heat



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 higherthan 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

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.

Intermezzo HeII Conduction through helium II

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

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

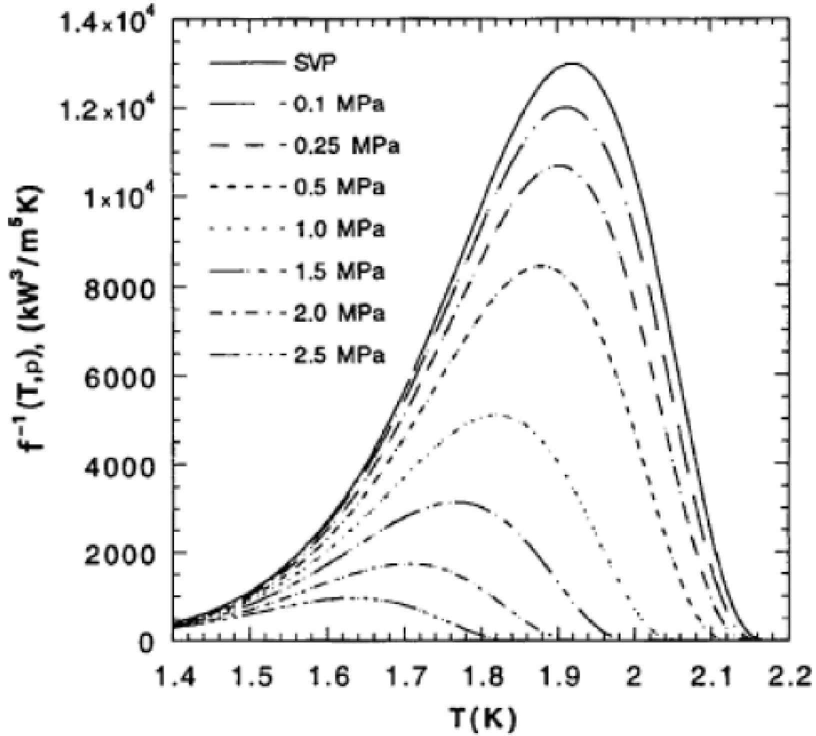
with

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

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 $1000\,\mathrm{W^3/cm^5}$, we get for $\mathrm{q} = 1\,\mathrm{W/cm^3}$ an effective conductivity of about $100\,\mathrm{kW/mK}$. 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

But: HeII conductivity is 1/q3 heat flux dependent and can easily break down!

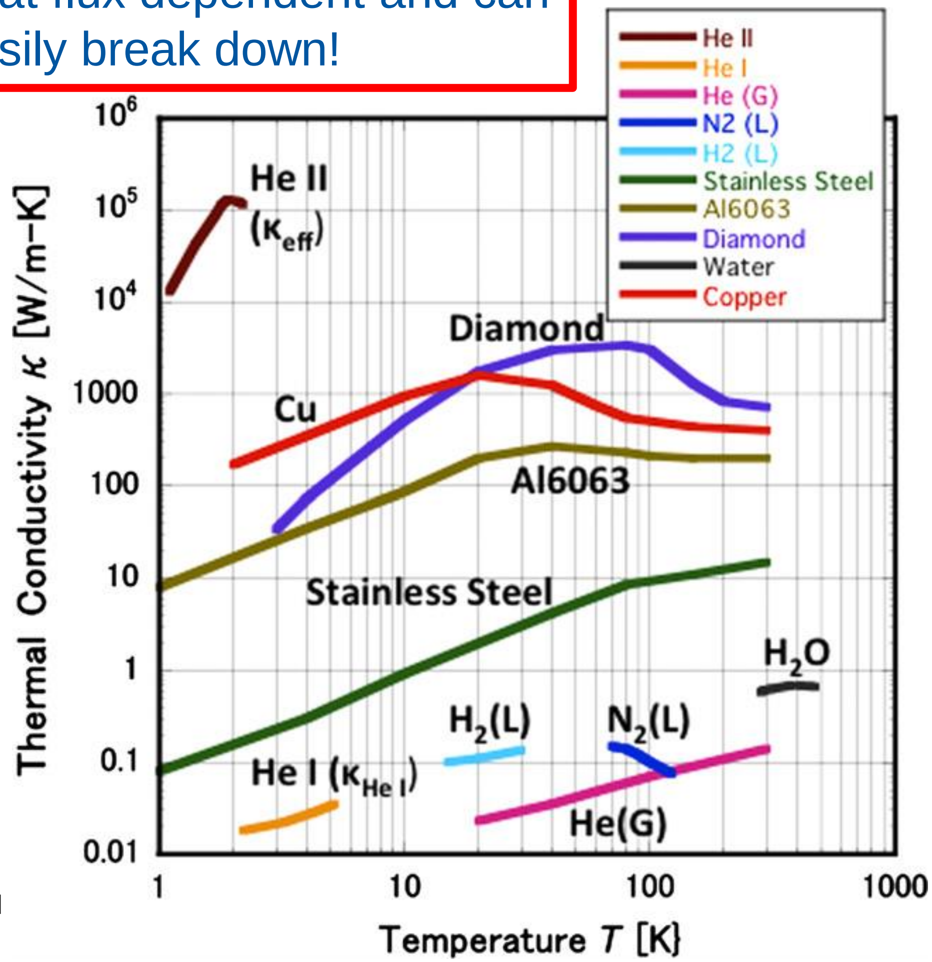
Normal helium (HeI):

- 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 than HeII is used as a conductive medium



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

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*

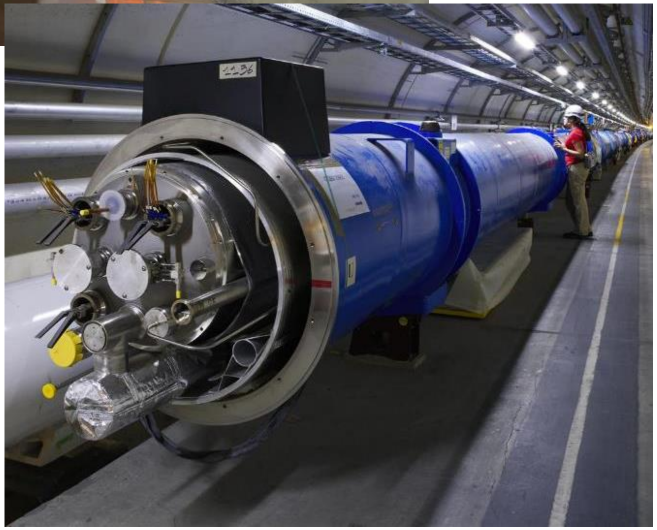
Limiting the heating power from the room temperature environment to reach the low-temperature environment of the coils requires *heat intercepts at intermediate temperatures* *(will be quantified later on)*

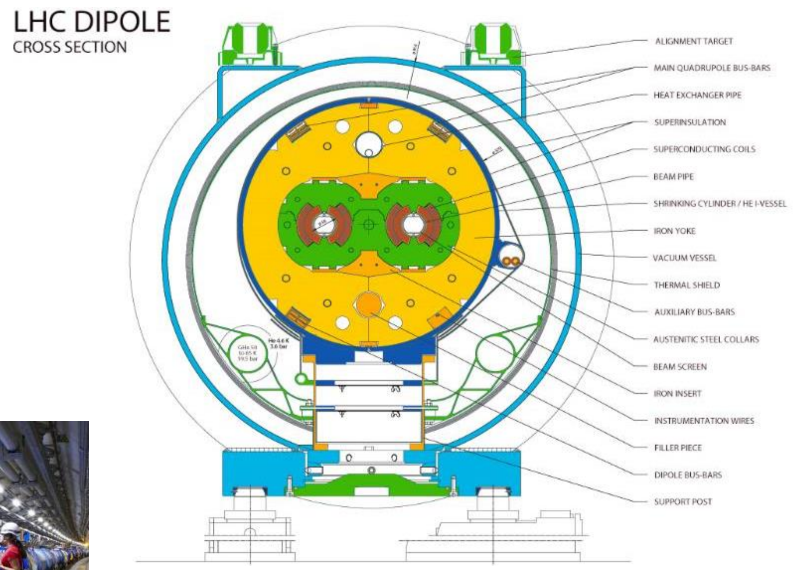
1. The superconducting magnet cryostats typically exhibit a “layered onion – shape”: High temperatures on one side and layers at decreasing temperature levels until the layer that incorporates the superconducting coil.
2. Temperature layers are separated by vacuum spaces to limit heat exchange by gas 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)

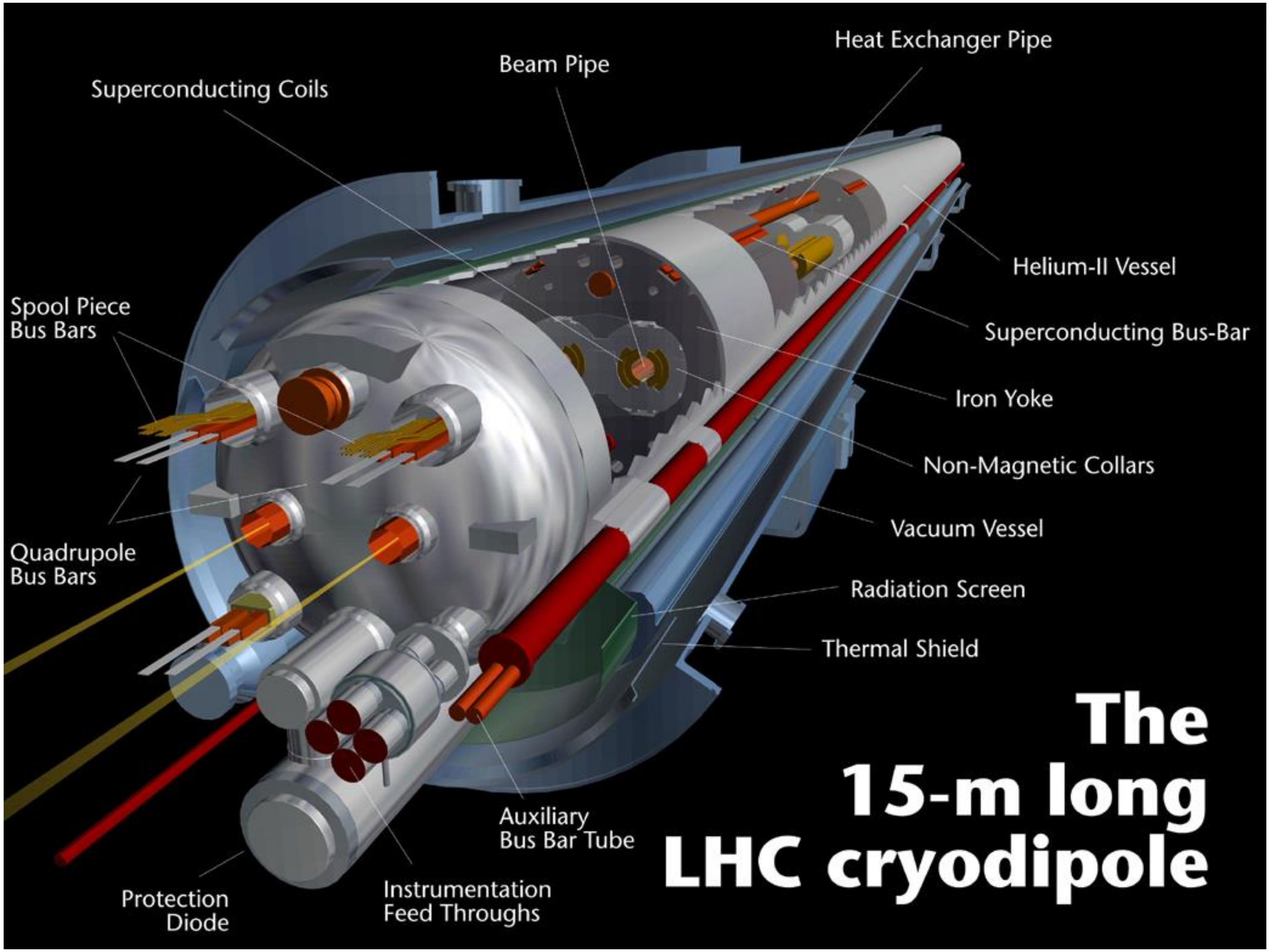
1232 dipoles, 474 quadrupoles, 7612 corrector magnets





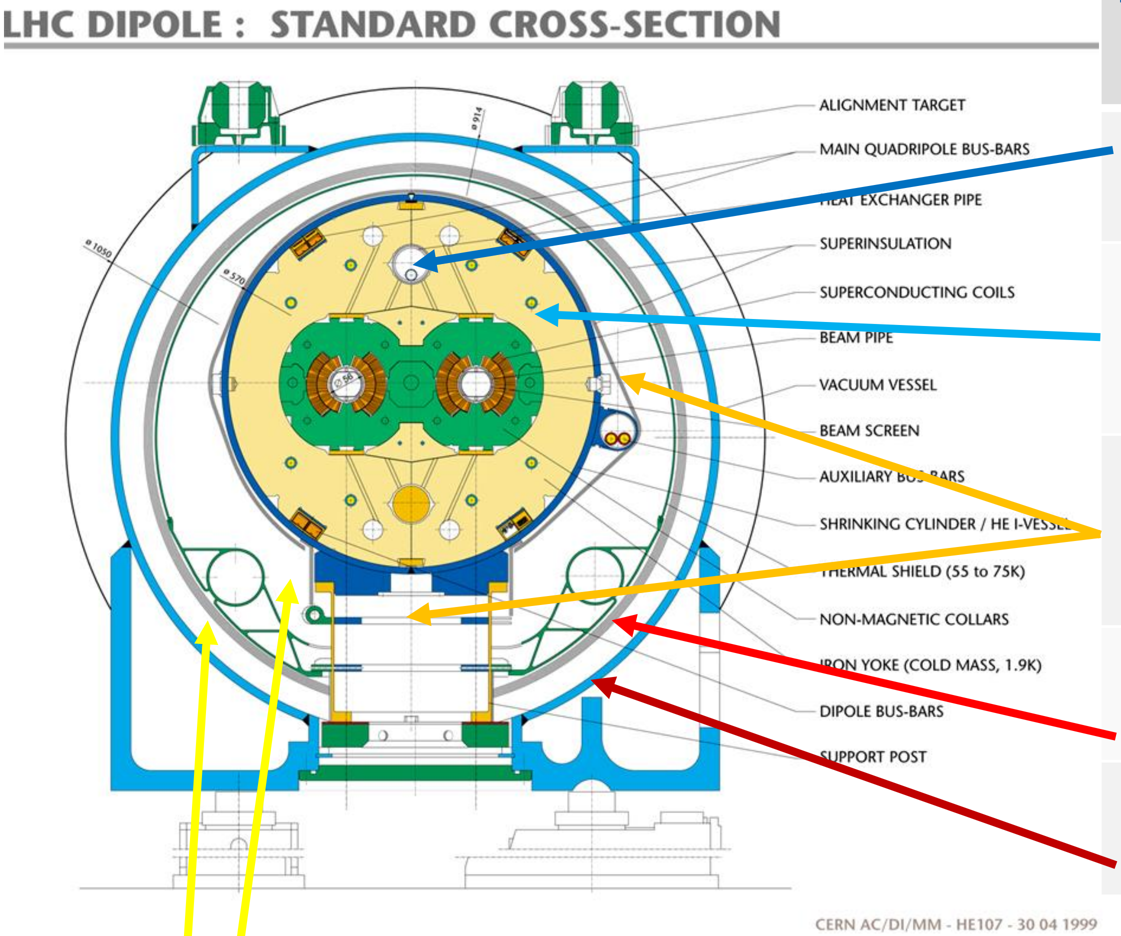
Fully helium- immersed magnet: coil, collars & yoke all @ 1.9 K (superfluid helium)

Magnet examples: LHC-dipole



Typical thermal environment & terminology

Magnet examples: LHC-dipole



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

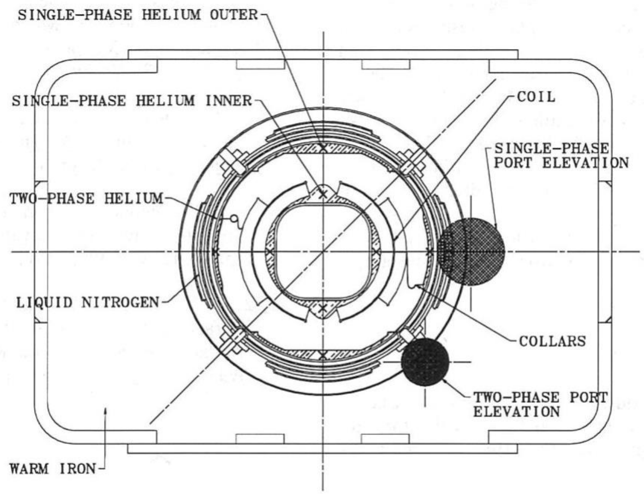
Vacuum spaces

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

Magnet examples: Tevatron-particle accelerator

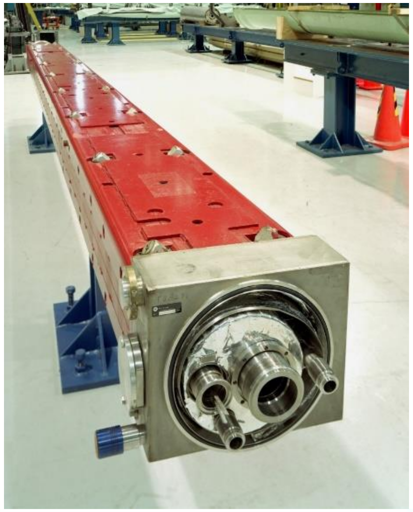
6.5 km of superconducting magnets operating @ 3.6 Kelvin, NbTi-cables & warm yoke

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



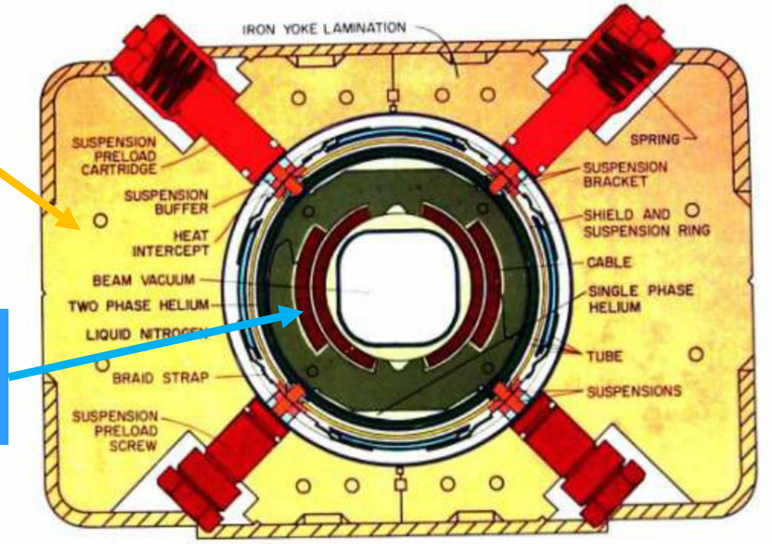
X = SINGLE-PHASE TEMPERATURE SENSOR LOCATION

TEVATRON CROSS-SECTION at SUSPENSION



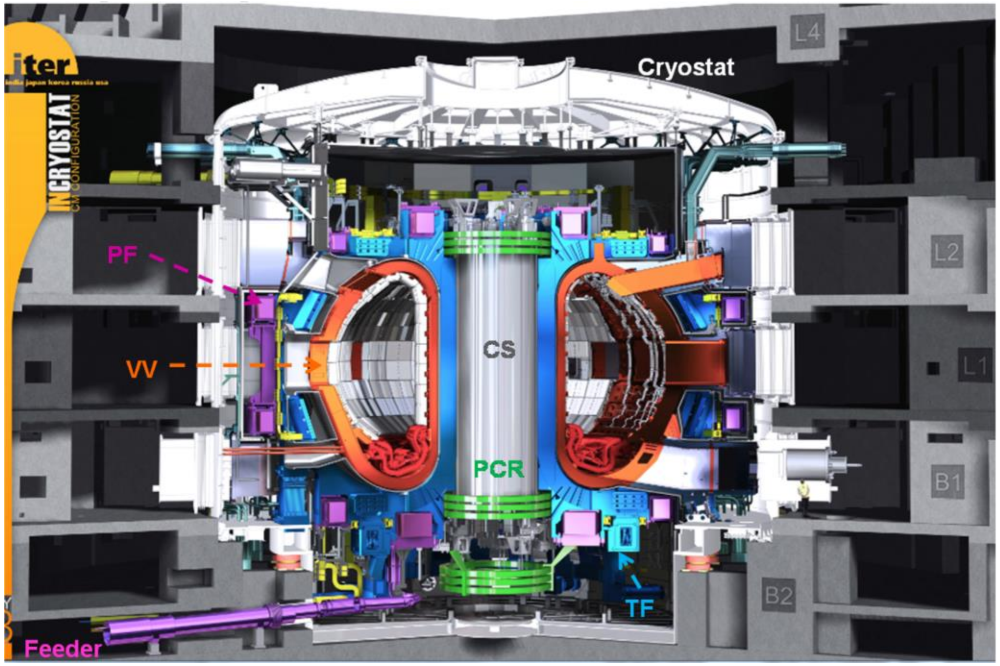
Warm Yoke

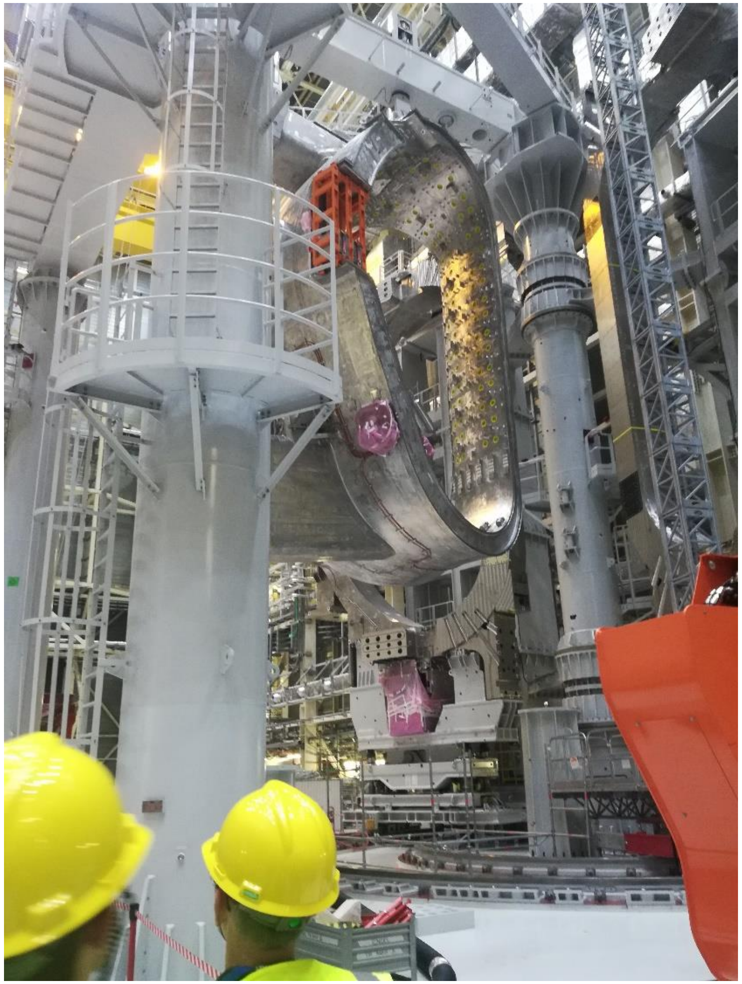
Coil @ 3.6 K



Magnet examples: ITER – fusion

Toroidal Field (TF) operating @ 4–6 K force flow cooled K, Nb3Sn-cables



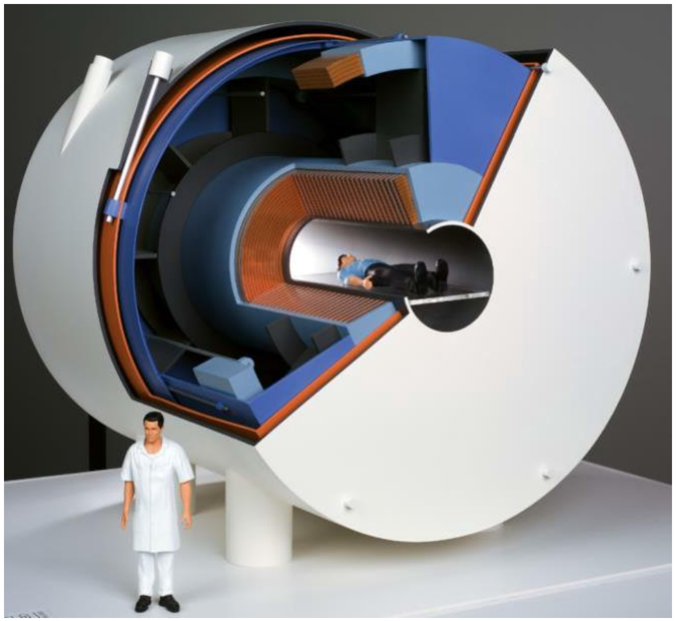


Nb_3Sn, operating at 4-6 K, force flow cooled

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

Magnet examples: MRI

CEA/Irfu for NeuroSpin (900mm bore 11.74T 500MHz) magnet



Nb3Sn @ 1.9 K

https://joliot.cea.fr/drf/joliot/en/Pages/research_entities/NeuroSpin.aspx

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		Coil level(s)
		• Conduction • Thermal radiation	
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”:

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

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)

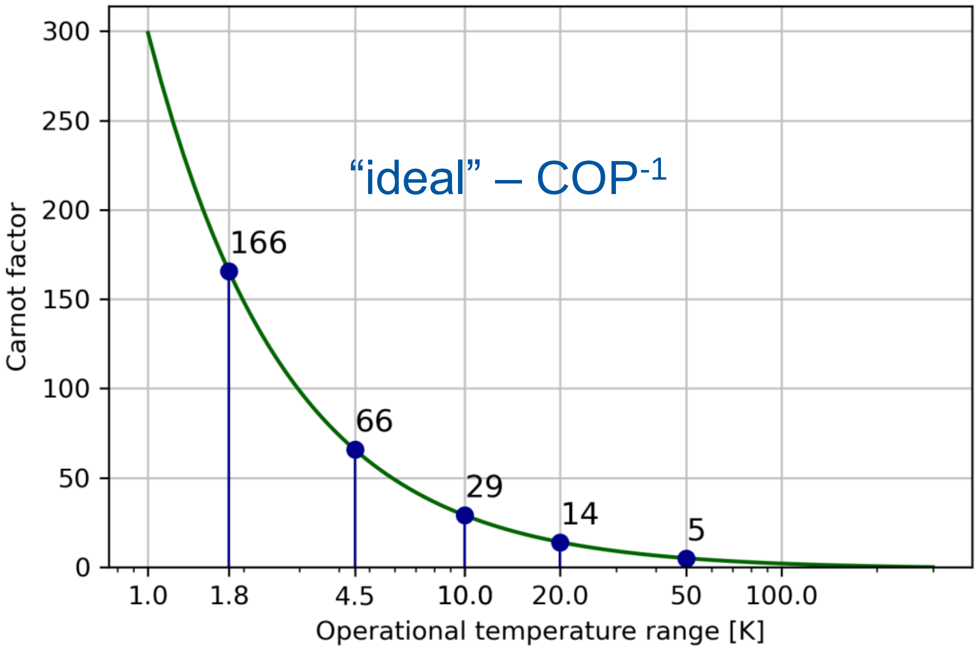
→ it is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures!

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).



→ 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.

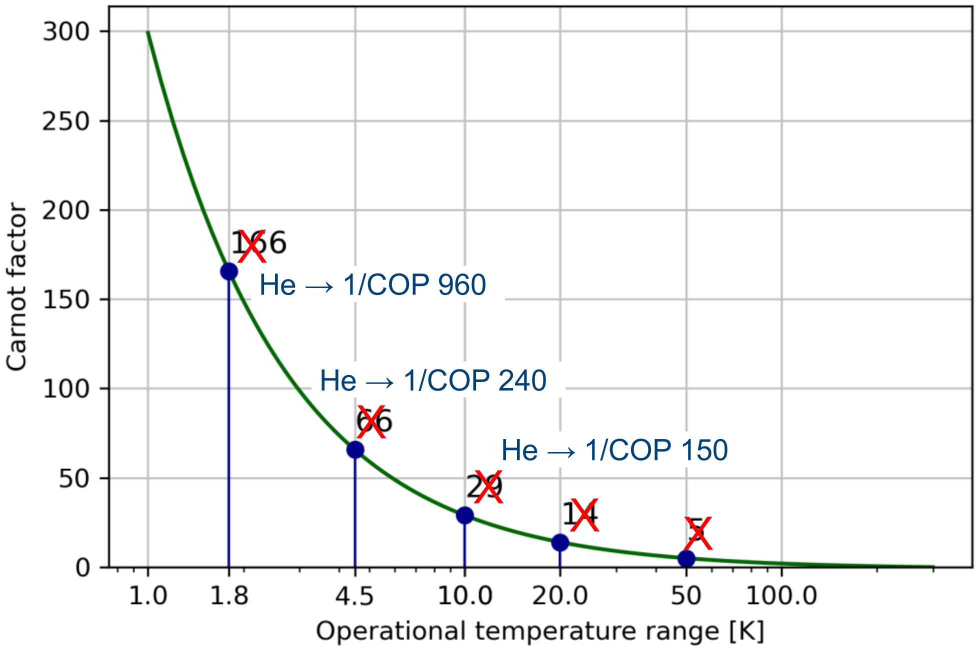
Temperature levels

("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 semi-realistic 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	Coil level(s)

Take away: try to incorporate in the magnet design, whenever possible, features to intercept heat at as high T as possible!