Thermomag-07

a CARE-HHH-AMT Workshop on Heat Generation & Transfer in Superconducting Magnets

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*H*eat transfer from the coils to the helium heat sink

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Outline

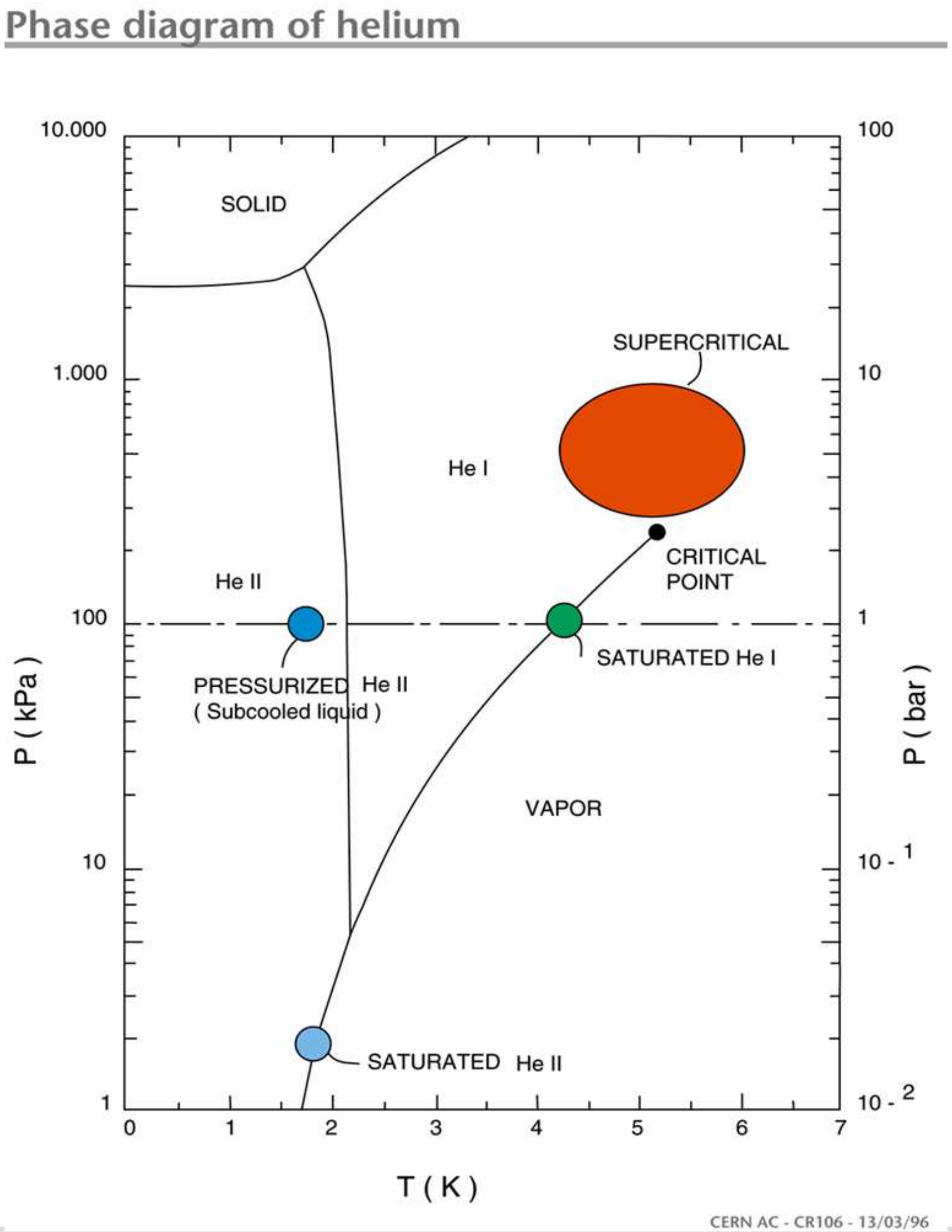
- Issues and first order cold mass design values for magnets operating in superfluid helium
- Generalized numerical approach

Issues

The cooling concepts and associated cold mass structure has to be determined such as to satisfy the following requirements:

– Static heat loads
– Dynamic heat loads
– Superconductive cable properties
– Coolant (Helium) properties
– Mechanical (space) constraints

Coolant (Helium) properties

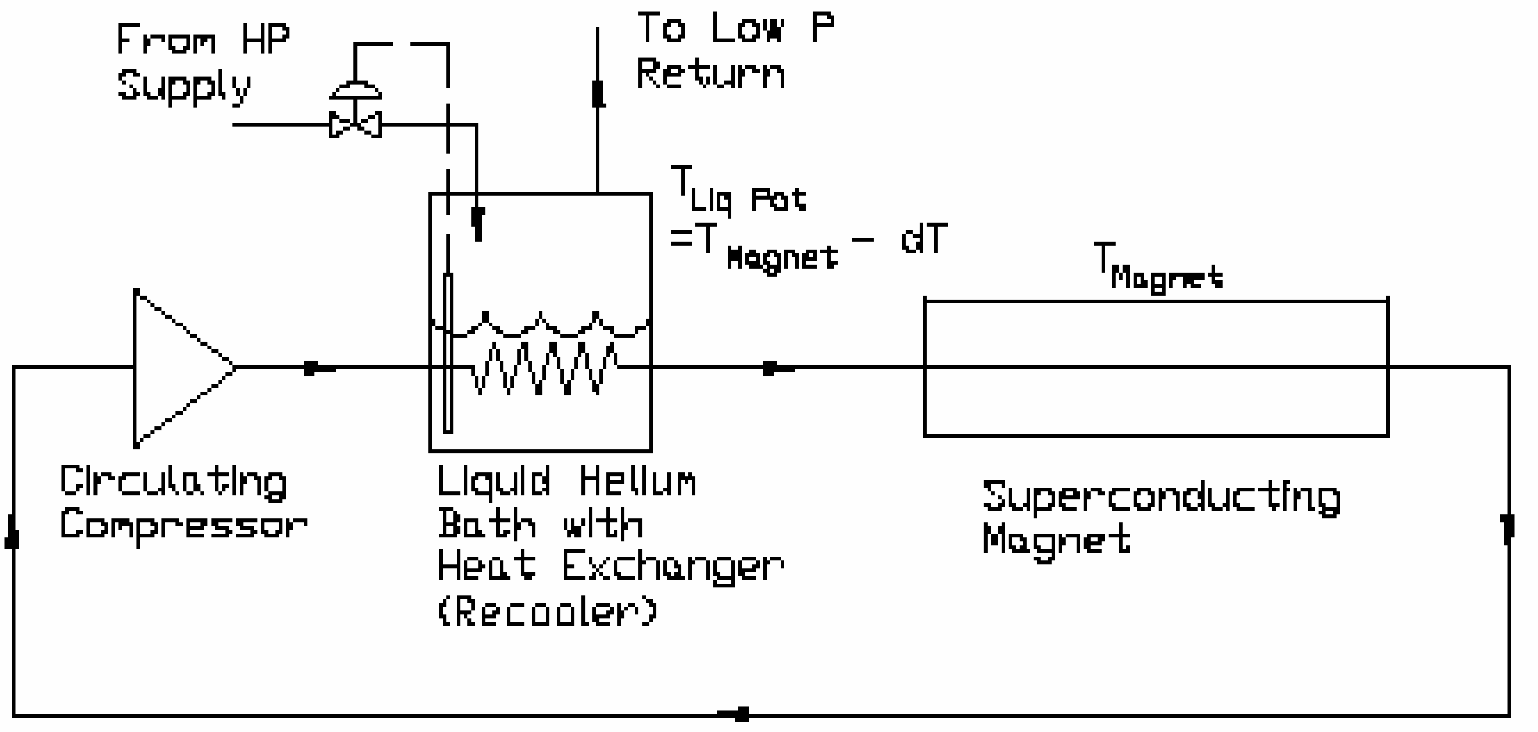


Basic cooling schemes and their practical limits

Cooling by means of:

- Forced convection of supercritical helium
- Pool boiling of normal helium (not covered)
- Forced convection of superfluid helium (not covered)
- Conductive cooling in pressurized superfluid helium

Forced convection of supercritical helium



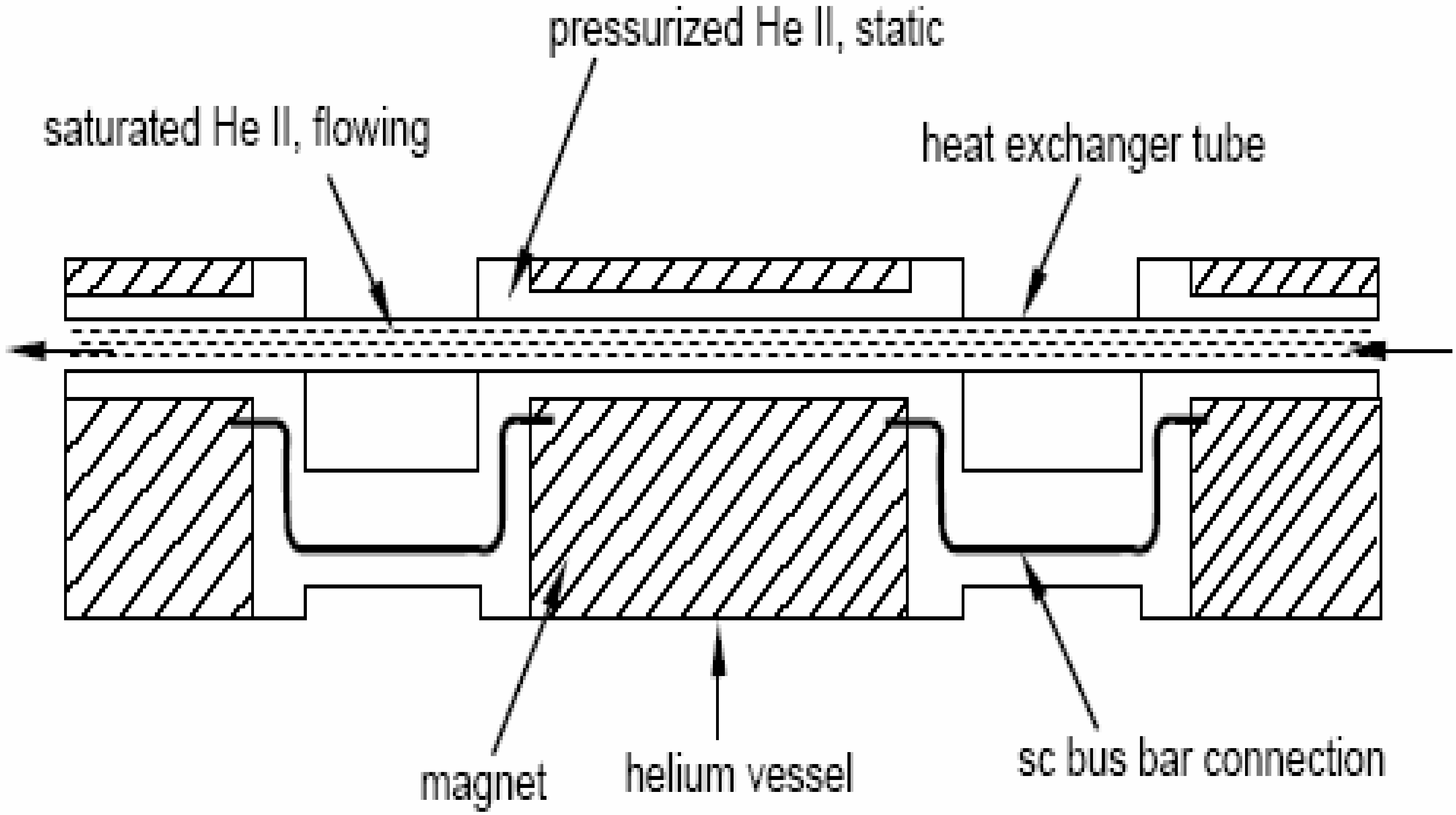
Forced convection of supercritical helium

- Forced convection cooling by supercritical helium is characterized by available pressure drop over a given length, and by allowed T difference between inlet and outlet.
- Over a given length covering a string of magnets, usually it is not the available pressure drop, but the allowed T difference that is limiting. As a consequence intermediate re-coolers need to be installed.
- Typical pressures are P≈3-8 bar, ΔP≈1-2 mbar per magnet
- Typical T≈4.4 K, ΔT≈50-150 mK per magnet
- Typical heat loads are ≈2 W per magnet (through flow, RHIC magnets) or ≈6 W per magnet (cross flow, i.e. helium forced close to the coil, as envisaged for SSC magnets).
- Horizontal flows. Typical gap sizes between cold bore and coil ≈2 mm
- Eric Willen: "Calculations and measurements of the heating in 17 m SSC magnets3 indicate that with crossflow cooling, a heat input to the 40 mm diameter SSC magnet coil of 2.4 W/m would result in a coil temperature rise of only 0.14 K. It is estimated that at least 30 W/m of heat could be tolerated in this coil structure."
- *If we propose to use extra T margin (6 K - 4.5 K), and at a ΔP=5 bar (8 in , 3 out) over the entire magnet we could in principle extract 1 kW using about 53 g/s of mass flow. Possible problems: high ΔP, orifice sizes, flow paths may lead to badly cooled "dead" spots.*

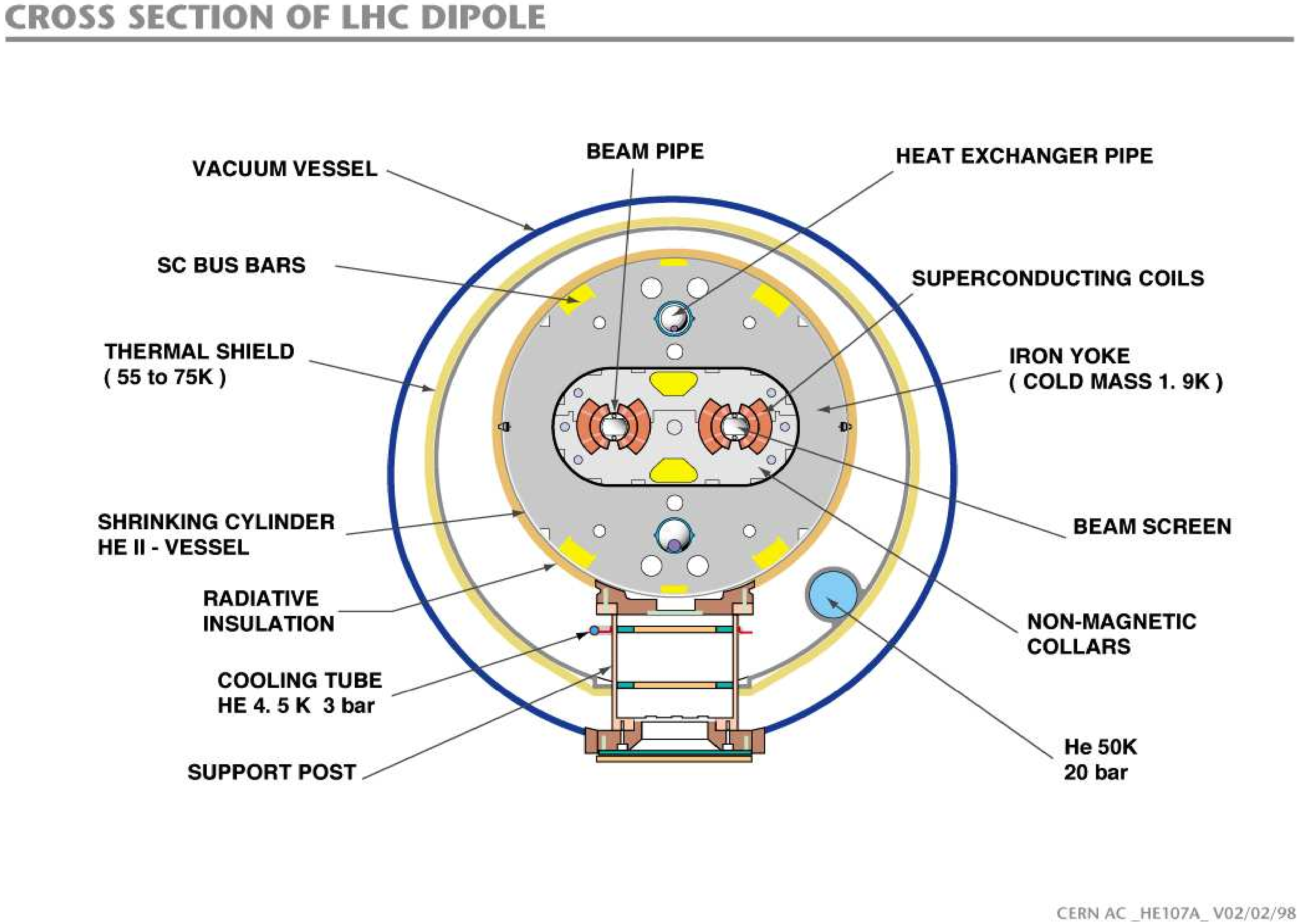
Conductive cooling of pressurized superfluid helium

- *Efficient, but if cold source is far away requires high conducting cross section (example 1 W/m over 50 m requires about 90 cm^2 between 1.8 and 1.9 K).*
- If cold source can be distributed over the length (thus only radial distances to cover) very efficient. Cold source provided by two-phase flow of saturated superfluid helium.
- Applied in LHC (main magnets ≈1 W/m), suitable for high heat loads (inner triplets ≈15 W/m).
- Requires attention to conduction paths, but is certainly extendable to heat loads of about 50-100 W/m.

Two-phase flow of saturated HeII



Two-phase flow of saturated HeII



CLASSIFICATION OF HEAT EXTRACTION PATHS

The total available ΔT for heat extraction is determined by T_λ=2.17 K at the coil to the suction pressure temperature of 1.776 K (15 mbar) provided by the cold compressors:

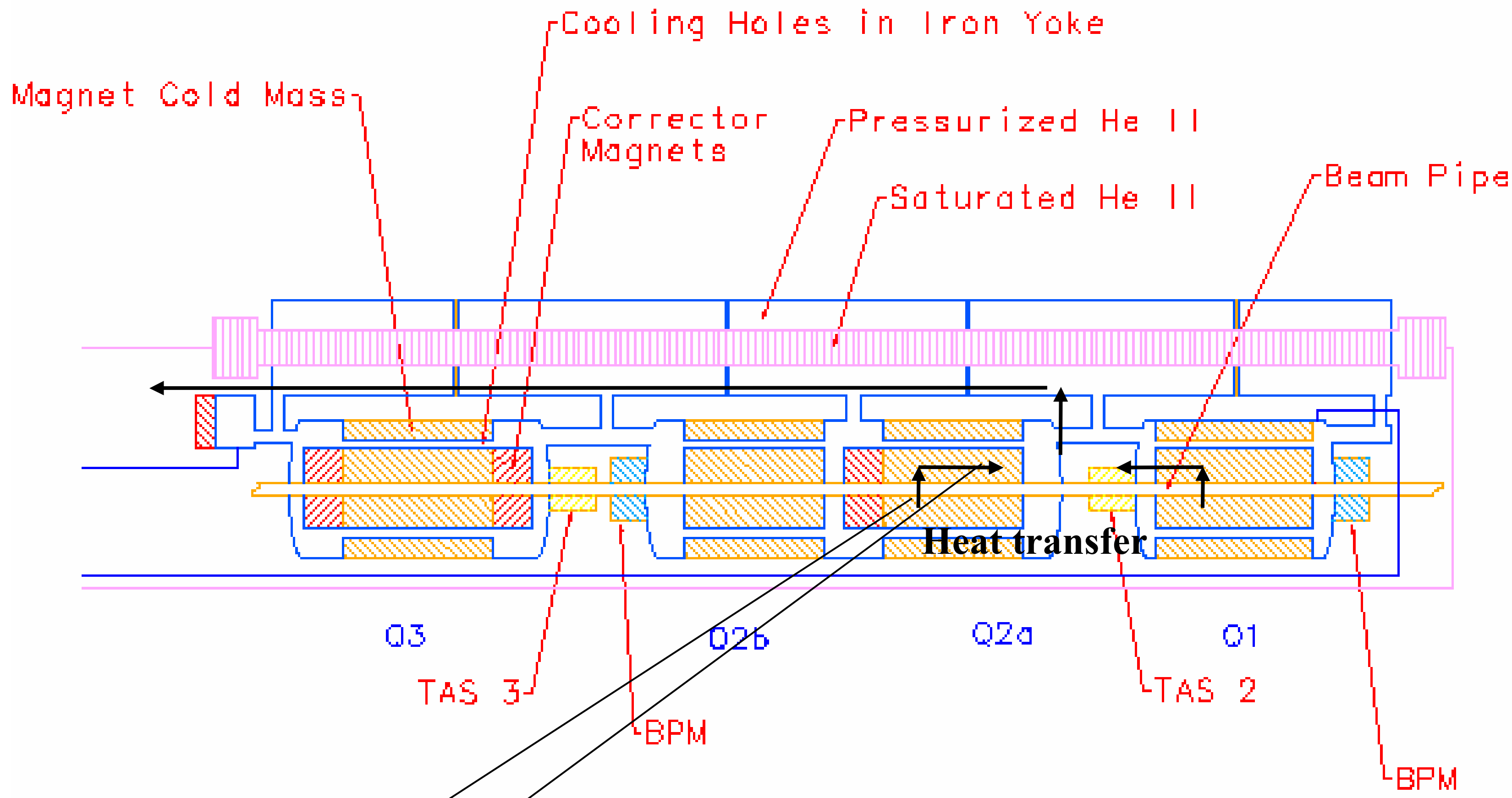
$$\Delta T = 394 \text{ mK}$$

We subdivide the total available ΔT into the parts relevant to the system design.

CLASSIFICATION OF HEAT EXTRACTION PATHS

- ΔTcoil: from the coil to the helium
- ΔTcoil-freeA (radial): the channels which collect the heat from the vicinity of the coil until it reaches the free conduction zone
- ΔTfreeA-bHX (longitudinal): the free helium conduction zone until the cold source (bayonet heat exchanger, bHX)
- ΔTbHXA: the bHX heat exchange area
- ΔTbHXdp: the bHX pressure drop induced temperature loss
- ΔTcfHX: the counterflow HX (cfHX) pressure drop induced temperature loss
- ΔTpiping: the piping to cold compressors, pressure drop induced temperature loss

CLASSIFICATION OF HEAT EXTRACTION PATHS



ΔTcoil: typically 80-90 mK available down from 2.17 K max
ΔTcoil-freeA (radial): typically 60-70 mK available around 2.050 K
ΔTfreeA-bHX (longitudinal): typically 80-90 mK available around 1.98 K
about 160 mK remains for heat transfer to cold source and up to cold compressors

CLASSIFICATION OF HEAT EXTRACTION PATHS

In general heat transfer through a HeII channel of length *L* and cross section *A*, subject to a linear heat load *q* can be characterized by:

$$L^{n+1}(q/A)^n=C(Tmax\ ,Tmin),$$

were n=3 (or 3.4), and Tmax, Tmin are temperatures at the channel extremities *(ref.: LHC project report 144).*

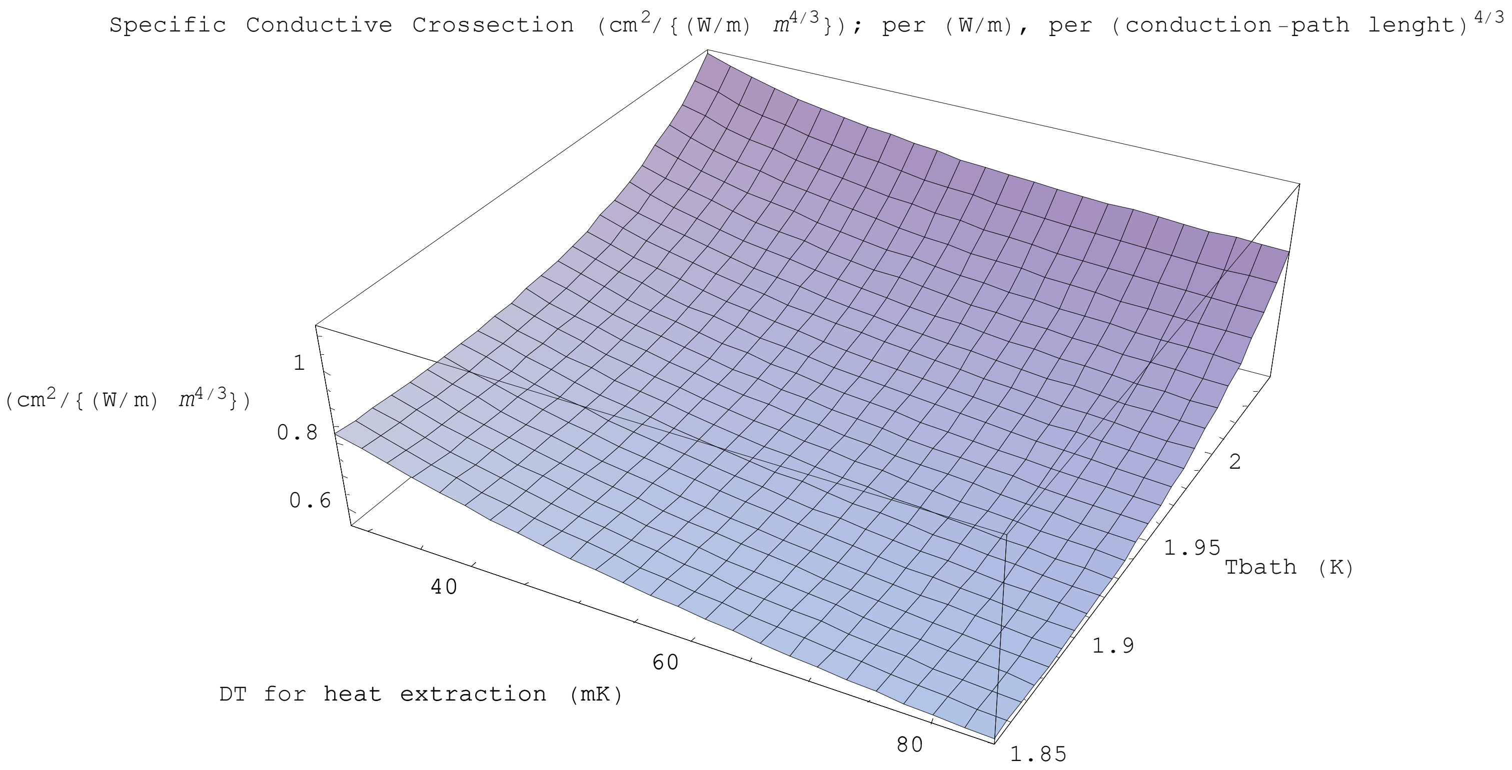
CLASSIFICATION OF HEAT EXTRACTION PATHS (1/4)

For initial conduction paths scaling estimates we define the specific area:

$$Aspec=A/(qL^{4/3})=1/C(Tmax\ ,Tmin)^{1/3}$$

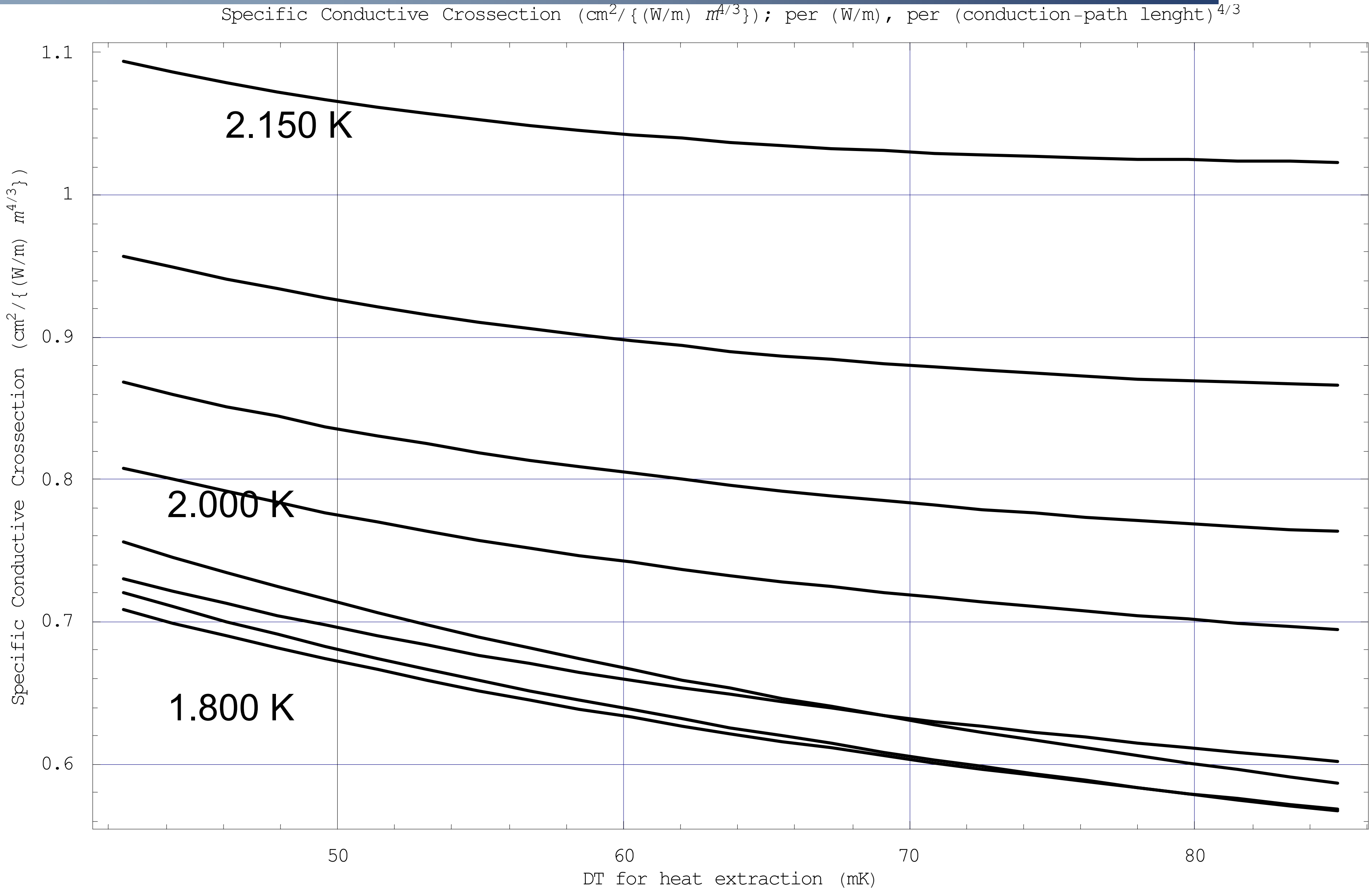
The above formula can be applied, using the typical temperature ranges, to provide an estimate for the necessary conduction areas inside the magnet.

Specific Conductive Cross section (cm^2/[W/m m$^{3/4}$])



Aspec is in the range of 0.3 to 1.1 cm^2/[W/m m$^{3/4}$]

Aspec for Tmn (=Tbath) 1.800 K to 2.150 K (cm^2/[W/m m$^{3/4}$])



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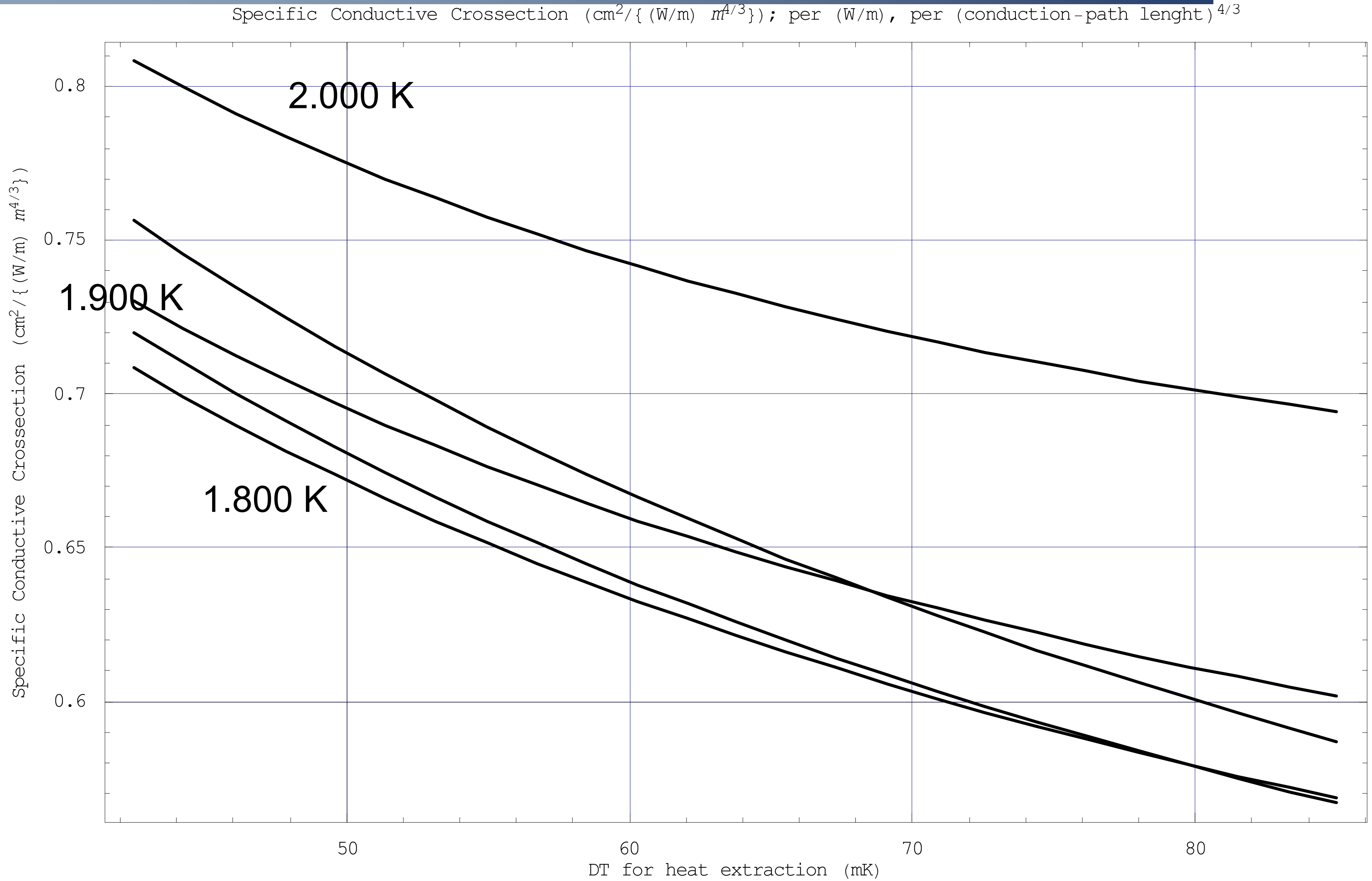


CLASSIFICATION OF HEAT EXTRACTION PATHS

Example:

NED dipole/Q1 LHC inner triplet upgrade, 100 W/m, up to 5 m longitudinal heat extraction length, Tbath~1.935 K, ΔT~85 mK, Aspec ~0.55:

--> A~470 cm^2 to be made in the yoke

Assuming 15% of the cold mass volume taken up by the coil, which is what needs to be condcuted our radially over ~ 0.05 m at Tbath~2.020 K, ΔT~65 mK, Aspec ~0.75:

--> A~0.21 cm^2 to be provided in the collar & yoke laminations every 10 cm

Conclusion: values are still in the "constructable" range

Beyond analytical estimates: framework of the CERN/WUT collaboration

Within the framework of K944/AT/LHC *Cooperation on operational safety for the LHC cryogenic system. Addendum No 2. Article 3: Part III Heat transfer flow from the magnet structure to the helium after resistive transition*, between CERN and Wroclaw University of Technology:

- Analysis of heat extraction from the magnet is made. This effort has evolved into a direction which is more generally applicable than to resistive transitions only.
- A cryostat for performing measurements of the heat transfer to and heat propagation in superfluid pressurized helium is designed and fabricated.

Numerical Approach: goals

The goals of the present work are to provide a numerical code which:

•Models the heat transfer throughout the whole magnet cold mass structure and the helium it contains with the exception of the heat transfer processes specific to the superconducting cable itself.

•Treats fluid hydro & thermodynamics in the same time as thermal conduction through solids.

•Can model magnets cooled in pool boiling-, supercritical- and pressurized superfluid helium.

•Can solve steady state and transients.

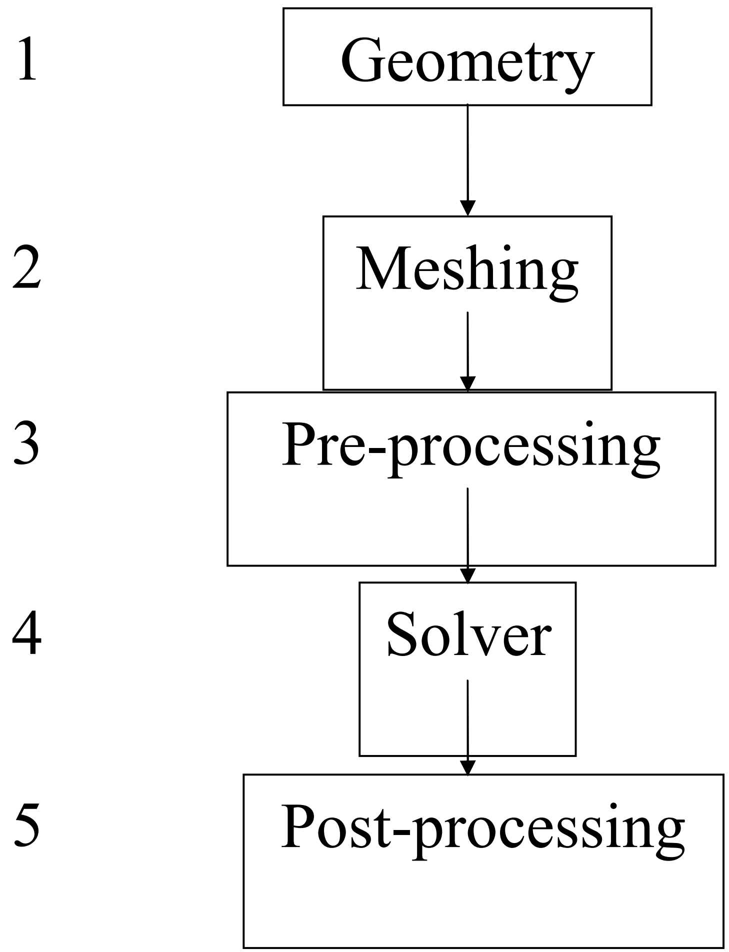
•Can use heat deposition data as function of geometry and time (i.e. Fluka results).

•Can use arbitrary heat transfer correlations specific to the accelerator magnet case.

•Is generic. I.e. in order to facilitate possibilities for long term use and development, the code should not be linked to a specific institute’s environment, and use as much as possible widely available software.

Numerical Approach: steps

The 5 steps of numerical solution



The whole processes can be solved in ANSYS Software

Numerical Approach: the CFD software

The software available at Wrocław University of Technology

Meshing:

– ANSYS ICEM v10.0;

Pre – processing, solver, post – processing:

– ANSYS CFX v10.0

CFD tool

CERN

The properties of Helium - Hepak

The possibility of creation the *.rgp (real gas properties) files which can be used in ANSYS CFX software

Properties of Helium

Numerical Approach: status

- Helium properties have been integrated
- Superfluid helium conduction module under development
- code comparison with analytical & literature data has started
- Trial examples, like the MQY magnet, are being explored

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