Chats 2015
Applied Superconductivity

Development and application of a generic CFD toolkit for heat flows in combined solid-liquid systems aimed at thermal design of HiLumi superconducting magnets

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- Implementation of thin solid-solid & solid-liquid boundarys
- Validation of HeII conduction implementation
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- Outlook & Conclusions

Motivation

Main objective:

Develop a robust multi-region numerical toolkit for the modelling of heat transfer in complex cryogenic system geometries involving super-fluid helium.

Purpose (and financing):

Support the design of superconductive magnets cooled by super-fluid helium in the framework of the HiLumi-LHC project.

Aim for extendability to other areas eg:

- Safety (pressure build up after quench in magnet strings)
- Cooling of structures (e.g heavy tungsten beam screens)
- ...?

Description of the problem

Up to now, generally (with very few exceptions) the thermal analysis and design is chopped up into isolated parts:

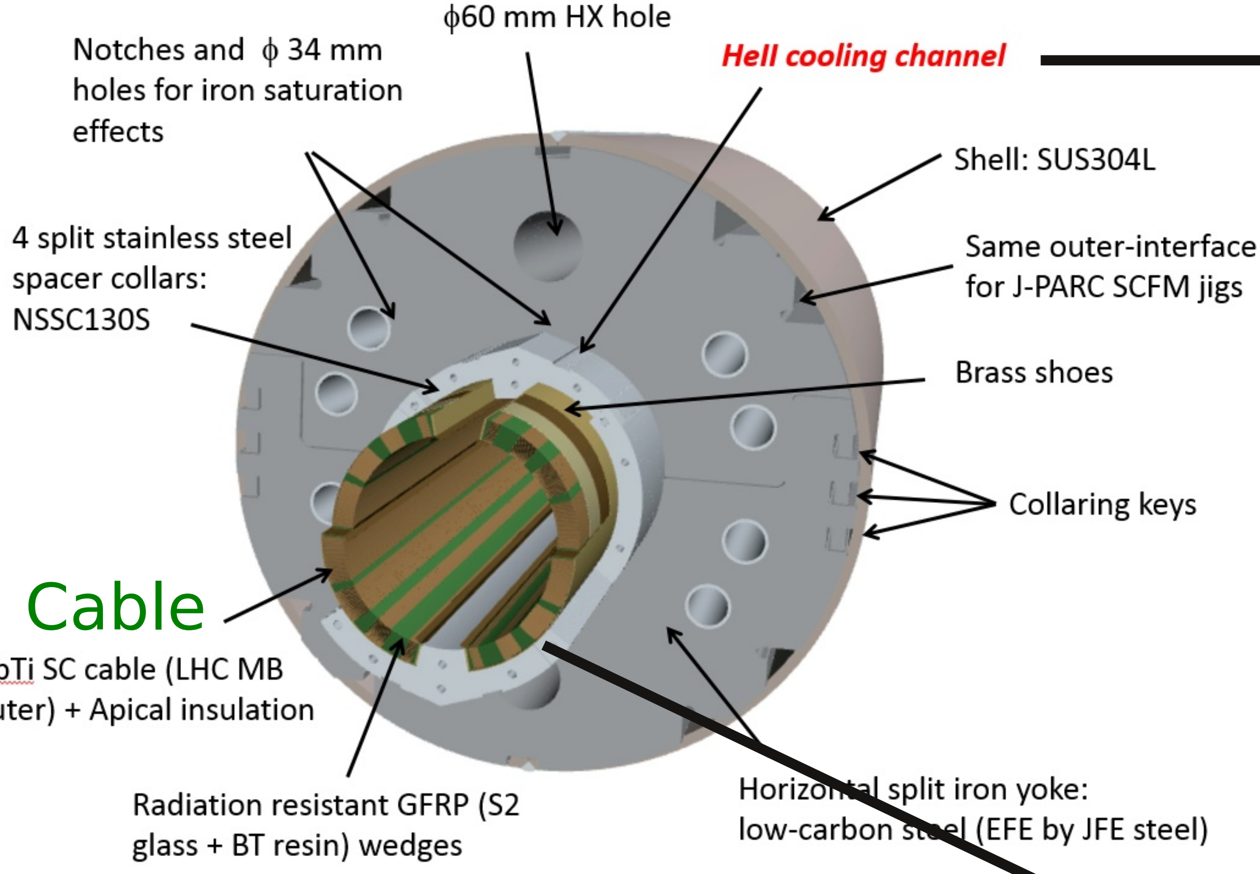
1) Individual helium channels

2) Coil blocks with isothermal boundaries

3) Cables

Where each part applies generic heat load estimates.

Description of the problem



1) Individual helium cooling channels -> fluid dynamics

3) Cable

2) Coil blocks with isothermal boundaries

Instead: we want to treat the whole in one go, including detailed heat load profiles!

Need to combine:

- fluid dynamics & fluid heat transport, notably in HeII,
- heat conduction through solids and interfaces
- transient respons in both fluids & solids

Multiple candidates:

ANSYS CFX
COMSOL
OpenFOAM
....

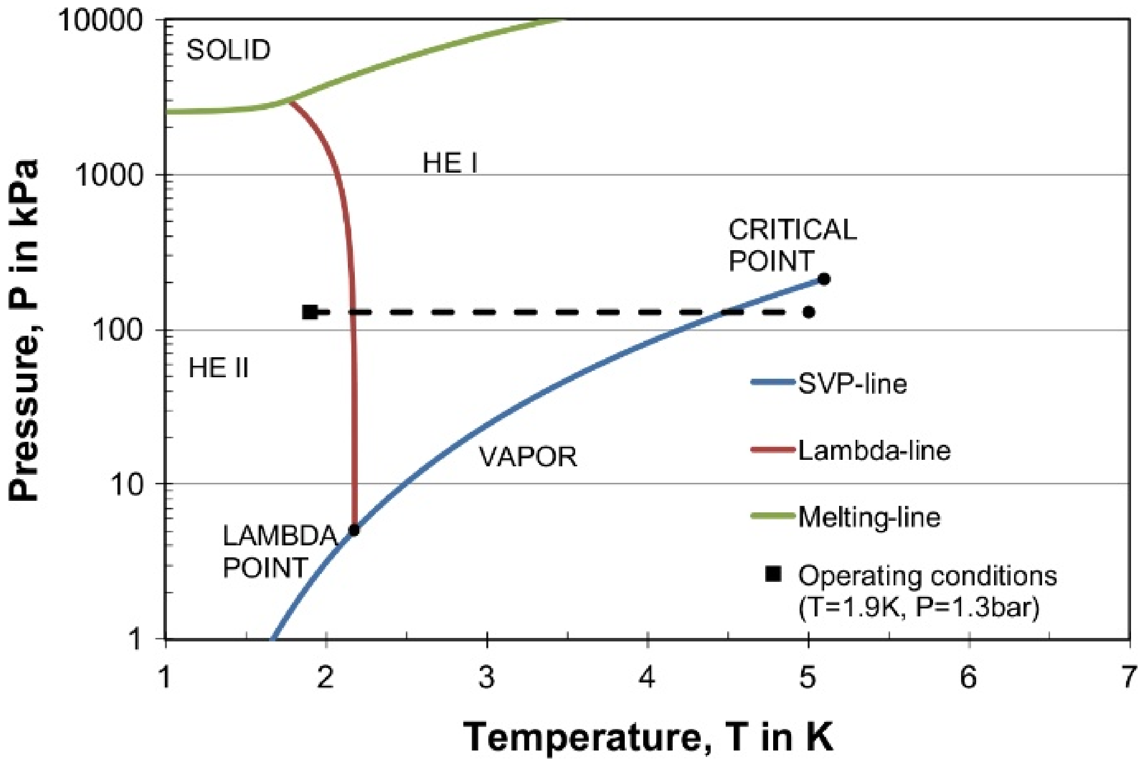
We've chosen to go with OpenFOAM

(mainly because we expected it to be easier to extend the mathematics if necessary,
as a bonus there is no licence penalty if we have to move to multi-processors)

The work is a continuation of Hervé Allain's, as shown at earlier CHATS (Frascati):

- Main implementation done by Gennaro Bozza,
- Specific OpenFOAM troubleshooting by Ziemovit Malecha.

Implementation of the turbulent HeII heat transport



The HiLumi magnets are to function in Helium which is:

- in the 1.8 K - 2.1 K T-range
- subcooled, at P ~1.3 bar.

As has been done already by numerous authors, we implemented the HeII equations for laminar flow and, when in the turbulent regime, the Gorter-Mellink transport model

Implementation of the turbulent HeII heat transport

The turbulent regime turns out to be the prevalent mode in our application:

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

with,

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

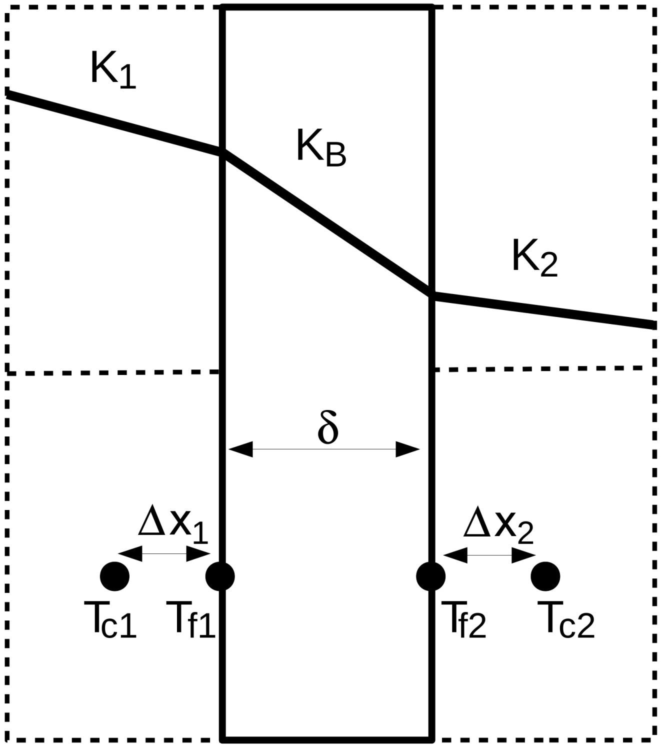
Different published functional dependencies for f(T, p) were implemented, showing no significant impact on results in our domain of application.

Implementation of solid conduction

Conduction through solid materials is standard in all CFD softwares and does not need any special treatment.

Only recurring caveat: search of material properties at temperatures between 1.8 K and 10 K is always a lot of work.

Implementation of thin solid-solid & solid-liquid boundarys



Kapitza resistance was implemented for all solid - liquid boundaries as:

$$h_k = 4\sigma T^4 \,,$$

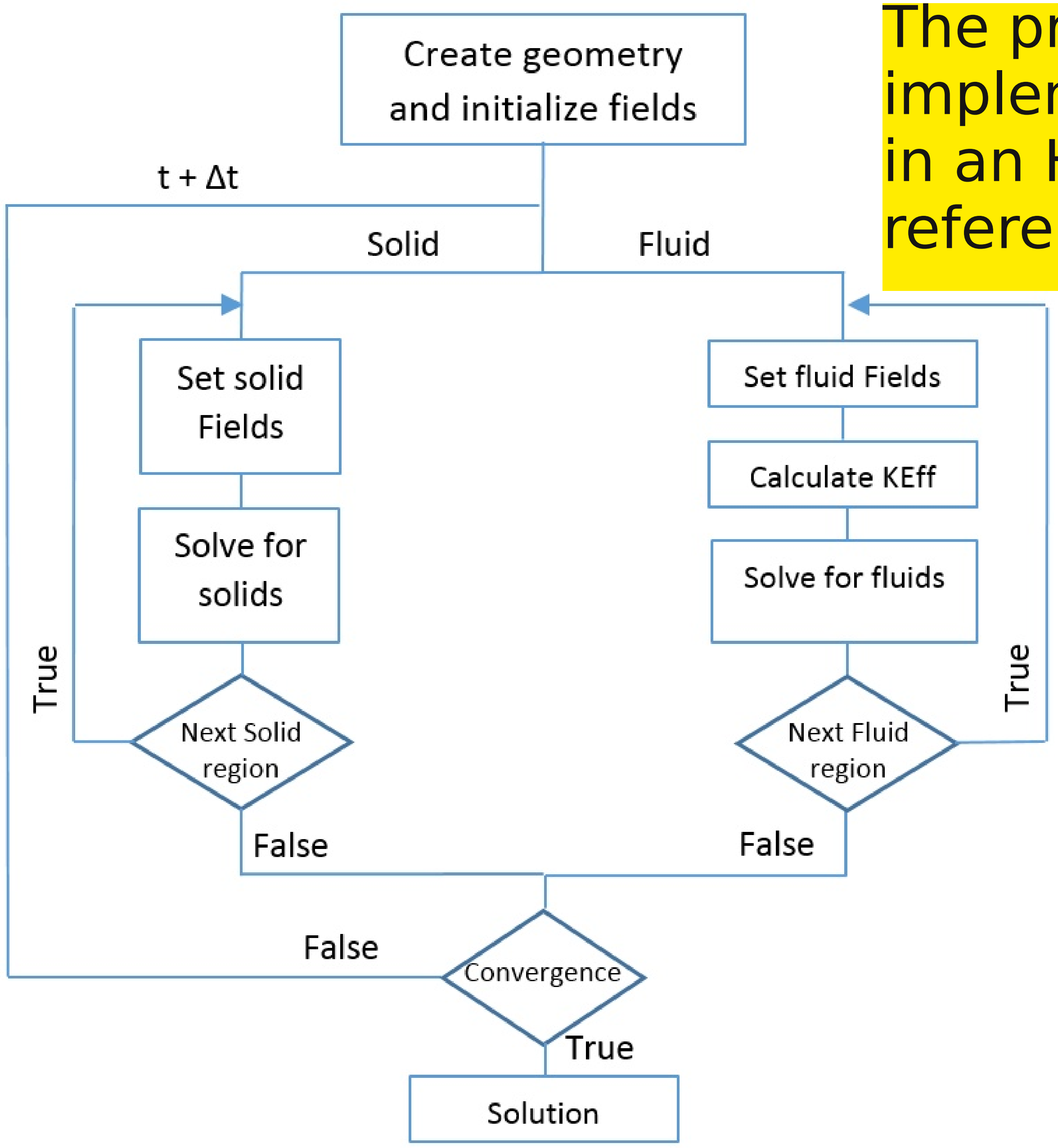
with

$$\sigma = 1100 \mathrm{W/m^2K^4}$$

To model thin layers of materials, typically employed as electrical insulation, the so-called temperature dependent "thermal-baffle" boundary condition was developped in OpenFOAM as an extension of an existing boundary condition which only used fixed thermal properties.

- This aliviated having to mesh these boundaries specifically
- The inclusion of temperature dependence of the thin electrical insulation materials has a notable effect on the temperature distribution of the magnet coils.

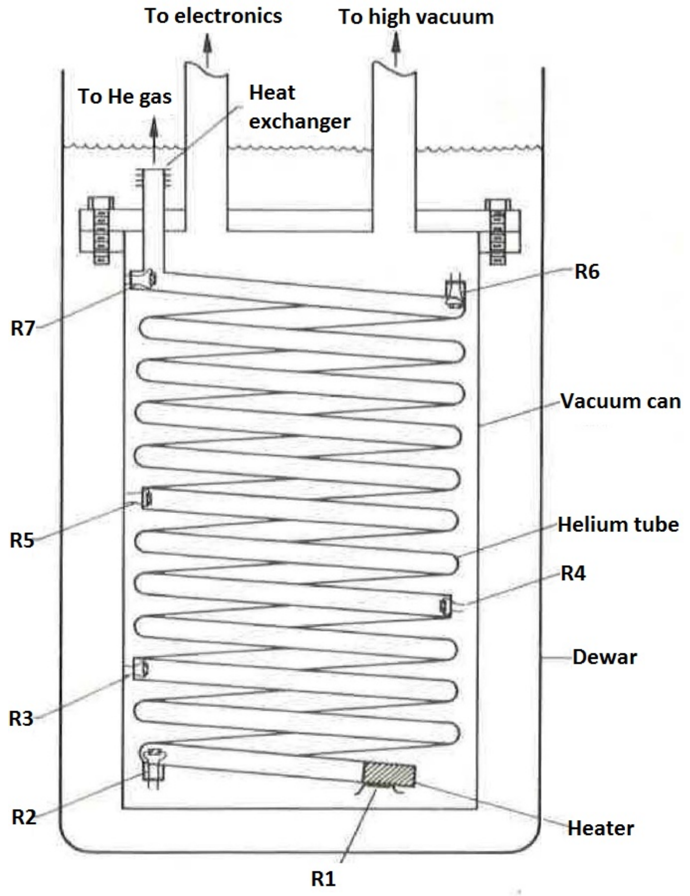
Workflow



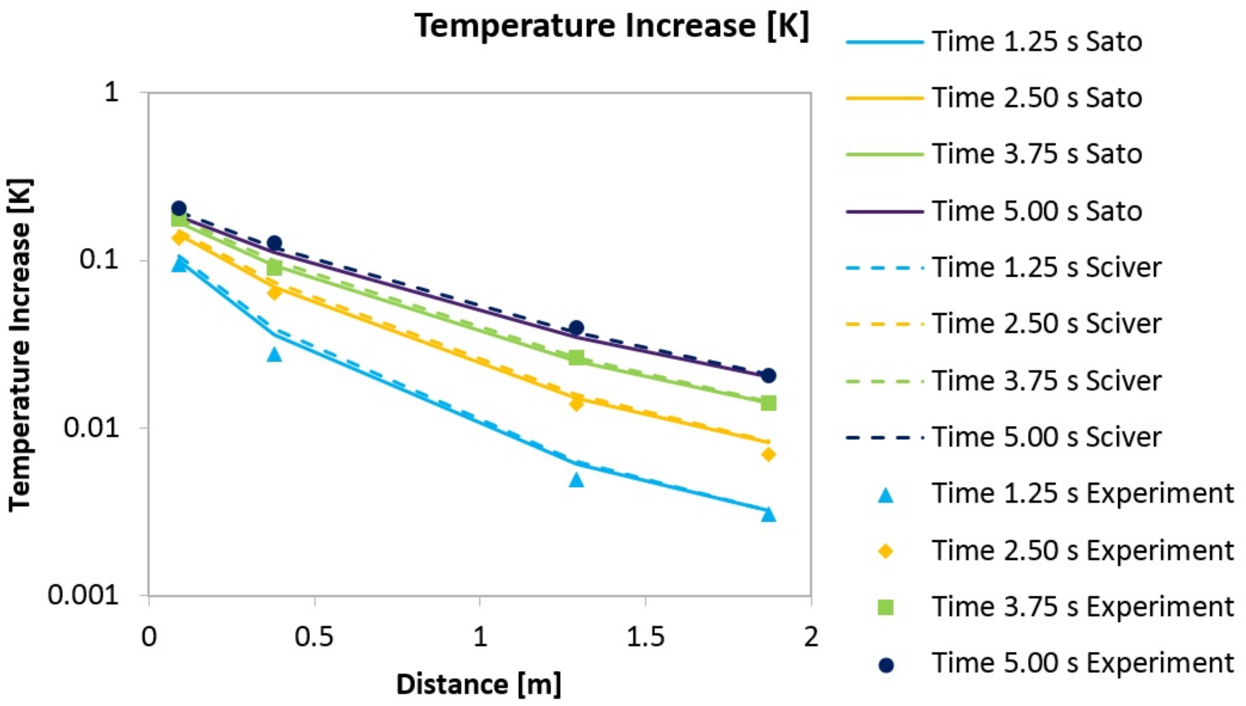
The precise workflow and OpenFOAM implementation is being documented in an HiLumi report to serve as reference for future collaborators

Validation of HeII conduction implementation

- against simple analytical solvable cases &
- against implementation using another CFD (Comsol) &
- against an HeII experiment by van Sciver:



Transient T-development of HeII in an adiabatic walled pipe, open to He bath at one end and heated at the other.

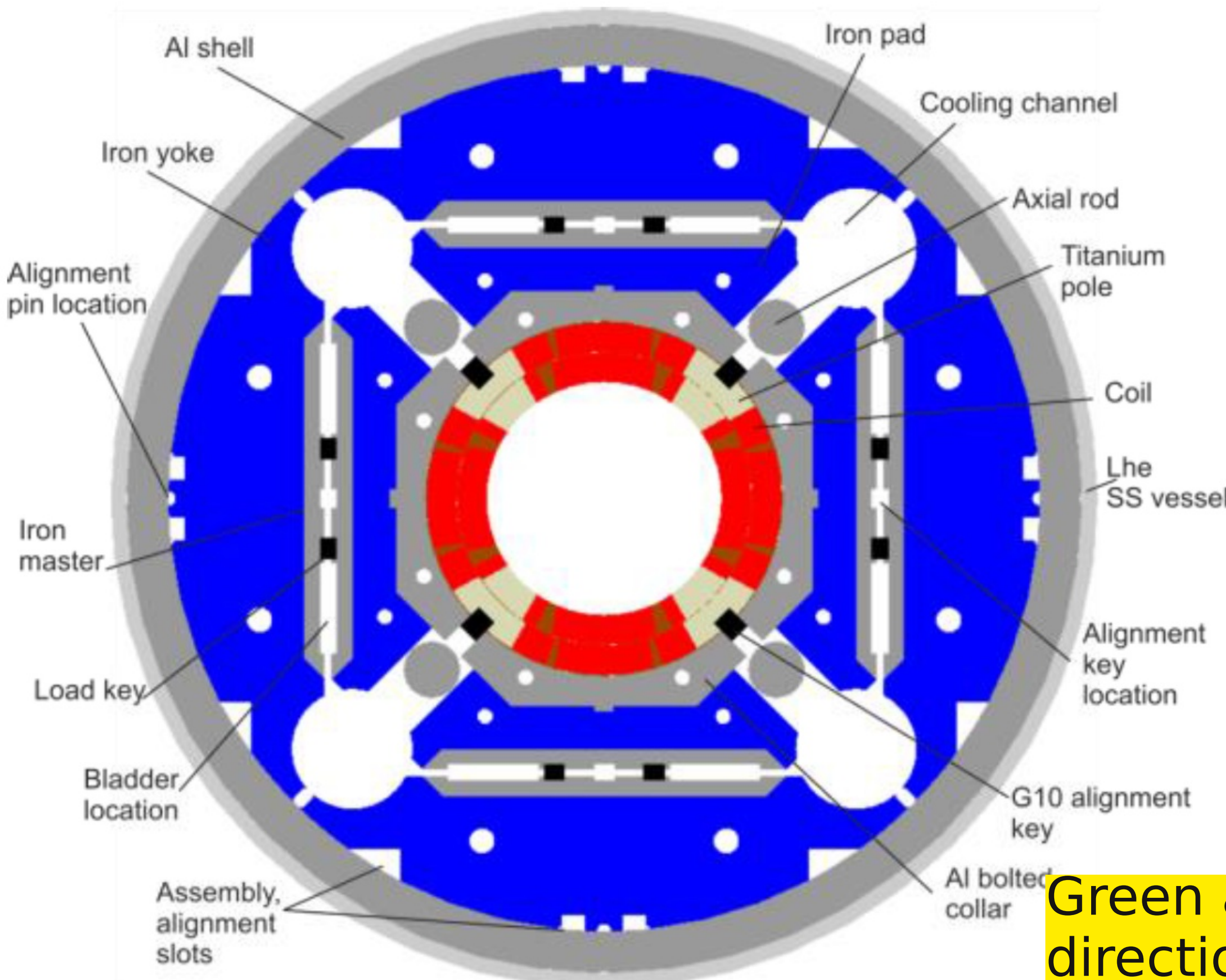


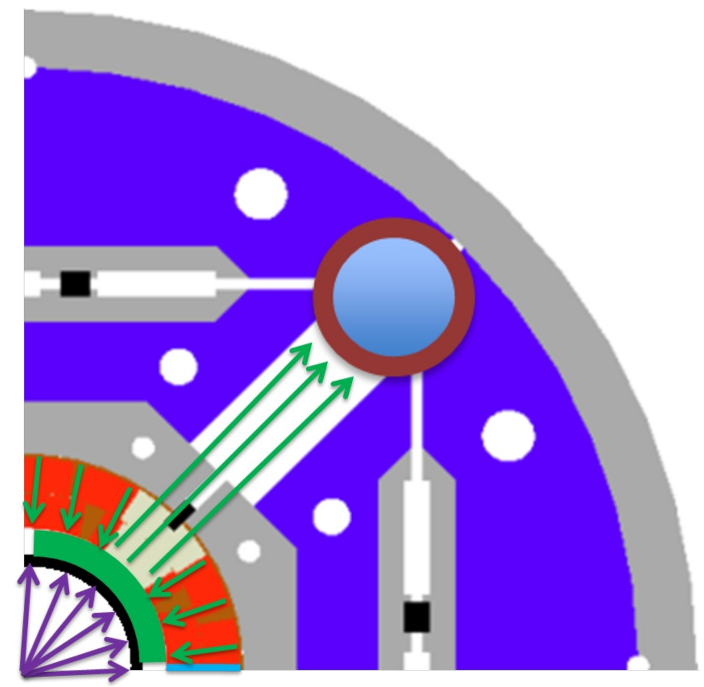
Agreement good for times > 2.5 s,
Deviations for shorter times become visible

Application to HiLumi maget design

MQXF-magnet in 1.8 K - 2.1 K static He, at P = ~1.3 bar:

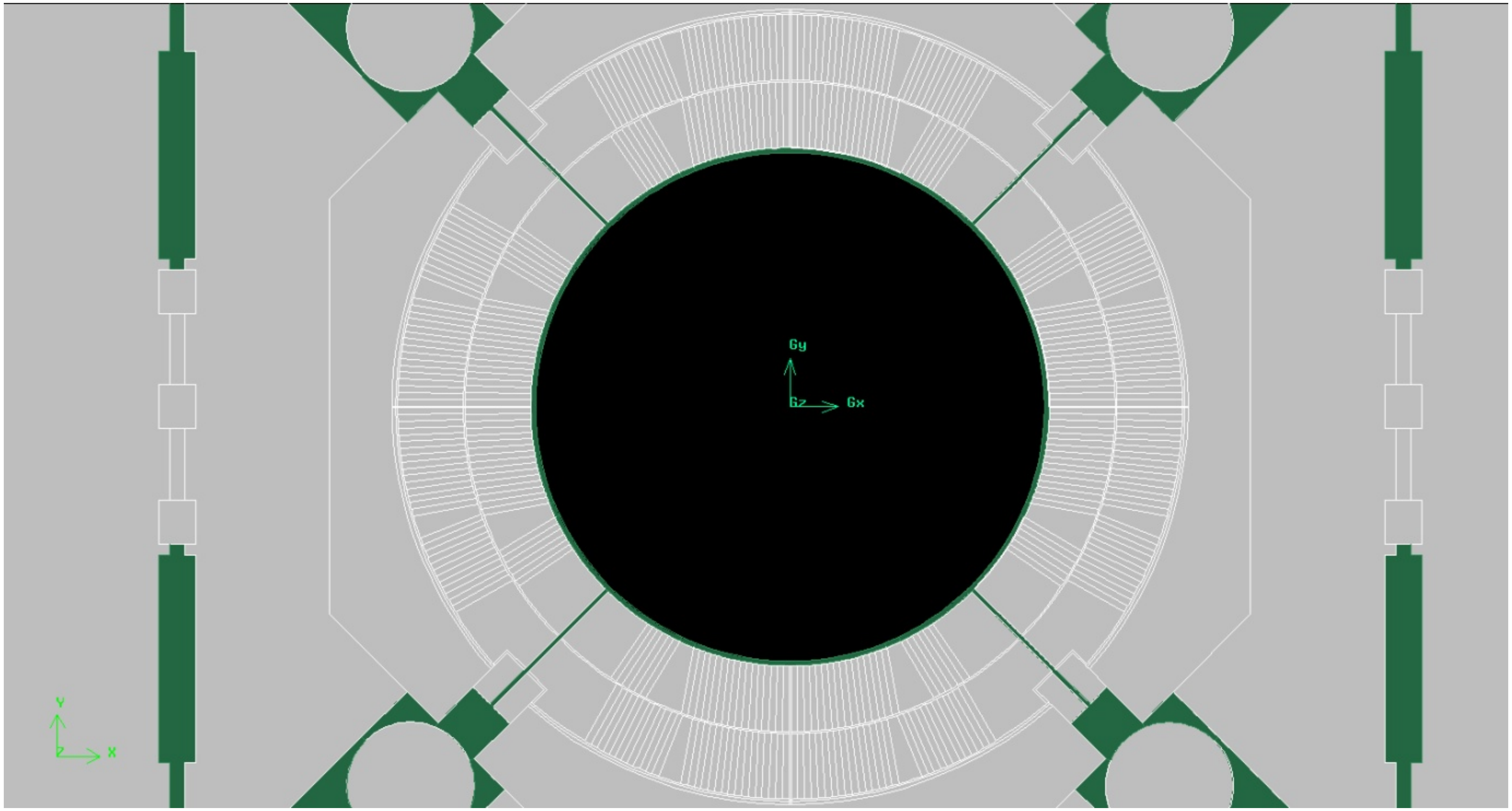
- Cables Nb_3Sn, Iron Yoke, Cold-source situated in the top 2 holes marked "cooling channel"
- Helium channels: annulus between cold bore and coil, perforated titanium pole, and yoke (see also next slide)





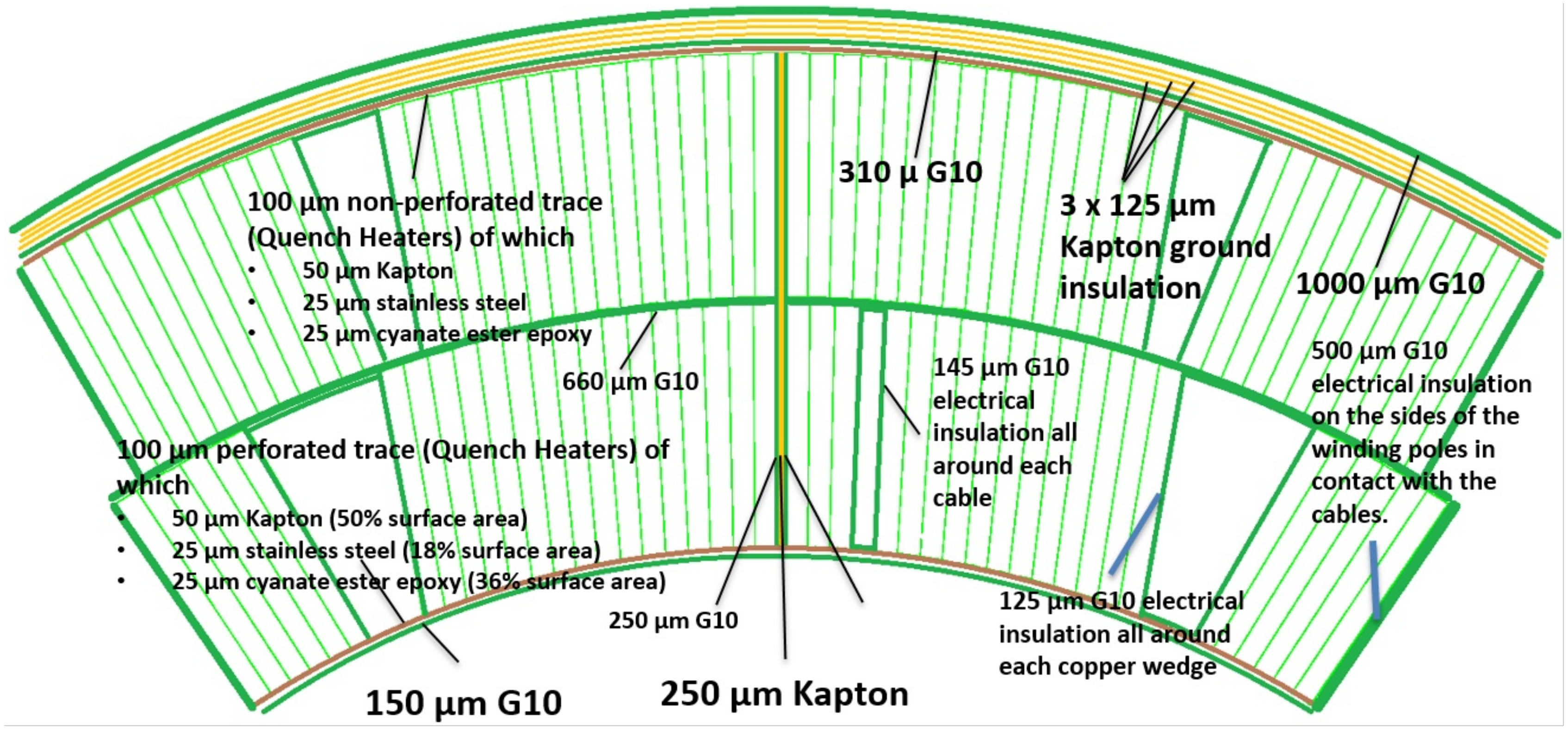
Green arrows show main heat flow directions from:
coil -> annullus -> pole -> cold-source

Application to HiLumi maget design



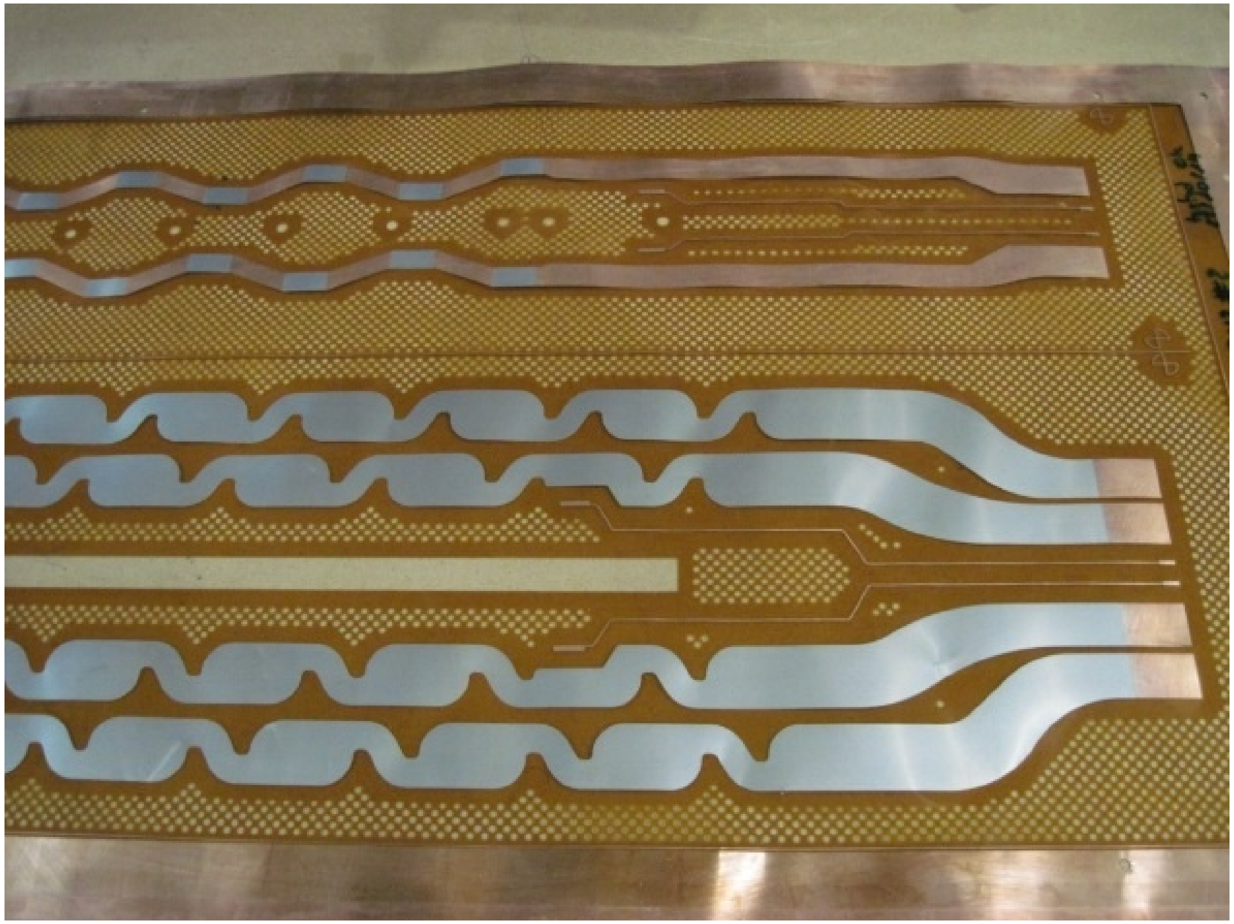
Helium in green:
(1.5 mm annulus at inner coil boundary barely visible)

Description of the thermally relevant magnet properties



Nb_3Sn coil block showing all materials used

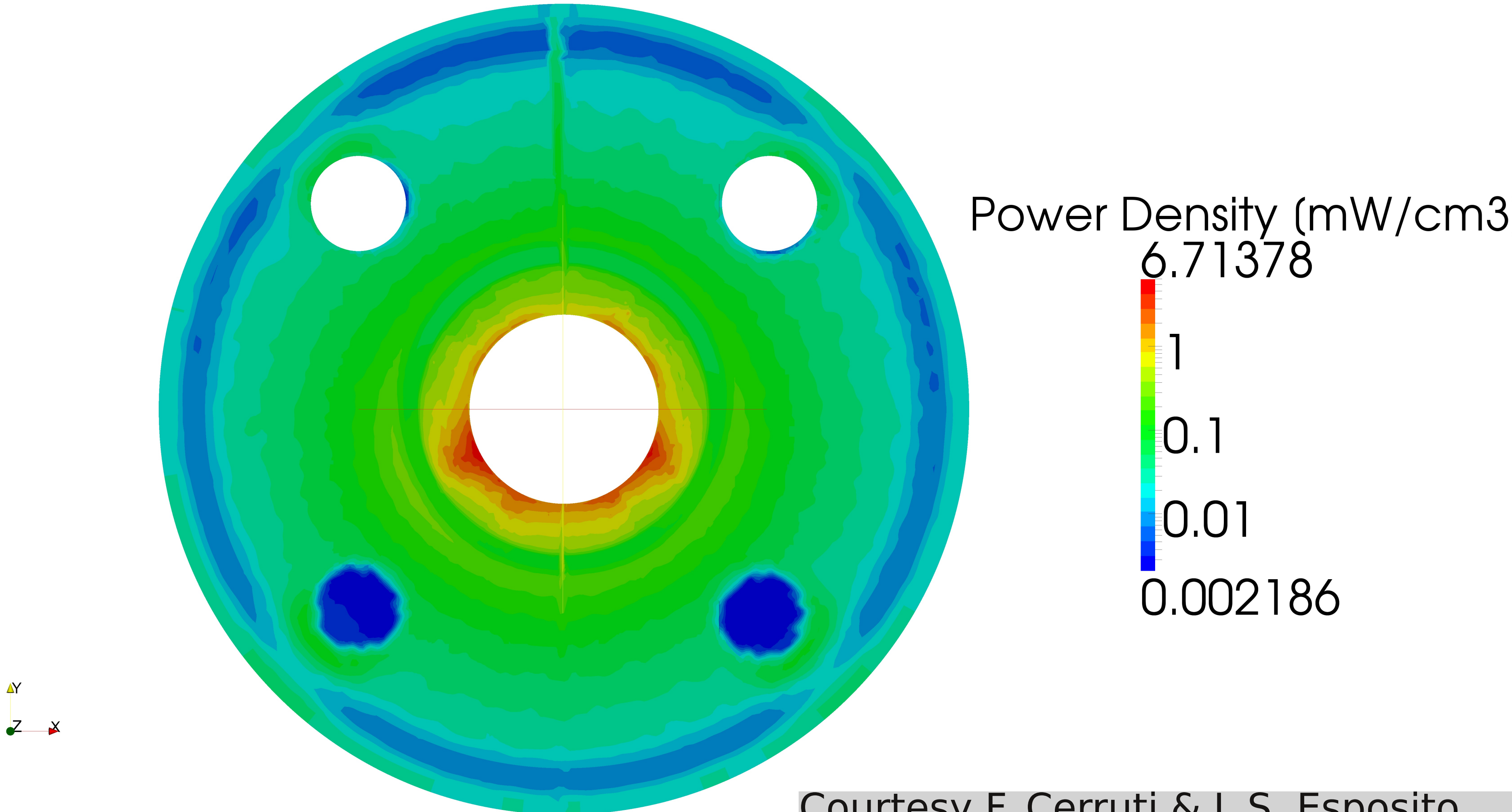
Description of the thermally relevant magnet properties



Perforated quench heaters, glued on inner coil layer, facing the helium annulus

(and thus directly on the main heat extraction path!)

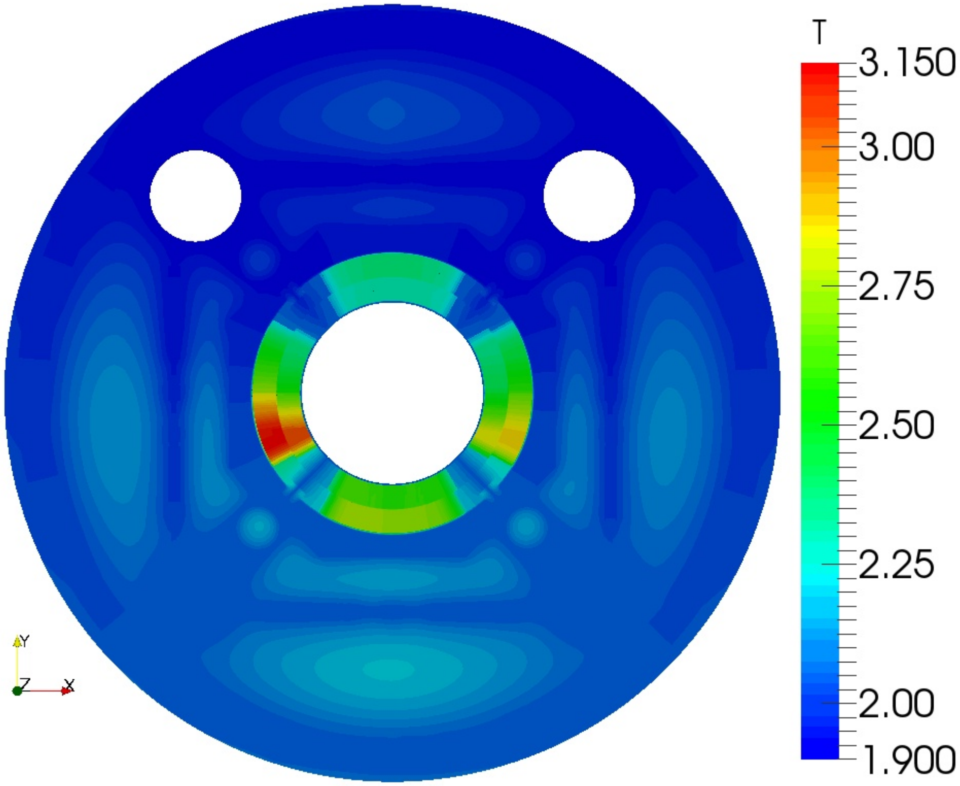
Energy deposition map

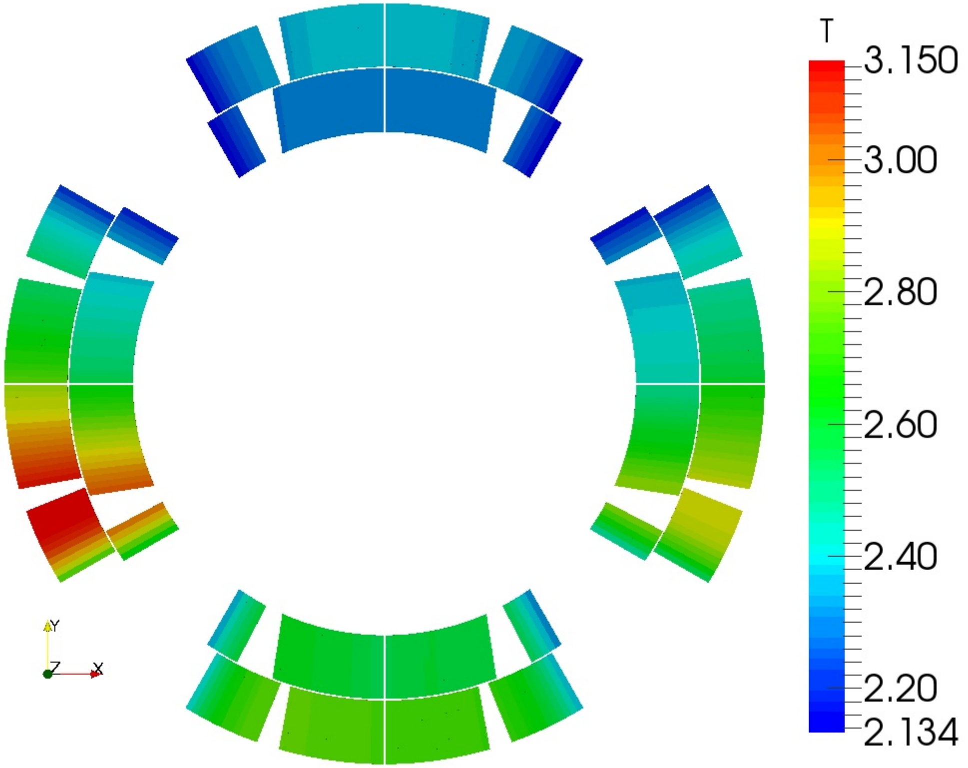


Courtesy F. Cerruti & L.S. Esposito

Highest power density in the inner coil layer ~ 7 mW/cm^3

Steady state results: Temperature map

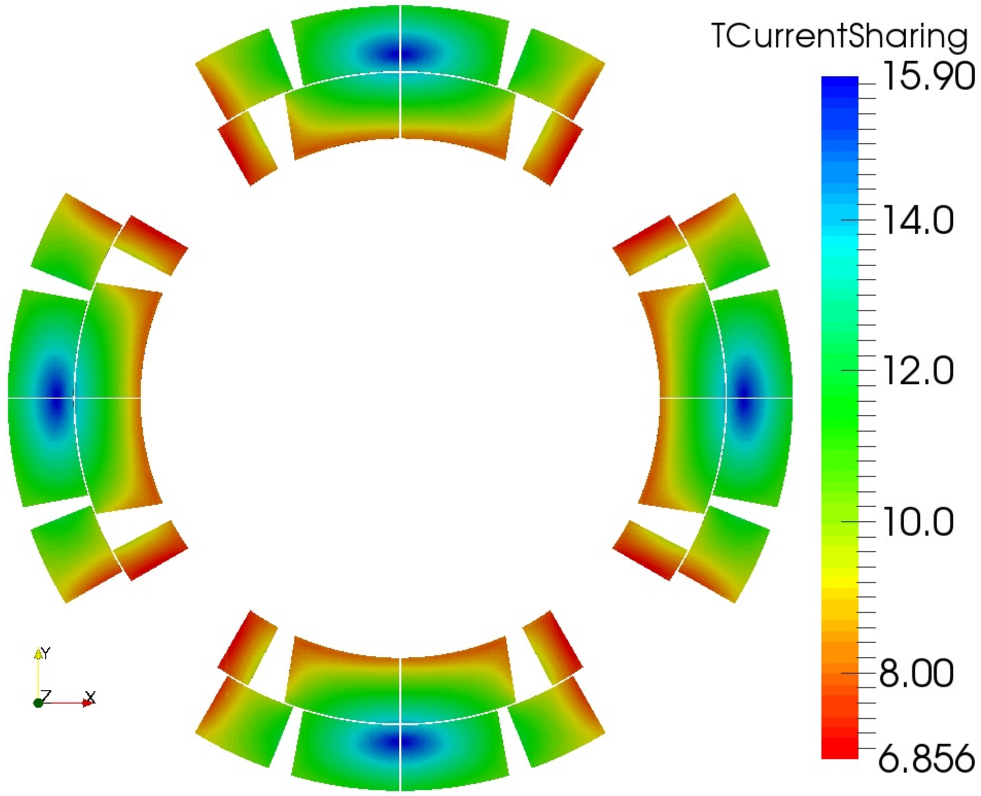




Modelisation gives highest temperature in the outer coil layer.

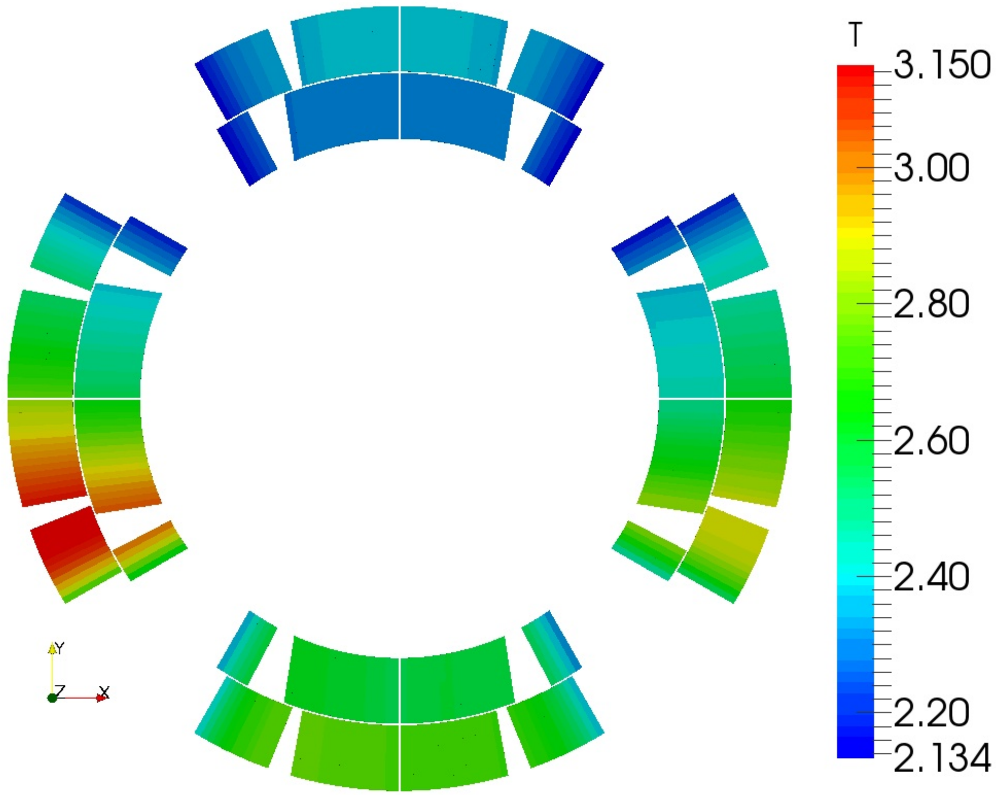
This high-T area is however not the most critical, as one has to evaluate the final temperature margin of the coil due the local magnetic field (see next slides)

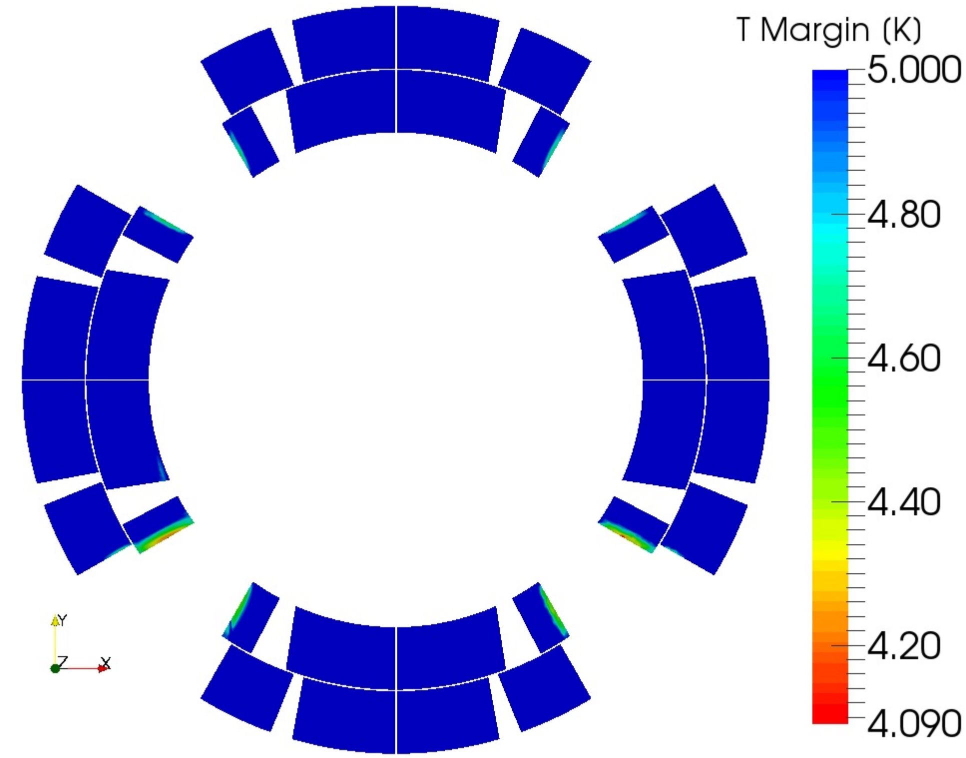
Steady state results: Current sharing map at 1.9 K, no heat load



This current sharing map, based on a 1.9 K coil temperature, has now to be combined with the calculated T-distribution due to the heat loads (see next slides)

Steady state results: T-margin





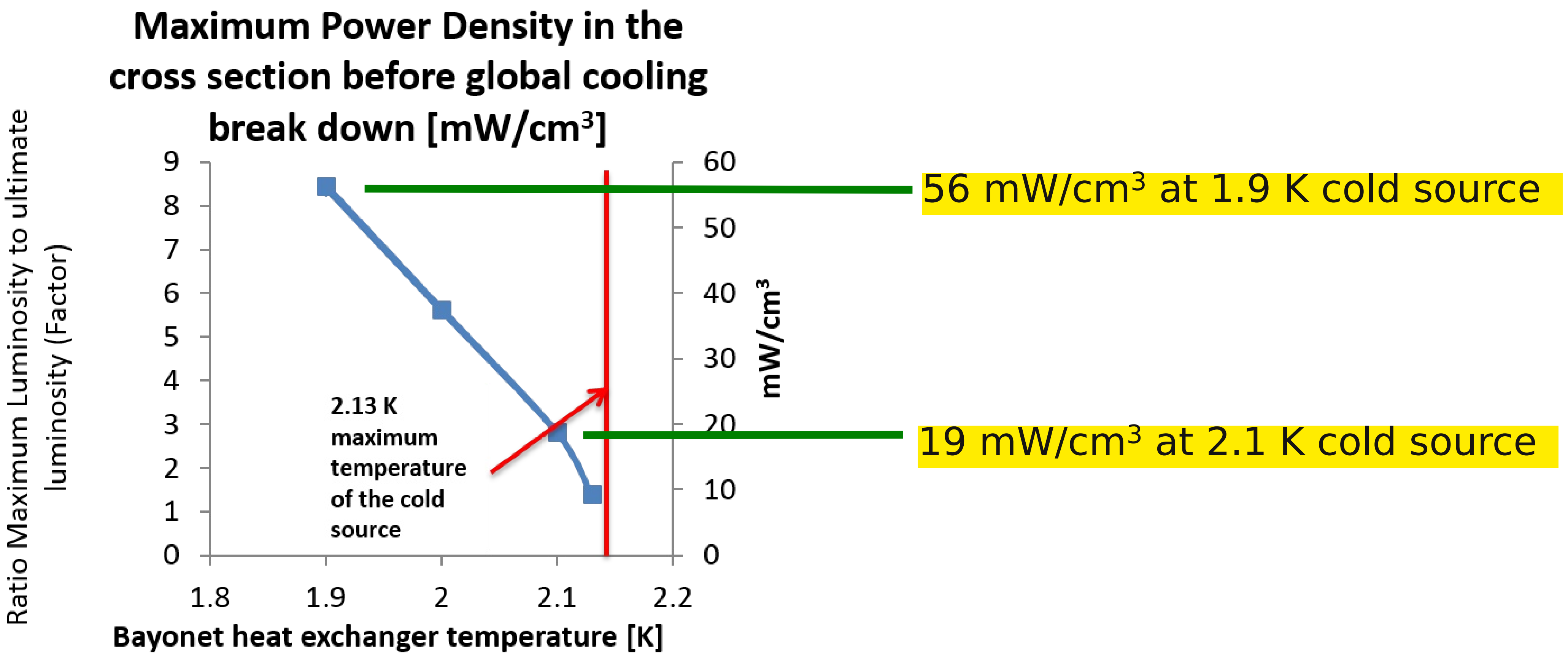
<u>Left figure:</u> full T-margin map, <u>Right figure:</u> values capped at 5.0 K to reveal details

--> Lowest T-margin is situated on the inner coil layer

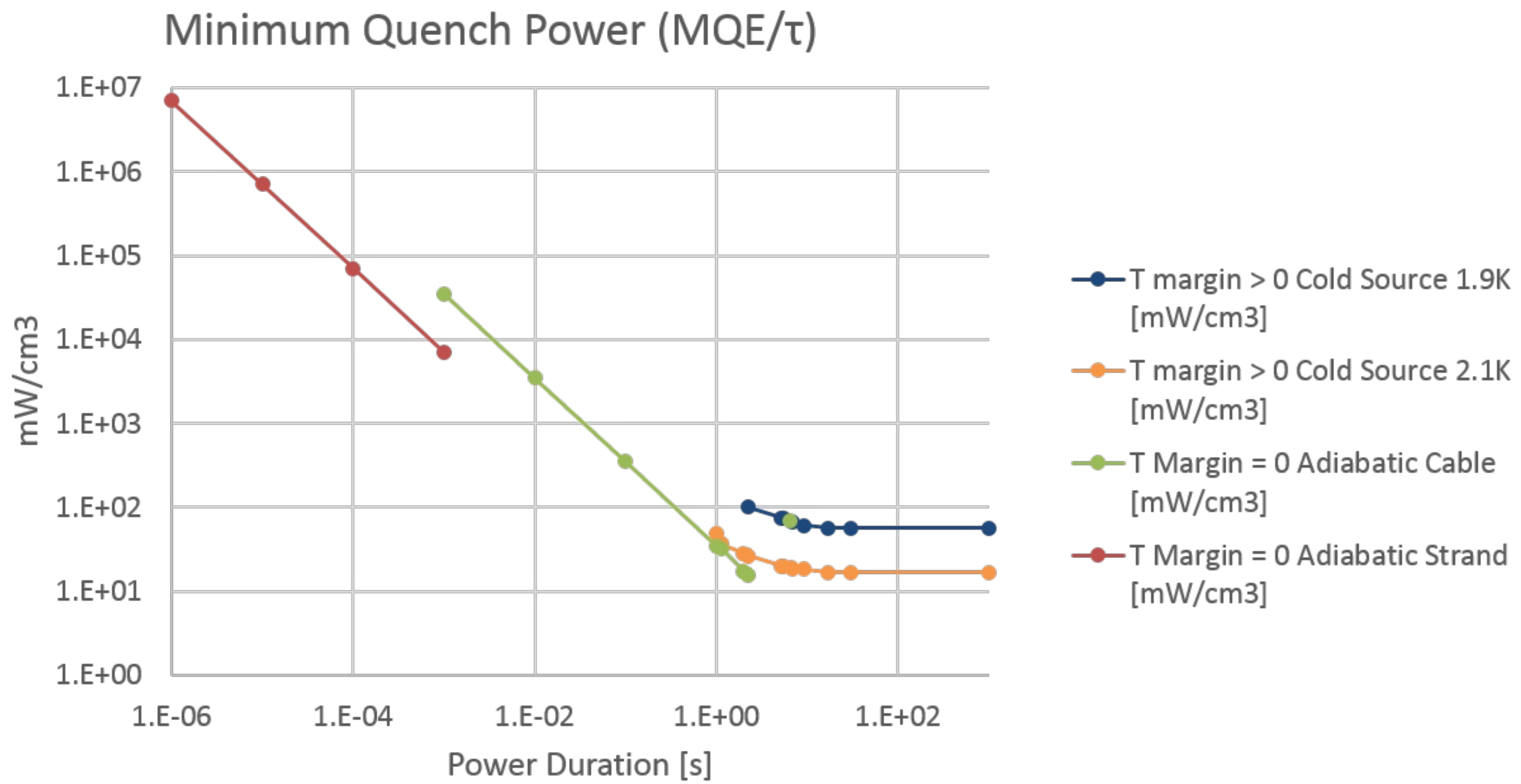
(these maps led to requesting adaptation of the tungsten shielding foreseen on the so-called "beam-screen")

Steady state results: max power density

Thermal runaway of global cooling as function of helium bath-T (nominal load ~ 7 mW/cm³)

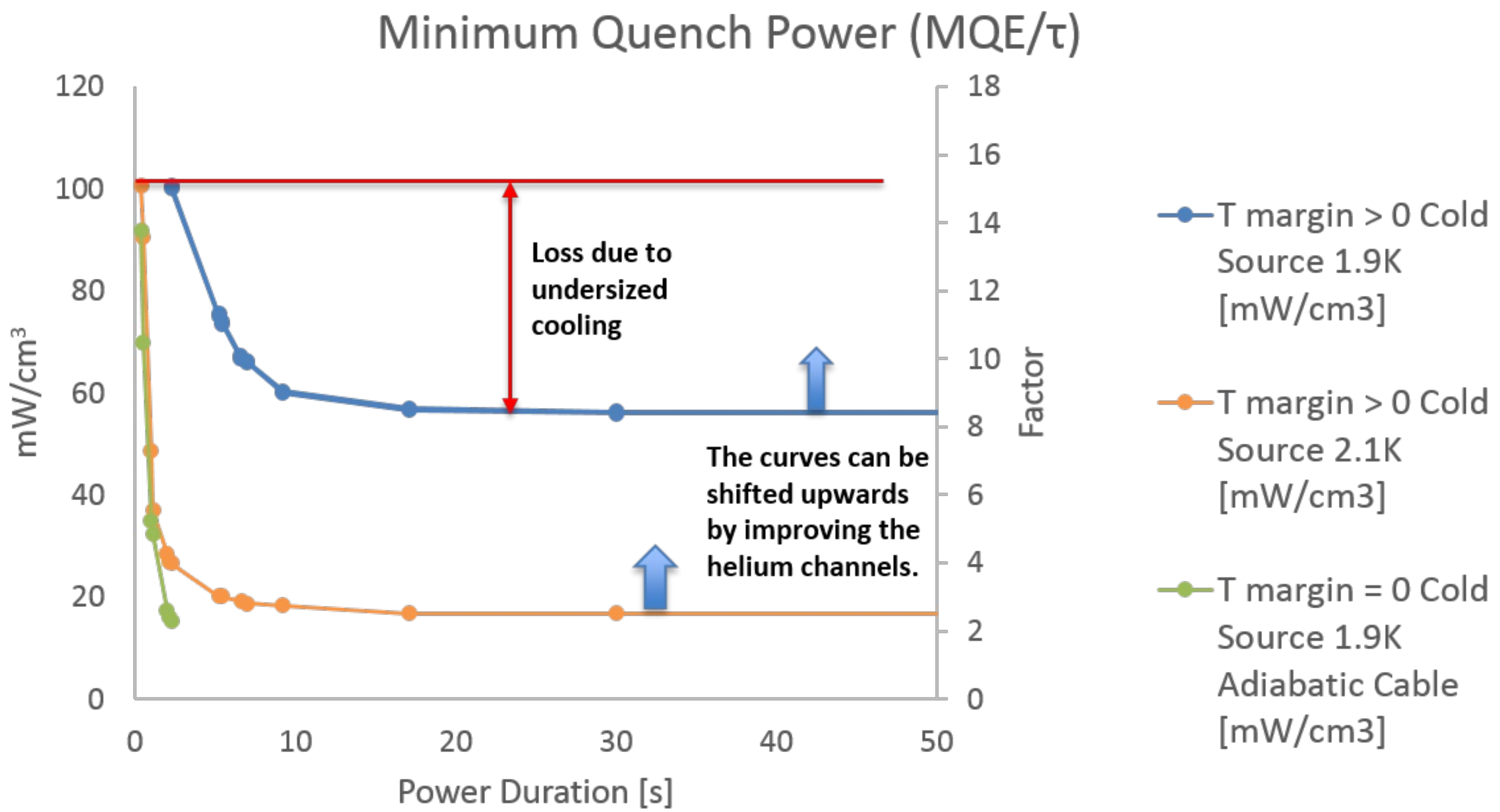


Transient results: how long can the system bear heat loads beyond 57 W/cm³? (slide 1 of 2)



Red = adiabatic of strand only
Green = adiabatic of full cable (including epoxies, etc)
Blue = simulation with cold-source at 1.9 K
Orange = simulation with cold-source at 2.1 K

Transient results: how long can the system bear heat loads beyond 57 W/cm³ (MQE)? (slide 2 of 2)



Green = adiabatic of full cable (including epoxies, etc)
Blue = simulation with cold-source at 1.9 K
Orange = simulation with cold-source at 2.1 K

- At 1.9 K we reach T_{margin} = 0 K for heat pulse duration = 2.3 s and 100 mW/cm³
- This value is determined by the cable insulation
- It demonstrates that there is room for increasing the steady state performance, (limited by Helium channels sizing)

Conclusions & Outlook

1) For the first time we have a tool to make an overall thermal assessment of a superconducting magnet!

2) It has served already well to influence the design of HiLumi magnet prototypes at the R&D phase.

3) As a bonus simulation of heat load transients (> ~ 2 s).

- Application of the analysis done for MQXF to other magnets, present and new (on its way for D1).

- inclusion of finer cable description so MQE transition from cooled -> partially cooled -> adiabatic can be made.

- Increasing the scope to higher temperatures allowing safety analysis of pressure development after magnet quench.

- and who knows...