Improvement of a numerical framework to systematically assess the temperature distribution in complex He II-cooled magnet geometries using open-source software

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CHATS in Applied Superconductivity 2023, 3-5 May 2023, Turin, Italy

Context

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

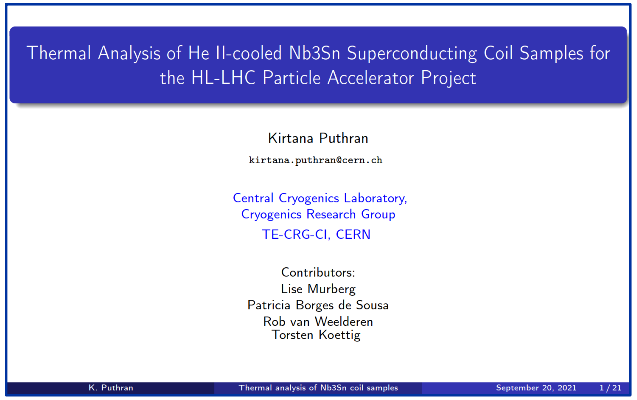
- Numerical tool allowed to **provide thermal design requirements early enough in the magnets' design phase**

CHATS on Applied Superconductivity 2015 (link)

- Now, **an 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

- The **development stages** of both the 1D and 2D versions of the numerical toolkit **were presented in past CHATS editions**

- This talk focuses on the matured stage of the **numerical toolkit** developed over the last few years, along with the steps taken to **validate it**, and **one case study** where **complex geometries are modelled** using the 2D framework

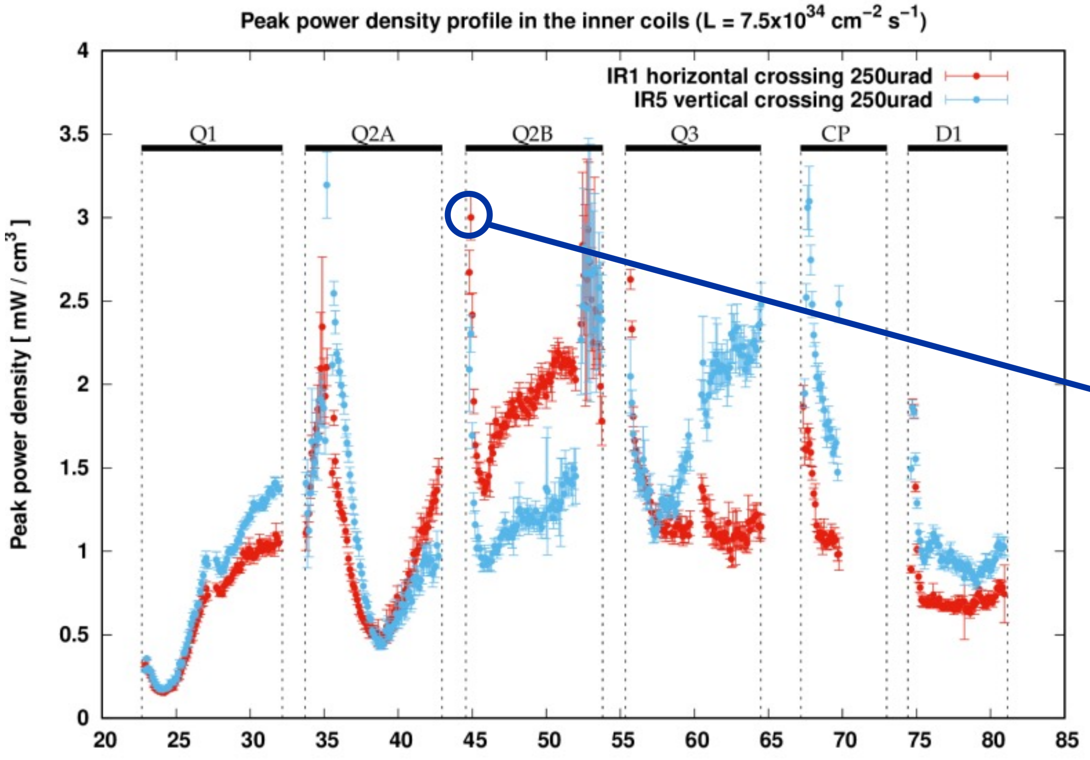


CHATS on Applied Superconductivity 2021 (link)

CHATS on Applied Superconductivity 2019 (link)

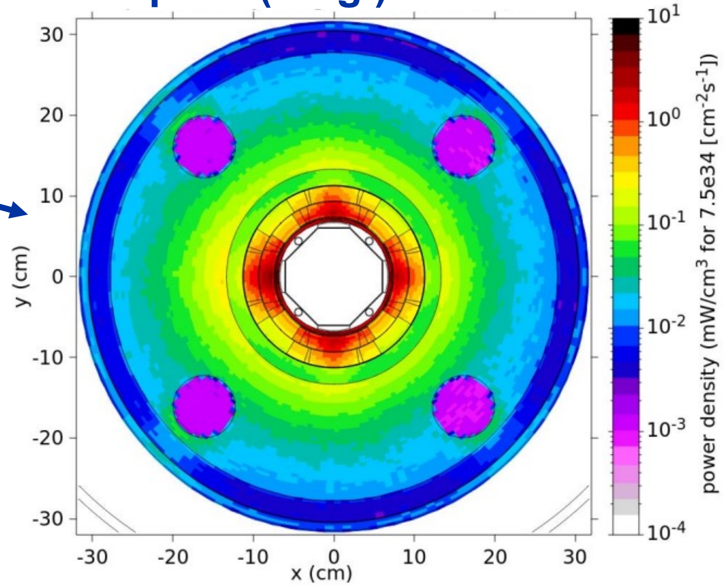
Problem statement

Goal is to provide an **assessment of the temperature distribution** (and consequently the available margins) **in complex He II-cooled magnet geometries** during operational conditions, **given an input power deposition**

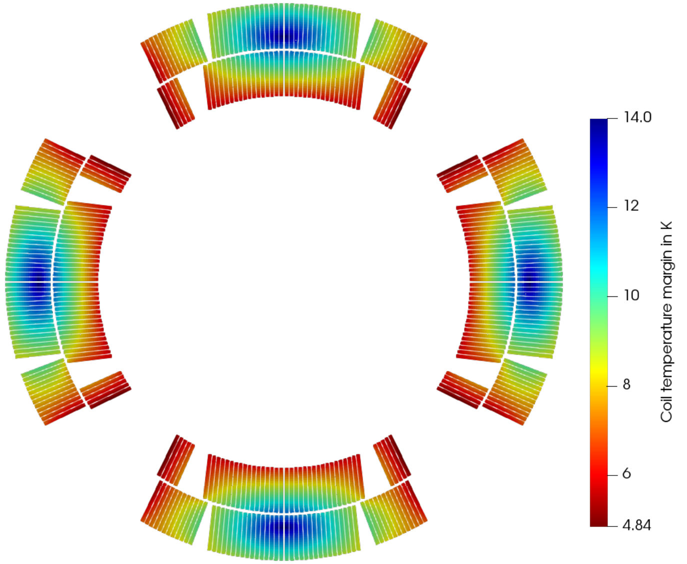


Operational margin for non-homogeneous temperature distribution?

Power density at peak (long.) location



Revised temperature margin



Source: Review of estimates of energy deposition, M. Sabate-Gilarte

Problem statement

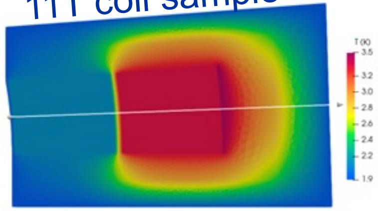
This study has been approached **in two ways:**

- By **modelling only the thermal conduction within the magnet structure**, where the surfaces exposed to He II are modelled via a Neumann convection boundary condition;
- By developing a **conjugate heat transfer model** wherein both the solid and fluid systems are solved separately and **exchange boundary conditions** specifying the temperature at each successive iteration.

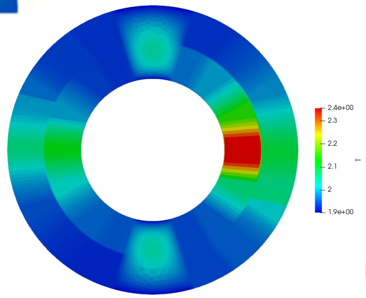
... and at **three different scales** (staged approach):

- By modelling impregnated **coil samples** (experimental data available)
- Then modelling a full **coil pack** (11 T, shown last CHATS)
- And finally modelling **the full cold mass** system **cooled by stagnant He II**

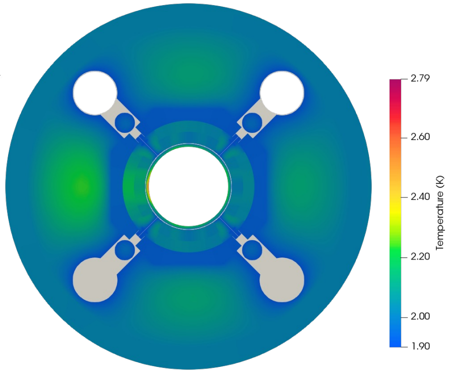
11T coil sample



11T coil pack

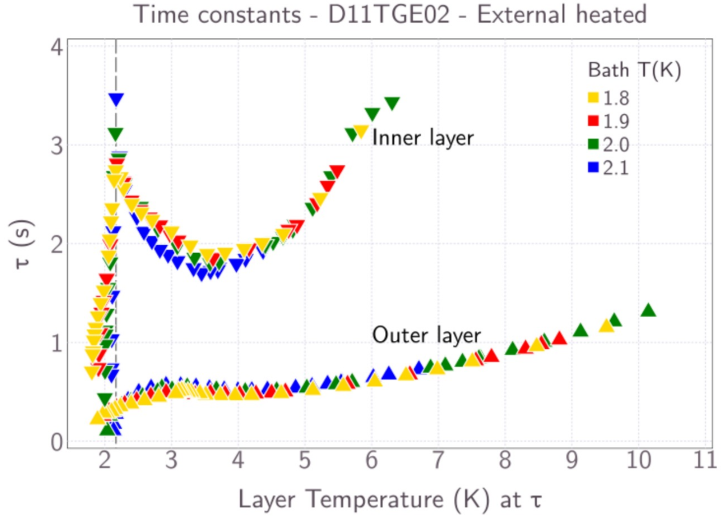


MQXF cold mass



Why change? Motivation for toolkit revision

- **Experimental results** from impregnated Nb_3Sn coil samples **revealed presence of He inside the coil structure**, *i.e.* in small pores inside the insulations layers (see **CHATS 2021**)



- These results were used to validate the previously developed model, **solving for 29 regions at each time-step**, with each cable and insulation layer as separate regions to allow for different material properties.

- However, **computation time was a major bottleneck** due to (notorious) high costs inherent to conjugate heat transfer models, high gradients in property variation, dense mesh requirements, etc.

- An added complication was the **presence of helium** within the composite solid magnet material. **Estimating the amount of He** that penetrated the solid regions **became prohibitive** with the existing strategy

Geometry and meshing – basis for a solid model

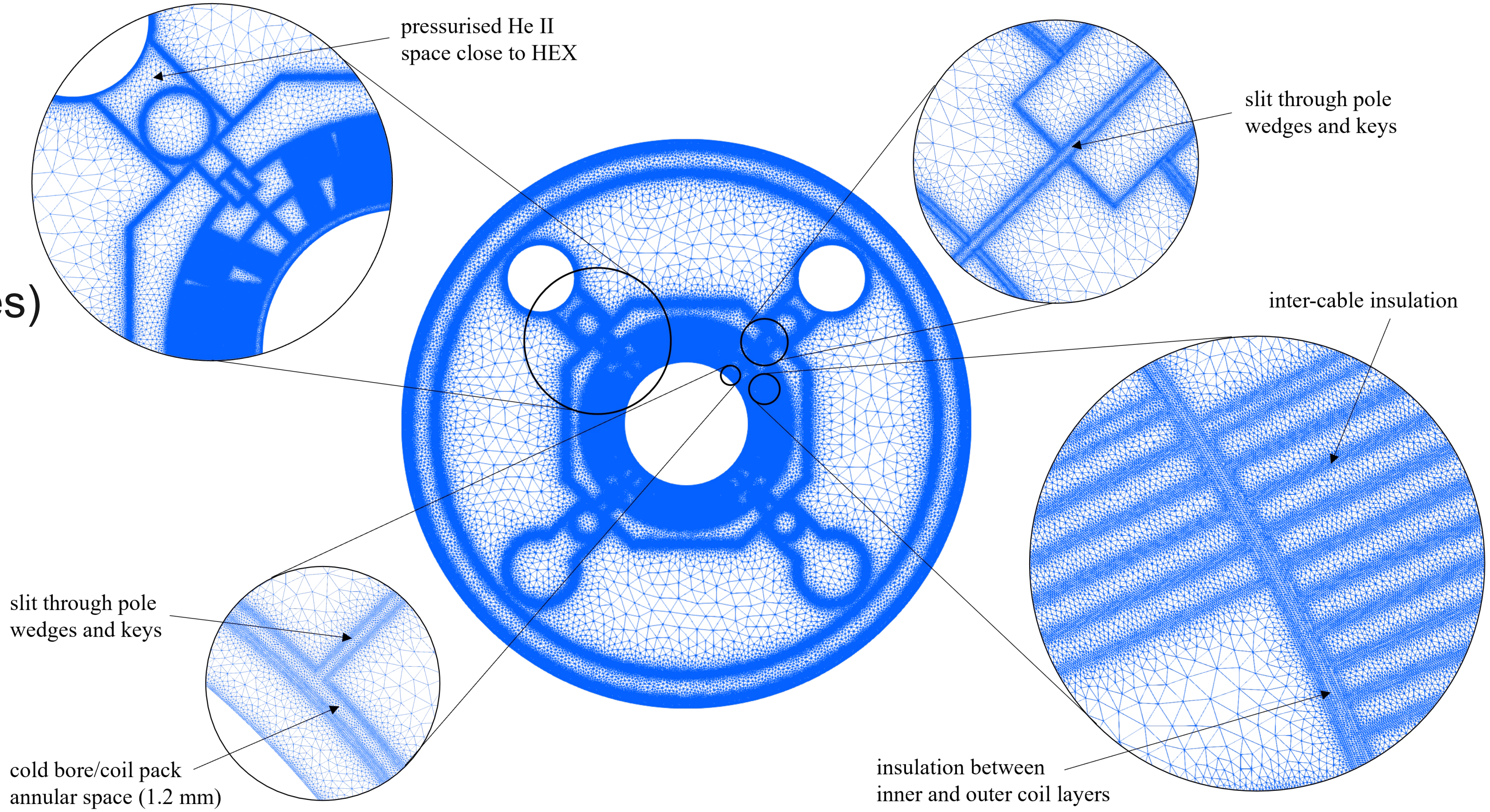
- **Goal:** to develop a workflow to create detailed parametric, easily changeable geometries that allow for the timely generation of high-quality conformal meshing across the interfaces of the model's various components

- Geometry and mesh generated using **Salome 9.7**, via **Python API**

- Special **refinement** possible (e.g. on the coil pack and thin layers such as insulation and helium passages)

- **Conformal mesh over both regions** (solid components and He space)

- **Insulation scheme part of the geometry**, avoiding modelling it as a thin resistive layer



Main challenges

- **Composite structure of the impregnated Nb_3Sn coils:** the superconducting cables are resolvable to the micron scale, while insulation is itself also a composite of glass-fibre, resin and binder. In this model, **each cable is represented by a single homogeneous region, as is the insulation between cables**.

- The thermal **properties of the** (sometimes composite) **materials involved are temperature-dependent**.
  - **Reliable data is difficult to come by** for temperatures below 4 K, especially for composite materials like the insulation scheme;
  - Temperature-dependent properties are usually expressed as **polynomial functions, adding to run-time computation cost.**

- **Interface thermal boundary** or **Kapitza resistance** results in a discontinuous temperature profile at the interfaces between helium and the solid materials.
  - Kapitza resistance **can easily vary by at least an order of magnitude** for the same material, and data for composites like insulation or metallic alloys is scarce in any case.

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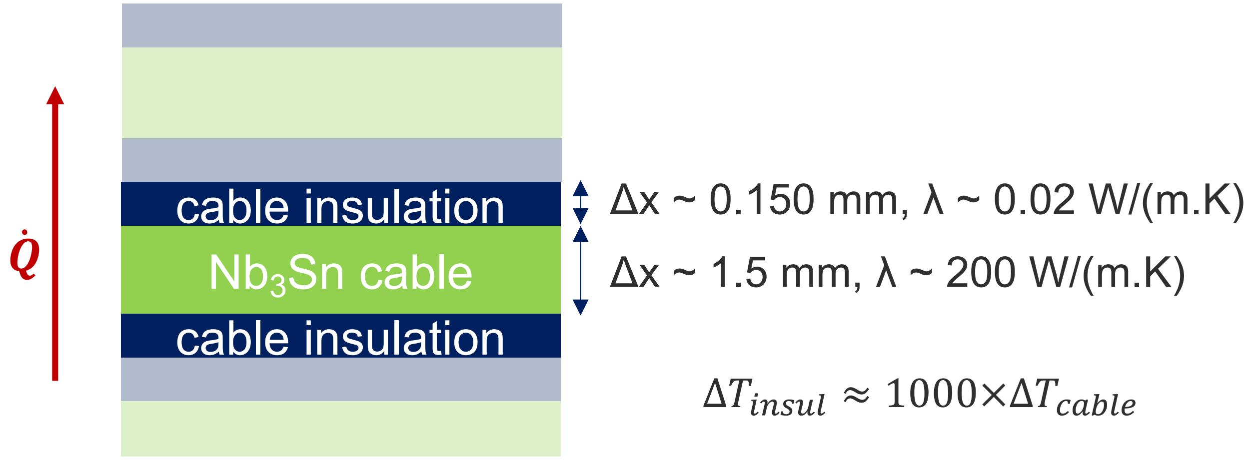
Geometric approximation to coil structure

- Previous strategy relied on the use of "baffles", **or thin solid structures**, to model the thin inter-cable insulation layers – **insulation was modelled as a thermal contact resistance**

- **Insulation layers are the critical driving components for thermal gradients** inside the coil, and their (possibly variable) thickness has an immediate impact on overall temperature distribution – **reasonable** geometric **approximation** must be made

- Insulation scheme is now modelled as part of the geometry, allowing for a temperature gradient to be established

- SC cables **remain as a single region** with averaged thermal properties



$$\Delta T_{insul} \approx 1000 \times \Delta T_{cable}$$

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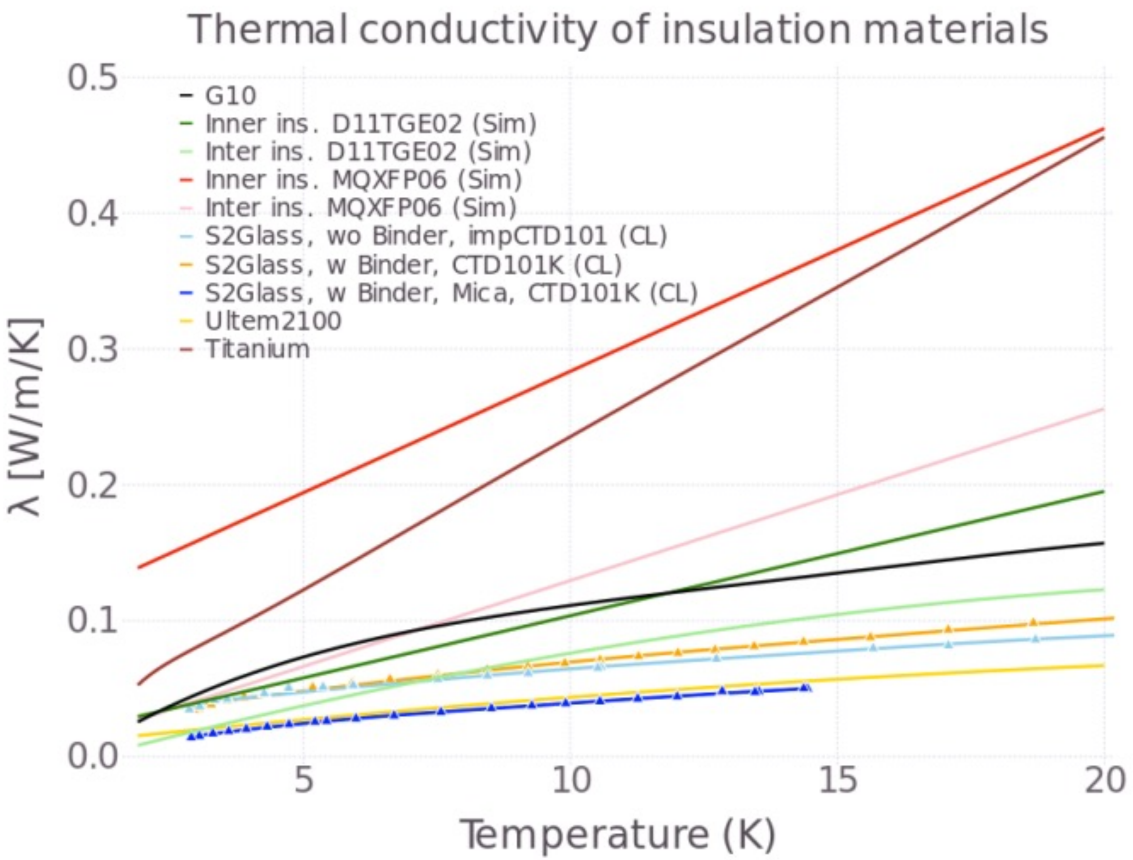
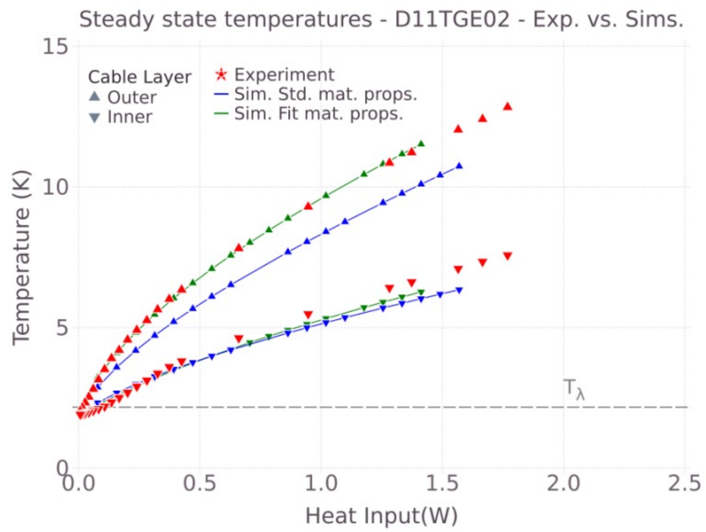
Thermal properties of materials

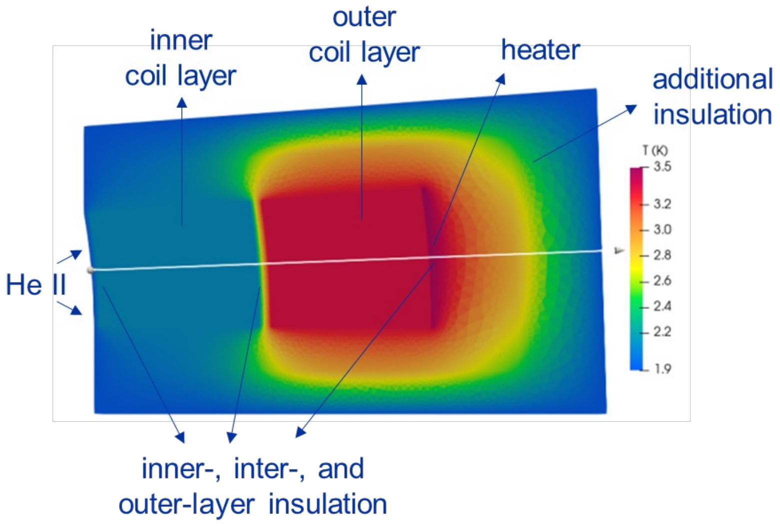


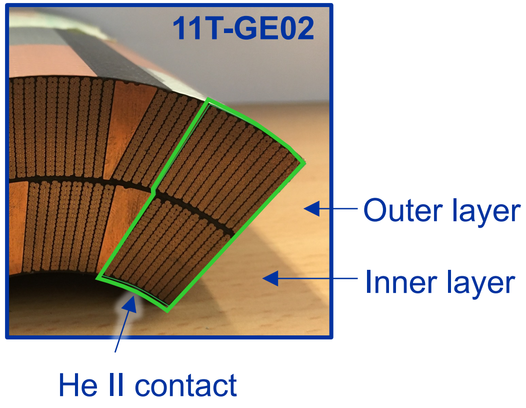
- Reliable and accurate data for material properties is **both critical to a meaningful simulation** and **difficult to source**, especially for temperatures below 4 K
- The same is true for **interface resistance** between the solid components and He II (Kapitza resistance)
- Whenever appropriate, literature data was used for standard materials such as Cu, stainless steel...
- However, properties of **composites** like the inter-cable insulation, as well as the inner-, inter-, and outer-layer insulation **could not be realistically approximated by literature data**
- **Data extracted from experimental measurements on coil samples was instrumental in bridging the gap** and getting properties of composite materials

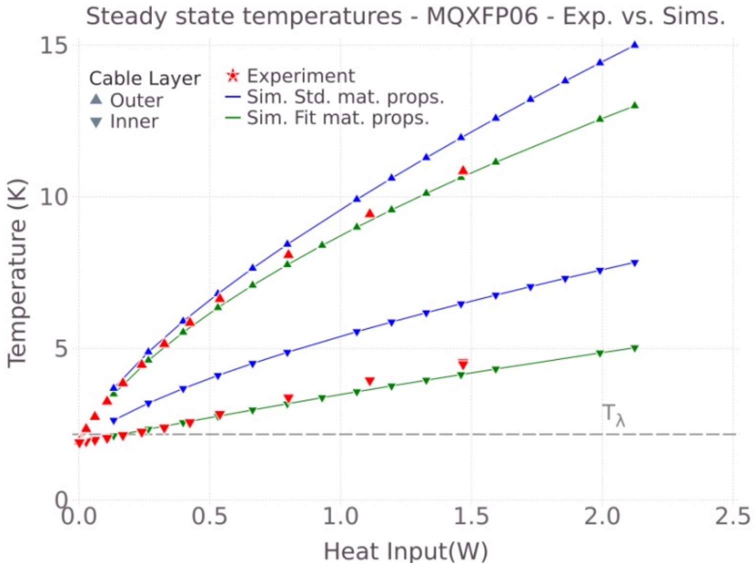
Use case: estimation of material properties

- The numerical framework can be used to simulate impregnated coil samples that were measured experimentally, and **extract the thermal properties of the composite insulation** in an iterative process:
  - Conduct steady-state simulations with “standard” properties;
  - Iterate properties of insulation to fit measurements above 3 K;
  - Use “fit” properties to simulate transient behaviour









1D transient heat conduction FVM model in julia

It is a **1D transient heat conduction FVM model** for a 4-region composite geometry **for parametric studies** in Julia (https://julialang.org/)

Development **idea came as a direct consequence of the prohibitive computational time** required to carry out comprehensive studies **to estimate helium content on measured impregnated coil samples** with the existing 2D multi-region model in OpenFOAM

Phenomenological model for composite system, with surface and/or volume fraction of He II inside the composite solid material as parameters, enabled parametric studies of He content:

- Thermal conductivity[3] described by $k = (1 - \phi_S)k_{solid} + \phi_S k_{He}$, with k_{He} described by eqns. for K_{eff}
- Heat capacity described by $\rho c_p = (1 - \phi_V)(\rho c_p)_{solid} + \phi_V\ (\rho c_p)_{He}$

In turn, the **lessons learned** while developing the 1D model **inspired a new strategy for re-development of the OpenFOAM numerical toolkit**

[3] Progelhof, R. C., J. L. Throne, and R. R. Ruetsch. "Methods for predicting the thermal conductivity of composite systems: a review." Polymer Engineering & Science 16.9 (1976): 615-625.

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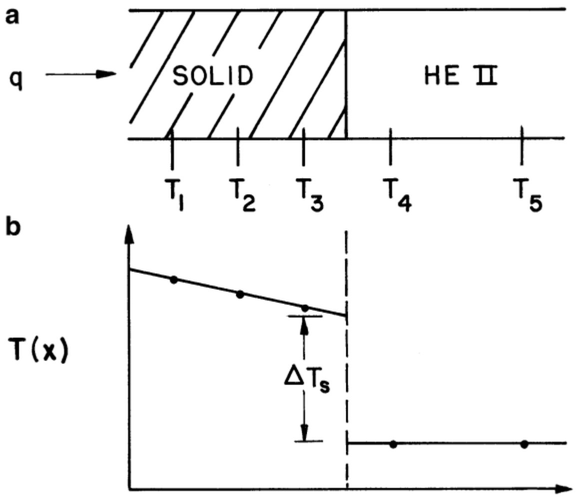
Solid-to-He boundary condition

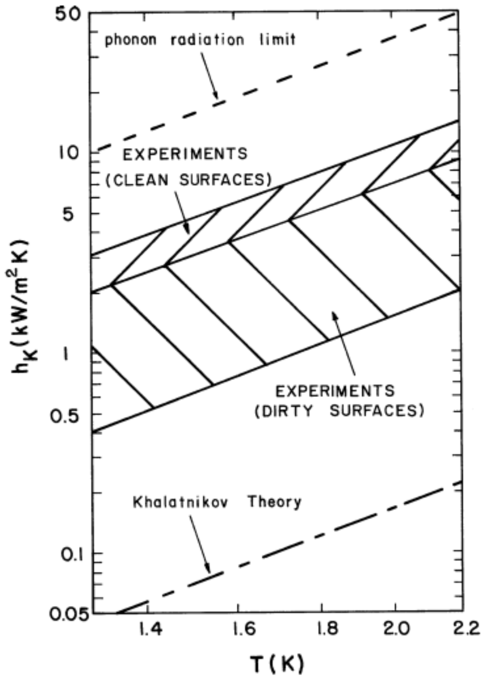
- **Kapitza-like interface conductance** $h_K = A{T_{He}}^n$, A and n (ideally) derived from experimental data whenever possible

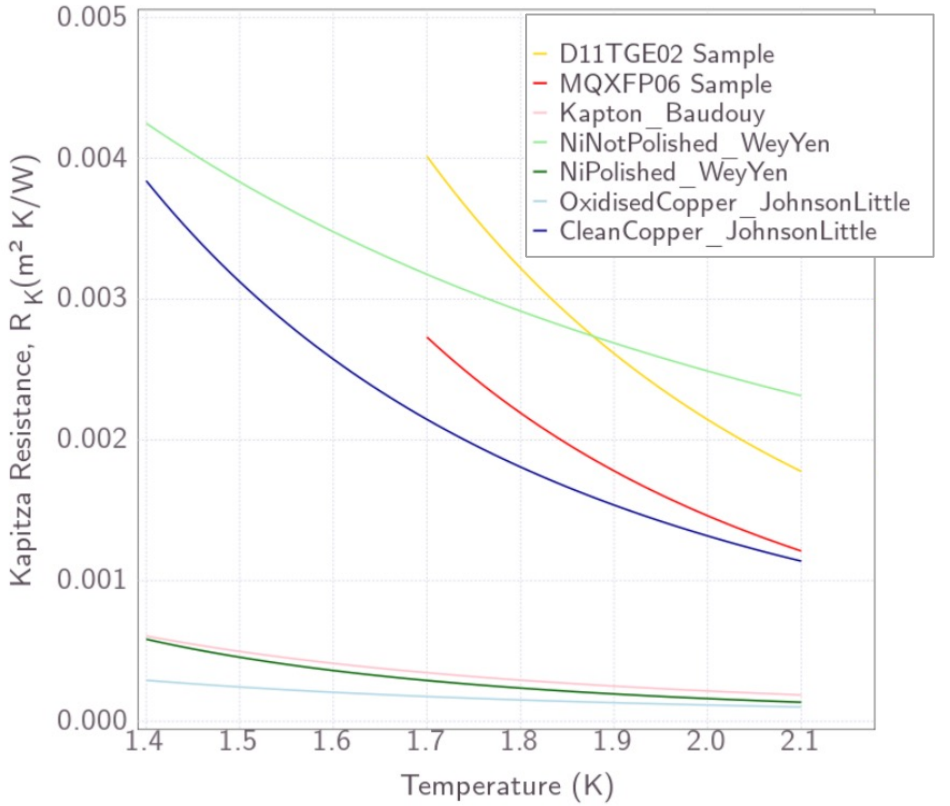
- Noticeable at **solid-liquid boundaries**, since high conductivity of He II creates negligible gradients inside the bulk He II



Source: Stephen van Sciver, *Helium Cryogenics*

Experimental values for Kapitza conductance of Cu

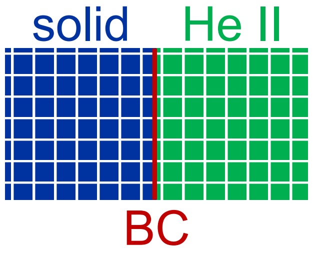




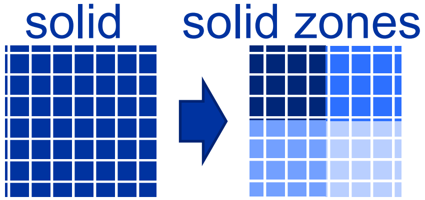
Strategies for implementation

The adopted strategy is to use a 2D multi-region solver consisting of a composite solid region which features various zones:

- A **region for solid materials** and a **region for He II**, allowing for different equations to be solved for each region, coupled via a thermal boundary condition and **solved sequentially**



- Instead of solving different matrices for each solid component, **custom library written so that only a single matrix is solved for the entire solid region.** Resulting **zones** each have a different material with **temperature dependent properties**



→ **Dramatic reduction in computation time** (*e.g.* the MQXF case shown later would have 478 regions)

Governing equations

- **Solid region**

Standard heat equation is solved, where $\dot{q}$ is the volumetric power density deposited onto the material:

$$\rho c_p(T)\frac{\partial T}{\partial t} = \nabla.(k(T)\nabla T) + \dot{q}$$

- **He II region**

Since there is no net mass flow, the He II stagnant bath is treated like a bulk (solid) material with a special thermal conductivity, leading to:

$$\rho c_p(p,T)\frac{\partial T}{\partial t} = \nabla.\big(K_{eff}(T,\nabla T)\nabla T\big) + \dot{q} \quad \text{with} \quad K_{eff}(T,\nabla T) = \begin{cases} \left(\frac{f^{-1}(T,p)}{|\nabla T|^2}\right)^{1/m} & \text{if } |\nabla T| > \gamma(T) \quad \text{(turbulent)} \\ \frac{d^2}{\beta}\frac{\rho^2 s^2 T}{\mu_n} & \text{if } |\nabla T| \leq \gamma(T) \quad \text{(laminar)} \end{cases}$$

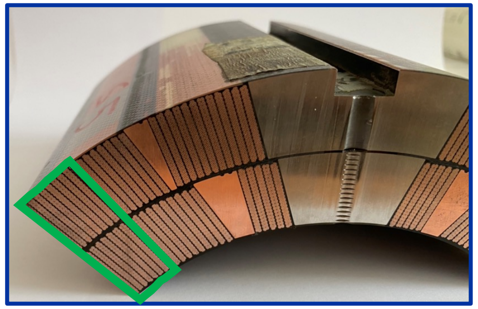
where $\gamma(T) = f^{-\frac{1}{m-1}}\left(\frac{d^2}{\beta}\frac{\rho^2 s^2 T}{\mu_n}\right)^{-\frac{m}{m-1}}$ is the temperature-dependent critical gradient $|\nabla T|$

Implementation - Summary

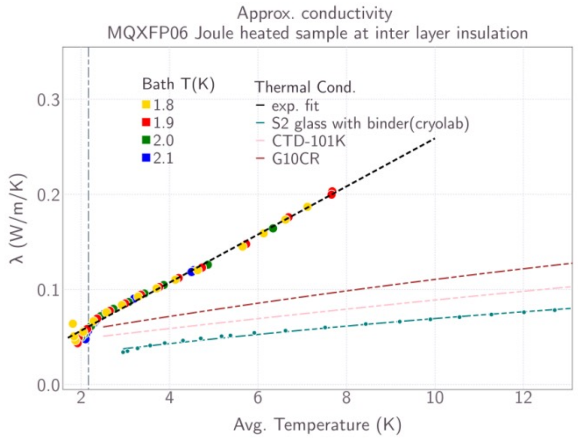
- He II region is modelled also as a bulk material with a **special thermal conductivity**.
- Helium properties are calculated at each time step for each cell using a C++ wrapper for **HEPAK.**
- The He II **thermal conductivity function** for Gorter-Mellink (turbulent) regime **was implemented using Sato's[1] empirical correlations**
- For a homogeneous initial condition, the gradient $|\nabla T|$ **is a singularity**; this is avoided by using a **direct transition model[2]** for effective thermal conductivity that assigns K_{eff} according to the **local gradient**
- For the solid part, added capability for **run-time calculation of custom thermodynamic properties by implementing Horner's method** to compute polynomials when calculating material properties at each time step at each cell.
- Result is a **2D** multi-region model with a **He II region** and a **composite solid region that can handle various zones with different material properties**

[1] A. Sato, M. Maeda, and Y. Kamioka, "Steady State Heat Transport in a Channel Containing He II at High Pressures up to 1.5 MPa", in: AIP Conference Proceedings 710.1 (2004), pp. 999-1006
[2] Winkler, T. (2017). Helium II heat transfer in LHC magnets: polyimide cable insulation. [PhD Thesis - Research UT, graduation UT, University of Twente]. University of Twente.

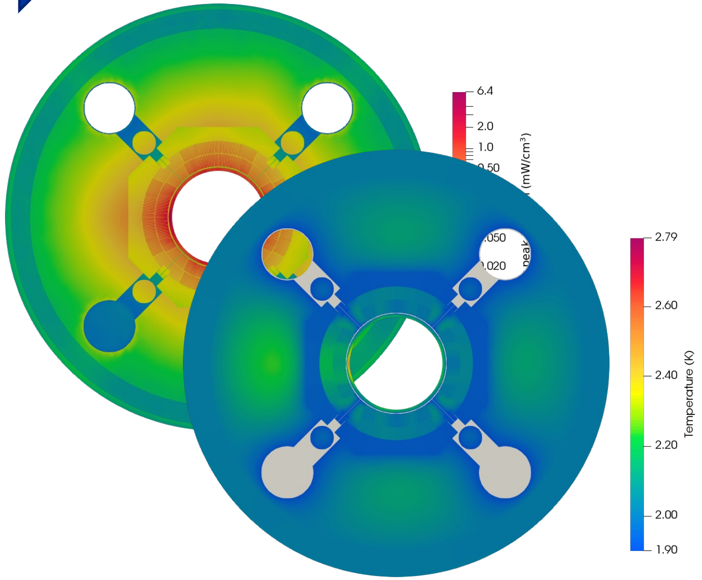
Experimental evaluation of heat transfer of coil samples in He II



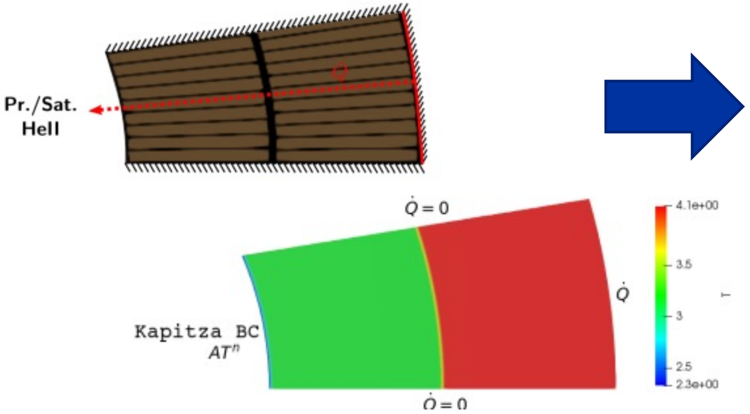
Extraction of material properties and interface resistance from exp. data

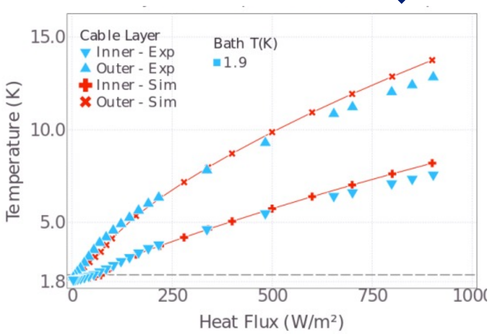


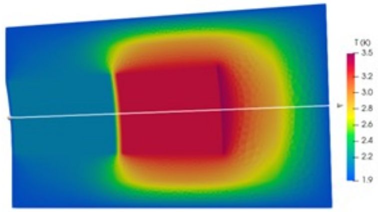
Numerical toolkit used to **validate heat extraction strategy** and temperature margins **of full-scale magnets and cold masses**



Numerical toolkit created, applied to experimental-size samples





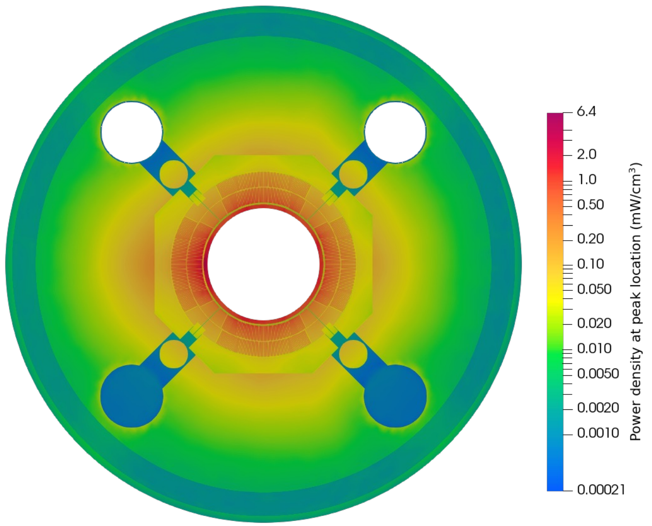


Validation of numerical toolkit by comparing exp. results with simulation using extracted props.

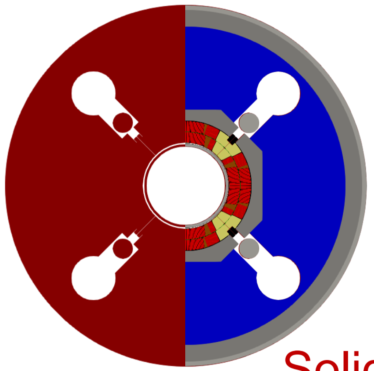
Case study: MQXF revised temperature margins (I)

- The 2D **power density** (mW/cm³) **at the peak** (maximum) **location** for nominal luminosity (7 TeV, 5.0x10^{34} cm^{-2}s^{-1}) is mapped onto the mesh created for the magnet's **cold mass + beam pipe**
- 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 (12 total)
- Here example of Q2B-IR1 shown; results for all 12 cases shown at ASC 2022, and published in IEEE TAS (link)

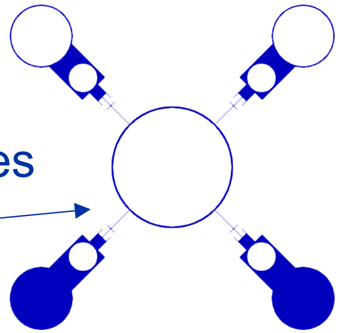
Q2B IR1-HC – power dep. @ peak loc.



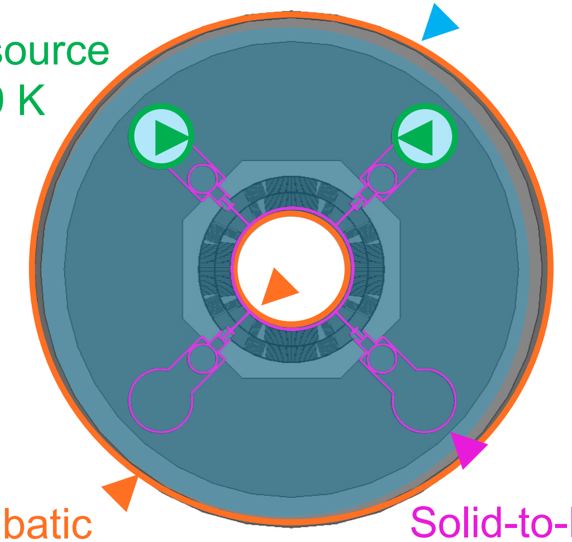
Luminosity 5.0x10^{34} cm^{-2}s^{-1} Cold bore included



He II region (connected passages via poles)



Solid region (17 parts)



Power density map

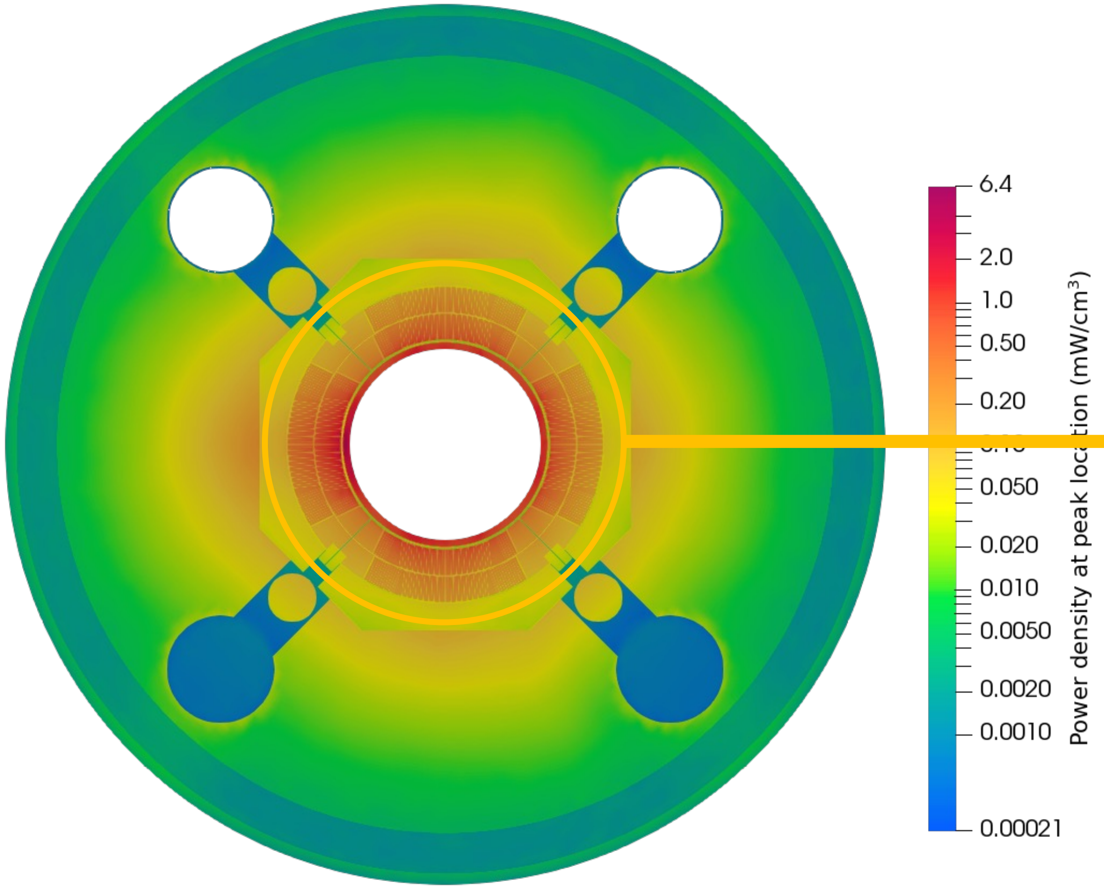
cold source 1.9 K

adiabatic

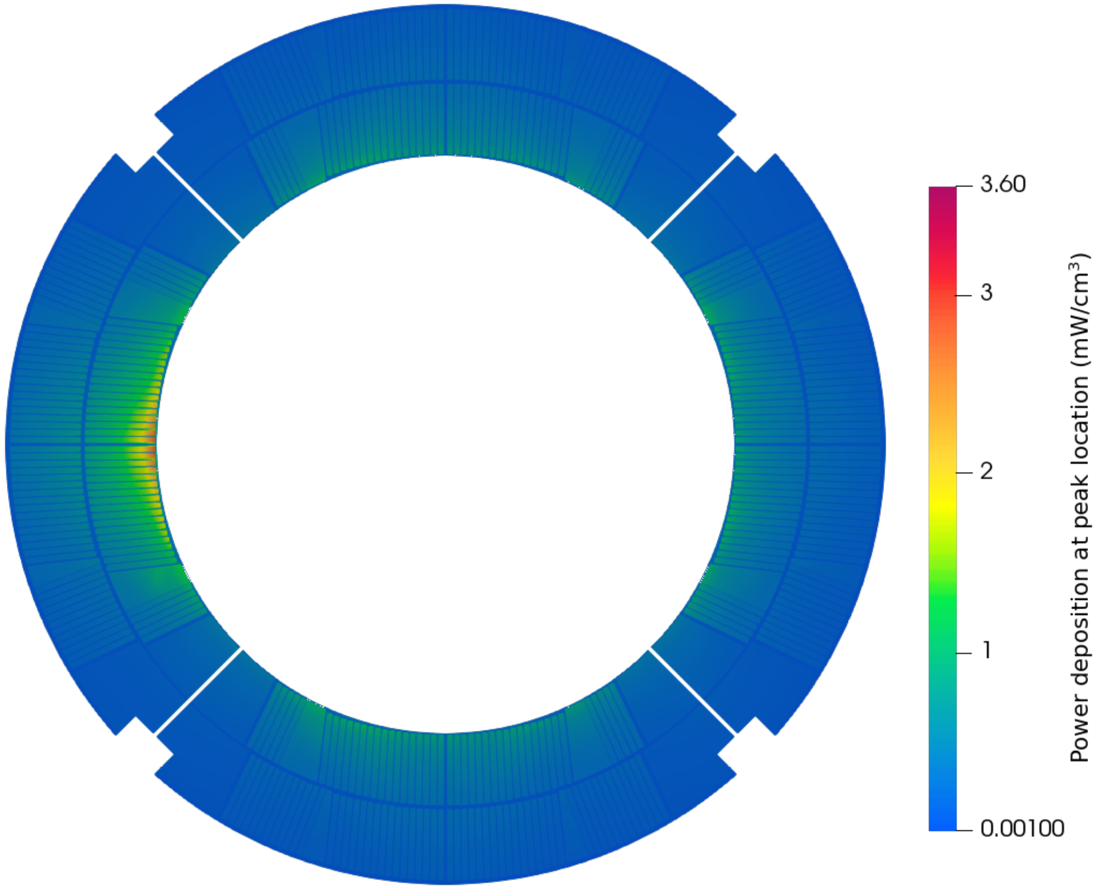
Solid-to-He II Kapitza resistance

Case study: MQXF revised temperature margins (II)

Power deposition at peak location



Power deposition at peak location (coil detail)

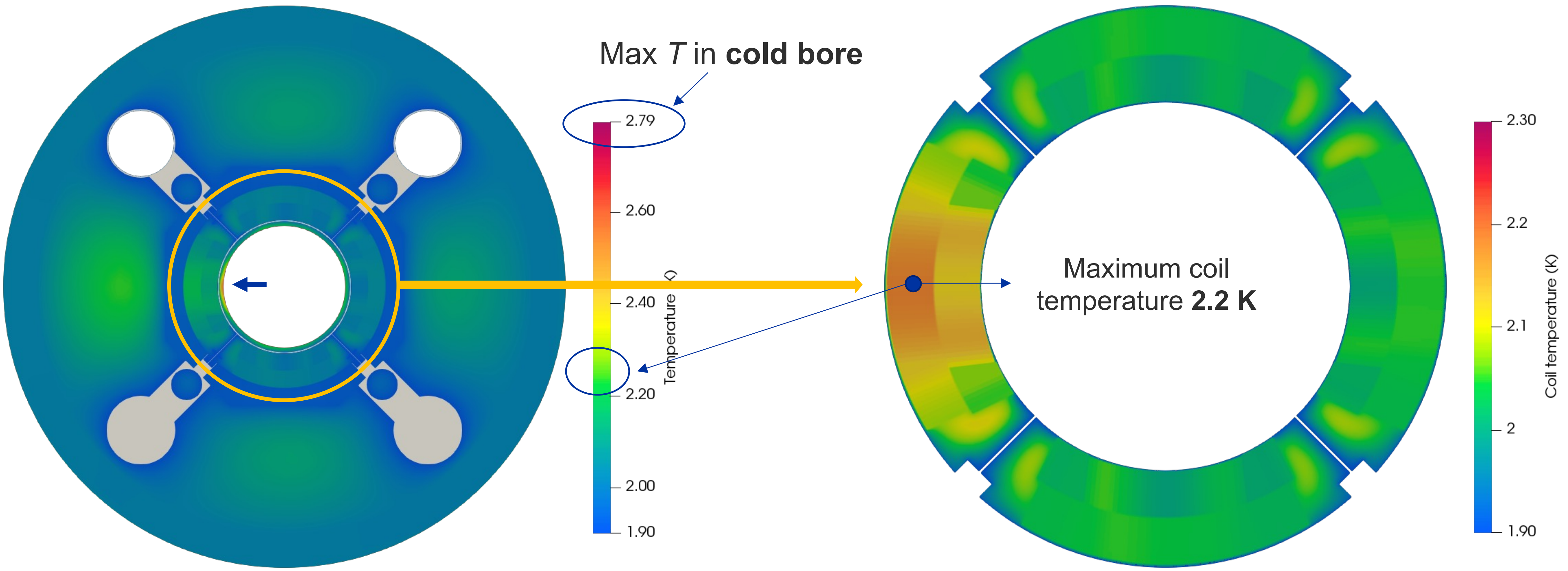


NB: Cold bore included, luminosity = 5.0×10^{34} cm^{-2}s^{-1}

Case study: MQXF revised temperature margins (II)

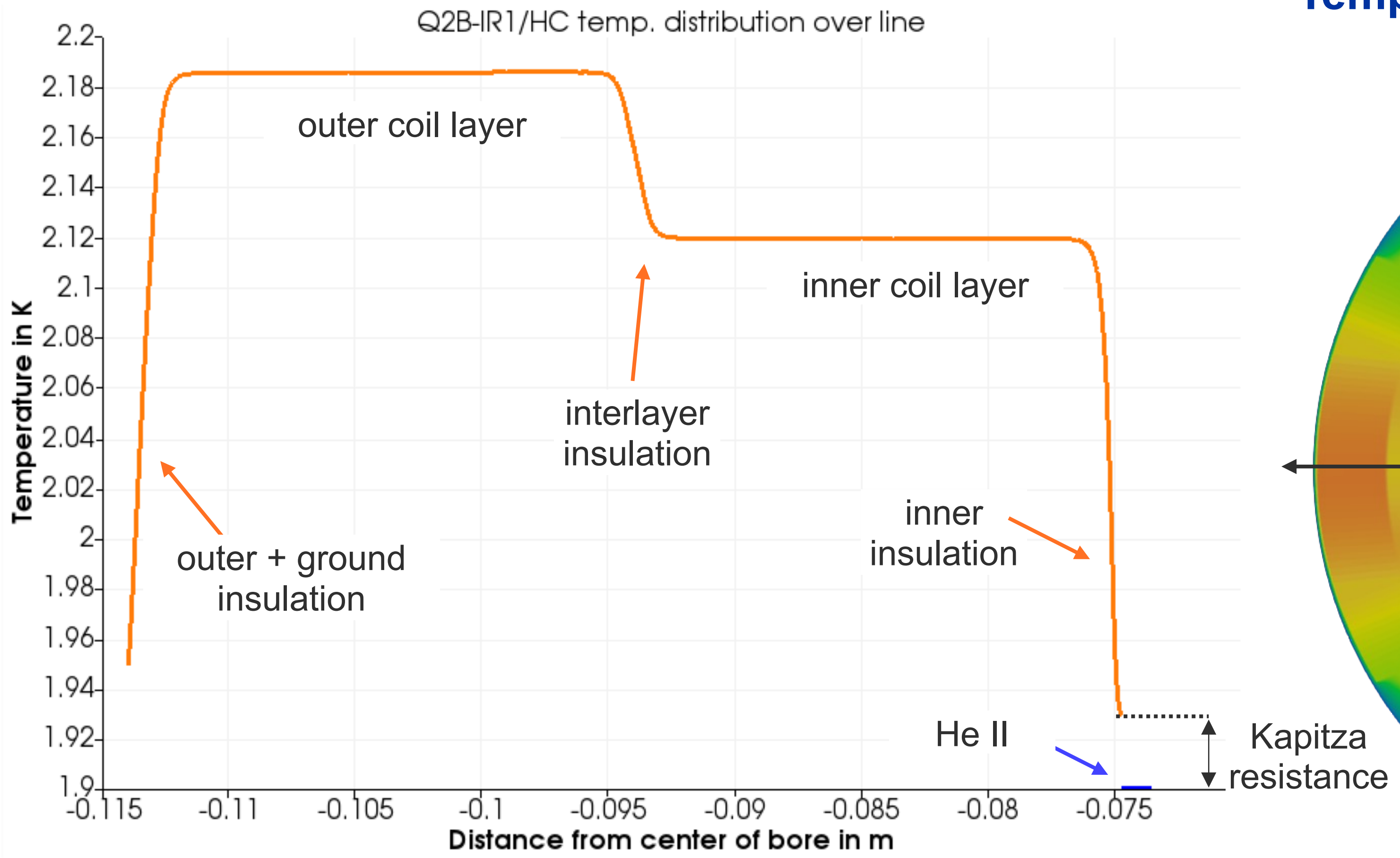
Temperature distribution at peak location

Temp. distribution at peak location (coil detail)

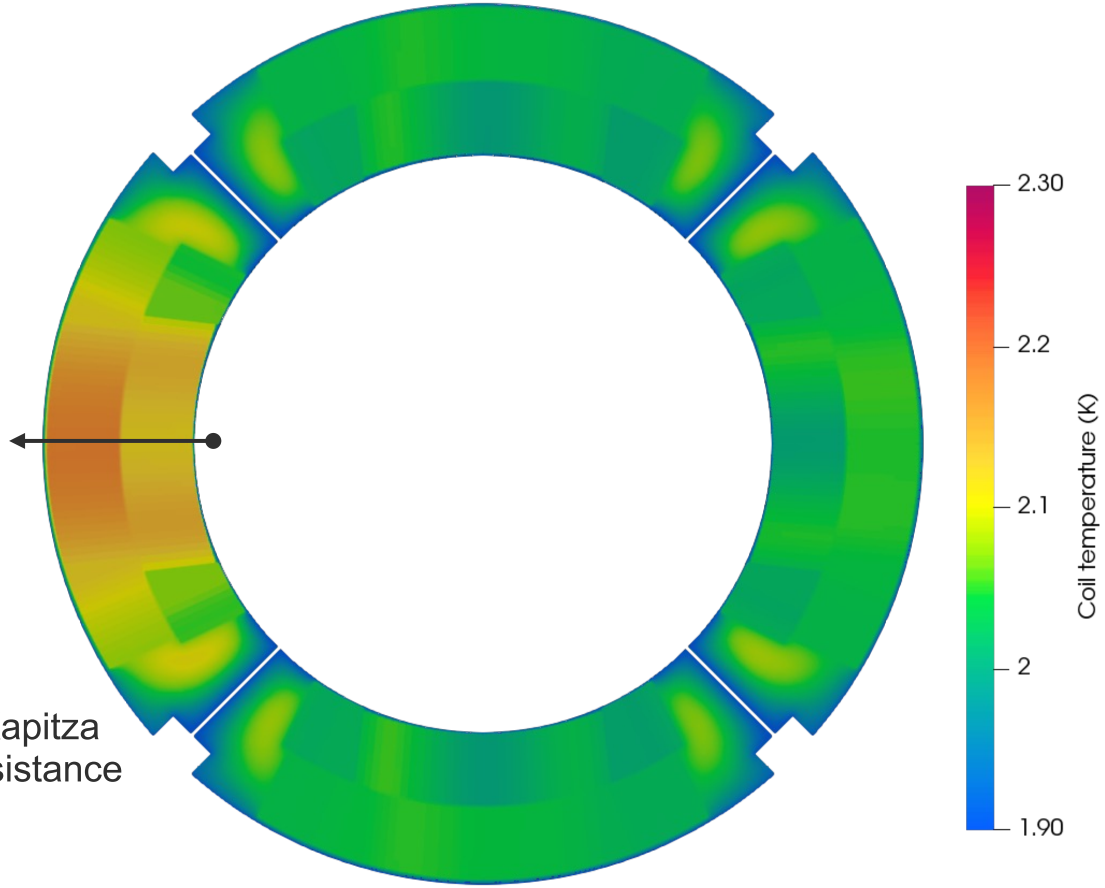


NB: Cold bore included, luminosity = 5.0×10^{34} $cm^{-2}s^{-1}$

Case study: MQXF revised temperature margins (III)



Temp. distribution at peak location (coil detail)



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**

Outlook

- Sustainable **energy consumption**, along with **He scarcity**, is forcing the community to make the move towards **magnet designs using reduced amounts of He and operating at higher temperatures**

- This numerical framework, as a design and thermal validation tool, **must evolve** to allow modelling of complex magnet structures **cooled using two-phase or supercritical He**. This implies:
  - Moving towards **a true CFD approach to He** in the model;
  - Moving towards a **(simplified) 3D geometry** to allow for assessment of longitudinal gradients

- Solver and shared libraries **continuously maintained** to ensure compatibility

Thank you for your attention!