2LOr2A – HL-LHC: Nb_3Sn Magnets II

Numerical assessment of the inhomogeneous temperature field and the quality of heat extraction from Nb_3Sn impregnated magnets for the High Luminosity upgrade of the LHC

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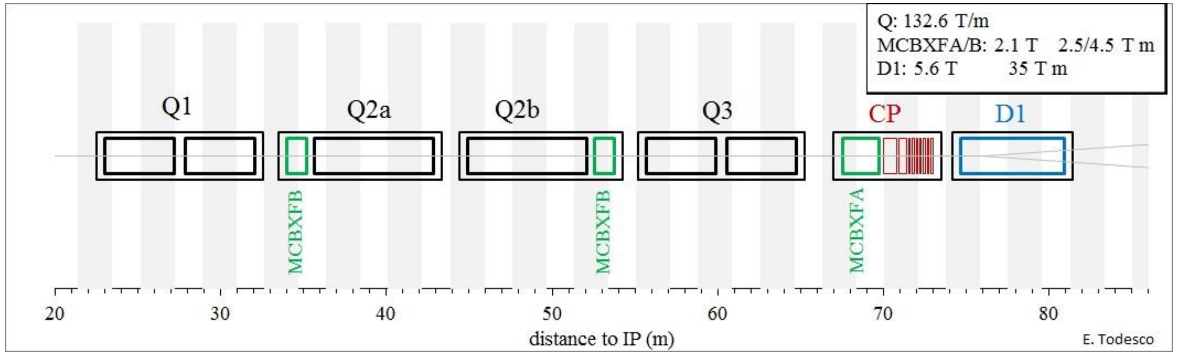
2LOr2A-03

Applied Superconductivity Conference, 23-28 October 2022, Honolulu, Hawaii, USA

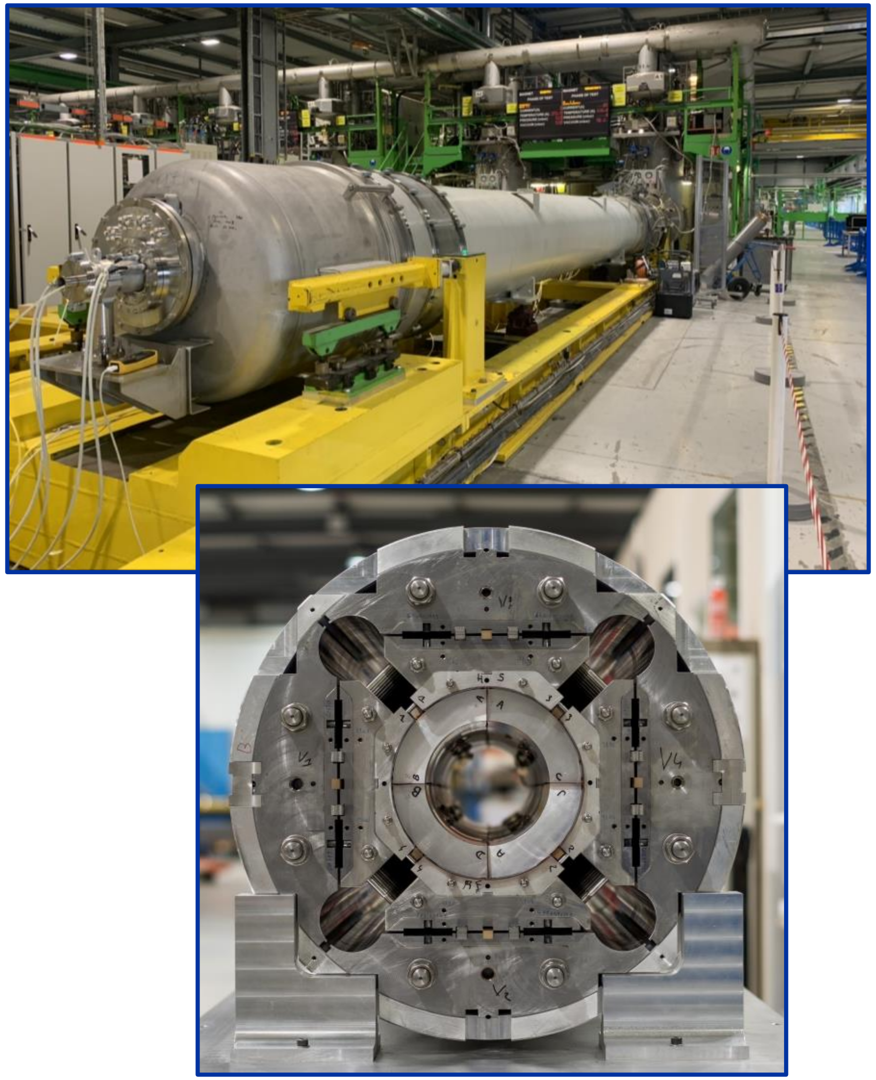
Framework

- In the context of the High-Luminosity upgrade of the LHC at CERN, **a robust multi-region CFD numerical toolkit for the modelling of heat transfer in complex cryogenic system geometries involving He II** has been developed
- **Initial work aimed to provide thermal design requirements early enough in the MQXF design phase** such that they could be implemented in the mechanical design
- The work presented here is a continuation of previous studies, implementing **updated MQXF geometry and dose maps** (April 2022) as well as a **fully upgraded numerical toolkit**



E. Todesco

Thermal mapping of HL-LHC inner triplets



Context:

- **Previously established temperature margins** along the full cross-section of Nb_3Sn magnets and enveloping cold masses **need to be reevaluated to reflect changes in both power deposition and geometry**, and to validate the heat extraction design.

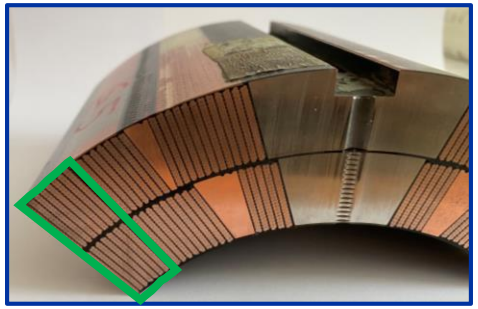
Objective:

- Systematic assessment of **temperature fields** and resulting theoretical margins in the magnet coils and **validation of the heat extraction design** of the cold mass under **peak power deposition conditions at nominal luminosity**

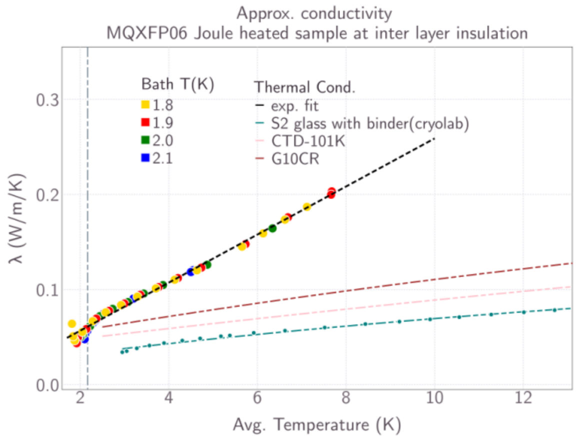
Tools:

- A 2D numerical framework has been developed to model the temperature distribution in the combined solid-superfluid He system of each magnet and enveloping cold mass using open-source software.

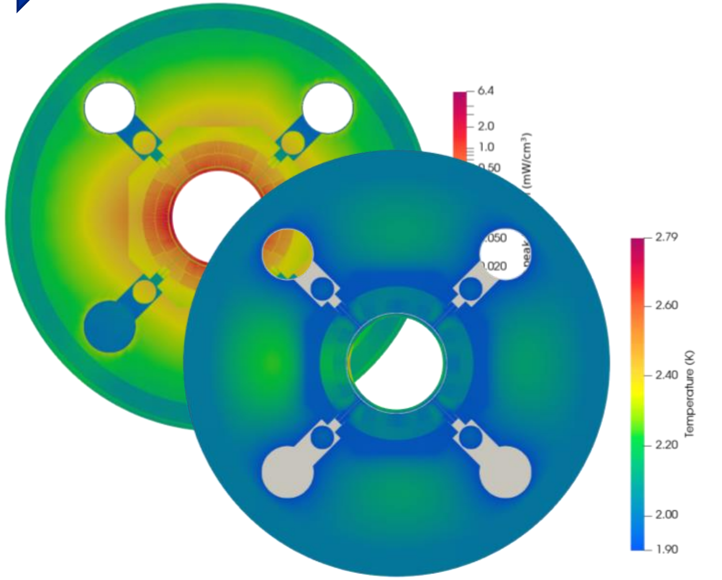
Experimental evaluation of heat transfer of coil samples in He II



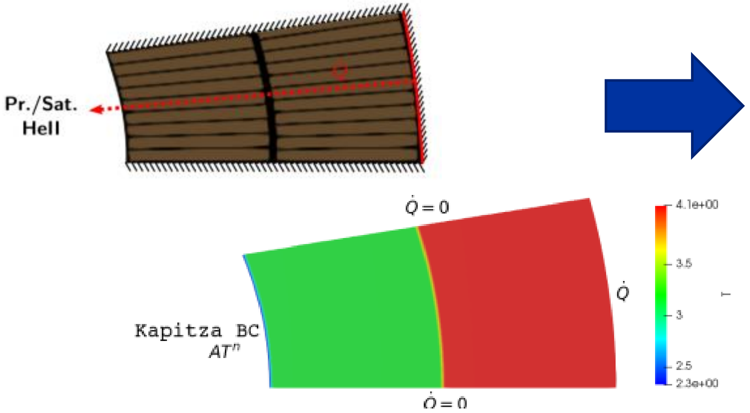
Extraction of material properties and interface resistance from exp. data

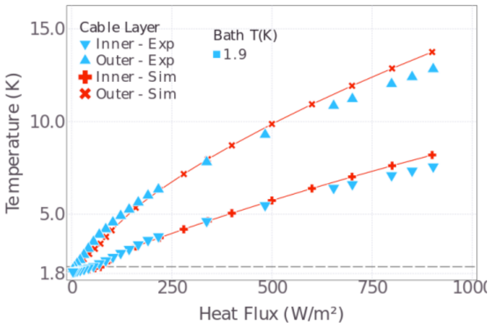


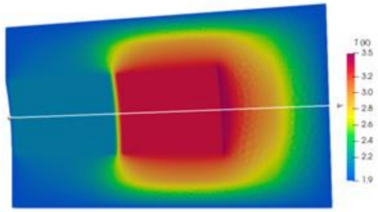
Numerical toolkit used to **validate heat extraction strategy** and temperature margins **of full-scale magnets and cold masses**



Numerical toolkit created, applied to experimental-size samples







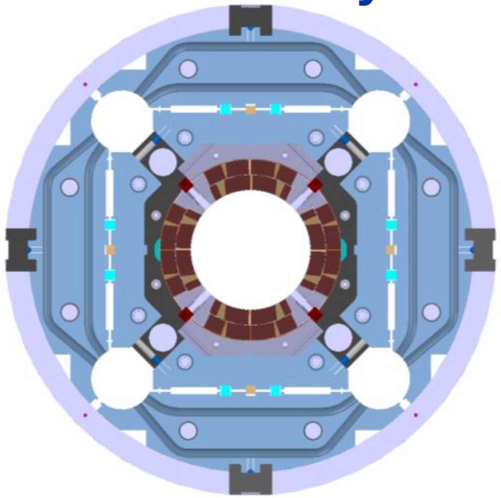
Validation of numerical toolkit by comparing exp. results with simulation using extracted props.

Numerical toolkit used to validate heat extraction of full-scale magnets and cold masses

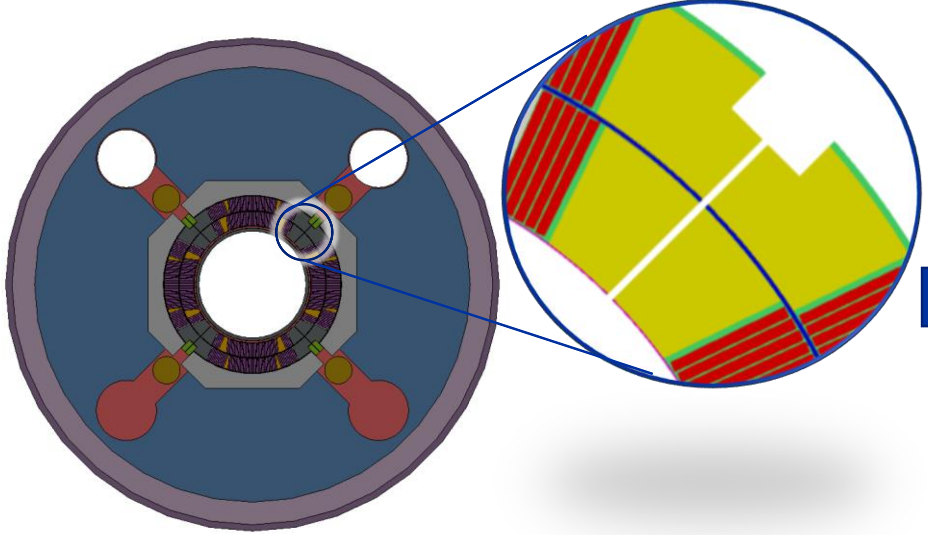
- **Libraries and solver** implemented in OpenFOAM v7
- **Geometry** of magnet/cold mass created via Python API for Salome 9.7, easily adjustable for **parametric studies**
- Currently, toolkit can handle **2D geometries** and **stagnant He II conditions** and **He II → He I transition** (no flow)
- **Dose maps** can be mapped onto the geometry and converted into **peak power deposition**; as dose scales linearly with luminosity, **peak power can be easily scaled**
- Alternatively, **direct heat input** can be applied to any part of the geometry for dedicated studies

Geometry MQXF coil + cold mass (I)

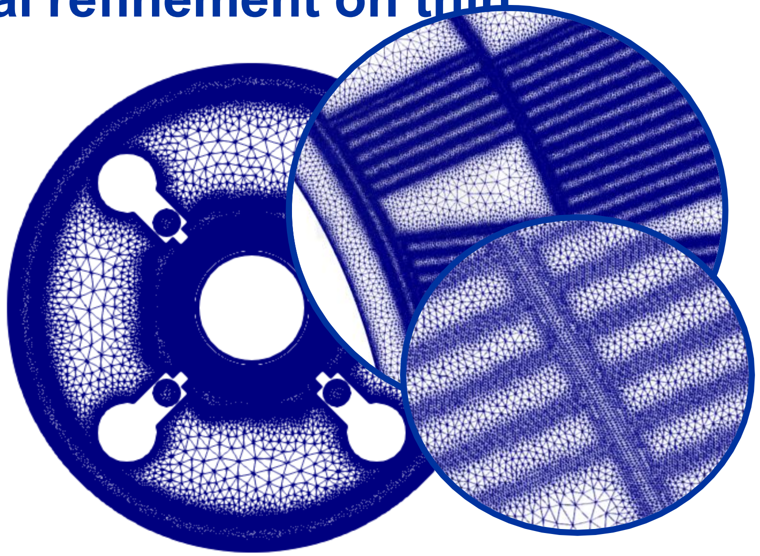
- Geometry created with dimensions in warm (300 K) conditions
- **Coil described in detail,** simplifications mainly on iron yoke (bladder structure omitted), **main He pathways included**
- **He II heat extraction passages** in Titanium pole/G10 keys (Ø8 mm hole every 50 mm) **converted to 1 mm slit in 2D geometry**
- Mesh composed of 3.5M cells, prisms; **coil pack refined → especial refinement on thin insulation layers**



MQXF v7 + cold mass (ST0703448)

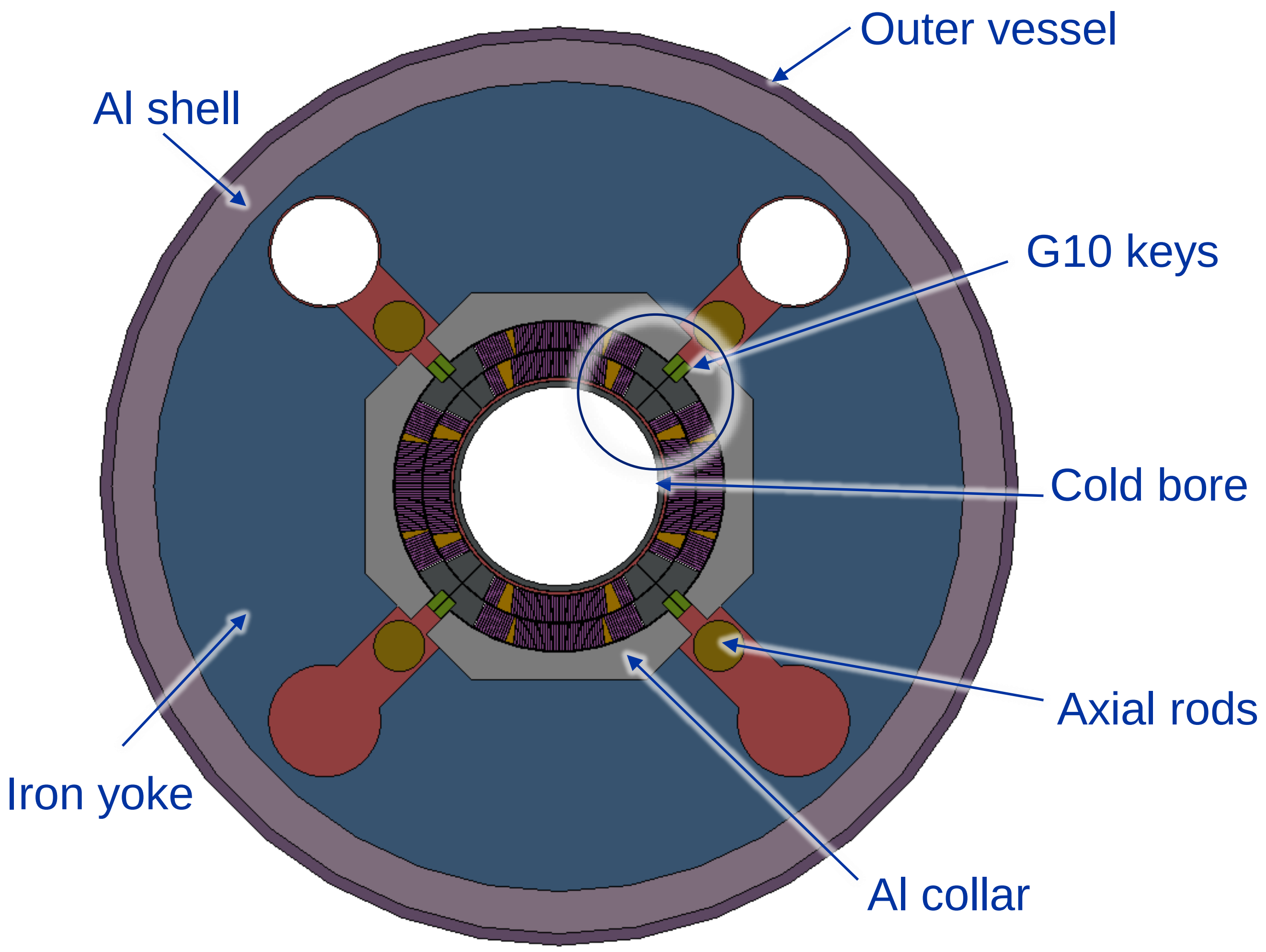


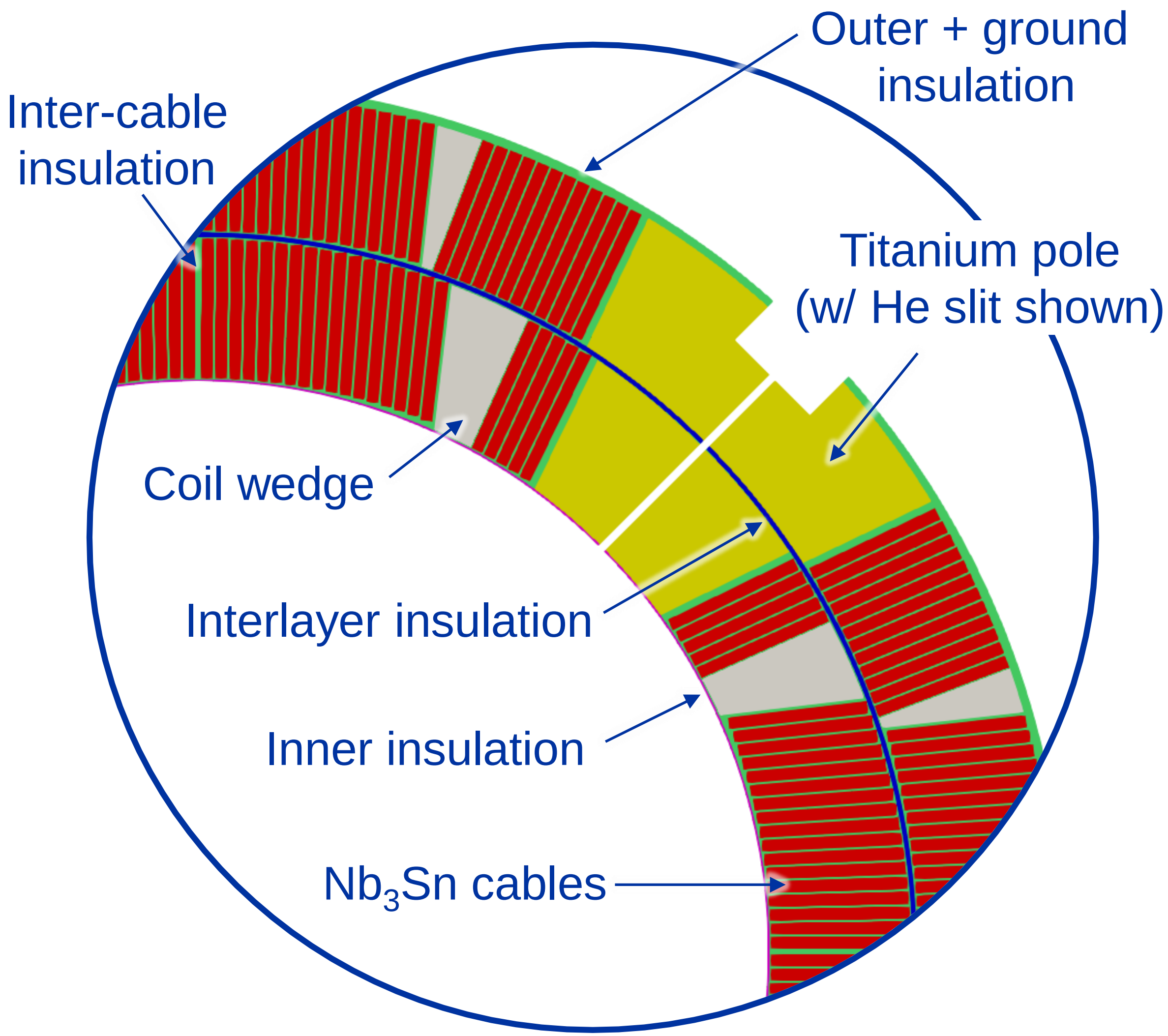
Simplified geometry for simulation (coded in Python and Salome)



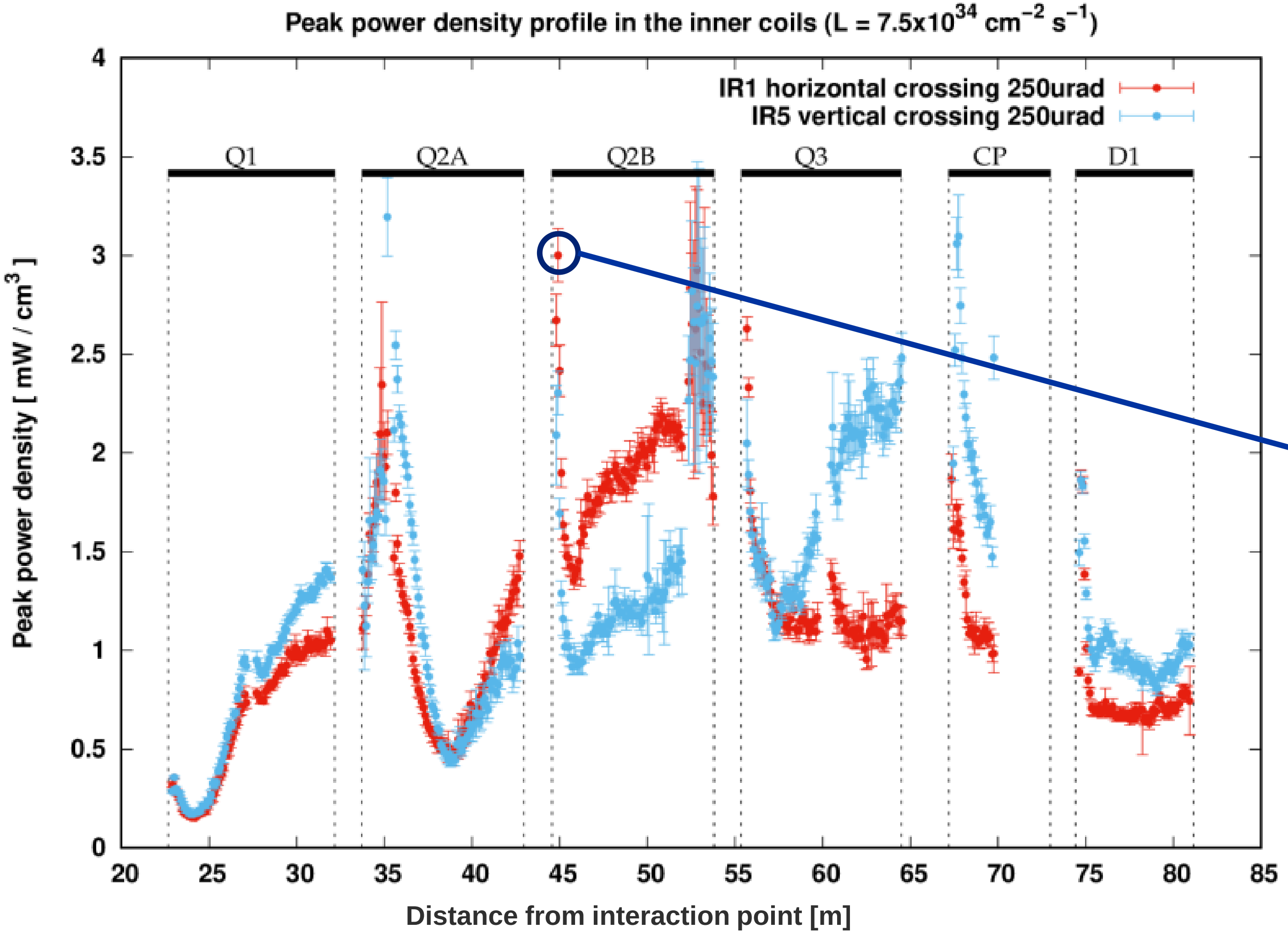
Resulting 2D meshed geometry (coded in Python and Salome)

Geometry MQXF coil + cold mass (II)

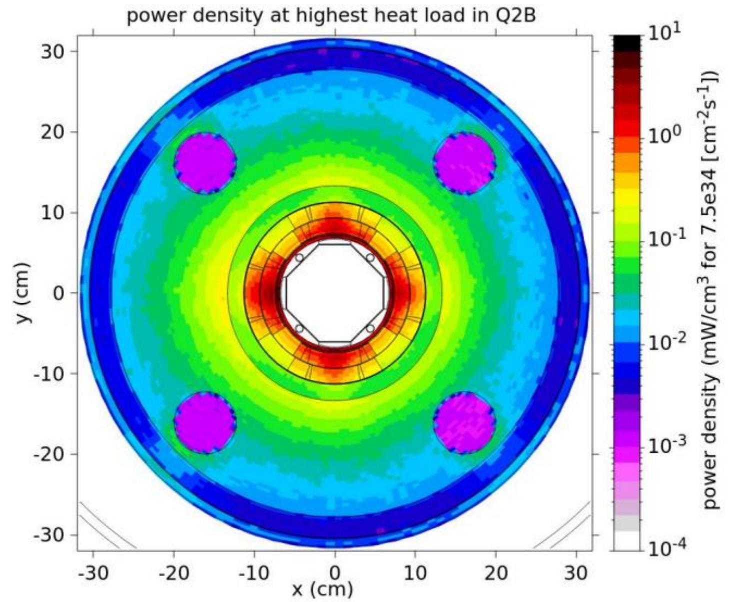




Input for heat deposition from dose calculations (I)



- 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)

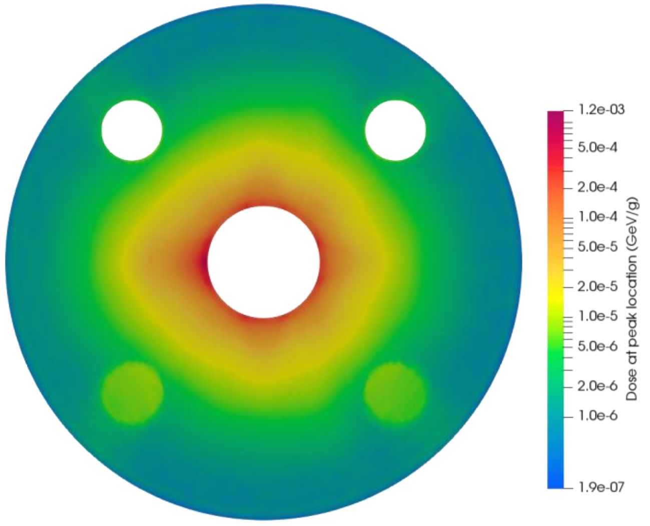


Source: Review of estimates of energy deposition, M. Sabate-Gilarte

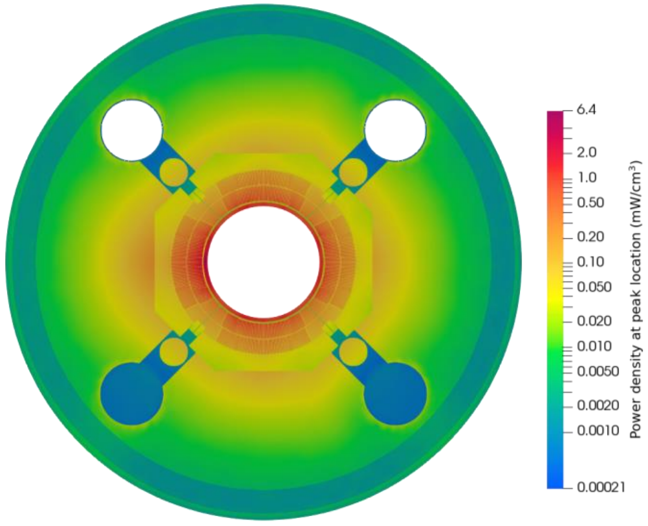
Input for heat deposition provided dose calculations (II)

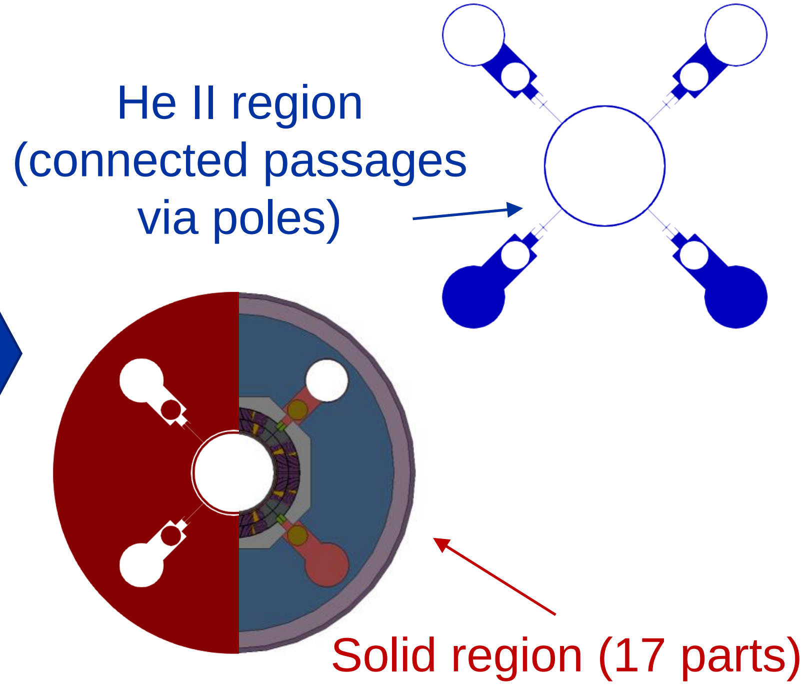
- For each magnet/cold mass, the **dose at peak location** for nominal luminosity (7 TeV, 5.0x10^{34} cm^{-2}s^{-1}) provided by FLUKA is mapped onto the mesh
- Mapped dose is converted to 2D **power density** (mW/cm^3) map **at the peak** (maximum) **location** according to each component's density
- Mesh is split into two regions, a **He II region** and a **solid region**. The solid region is composed of many different zones each with their own material properties

Q2B IR1-HC – dose @ peak loc.



Q2B IR1-HC – power dep. @ peak loc.





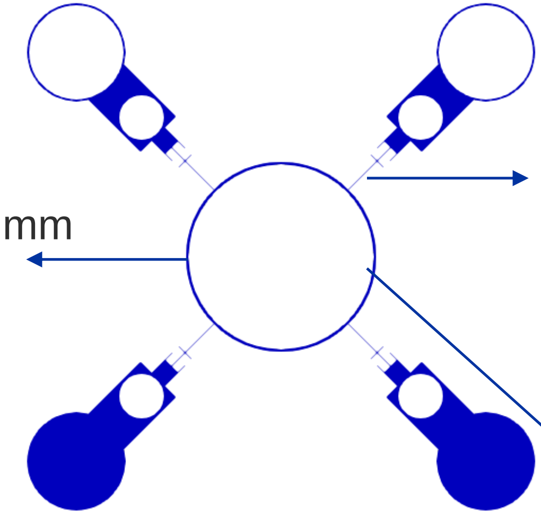
He II region (connected passages via poles)

Solid region (17 parts)

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

He II region and (composite) solid region

- Mesh is split into two regions: a **He II region** and a **solid region**
- The **solid region** is composed of many different zones each with their own temperature-dependent material properties

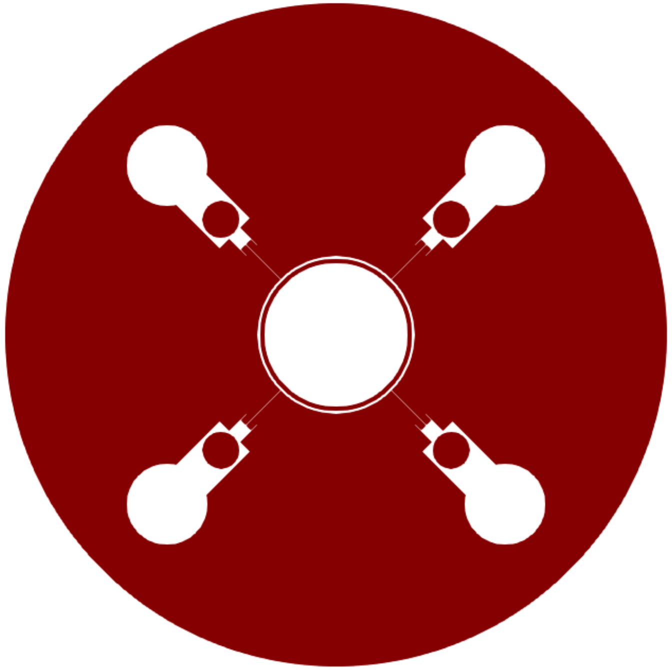


NB1: annular space 1.2 mm

NB2: 8 mm holes every 50 mm converted to 1 mm slit in 2D

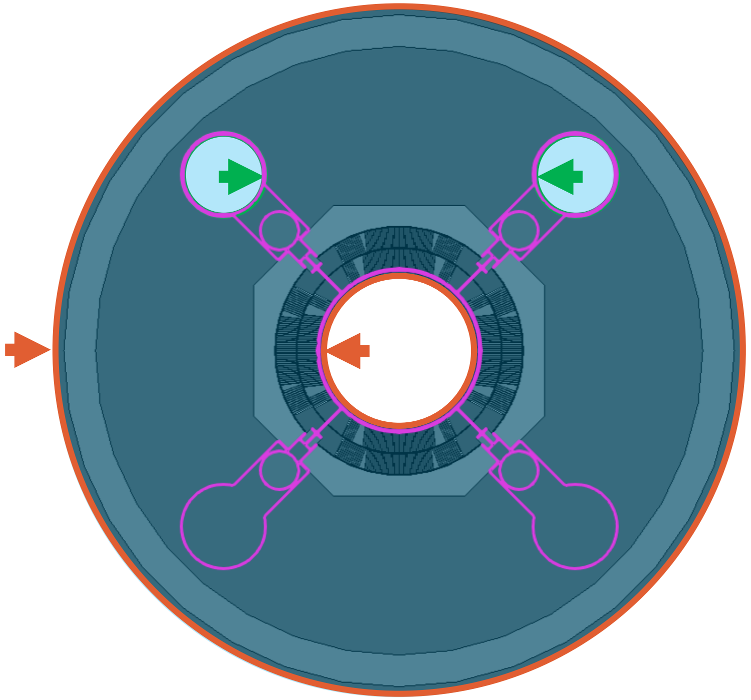
NB3: cold bore insulation thickness of 510 µm

Helium region
Connected passageways via Titanium poles/keys



Solid region
16 areas with different properties

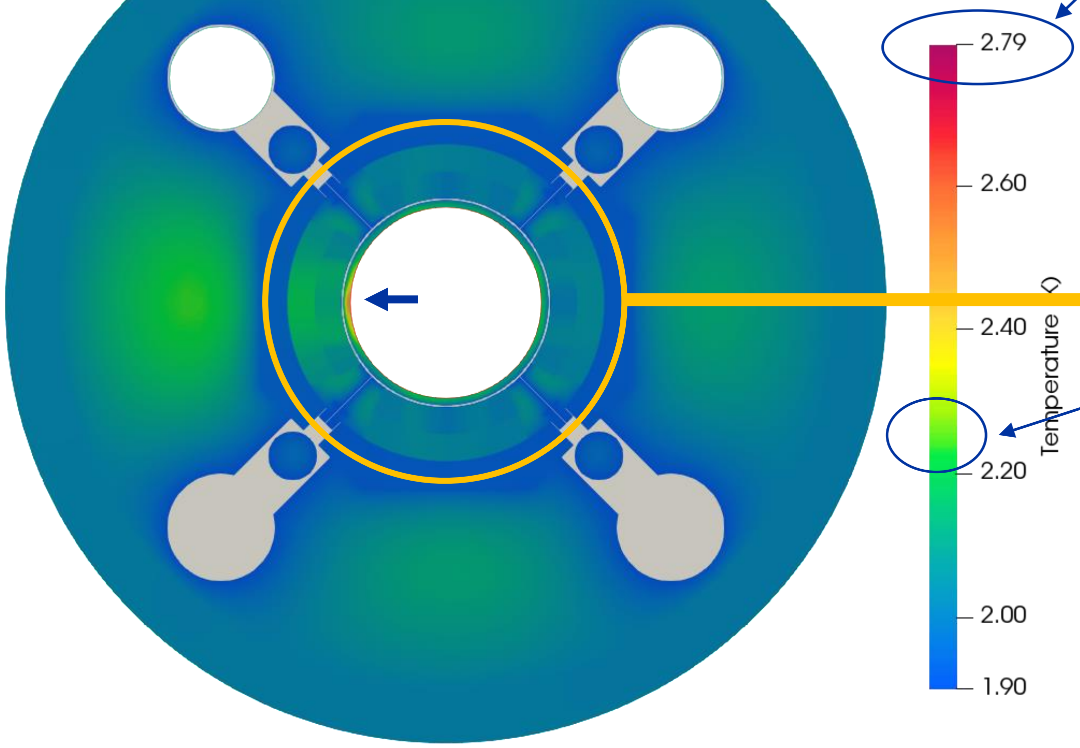
Boundary conditions for calculations



- **Outer surface** (inside of cold bore and outside of shell)**:**
  - Zero gradient $\frac{\partial}{\partial n}\varphi = 0$
- **Pressurized He II to saturated He II HEX:**
  - Fixed value *T* = 1.9 K
- **Solid-to-Helium interface:**
  - Kapitza-resistance mediated interface $h_K^0 = A{T_{He}}^n$, A and n derived from MQXF experimental data
- **On full cross-section:**
  - Resulting mapped power density computed from FLUKA, different for each magnet

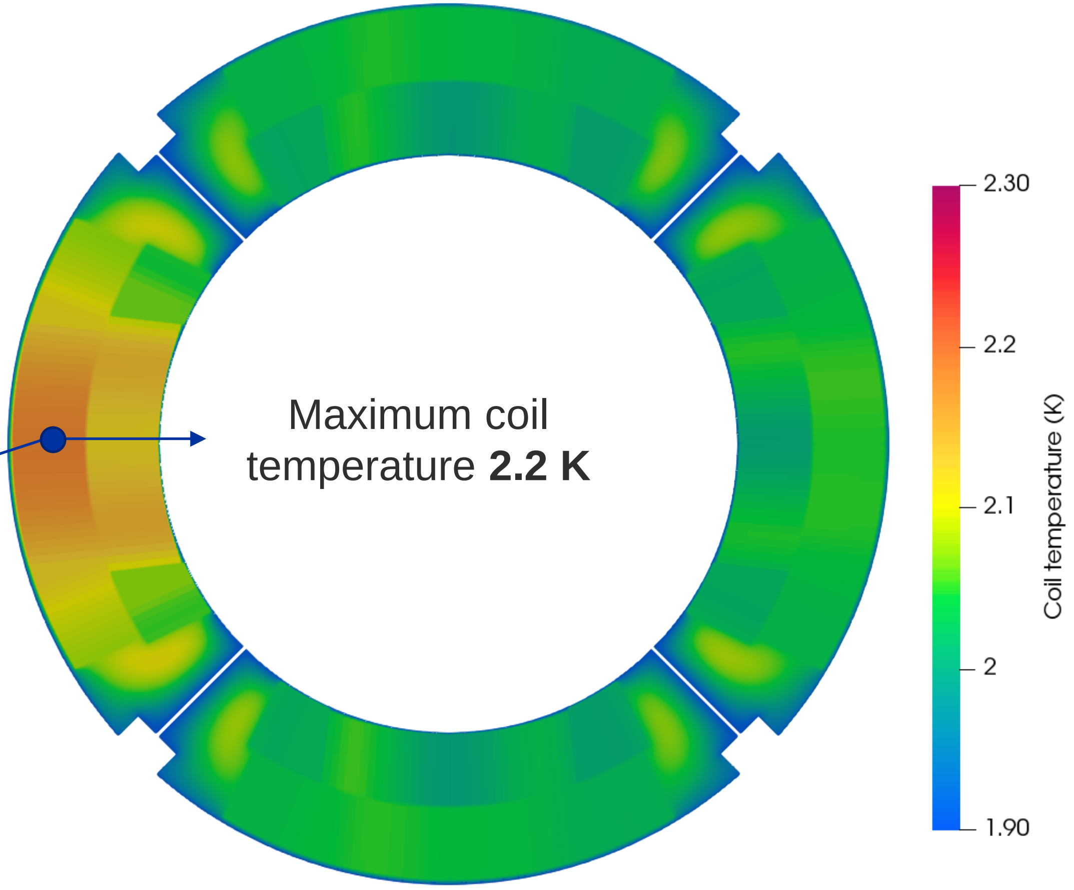
Results: example Q2B IR1-HC @ nominal luminosity

Temperature distribution at peak location



Max *T* in **cold bore**

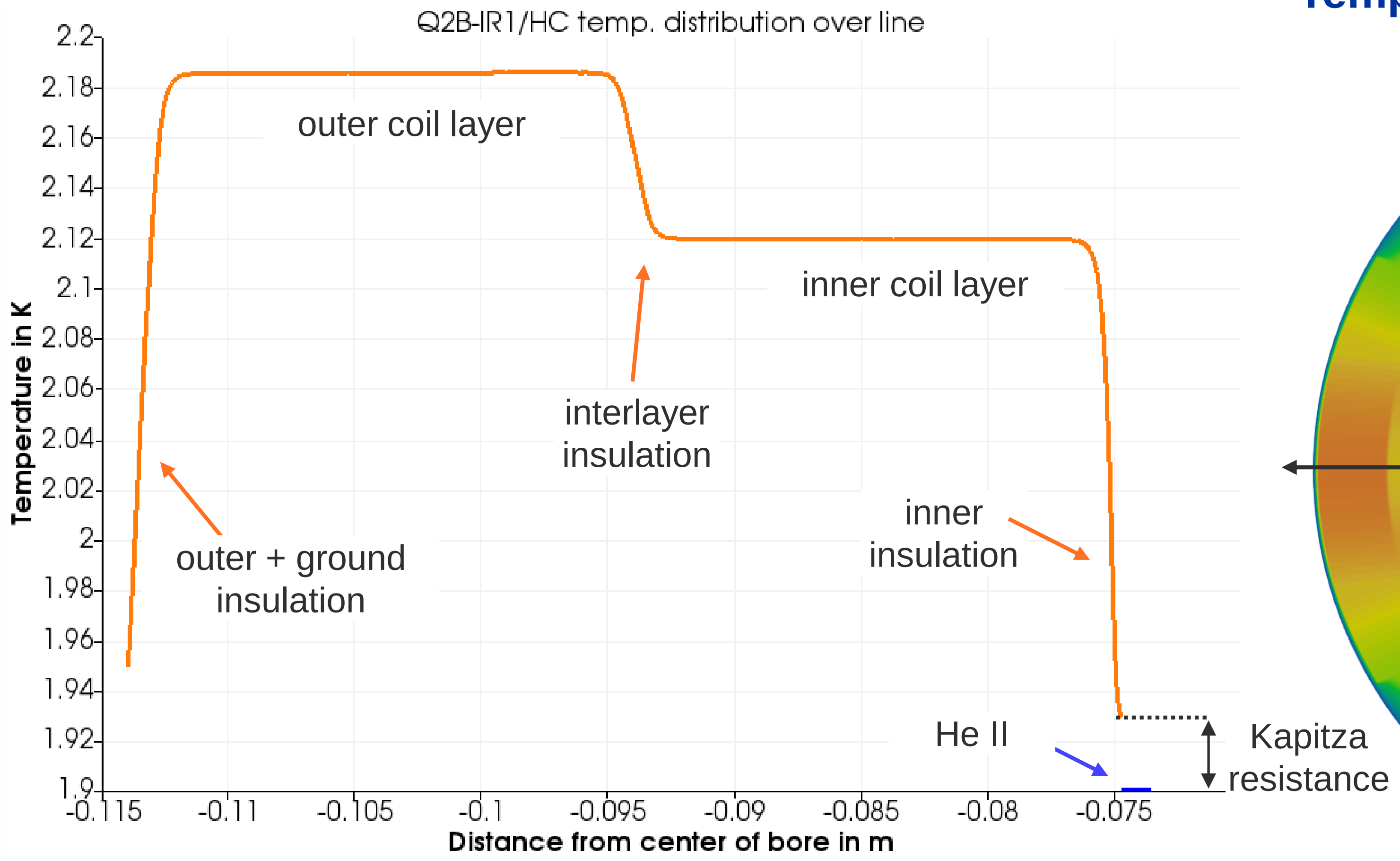
Temp. distribution at peak location (coil detail)



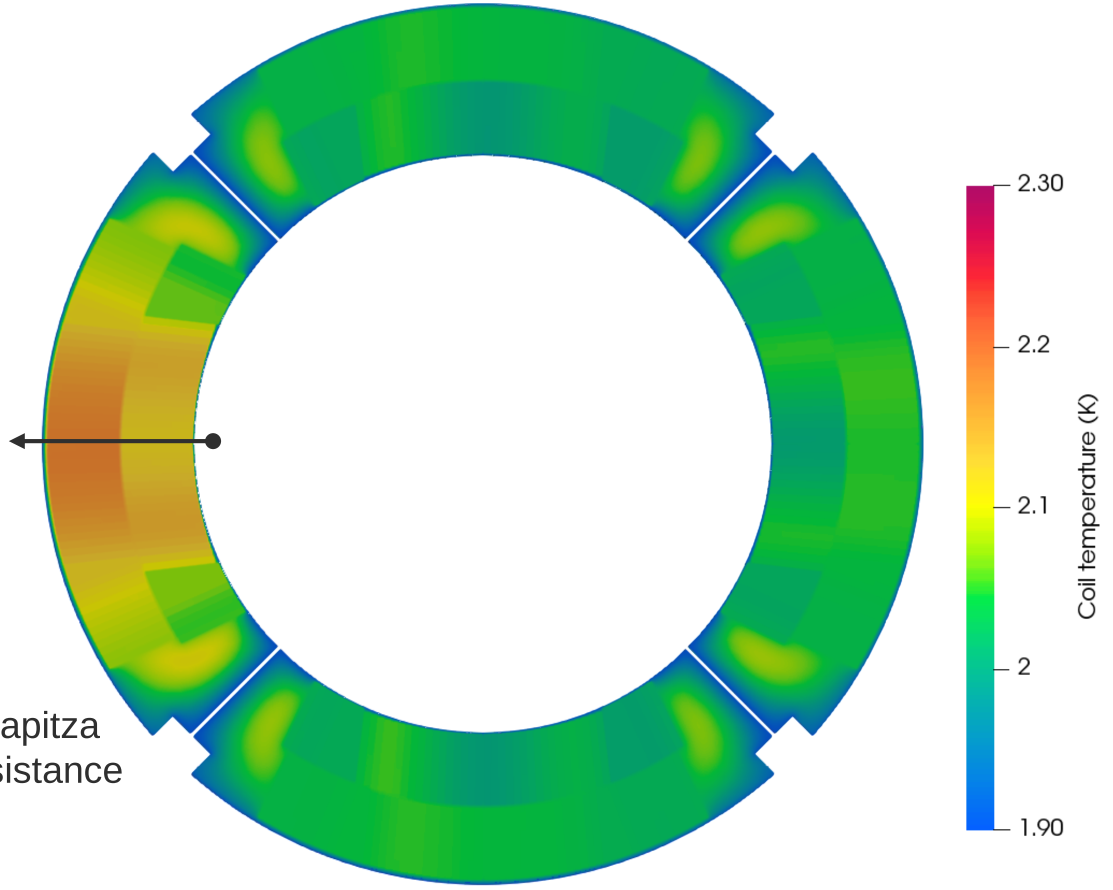
Maximum coil temperature **2.2 K**

NB: Cold bore included, dose for luminosity = $5.0\text{x}10^{34}$ cm^{-2}s^{-1}

Results: example Q2B IR1-HC @ nominal luminosity



Temp. distribution at peak location (coil detail)

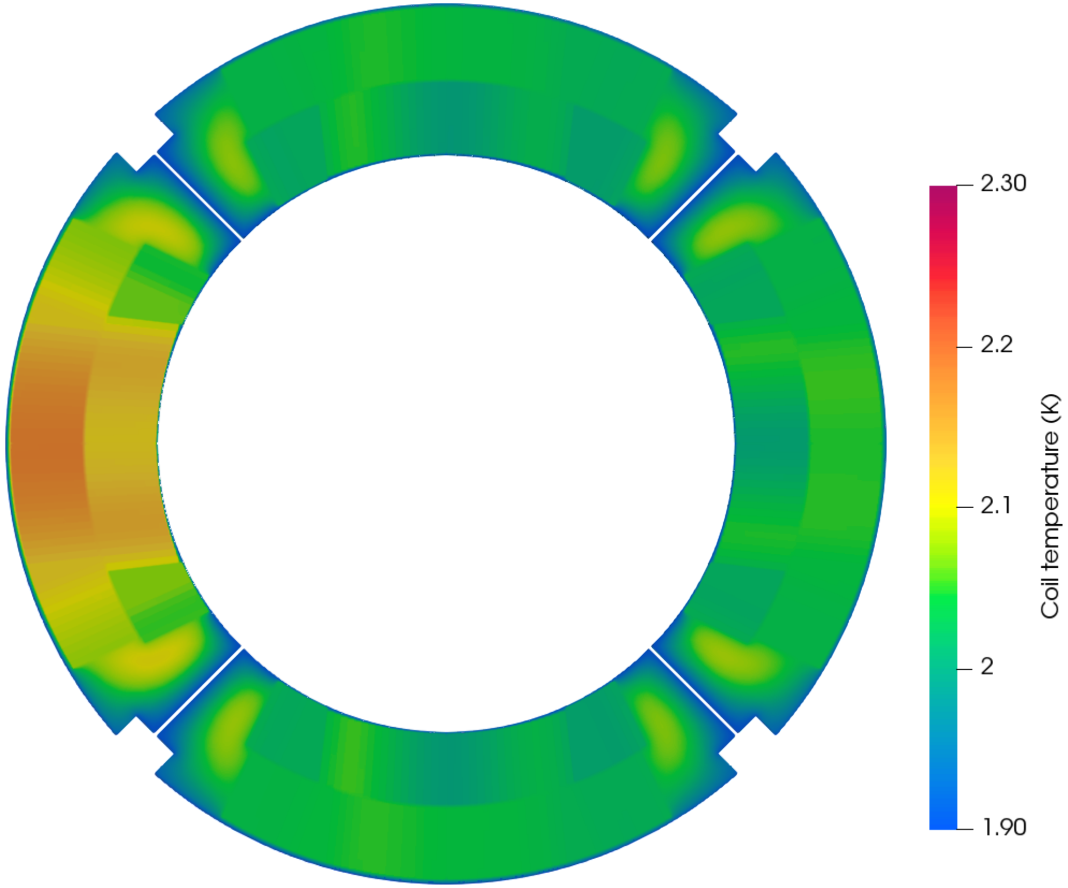


Results: example Q2B IR1-HC @ nominal luminosity

For the described **geometry**, **boundary conditions** and considering the **peak power deposition** generated by a luminosity of 5x10^{34} cm^{-2}s^{-1} for **each of the 12 magnet cross-sections**, we find:

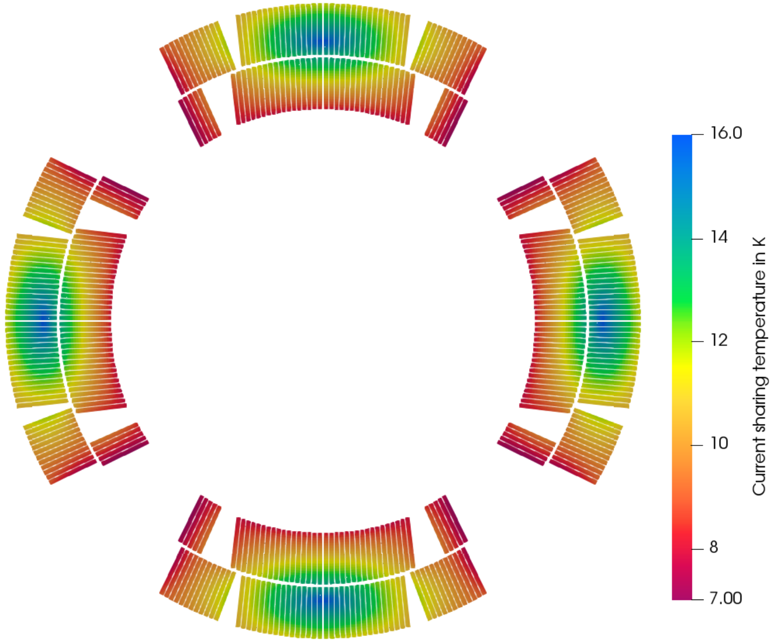
- Max. *T* in the coil = 2.3 K
- Max. *T* in cold mass = 2.8 K (on cold bore)
- He II *T* gradient O(100 µK)
- *T* gradient dominated by **inner insulation**, interlayer insulation and Kapitza

Temp. distribution at peak location (coil detail)



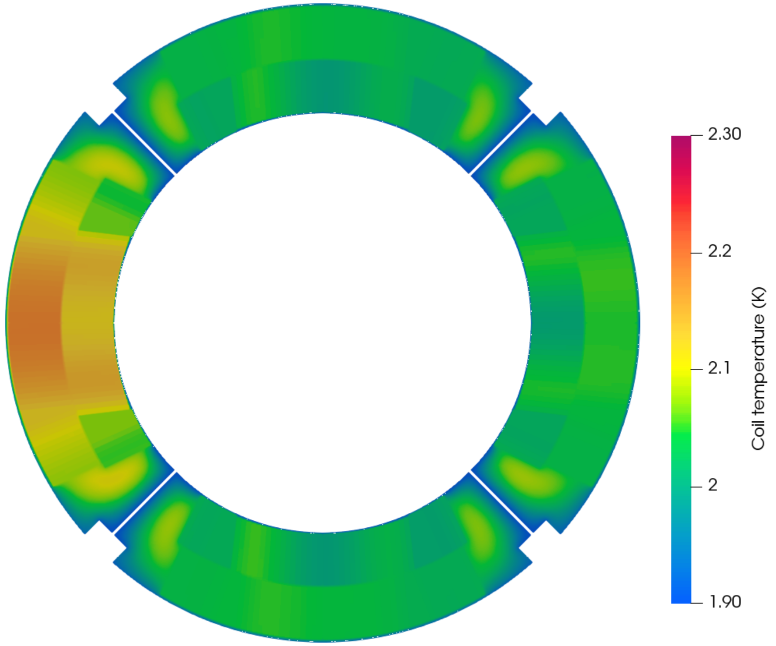
Resulting temperature margin for MQXF magnets

Based on the assumption of a **homogeneous T_{op} at 1.9 K**, margins for an ideal magnet



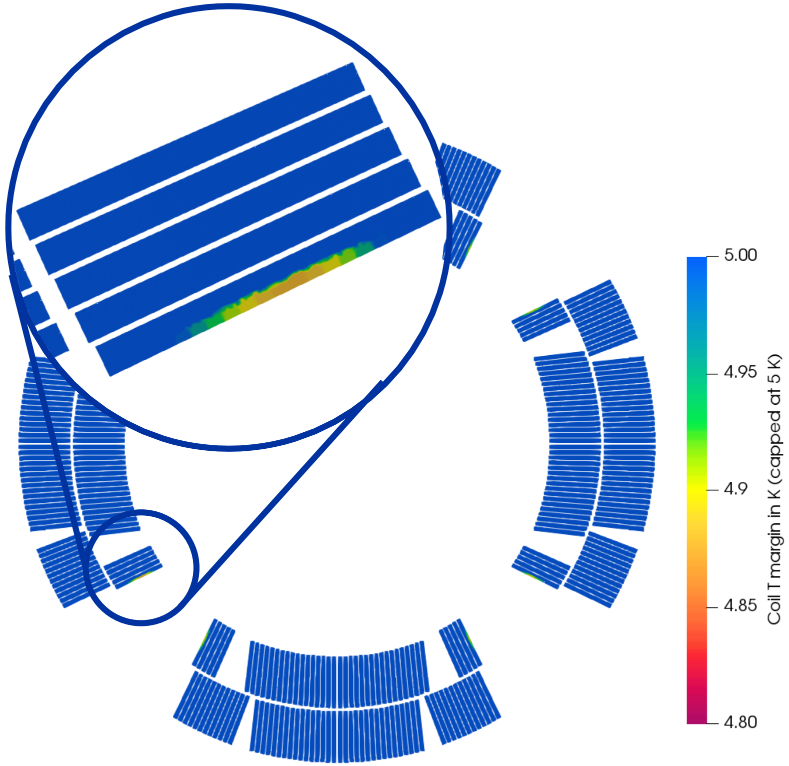
Current sharing temp.
MQXF @ J_{op}, B_{op}, T_{op}

T_{op} distribution considering conduction pathways and dose-generated heat deposition



Temperature profile
Q2B IR1-HC @ nom. lum.

Min T margin = 4.88 K



Temperature margin
Q2B IR1-HC @ nom. lum.
(scale truncated at 5 K!)

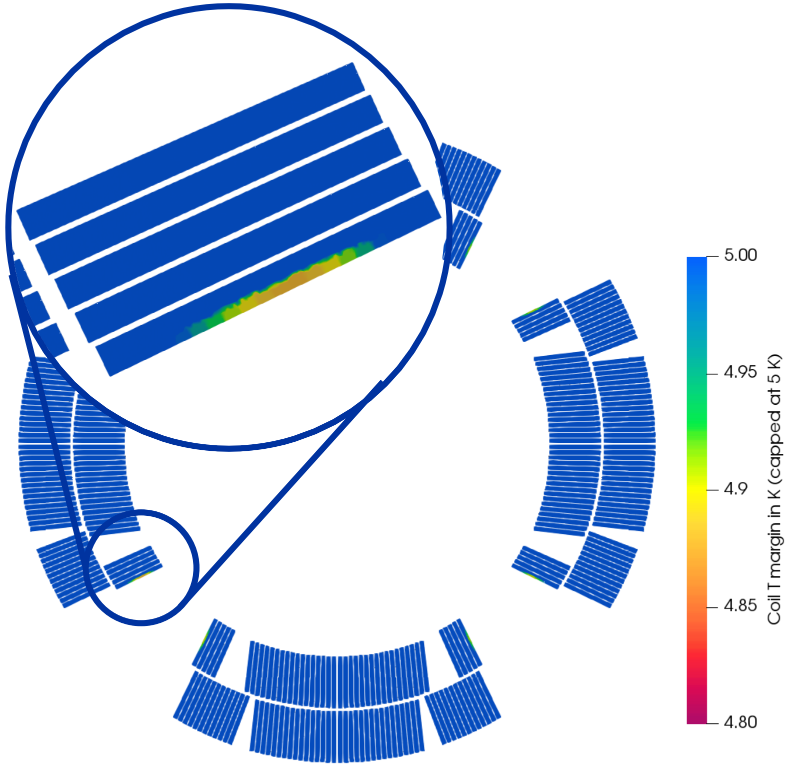
NB: Cold bore included, dose for luminosity = 5.0x10^{34} cm^{-2}s^{-1}

Resulting temperature margin for MQXF magnets

For the described **geometry**, **boundary conditions** and considering the **peak power deposition** generated by a luminosity of 5x10^{34} $cm^{-2}s^{-1}$ for **each of the 12 magnet cross-sections**, we find:

- Min. ***T* margin in the coil = 4.78 K**
- Invariably **located on the 8 turn(s) closest to the pole**
- The rest of the coil pack for each magnet cross-section has a **temperature margin higher than 5 K**

Min *T* margin = 4.88 K



Temperature margin
Q2B IR1-HC @ nom. lum.
(scale truncated at 5 K!)

Summary (I)

- Robust, easily adaptable **numerical toolkit has been consolidated** to produce results in a timeframe that allows for **parametric investigation of geometry, operational temperature, and power deposition** on magnet systems cooled by stagnant, pressurized He II

- **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** ($5.0\text{x}10^{34}$ $cm^{-2}s^{-1}$, 7 TeV), at 1.9 K cold source

Summary (II)

- The **temperature field** in MQXF coil and cold-mass cross-sections **has been updated** w.r.t. previous assessments, **considering the influence of the dose-generated power deposition for the peak position in each magnet**

- **The maximum calculated coil temperature is 2.3 K**, while the rest of the cold mass sees a localized maximum ≤ 2.8 K, located on the cold bore

- Considering the calculated temperature distribution, for the design B_{op}, J_{op}, and cold source at 1.9 K, the **minimum temperature margin is** calculated to be **between 4.78 K and 4.92 K**

MQXF cross-sections at peak dose, 7 TeV, 5.0x10^{34} cm^{-2}s^{-1},1.9 K cold source

	On coil pack	On cold mass
Maximum power density	3.6 mW/cm^3	6.4 mW/cm^3
Maximum temperature	2.30 K	2.79 K
Minimum temp. margin	4.78 K	N/A

Outlook

- **Consolidated strategy can be applied to investigate temperature distribution** & margins, as well as to **validate the heat extraction strategy**, on other geometries **including non-impregnated coil structures**

- Simulations of a **2D longitudinal section** of the cold masses will be carried out **to better evaluate the gradient along the pressurized He II region** with real He passageways (8 mm holes every 50 mm)

- Next major step is to **move to a 3D (simplified) geometry**: magnet configurations that rely on reduced He content and/or long conduction paths can profit from a 3D picture of temperature distribution

Thank you for your attention!