High-performance simulation of the magnetic field in superconducting magnets using the Sparselizard open source FEM library

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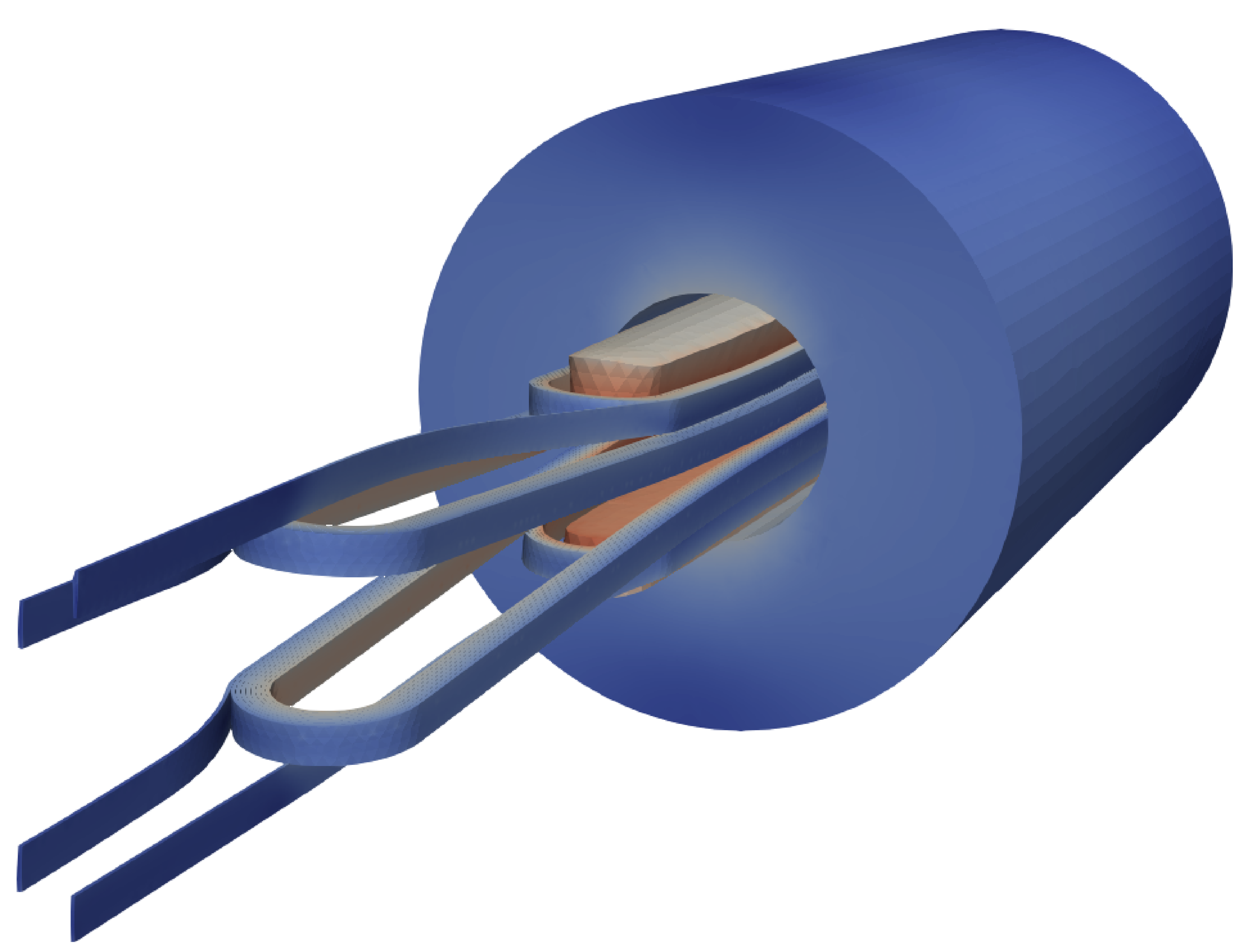
Introduction

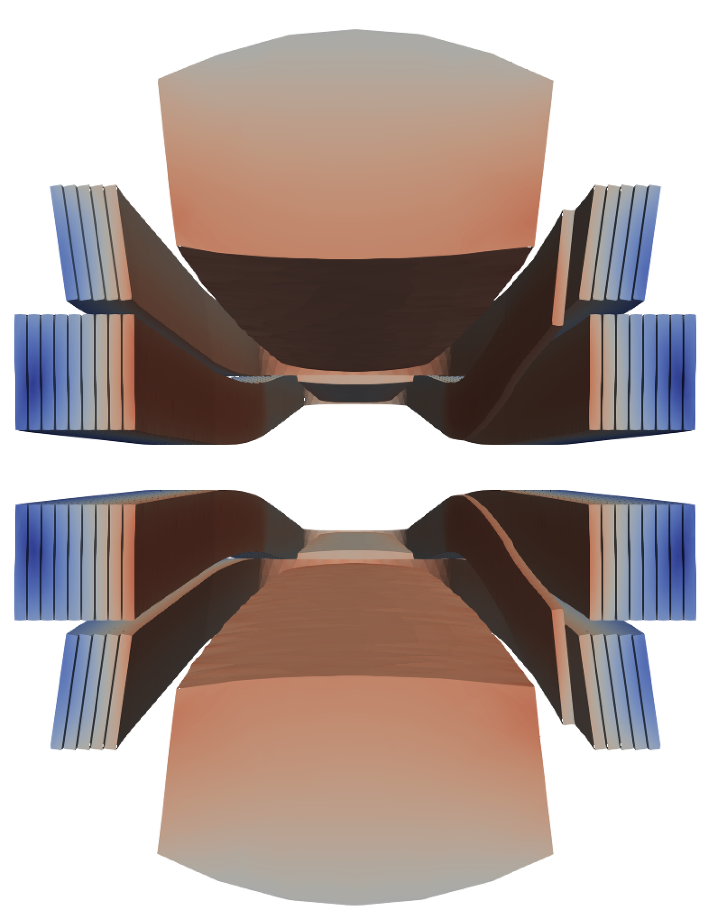
To get an understanding of the magnetic field distribution in a superconducting magnet, computer simulations are needed which take into account the actual geometry of the magnet and the magnetic saturation in different materials. It is a further advantage that the software efficiently tackles the large number of unknowns needed for accurate 3D simulations and also allows the coupling of additional physics of interest (e.g. thermo-electricity for quench propagation, mechanics).

Sparselizard provides the multiphysics and HPC capabilities required for 3D particle accelerator simulations.

Problem Definition

The 3D geometry of CERN's Feather M2 particle accelerator magnet is considered (illustrated below, details available in the PhD of J. van Nugteren). The geometry is captured accurately down to the cable-level (each cable is homogenized) as shown in the cross-section below. A FEM mesh with around 1 million tetrahedra is obtained from GMSH.





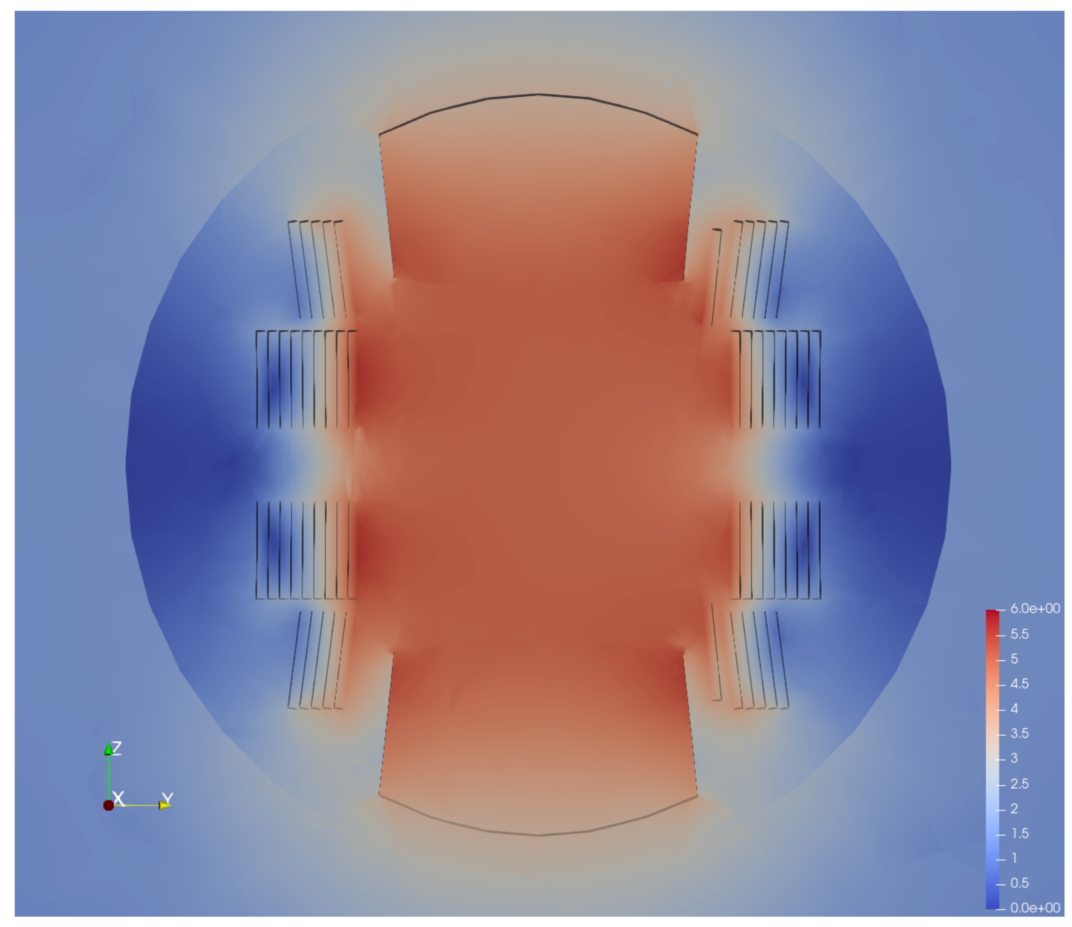
Maxwell's equations are solved in static regime for the magnetic field:

$$\text{curl}(h) = j \text{ and } \text{div}(b) = 0$$

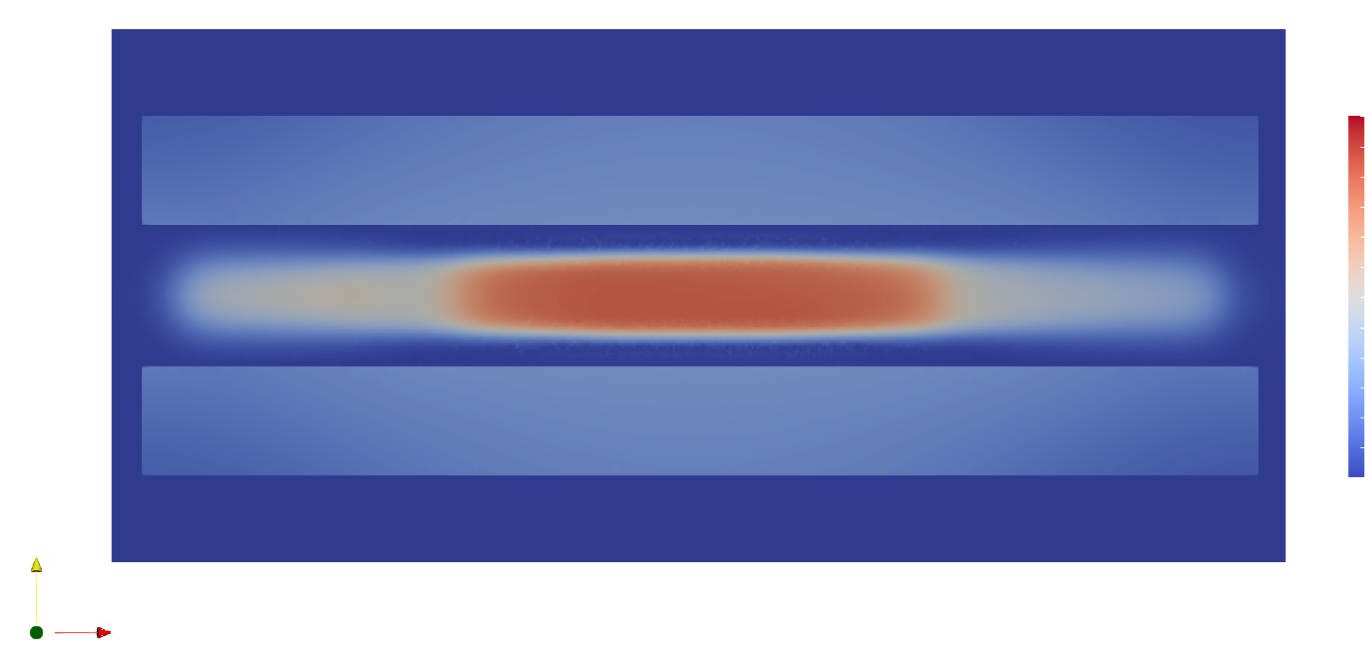
Saturation of the magnetic iron is taken into account using a measured anhysteretic BH curve. The A-v formulation with a spanning-tree based gauging of A is used to solve this problem. As an alternative a H-phi formulation can be implemented based on the example available online.

Results

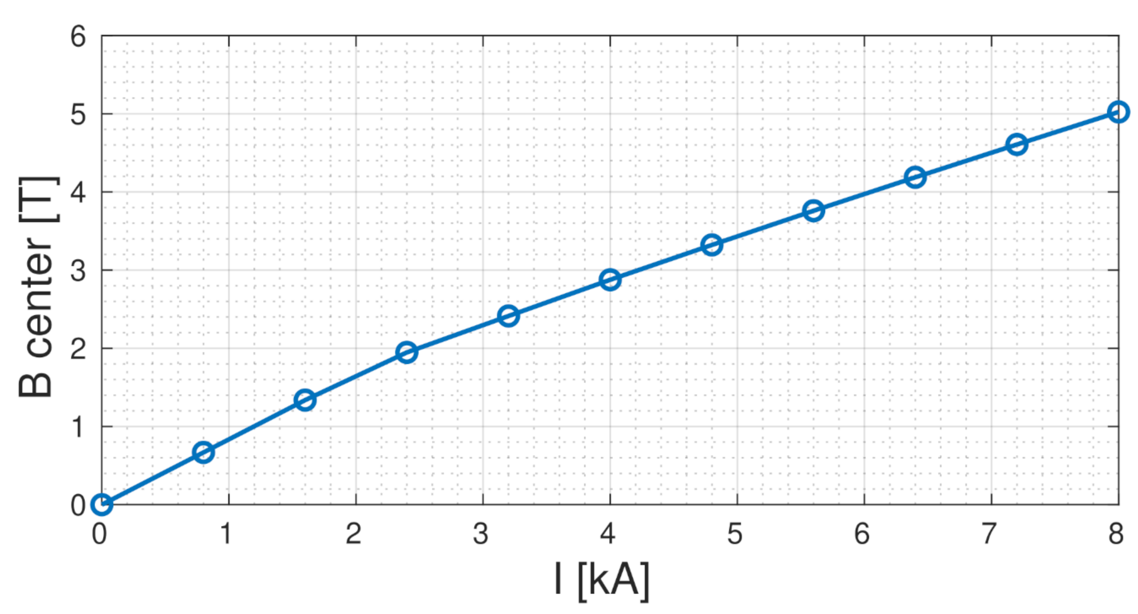
A supply current of 8 kA is set to the upper and lower magnet coil (the current is scaled up by a factor 18/14 to match the 18 windings considered in the reference thesis). On a regular laptop an accurate magnetic induction field (B) value at the magnet center can be obtained in less than a minute per nonlinear iteration. Three nonlinear iterations give a better than 1% accuracy on B at the center.



The center cross-section of field B is displayed above: a mostly uniform field is obtained in the area of interest of the magnet, with a center value of 5.02 T accurately matching the 5 T obtained in the 2D simulation of the reference thesis. While this could lead to the conclusion that a 2D analysis is enough, the cross-section in the x-y center plane below clearly indicates the need for a 3D analysis when the overall magnetic field felt by a particle is required.



The B center value was also calculated for a sweep of supply current and is shown below. The inner iron saturation effect is visible at the slope change above a 2 kA supply current. At that stage the cylindrical core around the coils is not yet saturated and still helps further increasing B with a larger supply current.



The magnetic simulation presented can be conveniently coupled in the same software package to electro-thermal, mechanical, fluid and other physics. A large set of examples is provided online at `sparselizard.org` for this purpose.