Eötvös Loránd University
Faculty of Natural Sciences
Institute of Physics

Design and construction of a high-field superconducting septum magnet for the Future Circular Collider

2nd semester research report
Material Physics and Solid State Physics PhD Programme

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1 Introduction

In order to test novel theories of theoretical particle physics, a new particle accelerator with collision energy higher than the LHCs is highly desirable. Since the time-scale of the realization of accelerators of this large scale is about 20-30 years, the Future Circular Collider Study was launched in 2014 in order to establish the conceptual design of a post-LHC proton-proton collider ring with 50+50 TeV collision energy. One key difficulty is the manipulation of the beam which has unprecedented rigidity, and the enormous 8.4 GJ energy stored in a single beam. The beam extraction system is affected by both issues. The aim of this PhD work is to design and construct a high-field septum magnet assembled from a superconducting magnet and a passive superconducting shield. In [4] two bulk superconducting materials were tested to investigate their feasibility to build the superconducting shield of this device.

The selection and study of the materials is the first step of the design. Since even one failure in the extraction system (or any part of a high-energy accelerator) could lead to catastrophic consequences, a precise and detailed study is mandatory for these systems. These include the coupled electromagnetic, mechanical and thermal study of these magnets. Mechanical simulations are important for example because mechanical distortions of magnets can ruin the field quality, or the critical parameters (like critical current J_c) are often dependent on the stresses inside the material. Movements, and small fissures of the materials can lead to so-called quenching of the magnet, which must be taken into account, and protection schemes must be built for the case if it happens. The numerical study of the quench phenomenon is extremely challenging, since its a coupled multiphysics problem, and it happens at very broad spatial and time scales.

The problems mentioned above are keystones in the design of an accelerator magnet. If the magnet concept passed all of these requirements, and it seems like a promising solution from the simulations, the construction of the first prototype can be started.

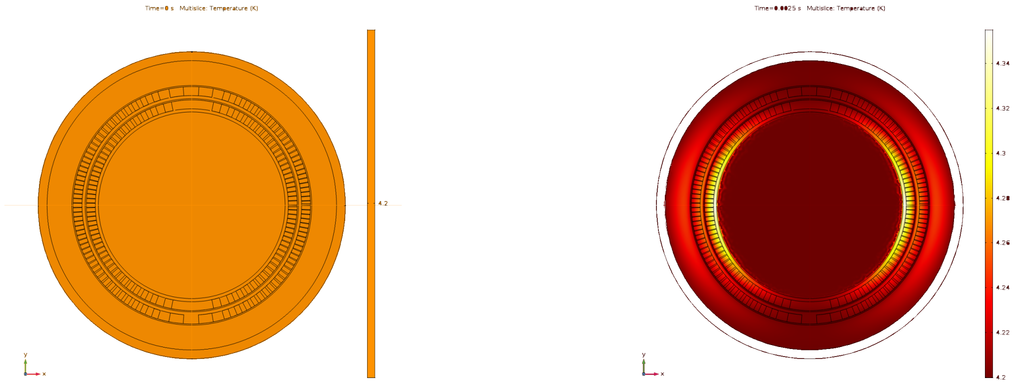
2 Achieved results in this semester

As mentioned in the previous semester report, the main focus of my work was the development of the 3D electrothermal simulation. I have developed a coupled electrothermal model in COMSOL 5.3a.

Running the simulations with the complete 3D design of the magnet would be computationally very intensive. To simplify the problem a so-called 'slice model' approach was used, where a cylinder with the height of the coil's pitch was taken, and every quantity was calculated in this much smaller simulation domain with periodic boundary conditions at the two ends of the cylinder.

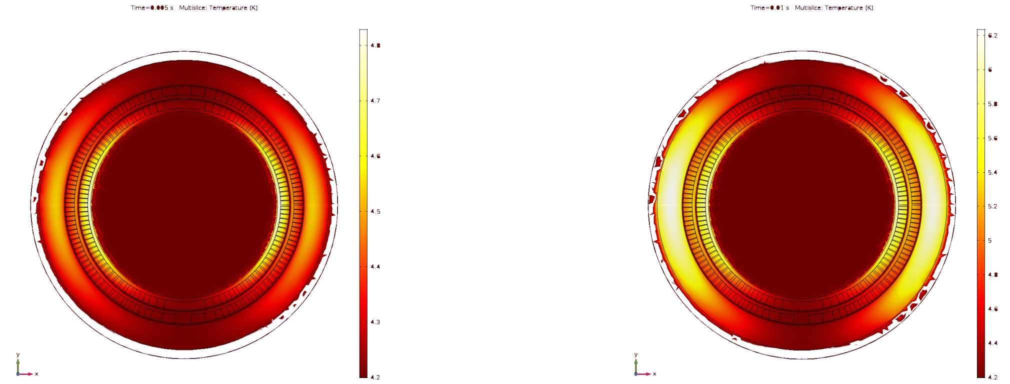
The magnet used in the model was the 2.2 m long CCT orbit corrector dipole, mentioned in [1]. In the simulation the heating caused by the induced currents was studied in a coupled electro-thermal manner. First steady state of the magnet during operation was determined in a simple A-formulation electromagnetic simulation. Then the operating current was ramped down to zero in 0.01 s. This time the electromagnetic simulation was coupled to a heat transfer simulation, with temperature dependent material properties[2] used in both the electric and the thermal parts.

If a quench event is detected in the magnet, it has to be turned off immediately in order to prevent the damage of the magnet. The quick decrease of the coil current induces large currents in the neighbouring aluminium formers and support tube. These induced currents start to heat up these parts due to the ohmic resistance of the material, which heats up the coil even more. This phenomenon is called quench-back and it helps to protect the magnet by quenching the entire coil faster, thereby distributing the energy in a larger volume . The heat generation in the coils was suppressed, because during operation the induced currents are much smaller than the operation current, thus they can be neglected. The heat generation happened only in the aluminium parts, and from there the heat could propagate towards the coils. The resulting temperatures are shown in Fig. 5



(a) Temperature at t=0 s

(b) Temperature at t=0.0025 s



(c) Temperature at t=0.005 s

(d) Temperature at t=0.01 s

Figure 2: Temperature profiles

The heating pattern shows very good correlation with the induced current(Fig. 3) pattern. The induced current patterns and magnitude seem valid, but the magnitude of the temperature increase is rather small compared to the result of a simple overapproximating model, where the whole energy stored in the magnetic field splits up to two parts, one part is dissipated at an external resistor due to the ramp down, and the other part is dissipated as heat in the aluminium parts. Using the material properties at 4.2 K, this suggests, that the temperature rise should be around 40 K. Understanding the discrepancy between the two models is under way, in collaboration with quench simulation experts at CERN.

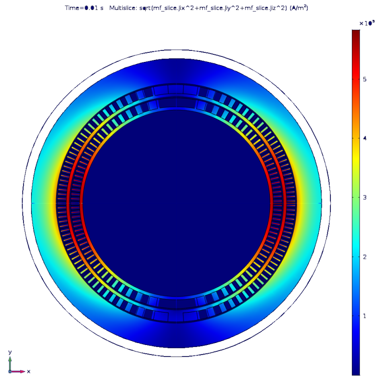


Figure 3: Induced currents at t=0.01 s

The mechanical simulation with the contact approach presented in [1] was performed for a small prototype of the SuShi septum magnet, including the shield and the designed support mechanism mentioned in [4]. The simulation ran with the operating conditions of the magnet, 3.5 T peak field, 3.2 T dipole field next to the shield. The boundaries with blue in Fig.4 could detach from each other separately. The coils were modeled as fixed objects in the groove because of the epoxy impregnation.

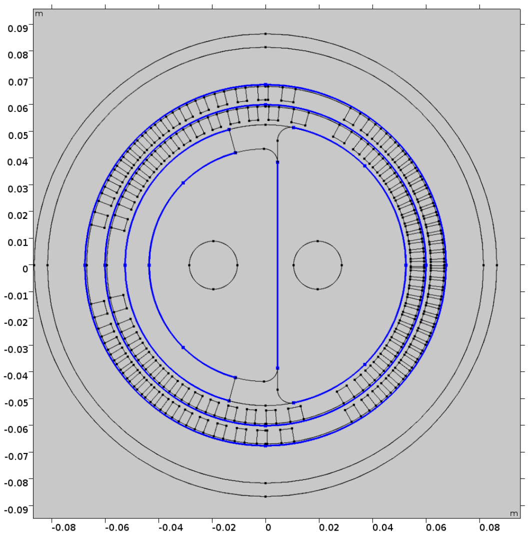
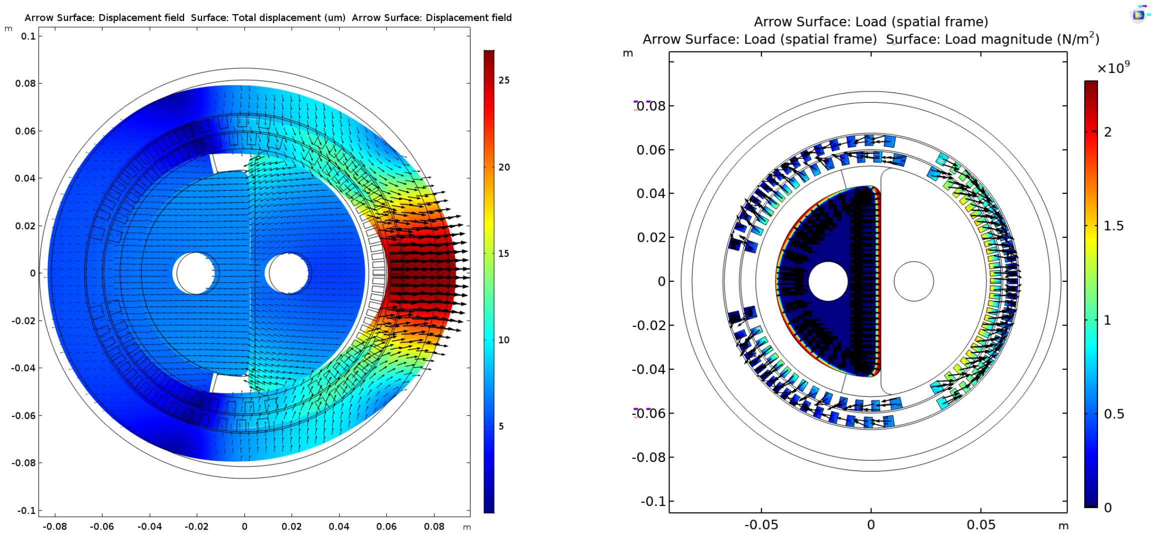


Figure 4: 'Free' boundaries in the mechanical simulation

To eliminate the rigid body modes all points of the y = 0 plane were constrainted to move only in this plane, and the points of the support tube in the x = 0 plane were constrainted to move only in that plane. The magnetic field was calculated with A-formulation with the operating current. The shield material is modelled using Campbell's model[5], with measured $J_c(B)$ of the NbTi/Nb/Cu composite material[3]. This made possible to calculate the acting force on the shield directly (since the flowing critical currents were known). As previously in [1], the loads (Lorentz forces) were applied everywhere, where currents were flowing. Figure 5a, 5a show the displacement field and the applied loads.



(a) Displacement field (b) Applied loads (Lorentz Force density)

Figure 5: Displacement field and loads

Figure 5a shows that the largest deformation happens on the right side of the magnet. The deformation of the left part is almost negligible, the shield with its backside fixer element supports the magnet structure very well. The deformation of the right side of the magnet is such that it presses the right side fixer element towards the shield, resulting in a self-supporting structure. The Lorentz force density integrated over the surface of the shield has $F_x = -1.3 \cdot 10^5 \ \frac{\mathrm{N}}{\mathrm{m}}$ and $F_y = -321 \ \frac{\mathrm{N}}{\mathrm{m}}$ components. The y component is probably caused by the numerical error, but the F_x component is much higher than expected before. Due to this the fixing mechanism mentioned in [4] has to be redesigned. The current idea is to replace the individual support elements with one large aluminium block that goes through the whole magnet, supporting and distributing the pressure at the whole front shield surface.

3 Publications

D. Barna, M. Novák, K. Brunner, G. Kirby, B. Goddard, J. Borburgh, M. Atanasov. A. Sanz Ull, E. Renner, W. Bartmann, M. Szakaly, *Conceptual design of a high-field septum magnet using a superconducting shield and a canted-cosine-theta magnet* IEEE Transactions on Applied Superconductivity (Date of publication 31 May 2019.

D. Barna, G. Giunchi, K. Brunner, M. Novák, A. Német, C. Petrone, M. Atanasov, H. Bajas, J. Feuvrier, M. Pascal, *An* MgB_2 *superconducting shield prototype for the Future Circular Collider septum magnet* IEEE Transactions on Applied Superconductivity (Date of publication 31 May 2019.

D. Barna, M. Novak, K. Brunner, C. Petrone, M. Atanasov, J. Feuvrier, M. Pascal: *NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum.* IEEE Transactions on Applied Superconductivity 29 (2019), 4900108 (Date of publication: 2 October 2018)

4 Conferences

- Participation at the '1st STEAM workshop' at CERN (2019.06.13-2019.06.14)

- Accepted presentation at the FCC Week 2019 conference in Brussels (2019.06.24-2019.06.28). Title: Status of the SuShi septum project

5 Education

Courses:

- Technology of Materials (5)
- Physical Material Science (5)
- Superconductivity (No grade yet)

References

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[2] Duthil, P. (2015). Material Properties at Low Temperature. https://doi.org/10.5170/CERN-2014-005.77

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[5] A. M. Wolsky, A. M. Campbell (2008). A new method for determining the critical state of three-dimensional superconductors: Explanation and examples. Superconductor Science and Technology, 21(7). https://doi.org/10.1088/0953-2048/21/7/075021