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

1st semester research report
Astronomy and Particle 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 [3] 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, 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 numercial 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 magnets. 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. To build such a prototype, special infrastructure is needed, like a vacuum epoxy impregnation system and a winding machine.

2 Achieved results in this semester

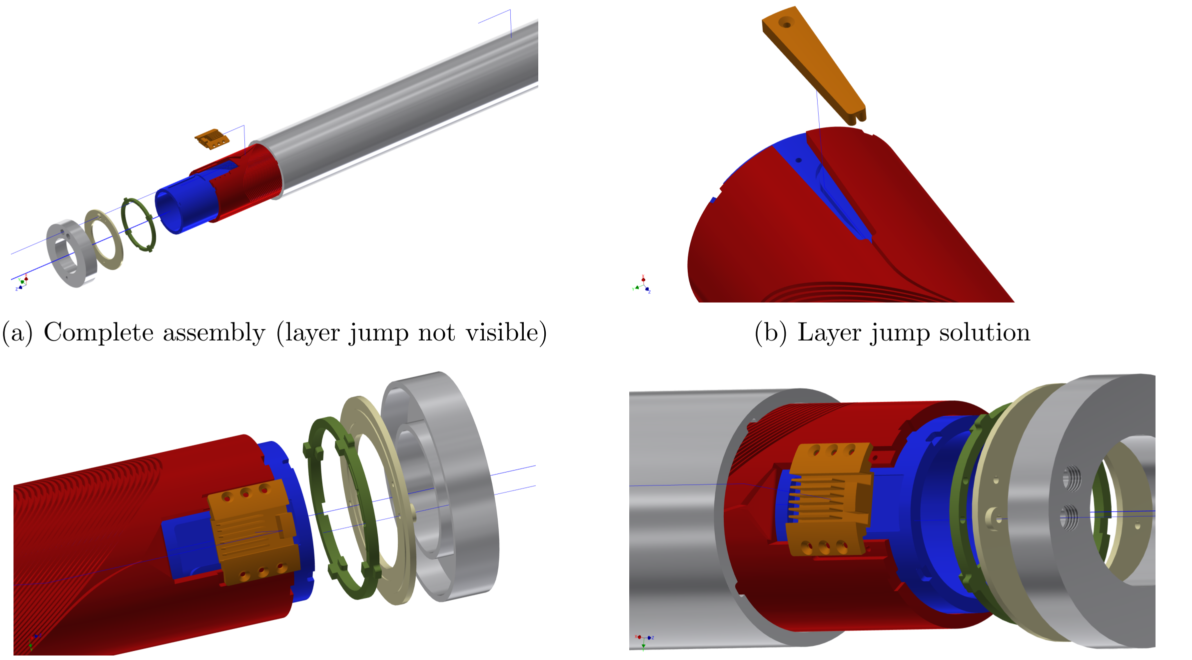
Compared to the Section 5. of [3] improvements have been made on every aspect of the topic. The necessary infrastructure for the production is being built in Wigner Research Centre for Physics. The current state of the winding machine is shown in Fig.2. The rotation speed of the motor can be controlled in both directions by foot pedals. The motor will drive a long shaft holding the so called formers of the superconducting magnet. The superconducting wires will be wound into the grooves machined into these formers.

(a) Frame of the winding machine

(b) The motor and the control pedals

Figure 2: The winding machine and its controlling pedals

I have developed the CAD model of the superconducting magnet, based on the 2.2 m long CCT corrector magnet being developed and tested at CERN for the high-luminosity upgrade of the LHC. We have introduced several improvements to the model. These include the simplifiication of the the assembly procedure, making the sealing during vacuum epoxy impregnation simpler and safer, the redesign of the alignment features to decrease the openings on the vacuum envelope, the redesign of the so called "layer jump" feature where the superconducting wires are passing from one former to the other, etc. Many of these improvements have been incorporated into the CERN designs of the next versions of these magnets.



(a) Complete assembly (layer jump not visible)

(b) Layer jump solution

(c) Former locking solution (outer support tube not shown)

(d) Former locking solution (outer support tube shown)

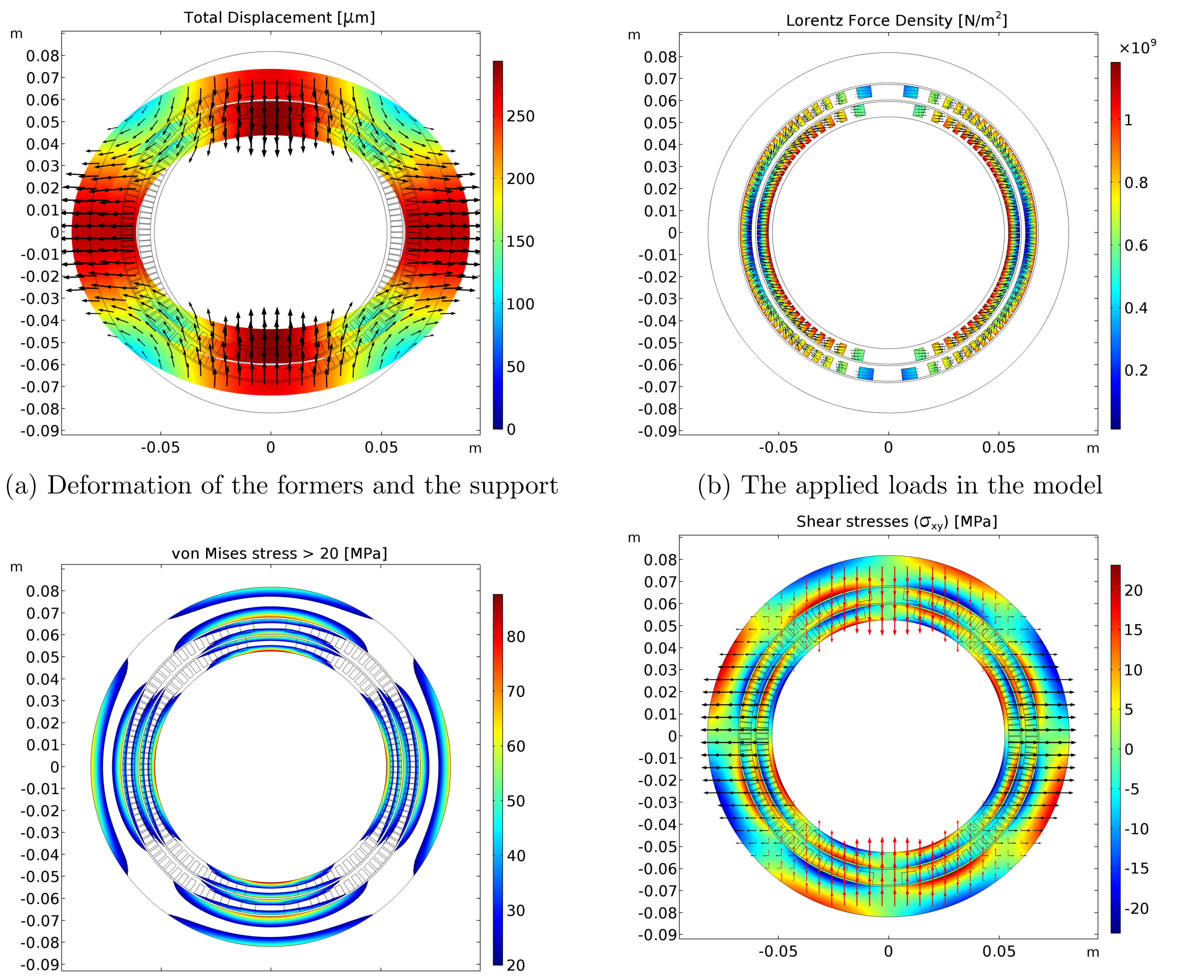
Figure 3: CAD model of the proposed CCT-like magnet

The CAD model is shown in Fig.3. In Fig.3a blue denotes the inner former, red the outer former, the gray the outer support tube and the end cap, green is a locking ring made from radiation hard material G10, frequently used in magnets. The yellow is a silicone seal for insulation, and the orange is the connection box (and the layer jump insert in Fig.3b). Figure 3c and Fig.3d show the solution to align the formers both azimuthally and longitudinally. Small gaps are machined into the formers and the support tube. An alignment ring made of G10 with protruding features is inserted into these gaps, locking the position of the formers. Then an end cap with a silicone seal is pressed to the magnet, which blocks longitudinal motions. The silicone seal is necessary only during the vacuum impregnation of the magnet. After this process it has to be removed, since silicone is not a radiation hard material, thus can not be placed into an accelerator tunnel.

The simulation "branch" also advanced. A model to calculate the critical state in 3D superconductors[4] have been implemented in a finite element software, but needs further development, since its convergence is quite bad. This will make possible to understand the experimental observations like the "end effect", where the breakdown of the shielding effect seemed to progress from the open end of the MgB_2 shield exposed to high field.

A 2D structural mechanics simulation has been built for the 2.2 m long orbit corrector magnets of the high-luminosity LHC project. The reason for this selection of geometry was the validation of the built model. There are independent numerical results available in[1] which are in great agreement with my first model. In this model the three tubes (inner, outer former and support tube) are sticked together, they can not separate. Also the load is applied everywhere in the inner and the outer formers, not only at the places where the coils are.

The new model avoids these simplifications and treats the geometry in more details, using a decoupled electromagnetic and mechanical simulation. The magnetic field was calculated in the first step, then the Lorentz-forces were calculated from this and applied to the coils in the structural simulation. The three tubes were modelled separately in the structured simulation. The epoxy layers could freely detach from the inner surface of the support tube, and the inner surface of the outer former. This is an important aspect, since the inner surface of the tubes are treated with an epoxy-repelling coating. The results are shown in Fig.4.



(a) Deformation of the formers and the support

(b) The applied loads in the model

(c) Von Mises stresses larger than 20 MPa

(d) Shear stresses inside the material, and the displacement plotted by components

Figure 4: Results of the mechanical simulation

One of the most interesting result of this simulation can be seen in Fig.4a. The outer former (with an epoxy layer bonded to the outer surface of it) detaches from the support tube, forming a small, empty gap. This has an important role in quenching. Superfluid helium will penetrate this narrow gap, providing extra cooling power during a quench, delaying the onset of quench-back and thereby leading to a lower ramp-down of the magnet current and higher hot-spot temperature. This may explain the inconsistency found between simulations and experimental result of the 2.2 m long magnet prototype carried out by Glyn Kirby and his team at CERN. Including this effect in their quench simulations greatly improved the agreement with the experimental results[2]. Figure 4d shows the shear stresses inside the material. The importance of this comes from that the hardened epoxy resin debonds from the surface of the former at stresses around 20 MPa. Increasing the operation current in the simulation, and continuously checking he maximum of the stress, one can predict the coil current at which the epoxy debonds from the surface, i.e. the current above which quenches are to be expected. The built simulation is parametric, so it can be easily modified to have our proposed magnets geometry.

Since the CAD model, the electromagnetic, and mechanical simulation are in quite advanced state, the biggest challenge left is the complete quench simulation of our magnet, and the parametrization of its quench protection system. In the latter few weeks I was reading publications on quench simulation, and tried to implement my own models. An agreement with the CERN machine protection group was reached, whereby I would start to participate in the development of standard quench protection simulation tools, and work on the quench protection system of our prototype magnet within the framework of standard tools.

3 Publications

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 in Applied Superconductivity 29 (2019), 4900108 (Date of publication: 2 October 2018)

D. Barna, G. Giunchi, K. Brunner, M. Novák, A. Németh, C. Petrone, M. Atanasov, H. Bajas, J. Feurier, M. Pascal, *An MgB_2 superconducting shield prototype for the Future Circular Collider septum magnet*, Last corrections of the text.

A planned paper on the mechanical simulation of HL-LHC 2.2 m CCT orbit corrector magnet with Glyn Kirby and his team. Probably the model will be upgraded into a 3D model, in order to study the longitudinal strains and stresses.

4 Education

- Weak Interaction course *(no grade yet)*
- Quantum Chromodynamics course *(no grade yet)*

Since my work mostly consists electrodynamical and structural mechanics finite element simulation, CAD modelling, and experiments with superconductors, I felt like that I would profit more if I was doing my PhD in the framework of Material Science and Solid State Physics programme. I have asked István Groma, Sándor Katz, and Tamás Tél, if it is possible to change programme, and they have all agreed, and accepted me to change to this programme from the next semester.

References

[1] Coil pack deflection under powering, Glyn Kirby's Researchgate post from 2018.06.25.

[2] Cooling in coil may effect quench some ideas in progress, Glyn Kirby's Researchgate post from 2018.11.01.

[3] Numerical and experimental study of superconducting magnetich shields for the construction of a high-field septum magnet, M. I. Novák, MSc thesis 2018.

[4] 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