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

4th 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.

2 Previous results

I have started working in this project during my **MSc**[1] studies, where I have studied numerically and experimentally the feasibility of different bulk superconducting materials as the shielding component of a high-field superconducting septum magnet (SuShi).

As the continuation of this project in the **first semester**[2] of my PhD studies I have worked mostly on the actual CAD design of the magnet, and the necessary infrastructure to build it, like a winding machine. In the same semester, I have actually built the frame of the winding machine from drawn aluminium profiles (ITEM) and built the rotation mechanism using a 3-phase electric motor, two pedals and an inverter. This way the speed and direction of the rotation can be controlled smoothly. I have made structural mechanical simulations of an existing CCT dipole orbit corrector to study its deflection under a given load. The results of my simulations were in very good agreement with the measured results.

In the **second semester**[3] I have started experimenting with electrothermal finite element simulations. At this time my plan was to do this simulation in a small 3D slice of the magnet using periodic boundary conditions. Unfortunately, the simulation was very unstable and computationally intensive, so I gave up on this approach and started to think about new ways. Next to these electrothermal simulations, I was working on the structural mechanics simulation of the SuShi prototype, trying to solve the fixing of the shield inside the magnet. These simulations are a very crucial point of the whole design since the different materials have a different thermal contraction, very large stresses can be present in the materials after cooling it down to 1.9 K from room temperature. Also, the deformation due to the Lorentz-force during operation is another significant contribution to the stress and pressure inside the magnet. If the internal support mechanism is not designed properly, then these together could damage the interior of the magnet or break the shield's material, especially if it is some ceramic superconductor, like MgB_2.

In the **third semester**[4] I have spent 1 month at CERN working with the Magnet Technology group, where I had the chance to watch and help the assembly of a 5 Tm CCT dipole orbit corrector magnet. This was a very useful experience and it will be a great help when building our own magnet. With my supervisor, we have developed a conceptual design of an iron-free opposite-field septum magnet. I have started to work on a new, quasi 3D approach of the quench simulation. The basic idea is that the transverse phenomenons are simulated in a 2D cross-section of the magnet, far away from the fringe-field region, while the longitudinal effects are simulated in multiple 1D simulations which are coupled to each other and the 2D cross-section simulation.

3 Work carried out this semester

In this semester I have worked on the quench simulation framework. As mentioned in[4] the simulation uses COMSOL Multiphysics's Java API to generate simulation models. With this approach the framework is very general, in theory, it can handle any coil shapes given by its multipole coefficients. The strand coupling method briefly described in[4] proved to be too simplistic since it neglects that heat conduction is a dynamical process. In the presence of materials with large heat capacity and low thermal conductivity, using the effective thermal conductivity from a steady-state simulation overestimates the heat conduction, leading to quicker quench-back thus an optimistic approximation.

To overcome this, another method was proposed. Having a linear thermal model with N objects, one can calculate the system's Green functions. $T^{(i)}(x, y, z)$ is the temperature solution, when all objects are at a temperature of T_0 , the ith object is at a temperature of T_e. Then, the solution for the general boundary value problem, when the temperatures of the objects are at:

$$T(x, y, z) = \sum_i \frac{T_i - T_0}{T_e - T_0} T^{(i)}(x, y, z) \tag{1}$$

and similarly, the heat flow into the object j can also be obtained as the linear combination of the basis solutions:

$$Q_j = \sum_i \frac{T_i - T_0}{T_e - T_0} Q^{(j,i)} \tag{2}$$

where

$$Q^{(j,i)} = \int\limits_{\text{surf}:j} \mathrm{d}\vec{n} \cdot \vec{q}^{(i)} \tag{3}$$

and $\vec{q}^{(i)}$ is the heat flow when object i is excited to a T_e temperature. Note that the sum in the expression of runs over the case $i = j$ as well, i.e. when the same object is excited only. The formula can be reformulated like this:

$$Q_j = \frac{T_j - T_0}{T_e - T_0} Q^{(j,j)} + \sum_{i \neq j} \frac{T_i - T_j + T_j - T_0}{T_e - T_0} Q^{(j,i)} = \frac{T_j - T_0}{T_e - T_0} \sum_i Q^{(j,i)} + \sum_{i \neq j} \frac{T_i - T_j}{T_e - T_0} Q^{(j,i)} \tag{4}$$

The sum in the first term is zero since the system is static and closed. So finally, as expected, the heat to the object j can be written as the contribution of all other objects, proportionally to their mutual temperature difference.

$$Q_j = \sum_{i \neq j} \frac{Q^{(j,i)}}{T_e - T_0} \Delta T_{i,j} \equiv \sum_{i \neq j} K_{i,j} \cdot \Delta T_{i,j} \tag{5}$$

The couplings $K_{i,j}$ can be calculated in static simulations where each object separately is set to a temperature T_e , while the others are kept at T_0. Assume that the heat coupling $K_{i,j}$ can be factorized to a geometrical factor $g_{i,j}$ and a temperature-dependent material heat conductivity factor

$$\overline{k}(T_j, T_i) = \frac{1}{T_i - T_j} \int\limits_{T_j}^{T_i} k(T)\,\mathrm{d}T \tag{6}$$

The geometry factor than can be calculated from these separate pilot simulations as

$$Q^{(j,i)} = g_{i,j} \cdot \overline{k}(T_j, T_i) \cdot (T_i - T_j) = g_{i,j} \int\limits_{T_0}^{T_e} k(T)\,\mathrm{d}T \tag{7}$$

$$g_{i,j} = Q^{(j,i)} \left[\int_{T_0}^{T_e} k(T) \, \mathrm{d}T \right]^{-1} \tag{8}$$

where $Q^{(j,i)}$ is the heat load to the jth object when the ith object receives a temperature excitation T_e, while all other objects are at T_0. Now, in our 2D transversal simulation with actual temperatures T_i , we can "measure" the net heat load Q_j to the jth object and decompose it as before, but let's allow a deviation factor F_j compared to the model:

$$Q_j = F_j \sum_{i \neq j} g_{i,j} \int_{T_j}^{T_i} k(T) \, \mathrm{d}T \tag{9}$$

Since Q_j, $g_{i,j}$, the actual temperatures and the integral function of the material's heat conductivity are known, the deviation factor F_j can be calculated for each j:

$$F_j = Q_j \left[\sum_{i \neq j} g_{i,j} \int_{T_j}^{T_i} k(T) \, \mathrm{d}T \right]^{-1} \tag{10}$$

This formula has a problem: at the beginning of the time-dependent simulation, all objects have the same temperature, therefore the definite integrals all evaluate to zero, and we divide by zero. Still need to find a solution for this.

In practice, this is implemented in the following way:

- A separate, static simulation is run, to calculate $g_{i,j}$ geometrical coupling, and stored in a file
- The definite integral of k is calculated in a wide range of temperature, and stored in a file since this integration needed to be done once, and later only evaluation of this function is needed. This spares some resources
- This definite integral is read back into the actual quench simulation as an interpolated function
- Two additional components are added to the actual, time-dependent quench simulation an additional. These have the same geometry as the static simulation, but here the temperature of the strands are locked to the maximum temperature of the corresponding 1D component and the minimum temperature of the corresponding 1D component
- The heat loads are calculated both with Eq. 7 (this is fast since everything is given, contains only simple function evaluations), and Eq. 3 (this is slow since it needs to evaluate many boundary integrals at every timestep)
- The discrepancy between the two heat load is corrected by F_j, and it is accounted to the dynamical nature of this process
- At intermediate temperature, a linear interpolation used between the F_j factors calculated in the low temperature and in the high-temperature models

This method works, but it is unstable at the initial conditions due to the initial division by zero, and the integrals from Eg. 3 can slow down the simulation. Another improvement of the framework that now the inductances are calculated on the run, and not need to be given before the simulation. A schematic representation of the current state of the simulation framework is shown in Fig. 2 (the figure is vector graphic, can be zoomed very well).

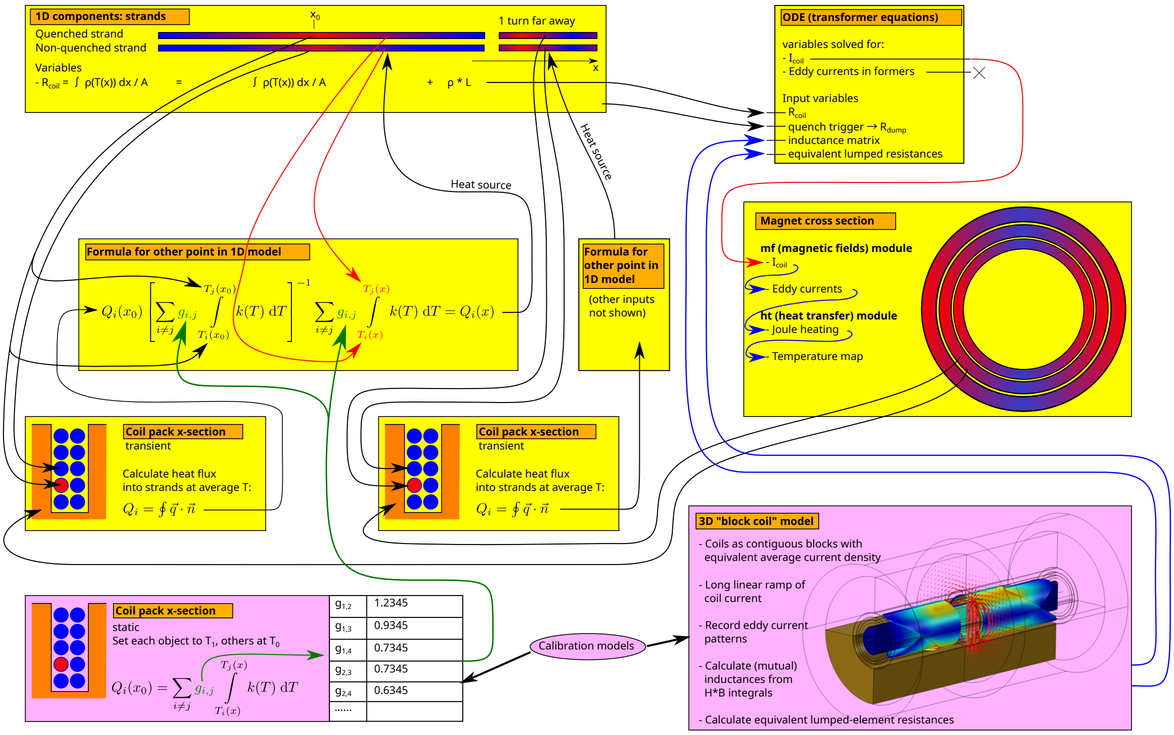

Figure 2: Dependency diagram of the simulation framework

4 Publications

D. Barna, M. Novák *Two-dimensional conceptual design of an iron-free opposite-field septum magnet* Nuclear Instruments and Methods in Physics Research
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

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

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

5 Conferences since the member of the SuShi septum project

- FCC Week 2019, Brussels, Belgium (2019.06.24-2019.06.28).
  Presentation: Status of the SuShi septum project
- STEAM Workshop 2019, CERN, Switzerland (2019.06.13-2019.06.14)
- 2nd International School on Numerical Modelling for Applied Superconductivity, Caparica, Portugal (2018.07.02-2018.07.06)
- FCC Week 2018, Amsterdam, Netherlands (2018.04.09.-2018.04.13.).

Poster: Numerical and experimental studies of the magnetic shielding performance of an MgB2 tube for the superconducting shield septum project.

6 Education

Courses:

- Lattice Defects II (5)
- Interacting Electrons in Solids (5)
- Deep Learning and Machine Learning in Sciences (5)

References

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

[2] M. I. Novák, 1st semester PhD report 2019.

[3] M. I. Novák, 2nd semester PhD report 2019

[4] M. I. Novák, 3nd semester PhD report 2020

[5] Status of the SuShi spetum project, M. I. Novák, FCC Week 2019 presentation