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Reduction of the hot spot temperature in HTS coils

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Reduction of the Hot Spot Temperature in HTS Coils

Holger Witte, William B Sampson, Robert Weggel, Robert Palmer and Ramesh Gupta

***Abstract*—A potential future Muon Collider requires high field solenoids (>30 T) for the final cooling stage; the Magnet Division at Brookhaven National Laboratory (BNL) is undertaking the task of demonstrating feasibility using High Temperature Superconductors (HTS). The aim is to construct an all HTS dual-coil system capable of delivering more than 20 T. Recently a new record for an all HTS solenoid has been established with a field of 15 T on-axis. In coil tests it was noticed that during a fast energy extraction the current in the solenoids decays faster in comparison to the expected exponential decay. This paper describes the effect and shows how it can be simulated using commercial finite element code. The faster current decay helps to lower the integral current density squared with time by about 10% and is therefore beneficial for quench protection.**

***Index Terms*—Accelerator magnets, electromagnetic analysis, electromagnets, superconducting magnets.**

I. INTRODUCTION

AT present various efforts are underway to demonstrate the technical feasibility of a potential future multi-TeV Muon Collider. An important technology of a muon collider is ionization cooling, which is the only method known fast enough to reduce the divergence of the short-lived muons. Suggestions for cooling lattices exist and in general all of them require high field, large bore solenoids. The required magnetic flux density, which is in excess of 30 T, dictates the use of high temperature superconductors.

Currently Brookhaven National Laboratory is undertaking an experimental program to demonstrate the feasibility of an all-HTS solenoid which can produce 20 T or more using (rare earth)-Ba-Cu-O tape [1]. The magnet system consists of two HTS coils (insert and midsert), which are planned to be extended by a low-temperature superconducting outsert to produce about 30 T. The midsert and insert coils have both been constructed. Both coils employ REBCO tape from SuperPower Inc[1].

Previous experience showed that pancakes made of this HTS tape do not respond well to thermal shocks and gradients. To mitigate this, copper discs were installed between each double-pancake, which leads to a more uniform cool-down. Individual pancakes as well as the entire coils were tested using a novel quench detection system, which at the onset of resistive voltage triggers a fast energy extraction via an external resistor [10]. It was noticed that the current in individual pancakes as well as the coils initially decayed much faster than anticipated from the time constant $\tau = L/R$.

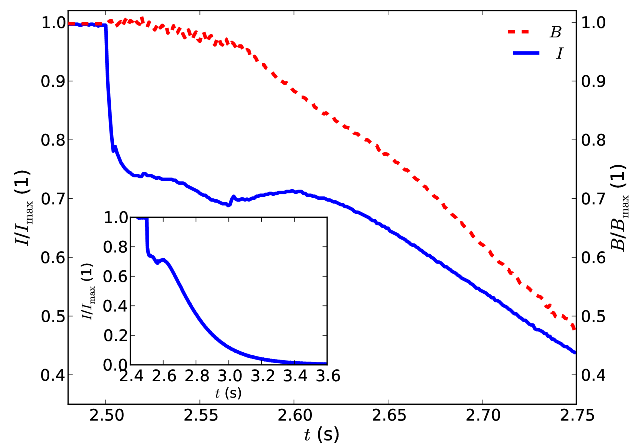

Fig. 1. Current and field decay during fast energy extraction at $t = 2.5$ s. The figure shows normalized values.

This is shown in Fig. 1, which shows measured data of the current and magnetic flux density (measured by a hall probe). The magnetic flux density as well as the current are normalized to their maximum values at $t = 0$ s to allow easy comparison. As shown in the figure, the current decays very quickly whereas the magnetic flux density decreases much more slowly.

It was speculated that the initial current drop is caused by the mutual coupling with the copper discs, that is a part of the energy of the coil is transferred to the copper discs. A multiphysics finite element simulation was set-up to verify this, which is described in this paper. An earlier paper describes a similar model for individual pancakes, whereas here we focus on the insert coil [2]. The next section describes the geometry of the coil and discs.

II. GEOMETRY

The insert coil consists of seven double pancakes which have an inner and outer radius of 12.5 mm and 45.5 mm, respectively. Each pancake consists of 260 turns of HTS tape which is co-wound with stainless steel tape. The HTS tape is 4 mm wide. The copper discs have the same inner and outer radius; each copper disc is 0.75 mm thick. Fig. 2 shows a schematic of the coil geometry.

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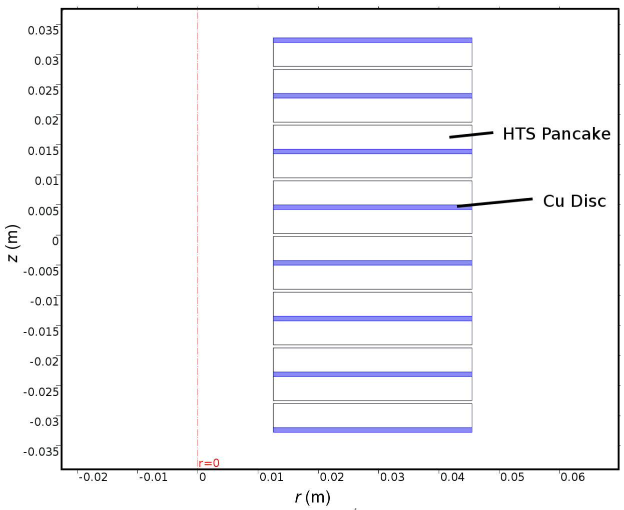

Fig. 2. Geometry of the HTS solenoid.

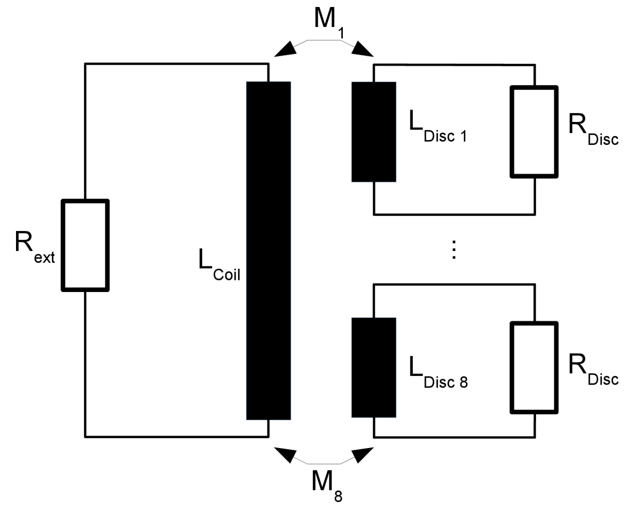

Fig. 3. Schematic of the electrical circuit.

TABLE I
MUTUAL INDUCTANCES COIL/DISCS (μH)

Disc No.	1	2	3	4	5	6	7	8
	38	51	58	60	60	58	51	38

TABLE II
INDUCTANCE MATRIX DISCS (nH)

Disc No.	1	2	3	4	5	6	7	8
1	55	33	21	14	9.2	6.4	4.6	3.3
2	33	55	33	21	14	9.2	6.4	4.6
3	21	33	55	33	21	14	9.2	6.4
4	14	21	33	55	33	21	14	9.2
5	9.2	14	21	33	55	33	21	14
6	6.4	9.2	14	21	33	55	33	21
7	4.6	6.4	9.2	14	21	33	55	33
8	3.3	4.6	6.4	9.2	14	21	33	55

III. FINITE ELEMENT MODEL

A. Governing Equations

The model is solved using COMSOL Multiphysics™ assuming axial symmetry, which involves three coupled application modes for the electromagnetic, thermal and electric part of the problem (circuit). The following PDE is solved for the electromagnetic part of the problem:

$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) + \sigma \nabla V = \mathbf{J}^{\mathrm{e}} \,. \qquad (1)$$

A is the magnetic vector potential, σ the electrical conductivity, V an electrical potential and J^e an externally applied current density. To calculate the magnetic flux density the average current density in the HTS pancakes is used.

It is assumed that heat transfer by radiation or convection does not play a role due to the short timescales involved. Heat transfer is modeled using the heat equation:

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \,. \qquad (2)$$

ρ is the density of the material, C the specific heat capacity, T the temperature, k the thermal heat conductivity and Q a heat source or sink.

The electrical circuit, shown schematically in Fig. 3, is solved using COMSOL's SPICE interface. Two electrical components have been omitted in the simulation: the magnet power supply and a diode, which is in series with the magnet. The power supply can be omitted as it is disconnected in reality when a quench is detected. The diode is operated always in forward mode (the current in the magnet never reverses) and therefore does not alter the simulation results.

In order to allow for an initial condition of the current in the circuit we use a similar approach to the one described in [3]. The inductances of the coil and the discs are included as 'U versus I' blocks; the voltages across each inductance is evaluated using a separate differential algebraic equation (DAE). For example, for the voltage across the coil is evaluated using

$$V_{\mathrm{Coil}} = L_{\mathrm{Coil}} \frac{\mathrm{d}I_{\mathrm{Coil}}}{\mathrm{dt}} + M_1 \frac{\mathrm{d}I_{\mathrm{Disc1}}}{\mathrm{dt}} + \cdots + M_8 \frac{\mathrm{d}I_{\mathrm{Disc8}}}{\mathrm{dt}} \,. \qquad (3)$$

L_{Coil} and M are the self and mutual inductances of the coil and the discs; similarly, I_{Coil} and I_{Disc} denote the currents of the coil and a particular disc. The values for the self and mutual inductances were evaluated in separate static simulations using the magnetic energy [4]. Tables I and II show the values for the mutual inductance between coil/discs and disc/disc.

For the electromagnetic problem a rectangular background volume is chosen large enough so that the field lines near the coil are not distorted. For the thermal simulation it is assumed that the discs heat up adiabatically.

B. Couplings

The current in the HTS coil is used in the eletromagnetic application mode to calculate the magnetic flux density. The electromagnetic and thermal simulation are directly coupled; the temperature in the discs is used to calculate the resistivity, thermal conductivity and specific heat of the copper discs. The induced current density in the copper discs is used as a heat source Q in the thermal module:

$$Q = \frac{J_{\text{ind}}^2}{\sigma}\,. \tag{4}$$

The resistance of each disc is calculated using Ohm's Law and used in the DAEs for calculating the voltages across each inductance in the circuit.

C. Material Properties

The electrical resistivity of copper as a function of temperature and residual resistivity ratio (RRR) is included using an expression from NIST (as cited in [5]). Magnetoresistance is included using the Kohler plot from [6]. The thermal conductivity is evaluated based on the Wiedemann-Franz law as described in [5]. The specific heat capacity is evaluated using data from [7]. The RRR value of the copper discs is assumed to be 50.

In practice the material properties are implemented in the COMSOL simulation using a C-library. The expressions are either evaluated directly (for example the resistivity) or interpolated using a cubic spline algorithm of the GNU Scientific Library [8].

IV. Simulation Results

A. Coil Current

Fig. 4 shows the simulated coil current and the experimentally obtained data. The figure shows that the simulation predicts accurately the sharp initial current drop from 280 A to about 200 A. The measured data shows a feature similar to a plateau around 0.1 s, which does not occur in the simulation. The exponential decay for $t > 0.1$s is similar for both the simulation and the experimentally observed values.

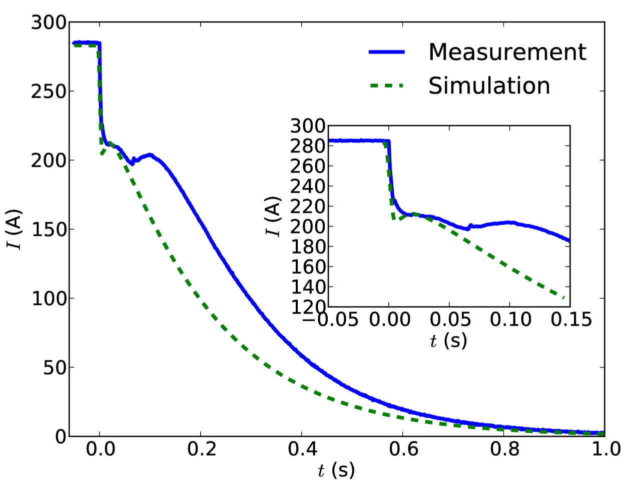

Fig. 4. Comparison of the measured and simulated coil current.

B. Temperature of the Discs

Fig. 5 shows the simulated temperature of the discs for half of the coil. The figure shows that the temperature of the copper discs increases quickly, which slows down for $t > 10$ ms. Discs 2–4 reach a final temperature of about 60 K, whereas disc 1 (the outermost one) heats up to about 50 K.

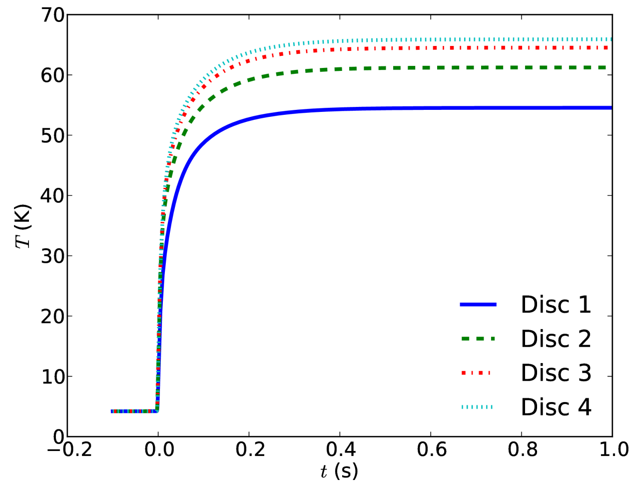

Fig. 5. Average temperature of the discs. Disc 1 is the furthest away from the coil center, whereas Disc 4 is the closest.

C. Current in Discs

The disc currents are shown in Fig. 6. The figure shows that the currents in discs 2-4 are approximately equal and increase almost linearly up to a peak current of 27 kA. For disc 1 the peak current is lower with 15 kA. After the peak current has been reached at approximately 5 ms the current decays exponentially to zero within 1 s.

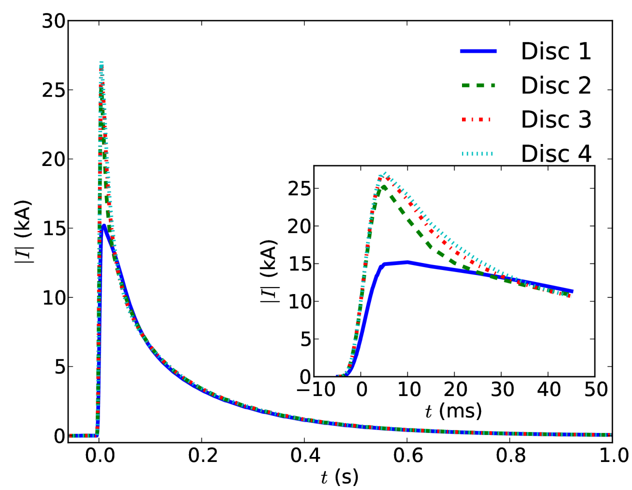

Fig. 6. Current in the discs. Disc 1 is furthest away from the coil center.

V. Discussion and Conclusion

The simulation shows that the mutual couplings between the copper discs within the coil and the solenoid itself are large enough to explain the initial sharp current drop. At the beginning of a fast energy extraction currents are induced in the copper discs, so a part of the energy is transferred from the coil to the discs. The currents in the discs increase, but are eventually limited by their rising resistance due to ohmic heating and decay exponentially. The negative $\mathrm{d}I/\mathrm{d}t$ in the discs causes the current in the solenoid to remain at the same value for a brief period of time, until it decreases further. The decrease of the slope of the temperature in the discs coincides approximately with the peak current in the discs.

The final temperatures of the copper discs are approximately equal with the exception of disc 1, which is the one furthest away from the coil center. The lower temperature of this disc can be explained by the lower mutual coupling to the solenoid itself as well as the other copper discs.

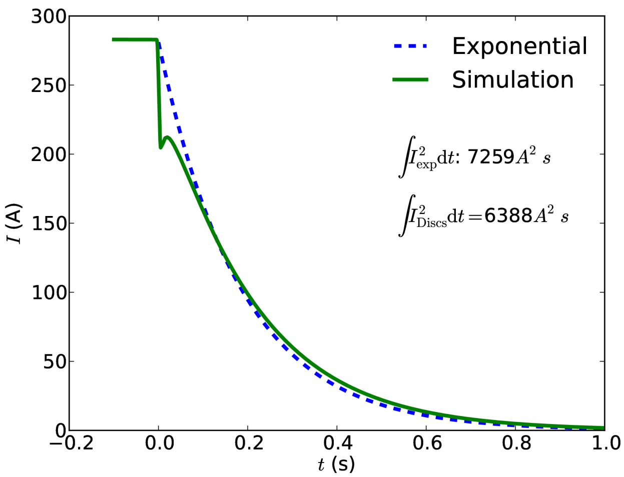

Fig. 7. Comparison of simulation results with expected exponential decay.

The concept of copper discs as described in this paper is not sufficient to provide complete quench protection by its own. However, copper discs have the advantage of reducing the integral of the current squared with time right after the detection of a quench. Other methods such as quench heaters can take a significant amount of time before they become effective. For example, quench heaters discussed in [9] quench an HTS coil only after $t > 0.3$s, at which the maximum permissible $\int I^2 \mathrm{dt}$ could already have been reached.

Further work should be done on improving the effectiveness of the copper discs. For the present coil design the $\int I^2 \mathrm{dt}$ is lowered by about 10% as shown in Fig. 7. Thicker copper discs can be expected to decrease the $\int I^2 \mathrm{dt}$ further.

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