Next generation fusion devices require high magnetic fields to adequately contain plasmas. Use of high temperature superconducting (HTS) coils to generate these magnetic fields would lower energy cost of operation as well compared to resistive coils as well as increase stability of the superconducting state compared to low temperature superconducting coils. However, use of HTS coils requires developing quench protection systems to quickly extract energy from the coils during quench scenarios to prevent damage to the coils. One energy extraction technique involves the utilization of copper discs mutually coupled to the HTS coil to more quickly extract the current from the coil. This project describes a parametric study of the coil and disc setup in order to determine limiting cases of the geometry in an attempt to optimize current extraction during quench scenarios.

Parametric Study of HTS Coil Quench Protection Strategies

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Introduction

When using high temperature superconducting (HTS) coils to generate high magnetic fields to contain burning plasmas, it is necessary to develop quench protection strategies to prevent damage to the coils.

- Quench protection in HTS coils is more difficult than in LTS coils because the normal zone propagation is over an order of magnitude slower. It is necessary to develop new quench protection strategies for HTS coils.
- In the event of a quench, high current (~70 kA in ITER TF coils) and large stored magnetic energy (over 2 GJ in one ITER TF coil) must be quickly extracted from the coils.
- One technique tested in high field HTS pancake coils [3] utilizes copper discs and other conductor geometries mutually coupled to the HTS coil to extract the current from the HTS coil substantially faster than the normal time constant associated with the system as shown in [1]-[3].
- Another technique with no organic insulation between turns in coil winding allows direct current sharing between HTS turns to reduce overall winding pack current density during quench for self-protection of the HTS magnet [5].

To properly model current extraction from the HTS coil, this project presents a flexible code that can be passed a variety of input parameters to perform parametric studies for a variety of coil/conductor configurations.

Geometry and Circuit Diagram

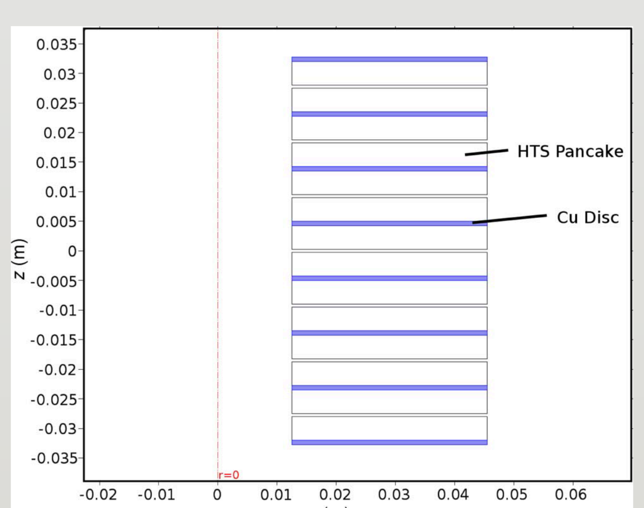

Figure 1 [1]

- Example geometry
- Cylindrical half-cross-section of coil and disc system
- 7 double pancakes and 8 copper discs
- Must consider self and mutual inductances between each pancake and disc in the system

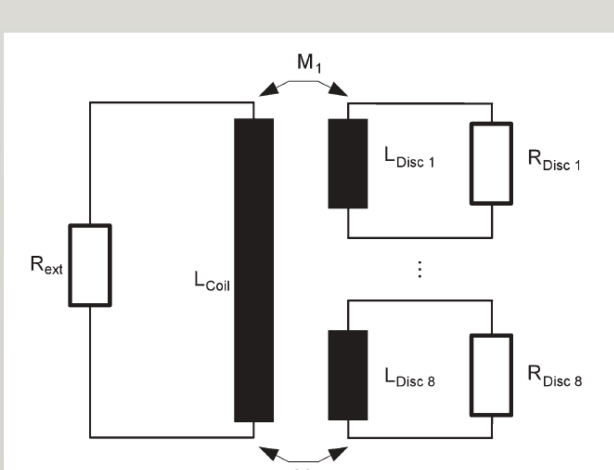

Figure 2 [1]

- System can be split into multiple circuits, all inductively coupled together
- The resistor connected to the coil is an external dump resistor
- Resistors connected to discs represent internal resistance of each disc

Methods

The code presented was developed to generate and solve the system of circuit equations governing the input geometry. The system of equations is a first-order system of ordinary differential equations (ODEs) of the general form

$$\vec{L}\frac{d\vec{I}}{dt} = -\vec{R}\vec{I}$$

where L is an inductance matrix for the system, R is a resistance matrix, and I is the current value in each element of the circuit. It is solved using MATLAB's ode45 ODE solver.

The inductance matrix containing self and mutual inductance values of the entire system is generated before the system is solved in an analytic-numerical calculation as described in [4]. The resistance matrix is calculated in real time as the discs heat up due to Ohmic heating (see below).

The dump resistor connected in series to the superconducting coil is calculated by specifying an L_{coil}/R_{dump} time constant, where L_{coil} is the self inductance of the superconducting coil and R_{dump} is the value of the dump resistor.

The temperature increase in the discs and coils is governed by Ohmic heating,

$$\rho_m c(T)\frac{dT}{dt} - \nabla\cdot(k\nabla T) = \frac{I^2}{A^2}\rho(T),$$

where ρ_m is the mass density, c(T) is the specific heat capacity, k is the heat conductivity, I is the current, A is the cross-sectional area, and ρ(T) is the resistivity. Since the time-scales in the quench scenarios are short, the heat conductivity is taken to be negligible.

Results: Example Parametric Simulation

- In the following simulation, inner and outer radii, disc and pancake thickness, number of discs, number of pancakes, number of turns, and number of disc elements are held constant.
- Figures 3(a), 4(a), and 5(a) are generated from a simulation with a dump resistor of R = 32.2 Ω.
- Figures 3(b), 4(b), and 5(b) are generated from a simulation with a dump resistor of R = 1.61 Ω.
- With a higher dump resistor, more current is extracted out of the coil and induced in the discs, but at the cost of much higher temperature in the discs close to the axis.

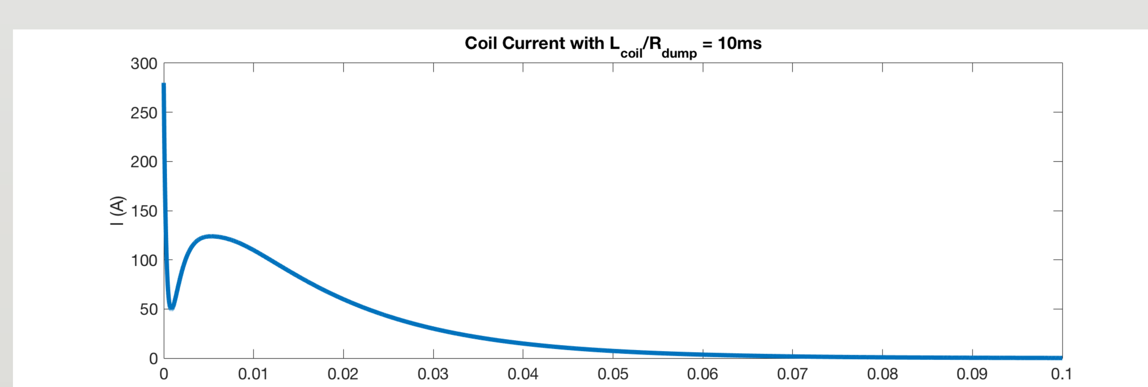

Figure 3(a)

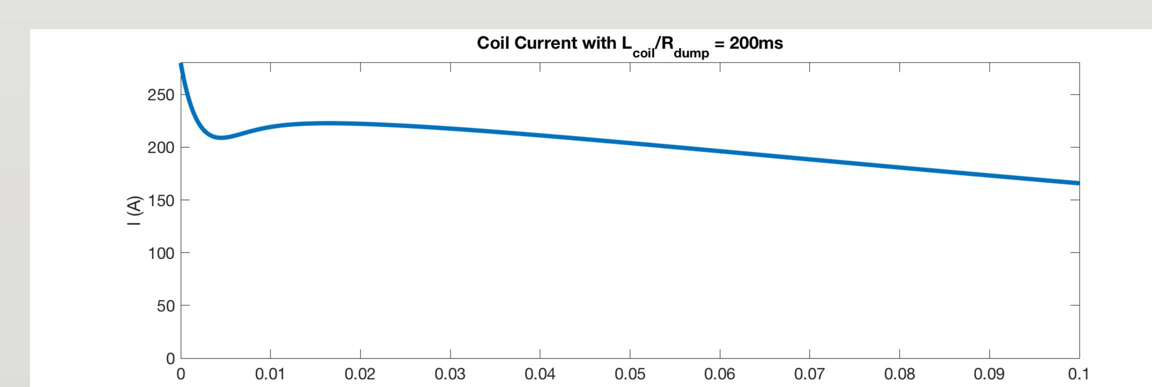

Figure 3(b)

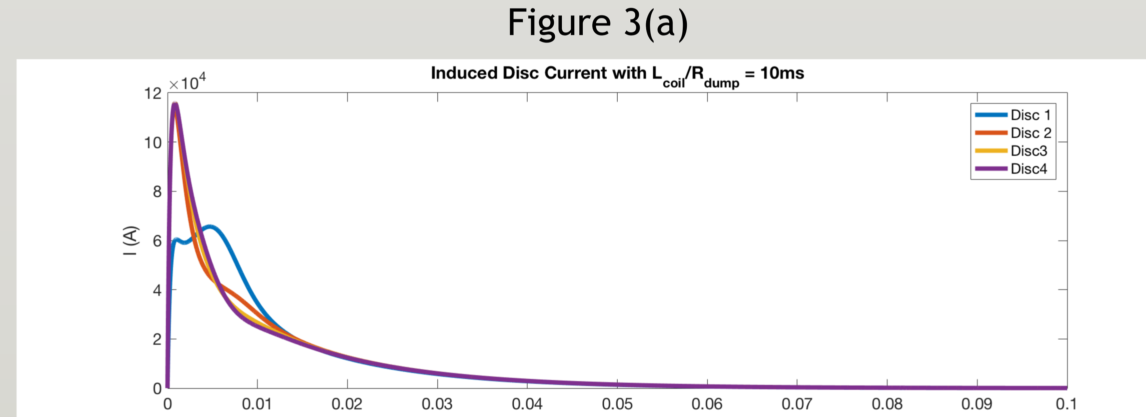

Figure 4(a)

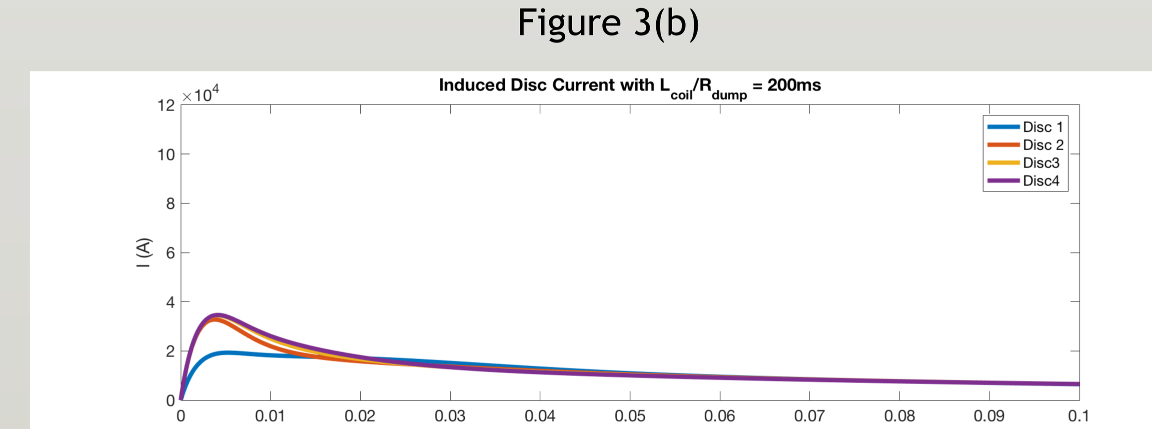

Figure 4(b)

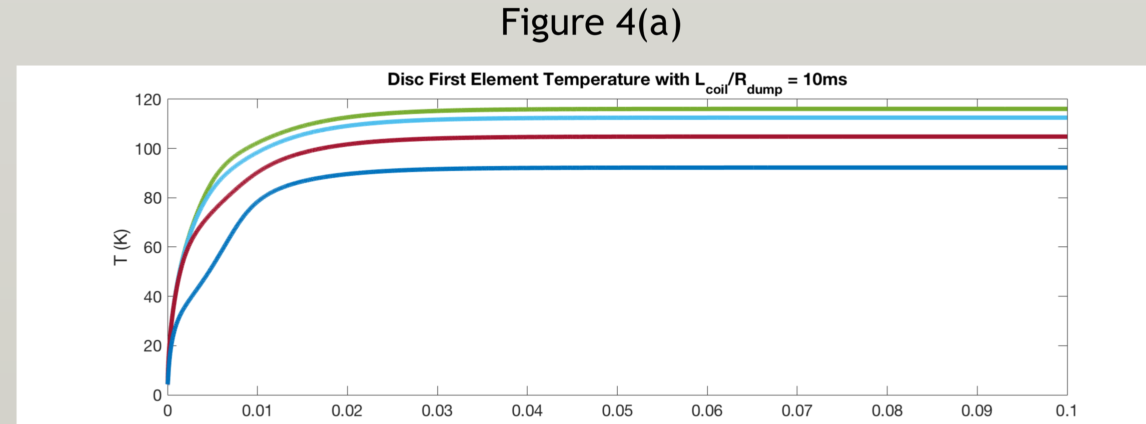

Figure 5(a)

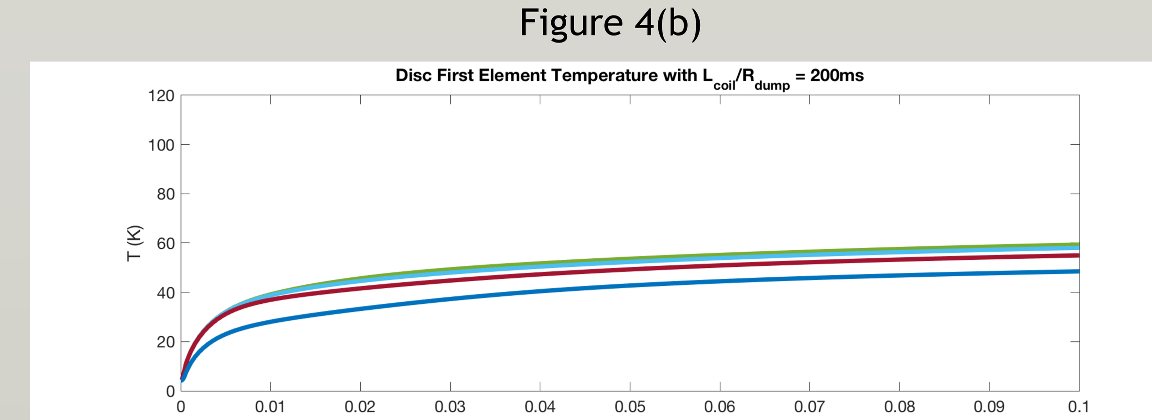

Figure 5(b)

Future Work

- Any number of parametric studies could be carried out in studying the properties of different geometries. Some basic studies that were briefly studied include a larger inner bore and thicker copper discs.
- In addition to discs, the code can implement copper cylinders on the inner and outer edges of the pancakes. Further work could be done in observing how these cylinders can optimize current extraction during quenches.
- Various material properties can be inserted to guide experiments in quench protection from both HTS and LTS tapes and wires.
- Since only 1% of the HTS is a superconductor, further work can be done by considering the effect of the copper protector and steel substrate in the composite YBCO tapes. This can be implemented through input parameters for radial and azimuthal resistance values (R_r and R_θ) in the HTS coil, as shown in Figure 6 [5], which have already been successfully added to the presented code as possible inputs.

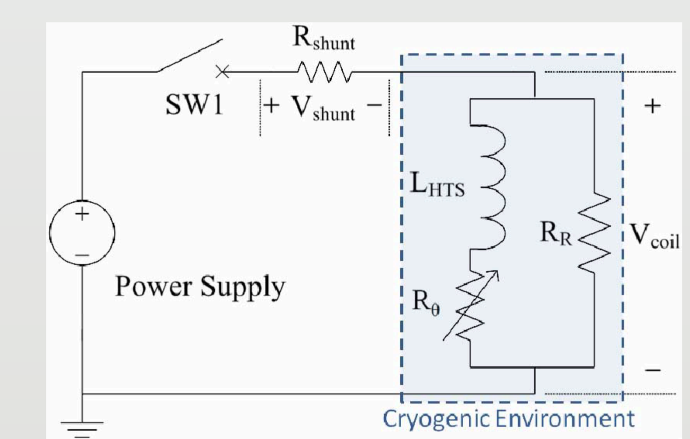

Figure 6

Acknowledgements

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