Coupled Transient Thermal and Electromagnetic Finite Element Analysis of Quench in MICE Coupling Magnet

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Abstract

The superconducting coupling magnet used for the international Muon Ionization Cooling Experiment (MICE) will be passively protected through coil subdivision and quench back simultaneously. The design of such type quench protection system requires detail understanding of the heat transfer and electromagnetic process in the magnet during quench process. A coupled transient thermal and electromagnetic finite element model was developed to study the quench process of the coupling magnet. This model sequentially solves two different physics environments, one is thermal physics environment and the other one is coupled-electromagnetic-circuit physics environment. The two environments are coupled by applying results from one environment as loads in another one. The results such as current, hot spot temperature, resistance and over voltage during quench process are presented. The results of this model were compared with that of a semi-empirical model, and the respective advantages of both models were pointed out. The quench propagation process in the coupling magnet and the effect of the quench back on the speeding up the quench process were analyzed. The goal of such work is to predict the quench evolution of the coupling magnet in detail and guide its protection scheme.

Keywords: Superconducting magnets; Quench; Quench back; Finite element analysis

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1. Introduction

The Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling in a short section of a realistic cooling channel using a muon beam at Rutherford Appleton Laboratory in the UK. The MICE cooling channel consists of three alternating three absorber focus coil module (AFC) and two RF coupling coil module (RFCC) where the process of muon cooling and reacceleration occurs. The coupling magnet is a superconducting solenoid, mounted around four 201MHz RF cavities, which produces magnetic induction up to 2.6 T on the magnet centerline to guide the muons and keep them within the RF cavities [1]. The coupling magnet, having inner diameter of 750 mm, length of 285 mm and thickness of 110 mm, is to be built using commercial copper matrix niobium titanium conductor (see details in [2]). The magnet will have a self inductance of 592 H. When operated at its maximum design current of 210 A (the highest momentum operation of MICE), its stored energy will be about 13 MJ [2].

In the case of quench, the high stored energy in the magnet and the high current densities in the NbTi superconductor can cause a high temperature rise in the region where the quench originally started, as well as high voltages in the coil and between the coil and ground. This coupling magnet will be protected in a completely passive manner. The most important method is the subdivision of the coil with cold diodes and resistors across the subdivisions to reduce both the voltage to ground and the hot spot temperature. The second method of quench protection is quench back from the mandrel, which speeds up the spread of the normal region within the coil [2] [3]. For the importance of quench protection system design, the demand for simulating the magnet quench behavior is quite pressing.

Over the past decades, various approaches to model the quench propagation in superconducting magnets have been proposed. The most diffused approach is a semi-empirical approach, and the volume of superconducting windings switched into the normal state is estimated with the introduction of the quench velocity concept that is the speed of the normal zone boundary [4-7]. This method is very fast, but neglects the heat diffusion inside the coil since adiabatic isothermal shells in normal state are added to the coil when the quench advances. Another approach is to treat the coil as an anisotropic solid and solve the nonlinear heat equation governing the quench process with methods like the finite element method (FEM). But due to the existence of very strong temperature gradients such simulation required a large computing effort [8-10]. In the recent years, some research groups have applied the commercial FEM code, such as ANSYS, and OPERA-3D in quench simulation [11-15]. However, few researches have pay attention to the quench back from the mandrel, which is an important phenomenon in the coupling magnet quench process.

We have developed a coupled transient thermal and electromagnetic finite element model including quench back phenomenon to study the MICE coupling magnet quench process. It is hoped that this model can give a detailed prediction of the quench evolution of the coupling magnet and guide its protection scheme.

2. Design of the coupling magnet

The coupling coil will work in two modes due to the polarity change of two focusing coils in the AFC module. One is gradient mode (flip mode), and the other is
solenoid mode (non-flip mode). Table 1 shows the coupling coil design parameters. The highest operation current for the coupling coil is 210 A operating the MICE in the flip mode at a muon average momentum of 240 MeV/c. Fig. 1 shows the coupling magnet cryostat. The coil is wound on a 6061-T6 aluminum mandrel and over-wrapped by high strength aluminum wires banding. The G-10 insulation thickness between the coil and the bobbin, the end plate and the banding are 1.0 mm, 3.5 mm and 1.0 mm respectively. The coil is indirectly cooled by liquid helium flowing in cooling tubes in the cover plate. Outside the 4 K cold mass, there are a 60 to 80 K thermal shield and a vacuum.

Fig. 2 shows the proposed protection circuit of the coupling magnet. A 300 A 20 V unipolar power supply is used to charge the magnet. The magnet will be discharged through a water-cooled varistor circuit. The current into the magnet will be carried by a single pair of copper and HTS leads. The coil will have eight subdivisions with a pair of back-to-back R620 diodes at ~5 K and a resistor about 20 mW across each subdivision. The coil rapid discharge system will consist of 25 diodes mounted on a water-cooled plate. The mandrel and banding act as shorted secondary circuits inductively coupled with each coil subdivision. Back-to-back cold diodes allow the magnet to be safely quenched at either magnet polarity. The high diode forward voltage (about 4 V at 5 K when the forward current is 1mA) across the diodes prevents current from bypassing the magnet coil during the magnet charging or discharging process at its design charging and discharging voltage. The mandrel and banding will absorb some energy from the magnet during its quench process. The inductive current in the mandrel and banding will heat them, which will eventually heat up the adjacent coil subdivisions and induce new normal zone. This process is called quench back. Quench back will speed up the quench process, and thus reduce the hot spot temperature.

3 Simulation model

Quench process analysis is a multi-field coupled analysis including transient thermal analysis, transient electromagnetic analysis and circuit analysis. These three analyses are divided into two physics environments. One is called thermal physics environment including only the transient thermal analysis, the other one is called coupled-electromagnetic-circuit physics environment including transient electromagnetic analysis and circuit analysis. These two physics environments are coupled and sequentially solved. The joule heat results from the coupled-electromagnetic-circuit physics environment are loaded to the thermal physics environment. The temperature results from the thermal physics environment are loaded to the coupled-electromagnetic-circuit physics environment.

3.1 Thermal physics environment

Fig. 3 shows the thermal physics environment model. If a disturbance is enough to raise the temperature of the superconducting conductor up to its current sharing temperature, the joule heat is generated in the coil. The lengths of the coupling coil in the q, r, and z directions are 4.89, 0.11 and 0.285 m respectively. For the NbTi coil, the normal zone longitudinal propagation is far faster than the transverse propagation. For the coupling coil the average quench propagation velocities in the q, r and z directions are about 3.477, 0.065 and 0.085 m/s respectively (see details in [3]). If the quench starts at the inner radius at the mid-plane of the coupling coil, the time for the normal zone reaches the boundary in the q, r and z directions are 0.70, 1.69 and 1.68 s respectively.
means that the normal zone grows in three dimensions before 0.7 s, grows in two dimensions from 0.7 to 1.68 s, and grows in one dimension from 1.68 to 1.69 s. Most volume of the coupling coil changes to normal state by the normal zone growing in the r and z two dimensions. So the 2-D axially symmetric model for the thermal phenomena is adopted. The coil impregnated with epoxy resin is treated as an anisotropic continuum medium model with thermal conductivity kr in the r direction and kz in the z direction of the magnet. Therefore, for the entire model including the coil, G-10 insulation, banding, cover plate and mandrel, the basic thermal diffusion is governed by the following equation (1).

\[ \gamma C \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r k_r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + \rho J^2 \]  

(1)

where \( t \) is the time, \( T \) is the temperature, \( g \) is the density, \( C \) is the specific heat capacity, \( J \) is the current density, and \( r \) is the local average resistivity. In the coil the local average resistivity \( r \) is a function of the local temperature and magnet induction, and it can be represented by equation (2);

\[ \rho(T, B) = \begin{cases} 
0 & T \leq T_{cs} \\
\rho_{cu} \frac{1}{f_{cu}} \frac{T - T_{cs}}{T_c - T_{cs}} & T_{cs} < T \leq T_c \\
\rho_{cu} \frac{1}{f_{cu}} & T_c \leq T 
\end{cases} \]  

(2)

where \( f \) is fraction in cross section of the materials in the unit cell cross section. The subscript \( cu \) stands for the material of Cu. \( T_{cs} \) is the local current share temperature, which is a function of the local magnet induction. \( T_c \) is the local critical temperature, which is a function of the local current and magnet induction. \( T_{cs} \) and \( T_c \) can be calculated by the following equations (3-1) and (3-2) [16].

\[ T_c(B) = 9.2 \left( 1 - \frac{B}{14.5} \right)^{0.59} \]  

(3-1)

\[ \frac{T_{cs}(I, B)}{T_c(B) - 4.2} = \frac{I - I_c(B, 4.2)}{0 - I_c(B, 4.2)} \]  

(3-2)

In equation (3-1) and (3-2), \( B \) is the local magnet induction, \( I_c(B, 4.2) \) is the critical current when the local magnet induction is \( B \) and the local temperature is 4.2 K. \( I_c(B, 4.2) \) usually can be found from the test results of the critical current at the boiling point of helium over a limited range of magnetic inductions (e.g., 2 T to 8 T) by the superconductor manufacturer.

In equation (2), \( g \) is a constant during quench process, \( C \) is a function on the local temperature. In the winding, the \( g \) and \( C \) are averaged over the different constituents of
the winding, according to the percentage of the materials in the unit cell. The $g$ and $C$ can be calculated by the following equations (4) and (5) respectively.

$$\gamma = f_{cu} \gamma_{cu} + f_{nbt} \gamma_{nbt} + f_{ins} \gamma_{ins}$$  \hspace{1cm} (4)

$$C(T) = \frac{f_{cu} \gamma_{cu} C_{cu} + f_{nbt} \gamma_{nbt} C_{nbt} + f_{ins} \gamma_{ins} C_{ins}}{f_{cu} \gamma_{cu} + f_{nbt} \gamma_{nbt} + f_{ins} \gamma_{ins}}$$  \hspace{1cm} (5)

In equations (4) and (5), the subscript nbt and ins stand for the material of NbTi and insulation (in our model this insulation is simple to epoxy).

In equation (2), $k_r$ and $k_z$ are functions of the local temperature. In the winding, the $k_r$ and $k_z$ are evaluated considering all the components of the unit cell like thermal conductance in series or in parallel respectively. Fig. 4 shows the unit cell model for thermal conductivity evaluation. The $k_r$ and $k_z$ can be calculated by the following equations (6) and (7) respectively.

$$k_r(T) = \frac{b_{cell} - b_{cond} k_{ins} + b_{cond} - b_{nbt}}{b_{cell}} \frac{a_{cell} - a_{cond}}{k_{ins} k_{cu}} + \frac{a_{nbt}}{b_{cell} a_{cell} - a_{cond} + a_{cond} - a_{nbt} + a_{nbt}}$$  \hspace{1cm} (6)

$$k_z(T) = \frac{a_{cell} - a_{cond}}{a_{cell}} k_{ins} + \frac{a_{cond} - a_{nbt}}{b_{cell} b_{cell} - b_{cond} + b_{cond}} \frac{b_{cell} k_{ins} k_{nbt}}{k_{cu}}$$  \hspace{1cm} (7)

where $a$ and $b$ are the length in the $r$ and $z$ directions respectively, subscript cell, cond and nbt stand for the unit cell, bare conductor and NbTi respectively. The calculation results of $k_r$ and $k_z$ are compared and shown in Fig. 5.

Because of the relatively low thermal conductivity of the winding, almost all of the energy stored in the magnet is dissipated in the winding. The heat transfer between the helium and cooling channel is negligible during quench process. So an adiabatic condition is adopted on the magnet outer boundary.

3.2 Coupled-electromagnetic-circuit physics environment

In order to decide the local state of unit cell in the coil, we need the transient magnetic induction in the coil. In order to considering the quench back from the mandrel and banding, we need to calculate the transient magnetic field and eddy current field in the mandrel and banding.

Fig.6 shows the coupled-electromagnetic-circuit physics environment model. From the magnetic point of view, thanks to the large number of series connected coil turns, it
is possible to assume the local current density uniformly distributed over the unit cell with only slight impact on the overall magnetic field map. Compared to the source current, the inductive eddy current can be negligible in the winding, and the AC-loss in the winding during the decaying current is neglected. Therefore the low-frequency electromagnetic behavior in the coil can be determined in terms of the j component of the magnetic vector potential A by the following 2-D equation (8). In the mandrel, cover plate and banding zones there is only eddy current without source current. In the insulation zone, the eddy current is nearly zero, because of the zero electrical conductivity. The electromagnetic behavior in the mandrel, cover plate, banding and insulation zones can be calculated by equation (9).

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial A_\phi}{\partial r} \right) + \frac{\partial^2 A_\phi}{\partial z^2} = -\mu J \quad (8)
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial A_\phi}{\partial r} \right) + \frac{\partial^2 A_\phi}{\partial z^2} = \mu \sigma \frac{\partial A_\phi}{\partial t} \quad (9)
\]

where \( m \) is the magnetic permeability, which is constant during quench process. \( s \) is the electrical conductivity, which varies with local temperature.

The magnetic field of the MICE coupling is an open boundary field problem. A simple method to solve this open boundary field problem is to specify \( A_j = 0 \) at the exterior edges of the model with very far boundary. But this simple method needs very large computing effort, if one wants to get exact enough magnetic field results. In solving this problem we introduced an interesting kind of element called “infinite element”, which can make a transition map between the close boundary and the exterior far boundary. By this “infinite element” the boundary of the model can be relatively close to the model region of interest. Combing the finite element and infinite element the open boundary field problem can be solved accurately with a relative small computing effort [15] [17]. Fig. 6 shows the model with infinite element.

The solving of equation (1) and equation (8), (9) needs the current in the coil, so a lumped parameters circuit model directly coupled to the electromagnetic model is developed. These two models are coupled through the inductive voltage of the coil [18].

In our model, as soon as the quench begins, the main switch of the power supply is assumed to be opened. In fact there is a delay time between the quench beginning and the main switch of the power supply opens. And this delay time make both the over heat and over voltage in the magnet during quench more serious. As shown in Fig.6, the circuit model includes the cold diodes, cold resistors, stranded coil and rapid discharge diodes. The circuit of the coil during quench process can be calculated by the following equations (10).

\[
\begin{cases}
\frac{1}{S_{\text{cell}}} \int_{\Omega_j} \frac{\partial A}{\partial t} \, d\Omega + R_{q,j}(t) I_j - R_{s,j}(I_0 - I_j) + V_{f,j} = 0 \\
\sum_{j=1}^{g} R_{s,j}(I_0 - I_j) + V_{f,0} = 0
\end{cases}
\]  

(10)

where \( j \) is the section number, \( W_j \) is the volume of section \( j \), \( S_{\text{cell}} \) is cross section area of the unit cell, \( R_q, j(t) \) is the normal zone resistance of section \( j \), \( R_s, j \) is the shunt resistance of section \( j \), \( I_j \) is the current in section \( j \), \( I_0 \) is the current through the rapid
discharge diodes. $V_f, j$ is forward voltage of the cold diodes at section $j$, which is mainly decided by its temperature. During the quench process the temperature of the cold diodes will be far higher than 5 K because of the large forward currents through the diodes, and the forward voltage of the cold diodes descants with the temperature of the cold diodes rising. So the forward voltage of the cold diodes during quench process will be lower than that at 5 K (about 4 V). In the quench simulation model, the forward voltages of the cold diodes are assumed to be 1 V during the quench process as an approximation. $V_f, 0$ is the forward voltage of the rapid discharge diodes, which is also mainly decided by its temperature and in this model it is assumed to be 24 V. In the first equation in equation (10), the first term is the inductive voltage of the section $j$, and this term includes the inductively coupling between the coil circuit and the mandrel. The second term is the normal zone resistive voltage in section $j$, and this term includes the coupling between the magnetic field and circuit. The third term is the voltage dropped on the shunt resistor. The fourth term is the voltage drop on the cold diode.

3.3 Simulation Process

The whole analysis is based on a single finite element mesh across different physics environments. These two physics environment analysis are coupled by applying results from one analysis as loads in another one.

The whole magnet system is initialized to the original temperature of 4.2K and the initial current $I_0$ of 210 A. All turns initially generate no heat, and a point pulsed power continuing about 1 ms is added at the position of the inner radius at the coil mid-plane. This energy should be enough to make the normal zone continue grow, and in our study about 0.36 J is added to the coil to initiate the quench. The power supply is assumed to be turn off and disconnected from the circuit once the quench happen. The current begins continuing flowing in the coil and protection circuit. Then the process enters the iterative portion of the simulation. The thermal physics environment and coupled-electromagnetic-circuit physics environment are coupled and sequential solved. The iteration continues until the 16th second after the quench starts in our modeling case. The iteration can restart from this time and continues in our calculation method, but it is found that we have gotten the key informations of the coupling magnet in the simulated quench case until the 16th second.

4 Results and analysis

4.1 Simulation results

The simulation results by this finite element model (FE model) are shown and compared to the results by a semi-empirical model (SE model) in Fig 7-10. The coil sections are number 1, 2…8 respectively from its inner radius to its outer radius. The SE normal zone grows model is based on the quench propagation velocities. The SE thermal model uses local adiabatic condition. The SE circuit model simplifies the non-linear circuit components: cold diode to be short circuit, and rapid discharging diode to be open circuit. An average magnetic induction and simplified quench back effect are used in the SE model [3].

Fig. 7 shows the current results of section 1 and section 5 calculated by different models. The current decay is similar in the two models. Current 1 starts to decay in the beginning stage, because the quench starts at section 1. Current 5 starts to rise in the beginning stage, because the induced electromotive force on section 5 increases current 5. With the time current 1 and current 5 both decay, because of the increasing of the coil
resistance. The current calculated by the FE model decays faster than that calculated by the SE model, this is mainly because the magnet resistance by the FE model grows faster than that by the SE model as shown in Fig. 6.

Fig. 8 shows the normal zone resistance results of section 1 and section 5 calculated by different models. The resistance results by the two models have the same trends. Resistance 1 is smaller than resistance 5, because of section 1’s small radius and shorter length. The final resistance results of each section calculated by the two models are near the same. The resistance results of FE model grows faster than that of SE model, maybe it's just because the normal zone in the FE model grows faster, and the average quench propagation velocities in the SE model are a little slower.

Fig. 9 shows the hot spot temperature results calculated by different models. The hot spot temperature rises rapidly at the quench beginning stage, because of the small specific heat of the coil and the large current in the coil at this stage. As the quench goes on and the current decays, the hot spot temperature rises slowly and tends to be constant. The difference between the hot spot temperature 1 and 5 calculated by the FE model is larger than that by the SE model, and the hot spot temperature results by the FE model is lower than that by the SE model. This is because the SE model assumes local adiabatic in the coil. The temperature distribution in the coil during quench is like onion skin layer by layer. The SE model does not consider the heat transfer between these isothermal layers.

Fig. 10 shows the internal voltage results calculated by different models. The trends of the internal voltage calculated by the two models are the same. The internal voltage has a maximum value during the quench process, and the maximum internal voltage results by the two models are very close. The internal voltage results, shown in Fig. 10, are the products of section currents, shown in Fig. 7, and the section normal zone resistances, shown in Fig. 8. This internal voltage estimation method by the resistive voltage dropped on the normal zone in each section is a conservative method, and the detailed information about the over voltage in the coil can be obtained by the method in reference [21]. The maximum internal voltage by the FE model appear earlier than that by the SE model, maybe it is just because the resistance of the coil by the FE model rise quicker than that by the SE model as shown in Fig. 8.

Quench simulation results of the coupling magnet by different models are summarized in Table 2. The hot spot temperature by the FE model and by the SE model is 105 K and 130 K respectively. The hot spot temperature is over estimated by the SE model because the local adiabatic assumption in the SE model. Both the maximum internal voltage and the layer-to-layer voltage by the FE model and SE model are very close. The maximum layer-to-layer voltage is calculated by the maximum internal voltage dividing by N-1, where N is the layer number in each section. The simulation results given by the two models are in good agreement with each other. According to the results in Table 2, we can be sure that the coupling magnet can quench safely with the designed protection system at the simulated quench case.

As a whole, the FE model has a series of respective advantages than the SE model does in MICE coupling magnet quench simulation. First the FE model considers the heat diffusion inside the coil more detailed. Second the FE model uses less empirical expressions and is easier to use. It does not depend on the empirical collection of the average quench propagation velocity and empirical modeling of the quench back phenomena. Finally but maybe the most significant for the coupling magnet quench process the FE model is able to study the eddy current, joule heat in the mandrel and
banding and the induced quench back phenomena in the coil. But the computing effort of the FE model is larger than that of the SE model. For the same one case, the time that the FE model need is ten times longer than that the SE model need. Usually the SE model is very fast and can give conservative results, and thus the worst case scenarios can be predicted rapidly.

4.2 The role of quench back

The mandrel is inductively coupled to the coupling coil circuit that is being quenched. Current induced in the mandrel by $\frac{di}{dt}$ in the magnet produces joule heat in the mandrel, which in turn causes the superconducting coil wound on the mandrel to quench. The banding attached to the coil also can play the same role. This process was predicted by the FE model in detail.

Fig. 11 shows joule heat in the mandrel, banding, and cover plate at 1.0 s. The maximum joule heat appears at the middle of bobbing near to the coil inner radius. The sequence of the joule heat generation from maximum to minimum is the bobbing, end flange, banding and cover plate. This is in consistent with the sequence of the inductance between different parts and the coil. Because the quench start from the inner radius at the coil mid-plane, the bobbing and end flange is most likely to induce new normal zone in the coil.

Fig. 12 shows temperature of the mandrel, banding, cover plate at 1.0 s. The maximum temperature appears at the middle of bobbing near to the coil inner radius. The temperature distribution is similar to the joule heat distribution as shown in Fig. 11. At 1.0 s the temperature of end flange is higher than 9 K. If the normal zone does not appear at the region attached to the end flange at 1.0 s, the quench back from the end flange will cause this superconducting region to quench.

Fig. 13 shows the quench propagation process in the coupling magnet with 6061-T6 aluminum mandrel and cover plate, and Fig. 14 shows the quench propagation process in the coupling magnet with 304 stainless steel mandrel and cover plate. The temperature distribution in the coil is like the onion skins layer by layer. The temperature of mandrel rises with the quench in the coil goes on because of the induced current and joule heat in the mandrel. The quench back causing new normal zone is very clear in the coupling magnet with 6061-T6 aluminum mandrel. But quench back does not appear in the coupling magnet with 304 stainless steel mandrel. The effect of quench back on the quench process is affected by the mandrel material. A mandrel with low resistivity and low specific heat per unit volume can cause the temperature of the mandrel rising to a specific value for example 10 K quickly, so the quench back in the mandrel can happen early. [19][20]

Quench back can effectively speed the whole coil to be normal and reduce the hot spot temperature. It is particularly effective in a situation where the normal zone hits boundaries rather early in one dimension in the quench process and thereafter spreads very slowly in the other dimensions [4]. For the coupling magnet’s quench process, the effect of quench back from 6061-T6 aluminum mandrel is limited, because the coupling coil is not very long in the z direction or not very thick in the r direction, and the times when the normal zone hits all coil boundaries are very close.
5 Conclusions

MICE coupling magnet is passively quench protected by coil subdivision and quench back from the mandrel. A special coupled transient thermal and electromagnetic finite element model has been developed to study its quench process. By this model, a more detailed prediction of quench process has been obtained. But it needs larger computing effort. It can be applied when detailed quench process results are needed. The eddy current and joule heat in the mandrel can be calculated by this finite element model, and the quench back’s effect of speeding the normal zone growth in the coil can be observed in detail. The simulation results indicate that the quench back effect from the 6061-T6 aluminum mandrel is limited. This finite element model can well help us understand the coupling coil quench protection principle and guide the protection scheme design.

Acknowledgement

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References

Figures

**Figure 1.** Cross section of the coupling magnet cryostat

**Figure 2.** Protection circuit of the coupling magnet
Figure 3. Thermal physics environment model

Figure 4. Unit cell model for thermal conductivity evaluation

Figure 5. Calculation results of $k_r$ and $k_z$ as functions of temperature
Figure 6. Coupled-electromagnetic-circuit physics environment model

$V_{f,0} = 24\text{V} \quad V_{i,0} = 1\text{V} \quad \text{Stranded coil section}$

$\text{Infinite element}$

$\text{Free space}$

$\text{Coil assembly}$

Figure 7. Current results calculated by different models

Figure 8. Resistance results calculated by different models
Figure 9. Hot spot temperature results calculated by different models

Figure 10. Internal voltage results calculated by different models

Figure 11. Joule heat in the mandrel, banding, cover plate at t=1.0s
Figure 12. Temperature of the mandrel, banding, cover plate at t=1.0s

Figure 13. Quench propagation process in the coupling magnet with 6061-T6 aluminum mandrel and cover plate
Figure 14. Quench propagation process in the coupling magnet with 304 stainless steel mandrel and cover plate

Tables

Table 1. Coupling coil specification

<table>
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<tr>
<th>Parameter</th>
<th>Flip</th>
<th>Non-flip</th>
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<td>Coil Length (mm)</td>
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<td>Coil Inner Radius (mm)</td>
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<td>Coil Thickness (mm)</td>
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<td>Number of Layers</td>
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<td>Number of Turns per Layer</td>
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<td>Self Inductance (H)</td>
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<td>Temperature Margin (K)</td>
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Table 2. Summary of quench simulation results by different models

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<tr>
<th>Parameter</th>
<th>FE model</th>
<th>SE model</th>
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<td>Hot spot temperature (K)</td>
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<td>Max internal voltage (V)</td>
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<td>Max layer-to-layer voltage (V)</td>
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