Title

A Comparison of the Quench Analysis on an Impregnated Solenoid Magnet wound on an Aluminum Mandrel using Three Computer Codes

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A Comparison of the Quench Analysis on an Impregnated Solenoid Magnet wound on an Aluminum Mandrel using Three Computer Codes

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Abstract— **The magnet used for the quench protection comparison has an ID of 1.5 m. At a maximum current of ~210-A, the stored energy is ~13 MJ. The impregnated magnet coil is 281 mm long and about 105.6 mm thick. The coil is wound on a 6061-aluminum mandrel. The magnet quench protection system is passive. The magnet coil is sub-divided with back-to-back diodes and resistors across each of the coil sub-division to reduce the magnet internal voltages. Conservative quench protection criteria were applied when the magnet was designed. These criteria are presented in this paper. Quench protection of the magnet was simulated using three computer codes from three different places. The results calculated using the three codes are compared to the original magnet quench protection criteria used to design the magnet. The three quench simulation codes assumptions are compared. The calculated hot-spot temperature and peak voltages are compared for the three quench simulation codes.**

Index *Terms*— NbTi, Passive Quench Protection, S/C magnets

I. INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) coupling magnet is part of an experiment that is being installed at the Rutherford Appleton Laboratory in the UK [1], [2]. The magnet will provide a field inside of the RF and coupling coil module (RFCC) module such that the beam stays within the beryllium windows that are attached to each of the four RF cavities in the RFCC module. The four RF cavities replace the muon beam longitudinal momentum that was removed by ionization cooling by the absorbers in the middle of absorber focus coil (AFC) modules [3]. The RFCC module is located between two AFC modules, which have centers that are separated by a distance of 2.75 m along the axis of MICE [4]. Each RFCC module has a single coupling coil that is between the couplers of the two center cavities of the module [5].

The original design parameters for the coupling magnet were set in 2004 [6]; the present design was set in the fall of 2010 [7]. The coupling magnet is a single coil with an inside diameter of ~1500 mm. The coil thickness became 105.6 mm, and the coil length became 281 mm. The magnet has 96 layers with a 166 turns per layer. At a maximum current of 210.1 A, the magnet stored energy will be just over 13 MJ. The coil is wound under tension onto a 6061-T6 aluminum-mandrel. The pre-stress in the conductor will ensure that the coil does not lift off of the mandrel after the magnet is cooled from 300 K to 4 K and after it is powered to its maximum current.

II. THE ORIGINAL QUENCH PROTECTION DESIGN FOR THE COUPLING COIL

The first quench protection calculations for the coupling coil were done on a spreadsheet based on the average magnetic induction within the coil. The following expression for the quench propagation velocity along the wire was used based on a fit of quench propagation velocity measurements made in potted coils by LBNL in the 1970's [8], [9];

$$V_\theta = 5.7x10^{-14}(1+B)^{0.62}J_M^{1.65}, \tag{1}$$

where V_θ is the quench velocity around the coil (along the wire). B is the average induction in the wire (or coil) and J_M is the current density in the matrix plus superconductor. The turn-to-turn velocity v_z and the layer-to-layer velocities are estimated with the following expressions;

$$V_r \approx 0.7V_\theta\left[\frac{\rho_M k_i}{LT_c}\frac{b}{S}\frac{r+1}{r}\right]^{0.5}, \text{ and} \tag{2a}$$

$$V_z \approx 0.7V_\theta\left[\frac{\rho_M k_i}{LT_c}\frac{a}{S}\frac{r+1}{r}\right]^{0.5}, \tag{2b}$$

where ρ_M is the copper resistivity in the conductor, L is the Lorenz ratio ($2.45x10^{-8}$ ΩWK^{-2}), T_c is the average critical temperature in the coil (T_c = 7 K)’ k_i is the insulation thermal conductivity, S is the insulation thickness, a is the conductor length in the z direction, b is the length of the conductor in the r direction, r is the copper to superconductor ratio for the conductor. The method given above was used in the original

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semi-empirical quench (SE) program that was written in the 1970's at the Rutherford Appleton Laboratory in the UK [10].

Using (1) (2a) and (2b) it was determined that average quench propagation along the wire V_o was ~3.5 m s^{-1} and V_r is ~0.065 m s^{-1}, and V_z is ~ 0.085 m s^{-1}. The current decay time constant for a safe quench is ~10 s as determined by the Ej^2 equation [9], [11]. Thus the time for the magnet to become completely normal is faster by a factor of over 2 that the time constant needed for a 300 K hot spot temperature [9]. The early conclusion was that the coupling magnet would quench passively, but the coil had to be sub-divided in order to reduce the peak voltages to ground within the coil [11].

Guo, while a graduate student at the Harbin Institute of Technology [12] [13], wrote an SE program that calculated the hot-spot temperature and a conservative estimate of the voltages to ground based on the L dI/dt within the coil section and the external resistance in series with the diodes. If the external resistance was zero, the peak voltage in the coil was the L dI/dt voltage divided by the number of sub-divisions. An external resistance of 5 ohms per sub-division reduced the voltage to ground considerably. The larger the number of sub-divisions, the greater is the reduction in the voltage to ground due to the resistance of the external resistor. By inference the effect of the external resistance voltage to ground is similar to the effect of coil internal resistance, which was not calculated in the original conservative model.

The original Guo program included the coupling between coil sections and the coupling between the coils and the mandrel. The original program written also included quench back from the magnet 6061-Al mandrel [14]. Quench-back from the mandrel was assumed to occur when the mandrel reached 10 K (~T_c for Nb-Ti at B = 0). Early calculations showed that quench back was not important for the coupling coil, but it is quite important for the spectrometer solenoid that has a long thin coil at its center [15]. Quench-back is dependent on the resistivity of the mandrel material. Lower resistivity mandrels cause faster quench-back [14], [15].

Calculations of quenches using the basic design quench criteria are compared with the results of three computer codes used for calculating quench behavior in the magnets. The codes compared are as follows; 1) the QUENCH module by Vector Fields OPERA 3D software [16], 2) a code written by Brad Smith of the MIT Fusion Magnet group [17], and 3) a modified code that uses ANSYS as a driver that was written by X. L. Guo of Jiangsu University in China [18].

III. CALCULATION USING THE VECTOR FIELDS PROGRAM

Several quench scenarios to quantify the adequacy of the overall protection system were performed through the use of a 3D model and the QUENCH module by Vector Fields OPERA 3D finite element FE software.

The coupling magnet FE model consists of the coil package, G10 sheets, the 5356 aluminum banding, the 6061-Al mandrel, which includes the cover plate. The following dimensions were used in the model; the coil inner radius was 750.7 mm, the coil width was 285 mm, the coil radial thickness was 104.8 mm, the number of layers was 96; the number of turns per layer was 166, the thickness of the 5356-Al banding layer was 27 mm. The mandrel and banding are coupled magnetically and thermally to the coil. The model mesh and time steps are set by the user. In theory one could mesh the coil down to the turn level. If one does this, the run time is very long. It is also important that the time steps be correctly set. Fig. 1 shows the Vector Fields model, which is one quarter of the coupling magnet cold mass. Fig 2 shows the circuit for the coupling magnet with 8 coil sub-divisions.

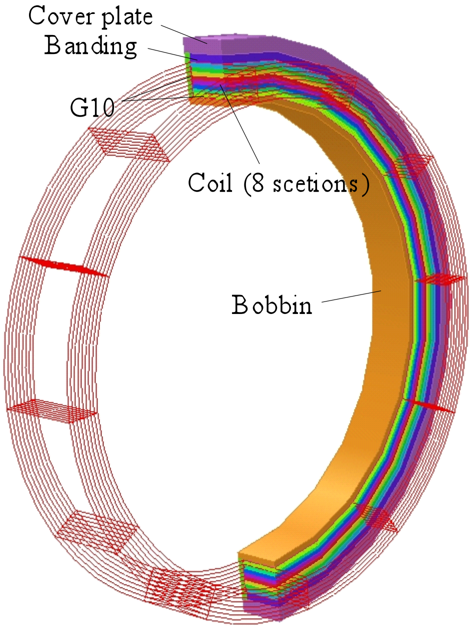

Fig. 1. The model used for the Vector Field QUENCH program when calculating the quench behavior of the MICE coupling magnet.

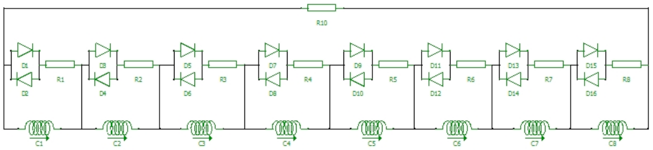

Fig. 2. The electrical circuit for the coupling magnet with 8-coil sub-divisions. The mandrel, cover plate and the banding are included in the magnet circuit.

The mandrel, cover plate, and banding are ~30 percent of the mass. They will absorb ~40 percent of the magnet stored-energy, which means that the coil hot-spot temperature will be lower than if these masses were not included in the circuit. Quench back occurs when the temperature reaches the local coil critical temperature. Fig. 3 shows the current decay within the coupling magnet for the eight sub-divisions. The outermost sub-division had the highest current because the current transferred inductively from the inner sub-divisions. Fig 4. Shows the hot-spot temperature for each sub-division. The peak magnet hot-spot temperature was ~104 K. This was found in an outer sub-division of the coil. Fig. 5 shows the peak voltage to ground for the magnet as a whole as a function of time. The peak voltage to ground was 345 V as compared to a peak voltage to ground of ~2800 V when there are no sub-divisions. The peak layer-to-layer voltage that was calculated with the Vector Fields Voltage was about 86 V. For four sub-divisions, the voltage to ground was almost doubled, but the layer-to-layer was increased by about 18 percent.

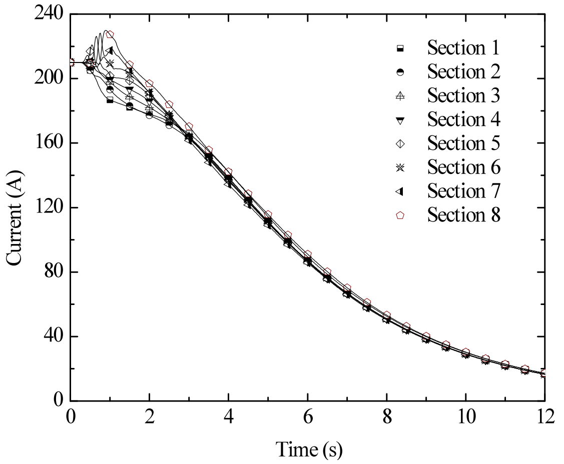

Fig. 3. The current decay in each of eight sub-divisions in the coupling magnet versus time during a magnet quench started at the high field point.

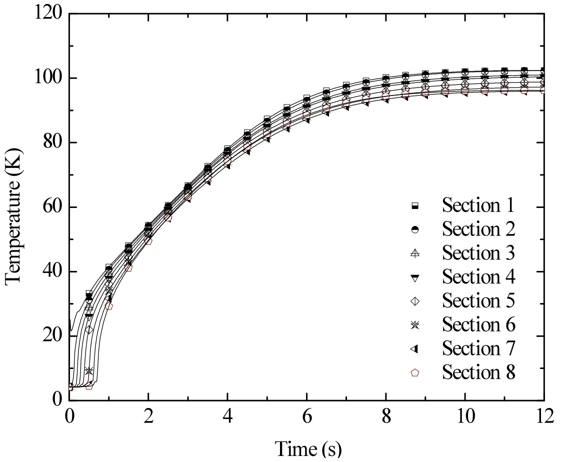

Fig. 4. The hot-spot temperature in each of eight sub-divisions in the coupling magnet versus time during a magnet quench started at the high field point.

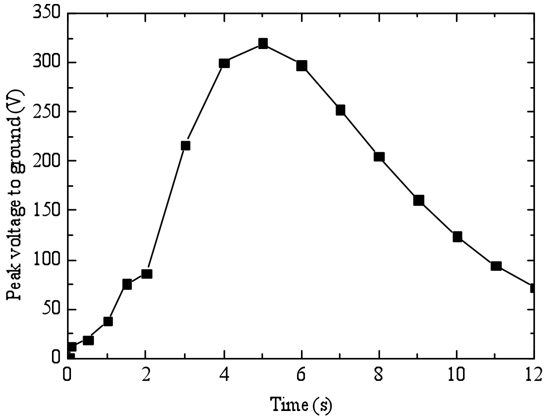

Fig. 5. The peak voltage to ground in the coupling magnet versus time during a magnet quench started at the magnet high field point.

Quench calculations were done with four coil sub-divisions as well as eight. Reducing the number of sub-divisions increased the hot spot temperature less than a degree. The peak voltage to ground with four sub-divisions is twice the value for eight sub-divisions. The peak layer-to-layer voltage was also increased by about a factor of two. Quench calculations with the Vector Fields program suggests that four coupling coil sub-divisions would enough to protect the coil.

IV. CALCULATION WITH THE MIT PROGRAM

The MIT program has many of the same features as the Vector Fields program. The MIT program considers the coils and their subdivisions as a coupled circuit. The mandrel, the cover plate and the banding were not included in the analysis. Quench-back from the mandrel and the banding were not included in the quench analysis at MIT. Like the Vector Field Quench program, the MIT program considers the internal resistances and inductances within the coil, but the MIT program does this at the level of a single turn.

For the details of the MIT program results one should look at reference [17]. At full current, the hot-spot temperature for the four and eight sub-division cases is 122 K when the quench is started at the maximum field point. If the quench is started at the minimum field point, the hot-spot temperature increases to 127 K for both the four and eight sub-division cases. When the magnet hasn't been sub-divided, the peak hot spot temperature is 135 K when the quench starts at the peak field point. The time to turn on the diodes is longer for quenches started at the minimum field point than for quenches started at the maximum field point. When one quenches at a lower current (lower stored energy), the hot-spot temperature goes down as expected. The time to fire the diodes increases. One reason that the hot-spot temperature is higher for the MIT program is the absence of the mandrel and banding to absorb magnet energy. Quench-back has only a small effect [13].

The peak voltages in the coil are lower for the MIT program. The maximum calculated ΔV for no sub-division is 2114 V. For the magnet divided into four parts, the peak voltage is 281 V. For eight subdivisions the calculated peak voltage is 78 V. The maximum layer-to-layer voltages vary from 155 V for no sub-divisions, to 68 V for the magnet divided into eight parts of 12 layers each. In general, the calculated voltages are lowest for the MIT model, and these voltages occur earlier in the quench (from 1 to 2 s earlier). The lower peak voltages calculated by the MIT program are difficult to explain in terms of model differences.

V. CALCULATIONS USING THE X. L. GUO PROGRAMS

X. L. Guo wrote an SE version and two FE versions of his program that use 2D ANSYS as a driver. The FE programs permit heat to be conducted from the coil where the quench started to other parts of the coil, the mandrel and the banding outside of the magnet coil. The effect of including heat transfer within the coil and to the material outside the coil was to reduce the peak hot-spot temperature in the magnet.

In neither SE program (Guo-1) nor the first FE program (Guo-2), were the internal resistive voltages or turn-to-turn inductances considered when calculating coil voltages. The second FE program (Guo-3) calculates internal resistive voltages and the internal inductances on a turn-by-turn basis. The external resistors reduce the hot-spot temperature and the voltages [12]. Energy extraction by the resistors reduced the hot-spot temperature. Adding resistance and inductance on a turn-by-turn basis reduces the coil voltage without changing the hot-spot temperature very much.

The calculated hot-spot temperature using the SE model was 130 K (based on an adiabatic hot-spot temperature). When the FE model is used and thermal diffusion comes into play, the hot-spot temperature goes down to 105 K. In both cases magnetic energy is being going into the mandrel and banding inductively.

The FE version of the program in Ref. [18] calculated maximum internal voltage for the coupling magnet with eight sub-divisions is ~ 2530 V. The maximum layer-to-layer voltage is ~230 V. The calculated voltages are almost the same for the SE and FE versions of the program (Gou1 and Guo2). Two versions of the Guo program do calculate the resistances of the coil sub-division with time, but they don't calculate the resistive voltage on a turn-by-turn basis. The third version of the Guo code (Guo-3) includes inductance and resistance voltage on a turn-by-turn basis. Since the inductance of the magnet can be calculated on a turn-by-turn basis, that the voltages to ground and the turn-by-turn voltages could be calculated for each turn.

There is a large difference between the Guo2 program discussed in [18] and the Guo3 program discussed in [19] in terms of peak voltages and the lay-to-layer voltage within the magnet. The effective external resistance per sub-division at the full current of the magnet at the start of the quench is ~0.058 ohms, of which 0.038 ohms is in the diode at a forward voltage of 8 V. When this diode heats up to 200 K, the effective resistance across each sub-section drops to ~0.025 ohms. The resistances across the sub-division don't have a large effect on the voltages within the coil. It is very clear that not including internal voltages and internal inductances in the quench calculation can lead to an overstatement of the voltage to ground and the layer to layer voltages, in a large magnet.

VI. CONCLUDING COMMENTS

A comparison of the coupling coil quench calculations are made in Tables I, II, and III. Table I shows the basic magnet design dimensions and the calculated stored energy used in the three codes. Table I compares the assumptions used in the magnet quench calculations for the other two tables. Tables I through III compare the hot-spot temperature, peak voltage to ground, and the layer-to-layer voltages calculated the OPERA 3D, MIT, Gou 2 and, Gou 3 codes.

TABLE I. A COMPARISON OF THE THREE FE QUENCH CODES WHEN USED TO SIMULATE QUENCHES OF THE MICE COUPLING MAGNET WITH EIGHT COIL SUB-DIVISIONS WITH A MAGNET CURRENT OF 210.1 A

Parameter	**Source of the Computer Code**		
	Opera 3D	**MIT**	**Gou-2**
Coil Inner Radius (mm)	750.7	750.0	750.0
Coil Thickness Used (mm)	105.8	102.5	110.0
Coil Width Used (mm)	285	285	285
Magnet Stored Energy (MJ)	13.2	12.9	13.1
Is mandrel considered?	Yes	No	Yes
Is quench-back considered?	Yes	No	Yes
Hot-Spot Temperature (K)	105	122	105
Peak Voltages to Ground (V)	~320	~78	~2530
Layer-to-layer Voltage (V)	~86	~68	~230
Turn-to-turn Voltages (V)	-NA-	~7	-NA-

TABLE II. A COMPARISON OF THE THREE FE QUENCH CODES WHEN USED TO SIMULATE QUENCHES OF THE MICE COUPLING MAGNET WITH FOUR COIL SUB-DIVISIONS WITH A MAGNET CURRENT OF 210.1 A

Parameter	**Source of the Computer Code**		
	Opera 3D	**MIT**	**Gou-2**
Hot-Spot Temperature (K)	104	122	105
Peak Voltages to Ground (V)	~736	~281	~5230
Layer-to-layer Voltage (V)	~100	~71	~230
Turn-to-turn Voltages (V)	-NA-	~21	-NA-

TABLE III. A COMPARISON OF THE VECTOR FIELD, MT AND X. L. GUO QUENCH CODES THAT INCLUDED TURN-BY-TURN RESISTANCES AND INDUCTANCES WHEN USED TO SIMULATE QUENCHES OF THE MICE COUPLING MAGNET WITH EIGHT COIL SUB-DIVISIONS WITH A CURRENT OF 210.1 A

Parameter	**Source of the Computer Code**		
	Opera 3D	**MIT**	**Gou-3**
Hot-Spot Temperature (K)	104	122	105
Peak Voltages to Ground (V)	~320	~78	~75
Layer-to-layer Voltage (V)	~86	~68	~42
Turn-to-turn Voltages (V)	-NA-	~7	-NA-

All of the programs consider the inductive coupling between the magnet coil sub-divisions. Four of the programs consider inductive coupling to the mandrel and the banding. These programs consider quench back and the energy that is absorbed by the mandrel and the banding. The FE versions of the programs consider the heat transport within the coil when calculating hot-spot temperature. The hot-spot temperature is lower for the four codes that apply inductive coupling to the mandrel, cover plate and the banding.

Three of the four FE programs are alike because they consider the internal resistances and internal inductances of the coils, as the coils are turning normal during the quench process. These three programs yield both lower voltages to ground and layer-layer voltages. The MIT and Gou3 programs use the turn-by-turn and resistance and inductances. The Vector Field program calculations were done with larger coil sections. We believe that this is the cause of the larger internal voltages. In all of the codes, the effects of the diode forward voltage and the 0.02-ohm resistances are small.

Three of the five programs suggest that the MICE coupling magnet can be sub-divided into four parts instead of eight parts. The MIT and the Guo-3 codes make a strong case for this assertion. It is clear that including the voltages are caused by internal resistance and inductances reduce the peak voltage to ground and the layer-to-layer voltages. There are differences between the three codes that consider internal resistance and internal inductance. The Vector Field program does not calculate the voltages to ground directly.

It is safe to point out that not all quench protection codes produce the same results. The assumption used to develop the model play a large role in determining the results of the calculation. It is also a good idea to see what happens when the quench is induced at other places besides the usual high field point in the magnet. When the magnet is built from more than one coil and these coils are separately powered, it is a good idea to look at quenches being induced in the remote coils of a multiple coil system [20]

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