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Calculating Quench Propagation with ANSYS®

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***Abstract*—A commercial Finite-Element-Analysis program, ANSYS®, is widely used in structural and thermal analysis. With the program's ability to include non-linear material properties and import complex CAD files, one can generate coil geometries and simulate quench propagation in superconducting magnets. A "proof-of-principle" finite element model was developed assuming a resistivity that increases linearly from zero to its normal value at a temperature consistent with the assumed B magnetic field. More sophisticated models could easily include finer-grained coil, cable, structural, and circuit details.**

A quench is provoked by raising the temperature of an arbitrary superconducting element above its T_c. The time response to this perturbation is calculated using small time-steps to allow convergence between steps. Snapshots of the temperature and voltage distributions allow examination of longitudinal and turn-to-turn quench propagation, quench-front annihilation, and cryo-stability. Modeling details are discussed, and a computed voltage history was compared with measurements from a recent magnet test.

***Index Terms*—ANSYS, quench propagation velocity, superconducting magnets, Nb_3Sn cable.**

I. INTRODUCTION

Magnet safety requires that temperature and voltage developed during a quench remain below certain levels. This subject has been studied extensively and is well documented in the literature[1]. Analytical solutions to the differential equation of heat transfer during a quench have been programmed and used in magnet design that vary from fully adiabatic to cryogenically stable conditions[2]-[4]. A variety of successful approximations have been introduced in order to simplify the solution, including properties that are temperature dependent[5]-[7].

It was always hoped that the commercial Finite-Element-Analysis (FEM) program ANSYS®, widely used to perform structural and thermal analysis of mechanical systems, could be used to solve problems that are coupled structurally, thermally and electrically, such as those seen in superconducting magnets. ANSYS's capability to use non-linear material properties and import CAD files has provided a way to generate complex coil geometries and simulate quench propagation in superconducting magnets. A "proof-of-principle" finite element model was developed using a racetrack coil (Fig. 1) that includes spacers. In this paper we explain the ANSYS model and examine computed results.

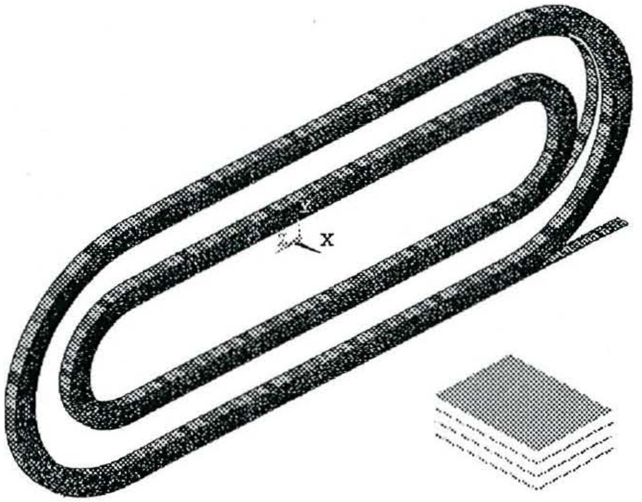

Fig. 1. A meshed inner layer of magnet RD3-C with a close-up showing turn-to-turn insulation (island and spacers not shown).

II. ANSYS MODEL

A. Assumptions

The model assumes the following: 1) the conductor is a cable simulated by an eight-node brick with uniform cross-section (this assumption is not mandatory and a more detailed model can be made based on strands), 2) the current remains constant, 3) the magnetic field remains constant, uniform and is introduced through material properties, 4) in the normal state the thermal conductivity and electrical resistivity are that of copper (Fig. 2) and the specific heat is averaged between copper, Nb_3Sn and epoxy, and are all a function of temperature, 5) spacers have copper properties and the insulation is assumed to have properties of epoxy-glass, 6) the entire coil is thermally isolated (adiabatic), (some of our unpublished results included heat transfer to liquid helium as well), 7) the electrical resistivity in the superconducting state assumes a finite value of 1.0e-13 (ohm-m), 8) the transition from the superconducting state to the normal state varies linearly over a temperature of 0.1 K starting at T_c, 9) T_c depends upon field and current density.

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B. Geometry and Preprocessor

Creating a coil geometry within ANSYS can be very demanding when details are important. The study of quench propagation in coils requires knowledge of both the conductor and the insulator. As part of LBNL's approach to integrated design and analysis, we have developed a computer program capable of modeling coils from cables. In the straight section, the conductor is composed of eight corner bricks and at the ends, the curved section takes the shape of short trapezoids. The coil is represented by a large orderly assembly, of numerous bricks that start and end with a pair of open leads. The coil and insulator files are read by our CAD program (Pro/Engineer), which has a direct connection to ANSYS. Should other components, such as spacers, wedges or structural elements be needed, they can be included in the CAD model or added within ANSYS at a later time as was done here. Initially, within ANSYS, the geometry is considered to be an assembly of many volumes that need to be interfaced. To properly create the cable, we glue and mesh all electrically conducting elements and assign them the element SOILD69. The insulator (2x0.1 mm between turns) and other materials are handled similarly and assigned element SOLID70. Finally, we couple (electrically) the 4 nodes at each lead and assign 0 volts to the lead at one end. One lead is also assigned a constant current value.

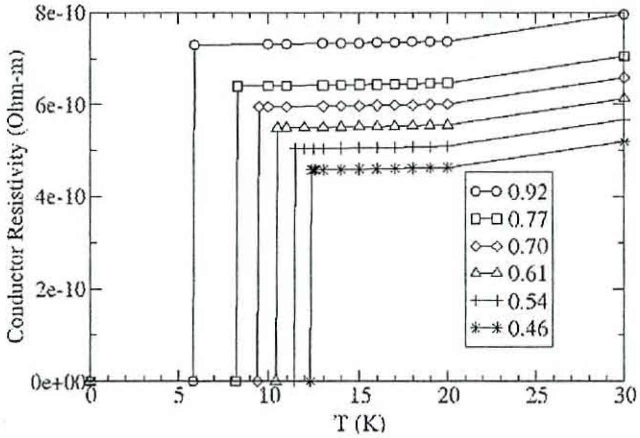

Fig. 2. For a given I/Ic, and below a critical temperature, the conductor is superconducting. At the normal state the resistivity is that of copper with a RRR of 90. For a RRR of 20 the normal resistivity is a factor of 2 higher.

C. Solution

A time dependent analysis was requested and an initial temperature of 4.35 K was imposed over the entire geometry. The quench was invoked by raising the **initial temperature** of selected nodes to 0.4 K above T_c. The minimum time step-size was set to 0.1μs, and the automatic time stepping key was turned on to ensure convergence. The maximum length of time over which the solution takes place is only limited by memory and disk space. We have limited our output to a time period between 50ms and 100ms, and data storage below 8 GB per case. A typical problem used approximately 20,000 elements and the solution required 24 hours on a 2 GHz PC computer.

III. RESULTS

Temperature and voltage records during a quench have been studied as a function of time and position. The animation feature in ANSYS was found to be informative during this process.

A. Quench propagation and annihilation

Thus far, all quenches have been initiated in only one location near the end of the straight section next to the lead-end of the pole turn. For a period of time the quench propagated along the conductor in both directions (Fig. 3) generating heat that raised the insulator temperature and pre-heated adjacent turns or spacers.

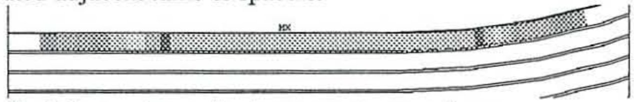

Fig. 3. Temperature profile along a quench propagation zone.

As the temperature increases, adjacent turns start to quench and the process is repeated from turn to turn. Along turns, the normal zone propagated around the coil until it joined with normal zones arriving from the opposite side (annihilation). Other components such as insulation (Fig. 4) and spacers (Fig. 5) react thermally by raising their temperatures.

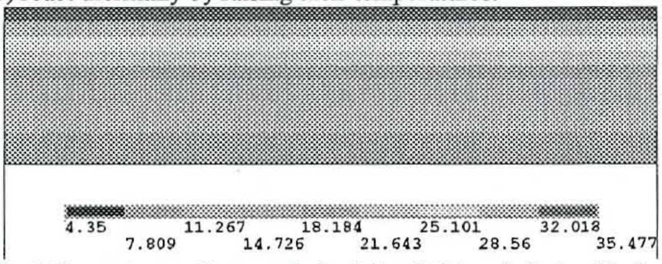

Fig. 4. Temperature profile across the insulation (2x0.1 mm). On top side, the conductor is normal at 35 K. On the lower side, the conductor is still superconducting.

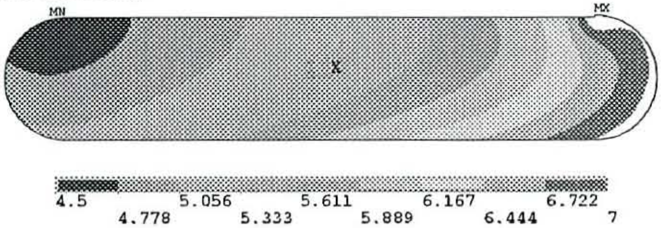

Fig. 5. Temperature distribution around the island (pole) generated by normal zone heat conductions.

The multitude of normal zones propagating and terminating (Fig. 6) in combination with non-linear material properties make the solution highly non-linear and reveals a great number of details.

A record of a typical voltage response to a quench is shown in Fig. 7. The turn-to-turn propagation is clearly visible as a change in slope during the voltage rise and has been recorded on many magnets in the past [8].

Since the late 1980's, LBNL has been routinely measuring the instantaneous voltage time-derivative across voltage taps during magnet tests. All magnets show that values of voltage derivatives are not constant but tend to rise sharply the instant a new turn becomes normal followed by what looks like an

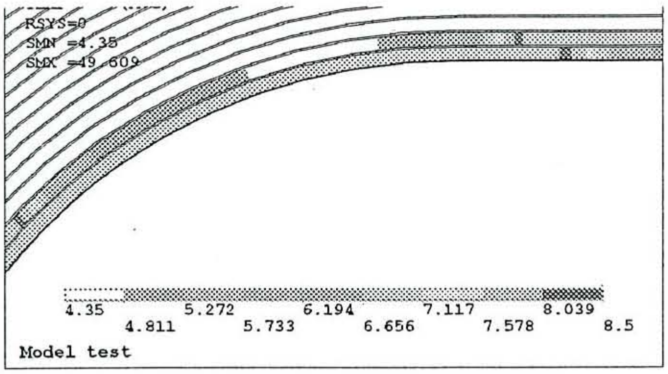

Fig. 6. Normal zone propagation and annihilation, temperature profiles show superconducting state.

exponential decrease. Temporarily high instantaneous quench velocities have been interpreted as the result of local pre-heating. Once pre-heating is exhausted the velocity decreases to a steady value. By the time a quench starts in a new turn, it had a chance to pre-heat it over a longer segment compared with previous turns. The result is an ever-increasing, instantaneous velocity that lasts over longer periods of time.

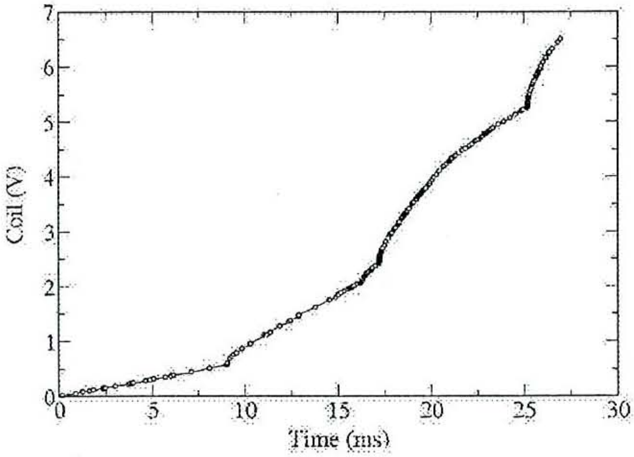

Fig. 7. Calculated voltage rise during a quench, 10T, I/I_c=0.77, RRR=90

The rapid instantaneous rising and slower falling of the voltage derivative has been confirmed by a numerical differentiation of the voltage time profile as shown in Fig. 8 (typical measured values are shown in Fig. 9). After a new turn starts quenching, the initial high quench velocity decreases as pre-heating is exhausted. The process repeats at larger values as additional turns start quenching. Eventually, normal zones that propagate in opposite directions collide, reducing the number of quench fronts by two.

B. *Magnet RD3-c*

As an example of comparison with quantitative data, we simulated a quench in the inner layer of magnet RD3-C [9] where the applied field on the coil could reach 11 Tesla. The transient problem was solved at five different field values with a corresponding reduced current I/I_c. Material properties for each field and two different triple R's, RRR=90 and RRR=20 have been used. We have summarized all results in the following set of figures. Quench velocities (Fig. 10), increase from a few m/s at low field to over 200m/s at 90% of short sample. The velocity as a function of the reduced current, closely fits an exponential curve and compares well with calculations using Wilson's formula [2]. The simplified formula however does not include additional axial heating and is thereby sensitive to the RRR. The ANSYS result shows that the velocity does not depend on RRR, in agreement with the measured values by Ghosh et al [11]. For turn-to-turn propagation, we define a delay time as the elapsed time for a quench in turn 2 to be initiated following the initial quench in turn 1. That time (Fig. 11) depends predominately on the insulation thermal diffusivity and is only a weak function of RRR.

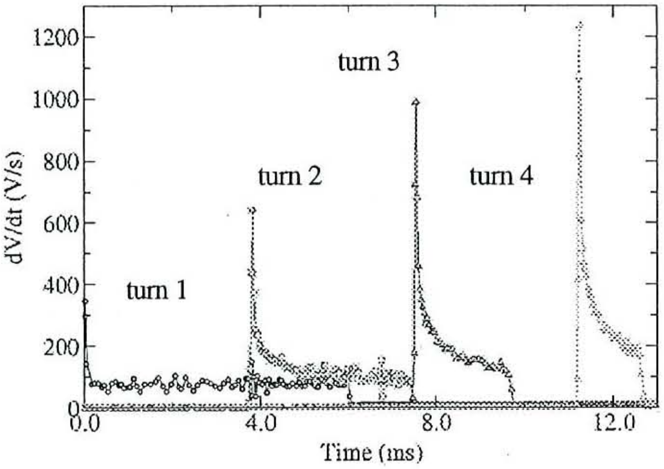

Fig. 8. Derivative of voltage with time shows local effects of turn-to-turn propagation and instantaneous changes of quench velocity due to pre-heating

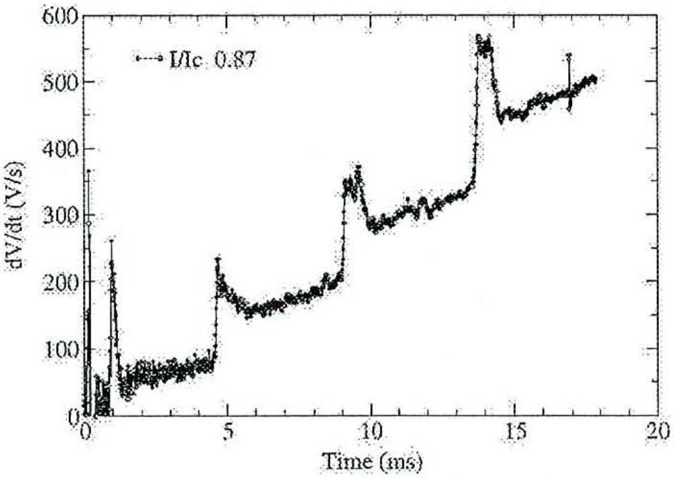

Fig. 9. Measured derivative of voltage verses time in magnet RD3-c

The voltage and temperature rise during a quench showed an exponential increase as a function of the reduced current (Fig. 12 and Fig. 13). Such values have been plotted at an arbitrary time of 30ms after quench initiation using two different RRR's. The RRR value makes a noticeable difference. We also point out that the voltage may be a factor of two higher if the quench was to originate within the coil rather than next to the island as was done here.

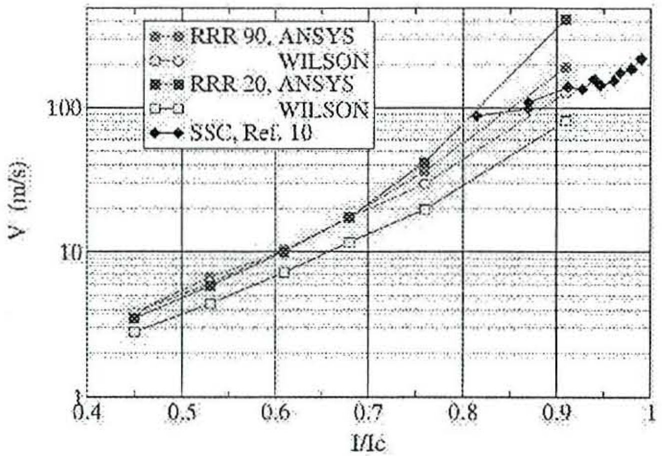

Fig. 10. Quench propagation in a impregnated Nb_3Sn coil. The SSC data was measured in NbTi magnets with B-stage epoxy and inter strand helium.

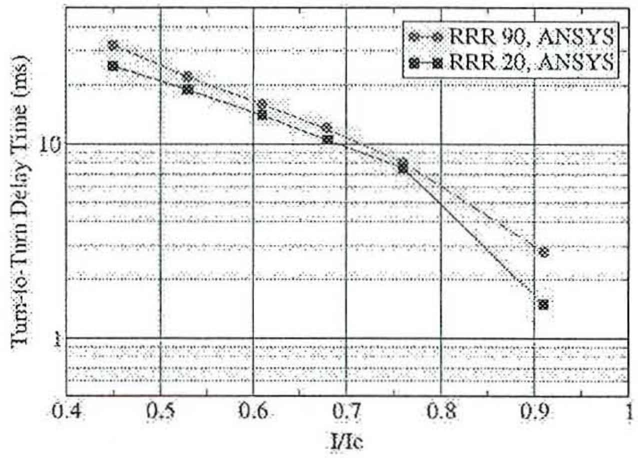

Fig. 11. Turn-to-turn quench delay time

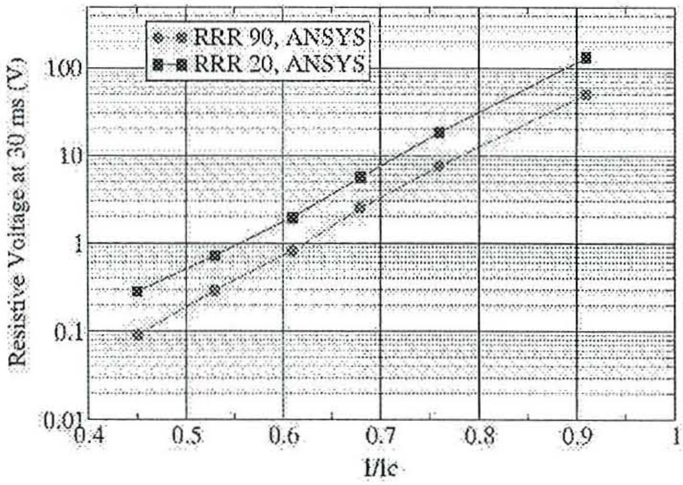

Fig. 12. Total resistive voltage at 30ms after quench initiation.

IV. CONCLUSION

The program ANSYS is a potential tool for studying normal zone propagation in superconducting magnets, and could be a greater benefit in the design of accelerator and fusion magnets by combining electrodynamics, thermal, mechanical and fluid dynamics analysis. Qualitative and quantitative information on voltage and temperature can easily be gained on conductor, spacers, insulation, structural material, and surrounding liquid helium. This tool, in particular, could aid in the design of passive quench heaters, mix-strand cables, intra-strand cores, joints, as well as the understanding of mechanical responses to a quench [12].

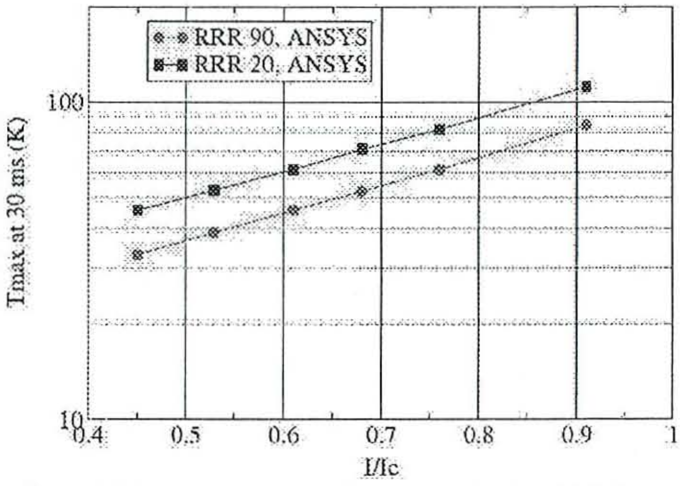

Fig. 13. Maximum coil temperature (local), 30 ms after quench initiation.

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