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# QUENCHES AND RESULTING THERMAL AND MECHANICAL EFFECTS ON EPOXY IMPREGNATED $NB_3SN$ HIGH FIELD MAGNETS

R. Yamada, S.W. Kim, A. Lee, R. Wands, J-M. Rey, FNAL, Batavia, IL 60510, USA
M. Wake, KEK, Tsukuba, Ibaraki, 305-0801, Japan

*Abstract*

Thermal and its resulting mechanical stress due to quenches inside the Epoxy impregnated $Nb_3Sn$ high field magnets are studied with a combination of a quench simulation program, and ANSYS program. We use the geometry of the high field cosine theta type dipole magnets with one meter and 10 meter length. The turns, where quenches started, are excessively heated up, up to 100 K to 300 K, depending on the coil length and time delay. The non quenching turns and surrounding material are not heated substantially. This elevated temperature and its gradient cause the excessive local stress in the quenching conductors and their insulation material. The stress and strain in the conductor as well as in the insulation become excessive, and they are studied using the ANSYS stress analysis.

## 1 INTRODUCTION

Recently there is a trend to develop high field accelerator magnets beyond 10 Tesla dipole magnets using $Nb_3Sn$ superconductor for the next generation accelerator/collider project. To protect a long high field magnet from burning due to quenches, we have to dissipate the stored energy, inside the magnet coil when it quenches. This problem is getting tougher when the magnet length is made longer. This problem is addressed in our previous paper [1].

Each LHC magnet is provided with a high current diode for dissipating individual magnet's stored energy into its own cold mass for its quench protection. It is reported the hot spot temperature is in the order of 320 to 350 K in the event of quenches with full energy deposit [2]. The Rutherford cable of the LHC magnet is made of NbTi superconducting strands, and wrapped with Kapton and glass tapes, and not Epoxy impregnated. Therefore the individual cabled conductor or individual conductor block has a freedom to expand in some extent during a quench. After the quench, when the conductor is cooled back, the cable will come back to the original position.

The $Nb_3Sn$ strand becomes brittle after its reaction. Therefore a coil wound with $Nb_3Sn$ Rutherford cable has to be completely Epoxy impregnated to keep the conductor rigid. The coil is Epoxy impregnated together with spacing wedges and other material. When the superconductor quenches, it is rapidly heated up, but the surrounding material will not be heated up except by the eddy current in itself due to the rapidly changing magnetic field.

We study the thermal and its resultant mechanical stresses in the conductor and its surrounding insulation in this paper.

## 2 ANSYS CALCULATIONS BEFORE AND AFTER QUENCH

In this paper we study the thermal effects due to the quench, using the geometry of the dipole magnet with cosine theta coil, which is being developed at Fermilab [3]. Its regular ANSYS analysis has been done and reported for its structural analysis at the room and at liquid Helium temperature, and for the mechanical stress analysis due to the Lorenz force at the operating temperature [4].

We assume the thermal effect due to a quench can be handled independently in a good approximation, because the electrical changes due to quench process will be finished much faster than the thermal effects. During that transient time we assume we can superimpose these two effects. But in this paper we will handle the thermal effects due to the quench separately.

For ANSYS analysis after the quench we use detailed meshes around the conductor area, separating insulation layer from the conductors to study the effect on the insulator layer.

## 3 THERMAL CALCULATION OF HEATER'S DELAY TIME

The heaters are installed on the outside surface of the outer layer of the coil, which can be turned on with a variable time delay. The time delay of starting a quench, after heaters are turned on is estimated using ANSYS. It is 15 ms in our geometry with 10 mm wide heater strip with a power of 100 W/cm$^2$.

## 4 KUENCH CALCULATION

Quench processes are simulated by "Kuench1. 1.6"[4]. In the simulation a magnet coil is considered as a long cable. This long cable is divided by elements. Heat balance equation for each element is used to calculate voltage and temperature of the element, and the circuit equation is used to calculate the current. Cooling and the thermal contact between turns and layers are considered also. To mimic the transverse heat transition, thermal contacts between elements with a certain distance (length of one turn) are taken in account. Figure 1 shows the calculation model and

Figure 2 shows the flow chart. Details of the simulation are described in a companion paper [4].

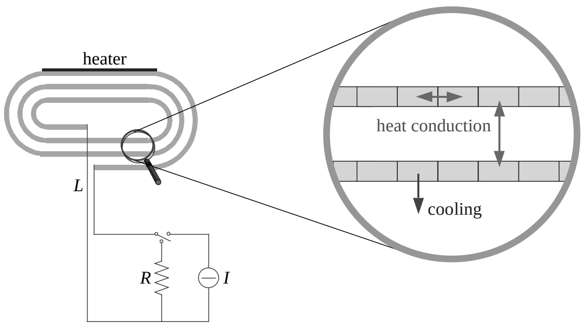


Figure 1: Quench Calculation model.

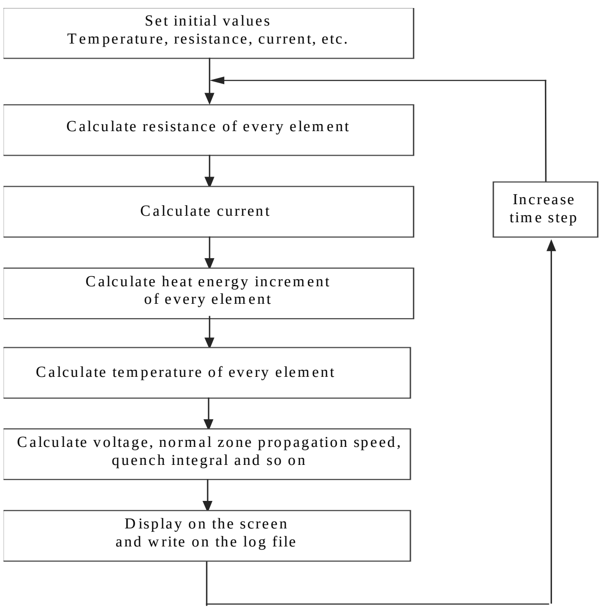


Figure 2: Flow chart of the calculation.

## 5 THERMAL CALCULATION BY ANSYS

The energy generated in every conductor turn is calculated with Kuench program every millisecond, and its data file is inputted into ANSYS program to calculate the temperature every ms in every turn.

Then using this information, the thermal distribution in two-dimensional magnet cross section is studied with different configurations of the magnets. First the one meter model magnet with a 30 mΩ dump resistor is estimated and then a 10 meter long magnet with the same dump resistor is estimated. The two-dimensional temperature distributions in the magnet cross section are quench propagation in 2-dimension intuitively. The quenching conductor cables get heated locally much higher than the surrounding material and non-quenching conductor cables. recorded every 5 ms, and visually displayed. This visual animation displays help to understand the thermal and

With a one meter magnet with a dump resistor of 30 mΩ, typically only the quench starting cables and its neighbor cables gets heated up to 100 K without a strong effect of the heaters. With a 10 meter magnet, heaters cause the quenches to most of the conductor blocks. In this case the quench initiating cables get up to 250 to 300 K in 100 ms, and the other conductor blocks go up to 150 to 200 K for the 10 meter magnets.

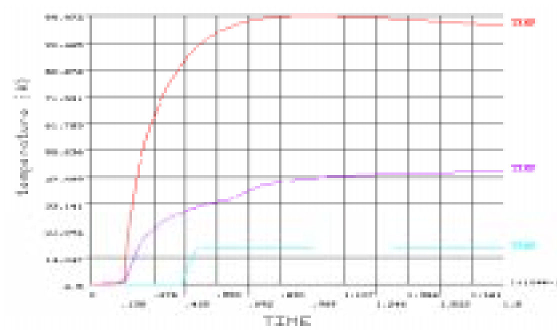

Fig.3: Temperature variation in time at the quenching conductor and at the outer coil of one meter magnet.

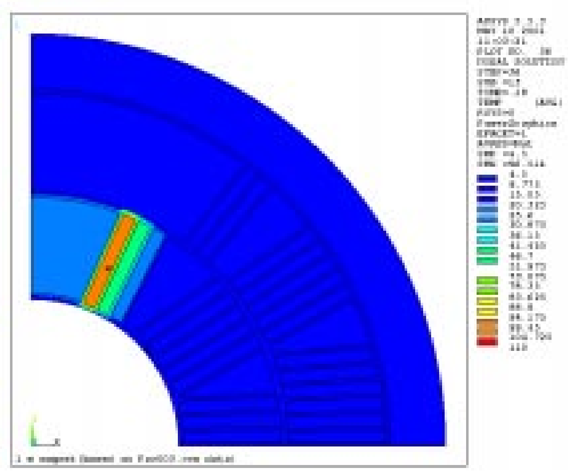

Fig.4: Temperature distribution in the cross section of a 1 m long magnet after 200 ms.

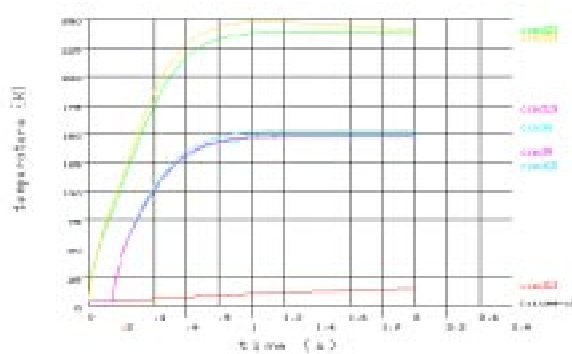

Fig.5: Temperature variation in time at the quenching conductor and at the outer coil of ten meter magnet.6 Mechanical Stress Analysis and its interpretation

## 6 MECHANICAL STRESS ANALYSIS AND ITS INTERPRETATION

The quenched conductor is locally heated up to 100 K to 300 K, depending on the condition, while the surrounding

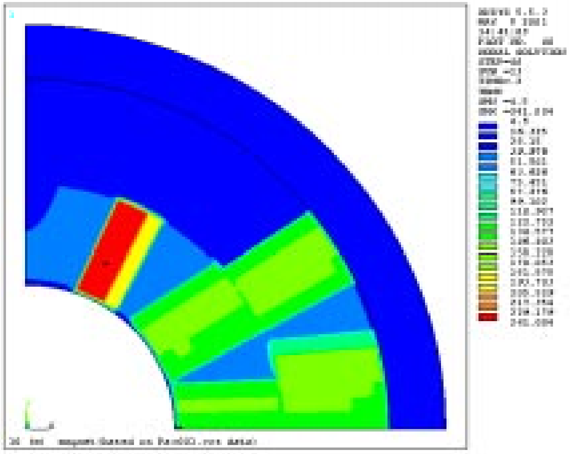

Fig. 6: Temperature distribution in the cross section of a 10m long magnet after 200 ms.

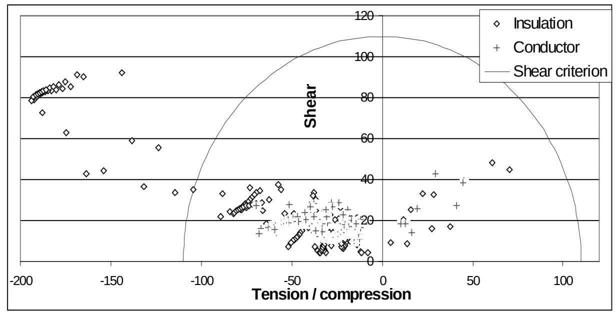


Fig.7: Von Mises criterion of thermal stress and strain for of a 1m long magnet after 100ms.

material is almost kept at cold temperature. In the 2-dimensional magnet cross section this will cause the compression in every parts of the coil, especially in the heated conductors and in their wrapping insulation material. Also this will cause shear forces between the heated conductor and the surrounding material through the insulation material in 3-dimension.

If the heating due to a quench is excessive, this will cause much more stress on the insulation, which is Epoxy impregnated. This will cause shearing cracks between the cable and the insulation layer, and cause cracking in the insulation itself.

The most common criterion to estimate the stress level in a structure is to use the Von-Mises criterion. Unfortunately this criterion does not reflect the relative contribution of tension or compression and shear on the local stress level. The representation of the stress distribution using a shear versus tension-compression diagram has been proved to be effective for the analysis of mechanical properties in insulation (6). This representation is a based on a Mohr circle representation for all the nodes of the mechanical analysis. Since the Mohr circle is defined by its radius and its center, by definition located on the abscissa axis, the plot of the radius versus the center for each of the node location summarizes the whole state of stress in the material.

The center of the Mohr circle is defined as $(\sigma_I + \sigma_{II}) / 2$, $\sigma_I$ and $\sigma_{II}$ being the two most distant principal stresses. The radius is the point of highest shear stress and its value is $(\sigma_I - \sigma_{II}) / 2$ (assuming $\sigma_I > \sigma_{II}$). Figure 7 gives a representation of the state of stress in the conductor and insulation for the 1 meter magnet, 100 milliseconds after the start of the quench.

## 8 ULTIMATE PROPERTIES OF EPOXY RESIN

Recent developments of epoxy resins have proved that the intrinsic properties of these materials are far higher than what had been considered before. Among the reasons for these progress are a better understanding in the design of the testing samples on one side, and an optimization of the molecular structure on the other. Failure in pure tension up to 249 MPa has been reported, shear failure reaching 110 MPa. These values coming from different sources are in good agreement, the shear failure being expected twice lower than the tensile one. A failure envelope for a pure shear sample for the epoxy resin is integrated to figure 7 using these published data. Some points of the graph are clearly out the failure envelope, indicating that a shear compression test is needed to qualify the insulation.

## 9 CONCLUSIONS

A new method to estimate the thermal stress in the conductor and insulator after quenches is explained. With a one meter magnet with an adequate dump resistor the stress may be acceptable, but with longer magnet, much more studies are needed.

## 10 EFERENCES


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