Thermal and Mechanical Effects of Quenches on Nb_3Sn High Field Hadron Collider Magnets

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Abstract:

Thermal and its resulting mechanical stress due to quenches inside short and long epoxy impregnated Nb_3Sn high field magnets are studied with a quench simulation program, Kuench, and ANSYS program. For the protection of a long high field magnet, we have to use heaters to dump the stored energy uniformly inside the magnet, after detection of a spontaneous quench. The time delay of starting a forced quench with heaters, is estimated using ANSYS. Using this information, the thermal distribution in two-dimensional magnet cross section is studied. First a one meter model magnet with a dump resistor is used to estimate the effects and then a 10 meter long magnet is studied. The two-dimensional temperature distributions in the magnet cross sections are recorded every 5 ms, and visually displayed. With this visual animation displays we can understand intuitively the thermal and quench propagation in 2-dimensional field. The quenching cables get heated locally much more than the surrounding material and non-quenching conductor cables. With a one meter magnet with a dump resistor of 30 mΩ, typically only the quench starting cables and its neighbor cables get heated up to 100 K without significant effects from the heaters. With a10 meter magnet, heaters cause the quenches to most of the conductor blocks. The quench initiating cables get up to 250 to 300 K in 100 ms, but the surrounding and wedges are not heated up significantly. This causes the excessive stress in the quenching conductors and in their insulation material locally. The stress and strain in the conductor as well as in the insulation become excessive, and they are studied using the ANSYS stress analysis, using Von Mises criterion. It is concluded that for the one meter magnet with the presented cross section and configuration, the thermal effects due to the quench is tolerable. But we need much more quench study and improvements in the design for the extended ten meter long magnet [1].

1. Introduction

With the NbTi superconductor, the dipole field magnet has been developed up to 8.4 Tesla as the practical accelerator magnet to be used for the LHC project. Each LHC magnet is provided with a high current bypassing diode for dissipating individual magnet's stored energy into its own cold mass for its quench protection. It is reported the magnet temperature rise is in the order of 300 to 350 K in the event of individual quench [2]. The Rutherford cable of the LHC magnet is made of NbTi superconducting strands, wrapped with Kapton and glass tapes, but not epoxy impregnated. Therefore the individual conductor cable 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 near to the original position.

To develop a collider magnet with stronger magnetic field, we have to use material other than NbTi. 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. If we keep a similarly sized aperture, the stored energy in the magnet is increased by the square of the magnetic field strength B. To protect a string of long high field magnets from burning due to quenches, we have to dissipate their stored energy, inside the individual magnet coil when it quenches. This problem is getting tougher when the magnet length is made longer, and was addressed in our previous paper [3].

The Nb_3Sn strand becomes brittle after its heat treatment. Therefore a coil wound with Nb_3Sn Rutherford cable has to be completely epoxy impregnated to keep the conductor rigidity. The coil is epoxy impregnated together with spacing wedges and other material. When the superconductor quenches, either spontaneously or with heaters, the superconductor cable is rapidly heated up, but the surrounding material will not be heated up, except by the eddy current in them due to the rapidly changing magnetic field. The quenched conductor is locally heated up to 100 K to 300 K, depending on the condition, while the surrounding 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 the wrapping insulation material. Also this will cause shear forces between the heated conductors and the surrounding material through the insulation material. In 3-dimension, the superconductor will expand longitudinally, causing shear stress with the surrounding material.

With a Nb_3Sn magnet, its stored energy density is much more higher than that of a NbTi magnet, and epoxy impregnated. Therefore the individual cable or individual conductor block cannot move individually. If the heating due to a quench is excessive, this will cause much more stress on the insulation. This will cause shearing forces between the cable and the insulation layer, and cause cracking in the insulation. This will be a cause of training of the magnet. We want to investigate what is a safe margin for a high field accelerator magnet made with Nb_3Sn strands.

2 Strategy

In this paper we will study the thermal and mechanical effects due to the quench, using the geometry of the dipole magnet with cosine theta design, which is being developed at Fermilab [4]. Its regular ANSYS analysis has been done and reported for its structural analysis at the room and at liquid Helium temperature, and for magnetic force analysis at the operating temperature [5]. We use the same geometry, but with more detailed meshes around the conductor area, separating insulation layer around the conductors to study the effect on the insulator layer. 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.

First a quench program Kuench [6] is used to calculate the generated instantaneous energy per ms in each conductor cable element, by inputting the geometrical and magnetic parameters of the model magnet, including the averaged magnetic field value at each conductor cable at the nominal current value. In the Kuench calculation, the heat transfer between adjacent conductors is calculated, which is also done in the ANSYS analysis. Both calculation results should agree. At present these calculations do not include the eddy current nor quenchback effect.

Every 5 ms, the thermal distribution in the whole magnet is calculated, and its 2-dimensional graphical display is stored during the whole cycle of the quench. Later the sequence of 5 ms graphs is combined into an animation display for the period of a quench. This gives a very intuitive understanding for the process of a quench.

We pick the time during a quench, when the conductor shows a maximum temperature. At that time we do the structure analysis using the ANSIS, and find the stress on the conductor, the surrounding insulation layer, as well as on the whole structure, to find out the stress is excessive or not.

During a quench, electrical and thermal effects occur simultaneously. However, because the electrical changes occur much more quickly than the thermal changes, we assume in this paper that the thermal effects due to a quench can be handled independently to a good approximation. For the ANSYS analysis of post-quench thermal deformation, we use detailed meshes around the conductor area, separating insulation layers from the conductors to study the characteristics in detail.

3. Thermal Calculation of Heater's Delay Time

The heaters are made of 10 mm wide stainless steel strips, and can be triggered with a variable time delay. They are mounted on the outer surfaces of the first and second outer conductor blocks from the median plane, as seen in the Fig.4, and they generate 100 W/cm^2 each. The time delay for starting a quench, after heaters are turned on, is estimated with the ANSYS analysis, at 15 ms for our geometry with the central field of 11 Tesla.

4. Kuench Calculation

In the quench simulation a magnet coil is considered as a long cable, which is divided short elements, as shown in Fig.1. Heat balance equation for each element is used to calculate its temperature and its incremental change, and the circuit equation is used to calculate the current. Cooling and the thermal contact between turns and layers are considered also. To simulate the transverse heat transition, thermal contacts between elements with a certain distance (length of one turn) are taken in account. Figure 2 shows the flow chart for the simulation calculation and details are reported in a previous paper [6].

5. Thermal calculation by ANSYS

The energy generated in every conductor turn is calculated by the Kuench simulation every millisecond, and its data file is input to the ANSYS program to calculate the temperature every five ms in every turn. With this information, the temperature distribution in the two-dimensional magnet cross section is studied for different magnet configurations. First, a one meter model magnet with a 30 mΩ dump resistor is analyzed; then a 10 meter long magnet with the same cross section and with the same dump resistor is considered. The temperature rise with time was animated using the ANSYS results, and it appears that the calculated two-dimensional temperature distributions in the magnet cross sections are consistent with an intuitive understanding of quench propagation. This animation allows the visual confirmation of heat transfer characteristics in a cross section very vividly. The quenching conductor cables are heated far more than the surrounding material and non-quenching conductors.

First a typical spontaneous quench is studied with a one meter magnet with a dump resistor of 30 mΩ. In Fig.3 is shown the temperature variation in time of the quench starting cable. The quench starting cable at the highest field point is heated up to 100 K, 83 ms after the quench start time, and the next neighboring cable is heated up to 45 K. The conductor cables, which are heated by heaters effectively 26 ms after the quench initiation, went up to 18 K as is shown also in Fig.3, without a strong effect from the heaters. Because of the short time constant system of 35 ms, the main current in the cables decay fast, not generating too much heat in the main part of the coil. In Fig 4 the calculated temperature at 180 ms is shown. From these data, we can judge that there will be no serious thermal and mechanical damage in the 1 meter magnet coil.

With a 10 meter magnet, after the spontaneous quench at the inner top cable, heaters cause most of the conductor blocks to quench 15 ms later. In this case, temperatures in the quench initiating cables rise to 250 K in 100 ms, and the other conductor blocks rise to 150 K, as is shown in Fig.5. The temperature distribution in the magnet at 200 ms later is shown in Fig.6. The inner two highest turns reach 250 K and 240 K at 100 ms, and the four conductor blocks, which are heated with heaters, reach 150 K at 120 ms. But the uppermost outside current block, which is not heated, reaches only at 13 K at 200 ms. The temperature of the wedges next to the quench initiating block is about 50 K at 200 ms. The time constant of the system is about 200 ms, so the thermal and mechanical stresses are much more in the long magnet case.

6. Mechanical Stress Analysis and Its Interpretation

The quenched conductor is locally heated to between 150 K and 250 K, depending on the condition, while the surrounding material remains at lower temperature. In the 2-dimensional magnet cross section this will cause compression in all parts of the coil, especially in the heated conductors and in their wrapped insulation material. Also, this will cause shear forces between the heated conductor and the surrounding material. This shear effect will be largest along the length of the magnet.

Shear stresses on the epoxy impregnated insulation increase with the intensity of a quench, resulting high temperature gradients. A sufficiently violent quench can cause shear cracking between the cable and the insulation layer, and cracking in the insulation itself.

A common criterion to assess the significance of the stress level in a structure is the Von-Mises criterion. Unfortunately, this criterion does not separate 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 effective for the analysis of mechanical properties in insulation [7, 8]. This approach is based on a Mohr circle representation for all nodes of the mechanical analysis. Since the Mohr circle is defined by its radius and 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 $(\sigma_I + \sigma_{II}) / 2$, where σ_I and σ_{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 represents the state of stress in the conductor and insulation for the 1 meter magnet, 100 milliseconds after the start of the quench.

7. Ultimate Properties of Epoxy Resin

Recent developments of epoxy resins have proved that the intrinsic properties of these materials are far greater than what had been considered before. Among the reasons for this progress are a better understanding of the proper design of testing samples on the one hand, and an optimization of the molecular structure on the other. Failure stresses in pure tension of up to 249 MPa have been reported, with shear failure reaching 110 MPa. These values come from different sources, and are in good agreement, because shear failures are typically expected at half the stress of tensile failures. A failure envelope for a pure shear sample of the epoxy resin is overlaid on Figure 7 using these published data. Some points of the graph are clearly outside of the failure envelope, indicating that a shear compression test is needed to qualify the insulation.

8. Conclusions

A new method to estimate the thermal and mechanical stress in the conductor and insulator after quench is explained. Thermal and mechanical stress after quench is shown to be a serious problem with epoxy filled long Nb_3Sn accelerator/collider magnets. In a one meter magnet with an adequate dump resistor the stress may be acceptable, but with longer magnets, much more study is needed for its magnet design and stress analysis. With the10 meter magnet with the present cross section, the situation seems very serious. We also should investigate the characteristics of the used material, like the epoxy, if they satisfy our criteria. Any simulation program, including the model presented in this paper, need comparison with experimental data for further investigation.

9. References

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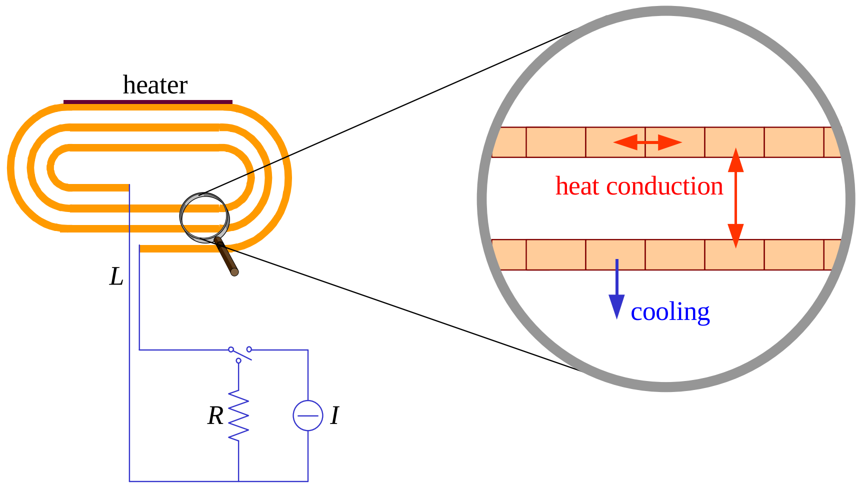

Figure 1: Quench calculation model.

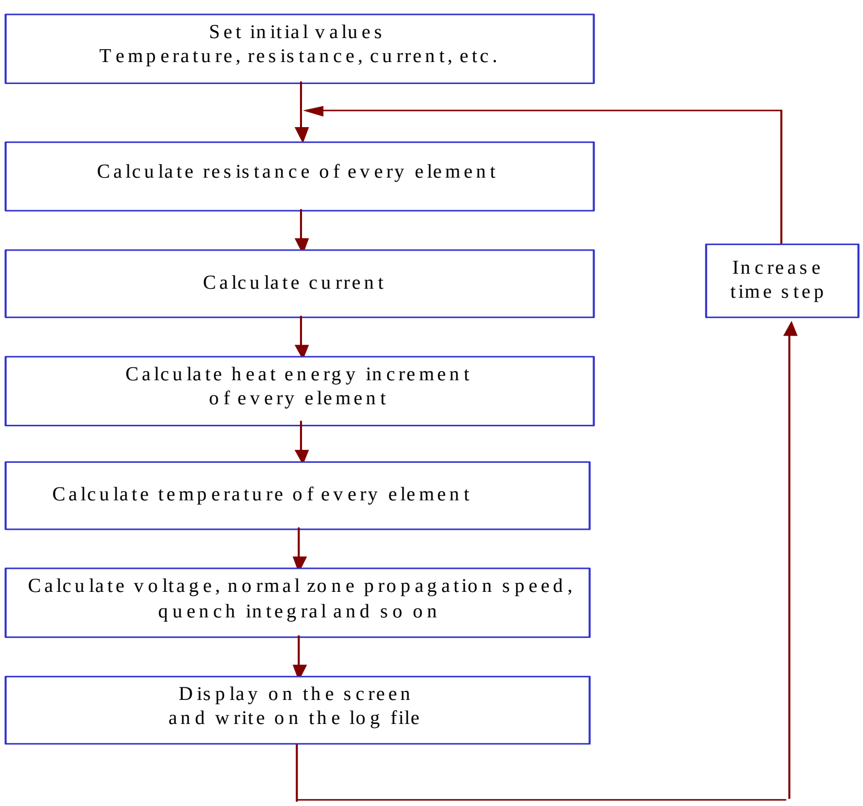

Figure 2: Flow chart of the calculation.

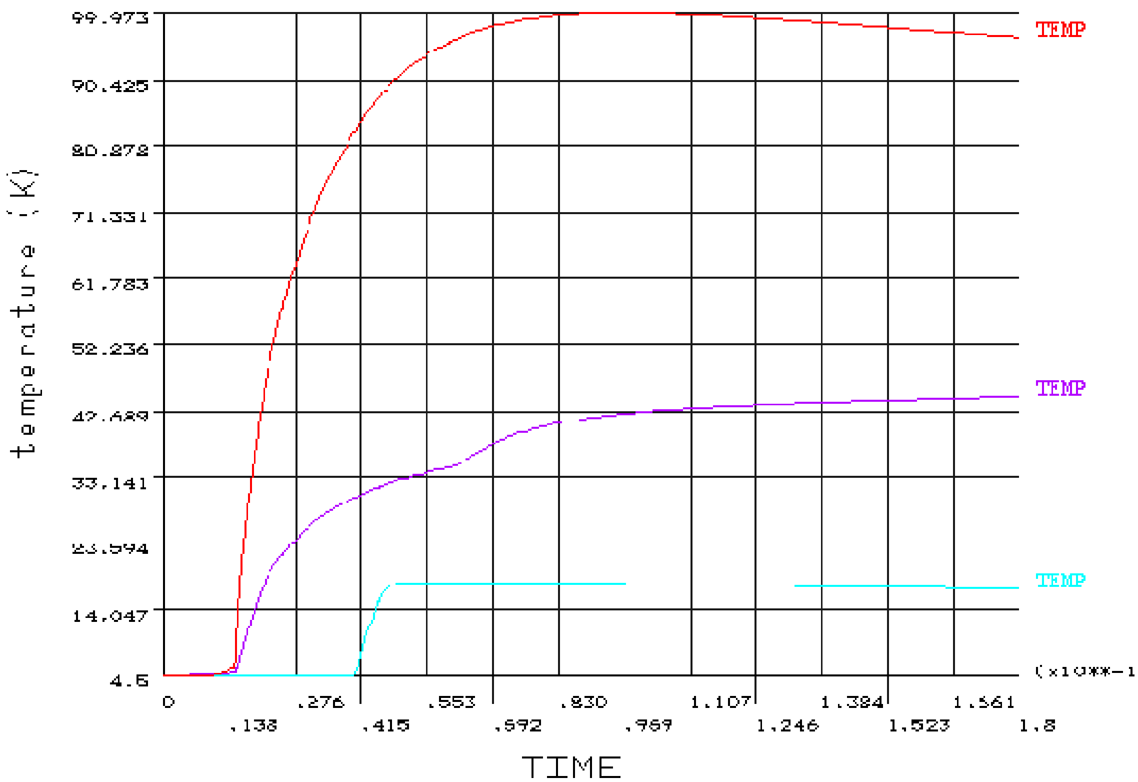

Fig. 3: Temperature variation in time at the quenching conductor and at the adjoining one of one meter magnet. In this case the cable at the highest filed quenched spontaneously at 14 ms (highest line) together with the next neighbor cable. The heaters are tuned on, and the other cables are heated up 19 K.

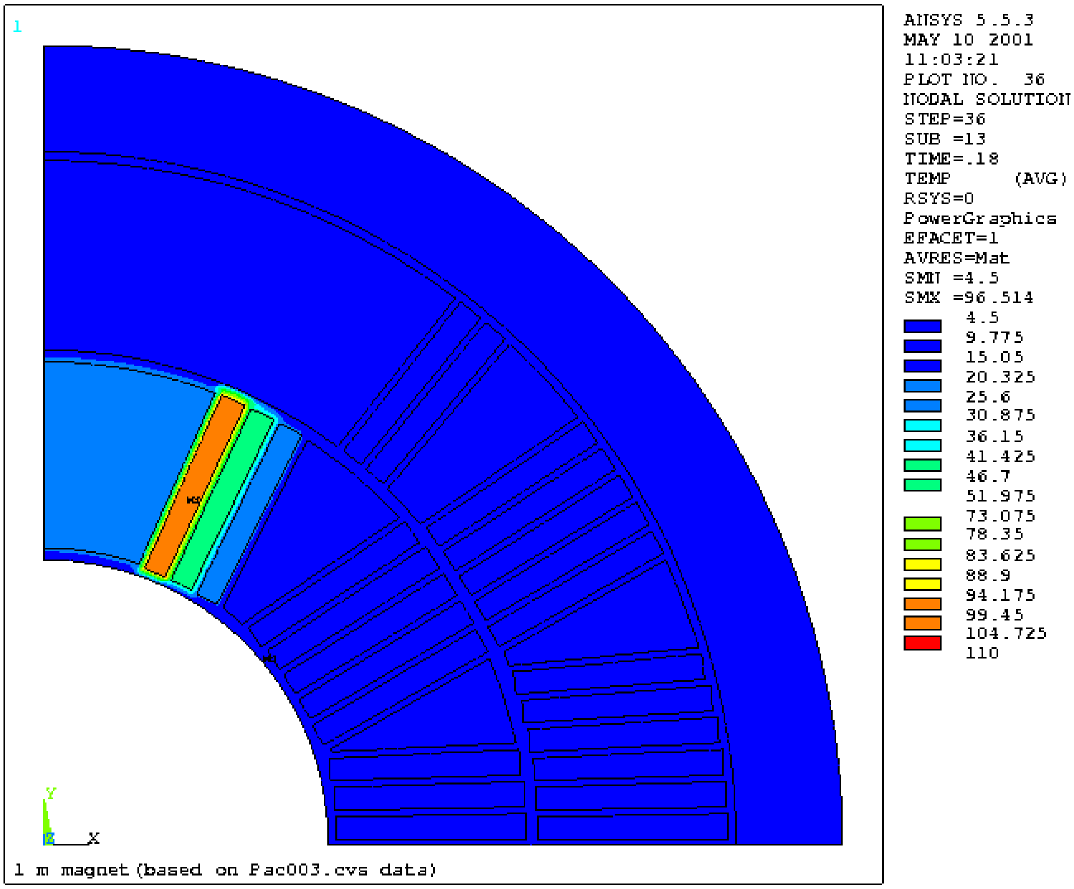

Fig. 4: Temperature distribution in the cross section of a 1 m long magnet after 180 ms, which quenched spontaneously. Only the top and its next cable got heated up significantly.

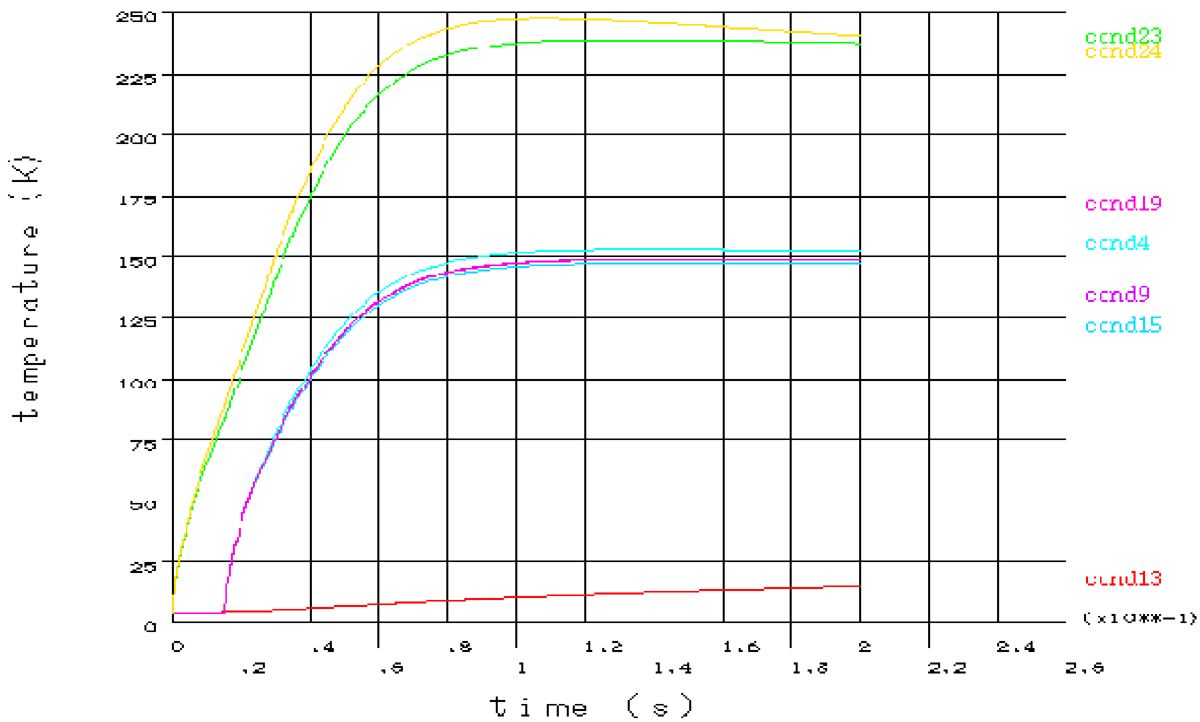

Fig. 5: Temperature variation in time at the quenching conductors and at other conductors of ten meter magnet. The spontaneously quenched cables are shown in the top group, reaching to 240-250 K. The heated cables are shown in the middle group, reaching 150 K. The non heated group is shown in the bottom group.

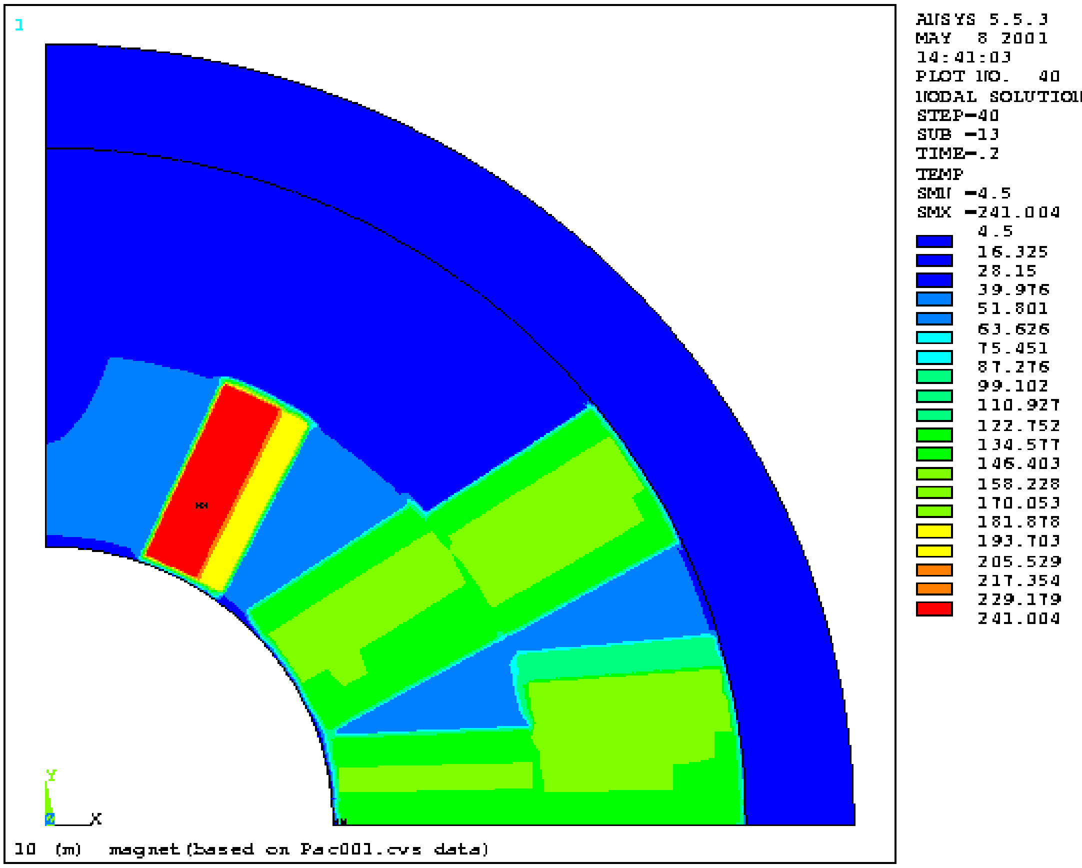

Fig. 6: Temperature distribution in the cross section of a 10 m long magnet after 200 ms. Spontaneously quenched cables are heated above 240 K. The heated cables reached about 150 K.

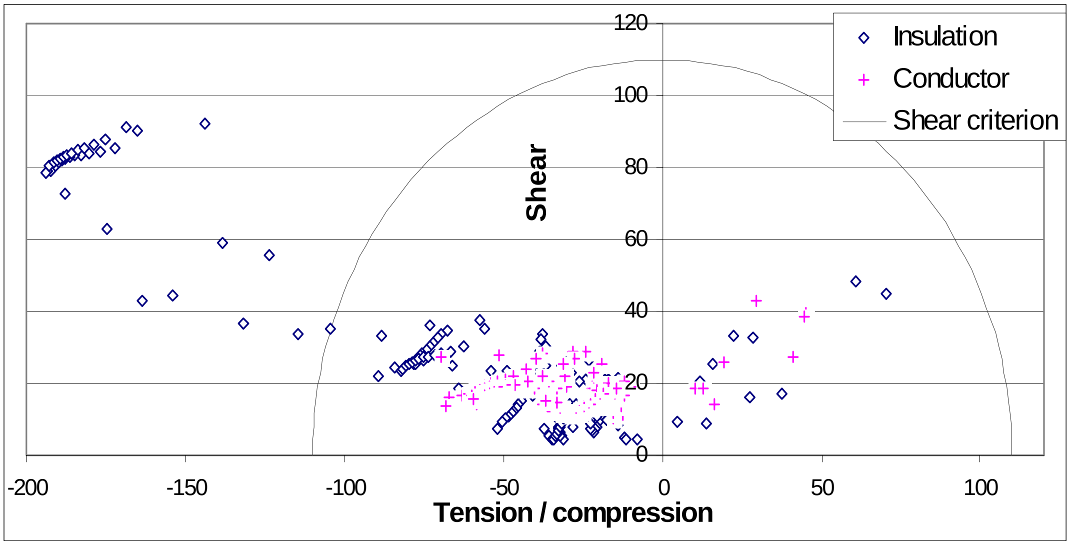

Fig. 7: Von Mises criterion of thermal stress and strain for of a 1m long magnet after 100ms. The negative side of the abscissa corresponds to compression, and the positive side to tension. The ordinate is for shear. Units are in MPa.