Effect of Thermo-Mechanical Stress during Quench on Nb_3Sn Cable Performance

L. Imbasciati, P. Bauer, G. Ambrosio, M.J. Lamm, J.R. Miller, G.E. Miller, A.V. Zlobin

***Abstract*—Several high field magnets using Nb_3Sn superconductor are under development for future particle accelerators. The high levels of stored energy in these magnets can cause high peak temperatures during a quench. The thermo-mechanical stress generated in the winding during the fast temperature rise can result in a permanent damage of the brittle Nb_3Sn. Although there are several studies of the critical current degradation of Nb_3Sn strands due to strain, little is known about how to apply the strain limitations to define a maximum acceptable temperature in the coils during a quench. Therefore, an experimental program was launched, aimed at improving the understanding of the effect of thermo-mechanical stress in coils made from brittle Nb_3Sn. A first experiment, reported here, was performed on cables. The experimental results were compared to analytical and finite element models. The next step in our experimental program will be to repeat similar measurements in small racetrack coils and later in full size magnets.**

***Index Terms*—accelerator magnets, Nb_3Sn, quench, stress**

I. Introduction

To prevent superconducting magnets from damage during high temperature excursions after a quench, it is necessary to determine temperature and voltage levels that can be sustained by the magnet components. This is especially true in high field magnets using Nb_3Sn superconductor, which is brittle and therefore susceptible to mechanical stress induced by fast thermal expansion of the coil. Simulations of the quench process for Fermilab's Nb_3Sn magnets for a Very Large Hadron Collider [1] have shown that 300-400 K is easily attained after a quench, even if protection measures are taken. An experimental program was launched to find the maximum acceptable temperatures that can be sustained in a high field magnet. This information would be useful, not only for preventing damage to the superconductor, but also for determining the minimum size and cost of the active quench protection system. An upper temperature limit is given by the melting point of solder (~500 K), since the quench may start near the conductor joints. For impregnated coils, a lower limit is the glass transition point of the insulation, which is at about 400 K for epoxy resins. At this temperature, the epoxy becomes soft and, even if the transition is reversible, the change of its electrical properties increases the probability of a short circuit. The temperature limit related to irreversible strain damage as a result of thermo-mechanical stress during a quench is the subject of this article. The first part of the experimental program was performed on cables, within a collaboration FNAL-NHMFL [2]. The continuation of the program foresees to perform similar experiments on small coils, within a collaboration FNAL-LBNL [3].

II. Quench Experiment

A. Concept of the Experiment

In a setting similar to that of critical current measurements of cables, a spot heater was used to induce quenches at high currents (just below the critical), in order to heat the cables to a chosen temperature. To that end, the current in the sample is kept constant, instead of switching it off immediately after the quench detection. Using a pre-defined delay, the cable can be heated to a chosen temperature, due to the high current density in the normal-conducting matrix. Since the process is very fast, the metallic structure surrounding the samples (i.e. the sample-holder) remains at a lower temperature, inducing the sought thermo-mechanical stress. A simple adiabatic heat-balance calculation yields an estimate of the hot spot temperature for the samples used in these tests: at 8 kA it takes about 400 ms to reach ~500 K. On the other hand, characteristic times of heat propagation through the sample holder are of the order of seconds. Repeated measurements of the cable critical current after every excursion to higher temperature allow assessing the critical current degradation as a function of the peak temperature during a quench.

B. Measurement Set-Up and Procedure

The experiments were conducted at the conductor characterization facility at NHMFL, which has been used in the past for critical current measurements in the frame of Fermilab's react-and-wind Nb_3Sn conductor study [4]. The NHMFL test facility provides a large bore, 12 T, split solenoid magnet and a 20 kA sample power supply. The sample-holder (Fig. 1) is introduced into the gap between the solenoids and is mechanically supported with a transverse, hydraulic pressure mechanism that is placed within the solenoid bore. The high field region on the sample is as long as the 15 cm diameter of the solenoid bore. Two insulated cable samples are stacked into the sample holder, which is a straight stainless steel U-channel with a bolted G10 cover plate.

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L. Imbasciati, P. Bauer, G. Ambrosio, M. Lamm, A.V. Zlobin are with Fermilab, Batavia, IL, USA (corresponding author phone: 630-840-6651; fax: 630-840-2383; e-mail: ilinda@ fnal.gov).

J. Miller and G. Miller are with the National High Magnetic Field Laboratory, Tallahassee, FL, USA.

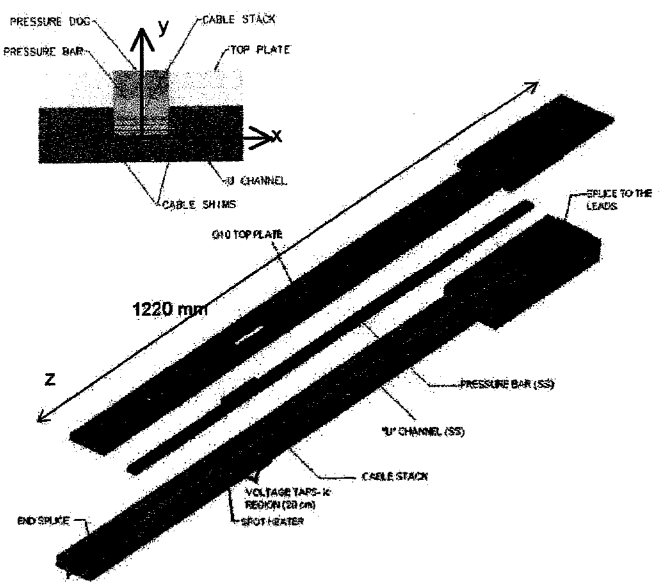

Fig. 1. Cable sample holder cross-section and assembly.

The cables are instrumented with voltage taps and 2.5 cm long spot heaters in the high field region. The samples are spliced at the bottom and soldered to the test-station current leads at the top. The sample stack is impregnated in situ in the holder. The two samples tested in this series are flat, coreless Rutherford-type cables wound from 41, 0.7 mm diameter, ITER-type Nb_3Sn/Cu strands with a Cu/non-Cu ratio of 1.4. One set of samples was reacted straight, while another set was reacted on a spool and straightened after the reaction during the sample-holder assembly, to induce bending strain (0.18% and 0.42%) such as in a react-and-wind magnet.

The experimental procedure consisted of the following steps: -1- critical current measurement at 8 T, and 20 MPa transverse pressure; -2- current ramp to a constant current below the critical current (8 kA and 7.5 kA for the two samples respectively); -3- quench initiation with a spot heater; -4- power supply ramps current to zero after a programmed delay; -5- analysis of the voltage data to estimate temperatures reached in the cable; -6- critical current measurement; This sequence was repeated, increasing the delay time in steps of 50 ms, until peak temperatures of ~500 K were reached.

C. *Summary of Results*

The results of the first cable experiment are shown in Fig.2. They reveal that no critical current degradation occurred after reaching peak temperatures of up to 420 K. During the last critical current measurement of sample 1, a premature quench occurred at 8820 A and the experiments had to be terminated because of a background magnet quench. Therefore, this result can only be regarded as a lower limit to the critical current and is not necessarily a sign of degradation. The samples with bending strain, although showing the expected reduced critical current [4] do not show a significantly different behavior from the samples without bending strain. Also in this case, the measurements could not be pursued to higher peak temperatures, because of a background magnet quench.

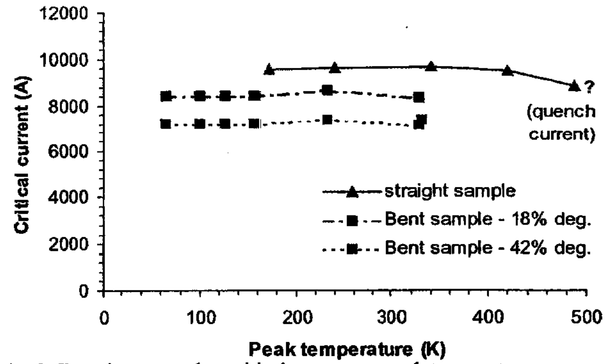

Fig. 2. Experiment results: critical current vs. peak temperature.

The temperature in the samples was estimated from the voltage over the 20 cm long high field section, where the quench was initiated with the spot heater. The measured voltage and current in the sample were converted to a resistance (Fig. 3), which was compared to a tabulated copper resistivity, function of temperature and field. This procedure assumes that the temperature is uniform within the 20 cm high field region.

D. *Adiabatic Thermal Model*

An adiabatic thermal model was developed to estimate the peak temperature in the cable as a function of the delay time. Fig. 3 shows a comparison of the simulated resistance and the measured resistance of the entire sample. The joule heating power is calculated from an electrical model representing the growing resistance in the sample due to spread of the normal zone (longitudinally and transversely to the other cable) and the rise in temperature. The longitudinal quench propagation velocity in the model was 10 m/s. The model also takes into account that the second active cable quenched after 20 ms, as a result of transverse heat diffusion through the insulation. The temperature rise is calculated with the adiabatic quench-integral, *QI*, method, (1), comparing the measured, time-integrated sample current profile, *I*(*t*), with the right-hand side expression containing the temperature integral of specific heat and resistivity of the composite cable (of cross-section *A*). The sought temperature is the upper limit of the right side integral at which both sides converge.

$$QI = 10^{-6}\int_0^t I^2(t')dt' = 10^{-6}A^2\int_{T_0}^{T(t)} \frac{cp_{comp}(T')}{\rho(T')}dT' \quad MIIts \qquad (1)$$

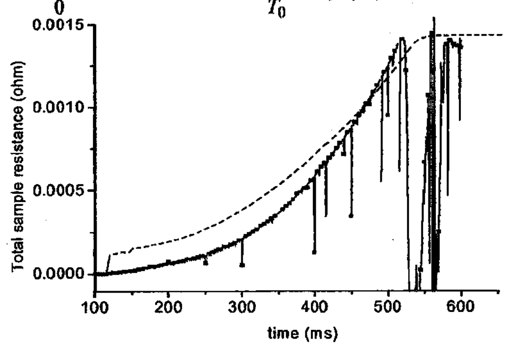

Fig. 3. Comparison of simulated (dashed) and measured (bold) resistance in the sample high field, high temperature region during the experiment.

E. Finite Element Simulation

The main goal of the theoretical investigation is to study the thermal-mechanical stress during a quench in high field, high current density Nb_3Sn magnets. The FE code ANSYS was chosen for this purpose. To gain confidence in the FE model and to calibrate the calculation procedures via a comparison with experimental data we decided to simulate, as a first step, the cable experiment described above. One of the procedures to be tested is the quench process simulation, which requires coupling of the electrical and thermal variables. The advantage of a completely integrated solution is that the heat conduction from the cable to the environment is already included in the ANSYS calculation, through a solid element with two degrees of freedom: voltage and temperature. The temperature gradient between the coil and the surroundings is the most important contributor of the thermal stress on the cable. The current is a time dependent input function, even though it is essentially constant in the cable test simulation. The quench propagation is determined by a resistivity function, varying from a very low value to the normal state value, with a fast rise at the generation temperature. In view of the simulation of the quench in the magnet, the electrical circuit is to be implemented to compute the magnet current decay. The stress analysis can be done at the end, when the peak temperature has been reached. The stress in the insulation layer is of particular interest, because the temperature gradients are the highest. In addition, epoxy cracking in the insulation is one of the concerns that have to be addressed in magnets. Therefore, the model must distinguish bare cable and insulation, and the mesh must be accordingly fine. Fig. 4 shows the temperature distribution in the cable hot spot (the model represents one half of the sample holder cross-section) 420 ms after a quench in the top cable. The input parameters (current, cable material properties, insulation type and thickness) correspond to the experimental conditions of the straight sample (8 kA current). The thermal conductivity of the impregnated cable and that of the insulation are as measured recently in especially dedicated experiments [5].

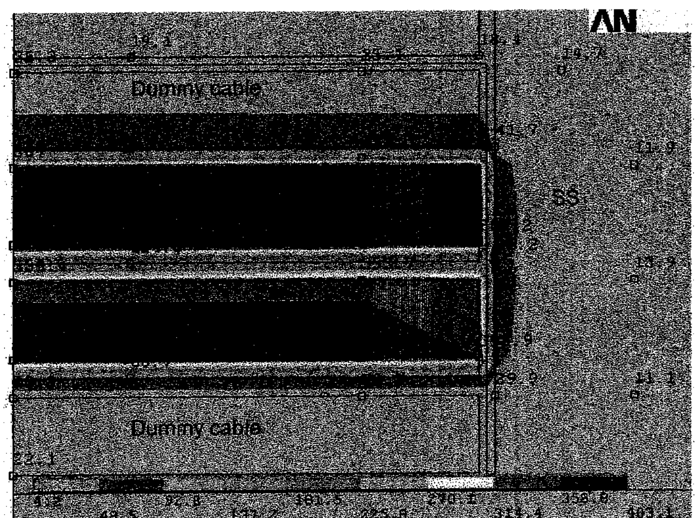

Fig. 4. Temperature distribution in the sample holder, 380 ms after a quench (enlargement of the hot spot region). Simulation with ANSYS.

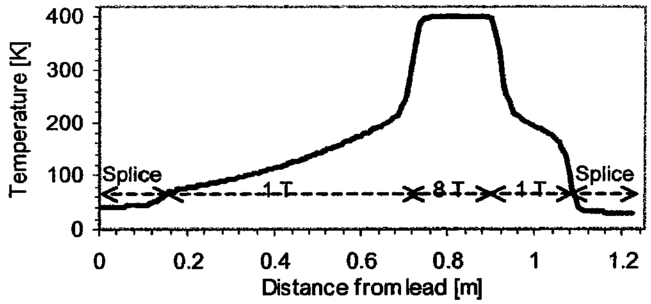

Fig. 5. Longitudinal temperature profile in the cable, 380 ms after the quench start. Simulation with ANSYS.

The maximum temperature predicted by the ANSYS model is in good agreement with the experimental value. A 10 % temperature overestimation occurs at 400 ms and later, which could be due to an underestimation of the cooling effect in the ends, or to inaccuracies in the material conductivities. The resulting temperature profile along the top cable is shown in Fig. 5. The FE model confirms also the assumption that the bulk of the sample holder remains at bath temperature during the experiment.

III. Thermo-Mechanical Stress Estimation

The total strain inside the Nb_3Sn filaments is determined, in general, by the sum of several contributions:

- the pre-compression of the Nb_3Sn filaments, due to the difference between the thermal contraction of Nb_3Sn and of the bronze/copper matrix, from the reaction temperature (typically 650 K) to the peak temperature after the quench,
- any applied strain, due to pre-stress, Lorentz force or thermo-mechanical stress as discussed here as well as bending in the case of react-and-wind magnets.

A. Intrinsic Pre-Compression

The measured intrinsic pre-compression for strands of the same type at 4.2 K [6] is 0.28 %, and the irreversible intrinsic tensile strain is 0.64 %. The irreversible intrinsic pre-compression strain was not measured, but it is known that the Nb_3Sn is less sensitive to compressive than to tensile strain. At 400 K the intrinsic pre-compression is reduced with respect to the 4.2 K level, due to the reduced thermal contraction of the materials from the reaction temperature. The intrinsic strain in the Nb_3Sn (ε_{int}) after cool-down from the reaction temperature T_{react} to the temperature T cannot easily be estimated because many other factors must be taken into account. These factors include the temperature dependence of the elasticity modulus of all the materials inside the strand, the yielding point of the copper/bronze matrix (depending on the previous thermal history), and the twist of the filaments inside the strand. Neglecting these factors, an estimate of the intrinsic strain $\varepsilon_{int}(T_{peak})/\varepsilon_{int}(4.2\text{K})$ can be made on the basis of (2), where Δ is the linear thermal contraction coefficient per K, E the elastic modulus and f is the bronze fraction in the superconductor (f = 0.5 in our samples). This procedure yields a 62 % decrease of the intrinsic pre-compression at T_{peak} = 400 K, with respect to the measured intrinsic strain at 4.2 K.

$$\varepsilon_{int}(T)=\frac{(\Delta_{Nb3Sn}-\Delta_{bronze})(T_{react}-T)}{1+E_{Nb3Sn}(T)f/[(1-f)E_{bronze}(T)]} \quad (2)$$

B. Quench Induced Strain

A conservative estimate of the stress level that develops inside the cable due to the high temperature differences with the surrounding mechanical structure is given by a simple model of a cable restrained from expansion while being heated uniformly to peak temperature (T_{peak}). This hypothesis corresponds to the approximation of an infinitely rigid and cold sample holder.

The strain is calculated using an integrated thermal contraction factor α, measured on an impregnated Nb_3Sn cable stack, from room temperature to 77 K, of 0.298 %, in z and x-directions, and 0.415 % in y-direction [5]. The integrated thermal contraction increases by ~10 % cooling the samples further to 4.2 K [7], giving $\alpha_z = \alpha_x = 0.34$ %, and $\alpha_y = 0.45$ %.

$$\varepsilon_{therm}(T_{peak}) = c\cdot(T_{peak}-T_{bath}); \quad c=-\frac{\alpha}{(297-4.2)\mathrm{K}} \quad (3)$$

The calculation indicates that a peak temperature of 400 K causes a thermal compressive strain ε_{therm} of 0.46 % in z and x-direction, and 0.62 % in y-direction. In the case of a triangular temperature profile with T_{peak} in the center and T_{bath} at the cold ends, the peak thermal strain is reduced to half (0.23 %). The simulation of the temperature profile with the finite element model (see Fig. 5) indicates a temperature profile that is close to the triangular case. The integrated thermal strain derived from the FE model is 0.22 %. Assuming also a triangular temperature profile of the cable stack in the y-direction (fig. 4), the transverse thermal strain calculated with (3) is 0.31 %.

C. Total Intrinsic Strain

In summary, the calculated axial compressive strain in the filaments in the cable samples at 400 K peak temperature is predicted to be: 0.11 % intrinsic strain, after a 62 % reduction from 4.2 K computed with (2), plus the cable thermal expansion, obtained with (3), of 0.46 %, 0.31 %, and 0.23 % in x, y, and z-direction respectively. The total compressive strains, in the straight sample, summing (2) and (3), in the three directions are 0.55%, 0.44 %, and 0.34 %. For the bent samples, adding a bending strain of 0.4 % as in the worst case, would give 0.9 % total strain, which exceeds the measured irreversible degradation tensile limit.

D. Quench Induced Stress

The stress is calculated as a function of temperature, from the temperature dependent elasticity modulus E of the cable stack. Measurements with a biaxial fixture [8] show that if the cable stack is impregnated under moderate pressure, the resulting modulus is about 22 GPa at 300 K, and 31 GPa at 4.2 K in z and x-direction, and 18 GPa at 300 K, and 24 GPa at 4.2 K in y-direction. Similar conditions are applied during impregnation of the cable samples. A Poisson ratio of 0.3 in the x-y plane and 0.15 in z-x and z-y planes were used to calculate the stress in all dimensions [7].

The resulting stresses for a peak temperature of 400 K are 130 MPa in x-direction, 92 MPa in y-direction, and 77 MPa in z-direction. These figures are conservative estimates, since the assumption of infinite rigidity sample-holder is not correct, especially for the transverse directions. In y-direction, for example, the pressure piston and the G10 plate restrain the sample. The pressure of the piston was set, before the quench, to 20 MPa. Even though the stress developed during the quench, might lead to a temporary increase in the pressure, the sample cannot be considered completely constrained.

IV. Conclusions and Outlook

The resulting strains and stresses in the straight sample are below the damaging levels [6]. This calculation is therefore in agreement with the measurements of the straight sample, which do not show any critical current degradation for peak temperatures up to 400 K.

For the next test run, the use of sub-sized cables with state of the art conductor is proposed. Because of the lack of a cable test-facility that can produce the high current and field required to measure the critical current of a state of the art conductor, the use of LBNL small coils was proposed to pursue the quench test program. The small coil approach allows testing of the cable in an environment, which is more like a magnet, than a straight sample-holder. The ultimate goal is to perform quench measurements in accelerator magnets. In order to see clearly a degradation of the critical current after quenching it is necessary to have a magnet performing at the short sample limit.

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