Study of the effects of high temperatures during quenches on the performance of a small Nb_3Sn racetrack magnet

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Abstract. Several high field Nb_3Sn magnets of different design are under development for future particle accelerators. The high levels of stored energy in these magnets and the high current densities in the conductor can cause high peak temperatures during a quench. The thermal gradients generated in the epoxy-impregnated magnet coils during the fast temperature rise can result in high thermo-mechanical stresses. Considering the sensitivity of Nb_3Sn to strain and epoxy cracks, it is important to define a maximum acceptable temperature in the coils during a quench which does not cause degradation of the magnet performance. A program was launched at Fermilab to study the effects of thermo-mechanical stress in Nb_3Sn coils, supported by experiments and by analysis. In collaboration with LBNL, a sub-scaled magnet was built and instrumented to measure the effect of the thermo-mechanical shock during magnet quenches. The magnet consisted of two racetrack coils, assembled in a common coil configuration with a small gap in between. During the test, the magnet reached the maximum field of ~11 T at the short sample current of 9100 A. Temperature excursions up to 400 K did not diminish the magnet quench performance; only after temperature excursions over 430 K, the magnet showed detraining effects, which reduced occasionally the quench current of about 6%. Signs of irreversible degradation (reducing the maximum current of about 3%) appeared only after temperature excursions over 550 K.

1. Introduction

Fermilab, LBNL, and several other laboratories around the world are developing Nb_3Sn magnets for future particle accelerators [1,2]. Simulations of the quench process for Fermilab's Nb_3Sn magnets, showed that parts of the coils can reach 300-400 K, even with an effective quench protection system [3]. The studies performed in the context of a Very Large Hadron Collider (VLHC) [4] in particular, have revealed the need to establish a maximum acceptable temperature, which strongly affects the size and the cost of the quench protection system. Fermilab and LBNL have started an experimental and theoretical program, in order to determine which level of temperatures and voltages a Nb_3Sn magnet can sustain without degradation.

An upper temperature limit is given by the melting point of the soldering (~500 K), since the quench might start near the conductor joints. Below this limit, there is the glass transition point of the epoxy resins, which are commonly used to impregnate Nb_3Sn coils in order to avoid stress concentrations on the brittle conductor. At about 430 K, epoxy resins undergo a reversible transition, during which they becomes soft, leading therefore to loose mechanical support of the brittle conductor. Furthermore, the weakening of the insulation could increase the probability of a short circuit.

An additional effect of a high peak temperature during a quench in a superconducting magnet is a very asymmetrical temperature distribution, since most of the magnet remains to a much lower temperature. The resulting thermal stresses could degrade the epoxy or even the brittle superconductor. A failure to adequately protect a magnet can lead to degradation of the magnet performance. For example, the superconducting outsert (10 kA/16 T peak field) of the 45 T NHMFL hybrid magnet system was recently degraded because of an "unprotected" quench [5]. Consequently, operation of the outsert has been limited to 8 kA (but insert upgrades and higher current allow the system to still provide 45 T).

2. Concept of the experiment

In order to measure the effects of high peak temperatures during quenches on Nb_3Sn magnets, an experimental program was launched at Fermilab. The concept of the experiment consists in repeating quenches to higher and higher peak temperatures ("thermal shock" tests), and measuring the critical current afterwards. The quenches for the thermal shock tests are initiated with a spot heater placed in the high field region, and the temperature is measured via the resistivity of a cable segment including the spot heater. The increasing peak temperatures are reached by programming increasing delay times for the activation of the current switch.

A first experiment was performed on cables, within a collaboration FNAL-NHMFL [6]. The results of this experiment showed no critical current degradation up to hot-spot temperatures of ~400 K. A subsequent thermo-electrical simulation of the quench up to 400 K was performed using a Finite Element model (described in detail in [7]). The resulting temperature distribution revealed that the thermal stresses were below the irreversible limit of the conductor, but close to the epoxy shear strength.

The experimental program continued within a collaboration between Fermilab and LBNL. A Subscale Magnet (SM), was built and instrumented at LBNL in order to perform the thermal shock experiment. The use of a LBNL SM ([8,9]) allowed a continuation and an improvement of the quench tests program. In fact, the facility at LBNL allowed the use of state-of-the-art Nb_3Sn conductor, in a mechanical environment similar to that of a real accelerator magnet. The LBNL Subscale Magnets, using standard cable and state-of-the-art Nb_3Sn strands, have routinely achieved the predicted short sample current in the past [10], which is a necessary condition in order to have a clear indication of the effects of the peak temperature on the magnet performance. In addition to reasons mentioned above, there were other factors, such as fabrication cost, helium consumption, and time required for measurement preparation, which made it more advantageous to perform the quench test on a Subscale Magnet (about 1/3 scale) than on an accelerator magnet model.

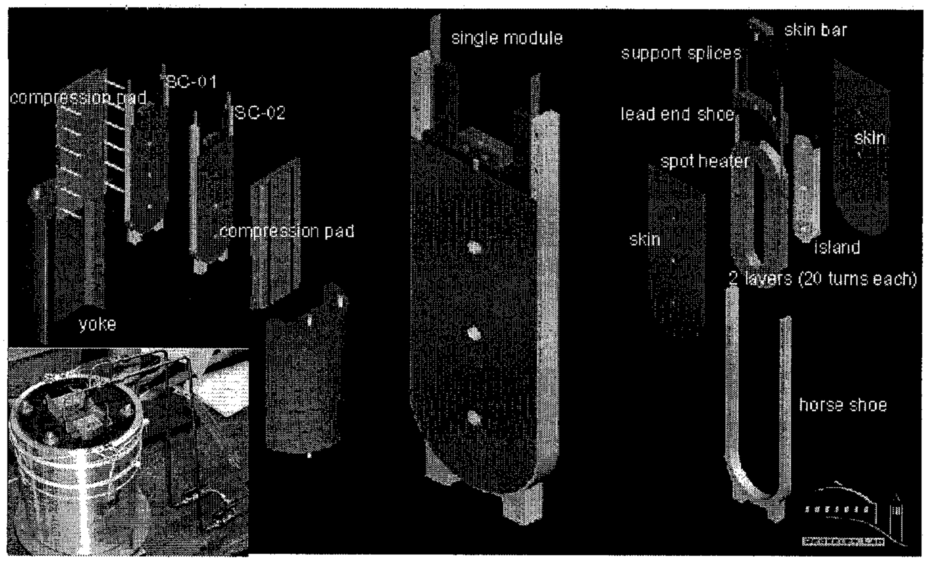

Figure 1. Subscale magnet assembly

3. Experiment setup

Subscale Magnets can reach fields of 8 – 12 T, with operating currents of 8 – 10 kA. They consist of two "double-pancake" racetrack coils (see Figure 1). Each coil is wound in two layers without splice using ~20-meter long sub-sized cable (8 mm wide, 1.3 mm thick). The magnet inductance is about 0.4 mH, for a total stored energy of about 20 kJ.

The thermal shock quench test was performed on the fifth SM assembled at LBNL (named SM05), consisting of SC10 (the tenth coil of the SM program fabricated and instrumented for this test) and SC01 (the first coil of the SM program) [11].

3.1. Conductor parameters

The cable for the Subscale Magnets is fabricated at LBNL-Supercon-AFRD, by the superconducting magnet cable group. The conductor used for SC10 consisted of Modified Jelly Roll (MJR) strands, produced by Oxford Superconducting Technology (OST). The cable and conductor parameters for the coils of SM05 are listed in Table 1 (details in [12]). The cable insulation consisted of epoxy impregnated S2-glass sleeve.

The conductor for SC10 had ~60% copper content, while the one used in SC01 had only 45%, in order to have a lower critical current in SC10 than in SC01.

Table 1: Conductor parameters of SM05 coils

Conductor parameters	Coil 1	Coil 10
N of strands	20	20
Cu:SC	0.81	1.5
Cable width (mm)	8	7.84
Cable thickness (mm)	1.3	1.27
Strand diameter (mm)	0.701	0.672
Pitch angle (°)	17	15.9
Packing factor	0.83	0.83
J_c (A/mm^2) @12T/4.2K	2265	1763
I_{SS} (A)*	9924	9101
B_{peak} (T) in the coil at I_{SS}	11.985	10.57
Cu RRR	41	54
Insulation (mm)	0.15	0.15

*Best performance of SM01 and SM05 respectively.

In addition, the reaction cycle chosen for SC10 was shorter than the reaction cycle for SC01. SC10 was kept at 650°C for 100 hours instead of 160 hours. Short sample tests from this reaction cycle showed a slightly lower J_c, and a RRR relatively high for this type of conductor. The lower critical current of SC10 than SC01 assured that the coil under investigation determined the magnet current limit. The short sample current (I_{ss}) reported in Table 1 is the maximum current reached during the test. The peak field corresponding to this current was computed using a Finite Element model of SM05. The peak field occurs in the central turn of the inner layer, straight section, thanks to the effect of the iron of the yoke. The point of intersection between the magnet load line and the strand critical current was 8.7 kA (10.34 T), slightly lower than the 9.1 kA maximum value reached during test.

3.2. Instrumentation

SMs are usually equipped with a couple of voltage taps across each splice, a temperature sensor for each coil close to splices, and some resistive strain gauges on the shell mid-plane. There are no quench protection heaters, since the protection system relies on energy extraction through an external dump resistor of ~50 mΩ. Additional instrumentation was added to SC10 in order to perform the "thermal shock" experiment: a spot heater, voltage taps across the spot heater, and a temperature sensor close to the spot heater (Figure 2). The spot heater was inserted in the highest field region (straight section of the inner layer), so that the effect of local degradation may result in a reduction of the magnet current.

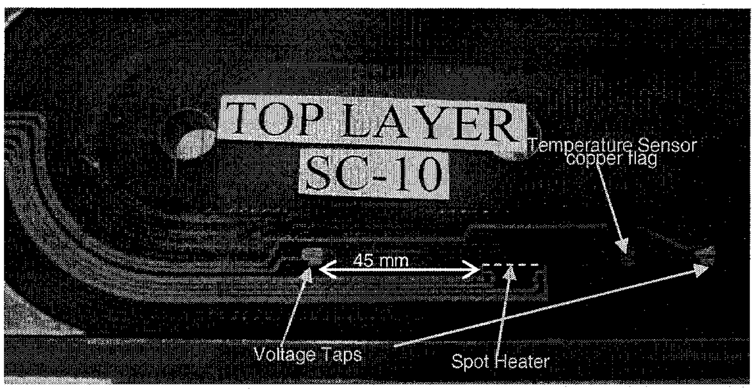

Figure 2. Coil dedicated to the thermal shock test (SC10), with instrumentation, after epoxy impregnation.

3.3. Magnet assembly

The assembly of SM05 was slightly modified from the assembly of previous SM, because previous SM testing had shown a rapid current decay after a quench. Among the causes of the fast current decay are high quench propagation velocities, small inductances, and quench-back induced by the current decay. In order to reduce the current decay after a quench, the gap between the coils was increased to 4.95 mm, which slightly increased the inductance, and decreased the mutual inductance of the two coils, thus helping to avoid quench-back of SC01. A low pre-stress was applied in order to allow separation, and therefore faster training (see training of SM01 [11]), by installing minimum size keys. The resulting pre-stress was calculated to be 6 MPa at 300 K and 97 MPa at 4.2 K.

4. Description of the experiment

The magnet was first trained, according the standard test procedure at LBNL, with a ramp rate of 15 A/s,. The very first quench occurred at low current due to low liquid helium level. The second quench occurred at 97.7% of the computed short sample current (I_{ss}). The magnet trained very fast, reaching 101.3 % of I_{ss} at the fifth quench. The highest current reached was 8757 A (10.47 T), with a ramp rate of 15 A/s.

After the magnet training, the ramp rate dependence was measured. The ramp rate dependence of SM05 was similar to that of other SMs. It is characterized by a large drop of the quench current at ramp rates between 100 and 200 A/s [10].

The first thermal shock tests were performed at a magnet current of 8000 A (I/I_{ss} = 93%) with short dump delay times (10 to 60 ms). Due to the initial settings of the power supply, the current did not remain constant after the quench, even though the voltage over the magnet was below the power supply voltage limit. The voltage signals of these events showed clearly that quench back occurred in SC01, ~14 ms after the quench started in SC10. After the quench back, the voltage over the magnet increased faster, inducing a faster current decay. To reduce the quench propagation velocity and to avoid quench back, the spot heater events series continued at lower the magnet current, using increasing dump delay times. During the last event of this thermal cycle, performed at 3 kA, the magnet reached about 340 K, and did not show any sign of degradation.

Before the second thermal cycle, the power supply was slightly modified, by removing capacitors from the circuit, which subtracted current from the magnet after the quench. This modification allowed a constant current for a longer time after the quench, until reaching the power supply limit of ~60 V. The first training quench of the second thermal cycle occurred at 8810 A, a current not yet reached during the first thermal cycle. After this quench, we proceeded with the thermal shock test. During the first few events, the peak temperature reached about 300 K. Thereafter, the experiment continued repeating spot heater induced quenches at 3000 A, with increasing time delays. The thermal shock events of the second thermal cycle are summarized in Figure 3.

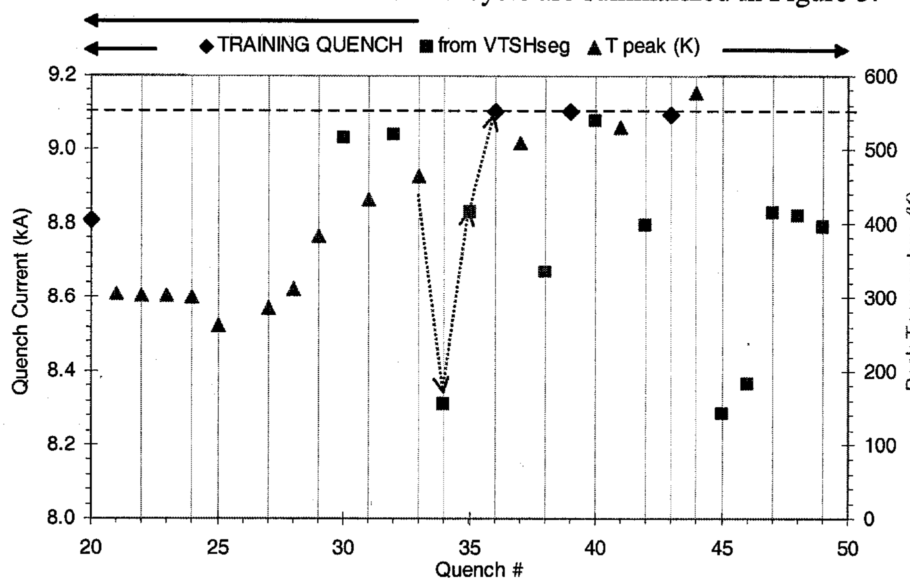

Figure 3. Thermal shock tests during the second thermal cycle: quench current for performance check tests (left axis) and peak temperatures during thermal shock tests (right axis). Arrows highlight the first occurrence of de-training and re-training.

Each event is represented by a quench number (numbers continued from the first thermal cycle) and a quench current (referred to the left axis), or a peak temperature (referred to the right axis). The quench current points (diamonds and squares) represent the case of *ramp-to-quench* events, performed in order to check the short sample limit, and therefore to assess the magnet performance. The peak temperature points (triangles) represent the case of *thermal shock* events. The quench current points are represented by squares in the case the quench started within, or at, the voltage taps close to the spot heater ("from VTSHseg" in Figure 3); by diamonds, in the case the quench did not start in the spot heater segment ("TRAINING QUENCH").

After reaching a peak temperature of 370 K in a thermal shock event (quench # 29), the magnet reached 9028 A in the following ramp-to-quench test, not showing any sign of degradation. During the following thermal shock event, the magnet peak temperature reached 420 K. The following quench current was at the same level as the previous.

During the next thermal shock event (quench # 33), the magnet peak temperature reached 450 K, and the following quench current was 8311 A, 700 A below the previous quench current (8% current decrease). The quench started close to the spot heater. During the following current ramps, the magnet quenched once at 8830 A, and then at 9100 A, the maximum current reached by the magnet. The quench did not start within the spot heater segment. Therefore, the 450 K peak temperature did not induce a permanent degradation, but the magnet suffered only from a temporary detraining.

The following thermal shock event, lasting two seconds, brought the temperature up to ~496 K, which also induced a degradation of ~4.3%. The following two quenches, at the maximum current of 9101 A, and 9077 A, respectively, showed that the magnet had recovered from detraining again. The following thermal shock event, lasting 2.5 s, brought the temperature up to ~518 K. The following quench occurred at a current of 8796 A (3.4% less than the maximum). The quench started simultaneously in all the three coil sections. During the final spot heater event, after a delay of 3.5 s, the temperature reached ~580 K. The following five quenches all occurred below the maximum current and started close to the spot heater segment. The quenches occurred at 8287 A (8.9% less than the maximum), at 8364 A, at 8830 A (3%), and finally, decreasing a small percentage, at 8791 A (3.4% below the maximum current). This was the last quench of the second thermal cycle.

5. Mechanical analysis

An analytical mechanical model was adopted to study the mechanical response of the magnet during a quench generating high temperatures. The model estimates the strain and stress that develop inside the coil assuming an infinitely rigid mechanical structure, a good approximation in the radial direction perpendicular to the racetrack (designated as x axis), since the forces are contained by the thick aluminum shell. In the other directions, the coil is restrained by the horseshoe, and the infinitely rigid boundary approximation is conservative. The pre-stress of 96 MPa given by the thermal contraction of the aluminum shell during cool-down, created a strain at 4.2 K, ε_{0x} = 0.185 %. The temperature distribution inside the magnet was assumed to be uniform along the cable (z-direction), and with a triangular profile in x and y direction (vertical). This distribution was estimated on the basis of quench propagation velocities measured during the tests [12]. The contribution of Lorentz forces was neglected in this analysis because of the low magnet current during the shock tests (3 kA). Since, in the general case of an accelerator magnet, the peak temperature is reached when the current is already moderate, this experiment, although performed at low current, is useful for understanding the general case of an accelerator magnet.

Table 2 reports the thermo-mechanical properties, and the main results. In the uni-axial approximation, a peak temperature of 400 K induced a -0.21% strain in x-direction, -0.27% in y-, and -0.42% in z-direction. The total strain inside the Nb_3Sn filaments (intrinsic strain) is given not only by the quench induced stresses, but also by 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 (650°C) to the peak temperature after the quench (T_{peak}). A typical intrinsic pre-compression for MJR Nb_3Sn strands is $\varepsilon_{int}(4.2\text{ K}) = 0.3\%$ [15]. The intrinsic strain in the Nb_3Sn after cool-down from the reaction temperature cannot easily be estimated, because many factors must be taken into account, including the yielding point of the copper/bronze matrix (depending on the previous thermal history), and the twist of the filaments inside the strand. A rough estimate of the intrinsic strain reduction $\varepsilon_{int}(T_{peak})/\varepsilon_{int}(4.2\text{ K})$, made on the basis of the thermal contraction coefficients, the elasticity moduli, and the Nb_3Sn fraction in the strand, yields a pre-compression reduction of about 50% at T_{peak} = 400 K with respect to the 4.2 K level. The total intrinsic strain (ε_{tot}) was calculated by adding the quench-induced strain, to the estimated thermal pre-strain at 400 K of -0.15%. The total intrinsic strain in z-direction (ε_{tot}= -0.57%) appears to be within the limits of irreversible degradation (> 0.7% [16]).

The stress in z-direction is calculated from the modulus $E(T)$, using a linear fit of data measured on cable stacks, at room temperature and at 4.2 K. For a peak temperature of 400 K, we obtain that the stress reported in Table 2. The Poisson effect was neglected because the coil support structure in y- and z-direction (horseshoe and end-shoe) was not completely rigid. The stresses in x- and y-directions are compared in Table 2, with experimental critical current measurements on cables as a function of applied stress. Table 2 also reports the shear stress caused by the high anisotropic thermal expansion during the quench tests, calculated applying the Mohr's circle in a 3-dimensional model: $\tau_{max} = ½\,|\sigma_{max} - \sigma_{min}|$, where σ_{max} and σ_{min}, are the maximum and minimum stress respectively, between the components of the stress vectors in the x-, y-, and z-directions (the principal directions). The resulting shear stress at 400 K, in the x,y plane, is above the shear strength of the epoxy resin, which is about 43 MPa.

Table 2: Mechanical properties and strain and stress model results, for T_{peak}=400K.

	x	y	z
Thermal expansion α 293-4.2 K (mm/m)	3.08 *	3.36 *	3.08 **
Young modulus E at 4.2 K/293 K (GPa)	52 *	44 *	56/47 **
Poisson ratio ν **	$\nu_{xy} = 0.3$	$\nu_{yz} = 0.15$	$\nu_{zx} = 0.15$
Thermal strain (%)	-0.21	-0.27	-0.42
Total intrinsic strain ε_{tot} (%)	-0.36		-0.57
Thermal stress σ (MPa)	-206	-111	-169
Shear stress τ (MPa)	$\tau_{x,y} = 47$	$\tau_{y,z} = 29$	$\tau_{x,z} = 18$
Irreversible limit	σ = -150/-200 MPa†	σ = -150/-200 MPa	$\varepsilon_{tot} < -0.7\%$

References: * [13], ** [14], † [17,18,19].

Conclusions and outlook

A thermal shock experiment was performed to measure the effects of the quench and the ensuing thermo-mechanical stress on a small Nb_3Sn magnet performance. The results showed that temperature excursions up to 420 K did not effect the magnet quench performance. Only after temperature excursions over 450 K, did the magnet show detraining effects, which occasionally reduced the quench current by about 8%. Signs of irreversible degradation (reduction of the quench current by about 3%) appeared after temperature excursions over 580 K. An analytical model showed that the stresses and strains, up to 400 K, were below the known limits of Nb_3Sn. Above 430 K, the mechanical state of the coil changed, due to the glass transition of the epoxy resin. A more detailed analysis of the quench and of the ensuing thermal stresses using a Finite Element model is under development at LBNL, and will be presented shortly.

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