

Measured Strain in Nb_3Sn Coils During Excitation and Quench

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Abstract—The strain in a high field Nb_3Sn coil was measured during magnet assembly, cool-down, excitation and spot heater quenches. Strain was measured with a full bridge strain gauge mounted directly over the turns and impregnated with the coil. Two such coils were placed in a “common coil” fashion capable of reaching 11 T at 4.2 K. The measured steady state strain in the coil is compared with results obtained using the FEM code ANSYS. During quenches, the transient strain (due to temperature rise) was also measured and compared with the calculated mechanical time response to a quench.

Index Terms—Quench, strain gauge, superconducting.

I. INTRODUCTION

PRE-STRESS in superconducting magnets has always been considered a necessary part in minimizing conductor motion and reduce “training”. Measuring pre-stress however required special consideration due to the complex and none-linear nature of the assembly. Measuring sensors such as strain gauges or capacitor gauges are usually placed on the coil peripheral structure or collars in an attempt to determine the coil stress [1], [2]. In the past measured strain during assembly, cool down, excitation and warm up, suggested that coil stress may vary in nonlinear fashion that is also history and time dependent. A phenomenon called “ratcheting” [3], measured in different magnet structures, suggested a possible connection between the behavior of coils under Lorentz forces, pre-stress, and training. We proceeded to impregnate strain gauges within the coil for the following reasons: 1) a simpler more reliable way to determine the coil stress 2) make strain measurements anywhere within coils 3) measure thermal and quench effects 4) shed light on training and better understand what can be done to eliminate it 5) compare with ANSYS strain calculations during a quench [4]–[6].

The method of placing strain gauges directly onto coils takes full advantage of the impregnation process typical in Nb_3Sn coils. An alternative method of attaching strain gauges to coils after impregnation has been tried elsewhere [7], [8].

We describe the technique of mounting strain gauges (Section II), discuss measured strain data during assembly, cool down, and excitation (Section III) and report on transient strain during spot-heater induced quenches (Section IV).

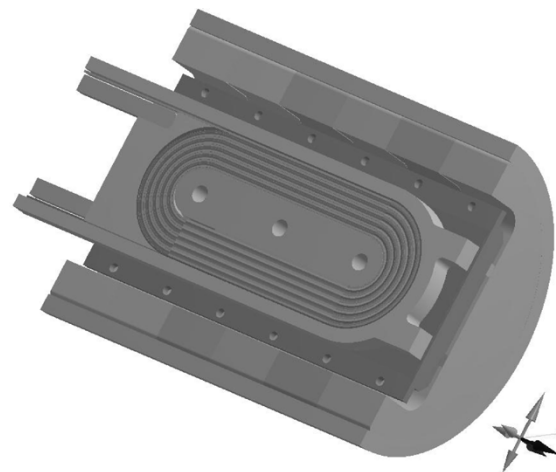


Fig. 1. Exposed racetrack coil surrounded by iron pads, iron yoke laminations, and aluminum shell.

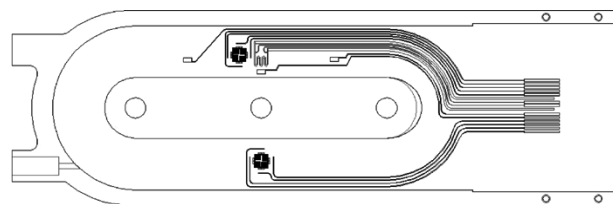


Fig. 2. Trace drawing of the strain gauges, voltage taps and heater.

II. STRAIN GAUGES AND TRACES

A. Superconducting Coils

Winding small Nb_3Sn racetrack coils (~ 2 kg each) is a good way of testing new ideas before their use in large magnets. The small coils, approximately 300 mm long and 90 mm wide, are wound as a double pancake and reacted at 650 C. Two such coils, SC13 and SC14, each with a surrounding stainless protection horseshoe, were placed facing each other in a “common coil” fashion and assembled into a structure (Fig. 1). The assembly used keys and bladders, taking full advantage of the difference in thermal expansion between the inner coils, iron yoke and the external aluminum shell. Testing coils this way was sufficient to withstand pre-stress requirements up to 11 T (at approximately 10 kA).

Attaching strain gauges to coils and securing their position was done with a coil trace overlay. The trace, a ProE (CAD) drawing, included two full-bridge strain gauges, a spot-heater, and several voltage-taps (Fig. 2). Drawn on vellum paper the trace was subjected to a photo etch process that resulted in a 25 μm thick stainless image over a 50 μm thick Kapton sheet.

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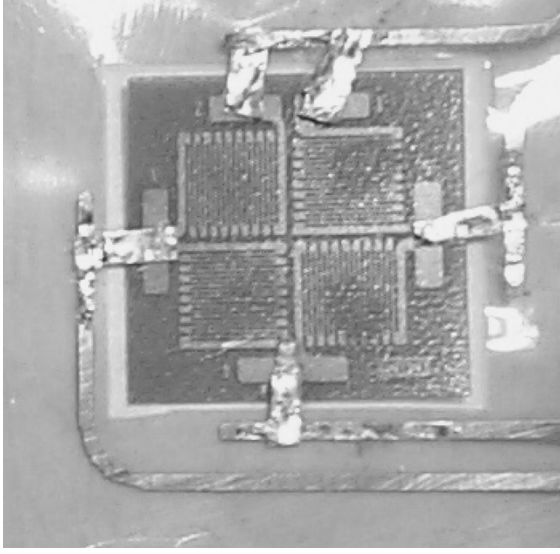


Fig. 3. Cut out in the Kapton sheet with attached strain gauge.

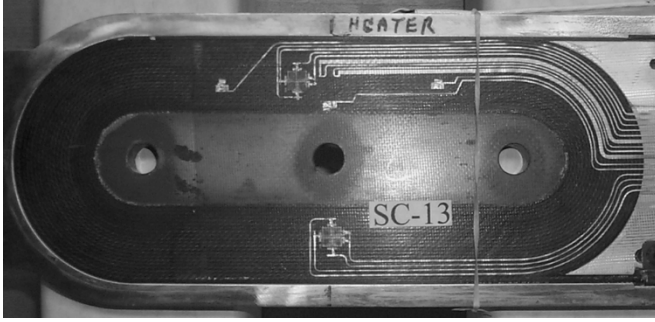


Fig. 4. Coil geometry showing impregnated traces, voltage taps, strain gauge SC13Heater next to the heater and SG13Lead on the opposite side of the island. Only part of the heater is shown above the turns.

Micro-Measurements full bridge strain gauges (350 Ω , SK-13-120NB-350) were used to replace cutout marked squares on the Kapton sheet. The gauges were aligned and soldered to the Kapton trace using short copper wires (Fig. 3). The heater was partially detached from the trace, folded side ways and tucked between two turns in the center block of the straight section. Voltage taps on both sides of the heater were extended over a 100 mm segment and attached to the trace as well. The measured RRR of that segment was later used to determine the average coil temperature near the spot heater. The gauges on coil SC13 were designated SG13heater for the one next to the heater and SG13Lead for the one on the lead side of the coil, opposite the heater. The second coil, SC14, had similar gauges. SC14Lead broke off shortly after cool down and was not used.

A 100 μm thick fiberglass cloth was placed between the coil and the trace. Because the gauges are wider than the turns, they measured the averaged strain across 5 turns (8 mm). After impregnation, the gauges, trace, turns and island become transparent making them completely visible through (Fig. 4).

We assume the thermal expansion of the coil to be isotropic and the bridge temperature to be self-compensating. The full bridge strain is bidirectional ($\epsilon_p - \epsilon_n$), measuring the strain difference between that along the turns (ϵ_p) and that across them (ϵ_n). We expected that in a short common coil configuration end

TABLE I
COOL-DOWN CHANGE IN COIL STRAIN

	$(\epsilon_p - \epsilon_n) \mu\epsilon$ ANSYS, $\mu=0$	$(\epsilon_p - \epsilon_n) \mu\epsilon$ ANSYS, $\mu=0.3$	$(\epsilon_p - \epsilon_n) \mu\epsilon$ measured
COIL	1015	1277	846 ± 120
Shoe	270	906	812 ± 70

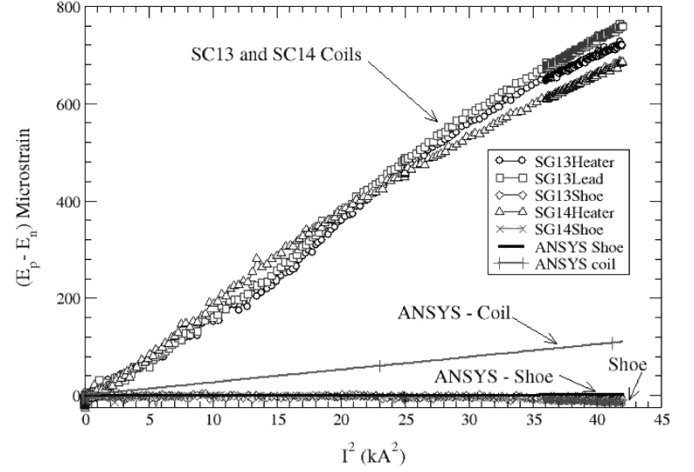


Fig. 5. Measured excitation strain of coil and shoe.

forces would dominate the measured axial strain ϵ_p compared with the transverse strain ϵ_n .

The stainless steel shoes were also instrumented with strain gauges measuring the bidirectional strain in the mid straight section of the shoe. The shoe strain ($\epsilon_p - \epsilon_n$) was that between the strain along the shoe and across it.

III. TEST RESULTS

1) *Cool-Down and Warm-Up:* Strain was measured during assembly, cool-down and excitation. Only a small pre-stress was required for assembly, since most of the pre-stress occurred during cool-down. The measured change of strain ($\epsilon_p - \epsilon_n$) in the coil and shoe during cool-down and warm up is compared with calculations.

2) *Excitation and Spontaneous Quenches:* The magnet performance was limited to 6.7 kA as a result of flux-jump instabilities (65% of short-sample). Up to that current the coil strain gauges responded linearly with the current squared (Fig. 5). However a zero friction ANSY model resulted in a much lower change in strain (a factor of 6 lower). Attempts to improve the model with varying friction factors and coil orthotropic properties made some improvement reducing the difference by 50%. The change of strain in the shoe with excitation was in good agreement with calculations (Fig. 5).

3) *Excitation and Pulsed Heater Quenches:* During the first six sequential spontaneous quenches around 6.7 kA the coil local strain was reduced by 20%. A series of spot-heater quenches followed. All spot-heater quenches were triggered at a current of 1.5 kA, using a 100 ms 1.5 V heater pulse. The magnet power supply could maintain the current level for about 0.5 s before voltage limitations were encountered. The current however was sufficiently high to raise the temperature at the heater location up to a maximum of 350 K (with a 3.5 s

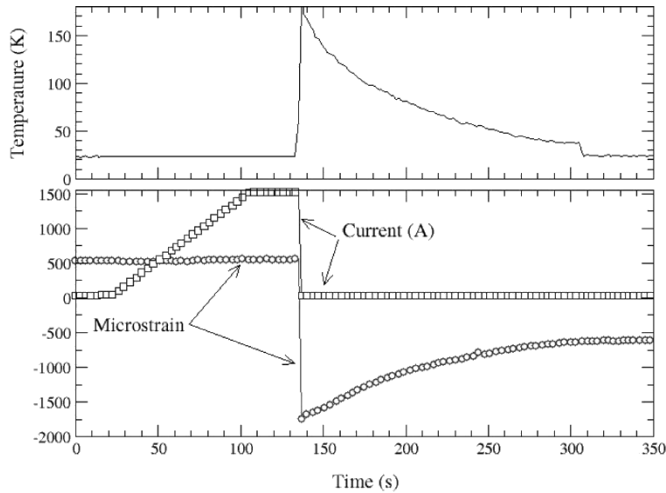


Fig. 6. Measured strain and temperature near the spot heater before and after a quench.

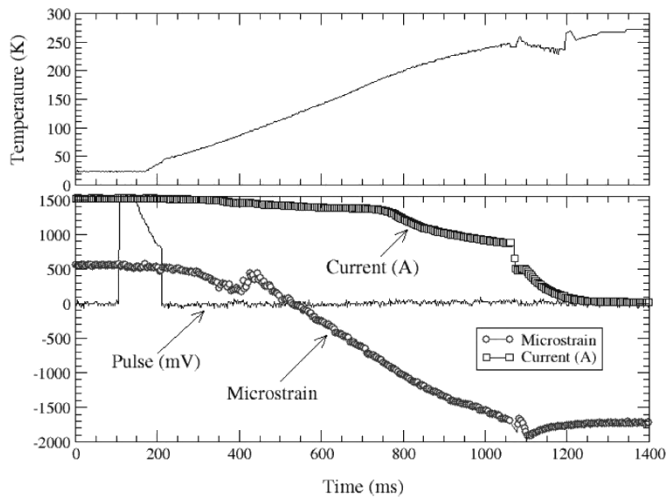


Fig. 7. Measured strain and temperature near the spot heater during a quench.

delay). After each power supply shut-off, a constant current of 20 A was sustained in the coil in order to monitor the segment resistivity and record the temperature decay.

Two data acquisition systems were used. A fast data acquisition system with a resolution of 2 ms measured the strain history during a quench, and a slower acquisition system took measurements at 1 s intervals. A typical time history for coil SC14 (case H11) is shown in Fig. 6 (pre and post quench), and Fig. 7 (during the quench). Recorded are the current, spot heater-pulse, strain, and segment temperature. The maximum temperature attained in case H11 was room temperature and the local change in strain was $2300\mu\epsilon$ (compressive). As the current drops to zero and superconductivity is recovered the strain near the heater location does not return to its original $+500\mu\epsilon$ level but rather remains suppressed at a temporary level of $-600\mu\epsilon$.

Shown in Fig. 8 are three consecutive spot heater quenches (at 1.5 kA each) followed by a spontaneous quench, Q03, at 6.1 kA. The fast changing strain during a pulsed quench is negative (indicating compression) resulting from the local rise in temperature. Cool-down to 4.3 K following the spot heater quench does not cause a return in the local strain to its

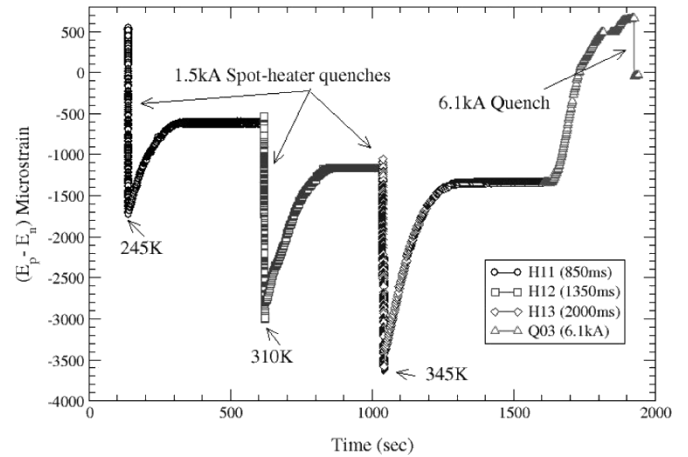


Fig. 8. Three spot-heater quenches, followed by a spontaneous 6.1 kA quench.

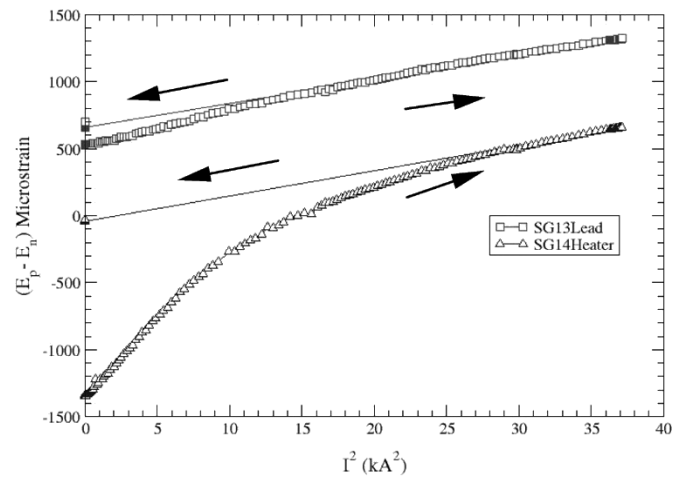


Fig. 9. Thermally induced compression is relaxing during a training ramp to a quench. The degree of relaxation depends on the local temperature reached during the thermally induced quench.

pre-quench level. Subsequent spot heater quenches, with longer time durations before power shut off (higher temperatures), successively increase the compressive strain and its departure from its original strain level.

The temperature dependence of strain during the same three spot heater quenches is shown in Fig. 10. Above 100 K a linear behavior in the strain-temperature curve suggests a linear thermal behavior for the coil in that range. The nonlinear and hysteretic behavior of coils between loading and unloading has been seen before in mechanical stress-strain curves of coil samples [9].

A. Comparison With ANSYS

A complete ANSYS 3D electro-thermal-mechanical transient analysis has been reported on a similar magnet [4]. Computations suggested that a local heating causes the strain in the coil near that location to undergo substantial compression as a result of local thermal expansion. The measured strain in coil SC13 and SC14 as a function of local temperatures is compared with ANSYS results (Fig. 11). ANSYS strain values are plotted at the heater location (T_{max}) and the end of the segment ($T_{min} = \pm 45$ mm away). The results are in fair agreement.

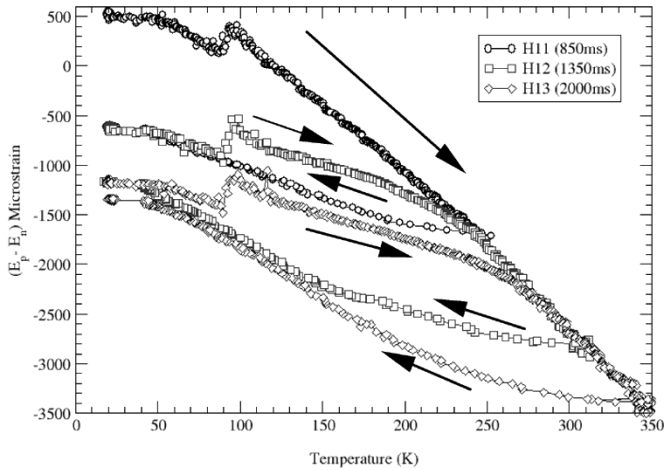


Fig. 10. Change in coil strain as a function of local temperature during and after three consecutive spot heater quenches.

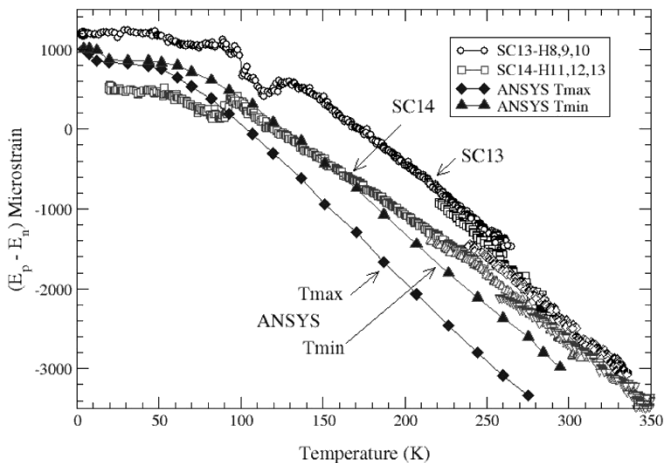


Fig. 11. Comparing measured strain and ANSYS calculations during a spot-heater quench.

Raising the current to 6.1 kA raises the strain from $-1350\mu\epsilon$ to $+650\mu\epsilon$ due to Lorentz forces. Following the spontaneous quench (which does not originate next to the spot heater) the local coil strain recovers most of its original value. During the current increase Lorentz forces remove most of the ratcheting that occurred during the previous 3 spot heater tests. The recovery is therefore highly non linear. Fig. 9 shows the rise in strain as a function of the current square. The gauge recovers

most of its strain as the Lorentz forces increase, replacing its initial non linear behavior with a linear one. The quench resets the coil and recovers most of its original strain. The gauge in the second coil (SC13), which didn't undergo a high temperature excursion, continues to exhibit a linear dependence on Lorentz force induced stress.

IV. CONCLUSIONS

A technique of adding strain gauges to coils has been described. Measuring coil strain during steady state and transient conditions suggests a possible new way of studying magnet training and quench propagation. Preliminary results suggest:

- 1) Local high compressive strain during a quench.
- 2) The coil stores strain energy.
- 3) The stored strain energy is localized and temperature dependent.
- 4) Stored strain energy can be "released" with Lorentz forces.
- 5) No agreement between measured strain-Lorentz force relation and calculations.
- 6) Agreement between measured strain-temperature build up during a quench and calculations.

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