Training Curves of Nb_3Sn Rutherford Cables With a Wide Range of Impregnation Materials Measured in the BOX Facility

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***Abstract*—Training of accelerator magnets is a costly and time consuming process. The number of training quenches must therefore be reduced to a minimum. We investigate training of impregnated Nb_3Sn Rutherford cable in a small-scale experiment named BOX (BOnding Experiment). The test involves a Rutherford cable impregnated in a meandering channel simulating the environment of a canted-cosine-theta (CCT) coil. The sample is powered using a transformer and the Lorentz force is generated by an externally applied magnetic field. The low material and helium consumption enable the test of a larger number of samples. In this article, we present training of samples impregnated with alumina-filled epoxy resins, a modified resin with paraffin-like mechanical properties, and a new tough resin in development at ETH Zürich. These new data are compared with previous results published earlier. Compared to samples with unfilled epoxy resin, those with alumina-filled epoxy show favorable training properties with higher initial quench currents and fewer training quenches before reaching 80% of the critical current.**

***Index Terms*—Nb_3Sn, Rutherford cable, impregnation, training, quench.**

I. Introduction

LENGTHY training remains an issue for epoxy resin impregnated Nb_3Sn accelerator magnets [1]. A high number of training quenches before reaching nominal current is not considered acceptable for large-scale application due to the high cost. Although the precise cause of a training quench is hard to detect, there is a theory that it is related to strain energy from cool-down and Lorentz force, which is released on failure of the impregnant [2]. Possible failures include cracks within the resin volume and debonding between the resin and metal surfaces. To prevent formation of cracks, resins with high toughness are currently being developed [3], [4], [5]. Another supposable solution is to add fillers to the resin, which reduces the thermal expansion mismatch and prevents propagation of cracks.

In a collaboration of the Paul Scherrer Institute (PSI) and the University of Twente, we developed a small-scale training experiment for impregnated Rutherford cables called BOnding eXperiment (BOX) [6]. The experiment requires only 1 m of cable, and the sample is energized by a transformer which needs only 50 A for the primary coil. The relatively low cost of the experiment allows us to test a larger number of samples. The BOX experiment is complementary to the subscale CCT coils built at the Lawrence Berkeley National Laboratory (LBNL), which are more representative of a full-size magnet [7].

In our previous publication [8], we presented training curves of cables impregnated with different unfilled resins and paraffin wax. In this work, we present new results on BOX samples modified to reduce training by adding glass fiber or Al_2O_3 filler. A new tough resin developed at ETHZ is also tested [9].

TABLE I
Cable and Strand Specifications

Parameter	Value	Unit
Strand diameter	0.85	mm
Sub-element size	≤55	µm
Filament twist pitch	19 ± 3	mm
Cu/Sc ratio	1.2 ± 0.1	-
Sub-element configuration	RRP 108/127	-
Number of strands	21	-
Keystone angle	0°	-
Cable twist pitch	70	mm
Cable height without insulation	1.475*	mm
Cable height with insulation	1.785*	mm
Cable width without insulation	9.85*	mm
Cable width with insulation	10.16*	mm

* Dimensions are specified for 17 MPa transverse stress.

II. Experimental Method

A. Sample Preparation

The training curves are measured on Nb_3Sn Rutherford cables made at LBNL [10]. The cables consist of 21 strands of Bruker OST RRP 108/127 wire with a diameter of 0.85 mm. The cables are insulated using a braid of S-2 glass of 0.075 mm thickness. Specifications of the cable can be found in Table I. The cable was

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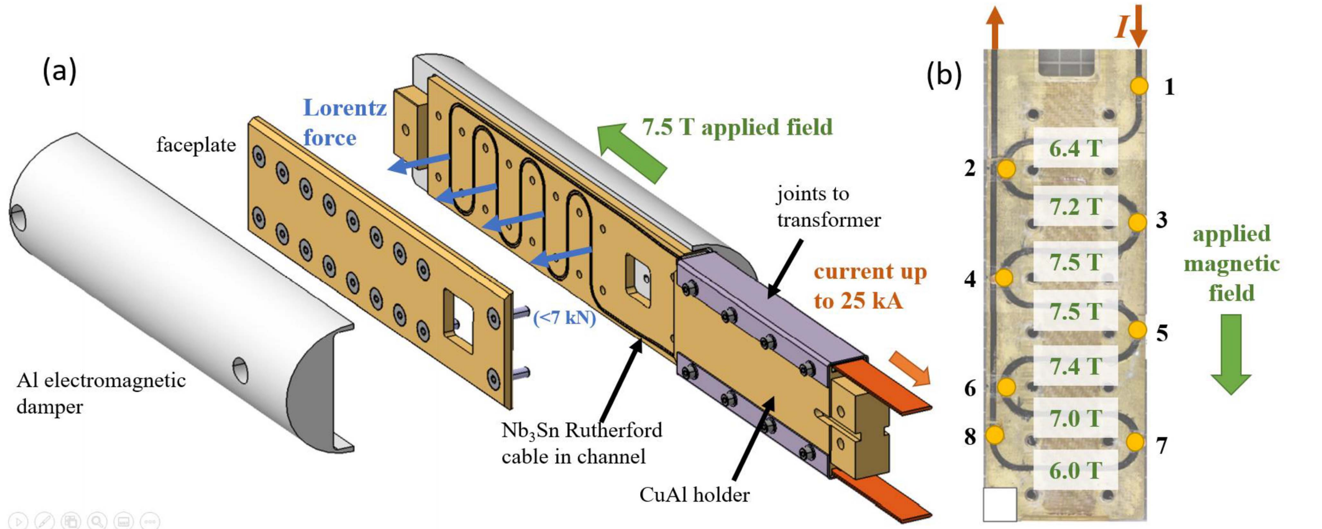

Fig. 1. (a) "BOX" sample holder for measurement of training curves. (b) Location of the voltage taps and applied magnetic field magnitude at each of the seven perpendicular segments.

TABLE II
BOX SAMPLES: IMPREGNATION AND CURING CONDITIONS

Sample/impregnation	Cure	T_g, melting temperature
Paraffin (1)*	-	52-56 °C
Paraffin (2)*	-	52-56 °C
Stycast 2850FT/23LV	24 h at 25 °C	68 °C
NHMFL mix 61*[12]	16 h at 25 °C + 24 h at 102 °C	73 °C
Araldite MY750*	6 h at 40 °C + 3 h at 80 °C	57 °C
CTD-101K (1)*	5 h at 110 °C + 16 h at 125 °C	145 °C
CTD-101K (2)*	5 h at 110 °C + 16 h at 125 °C	145 °C
CTD-101K with Al_2O_3	5 h at 110 °C + 16 h at 125 °C	145 °C
CTD-101K double sleeve	5 h at 110 °C + 16 h at 125 °C	145 °C
CTD-101K weakened	5 h at 110 °C + 16 h at 125 °C	
CTD-701X*	1 h at 40 °C + 2 h linear ramp 40-120 °C + 1 h at 120 °C	131 °C
ETHZ Cryoset 2 M	2 h at 80 °C + 3 h at 150 °C	

Samples with * are from our previous publication [8] and are included for comparison. Glass transition temperatures T_g from [5] and [13] or datasheets.

annealed between subsequent compaction steps. The measured final cable width and thickness are 9.935 mm and 1.494 mm, respectively [11]. The same cable has been used for all samples measured until now (cable ID B13OL1087-"R").

The cable is placed in an aluminum bronze or stainless steel holder with a meandering channel, which was sand blasted and cleaned in a sonication bath with a light solvent (see Fig. 1). The dimensions of the channel are 2.5 mm × 10.8 mm. This holder is used for both heat treatment and the training experiment. The cable is heat treated at 210 °C for 72 hour, 400 °C for 48 hour and 665 °C for 50 hour in argon atmosphere. After heat treatment, voltage taps are placed in each bend using silver epoxy, and finally the sample is impregnated.

The different samples presented in this paper are listed in Table II. There are five new samples with different resins and cable insulation in an attempt to reduce training:

- *CTD-101K with Al_2O_3 filler:* the channel was filled with alumina powder by sedimentation before vacuum impregnation with CTD-101K with alumina filler. The glass insulation was removed from this cable because it is incompatible with the filler. Instead, the holder has a ceramic coating for insulation (Aremco SGC4000);
- *CTD-101K double sleeve:* the cable was inserted into a second S-2 glass sleeve in order to increase the ratio of glass/epoxy;
- *CTD-101K weakened:* a non-stoichiometric mixture of the CTD101K resin components with about 5 times lower fracture toughness than CTD101K;
- *Stycast 2850FT:* an alumina-filled resin cured at room temperature. The glass insulation was removed from this cable because it is incompatible with the flow of the filler (filtration effect). Instead, the holder has a ceramic coating for insulation (Aremco SGC4000);
- *ETHZ Cryoset 2 M:* an interim version of a new tough epoxy resin in development at the ETH Zürich [9].

The ceramic coating used with the filled resins requires glazing at 700 °C. Because of the low yield strength of aluminum bronze at this temperature, the holders with the ceramic coating were made from stainless steel. All other holders were made from aluminum bronze, which is easier to machine.

B. Training Curve and Critical Current Measurement

To generate the Lorentz force, a magnetic field of $B_a = 7.5$ T is applied using a solenoid magnet. A magnetic field of 7.5 T was chosen because maximum Lorentz force of $B_a * I_c(B_a)$ peaks at this magnitude [6]. Although the pinning force peaks around 5 T, decreasing the applied field below 7.5 T would not increase the net Lorentz force because the critical current becomes limited by the self-field effect. The channel with the cable has seven 35-mm-long segments perpendicular to the applied magnetic field. At the expected critical current of 23.6 kA, these segments

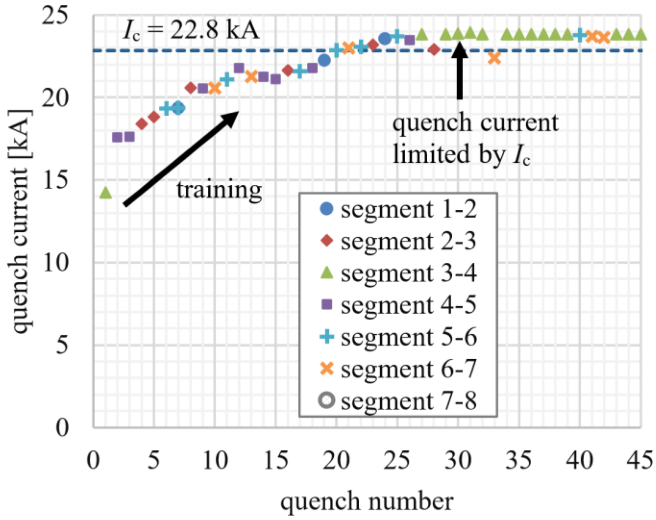

Fig. 2. Training curve of the BOX sample impregnated with Araldite MY750. The symbols correspond to quenches starting in different segments.

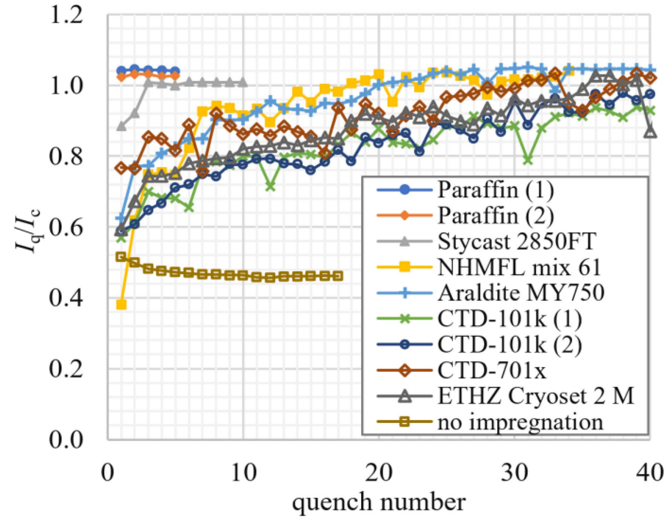

Fig. 3. Training curves for different resins. The quench currents I_q of impregnated samples are normalized to their critical current I_c. The quench currents of the heavily damaged sample without impregnation are normalized to the average I_c of other samples of 23.6 kA.

experience a Lorentz force of 6.2 kN parallel to the wide cable surface and perpendicular to the longitudinal axis of the cable.

In order to provoke a training quench, the sample current is ramped up at 200 A/s until a quench occurs. The current as well as the voltage over each segment are recorded using a multichannel oscilloscope (Yokogawa DL850EV).

After training, the critical current is measured with a criterion of $E_c = 10\ \mu$V/m. The in-field sample length is not well defined due to the meandering shape. Therefore we assume a length of 40 mm and define the critical current at the lowest current at which the voltage in at least one segment reaches 0.4 μV.

All measurements are performed in a bath of boiling liquid helium at atmospheric pressure ($T = 4.2$ K).

III. Result

A. Training Curves

In Fig. 2, the training curve for the sample impregnated with Araldite MY750 is shown. There are two regimes that can be distinguished. The first quench occurs at 14.2 kA. The following quenches are at gradually higher currents until the critical current of 22.8 kA is reached at quench 20. These quenches start in unpredictable locations, which is indicative of training. After 25 quenches, most quenches start in the high-field region (segment 3-4) at 104% of the critical current. These quenches are most likely caused by heating due to the superconducting to normal transition.

In Fig. 3, the quench currents I_q of different samples are plotted normalized to the critical current I_c, which can be found in Table III. As already presented before [8], the paraffin-impregnated sample showed no training with all quenches starting at 102–104% of the critical current. The sample with Stycast 2850FT also showed decent training behavior with the first quench at 88%, higher than all other resin-impregnated samples. This sample reached the critical current at quench 3.

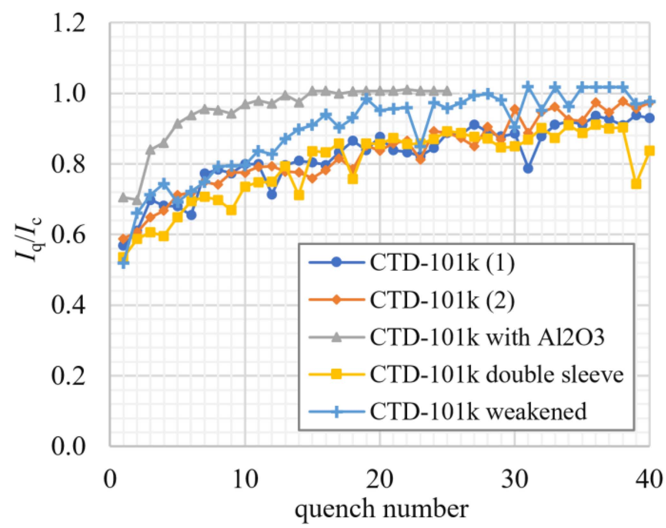

Fig. 4. Training curves for samples impregnated with CTD-101K.

Fig. 4 compares all samples impregnated with CTD-101K. Two unmodified samples were prepared in the same way (CTD-101K (1/2)). The similar quench currents of 57% and 59% of the critical current and overall similarity of the training curves demonstrate that the experiment is repeatable. The sample filled with Al_2O_3 had a higher initial quench current of 71% of the critical current compared to 52% to 59% for other samples impregnated with CTD-101K. Cross-sections of the alumina-filled sample revealed some voids, which may have limited the training performance. Therefore we plan a new test with a more properly filled sample. No increase in initial quench current was observed for the samples with double glass sleeves and weakened resin.

The initial quench currents for all impregnated samples are listed in Fig. 5. For an objective comparison of training behavior between different samples, we define as criterion the number of

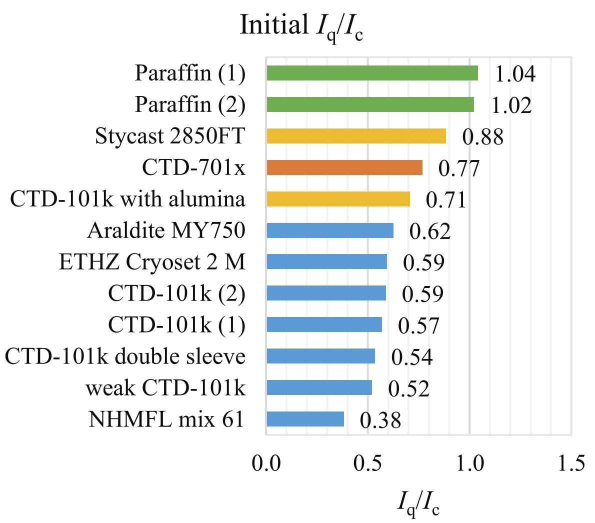

Fig. 5. Initial quench current normalized to the critical current for impregnated samples. Unfilled epoxy resins are shown in blue, alumina-filled epoxy resins in orange, polyolefin resin in red, and paraffin in green.

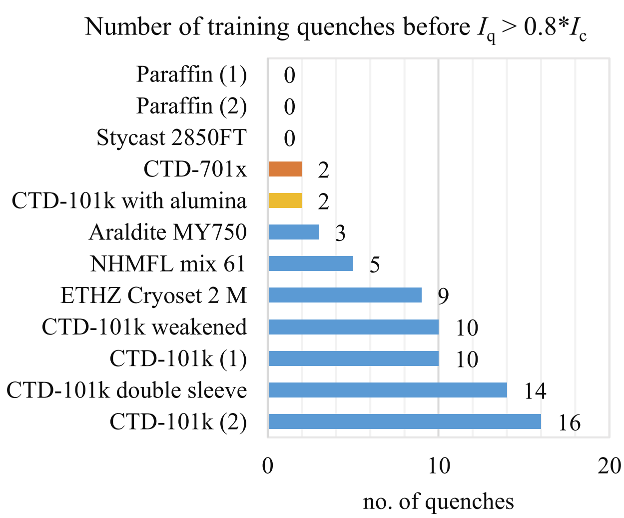

Fig. 6. Number of training quenches before 80% of the critical current is reached.

training quenches before 80% of the critical current is reached. At this current, the Lorentz force in the high-field region ranges from 171 kN/m to 188 kN/m depending on the critical current of the sample. This corresponds to an average shear stress of 8.7 MPa to 9.6 MPa if all force would be transferred to the impregnant through the wide surface of the cable. The number of quenches before reaching 80% of the critical current is shown in Fig. 6. It is noted that the six samples with the highest initial quench current also reach 80% of the critical current in the same order.

B. Critical Currents

The critical current was measured at applied magnetic fields of 7.5 T and 10 T and is listed in Table III. Some samples were not stable enough for a measurement at 7.5 T. For these samples, the critical current was estimated from the value at 10 T and the

TABLE III
CRITICAL CURRENT MEASUREMENTS

Sample/impregnation	Cable I_c (B_a = 7.5 T)	Cable I_c (B_a = 10 T)	I_c per strand (B_{peak} = 12.3 T)
Paraffin (1)	23.6 kA	16.5 kA	638 A
Paraffin (2)	24.0 kA	16.7 kA	645 A
Stycast 2850FT/23LV	25.1 kA	17.2 kA	656 A
NHMFL mix 61	23.3 kA	16.4 kA	638 A
Araldite MY750	22.8 kA	15.9 kA	610 A
CTD-101K (1)	22.8 kA*	15.9 kA	611 A
CTD-101K (2)	23.0 kA*	16.0 kA	614 A
CTD-101K with Al_2O_3	23.9 kA*	16.6 kA	644 A
CTD-101K double sleeve	23.6 kA**	-	-
CTD-101K weakened	24.3 kA*	16.9 kA	654 A
CTD-701x	23.6 kA**	-	-
ETHZ Cryoset 2 M	23.0 kA	16.0 kA	614 A
No impregnation	6.8 kA***	4.4 kA***	140 A
Average	23.6 kA	16.4 kA	632 A

* Critical current at 7.5 T estimated from value at 10 T.
** Critical current not measured, average value of other samples used.
*** The sample without impregnation was heavily degraded and its I_c data was excluded from the average.

I_c ratio between 7.5 T and 10 T for other samples of 1.44. The critical currents at 7.5 T range from 22.8 kA to 25.1 kA with an average of 23.6 kA. This excludes the degraded cable without impregnation, which had a critical current of only 6.8 kA.

The Nb_3Sn wire has a specified critical current of 632 A [14] and a measured value of 636 A [15] at 4.2 K and in 12 T applied magnetic field, which corresponds to 12.3 T peak magnetic field. Considering a cabling degradation of less than 5% percent, the critical current per strand is expected to be about 600 A. The actual critical current per strand at 12.3 T peak magnetic field was estimated using a cable self-field correction of 73 mT/kA and an extrapolation using the following scaling law [16]:

$$I_c \propto B_{\mathrm{peak}}^{-1} B_{c2}^2 \sqrt{\frac{B_{\mathrm{peak}}}{B_{c2}}} \left(1 - \frac{B_{\mathrm{peak}}}{B_{c2}}\right)^2.$$

The resulting strand critical currents are listed in Table III and averaged 632 A for all samples except the one without impregnation. We can thus conclude that none of the impregnated samples were significantly damaged by sample preparation or the experiment, although smaller changes in I_c cannot be ruled out.

IV. CONCLUSION

In addition to using paraffin [8], favorable training behavior was observed in Rutherford cables impregnated with alumina-filled epoxy resins. A first sample impregnated with the alumina-filled epoxy resin Stycast 2850FT remarkably showed an initial quench current at 88% of the critical current, which is higher than in all other resin-impregnated samples. A second sample was filled with Al_2O_3 particles by sedimentation followed by impregnation with CTD-101K epoxy resin. This sample showed a higher initial quench current (71% of I_c) compared to samples with unfilled CTD-101K (57% to 59%). The sample also reached 80% of I_c after 2 quenches compared to 10 to 16 quenches for the unfilled samples, despite the imperfect filling. It should be noted that the filled and unfilled samples have different insulation systems, because the glass braid is incompatible with filled resins. Nevertheless, the results indicate that the use of alumina filler may help to reduce the number of training quenches in Nb_3Sn accelerator magnets. The physics behind this improvement is still to be investigated in detail.

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