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Stability of High-J_c Nb_3Sn Wires in the Adiabatic Limit

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***Abstract*—High-J_c Nb_3Sn strands often exhibit instabilities in 4.2 K liquid helium at low fields ~0.5 to 3 T which are associated with magnetization flux-jumps. However at 1.9 K in superfluid helium, a minimum in premature quench currents at intermediate fields of 5 to 7 T has been observed in voltage-current measurements. These measurements are typically used for critical current determinations, and the premature quenching is driven by current redistribution within the strand as the current is increased and is termed "self-field" instability. In this paper, the magnetization and self-field stability of Nb_3Sn strands with $J_c \sim 2000\ A/mm^2$ at 12 T are described for a series of wires made using the Sn-tube approach with filament diameters ranging from 13 to 65 μm. The copper stabilizer of these wires after reaction has residual resistivity ratio, RRR, of ~5, which in effect means that any dynamic stabilization from thermal conduction effects is negligible. In this regime of RRR, we find that the magnetization stability with transport current increases with decreasing filament diameter as predicted by simple adiabatic theory. We also observed that at 4.2 K the self-field stability improved with decreasing filament size, but became worse with decreasing temperature as seen in measurements at 2.0 K.**

***Index Terms*—Magnetization, Nb_3Sn superconducting wires, quench current, self-field instability.**

I. Introduction

STRANDS of Nb_3Sn with high critical current density J_c and large filament diameters d often exhibit instabilities in 4.2 K liquid helium at low fields ~0 to 3 T which is associated with the collapse of large persistent current magnetization i.e., flux-jumps. These flux-jumps are quite evident in magnetization measurements [1]–[4], and manifest themselves in pre-mature quenching of wires carrying transport current in changing magnetic fields [5]. In one of the earliest analytical description of this phenomenon, M. Wilson [6] derived a simple criterion for adiabatic stability against magnetization flux-jumps as given in (1). Here β is the stability parameter, γC is the volume heat capacity, Tc is the transition temperature and Tb is the bath temperature.

$$\beta = \frac{\mu_0 J_c^2 d^2}{4\gamma C(Tc - Tb)} \leq 3 \tag{1}$$

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Using the following in (1): $J_c\ (0.5\ T) = 40,000\ A/mm^2$ (this is equivalent to $2000\ A/mm^2$ at 12 T) $Tc = 16.7\ K$ $Tb = 4.2\ K$ $\gamma C = 1700\ J/m^3 - K$, the stability criterion requires that the filament diameter d is less than 11 μm for no magnetization flux jumps. The incidence of a flux-jump does not mean that a wire carrying a transport current will always quench. It depends on the magnitude of the current and whether there is any stabilization due to "dynamic" or time-dependent effects. In typical multi-filamentary wires, the process of heat conduction through the copper matrix (which typically has a residual resistivity ratio $RRR \sim 100$) to a cooled surface and heat transfer to the bath, can increase β significantly. In fact it has been established that even for large filament conductor this form of instability can be markedly improved by increasing RRR from 10 to 100 [5]. As we shall show later, in the present study, we examine the stability in the quasi-adiabatic limit where (1) applies.

Besides the magnetization driven instability, which is mitigated by the multi-filamentary structure of the wire, there is an additional instability due to the self-field of the transport current in the composite. This "self-field" instability is often observed as premature quenching during critical current measurements when the current is being ramped up in a fixed magnetic field $V - I$. Expressions similar to (1) has been calculated by Wilson [6] where d is replaced by the wire diameter D and the term on the right varies rapidly with i, with β_t. the self-field stability parameter $\rightarrow 1$ as $i \rightarrow 1$. In Wilson's simple model, the multifilamentary nature of the wire does not play a role. However, he did note that measurements of stability on multi-filamentary wirers show a discrepancy between theory and experiment, and that twisted filamentary composites work better than theory would predict. More recent measurements by Barzi *et al.* [7] on high-J_c wires showed that the instability observed in $V - I$ measurements improved by reducing the filament diameter. However, the comparisons made in that paper are not altogether clear as the wire diameter, filament diameter and the RRR were different for the wires being compared. Since Wilson's model, there have been several attempts at a theoretical understanding of instability [8]–[11]. Kashikhin and Zlobin [8] refine Wilson's adiabatic model and solve it numerically, and show that stability improves as filament diameter is decreased from 170 to 80 μm. More recently, Bordini *et al.* [11] developed a finite element model which takes into account the filamentary distribution in the wire. However, the model was not used so far to study the effects of the filament size on self-field instability and does not explicitly show the effects of filament size on this stability. Stability is calculated to improve only with wire diameter and with dynamic stabilization by increasing RRR from ~5 to 120. The model also predicts that in superfluid helium the premature quench current at a given field would become lower due

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TABLE I
SAMPLE PARAMETERS AND EXPERIMENTAL RESULTS

Sample ID	D mm	λ	Temp °C	Time h	J_c(12T) A/mm^2	N	d μm	J_s A/mm^2	RRR
T1339	0.70	0.41	650	90	2162	169	35	2378	3.2
T1403	0.70	0.47	650	150	2079	54	65	1384	3.4
T1424-1	0.70	0.47	650	80	1888	192	35	2491	3.3
T1424-2	1.00	0.47	650	130	1934	192	49	1559	3.8
T1424-3	0.70	0.47	650	90	1945	192	35	2352	2.3
T1489-1	0.42	0.47	650	60	2051	246	18	8495	3.4
T1489-2	0.70	0.47	650	90	2030	246	31	4170	5.5
T1489-3	0.70	0.47	665	48	1919	246	31	4310	7.5
T1489-4	0.70	0.47	635	288	2222	246	31	4310	5.1
T1692-1	0.70	0.38	635	100	1898	388	22	5787	5.5
T1692-2	1.00	0.38	625	250	2061	388	31	2752	7.9
T1692-3	0.80	0.38	625	150	1962	388	25	4561	8.7
T1692-4	0.70	0.38	625	100	1906	388	22	5276	9.3
T1692-5	0.42	0.38	625	75	2041	388	13	12765	3.2

D: Wire Diameter, l: Fraction of non-Cu Region, N: Filament Number, d: Filament Diameter Js: Stability Threshold Current Density, RRR: Residual Resistivity Ratio of the Copper Matrix.

to the lower heat capacity of the wire resulting in a larger ΔT (temperature pulse) at 1.9 than at 4.2 K with the same perturbation energy ΔQ. These conclusions were verified by Bordini *et al.* with quench experiments on several high-J_c wires at 4.2 and 1.9 K [11]. A complete list of references to other published work in this field of research can be found in [11].

In this study we examine the magnetization stability limits of wires that have $J_c(12\ \mathrm{T}) \sim 2000\ \mathrm{A/mm^2}$, and where the wire *is in the quasi-adiabatic regime as the copper matrix has a low* RRR and therefore has a low thermal conductivity and does not provide any dynamic stabilization. We use these same wires to study the self-field instability in the adiabatic limit in 4.2 K pool-boiling and in superfluid helium at 2 K.

II. SAMPLES AND MEASUREMENT PROCEDURES

The tubular process [11] was used to fabricate billets by Supergenics and Hyper Tech. A simple process has been developed of inserting Cu clad Sn into Nb7.5wt.%Ta tubes and these in turn are inserted into larger Cu tubes. We previously reported [12] restacking 54, 108, 169 and 198 of these tubes (hereto termed as filaments) and drawing to wire of diameter 0.7 mm. This was accomplished without ductility and piece length problems. The best reported critical current density in the non-Cu region J_c was 2500 $\mathrm{A/mm^2}$ at 12 T in material with 32 μm diameter filaments [13]. For this study samples of wire were taken from billets with the number of filaments N ranging from 54 to 388. The wire diameter D ranged from 0.42 to 1.0 mm and the fraction of non-Cu region in the wire λ ranged from 0.38 to 0.47. The filament diameter d was calculated from D, N and λ. The samples and its relevant parameters used for this study are listed in Table I.

Strand samples from the various billets of wire were reacted in vacuum on stainless steel barrels and then transferred to Ti-6Al-4V alloy test barrels. The typical reaction cycle was a temperature ramp from room temperature to the final temperature at 25 C/hr, and then held at that temperature which is of the ~650 C for 50–250 hrs. The actual time/temperature (shown in Table I) was optimized to provide a J_c (non-Cu) of $\sim 2000\ \mathrm{A/mm^2}$ at 12 T and 4.2 K.

The critical current I_c at 4.2 K was measured at BNL as a function of field as described earlier [14]. The following procedure was used during the test. The field was initially set to the highest available field of 11.5 T and the sample was quenched. Following that, voltage-current $V-I$ measurements were taken to determine the critical current and the quench current. Ic (or J_c) is defined using the resistivity criterion of $10^{-14}\ \Omega - \mathrm{m}$. The field was then *reduced in steps* to zero-field and the $V-I$ procedure was repeated at each field. At every field the wire was quenched at least twice for each field. Below a certain field level either the quench current was higher than the power supply limit of 1500 A, or the wire quenched pre-maturely without developing any voltage. In the field range of 7 to 11.5 T, the product $J_c^{0.5}H^{0.25}$ plotted vs. field H (a Kramer plot) could be fit by a line with a high degree of accuracy, and this fit was used to determine J_c at the 12 T conductor benchmark field.

Following the $V-I$ measurements, the low field stability was determined by measuring the voltage in a wire carrying a fixed current while the field is swept between 0 and 3 T, $V-H$ measurements. By doing repeated cycles using different currents, it was possible to determine a stability current density J_s, above which flux-jumps quenched the wire. More details of this procedure are in [5].

III. MEASUREMENT RESULTS AND DISCUSSION

A. Low Field Magnetization Stability

In Table I we tabulate the J_c (12 T, 4.2 K), the Js and the measured RRR of the wires. We find that the J_c are all $\sim 2000\ \mathrm{A/mm^2}$ and the RRR are uniformly low ~5. The low value of the RRR is due to the fact that for wires made using the tube-process, tin seems to react through the tube in some regions and contaminates the copper. Fig. 1 is a plot of Js versus d, where we find that J_s scales as $1/d^2$ and the solid curve represents the fit shown below (2) where Js is in $\mathrm{A/mm^2}$ and d is in mm.

$$J_S = 1100 + \frac{2.109}{d^2} \tag{2}$$

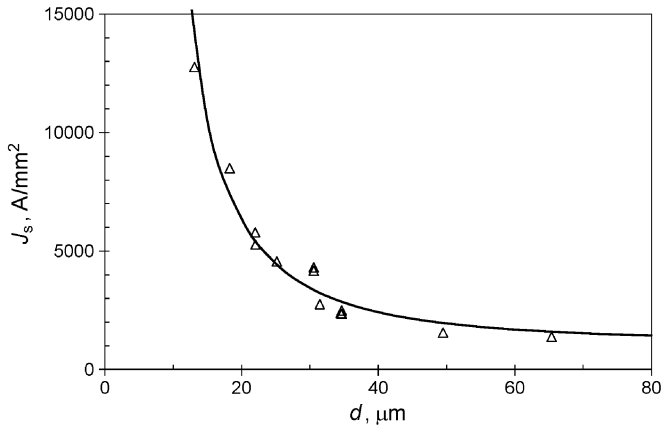

Fig. 1. Plot of J_s versus filament diameter d. The solid line corresponds to (2).

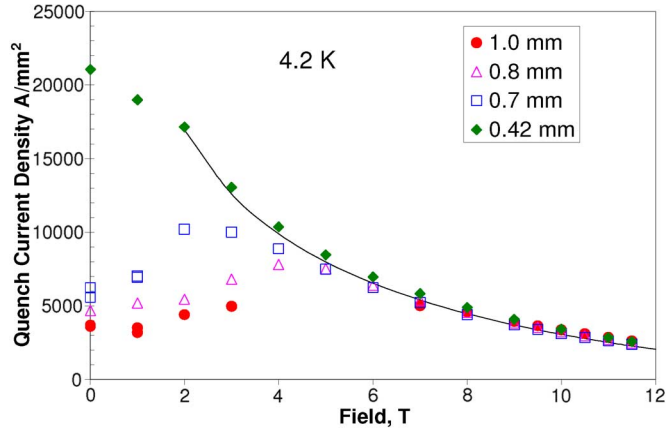

Fig. 2. Quench current density as a function of applied field at 4.2 K, for wires from billet T1692 with different wire diameters. The solid line corresponds to the critical current density measured for the 0.42 mm wire.

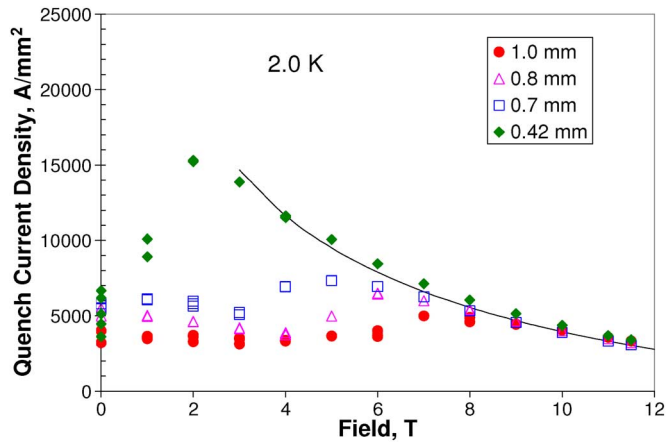

Fig. 3. Quench current density as a function of applied field at 2 K for the wires from billet T1692. The solid line corresponds to the critical current density measured for the 0.42 mm wire at 2 K.

Equation (2) predicts that for wires which have a $J_c(12\,\mathrm{T}) \sim 2000\ \mathrm{A/mm^2}$, it can carry its full critical current density of 40,000 $\mathrm{A/mm^2}$ at ~0.5 T when the filaments are $\sim 7\ \mu\mathrm{m}$. This is consistent with the estimate using (1) and is a good confirmation of the simple adiabatic model by M. Wilson.

B. Self-Field Stability, V-I Measurements

1) Effect of Wire Diameter on Stability at 4.2 and 2 K: We begin by examining the effect of wire diameter on the behavior of quench current density as a function of field by using wires from billet T1692 that was drawn down and twisted to 4 different wire diameters. At high fields and in 4.2 K helium, the samples of wire with different wire diameters quenched at currents higher than the critical current. However, as the field is reduced, quench currents were seen to be less than the expected critical current. In Fig. 2, the quench current density is plotted as a function of field for the wires with $\mathrm{D} = 1.0$, 0.8, 0.7 and 0.42 mm (samples T1692-2, 3, 4, 5). For the 1.0 mm wire, no data are shown for 4–6 T, as quench currents were greater than the power supply limit of 1500 A. The dashed line is the critical current density that was measured for the 0.42 mm wire to 2 T. The plot shows that as the wire diameter is increased, self-field induced stability at a field like 3 T deteriorates. Also, with increasing diameter, the onset of this instability appears at progressively higher fields. Similar behavior has been observed by Bordini *et al.* [11].

The measurements at 4.2 K were extended to superfluid helium at 2 K to see the effect of temperature on J_c and premature quenching. Fig. 3 shows the quench current density plotted on the same scale as in Fig. 2. Although the J_c at high fields is, as expected, higher at 2 K (2540–2750 $\mathrm{A/mm^2}$ at 12 T) than at 4.2 K, the quench current at intermediate fields 4–6 T gets noticeably worse at this temperature compared to 4.2 K and furthermore the onset of instability moves to higher fields when compared to 4.2 K.

While the data in Figs. 2 and 3 would seem to validate the notion that self-field instability increases with wire diameter, however, for this set of wires *the filament diameter d is also changing from* 35 $\mu\mathrm{m}$ *to* 13 $\mu\mathrm{m}$ *as D changes from 1.0 mm to 0.42 mm*. What role does filament size play in the stability of the wire? To separate these two aspects, we examine the behavior of 0.7 mm wires with different filament diameters.

2) Effect of Filament Diameter on Stability at 4.2 and 2 K: In this section we compare the quench current behavior as a function of field for three 0.7 mm diameter wires with different number of filaments: T1403, T1489-4 and T1692-4, with d of 65, 35 and 22 $\mu\mathrm{m}$ (see Table I). Figs. 4 and 5 are plots of quench current density as function of field at 4.2 and 2.0 K respectively. The vertical scale is the same for both plots to show the significant follow-off in stability at 2 K. The solid lines are the critical current densities measured for the 22 $\mu\mathrm{m}$ filament wire. The main observation is that at intermediate fields of 3 to 5 T, the quench current density falls sharply with increasing filament diameter and gets considerably lower in superfluid helium (Fig. 5). In fact in superfluid helium for the wire with 65 $\mu\mathrm{m}$ filaments, the minimum at 6 T is lower than the J_c at higher fields of 10 to 12 T. The onset of instability at the lower temperature at 2 K appears at a higher field than at 4.2 K. Note that in this comparison, billet T1692 has more copper than the other two, but the effect of the copper content would be negligible in the "quasi-adiabatic" regime.

These experiments clearly indicate that sub-division of the superconductor dramatically improves stability so that critical currents can be reached at fields lower than possible in wires with

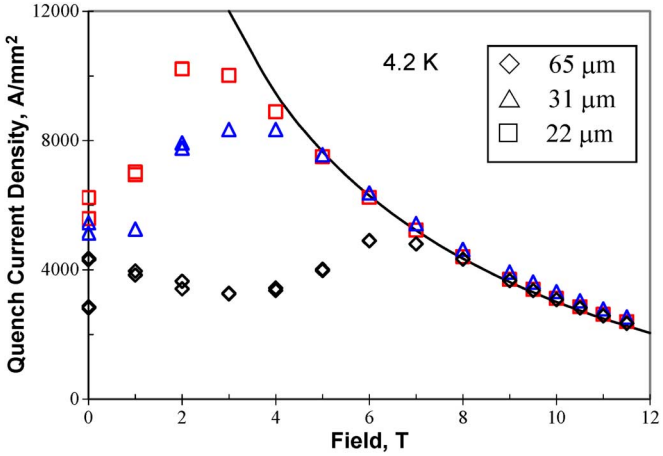

Fig. 4. Quench current density measured at 4.2 K for wires with different filament diameters, d. Solid line is the J_c measured for the wire with $d = 22\ \mu\mathrm{m}$.

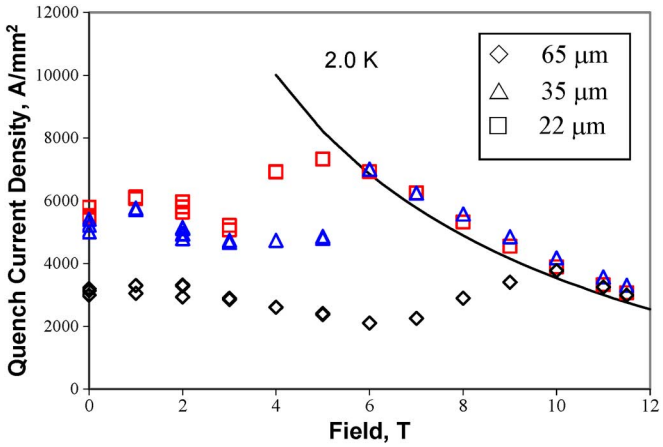

Fig. 5. Quench current density measured at 2 K for wires with different filament diameters, d. Solid line is the J_c measured for the wire with $d = 22\ \mu\mathrm{m}$.

larger filaments. For wires with J_c higher than 2000 $\mathrm{A/mm^2}$ at 12 T, one would have to make wires with even finer filaments for cryogenic stability.

IV. Summary

For high-J_c Nb_3Sn wires, magnetization stability under adiabatic conditions can only be achieved in wires with very small filaments $\sim 7\ \mu\mathrm{m}$ as calculated using Wilson's model and demonstrated experimentally here. Such small filaments have been achieved in low-J_c composites. For high-J_c internal-Sn wires Wilson's model would predict that dynamic effects in wires having an $\mathrm{RRR} > 100$ can provide full cryogenic stability for filaments of the $\sim 15\ \mu\mathrm{m}$. To reach this goal, we at Supergenics and Hyper Tech have successfully fabricated restacks with 744 and 1248 filaments. The first billet with 744 filaments T1791 achieved a J_c (12 T) of 1800 $\mathrm{A/mm^2}$ in a 0.7 mm wire with $d = 16\ \mu\mathrm{m}$. This wire although having a low RRR showed no signs of either magnetization or self-field instability at 4.2 K to the measurement limits of the power supply ($J_c > 9500\ \mathrm{A/mm^2}$, $J_s > 7600\ \mathrm{A/mm^2}$), Fig. 6. Recent optimization of reaction has raised the J_c to 2000 $\mathrm{A/mm^2}$ at 12 T. Characterization of the 1248 filament billet T1982 at 0.7 mm and $d = 12\ \mu\mathrm{m}$ is underway.

The results of the $V - I$ measurements clearly show that like the magnetization stability, the self-field stability can also be

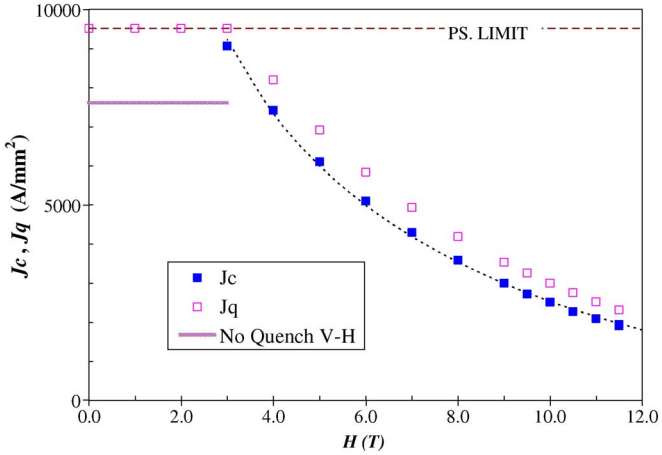

Fig. 6. The critical current J_c and quench current J_q measured at 4.2 K is plotted vs. field. The "No-quench" line is that from V-H measurements showing that $J_s > 7600\ \mathrm{A/mm^2}$.

improved by decreasing filament size. We also find that self-field stability significantly decreases from 4.2 K to superfluid 2 K.

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