PARAMETRIC STUDY OF THE STABILITY MARGINS OF CABLE-IN-CONDUIT SUPERCONDUCTORS: EXPERIMENT*

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Summary

In a previous experiment on the stability of cable-in-conduit superconductors, we sometimes observed multivalued stability margins, which we attributed to strong heating-induced transient flows. We proposed a schematic theory from which we derived a scaling relation for the limiting current below which the stability margin is always singlevalued. Measurements at different magnetic fields are used to test the scaling with critical temperature and resistivity. We also examine the scaling with heated length and heat pulse duration. The results of these experiments are given and compared with theory.

Introduction

In a previous experiment on cable-in-conduit NbTi superconductor, we observed that the stability margin is sometimes multivalued.[1] There is an upper stability margin of the order of hundreds of millijoules per cubic centimeter of conductor, above which there can be no recovery of the conductor. For a range of heat input lower than this margin, recovery is obtained within tens of milliseconds after the conductor has gone normal. At somewhat lower heat input a second instability zone appeared. The conductor cannot recover from these lower values of heat deposition. A slower drop in the conductor resistive voltage is observed, which is followed by a turnaround and even slower quenching of the conductor. Finally, there is a lower stability margin (on the order of 30-50 mJ/cm^3) below which no quenching of the conductor was observed. This is accompanied by little resistive voltage during heat pulse.

Figure 1 is a typical plot of stability margin vs transport current showing multiple stabilities in a certain range of current values. Similar curves have been obtained from stability margin vs helium pressure plots.[1] Plots of stability margin vs imposed helium flow, though different in appearance, also have multiple stability regions.[1]

Scaling Relationships

A qualitative model based on the idea that heating induces local flow was successfully used to explain the complex multivalued stability margin.[1] At the onset of heat input there is a high conductive heat transfer from conductor to helium; the surface temperature remaining low. After a short while the surface goes into film boiling (or more precisely for supercritical helium — a blanketing with low-density helium) and the surface temperature rises. This is responsible for the low stability margin. The time for the temperature to takeoff depends on the interfacial heat flux. The transferred heat causes the helium in the tube to undergo a thermoacoustic vibration. The time and space average of the induced velocity turns out to be proportional to the heating rate. Induced flow on the order of 1-10 m/s is reached for heat input of 100 mJ/cm^3 or more. A local heat transfer proportional to the induced flow is produced. If this induced heat transfer is large enough, the conductor can recover. Since the helium inside the tube cannot be replenished in the time required for recovery, available heat capacity is limited, which determines the ultimate limit to stability.

From the magnet designer's point of view, one of the most important points in Fig. 1 is the limiting current I_{lim}, below which only the upper stability margin prevails. If we could know how this current scales with various parameters, we can then design a conductor to operate below I_{lim} and ensure high stability for the magnet. Based on the above model, a semiquantitative theory[2] has been developed that results in a scaling relationship for the limiting current density of the conductor J_{lim} as:

$$J_{lim} \simeq [f_{Cu}(1 - f_{co})/f_{co}]^{1/2}(T_c - T_b)^{1/2}\rho^{-1/2} \cdot \tau_h^{-1/5}\ell^{2/5}D^{-1} , \tag{1}$$

where

- f_{co} = volume fraction of metal in the cable space
- f_{Cu} = volume fraction of copper in the metal
- T_c = critical temperature of the superconductor
- T_b = ambient helium temperature
- ρ = resistivity of copper including magnetoresistance
- τ_h = heat pulse duration
- ℓ = heated zone length
- D = hydraulic diameter of the void in the cable space.

The first three factors reflect the balance of heat transfer and the joule heating of the conductor, with the heat transfer coefficient derived from induced flow governed by the last three factors. (More precisely, D came from both groups.) The validity of Eq. (1) can thus be tested by these two separate groups.

Detail Testing of the Scaling Law

Detail testing of the scaling law given by Eq. (1) was performed on an experimental setup similar to that reported in Ref. 1. A single triplex of NbTi strands was sheathed in a stainless steel tube to form the internally cooled conductor. Pulse heating was accomplished by passing current through the heater wire embedded inside the interstice of the triplex. With a fixed external field, transport current, and helium pressure and flow, heater pulses of a given duration were applied to the conductor. The resistive voltage of the conductor was monitored to determine whether the conductor is stable against the applied heater pulse.

Stability margins of the conductor at different transport currents were mapped to generate a stability margin ΔH vs current I_s curve typified by Fig. 1. To test the scaling on critical temperature and resistivity, a series of ΔH vs I_s curves at different magnetic fields was produced. These are shown in Fig. 2. Multiple stability margins are present at every field value. The data-taking on the high current side of

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each curve was arbitrarily terminated after only the lower stability margin was apparent. The data-taking on the low current side was terminated when the heater power supply limit was reached. At a 16.7-ms pulse length the maximum heater input was about 300 mJ/cm^3 for a sample length of 3.8 m as shown.

The limiting currents I_{lim} for each field can be obtained from Fig. 2. They are plotted against B in Fig. 3 for three different run conditions. The solid curves, which have the form $I_{lim} \propto (T_c - T_b)^{1/2} \ldots^{1/2}$, are drawn to fit the data at B = 6 T. The very good agreement here gives confidence in the validity of the first group factors in Eq. (1).

For different heat pulse durations, different heater power is used to obtain a given heat input. Higher heater power at shorter pulse length induces higher helium flow. Thus a high stability margin can be reached more easily. Figure 4 is a plot of ΔH vs I_s at four different heat pulse lengths. The data on the low current side again represent a heater power supply limit. The limiting currents for the different heater pulse durations compare favorably with the scaling law in Fig. 5.

Testing was begun with a 4.8-m-long sample. After a data set like that described above was taken, the sample was cut short and the ends reconnected to the current-hydraulic junctions. A new set of stability data was then taken. This process was repeated until a minimum sample length of 1.8 m was tested. To illustrate the effect of different sample lengths, a stability margin vs sample current plot for all the lengths tested is shown in Fig. 6. Though all curves show multiple stabilities over some current range, there is a vast difference in the behavior of the upper stability margin. Also significant is the fact that the lower stability margin is essentially invariant with sample length. This confirms our hypothesis that the lower stability margin is due to the conductive transient heat transfer, which is independent of the variable induced flow.

When plotted against sample lengths, limiting currents from plots like Fig. 6 clearly do not agree with the simple ... scaling given in Eq. (1). Instead, they show a periodic behavior. This apparent discrepancy is successfully explained in Ref. 2 by the fact that the present experiment was performed on samples of such short length that acoustic waves traverse the sample several times before the conductor recovers. The space-time average of the induced flow for a given heat pulse goes through periodic peaks as the sample length is varied. This also gives a similar but not as prominent periodicity in time as can be seen by careful scrutiny of the data of Fig. 5.

Other Experimental Results

Plots of stability margin vs helium pressure[1] showed exactly the same characteristics as Fig. 1. Although thermodynamically it might not be advantageous (especially for higher critical temperature Nb_3Sn superconductor) to operate at lower pressures,[3] the higher compressibility of helium at lower pressures lends itself to easier access to upper stability margin. A dramatic contrast can be seen in Fig. 7, where ΔH is plotted vs I_s for 5.0-atm and 1.0-atm tests. The limiting current was increased from ~260 A to 340 A by dropping the pressure from 5.0 atm to 1.0 atm. The much higher "lower" stability margin at 1.0 atm indicates a higher transient heat transfer at this pressure than at supercritical pressures.[4] At up to 95% of the critical current, a stability margin of nearly 200 mJ/cm^3 was observed at 1.0 atm helium. The extra break in the curve corresponding to the 2.3-m-long sample is not understood.

A stability margin vs sample current map for different imposed helium flows v_{He} is shown in Fig. 8. Imposed helium flow pushes the limiting current to higher and higher values and finally washes out the boundary between the upper and lower stability margins. A slice through the curves at a current that shows multiple stability at zero flow will result in a ΔH vs v_{He} curve with a smooth and continuous upper stability margin above a shrinking instability zone, as was shown in Ref. 1.

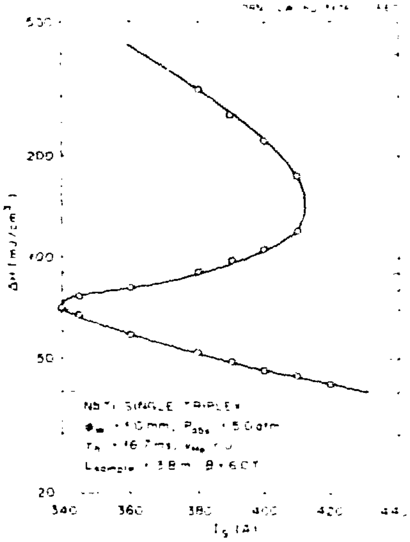

Fig. 1. A typical stability margin vs transport current plot. Multiple stabilities are apparent.

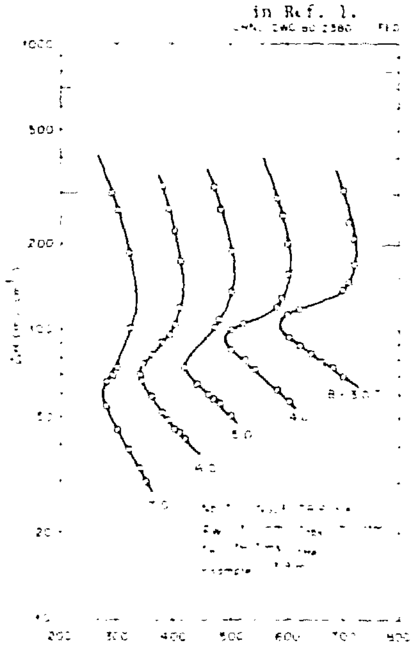

Fig. 2. Stability margin vs transport currents at different fields.

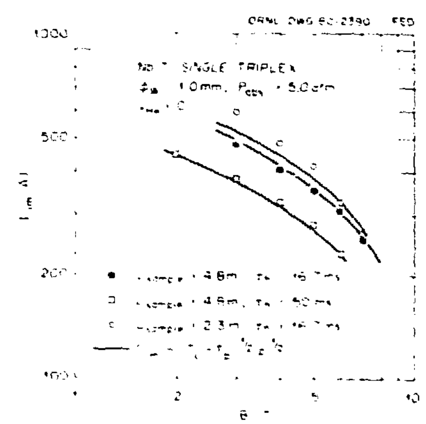

Fig. 3. Limiting current vs magnetic field plot. Scaling curves are drawn to fit the data at B = 6.0 T.

Larger Conductor Tests

Several other experiments on conductors larger than a single triplex have also been performed. Although they did not generate data as clean and copious as that described above, no contradiction to the existence and form of the multiple stability margins and scaling relationships was observed.

Several attempts were made to measure the stability margin of conductors made of 19 triplex strands similar to those used in the above experiments. Because of the complexity of bringing out 19 heaters, one from each of the triplexes, and the high current capacity involved [$I_c(6\ T) \sim 10$ kA], problems persisted in the current-hydraulic junctions. Leakage, shorted heaters, and deteriorated current junctions foreshortened the tests. However, on one occasion an upper stability margin of about 200 mJ/cm^3 was observed at I_s = 5300 A, B = 6.0 T with 5 atm of stagnant helium. The lower stability margin was found to be 30 mJ/cm^3. The boundary between the upper stable zone and the lower unstable zone was not pinned down. The observed upper stability margin is low compared to the single triplex data. This could be the results of hot current junction and uneven current distribution of the non-fully transposed 19 × 3 cable. It was also observed that a higher stability margin was achieved by using a fewer number of heaters. This indicated that the current in the cable redistributed when only some of the strands went normal, thus reducing the joule heating.

Another experiment was performed on a 4 × 3 cable with a smaller strand size (0.72 mm as compared to 1.0 mm in the above experiments). With 49% void in a conduit of 3.66 mm ID, it had a hydraulic diameter of 0.904 mm (as compared to 1.02 mm for the above single triplex). A single heater wire was cabled inside the interstice of the four triplexes. The stability margins vs transport currents at 6 and 7 T are shown in Fig. 7. Only the upper stability margin was observed for this sample. Using Eq. (1) and single triplex data, the scaled limiting currents are 800 A at 7 T and 1050 A at 6 T. Both values are higher than the critical currents at these fields. Thus no lower stability margin should be observed, and none was observed. Similar results were found earlier[5] in our test of a multifilamentary Nb_3Sn internally cooled superconductor smaller (1/3 in scale) to that to be used in the Westinghouse Large Coil Program coil.

In Figs. 4, 6, 8, and 9, curves of ΔH_{cp}, which represent the available helium heat absorption capacity between bath temperature and superconductor current-sharing temperature in a constant pressure process are drawn for comparison. Upper stability margins of this magnitude or higher were observed in various cases. The possibility of the stability margin being higher than ΔH_{cp} was accounted for in Ref. 1 on the fact that helium went through a process of pressure buildup and release.

Conclusion

Scaling relationships of a limiting current below which there is only upper stability margin in an internally cooled cable-in-conduit superconductor has been extensively tested in a single triplex experiment. Although not every factor was tested the validity of the relationships is verified by the tests of factors in two distinctive groups. The factors in a group are derived from a distinct physical phenomenon. The correctness of most of the factors in a group can be used to infer the correctness of the untested factors in the same group. The existence and scaling of multivalued stability were also tested in several cabled conductors larger than a single triplex without contradictory results. We have, therefore, concluded that the relationships developed can be confidently used by magnet designers.

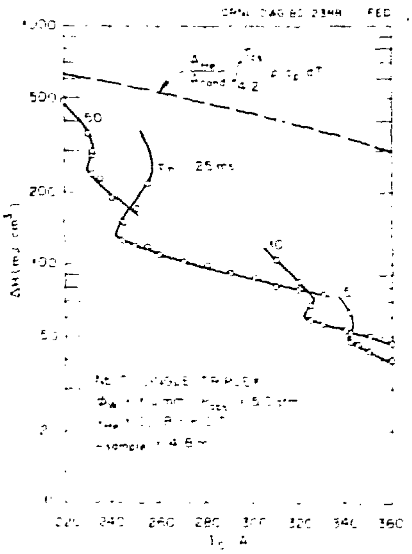

Fig. 4. Stability margin vs transport currents at different heat pulse durations.

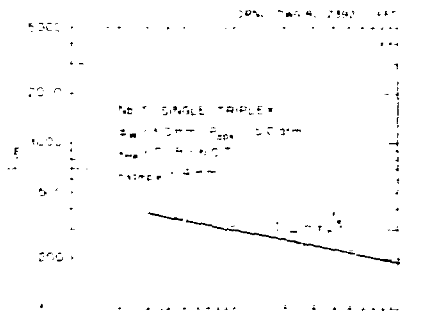

Fig. 5. Limiting current vs heat pulse duration. The scaling line is drawn to fit the data at τ_h = 5.0 ms.

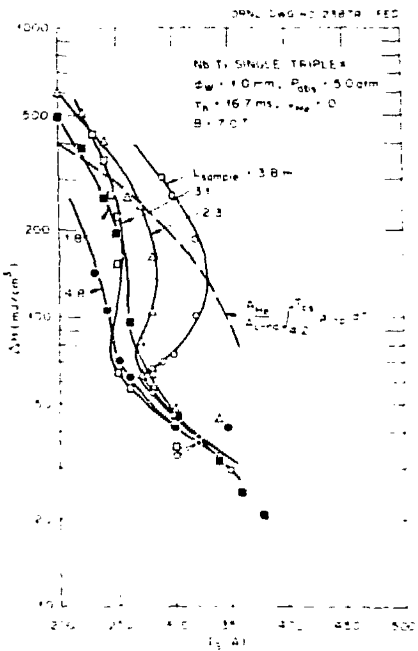

Fig. 6. Stability margin vs transport currents at different sample lengths.

Acknowledgments

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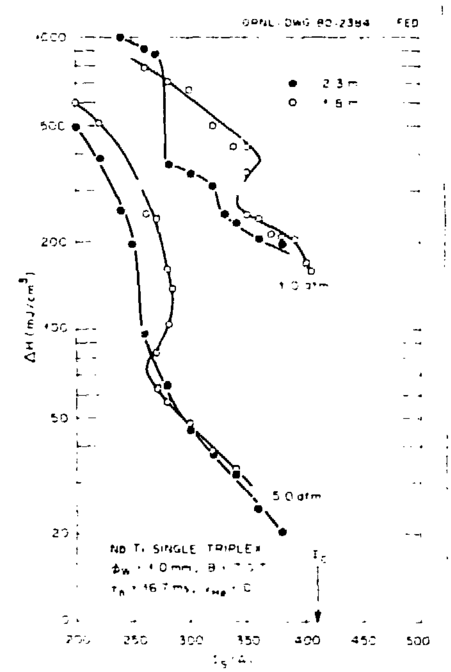

Fig. 7. Stability margin vs transport current at 5.0 atm and 1.0 atm.

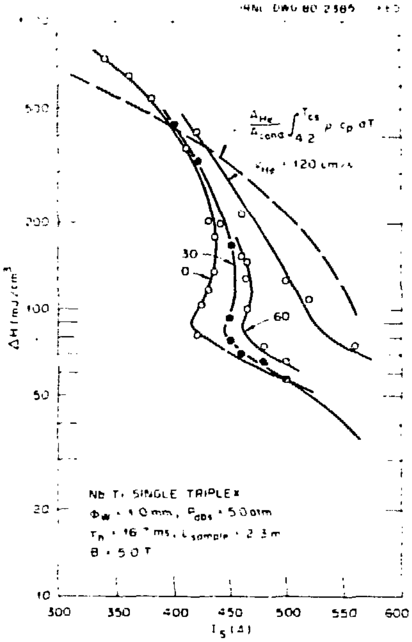

Fig. 8. Stability margin vs transport current at different imposed flow.

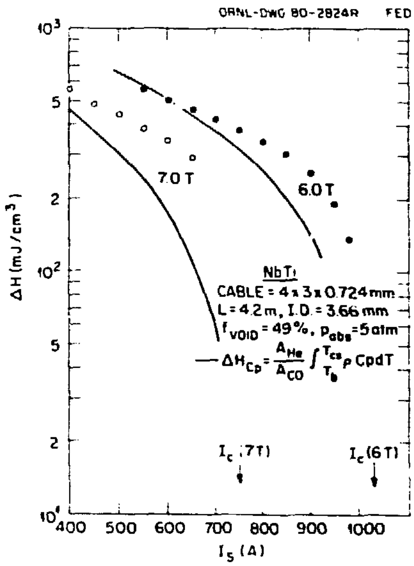

Fig. 9. Stability margin vs transport current for a 4 × 3 cable conductor.