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V-I transition and *n*-value of multifilamentary LTS and HTS wires and cables*

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Abstract

For low T_c multifilamentary conductors like NbTi and Nb_3Sn, the V-I transition to the normal state is typically quantified by the parameter, *n*, defined by $(\rho/\rho_c)= (I/I_c)^n$. For NbTi, this parameterization has been very useful in the development of high Jc wires, where the *n*-value is regarded as an index of the filament quality. In copper-matrix wires with undistorted filaments, the *n*-value at 5T is ~ 40-60, and drops monotonically with increasing field. However, *n* can vary significantly in conductors with higher resistivity matrices and those with a low copper fraction. Usually high *n*-values are associated with unstable resistive behavior and premature quenching. The *n*-value in NbTi Rutherford cables, when compared to that in the wires is useful in evaluating cabling degradation of the critical current due to compaction at the edges of the cable. In Nb_3Sn wires, *n*-value has been a less useful tool, since often the resistive transition shows small voltages ~ a few μV prior to quenching. However, in "well behaved" wires, *n* is ~ 30-40 at 12T and also shows a monotonic behavior with field. Strain induced I_c degradation in these wires is usually associated with lower *n*-values. For high T_c multifilamentary wires and tapes, a similar power law often describes the resistive transition. At 4.2K, Bi-2223 tapes as well as Bi-2212 wires exhibit *n*-values ~ 15-20. In either case, *n* does not change appreciably with field. Rutherford cables of Bi-2212 wire show lower values of *n* than the virgin wire.

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1. Introduction

The resistive transition of multifilamentary superconductors has been widely studied for both the low temperature superconductors (LTS), namely NbTi and Nb_3Sn, and the high-temperature superconductors (HTS), in particular Bi-2223 and Bi-2212. For the LTS conductors, the transition is frequently quantified by the parameter n defined by either

$$\left(\rho/\rho_c\right)=\left(I/I_c\right)^n, \text{ or } \left(E/E_c\right)=\left(I/I_c\right)^n \qquad (1)$$

where ρ is the resistivity, E_c is the voltage per unit length of conductor and I_c is the critical current defined by either the resistivity criterion $\rho_c=10^{-14}\Omega\text{-}m$ or by the voltage criterion E_c=10μV/m. The n-value which is usually a fairly large number is inversely related to the width of the V-I transition. It is also generally accepted that the measured I_c and n-value for practical LTS wires are affected both by extrinsic effects like filament uniformity and intrinsic effects related to flux-pinning and material in-homogeneities.

For Bi-based HTS conductors, the functional form of the *V-I* has also been studied extensively. In analogy with LTS conductors, the resistive transition of HTS/Ag multifilamentary tapes and wires has also been described by a power relation given by Eq.(1). Typically Ic for Bi-2223 and Bi-2212 conductors is given for E_c=1μV/cm, as field dependent measurements are made on samples, a few cm in length making it difficult to probe lower electric fields. Using a voltage resolution of 10^{-3} μv/cm, Fukumoto et al [1] have observed resistive tails for E<0.1μV/cm in Bi-2223 tapes which were attributed to grain-boundaries or micro-cracks which act as serially connected weak links. Such weak links can be intrinsic to tape fabrication, stochiometry of the powder, and the process used, or it can be induced by strain after tape fabrication. In general the HTS conductors tend to be limited by grain connectivity, voids, and non-superconducting precipitates. Improvements in J_c (defined for superconductor area) have been accompanied by higher n-values measured in the range of ~ 0.3 and 3.0 μV/cm [2].

In this paper, the use of n-value parameterization of the resistive transition is examined for multifilamentary wires and cables of NbTi, Nb_3Sn and Bi-2212 superconductors.

2. NbTi

The power relation, first introduced by F. Volker [3]and the concept of an effective resistivity [4]of composite superconductors has been used to study NbTi multifilamentary wires for over 30 years, and is routinely used in the specification of wires for accelerator magnets. During the early 1980's, a study of a large number of wires (filament diameter~ 9 μm) from one manufacturer which are nominally the same in composition and processing, showed a large variation in J_c (the transport critical current density of NbTi) and n [5].This problem in NbTi wires was first observed by Sampson et al [4]. Low Jc was correlated to a lower n. Metallographic examination of the filaments showed that wires with low J_c and n had filaments with significant variation in the cross-section along the length. This was shown to be due to the formation of hard nodules of Cu_4Ti particles on the surface of the NbTi filaments during the multiple heat-treatments designed to precipitate the a-Ti for flux-pinning[6,7]. As the wire is drawn to final size from the last heat-treat, the micron size nodules do not deform with the filaments as they are drawn down to a smaller size and cause filament "sausaging" along the length. Hence, n can be used as *index of geometric filament quality* to evaluate different wires for practical applications [5, 8].

Several groups [9-11] have modeled the resistive transition assuming a critical current distribution which is characterized by a width σ and an average $<I_c>$. This is extracted from the second derivative of the voltage (d^2V/dI^2). In general, the width of the distribution is reflected in the n-value, where $n \propto 1/\sigma$. From a practical point of view, the improvement in J_c of strands, (with filament diameters ~ 5-7 mm), in the mid-1980's, resulted from eliminating non-uniform deformation of the filaments. This was achieved by cladding the alloy rods with niobium [12], which prevents the Cu-Ti intermetallic from forming, and by reducing the spacing between the filaments to improve the co-deformation of the alloy filaments and the matrix [13]. With the Nb-barrier, better metallurgical processing further helped to increase the intrinsic J_c of NbTi wires [14].

Fig. 1 shows the V-I curve for a closely spaced 5μm filament wire of diameter 0.81mm with a Cu/Sc ratio of 1.45. Voltage taps are spaced 60cm apart. The V-I curve fits very well to Eq. 1 (shown by a dashed curve). The inset shows the same data plotted as log (ρ) versus (I/I_c). Note that the fit extends over two decades of resistivity. In this case the E_c criterion gives an I_c of 354A. NbTi conductors used in superconducting accelerators magnets typically have J_c (6T, 4.22K) ~ 2100-2300 A/mm^2, and n-value ~ 40-60. Fig. 2 is a plot of *n* as a function of field for accelerator-magnet type wires which all have filament diameters ~ 6-7 μm. All of these wires have Cu-matrix and all except one show a monotonic behavior with field. The one which has the lowest *n* is an early LHC outer wire which is fabricated using the "double-stack" approach as opposed to a "single-stack' multi-billet assembly. Although this billet has Nb-barrier mono-rods, the filaments in the "double-stack" billet draw down non-uniformly, leading to a poor filament quality and an *n* that does not change appreciably with field as has been observed in earlier studies [5, 15]. Included also is a wire made by the APC process [16-17], which shows high *n* which is typically seen in mono-filament wires. A micro-graph of this multifilamentary wire is shown in Ref. [17]. Also note from the three LHC 1.06mm wires with varying Cu/Sc ratio, that the *n*-value seems to be higher the lower the fraction of Cu-stabilizer. Possibly this accounts for the high-*n* for the APC wire which has a very low Cu/sc ~ 0.85.

Does the interfilament matrix effect the resistive transition of NbTi wires? It would appear not to be significant when the filaments are uniform with little "sausaging". Fig. 3 is a plot of the V-I curves for wires from two billets which are similar except that one has an inter-filament matrix of Cu-0.5%Mn, with a central core and an outer ring of copper. This alloy has a 10K resistivity of 1.5 μΩ-cm. Both wires are 0.81mm in diameter, with 11000 filaments of size ~ 5μm and have an overall Cu(Cu+CuMn)/NbTi ~ 1.45 [18]. Excluding the inter-filament region, the Cu-stabilizer volume in both wires is ~ 50%. Both wires show very similar J_c and *n*-values, the one minor difference being that the Cu-Mn matrix wire develops a lower voltage at quench. However, the stability of a wire can be significantly reduced when both the inter-filament region and the stabilizer are highly resistive. An example of that is a 1 mm wire with 500 filaments in Cu30%Ni matrix with an outer jacket of Cu10%Ni. This wire when mounted in the regular insulated holder, quenched prematurely at low currents as shown in Fig. 4. However, when soldered to a copper tube-barrel, resistive transition was obtained only at high fields. At 8T, the *n*-value was ~ 16. Below 8T, only quench currents (Iq) are obtained, and as shown these soon fall below the expected I_c (dashed line).

The *n*-value is also a useful tool in evaluating keystoned Rutherford cables, where the minor-edge ratio (minor-edge cable thickness / 2 x wire diameter) is ~ 80%. In this region the wire is heavily deformed as compared to that at the major edge where the ratio is close to 1. In tests of such cables, the measurement conditions can be altered so that the peak field can be located at the minor or at the major edge of a pair of cables [19]. Fig. 5 is an example of the resistive transition of a 28-strand cable at an applied transverse field of 7T under these conditions. Note that Ic and *n* when the peak field is at the minor edge of the cable is lower than that at the major edge. The major edge *n* is similar to the un-cabled wire. When there is excessive compaction of the wire at the minor-edge, *n* can become very low as shown in Fig. 6 which compares a cable of the same width fabricated with 37 and 38 strands. The resistive transition at the minor edge is severely degraded for the 38-strand cable. Even the 37-strand cable shows mechanical damage of the filaments [5] as evidenced by *n* of 23 as compared to the strand *n* of 44 at 7T. By increasing the cable width of the 37-strand cable, *n* was increased to ~ 35-40.

3. Nb_3Sn

The development of Nb_3Sn has been more diverse than NbTi, as the fabrication of multi-filamentary wires has followed several different paths depending on the end application. The *n*-value variation from wire to wire is very significant. This is because a large number of factors affect *n*: non-uniform filaments, filament distribution in the bronze-matrix, compositional variation from filament to filament, grain size variation across the filament cross-section, strain-state of the wire after reaction. For Nb_3Sn wires the *n*-value has been a less useful tool, since often the resistive transition shows small voltages ~ a few μV prior to quenching. Often one can only test high Jc wires in the field range of 14-16T, and then extrapolate the Ic to lower fields. In "well-behaved" optimized wires, *n* is ~ 40 at 12T, and it decreases monotonically with field [20]. However, in general it is observed (similar to NbTi) that wires which have a low *n* tend to have a flat *n* vs. B curve than the optimized wires [21].

At Brookhaven Laboratory (BNL), we are developing flexible 6-around-1 cable using small-diameter wires suitable for "react-and wind" magnets. Normally when the cable is reacted at ~ 650-700C, the clean copper surfaces of the strands sinter together, so that the cable is stiff and behaves like a monolithic wire of a much larger diameter. To maintain the bend strain characteristic of the fine wire, the wire surface is coated with a lubricant, Mobil 1™, which prevents the wires from sintering together. This flexible cable is then insulated with a Kapton™ tape and wound into a magnet coil with a small minimum bend diameter. Fig. 7 shows the Jc-H curve for the cable fabricated from low-loss ITER strand [22] drawn down to 0.33mm and that has undergone heat-treatment and insulation. The J_c measured on an insulated barrel 50mm in diameter (effective bend strain $\varepsilon_b \sim 0.55$) shows no degradation from the strand which was tested in the conventional ITER-barrel "wind-and react" method. However, when the same cable sample is bent around a 32mm barrel and then re-measured on the standard holder, the I_c is nearly the same, but *n* is reduced indicating onset of filament damage due to bending strain [23]. Prototype cables fabricated from 18-filament Powder-in-Tube wire (J_c @12T ~ 1300 A/mm^2) [24] show ~ 25% degradation at similar bending strains. To reduce this strain the reaction mandrel diameter will be reduced from 290mm to 150mm, such that the effective bending strain at 50mm would be ~ 0.45. Mono-element high Jc Internal-Sn wires (J_c ~ 2700 A/mm^2) [25] are also being evaluated.

4. Bi-based conductors

The critical currents of HTS conductors are usually quoted for E_c=1.0 μV/cm. This would seem appropriate at temperatures where the currents are small. However, at 4.2K, the currents for wires or tapes with cross-sectional area ~ 0.5-0.6 cm^2 can be several hundred amps so that the resistive transitions can be measured at a smaller E_c or effective resistivity. In fact HTS conductors seem to have V-I characteristics similar to LTS wires of low n. Fig. 8 is a plot of ρ vs. I/I_c at 5T for a 100 cm long piece of commercially available Bi-2223 tape (3.1mm x 0.175mm), wound on a 50mm diameter holder. This tape showed no degradation at this bending strain $\varepsilon \sim 0.35$.

Multifilamentary Bi-2212 is of particular interest for magnet builders as it can be processed as a wire with high J_c [23], and Rutherford cables can be fabricated for making magnets using the "react-and-wind" method. Wire testing at 4.2K is limited by the use of short lengths of a few cm as the magnet bore is only 60mm, whereby the critical current is defined for E_c=1.0 μV/cm. Shortly, we are developing testing of wires using an appropriate barrel so that longer sample lengths can be used to measure the transition at much lower electric fields. Fig. 9 is a plot of the critical current normalized to that at zero-field, I_c/I_c0 and n for a 1.0mm strand (I_c0=790 A, $J_c \sim 3800$ A/mm^2) and a 0.8mm strand (I_c0=653 A, $J_c \sim 4500$ A/mm^2) from two different manufacturers. The normalized I_c is similar for the two wires. However, n for the higher J_c, 0.8mm wire, is greater than the other. Also n decreases rapidly at low fields and then is relatively independent of field for B>0.5T [24]. Additionally, I_c does not exhibit hysteretic behavior with field as has been observed in lower J_c wires [25].

In collaboration with T. Hasegawa (Showa Electric in Japan) and R. Scanlan (LBL), Rutherford cables of 18, 20 and 30-strands were fabricated at LBL from Showa-wire and heat-treated at Showa. These were tested at BNL, in background fields to 7T. In these tests the field is applied either parallel or perpendicular to the wide face of the cable. The V-tap length is typically 60cm in uniform field, so that the resistive transition can be measured at levels similar to LTS cables. Fig. 10 depicts the resistive transition for a 30-strand cable that has an I_c of 8643 A with n=10.1. Note that the power relation (shown by the dashed line) fits the data over almost two decades of electric field. Fig. 11 summarizes the Ic (for both criteria) and n for this cable. The difference in I_c between the two criteria is ~ 35%. In these measurements, the sample configuration is such that the applied parallel field opposes the self-field of the cables, hence at low fields the I_c initially increases with applied field. The cable n-value is smaller than that of the uncabled strand. This is under further investigation.

5. Summary

There is a great deal of literature on the resistive transition of superconducting wires and tapes. In this paper, an attempt has been made to show that the power relation is a practical way to analyze the transition, and that the n-value is a useful tool to evaluate a conductor. However, a detailed theory of the n-value is lacking, or even whether Eq. (1) is the correct functional dependence for the voltage development. In multifilamentary NbTi the behavior of n seems to be widely accepted. Not so clear are the effect of the inter-filament matrix and the role of the stabilizer. This is all the more apparent for Nb_3Sn where, either a resistive transition is not observed for H < 12-14T for high I_c wires, or the voltage is only a few μV making n determination unreliable.

The resistive transition of Bi-based wires and tapes is similar to LTS wires. For recent conductors, n is relatively higher than earlier wires, indicating substantial improvement in J_c. The sharp decrease in both n and I_c at low fields for Bi-2212 wires could imply that the connectivity of the grains is still limiting its performance and that there is considerable room for Jc increase. Filament uniformity and compositional in-homogeneity also need to be improved. With the present I_c's of these wires, we propose that the critical current be defined similarly to LTS wires and cables as power dissipation at 1μV/cm would be very significant in a large device like a dipole magnet.

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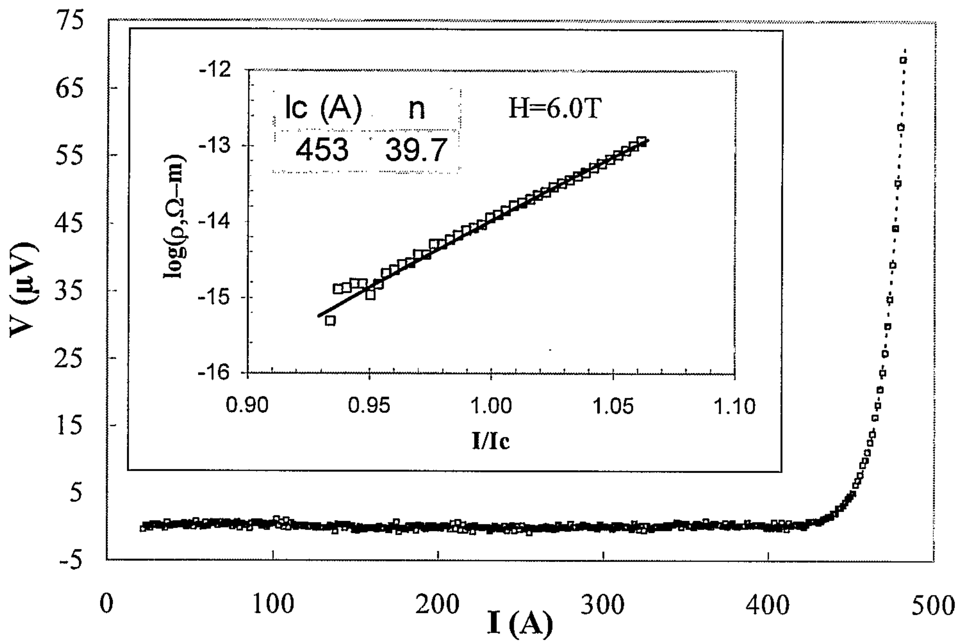

Figure 1 V-I curve for a 5mm filament NbTi wire. Inset is a plot of the effective resistivity vs. I/Ic

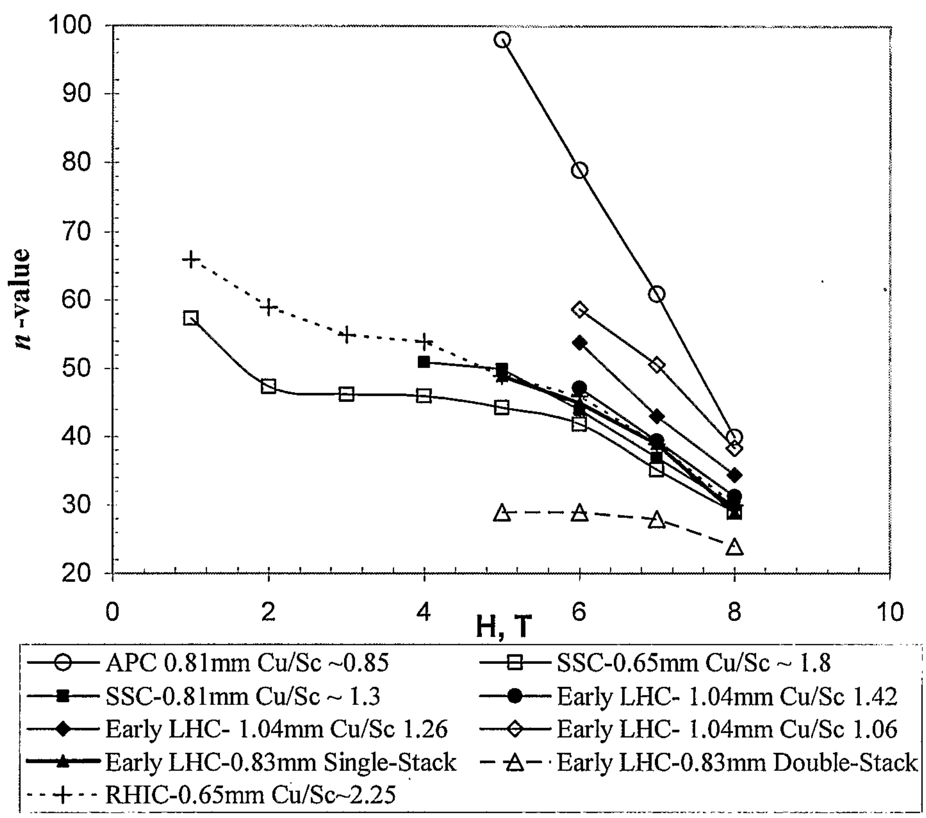

Figure 2 *n*-value vs. H for conductors used in accelerator magnets

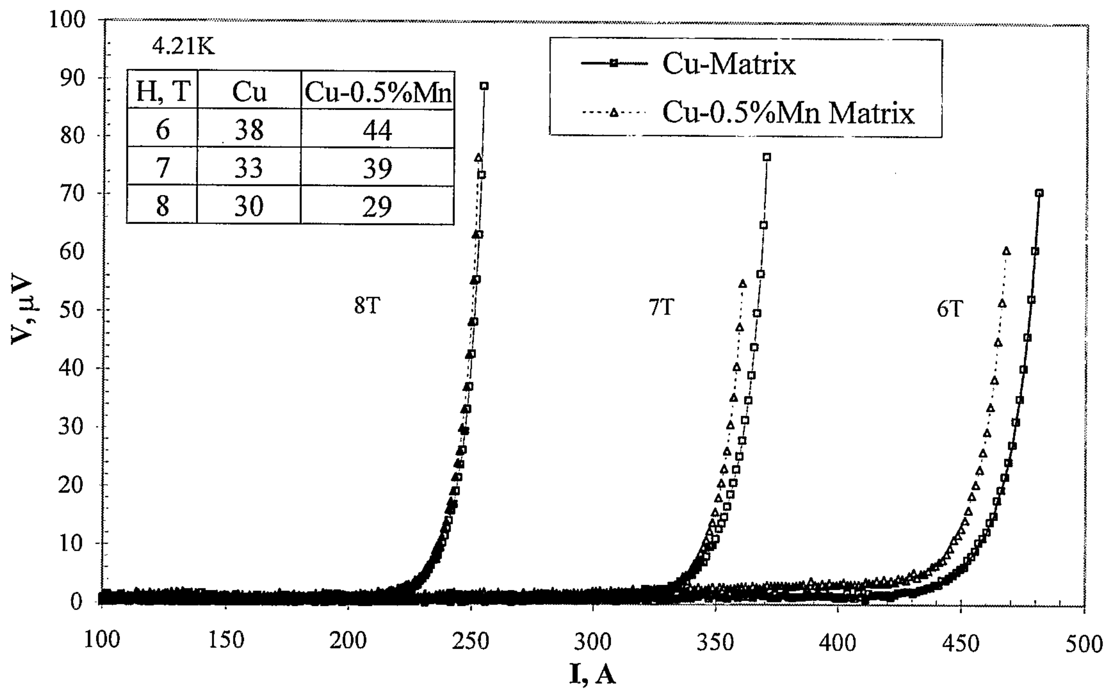

Figure 3 V-I traces for two wires, one with Cu-in the interfilament region, the other with Cu-0.5%Mn. Inset gives the n at different fields.

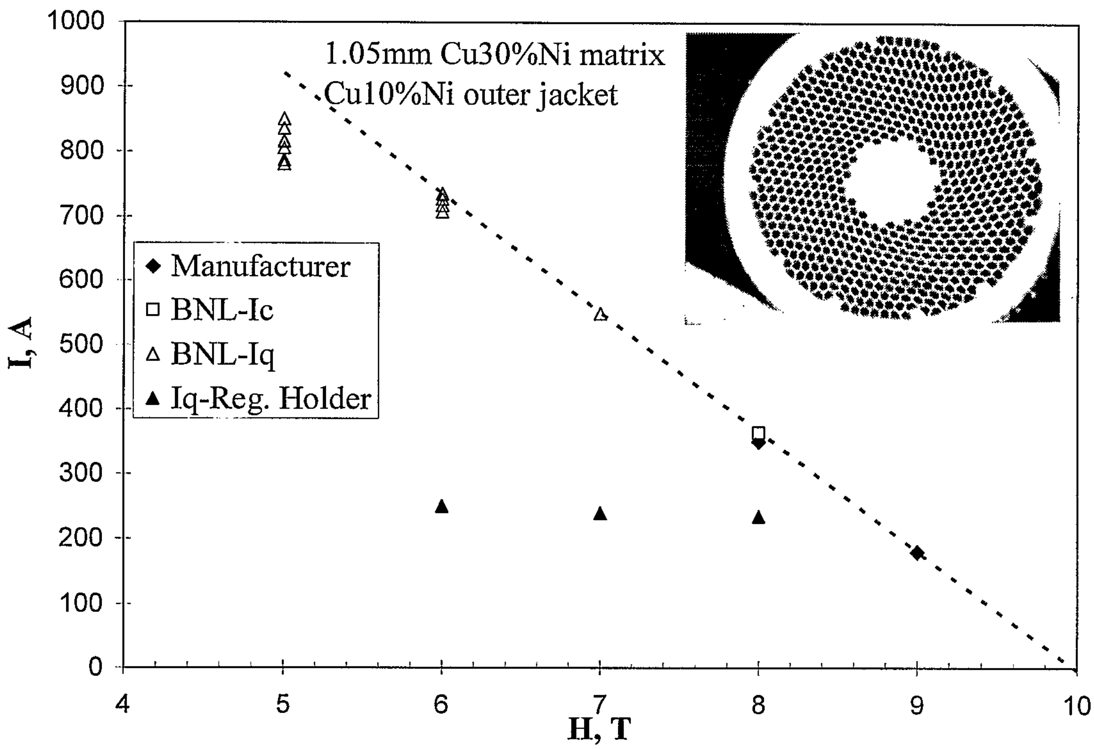

Figure 4 Ic and quench current Iq for a Cu-Ni stabilized wire. Dashed line is the expected Ic as a function of H. Inset is a micrograph of this wire.

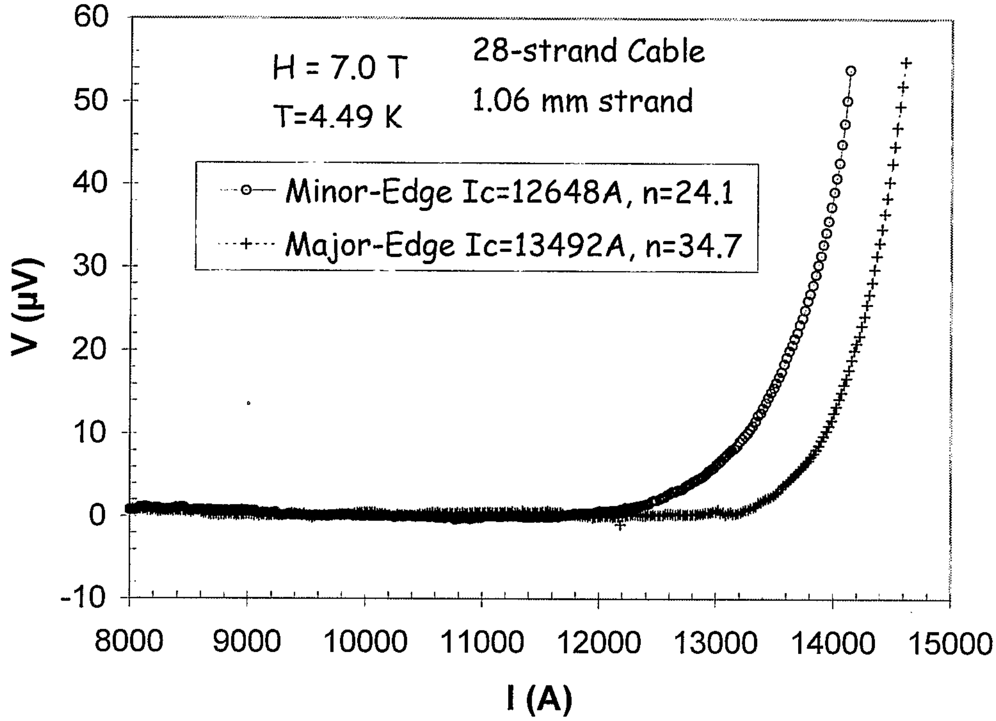

Figure 5 V-I trace of a cable sample where the peak-field is either at the minor or at the major edge.

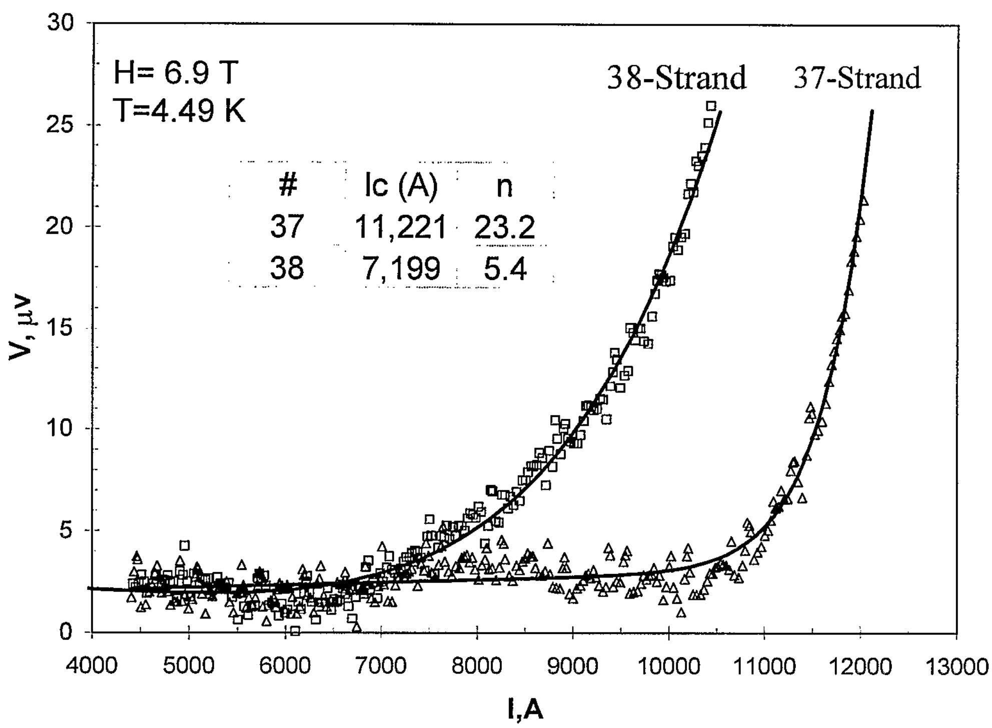

Figure 6 V-I measurement of a 37-strand and a 38-strand cable with the peak field at the minor edge.

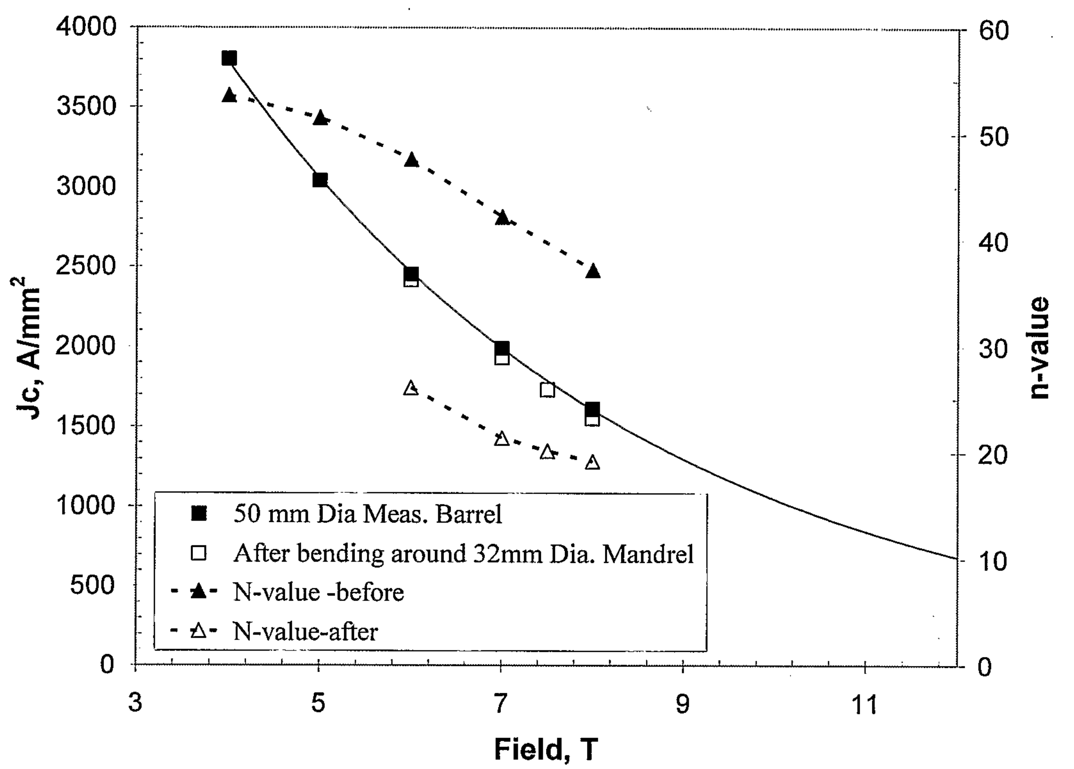

Figure 7 Jc and n for a 6 x1 cable of 0.33mm Nb_3Sn strand.

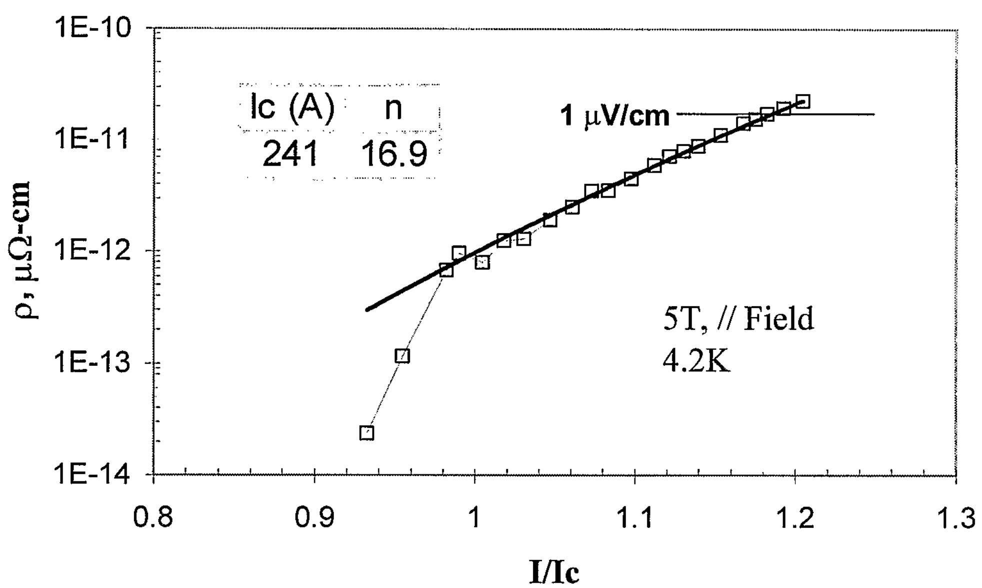

Figure 8 ρ vs. I/Ic for a Bi-2223 tape in 5T field applied // to the wide face of the tape

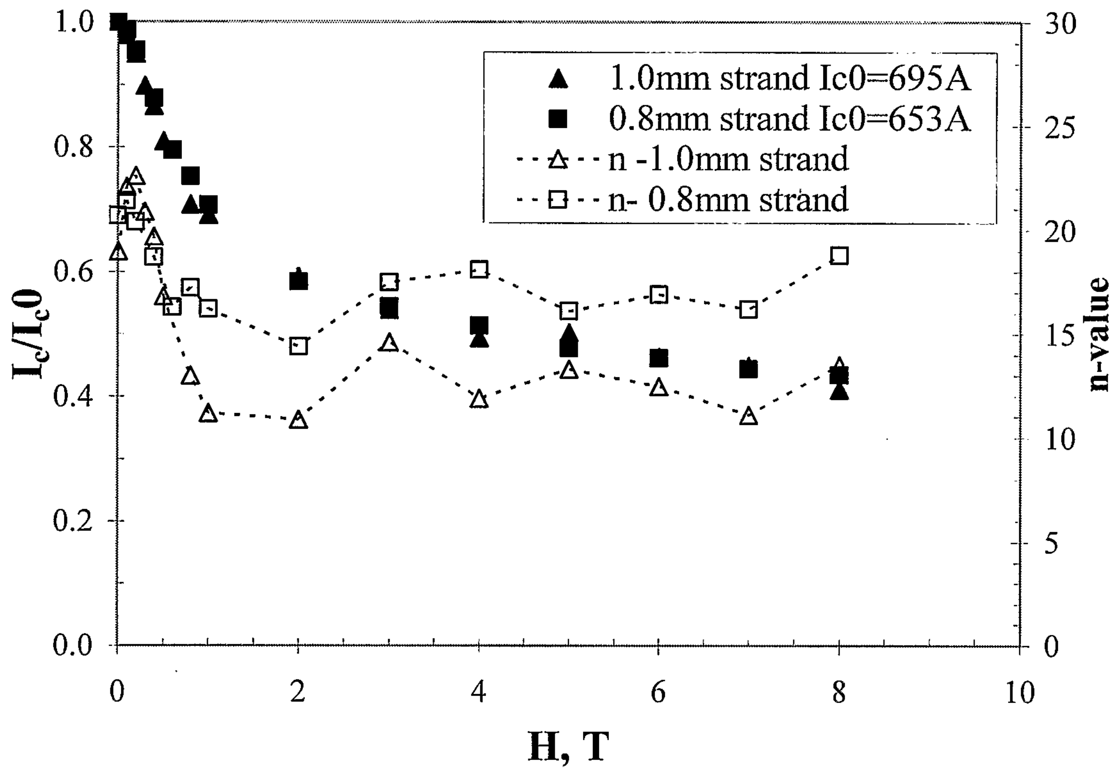

Figure 9 Normalized Ic and *n* vs. H for Bi-22212 wires from two manufacturers.

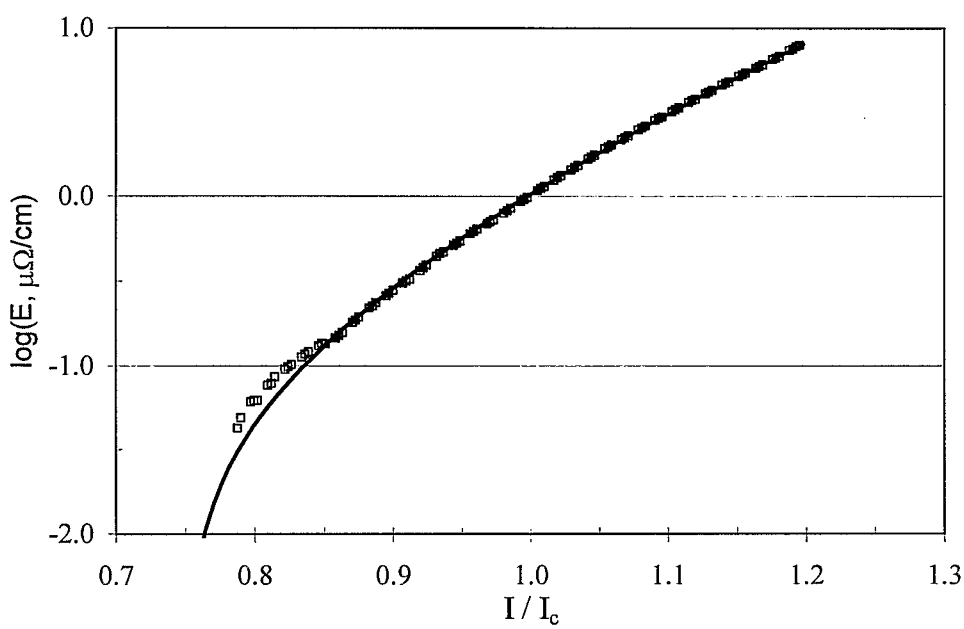

Figure 10 Plot of log(E) vs. I/Ic for a Rutherford cable of Bi-2212 at 4.2K. Ic=8643A for *Ec*=1μV/cm

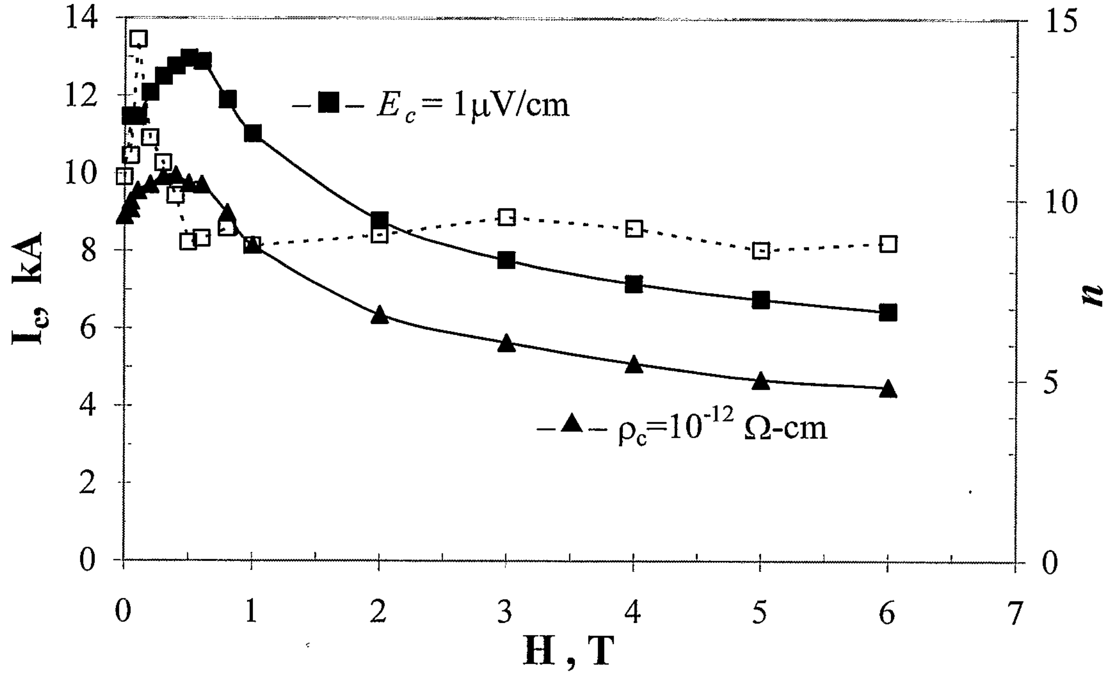

Figure 11 Ic and *n*-value as a function of applied field for a 30-strand Bi-2212 cable.