BROOKHAVEN NATIONAL LABORATORY

*Superconducting Magnet Division*

*Magnet Note*

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**Title:** Critical Current Measurements of Bi-2212 Wires

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# Critical Current Measurements of Bi-2212 wires

Arup K. Ghosh and W. B. Sampson

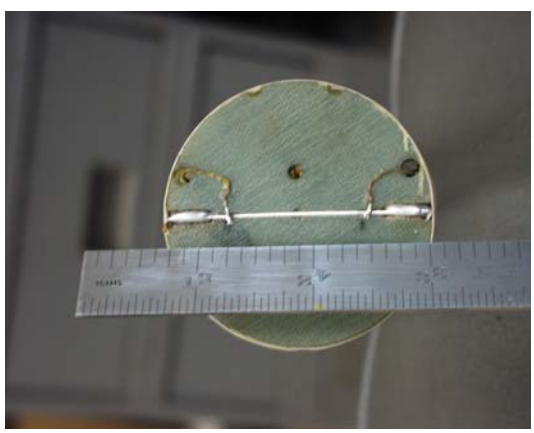

## Abstract

Short lengths of Bi-2212 wires manufactured by SHOWA and OST were measured at 4.2K in fields up to 8T. The data have been analyzed in terms of an exponential field function at low fields and pinning-force functions at higher fields. In addition strands extracted from a 30-strand SHOWA cable were also measured. These are compared to the critical currents measured for the cable samples at BNL's Short Sample Test facility. A 0.8mm diameter strand from OST showed the highest Jc of 4350 A/mm$^2$ at zero-field and ~ 1900 A/mm$^2$ at 8T. The high Jc wires tend to be $O_2$-overdoped and have Tc's ~ 80K.


## Introduction

The critical currents of HTS conductors are usually quoted for an electric field gradient, $E_c$=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 mm$^2$ can be several hundred amps so that the resistive transitions should be measured at a smaller electric field gradient or effective resistivity. In fact HTS conductors seem to have V-I characteristics similar to LTS wires of low *n-value*. Multifilamentary Bi-2212 is of particular interest for magnet builders as it can be processed as a wire, and Rutherford cables can be fabricated for making magnets using the "react-and-wind" method. At present, straight wire testing at 4.2K is limited lengths of a few cm since the solenoid bore is only 60mm, so that the critical current $I_c$ is defined at $E_c$=1.0 μV/cm. In the future testing of wires using an appropriate barrel needs to be developed so that longer sample lengths can be used to measure the transition at much lower electric fields.

Tests of three wire samples are described here. One from Showa is a 1.0mm strand (B1152DE28) with Ag/SC ratio of ~ 2.8. The others are a 0.82mm and 0.72mm strand (PMM030224) from OST with a Ag/SC ratio of ~ 2.5. Typical sample lengths were ~ 5cm and voltage-tap separation was ~ 30mm. The picture below shows the arrangement.



## Results

Figure 1 shows the *E-I* measurements for B1152 wire for different fields applied perpendicular to the wire. A log-log plot is shown to display the characteristic power-law behaviour seen in LTS wires. However, the *E-I* curve often does not have a unique *n-value*. For analysis the *n-value* is averaged for electric fields between 0.3 and 3.0 μV/cm. Figure 2 summarizes the critical current and n as a function of field. Note that $I_c$ initially falls rapidly with field and then gradually decreases with field.

Figures 3 and 4 show the critical current and n-value for the 0.82mm and 0.72mm wires from OST. Although the $J_c$ of these three strands vary, the $I_c1$ behaviour as a function of field is very similar. This can be seen in Figure 5, where the normalized critical current $I_c(H)/I_c(1T)$ is plotted versus the applied field. The similar $J_c$-H dependence would imply that the basic material properties at these fields are similar for these wires. Indeed if one analyzes the $J_c$ in the two field regimes, H<1T and H>1T, it appears that for H<1T, the dependence is exponential in H,

$$J_c = J_{c0} \exp^{-bH} \quad (1)$$

and above 1T, the data fit a power law

$$J_c = J_{c1} H^{-m} \quad (2)$$

An example of the fit is shown in Figure 6, and the fitting parameters for the three wires are summarized in Table 1.

Table 1

| | | | | | H< 1T | H< 1T | H> 1T | H> 1T |
|---|---|---|---|---|---|---|---|---|
| Wire ID | No. of Fils | Diameter | Jc (1T) | Jc (5T) | Jc0 | *b* | Jc1 | m |
| | | *mm* | *A/mm²* | *A/mm²* | *A/mm²* | *T* | *A/mm²* | |
| B1152 | 127x7 | 1.00 | 2617 | 1863 | 3864 | 2.5 | 2572 | 0.21 |
| PMM030224 | 85x7 | 0.82 | 3076 | 2080 | 4410 | 2.7 | 3052 | 0.23 |
| PMM030224 | 85x7 | 0.72 | 2738 | 1872 | 3980 | 2.6 | 2740 | 0.24 |

The low field exponential behaviour suggests the possibility of weak link coupling between the filaments or between the grains. In this region the n-value also decreases rapidly. It would be interesting to compare the magnetization with the transport current at low fields. At fields > 1T, it is common in the literature to show that the critical current density of Bi-2212 wires varies exponentially with field [1, 2]. The data shown here can also be fit to a form of Eq.(1) with *(1/b)* ~ 20T. However in this limited field region at 4.2K, one would have to measure to high fields ~ 20T to clarify which is the better functional dependence. Behaviour similar to Eq. (2) has been reported [1], where at 4.2K $J_c$ has been found to be proportional to $H^{-0.19}$. In the next section we shall examine the pinning force where other considerations suggest a different dependence on field.

### *Pinning Force*

The pinning force calculated for these wires are shown in Figure 7. In the range of 0.1T<H<8T, Fp is proportional to $H^{0.8}$. This field dependence can only be a limiting form of the full field behaviour, otherwise this would be unphysical. In analogy with metallic superconductors, the pinning force must have a maximum and can be discussed in the context of a scaling law of the form:

$$F_p(H,T) = C(T)h^p(1-h)^q \quad (3)$$

where *C* is a proportionality constant which is temperature dependent, and $h=H/H_{c2}$ For HTS $H_{c2}$ is replaced by the irreversibility field $H^*$. For NbTi, $p=q=1$, and for $Nb_3Sn$ the Kramer-law [3] prediction is $p=1/2$, $q=2$. When h<<1 (which is the case for HTS at 4.2K), the observed $J_c$ behaviour would imply that $p\sim 0.8$. However, From a study of Bi-2212 wires at different temperatures, R. Wesche [1] has shown that Eq. (3) does fit the observed data using the following values for the exponents, *p=0.9 and q of either 3 or 5.* For low temperatures T<10K, the much smaller accessible values of *h* make it difficult to predict the true value of $H^*$. To study Eq.(3) at 4.2K, $I_c$ measurements have to be extended to the range of 50T as the peak in *Fp* is indicated to be at $h\sim 0.2$. In Figure 8 the $J_c$ for the SHOWA wire is shown with the various fits to $J_c$, all of which describe the $J_c$ well in the range of applied field used for the present measurements. Some recent measurements of $I_c$ from OST taken at 4.2K and to fields of 25T seems to have the best fit to *p=0.8 and q=3.0* with $H^*\sim$ 400T!

***Extracted Strands***

In an attempt to compare the critical current measured for a cable to the strands in the cable, individual strands were carefully separated from a section of the cable **HTS-S-R007B147-1**. The straight section of the wire between the two edges of the cable was used to measure $I_c$ as a function of field at 4.2K. 5 such samples were tested and the $I_c$ at 1T was found to vary from 150 to 382A. The large variation of $I_c$ in the strands might be due to some degradation in Ic sustained during the extraction process. The strands are fairly well sintered in the cable making the extraction procedure difficult. Cable measurements when corrected for self-field give an average strand $I_c$ of 360A. Although the critical currents vary significantly, the normalized $I_c$ behaviour is very similar as shown in Figure 9. Details of the cable measurements appear in the appendix.

## Summary

Although the wires tested were from two different manufacturers with their own heat-treatments, the $J_c$ behaviour with field is very similar at 4.2K. Also these wires have a low Tc ~ 80K and negligible $I_c$ at 77K.The low Tc is indicative of wires which are $O_2$-overdoped. In contrast the wires extracted from the cable sample have Tc's ~ 90K and have measurable critical currents at 77K, and lower $J_c$ at 4.2K

Below 1T, the $J_c$ dependence on field is exponential, indicative of weak-link coupling of the grains. Decoupling fields are ~ 2.5T. In the field range studied, the $J_c$ above 1T seems to fit a power law of $H^{-0.8}$. This however is only a limiting form of the general pinning-force function. Measurements to fields ~ 50T are necessary to clearly estimate the upper critical field at 4.2K

## Acknowledgements

We thank Dr. T. Hasegawa of Showa Electric Wire and Cable Co., and Dr. K. Marken of Oxford Superconducting Technology for providing the heat-treated samples for test.

## References

1. R. Wesche, "Temperature dependence of critical currents in superconducting Bi-2212/Ag wires", *Physica C*, 246 (1995) 186-194.
2. C.M. Friend, J. Tenbrink, D.P. Hampshire, "Critical current density of Bi2Sr2Ca1Cu2Od monocore and multifilamentary wires from 4.2 K up to Tc in high magnetic fields", *Physica C*, 248 (1995) 213-221.
3. E.J. Kramer, *J. Appl. Phys*. 44 (1993) 1360.

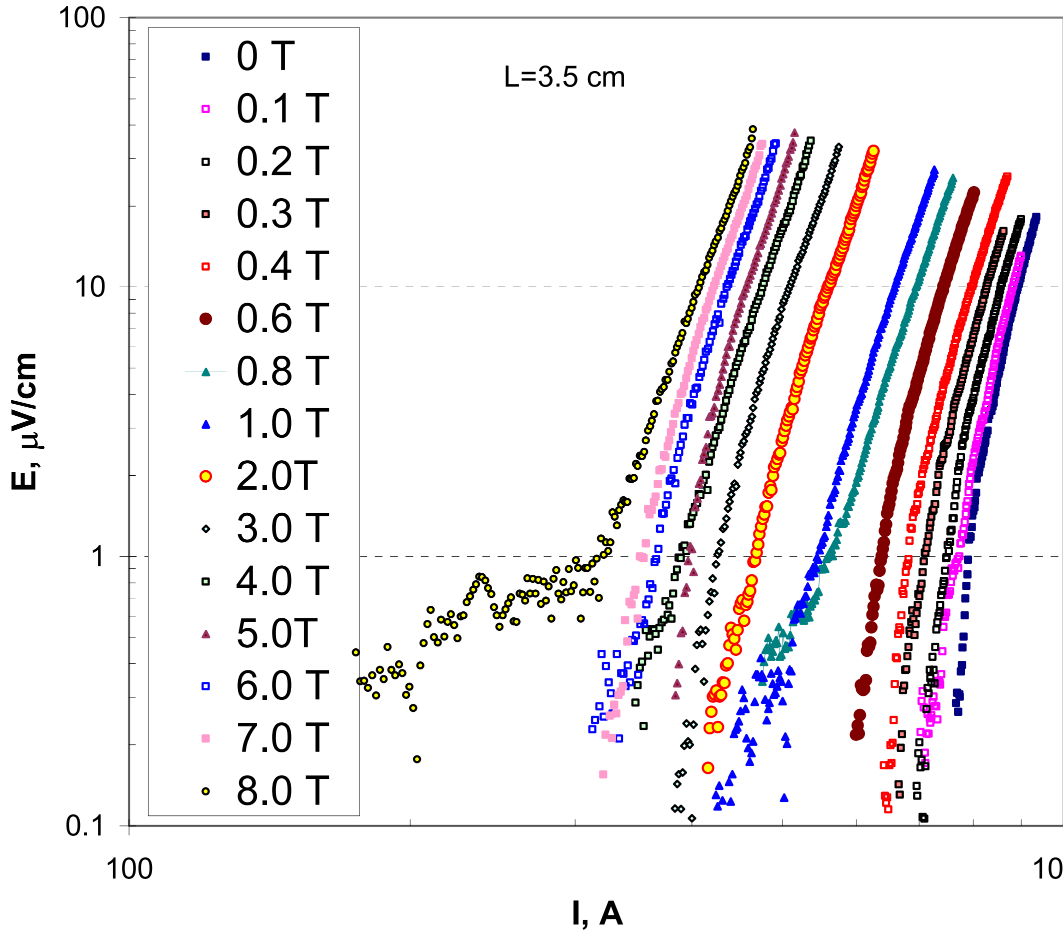



**Figure 1** E-I curves for B1152DE28 strand at 4.2K and in applied fields to 8T.

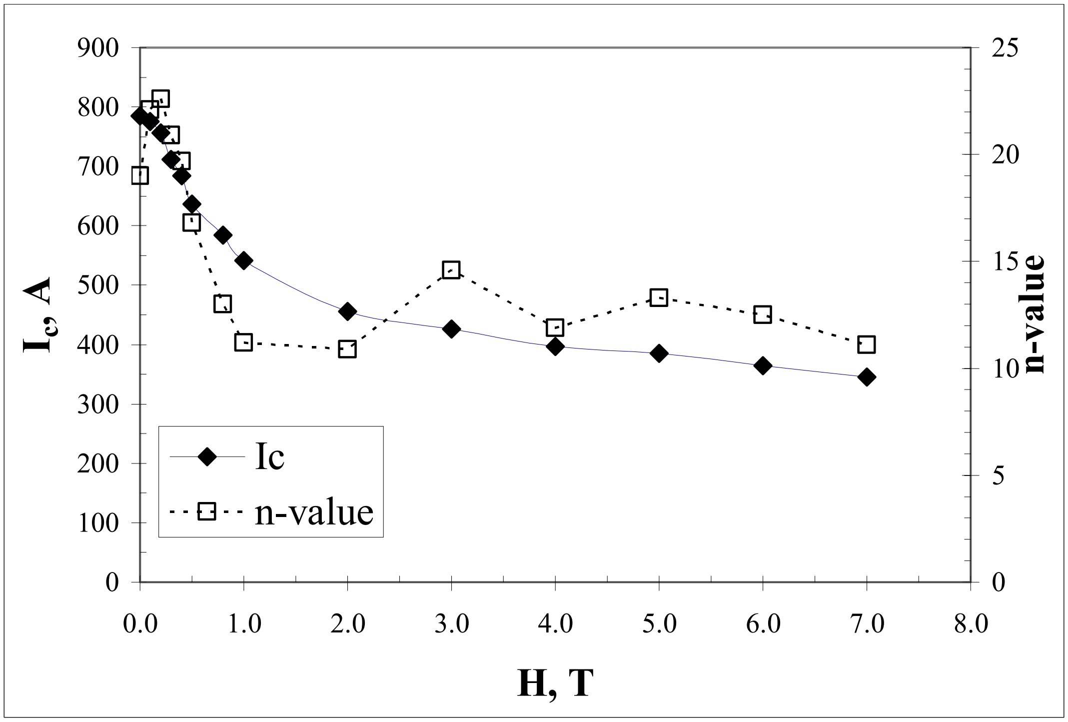



**Figure 2** $I_c$ and n-value for B1152DE28 strand from Showa

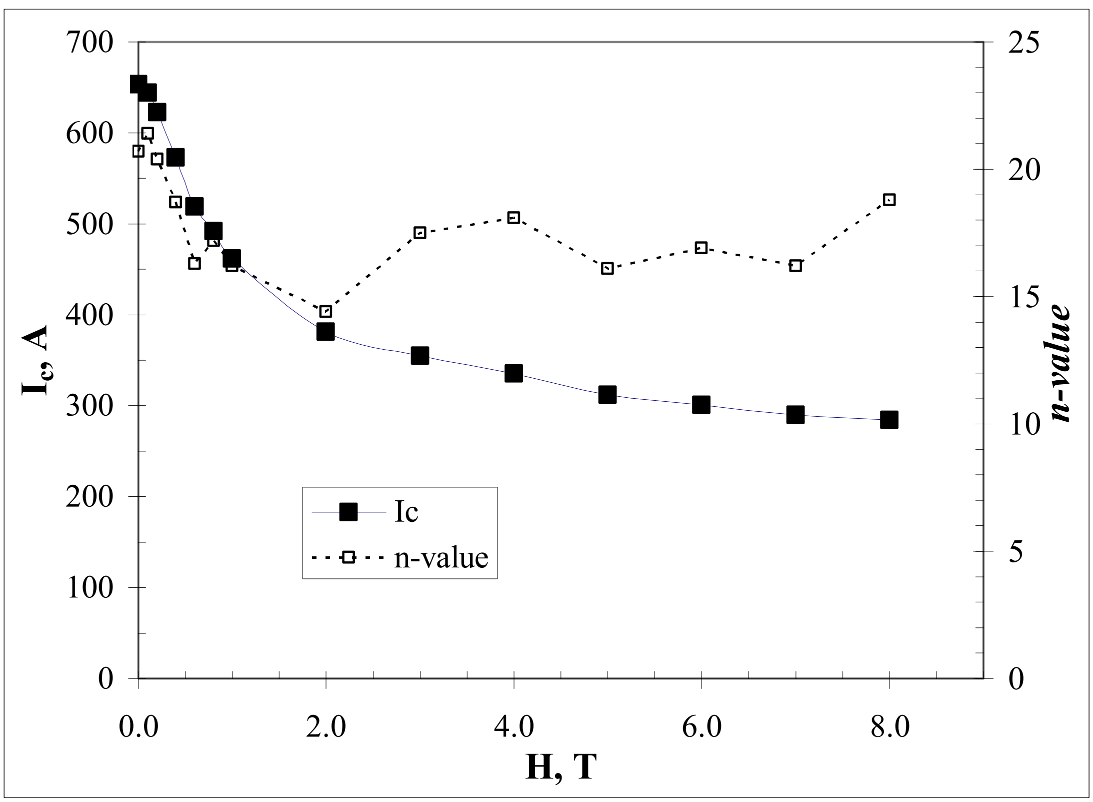



**Figure 3** $I_c$ and n-value for the 0.82 mm strand PMM030224 from OST

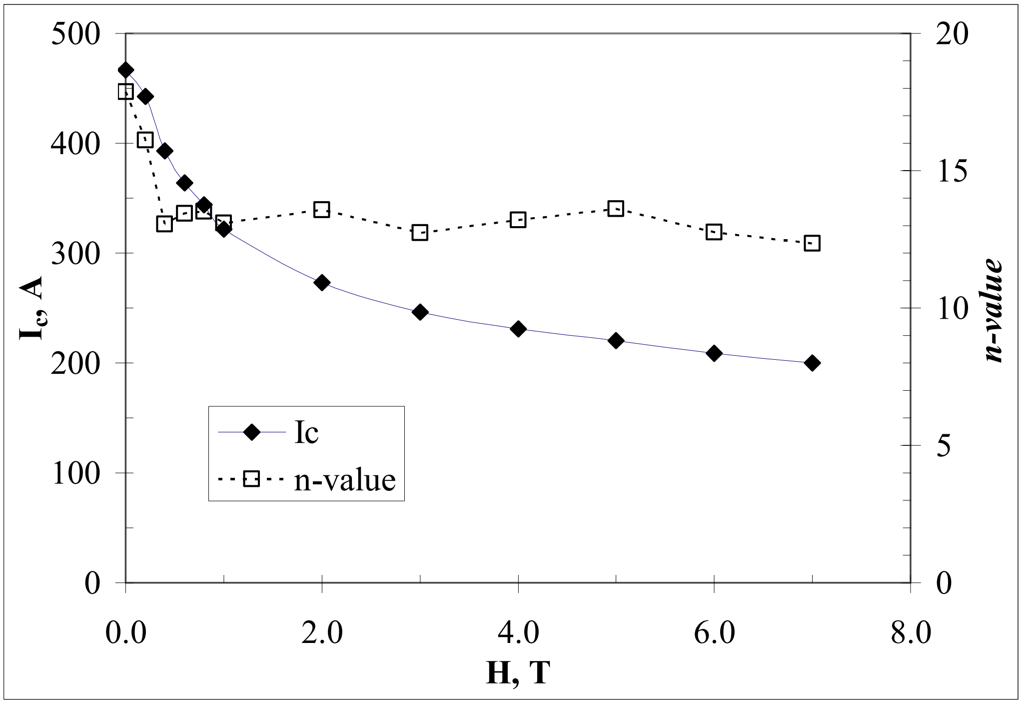



**Figure 4** $I_c$ and n-value for 0.72mm strand (PMM030224) from OST.

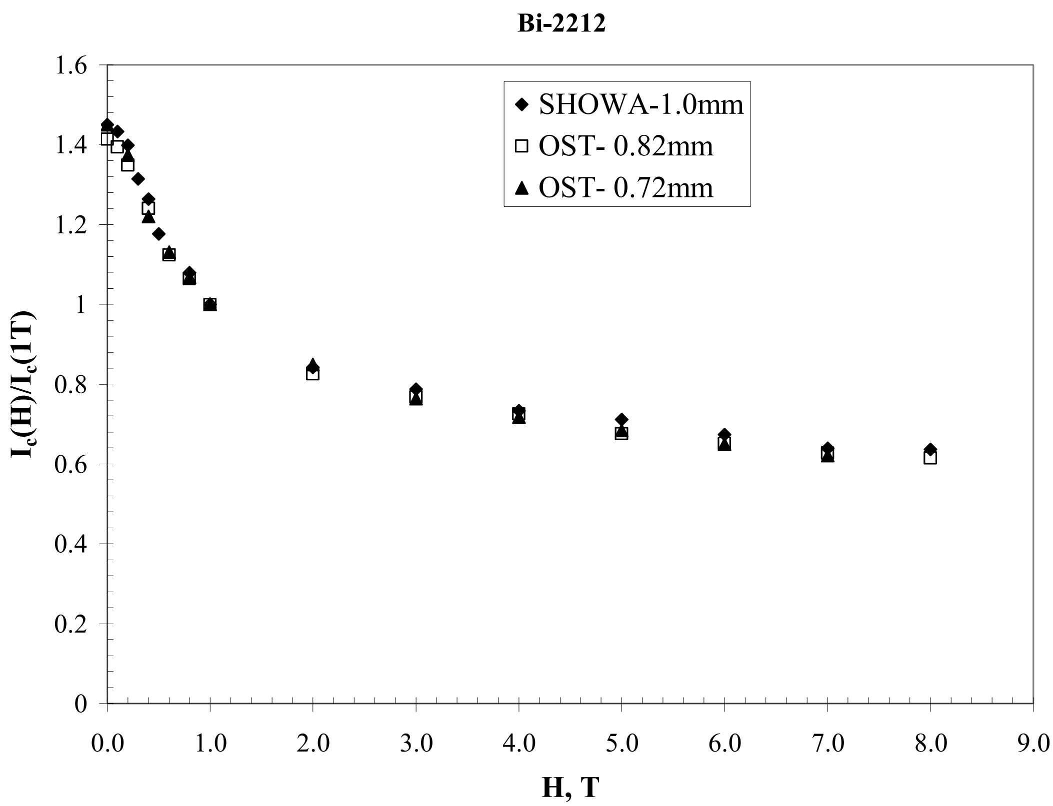



**Figure 5** Normalized critical current as a function of field.

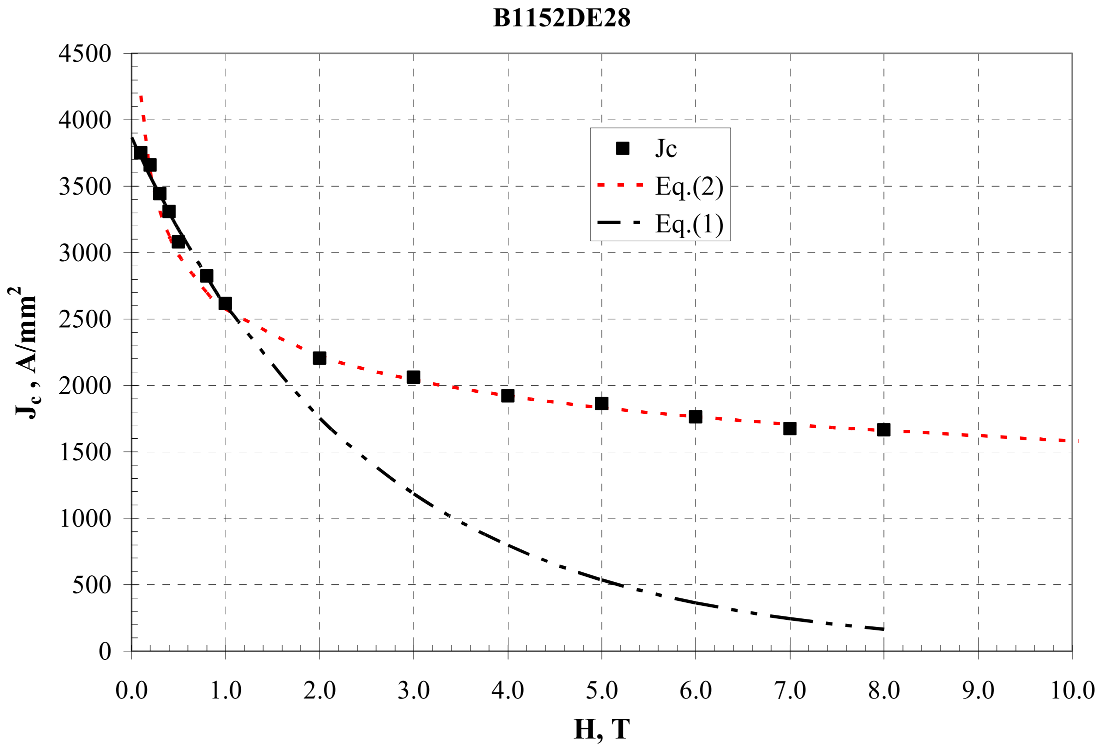



**Figure 6**. $J_c$ vs. H for the SHOWA wire. The fit to Eq.(1) for H<1T and Eq.(2) for H>1T are also shown.

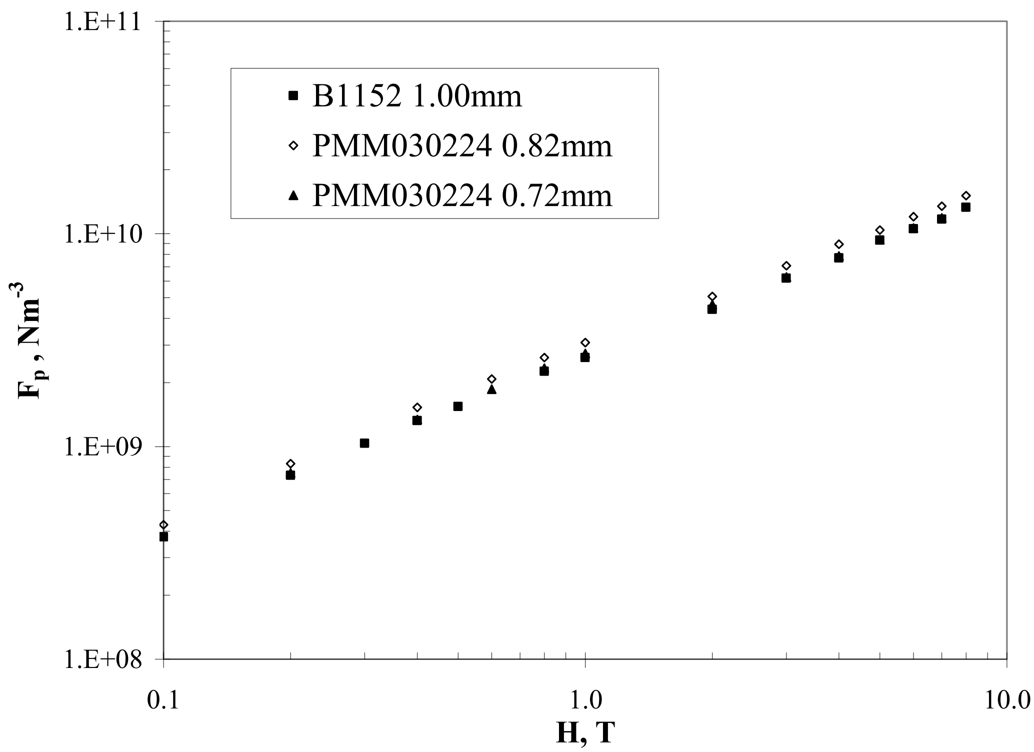



**Figure 7.** *Fp* as a function of H in the field range 0.1 < H <8.0 T

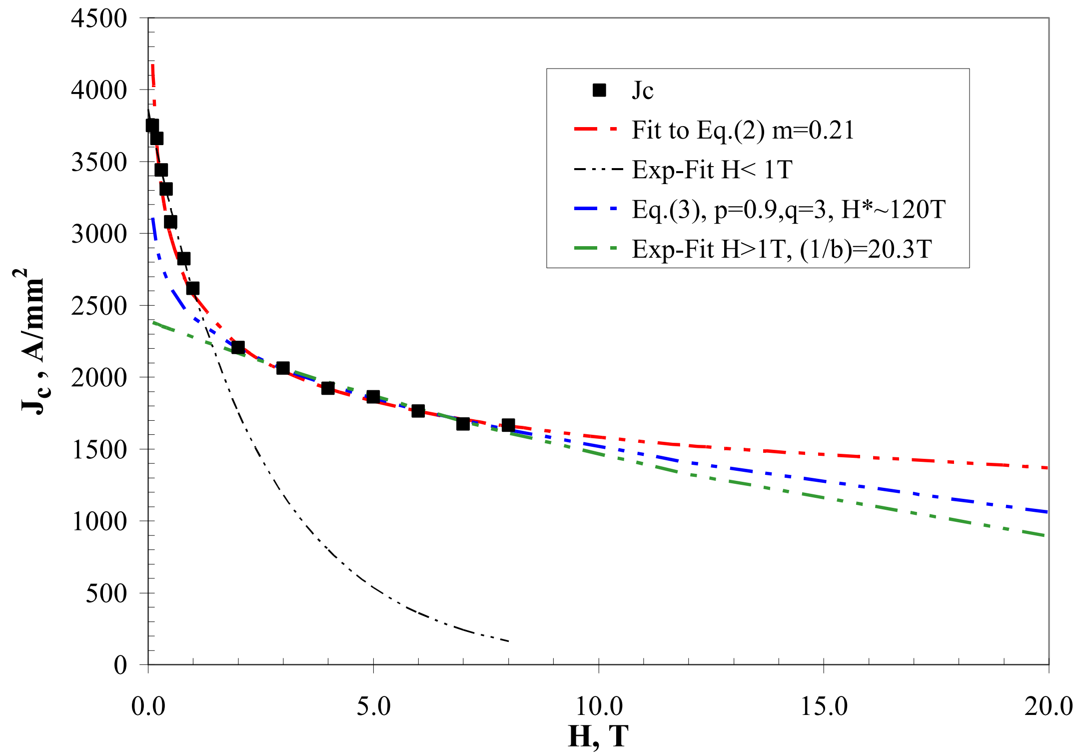



**Figure 8.** $J_c$-H for BII52 wire and the various fits are shown**.**

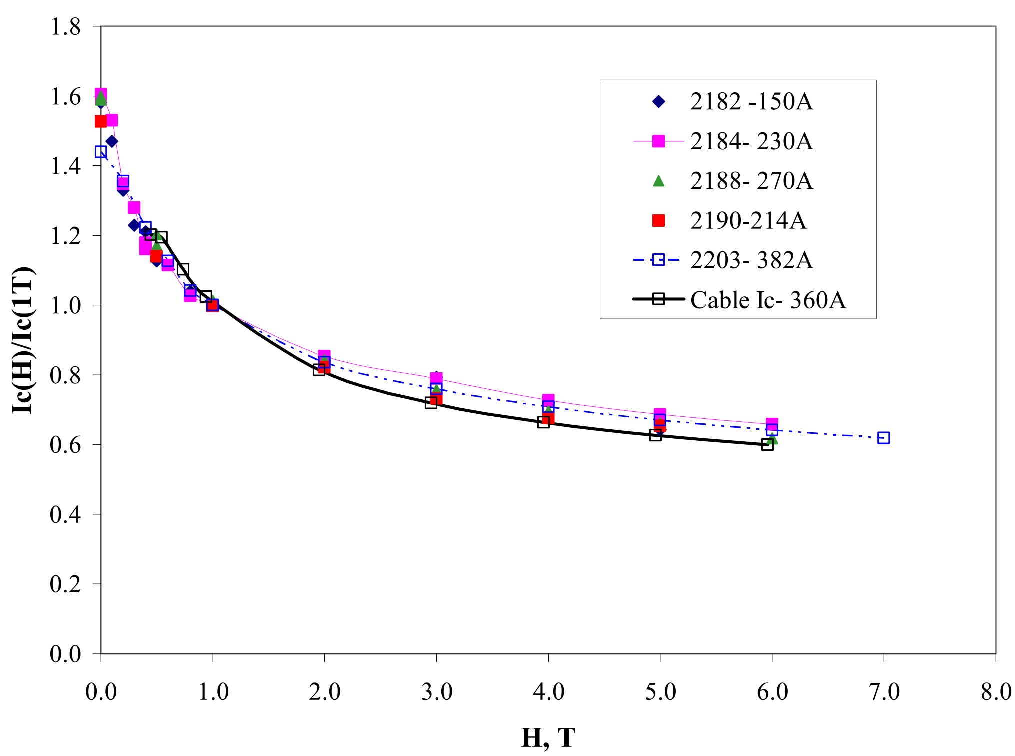



**Figure 9** Normalized $I_c$ as a function of field for strands extracted from cable HTS-S-R007B147-1

# Appendix

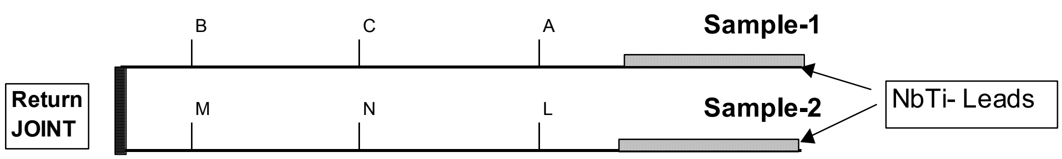
**Test Report for Cool-down # 4285**

Cable Description

| | |
|---|---|
| Strand Diameter | 0.81 mm (nominal) |
| No. of Strands | 30 |
| Cable width | 13.2 mm |
| Cable thickness | 1.52 mm |
| No Keystone | |

The two lengths received Apr-3-03 are identified in the database as HTS-1-S-R007B147-1 and HTS-1-S-R013B147-1.

Sample configuration is shown below:

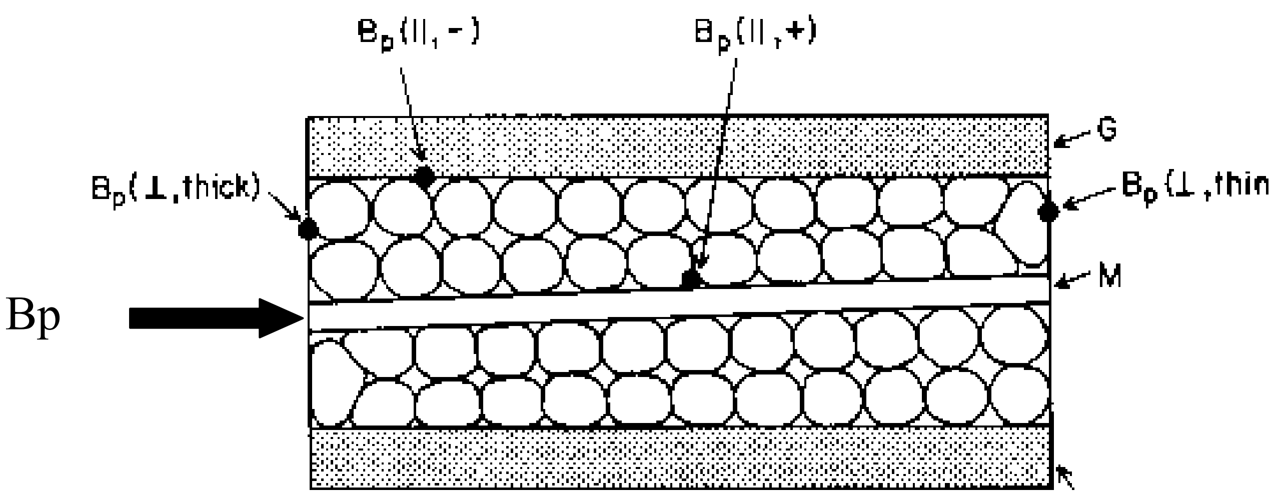



Voltage tap separation is as follows:

| | |
|---|---|
| AC | 300 mm |
| BC | 300 mm |
| MN | 300 mm |
| LN | 300 mm |

Section AB is HTS-S-R007B147-1
Section LM is HTS-S-R013B147-1

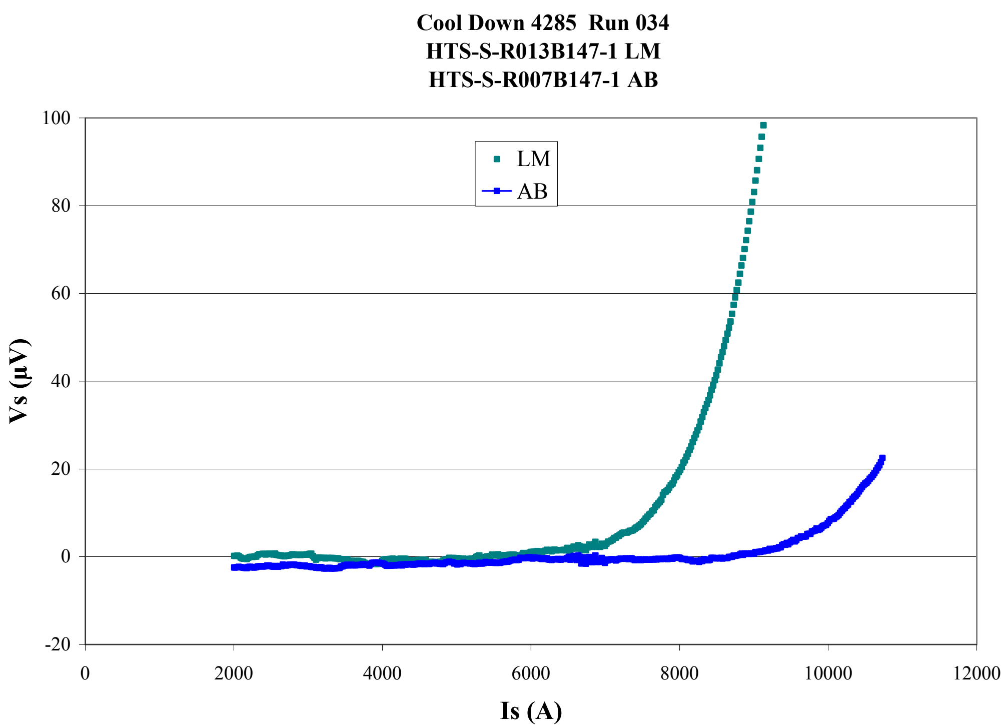
The samples were assembled into the test fixture with a transverse compression of 6 MPa. The test fixture was aligned in the dipole magnet with the field direction parallel to the flat face of the cable. A schematic of a cable pair is shown below:



This picture depicts a keystone-cable rather than a rectangular cable. The purpose of this is to show, that with this orientation of the field, the peak field is at location indicated as Bp(//+) at zero applied field, but moves to Bp(//-) at fields greater than 0.4T. The other locations are for the case when the field is perpendicular to the wide face of the cable. The uniform field is 610mm covering the section AB and LM.
In analyzing the data, the V-I curve is fitted to the usual expression used to extract the Ic of LTS cables. After a base-line is subtracted, the data is fit to

$$\rho\ (\mu\Omega\text{-cm}) = 10^{-12}\ (I/I_c)^n$$

where $\rho = (V/I)\ L/A$ , L=length of V-Tap and A is the cross-sectional area which is taken as 30 times wire area and Ic is defined for a resistivity of $10^{-12}$ μΩ-cm. We also show the Ic defined for 1 μV/cm criterion and all plots are for this definition of Ic. The two Ic's are related with the n-value.
It appears that the critical currents of the two samples differ appreciably, with section LM showing much more voltage than AB. In fact the cable samples quench before AB reaches 1 μV/cm. *The data for the 1 μV/cm is an extrapolation for the section AB and a measured value for section LM*. This is shown below for an applied field of 0.1T:




In the attached reports, the self-field has not been taken into account. With the field direction and current polarity used, the applied filed is used to reduce the self-field thereby accessing the field region below the zero-applied-field region. It would be a lot easier to evaluate wires and cable if one moved away from zero-field and benchmarked conductors at a higher field, for instance 5T.
Below is the summary of the analysis for the two samples:

**Superconductor Cable Test Report** 10 Apr 2003

**Cable: HTS-S-R007B147-1** || Low
**Cool Down 4285**

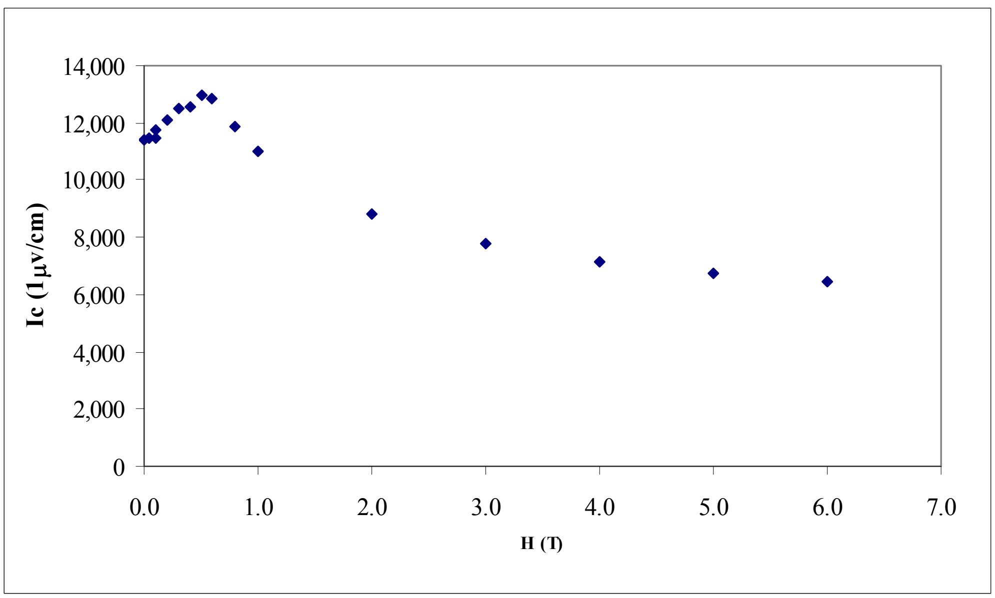
**Ic(5 T) =** 6748 **A**
**$2\sigma$ Ic(5) =** 0.021 **A**

| B (T) | T (K) | Imin Fit (A) | Ic (A) | $\sigma$Ic (A) | Iq (A) | n | Ic(1.0$\mu$v/cm) (A) | File |
|---|---|---|---|---|---|---|---|---|
| 0.00 | 4.443 | 2,004 | 8,906 | 9 | 10,399 | 10.6 | 11,406 | 4285_AB.002 |
| 0.05 | 4.441 | 2,002 | 9,274 | 10 | 10,524 | 12.3 | 11,473 | 4285_AB.008 |
| 0.05 | 4.436 | 2,006 | 9,075 | 22 | 10,673 | 11.2 | 11,464 | 4285_AB.009 |
| 0.10 | 4.439 | 4,066 | 9,104 | 26 | 10,249 | 10.2 | 11,740 | 4285_AB.014 |
| 0.10 | 4.436 | 2,006 | 9,550 | 12 | 10,792 | 14.4 | 11,454 | 4285_AB.016 |
| 0.20 | 4.445 | 2,008 | 9,702 | 20 | 11,258 | 11.7 | 12,080 | 4285_AB.017 |
| 0.30 | 4.444 | 2,008 | 9,921 | 18 | 11,447 | 11.0 | 12,489 | 4285_AB.018 |
| 0.40 | 4.442 | 2,008 | 10,225 | 30 | 11,215 | 12.4 | 12,537 | 4285_AB.019 |
| 0.50 | 4.434 | 4,101 | 9,747 | 36 | 11,256 | 8.8 | 12,944 | 4285_AB.020 |
| 0.60 | 4.444 | 2,007 | 9,716 | 36 | 11,675 | 8.9 | 12,870 | 4285_AB.021 |
| 0.80 | 4.446 | 2,007 | 8,974 | 19 | 11,072 | 9.2 | 11,881 | 4285_AB.022 |
| 1.00 | 4.437 | 2,007 | 8,130 | 11 | 10,285 | 8.7 | 11,033 | 4285_AB.023 |
| 2.00 | 4.434 | 2,070 | 6,363 | 8 | 8,238 | 8.9 | 8,797 | 4285_AB.024 |
| 3.00 | 4.442 | 2,070 | 5,646 | 17 | 7,370 | 9.5 | 7,750 | 4285_AB.025 |
| 4.00 | 4.444 | 2,070 | 5,106 | 14 | 6,842 | 9.2 | 7,145 | 4285_AB.026 |
| 5.00 | 4.434 | 2,219 | 4,680 | 21 | 6,454 | 8.6 | 6,748 | 4285_AB.033 |
| 6.00 | 4.440 | 2,118 | 4,494 | 17 | 6,215 | 8.8 | 6,459 | 4285_AB.034 |

| B (T) | Ic (A) | $2\sigma$ (Ic) (A) | Jc (A/mm$^2$) |
|---|---|---|---|
| 4.00 | 7145 | 14 | 1,861 |
| 5.00 | 6748 | 21 | 1,757 |
| 6.00 | 6459 | 17 | 1,682 |

**R(293) =** 18.958 **$\mu\Omega$/cm** **Ag/Sc =** 3.0

**Comments:** Short Length Sample **HT (rcvd):** HT@Showa
**Paired with:** HTS-S-R013B147-1



## Superconductor Cable Test Report

10 Apr 2003

**Cable: HTS-S-R013B147-1** || Low

**Cool Down 4285**

**Ic(5 T) =** 4861 **A**

**2σ Ic(5) =** 4 **A**

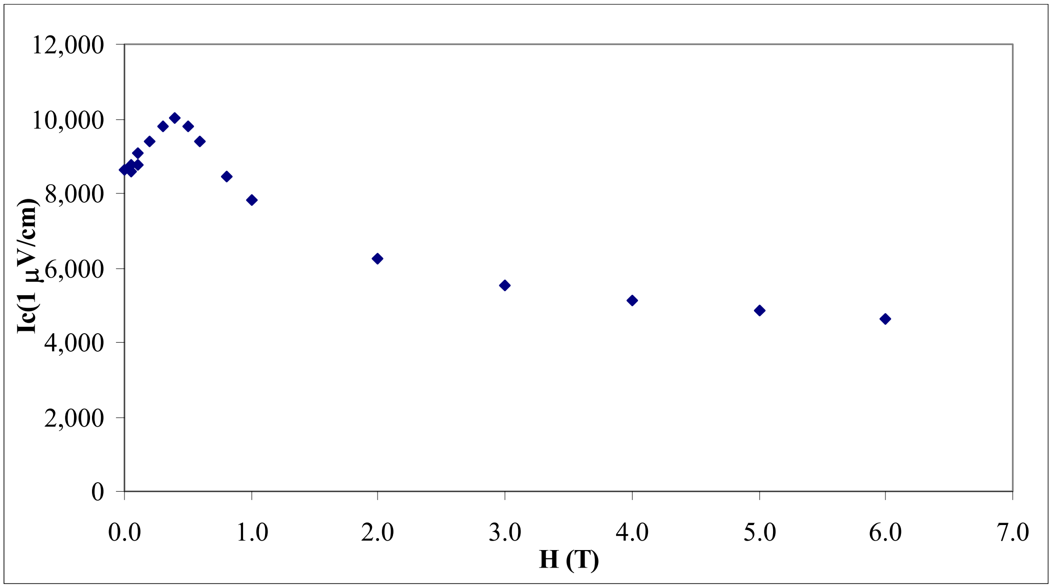
| B (T) | T (K) | Imin Fit (A) | Ic (A) | σIc (A) | Iq (A) | n | Ic(1.0μv/cm) (A) | File |
|---|---|---|---|---|---|---|---|---|
| 0.00 | 4.443 | 2,004 | 6,549 | 2 | 10,399 | 10.5 | 8,633 | 4285_LM.002 |
| 0.05 | 4.441 | 2,002 | 6,670 | 2 | 10,524 | 10.5 | 8,779 | 4285_LM.008 |
| 0.05 | 4.436 | 2,006 | 6,441 | 4 | 10,673 | 10.1 | 8,589 | 4285_LM.033 |
| 0.10 | 4.439 | 2,002 | 7,164 | 3 | 10,249 | 12.0 | 9,085 | 4285_LM.009 |
| 0.10 | 4.436 | 2,006 | 6,613 | 4 | 10,792 | 10.3 | 8,753 | 4285_LM.034 |
| 0.20 | 4.445 | 2,008 | 7,385 | 3 | 11,258 | 11.8 | 9,377 | 4285_LM.014 |
| 0.30 | 4.444 | 2,008 | 7,863 | 3 | 11,447 | 12.6 | 9,800 | 4285_LM.016 |
| 0.40 | 4.442 | 2,008 | 7,936 | 15 | 11,215 | 11.9 | 10,003 | 4285_LM.017 |
| 0.50 | 4.434 | 2,006 | 7,264 | 6 | 11,256 | 9.3 | 9,790 | 4285_LM.018 |
| 0.60 | 4.444 | 2,007 | 6,650 | 4 | 11,675 | 8.2 | 9,378 | 4285_LM.019 |
| 0.80 | 4.446 | 2,007 | 5,687 | 5 | 11,072 | 7.4 | 8,442 | 4285_LM.020 |
| 1.00 | 4.437 | 2,007 | 5,151 | 7 | 10,285 | 7.2 | 7,815 | 4285_LM.021 |
| 2.00 | 4.434 | 1,540 | 4,097 | 2 | 8,238 | 7.7 | 6,230 | 4285_LM.022 |
| 3.00 | 4.442 | 2,070 | 3,645 | 3 | 7,370 | 8.0 | 5,537 | 4285_LM.023 |
| 4.00 | 4.444 | 2,070 | 3,347 | 3 | 6,842 | 8.0 | 5,133 | 4285_LM.024 |
| 5.00 | 4.434 | 2,117 | 3,165 | 4 | 6,454 | 8.1 | 4,861 | 4285_LM.025 |
| 6.00 | 4.440 | 2,118 | 3,012 | 6 | 6,215 | 8.2 | 4,629 | 4285_LM.026 |

| B (T) | Ic (A) | 2σ (Ic) (A) | Jc (A/mm²) |
|---|---|---|---|
| 4.00 | 5133 | 3 | 1,337 |
| 5.00 | 4861 | 4 | 1,266 |
| 6.00 | 4629 | 6 | 1,206 |

**R(293) =** 19.755 **μΩ/cm** **Cu/Sc =** 3.0

**Comments:** Long Coil Sample **HT (rcvd):** HT@ Showa

**Paired with:** HTS-S-R007B147-1



Also summarized below are the tests in $LN_2$:

In Low-Temp Holder as a bifilar sample

| Field (T) | Hsf T | T (K) | Ic (A) | Ic(1.0μv) (A) | n | Section |
|---|---|---|---|---|---|---|
| 0.00 | | 77 | | 148 | 6.4 | AC |
| 0.00 | | 77 | | 149 | 6.7 | BC |
| 0.00 | | 77 | | 130 | 6.2 | LN |
| 0.00 | | 77 | | 132 | 6.6 | NM |