High T_c superconductors and critical current measurement*

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With the introduction of high T_c superconductors, a number of problems associated with critical current, I_c, measurement have arisen. The existing I_c measurement practices were developed and proved for low T_c superconductors. There are substantial differences between the two classes of materials. When the I_c concept was casually extended to the high T_c conductors, measurement inconsistency, ambiguity and, in some cases, invalidity followed. A discussion of the underlying philosophy of I_c measurement is presented and a number of measurement variables that can influence the measured I_c are discussed. Many of the problems stem from inadequate reporting practices, and recommendations are given for improving measurement reports.

Keywords: high T_c superconductors; critical currents; measuring methods

The critical current density, J_c, is an important parameter for characterizing a superconductor; it is a measure of the conductor's current carrying capacity. For conventional or low critical temperature (low T_c) superconducting materials (Nb–Ti, Nb_3Sn, etc.), J_c varies for different materials and, depending on the manufacturing process, it varies for different conductors made from the same material. In contrast, the critical temperature, T_c, and the upper critical field, H_{c2}, are relatively constant for a given material. Consequently, proper J_c measurement is critical to the development and application of superconductors of all types.

Figure 1 shows a plot of the critical surface where J_c is plotted as a function of temperature, T, and magnetic field, H. This surface represents the maximum current density that a superconductor can carry as a function of temperature and magnetic field, with zero resistivity. J_c measurement data based on a selected criterion can be used to construct a useful approximation of this ideal, but immeasurable, surface; however, imprudent selection of the J_c criterion can result in large discrepancies between the measured J_c and the zero resistivity J_c. Consequently, a somewhat detailed discussion of the J_c concept and criteria will be presented.

Strictly speaking, J_c is not measured; rather, it is calculated from the critical current, I_c, by dividing I_c by the specimen's cross-sectional area (for composite superconductors, the actual superconductor area rather than the total specimen area is sometimes used). However, J_c is a useful parameter for comparing the current capacity of different sized conductors. Consequently, both J_c and I_c will be used in this paper as appropriate.

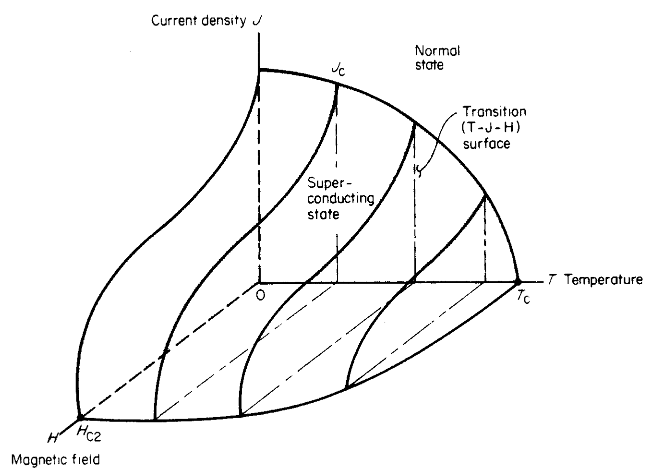

Figure 1 Ideal critical surface between the superconducting and normal states

A substantial portion of this paper is based on the relatively large body of knowledge that has been acquired through the study of conventional (low temperature) superconductors[1]. To this extent, the paper is a review of existing measurement philosophies and practices; however, a number of measurement concerns that are unique to high T_c superconductors are also presented.

An American Society for Testing and Materials (ASTM) Standard Test Method for critical current measurements is available[2] as well as a list of standard definitions relating to superconductors[3]. These are consensual standards that were originally developed for conventional

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superconductors; however, they are pertinent for high T_c superconductors as well. The NIST Office of Standard Reference Materials has a Standard Reference Material (SRM) for the measurement of superconducting critical current, identification number SRM-1457. It is a multifilamentary niobium–titanium, copper stabilized, superconducting wire that is characterized over a range of magnetic fields, temperatures and electric field criteria[4]. As applied to high T_c materials, the existing standards could be characterized as necessary but not sufficient.

In general, the high T_c materials present a number of new measurement problems that are not addressed by the existing standards. However, a distinction has to be made among the different forms of high T_c superconductors (bulk, aligned bulk, thin film, single crystal) and among the different compounds (La–Sr–Cu–O, Y–Ba–Cu–O, Bi–Sr–Ca–Cu–O, Tl–Ba–Ca–Cu–O and many others). Some of these superconductors present greater measurement problems than others. For some high T_c specimens that have relatively high J_c, the conventional measurement methods are adequate with the exception of the technique to be used for making electrical contacts. This paper does not provide answers for all of the measurement problems that are associated with the high T_c materials. The measurement techniques, as well as the materials themselves, are now in a state of evolution and, as was the case with low T_c superconductors, time and experience will be required to fully develop appropriate measurement methods.

In the preferred method for measuring I_c, a direct current is applied to the superconductor while the voltage across it is measured (d.c. transport method). The superconductor's voltage–current ($V-I$) characteristic is determined by recording the voltage as the current is increased. This $V-I$ characteristic is typically measured at a selected temperature (usually in liquid helium or liquid nitrogen) and over an appropriate range of applied magnetic fields, which depend on T_c, H_{c2} and the intended application of the superconductor. I_c is determined by applying a criterion to the measured $V-I$ curve. The preference for this d.c. measurement technique is based on its conceptual simplicity, direct nature and close approximation to actual use; the focus of this paper is on this technique. However, several other measurement methods are addressed in the discussion section.

The I_c measurement is sensitive to a variety of subtle variables. This is particularly true for the high T_c superconductors. Small changes in these measurement variables can result in large changes in the measured I_c. Consequently, a thorough report of the measurement conditions is an essential element of the I_c data. Recommendations regarding the contents of the I_c report are presented later.

Critical current concept and criteria

An absolute and functional definition of I_c does not exist. I_c can be defined as the maximum current that a superconductor can carry at a particular temperature and applied magnetic field, with zero resistivity. The critical surface shown in *Figure 1* depicts this conceptual definition of the critical current. However, this definition is impractical from a measurement standpoint because it requires the detection of an infinitesimally small voltage. All functional I_c definitions are based on an I_c criterion and the measurement of a finite voltage. The effect that the use of an I_c criterion has on the measured I_c depends on the superconductor's $V-I$ characteristic, which can usually be approximated by the empirical equation

$$V = V_o(I/I_o)^n \qquad (1)$$

where I_o is a reference current at a voltage V_o and n reflects the general shape of the $V-I$ curve. Typical values of n range from 20 to 60 for commercial superconductors. Specifically, n indicates the abruptness of the transition from the superconducting to the normal state. In a limiting case where n is imagined to be infinite, the zero resistivity value (I_{c0} or J_{c0}) and the measured value of I_c (I_{cm} or J_{cm}) are equal. However, for a fixed value of the measured voltage at I_c, the discrepancy between I_{c0} and I_{cm} increases as the value of n decreases. Consequently, an arbitrary selection of the I_c criterion can cause misleading measurement results. The voltage that is modelled by Equation (1) is caused by the steady state flow of magnetic flux in the specimen. Unlike a thermal runaway or flux jump, this is a stable and reversible condition.

The two most commonly used I_c criteria are the electric field criterion and the resistivity criterion. Both criteria are based on the measurement of a finite voltage across the test specimen. The electric field criterion defines I_c as the current where the electric field strength, which is calculated by dividing the measured voltage by the distance between the specimen's voltage taps, equals a selected value. The resistivity criterion defines I_c as the current where the resistivity of the test specimen equals a selected value. The resistivity is calculated by dividing the measured voltage by the measured current, multiplying this quotient by the cross-sectional area of the specimen (or the superconductor area) and then dividing this product by the distance between the specimen's voltage taps. The values of the electric field strength and the resistivity at I_c are called the critical electric field, E_c, and the critical resistivity, ρ_c. Since these criteria are based on a measured voltage, in both cases there is a critical voltage, V_c, associated with I_c. However, V_c is a constant in the case of the electric field criterion and it depends on I_c in the case of the resistivity criterion.

Figure 2 is a two-dimensional cross-sectional view of the critical surface (labelled $\rho = 0$) at a fixed temperature. This figure illustrates the effect of the criterion on J_{cm}. For comparison with the J_{c0} curve, J_{cm} is plotted as a function of the applied magnetic field, H, for an electric field and a resistivity criterion. The J_{c0} curve lies below the other two curves. Ideally, J_{cm} and J_{c0} would be the same; however, the minimum discrepancy between the two curves is limited by the sensitivity of the voltage measurement and the length of the specimen that is spanned by the voltage taps. The area (volume) between these lines (surfaces) could be called a 'grey area' (volume). J_{cm} is a functional approximation of J_{c0}. The usefulness, and thus the validity, of J_{cm} is dependent upon its close approximation of J_{c0}, i.e. a small grey area.

Typical values of E_c and ρ_c are 0.1 μV cm^{-1} and 10^{-12} Ω cm, respectively. The electric field strength and the resistivity are related to each other by the current density

$$E/\rho = J \qquad (2)$$

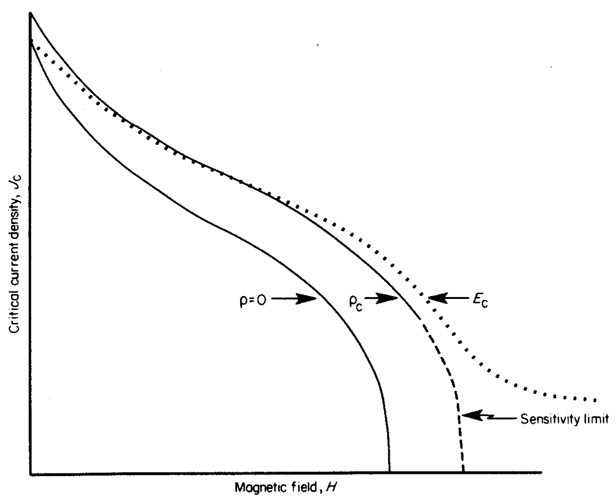

Figure 2 Two-dimensional cross-sectional view of the critical surface at a fixed temperature with measured curves based on two criteria

If the typical values of E_c and ρ_c are inserted in this equation the result is a value of J_c of 10^5 A cm^{-2}. This is the point in *Figure 2* where the electric field and resistivity curves cross, and it is the approximate J_c of commercial Nb–Ti superconductors at a temperature of 4.2 K and a magnetic field of 5 T. In the region from zero field to this crossing point, either criterion yields similar values of J_{cm} and this value is a good approximation of J_{c0}. However, as H_{c2} is approached, the discrepancy between the three curves increases dramatically, i.e. a larger grey area. *Figure 2* shows that for both the electric field criterion and the resistivity criterion, the discrepancy between J_{cm} and J_{c0} increases as J_c decreases. In the extreme cases where $H > H_{c2}$ and $J_{c0} = 0$, the use of either criterion can result in a finite and obviously invalid value of J_{cm}. *Figure 1* indicates that artificial J_c measurements are not limited to the region of H_{c2}; in fact, they can occur any time the combination of temperature and magnetic field are such that the conductor is operating near the intersection of the critical surface and the $H-T$ plane. An inherent difference between an electric field criterion and a resistivity criterion is apparent in the region of low J_c of *Figure 2*. The electric field criterion continues to indicate a J_c regardless of how far outside the critical surface the operating point of the conductor is, whereas the resistivity criterion restricts the range of J_{cm} because its application is limited by measurement sensitivity. Once again, this behaviour is not limited to the region near H_{c2}; it is characteristic of the low J_c region of the critical surface. In this $H-T$ region the arbitrary application of a J_c criterion can produce meaningless results.

In the low J_c region of the critical surface, the measurement cannot be sensitive to the superconducting (zero resistivity) state, and the grey volume may extend all the way to zero current density. This is especially true for materials that have a gradual $V-I$ characteristic (low n) for which the grey volume extends to nearly zero J for much of the measured surface. It is true that some applications allow for finite power dissipation and non-negligible resistivity. In these cases, the critical current concept could be extended to higher resistivities with explicit qualification of the reported I_c value.

Turning to the low magnetic field region of the curves, there is a practical difference between the electric field and resistivity criteria although they yield similar values of J_c. For the electric field criterion, the maximum required operating voltage, V_c, is fixed regardless of J_c; but, in the case of the resistivity criterion, V_c increases with J_c. At some point V_c may become large enough for the superconductor to become unstable, and, consequently, it is not possible to measure the $V-I$ characteristic at ρ_c. The reason that J_{cm} is similar for either criterion, even though V_c is considerably different, is that n is large at low magnetic fields.

The utility of the I_c concept is two-fold; it allows valid comparisons between the current capacities of different superconductors and, from an applications standpoint, it provides the necessary performance data. Accordingly, the prime consideration is selecting an I_c criterion should be whether or not the criterion will yield I_c values that are truly representative of the conductor's current capacity over the applicable range of temperatures and magnetic fields.

Measurement considerations

Interfering voltages

In the ideal case, the voltage–current relationship for a superconductor can be modelled by Equation (1). In addition to the intrinsic voltage that is approximated by this equation, there are numerous sources of interfering voltages that can complicate the I_c measurement. The polarities of these voltages, relative to the direction of the test current, can be either positive or negative. Some of these voltages are actually present at the test specimen while others are artefacts of the measurement system. Although the interfering voltages cannot be completely eliminated, in many cases they can be reduced to acceptable levels if their sources can be isolated. A general precept regarding the acceptable level of interference is that the sum of the interfering voltages, at any current along the $V-I$ characteristic, should be smaller than the critical voltage.

Voltage noise is an interfering voltage that is present in all I_c measurements; however, its magnitude can be reduced by using low noise instruments for sensing, amplifying and recording the specimen's voltage. Also, the voltage sensing leads should be twisted and shielded, and the resistance of any joints in these leads should be minimized to reduce noise pick-up. The test apparatus should be designed to minimize motion of the specimen and its voltage sensing leads relative to the background magnet as motion will induce additional voltages. The residual noise is easier to deal with than other sources of interference because of its random and periodic nature. The amplified voltage signal can be continuously filtered and/or time averaged at discrete current set points to reduce the noise and increase the sensitivity of the measurement.

The voltage induced about the loop formed by the test specimen and the voltage sensing leads is one source of interference. There are two primary sources of this induced voltage, changes in the test current level and relative motion between the test specimen and the applied magnetic field. The former appears as an offset voltage when the rate of change of the current is constant and, in this case, presents no problem in the I_c measurement, while the latter appears as an increase in the voltage noise. Both of these voltages can be reduced by twisting the voltage sensing leads and by minimizing the area of the loop formed by the voltage leads and the specimen. It is also important that the test fixture minimizes the motion of the specimen relative to the background magnet.

Another source of interference that can exist in the presence of an applied magnetic field is the Hall effect. This type of interfering voltage can exist when there is a relatively large applied magnetic field transverse to the specimen and the voltage sensing leads have a wide transverse separation. The Hall effect voltage scales with the test current and the applied magnetic field. This source can be eliminated by simply placing the connection points of the voltage sensing lead on a line that is parallel to the longitudinal axis of the specimen.

The difficulty of making low resistance electrical contacts to the high T_c ceramic materials can lead to excessive heat dissipation at the current contacts. Substantial thermoelectric voltages can be generated at the specimen's voltage contacts if their separation from the current contacts is small and the current contact heating is sufficient to cause local boiling of the liquid cryogen. Also, the temperature of the voltage sensing region of the specimen can be raised by heat conduction through the specimen from the current contact region. This type of heating can also result in thermoelectric voltages. A significant difference in the resistance of the two current contacts is common and it can aggravate this condition by creating a temperature gradient along the specimen and a resulting difference in the thermoelectric voltages generated at each of the voltage contacts. The thermoelectric voltages can be positive or negative in polarity and they may appear as an erratic drift in the zero current portion of the $V-I$ characteristic.

If contact heating is suspected as a source of interference, the specimen should be connected to monitoring instruments so as to allow a four wire measurement of the resistance of each of the current contacts. The acceptable resistance depends on the maximum current that the contacts will be expected to carry. The heat flux (power dissipation per unit surface area) can be calculated from the resistance of the contact, the applied current and the area of the contact. In the pool boiling condition, the maximum steady state power density for nucleate boiling of liquid helium is ≈ 1 W cm^{-2} and ≈ 15 W cm^{-2} for liquid nitrogen[5]. When the power density is higher than these limits, film boiling conduction can occur and there will be a large temperature difference between the specimen and the bath. If the resistance of the contacts is too high, the contact area can be increased and/or the resistivity of the contacts can be reduced. Various methods for making low resistance current contacts have been reported[6].

Thermoelectric voltages can also be generated at points in the voltage sensing circuit that are outside the cryogen bath. Consequently, any intermediate connections along the voltage sensing leads between the bath and the voltage sensing instrument should be of the solderless, low thermal type or be thermally anchored.

The low level nature of the voltage measurements that are necessary for an I_c test can result in two related sources of interfering voltages, ground loops and common mode voltages[7]. The former are due to multiple ground points in the test circuit and the latter are due to

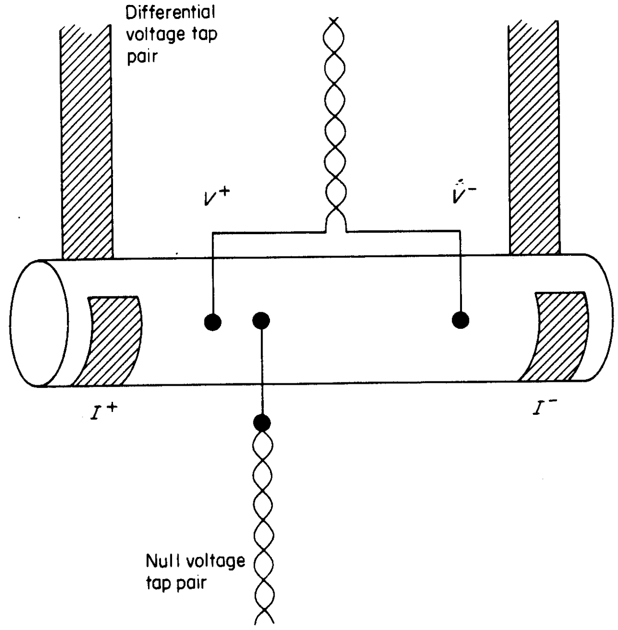

Figure 3 Illustration of specimen and lead configuration for zero resistance test

a common mode voltage, with respect to ground, being impressed on the input of the voltage sensing instrument. Although the existence of these voltages is often difficult to detect by examining the $V-I$ characteristic, a simple test[8] will indicate whether either of these sources of interference are present (see *Figure 3*). The test requires that a single point on the specimen be instrumented with two voltage sensing leads (a null voltage tap). The voltage sensing instrument that is normally used to measure the differential voltage across the specimen can be connected to these leads while the test current is cycled as in normal data acquisition. The null voltage tap leads should be tightly twisted to reduce inductive voltages. Any significant voltage that is detected in this configuration is an interfering voltage.

Common mode voltages can often be reduced by grounding the output of the test current supply. Where possible, all other ground paths should be removed from the measurement system. In cases where it is impractical to remove all ground paths, optical coupling between appropriate segments of the measurement system can reduce the ground loop problem[8]. The level of interfering voltage for the measurements reported later in this paper was about ± 5 nV. The estimated uncertainty for the voltage measurements was ± 5 nV $\pm 2\%$ of the signal and $\pm 0.5\%$ for the current measurements.

Another type of voltage that can present a measurement problem is 'convoluted voltage'. Such voltages occur when the current path is not parallel to the conductor's longitudinal axis. In low T_c superconductors this distortion, or convolution, of the current path is caused by the composite nature of the conductor, its filament twist and non-uniform current injection over its cross-section. In high T_c superconductors it is caused by specimen inhomogeneity that causes the current to follow what have commonly been called percolation paths. This current distortion results in a distortion of the electric field inside the specimen that can, in turn, cause anomalous voltages. These voltages can be either positive or negative in polarity (with respect to the polarity of the applied current) and their magnitude is often large enough to significantly distort the $V-I$ characteristic. This phenomenon has been observed in both low T_c and high T_c materials. The low T_c case has been rigorously studied and a detailed model that explains the source of the convoluted voltages has been developed[9]. The high T_c case requires more study to positively determine whether the source of these voltages is analogous to the low T_c case.

Specimen damage

The electromagnetic properties of ceramic superconductors can be significantly changed during handling and preparation for testing. Specifically, chemical reactions between the specimen and soldering flux or water in the atmosphere can degrade the conductor's I_c. The use of an ultrasonic soldering iron eliminates the need for soldering flux and exposure to moisture can be reduced by storing the sample in a desiccator. If the specimen is thermally cycled between room temperature and that of the liquid cryogen, it must be protected against condensed moisture from the atmosphere. This can be achieved through the use of a sealed warming chamber that is incorporated in the test fixture and allows the specimen to be extracted from the bath into the chamber without exposure to the atmosphere.

Excessive heating of the specimen during soldering may also result in damage. The use of silver paint or pressure contacts instead of soldered contacts will avoid heating, but the resulting contact resistivity is often unacceptable. In this case, low resistivity, vacuum deposited contacts may be required. The specimen may also require an oxygen annealing treatment following the contact deposition to replace oxygen that was lost during the vacuum process and to reduce the contact resistivity.

Specimen damage can occur when resistive heating causes thermal runaway, or quench, which can result in open current contacts, excessive heating or rapid heating of the specimen. This is generally not a problem unless the current density is high and cooling conditions are poor. A simple electronic device, a quench detector[10], can be used to monitor the voltage drop across the specimen and current contacts and reset the power supply current to zero when a voltage threshold is reached.

The brittle nature of the high T_c materials makes them extremely susceptible to mechanical damage. Very small strains, e.g. 0.05%, can cause cracking and a degradation in I_c. Damage can occur in handling, cooling or during I_c measurement.

High T_c superconductors are ceramics which have relatively low coefficients of thermal expansion. If the specimen is mounted on a material that has a larger thermal expansion than its own, damage may occur when it is cooled from room temperature to the test temperature. This problem can be avoided by either selecting a specimen mount whose thermal contraction is well matched to the specimen's or by avoiding a rigid bond between the specimen and the mount.

Even in the absence of externally applied forces, abrupt cooling of the specimen can cause internal stresses and damage. This source of damage is of greatest concern in the case of larger bulk specimens which can develop large internal temperature gradients when rapidly cooled. Consequently, the specimen should be slowly cooled in the cryogen vapour prior to submersion.

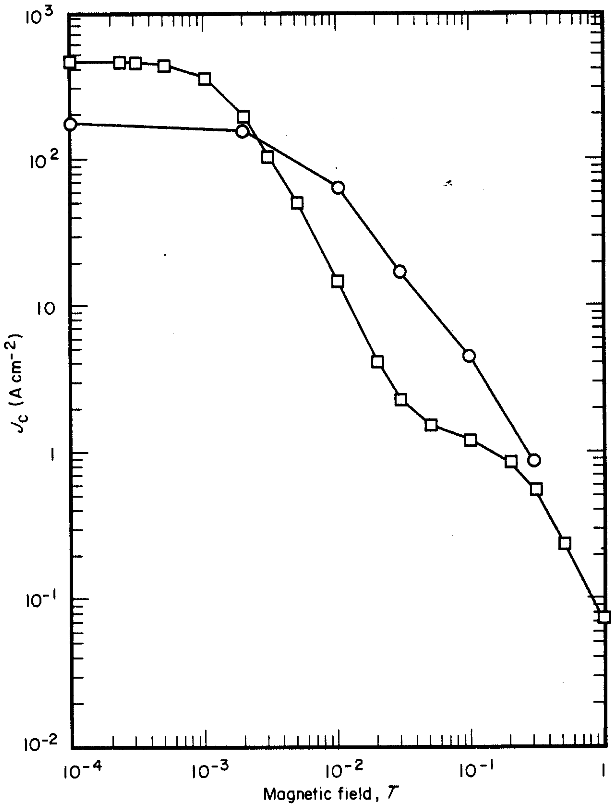

Figure 4 Logarithmic plot of J_c as a function of magnetic field for increasing (□) and decreasing (○) magnetic field

The Lorentz force, which is produced by the interaction of the specimen current and the background magnetic field, can produce damaging mechanical stress in the specimen if adequate support is not provided by the test apparatus. Even small Lorentz forces can cause an increase in noise, due to specimen motion if the specimen is not supported. The direction and magnitude of this force should be addressed in the design of the test apparatus.

Magnetic field considerations

High T_c superconductors have demonstrated much higher sensitivity to magnetic fields than low T_c superconductors. This sensitivity has a number of implications with regard to I_c measurement. *Figure 4* is a logarithmic plot of J_c as a function of magnetic field for a 0.86 mm diameter $YBa_2Cu_3O_{7-\delta}$ (YBCO) specimen. The specimen was 3.4 cm long and the voltage taps were separated by 0.9 cm. The resistance of each current contact was less than 0.04 Ω. Two different symbols are used to show the hysteresis of J_c; squares for increasing field and circles for decreasing field. The decreasing field J_c is ≈350% higher than the increasing field J_c at 3×10^{-2} T and ≈58% lower at 1×10^{-4} T. This hysteretic behaviour is most likely caused by trapped flux in the superconductor. Regardless of the source of the hysteresis, the magnetic history of the specimen can have a dramatic effect on the measured I_c[11]. Ideally, a specimen's I_c should be measured and reported over its full range of application for both increasing and decreasing magnetic field. If only one I_c value is measured at each field, it should be for an increasing magnetic field (virgin data).

Virgin data are preferable because of their simple replication. In other words, they are logistically the most fundamental.

An angular hysteresis has also been observed for YBCO specimens[12]. In this case, the measured I_c depends on the history of the magnetic field's orientation with respect to the specimen. For orientated YBCO thin film specimens, the size of the effect can be similar to that of the magnetic field hysteresis.

Both of these hysteretic effects have implications for I_c measurement. First, precise control of the applied magnetic field is necessary to avoid overshooting the desired set point. In the event of overshoot, the specimen must be warmed above its critical temperature and the magnetic field must be reduced to zero before data acquisition can continue. Also, the specimen should not be moved when it is in the presence of an applied field. This implies that, for a study of the effect of various field orientations on the measured I_c, the specimen must be warmed above T_c and the magnet must be de-energized between each measurement. Finally, if the background field is supplied by a superconducting magnet that exhibits hysteresis, it may actually be necessary to warm the magnet above its T_c between I_c measurements in order to remove any remanent magnetic field.

The sensitivity of the YBCO specimen to magnetic fields is evident in the increasing field data of *Figure 4*, where J_c is degraded by an order of magnitude for an applied field of ≈ 6.3 mT. At the maximum J_c of ≈ 500 A cm^{-2} the magnetic field that is produced by the specimen current (self-field) is ≈ 1.3 mT at the surface of the specimen. This comparison demonstrates that the effect of the specimen's self-field must be taken into account when interpreting I_c data taken at small applied magnetic fields.

The magnitude of the self-field and its effect on I_c depend on the specimen's current and cross-sectional area. Consequently, different sized specimens that are cut from the same material may have significantly different measured J_cs at low magnetic fields. This may explain the low field plateaus in J_c that are shown in *Figure 4*. For the increasing field curve, there is an abrupt increase in J_c degradation at ≈ 1 mT. This is the region where the magnitude of the applied magnetic field is approaching that of the self-field. In other words, when the applied magnetic field is below 1 mT, the total magnetic field (the self-field plus the applied field) is dominated by the self-field, which is nearly constant in the plateau region. Consequently, J_c appears to be constant with increasing magnetic field. Comparison of measured J_c values for different specimens is valid only when the measurements are made at the same total magnetic field. Furthermore, it is meaningless to report a measured J_c value for an applied magnetic field that is comparable to the self-field unless the sample dimensions or an estimated value of the self-field is also reported.

The orientation of magnetic field and specimen current with respect to the specimen geometry and with respect to the crystallographic orientation of the specimen can change the measured I_c. For fundamental research, and some applications, measurements with a number of orientations may be necessary.

For I_c measurements where the applied magnetic field is extremely low, the earth's magnetic field, which is ≈ 0.05 mT, must also be considered. Usually, the local value of the earth's field can simply be added to the calculated value of the self-field; however, in cases where the self-field is extremely low, the use of a high permeability magnetic shield may be warranted. The magnetic shield can reduce the background field to $< 10^{-6}$ T.

Electrical contacts

Electrical contacts have been a consistent source of I_c measurement problems on high T_c superconductors. One undesirable effect of high resistance current contacts, the production of thermoelectric voltages, has already been discussed. In addition, high resistance current contacts can cause a reduction in the measured value of I_c by raising the operating temperature of the specimen above the ambient temperature. Also, high resistance voltage contacts can cause a significant increase in the signal to noise ratio and a corresponding reduction in measurement sensitivity. *Figure 5* presents a line graph of approximate contact resistivity data for various techniques and application limits.

The outside surface of commercial low T_c superconductors is usually made of copper, which permits low resistivity soldered electrical contacts. Furthermore, the length of the specimen, and thus the length of the current contact joints, is restricted only by the design of the test

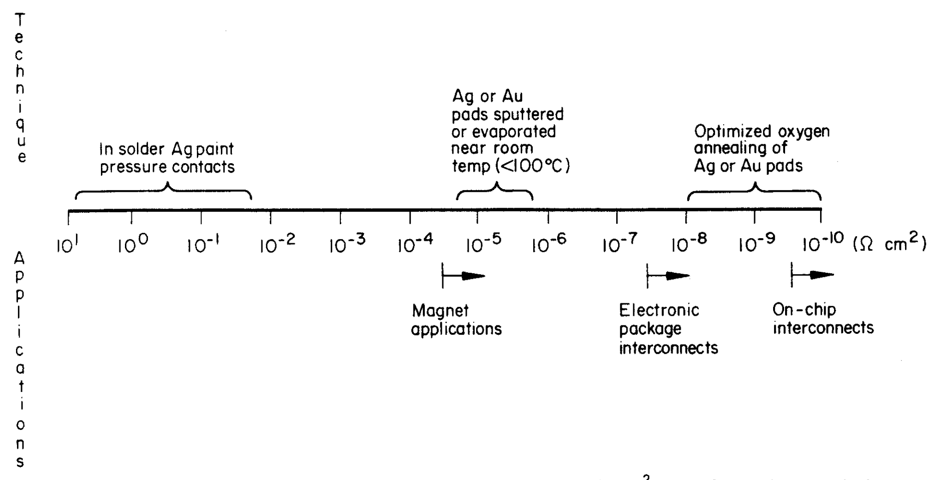

Figure 5 Line graph of approximate contact resistivity ($=R_cA_c$ Ω cm^2) data for various techniques and application limits for Y, Bi and Tl based high T_c superconductors at 76 K (courtesy of J.W. Ekin)

apparatus. These two factors are usually fully exploited in the design of I_c test apparatus for low T_c superconductors, which results in extremely low current contact resistances. Because of the low current contact and specimen resistances, there is little concern about parallel current paths in such test apparatus. For example, the specimen is sometimes soldered directly to a stainless steel holder. In contrast, the resistance of high T_c current contacts is often large enough that, unless the current path is well isolated, current sharing between the apparatus and the specimen can artificially increase the measured I_c.

High T_c wires have been made by encasing the superconductor compound in a silver jacket and then drawing the resulting composite conductor. When measuring the values of I_c of a conductor of this type, the shunt current that is carried by the silver jacket must be considered. The current that is carried by the silver can be approximated from its cross-sectional area, its low temperature resistance and the specimen voltage. I_c can then be adjusted accordingly.

I_c criteria

An I_c criterion is a practical device that can yield a useful measure of a superconductor's current capacity. However, if the criterion is not carefully selected, the I_c results can be misleading. As an example, consider a typical I_c measurement for a high T_c superconductor where an electric field criterion of 10 μV cm^{-1} is selected, the measured I_c is 20 A and the cross-sectional dimensions of the specimen are 0.2×0.2 cm^2. This results in calculated J_c and ρ_c values of 500 A cm^{-2} and 2×10^{-8} Ω cm. The electrical resistivity of oxygen-free copper at liquid nitrogen temperature is approximately 2×10^{-7} Ω cm, so the resistivity of the superconductor at its measured I_c is only one-tenth that of copper (a normal metal) at the same temperature.

The natural solution to this problem may appear to be the use of a resistivity criterion, 10^{-12} Ω cm for example (a typical ρ_c for low T_c superconductors). The value of the E_c for this value of ρ_c and J_c of 500 A cm^{-2} is 5×10^{-10} V cm^{-1}. For a typical voltage tap separation of 0.5 cm, the required measurement sensitivity is 0.25 nV. Very few, if any, laboratories can make I_c measurements with this voltage sensitivity. Since the sensitivity of the measured I_c to the criterion increases as the value of n decreases, this situation is aggravated by the fact that n is usually much lower for high T_c than for low T_c superconductors.

Figure 6 is a logarithmic plot of J_c as a function of increasing magnetic field for the same YBCO specimen that was the subject of *Figure 4*. In this plot J_c is plotted for four electric field criteria (10, 1, 0.1 and 0.01 μV cm^{-1}) and one resistivity criterion (2×10^{-8} Ω cm). The raw data are the same for each of the electric field criterion curves; only the data analysis is different. The four upper field data points on the resistivity curve were extrapolated from the electric field data at 0.01 and 0.1 μV cm^{-1} (due to insufficient voltage sensitivity). The other data points on the resistivity curve were calculated from the same raw data as the electric field data. The discrepancy between the curves increases as the field increases. At 10^{-4} T the 10 μV cm^{-1} J_c is ≈ 1.1 times as large as the 1 μV cm^{-1} J_c, and at 1 T the 10 μV cm^{-1} J_c is ≈ 9.0 times as large as the 1 μV cm^{-2} J_c. This in-

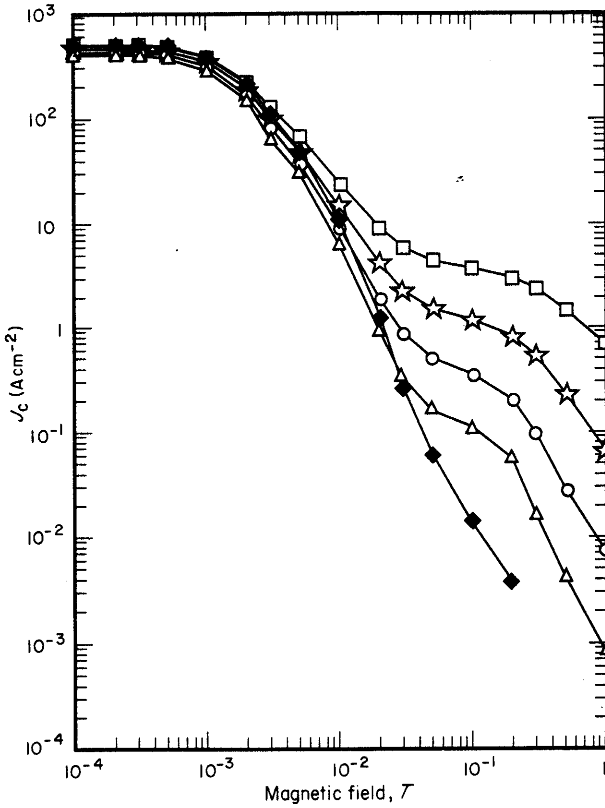

Figure 6 Logarithmic plot of J_c as a function of magnetic field for four electric field and one resistivity criteria. □, 10 μV cm^{-1}; ☆, 1.0 μV cm^{-1}; ○, 0.1 μV cm^{-1}; △, 0.01 μV cm^{-1}; ◆, 2×10^{-8} Ω cm

creasing difference in J_c for the two criteria is due to the reduction in n with increasing magnetic field. The calculated value of n is 20 at 10^{-4} T and 1.0 at 1 T. In contrast, for a commercial Nb–Ti conductor n is typically >30 at 5 T. The low field portion of the resistivity curve agrees well with the electric field curves; however, at high fields the resistivity curve indicates much lower I_cs than the other curves, and it lacks the step that is present in the other curves. The resistivity curve is truncated because of limited voltage measurement sensitivity, whereas the electric field curves continue to indicate a value of I_c regardless of the resistance of the specimen. In this sense, the resistivity criterion is more sensitive to the superconducting state than the electric field criterion. However, an electric field criterion is more expedient and can be used over a wider range of J_c than a resistivity criterion.

Traditionally, I_c has been a very useful engineering parameter for quantifying the current capacity of commercial superconductors. Because of their low J_cs and less abrupt transition from the superconducting to the normal state (low n), some high T_c superconductors are not well suited to this type of characterization. The problem is largely one of implication, where stating the I_c of a high T_c superconductor suggests that the conductor can carry the specified current with a negligible resistivity, as is the case for low T_c conductors. In part, the solution to the problem is a more detailed and explicit characterization of these conductors. Primarily this requires more thorough reporting of the I_c measurement details; however, the practical validity of the I_c measurement is directly related to measurement sensitivity. Consequently, valid I_c measurements of high T_c superconductors require state of the art measurement techniques. Presently accepted criteria are 1 μV cm^{-1} and 10^{-9} Ω cm, but lower values are achievable and would decrease the grey area between the measured and ideal critical surface.

Reporting I_c data

Because of the large number of variables that can significantly affect the measured value of I_c, a thorough report of the data acquisition and analysis technique is essential. The elements of the report can be divided into four general categories: measurement conditions, specimen details, data and data analysis. The purpose of this section is not to prescribe a rigid format for reporting I_c measurements; rather, the purpose is to suggest a number of reporting points that might clarify the meaning of I_c data. This is not a definitive catalogue of I_c reporting points. This list should be abbreviated or augmented to suit the specifics of the measurement and the ultimate use of the I_c data.

A number of considerably different techniques are presently being used for measuring the $V-I$ characteristic of high T_c superconductors. Consequently, it is important to give a summary of the data acquisition technique. This summary should include an estimate of the precision and accuracy of the voltage and current measurements.

In reporting the measurement conditions, the temperature at which the measurements were made and the method of temperature control should be described. If the measurements were conducted in a liquid cryogen bath, the pressure of the bath should be indicated. If the measurements are conducted in vapour, the method for maintaining and monitoring the specimen's temperature should be reported. Critical current measurements performed in vapour should be verified by a comparison measurement made in a liquid cryogen. Another important measurement condition that can vary greatly between different measurement systems and test specimens is the level of interfering voltage. As a minimum, the voltage noise should be reported. If other sources of interfering voltages are present, they should also be noted. The orientation of the applied magnetic field, with respect to the direction of the specimen current and the specimen's crystallographic orientation (for orientated specimens), should be reported in addition to the magnitude of the field.

There are several specimen details that should be reported. First, the compound, the specimen type (bulk or thin film) and substrate material should be indicated. The dimensions of the specimen, including its cross-sectional area in the vicinity of the voltage taps, should be stated. The average grain size and microstructure should be reported when available. The specimen's geometry (straight, coil, hairpin) should also be reported. The method that was used for making the electrical contacts should be described and, when available, the measured resistance of the contacts should be noted Furthermore, the size and position of the contacts should be reported because these can affect the I_c measurement. When current is injected in the specimen through its current contacts, it begins to redistribute itself throughout the specimen's cross-section. If the voltage contacts are located too close to the current contacts, voltages that are a result of the current redistribution and not intrinsic to the superconductor may be detected. The degree of current redistribution, and, therefore, the required distance between the current and voltage contacts depends on the size and location of the current contacts. For example, the current redistribution for a small current contact located on the edge of a large bulk specimen is greater than for a large contact on the end of the specimen. The separation of the voltage taps also indicates the degree to which the local properties are averaged by the measurement. A voltage tap separation that is several times a cross-sectional dimension of the sample may be necessary for a valid test of the conductor's current capacity. If a specimen has a parallel conductive path, an estimate should be made of the current that could flow in this path considering the contact resistance in the superconductor path.

It seems obvious that a necessary element of the report is the I_c values; however, in some cases it may be inappropriate to present I_c data unless it is accompanied by the raw $V-I$ data. The $V-I$ characteristics of high T_c superconductors often exhibit anomalous features that may invalidate the implications of a reported I_c value. For example, some high T_c $V-I$ curves have an initial ohmic character that begins at zero current. It can be argued that the condition of zero resistivity, which an I_c value implies, is not valid for this $V-I$ characteristic. The prudent course in this case is to qualify the I_c data by presenting the $V-I$ curve or at least noting the non-ideal nature of the curve. This same philosophy applies to I_c data that are based on an electric field criterion that, because of a low J_c, results in high resistivity of the specimen at the I_c. In this case, the resistivity should be stated along with the I_c data. Because of the hysteretic nature of the high T_c conductors, the magnetic field history (magnitude and angle) should be indicated when I_c data are reported as a function of magnetic field. For comparison purposes and to reduce the self-field effect, it is desirable to make measurements at a number of selected applied magnetic fields such as 0.01, 0.1 and 1 T. This would be useful but not essential for electronic applications.

In the area of data analysis, the selected criterion (resistivity or electric field) and magnitude should always be reported. Also, the $V-I$ curves should be analysed to determine the value of n and this value, along with the voltage range for which it was determined, should be reported. The discrepancy between I_{c0} and I_{cm} depends on the abruptness of the superconducting transition; consequently, the importance of reporting n along with the I_c data is obvious.

Discussion

Superconductor characterization

With the introduction of high T_c superconductors, the critical current concept has frequently been stretched to the point where any non-linearity in a low resolution $V-I$ curve, regardless of what precedes or follows that non-linearity, is reported as an I_c. As an example, it is not uncommon for high T_c $V-I$ curves to have an ohmic character between zero current and the reported I_c. This initial resistive behaviour has been attributed to various sources including flux creep[13]. Short test specimens of low T_c superconductors sometimes display a similar resistive behaviour that is due to current transfer. In this case, the resistive voltage can legitimately be ignored when analysing the $V-I$ curve because it is an artefact of the measurement technique and not intrinsic to the superconductor. In contrast, the resistive behaviour of the high T_c conductors may be an inherent characteristic of the material. If this is the case, the material may not have an actual I_c. This does not imply that the presence of an ohmic component negates the importance of non-linear transitions in the $V-I$ curve; it simply means that they should not be reported, without qualification, as a critical current. Innovative approaches such as the offset criterion recently reported[14] should be considered for these materials. In this approach, I_c is defined as the current where the tangent to the $V-I$ curve at a given electric field extrapolates to zero voltage. This is similar to the electric field criterion, but defines an I_c that intrinsically goes to zero when the superconductor becomes ohmic.

Although the high T_c materials are a new and distinct class of superconductors, low T_c superconductors are part of a mature technology that includes well developed methods of characterization. This technology is pertinent to high T_c materials and it should not be overlooked in the development of high T_c critical current measurement methods.

Other I_c measurement techniques

Several I_c measurement techniques that are not of the d.c. transport type are being used for high T_c superconductors. The most common of these alternative measurement methods are the lock-in, pulse and magnetization techniques.

The primary reason for using the lock-in method is equipment availability. A lock-in amplifier is a common laboratory instrument that is adaptable to a variety of measurements that require high sensitivity. For this method, a d.c. bias current is applied to the superconductor specimen along with a low amplitude (compared to the bias current) a.c. current, and the lock-in amplifier measures the resulting voltage. The lock-in method employs frequency selective amplification to achieve its high sensitivity. It is sensitive to the frequency of the a.c. specimen current, but it rejects all other signals, a.c. and d.c. A significant benefit of the lock-in method is the fact that it is insensitive to thermoelectric voltages that are generated at joints in the voltage sensing leads. When the lock-in method is used on a Josephson junction, the resulting data does have a well defined characteristic current, but this advantage does not apply to the critical current of superconductors. The basic limitation of the lock-in method is that it cannot be used to directly measure the specimen's $V-I$ characteristic; it measures the local slope of the $V-I$ characteristic. The $V-I$ characteristic can be constructed by integrating the measured signal; however, the accuracy of the derived characteristic depends on a number of interrelated variables including the sensitivity of the lock-in amplifier, the amplitude of the a.c. specimen current, the shape of the characteristic (n) and the intrinsic effect of the a.c. current on the superconductor which is not necessarily lossless. Comparisons between the lock-in and the d.c. transport I_c measurement methods that are based simply on the relative sensitivities of the two voltage sensing instruments, the lock-in amplifier and the d.c. nanovoltmeter, can be misleading.

The motivation for using the pulse method is that it reduces the problem of current contact heating. A short duration (typically 0.5 – 10 ms) current pulse is applied to the specimen while the voltage is monitored with an oscilloscope. The amplitude of the pulse is increased until a voltage is sensed across the specimen. The duration of the pulse and the delay between pulses are adjusted to avoid heating problems. The fundamental question regarding this technique is whether or not it yields the same I_c value as the d.c. transport method. If the duration of the pulse is inadequate, it is possible that the specimen does not have time to reach steady state. Specifically, the time scale of the magnetic flux dynamics might be comparable to the pulse duration. I_c data have been presented where the effect of the pulse duration on the measured value of I_c was examined[15]. In this case, there was a substantial decrease in I_c as the pulse duration was increased and this trend continued in the limiting case where I_c was measured using the d.c. transport method. On the other hand, comparative measurements between the pulse and d.c. transport methods have been reported where good agreement was achieved[16]. At present, the pulse method should always be used with caution and whenever possible it should be confirmed with the d.c. transport method.

Magnetization techniques have also been used to measure I_c. This is a convenient method because it does not require any electrical contacts to the specimen. Magnetization I_c measurements are based on the Bean critical state model[17] which provides a mathematical relationship between a superconductor's magnetic behaviour and its I_c, with a number of restrictions. These restrictions, or requirements, involve specimen geometry, microstructure, field penetration, field orientation, pinning and temperature margin ($T << T_c$). In applying the model, the specimen's intergranular coupling must be considered. In the case of a weak linked specimen (bulk sintered), the model can yield the intragrain I_c but not the intergrain (d.c. transport) I_c. For non-weak linked specimens (single crystals, orientated specimens), the model can yield the intergrain I_c but only under restricted conditions.

Novel non-contact I_c measurement techniques, which require a specimen with ring geometry, have been employed to address the problem of intragrain I_c[18,19]. These techniques employ materials of high magnetic permeability to confine and link an applied magnetic flux with the superconducting ring. The ring is effectively the secondary winding of a transformer. The primary winding applies the magnetic flux to the specimen and a sensing coil is used to detect flux in the magnetic circuit. The transformer's turn ratio can be used to calculate the current in the specimen at the point of flux penetration, which is theoretically the approximate transport I_c.

Round robin studies

Interlaboratory comparative I_c measurements have been, and continue to be, a fruitful method for quantifying and improving the measurement consistency between different laboratories for low T_c superconductors[20]. These collaborative measurements are commonly called a 'round robin'. This is actually a misnomer because the label of round robin implies that the same superconductor specimen is measured by each of the participating laboratories, which is usually not the case.

It is often possible to distinguish inconsistencies that are due to specimen variations from those that are due to measurement variations. Consequently, the specimens must have relatively consistent properties for a round robin of this type. In the case of low T_c conductors, high consistency has been established. In contrast, the sensitivity of the high T_c materials to fabrication variables has not yet been fully established; consequently, specimen inconsistency is a significant problem for round robins that deal with high T_c critical currents. This problem is further complicated by the fact that the high T_c materials are highly susceptible to damage and degradation. In other words, even if the specimens are manufactured so that their properties are initially consistent, they may be quite different at the time of the I_c measurement depending on handling, storage and the elapsed time since manufacture. This is evidenced by the results of two recent high T_c round robins (Japan, January 1988[21] and DARPA, April 1989[22]) where sample variation was clearly a major source of measurement inconsistency. In both round robins, T_c was also measured and in both cases the measurement discrepancies were much smaller for T_c than for I_c, which demonstrates the sensitivity of I_c to specimen variation.

A single round robin study can be used to evaluate the precision of existing measurement techniques in a broad sense; however, the improvement of measurement techniques usually requires several round robins. In the first round robin, very few measurement constraints should be placed on the participants; they simply use their normal measurement technique and provide a detailed report along with their I_c data. This allows the identification of major sources of measurement variations. In later round robins, measurement constraints are employed to reduce the variation. This approach is designed to yield the required measurement consistency with the least number of constraints on the measurement technique.

The fact that the consistency of some high T_c specimens is not yet equal to that of low T_c specimens does not eliminate the value of a round robin study for improving measurement methods. However, the round robin will have to be of the more classical type, where the same specimen is measured by several different laboratories. Also, the specimens will have to be designed (and demonstrated) to be relatively immune to degradation with time and handling. A preliminary plan for a study of this type has been completed and it is intended to begin fabrication and testing of candidate specimens in the near future to attempt to identify the major sources of I_c measurement discrepancies.

Conclusions

Critical current measurement techniques have developed along with commercial superconductors to the point where I_c has become the accepted characterization parameter for the development and application of these materials. However, a number of problems developed when the I_c measurement, along with its traditional implications, was casually extended to a new class of materials, high T_c superconductors. The resulting inconsistency in I_c measurements has diminished their credibility.

When an I_c value is reported, it implies that the tested specimen is capable of carrying the reported current with a negligible resistivity. If the measurement sensitivity and criterion are not consistent with this implication, I_c should not be reported without explicit qualification. Higher measurement sensitivity would decrease the grey area between the measured value of J_c and the ideal.

The useful extension of I_c measurements to high T_c superconductors requires optimized measurement techniques as well as thorough reporting practices. Many of the problems that are presently associated with high T_c I_c measurements, such as low current density and magnetic hysteresis, may disappear as the materials are improved. Simultaneously, the distinction between high T_c and low T_c measurements will also disappear. Presently, special care in measuring and reporting the critical currents of high T_c superconductors is required, especially if the results of these measurements are to be used to understand the physics of the still unknown mechanisms of the high T_c superconductors.

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References

1 **Goodrich, L.F. and Fickett, F.R.** Critical current measurements: a compendium of experimental results *Cryogenics* (1982) **22** 255

2 Standard test method for d.c. critical current of composite superconductors *Annual Book of ASTM Standards* ASTM B714-82, Part 02.03, American Society for Testing and Materials, Philadelphia, Pennsylvania, USA (1983) 595–598

3 Standard definitions of terms relating to superconductors *Annual Book of ASTM Standards* ASTM B714-82, Part 02.02, American Society for Testing and Materials, Philadelphia, Pennsylvania, USA (1983) 592–594

4 **Goodrich, L.F., Vecchia, D.F., Pittman, E.S., Ekin, J.W. and Clark, A.F.** Critical current measurements on an NbTi superconducting wire standard reference material, NBS Special Publication 260-91, National Bureau of Standards, Boulder, Colorado, USA (September 1984)

5 **Steward, W.G.** Transient helium heat transfer phase I static coolant *Int J Heat Mass Transfer* (1978) **21** 863

6 **Ekin, J.W., Larson, T.M., Bergren, N.F., Nelson, A.J., Swartzlander, A.B., Kazmerski, L.L., Panson, A.J. and Blankenship, B.A.** High T_c superconductor/noble-metal contacts with surface resistivities in the 10^{-10} Ω cm^2 range *Appl Phys Lett* (1988) **52** 1819

7 **Morrison, R.** *Grounding and Shielding Techniques in Instrumentation* John Wiley & Sons, New York, USA (1977)

8 **Goodrich, L.F. and Bray, S.L.** Integrity test for high-T_c and conventional critical-current measurement systems *Adv Cryog Eng Mater* (1990) **36A** 43

9 **Goodrich, L.F., Ekin J.W. and Fickett, F.R.** Effect of twist pitch on short-sample V–I characteristics of multifilamentary superconductors *Adv Cryog Eng Mater* (1982) **28** 571

10 **Dube, W.P. and Goodrich L.F.** Quench detector circuit for superconductor testing *Rev Sci Instrum* (1986) **57** (4) 680

11 **Watanbe, K., Noto, K., Morita, H., Fujimori, H., Mizuno, K., Aomine, T., Ni, B., Matsushita, T., Yamafuji, K. and Muto, Y.** Anisotropy and hysteresis of transport critical currents in high temperature Ln–Y–Ba–Cu–O superconductors *Cryogenics* (1989) **29** 263

12 **Evetts, J.E. and Glowacki, B.A.** Relationship of critical current irreversibility to trapped flux and microstructure in polycrystalline $YBa_2Cu_3O_7$ *Cryogenics* (1988) **28** 641

13 **Palstra, T.T.M., Batlogg, B., van Dover, R.B., Schneemeyer, L.F. and Waszczak, J.V.** Critical currents and thermally activated flux motion in high-temperature superconductors *Appl Phys Lett* (1989) **54** 763
14 **Ekin, J.W.** Offset criterion for determining superconductor critical current *Appl Phys Lett* (1989) **55** 905
15 **Salama, K., Selvamanickam, V., Gao, L. and Sun, K.** High current density in bulk $YBa_2Cu_3O_x$ superconductor *Appl Phys Lett* (1989) **54** 2352
16 **Kwak, J.F., Venturini, E.L., Baughman, R.J., Morosin, B. and Ginley, D.S.** High critical currents in polycrystalline Tl–Ca–Ba–Cu–O films *Cryogenics* (1989) **29** (3A) 291
17 **Bean, C.P.** Magnetization of high field superconductors *Rev Mod Phys* (1964) **36** 31
18 **Kuchnir, M. and Markley, F.** Simple instrumentation for testing of ceramic superconductors, Fermi National Accelerator Laboratory technical memo, TM-1464, 5501.000 (1987)
19 **Metra, P., Gheradi, L. and Mele, R.** Characterizing the current carrying capacity of different high T_c superconductors with as much sensitivity as versatility *IEEE Trans Magn* (1989) **MAG-25** 2297
20 **Tachikawa, K., Itoh, K., Wada, H., Gould, D., Jones, H., Walters, C.R., Goodrich, L.F., Ekin, J.W. and Bray, S.L.** VAMAS intercomparison of critical current measurement in Nb_3Sn wires *IEEE Trans Magn* (1989) **MAG-25** 2368
21 **Kimura, Y., Higuchi, N., Meguro, S., Takahashi, K., Uyeda, K., Ishihara, T., Inukai, E. and Umeda, M.** Round robin tests of T_c and I_c on $YBa_2Cu_3O_x$ *IEEE Trans Magn* (1989) **MAG-25** 2033
22 **Soulen, R.J.** Personal communication, Naval Research Laboratory, Washington DC, USA (1989)