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NOVEL METHODS FOR THE MEASUREMENT OF THE CRITICAL CURRENT OF SUPERCONDUCTING WIRES

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ABSTRACT

The critical current as a function of magnetic field of superconducting wires is commonly measured using about 60 mm short straight, or U-shaped samples, or about 1 m long samples on helical mandrels (so-called ITER barrels). The ITER barrel is designed for low to medium currents, but is commonly modified for high current wires. This often results in increased complexity, errors from reacted sample handling, preparation time, and cost. We have developed a method that retains the standard ITER barrel, but uses disposable, off-the-shelf, plumbers, Cu tube fittings instead of machined end-rings, thereby resolving the aforementioned issues. The improved sample holder also solves a number of disadvantages of the original ITER barrel method. A second method involves the improvement of straight wire measurements. Current redistributions, resulting from the limited length in perpendicular magnetic field, reduce the achievable voltage resolution in short straight, or U-shaped samples. We have introduced “wiggles” in U-shaped short samples, which impose the appropriate current distribution far before the region of interest, thereby mitigating undesired redistributions around the voltage measurement region. Both improved methods allow for an increased throughput and reliability of critical current measurements on superconducting wires.

KEYWORDS: Critical current, superconducting wire, ITER barrel.

INTRODUCTION

The US Large Hadron Collider Accelerator Research Program (LARP), in which Lawrence Berkeley National Laboratory (LBNL) is a key contributor, is in the production R&D



FIGURE 1: a) Dimensions of a standard ITER barrel. b) Detail of a standard ITER barrel with Cu end-ring and sample and shunt mounted. c) LBNL improved system to accommodate larger currents.

phase of several series of prototype coils for accelerator quality Nb_3Sn magnets [1]. Additionally, LBNL is developing two Nb_3Sn dipole magnets as part of their base program: The high field dipole HD3 and the large dipole LD1. These efforts result in an increasing demand for reliable, high throughput, and cost effective wire (“short sample”) critical current (I_c) measurements as a function of magnetic field (H). Such I_c measurements are key to cable development and accurate analyses of coil and magnet performance.

Short sample measurements commonly use about 1.2 m long wires that are coiled onto a Ti-6Al-4V helical sample holder, as depicted in FIGURE 1. Such holders were originally developed for the second and third benchmark tests on wires for the International Thermonuclear Experimental Reactor (ITER) [2, 3, 4], and are commonly referred to as an “ITER barrel”. The original ITER barrel testing system, depicted in FIGURE 1a and b, significantly reduced the differences in inter-laboratory comparisons. The system works well for low and medium current wires, but relies on a small surface area through which the current is transferred from the barrel holder to the Cu end-rings. It is therefore less suited for high current wires. The Cu end-rings go through the reaction cycle for Nb_3Sn wires, and cannot be re-used after a wire has been soldered to them for measurement. This is costly since the end-rings have to be precision machined. The end-rings are held in place with small stainless steel wires, and the tightness of the end-ring to barrel fit depends on the machining tolerances. Because of this, some end-rings have too loose a contact fit, which hinders reliability. The Cu to Ti-alloy interface causes a discontinuity in the strain-state of the wire, which is commonly solved by shunting this section with an additional wire, as shown in FIGURE 1b.

These disadvantages, and specifically the requirement to measure modern high current wires, triggered design changes in a number of institutes, which caused losing the ability to exchange samples in a number of cases. LBNL’s modification to the standard ITER barrel system is depicted in FIGURE 1c. In this example, reusable Ti-alloy end-rings are used for the sample reaction, and the Ti-alloy end-rings are replaced by large Cu end-rings for the I_c tests. These Cu end-rings are rigidly clamped to the barrel by stainless steel bolts, and connected to threaded Cu leads. This system solved a number of issues of the original ITER barrel system and enables the measurement of high current wires, but it introduced post-reaction handling of the brittle wires, which sometimes caused sample failure due to handling error, and reduced sample throughput. A new system was developed, to mitigate these issues, while being cost-effective, reliable, and allowing a high sample throughput.

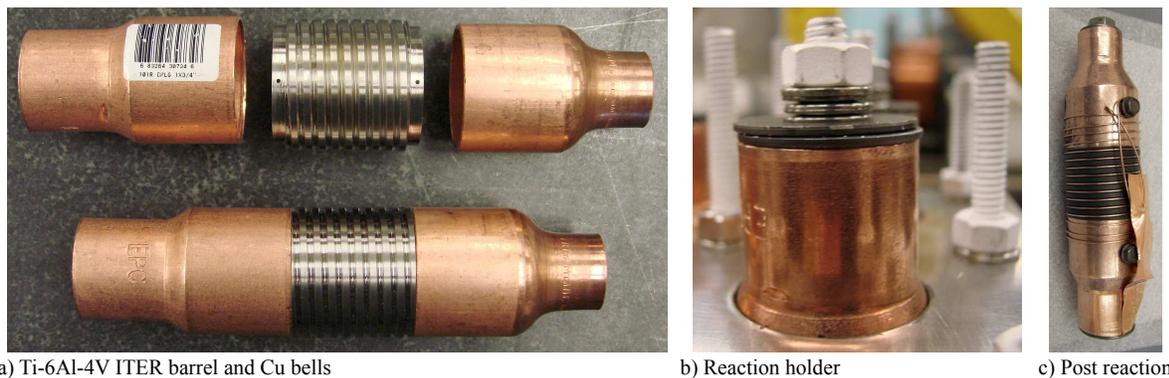


FIGURE 2: Improved barrel system using press-fitted off-the-shelf wrought-Cu reducer bells.

IMPROVED ITER BARREL SYSTEM

Improved barrel design

A new barrel sample holder method was designed that uses disposable, commercially available, off-the-shelf, wrought-Cu, 1"×0.5" and 1"×0.75" reducer fittings for Cu tube plumbing, as depicted in FIGURE 2a. These Cu bells are forged with accurate inside diameters that are nominally 28.68 mm at the 1" side. The bells' ends are squared and lightly chamfered in a lathe, which takes only a few minutes per item when done in series. Then, a single hole is drilled for a self-tapping screw to clamp the sample wire upon assembly of the holder. The bells are pressed onto pre-seasoned standard ITER Ti-alloy barrels, which can be retained for backward compatibility with the large number of barrels that are in use at laboratories around the world. The interference fit on the nominally 28.91 mm outer diameter rim of the barrel provides a sufficiently rigid connection at room temperature. A wire is then mounted and held in place with two self-tapping screws.

During reaction of the wire it is critical to retain some positive clamping pressure on the bells, due to the larger expansion of Cu compared to the Ti-alloy. Graphite-coated stainless steel plugs are placed in the Cu bells and held in place with a stainless steel threaded rod that is pre-loaded with Belleville washers, as shown in FIGURE 2b. The stainless steel rod has a similar coefficient of thermal expansion as the bells and the barrel combined. The plugs have the added benefit of additional alignment of the bells in case they come loose at high temperature. The bell-barrel assembly is held between stainless steel plates that are also pre-loaded with stainless steel threaded rods as an additional safety precaution during the reaction. One side with the connecting bolts is seen in FIGURE 2b. The bells contract onto the barrel again during cool-down, after which the stainless steel plates, rods, and plugs are removed. The wire is then soldered to the bells, using solder flux on the inside diameters of the bells to prevent oxidation, and on the wire to prevent movement during the measurement. The self-tapping screws are then removed and the sample is ready for measurement.

Measurements and results

A testing holder has been designed to accommodate the improved barrel system. A cross-section of the holder is shown in FIGURE 3a, and an assembled view is shown in FIGURE 3b. The holder consists of a concentric OFHC Cu tube and rod, designed to carry currents up to 2 kA. The rod is provided with helium channels to allow internal cooling of the barrel during measurement. The rod and tube are connected to existing 2 kA leads. The

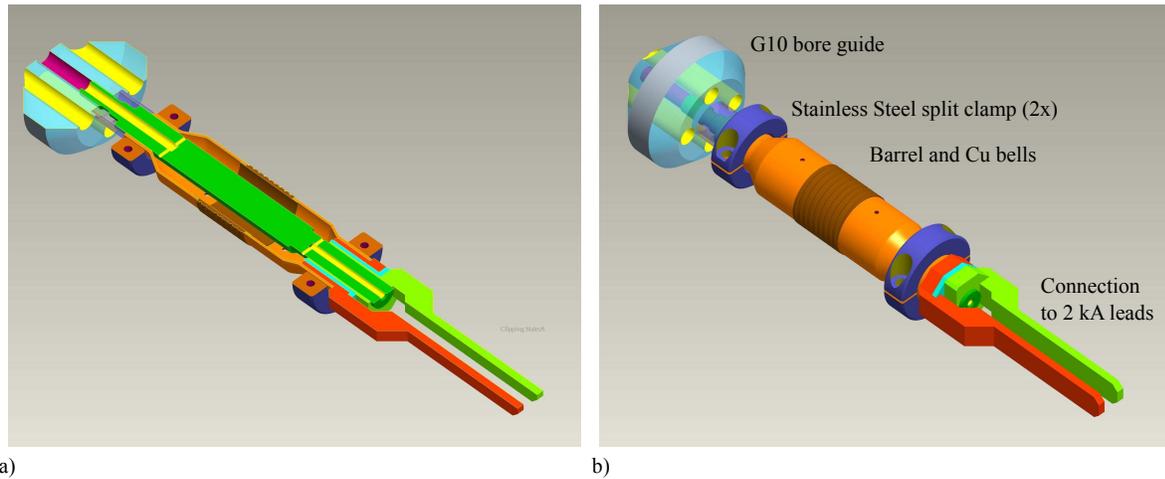


FIGURE 3: Holder for the improved barrel measurement system. a) Cross-section. b) Assembled.

barrel is mounted on the holder by sliding it up over the rod and tube, and clamped with stainless steel split clamps. The G10 bore guide is attached to center the test assembly in the bore of the background field solenoid magnet. The clamps are torqued tight to assure a large surface contact area Cu-to-Cu press-fit to the rod and tube. The softness of the Cu bells after reaction allows for easy clamping onto the rod and tube.

The cool-down cycle during measurement causes the bells to further contract onto the barrel, perhaps even introducing yield. This is not an issue during the measurement since the bells are compressed onto the barrel by the larger longitudinal contraction of the central Cu rod in comparison to the bells and Ti-alloy barrel. The additional deformation does, however, potentially ease the removal of the bells from the Ti-alloy barrel after testing. The used bells are discarded after the measurement, the central part of the wire is saved for residual resistivity ratio (RRR) measurements, and the Ti-alloy barrel is recycled.

Twenty-one Nb₃Sn and four Bi-2212 wires have so far been successfully measured using the improved barrel system. The tests were so far limited to currents up to 1 kA due to power supply issues. Tests up to 2 kA will be performed in the near future. The efficiency and reliability has been improved compared to LBNL's previous system. No sample failures occurred so far, and the improved system is less susceptible to operator error. A typical measurement result on a high current 108/127 Ta-alloyed 0.778 mm diameter Nb₃Sn wire, manufactured by Oxford Instruments - Superconducting Technology, Carteret, NJ, is shown in FIGURE 4. The resulting I_c and n -values are identical to measurements using LBNL's previous system, and the I_c values were confirmed by cross-checking within the LARP collaboration.

IMPROVED VOLTAGE RESOLUTION IN SHORT WIRE MEASUREMENTS

A second route towards increased statistics in short sample measurements is the use of short (about 60 mm) straight wires, since it is comparably much easier to design a holder that allows for the measurement of multiple samples in one cool-down than it is for barrel-type holders. A disadvantage of the measurement of short straight wires, however, is that it requires typically a few centimeters wire length for the current to transfer into the superconducting filaments [5]. This causes the appearance of a current transfer resistivity – caused by current flowing through the matrix – in the voltage-current transition. This undesired resistive voltage limits the usable length over which voltages can reliably be measured to a central

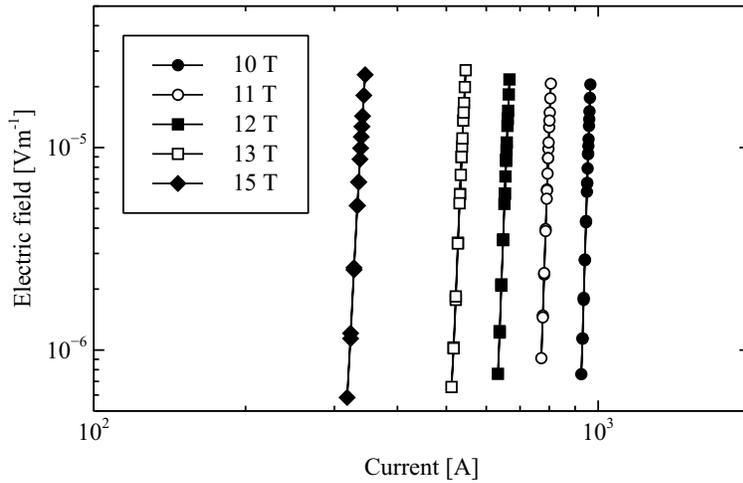


FIGURE 4: Typical electric field as a function of current data, measured using the improved barrel system on a typical high current Nb₃Sn wire at 4.2 K.

10 mm or shorter for typical magnet bore diameters of around 60 mm. The fact that this 10 mm length is comparable to the typical twist pitch in wires, renders the current transfer resistivity dependent on the exact position of the voltage taps with respect to the twisted filaments.

The current transfer resistivity also prevents reliable determination of the critical current at typical barrel electric field criteria of $E_c = 10^{-5} \text{ Vm}^{-1}$, even for such small voltage tap distances, at currents above a few hundred amperes. More common I_c criteria for short straight wires are therefore one decade higher at $E_c = 10^{-4} \text{ Vm}^{-1}$. Although the I_c values at 10^{-4} Vm^{-1} can in principle be extrapolated down to 10^{-5} Vm^{-1} by assuming a constant n -value, a direct comparison of the I_c values is usually not possible.

A novel method, which enables the measurement of high resolution voltage-current transitions on short straight wires, has been developed to mitigate the above disadvantages. The method has been verified on a NbTi reference wire [6], and is shown to enable a reliable determination of the critical current at 10^{-5} Vm^{-1} for currents at least up to 550 A, using a voltage tap separation of 35 mm, or roughly 2 times the wire twist pitch.

Experiment

The high voltage resolution method is tested using a G10 holder using two Cu bars as current leads, as depicted in FIGURE 5. Three different sample configurations are compared, in which the samples are soldered to the Cu leads over the entire wire length that is on the leads. In the first configuration a straight, 55 mm wire is tested with voltage tap pairs at 10, 25, and 35 mm separation (FIGURE 5a). In this configuration, only 10 mm on each side is available for the current to enter and leave the wire. In the second configuration a wire is tested with identical voltage tap positions, but with the wire bent into a U-shape (FIGURE 5b). This situation is similar to the configuration in which the strain sensitivity of the critical properties is measured on U-shaped bending springs [7, 8]. In this configuration the available length for the current to enter and leave the wire is significantly increased, but the current in the wire will still need to redistribute from the region where the current is parallel to the applied magnetic field, to the measurement region in which the current is perpendicular to the applied magnetic field. This redistribution will also cause resistive voltages in the voltage-current transition that are similar to those caused by current entrance effects. In the

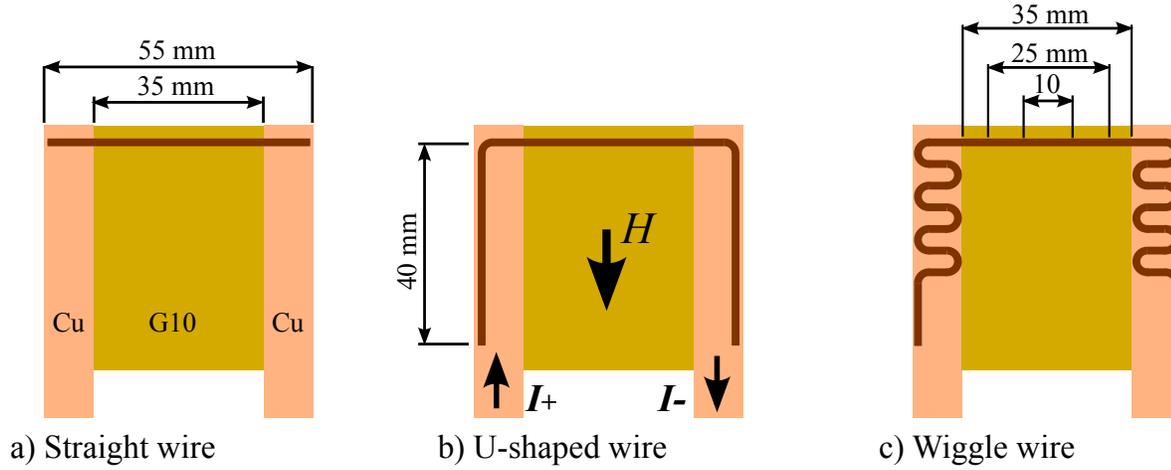


FIGURE 5: Test configurations for NbTi reference wire. a) A straight 55 mm wire configuration with holder dimensions. b) A U-shaped configuration with field and current orientation. c) A wiggle configuration with voltage tap positions and tap separation length.

third configuration the wire is “wiggled” in the lead section, to create regions where the wire is perpendicular to the applied magnetic field, thereby imposing a current distribution in the filaments that is similar to the measurement region, but long before the current enters the measurement region. Since there is no physical driving force for the current to redistribute differently in the regions where the current is parallel to the applied magnetic field, the current will retain its distribution for the perpendicular field direction once it is achieved.

Voltage current measurements were performed at an applied magnetic field of 5 T and a temperature of 4.23 K in the 64 mm bore of a 15 T solenoid magnet. The used wire is a 0.825 mm diameter NbTi reference wire with a twist pitch of 15 mm. The wire has an I_c of about 540 A at 5 T. More details on the wire used are given elsewhere [6]. A NbTi wire was selected for these proof-of-principle measurements, since it can be deformed into the desired shape without significant I_c loss, and without the need to react it in the selected shape.

Results

The measured electric fields as a function of current for the three different sample configurations for a 10, 25, and 35 mm voltage tap separation are shown in FIGURE 6. The straight wire results (FIGURE 6a) clearly show the typical current transfer resistivity in the bottom of the transitions. It should be emphasized that the magnitude of the current transfer resistivity depends on the matrix resistivity and the Cu to filament resistivity of the wire [5], as well as on the positioning of the voltage taps with respect to the twist pitch of the filaments. A reliable determination of the I_c at the desired $E_c = 10^{-5} \text{ Vm}^{-1}$ criterion is not possible for this wire in this configuration. The fact that the resistive voltages do not change proportionally to the voltage tap separation is due to the fact the the 10, 25, and 35 mm voltage tap distances detect $\frac{2}{3}$, $1\frac{2}{3}$, and $2\frac{1}{3}$ of the filament twist pitch length, respectively. It should also be noted that the electric field levels below 10^{-5} Vm^{-1} approach the offset drift and noise levels in the nano-volt meters, which are several tens of nano-volts. This specifically affects the signals for the shorter voltage tap separations.

The voltage resolution significantly improves when the wire is bent into a U-shape, as is evident from FIGURE 6b. Here, a reliable determination of the critical current at $E_c = 10^{-5} \text{ Vm}^{-1}$ is in principle possible for the 10 mm tap separation, but the voltage measurement

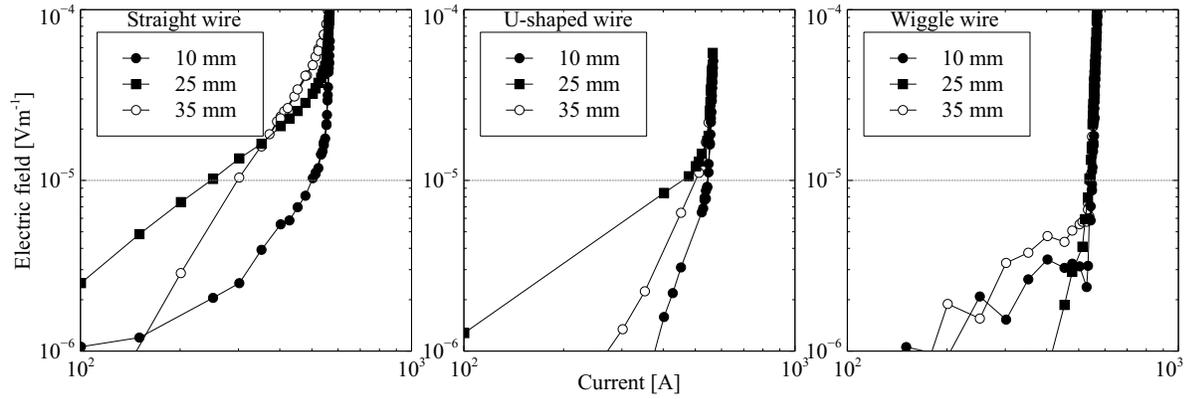


FIGURE 6: Electric field as a function of current for a reference NbTi wire at 5 T and 4.23 K for different voltage tap separations on a straight (a), U-shaped (b), and wiggled sample (c).

still occurs over a length that is less than the filament twist pitch and the voltage resolution is, due to the short length, limited by the resolution of the nano-volt meters. It should be emphasized that a 10 mm voltage tap separation might not be sufficient for other wire types, as is demonstrated elsewhere for Nb₃Sn wires, where a reliable determination of the critical current at $E_c = 10^{-5} \text{ Vm}^{-1}$ was not possible for currents above 100 A, even for a voltage tap separation of only 5 mm [9].

The data on the wiggle wire configuration (FIGURE 6c) demonstrate a voltage resolution that is more than a factor 3 improved with respect to the U-shaped configuration. The resistive voltages are still visible below $E = 6 \times 10^{-6} \text{ Vm}^{-1}$, but are significantly below the desired $E_c = 10^{-5} \text{ Vm}^{-1}$ criterion, even for the 35 mm voltage tap separation. These data unambiguously demonstrate the possibility to distribute the current in a way that corresponds to the perpendicular magnetic field direction through the introduction of wiggles, long before the current enters the measurement region. This has the triple benefit of reducing the resistive voltages to below the desired criterion, to increase the voltage length sufficiently so that multiple twist pitches are measured, and to increase the voltage signal level above the typical drift and noise levels of nano-volt meters.

DISCUSSION

The improved barrel system allows for improved efficiency in the measurement of 1.2 m long helical wire sections for high current wires without the need to handle the wires after the reaction that forms the brittle Nb₃Sn phase. The system has so far been tested up to 1 kA, and higher current tests will be performed in the near future. Electric field versus current transitions were extensively cycled close to 1 kA, but no sample heating was observed. It can reasonably be expected that, since the power dissipation increases quadratically with the current, at a certain current sample heating by the bells could occur, due to the presumably relatively low RRR of the Cu of the bells of perhaps 10 or lower (the Cu alloy was not specified and the RRR so far not measured). A special order of OFHC quality bells could be considered in the event that this occurs, but so far there is no indication that the quality of the Cu of the bells is limiting our measurement capabilities.

The introduction of wiggles to enforce a favorable current distribution before the measurement region clearly is effective. It could perhaps allow for the use of voltage tap separations that are close to the bore diameter of the solenoid magnet used. Further tests, specifically for Nb₃Sn wires, are needed, but the method has favorable implications beyond I_c tests on

short wire sections. When applied on U-shaped bending springs for the measurement of the strain dependence of superconducting wires, it could increase the achievable voltage resolution sufficiently to remove the need for more complicated systems such as the “Pacman” [8] or “Walters” spring [10]. It also has relevance for joint design, in situations where a similar current distribution has to be enforced in a short distance. Such applications require further testing to determine the applicability and effectiveness of the method.

CONCLUSIONS

An improved system was developed that allows for reliable, cost effective, and efficient measurement of 1.2 m long helical wire samples. The system is compatible with the existing ITER Ti-alloy barrel, and is suitable for the measurement of modern high current wires. The method is so far commissioned up to 1 kA. Further tests will be performed in the near future to determine whether the improved barrel system is able to test wires up to 2 kA. The introduction of “wiggles” that dictate a favorable current distribution in wires before the measurement region, enables high voltage resolution critical current measurements on short straight wire sections, even for voltage taps that are located immediately next to the current connections. Both methods are being developed to allow for increased statistics and reliability in short sample characterizations for conductor development, reaction optimizations, and superconducting cable and magnet development.

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