Strain and Magnetic-Field Characterization of a Bronze-Route Nb_3Sn ITER Wire: Benchmarking of Strain Measurement Facilities at NIST and University of Twente

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***Abstract*—A benchmarking experiment was conducted to compare strain measurement facilities at the National Institute of Standards and Technology (NIST) and the University of Twente. The critical current of a bronze-route Nb_3Sn wire, which was fabricated for the International Thermonuclear Experimental Reactor (ITER), was measured as a function of axial strain and magnetic field in liquid helium at both institutes. NIST used a Walters' spring strain device and University of Twente used a bending beam ("Pacman") apparatus. The ITER bronze-route wire investigated had a very high irreversible strain limit that allowed comparing data over a wide range of applied strain between -1% and $+1\%$. Similarities of the data obtained by use of the two apparatuses were remarkable, despite the many differences in their design and techniques.**

***Index Terms*—Benchmarking, ITER, niobium-tin, strain.**

I. Introduction

STRAIN measurement facilities have flourished world-wide to enable in-depth studies of the effect of strain on transport properties of superconductors [1]–[12]. The brittle nature of most of the technological superconductors, and the ever-increasing challenges that the mechanical forces on the conductor pose in large-scale and high magnetic-field applications, have made strain measurements so crucial for the development of these applications. An example of such demanding applications in terms of strain tolerance is the International Thermonuclear Experimental Reactor (ITER) currently under construction [13]–[15].

Measurement techniques for investigating the effect of longitudinal strain ε are quite diverse, ranging from a standing sample that can freely contract during cool down [1], to a variety of techniques where the sample is attached to a support structure used to apply strain to the sample [2]–[12]. The first category allows determining the natural pre-compressive strain $\varepsilon_{\max}$ of the sample, but cannot be used to apply compressive axial strain to the sample, and has some limitations for performing measurements in variable temperatures. The second category, where the sample is soldered to a thick ring or multi-turn spring device, does not allow for an accurate determination of the pre-compressive strain, but offers vast possibilities for studying the effect of both tensile and compressive axial strain in a controllable variable-temperature environment. The latter category was more in vogue in the last two decades, and was particularly useful for extending the strain studies originally made in liquid helium to a whole range of strain and temperatures that now cover most useful conditions experienced by a conductor in real applications.

Despite the diversity in the techniques and design of the strain facilities, very little was done to directly compare results obtained with these apparatuses for cross benchmarking. Such inter-laboratory comparisons can be conducted at different levels of complexity: compare critical-current I_c data obtained as a function of (a) strain, (b) strain and magnetic field B, or (c) strain, temperature T, and magnetic field. In this paper, we start this benchmarking exercise by comparing data obtained at NIST and at the University of Twente by use of Walters' spring and "Pacman" apparatuses, respectively. At this stage, we restrict comparisons to $I_c(\varepsilon)$ data obtained at fixed T and B, and $I_c(\varepsilon)$ data obtained at fixed T and ε.

II. Strain Measurement Facilities

A. Walters' Spring Apparatus at NIST

The NIST apparatus for measuring $I_c(\varepsilon)$ utilizes a Walters' spring device [2], [4]. The spring is made of cold-worked and precipitate-hardened Cu-2%Be alloy [4], and has four active turns and a T-section design that maximizes its elastic strain range to a wide window from -1% to $+1\%$. The spring's outer diameter is 25 mm. A torque applied to the spring puts the sample that is attached to the spring's outer surface into either tension or compression. Multiple strain gauges were attached to the spring to calibrate the relative angular displacement of the spring ends versus strain at the spring's outer surface. Strain of

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the sample is quoted at the sample's centerline. Nb_3Sn samples were reacted on stainless-steel mandrels, transferred onto the spring, and soldered to it at $\approx 200°C$ with Pb-Sn solder. Three pairs of voltage taps were attached to the sample, allowing measurement of three segments of each specimen. Each pair covered one full turn ≈80 mm long. Measurements were performed in liquid helium at a temperature of 4.03 K, and in magnetic fields from 5 T to 16 T. NIST I_c data were determined at an electric-field criterion $E_c = 0.1\ \mu V/cm$.

B. "Pacman" Apparatus at the University of Twente

The apparatus of University of Twente for measuring $I_c(\varepsilon)$ utilizes a circular bending beam with a T-shaped cross-section made of Ti-6Al-4V alloy [6]. This device is referred to as "Pacman." It has an outer diameter of 36 mm, and an elastic strain window from -0.8% to $+0.8\%$. A torque is applied to the device by a worm-gear system at room temperature through a set of concentric tubes coupled mechanically to two revolving halves of the Pacman spring support. Strain on the outer surface of the beam is measured by two strain gauges. Strain of the sample is calculated at the sample's centerline from the strain value measured on the spring surface [6].

A heat-treated sample is transferred onto the Pacman spring and soldered to it by use of Sn-5% Ag solder at $\approx 230°C$. Voltage taps for I_c measurements were placed symmetrically around the center of the sample and were spaced 20 mm apart. Measurements were performed in liquid helium at a temperature of 4.23 K, and in magnetic fields from 8 T to 14 T. I_c data of University of Twente were determined at an $E_c = 0.1\ \mu V/cm$. For comparisons with NIST data, I_c values obtained by the University of Twente at 4.23 K were used to calculate the corresponding I_c values at a temperature of 4.03 K. A scaling law was used for this purpose.

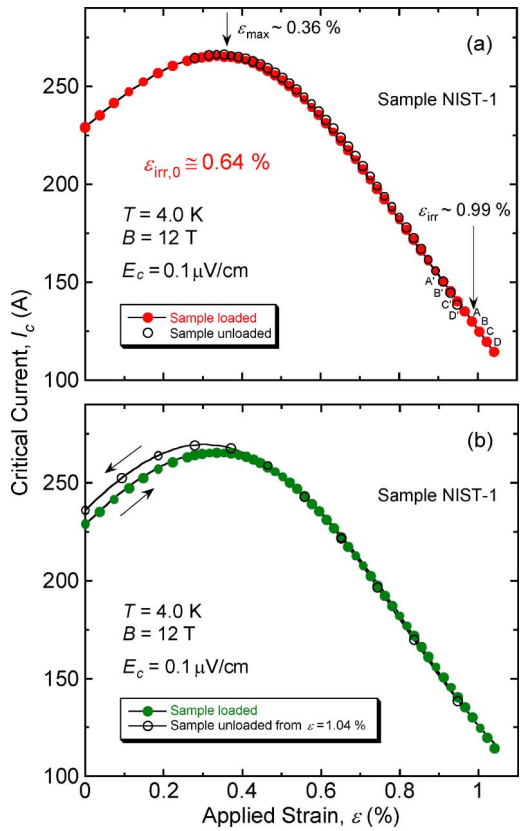

Fig. 1. (a) NIST data of $I_c(\varepsilon)$ for an ITER bronze-route Nb_3Sn, obtained at 4.03 K and 12 T at 0.1 $\mu V/cm$. There was a very small degradation of I_c after an irreversible strain limit of 0.99% (intrinsic strain $\approx 0.64\%$). (b) Despite the little $I_c(\varepsilon)$ degradation measured after small strain releases from 1.04% applied strain, I_c showed an improvement when strain was released below ε_{max}. The high values of applied strain likely induced a yielding of the wire matrix, which in turn generated a reduction in the three-dimensional strain of Nb_3Sn for $\varepsilon \leq \varepsilon_{max}$; hence the observed improvement of I_c.

III. Conductor Used for Benchmarking

The conductor used for the benchmarking was an ITER, bronze-route, Nb_3Sn wire. It contained 583 sub-elements having 19 Nb_3Sn filaments each. Bronze was doped with 0.3% Ti, and Nb was doped with 1% Ta. The wire diameter was 0.82 mm. This wire had a particularly high irreversible strain limit ε_{irr}, so it was a very good candidate for comparing the two apparatuses over a wide range of strain within the conductor's reversible regime.

All samples were reacted at the University of Twente at $650°C$ for 100 hours. Three samples (NIST-1, NIST-2, and NIST-3) were measured at NIST, and one sample (Twente-1) was measured at the University of Twente. Due to limited conductor length, sample NIST-2 was from a different billet than all the other samples (NIST-1, NIST-3, and Twente-1).

IV. Results and Discussion

A. Irreversible Strain Limit ε_{irr}

Fig. 1(a) depicts $I_c(\varepsilon)$ data obtained at NIST at 4.03 K and 12 T on sample NIST-1. The sample was loaded and (partially) unloaded several times to determine ε_{irr} where unloaded points (empty symbols) start to deviate from the loaded points (solid symbols) due presumably to the formation of cracks in Nb_3Sn filaments [16], [17]. The last loaded and unloaded points were labeled with unprimed and primed letters, respectively, to point out where permanent damage started to occur. The intrinsic irreversible strain limit $\varepsilon_{irr,0} = \varepsilon_{irr} - \varepsilon_{max}$ was as high as 0.64%. This wire was a rare example of Nb_3Sn conductor for which the NIST spring device had to be used up to its maximum tensile elastic limit of $+1\%$. Even so, the irreversible degradation of $I_c(\varepsilon)$ was just barely noticeable. The University of Twente used the dependence of the n-value (defining the steepness of the voltage-current curve) on strain to determine ε_{irr} [18]. This method yielded a value of $\varepsilon_{irr} \approx 0.65\%$. Despite this good agreement, we should point out that the current benchmarking is intended solely for comparing $I_c(\varepsilon)$ and $I_c(B)$ data, and does not include comparisons of methods for determining ε_{irr}. Such comparisons of analytical methods could be treated in depth perhaps in a different paper.

Fig. 1(b) shows $I_c(\varepsilon)$ for strain applied from 0% up to about 1% (solid symbols), and for strain gradually released from 1% down to 0% (empty symbols). The $I_c(\varepsilon)$ curve while releasing strain shows good reversibility, but goes above the virgin $I_c(\varepsilon)$ curve at $\varepsilon \leq \varepsilon_{max}$. The value of ε_{max} was also shifted to a lower value upon releasing strain, due probably to the yielding of the matrix. The increase of I_c reflects the three-dimensional nature

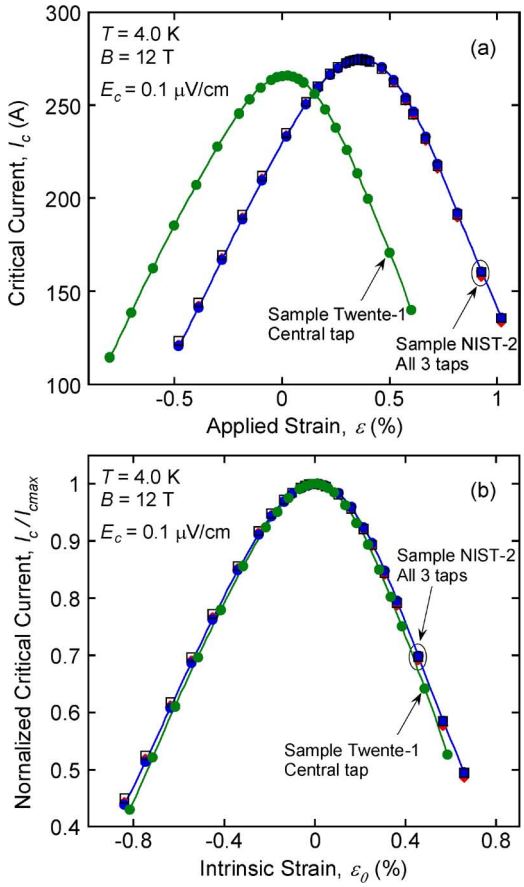

Fig. 2. (a) Comparison of $I_c(\varepsilon)$ data obtained at NIST and University of Twente for an ITER bronze-route Nb_3Sn wire at 4.03 K and 12 T. The shape of the $I_c(\varepsilon)$ curves and values of I_c at the peak were very similar. (b) Normalized I_c vs. intrinsic strain ε_0 showed that the two sets of data are remarkably similar, despite the significant differences between the two strain measurement facilities at NIST and University of Twente.

of the strain effect in Nb_3Sn material [19], [20], and shows that the protocol used for measuring $I_c(\varepsilon)$ can affect the results significantly. This point must be considered when a benchmarking experiment is performed; namely, the sequence for applying strain should be discussed and followed as closely as possible by the laboratories involved to make data comparisons meaningful, as was done in this work.

B. Comparisons of $I_c(\varepsilon)$ at 4.0 K and 12 T

The sequence of strain application used by NIST and the University of Twente was as follows: An intrinsic strain $\varepsilon_0 (= \varepsilon - \varepsilon_{max})$ corresponding to $\approx -0.83\% \pm 0.015\%$ was applied to the sample, and I_c was measured while increasing this intrinsic strain to 0% in increments of $\approx 0.1\%$. This increment was gradually decreased around $\varepsilon_{\max}$. Beyond the peak, I_c was measured during strain loading and strain (partial) unloading back to $\varepsilon_{\max}$. Fig. 2(a) shows a comparison of the $I_c(\varepsilon)$ data obtained at NIST and University of Twente on samples NIST-2 and Twente-1, respectively. NIST data were plotted for the three voltage taps that covered each of the three middle turns of the sample, and showed a very good reproducibility. The $I_c(\varepsilon)$ curves obtained by the two institutes were very similar in shape. Values of I_c at $\varepsilon_{\max}$ were close (274.5 A for NIST and 266.1 A for University of Twente) even though the two samples were not from the same billet, but $\varepsilon_{\max}$ values were very dissimilar (0.36% and 0.017%, respectively) due to the very different thermal contraction coefficient of the Cu-Be and Ti alloys used to make the Walters' spring and Pacman bending beam. When I_c was normalized with respect to the peak values, and plotted against the intrinsic strain ε_0, data of NIST and University of Twente were in very good agreement. The normalized curves for NIST data were slightly shallower than those for data of University of Twente. Discrepancy grew at high ε_0 both in compression and tension, but the difference seems to be only $\approx$4% at $\varepsilon_0 \approx +0.6\%$, and $\approx$3% at $\varepsilon_0 \approx -0.8\%$, when normalized scale is used to estimate these percent differences. If absolute scale is used instead, percent differences are about doubled for these two particular strain points.

It is important to mention that the difficulty in estimating the value of $\varepsilon_{\max}$ can increase or decrease the differences between the two sets of data. $\varepsilon_{\max}$ cannot be estimated reliably to better than $\approx \pm 0.015\%$. If, for example, the estimated $\varepsilon_{\max}$ for NIST data is 0.345% (instead of 0.36% as in Fig. 2(b)), the two sets of data are better matched in the compressive strain regime, but then discrepancies grow more in the tensile strain regime. If the estimated value of $\varepsilon_{\max}$ for NIST data is 0.375% instead, the opposite happens, as the two sets of data are better matched in the tensile strain regime, and discrepancies grow more in the compressive strain regime.

Comparisons should be made at a given, same, intrinsic strain. But the uncertainty in $\varepsilon_{\max}$ somewhat adds to the complexity of the benchmarking. Nevertheless, $I_c(\varepsilon)$ data obtained by NIST and University of Twente clearly show remarkable similarities, despite the significant differences between the two measurement systems in their concept, design, and materials used.

C. Comparisons of $I_c(B)$ at 4.0 K and $\varepsilon_{\max}$.

Comparisons were also made of $I_c(B)$ data obtained at NIST and University of Twente on samples NIST-3 and Twente-1. To circumvent the difficulties discussed above that arise from uncertainties in determining the value of $\varepsilon_{\max}$—which makes it hard to choose the same intrinsic strain value—and given that the effect of strain on I_c is very small near the peak, it is best to compare data obtained near $\varepsilon_{\max}$ so that any discrepancy in the value of ε_0 used by the laboratories does not induce significant differences in I_c values.

Fig. 3 compares $I_c(B)$ data obtained on samples NIST-3 and Twente-1 at 4.03 K and $\varepsilon_0 \approx 0\%$. Differences between I_c values at 14 T were within 1.2%, and tend to diminish as I_c is increased (B decreased). This 1.2% variation is not due only to possible differences between the two measurement systems. Some of the other factors contributing to it could be related perhaps to inhomogeneity of I_c from sample to sample, differences in the values of B and T between the two institutes, and errors in extrapolating I_c at 4.03 K from data of University of Twente obtained at 4.23 K. Therefore, the 1.2% difference is very satisfactory, and shows that the two apparatuses can yield very similar results. The 1.2% variation is significantly smaller than that reported in Fig. 2(a) ($\approx$3.1% variation in I_c values at $\varepsilon_{\max}$, measured at 12 T) because, this time, the samples measured (NIST-3

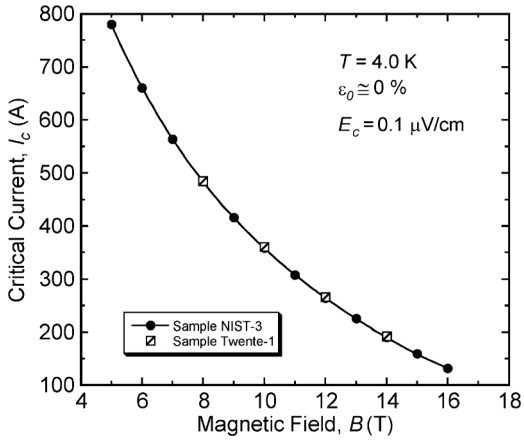

Fig. 3. Comparison of $I_c(B)$ data obtained at NIST and University of Twente for an ITER bronze-route Nb_3Sn wire at 4.03 K and an intrinsic strain $\varepsilon_0 \approx 0\%$. Differences between the two sets of data are within 1.2% at 14 T, and tend to decrease as magnetic field is decreased.

and Twente-1) were from the same billet. This suggests that, for benchmarking experiments, it may be best to use samples from the same billet.

V. Conclusion

A benchmarking experiment was conducted to compare the two strain measurement facilities at NIST and University of Twente that utilize Walters' spring and Pacman bending beam devices, respectively. Despite obvious and significant differences in the conceptual and design aspects of the two systems, results obtained on an ITER bronze-route Nb_3Sn wire showed remarkable similarities both in $I_c(\varepsilon)$ and $I_c(B)$ data obtained by the two apparatuses in liquid helium. The importance of utilizing the same sequence for applying strain in such benchmarking experiments was highlighted, and the consequences of the uncertainties in determining the value of the samples' pre-compressive strain ε_{max} were discussed. Due to the current and crucial need for reliable strain data, more benchmarking experiments are required to compare the existing strain measurement systems in different laboratories.

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