20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Experimental Techniques for Measuring the Critical Current in Superconducting Strands

Valentina Corato[1], Gianluca De Marzi[1], Chiarasole Fiamozzi Zignani[1], Luigi Muzzi[1], Rosario Viola[1], Antonio della Corte[1]

[1] *ENEA, via Fermi 45, 00044, Frascati (Rome), valentina.corato@enea.it*

***Abstract* – The characterization of the critical current I_c in superconducting NbTi and Nb_3Sn strands is carried out through a four-probe technique. Besides the dependence on temperature and magnetic field, which can be measured with a standard Variable Temperature Insert, the I_c of Nb_3Sn samples is also sensitive to axial strain. For this measurement, specially dedicated probes can be used, among them we recall the Walters spring insert. Both systems and corresponding experimental techniques are here described.**

I. INTRODUCTION

A proper assessment of transport properties of superconducting strands is required for their employment in fusion [1,2] and accelerator [3] magnets. Both NbTi and Nb_3Sn materials - in the form of multi-filamentary composite strands - are the most commonly used in large scale applications. In the following, we will describe in detail some of the measurement equipments adopted to characterize the critical current (I_c) of these superconductors under various measurement conditions. Besides the usual dependence of the critical current on temperature (T) and magnetic field (B), in Nb_3Sn samples an additional dependence on the applied strain (ε) has been observed [4].

In Section II the standard Variable Temperature Insert (VTI), used for strands transport properties measurements, is described, and in Section III the corresponding results obtained on several NbTi samples are reported. In Section IV we describe one of the most commonly used inserts for the strain-dependence characterization of Nb_3Sn samples, that is the Walter Spring system. Results obtained using this probe are shown in Section V. Conclusions are drawn in Section VI.

II. EXPERIMENTAL SET-UP FOR CRITICAL CURRENT MEASUREMENTS

Direct transport critical current I_c(T, B) measurements have been performed using the ENEA VTI test facility [5], with a transversal external field up to 12.5 T. A sketch of the insert is shown in Fig. 1. A warm hole of 47 mm bore allows to insert a sample wound on a stainless steel cylindrical barrel (pitch = 4 mm, diameter = 30 mm, sample length = 1 m) for transverse field measurement of wires, or a flat sample-holder for the characterization of short tapes (up to 20 mm), in both longitudinal and transverse field configuration. Sample temperature is regulated by helium gas flow, pumped through a needle-valve from the same LHe bath of the background field superconducting coil. The acquisition system, developed at ENEA, is able to control the He temperature by acting on a resistive heater installed on the needle valve, whose power is tuned by the temperature read on sensors in contact with the sample.

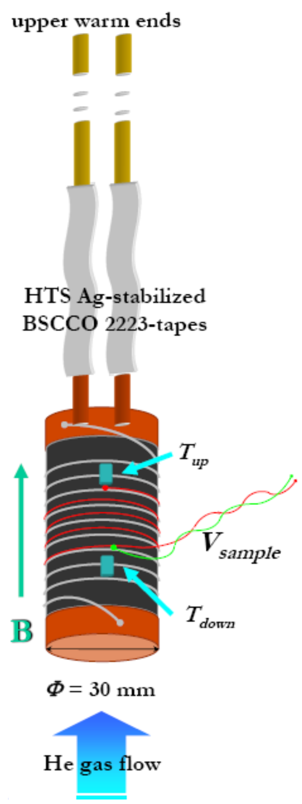

Fig. 1. A sketch of the ENEA VTI.

Two calibrated Cernox sensors are glued to the opposite ends of the sample, kept parallel to the field. The temperature is determined with an error bar of ±10 mK, including the magneto-resistive shift of the Cernox [6], the sensor and the data acquisition system accuracy, and the gradient between the two thermometers. Temperature stability during the measurement is within the error bar up to the electric field of 1 μV/cm.

Our test facility is capable to feed currents up to 300 A at maximum flow rate and below 6 K. Above this limit, it is difficult to remove the Joule heating by means of He flow. Therefore, the increasing thermal gradient on the sample leads to less accurate measurements.

The current is ramped slowly to keep the inductive electric field at negligible values. Two High-T_c superconducting Ag-stabilized BSCCO 2223-tapes, provided by SUMITOMO Electric Industries Ltd, have been soldered in parallel to the lowest section of the original brass current leads, in order to minimize heat transfer from the upper warm ends, and heat load due to resistive power dissipation.

III. CRITICAL CURRENT MEASUREMENTS ON NBTI STRANDS

In the framework of JT60-SA project, a set of NbTi strands have been characterized in order to verify the $I_c(T,B)$ performances and qualify the production procedure[7]. Critical current values have been determined at a voltage of 5 μV on a 50 cm voltage taps distance, corresponding to the critical value of the electric field E_c=0.1 μV/cm. The electric field, E, and the current, I, are linked by the relation:

$$\frac{E}{E_c} = \left(\frac{I}{I_c}\right)^n \qquad (1)$$

where the n-index indicates the steepness of the transition. The n-index is estimated by fitting the slope of the E(I) curve in log-log scale in the range 0.1-1 μV/cm. Fig. 2 shows an example of E/E_c curves as function of the current for different values of the magnetic field. The dashed line corresponds to the I_c criterion, whereas the dotted line defines the upper limit for the n-index fitting.

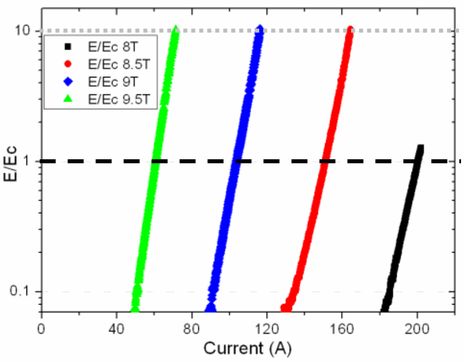

Fig. 2. Experimental E/Ec curves at different values of B.

The measured samples have been produced by Furukawa for the manufacturing of the Toroidal Field coils of the JT60-SA tokamak and their main features are reported in Table 1.

Table 1. Sample features

Sample	Diameter (mm)	Cu/non Cu ratio	I_c @4.2K,8.5T (A)
K010-01A	0.81	1.886	165.0
K027-02A	0.81	1.922	158.8
K032-02A	0.81	1.919	149.5

The dependence of the critical current on the magnetic field at different temperatures is reported in Fig. 3 for the measured samples. All samples have passed the acceptance test, requiring at least I_c=79A @ 5.65T, 6.2K [7].

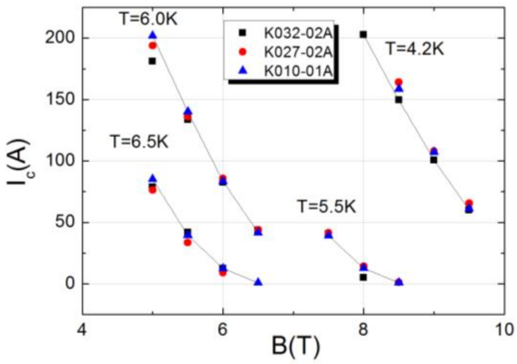

Fig. 3. Experimental $I_c(B)$ curves at different values of temperature. The solid lines are guides for eye.

Fig. 4 shows the n-index behavior as a function of I_c.

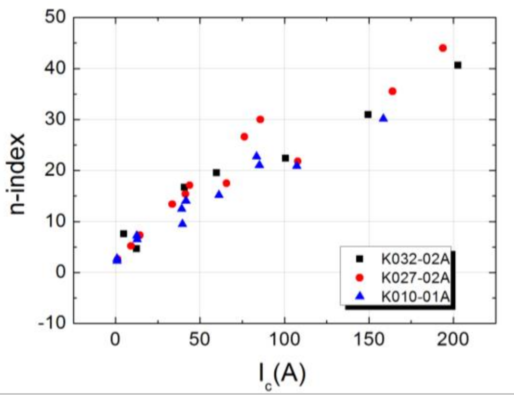

Fig. 4. The curve of n-index vs. $I_c(B,T)$ is shown for the three samples.

It's worth noting that, although the Cu/no-Cu ratio is slightly different for the three samples, both I_c and n-index curves are very similar. This attests that the strand production carried out by Furukawa is rather reproducible.

IV. MEASUREMENT APPARATUS FOR STRAIN-DEPENDENT SAMPLES

As mentioned in the Introduction, the critical current in Nb_3Sn strands strongly depends on the applied axial strain, ε. Different tools have been proposed to apply the axial strain in situ [8, 9, 10]. Nevertheless, the most common system is the Walters spring probe (WASP) [11, 12]. The equipment (see Fig. 5) and the technique that we have used to measure the variation of critical current vs. axial strain at the University of Geneve [4] is here described.

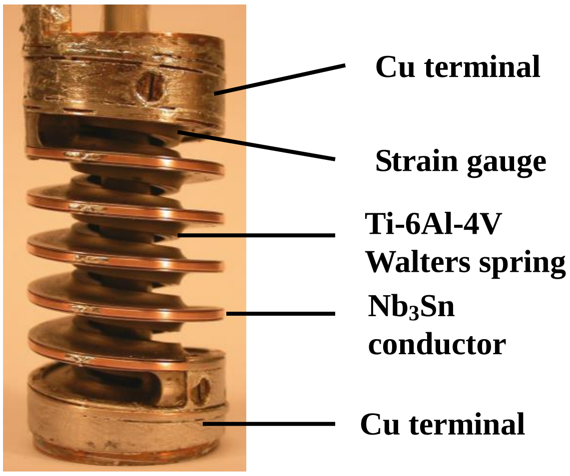

Fig. 5. Walters Spring Probe. Courtesy of the Applied Superconductivity Group of the University of Geneve.

The outer diameter of the spring is 39 mm. Following the reaction heat treatment, the Nb_3Sn wire is mounted on the WASP and soldered to the current terminals at both ends. After a strain free cool down to 4.2 K the WASP is rotated in the tensile direction and the critical current, I_c, is measured. As long as the wire is not strained, the critical current as a function of rotation angle stays constant. In contrast, I_c starts to increase at the angle where the rotation causes the first initial tensile strain. By this procedure, I_c at zero applied strain can be determined. As a next step, the wire is soldered over its entire length on the WASP. This is imperative when measurements under axial compression are scheduled and also for the determination of the irreversibility limit. Then the wire is cooled again to 4.2 K and zero applied strain can be found by searching I_c as measured after the first cool down. This implies that the I_c stays reversible and is unchanged upon thermal cycling, which is normally the case as long as the strain for maximum critical current, ε_m, is not reached.

Critical currents is obtained according to IEC international standard 61788-2. The voltage-current characteristics at different applied strains and magnetic fields are measured by the sample current power supply with a resolution of 16 bits and three Keithley nanovoltmeters. There are three pairs of voltage taps measuring three turns (gauge length = 338 mm), one (central) turn (gauge length = 126 mm) and the current injection at the terminals (total length = 630 mm). The current is increased stepwise and the voltage measured during the hold time. The resulting Lorentz force is directed towards the center of the measurement mandrel. Finally the temperature of the helium bath, measured by a CERNOX sensor, is recorded continuously during the sample current ramp.

V. STRAIN DEPENDENT MEASUREMENTS ON NB_3SN STRANDS

In order to evaluate the I_c the 0.1 μV/cm criterion has been adopted, as described in Section III. Measurements have been carried out on internal tin Nb_3Sn samples produced by Oxford Instruments Superconducting Technologies (OST) for ITER [13] (OST-I wire; billet #7567). The wire is characterized by a filamentary region, separated from the surrounding Cu stabilization matrix by a single tantalum (Ta) diffusion barrier. The filamentary region is made of 19 filament bundles, each containing 151 closely spaced superconducting filaments of about 6 μm diameter. The Cu/no-Cu ratio is 1 and the strand diameter 0.81mm.

In order to reproduce the condition of wires in a Cable in Conduit Conductor, some lengths of the same strand have been compacted into SS tubes (AISI 316L) of 0.2 mm thickness, obtaining a final outer diameter of 1.19 mm. At this size, only a small variation of the Nb_3Sn strand cross-section and a perfect bonding with the surrounding reinforcing tube was observed. The reaction heat treatment (HT) of the conductor has been carried out under vacuum. The HT parameters are as follows: 210°C/50h – 340°C/25h – 575°C/100h – 650°C/100h – 10°C/h heating/cooling rate.

Figs.6 and 7 report on the I_c curve vs. the applied strain at different values of B, measured on bare and SS jacketed strand, respectively. The temperature is fixed at 4.2K.

Comparing Figs. 6 and 7, the shift of ε_m, the axial strain at which the maximum of I_c is reached, is rather important. For the bare wire ε_m = 0.25% whereas this value is shifted to 0.57% for the jacketed wire. The maximum value of the critical current corresponds to the stress-free condition of the sample, which differs from the zero applied strain. In fact, due to the different thermal expansion coefficient between copper, tantalum and Nb_3Sn, a pre-compression of the superconductor occurs during the cooling process from the reaction temperature to 4.2 K. As a consequence, the stress- free condition is recovered after pulling the sample. The different value of ε_m for the two samples is due to the much higher thermal expansion coefficient and yield strength of stainless steel with respect to the bare Nb_3Sn conductor.

It's worth noting that the maximum values of I_c are almost identical for the bare and the jacketed wire, in the same operative conditions. This indicates that jacketing does not influence basic superconducting properties of the wire.

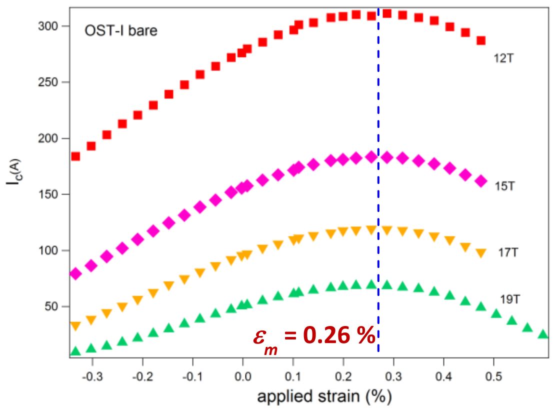

Fig. 6. Plot of $I_c(\varepsilon)$ at different values of B and T=4.2K measured on the OST-I bare strand.

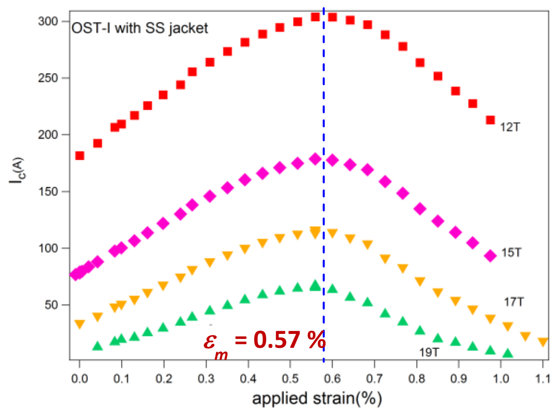

Fig. 7. Plot of $I_c(\varepsilon)$ at different values of B and T=4.2K measured on the OST-I SS jacketed strand.

However, due to the thermal pre-compression of 0.57%, the critical current is considerably decreased at zero applied strain. For instance, at 12 T I_c = 184 A for the jacketed wire instead of 278 A for the bare one.

It is interesting to note that the irreversibility limit, ε_{irr}, increases from about 0.50% applied strain for the bare wire (Fig. 6) to > 1.1% for the jacketed wire (Fig. 7). A possible explanation of this phenomenon might be the reduced number of voids in the jacketed wire, which helps in preventing the breakage of the strand.

VI. CONCLUSIONS

The four-probe technique is a very powerful tool for measuring the critical current of superconducting materials. For large scale applications, the assessment of the superconducting properties at low temperatures and high magnetic fields is mandatory, as shown for NbTi strands. For Nb_3Sn strands, the additional effect of the strain has to be considered in order to evaluate the performances. In particular, the measurements carried out with the Walters Spring probe on bare and jacketed strands show the relevant role of the pre-compression on the transport properties of the wire. This result is very useful for the design of Cable in Conduit Conductors, where the superconducting strands are inserted and compacted into a SS tube.

REFERENCES

[1] A.Pizzuto, L.Semeraro, L.Zani, P.Bayetti, A.Cucchiaro, P.Decool, A.dellaCorte, A.DiZenobio, N.Dolgetta, J.L.Duchateau, W.H.Fietz, R.Heller, P.Hertout, M.Kikuchi, K.Kizu, B.Lacroix, L.Muzzi, S.Nicollet, G.M.Polli, C.PortafaixL.Reccia, S.Turtu, J.M.Verger, R.Villari, K.Yoshida, "JT-60SA Toroidal Field Magnet System", IEEE TAS vol.18, 2008, pp. 505–508.

[2] Iter Final Design Report, IAEA Vienna and ITER IT Team Design Description Document 1.1 update, January, 2004

[3] L.Rossi, "Superconducting Magnets for Accelerators and Detectors", Cryogenics, vol.43, No.3-5, 2003, pp.281-301.

[4] G. Mondonico, B. Seeber, C.Senatore, R.Flukiger, V.Corato, G.De Marzi, and L.Muzzi, "Improvement of electromechanical properties of an ITER internal tin Nb3Sn wire", Journ. of Appl. Phys., vol. 108, 2010, pp. 0939061-8.

[5] L.Affinito, S.Chiarelli, V.Corato, A.della Corte, G.De Marzi, A.Di Zenobio, C.Fiamozzi Zignani, G. Messina, L.Muzzi, M.Napolitano, and S.Turtù, "Variable-Temperature characterization of NbTi strands in the low critical-current density range", J. Phys.: Conf. Ser., vol. 97, 2008, p.012306.

[6] B.L.Brandt, D.W. Liu, and L.G.Rubin, "Low temperature thermometry in high magnetic field", Rev. Sci. Intr. Vol. 70, 1999, p. 104.

[7] L. Zani, P. Barabaschi, P. Bruzzone, H. Cloez, E. Di Pietro, C. Fiamozzi-Zignani, G. Gros, B. Stepanov, V. Tomarchio, and A. Torre, "Experimental and Analytical Approaches on JT—60SA TF Strand and TF Conductor Quality Control During Qualification and Production Manufacture Stages", IEEE TAS, Vol. 23, No. 3, June 2013.

[8] A. Godeke, M. Dhalle, A. Morelli, L. Stobbelaar, H. van Weeren, H. J. N. van Eck, W. Abbas, A. Nijhuis, A. den Ouden, and B. ten Haken, "A device to investigate the axial strain dependence of the critical

current density in superconductors", Rev. Sci. Instrum. Vol.75, 2004, p.5112.
[9] J.N. van Eck, D. C. van der Laan, M Dhalle, B ten Haken and H H J ten Kate, "Critical current versus strain research at the University of Twente", SUST, Vol. 16, July 2003, pp. 1026-1030.
[10] J.W. Ekin, "Strain scaling law for flux pinning in practical Superconductors", Cryogenics, vol. 20, 1980, pp. 611-624.
[11] C.R.Walters, I.M.Davidson, and G.E.Tuck, "Long Sample High Sensitivity Critical Current Measurements Under Strain", Cryogenics, vol. 26, 1986, pp. 406-412.
[12] B. Seeber, D. Uglietti, V. Abacherli, P. A. Bovier, D. Eckert, G. Kubler, P. Lezza, A. Pollini, and R. Flukiger, "Critical current versus strain measurement up to 21 T and 1000 A of long length superconducting wires and tapes", Rev. Sci. Instrum. Vol.76, 2005, p.093901.
[13] J. A. Parrell, M. B. Field, Y. Zhang and S. Hong, "Advances in Nb3Sn strand for fusion and particle accelerator applications" IEEE TAS, vol. 15, 2005, p.120