The Critical Current of Nb₃Sn Wires for ITER as a Function of the Axial Tension and Compression

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Abstract — The influence of compressive and tensile axial strains on the critical current of various Nb₃Sn conductors is investigated. The investigated multifilamentary wires are especially developed for the ITER project. The critical current is determined as a function of an axial tension in a standard pull set-up. These results are compared with the results that are obtained on a bending spring-type strain device. In this second device an axial compression larger than the integral thermal shrinkage of the matrix, can be achieved. A study of the field dependence of the critical current yields the strain dependence of the extrapolated upper-critical field versus the axial strain. A good correlation is found between the two different strain devices in the tensile strain regime. There is a difference in the (limited) compressive strain regime where such a comparison can be made.

I. INTRODUCTION

The Nb₃Sn filaments, in wires in a Cable In Conduit Conductor (CICC), are subjected to a large thermal contraction. An important application, based on Nb₃Sn CICC's, is the magnet system for the ITER fusion reactor. In a previous study on sub-sized NET/ITER conductors high pre-strain values around -0.7% strain are determined for a stainless steel conduit [1]. At a magnetic field of 12.5 tesla this leads to a critical current (I_c) that is reduced to about 50% of its maximum value. This reduction in the I_c , could be a serious limitation for the performance of the entire magnet system and precise knowledge about the reduction is required.

The critical properties of Nb₃Sn, and other A15 superconductors are monitored in various conductor geometries. This has lead to the formulation of the so-called strain scaling law that describes the critical properties of axially deformed A15 superconductors [2]. This scaling law is based on axial elongation experiments in high magnetic fields and at low temperatures. The compressive strain range, that is accessible in such an axial pull experiment, is restricted by the thermal contraction of the matrix materials.

The low matrix to superconductor ratio of the wires for ITER, restricts the thermal pre-strain, in the Nb₃Sn filaments, to a low value in the range from -0.2% to -0.1%. This is small compared to the strain that occurs in the final CICC system. The I_c in the compressive strain regime, is investigated in two different set-ups. In the first option the thermal compression is enlarged by soldering a stainless steel casing to the conductor. In the second option a bending spring type strain experiment is used.

A comparison between the different strain set-ups is presented in the following section. After that, the experimental results on four ITER related Nb₃Sn wires are considered. First the axial strain results are compared at a constant magnetic field. Then the compressive strain regime is considered in more detail. Finally the (extrapolated) upper-critical field is considered.

II. AXIAL PULL VERSUS BENDING SPRING

Two different axial strain set-ups are applied (figure 1). The first set-up is a tensile test bench that is combined with a helium cryostat and a 13 T split-pair magnet at Karlsruhe. After the wire is cooled down to 4.2 K it remains in a force-free condition. The initial thermal strain in the Nb₃Sn filaments is determined by the force balance between the filaments and the matrix materials. During the elongation both the axial force and the elongation of the sample are measured. The Lorentz forces during the $I_c(B)$ determination have to be counteracted in the transverse direction. A more detailed description of a comparable axial-pull set-up is presented in a previous paper [3].

Fig. 1: A schematic view on the two different axial strain experiments: "axial pull" and the U-shaped "bending spring".

The axial strain in the second strain set-up is obtained by bending a thick substrate with a superconducting wire on top of it. Because of this bending there exists a small strain gradient along the cross-section of the wire. A second important fact is that the thermal strain in the Nb₃Sn filaments is also determined by the thermal contraction of the (brass) sub-

strate. The strain in the sample is measured by a set of strain-gauges connected to the substrate. The force that acts on the sample cannot be measured in this set-up. The bending spring is inserted in a 16 T solenoid magnet at the University of Twente [4].

The properties of the two types of strain set-ups are summarised in table 1. An important difference is the strain state after cooling down the sample. In a standard axial pull set-up the pre-strain on the filaments is determined by the wire composition. In the bending spring type experiment there is an additional strain due to the thermal contraction of the substrate. The most important feature of the bending spring type experiment is that large compressive strains can be achieved in the filaments. An important advantages of the axial pull experiment is that the force on the sample is measured in combination with the strain.

TABLE 1:
TYPICAL PROPERTIES OF BOTH THE AXIAL STRAIN EXPERIMENTS

Considered property	Axial pull exp.	Bending spring
Upper strain limit	>2%	1%
Lower strain limit	0	-1%
Strain gradient	0	$\pm 7\%$
Mechanical balance	Wire	Wire + Substrate
Thermal pre-strain (Nb ₃ Sn)	-0.3 to -0.1%	-0.6 to -0.4%
Axial force measurement	Yes	No
Total sample length	120 mm	50 mm
Electrical length (V-taps)	20 mm	5 to 15 mm
Magnet system	Split-pair	Solenoid

III. EXPERIMENTAL RESULTS

The experimental result are obtained from four different wires, all developed in the framework of the ITER program. The different conductors are labelled according to their origin (EU=Europe, JA=Japan, RF=Russian Federation and US=United States). The US conductor is produced with the internal Sn process, all the others are Bronze route conductors. The wire compositions are summarised in table 2. The wires are heat-treated in a separate batches for each conductor type.

Multiple samples of each conductor are investigated in the axial pull set-up (subscript 1 to 8). From each conductor one sample with a stainless steel casing is investigated in the axial pull set-up (subscript SS). The thermal compression in these wires is enlarged typically with 0.15% at 4.2 K. Finally one sample from each source is investigated in a bending spring type experiment (subscript B).

TABLE 2:
PARAMETERS OF THE INVESTIGATED Nb₃Sn WIRES

Code/Origin	EU	JA	RF	US
Manufacturer	VAC	Furukawa	Bochvar	TWCA
Technique	Bronze	Bronze	Bronze	Int. Sn
Diameter [mm]	0.73	0.92	0.83	0.73
Cu / non-Cu	1.50	1.58	1.22	1.22
Twist pitch [mm]	9	20	7	9.5
Ternary addition	Ta	n.a.	-	Ti

A. The critical current as a function of the axial strain

The critical current in the axial pull set-up is determined at a constant magnetic field of 12.1 T. The critical current on the bending spring is determined at various magnetic fields in the field range from 10 to 16 T. The I_c value at 12.1 T is obtained by interpolation of the $I_c(B)$ data. The resulting $I_c(\epsilon)$ curves are normalised at 1. This defines also the zero value for the "intrinsic" strain. There occurs a good correspondence between the results that are obtained in the two strain set-ups. A set of EU and US samples in the tensile strain regime are selected in figure 2 as typical examples. In the RF wires the spread in $I_c(\epsilon)$ is slightly smaller and in the JA and the other EU and US conductors it is comparable with the samples as depicted in figure 2.

Fig. 2: The normalised $I_c(\epsilon)$ at 12.1 T and 4.2 K. The data obtained on the bending spring are connected with lines, as a guide for the eye.

In all these 4 conductors the reduction of $I_c(\epsilon)$, as determined on the bending spring, corresponds with the largest I_c reductions that are measured in the axial pull set-up. This difference is small compared to the accuracy of the strain determination. For instance the strain gradient that occurs across the cross-section of the bend wire is approximately $\pm 7\%$ of the applied strain. Thus near the maximum, where

the strain applied on the wire is 0.5%, this gives a deviation of $\pm 0.04\%$ at the outer most positions.

B. The critical current in the compressive strain regime

The compressive strain regime is investigated in both the strain set-ups. A fit of the data from the axial pull set-up, with the scaling-law according to Ekin [1], is compared with the measurements on the bending spring. Because of the larger available strain range the measurements with the stainless steel casing are considered in this comparison. The strain dependence of these wires, in combination with the measurements on the bending spring, is presented in figure 3. The vertical axis in this graph is shifted in steps of 0.2 for each conductor, in order to improve the visibility.

The experimental data obtained with the axial pull set-up are fitted with Ekin's scaling law:

$$i_c = \frac{(1 - a|\epsilon|^u)^{v-p}}{(1 - B/B_{c2,max})} \left(1 - \frac{B}{B_{c2,max}(1 - a|\epsilon|^u)} \right)^q, \quad (1)$$

with constant values for the exponents (p, q, u, v). The resulting values are summarised in table 3. The values for the parameters a_1 and a_2 are relatively high compared to the values determined on other Nb₃Sn conductors. This fit is compared with the measurements on the compressed bending spring in figure 3. For small compressive strains, between -0.5% and 0.2%, the measured data represent lower I_c values than the fit. This difference is already present between the measured data of both the set-ups in the compressive regime. For extremely strong compression, typically below -0.7% strain, the measured I_c is larger than the data fit.

TABLE 3:
SCALING PARAMETERS FOR THE WIRES INVESTIGATED
COMBINED WITH: $p = 0.5, q = 2, u = 1.7, v = 1$.

Code/Origin	EU	JA	RF	US
$a_1 (\epsilon < 0)$	800	1100	870	1200
$a_2 (\epsilon > 0)$	1600	1600	1350	3000
$B_{c2,max}$	24.5	24.5	21	25

The shape of the measured $I_c(\epsilon)$ relation, on the bending spring in compression, is different from the extrapolated data of axially pulled conductors. The line crosses the measured data near -0.7% strain at approximately 40% of the maximum current value. A possible way to improve the quality of the data fit over the entire strain range is to consider the magnetic field dependence of the critical current of a strained conductor.

Fig. 3: The normalised $I_c(\epsilon)$ at 12.1 T and 4.2 K. The lines represent a fit based on the axial pull data. The dark markers represent the data obtained on the bending spring.

C. The upper-critical field as a function of the axial strain

The field dependence of the critical current in the deformed wire is only determined in combination with the bending spring. The field dependence is described by the Kramer pinning relation with $p = 0.5$ and $q = 2$. Then the upper-critical field is determined by extrapolating the so-called "Kramer current" ($I_c^{0.5} B^{0.25}$). An example of such an extrapolation, on a strained EU conductor, is presented in figure 5. The measured data follow the expected linear dependence very well. The largest deviation occurs for the lowest critical current value, at -0.89% and 16 T. This type of non-linearity can be explained by a non-uniform B_{c2} inside the wire.

Fig. 4: A Kramer plot of the critical current versus field of an axially compressed conductor.

The upper-critical field value that is determined by the Kramer extrapolation (B_{c2*}) is presented for all four conductor types in figure 5. This axial strain dependence, measured on the bending spring, is compared with the $B_{c2}(\epsilon)$ relation that is implemented in the scaling relation for the $I_c(\epsilon)$ data of the axial pull set-up at 12.1 tesla. The dotted lines, that represent this scaled upper-critical field for the US and the RF, deviate from the measured points. The maximum B_{c2} in the EU and the JA conductor is much higher than the value obtained by fitting the axial strain measurements. This leads to an even larger deviation from the measured data for these conductors.

Fig. 5: The extrapolated upper-critical field as a function of the intrinsic axial strain in four different wires.

An alternative method to describe the extrapolated upper-critical field values in Nb_3Sn conductors is presented in a previous paper [4]. This modified scaling formula is based on a linear reduction of the B_{c2} that is proportional with the second strain invariant defined as the "deviatoric" strain: $\sqrt{((\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2)}$. The indices in this term denote the three principal strain directions. This relation is deduced from various strain experiments on Nb_3Sn tapes and wires, all based on the bending spring method. The maximum in the B_{c2*} occurs in this description, occurs at the axial strain where the deviatoric strain is minimum.

The B_{c2} of a composite conductor, that is deformed in the axial direction, is in the elastic case described by :

$$B_{c2} = B_0 - C_a \sqrt{\epsilon^2 + C_0^2} \quad (2)$$

In this model the parameters B_0 , C_a and C_0 , are fitted with the data. The continuous lines in figure 5 represent the fit according to this model. A good correlation is achieved, especially in the compressive strain regime from -0.6% to 0% strain, where the matrix deformation is elastic.

The measured dependence of the B_{c2} in the compressive strain regime clearly deviates from the B_{c2} dependence that is obtained by scaling the I_c data at 12 T. For compressive

strains the reduction of the B_{c2} is less than predicted by the power formula in the scaling law. The observed dependence is in better agreement with the deviatoric strain model, that predicts a linear $B_{c2}(\epsilon)$ dependence for large compressive strains.

V. CONCLUSIONS

The Nb_3Sn filaments in the ITER magnets will be subjected to a certain compression, due to the thermal contraction of the jacket and the additional construction materials that surround the superconducting strands. It is valuable to determine the critical properties of the conductors in the ITER relevant strain range. The experimental results on four different conductors, presented in this paper, lead to the following conclusions:

1 - In the tensile strain regime up to 0.3% strain, the $I_c(\epsilon)$ measurements on the axial pull set-up are in good agreement with the results as determined on the bending spring.

2 - The $I_c(\epsilon)$ of a pre-compressed wire in the axial strain set-up is slightly higher than the I_c that is determined on a wire that is compressed with the bending spring.

3 - The $I_c(\epsilon)$ of a strongly compressed wire, as measured on the bending spring, deviates from the power-law description of Ekin.

4 - Although the $I_c(\epsilon)$ measurements on compressed wires deviate slightly in both the different strain set-ups, there is a reasonable agreement between the measured and the extrapolated values around -0.7% strain. Both methods determine an I_c reduction to typically 40% of the maximum value.

5 - The B_{c2*} of wires deformed by the bending spring deviates from the existing power-law dependence in Ekin's scaling law. Especially for compressive strains there is a better correlation with the more fundamental deviatoric strain description.

6 - The differences that occur between the two strain experiments in the compressive regime and the discussion about the best method to describe the B_{c2} in this strain range, indicate that it is difficult to accurately predict the I_c of a conductor that is axially compressed.

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