THE EFFECT OF TRANSVERSE LOADS UP TO 300 MPa ON THE CRITICAL CURRENTS OF Nb_3Sn CABLES.

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Abstract

In the framework of the development of an experimental 10 T Nb_3Sn dipole coil for the LHC at CERN the effects of transverse stress on Rutherford type of Nb_3Sn cables have been investigated. For this purpose a special facility was designed and taken into operation in which the voltage-current behaviour of short pieces of Nb_3Sn cables can be investigated in a background field up to 11 T and an applied stress of 300 MPa. The repulsive Lorentz force of 250 kN, generated by a set of superconducting coils, is used to impress the cable over an area of 20×42 mm^2 maximum, in presence of a transport current up to 40 kA. In this paper the testing equipment is described and the first results of the observed critical current degradation of two Nb_3Sn cables are discussed. It was found, that current reduction starts immediately upon loading and that already at transverse compressive stress of 100 MPa the critical current at 11 T is reduced by more than 20 % for one cable and even about 60 % for the other one. Furthermore, it seems, that the edges of the Rutherford type of cable are much more sensitive to the applied force than the cross-over points of the strands.

Introduction

Previous investigations on multifilamentary Nb_3Sn wires have shown that this type of wire is very sensitive to stress and strain. Large current degradation effects were measured, in particular for wires under transverse compression.[1-8] The results mentioned in each of the publications do not give a clear pattern (yet) in the current-degradation effects of transverse compressive stress. However, it is certain that the effects are larger than in case of axial stress. At 100 MPa transverse stress and applied fields above 8 T the wires show at least a 10 % critical current reduction and in most cases even more. For cables larger current reductions can be expected due to their inhomogeneous composition which leads to local stress concentrations. Although measurements on the current reduction of a single strand in a compressed cable have been reported,[9] systematic investigations of the stress sensitivity of Nb_3Sn cables with full transport currents have not yet been made.

The 10 T model dipole coil for LHC in CERN is designed with a keystoned Rutherford type of Nb_3Sn cable.[10] The cables are closely packed into windings without using a casing to transfer the mechanical forces. Analysis of the stress patterns in this coil leads to the conclusion that the central windings experience transverse compressive stresses in the order of 100 to 200 MPa.[10] In the strands of the cable stress concentrations can be expected at the cross-over points, but also at the edge of the flat cables, where the strands are bent and change from the upper to the lower side of the cable. In order to investigate the behaviour of this type of cable under realistic operating conditions, a special arrangement has been developed.

Experimental arrangement

Figure 1 gives a schematic view of this experimental arrangement, in which the voltage-current characteristics of cables can be measured as a function of applied magnetic field and transverse compressive stress. After the samples with a length of approximately 60 cm have been reacted in a U-shaped form, they are inserted in a 11 T magnet. Because the bore of the dipole magnet is only 80 mm and the cables need a bending radius of about 10 mm, the sample section that is perpendicular to the applied field is limited to about 55 mm. On top of the magnet which provides the background field a transformer is placed which is used to generate the transport current in the sample. While the voltage-current characteristics are being measured, a compressive force is exerted onto the sample. This force is generated by the repulsive Lorentz force of a superconducting coil system that is mounted under the magnet. The size and shape of the compressed area of the cable can be chosen by means of a replaceable pressure block. Two displacement meters provide information on the distance between the two repelling coils (Δz_c) and of the compression of the sample together with the pressure block (Δz_s). The transformer circuit supplying the sample current and the force generating equipment will now be discussed in some more detail.

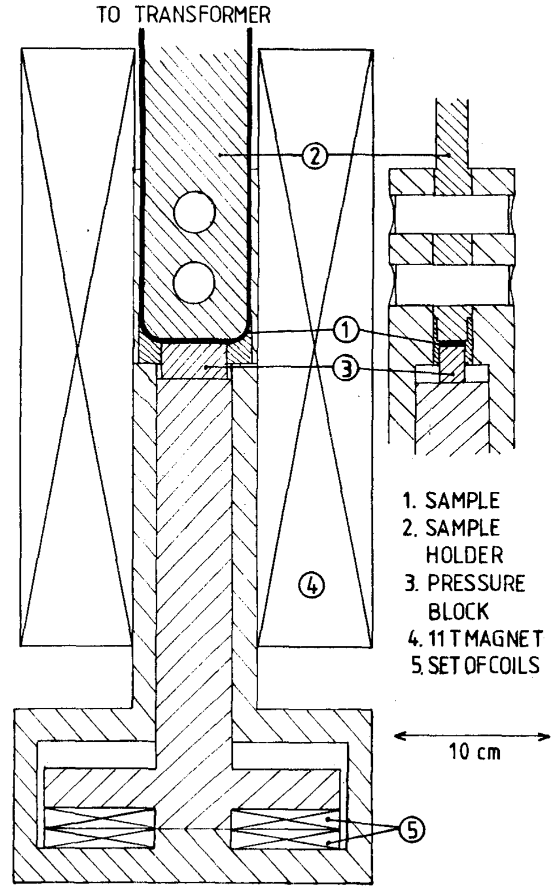

Fig. 1. Schematic view of press-arrangement.

Current supply and voltage measurement.

The transport current is induced in the sample by means of a transformer. Important advantages of such a type of current supply over a conventional power supply are low lead losses, hardly any ripple and relatively low costs.[11] The primary part of the transformer consists of a coil with 3600 turns, while the secondary is formed by two turns of a NbTi-cable (50 kA at 5 T) which is soldered to the sample over a length of approximately 20 cm with AgSn solder. During the experiments the resistances of these connections were measured and in all cases they were smaller than 0.4 nΩ. This configuration gives a current amplification of approximately 500 times. A primary current of only 40 A is sufficient to induce and maintain a constant

Manuscript received September 24, 1990.

0018-9464/91/0300-1831$01.00 © 1991 IEEE

current of 20 kA in the sample, if the resistance in the secondary circuit is sufficiently low. The secondary current is measured using a superconducting current meter especially developed for this type of circuits.[12] Its accuracy is better than 1 %. The signal of this current meter is compared with a desired value and fed back to the primary power supply.[13] In such a way, the loss of the secondary current (caused by losses in the joints and by the resistive transition in the sample) can be compensated and a constant measuring current is obtained. It is possible to achieve a high sensitivity in the voltage measurements, because the back-ground noise and current ripple are very low in this configuration. Using a Keithley nano-voltmeter, the accuracy is better than approximately 30 nV.

Calculation of the compressive force.

The compressive force on the Nb_3Sn cables is for the major part delivered by two superconducting coils. For a precise calculation of the applied force the interaction of the 11 T magnet and the set of coils as well as the mass of the movable parts of the press-arrangement must be taken into account. In general, forces between two coils that are aligned coaxially can be given by:

$$F_L(z) = I_1 I_2 \frac{\partial M_{12}}{\partial z} , \qquad (1)$$

in which I_i is the current in the coils with inductance L_i and the indices 1 and 2 refer to each of the two coils. M_{12} is the mutual inductance between both coils and can also be written as: $M_{12} = k_{12} \sqrt{(L_1 L_2)}$, in which k_{12} is the coupling coefficient. This relation can be used to calculate both the repulsive force between the two pressing coils and the influence of the stray fields of the 11 T magnet.

Since both pressing coils and their currents are identical ($L_1=L_2=L$ and $I_1=I_2=I$), equation (1) reduces to:

$$F_L(z) = I^2 \frac{\partial M_{12}}{\partial z} = L I^2 \frac{\partial k_{12}}{\partial z} . \qquad (2)$$

This equation has important implications for the design of the set of coils. Generally, a maximum of $\partial k_{12}/\partial z$ is obtained if the distance Δz_c is very small. For this reason, a set of coils that repel each other is preferred over an attracting set. In the latter case, the structure that is necessary to support the windings has to be placed between the two coils. Moreover, equation (2) implies that the size of the coils in the z-direction should be limited, because the influence of a small variation in z is much more effective in such a case (i.e. leads to larger differences in the coupling coefficient). The optimum value of the term LI^2 is determined by the critical current of the superconducting wire in relation to the maximum field in the coil configuration. All these considerations have led to a design of which the characteristic data are given in table 1.

Table 1: Data of the coil system.

Conductor:	
Manufacturer:	Vacuumschmelze
Number of filaments:	54
Diameter of insulated wire:	0.33 mm
Cu/NbTi-ratio:	1.35
Single coils:	
Number of turns:	6360
Inductances L_1 and L_2:	3.858 H
Resin (wet wound):	Stycast 2850 FT/LV24
Inner diameter:	46.8 mm
Outer diameter:	181.0 mm
Height:	12.1 mm
Coil system and interaction field magnet:	
Nominal current in set of coils:	55 A
Nominal compressive force:	250 kN
Field factor magnet:	0.1246 T/A
$\partial M_{ij}/\partial z$ (H/m) between:	
two coils:	82.47-2.71 Δz_c
upper coil and field magnet:	2.277+0.023 Δz_c
lower coil and field magnet:	1.955
(Δz_c is distance in mm between two coils of the set)	

Further, to calculate the actual force present on the sample, also the forces between the coils and the 11 T magnet have to be considered. The upper coil of the system experiences an additional force due to the magnet with current I_m which can be written as: $\pm I_m I_1 \partial M_{m1}/\partial z$. The derivative of the mutual inductance M_{m1} between magnet and upper coil is determined at the distance between the middle of the magnet (where the sample is) and the midplane of the set of coils and M_{m1} is the mutual inductance between the magnet and the upper coil. The plus-sign is valid (i.e. the force is directed upward and adds to the force on the sample), if I_m and I_1 are in the same direction, which is the case during the measurements. Note, that the magnet current also interacts with the lower coil of the system. However, this force doesn't contribute to the force on the sample, because the magnet and lower coil cannot move with respect to each other. The stray-field of the transformer has a negligible effect on the forces.

Finally, the mass m of 11 kg of the movable parts of the press-arrangement has to be considered. Before the sample is compressed, these parts have to be lifted up. Hence, the force on the sample must be diminished with a term: mg. As a result, the total force exerted on the sample can be written as:

$$F_{sample} = I^2 \frac{\partial M_{12}}{\partial z} + I I_m \frac{\partial M_{m1}}{\partial z} - mg . \qquad (3)$$

The influence of the latter two terms are relatively small compared to the repulsive force of the set of coils. Because the distance between the coils Δz_c can be measured accurately, the force on the sample can be calculated with an accuracy of 2 %.

Investigated cables and sample preparation

Two Rutherford type of flat cables have been investigated. Table 2 gives their characteristic data. Both cables have been produced according to the "powder method", a development of the Netherlands Energy Research Foundation ECN.[14] Characteristic properties of these conductors are the pure copper matrix and the relatively thick filaments. Due to problems with the furnace during the heat treatment of the first sample, its total reaction time was insufficient to obtain optimal critical current densities. However, it is not expected that this affected the relative current reduction due to compression to a large extent. Before the experiments both cables were impregnated with an epoxy resin (Stycast 2850 FT). For sample 1 only the outside was covered with resin, while the central part was not filled. Sample 2, however, was impregnated completely.

Table 2: Characteristics of investigated cables

	sample 1	sample 2
Type:	ECN LHC-B	ECN-SULTAN
Model:	Keystoned Rutherford	Rectangular Rutherford
Dimensions:	(1.53/1.85)×16.6 mm^2	1.82×18.2 mm^2
Compressed region:	16.6×41.0 mm^2	18.2×40.0 mm^2
Number of strands:	36	36
Number of filaments per strand:	192	192
Diameter strand:	0.9 mm	1.0 mm
Ratio Cu/non-Cu:	1.35	1.22
Twist pitch cable:	120 mm	160 mm
Expected I_c at 11 T:	16.5 kA	19.6 kA

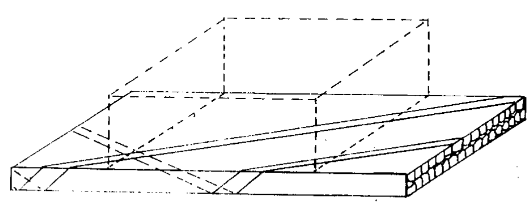

Fig. 2. Schematic view of compressed area of samples, showing two types of strands.

For each sample a different pressure block was used. For sample 2 the block was rectangular, but for the first sample it had a small slope to account for the shape of the keystoned cable. However, in both cases the pressure blocks had rounded edges to avoid stress concentrations where the sample enters and leaves the compressed section. Figure 2 shows that the length of the pressure block may be an important factor for the observed current reductions. In fact, two different types of strands can be distinguished, because the compressed lengths of the cables are smaller than their twist pitches. The first one is straight over the entire length of the compressed region and remains in the upper or lower layer of the cable. The second type, however, is bent under the pressure block and changes from upper to lower layer. Both strands experience the compression of the cross-over points with strands in the other layer, but in contrast to the straight strand, the second type of strand is also subject to a completely different stress pattern at the edge of the cable. The influence of the length of the pressure block will be especially important if the edge-effects are the dominant source of current reduction. Note, that additional stresses caused by Lorentz forces due to field and transport current cannot be avoided. For sample 2 this Lorentz force could be in the order of some 220 kN/m. Movement of the cable is prevented by appropriate bonding.

The position of the voltage taps on a multistrand cable can be of major importance for the shape of the voltage-current curves. If they are soldered to one strand, the voltage measurements are very precise, but the exact current through the strand is uncertain. Moreover, the strand may not be a good representative for the behaviour of the entire cable, due to differences in stress patterns. On the other hand, if a tap is soldered to more strands, the solder will generally not form an equipotential surface perpendicular to the cable. The interpretation of measured voltages on (strands of) cables and their relevance for practical applications is a field of further investigation.

Measured critical current reductions

Figure 3 shows the critical current of sample 1 at 11 T as function of applied stress. Voltages were recorded from taps that had been soldered over the entire width of the cable and increased very gradually with transport current. As a consequence, the critical current is very strongly dependent on the applied I_c-criterion, which results in figure 3 in differences up to 20 %. However, the current reduction can be quite adequately described if it is scaled with the original critical current at zero load. Furthermore, figure 3 shows that a very large current degradation is obtained immediately upon loading. Beyond about 100 MPa, however, the decrease of I_c gets slower. Complete recovery of the original current after unloading of the sample is found up to 35 MPa. After a stress of 50 MPa, however, an irreversible degradation takes place. The $I_c(P)$ behaviour is similar for all investigated fields (8-11 T) and no strong field dependence can be discovered for sample 1 (see figure 4). For sample 2 the current reduction at 11 T is also considerable, although it is significantly lower than for sample 1. The irreversible current reduction begins for sample 2 after 40 MPa and at higher loads the rate of current reduction diminishes.

Comparison with other results on Nb_3Sn conductors

Figure 5 shows a survey of critical-current reductions measured on multifilamentary Nb_3Sn wires and cables under transverse compressive stress. The above-mentioned current reductions are compared with results that were reported in a number of publications and were obtained on round wires (EKI87[2], BOS89[6]), on rectangular wires (SPE87[4], SPE88[5]) and on a strand in a cable (JAK89[3]). Large differences can be seen in the $I_c(P)$ behaviour. For example, at 100 MPa transverse stress current degradation effects ranging from 10 to 60 % were measured. Furthermore, the initial slopes of the curves at zero load are very different. It is expected that many parameters such as magnetic field, geometry of conductor, test apparatus and fabrication method of the Nb_3Sn are responsible for the observed

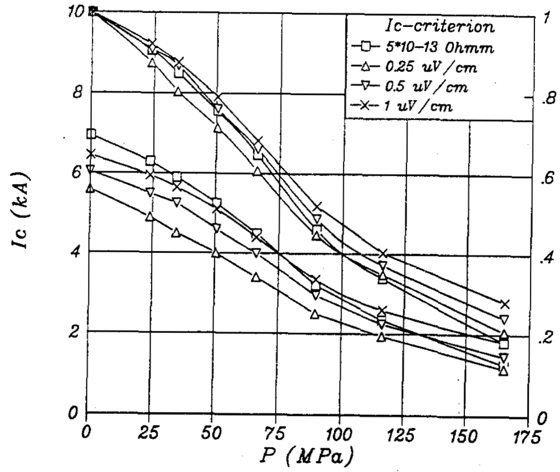

Fig. 3. Actual (lower curves, left axis) and scaled (upper curves, right axis) values of I_c of sample 1 as function of compressive stress at 11 T, determined with different I_c-criteria.

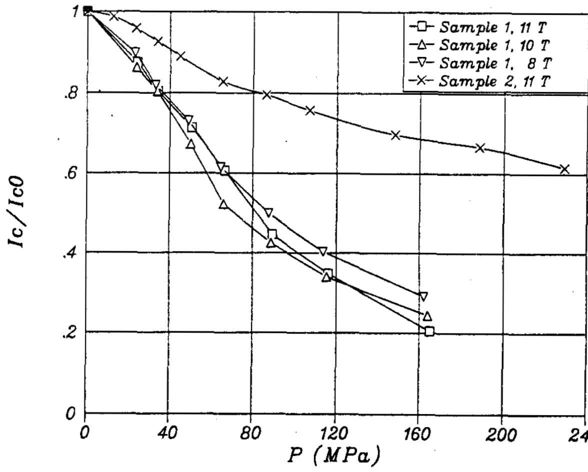

Fig. 4 Scaled I_c-reduction of sample 1 and 2 as function of applied stress. I_{c0}-values: 5.6, 7.7 and 10.8 kA (sample 1 at 11, 10 and 8 T) and 18.4 kA (sample 2 at 11 T).

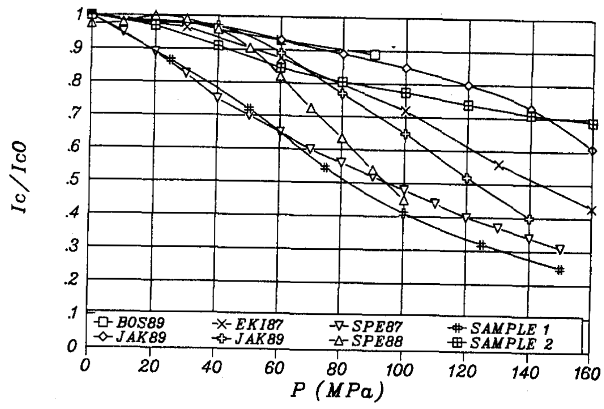

Fig. 5. Current degradation effects of the two cables due to transverse stress compared with results of other conductors collected from several publications.

differences in stress sensitivity. However, the importance of each of these parameters is not completely clear. In case of the two cables, the sample preparation and test arrangement are very important factors, as will be argued next.

Discussion

As a possible explanation for the differences in current degradation between both cables, two causes can be mentioned. First, because sample 1 was not filled with resin between the strands (as was sample 2), it is expected that the stress concentrations at the cross-over points are more severe and consequently the current degradation is larger. Second, the twist lengths for both cables are different. Therefore, about 70 % of the strands in sample 1 are bent under the pressure block, while this number is only approximately 50 % for sample 2. If the compression at the edges of the cable has more effect on the current degradation of a strand, then the shorter twist length of sample 1 can also account for the larger amount of current reduction.

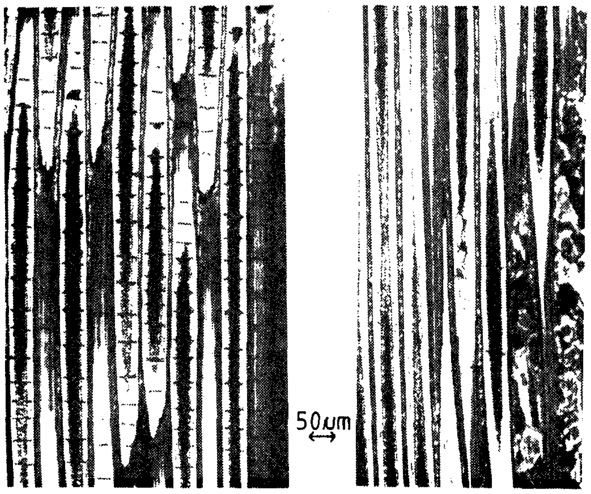

Fig. 6. Photographs of oblique sections of two strands of sample 2 after a load of 300 MPa. Left: strand at edge of cable, showing damaged filaments. Right: strand in the central part of the cable.

Photographs taken from oblique sections of several strands of sample 2 after it had been compressed with 300 MPa show a concentration of cracks in the filaments at the edge of the cable. Figure 6 shows two of these pictures. In the filaments a powder core (black) can be distinguished. This core is surrounded first by Nb_3Sn and then by Nb, which is in contact with the copper matrix. In the filaments of the straight strand hardly any fractures can be seen in the Nb_3Sn. However, in the filaments at the edge of the cable a large number of cracks can be distinguished at regular intervals. These cracks are perpendicular to the direction of the filaments, they occur only in the Nb_3Sn and stop at the Nb-Nb_3Sn interface. Hence, it can be concluded that the edges of the cable are the most stress-sensitive part of the cable.

With these conclusions the measured current reductions as function applied stress can be understood qualitatively. The first very sharp decrease of current is mainly caused by the strands that are bent under the pressure block. For sample 1 both the number of this type of strands and the initial current reduction are larger. Moreover, at large applied loads the strands at the edges are already very badly damaged and further current reduction of the cable is mainly caused by the cross-over points for the straight strands. Under large transverse loads the current reduction is less severe in sample 2 due to the complete impregnation which causes a reduction of the stress peaks.

Conclusion

The first experiments with the described press-arrangement lead to the conclusion that accurate voltage-current curves can be recorded on high-current cables at high fields and under large transverse stresses. Large current reductions were measured on two Rutherford type of cables. There is strong evidence that the length of the pressure block determines the observed current reductions to a large extent, due to the high stress sensitivity of the strands at the edges of the cables. Further investigations will be made on this issue and also on the interpretation and relevance of the measured voltages. At this moment it is uncertain which strand (and the U-I curve belonging to this strand) in a cable represents the true limiting effect of the entire cable in practical applications as in the windings of large dipole magnets.

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