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The Reduction of the Critical Current in Nb3Sn Cables under Transverse Forces.

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Abstract---The degradation of the critical current of impregnated Rutherford type of Nb_3Sn cables has been investigated as function of the transverse force applied to the cable surface. Voltage-current characteristics were measured between 9 and 11 tesla by which the cable is supplied with the full transport current while a section on the broad side of the cable with a length of 40 mm is under pressure. A few samples are investigated as a function of the transverse force strands in the cable. It appears that the degradation of the strands is not uniform, for example, at 200 MPa some strands show 10 % while others have 40 % critical current degradation also depending on the critical current criterion used. The global degradation of the cable is 12±2% at 200 MPa though it is possible that a single bad strand in a cable limits the cable to below this value due to premature quenching of that strand.

I. INTRODUCTION

The presence of large compressive forces in high-field magnets can drastically influence the current carrying capacity of the superconductor in the windings especially if Nb_3Sn is used. In the case of 10 to 13 tesla accelerator magnets, for example, the required current density in the windings is so extreme that no additional force retaining structures like a steel casing around the conductor is allowed for. This means that the transverse compressive stresses which are in the range 150 to 200 MPa have to be absorbed by the conductor itself.

As part of a development programme for a high field Nb_3Sn accelerator dipole magnet [1] we investigated the voltage-current characteristics of Rutherford type of Nb_3Sn cables and the wires of which they are made of. The measurements were performed in a new facility which was taken into operation to test pieces of Nb_3Sn cables in a background field of 11 T maximum and an applied stress of up to 300 MPa.

In this paper the experience obtained with Nb_3Sn cables is dealt with. Moreover, a discussion of the measuring method in general and this specific equipment and the validity of the results to predict the behaviour of the cable under coil operating conditions is presented.

II. Ic DEGRADATION IN WIRES, CABLES AND WINDINGS

The application of Nb_3Sn material in magnets puts severe demands on the mechanical properties of the construction. The Nb_3Sn is subjected to forces due to prestress, cooling and electro-magnetic loading. Since Nb_3Sn is a brittle material the current carrying capacity can be reduced considerably. However, in practical situations the Nb_3Sn crystals are loaded indirectly because they are surrounded by other materials like bronze, soft copper, solder, steel, insulation materials and resin impregnants. As a consequence the specific application of the material and the mechanical properties of the adjacent materials has a major impact on the actual current carrying capacity. More knowledge about the complex interactions can be obtained by experimental study of all the different types of conductors available, i.e. Nb_3Sn films and tapes, wires in different shapes and of different compositions, cables and windings.

The effects of axial strain and compression in wires have been investigated thoroughly and it can be predicted fairly well with scaling laws [2]. Transverse compression, however, leads to much more degradation and it is therefore that during the last years experiments are carried out by which bare round and rectangular Nb_3Sn conductors are compressed between parallel plates [3-5]. It was observed that transverse stress not only causes a reduction of the maximum current with about 10 % at 10 T and 100 MPa, but the large stress level also leads to drastic changes in the shape of the voltage-current curve [5].

However, the number of experiments with cables are very few and the interpretation is very questionable [6-8]. The main problem is that cables can have a very different shape and internal lay-out. Moreover, bare Nb_3Sn cables can, in general, not be investigated so a partly filling of solder or resin is present and eventually the cable are covered with insulation materials like glass/mica and resin. In the case of a bare or an unfilled cable one would expect degradation properties similar or even worse than that of the strand because of the stress concentrations at cross over points. On the other hand if the cable is internally impregnated or soldered and essentially covered with epoxy resin, then less degradation is expected due to the more uniform stress distribution around the strands in the cable.

In any case it is a complex problem and it is recommended to have more experimental results. For this purpose a special facility was taken into operation in which the voltage-current behaviour of cables supplied with the full operating current can be investigated. An analysis of the voltages simultaneously measured across several strands in the cable is made.

III. CABLE PRESS AND MEASURING ARRANGEMENT

A schematic view of the cable press is shown in Fig. 1. The sample with a length of about 0.7 m has a U shape to facilitate the insert in an 11 tesla magnet with a bore of 80 mm. The field is within 1 % uniform and perpendicular to the broad side of the cable across 55 mm. In this section a pressure is applied on the cable across the mid 40 mm. The compressive force is generated by a set of two repulsing superconducting coils (5) and transferred to the cable via a pressure block (3). The force can be adjusted by control of the current through the coils in the range 0 to 250 kN which corresponds to a compressive stress level of 0 to about 300 MPa.

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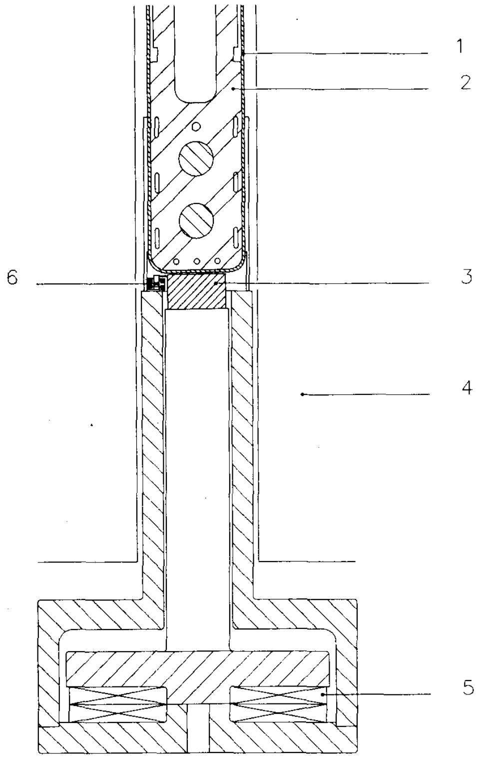

Fig. 1 Longitudinal section of the cryogenic cable press showing: (1) the U shaped sample, (2) the ss sample holder, (3) the pressure block, (4) the 11 tesla magnet providing the background field, (5) the set of coils to generate the force compressing the cable and (6) the displacement meter.

The sample current is generated by a superconducting transformer system [9,10] by which the secondary coil is connected to the sample with two low ohmic joints. The circuit operates in a feed back mode. This enables to keep the sample current perfectly constant which is necessary to measure the voltages of the cable with a nanoVolt sensitivity. The maximum current that can be made is about 50 kA and the measuring accuracy of the current is within 1 %. Because there is no relevant current ripple and the noise is low, it is possible to obtain an accuracy of about 50 nV when a Keithley 182 nV meter is applied in combination with a nanoVolt switching card and a scanner. In this way up to 9 channels are used to measure the voltage across several strands in a cable.

The impression of the cable is measured using an inductive method. It consists of a coupled concentric coil system by which the primary is connected to the pressure block and the secondary is connected to the sample holder. Both fixing points are as close as possible to both edges of the cable just to exclude the impression of the other parts. When the cable is pressed the coils move, the mutual inductance changes and the secondary voltage is a measure for the displacement. This displacement meter especially developed for this purpose has outer dimensions of 16x18 mm^2. The output voltage is measured with a phase sensitive amplifier and it shows a sensitivity of 35 V/m at 1 kHz and 10 mA operating current.

More information concerning this cryogenic method of force generation and current supply of samples in a cryostat as well as the details of the coil systems are given elsewhere [6].

IV. SAMPLE PREPARATION

The main properties of the conductor which is investigated are collected in Table 1. The Nb_3Sn cable is a conductor made according to the ECN powder process [11]. This type of Nb_3Sn will also be used for an experimental high field dipole accelerator magnet as reported elsewhere [1]. It is characterized by the 50-55 % pure copper matrix in combination with relatively thick filaments and an extremely high current density of about 2000 A/mm^2 at 10 T. The samples are bend on a stainless steel former, heat treated and impregnated with STYCAST 2850FT epoxy. A cross section of the cable is shown in Fig. 2.

Table 1. Basic properties of the investigated cable.

type:	ECN-powder method	
model:	rectangular Rutherford	
dimensions:	1.82x18.2	mm^2
compressed area:	18.2x40.0	mm^2
number of strands:	36	
filaments per strand:	192	
diameter strand:	1.000	mm
ratio Cu/non-Cu:	1.22	
cable pitch:	160.	mm
strand pitch:	20.	mm
expected Ic(11T):	19.6	kA

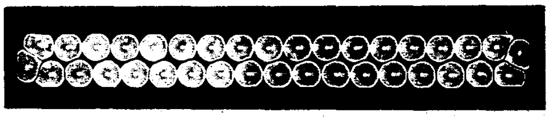

Fig. 2. Cross section of the cable investigated.

Two samples are made which are prepared exactly in the same way to test the reproducibility of the results. The major part of the voltage taps are soldered in pairs on individual strands. In this way it is possible to measure the differences between the strands in the same cable. Special types of strands were selected, see Fig. 3.

We can distinguish, first, strands which are positioned straight under the pressure block in the upper and lower layer of the cable, and second, strands that are bent under the pressure block. The second type of strands is subject to a different and non uniform loading at the edge of the cable by which an enhanced degradation may be expected. Furthermore one pair of taps are soldered on the cable far from the pressed

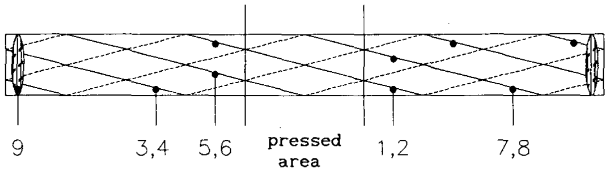

Fig. 3. Schematic view of the position of the strands under the pressure block of which the voltages are measured.

area by which the cable section at the tap position is filled with solder. It means that with this pair the global voltage of the cable is measured. Table 2. provides a survey of the type of voltage taps used.

Table 2. Numbering of the different pairs of taps.

taps	1,2 =	2 straight strands in upper layer
	3,4 =	2 straight strands in lower layer
	5,6 =	2 strands bent at right edge
	7,8 =	2 strands bent at left edge
	9 =	1 global contact on cable

The positioning of voltage taps on the strands could be good idea toextend the understanding of what happens in a cable. When the taps are on a single strand then the voltage of that strand is measured accurately but the current in that particular strand is not known. But, global taps on the cable perhaps provide a better average result though the soldered spots is not an equipotential plane in the cable section.

V. RESULTS

Fig. 4 shows the voltage current curves of 8 strands in the cable and the global voltage at 11 T for sample 2 at 0 MPa when no pressure is applied. Large differences between the strands are observed while the global contact 9 indeed represents approximately the average value. Note that the critical current is very dependent on the criterion used. At $2\text{x}10^{-14}\Omega\text{m}$ we find an Ic between 15 and 19 kA depending on the strands used while at a level of 0.5 μV/cm the Ic is in the range 19-20 kA. Apparently the differences between the strands are extreme at a low voltage. Both, strands with a sharp transition as well as strands having a low ohmic behaviour followed by a gradual transition are present. There is no clear correlation between the position of the strand in the cable and the value of the voltage it has. This conclusion remains valid also if a pressure is applied. For the greater part this sequence of voltages even remains if the stress is increased up to 200 MPa. The large spreading of the voltages of the strands is probably due to the U-shape of the sample by which only a short section of 40 mm is in a uniform transverse field. Other Ic measurements on long samples in a spiral coil geometry of this type of cable showed that this spreading was never so pronounced [10]. So, it is not allowed to interpret the spreading as a nonuniformity of the local stress on the strands.

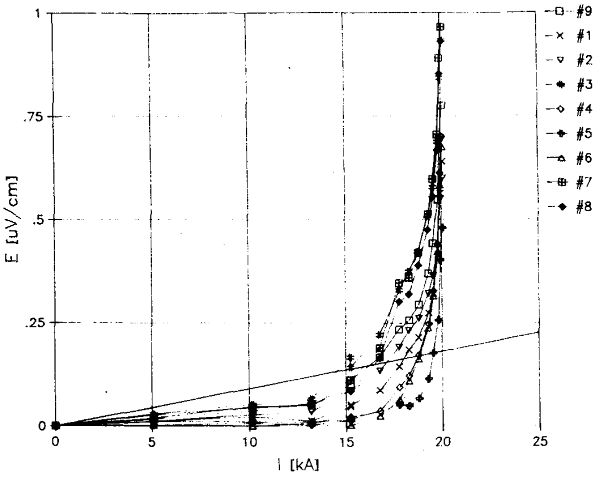

Fig. 4. Voltage-current curves of the cable, sample 2, at 11 tesla. The numbers are corresponding to those given in Table 2.

In Fig.5 the effect of a transverse stress of 200 MPa at 11 tesla is shown. The different curves of the strands found for 0 and 200 MPa are indicated. Note that the spreading remains the same. The effect of the applied field on the qualitative behaviour is marginal so the curves at 9 T look the same.

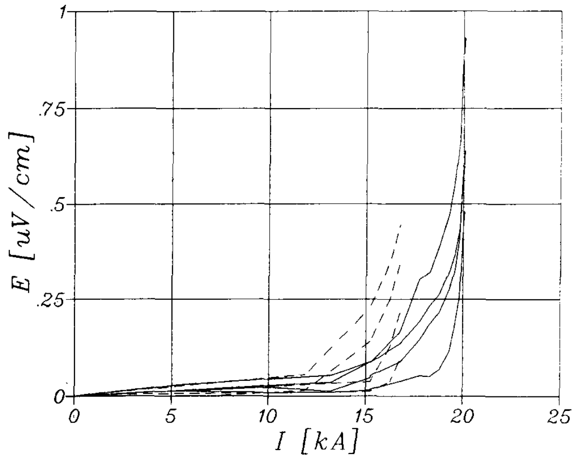

Fig. 5. Voltage-current curves at 11 T, 0 and 200 MPa.
The ——— curves are at a stress of 0 MPa,
the - - - - curves are at a stress of 200 MPa.

The influence of the increase of the stress from 0 to 200 MPa on a single voltage tap is illustrated in Fig. 6. Using a criterion of $5\text{x}10^{-14}\Omega\text{m}$ the critical current decreases from 19.6 to 17.1, which corresponds to a decrease of the critical current with 8 %.

When the applied field is changed from 11 to 9 tesla the qualitative behaviour of the voltage-current characteristics remains the same.

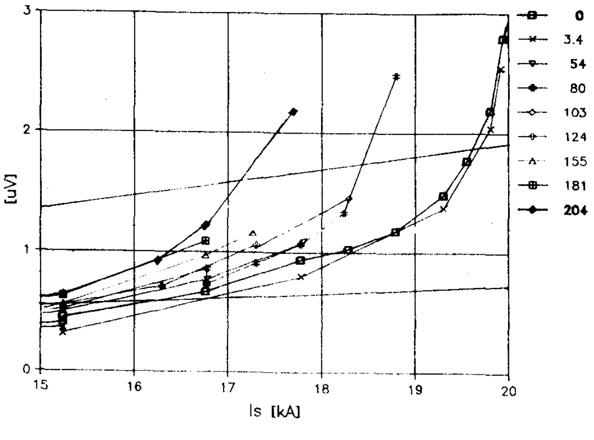

Fig. 6. Voltage across the cable measured with taps 9, as function of the current while the applied stress increases from 0 to 204 MPa. The two extra lines correspond to the criteria 2 and $5\text{x}10^{-14}\Omega\text{m}$.

The critical current reduction has been analyzed for all the voltage taps. In Fig. 7 the critical current reduction determined by the global taps 9 is shown as function of the applied stress for two Ic criteria, 0.2 μV/cm and $2x10^{-14}$ Ωm. Moreover a comparison is made with the worst strand in the first sample.

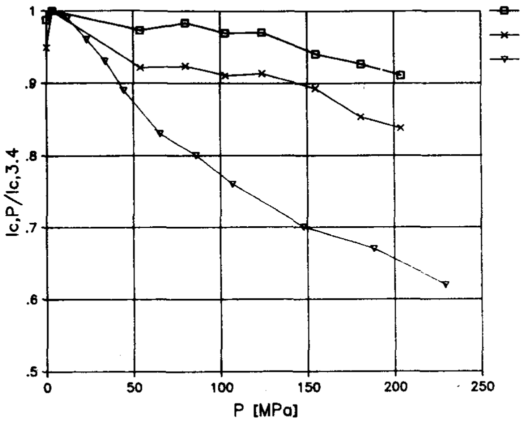

Fig. 7. Reduction of the critical current density as function of the applied stress for sample 2, global taps 9 and two Ic-criteria (□ = 0.2 μV/cm, x = 2.10^{-14} Ωm). Degradation of the worst strand in sample 1 (▽).

The critical current reduction increases with the applied stress and amounts to about 9 % when the criterion of 0.2 μV/cm is used and about 16 % in the case of the $2x10^{-14}$ Ωm criterion. This difference is caused by the spreading in the voltage curves if the voltage level is below about 0.1 μV/cm.

The degradation of about 3 % at 100 MPa and 10 % at 200 MPa is in good agreement with the results found by Jakob [8] by which the degradation is measured of a single strand in an impregnated Nb_3Sn cable.

In sample 2 we found a degradation of maximum 15 % applying the 0.2 μV/cm criterion for the worst strand. This is far less than what we found for the worst strand in sample 1. Here a degradation of 35 % was measured. The reason for this could not be found. Tests of more pieces of cables are underway in order to get more information regarding the reproducibility of this type of measurements.

The effective E-modulus of the impregnated cable is determined by the applied stress and the measured impression of the cable. An E-modulus of 12±2 GPa is found which is a reasonable value.

After a load of 200 MPa the critical current recovers to about 98 % of its initial value. This means that the degradation is almost reversible up to a level of 200 MPa. It means that no serious damage is caused in the case of impregnated cables.

VII. CONCLUSIONS

Accurate voltage-current curves can be measured on strands in a cable when a transverse stress is applied and the cable is in a background field of 9 to 11 tesla. However accurate measurements of the voltages of individual strands does not imply that everything is known. The current in a strand can not be measured and, moreover, the strands are electrically connected so current transfer between the strands is possible. A further complication is the short length across which the field is transverse and uniform and across which the pressure is applied. Entrance effects due to field and force gradients can have a large influence on the local voltage in a strand. Therefore one has to be careful with the interpretation of the U-I curves found especially at low values of the voltage.

Two impregnated Nb_3Sn cable samples were investigated. The first sample has a "bad" strand limiting the performance of the whole cable. An Ic degradation of 35 % at 200 MPa was found in that strand. However, the Ic degradation in sample 1 is between 8 and 15 % depending on the criteria used for Ic. The global voltage taps connected to a soldered spot covering the entire cable section provides average results in comparison to the taps connected to individual strands. Using this as a measure an overall degradation of 12±2 % is found for an impregnated Nb_3Sn cable at 11 tesla and a transverse stress of 200 MPa. The degradation is almost reversible. After unloading 98 % of the critical current is still present.

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