CRITICAL CURRENT DEGRADATION IN Nb3Sn CABLES UNDER TRANSVERSE PRESSURE

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Abstract--The critical current degradation of a few Rutherford type of Nb_3Sn cables are investigated as function of transverse pressure. Moreover a comparison is made between Nb_3Sn strands produced according to the Powder-in-Tube, the Bronze and the Modified Jelly Roll process. The (keystoned) Rutherford cables are charged at 11 T with transverse pressures up to 250 MPa. Large differences in critical current reduction are observed, ranging from 6 to about 60% at 200 MPa depending on the type of Nb_3Sn. It appears that the irreversible part is about 40% of the total reduction. Moreover, the "irreversible" part shows relaxation and a partial recovery is possible by thermal cycling.

I. INTRODUCTION.

The generation of magnetic fields beyond 10 tesla requires the application of Nb_3Sn cables which material in general is characterized as very sensitive to mechanical deformations. Therefore, in the framework of the development of an experimental 11.5 T LHC type of dipole magnet ([1]), a study of the transverse stress effects on Nb_3Sn was started since in these magnets stress levels up to 150 MPa can be expected. Further on a collaboration with LBL was set up in connection to the LBL development project for their 13 T magnet D20.

The program is carried out along three routes:
* study of the basic stress tensor by investigating a simple 2 dimensional Nb_3Sn layer or tapes ([2]),
* experiments on strand materials ([3]), and
* the investigation of complex cables ([4,5]), which will be dealt with in this paper.

The execution of these routes in parallel should yield a better understanding of the basic degradation mechanism. The electric field E along the superconductor is a well known function of the current, the field and the temperature but the additional effect of the strain tensor has still to be clarified in detail.

A lot is known about the effect of axial stress on superconducting wires and even the effect of transverse stress on single wires has been studied by many authors ([3,6]). However experimental data about cables are scarce ([4,5,7]). It is the aim of our research to investigate the behaviour of Rutherford cables under realistic operation conditions and to study the reproducibility of the results as well as to learn about the differences between various types of Nb_3Sn. Especially for this a test facility was developed and during the last 2 years 11 cable pieces have been investigated.

II TEST FACILITY

The test facility consist of an a 16 T/80 mm magnet in combination with a current supply and a cryogenic press. The current supply is a superconducting transformer system operated in a feedback mode to generate a truly stationary current in the sample of 50 kA maximum. The press, capable of producing 250 kN which is equivalent to about 300 MPa transverse pressure onto the cable, also is a special development. It consists of a superconducting coil system by which the repulsing force between the coils is transferred to the pressure blocks which impresses a prepared section of the cable. The force put on the cable can be easily adjusted by control of the current in the coil system.

The cable to be investigated is formed into a U-shape. The legs are in parallel field and connected to the current supply. In the intermediate section which is in transverse field, the pressure is applied across 40 mm of conductor, see Fig. 1. Both the field homogeneity and the accuracy of the current measurement are better then 1%. The uncertainty in the applied pressure is about 2%.

Several nV-meters (Keithley 181/182) are used to measure sample voltages. In combination with the ripple free sample current, very accurate voltage-current measurements on the cables can be performed with a resolution of about 50 nV. More details are in ([5]).

III. THE SAMPLES

Results obtained with 7 new samples are presented while the former 4 measurements are memorized. The main parameters of the cables are given in Table 1.

Cable (1), made by ECN in the Netherlands of wires produced according to the Powder-in-Tube (PT) method ([8]), was used by CERN for the construction of an experimental LHC model mirror magnet.

Cable (2) is also made by ECN and it was used for magnets in the EURATOM SULTAN project.

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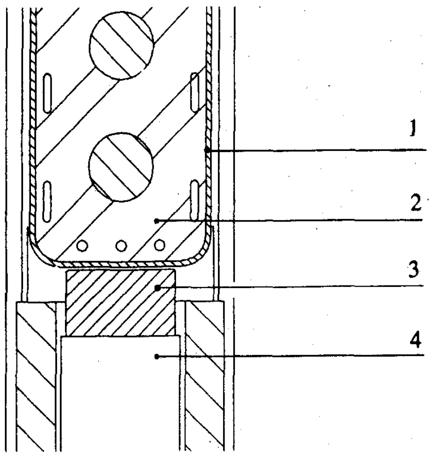

Fig. 1 The central part of the pressing arrangement:
(1) U shape cable, (2) sample holder,
(3) pressure block, (4) pressure pin.

Cables (3) and (4) are experimental conductors made by LBL of Modified Jelly Roll (MJR) wires of Teledyne Wah Chang Albany. Note that cable (4) has strands with 6 sub elements which is a relatively old conductor.

Cable (5), made by Vacuumschmelze in Germany according to the Bronze Route (BR), was applied by CERN and ELIN in an LHC model magnet.

All samples are prepared and measured using the same techniques and equipment. A few cables were tested a few times to check reproducibility. The samples are marked by an abbreviation indicating the production technique preceded by a serial number. For the MJR samples also the number of strands is indicated.
The heat treatments of the cable were as specified:
ECN PT: 64 hrs. at 675^{o}C; VAC-BR: 144 hrs. at 650^{o}C;
TWCA-MJR: 100 hrs. at 200^{o}C, 24 hrs. at 340^{o}C,
48 hrs. at 580^{o}C, 48 hrs. at 650^{o}C.
Except 1PT, all the samples were impregnated with resin (STYCAST2850FT). Sample 1PT was covered only partly.

IV. RESULTS.

The cables 1 and 2 were investigated before. Sample 1PT showed a severe degradation of about 50% at 100 MPa caused by a bad impregnation ([4]). Moreover the pressure block was in direct contact with the cable surface which prohibited a uniform pressing of the cable. Therefore, also samples 2PT and 3PT gave rather large degradations of about 25% at 200 MPa. After some improvements the Ic reductions were lower and became reproducible. The Ic degradation of the fourth sample 4PT is 3% at 100 and 9% at 200 MPa respectively ([5]), which data are confirmed by the result of sample 5PT.

A. The shape of the voltage-current curves

The voltage of several individual strands are measured as well as the global voltage of the cable by which the taps cover the entire cable section. A nice example of the differences are shown in Fig. 2, in which also the Ic criterion lines 5e-14, 1e-13 are indicated. It was not possible to correlate the voltages of strands with their position in the cable. For example, taps #4 showing the lowest voltage is a strand which lies at the thin edge of the cable where one would expect the highest voltage. Note that the global contact gives about the average voltage and at a level of 5 µV all taps give the same critical current.

Further conclusions are that the spread of the voltages slightly increases at higher pressures but the sequence is not changed. This means that the applied pressure is about uniform. Moreover is has been proven that the self field and the direction of the Lorentz force on the test section do not effect the U-I behaviour within the measuring accuracy.

In Fig.3 an example is given of the U-I curves as function of the applied transverse stress. The nice shifting of the voltage for increasing stress can be recognized. Further examination of these curves for all

Table 1. Characteristics of the Nb_3Sn Rutherford type of cabled conductors.

Type:	(1) ecn lhc-b	(2) ecn sultan	twca/lbl (3)	twca/lbl (4)	vac-lhc-a (5)
Production:	powder in tube	powder in tube	MJR 26	MJR 48	bronze route
Model:	keystoned	rectangular	keystoned	keystoned	keystoned
Dimensions [mm]:	(1.53/1.85)16.6	(1.82/1.82)18.2	(2.21/2.51)17.0	(1.07/1.29)15.8	(2.19/2.69)16.8
Number of strands:	36	36	26	48	24
Number of filaments:	192	192	6 subelements	36 subelements	50000
Diameter strand [mm]:	0.90	1.00	1.29	0.65	1.38
Matrix:	Cu	Cu	Cu/CuSn/barr.	Cu/CuSn/barr.	Cu/CuSn/barr.
% Cu [%]	57	55	48	56	29
Pitch cable [mm]	120	160	119	109	150
Measured Ic@11T [kA]:	16.5	19.6	9.2	3.3	15.1
Samples:	1PT	2,3,4,5 PT	7,8,9 MJR26	6 MJR48	10,11 BR

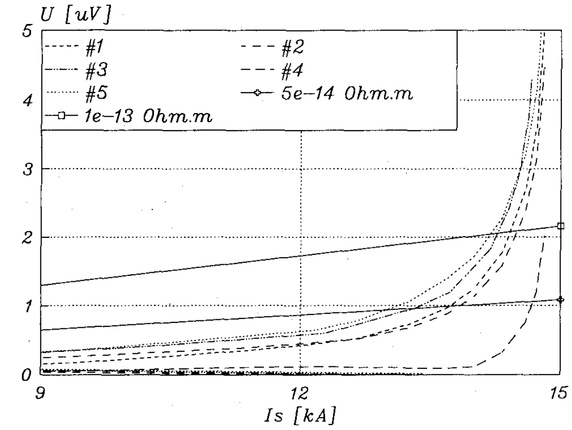

Fig. 2 Example of the spread in voltages measured on strands in the cable. #1=global taps, #2,3,4,5 are various strands under the pressure block.

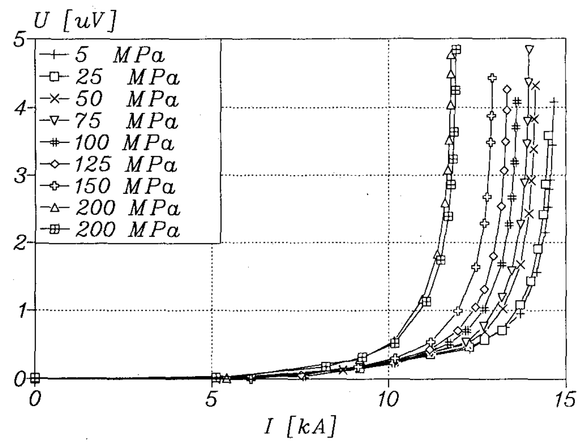

Fig. 3 U-I curves at 11 T and a stress of 5-200 MPa. 0<U<5 μV, 0<I<15 kA. Sample 10BR (VAC).

samples has yielded the following conclusions.

The U-I curves can not be described by the n-power law U(I) = constant x I^n, as usually applied satisfactory in the case of monolithic wires. For example, in the case of Fig. 3, the n value is 4 at 10 kA,5MPa and increases to 40 at the voltage level of 5 μV.

The applied stress does not influence the current sharing part of the U-I curve but only the superconducting part. The shape of the transition remains within the available accuracy unchanged.

B. Critical current versus strain, summary of results

The main differences between the three types of Nb_3Sn are presented in Fig. 4 in which the critical current reduction (applying the 1 μV/cm criterion) is

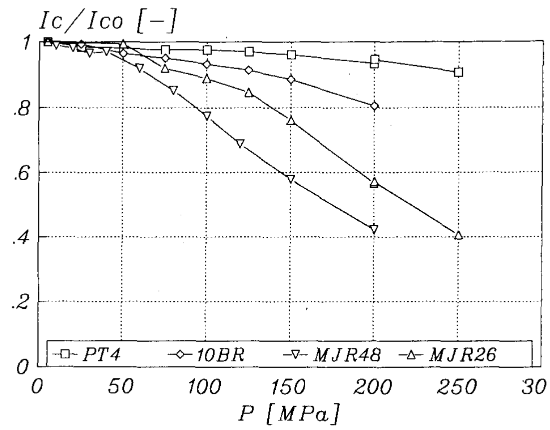

Fig. 4 Scaled critical current versus the applied transverse stress for several cable samples.

given as function of the applied transverse stress up 250 MPa. This picture is based on the samples 5-12. Within the measuring error of about 2% the results have been reproduced by second samples. The conclusions that can be drawn from the picture are collected in Table 2.

Table 2. Summary critical current reductions vs stress.

B=11 T. and 1 μV/cm criterion:	100 MPa	200 MPa
ECN type powder-in-tube:	2-4 %	5-8 %
VAC type bronze route:	7-10%	18-22%
TWCA MJR route, 6 subelements:	20-25%	55-60%
,36 subelements:	10-12%	40-45%

It appears that the PT conductor, characterized by the thick Nb tubes that enclose the Nb_3Sn layers, shows the best strain resistance. The MJR wires as far as tested here are extremely sensitive to stress. Especially the "old" conductor with 6 sub elements shows a severe degradation. It is recommended to investigate the more recently produced MJR wires with 120 and 378 sub elements to check possible improvements.

All samples are also investigated at 9 T. The qualitative behaviour is the same but the critical reductions at 9 T are about 75% of those at 11 T.

Sample 8MJR26 is tested with a pressure block not matching the keystone angle of the cable. In this case the pressure is not uniform and consequently the measured degradations are 50 and 90% at 100 and 200 MPa respectively. Also the irreversible part of the Ic degradation has increased compared to the normal case.

C. Relaxation of the "irreversible" degradation

Another important observation concerns the "irwhen the applied stress is made zero again. It appears that the irreversible part after applying a certain stress amounts to 30-50% of the actual degradation under stress. This is valid for all the samples 4-11.

However by chance it was discovered that in the case of sample 11BR the irreversible part is not persistent. After thermal cycling, i.e. a repeat of the measurement after 15 days and a warming up to room temperature, the critical current of this particular sample has attained its virgin value again (even a little bit more). In Fig. 5 this "relaxation" is demonstrated for the 11BR sample. After an interval and a

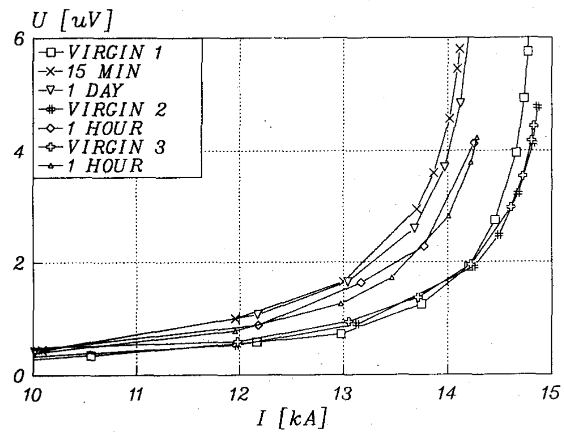

Fig. 5 U-I curves of sample 11BR showing relaxation of the "irreversible" part of the critical current.

thermal cycle the virgin critical current could be restored. This observation proves that (at least) in the BR sample up to 200 MPa, no permanent damage has occurred. To check this the filaments in the sample have been examined with SEM and it appeared that there is no difference in the small number of interrupts as present in unpressed and pressed strands.

Obviously the Ic reduction in the BR sample of 20-25% is completely reversible by relaxation and consequently the Ic reduction under transverse stress of 200 MPa is **not** caused by damage to the Nb_3Sn filaments. Quite a different behaviour occurs in the MJR conductor. The irreversible reduction is 20 to 50% and is persistent. A SEM micro analysis of the strands clearly shows visible damage ([9]).

CONCLUSIONS

For the first time a systematic study of the Ic reduction of impregnated Nb_3Sn Rutherford cables caused by transverse stress has been carried out. Remarkable and reproducible differences between three types of Nb_3Sn are found.

At a stress level of 200 MPa Ic reductions of about 7, 20 and 40-60% are found for the Powder in Tube, the Bronze type and the Modified Jelly Roll conductors respectively.

About 40% of the Ic reduction under stress is "irreversible". It is found for the first time (in one sample) that in principle relaxation of the "irreversible" part can occur by thermal cycling. In that case also no visible additional damage to the Nb_3Sn filaments due to applying the transverse pressure is found.

The major part of the actual Ic reduction is determined very strongly by the internal lay-out of the filaments and the material composition of the conductor. In the (old) MJR conductors a lot of cracks are observed and it correlates with a large irreversible (when cold) and permanent (in time) degradation. On the other hand, the bronze conductor shows a moderate Ic reduction and after thermal cycling the virgin critical current could be restored.

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