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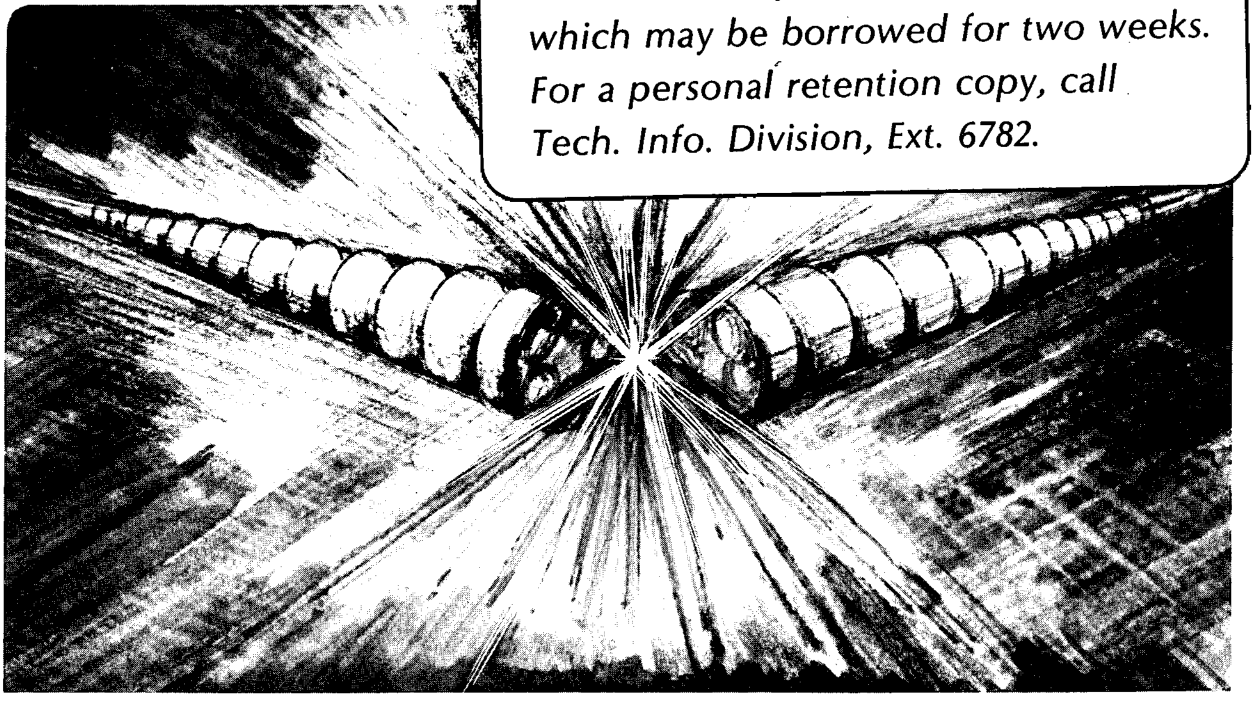

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THE EFFECT OF HIGH COMPRESSIVE STRESS ON THE CRITICAL CURRENT IN MULTISTRAND Nb_3Sn CONDUCTORS

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INTRODUCTION

The materials in superconducting accelerator magnets are subjected to high local stresses even though the coils are relatively small. A cross section of the 4.2-T Fermilab doubler dipole is shown in Fig. 1. The maximum compressive stress due to Lorentz forces is 9300 psi (64 MPa). Because the coils are precompressed during fabrication, the maximum stress in the windings is increased to about 12,000 psi (83 MPa) or higher. The NbTi conductors used today withstand this force with no apparent degradation.

Accelerators in the future will likely operate at fields of about 10 T. The stress in 10-T coils having designs similar to Fig. 1 could approach 40,000 psi (276 MPa). However, by redistributing the conductors[1] the maximum stress, including precompression, may be held to slightly more than 20,000 psi (138 MPa).

Three types of conductors have been proposed for 10-T accelerator magnets: niobium titanium (NbTi) and niobium titanium tantalum (NbTiTa) at 1.8 K and niobium tin (Nb_3Sn) at 4.2 K.[2] All three materials have acceptable current densities at 10 T in a stress-free state, but the performance of the brittle compound Nb_3Sn is known to be degraded by high tensile stress.[3,4]

The effects of tensile stress on multifilamentary Nb_3Sn wire have been thoroughly investigated.[3-7] This superconductor, which is formed by a reaction between niobium and tin at temperatures

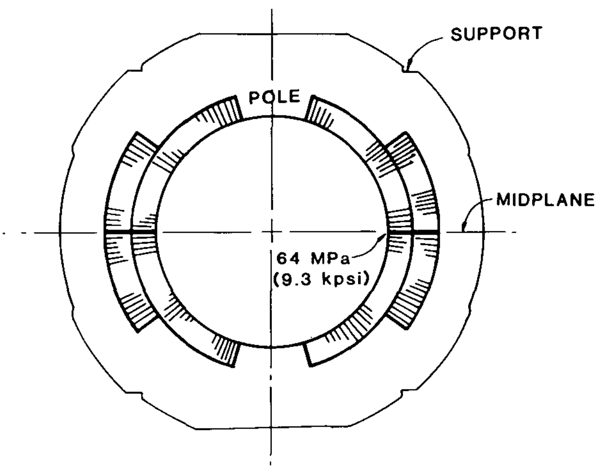

Fig. 1. Cross section of the 76.22-mm (3-in) bore Fermilab doubler magnet. The maximum load due to Lorentz forces is 64 MPa (9.3 kpsi) at the midplane.

between 600 and 800°C, has a low coefficient of thermal contraction relative to the rest of the conductor, i.e., the depleted bronze matrix and copper. As the conductor cools to room temperature, and eventually to 4 K for operation, the contraction of the matrix causes the Nb_3Sn to be under an axial compressive load. The magnitude of the compressive load depends on the area ratio of Nb_3Sn to bronze and copper[8] and significantly affects the performance of multifilamentary Nb_3Sn conductors subjected to tensile stress. This compression causes a reduction in J_c, but small tensile loads applied to the composite structure decrease this compression and improve the critical current.

The conductors in accelerator dipoles are subjected to some tensile stress, but the major stress in these conductors is a circumferential compressive load. The effects of transverse compressive loads on Nb_3Sn conductors have not been studied previously because conductors in most large, high-field magnets are subjected primarily to tensile loads, whereas the compressive load is either inherently small or is limited through the design and choice of structural materials.

During the final stage of construction of an accelerator dipole, the conductors are subjected to a large compressive load at ambient temperature. Ideally most of this load remains on the conductor as it is cooled to liquid helium temperatures. Then, as the coil is charged the local pressure will change. In the pole or high-field region the load decreases; at the midplane or low-field region (the fields at these two areas differ by only a few percent) the force increases. At maximum field the load varies from nearly zero to almost twice the initial precompression.

This paper describes a study to determine the irreversible effects of transverse compressive loads applied at room temperature and then released on a 23-strand Nb_3Sn Rutherford cable and its constituent strands.

EFFECTS OF COMPRESSIVE LOADS ON Nb_3Sn WIRE

The 0.027-in (0.69-mm) diameter wire used in these tests is similar to the Westinghouse LCP conductor.[9] Airco supplied the wire to LBL and also fabricated a 23-strand Rutherford cable that had nearly the same final dimensions as the Fermilab doubler conductor. The wire has a copper jacket occupying 64% of the cross section. The remaining 36% is niobium, bronze, and a tantalum barrier. Studies at Airco[9] showed that reacting at 730°C for 48 h gave nearly optimum performance at 10 T. (Possible improvement in critical current based on a double heat treatment is described in a separate report at this conference.)[10]

A series of U-shaped samples of this conductor were reacted at 730°C for 48 h at LBL and then subjected to different compressive forces. The samples were 45-mm long and had a 25-mm-long central straight section. The 10-mm-long side sections were soldered to the current leads. During critical current measurements, voltage taps were soldered 5 mm apart near the center of the straight section. Each sample was subjected to one compression cycle at room temperature, so that any observed effects were irreversible.

The forces were converted to an equivalent pressure on a complete cable and correspond to pressures as great as 40,000 psi (276 MPa). The method used to determine the relationship between pressure on the cable and the force on the sample was to calculate the force per unit length of conductor in the cable as a function of pressure, neglecting any stress enhancement due to conductor contact at the cable midplane. For example, at 10,000 psi (69 MPa) the force on 25.4 mm of cable was 3100 lbf (14,000 N). Since the cable was 11.5 conductors wide, the force per millimeter of conductor was 10.6 lbf (47.2 N). The force applied to the sample for 10,000 psi (69 MPa) was 480 lbf (2,100 N).

After compression at room temperature, the samples were taken to the Francis Bitter National Magnet Laboratory at MIT where the critical current was measured in fields up to 15 T. The results of these measurements are given in Fig. 2 and Table 1. The variations in the critical current in several unstressed samples give the range of data in the figure and the table and show that the measurement precision is ~3 A at 15 T and ~7 A at 7 T. The critical current values for the compressed samples are the average of two or three samples. The critical current values listed are for a voltage of 0.1 μV/mm, independent of sample current or field.

The critical currents were reduced for stress as low as 69 MPa, especially at the lower fields and higher currents. At 10 T and higher, however, the degradation was only about 25% at 138 MPa. Samples subjected to pressures of 276 MPa showed resistance at zero current, indicating severe damage. Nevertheless, these conductors showed some superconducting properties and carried 40 to 50% of the unstressed sample current at 0.1 μV/mm.

EFFECTS OF COMPRESSIVE LOADS ON Nb_3Sn CABLE

Some measurements have been made on the effects of compressive loads on the reacted cable to 276 MPa. The preliminary quantitative

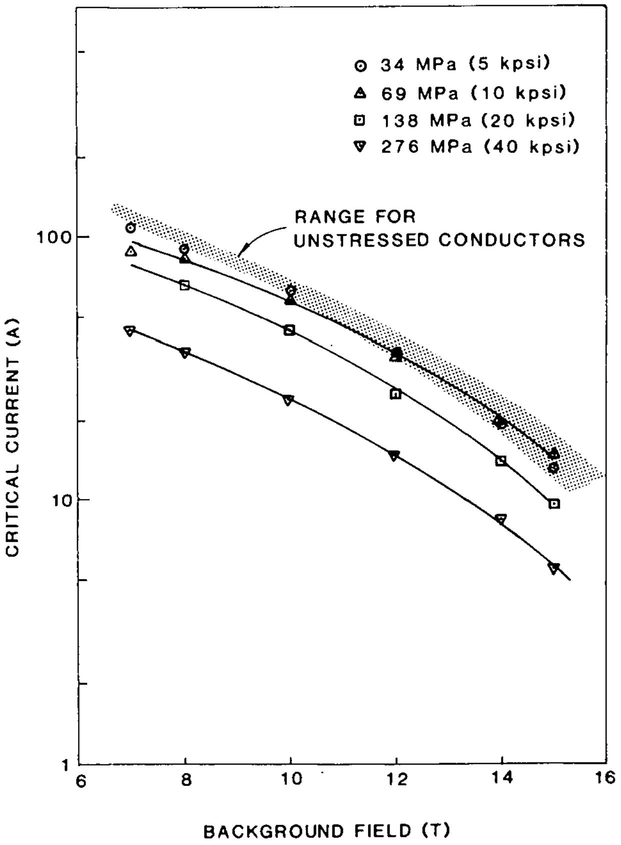

Fig. 2. Critical current in Nb_3Sn conductors subjected to compressive loads up to 276 MPa (40 kpsi). Little degradation is observed for pressures up to 138 MPa (20 kpsi).

Table 1. Critical Current in Amperes at 0.1 μV/mm Sensitivity in Nb_3Sn Strands Compressed after Reacting

Field, T	Compressive Loads, psi (MPa)				
	0	5,000 (35)	10,000 (69)	20,000 (138)	40,000 (276)
15	11-18	13	15	9.6	5.4
14	19-25	19.3	19.6	14	8.3
12	34-42	34.5	35.0	25	14.8
10	60-68	62	58.5	44	24.2
8	93-104	90	82.8	66	36.5
7	112-129	108	87		44.1

Table 2. Comparison of Observed Critical Current in Nb_3Sn Cable and Predicted Current Based on Single, Uncabled Strand Data

Field, T	Expected Current, A	Measured Current	
		No Compression, A	15,000-psi (104-MPa) Compression, A
12	780-970	760-800	850
10	1380-1565	1100-1350	1300
8	2140-2390	1600-2000	1900

results available from these measurements are given in Table 2 and show no degradation in the sample compressed with 104 MPa. (The higher current at 12 T in the compressed sample is not considered meaningful at this time.) A sample subjected to 207 MPa for 10 cycles was severely damaged and too resistive to measure, as was a single-cycle 276-MPa sample.

A COMPARISON BETWEEN CABLE AND STRAND PERFORMANCE

Most multistrand conductors exhibit some reduction in performance from that expected on the basis of individual strand characteristics. Reasons for this effect include physical damage to the strand, reduced cooling, and increased eddy currents. For our short sample tests on Nb_3Sn cables, we believe any reduction in performance would have to be due to physical effects in the strands.

Table 2 shows the expected short sample characteristics of individual strands. The cable I_c was 15 to 25% lower than expected. To determine the cause of this decrease in critical current, two types of samples were made from individual strands of conductor taken from the cable. One consisted almost entirely of the straight section of conductor from the cable; the other included the highly deformed, kinked section that occurs at the edge of the cable. These samples were the same size as and reacted in the same way as the uncabled wires. Their short sample critical currents are given in Table 3. The kinked samples showed some degradation, but the results varied by a factor of two. This variation may be a result of sample preparation or it may be a real variation in the properties of the materials. Both the straight and kinked samples showed consistently poorer current sharing characteristics than the uncabled samples. Again this may be caused by sample preparation, but it appears to be a characteristic of the cabling process.

The reduced I_c of the kinked section approximately accounts for the reduced I_c of the cable. To determine the cause of this effect, we mounted a sample of conductor with a kinked section in plastic and sliced sections perpendicular to the axis of the conductor in the region of and adjacent to the kink. After polishing,

Table 3. Comparison of the Critical Current in Amperes at 0.1 μV/mm Sensitivity of Superconducting Strands from a Nb_3Sn Cable with Identical Uncabled Conductors

Field T	Uncabled	Cable Straight Section	Cable Kinked Section
15	11-18	13-18	9-16
14	19-25	19-25	13-21
12	34-42	35-43	19-38
10	60-68	56-67	32-52
8	93-104	89*-105	44-83
7	112-129	97*-120	44-91

*Conductor transitions with no current sharing.

these samples were observed with an optical microscope. There was considerable distortion of the copper matrix, but the bronze and superconductors were relatively unaffected. The bronze/superconductor area was reduced by 1 to 7% over a length of about 5 mm. The section reduced 7% in area was less than 1-mm long.

Although this deformation may affect the performance slightly, it should not lead to a 10-20% reduction in I_c. To further pursue the possibility of some damage occurring during the fabrication process, we took several kinked sections of unreacted cabled strands and mounted them on copper bars with the kinked region free of the bar and unstressed. The outer copper shell was etched away with dilute nitric acid, the tantalum barrier was removed with a mixture of dilute nitric and hydrofluoric acids, and finally, the bronze was removed with dilute nitric acid. The exposed filaments of unreacted niobium were observed with a scanning electron microscope (SEM). Some groups of broken niobium filaments were observed.

The exact cause of these breaks is not known at present, but several possibilities are being considered. First, if there are irregularities in the filaments due to the drawing process and the reaction between niobium and tin is significant during the final annealing heat treatment, then the production of Nb_3Sn might weaken the filaments and cause them to break when the conductor is severely deformed. A second possibility is that the bronze fails under the severe deformation at the edge of the cable during the cabling process and causes the niobium to fail.

Further study will be required to determine which, if either of these effects, is the cause of degradation. A first step in this study will be to look at conductors with more moderate deformations in the final sizing operation.

CONCLUSIONS

This study indicates that multifilamentary Nb_3Sn bronze-process conductors exhibit little irreversible damage for compressive loads up to 15,000 psi (104 MPa), indicating there is no significant damage to the brittle Nb_3Sn compound. Higher stresses are expected in 10-T accelerator dipoles, so further study will be required, but this preliminary result is promising.

The Nb_3Sn cable did not perform as well as expected on the basis of individual strand tests. It appears that a major part of the degradation was associated with the highly deformed area near the edge of the cable though the cabled strands did not exhibit a good current sharing region. Reducing the degree of compaction may reduce the size of this effect.

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