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Study of the React and Wind Technique for a Nb_3Sn Common Coil Dipole

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Abstract— **Fermilab, in collaboration with LBNL, is exploring the use of the react and wind technique for a common coil dipole with a Nb_3Sn Rutherford cable. An R&D program on conductor design and magnet technology was begun aiming at an 11 T, 2 layer, 30 mm aperture design operating at 4.5 K. The goal is to explore the feasibility of the react and wind technique for flat coils with a minimum bending radius of 90 mm. In order to improve the understanding of the I_c degradation caused by bending after reaction this effect will be studied on both strands and cables. In this paper we present two techniques to measure the critical current degradation due to bending, both in wires and cables, using standard test facilities. Together with the description of the program we show the results of the first measurements on strands and the layout of the cables that are being produced.**

I. INTRODUCTION

In April '99 Fermilab and LBNL started an R&D effort to explore the react-and-wind technique for fabrication of accelerator magnets using brittle superconductors. The "common coil" design concept has been previously proposed as a conductor friendly option for high-field dipoles suitable for a post-LHC, 100 TeV hadron collider [1]. This study supports the design and fabrication of an 11 T, 30 mm aperture dipole operating at 4.5 K [2]. For its cost effectiveness a hybrid design (1st layer Nb_3Sn, 2nd layer NbTi) has been chosen.

The react and wind technique has been attempted several times during the history of Nb_3Sn magnet development and revealed the difficulty of its use for shell type accelerator magnets. The ends of these magnets require excessive bending of the reacted Nb_3Sn cables resulting in severe critical current degradation. Solutions like compensating for the degradation in the ends by adding cables [3], dog bone ends, or restricting react and wind coils to the outer layer only [4] have been attempted. Common coil dipoles are more conductor friendly because the coils can take the shape of flat pancakes with a large bending radius, determined by the distance between the apertures rather than the bore size.

In the present design the minimum bending radius is 91 mm. If the radius of the reaction spool is twice the minimum bending radius of the coil the same bending strain will be applied to the conductor in the straight part and in the ends of the coil (see Fig. 1). The maximum strain in a wire subjected to bending (ε_b) is given in the following relation:

$$\varepsilon_b = \frac{\phi}{2}\frac{(1-R1/R2)}{R1-\phi/2} \qquad (1.)$$

where $\phi/2$ is the distance of the outermost filament from the center of the wire, R1 and R2 the radius of curvature before and after bending, and ε_b is the strain applied to the outermost filaments. If R1 and R2 are much bigger than ϕ the following simplified formula can be used:

$$\varepsilon_b = \frac{\phi}{2}\left(\frac{1}{R1}-\frac{1}{R2}\right). \qquad (2.)$$

Bending a wire generates both compressive and tensile strains since the center of the wire is without strain (see Fig. 1). If R1 and R2 are respectively 180 mm and 90 mm, the maximum ε_b is 0.14% for a 0.5 mm diameter wire and 0.19% for a 0.7 mm wire. Strain degradation of Ic was extensively studied in the past [5]. Recent works have focused attention on ITER wires [6]. According to reported results a maximum bending strain of 0.15% should give an acceptable Ic degradation. However this has to be confirmed for the most recent high Jc Nb_3Sn wires.

If strands in a cable are bonded together, the thickness of the Rutherford cable instead of the strand diameter is used as ϕ in Eq.(2), and the maximum strain is almost doubled. Ekin [5] reports that braided cables can behave as if made of independent strands. It is part of our program to repeat a similar study on Rutherford cables.

The conductor R&D program consists of two stages: strand study, cable development and testing. The conductor R&D is oriented toward the development of cables for the magnet short models. It is therefore not meant to be an extensive study of the bending strain dependence of the critical current in Nb_3Sn strands and cables, but will involve tests and comparisons of different strand materials and cable designs.

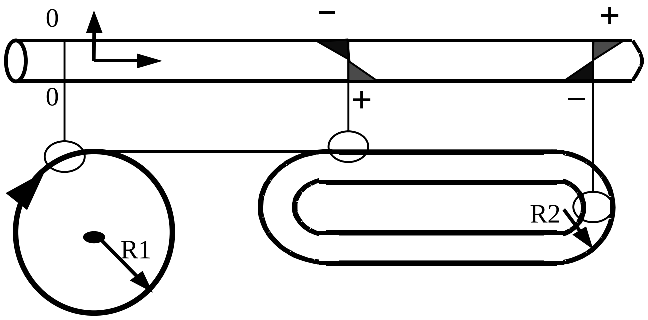

Fig. 1. Schematic of bending strain distribution in strand during coil winding.

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In this paper program steps are presented together with sample holders, tools, and experimental procedures that have been developed. We also present the first results of wire tests.

II. WIRE R & D

The wire study investigates the critical current degradation in wires due to bending and compares Nb_3Sn wires produced with different techniques (Internal tin, Modified jellyroll, Powder in tube).

A. *Measurement Technique*

In order to use the standard short sample test facility operating at Fermilab [7] for measurement of Ic degradation due to bending, a special experimental procedure was developed. The test facility consists of a superconducting magnet providing 17 T in a 49 mm bore.

The experimental procedure utilizes sample holders for the reaction with a smaller diameter than those used for measurement. The bending is produced when the sample, after reaction, is moved to the bigger measurement sample holder (see Fig. 2).

At present the standard Ti-6Al-4V barrels adopted by the ITER collaboration are used as sample holders for this apparatus. Because of the small thermal contraction of this material ($\Delta l/l=0.18\%$ from 300 to 4.2 K) the wire undergoes tension upon cool down. To reduce this effect we also used stainless steel (316L) sample holders whose thermal contraction ($\Delta l/l=0.29\%$ from 300 to 4.2 K) is more similar to that of Nb_3Sn wires. In this case the samples are measured in a condition more similar to a real magnet.

The reaction sample holders (see Fig. 2), made of stainless steel 304, consist of a cylindrical and a conical part. A continuous groove identical to the groove on the measurement sample holder extends all along the reaction sample holder keeping a constant pitch.

The sample is reacted on the cylindrical part. Graphite lubricant is sprayed on the sample holder prior to winding the sample in order to avoid sticking during reaction. After reaction the two sample holders are tightly connected using an appropriate fixture (Fig. 2) in such a way that the grooves match. The sample is slipped inside the groove from one holder to the other.

Only one bending condition can be explored for each sample. We built reaction sample holders to apply a maximum bending strain (computed for filaments located on the outer surface of the wire) of 0.2% and 0.4% to wires with 1 and 0.5 mm diameter.

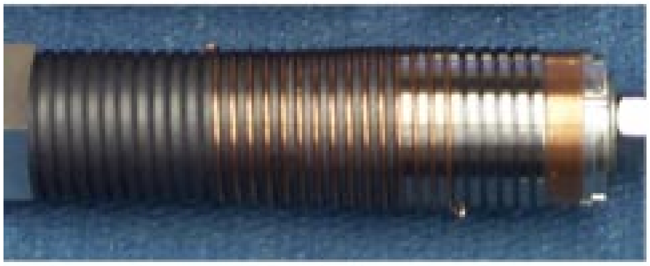

Fig. 2. Photograph of reaction (left) and measurement (right) sample holders during displacement of a sample.

B. *Program*

To measure the Ic degradation due to bending strain we use ITER material produced by IGC and drawn to 1, 0.7, 0.5 and 0.3 mm diameter. At present wires with 1 mm diameter are being measured and the first results are presented here.

Samples with 1 mm diameter are being measured because Fermilab is purchasing these wires for the HFM project [8]. Strands with 0.3 mm diameter will also be studied in case the results of 0.5 and 0.7 mm wire tests show that cables with thinner strands are needed.

C. *First Measurements*

Up to now 10 samples of 1 mm diameter strand have been measured. They are from the same internal tin diffusion Nb_3Sn wire produced by IGC for the ITER project (HPI type). The copper to non-copper ratio is 1.42 and the nominal Jc is 680 A/mm^2 for a two week long heat treatment at 660 ºC. Six samples have been reacted on the reaction sample holders previously described in order to measure them in a state of 0.15% maximum bending strain. Four samples were reacted directly on the measurement sample holders to measure Ic in the unbent condition. Two samples of the former set and two of the latter were measured on Ti-6Al-4V holders in order to test the effect of longitudinal strain on both bent and unbent samples. The remaining samples were measured on stainless steel sample holders to measure the effect of bending only.

The critical current was measured at 4.2 K in magnetic fields from 6 to 15 T. A 0.1 μV/cm criterion is used to estimate the critical current. A fit over one decade ($0.05<V<0.5$ μV/cm) is made to compute Ic and the n value. Voltages were measured on 50 and 70 mm long central sections of the sample. The field generated by the sample coil is oriented in the opposite direction with respect to the main field.

TABLE I
STRAIN STATE OF THE SAMPLES OF THE 1st TEST SERIES

	not stretched (s.steel holder)	stretched (Ti-6Al-4V holder)
unbent	#3, #8	#1, #2
bent	#5, #6, #7, #9	#4, #10

D. *Results and Analysis*

Fig. 3 shows the critical current measured for all samples at 4.2 K in magnetic fields from 6 to 15 T. The highest values are reached by the stretched, unbent samples. Their average non-copper Jc at 12 T is 690 A/mm^2. The second best performing samples were stretched and bent samples. The non-stretched, unbent samples came next and finally the non-stretched, bent samples had the lowest critical current.

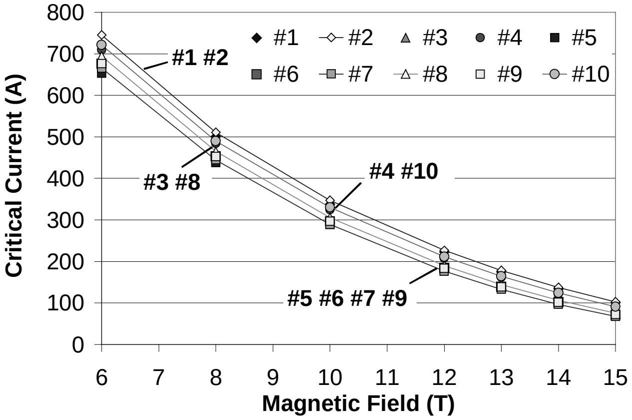

Fig. 3. Critical current versus field of all samples (T=4.2K).

Fig. 4 shows the critical current normalized to the average Ic of the non-stretched, unbent samples (Ic0). It can be seen that the ΔIc/Ic0 increases strongly with the magnetic field in the stretched samples. It's interesting to note (sample #4 and #10) that the gain due to the longitudinal strain (ε_l=0.12%) is higher than the degradation caused by the bending (ε_b=0.15%). At 10 tesla the combination of the two effects gives an overall gain of about 10%. The non-stretched, bent samples show a degradation of the critical current increasing with the field (from 2% to 5% for samples #6 and #9, from 3% to 9% for sample #7) or almost constant (5% for sample #5).

Among stretched samples the comparison between bent and unbent samples reveals degradation of the critical current that increases with field from 3% to 11%. All samples showed the same n-value dependence with magnetic field.

We compared our data to a model by Ekin[5] which predicts Ic degradation of multifilamentary Nb_3Sn wires subject to uniaxial and bending strain. We have no precise knowledge of the intrinsic strain in our samples. Ten Haken[6] reported an intrinsic strain in ITER wires made by different companies ranging from 0.02% to 0.2%. Since we measured a strong variation of critical current under stretching, we believe that our samples lie on the outer boundary of the range indicated by ten Haken. Therefore we assume ε_{int}=0.2% as intrinsic strain in the Nb_3Sn filaments when the sample is mounted on the Ti-6Al-4V holder. The maximum bending strain for our samples is ε_b=0.15%. Using the parameters proposed by Ekin for most Nb_3Sn wires, the critical current degradation at 10 T, 4.2 K, ε_b=0.15%, should be about 5% for the samples measured on Ti-6Al-4V holders and higher for samples measured on stainless steel barrels.

The degradations measured on Ti-6Al-4V barrels are in good agreement with this prediction (3.7% and 5.4%) while the degradations measured on some stainless steel samples are significantly lower. This behavior is at present unexplained and will be investigated in the continuation of these tests.

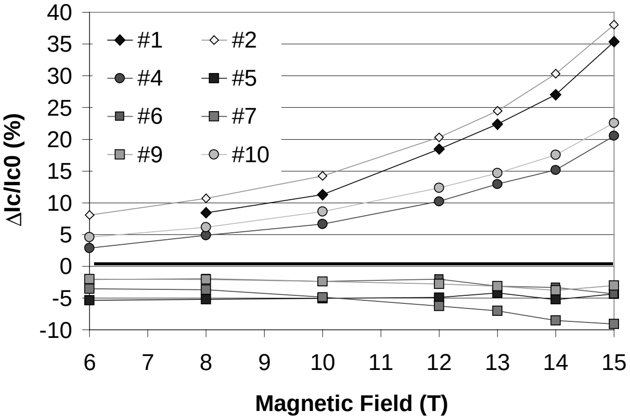

Fig. 4. Comparison with the average Ic of unbent samples measured on stainless steel barrels ('non-stretched').

III. CABLE R & D

The aim of the cable R&D program is to study the critical current degradation of cables due to bending and to develop cables and reaction procedures that minimize the degradation. In order to measure the degradation of reacted and bent cables, the cables will be reacted in a bent shape and straightened before impregnation and measurement. In this way they can be measured flat in a standard cable test facility and their critical current will be compared with similar cables that were reacted straight.

Different cables will be produced to explore the effect of a stainless steel core, different packing factors and strand diameters. A major task will be the optimization of the cable reaction procedure. The aim is to avoid any sticking between strands to preserve maximum flexibility in the cable so that the degradation should be on the same level of that measured on wires.

A first test of reaction and winding has been performed using a 15 mm wide cable with 36 strands of diameter 0.825 mm. A coil with 6 turns was reacted on a 300 mm diameter reel. After reaction the cable was straightened and wound on a 150 mm diameter reel. The reacted coil revealed a tendency for strands to pop out from the outer turn that was the only one not completely constrained. The use of an outer wrapping will be explored in future tests.

A. Program

The baseline material for the cable program will be 15 mm cables made from 0.5 mm ITER strands. Cables will be produced with and without a 127 μm stainless steel core and reacted on 360 mm and 250 mm diameter reels as well as flat. An additional parameter will be the use of synthetic oil during the reaction process. This will enable us to assess the effect of two different bending strains on cables with/without core and reacted with/without oil on the critical current. Depending on the Ic degradation measured in these samples, we will eventually extend the program to 15 mm wide cables made from 0.7 or 0.3 mm strands. A Rutherford cable made from 0.3 mm strand would be too thin and cannot be accepted from the magnet design point of view. Therefore we are studying the possibility of using double transposed Rutherford cables in this case. These cables are wound from 37 strands, each consisting of 6 wires twisted around a 0.3 mm diameter copper core-strand.

B. Description of Cable Sample Holder

Studies of the effect of transverse pressure on the critical current of Nb_3Sn cables have been performed using the cable test facility at the NHMFL in Florida [9]. A fixture has been designed for use in this cable test facility. The sample test holder is designed to securely hold cable samples in place while transverse stresses up to 100 MPa are applied to the cable broad face. This holder consists of a stainless steel "U" channel base which holds two Nb_3Sn cables in a groove running along its length, as shown in Fig. 5. An adjustable shim system provides lateral support of the cables. The cables are spliced together in a copper case at the lower end to provide a continuous current path, and are soldered to NbTi cables at the upper end where the connection to the test system current supply is made. Additional NbTi cables, that are not electrically part of the circuit, surround the Nb_3Sn cable samples under test. These additional cables contribute to a mechanical environment in the test fixture that closely matches that of the magnet coil. The cable samples are vacuum impregnated with epoxy in situ in order to provide additional cable support and again reproduce the magnet coil mechanical environment. A pressure bar, held in place with a G-10 cover plate that runs the length of the fixture, applies uniform transverse pressure to the cable sample by means of a pressure dog that contacts the He-gas driven ram at the test facility (see Fig. 6). A capacitative pressure transducer is built into the sample holder underneath the center of the pressure plate, in order to provide a measurement of the stress applied to the cable sample during testing. Pressure sensitive film (Fuji film) will be used in room temperature tests of the assembly to check loading uniformity. Voltage taps spaced 100 and 200 mm apart surround the section of the cable underneath the pressure plate, and are used to monitor sample voltages during Ic testing.

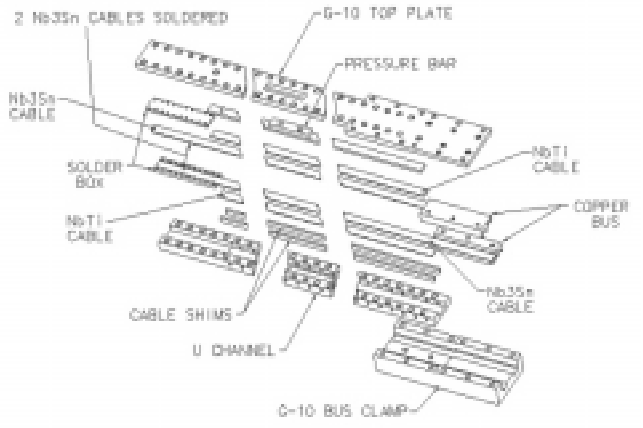

Fig. 5. Exploded view of sample holder for measurements of the critical current of Rutherford cables.

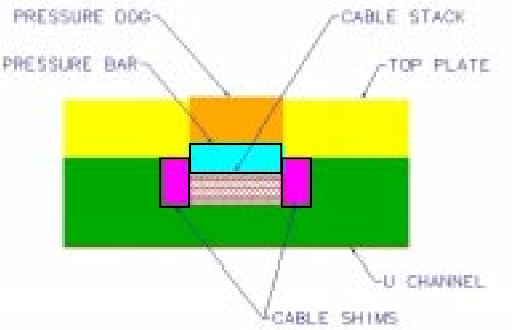

Fig. 6. Cross-sectional view of cable Ic sample holder.

IV. CONCLUSIONS

A conductor R&D program has been launched at Fermilab and LBNL to explore the react and wind technique with state of the art Nb_3Sn superconductor for a common coil accelerator magnet. The program aims to determine the critical current degradation of Nb_3Sn strands and Rutherford cables subject to a bending strain in the range form 0 to 0.4%. A technique was developed to measure the bending degradation of wires using Fermilab short sample test facility. First measurements were done applying a maximum bending strain of 0.15%. Ti-6Al-4V and stainless steel sample holders were used to measure the bending degradation in both stretched and non-stretched conditions. The degradation obtained in the stretched condition (4.6 % at 10 T) matches the prediction of Ekin's model. The degradation measured in the non-stretched condition is lower than expected. Cable degradation will be measured by reacting samples in the bent condition and testing them straight. Reaction procedures will be developed in order to maintain the cable degradation at the same level as the wire degradation. The results of the conductor R&D program should determine the optimal cable design for the first Fermilab common coil react and wind model dipole. Procedure development for coil reaction, winding and assembly will be the next milestones after completion of the conductor program.

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