REBCO Coils With Variable Co-Wind Dimensions Under Static and Cyclic Axial Pressure Loads at 77 K

Iain R. Dixon, *Senior Member, IEEE*, Ernesto S. Bosque, Kyle Buchholz, Robert P. Walsh, and Hongyu Bai

***Abstract*—An investigation into the effects of high cycle fatigue on REBCO coils along their axis of rotation was performed to establish design limits. Three coils were tested in liquid nitrogen via a hydraulic materials testing machine. The coils were fabricated with the same type of REBCO tape but had different co-wind materials and dimensions. The results showed that for a coil with REBCO tape wider than its co-wind, where the loads bear directly on the conductor, had 5% permanent critical current degradation at pressures near 100 MPa. A significant improvement was observed in a wax impregnated coil, which aided to distribute loads, with a 1.2% permanent critical current reduction after 50,000 load cycles to 125 MPa. Additionally, a coil with co-wind wider than its REBCO tape was also improved and reached 5% reduction after 50,000 cycles at pressures up to 100 MPa and continued loading to 151 MPa.**

***Index Terms*—Critical current, fatigue, HTS magnets, mechanical limits, REBCO.**

I. Introduction

REBCO tape with its high-strength substrate is the preferred superconductor for high-field applications and is the choice for the NHMFL's 40 T all-superconducting magnet [1]. Many electromechanical characterizations of this conductor have been performed in its longitudinal direction which is its primary load path. Little has been reported on structural limits in its transverse direction or axial with respect to a solenoid's coordinates. In [2], the critical current (I_c) in double pancake REBCO coils was found to be reversible when axial coil stress is less than 100 MPa. The axial strength of single layer REBCO coils with outer aluminum rings was investigated in [3].

The NHMFL's 40 T magnet project is presently in a conceptual design phase and the influence of high axial coil stress is a concern. There are two basic design configurations, one is a metal insulated style with a single REBCO tape co-wound along with a bare stainless steel tape. The other is insulated and vacuum impregnated with paraffin wax as was done with the 32 T superconducting magnet [4], but with two key differences. The REBCO tape is wound two-in-hand to be more defect tolerant and contains additional copper co-wind to maintain an acceptable copper current density. The 40 T is being designed for 50,000 operational cycles and the nominal axial mid-plane pressure is 100 MPa.

This paper discusses results of compressive axial tests conducted in liquid nitrogen on sample coils representative of the 40 T conceptual designs. The two objectives of the tests were to determine the axial coil stress that causes irreversible I_c degradation and to confirm whether the coils could withstand 50,000 cycles at a nominal applied pressure of 100 MPa.

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II. Sample Configurations and Test Setup

The REBCO tape used in the test coils was from SuperPower with 40 μm total copper thickness and 50 μm substrate thickness. The stainless steel was type 316L with a general specification of 760 MPa room temperature yield strength. The copper co-wind was C10100 with a half-hard designation.

Co-wind tapes are nominally the same width as the REBCO conductor but there is a high probability that the superconductor and co-wind width dimensions will differ due to manufacturing tolerances. Thus the axial loads will bear directly on either the REBCO tape or the co-wind. To evaluate the impact of this, two near identical coils were tested, one coil contained co-wind wider and one contained co-wind narrower than the REBCO tape. The conductors in these two test coils came from the same spool and the test coils are designated as STWC for "single tape, wider co-wind", STNC for "single tape, narrower co-wind"

The third test coil, designated MT for "multi-tape", was wound four tapes in parallel with two conductors (REBCO facing inward) overwound with copper and then stainless steel, which were both more narrow than the REBCO tape. Table I contains the coil and material parameters.

A test coil is pictured in Fig. 1. The coil hardware is constructed of G-10 and the upper flange, where the mechanical load is applied, is designed to guide freely along the bore tube. The double pancakes do not have internal joints but do have joints on the outer diameter where they are connected to REBCO leads. The outer joints are not in the load path. The critical current measurements that are discussed herein only include the coil, the joints are excluded.

TABLE I
COIL, CONDUCTOR, AND CO-WIND PARAMETERS FOR EACH REBCO DOUBLE PANCAKE TEST SPECIMEN

Parameter	STWC	STNC	MT
Inner Radius (mm)	15	15	15
Outer Radius (mm)	25	25	25
REBCO width (mm)	4.01	4.01	4.05
REBCO thickness (mm)	0.095	0.095	0.093
SS Co-wind width (mm)	4.09	3.95	3.95
SS Co-wind thickness (mm)	0.050	0.050	0.050
Cu Co-wind width (mm)	-	-	4.00
Cu Co-wind thickness (mm)	-	-	0.127
REBCO turns / disk	68	68	54
SS Co-wind turns / disk	68	68	27
Cu Co-wind turns / disk	-	-	27

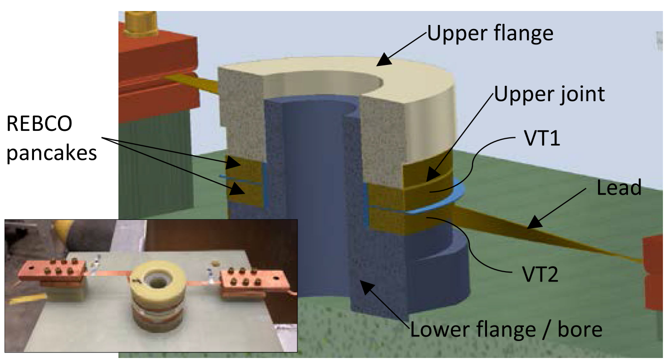

Fig. 1. Section view of a test coil and its primary components. The coil voltage tap locations are approximated by VT1 and VT2. A photograph of a test coil is shown in the inset.

The coil shown in the figure reacts against a supporting plate and the assembly is tested in a 500 kN MTS materials testing machine. The mechanical loads were applied at a rate of 1 kN/s and the load cycling occurred with a stress ratio of 0.1. All critical current measurements were evaluated using a 0.1 μV/cm criterion (with a voltage tap spacing of 17 m) on curve fit data.

III. RESULTS AND DISCUSSION

The conductor I_c at 77 K and self-field is on average 147 A. At 50 A the central field is 0.22 T (for the single tape version) and the highest field in the windings is 0.38 T at an angle less than 2 degrees. The I_c as a function of field at 77 K is not known.

In all of the test cases that follow, the I_c of the test coil is measured with a static axial load applied (I_c^L) and then removed (I_c^U). This is performed several times with sequentially increasing loads up until load cycling is performed. The load cycling is paused periodically to measure I_c, with and without the load applied. A warm up-cool down (WUCD) cycle was required to ensure the coils were thoroughly dry, if testing continued into the next day because of nitrogen boil-off.

Permanent or irreversible damage is indicated by the deviation between I_c^U and the initial critical current (I_{c0}) as $(I_{c0} - I_c^U)/I_{c0}$. It is observed that there is an I_c reduction with the load applied that is reversible. This sensitivity to axial loads is expressed as the percent deviation between I_c^L and I_c^U as $(I_c^U - I_c^L)/I_c^U$.

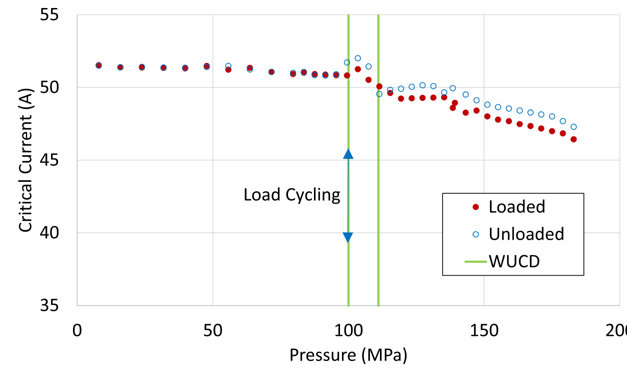

Fig. 2. Critical current of the STWC coil at static axial pressures up to 185 MPa (closed symbols). Open symbols are is the critical current after unloading but is recorded on the graph at pressure for clarity. The warm up-cool down (WUCD) events are indicated by the vertical lines and load cycling by the vertical arrows.

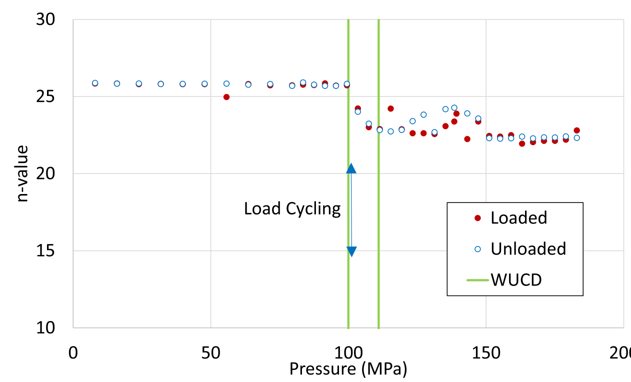

Fig. 3. n-value of the STWC coil at static axial pressures up to 185 MPa. The warm up-cool down (WUCD) events are indicated by the vertical lines and load cycling by the vertical arrows.

A. *Single Tape, Wider Co-Wind*

The test coil with wider co-wind, STWC, was tested over three days and experienced two warm up-cool down cycles (WUCD). Fig. 2 shows the I_c for the full test campaign and Fig. 3 contains the n-values. The thermal cycles are indicated by the vertical lines. Cyclic loading occurred at 100 MPa but the data are not shown in the figures. The pressure is the load divided by the coil's full cross-sectional area (from inner and outer radii in Table I). Since the steel extends beyond the REBCO tape, part of the co-wind will carry the full load, up until the load is transferred into the neighboring REBCO turns through shear. The axial stress in that section will be approximately three times that of the applied pressure.

The I_{c0} at 12 kN (10 MPa) is 51.5 A. In the loading up to 100 MPa, the I_c appears to be degrading slightly but after the first WUCD cycle, the I_c is fully recovered to 51.7 A, influenced by screening currents. Fig. 4 contains the cyclic data collected during the 50,000 cycles at 100 MPa. At the average pressure of 100 MPa, the bearing stress on the co-wind is 294 MPa. During the period of cycling, the loaded I_c data is higher than the unloaded, which is not intuitive but is thought to be caused by slight variations in temperature. The increase in I_c over the cycles may be from boil-off of nitrogen, which reduces the pressure at the sample. The temperature change is calculated to be up to a

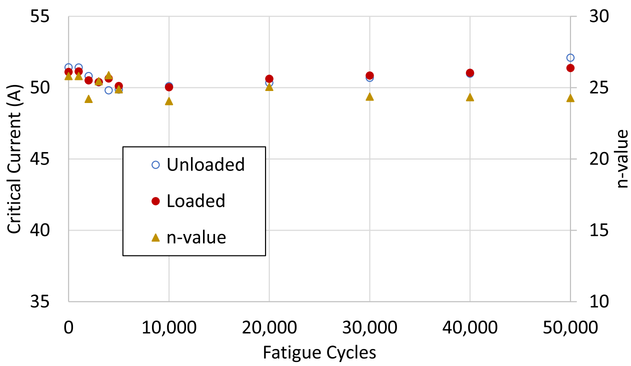

Fig. 4. Critical current and n-value of the STWC coil during fatigue cycling up to 100 MPa. The n-value shown is only with the load applied.

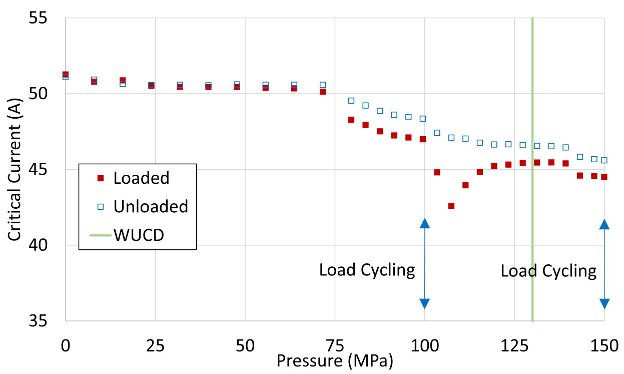

Fig. 5. Critical current of the STNC coil at static axial pressures up to 150 MPa.

couple tenths of a degree from the anticipated 40 cm reduction in nitrogen level. The I_c at the end of the 100 MPa cycles was 52.1 A (unloaded) and after a WUCD.

The I_c after the second WUCD was 49.5 A but it drifted up with increased loading. A sharper decline in the I_c is apparent beyond 140 MPa. A 5% permanent degradation in I_c was reached at 151 MPa ($I_c^U = 48.9$ A, $I_{c0} = 51.5$ A). Beyond 150 MPa the degradation increased more rapidly. Testing ended at 185 MPa where it attained 8% permanent degradation.

B. Single Tape, Narrower Co-Wind

The second test coil with the narrow co-wind was tested over two days and was exposed to one WUCD cycle. Cyclic runs were performed at 100 MPa and 150 MPa. Figs. 5 and 6 show the I_c and n-value for the STNC coil respectively but do not contain the cyclic data. Here, the REBCO that extends beyond the co-wind will have an axial stress 1.6 times that of the applied pressure. At 80 MPa there is a sudden 3% permanent I_c reduction and an additional 2.5% reduction in I_c from sensitivity to the applied load. After the 100 MPa cycling the loaded I_c drops faster than unloaded but starts to recover after about 110 MPa. This anomalous behavior doesn't appear to be permanent damage because it recovers. It may be due to load sharing changes between the REBCO and stainless steel tapes. The n-value has a similar pattern as the I_c.

Fig. 7 is a plot of the I_c and n-value of the specimen during the 100 MPa cycles. Even though the I_c at the start of the cycling is reduced from I_{c0} of 51.1 A, the I_c does not appear to degrade

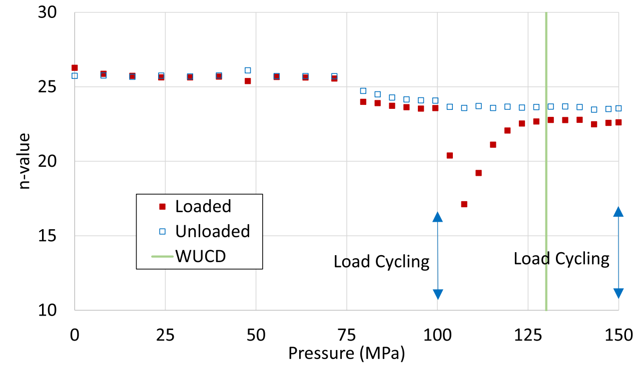

Fig. 6. n-value of the STNC coil at static axial pressures up to 150 MPa.

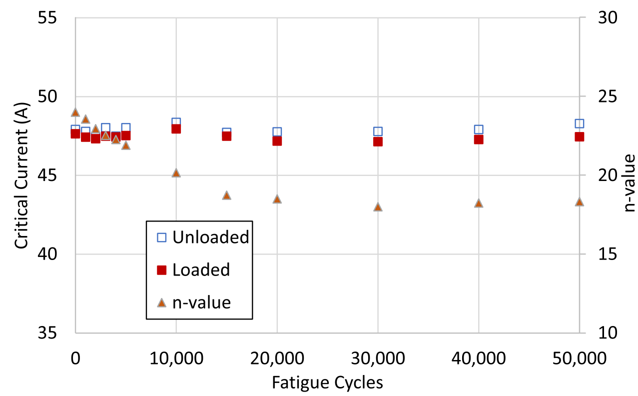

Fig. 7. Critical current and n-value of the STNC coil during fatigue cycling up to 100 MPa.

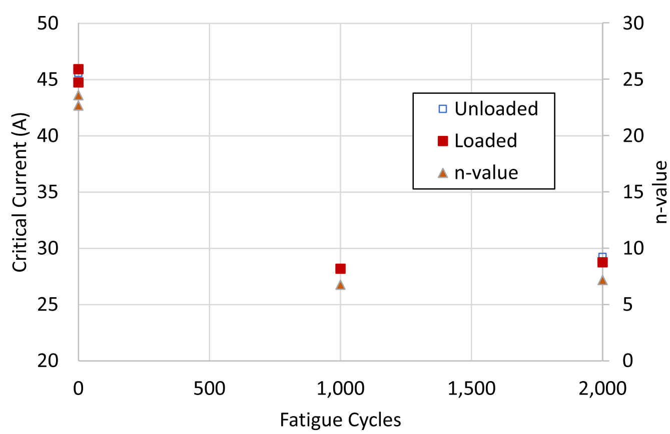

Fig. 8. Critical current and n-value of the STWC coil during fatigue cycling up to 150 MPa.

through the 50,000 cycles. There is however a reduction in the n-value down to 18. It may not be an issues because after the cycling the n-value improved, see Fig. 6.

The I_c did degrade significantly during the 150 MPa cycling operation. Only 2000 cycles were applied before the tests were halted. The results for the cycling are shown in Fig. 8.

C. Multi-Tape

The MT coil completed testing without a WUCD cycle and was cycled at maximum axial compressive pressure of 125 MPa

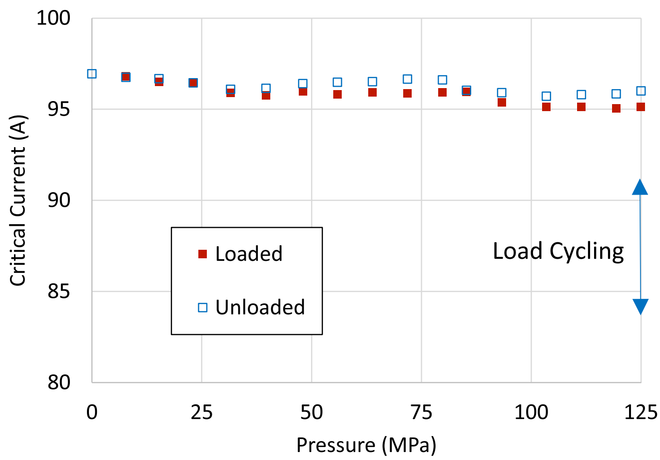

Fig. 9. Critical current of the MT coil at static axial pressures up to 125 MPa.

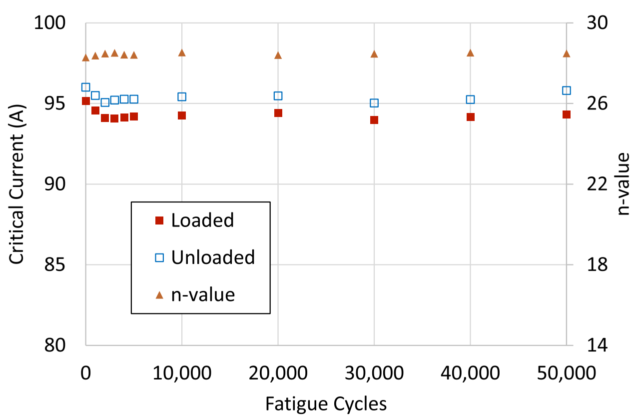

Fig. 10. Critical current and n-value of the MT coil during fatigue cycling up to 125 MPa.

(stress ratio of 0.1), This test includes a 25% factor of safety over the design load. The I_c for the incremental load steps to 125 MPa are shown in Fig. 9. At 125 MPa a permanent reduction in I_c of 1.1% is measured, with $I_{c0} = 97$ A. The n-value remained constant at 28.4 $\pm$0.2. Fig. 10 contains the I_c and n-value while cycling at 125 MPa. The permanent I_c reduced slightly to 1.2% but has an additional, recoverable, 1.6% reduction from sensitivity to the axial load. Testing ended to inspect the conductor after the 125 MPa cycling.

D. *Post-Test Inspection*

All coils were inspected following the tests. The STWC coil was highly deformed with the tapes flared out along one edge, around the full circumference, as if the coil had buckled. When unwound, the co-wind and REBCO tapes along the flared edge were highly deformed and cracked. The STNC coil had a similar pattern of damage. One edge of the tape had a wavy appearance as if it had yielded. Some edges had also burst, delaminating the REBCO tape, pictured in Fig. 11. There were no indications of damage to the MT coil. The REBCO and co-wind tapes remained flat and in very good condition.

It is important to note again that the pressure at 125 MPa is based on the area of the full coil windings. If only the REBCO tape area is considered the pressure is 244 MPa for the MT coil. This can be compared to the STNC coil at an average pressure of 150 MPa, or 233 MPa pressure on the REBCO tape. No observable damage was seen in the MT coil but severe damage was observed in the STNC coil. This difference must be attributed to the wax impregnation of the MT test coil. While wax has extremely low strength, it is captured between neighboring turns and can distribute the load into the co-wind tapes in a hydroscopic manner.

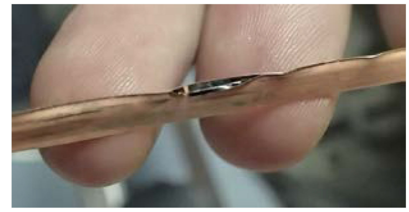

Fig. 11. A section of REBCO tape from the STNC coil showing high deformation and delamination along one edge.

The STWC attained a 2.6% permanent at 125 MPa and after load cycling to 100 MPa. Thus in comparison, the MT performed moderately better at 1.2%.

IV. Conclusion

This study has shown that the axial cyclic load limits of REBCO coils can exceed 100 MPa depending on the details of their construction. Three REBCO coils consisting of a single double pancake with various co-wind materials and dimensions were tested to high compressive, cyclic loads in liquid nitrogen. Of the three coils considered the one with stainless steel co-wind more narrow than the REBCO tape performed the worst because the loads were applied directly on the REBCO tape. The coil reached 5% permanent degradation of I_c at 95 MPa, prior to cycling at 100 MPa. The coil did not survive cycling at 150 MPa.

The axial load limit was shown to be improved with a coil comprised of stainless steel co-wind wider than its REBCO tape. A 5% permanent degradation was reached at 151 MPa and after load cycling 50000 times to 100 MPa. The coil was damaged as the pressure approached 200 MPa.

The wax-impregnated, two-in hand REBCO coil with copper and stainless steel co-wind showed only a 1.2% I_c reduction after load cycling to 125 MPa, which was the best performing under comparable loads. The inclusion of wax is attributed to distributing the loads more evenly into the co-wind materials.

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