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ROEBEL Assembled Coated Conductors (RACC): Preparation, Properties and Progress

W. Goldacker, A. Frank, R. Heller, S.I. Schlachter, B. Ringsdorf, K.-P. Weiss, C. Schmidt, S.Schuller

Abstract**—RBCO (*R*=Y or Rare Earth element) coated conductors (CC) are the most promising HTS materials for future high field coils operated at moderately high temperature (40-50 K) as is planned for the second generation of fusion reactors (DEMO) and beyond. A ROEBEL bar concept for a high current (kA-class) low AC loss cable is the most suitable assembling technique for conductors in magnet windings due to the flat rectangular cross section. The presented RACC-cable technique (RACC = ROEBEL Assembled Coated Conductors) works with pre-shaping of tapes into strands with the ROEBEL specific meander geometry. The usually very good bending properties of the CC support the assembling procedure of the RACC-cable. We report on a 16 strand RACC-cable with 19 cm transposition length made from CC material from the commercial supplier SuperPower which reached 1020 A transport critical current at 77 K (J_{eng} = 11.3 kAcm^{-2}). The basic properties of the virgin YBCO tapes and the shaped strands like orientation and field dependent transport currents, current homogeneity and bending effects, were investigated and correlated with the measured properties of the RACC-cable. Calculation of the self field effects by means of a model adapted to the specific RACC-cable geometry and in particular taking into account the current distribution in the cable, explained the 30% current reduction in the cable quantitatively.**

Index Terms— HTS Coated conductors, Roebel bar, self field effects

I. INTRODUCTION

COATED conductors (CC) are the second generation (2G) of HTS superconductors with the prospects to be finally 3-5 times cheaper than BSCCO tapes. In addition they have the potential of an application regime at significantly higher fields of a few TESLA at 77 K and in particular in the high field regime $B > 10$ T at temperatures around 50 K. Quite recently numerous results for CC with implemented artificial and tailored pinning sites demonstrate the potential for a significant improvement of the transport currents, the irreversibility field and the angular dependence and field dependence of the critical currents. This favors the prospects for the future preparation of optimized CC for the specific applications in windings of transformers, motors, generators and magnets. An important aspect however is that low AC loss modifications of the CC will be available and high current cable structures can be realized. High field coils from CC could benefit crucially from the elevated operation temperature compared to lHe and the resulting drastically lowered cooling costs. As a very important future large scale application, the possibility of HTS coils for Fusion reactors is already investigated, in particular for the next demonstration version DEMO following up ITER. For this purpose cables with an operation current of 30-70 kA are asked [1] and a first step towards a realization of such a cable is presented here.

Coated conductors are actually developed with a final tape width in the range of 4-12 mm and a thickness of approximately 0.1 mm applying a large variety of preparation methods and more or less complicated architectures of the layers. The actual global activities focus on getting high current densities over long lengths in a reliable way, on improving the preparation speed and on simplifying the architecture to fewer layers reducing costs and improving the overall production speed. Actually 322m tape length with 219 A/cm-w. (77K,s.f.) applying IBAD-MgO buffers and MOCVD YBCO coating are achieved [2].

Low AC loss versions and modifications of CC-tapes are still at the beginning. The high aspect ratio of the cross section of the YBCO layer causes hysteresis losses and asks for filamentary structures to reduce these losses. Striation experiments structuring the YBCO-layer by means of laser scribing or photolithography, already showed the expected effect on reduction of the AC losses by reducing the effective width of the superconducting layer [3]. A transposition of this filamentary structure has not been realized so far in the flat tape.

The application of CC in devices often requires higher transport currents than the actually reached 200-600 A/cm-width in single tapes. For motors, generators, cables and transformers, operation currents of a few kA are required and for future HTS fusion reactor magnets even higher currents are requested exceeding 30 kA. As a consequence a development of a high-transport-current low-AC-loss cable design with CC tapes as strands is needed. Very suitable for windings is the ROEBEL bar design, being invented by Ludwig ROEBEL in the year 1914 (patent application) to reduce AC losses in copper cables for generators. The flat ROEBEL bar design is in particular suitable for the application in windings where the cable experiences a bending

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W. Goldacker is with the Forschungszentrum Karlsruhe ITP, P.O. Box 3640, 76021 Karlsruhe Germany (corresponding author, phone: +49 7247 824179; fax: +49 7247 825398; e-mail: wilfried.goldacker@itp.fzk.de).

A. Frank, R. Heller, S.I. Schlachter, B. Ringsdorf, K.-P. Weiss, C. Schmidt, S. Schuller, are with the Forschungszentrum Karlsruhe ITP, P.O. Box 3640, 76021 Karlsruhe Germany

strain. The ROEBEL bar concept was already successfully applied as NbTi cable for the LCT-coil [4], a fusion reactor model coil, and as HTS BSCCO(2223) ROEBEL bar for use in a transformer [5]. Since coated conductor tapes possess equivalent limitations for in plane bending compared to BSCCO tapes, the new concept of pre-shaping the meander like ROEBEL strand structure from single CC tapes, followed by the assembling process to the RACC-cable structure (**RACC**=**R**OEBEL **A**ssembled **CC**) was introduced recently [ ]. In this paper a significantly improved second cable on the basis of MOCVD-CC from SuperPower will be presented.

II. EXPERIMENTAL

Key point of the RACC-idea is that CC can be mechanically cut into a ROEBEL strand shape. Cutting is already used in a similar way to split a broad coated conductor into narrower straight stripes. For the actual pioneering investigations, readily coated materials were used as starting materials which causes approximately 60% loss of material. Formerly THEVA ISD-MgO buffered DyBCO-tapes were used for the first cable (see details in ref. [6]). In this work IBAD-MgO-LMO buffered and Cu clad MOCVD-CC from SuperPower with a broader width of 12 mm and a thickness of 0.9 mm (50 µm Hastelloy, 70 nm buffer, 1 µm HTS and 20 µm surrounding Cu) were used. The strands with a length of 45 cm were cut from the CC tapes by means of a mechanical precision punch tool. A twist pitch of 190 mm was selected, the step over angle was 30°, and the strand width was 5 mm. The 16 prepared ROEBEL strands (figure 1) allowed sequential winding of the strands around each other by applying a kind of torsion bending. After assembling, the 16 strands of the RACC cable (figure 2) were soldered together at the ends over a section of 3 cm by means of a low temperature InSn solder. Connection to the current leads was performed with In press contacts. Between the current leads the loose strands were not insulated against each other. At the voltage taps all strands were connected with silver paste.

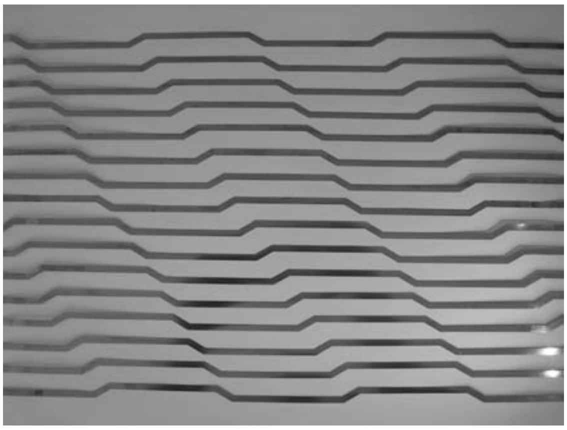

Fig. 1: 16 punched strands from MOCVD SuperPower coated conductor

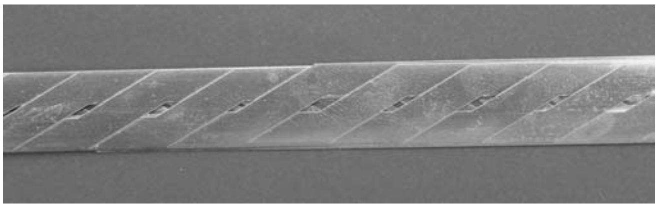

Fig. 2 View on a section of the assembled RACC-cable (width 12 mm)

Transport current data of the original 10 m long tape were supplied by SuperPower and before assembling the single strands to a cable the critical current of each prepared strand was measured. For 4 mm wide short CC tapes from a comparable batch we also measured transport current as function of applied field parallel and perpendicular to the tape surface (0-0.6 T, 77 K). Furthermore bending properties of the 4 mm wide CC tape were investigated by a continuous bending strain rig and were found to be excellent and compatible with the assembling procedure.

III. RESULTS

A. Bending measurements

The bending properties of the used CC were measured by applying continuous bending at 77 K [7]. The observed tolerable bending radius was > 11 mm (see figure 3) which can be correlated to a bending strain of 0.24% in the YBCO layer. This value is significantly smaller compared to other CC due to the 50 microns thin Hastelloy substrate and the Cu clad. In a second experiment torsion bending around the central tape axis was applied to a 5mm wide piece of the tape used to prepare the strands for the cable. The tolerable torsion angle was 20°/cm-length corresponding with 0.38% strain at the outer edge of the tape. This excellent bending performance of the tapes gave a large safety margin for the assembling process of the cable, which applies a mixture of torsion and bending to the strands during handling.

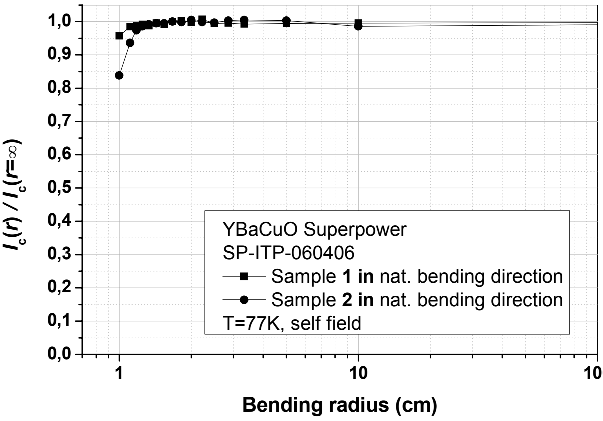

Fig. 3 Critical current of MOCVD SP CC with bending applied at 77 K

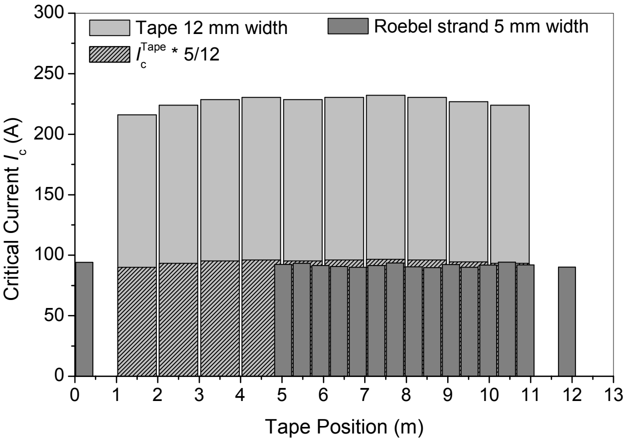

Fig. 4 Critical currents of original CC tape, measured on 1 m sections by SuperPower and of the corresponding ROEBEL strands measured over 38 cm length. Two strands were from end pieces being prepared in advance as feasibility test. Expected currents are indicated by 5/12 values.

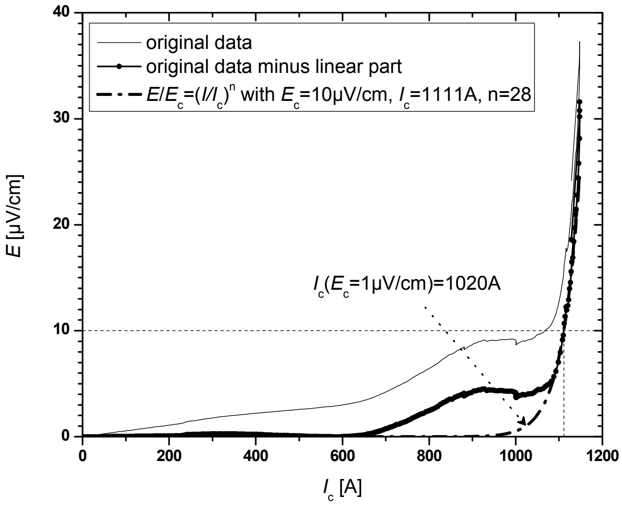

Fig. 5 $U(I)$ trace of the superconducting transition of the RACC-cable. A small linear resistive contribution was substracted before fitting a model transition curve.

B. Transport currents of tapes and strands

The transport current of the original 10 m tape length was measured by SuperPower on 1 m sections (see figure 4). An average critical current of I_c = 227 A (StDev. 2.1%) was found which corresponds to 189.2 A/cm-w.

For the cable, the critical currents of the 16 punched strands were measured over the whole length at 77 K (see figure 4). The average value was 91.7 A (StDev. 1.6%) corresponding to 183.4 A/cm-w. The material exhibits an excellent homogeneity with strand currents between 89.7 A and 94.2 A, which is expressed through the very low standard deviation of 1.6%. This also means that in average only 3% of the current carrying capability of the tapes was lost due to the shaping into the ROEBEL geometry, which can be explained by the accuracy of the strand dimensions and the not optimum current distribution at the edges of the step-over section. Although the punching opened the surrounding Cu stabilization layer, no de-lamination effects were observed, even after several cooling cycles. A correlation between tape and strand transport current is illustrated in figure 4.

C. Transport current of the RACC cable

The transport current of the RACC cable was measured using two pairs of voltage contacts, one being attached very close to the current leads (38 cm spacing), the second being attached 5 cm away from the current leads (28 cm spacing). The $U(I)$ graphs measured on both contacts showed slightly different shapes due to current redistribution effects but identical critical currents.

The transport critical current (inner contacts) was I_c=1020 A (1 µV/cm criterion), which corresponds to J_{eng}=11.3 kAcm^{-2}, which is 30.5 % less than the design value of 1467 A. This current value was determined by fitting a model curve to the $U(I)$ curve which was obtained by substracting a very small resistive ramp coming from the contacts from the original data (see figure 5). Above 700 A current redistribution leads to a small voltage signal. The n-value of the fitted curve is 28 which is similar to the n-value of the original tapes being 33 in average.

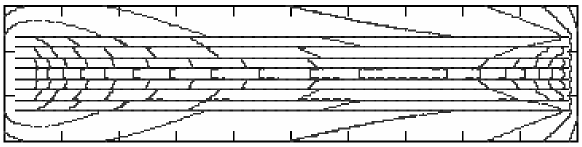

Fig. 6 Contour plot of the magnetic field in one stack (8 strands) in the background field of the parallel second stack (8 strands) separated by a gap of 2 mm. Stack cross section was 5 x 0.75 mm. Outer cable side left, inner cable side right.

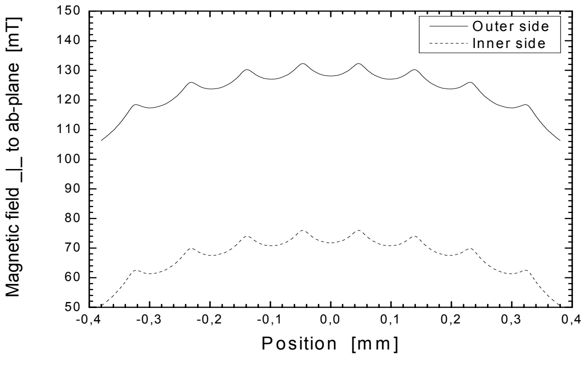

Fig. 7 Magnetic field perpendicular to the ab-plane of the tapes along the thickness of the stack at its inner and outer edge

D. Estimation of self field effects

To evaluate the magnetic self field, a simplified model of the RACC has been used. Two parallel stacks consisting of 8 YBCO tapes each, with a width of 5 mm, a height of 0.75 mm and a distance of 2 mm are used, the step over sections were neglected. Because the current of 91.7 A flows only in the

1 µm thick YBCO layer, the magnetic field calculations can only be done by using the Biot-Savart law and summing up the field contributions from the current carrying filaments. Figure 6 shows the contour plot of the magnetic field in one stack in the background field of the second stack. Figure 7 shows the magnetic field perpendicular to the ab-plane of the tapes along the thickness of the stack at its outer edges. The maximum and average magnetic fields were calculated in each individual YBCO layer. The resultant fields for the direction perpendicular to the ab-plane are $B_{\max}/I$ = 1.3239 mT/A, and B_{av}/I = 0.4603 mT/A.

Figure 8 shows the critical current of a 4 mm SuperPower CC as a function of the magnetic field perpendicular and parallel to the tape, being scaled up to the design current value of the RACC cable. The load-lines for the self-field-corrected calculated cable current are indicated for both, the maximum and the average magnetic field. The intersection of the load-lines with the $I_c(B)$ line gives the expected critical current of the RACC-cable. Using the average-field-load-line one gets a critical current of 1040-A whereas for the maximum-field-load-line, the corresponding critical current is only 736 A being much lower than the measured 1020 A. The average field approach leads to a very good and realistic description of the self field effects and has to be used for characterizing the RACC-cable transport current performance. The reason for this result can be explained by current redistribution taking place within each YBCO layer and between the tapes.

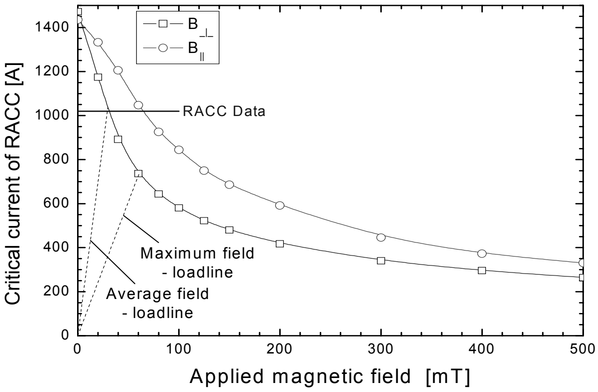

Fig. 8 Critical current of 16 tapes as used in the RACC as a function of the magnetic field and orientation (scaled up from single tape measurements) and the load line of the RACC for the maximum and also for the average magnetic field approach. The intersection with the $I_c(B^{\perp})$ gives the self field corrected transport current of the cable.

IV. DISCUSSIONS AND CONCLUSIONS

The RACC cable approach was successfully demonstrated with the second cable using an improved quality of Coated Conductors from SuperPower. The transport current reached 1020 A at 77 K, the 30% current degradation from self field influence could quite precisely be calculated applying a model based on a Biot-Savart law approach and taking into account current redistribution in the filament layers from the inhomogeneous self fields. An average value for the self field perpendicular to the cable surface was found to be the correct description, delivering with 2% deviation the measured transport current.

The presented cable length of more than 2 twist pitches demonstrates that a continuous cable production is possible. The scattering of the strand transport currents was equivalent to the current uniformity of the original CC tapes, which proves an excellent homogeneity of the basic tape and an absolutely reliable strand shaping technique. The tape bending performance is a crucial parameter and was found to be sufficient for a reliable non destructive assembling process. Compared to a ROEBEL approach on basis of BSCCO(2223) tapes [8], the presented RACC-cable surpassed the engineering current density of that cable by more than a factor of 2, showing the advantage from applying 2G HTS materials. Regarding the possible gain of current improvement of a factor of 3, demonstrated in short samples and an operation temperature around 50 K, a cable well exceeding 10 kA transport current should be possible. AC loss investigations are actually in work [9].

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