IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 5MY02 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)
The published version of this manuscript appeared in *IEEE Transactions on Applied Superconductivity* **19**, No. 3, Part 3, 3098 - 3101 (2009)

Improvement of superconducting properties in ROEBEL Assembled Coated Conductors (RACC)

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Abstract*— Assembling coated conductors (CC) into flat ROEBEL bars (RACC-cable) is a practicable method to reach high transport currents in a low AC loss cable design being suitable for windings. Electrical machinery as large transformers and generators/motors need a few kAmps. transport current. The aim of the presented work was demonstrating the possibility of a strong increase of the transport current of such RACC-cables, which was so far 1 kAmp. We present a changed cable design with 3-fold layered strands, an unchanged transposition pitch of 18.8 cm and finally application of 45 coated conductors in the cable. A 1.1 m long sample (equivalent to 6 transposition lengths) was prepared. Cu stabilized coated conductors purchased from SuperPower were used for formatting the ROEBEL strands and assembling the new cable. The new cable reached a record transport current of 2628 Amps. at 77 K in self field (5 µV/cm criterion). A special feature of the cable was the use of 3 slightly different current carrying (± 10 %) batches of strand material. Although current sharing and redistribution effects could be observed, the behavior of the cable was found as absolutely stable under all operation conditions. The estimation of the self field degradation of the critical currents, being of the order of 60% at 77 K could be modeled satisfactory by means of a Biot-Savart-Law approach.

***Index* AC losses, cable, coated conductors, high transport current, ROEBEL bar**

I. INTRODUCTION

The second generation (2G) HTS superconductors, the Coated Conductors (CC), are meanwhile available as industrial products in excellent quality, reaching critical transport currents up to 250-350 A/cm-width in long lengths. The available piece lengths of a few hundreds meters favors first applications in small devices as fault current limiters, motors and cables. For devices of electrical machinery, high amperage cables in the “several kA regime” are requested to meet the technical demands. In particular conductors or cables with low AC losses are requested. Hysteresis losses are the dominant component of the AC losses favored by the high aspect ratio of the flat CC structure. A filamentary structure of the YBCO layer, realized in first short CC samples, and additional transposition of the current percolation paths, not demonstrated with supercurrents so far, are necessary features of future coated conductors with much lower AC losses.

For high current AC cables equivalent features are asked scaled up to the cable dimensions. The ROEBEL bar technique [1], introduced for CC by assembling especially meander like formatted CC to the so called **RACC** conductors (**RACC** = **R**OEBEL **A**ssembled **C**oated **C**onductor), represents such a low AC loss structure in a high amperage cable [2]. It is the first concept providing fully transposed superconducting percolation paths in a flat cable structure made from CC. CC tapes possess strong inherent limitations for in plane bending, which limits cabling procedures, but are very rigid against out-of-plane bending and torsion bending [3]. The new concept of pre-shaping the meander like ROEBEL strand structure from single CC tapes, followed by the assembling process to the RACC structure, requires only a moderate twist-bending of the CC, solving the handling problems.

The first RACC-cables finally reached a DC transport current of 1.02 kAmps. at 77 K s.f. in a 0.36 m long sample made with MOCVD-CC from Superpower [4]. This cable already proves the principal capability of the concept. Strand coupling, thermal stability and balanced coupling losses between strands were already investigated recently with a specially prepared RACC sample using very high performance THEVA CC. The goal of moderate coupling of the strands was achieved [5]. First AC loss investigations were done identifying hysteresis and coupling loss contributions and indicating contributions from Eddy current losses [6]. But also a quite complex behavior of currents, current sharing and self fields in the actual RACC - cable design was recognized.

As a consequence of strong self field effects of 30% and more and further transport current degradation in external fields the need of drastically improved transport currents of RACC cables for the different applications at 65-77 K became a challenge.

In this contribution a progressed cable design is presented which focuses primary on a strongly improved

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Manuscript received 19 August 2008. This work was supported in part by the EU fusion programme.

We like to acknowledge fruitful discussions and support and provided informations from V.Selvamanikam (Superpower)

We appreciate valuable contributions and discussion from our collegues S.I.Schlachter, B.Ringsdorf and U.Braun

transport current as first step. An unchanged transposition width of 188 mm of the filaments was applied, but a longer cable length of now 1.1 m was prepared to match the specific test equipments in the lab. Increase of the filament number in the single strands was achieved with a stack of CC's. We used 3 CC tapes in each strand in the new approach (see Fig. 2.), which is not limited to this number, but increased the number of tapes in the cable from 16 to 45. One strand less in the cable compared to the former one should avoid problems from strain hot spots in the step over sections. The aspect ratio of the sample was reduced by approximately a factor of 2.5 which is favorable for lowered AC losses

Fig. 1. CAD drawing of a ROEBEL-cable made from 16 strands. One strand is colored to illustrate the full transposition of the strands

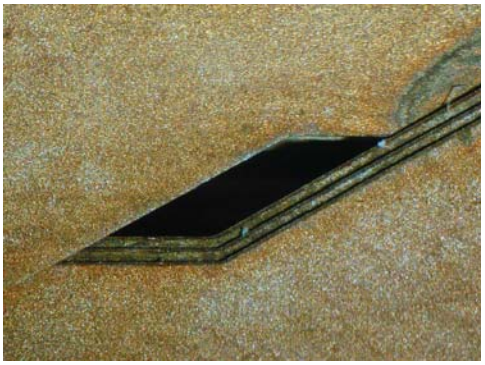

Fig. 2. Detail of the ROEBEL cable in the step-over regime showing 2 details, first the 3-fold CC-stacking in one strand, second the very precise punched edges of the CC achieved by means of the PPP (precision punching process). The shown section is approx. 6x8 mm.

II. EXPERIMENTAL

TABLE 1 Data of used CC from SuperPower

	CC batch A	CC batch B	CC batch C
Length	**20 m**	**20 m**	**10 m**
Width	**12 mm**	**12 mm**	**12 mm**
Thickness	**0.088 mm**	**0.091 mm**	**0.093 mm**
I_c (77 K , s.f.) average (1 µV/cm criterion)	**391 A ± 0.8%**	**333 A ± 4.5%**	**346 A**
I_c of strand (calculated as 5/12 of CC)	**162.9 A**	**138.7 A**	**144.2 A**
No. of ROEBEL tapes	**18**	**18**	**9**
No. of ROEBEL strands (3 tapes)	**6**	**6**	**3**

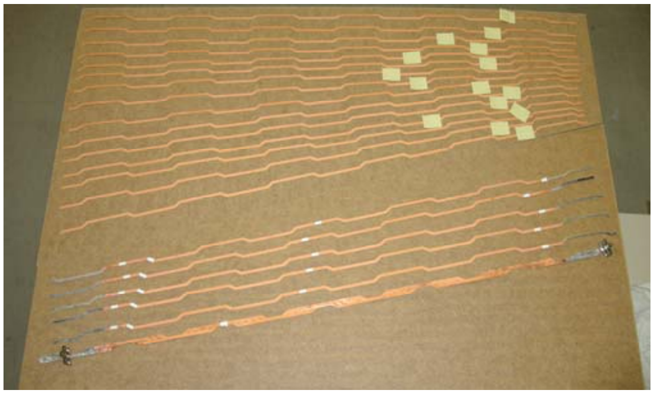

Fig. 3. Punched coated conductors (15 samples topside), assembled 3-fold strands (5 strands middle) and 1/3 assembled RACC-cable (front side)

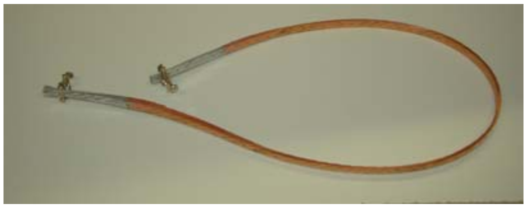

Fig. 4. Assembled RACC-cable with 1.1 m lengths and pre-tinned strand ends

The principal of the RACC design and the preparation scheme of RACC cables was already presented in recent papers [2,4] and is shown in the CAD design in figure 1 with one strand drawn in bold illustrating the transposition. A precision punching process (PPP) was qualified forming the CC to the meander like ROEBEL shaped strand. PPP provides very sharp cutting edges, shown in the cable detail of Fig.2, with a minimum damage to the coated layers and provides a geometrical accuracy of 1% of the punched strand width of 5 mm. [7]. This is significantly less than is caused by the current reduction of 3% after punching [4].

The new RACC cable was prepared from three batches A (20m), B (20m) and C (10m) of significantly improved 12 mm wide CC of SuperPower (60% higher transport currents compared to the former cable) with the standard 20 microns copper stabilization applied around the tape. The batches gave 18 + 18 + 9 ROEBEL shaped tapes, a 3-fold CC stack forming a strand. The average transport currents of the original CC were 332 – 388 Amps (1 µV/cm criterion, measured on 5 m sections by SuperPower) as summarized in table 1. The RACC strand width 5 mm, the transposition section with an angle of 30° and the transposition pitch of 188 mm were kept unchanged and the assembling procedure was done in a sequential kind, adding one strand after the other to the RACC cable assembly. The assembled RACC-cable was 110 cm long, which is approximately equivalent to 6 transposition lengths. ROEBEL formatted CC, strands and the partly assembled (1/3) cable are shown in the photograph of Figure 3. The final assembled cable is shown in Fig. 4. No inter-strand connection was applied to the cable section between the current clamps.

Transport currents of the single strands were not measured before performing the cabling process, since all CC data indicate a similar good performance of the CC homogeneity as in the earlier cable in reference [4]. The cable current was measured in atmosphere pressured lN_2 and self field on 3 selected strands (one each from Batch A, B, C) applying a 1, 3 or 5 μV/cm criterion. A cable section is shown in Figure 7 in the test rig. Voltage potentials were attached on the three selected strands over 3-4 transposition sections.

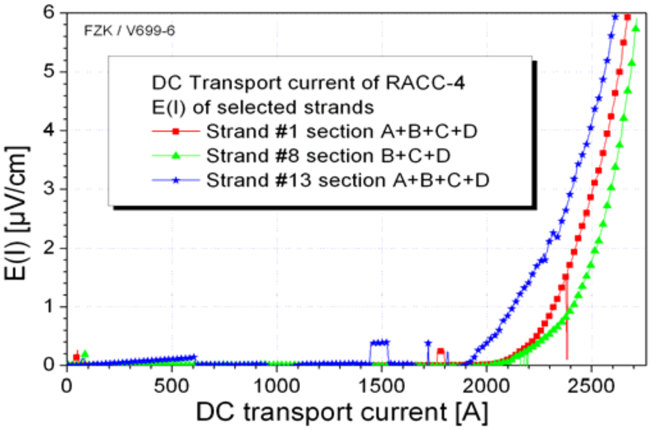

Fig. 5 Transport measurement on the RACC-cable. Voltage was detected at strand No. 1, 8 and 13, over a length of 3-4 transposition pitches (A, B, C, D)

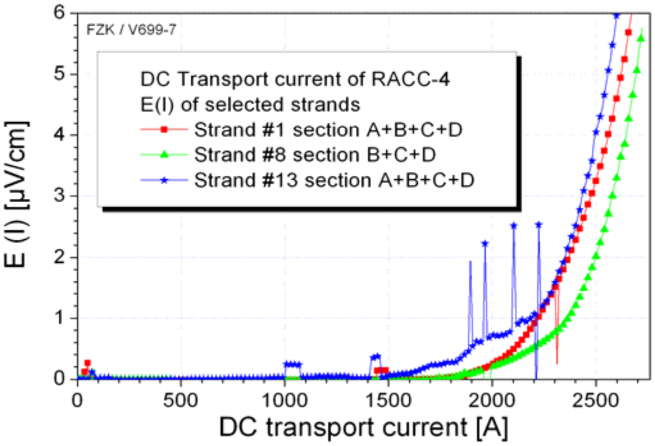

Fig. 6. Critical current measurement on RACC cable in equivalent arrangement as for Fig.5 after one warm-up cycle.

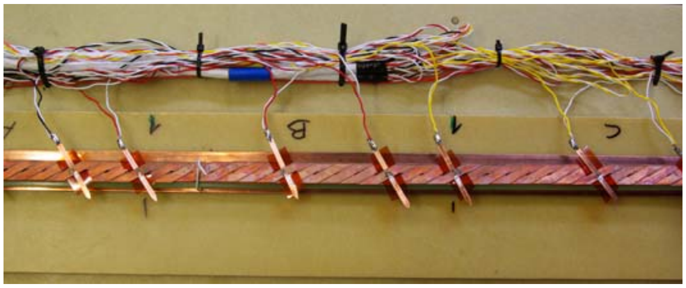

Fig. 7. RACC-cable with voltage taps on selected strands. Below the cable and insulated from the cable by Kapton foil a copper shunt is applied for quench protection

III. RESULTS

A. *Critical Currents*

Detecting the *E(I)* transition on the three selected strands, shown in Fig.5, gave slightly different current values, indicating the influence of current distribution and sharing among the CC,. The cable current was defined as the average of all three measured strands, the Cu bypass current was taken into account. Transport currents of 2290 Amps. (1 μV/cm criterion), 2500 Amps. (3 μV/cm criterion) and 2628 Amps. (5 μV/cm criterion) were achieved in self field at 77 K (see Fig. 5). The deviation between the strands depends on the criterion and was approximately ±60 Amps. (±2.3%) deviating from the mean value applying the 5 μV/cm criterion. Since current redistribution effects contribute to voltages of a few μV, the 5 μV criterion was used as relevant criterion for the cable current. The current measurement was reproducible after a cooling cycle, only the current redistribution behaves slightly different obviously from locally changed inter-strand contact between the loose packed strands (see Figure 6). Current redistribution effects in the cable and the situation in the current grips occur to be very complex and are under investigation in more detail and will be presented in an upcoming extended paper [8]. Steps or spikes observed in the *E(I)* graphs are also attributed to sudden changes of inter-strand contact in the loose cable packing, when the Lorentz forces increase with ramped current. The measured $I_c = 2628$ Amps. transport current correspond to an engineering current density of the whole cable cross section of $J_c^{eng}.= 9.53$ kA/cm^2.

B. *Modelling the self field effects*

The self field effect causing current degradation was modeled in an identical approach applied for the earlier 1.02 kA – cable in ref. [4]. The calculations use the Biot-Savart-Law formulism and are made in an iterative approach. A simplification of the model is the restriction to 2 stacks of strands neglecting the contributions of the ROEBEL step over sections which is a low field regime with negligible influence (see Hall-probe scans in ref. [9]) on current performance of the cable. Therefore 3-fold CC are regarded as 3 stacked strands, which gives stacks of 21 and 24 “strands” in the idealized RACC cable with overall 45 CC.

The modeling results are represented as field distributions in one stack (one cable side) in the self field of the other stack located virtually on the right side (Figure 8). The highest value of the self field component perpendicular to the cable surface is now found in the outer volume of the stack itself close to the side surface of the cable in contrast to the earlier cable [4]. The maximum value was more than doubled to a peak field of about 280 mT at the outside edge of the stack.

Load lines of the cable were calculated from the model. An earlier measurement of I_c of a single SuperPower CC in the two external field orientations was used [4], extrapolating the graphs to the design value of the cable, in this case being 6727 Amps. (design value = sum of strand currents). The cross-over points for the load lines with the current vs. field graph are shown in Figure 9. The cable behaves between the average perpendicular field load line $\langle B_{perp.} \rangle$ and the maximum perpendicular field load line $B_{\mathrm{max..}}$ In the former 1.02 kA RACC cable (ref. [4]) a perfect match of the average field approach to the observed data was found. The deviation in this new cable may be attributed to some simplifications as the loss of transport current from strand punching which was not taken into account. Additional significant corrections may occur from the moderate different batch performance of the used CC and the consequences on the self field. Further a changed $I(B)$ profile of the used CC cannot be excluded, a reference graph was not available until the papers deadline. However the model could also explain in this case the 60% self field degradation of the critical currents satisfactory.

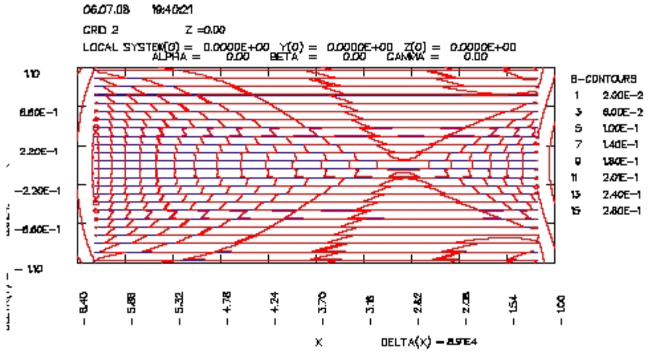

Fig. 8 Modeled self field distribution in one half of the RACC-cable (left cable side). Explanation see text

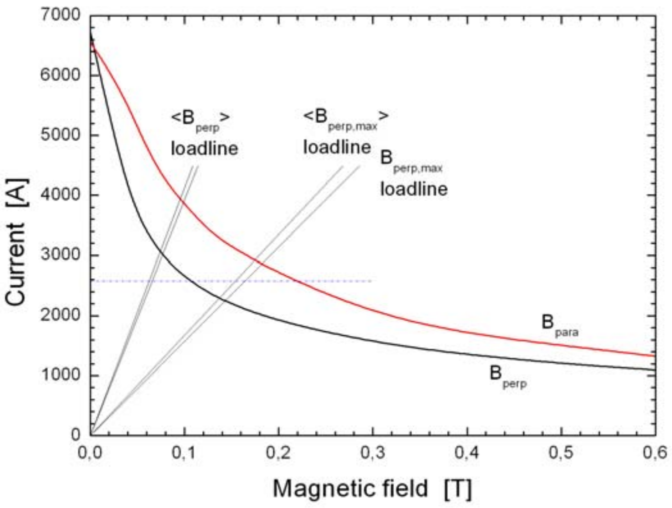

Fig. 9 Load lines from modeling the self field effects on the degradation of the critical currents. The design transport current 6727 Amps in s.f. was calculated from the expected strand currents, the field dependency was measured on a single CC from Superpower [4].

IV. CONCLUSIONS

It was the priority aim of this work to demonstrate the increase of the current carrying potential of the RACC cable applying an upgraded design and proving the reliability of the production technique. The successful realization of a 1.1 m cable of the 2-5 kA class of RACC-cables could be achieved with a modified cable design, applying 3-fold strands. The achieved transport current level qualifies the RACC-cable already for many applications. The 1.1 m long RACC-cable shows a complex current redistribution, sharing and feed-in effects which need further detailed investigations being actually under way that will published very soon [8]. This upgraded cable design can provide even significantly higher transport currents by further increasing the number of CC in the strands even with unchanged transposition length or with the option extending the transposition pitch too. Supposition is a CC with minimized thickness as in the architecture of the MOCVD-CC from Superpower to facilitate the assembling of the cable. The decrease of the cable aspect ratio in the new RACC cable design favors significantly lower AC losses.

In future in addition lower AC losses are requested. One way is to reduce the ROEBEL bar width [10,11], the other is the application of a filament structure in the YBCO layer made by striations, which is still a big challenge and will be one of the new features of the next generation RACC-cables actually being under investigation. A further reduction of the AC losses scaling with the filament number in the strands is expected.

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