Roebel Assembled Coated Conductor Cables (RACC):

Ac-Losses and Current Carrying Potential

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Abstract - **Low ac loss HTS cables for transport currents well above 1 kA are required for application in transformers and generators, and are also taken into consideration for future generations of fusion reactor coils. Coated conductors (CC) are suitable candidates for high field application at an operation temperature in the range of 50 to 77 K. Ac field applications require cables with low ac losses and hence twisting of the individual strands. We solved this problem using the Roebel technique. Short lengths of Roebel bar cables were prepared from industrial DyBCO and YBCO-CC. Meander-shaped tapes of 4 or 5 mm width with twist pitches of 123 or 127 mm were cut from the 10 or 12 mm wide CC tapes using a specially designed tool. Eleven or twelve of these strands were assembled to a cable. The electrical and mechanical connection of the tapes was achieved using a silver-powder-filled conductive epoxy resin. Ac losses of a short sample in an external ac field were measured as a function of frequency and field amplitude. Coupling current decay time constants were also measured. We discuss the results in terms of available theories and correlate time constants measured in transverse field with measured coupling losses. Finally the potential of this cable type for ac use is discussed with respect to ac losses and current carrying capability.**

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I. INTRODUCTION

Coated conductors (CC), the second generation of high temperature superconducting tapes are, at present, the most promising candidates for ac applications like transformers, motors, generators and magnets for fusion research. Coated conductors can be used at 77 K in magnetic fields of a few Tesla and at temperatures around 50 K in high fields above 10 T. Recent results showed the potential of high critical currents (more than 700 A at 77 K in self field) and of sufficient long lengths (several hundreds of meters).

The main challenge is still, for many applications, the high necessary transport current in the kA range, which requires fabrication of cables with sufficiently low ac losses. However, cabling of flat CC tapes with a reasonable twist length is not possible. We solved this problem using the nearly 100 year's old invention of Ludwig Roebel introduced for ac loss reduction in copper cables. We assembled pre-shaped meander-like tapes into the RACC cable structure (Roebel Assembled Coated Conductor). The tapes were then impregnated with a conductive epoxy resin, which allows current redistribution between tapes and assures mechanical stability.

We prepared short lengths of cables using industrial tapes of two manufacturers. We measured critical currents of all individual tapes, contact resistances between tapes via the conductive epoxy, ac-losses and coupling current time constants of the final cable samples.

II. PREPARATION OF ROEBEL CABLE SAMPLES

Coated conductor tapes are cut into the meander-shaped Roebel strands shown in Fig. 1, using a mechanical precision punch tool. For the actual preparation of short samples of cable, commercially available coated tapes of two manufacturers were used. Punching the strands leads to a ~60% loss of material, which is acceptable for preliminary investigations. DyBCO-tapes on 90µm Hastelloy substrate supplied by THEVA are produced by the ISD (Inclined Substrate Deposition) - MgO + TCE (Thermal Co-Evaporation) method. The YBCO-tapes on 50µm Hastelloy substrate from SuperPower (SP) are made by the IBAD (Ion Beam Assisted Deposition) - MgO + MOCVD (Metal-Organic Chemical Vapor Deposition) method. The SP tapes are stabilized with a 20 µm Cu-layer electroplated on both sides.

Eleven or twelve strands are then sequentially wound around each other by applying kind torsion bending. Geometrical parameters of strands and cable samples are listed in Table 1. During assembling, the tapes are impregnated with a silver-powder-filled conductive epoxy and pressed in a Teflon mould during curing. This assures the mechanical stability and allows the current to redistribute between strands which is necessary for a stable operation in magnets. The resistivity of the epoxy was measured to be 1.26 µΩm at 77 K. This is high enough to limit the coupling losses between strands.

The ends of the strands were left unimpregnated. They were supplied with current and voltage taps (two per strand for Theva, only one for SP-sample) for measurement of contact resistances between strands. After this measurement, the non-impregnated ends were cut and a completely impregnated sample of cabling length *L* was subjected to the ac-loss and time constant measurement.

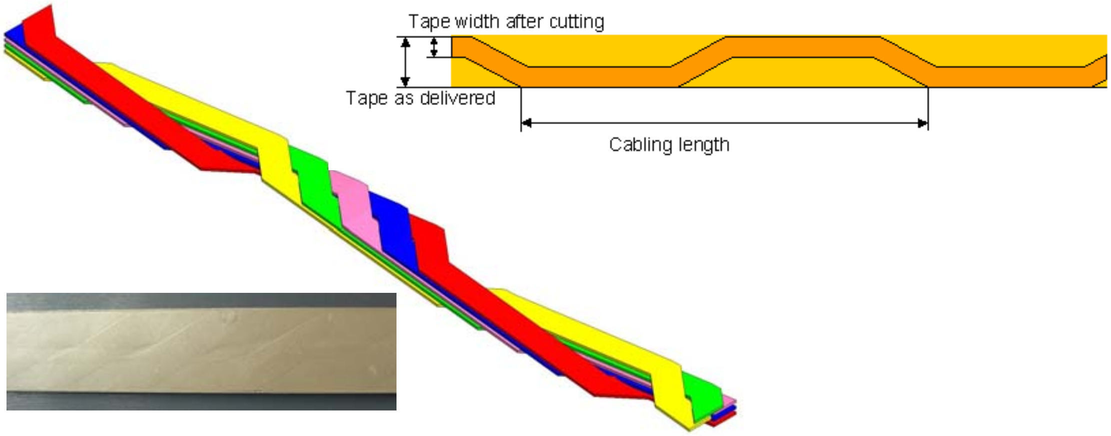

Fig 1. Meander geometry of the Roebel strand, the assembled cable (schematic, for clarity with only part of the strands) and the surface of the epoxy impregnated Roebel cable.

Table 1. Basic DyBCO and YBCO tapes and geometry of Roebel cable

Manufacturer	**Theva (**DyBCO)	**SuperPower** (YBCO)
Original tape width × thickness Mean I_c, self field at 77 K	10×0.1 mm² 317A ± 12A	12×0.1 mm² 230A ± 5A
Meander shaped strands width Mean I_c, self field at 77 K	4 mm 99.7A ± 9.5A	5 mm 89.5A ± 1.7A
N° of tapes in cable N	11	12
Cable cross section $d{\cdot}h$	10×0.9 mm²	12×0.8 mm²
Cabling (= sample) length L	123 mm	127 mm

III. MEASUREMENTS OF CRITICAL CURRENT AND RESISTANCE

A. Critical Current of Tapes

Critical currents of the original tapes and of the meander shaped strands are measured in self field at 77 K, see Table 1. The tapes of both manufacturers showed a good homogeneity of critical currents before and after cutting, which is expressed through a low standard deviation of <10 %. Between 7 % (SP) and 26 % (Theva) of the current carrying capability of the tapes was lost due to shaping into the Roebel geometry. Only ~1.5 % degradation can be attributed to the punching precision, higher values of degradation result from local inhomogeneities of the tapes.

B. Contact Resistances Between Tapes

The contact resistances between strands (through the conductive epoxy) were measured by a four-wire measurement at 77 K on the Theva cable. The measured mean resistance between neighbouring strands for the 123 mm long sample of was 30.7 µΩ ± 22% standard deviation; between nearly opposite strands it was 54.6 µΩ ± 4% (due to the odd number of strands no exactly opposite strands existed). For the SP sample only the measurement of voltage drop between strands was performed with a measuring current between opposite strands. Therefore, the results are not directly comparable with those on the Theva sample. A comparison with the result of the same kind of measurement on the Theva sample shows, however, that the resistance values between strands should be similar within ~20% for both sample types.

For the Theva sample, the electrical contact is only possible at the tape edges via the conductive epoxy, since the buffer layer within the tapes is an insulator. In the case of the SP tape the 20 µm copper layer connects superconductor and substrate at the non-punched edges. The interstrand resistance determines the coupling losses. Adjusting the resistivity value of the conducting epoxy could help to optimize cables for ac-application with respect to coupling losses and stability.

IV. MEASUREMENT OF AC LOSSES

A. Hysteretic Losses

The measurement was performed using the standard ac-loss magnetization measurement technique with a pick-up coil and a compensation coil. Absolute loss values are obtained by a calorimetric calibration, for details see [1]. Fig. 2 shows the loss function $\Gamma(B_0) = \mu_0 Q/(2B_0^2)$, where the energy loss per unit volume and per cycle, Q, is related to the total cable volume and B_0 is the magnetic ac field amplitude perpendicular to the wide face of the cable. The plot shows that for both samples the losses only slightly increase with frequency f, the contribution of coupling losses is therefore small and the main loss component is given by the hysteretic losses in the superconducting layer of the tapes.

The maximum of $\Gamma(B_0)$, $\Gamma_{\max}$, is a factor of 1.65 higher for the SP-cable sample, as can be inferred from the 10 Hz data where the coupling losses are almost negligible. According to the theory of Brandt and Indenbom [2] for a thin (nearly two-dimensional) superconducting layer, hysteresis losses result in $\Gamma_{\max} = 0.2917\ d/h$ (d = width, h = thickness of the layer). Applying this model with our tape dimensions and accounting for the different N and the different volumes of the samples, gives a ratio of 1.3 between both values of $\Gamma_{\max}$. The agreement with the measured factor is only qualitative due to the bulky geometry of the cable samples. The same remark holds for the position of the maxima, calculated to be at $B_{0\max} = 2.464\ \mu_0\ I_c/(\pi\ d)$. This relation yields for the two samples the $B_{0\max}$ ratio of 1.34, while the measurement gives ~ 1.5.

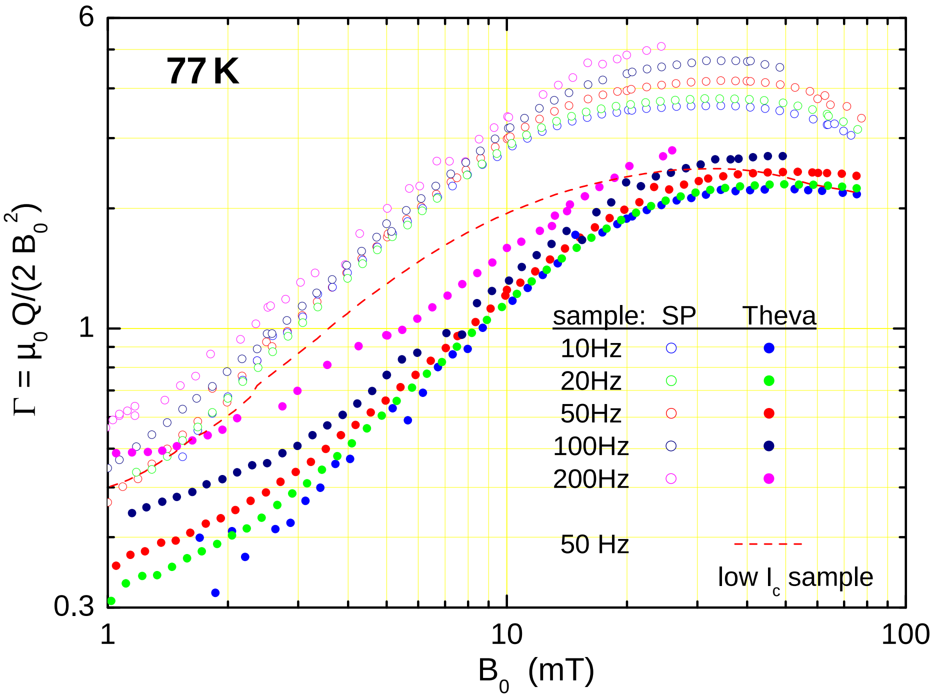

Fig 2. Loss function vs. ac-field amplitude, with the frequency as a parameter for both cable samples. $\Gamma(B_0)$ is related to the total volume of the samples. For comparison data of a preliminary sample with a critical current lower by a factor of ~2 are shown [3].

B. Coupling Losses

The frequency dependence of total losses divided by B_0^2 is plotted in Fig. 3. Under the assumption of constant hysteresis losses for given B_0 the slope of the curves yields the coupling losses Q_c, which are in a first approximation expected to be $Q_c \propto f B_0^2$ for $2\pi f \tau \ll 1$, where τ is the coupling current time constant. However, this correlation doesn't fit the data properly. In the frequency range below ~100 Hz, where the losses are roughly linearly increasing with f, the slope increases with the field amplitude. This is attributed to the increase of the effective permeability of the sample, μ_{ef}, with B_0 [4].

Figure 4 shows the coupling losses at 50 Hz, calculated as $Q_c = Q(50\text{Hz}) - Q(f \rightarrow 0)$. Coupling losses are expected to be proportional to the squares of cabling length and cable width. The SP data are therefore normalized to the Theva sample geometry by multiplying with the ratio of $d^2 \cdot L^2$. The normalized losses of the SP-sample are still above the Theva-sample values, which might be attributed to the stabilizing Cu-layers on the SP-tapes.

Above the penetration fields of ~33 mT and ~50 mT (B_{0max} of the $\Gamma(B_0)$ curves in Fig. 2), Q_c/B_0^2 tends to approach constant values for both samples.

We should mention that the assumption of constant hysteresis losses per cycle is a strong

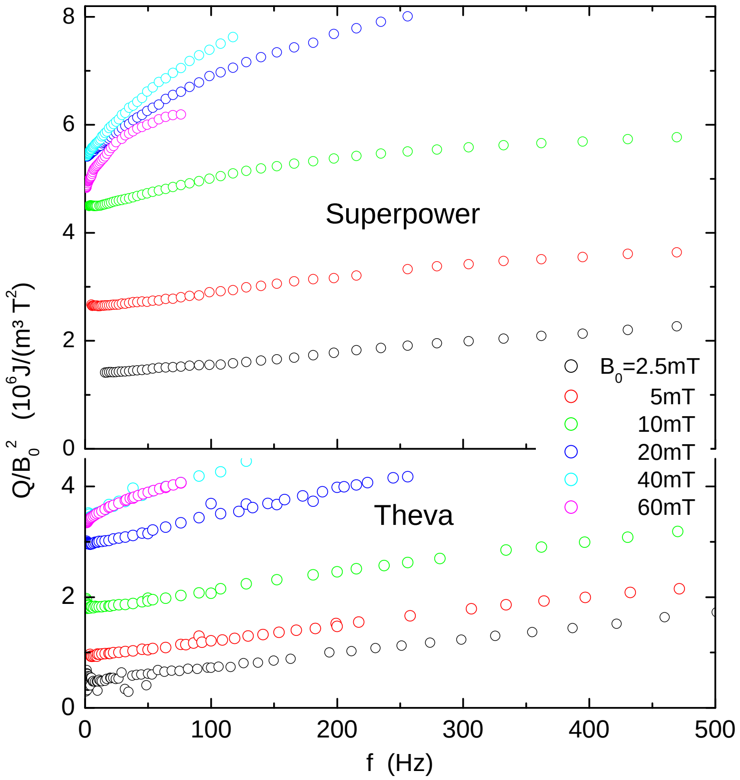

Fig 3. Total cable losses divided by B_0^2, in order to remove most of the field amplitude dependence, as a function of frequency. The amplitude of the ac field is the parameter.

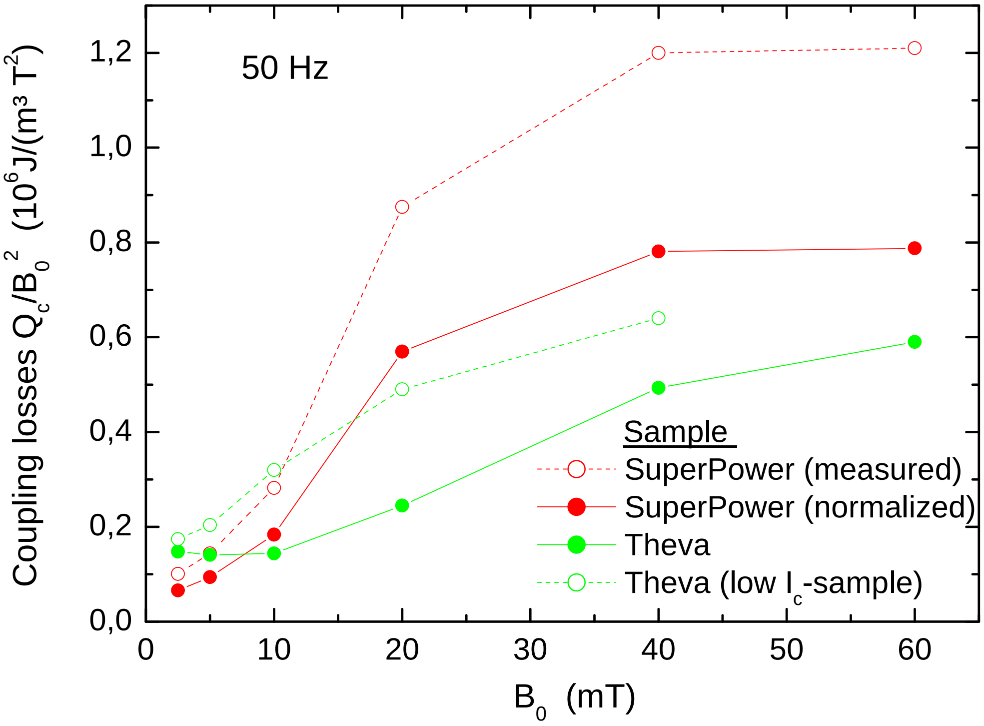

Fig 4. Coupling losses at 50 Hz divided by B_0^2 vs. field amplitude. The SuperPower data are normalized to the Theva sample geometry in order to account for the larger cable width and cabling length. For comparison data of the low I_c sample [3] are also shown.

simplification. Hysteresis losses decrease with increasing frequency due to the shielding effect of coupling currents, which explains the nonlinearity of the Q/B_0^2 curves in Fig. 3 for higher frequencies. Therefore, the separation of total losses in coupling and hysteresis losses is a valid approach only for $2\pi f \tau \ll 1$.

V. COUPLING CURRENT TIME CONSTANTS

Coupling currents are induced in the cable samples by a half-cycle sinusoidal field pulse. A compensated pick-up coil records their decay after the end of the field pulse [1]. Measured time constants are shown in Fig. 5 as a function of the field pulse amplitude. A dependence on B_0 is expected due to the increase of the effective permeability with B_0 [5]. Time constants of $\tau \sim 0.1$ ms and 0.15 ms for $B_0 \rightarrow 0$ can be extracted for the samples.

The correlation between coupling losses and time constant is given, for $2\pi f \tau \ll 1$, by $Q_c = 16n(\mu_{ef}/\mu_0) f B_0^2 \tau$ [6], where the shape factor n can be calculated to be 12 and 16 for the Theva and the SP samples, respectively. We cannot easily calculate the effective permeability of the samples $0 < \mu_{ef} < 1$, but we may use the data of Fig. 4 and the above correlation to estimate the range of μ_{ef}. We obtain values of μ_{ef} between 0.07 for small field amplitudes and 0.78 for full penetration which seems to be a very plausible result.

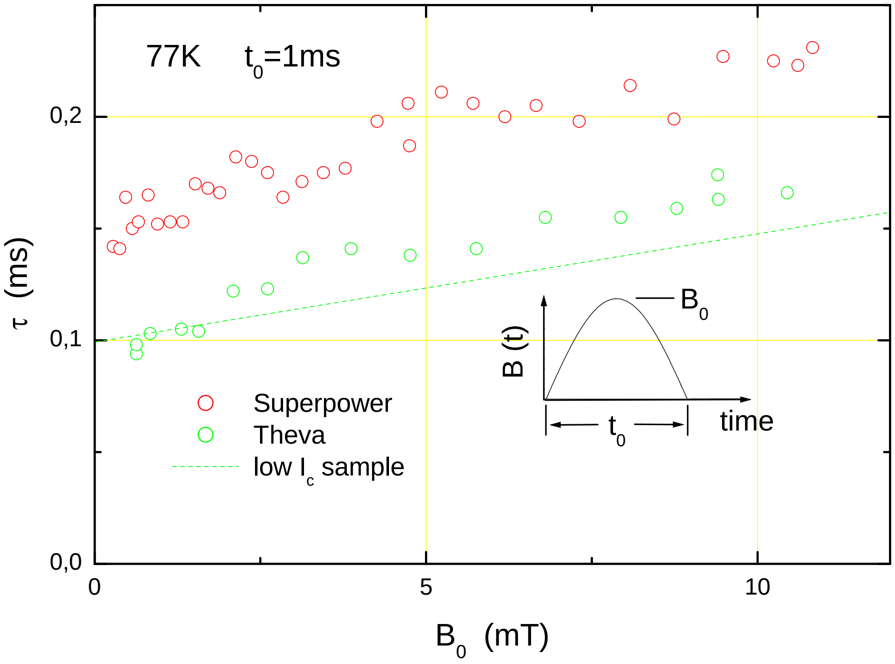

Fig 5. Coupling current time constants as a function of the amplitude of the half cycle magnetic field pulse inducing the coupling currents. The dashed line gives the result of the low I_c sample [3] for comparison.

VI. OUTLOOK FOR ROEBEL CABLES

The concept of structuring CC tapes to a Roebel strand and assembling a number of strands into a cable is the first approach to attain high transport currents and a low ac-loss structure in a flat cable suitable for windings. The number of strands can easily be increased to a multiple with longer cabling length. With the actual CC performance a transport current of a few kA at 77 K in low field with a cabling length below 1 m seems to be possible, with a further significant current increase when operating at 64 K.

Let us consider as an example a Roebel cable made of 30 tapes of 5 mm width each. Since the cabling length is roughly proportional to the number of strands N, we obtain a value of $L \sim 32$ cm. Coupling losses, which are expected to be $\propto L^2$, are therefore a factor of ~6.5 higher compared to the actual SP sample, while hysteresis losses, which are proportional to N, are increased by a factor of 2.5. At the frequency of 50 Hz hysteretic losses represent thus still the main loss component, please refer to Figs. 3 and 4. A striation of the tapes would therefore be indicated in order to reduce the hysteresis losses.

The critical current of such a cable as a function of temperature and magnetic field was extrapolated from measured single tape data [7] to tapes with a critical current of 500 A/cm-width at 77 K in self field. Tapes with such I_c values and sufficient lengths are expected to be commercially available in the near future. Figure 6 shows, under these assumptions, the

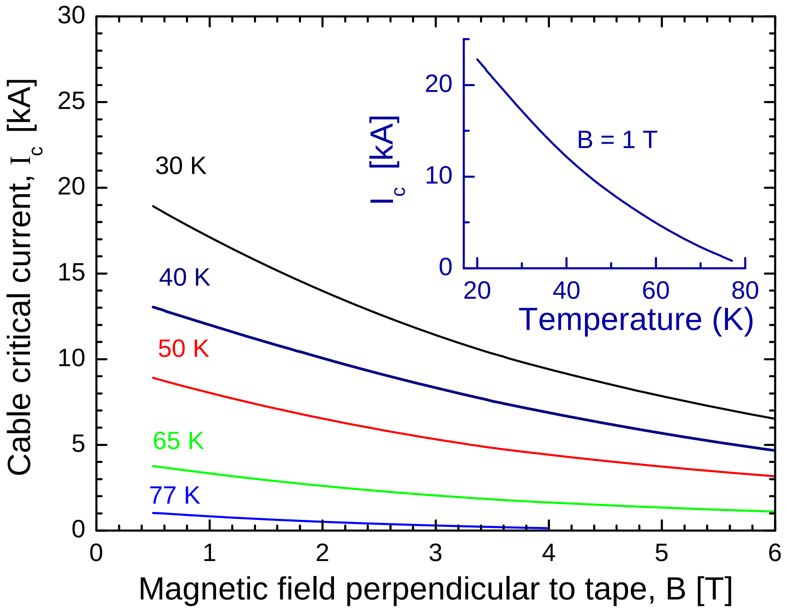

Fig 6. Calculated critical current of a Roebel cable made of 30 YBCO coated conductor tapes *vs* magnetic field for different temperatures. The values are extrapolated from single tape data to a critical current of 500 A/cm-width at 77 K and self field. The inset shows the calculated critical current as a function of temperature in a background field of 1 T.

calculated critical current as a function of perpendicular field for different temperatures. The inset of Fig. 6 is a plot of critical current at 1 T as a function of temperature. It shows that a cable of the 1 kA class, operating at 77 K appears to be feasible. Such cables are useful for electro-technical devices as transformers and motors/generators.

If either a higher cable current or higher magnetic field is required, the operation temperature has to be reduced. Figure 6 shows that I_c increases by more than an order of magnitude in the temperature range between 40 and 50 K, compared to the 77 K values. Even at 65 K, which can be obtained in a liquid nitrogen bath at reduced pressure, the increase of I_c is still more than a factor of four. Another possibility would be a further increasing of N. The assembly of 100 tapes does not seem impossible in a cable of ~12×12 mm^2 cross section and a cabling length on the order of 1 m.

For future fusion magnets with required coil currents of >30 kA at 64 K, operating in typical background fields of 12–15 T, a Roebel cable of the design presented here and with actual CC performance seems not to be possible and new approaches are required.

As we have shown, hysteresis losses are still dominant in the Roebel cable at 50 Hz. Future CC tape generations will perhaps have striated multiple layers for further reduction of hysteresis losses. The problem is the twist of striations with superconducting interconnections at the tape edges. Such twist is necessary to avoid additional coupling losses in the tapes.

An increase of critical current can be achieved by enhancing the irreversibility field and by reducing the anisotropy. It has already been demonstrated in laboratory scale conductors that tailored flux pinning reduces self-field effects and can significantly contribute to an increased current carrying capability.

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