

AC loss in pancake coil made from 12 mm wide REBCO tape

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Abstract— The design of a superconducting coil from high performance REBCO coated conductors is often complicated because of the complex anisotropy of the critical current density, J_c . It is important to understand how much in detail this feature must be taken into consideration in the prediction of maximum achievable current and the expected AC loss. We present the results of investigation performed with a small (10 turns, 60 mm inner diameter) coil made from SuperPower tape of 12 mm width. The knowledge of $J_c(B, \theta)$ determined on short sample allowed to predict the maximum achievable current of the coil and the AC loss behavior with surprising accuracy. We have also investigated the effect of a tape non-uniformity. Our results confirm that the lateral non-uniformity when J_c at tape edges is lower than in its centre leads to significant increase of AC loss. A longitudinal non-uniformity, in particular the reduction of critical current in some portion along the tape length is hardly observable in AC loss result. Regarding the achievable coil current only the innermost turn is critical, thus using a piece of tape with lower J_c there would significantly reduce the maximum current. We present also calculations showing the change in current-voltage curve and redistribution of AC dissipation in the case of non-uniform tape quality.

Index Terms—superconducting magnets, high-temperature superconductors, AC losses, numerical computations

I. INTRODUCTION

COATED conductor (CC) tapes from high temperature superconductors (HTS) are more and more available in lengths and amperages that allow considering a replacement of copper electromagnets in different kinds of electric power devices (transformers, motors) by coils from HTS CC. There are several significant differences between these two materials (working temperature, shape and sensitivity to mechanical strain, ...). From the electromagnetic point of view the HTS material is completely dissimilar to a normal metal that is well characterized by its electrical resistivity. The conductivity of HTS depends in highly non-linear way on the electric and magnetic field and thence the distribution of current is

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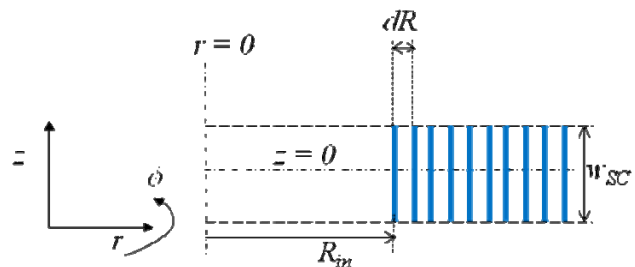


Fig. 1. Photograph of the coil (top) assembled with current leads and voltage taps and (bottom) its geometry used in calculations: $R_{in} = 60$ mm, $dR = 0.4$ mm, $w_{SC} = 12$ mm. Number of turns is 10.

generally non-uniform. As a result the procedure of designing a coil from HTS as well as the interpretation of results from its experimental testing requires particular rules to be obeyed. We illustrate this approach on the example of a small coil (10 turns, inner diameter 60 mm) made from 12 mm wide CC tape [1]. Individual turns were insulated by textile tape 0.25 mm thick and then the winding was impregnated by polyesterimide resin dissolved in styrene [2]. The winding was self-supported – Fig. 1 - but to some extent deformable without damage. We assume that CC tapes did not experience significant mechanical load during thermal cycling.

Coated conductor coils have been the object of study of several works, either by measurements [3, 4, 5, 6, 7] or computations [4, 6, 7, 8, 9, 10]. However, the effect of degradation of the tape across its width or its length has not been studied. This article not only presents such study but also a full systematic for the characterization and numerical simulation of pancake coils.

In the first part of the paper we show how the coil performance can be predicted from the data obtained on a

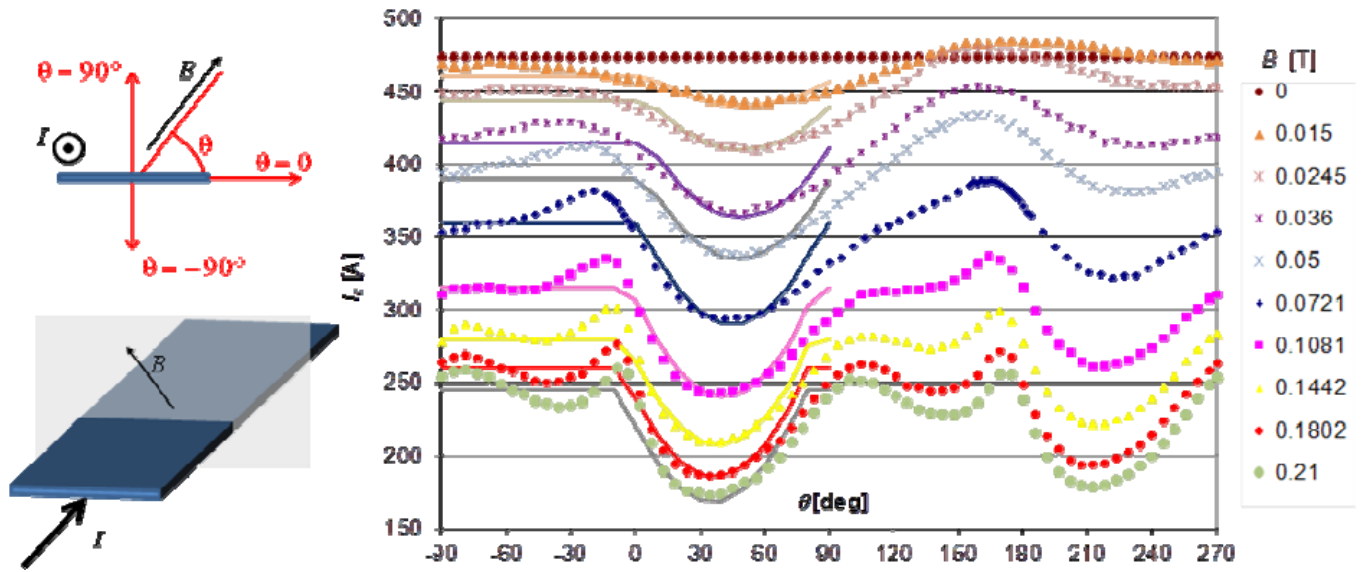


Fig. 2 Short-sample data (symbols) of the critical current dependence on the magnetic field magnitude (different symbol for each value explained in the legend) and its orientation with respect to the CC tape wide face, defined by the angle θ . Empirical fits with the expression (1) are shown by lines. The measured dependence has explicit 360° periodicity at low magnetic fields, however beyond 100 mT the values for 90° - 270° could be considered a repetition of those obtained in the -90° - 90° range.

short sample. Because of highly non-linear properties of HTS tape it is necessary to employ numerical computation technique in the design of the coil. It is also useful in analysis of the observed behavior and allows to calculate the quantities that are not easily accessible in experimental way like the distribution of heat generated by AC current in the coil.

II. TAPE PROPERTIES

Basic information in the design of a superconducting coil is the dependence of critical current on magnetic field and its orientation. In the case of SuperPower tape SCS12050-AP this dependence is rather complicated as shows Fig. 2. Explanation of this complex dependence is beyond the scope of our investigation. However its description is essential in the coil design and performance prediction. We have used several approximations [11], the results presented here have been obtained by using the empirical description:

$$J_c(B, \theta) = \frac{I_1(B)}{S_{SC}} \times \begin{cases} 1 + \left(\frac{\theta - \theta_0(B)}{\Delta\theta} \right)^2 \left(\frac{I_2(B)}{I_1(B)} - 1 \right) & \text{for } |\theta - \theta_0| < \Delta\theta \\ 1 & \text{for } |\theta - \theta_0| \geq \Delta\theta \end{cases} \quad (1)$$

where $\Delta\theta = 0.75$ radians and

$$I_1(B) = I_{\min 0} \left[1 + k_{\min} \left(1 - \frac{B}{B_0} \right)^\beta \right]$$

$$I_2(B) = I_{\max 0} \left[1 + k_{\max} \left(1 - \frac{B}{B_0} \right)^\beta \right]$$

$$\theta_0(B) = \theta_{00} \left[1 + k_\theta \left(1 - \frac{B}{B_0} \right)^\beta \right]$$

with the parameters $B_0 = 0.5$ T, $\beta = 4.5$, $I_{\min 0} = 136$ A, $I_{\max 0} = 218$ A, $\theta_{00} = 0.58$ radians and S_{SC} is the cross-section of the

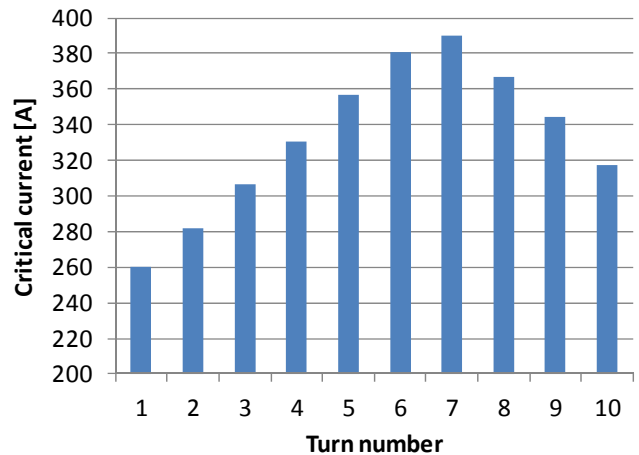


Fig. 3. Critical currents of coil turns estimated with the help of (1). Turns are numbered from inside towards outside, the innermost turn has number 1.

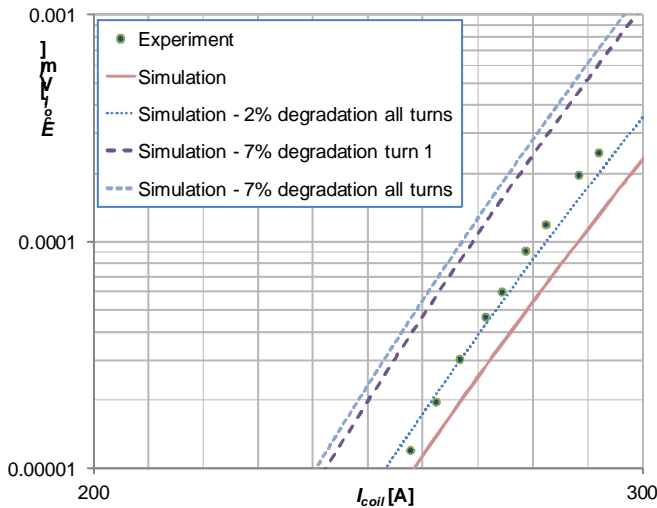


Fig. 4. Current-voltage dependence calculated for the coil (full line) compared with the experimental data (circles). Better agreement is reached assuming the critical current data lowered by 2% (dotted). Simulations for a 7% degradation of the innermost turn (long dashes) and of all the coil turns (short dashes) were carried out to see how much such damage could be detected in the $E(I)$ tests.

superconducting layer that in our calculations was represented by the rectangle of width $w_{SC} = 12$ mm and thickness $h_{SC} = 1$ μm . The expression (1) with these parameters fits the data for angles θ from -90° to 90° and magnetic fields higher than 0.1 T, the critical currents for lower fields are slightly higher in the range of angles θ between 90° and 270° .

III. MAXIMUM DC CURRENT OF THE COIL

Knowledge of the tape critical current described by the expression (1) allows to predict the maximal DC current the coil could carry. For this purpose we created the finite-element model based on the geometry shown in Fig. 1. Rotational symmetry is used i.e. the real spiral turns have been replaced by circular ones. The approximation of uniform current density in the winding was used to calculate the magnetic field distribution in the coil. Then in an iterative procedure the level of coil current that would generate the electrical field $E_c = 1$ $\mu\text{V}/\text{cm}$ in various turns has been identified. The result – that could be with certain simplification called the critical currents of individual turns – is shown in Fig. 3. As expected, the innermost turn (assigned No. 1) limits the maximum DC current the coil could carry. Then it does not make much sense to calculate the current that would create 1 $\mu\text{V}/\text{cm}$ electrical field in the whole coil. Instead we estimated the current-voltage curve of the whole coil. A rigorous calculation would require in the finite element calculation a dense mesh of current-voltage dependences taken on short sample at different field values and orientations. We used a simplified procedure instead: First, the measured short sample curves were approximated by the power-law function $E(I) = E_c (I/I_c)^n$ (from which the values of I_c found at $E_c = 1$ $\mu\text{V}/\text{cm}$ were used in Fig. 2) where the exponent n was found to vary between 17 and 25 in the range of magnetic fields 0.08-0.14 T that would

appear in the coil winding at carrying maximum current. Then we took the “critical currents” of individual turns, I_{ci} , and the power-law exponent in the mid of its range, $n = 21$ to estimate the current-voltage curve of the coil:

$$E_{coil}(I_{coil}) = \frac{\sum_{i=1}^N 2\pi r_i E_c \left(\frac{I_{coil}}{I_{ci}}\right)^n}{\sum_{i=1}^N 2\pi r_i} \quad (2)$$

In this expression $N = 10$ is the number of turns, each of them at the radius r_i . The result was confronted with experimental data as shown in Fig. 4. Calculated prediction is slightly higher than the experimental finding. Key role of the innermost turn is illustrated by $E(I)$ curve calculated considering the degradation of critical current by e.g. 7%. The shift towards lower currents obtained for a uniform reduction of I_{ci} in all the turns is close to the result obtained assuming such degradation in the innermost turn alone.

IV. AC LOSS BEHAVIOR

In the case of a coil considered for power application the dissipation at AC transport (AC loss) is an important parameter. We performed numerical calculations based on the $A-\varphi$ - j formulation of critical state utilizing the finite-element code Comsol Multiphysics [12]. The original stepwise current-voltage curve proposed for hard superconductor [13] is replaced by its smooth approximation

$$J_{s,\theta}(r, z) = J_c \tanh\left(\frac{E_\phi(r, z)}{E_c}\right). \quad (3)$$

where the critical current density J_c is now the upper limit for the current density in superconductor, J_s , and the cylindrical geometry shown in Fig.1 was introduced. Because the electrical field is generated by the electrostatic gradient $\nabla\varphi$ as well as the time variation of the magnetic vector potential, \vec{A} , the expression (3) can be rewritten [6] as

$$J_{s,\theta}(r, z) = J_c(B, \theta) \tanh\left(\frac{-\nabla\varphi(r, z) - \frac{\partial A_\phi(r, z)}{\partial t}}{E_c}\right) \quad (4)$$

where we also indicated that J_c depends on the local value of magnetic field and its orientation with respect to the tape. In the finite element calculation the distribution of A and $\nabla\varphi$ is found that obeys the Maxwell equations with the additional constraint that the total current in each turn is equal to the current delivered by the power supply

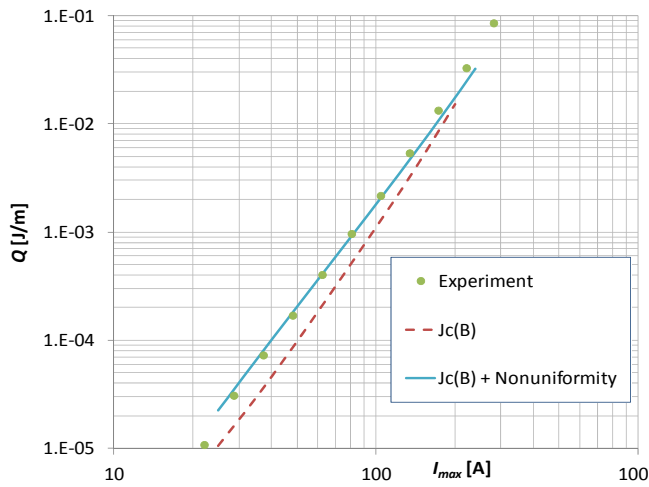


Fig. 5. AC loss in the coil calculated by finite-element method (lines) compared with experimental data (symbols). Taking into account the $J_c(B, \theta)$ is not enough to reproduce the measurements (dashed line). Sufficient agreement was obtained when the lateral non-uniformity in the critical current density was considered (full line).

$$\int_{S_i} J_{s,\theta}(r, z) \Big|_{i=1..N} = I_{coil} \quad (5)$$

Series of distributions are calculated for

$$I_{coil,j} = I_{max} \sin(\omega t_j) = I_{max} \sin(\alpha_j) \quad (6)$$

where ω is the angle frequency and $\alpha_j = 0, \omega \Delta t_j, 2\omega \Delta t_j, \dots, 2\pi$ are the angles corresponding to the time instants t_j when the distributions are resolved. We have found that calculation of $M = 40$ distributions in one AC period is sufficient to obtain the representative result within reasonable computation time. The power dissipated in the coil at the time instant t_j is the sum of contributions from individual turns

$$P_j = \sum_{i=1}^N \int_{S_i} J_s(r, z) E_{i,j}(r, z) dS \quad (7)$$

where J_s is calculated using (4) and the electrical field in the i -th turn at the instant defined by α_j is

$$E_{i,j}(r, z) = -\nabla \varphi_{i,j} - \omega \frac{A_\phi(r, z)_j - A_\phi(r, z)_{j-1}}{\alpha_j - \alpha_{j-1}} \quad (8)$$

In the last expression we took into account that $\nabla \varphi$ is constant in the cross-section of one turn and it thus attains discrete values $\nabla \varphi_i$ for different turns [14, 15]. The power dissipated in all the turns is integrated over one cycle to obtain the total loss in the winding. In order to allow comparison with results obtained on different coils we prefer to present the dissipation

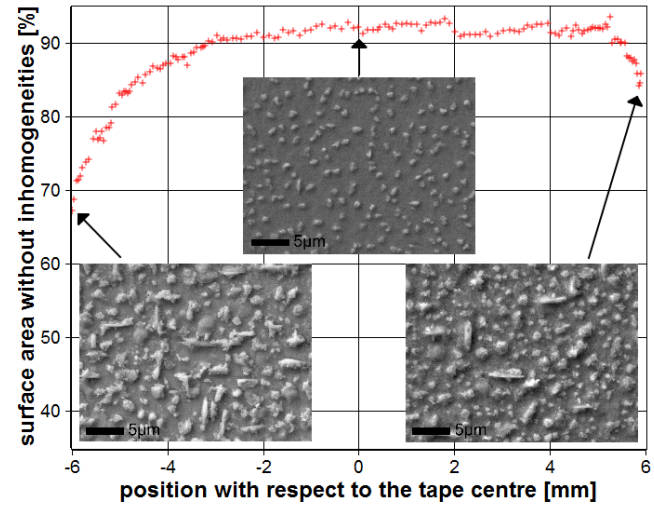
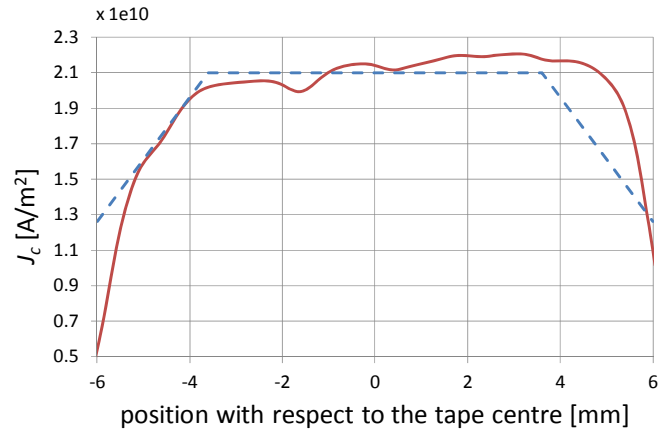


Fig. 6. Nonuniformity of the tape across its width illustrated by (top) profile of the critical current density and (bottom) morphology of the superconducting layer. The profile of J_c (full line) was obtained from the measured distribution of magnetic field above the tape carrying critical current at DC background field of 250 mT. Its linear approximation is shown by the dashed line. Electron microscope pictures were taken after removing the protecting Ag and stabilizing Cu layer. The inhomogeneities – seen as “islands” in the superconducting layer - occupy bigger portion at tape edges.

divided by the total length of the tape in Joule/meter units:

$$Q = \frac{\sum_{j=1}^M P_j \Delta t}{L_{coil}} = \frac{2\pi}{\omega M} \frac{\sum_{j=1}^M P_j}{\sum_{i=1}^N 2\pi r_i} \quad (9)$$

The prediction obtained by such calculation incorporating the $J_c(B, \theta)$ expression (1) is compared in Fig. 5 with experimental data determined by standard lock-in technique. The loss per cycle measured at frequencies of 36, 72 and 144 Hz, respectively, was identical testifying pure hysteretic character consistent with the critical state model. As one can see, the calculated prediction (dashed line) was below the experimental data. The observed discrepancy was removed when we took into account the fact that the tape edges exhibit

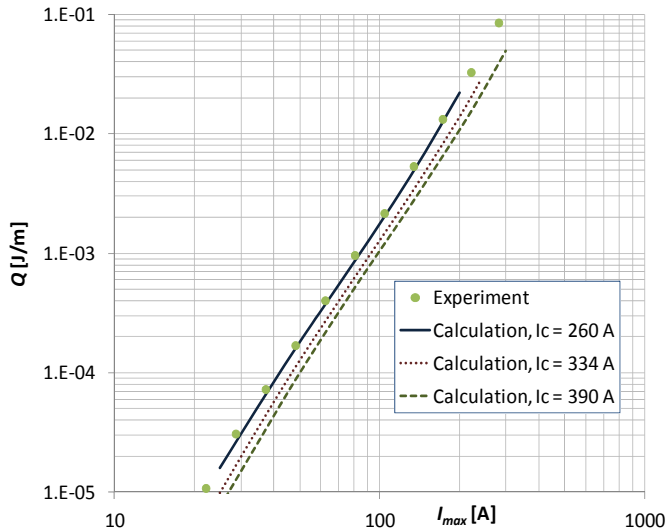


Fig. 7. AC loss in the coil calculated in simplified manner assuming a constant critical current density, J_c , (lines) compared with experimental data (symbols). The results are shown for three values of J_c corresponding to the tape critical currents shown in the legend.

reduced current transport capability compared to the central part. Such reduction was observed in separate experiment mapping the magnetic field distribution above the tape transporting DC current. The variation of J_c across the tape width shown in Fig. 6 has been derived by an inversion calculation [16]. Also the structural investigations we performed by scanning electron microscopy revealed that there is significant difference in the superconducting layer morphology across the tape width. The structural analysis suggests that the volume ratio of inhomogeneities in the superconducting layer is increased towards both edges of the tape. Such non-uniformity can never be deduced from the $I_c(B, \theta)$ data. On the other hand at AC transport the dissipation depends on details of the flux front movement resulting in significant difference between two calculated curves in Fig. 5.

However, the coincidence of the measured AC loss data with the calculation is not always the proof of a valid description of superconductor properties. We performed a series of AC loss calculations neglecting the magnetic-field dependence of the critical current density. Main motivation for such exercise was to check how much the improvement (or degradation) of the critical current would affect the AC loss. Here we show the results for three values of J_c that for the considered cross-section of superconducting layer (12 mm wide and 1 μm thick) correspond to the critical currents equal to 260, 334 and 390 A, respectively. The lowest and highest of these values are the extreme levels of critical currents that were calculated for individual turns in the coil taking the complex $I_c(B, \theta)$ of the tape into account. The middle value is obtained from an average of these values shown in Fig. 2.

The main conclusion is that the coil loss calculated assuming a field-independent critical current density $J_c = \text{const.}$ – see Fig. 7 – is inversely proportional to J_c . Such behavior is typical for the self-field (transport) regime [17]. Maybe in a coil with significantly larger number of turns this

conclusion could not apply. Rather surprising however is that the result calculated in such simplified manner - assuming that the critical current density in all the winding is equal to that of the innermost turn - does very well match the experimental data. We believe this is a mere coincidence: As shown by the dashed line in Fig. 5 the slope of the loss curve obtained assuming $J_c(B)$ dependence - without lateral non-uniformity - would be higher than that one resulting from a $J_c = \text{const.}$ assumption.

As we have found, the lateral non-uniformity of J_c with respect to the tape width has significant influence on the coil loss. This effect has already been found in the case of power transmission cable [18] or fault current limiter [19]. In the following we present the results of our analysis about the possible consequence of J_c variation along the tape length. In particular we calculated the AC loss and its distribution in the winding in the case when J_c in one of the turns is lower than in the rest.

V. INFLUENCE OF LOCAL I_c DEGRADATION

In this section we show the results of AC loss calculation performed following the procedure described by the formulas (4) to (9) i.e. taking into account the complex $J_c(B, \theta)$ established on the short sample assuming however that the superconductor in some turns has J_c that is proportionally lowered at all the field magnitudes and orientations.

First notable feature is that the AC loss is far less sensitive to a single turn degradation than the current-voltage curve. This is obvious when comparing the effect of reducing the critical current of the innermost turn to 93% of original value on the current-voltage curve in Fig. 4 with the AC loss result shown in Fig. 8. Even a drop to 75% of the original value does not produce an increase of AC loss in the coil that would be distinctively beyond the experimental noise.

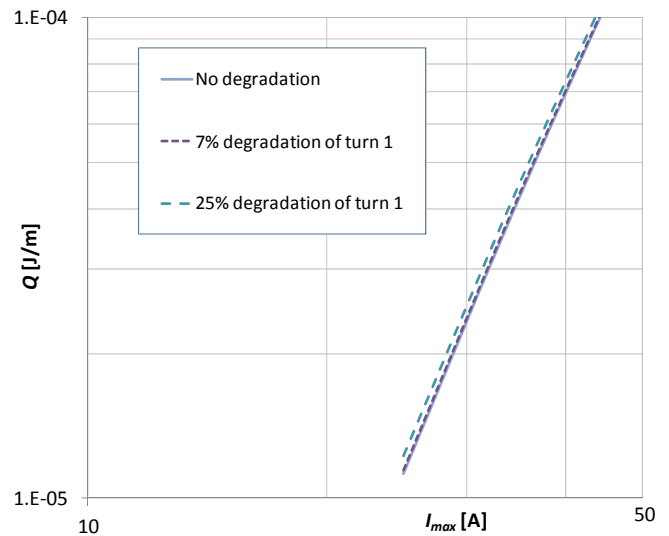


Fig. 8. Calculated effect of a reduced critical current in the innermost turn on AC loss: loss in the coil (full line from Fig. 5) compared with the result obtained assuming critical current of the turn N.1 reduced to 93% and 75%, respectively. As one can see, such degradation produces an effect that is hardly visible.

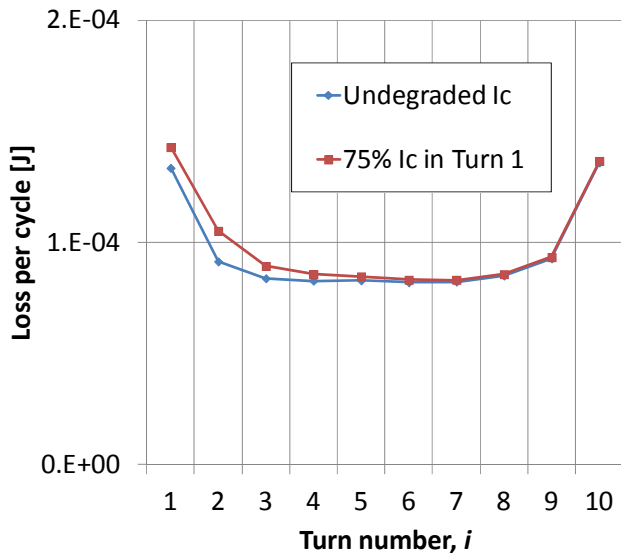


Fig. 9. Distribution of dissipation in the coil turns at AC amplitude of 70 A (27% of undegraded I_c of inner turn): Line with diamonds shows the values calculated for the coil made of identical turns from the tape with properties shown in Fig.2. The full squares have been obtained assuming that in the innermost turn the critical current has been lowered by 25%.

This result can be better understood when we analyze the distribution of dissipation in the coil winding. In Fig. 9 the dissipation is plotted as calculated for individual turns in the AC cycle with amplitude of 70 A. The dissipation is rather uniformly distributed inside the coil, the extreme turns (the innermost and the outermost ones) producing heat about 50% above the average. Then one can better understand why a reduction of the critical current in one turn causes a minor increase of the dissipation in the whole coil. It is interesting is that an increase of dissipation is predicted also for the neighboring turns in spite of the fact that their properties have not changed. Surprising is the result we have found for higher AC amplitudes as shown in Fig. 10: In the case of coil made of tape with the same properties in all the turns the dissipation pattern is similar to that found at lower currents. Striking is the prediction that using a degraded tape in the innermost turn would reduce the dissipation in that turn at higher currents. The elevated AC loss in the whole coil should be borne by nearly all the remaining turns, the additional dissipation peaking at the neighboring turn N.2. We have checked this prediction also by a different numerical method based on the critical state principles [10] with identical results. Unfortunately there is no easy way to detect the local dissipation in coil turns in experiment.

VI. CONCLUSION

Properties of a small coil made from 12 mm wide CC tape have been investigated experimentally and by finite element numerical models. Taking into account the complexity of J_c dependence on magnetic field and its orientation in the calculation we achieved rather precise prediction of the DC current-voltage curve of the coil as well as the dissipation in AC regime.

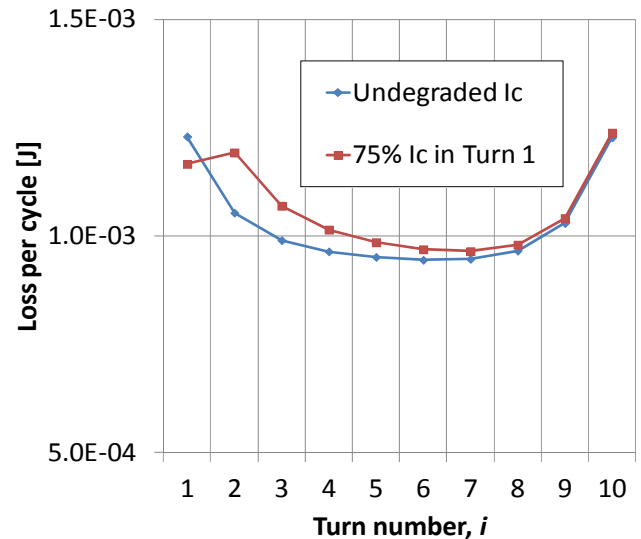


Fig. 10. The same as Fig. 9 but the AC amplitude is now 140 A (54% of undegraded I_c of inner turn). Surprising is that the turn with lowered critical current exhibits lower dissipation than in the case it were undegraded. The increased dissipation is distributed in the remaining coil turns.

Similar to the results of other groups analyzing the AC loss in superconducting cables or fault current limiters we have found that a non-uniform transport capability of the HTS material across the tape width leads to significant increase in AC dissipation. Our structural investigations provide strong indication that this phenomenon is caused by increased share of “islands” not participating in the current flow at the tape edges.

Longitudinal non-uniformity of tape critical current can have severe consequences on the maximum current it is able to reach. On the other hand the AC loss is rather insensitive to this matter. This could maybe explain surprising similarity of AC loss of coils with rather different critical current [20]. Our calculations confirmed that for a coil with constant J_c the AC loss would be inversely proportional to J_c .

Rather interesting is the result of numerical calculation showing that a turn from tape with reduced J_c could transfer the surplus dissipation to neighboring turns. At AC currents with amplitude approaching the critical current this would even make the actual dissipation in weaker turn lower compared to the case when all the turns are made from identical tape. Experimental verification of this theoretical prediction would be very desirable.

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