AC Loss Reduction in Round HTS Cables Achieved by Low-Cost Filamentization of Tape Conductors

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***Abstract*—Knowledge of the ac loss generated in a superconducting cable during variation of magnetic field is essential when considering its use in pulsed magnets. In round high-temperature superconducting (HTS) cables made from coated conductor (CC) tapes, the hysteresis loss is proportional to the tape width. Then an effective measure for reducing the loss is the division of the superconducting layer into parallel filaments. We investigated the ac loss in short models of round cables, containing in different arrangements two layers of 10 standard helically laid tapes. At magnetic field amplitudes surpassing 0.1 T the loss did not depend on the cable architecture, in agreement with simple analytical prediction. Substantial reduction of magnetization loss was obtained in the cable models from novel coated conductor (CC) tapes with a low-cost filamentized REBCO layer produced in an industrial process utilizing a special 3D patterned metal substrate. Further research should address the improvement of critical current and optimization of metallic layers, allowing a migration of current between filaments without substantial increase of coupling loss.**

***Index Terms*—AC loss, coated conductors, filamentization, round HTS cables.**

I. Introduction

THERE is continuing interest in upgrading the magnets, generating pulsed magnetic fields, with high-temperature superconductors (HTS). Round cables made by assembling the tapes with a REBCO superconductor in a helical fashion are attractive as they allow bending in any direction [1], [2], [3]. Also, this arrangement minimizes electrical currents forming the loops connecting different tapes [4], [5], [6]. Therefore, such a cable is a promising candidate for use in accelerator magnets [7], [8] or fusion tokamaks [9], [10]. Still, the hysteresis loss in CC exposed to a magnetic field poses substantial difficulty. The obvious solution is the division of the superconducting layer into many parallel strips by filamentization [11], [12], [13], [14], [15], [16]. Crucial is to obtain the filamentized tape in kilometer-range length with acceptable cost.

Here we compare the loss in CORT (Conductor-On-Round-Tube) cables made from standard tapes with those obtained in the cable samples made from low cost filamentized tapes prepared by the two-level undercut-profile substrate (2LUPS) process [17], [18], [19]. Analytical models are sufficient to obtain theoretical predictions in the relevant range of (high) magnetic fields. In this way, we avoided time-consuming numerical modeling [20], [21], [22], [23].

In CORT cables from filamentized tape, additional dissipation is created by the currents coupling individual filaments. However, our study confirmed one order of magnitude lower total magnetization loss at the ramp rates exceeding 10 T/s.

II. Reference Samples (Non-Filamentized Tapes)

In order to verify the soundness of theoretical models allowing the estimation of the hysteresis ac loss in CORT samples, two short models with different arrangements of 3 mm wide SuperPower tapes SCS3050-AP have been manufactured.

A tube from a carbon composite [24] with 7 mm outer diameter served as the core for 2 layers, each containing 5 tapes, with four transpositions of 22 mm wrap-pitch. The CORT samples differ in the relative arrangement of the outer layer with respect to the inner one as illustrated in Fig. 1.

A. Theoretical Prediction of AC Loss

In a magnet winding, the single CC tape experiences magnetic fields significantly exceeding the self-field produced due to the current flowing in the individual tape. Thus, for most of the field cycle the superconductor is saturated with the critical current density [26], [27]. Then, the approximation of hysteresis loss in the ac field with amplitude $B_{\max}$ oriented perpendicular to the

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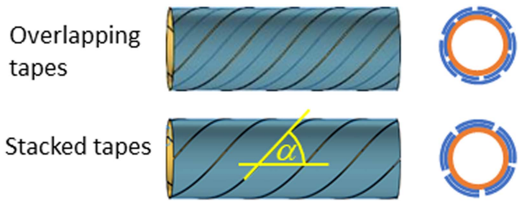

Fig. 1. 2-layer CORT samples made from non-filamentized tapes with different arrangement of the layers, laid with the same helicity angle, $\alpha = 45$ degrees.

wide face of the CC tape, which is w_{CC} wide and l_{CC} long, with the critical current $I_{c,CC}$, per cycle and unit length is

$$\frac{Q_{h,CC}}{l_{CC}} = B_{\max}\, I_{c,CC} w_{CC}. \quad (1)$$

In a round cable, there are N_T tapes, helically laid with the angle α (see Fig. 1), exposed to a magnetic field oriented perpendicular to the longitudinal axis of the cable. Simple geometrical considerations, taking into account the rotation of the tape with respect to the magnetic field, as well as the number of tapes necessary to assemble the cable, allow to predict the dissipation due to hysteresis loss in the cable of length l_{Cable} as:

$$\frac{Q_{h,Cable}}{l_{Cable}} = B_{\max}\, N_T I_{c,CC} \frac{2}{\pi \cos\alpha} w_{CC} \quad (2)$$

The product $N_T I_{c,CC}$ is fixed in the cable design, similarly as the magnetic field value $B_{\max}$. Then the expression (2) clearly shows that the only way to reduce the hysteresis loss in a round cable is the use of narrower conducting elements [28], [29].

We also utilized the model for magnetization of horizontal array of strips w_S wide and thick d_s, each with the critical current of I_{cS}, separated by the gaps wide w_G. The hysteresis loss per unit volume in this x-array of strips is [30]

$$Q_s = \frac{-4s^2}{\pi w_s d_s \mu_0} \int_0^{B_{\max}} (B_{\max} - 2B)\, ln \left[1 - \frac{X}{\cos h^2 (B/B_0)}\right] dB \quad (3)$$

where $s = w_S + w_G$, $X = \sin^2(\pi w_s / 2s)$ and $B_0 = I_{cS}/\pi w_S$. In the round cable consisting of N_S strips, after accounting for the conductor helicity with the angle α, the expected hysteresis loss per unit length of the cable is

$$\frac{Q_{Cable}}{l_{Cable}} = N_S w_S d_S Q_S \frac{2}{\pi \cos\alpha} \quad (4)$$

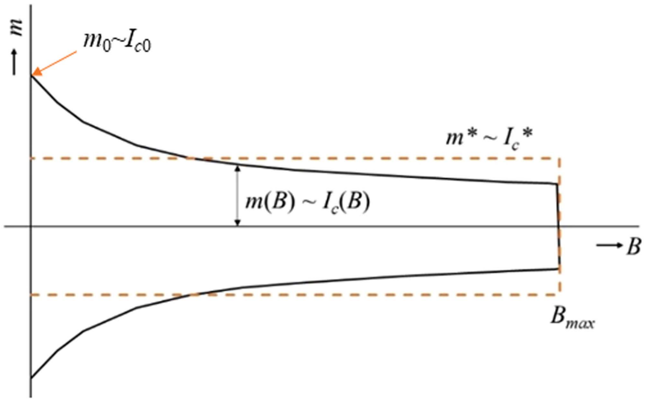

Fig. 2. Replacing the field-dependent critical current, I_c by the field-independent equivalent value I_c*, resulting in the same area of magnetization i.e., the same hysteresis loss.

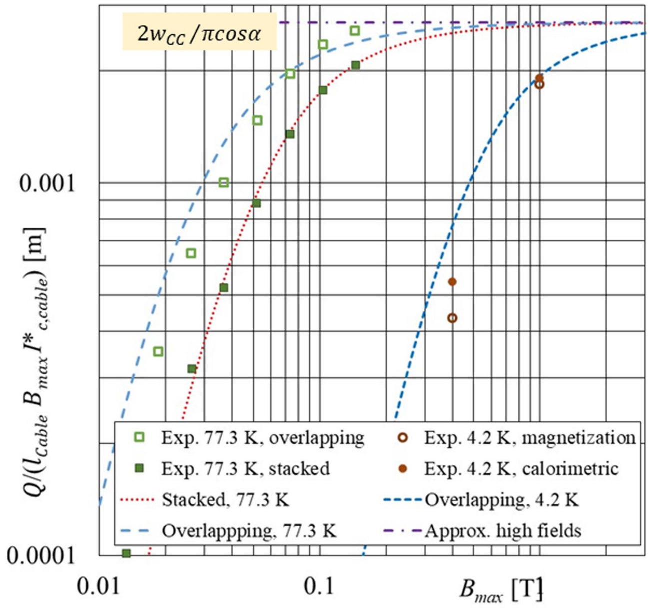

Fig. 3. Plot of the quantity w_{eq} derived according to (5) from the ac loss measurements at two different temperatures (symbols), and the expectations (dashed lines) obtained from the strip array model [30]. The horizontal dot-dashed line indicates the value that the data should approach at high ac field amplitudes.

B. Experiments

Reference [25] reported the results of the calibration-free ac loss measurements [31] on these reference samples exposed to ac magnetic field oriented in a direction transverse to the sample longitudinal axis. We found negligible frequency dependent contribution in the loss measured on both samples at 77.3 K, and frequencies ranging from 36 Hz to 144 Hz, confirming that it is the hysteresis loss. In order to check, whether at high field amplitudes the results approach the prediction (2), we express from the 36 Hz data the quantity

$$w_{eq} = \frac{Q_{h,Cable}}{l_{Cable} B_{\max} I^*_{c,cable}}. \quad (5)$$

For a valid comparison with theory, it was necessary in (2) and (3) to replace the critical current, $I_{c,CC}$, with an equivalent value $I_c{}^*$ causing the same area of magnetization loop as shown in Fig. 2. Details of this procedure are described in the Appendix.

Then, in (5) is used the equivalent value of tape critical current, I_c^*, and for the cable consisting of N_T tapes is $I^*_{c,cable} = N_T\, I_c^*$.

The results of ac loss analysis are presented in Fig. 3 based on the data taken from [25] as well as the results of magnetization and calorimetric measurements at 40 mHz in the sample with overlapping tapes in liquid helium bath. A theoretical prediction deduced from the x-array model (4) for the sample with stacked tapes, calculated with $N_S = 5$, and I_c^* twice the value found for a single tape, coincides surprisingly well with experimental data. Calculation for $N_S = 10$, and I_c^* of single tape, performed as an attempt to interpret the loss in sample with overlapping tapes, has worse agreement with experimental data. Nevertheless, towards higher $B_{\max}$ both the experimental results and theoretical models are in good correspondence with the high-field expectation $w_{eq} = 2w_{CC}/\pi \cos\alpha$ following from (2). This shows that reducing the width of the superconductor is essential for lowering the ac loss in a round CC cable serving for generation of time-varying magnetic field.

III. Cable Samples From Filamentized Tapes

A technology for low-cost industrial production of CC tapes with a filamentized superconducting layer has been demonstrated in the frame of the Eurostars-2 project Filaments4Fusion [31]. A particular feature of this technology is that the multi-filamentary structure is achieved by depositing REBCO by a standard large-scale industrial process [32], utilizing 3D surface modified metal tapes as substrates. Superconductor stacks are deposited using large-scale production systems at THEVA applying the Inclined Substrate Deposition technique and electron-beam physical vapor deposition, for the buffer MgO layers and the $GdBa_2Cu_3O_7$ superconducting layers, respectively.

The 3D multifilamentary substrates are produced by SUBRA starting from Hastelloy C276 tape and applying the two-level undercut-profile substrate (2LUPS) technique in a large-scale reel-to-reel manufacturing process. This technique was developed by Wulff et al. and processing details are given in [17], [18], [19] Further, an economic analysis of multifilamentary CCs is presented in [33]. Achieving filamentization through this bottom-up process has major production and economic advantages in that the substrate surface topography can be screened and quality assured in the very beginning of the CC production run, prior to the REBCO stack deposition and final metallization, see [33]. This significantly reduces inherent risks and thus costs of large-scale production. The filamentization process is simplified as the filaments self-form during ceramic layer depositions [17] due to the under-cut profile, requiring no post treatment. As an example, Fig. 4 shows a scanning electron microscopy image of a cross-section of a multifilamentary CC produced in the Filament4Fusion project, displaying a profile with a 1.2 µm under-cut (at "A") and complete physical decoupling of the REBCO layer (layer 3).

Large-scale 2LUPS production entails very cost effective wet chemical substrate processing and the subsequent superconductor stack is coated without any system modifications in the industrial production at THEVA.

The experimental results presented here were obtained on short CORT cable samples containing 230 mm of 12 mm wide tape with 19 filaments helically laid with the angle $\alpha = 67$ degrees on a non-conducting 10 mm diameter rod. The filaments were $w_f = 0.5$ mm wide, separated by the gaps of $w_g = 0.1$ mm. dc transport testing in a liquid nitrogen bath showed that the critical current determined with the 1 µV/cm criterion in self-field conditions is $I_{c,sf} = 100$ A.

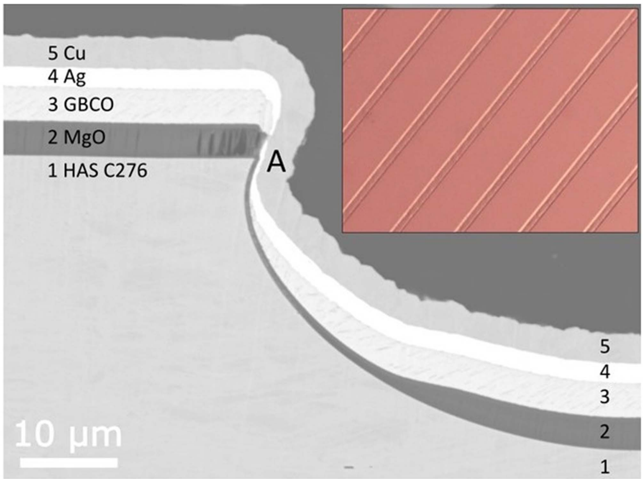

Fig. 4. Detail from the cross-section of the multifilamentary CC obtained by electron microscopy. The inset shows a view of the filaments on the top side of the CC after copper plating (layer 5). It shows 500 µm filaments separated by 100 µm grooves.

A. Theoretical Prediction for AC Loss

Expected value of hysteresis loss in the CORT cable samples from filamentized tapes were obtained utilizing the formula (3) with $N_S = 19$ now being the number of filaments, $s = w_f + w_g = 0.6$ mm, $X = \sin^2(\pi w_f / 2s)$. The value of characteristic magnetic field $B_0 = I_{cf}/\pi w_f$ was evaluated assuming the critical current of one filament $I_{cf} = 5.26$ A. For comparison, the expected loss in the CORT cable of the same geometry, but from non-filamentized tape with the same width $w_T = 12$ mm and critical current of 100 A was evaluated using the model for single strip [34].

B. Experiments

The results of ac loss measurements in two cable samples of identical geometry are presented in Fig. 5. The difference between samples is that in the tape used for the first model the filaments are covered by a $\sim$2 µm thick Ag cap layer, and the second sample used the same tape but additionally covered by $\sim$10 µm Cu surrounding the tape. This step improved significantly the ability to withstand currents considerably higher than the critical current. On the other hand, currents coupling different filaments could now better circulate, and this results in additional loss that is frequency dependent [35]. This is shown in Fig. 6 together with two reference models: for the cable made from a no-filament tape of the same dimensions and critical current [34], as well as the model representing the filamentized tape by the x-array of filaments [30].

The hysteresis loss in x-array model is the minimum of dissipation we expect, while the one calculated for the cable from non-filamentized tape is the upper limit. Experimental data show that at 36 Hz, 100 mT, equivalent to the field change at the rate of $\sim$14 T/s, the loss in the round cable from filamentized tape is one order of magnitude lower than for the non-filamentized

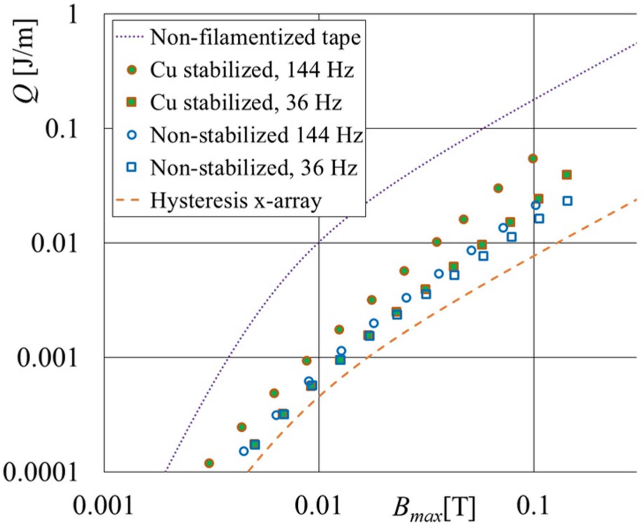

Fig. 5. Experimentally determined ac magnetization loss in CORT cable models from filamentized tapes 12 mm wide, with critical current of 100 A at 77.3 K (symbols). The observed frequency dependence indicates the presence of coupling currents, that are stronger for the cable from Cu stabilized tape. The dotted line is the prediction for the cable made from an equivalent non-filamentized tape [33]. The dashed line is the hysteresis loss (4) obtained when representing the filamentized tape by the x-array of strips [30].

tape. By optimizing the thickness of metallic layers, the balance between improved stability and additional coupling loss can be reached [35], [36].

IV. CONCLUSION

Round conductors from CC tapes represent a promising concept for winding large magnets generating pulsed magnets fields, where assembling many conductors in a cable is the way to reduce the magnet inductance. Our experimental study on short cable samples with two different arrangements of tapes has confirmed, that at high ac amplitudes - which is the regime relevant for large magnetic systems - the loss is approaching the value controlled exclusively by the tape width. Then, plausible solution for reaching an acceptable level of ac loss is the division of the REBCO layer into many parallel filaments. In difference to numerous studies introducing trenches into the REBCO layer *after its deposition*, in our case the superconductor is filamentized *already during its deposition*, using low-cost industrially produced 3D multifilamentary substrates with significantly lower processing cost. Encouraging is that the filamentized tapes, prepared in industrial conditions, exhibited a substantial reduction of ac loss at the magnetic field ramp rates relevant for pulsed magnets. Further research is necessary to improve the properties of the superconducting layer and to optimize the architecture of stabilizing metallic layers.

APPENDIX

When the critical current of a CC tape changes in the range of magnetic fields used in experiments, it is worth effort to replace the constant I_c, assumed in theory, by an equivalent I_c* representing the whole $I_c(B)$ in the given field cycle. Because the width of the magnetization loop at any value of B is proportional to $I_c(B)$, the equivalence is based on reaching the same area of the hysteresis loop as shown in Fig. 2. Let us express the I_c dependence (at a constant temperature) as

$$I_c\left(B\right) = I_{c0}\ f\left(B\right) \tag{A1}$$

where $I_{c0} = I_c(B = 0)$ and f is the expression for field dependence. The area of the hysteresis loop in the cycle $0 \rightarrow B_{\max} \rightarrow 0$ is

$$P = 2\int_0^{B_{\max}} I_c\left(B\right) dB = 2I_c\int_0^{B_{\max}} f\left(B\right) dB. \tag{A2}$$

The equivalent rectangular loop in Fig. 1 has the area $2I_c{*}B_{\max}$, and then for the cycle ranging from 0 to $B_{\max}$ and back

$$I_c^*\left(B_{\max}\right) = \frac{I_{c0}}{B_{\max}}\int_0^{B_{\max}} f\left(B\right) dB. \tag{A3}$$

We found suitable the approximation [21]

$$f\left(B\right) = a_1\exp\left(B/B_1\right) + a_2\exp\left(B/B_2\right) \tag{A4}$$

with four parameters a_1, B_1, a_2, B_2. After entering this expression into (A3) and performing the integration we find that

$$I_c^*\left(B_{\max}\right) = \frac{I_{c0}}{B_{\max}}\left[\begin{array}{l} a_1B_1\left(1 - exp\left(-\frac{B_{\max}}{B_1}\right)\right) \\ +a_2B_2\left(1 - exp\left(-\frac{B_{\max}}{B_2}\right)\right)\end{array}\right]. \tag{A5}$$

The parameters used for the non-filamentized SuperPower tape at 77.3 K were $I_{c0} = 135$ A, $a_1 = 0.5439$, $B_1 = 0.1285$ T, $a_2 = 0.4739$, $B_2 = 1.945$ T. For the temperature of 4.2 K we used $I_{c0} = 2600$ A, $a_1 = 0.5$, $B_1 = 0.5$ T, $a_2 = 0.5$, $B_2 = 6$ T.

No such correction was done for the cable from filamentized tape because at the moment the $I_c(B)$ data are not sufficient.

REFERENCES

[1] D. C. van der Laan, K. Radcliff, V. A. Anvar, K. Wang, A. Nijhuis, and J. D. Weiss, "High-temperature superconducting CORC wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets," *Supercond. Sci. Technol.*, vol. 34, no. 9, Sep. 2021, Art. no. 10LT01.

[2] J. Šouc, M. Vojenčiak, and F. Gömöry, "Experimentally determined transport and magnetization ac losses of small cable models constructed from YBCO coated conductors," *Supercond. Sci. Technol.*, vol. 23, no. 3, Mar. 2010, Art. no. 045029.

[3] S. Kar et al., "Progress in scale-up of REBCO STAR$^{\text{TM}}$ wire for canted cosine theta coils and future strategies with enhanced flexibility," *Supercond. Sci. Technol.*, vol. 33, no. 7, Jul. 2020, Art. no. 094001.

[4] K. Yagotintsev et al., "AC loss and contact resistance in REBCO CORC, Roebel, and stacked tape cables," *Supercond. Sci. Technol.*, vol. 33, no. 7, Jul. 2020, Art. no. 085009.

[5] J. Han, W.-S. Kim, K. Choi, and J.-K. Lee, "Magnetization loss of multilayered CORC according to various winding types," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 5900705.

[6] J. Zhao et al., "Effect of winding methods: Transport AC losses in CORC coils," *Supercond. Sci. Technol.*, vol. 35, no. 10, Oct. 2022, Art. no. 115007.

[7] X. Wang et al., "Development and performance of a 2.9 tesla dipole magnet using high-temperature superconducting CORC wires," *Supercond. Sci. Technol.*, vol. 34, no. 1, Jan. 2021, Art. no. 015012.

[8] P. Ferracin et al., "Towards 20 T hybrid accelerator dipole magnets," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4000906.

[9] Y. Zhai, T. Brown, J. E. Menard, D. C. van der Laan, J. D. Weiss, and Z. Johnson, "HTS cable conductor for compact fusion tokamak solenoids," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4203005.

[10] H. Jin et al., “The performance of first CORC cable solenoid insert for development of CFETR high-field magnet,” *Nucl. Fusion*, vol. 60, 2020, Art. no. 096028.

[11] W. J. Carr and C. E. Oberly, “Filamentary YBCO conductors for AC applications,” *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 1475–1478, Jun. 1999.

[12] M. D. Sumption, E. W. Collings, and P. N. Barnes, “AC loss in striped (filamentary) YBCO coated conductors leading to designs for high frequencies and field-sweep amplitudes,” *Supercond. Sci. Technol.*, vol. 18, no. 11, pp. 122–134, Nov. 2004.

[13] J. Šouc et al., “Low AC loss cable produced from transported striated CC tapes,” *Supercond. Sci. Technol.*, vol. 26, no. 7, Jul. 2013, Art. no. 075020.

[14] N. Amemiya et al., “AC loss characteristics of multifilamentary YBCO coated conductors,” *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1637–1642, Jun. 2005.

[15] M. Vojenčiak et al., “Magnetization ac loss reduction in HTS CORC cables made of striated coated conductors,” *Supercond. Sci. Technol.*, vol. 28, no. 9, Sep. 2015, Art. no. 104006.

[16] W. Li et al., “Study on reducing magnetization loss in CORC cables by laser cutting technology,” *IEEE Trans. Appl. Supercond.*, vol. 31, no. 4, Jun. 2021, Art. no. 4802009.

[17] A. Wulff et al., “Two level undercut-profile substrate for filamentary YBa2Cu3O7 coated conductors,” *Supercond. Sci. Technol.*, vol. 28, no. 7, Jul. 2015, Art. no. 072001.

[18] A. Insinga et al., “Lift factor analysis of multifilamentary coated conductor produced using two level undercut-profile substrates,” *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019, Art. no. 8200704.

[19] A. R. Insinga et al., “Two level undercut-profile substrate-based filamentary coated conductors produced using metal organic chemical vapor deposition,” *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018, Art. no. 6601705.

[20] N. Amemiya, F. Kimura, and T. Ito, “Total AC loss in twisted multifilamentary coated conductors carrying AC transport current in AC transverse magnetic field,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 3183–3186, Jun. 2007.

[21] J. Sheng, M. Vojenčiak, R. Terzioglu, L. Frolek, and F. Gömöry, “Numerical study on magnetization characteristics of superconducting conductor on round core cables,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4800305.

[22] Y. Wang, M. Zhang, F. Grilli, Z. Zhu, and W. Yuan, “Study of the magnetization loss of CORC cables using a 3D T-A formulation,” *Supercond. Sci. Technol.*, vol. 32, no. 2, Feb. 2019, Art. no. 025003.

[23] Y. Sogabe, Y. Mizobata, and N. Amemiya, “Shielding currents in multifilament coated conductors wound into pancake coils and layer-wound coils,” *Supercond. Sci. Technol.*, vol. 34, no. 10, Oct. 2021, Art. no. 105009.

[24] E. Cuninková et al., “Numerical and experimental design of the former for TORT cables,” *IEEE Trans. Appl. Supercond.*, vol. 33, no. 3, Aug. 2023, Art. no. 4800805.

[25] M. Solovyov, J. Šouc, T. Kujovič, L. Frolek, and F. Gömöry, “Magnetization AC losses in multilayer superconducting round cables with coinciding and opposite lay angles,” *Supercond. Sci. Technol.*, vol. 36, no. 3, Mar. 2023, Art. no. 034001.

[26] M. D. Sumption et al., “AC losses of Roebel and CORC cables at higher AC magnetic fields and ramp rates,” *Supercond. Sci. Technol.*, vol. 35, no. 2, Feb. 2022, Art. no. 025006.

[27] D. Uglietti, R. Kang, R. Wesche, and F. Grilli, “Non-twisted stacks of coated conductors for magnets: Analysis of inductance and AC losses,” *Cryogenics*, vol. 110, no. 9, Sep. 2020, Art. no. 103118.

[28] N. Amemiya, N. Enomoto, Z. Jiang, S. Kasai, T. Saitoh, and Y. Shiohara, “AC loss characteristics of coated conductor and the perspective for its AC loss reduction,” *Physica C*, vol. 426-431, pp. 1267–1275, 2005.

[29] F. Grilli and A. Kario, “How filaments can reduce AC losses in HTS coated conductors: A review,” *Supercond. Sci. Technol.*, vol. 29, no. 8, Aug. 2016, Art. no. 083002.

[30] Y. Mawatari, “Critical state of periodically arranged superconducting-strip lines in perpendicular fields,” *Phys. Rev. B*, vol. 54, no. 18, pp. 13215–13221, Nov. 1996.

[31] [Online]. Available: https://subra.dk/2023/05/why-do-we-need-filaments-for-fusion

[32] W. Prusseit, R. Nemetschek, C. Hoffmann, G. Sigl, A. Lumkemann, and H. Kinder, “ISD process development for coated conductors,” *Physica C*, vol. 426-431, pp. 866–871, 2005.

[33] A. C. Wulff, A. B. Abrahamsen, and A. R. Insinga, “Multifilamentary coated conductors for ultra-high magnetic field applications,” *Supercond. Sci. Technol.*, vol. 34, no. 5, May 2021, Art. no. 053003.

[34] E. H. Brandt and M. Indenbom, “Type-II-superconductor strip with current in a perpendicular magnetic field,” *Phys. Rev. B*, vol. 48, no. 17, pp. 12893–12906, Nov. 1993.

[35] M. D. Sumption, S. Kawabata, and E. W. Collings, “Ac loss in YBCO coated conductors exposed to external magnetic fields at 50–200 Hz,” *Physica C*, vol. 446, pp. 29–36, 2007.

[36] N. Amemiya et al., “Effective reduction of magnetization losses in copper-plated multifilament coated conductors using spiral geometry,” *Supercond. Sci. Technol.*, vol. 35, no. 2, Feb. 2022, Art. no. 025003.