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Magnetization Losses of Roebel Cable Samples with 2G YBCO Coated Conductor Strands

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***Abstract*—Roebel cable with 2G YBCO strands is one of the promising HTS solutions of fully transposed high current conductors for high field accelerator magnets. Following the considerable research effort on the manufacturing of Roebel cables in recent years, sample conductors are now available in useful lengths with reproducible performances to allow detailed characterizations beyond the standard critical current measurements. The ac loss and strands coupling are of significant interest for the field quality of the accelerator magnets. We report a set of systematic ac loss measurements on two different Roebel cable samples prepared for the EuCARD2 collaboration. The measurements were performed over a wide range of temperature between 5 K and 90 K and the results were analyzed in the context of strands architecture and coupling. The results show that the transposed bundles are partially decoupled and the strands in transposition sections behave as an isolated single tape if the strands are insulated.**

***Index Terms*— Accelerator Magnets, AC Loss Measurements, Magnetization, HTS, ReBCO, Roebel Cable**

I. Introduction

Alternative cabling technology is required for constructing cables with transposed strands using high temperature superconducting (HTS) flat tapes, a necessary geometry for attaining high critical current density by texturing Roebel cables [1], originally invented more than a hundred years ago for reducing ac loss in conventional machines, is a promising configuration which have received considerable research and development effort for adapting to HTS conductors [2-4]. While the initial driver for HTS Roebel cables has been the reduction of hysteretic loss in superconductors for power applications, interests in future high field accelerators beyond the Large Hadron Collider (LHC) have brought new impetus and prospects.

Accelerator magnets require high current cables for lower induction and uniform current distribution as well as minimum magnetization among strands for reproducible high field quality. While the potential for high current and the strong flux pinning in high magnetic fields favor the YBCO 2G coated conductors, the effectiveness of current homogenization and magnetization reduction by strand uncoupling using Roebel transposition remains to be optimized and verified. While there have been a number of experimental studies [6-8,12-13] on the ac loss in Roebel cables, their scopes have been limited to 77 K. The published results are not quite sufficient for the accelerator applications, in particular for quantifying strand coupling and identifying the transposition effects.

The present work aims at furthering our understanding on the magnetization of HTS Roebel cable with a comparative study of single Roebel strands and representative simple assemblies of Roebel structure with different Roebel cable samples. Measurements were made at different temperatures between 5 K and 90 K to significantly alter the critical current, which underlies the magnetization in the strands.

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II. Samples, Methods and Approximate Models

A. Samples

Roebel strands and cables with 9 and 15 strands were prepared at KIT using SuperPower tapes (0.1 mm thick of 50 µm Hastelloy with 20 µm Cu on each side) by laser cutting and punching respectively. The 15-strand cable was assembled at CERN with insulations applied to each strand followed by epoxy impregnation uder pressure. The simple assemblies of Roebel strands used in this study were taken from the strand stock supplied by KIT.

B. Measurement of AC Losses

The ac loss measurement setup [9] allows ac field up to 0.2 T and sample temperature down to 5 K by contact cooling. As primarily concern is on the magnetization, the ac field was set at 5 Hz throughout this study.

III. Results and Discussion

A. Single Roebel Strand

The magnetization of an isolated single Roebel strand is expected to behave as a Norris' strip of zero thickness [10] with the loss per unit length and per cycle of an ac field of amplitude H_0 is given by

$$Q = \mu_0 H_0 \sigma_c w^2 \left(\frac{2\sigma_c}{\pi H_0}\ln\cosh\left(\frac{\pi H_0}{\sigma_c}\right) - \tanh\left(\frac{\pi H_0}{\sigma_c}\right)\right)$$

$$\sim\begin{cases}\frac{625}{96\pi}\mu_0\sigma_c^2w^2\left(\frac{H_0}{H_p}\right)^4, H_0 \ll H_p = \frac{5}{2\pi}\sigma_c \\ \mu_0\sigma_c w^2 H_0, H_0 \gg H_p\end{cases} \quad (1)$$

where, for a thin tape of a critical current I_c, and width w, $\sigma_c = I_c/w$ is the sheet critical current density and H_p is the saturation field for the full penetration.

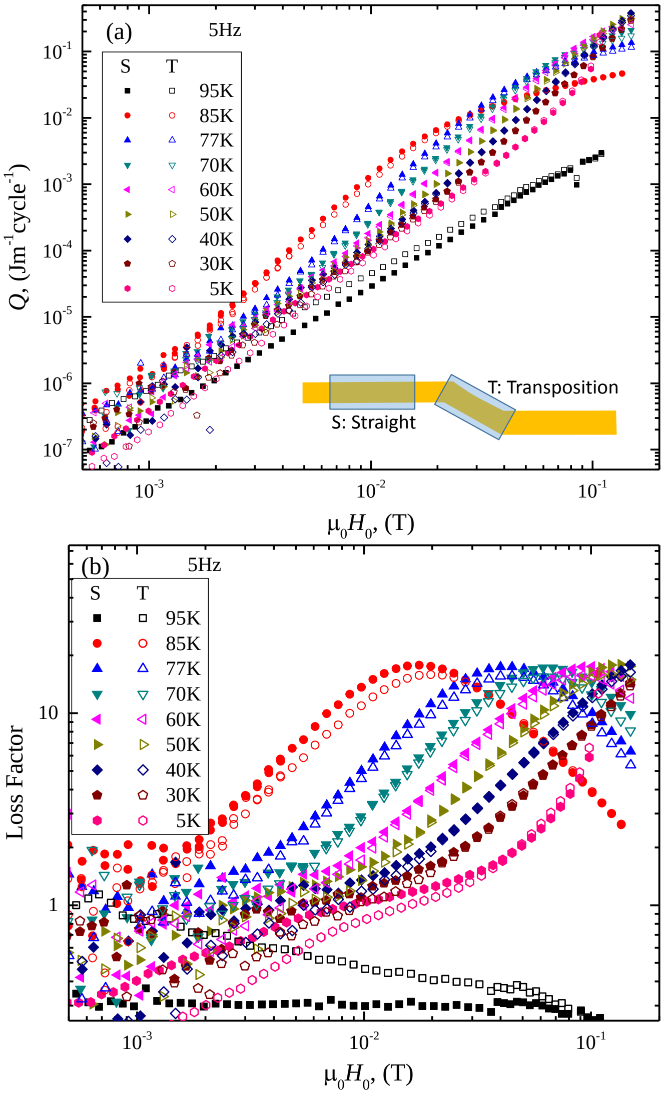

Fig. 1. (a) shows the magnetization losses of a single Roebel strand as a function of ac field amplitude H_0 at different temperatures and (b) shows the corresponding loss factor as defined in (2).

The losses of a single Roebel strand of 2G YBCO from SuperPower (SP) measured at different temperatures between 5 K and 95 K are shown in Fig. 1(a) as a function of the ac field amplitude, H_0, at 5 Hz. At the normal state of 95 K, the losses exhibit an eddy-current like behavior of $\sim H_0^2$. In the superconducting state at lower temperatures, the losses become higher and the transition from $\sim H_0^{3+}$ to $\sim H_0$ upon full penetration is clearly evident. The saturation field H_p moves to higher values at lower temperatures as the critical current increases. The losses in the straight section (S: solid symbols) and transposition section (T: open symbols) are quite similar.

A useful tool for a detailed examination of the loss over several orders of magnitude is the *dimensionless* loss factor Γ, which is defined as

$$\Gamma = \frac{Q}{2\mu_0 H_0^2 A}\ , \quad (2)$$

Where, A, is the conductor cross-section transverse to the ac field, i.e. Γ is the ratio between the loss per unit volume Q/A and the rms field energy $2\mu_0 H_0^2$ over a cycle. To compare the losses in multiple strand cables, we use the loss factor per volume of a *single* strand defined as

$$\Gamma_{T,1} = \frac{Q_T}{2\mu_0 H_0^2 A_1}\ , \quad (3)$$

where Q_T is the total loss per unit length and A_1 is the cross-section of a *single* strand.

A key characteristic of Γ is a distinct peak at $H_0 = H_p$, where it changes from $\sim H_0^2$ to $\sim H_0^{-1}$. The loss factor corresponding to the single strand losses in Fig. 1(a) is shown as a function of field in Fig. 1(b), where the expected peak in Γ at H_p can be seen to move steadily to higher field with reducing temperature and reaches 0.15 T at 50 K. At lower temperatures, only the partially penetrated branch has been measured as the saturation field is out of the range of our ac field. According to (1), $\mu_0 H_p = 0.1$ T at ~ 60 K corresponds to a sheet critical current $\sigma_c = 1000$ A/cm which is broadly consistent with the performance of standard SP tapes. It can be shown that equations (1-2) lead to a constant peak value of the loss factor at $\Gamma_{max} \sim 0.3w^2/A$. For a *single* strand of width $w = 6$ mm, thickness $d = 0.1$ mm and cross-section $A = w \times d$, the peak value is $\Gamma_{max} \sim 18$, which coincides well with the experimental results shown in Fig. 1(b).

B. *Simple Assemblies of Roebel Strands*

Roebel cables, essentially two side-by-side transposed *bundles* of stacked tapes, are designed to decouple the strands by magnetic fields perpendicular to the tape face and do not offer transposition to parallel fields. In terms of the magnetization, there are two distinct elements: tapes side-by-side along the width and tapes stacked along the thickness. The magnetization losses of two side-by-side Roebel strands and a stack of 4 Roebel strands have been measured. The study of the magnetic coupling in such simple assemblies is intended a precursor towards understanding the more complex full Roebel cable. For the side-by-side configuration, equation (1) suggests an unchanged full saturation field regardless whether the two strands are coupled, while the loss factor per volume of a *single* strand $\Gamma_{T,1}$ (i.e., $A_1 = w \times d$ of a single strand) either doubles or quadruples for the uncoupled or fully coupled scenarios respectively. The experimental results for two side-by-side strands (○) at 85 K and 50 K shown in Fig. 2(a) point to a loss factor about 2.8 times that of a *single* strand (□). At the same time, the saturation field is reduced by about 25%. This leads to a picture of partial coupling between two side-by-side strands. The reduction of the saturation field, however, could not be fully attributed to a reduction of the sheet current density σ_c by the small gap (~1 mm) between the two strands.

If behaving as a thin Norris' strip, n Roebel strands stacked along the thickness should have a saturation field n times that of a single strand for the sheet critical current of $n\sigma_c$, while the $\Gamma_{T,1}$ should have the same peak value as that of an isolated strand. Compared to a single strand (□), however, the experimental result for a stack of 4 tapes at 70 K (○, Fig. 2(b)) shows that the saturation field is only increased to 2.5 times instead of 4 times while peak loss factor is 20% higher. Although the exact mechanism is not clear, a deviation from Norris' strip due to an increased thickness seems plausible. It is noted that, for the same I_c and w, the saturation field *reduces* from $H_p = \frac{5}{2\pi}\sigma_c \sim 0.8\sigma_c$ with increasing conductor thickness, e.g. $H_p = \frac{4I_c}{\pi^2 w} \sim 0.4\sigma_c$ for square/round conductor [11]. For the 4-tape stack, the experimental result indicates an effective saturation field of $H_{p,4} \sim 0.5\sigma_{c,4} = 2\sigma_{c,1} = 2.5H_{p,1}$. Here the subscript indices denote the number of tapes in a stack/assembly.

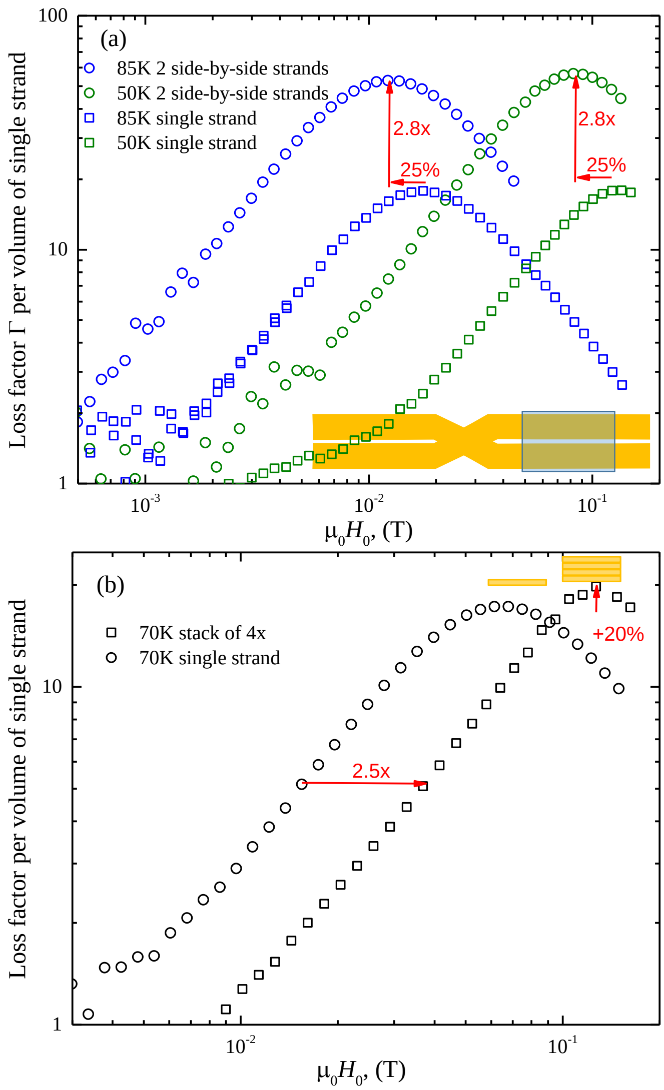

Fig. 2 shows the magnetization loss factor per volume of a *single* strand $\Gamma_{T,1}$ of a single as a function of ac field amplitude H_0 for (a) two side-by-side strands (○) at 85 K and 50 K and (b) a stack of 4 tapes at 70 K (○). The loss factor of a single strand at the corresponding temperatures is also shown (□).

With reference to Roebel cables, the results from the simple assemblies point to a partial coupling of side-by-side transposed bundles, while each bundle exhibits the behavior of conductors of a finite thickness instead of a Norris' strip of zero thickness.

C. Roebel Samples

The magnetization losses measured between 6.5 K and 89 K on a 9-strand *uninsulated* Roebel sample of a 100 mm transposition pitch are shown as a function of field amplitude in Fig. 3(a). The saturation of the cable can be seen to increase to 0.12 T at 70 K, about 20 K higher than the full saturation of a single strand in the same field. In the partially penetrated regime, the losses follows approximately H_0^{3+}, similar to that of a single strand.

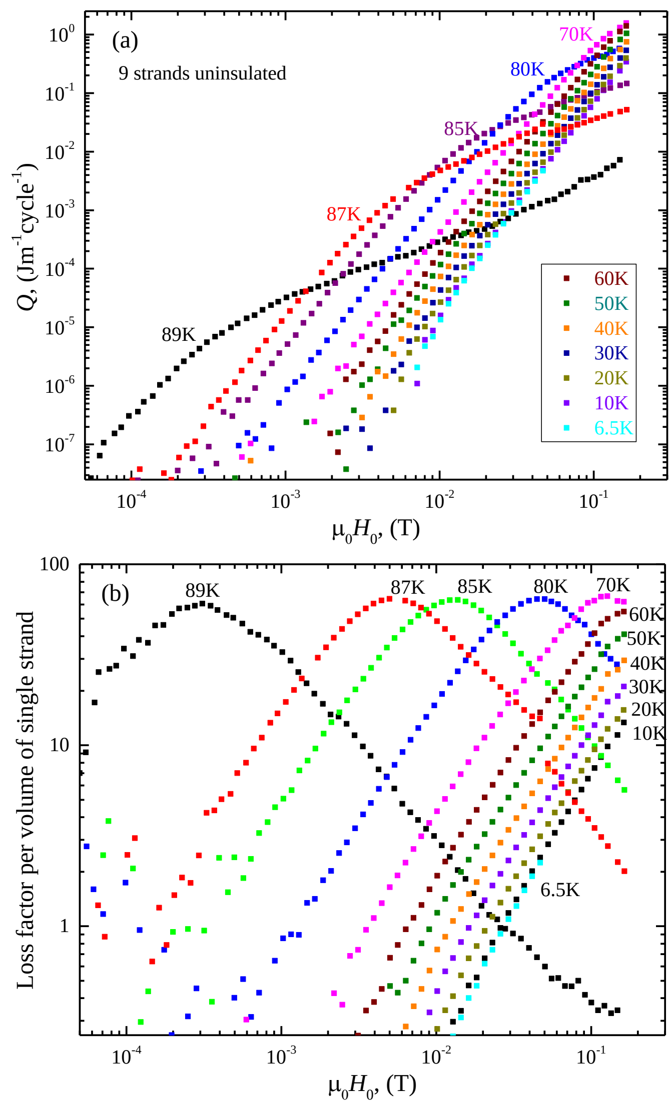

Fig. 3. (a) shows the magnetization losses of a Roebel cable with 9 *uninsulated* strands as a function of ac field amplitude H_0 at different temperatures and (b) shows the corresponding loss factor per volume of a single strand $\Gamma_{T,1}$ as defined in (3).

The corresponding loss factor per volume of a single strand $\Gamma_{T,1}$ is shown in Fig. 3(b), where the saturation field $H_{p,9/2}$ of the 9-strand Roebel cable is about 2 - 2.5 times $H_{p,1}$ of the single strand, e.g. 0.12 T and 0.06 T at 70 K for the cable and strand respectively. Once again the saturation field of the cable is about a half that of a Norris' strip, similar to the behavior exhibited by the 4-tape stack as shown in Fig. 2(b).

Hence the 9/2 strands of transposed bundle has effectively a *finite* thickness with $H_{p,9/2} \sim 0.5(9/2)\sigma_{c,1}$.

Fig. 3(b) also reveals a peak loss factor $\Gamma_{T,1}$ of ~ 65 about 3.6 times that of a single strand. Allowing a potential increase of 20% due to the finite bundle thickness as found in the 4-strand stack (Fig. 2(b)), the increase of the peak value is by an approximately factor of 3. Note two side-by-side *single* strands have a peak $\Gamma_{T,1}$ of 2.8. Hence the coupling between the two side-by-side transposed bundles is also partial and at a comparable level.

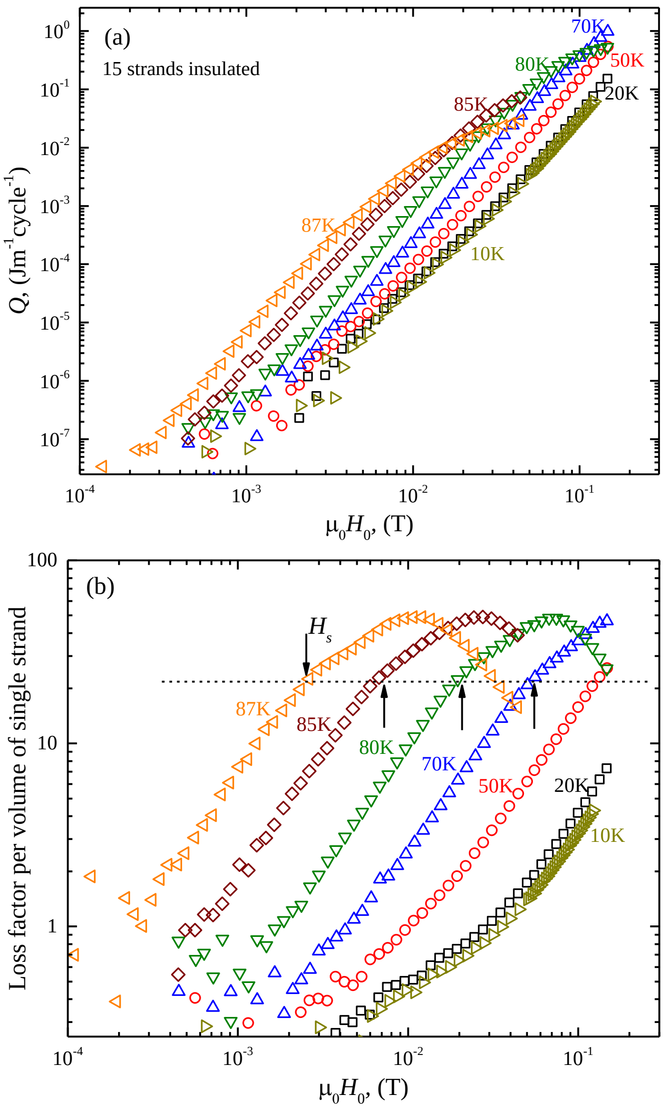

Fig. 4. (a) shows the magnetization losses of a Roebel cable with 15 *insulated* strands as a function of ac field amplitude H_0 at different temperatures and (b) shows the corresponding loss factor per volume of a single strand $\Gamma_{T,1}$ as defined in (3).

Fig. 4(a)-(b) show the magnetization losses and loss factor $\Gamma_{T,1}$ of a 15-strand *insulated* Roebel sample of a transposition pitch of 226 mm at different temperatures between 10 K and 87 K. The losses in the partially penetrated regime remain $\sim H_0^{3+}$ and the full saturation field is further increased but still satisfies $H_{p,n} \sim 0.5n\sigma_{c,1}$ where $n \sim 15/2$ is the number of tapes in each transposed bundle or a half of the total number of strands in the cable. For example the saturation field at 80 K is at 0.07 T, increased from 0.045 T by a factor of 1.6, which is approximately the ratio between 15 and 9 of the respective number of strands.

Prior to the full saturation of the insulated Roebel cable, the loss factor (Fig. 4(b)) exhibits a distinct change of slope at a field H_s where $\Gamma(H_0)$ slows sharply from $\sim H_0^{1.5}$ to $\sim H_0^{0.75}$ (see arrows in Fig. 4(b)). With the logarithmic scale of Fig. 4(b), it is evident that the locations of $H_s(T)$ are approximately at a quarter of the corresponding saturation field $H_p(T)$, i.e., almost the *same* as $H_{p,1}(T)$ of a single strand. Furthermore, as indicated by the dash line, $H_s(T)$ occurs at $\Gamma \sim 20$, which coincides with the peak value for a single strand. The above characteristics of $H_s(T)$ are consistent with the saturation of a *single* strand, pointing to the transposition segment where a strand is switched from one side to the other. The saturation of the transposition section as an isolated single strand is intuitively expected for *insulated* Roebel cables, as indeed found by numerical modelling (shown in Fig. 5). In contrast, the *absence* of such a feature in the *uninsulated* 9-strand Roebel also suggests that the electrical contacts between the transposition section and the parallel bundles underneath are sufficient for preventing the early saturation by sharing the induced current. As the current sharing among the Roebel strands is pressure dependent [12-13], a weak contact was expected for the 9 uninsulated strands which held together by thinly spread N grease without an applied pressure.

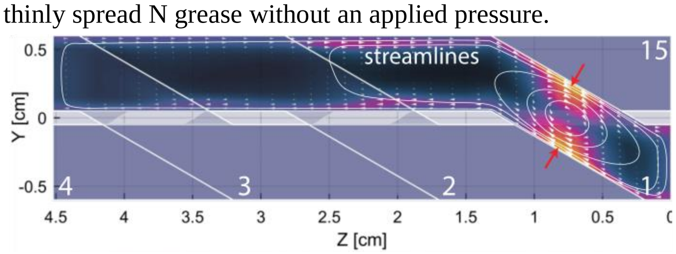

Fig. 5. An example of the magnetisation current in a 15-strand Roebel cable in external ac field perpendicular to the strand face. Only the top strand is shown while the positions of the neighbouring strands are indicated.

IV. Conclusion

Comparative studies on the magnetization loss of a single Roebel strand, reprehensive simple assemblies and Roebel cable samples of 9 and 15 strands showed that the transposed bundles are partially coupled, while each bundle has a magnetization that significantly deviates from a Norris' strip of zero thickness. Insulation between strands has shown to isolate the transposition segments switching between the two bundles, while uninsulated strands seem unaffected. The isolated transposition segments have a lower saturation field than the n-tape bundle by a factor $n/2$. Such a localized penetration potentially provides a mechanism for longitudinal interruptions to the partial coupling of the transposed bundles. This feature should be implemented in the 3d field models of the accelerator magnets in order to verify its effectiveness for or hindrance to reducing the overall magnetization and improving the field quality. Further experimental and numerical studies should also be carried out to account quantitatively for the role of thickness magnetization and full penetration of transposed Roebel bundles.

REFERENCES

[1] L Roebel (BBC Company) 1912 German Patent 19 March.

[2] M. Leghissa, V. Hussennether, H. W. Neumüller, "kA-Class High-Current HTS Conductors and Windings for Large Scale Applications", *Advances in Science and Technology*, Vol. 47, pp. 212-219, Oct. 2006.

[3] N. J. Long, R. A. Badcock, K. Hamilton, A. Wright, Z. Jiang and L. S. Lakshmi, "A Treatise on Electricity and Magnetism Development of YBCO Roebel cables for high current transport and low AC loss applications", *Journal of Physics: Conference Series*, Vol. 234, (2010) 022021.

[4] W. Goldacker1, A. Frank, A. Kudymow, R. Heller, A. Kling, S. Terzieva and C. Schmidt "Status of high transport current ROEBEL assembled coated conductor cables", *Supercond. Sci. Techno*l. Vol. 22, 034003, 2009.

[5] A. Badel, A. Ballarino, C. Barth, L. Bottura, M.M.J. Dhalle, J. Fleiter, W. Goldacker, J. Himbele, A. Kario, L. Rossi, A. Rutt, C. Scheuerlein, C. Senatore, P. Tixador, A. Usoskin, Y. Yang, "REBCO cable for the EuCARD2 Demonstrator Magnet", *IEEE Trans. Appl. Supercond*, to be published in this volume.

[6] L. S. Lakshmi, K. P. Thakur, M. P. Staines, R. A. Badcock and N. J. Long, "Magnetic AC Loss Characteristics of 2G Roebel Cabl*e*", *IEEE Trans. Appl. Supercond*, Vol. 19, pp3361-3364 (2009).

[7] S. Terzieva, M. Vojenciak , E. Pardo, F. Grilli , A. Drechsler, A. Kling, A. Kudymow, F. Gömöry and W. Goldacker, "Transport and magnetization ac losses of ROEBEL assembled coated conductor cables: measurements and calculations", *Supercond. Sci. Techno*l, Vol. 23 014023-014030 (2010).

[8] Z. Jiang, T. Komeda, N. Amemiya, N. J. Long, M. Staines, R. A. Badcock, C. Bumby and R. G. Buckley, "Conductor choices for upgrades of CERN magnetsTotal AC loss measurements in a six strand Roebel cable carrying an AC current in an AC magnetic field", *Supercond. Sci. Techno*l, Vol. 26 035014-035013 (2013).

[9] Y. Yang, E. A. Young, M. Bianchetti, E. Martinez and G. Giunchi, "Measurement of AC losses in MgB2 wire and bulk conductors at different temperatures", *IEEE Trans. Appl. Supercond,* Vol. 19 pp 2883-2886 (2005).

[10] E. H. Brandt abd M Indenbom, "Type-II-superconductor strip with current in a perpendicular magnetic field" *Phys. Rev. B,* Vol. 48 pp12893-12906 (1993).

[11] V. B. Zenkevitch, A. S. Romanyuk and V. V. Zheltov, "Losses in composite superconductors at high levels of magnetic field excitation", *Cryogenics* Vol. 20 pp703-710 (1980).

[12] M. Majoros, M. D. Sumption, E. W. Collings and N. J. Long, "Stability, inter-Strand contact resistance, and AC Losses in YBCO Rebel cables", IEEE Trans. Appl. Supercond, Vol. 24 6600505 (2014).

[13] M. Majoros, M. D. Sumption, E. W. Collings and N. J. Long, "Inter-strand current sharing and ac loss measurements in YBCO Rebel Cables", *Supercond. Sci. Techno*l, Vol. 28 055010-055020 (2015)