AC Loss Measurements on Multi-filamentary MgB_2 Wires with Non-magnetic Sheath Materials

Henning Taxt, Niklas Magnusson, Magne Runde, and Silvia Brisigotti

Abstract—**The MgB_2 superconductor is an attractive choice for many high-current DC applications, particularly for its low cost compared to e.g. YBCO, and the higher operating temperature than the low-temperature superconductors. To extend the operating range to include also AC applications, the AC losses need to be determined and a path towards a low-loss conductor needs to be established and verified. To accomplish this development, systematic and reliable measurements of the losses are essential. In this paper we present AC loss measurement results on non-twisted MgB_2 wires with titanium and copper-nickel matrices. 50 Hz AC losses were measured calorimetrically in applied magnetic fields, with transport currents, and with combinations of both. The temperature range was between 25 K and T_c, the magnetic field was varied up to 300 mT, and the transport current up to 113 A. The measurement results are used as a basis to discuss the necessary AC loss reduction steps in MgB_2 superconductors.**

Index Terms—**superconductors, AC losses, MgB_2, calorimetric measurements**

I. INTRODUCTION

SUPERCONDUCTORS have for a long time been seen as a valid replacement of conventional copper and aluminum conductors to increase performance, lower losses and enable new features in electrotechnical devices. A major obstacle has so far been the cost level of the superconductors themselves. Nevertheless, several large projects of e.g. power cables [1], [2] and motors [3] have demonstrated the technical feasibility, and a few systems of a high-temperature superconductor based induction heater have been sold on a commercial basis [4]. These devices operate either under DC conditions or at low AC magnetic fields. To open the much larger AC market, a low cost, high performance AC superconductor is needed.

In the late 1990s, significant efforts were put into the development of BSCCO/Ag wires with low AC losses [5]-[8]. The key is to decouple the filaments by applying a high resistive matrix and by twisting the filament. Today AC loss levels of 0.3 W/kAm at 100 mT, 50 Hz and 77 K (AC losses divided by the self-field critical current) have been reported in comercial BSCCO/Ag superconductors [9], without leading to a commercial breakthrough. For the YBCO tape, work on AC loss reduction is under way [10], [11], but still the outcome is unknown.

An interesting alternative is the MgB_2 wire with its low material cost and relatively simple manufacturing process. Work on loss reduction in the MgB_2 wire is just initiated [12], and needs to aim for lower losses than in the BSCCO/Ag and YBCO superconductors to compensate for its lower operating temperature of 20-30 K. The optimization of an MgB_2 AC wire follows the same principles as that of BSCCO/Ag wires, namely decoupling of thin filaments by twisting and the use of high resistivity matrices.

On the path towards a good MgB_2 conductor for AC use, reliable loss measurements under application-like conditions, i.e. with simultaneously applied magnetic fields and transport currents at variable temperatures, are necessary. In the literature AC loss measurement results due to either AC transport currents [13], [14] or AC applied magnetic fields [14]-[16] have been reported.

In this work, we present AC loss measurement results obtained on two non-twisted MgB_2 wires with non-magnetic sheath materials. Both conductors are exposed to external magnetic fields and for one of the conductors, loss measurements from the combined action of magnetic fields and transport currents have been performed. The obtained measurement results can set the baseline for the AC wire development, and they are used to discuss the requirements on the MgB_2 AC wire development.

II. SAMPLES

Two MgB_2 samples, manufactured by Columbus Superconductors for development purposes, were investigated. The first sample was a round wire with 19 MgB_2 filaments imbedded in a titanium matrix. The second sample was rectangular shaped with 37 MgB_2 filaments embedded in a cupronickel (70/30) matrix and with a niobium barrier around each filament (to avoid reaction between MgB_2 and copper during the heat treatment in the manufacturing process, and to increase the matrix electrical resistivity). Both sheath materials were non-magnetic, replacing the commonly used pure nickel matrix in standard DC wires, and in that way avoiding magnetic hysteresis losses which otherwise would

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H. Taxt was with the department of Electric Power Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway. He is now with SINTEF Energy Research, NO-7465 Trondheim, Norway (e-mail: henning.taxt@sintef.no).

N. Magnusson is with SINTEF Energy Research, NO-7465 Trondheim, Norway (phone: +47 73597269; fax: +47 73597250; e-mail: niklas.magnusson@sintef.no).

M. Runde is with SINTEF Energy Research, NO-7465 Trondheim, Norway and with the Department of Electric Power Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway (e-mail: magne.runde@sintef.no).

S. Brisigotti is with Columbus Superconductors SpA, Via delle Terre Rosse 30, IT-16133 Genova, Italy (e-mail: brisigotti.silvia@clbs.it).

make the interpretation of the results difficult. The cross-sections of the samples are shown in Fig. 1, and dimensions and materials are summarized in Table I.

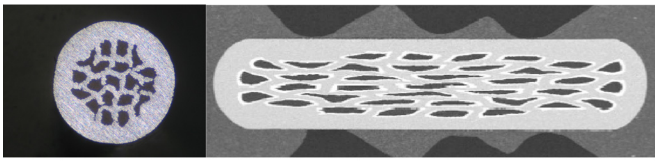

Fig. 1. Cross-section of the round sample (left) and the rectangular shaped sample (right). The diameter of the round sample is 1.14 mm and the dimensions of the rectangular sample 0.95 mm x 4.2 mm.

TABLE I
SAMPLE DIMENSIONS AND SHEATH MATERIALS

Wire shape	Total area (mm^2)	MgB_2 area (mm^2)	No. filaments	Sheath material	Barrier
Round	1.01	0.25	19	titanium	no
Rectangular	3.99	0.73	37	cupronickel	niobium

III. MEASUREMENT METHOD

The measurement method was calorimetric. Measurements were made in vacuum over a 40 cm long part of the sample wires which was exposed to an injected transport current and/or an AC magnetic field generated by a separate set of field coils. The power losses were derived from the sample's temperature increase, which was calibrated against the temperature increase due to a known power input to a heater wound together with the sample. The measurement system is described in detail elsewhere [17].

For the rectangular shaped sample, the magnetic field is applied in parallel with its wide face.

All AC loss measurements were performed at 50 Hz and simultaneously applied transport currents and magnetic fields were in-phase.

The DC I-V measurements, to determine the critical current, were performed in the same apparatus.

IV. RESULTS AND DISCUSSION

A. *Critical Currents*

From I-V measurements, critical currents were determined for the rectangular sample using the standard 1 μV/cm criterion. Fig. 2 shows the self-field critical current as function of temperature. Limitations in the current leads of the measurement system restricted the measurements to below 200 A. In [13] a linear approximation is suggested for the critical current up to 35 K. The results for the rectangular sample indicate linearity up to approximately 35.5 K, and an extrapolation is used to determine the critical current at 33.5 K, the lowest temperature used in the following AC loss measurements on that sample.

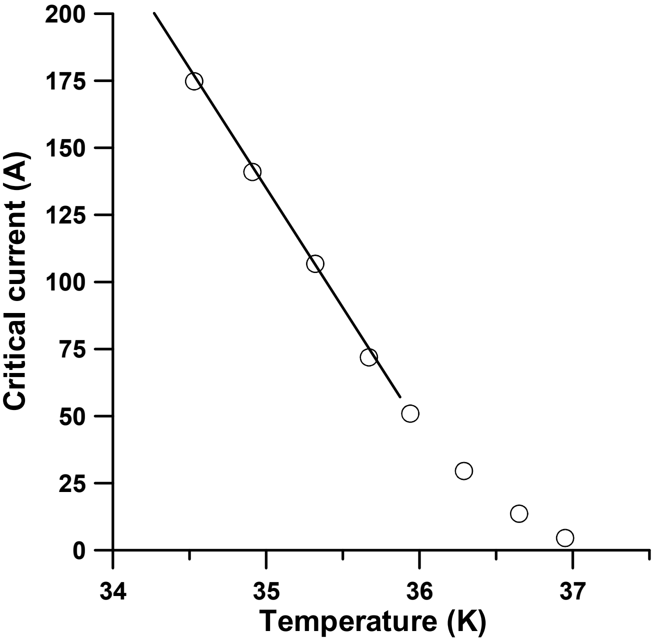

Fig. 2. Self-field critical currents for the rectangular sample. The line is a linear fit to the values below 35.5 K.

B. *AC Losses*

The high critical currents at low temperatures limit the interesting measurement region to temperatures above 30 K (given the non-AC optimized nature of the wires, lower temperatures would have resulted in too high losses for the measurement system). Furthermore, in this region the critical current varies strongly with the temperature, and hence, a small change in temperature gives rise to a large change in the AC losses, making the region decisive when evaluating the wires' loss behavior.

Figs. 3 and 4 show the losses due to applied fields only, for the round and the rectangular samples, respectively. The data follow the, from the critical state model [18], expected $P \propto B^3$ behavior for low magnetic fields, and $P \propto B$ for high magnetic fields. Furthermore, as the temperature increases and consequently the critical current decreases, the transition region between the $P \propto B^3$ and $P \propto B$ dependencies shifts to lower magnetic fields.

The difference in loss level at a given temperature of the two samples is notable (a factor of 3-5 in the high field region). The higher losses in the rectangular wire can be attributed to its larger area (a factor of 4) given that the thickness is about the same, and assuming comparable critical current densities.

In Fig. 4, the solid lines are fitted to the equation for the hysteresis losses per unit length of a slab without transport current [18], [19],

$$P=\begin{cases}\dfrac{2fCA}{3\mu_0}\dfrac{B_a^3}{B_p} & for \quad \dfrac{B_a}{B_p}\le 1\\[2ex] \dfrac{2fCA}{3\mu_0}\left(3B_pB_a-2B_p^2\right) & for \quad \dfrac{B_a}{B_p}\ge 1\end{cases}, \qquad (1)$$

where f is the frequency, C is a fitting parameter, CA the effective area, B_p the penetration field (approximately $\mu_0 J_c\, a$, where a is the half width of the slab), and B_a the externally applied magnetic field. For the rectangular sample, C becomes 0.8, effectively equal to the filament region (including the cupronickel in-between the filaments), and B_p becomes 67 mT, 40 mT and 10 mT at 33.5 K, 34.7 K and 36 K, respectively (proportional to the self-field critical current) and corresponding to approximately $\mu_0 J_e\, a$. (Note the use of the engineering critical current, J_e). Hence, the non-twisted multifilamentary MgB_2 sample acts fully coupled, with losses equal to those in a single filament with the same critical current and cross-section as the entire sample (including the cupronickel matrix).

In Fig. 4 it can be seen that the model at high magnetic fields, particularly at 36 K, overestimates the losses, and likewise in Fig. 3, the power law dependency at high fields at 36 K is below 1. This can be attributed to the magnetic field dependency of the critical current density. At high fields, the critical current density significantly reduces, leading to a lower loss than predicted by (1).

Fig. 5 shows the losses due to applied magnetic fields combined with transport currents for the rectangular sample at 34.7 K. The currents correspond to 44%, 62%, and 71% of the self-field critical current. The two highest currents give a significant additional contribution to the losses even in the 70 mT region. In fact, the addition of the current doubles the losses in the conductor, compared to the losses with field only.

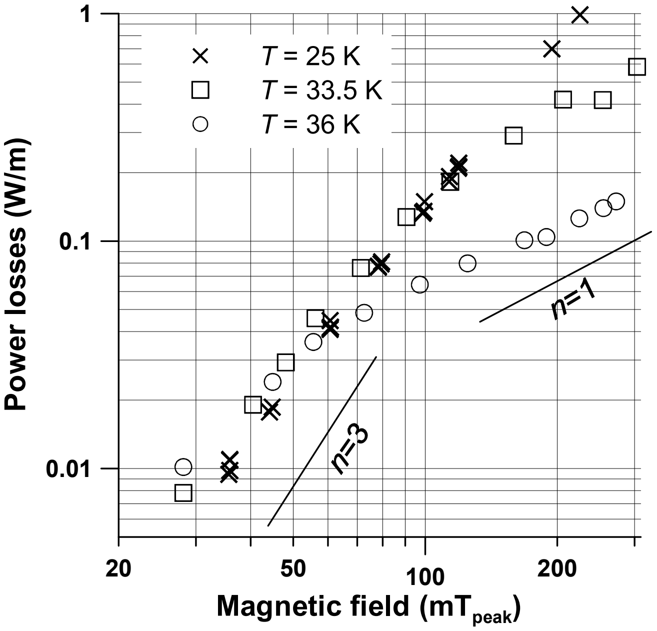

Fig. 3. AC losses as function of magnetic field for the round sample at 25 K 33.5 K, and 36.0 K. The $P \propto B^n$ slopes are shown for comparison.

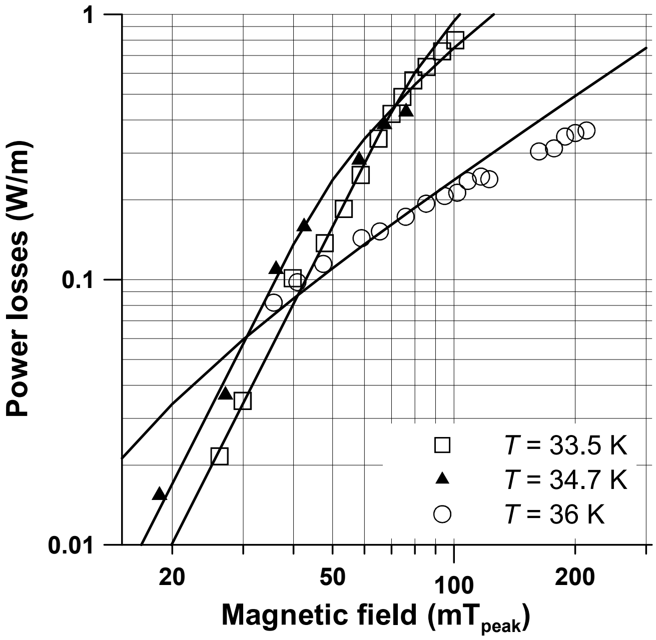

Fig. 4. AC losses as function of magnetic field for the rectangular sample at 33.5 K (I_c = 268 A), 34.7 K (I_c = 160 A), and 36.0 K (I_c = 42 A). The lines are fitted to equation 1.

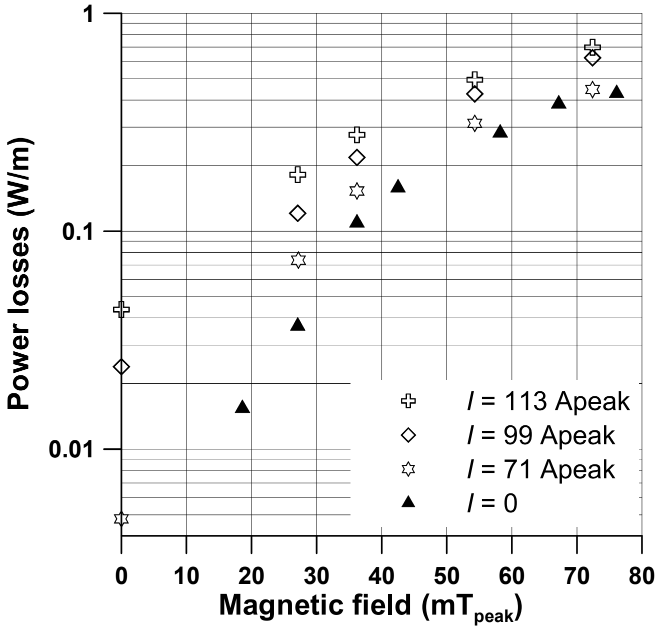

Fig. 5. AC losses as function of magnetic field combined with different transport currents for the rectangular sample at 34.7 K.

The figure of merit of the conductor in terms of losses is the losses per kAm. In the 70-80 mT range, and for 113 A, this number becomes 6.5 W/kAm. This number should not be confused with the less illustrative number sometimes used calculated by dividing the magnetic field losses by the self-field critical current. That number is a factor of 2.4 lower for this conductor, namely 2.5 W/kAm. However, neither of these numbers is attractive for large scale power frequency applications.

V. MgB_2 WIRE DEVELOPMENT REQUIREMENTS

To set the targets for tolerable losses of an AC MgB_2 wire, one can use the same approach as for BSCCO/Ag wires in the 1990s [20]. Conventional copper conductors are typically operated with current densities of around 2 A/mm^2, resulting in power losses of 40 W/kAm. The MgB_2 wire needs to perform better than that at its operating temperature when including the power required for the cooling system.

A likely temperature for AC operation of MgB_2 wires in magnetic fields up to 200-300 mT is 30 K. At this temperature the cooling penalty factor (the number of watts needed in a cooling machine at room temperature to withdraw 1 W dissipated in the superconductor at 30 K) is approximately 45 (a factor of 9 for the theoretical carnot cycle and a factor of 5 for the efficiency of the cooling machine). Hence, to achieve equally low losses in the MgB_2 wire (including the cooling) as in the copper conductor, the losses in the MgB_2 should be 0.88 W/kAm.

However, to really gain something with the MgB_2 wire, and to reduce the capacity and costs needed for cooling, the losses in most cases have to be lowered another factor of 5-10, resulting in tolerable losses of around 0.1 W/kAm.

Consider an application where the conductor is exposed to 100 mT in average (as may be the case in a power transformer). Taking the starting point in the measured values in Fig. 5, the losses at 100 mT can be extrapolated to amount to 8 W/kAm, and hence, a loss reduction of a factor of 80 is needed in the development of an AC MgB_2 wire to reach the 0.1 W/kAm target.

The steps to be taken to reach such a good conductor include filament twisting and insertion of high resistivity matrices to completely decouple the filaments. Achieving this, the filaments acts independently and the losses become determined by the filament size instead of the conductor size as for the present wires. Consider the lower part of (1), insert $\mu_0\, aI_c / A$ for B_p, and ignore the second term which becomes insignificant at high fields. Then (1), for a fully coupled sample becomes,

$$P_{coupled} = 2fCI_c aB_a \quad , \tag{2}$$

and for a completely decoupled sample with the same area of superconducting filaments, inserting $\mu_0\, a_{filament}\, I_c / A_{MgB2}$, the corresponding equation becomes,

$$P_{decoupled} = 2fI_c a_{filament} B_a \, , \tag{3}$$

where $a_{filament}$ is the filament half width and A_{MgB2} is the total area of the MgB_2 filaments. Note that in (2) the full area and the engineering critical current density, J_e, are used, whereas in (3) the area of the MgB_2 filaments and the critical current density, J_c, are used. By combining (2) and (3) we obtain,

$$\frac{P_{decoupled}}{P_{coupled}} = \frac{a_{filament}}{Ca} \, . \tag{4}$$

With $C = 0.8$, $a = 0.5$ mm, and the desired $P_{decoupled} / P_{coupled}$ ratio of 1/80, then $a_{filament}$ becomes 5 μm. Consequently, the filament width, or diameter for round filaments, should be of the order 10 μm to enable a good AC MgB_2 conductor.

The derivation of the 10 μm filament diameter includes several simplifications. Also, one may be interested in applications where higher or lower losses can be tolerated, or one may operate with other frequencies or magnetic fields. All those circumstances change the requirement on the filament width. Nevertheless, it points out to what region an AC loss reduction must aim to become successful.

VI. CONCLUSIONS

The AC losses of the two non-twisted multifilamentary MgB_2 samples basically follow the losses predicted by the critical state model for a fully coupled superconductor. The losses for this DC wire are far too high for AC applications (of the order 8 W/kAm at 50 Hz, 100 mT and the operating current 113 A). Decoupling of filaments is necessary to reduce losses, and in addition, the filament size needs to be reduced to a diameter of the order of 10 μm to become competitive in a wide range of AC applications.

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