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# A Method to Estimate the Necessary Twist Pitch in Multi-filamentary Superconductors

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**Abstract**. Twisting of multi-filamentary superconductors is an important step in the development of wires with AC losses at an acceptable level for AC applications. The necessary twist pitch depends on wire architecture, critical current density, matrix material, and external factors such as temperature, frequency and applied magnetic field. The development of an AC optimized $MgB_2$ superconductor would be facilitated by a fast method to set the requirements for the twist pitch. A problem often encountered when comparing wires with different twist pitches is the degradation in critical current occurring at small twist pitches due to mechanical deformation. In this work we propose to use a non-twisted conductor to estimate the influence of twisting on the AC losses. A long superconductor is cut into smaller lengths, each simulating one third of the twist pitch, and the AC losses due to applied magnetic fields are compared between samples of different lengths. With this method, the effect of reducing the size of the loop of the coupling currents is studied without changing the superconducting parameters. AC loss measurement results are presented for a round titanium matrix $MgB_2$ wire with simulated twist pitches between 9 mm and 87 mm.

## 1. Introduction

Medium- and high-temperature superconductors on or close to the market have the technical performances necessary for consideration in several large-scale applications, like DC [1] or low-field AC [2]-[3] cables, generator rotors [4], and induction heaters [5]. These applications set only minor requirements on the wire's behavior under AC operation. To broaden the possible range of applications to include components like transformers, reactors, and generator stators, where the AC magnetic field is significant, low AC loss conductors are required.

For YBCO coated conductors there is ongoing research aiming at reducing the AC losses by e.g. transverse cuts [6]-[7]. For the multi-filamentary conductors, BSCCO and $MgB_2$, the key is to manufacture wires with thin, electromagnetically decoupled filaments. For BSSCO conductors the research toward such wires was intensive in the late 1990s [8]-[11], without reaching loss levels which lead to a commercial breakthrough, mainly due to difficulties to obtain a sufficiently short twist pitch without degradation of the superconducting properties.

For $MgB_2$ conductors the AC optimization step is yet to be taken. The route towards a low AC loss wire includes twisting of the filaments, use of high resistivity (and non-magnetic) matrices, and reduction of filament size. To significantly reduce the losses compared to the losses in conventional copper conductors, the AC losses need to be about or below 0.1 W/kAm at an operating temperature of $MgB_2$ of 20 K. To reach that target the filaments need to be fully decoupled and their size to be of the order 10 μm [12], although a larger filament size can be accepted for applications with other benefits than only loss reduction.

When twisting the filaments, the conductor may suffer from degradation in the critical current density, due to the mechanical deformation [13]. The effect of the twisting with respect to reduction of AC losses may therefore be difficult to assess, since the AC losses are highly dependent on the critical current density [14]. However, in the conductor development phase, the knowledge of the necessary twist pitch for different wire architectures is crucial to set the development target, and to balance the efforts of inserting resistive barriers and applying strong filament twisting.

Some guidance of the necessary twist pitch can be obtained by equation (1) defining a critical length $L_c$ of the twist pitch [15],

$$L_c = 4\sqrt{\frac{I_c \rho}{2\pi f B}}\,, \tag{1}$$

where $I_c$ is the critical current, $\rho$ the electrical resistivity of the matrix, and $f$ and $B$ are the frequency and amplitude of an applied sinusoidal magnetic field. At twist pitches longer than $L_c$, the filaments are fully coupled, at shorter twist pitches the filaments become first partly decoupled, and at twist pitches much shorter than $L_c$, fully decoupled.

In real situations, the matrix architecture may be complicated and $\rho$ difficult to predict. Furthermore, one would not only be interested in the twist pitch where decoupling starts, but also of the twist pitch leading to sufficient decoupling for a given wire architecture.

In this work we propose an experimental technique to estimate the necessary twist pitch in multi-filamentary conductors by measurements on non-twisted wires.

## 2. Simulating the twist pitch by cutting non-twisted wires

When a multi-filamentary wire is exposed to a time-varying magnetic field, currents are induced in a loop consisting of two filaments and bridges in the metal matrix between them. These currents contribute to the total losses by an increase in the superconductor hysteresis losses and by the ohmic losses caused by the coupling currents crossing the metal matrix.

In a non-twisted multi-filamentary superconducting wire, the loop becomes infinitely long, and the filaments are fully coupled, i.e. the filaments act as one bundle leading to larger hysteresis losses than if they were acting separately. To reduce the loop and thereby the losses, the wire can be twisted, as in figure 1 (right). The enclosed magnetic flux (and change in flux) in the loop becomes smaller with a smaller twist pitch, and hence the driving voltage for the coupling currents becomes smaller. With strong enough twisting, the driving voltage becomes lower than necessary for the currents to cross the metal matrix and the filaments become decoupled and the losses thereby reduced.

To study the effect of twisting we propose to cut a non-twisted multi-filamentary wire into shorter lengths each approximately representing one third of the twist pitch. Compare the drawings in figure 1. For the twisted wire to the right, the area of an enclosed loop for half a twist pitch is $2/\pi$ of the area of the loop for the cut non-twisted wire to the left (assuming the loop is closed at the ends). Hence, the behavior of a twisted wire, when exposed to an AC magnetic field, can approximately be studied considering short non-twisted wires. The lengths of the samples correspond to one third of the twist pitch of twisted wires.

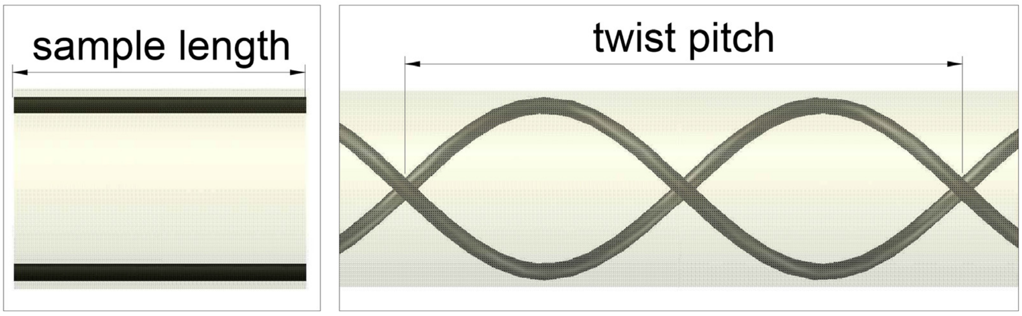

**Figure 1**. Schematic drawings of a twisted wire (right) and a non-twisted sample cut to a length corresponding to one third of the twist pitch. Only two filaments are shown in each sample.

## 3. Experimental

### *3.1 Sample and sample preparation*

A 37 filament $MgB_2$ non-twisted round wire with a titanium matrix was studied, see figure 2 (left) for a cross-section photo. The wire was manufactured by Columbus Superconductors for research purposes. The wire diameter was 1.14 mm, the total cross-sectional area 1.01 $mm^2$, and the superconducting part 0.25 $mm^2$.

The sample wire was cut into six pieces. To each piece a thin copper wire (used for temperature measurements) and a high resistance wire (used as heater) were attached, and the assembly was placed in a mold and casted in Stycast 2850 epoxy, see figure 2 (right).

**Figure 2.** Cross-section of the sample wire (left) and the principle sample configuration (right) [16].

The six pieces were then carefully sanded from the ends and inwards about 4 mm to remove parts at the ends potentially mechanically damaged during cutting. The remaining sample lengths were 3, 3, 4, 7, 12, and 29 mm.

### *3.2 Measurement method*

The measurement method was calorimetric. The system used is presented in detail elsewhere [16], here a short summary is given. The samples were glued with Stycast 2850 to the top of the sample holder. The samples and the sample holder were placed in vacuum and were in thermal contact with the cold head of a cooling machine. In a nitrogen bath just outside the cryostat, a set of magnetizing copper coils was placed, generating a magnetic field over the samples. The exposures of time-varying magnetic fields resulted in temperature increases in the samples due to AC losses. These increases were calibrated against the temperature increases (determined by measuring the change in resistance in a copper wires glued to each sample) due to the known power dissipation in heaters wound around the samples and fed by a low DC current. The samples of different lengths were placed after each other and were thereby simultaneously exposed to practically identical magnetic fields.

## 4. Results and discussion

Measurements were performed at 35 K. At this for $MgB_2$ conductors relatively high temperature, the critical current and hence the penetration field is low, allowing us to study the losses in the for medium field applications interesting region above the penetration field. Figure 3 shows the losses per unit length at 50 Hz as function of magnetic field for different sample lengths. Clearly the losses per unit length are reduced for sample lengths of 7 mm and below, whereas the losses for the 12 and 29 mm samples show only minor differences. The loss reduction can be attributed to the reduction in hysteresis losses due to the decoupling of filaments with reduced sample length. From the results it can be seen that the decoupling starts between sample lengths of 7 mm and 12 mm, corresponding to twist pitches of 21 to 36 mm, and decoupling further reduces losses down to the shortest sample length of 3 mm (corresponding to a twist pitch of 9 mm).

It is important to notice that the indicated $L_c$ of about 30 mm is valid for this wire alone. The wire architecture, including the effective resistivity of the matrix, will strongly influence $L_c$ as well as the loss reduction for twist pitches below $L_c$.

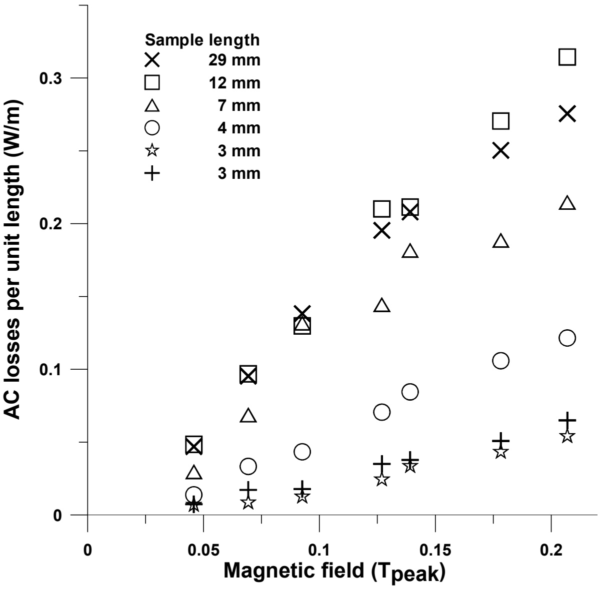

**Figure 3.** AC losses per unit length as function of applied magnetic field for non-twisted samples cut to different lengths. The temperature was 35 K and the frequency 50 Hz.

## 5. Conclusions

It has been presented how the necessary twist pitch in multi-filamentary superconductors can be predicted by studying short non-twisted samples. For an $MgB_2$ superconductor with a titanium matrix, the decoupling was estimated to start at a twist pitch corresponding to about 30 mm.

## Acknowledgment

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