Current sharing and stability in an extremely low AC-loss MgB₂ conductor

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Abstract. In the push to develop high power electric aircraft, superconducting technology promises to significantly reduce mass and volume of motors and generators. However, challenges related to AC-loss and thermal management are a significant factor in preventing the proliferation of aerospace superconducting technologies. Increasing the resistance of the metal matrix stabilization has only gone so far in reducing coupling currents for higher frequency applications. In this research, Multiphysics simulations of a single composite filament were used to investigate stability decreases when using very high thermal conductivity electrical insulator (CsI) or metal-to-insulator transitioning material (V²O₃) to replace the slightly resistive metal matrix typically used for a low AC loss MgB₂ composite wire. The insulators separate the MgB₂ filaments entirely, only allowing transient current sharing to occur with the high purity Nb diffusion barrier or with the metallic state V²O₃. These simulations show that for these very low AC-loss composites at 20 K, instability will become a major issue due to reductions in current sharing. With higher electrical conductivity metal-to-insulator materials, higher thermal conductivity impregnation materials, and thicker metallic diffusion barriers it may be possible to find a reasonable balance between AC-loss and stability.

1. Introduction

Single aisle and twin aisle large commercial aircraft presently contribute approximately 1.9 to 2.3% of global CO₂ emissions [1]. While this appears to be a small portion, decreasing global greenhouse gas emissions will require a many pronged approach. Of the many initiatives and programs to develop remarkably high efficiency commercial aircraft by 2035 [2–5], a later generation NASA N+3 vehicle will require roughly 45 MW of electrical power [6]. At powers this high, nearly every electrical component will require significant breakthroughs in light weighting and performance [7]. There is substantial focus on increasing the efficiency and performance of motors and generators, and some design teams have proposed the use of cryogenic Hydrogen cooling [8] and superconducting composites in armature windings [9]. While it is true superconducting composites generate zero DC losses, under AC conditions there are still eddy current, magnetization, and coupling loss components [10]. Analytical descriptions exist, shown in equations 1 and 2, which describe loss components of a filamentary metal-superconductor composite wire under a DC transport current and alternating magnetic field.
\[
\overline{P_{\text{mag}}} = \frac{8}{3\pi} B_0 f J_{\text{c}} d_{\text{eff}} \quad \text{[W/m}^3\text{]} \quad (1)
\]

Where \(\overline{P_{\text{mag}}}\) is magnetization loss averaged over a field cycle, \(J_{\text{c}}\) is the critical current density of the superconductor, \(f\) is frequency, \(B_0\) is the alternating field amplitude, and \(d_{\text{eff}}\) is an effective filament diameter.

\[
P_{\text{coup-eddy}} = \frac{r_x^2}{r_o^2} \left( \frac{dB}{dt} \right)^2 \left( \frac{L_p}{2\pi} \right)^2 \left( \frac{1}{\rho_{\text{ms}} r_o^2 + r_x^2} + \frac{1}{\rho_{\text{mf}} r_x^2} + \frac{1}{4\rho_{\text{mf}} r_x^2} \right) \left( \frac{r_o^4 - r_x^4}{r_o^2} \right) \quad \text{[W/m}^3\text{]} \quad (2)
\]

Where \(P_{\text{coup-eddy}}\) is the sum of eddy and coupling loss, \(dB/dt\) is equal to \(4B_0 f\), \(r_{xxx}\) refers to different radii within the composite (\(r = \) outer filament region, \(c = \) filament free core, \(o = \) strand), \(\rho_{xxx}\) refers to different resistivities within composite (\(ms = \) outer sheath, \(mc = \) core, \(tf = \) interfilamentary region, and \(L_p\) is the twist pitch of superconducting filaments. From equations 1 and 2 it is clear that minimizing filament size and increasing the metal matrix resistivities are ways to reduce AC-loss.

One of the promising superconducting composites for armature windings is metal-MgB\(_2\). MgB\(_2\) superconducting composites can be fabricated as an isotropic wire conductor with very fine filaments (~20 µm) embedded in a somewhat resistive metal matrix [11]. Doped high-\(J_c\) MgB\(_2\) composites generally have a transition temperature, \(T_c\), near 36 K which allows operation in LH\(_2\) with a 16 K temperature window [12]. MgB\(_2\) composites are cheaper than similar current carrying REBCO high temperature superconducting coated conductors and BSCCO composite wire at low fields. While attempts have been made to reduce AC-loss of MgB\(_2\) conductor, the AC-loss remains too large for higher frequency (200 Hz and up) proposed next generation aerospace motors [13]. Because higher frequency operation is generally desired to meet the aggressive power density targets, new steps have to be taken to reduce AC-Loss, and particularly coupling losses which become dominant at higher frequencies.

Interfilamentary metal could in theory be removed, greatly reducing higher frequency losses, but interfilamentary metal provides an important role in “stabilizing” the superconducting composite from thermal perturbations, such as magnetothermal instabilities [14]. Without metal stabilizer and the ability to current share with neighbouring superconducting filaments, when an isolated superconductor filament transitions to the normal state, there will likely be irreversible damage due to excess Joule heating. The metal stabilizer also conducts heat away from thermal perturbations so the superconducting filaments can rapidly thermally recover back to the normal state before critical instability limits are reached. Metal stabilizer directly increases minimum quench energy “MQE”, i.e. the thermal energy required to initiate normal zone propagation (“NZP”) which continue to expand and do not shrink and recover. Normal zone propagation velocity “NZPV” is the growth rate of irrecoverable normal zones along a conductor once instability has been reached.

The purpose of the simulations in this paper is to investigate the possibility of total electrical separation of superconducting filaments, greatly reducing high frequency AC-loss, but maintaining enough stability to be operable. One investigated method was using a high thermal conductivity impregnatable ceramic, CsI, to isolate MgB\(_2\) filaments which individually have minimal metal stabilization via the Nb barrier. If the electrically isolating matrix has high enough thermal conductivity, it may be possible to have only a moderate reduction in MQE even without filament-to-filament current sharing. From a realistic perspective, depending on the composite construction, it is possible to chemically etch the stabilizer of a metal-MgB\(_2\) composite and leave only Nb sheathed separated filaments. CsI melt impregnation can occur near 630 °C, i.e. safe temperatures for Nb\(_3\)Sn, MgB\(_2\), and BSCCO conductors. The use of CsI in stabilizing superconducting wires and magnets has previously been proposed, due to its high thermal conductivity and dielectric strength [15–17].

The other investigated method to isolate filaments is using a thin sheath of metal-to-insulator transitioning material, V\(_2\)O\(_3\) which behaves as electrical isolation at low temperatures but allows current sharing at higher temperatures experienced during normal zone growth [18]. For both of these
approaches to remove coupling losses, MQE will definitely be reduced. The question is whether the reductions in stability are acceptable for the enabling of higher frequency operation.

2. Details of simulations
A single MgB$_2$ filament, Nb diffusion barrier, and surrounding CsI, V$_2$O$_3$, or Cu was first created using Onshape® cloud-based computer-aided design software. The components were then imported and created into a three-dimensional assembly in COMSOL Multiphysics® version 5.3.0.223 with 64-bit Windows 10. The “Heat Transfer” and “AC/DC” modules were utilized along with the “Electromagnetic Heating” and “Temperature Coupling” interfaces [19–20]. All COMSOL simulations were transient solutions with start time (t$_0$) of 975 µs, end time (t$_f$) of 2.7 ms, with a continuously increasing step size described as the equation below.

$$t_{step} = 2^{(-10 \text{ stepping by 0.05 to -8.5})} \text{[s]} \quad (3)$$

An actual low-loss MgB$_2$ conductor, an example mesh for V$_2$O$_3$, and the geometry of the three situations examined are shown in figure 1 below from left to right respectively. The single filament composite was 1 mm long, the MgB$_2$ filament diameter was 20 µm, the Nb diffusion barrier was 7.5 µm thick, and the outer diameter was 55 µm in all cases.

![Figure 1](image)

The material properties required for the Multiphysics simulations were heat capacity “C$_p$ (T)”, thermal conductivity “k(T)”, electrical conductivity “σ(T)”, and mass density. The sources for the temperature dependent properties of the five materials used (polycrystalline MgB$_2$, Nb, Cu, V$_2$O$_3$, CsI) are shown in table 1. The material properties were assumed to be magnetic field independent. Data points were taken from literature plots using Graph Grabber v2.0, and were input into COMSOL Multiphysics. For continuous material property data from 20 K to elevated temperatures, a linear interpolation was used between a fine data point collection and a constant extrapolation equal to the highest temperature data point was used. The data utilized from literature went up to at least 300 K. The highly non-linear electrical conductivity data for V$_2$O$_3$ was simulated directly from literature data. The highly non-linear electrical conductivity data for MgB$_2$ was simulated by overlapping a continuous
function onto a transition region curvature from literature. Below 36 K, MgB$_2$ was assumed to have a conductivity described by the inverse of the continuous equation 4 which matched well with literature data. Above 36 K, MgB$_2$ was assumed to have a constant conductivity equal to the inverse of equation 4 with $T$ equal to 36 K.

$$\rho_{\text{MgB}_2} = \frac{E_0 + E_0 \left( \frac{T - T_b}{T_{cs} - T_b} \right)^n}{J_0} \quad [\Omega\text{m}] \quad (4)$$

In the equation above, $E_0 = 1 \times 10^{-5}$ V/m, $T_b = 20$ K, $T_{cs} = 25$ K, $n = 20$, and $J_0$ was the starting current density in the MgB$_2$ filament for that simulation in A/m$^2$.

Table 1. Literature sources for heat capacity, thermal conductivity, and electrical conductivity used for the Multiphysics simulations of a polycrystalline MgB$_2$ composite filament. Material properties which have multiple sources were needed to span as much of the temperature range of interest as possible, 20 K to greater than 300 K. This data is presented in graphs in the appendix.

| Material | Heat Capacity ($C_p(T)$) | Thermal Conductivity ($\kappa(T)$) | Electrical Conductivity ($\sigma(T)$) |
|----------|--------------------------|-----------------------------------|-------------------------------------|
| Poly-MgB$_2$ | Wang 2001 [21] | Bauer 2018 [22] | Kulich 2013 [23] |
| Nb | Chou 1958 [24] | Arblaster 2017 [25] | Powell 1954 [26] | Hall 1968 [27] |
| Cu | Simon 1992 [28] | Simon 1992 [28] | Simon 1992 [28] |
| CsI | Taylor 1963 [29] | Gerlich 1982 [30] | Lawless 1984 [17] | “Perfect Insulator” |
| V$_2$O$_3$ | Keer 1976 [32] | Andreev 1978 [33] | Morin 1959 [34] |

Starting at 1 ms into a transient simulation, a 0.5 W, 20 µm diameter, 100 µs spherical thermal perturbation was initiated at the geometric center of the composite filament, within the MgB$_2$. This was performed to simulate a magnetothermal instability. A fixed temperature of 20 K was on the outer surface of the filamentary composite and current terminals, located at the ends of the geometry, injected current into the MgB$_2$ cores. Transient simulations were performed with fixed thermal perturbation pulse parameters and different current densities until generated normal-zones no longer recovered and continued to grow towards the ends of the geometry, i.e. at MQE for the given current density. Temperature probes were located near the thermal perturbation, and because of the lengthy time of simulations, any simulation which had internal temperatures (after the thermal perturbation) greater than 1500 K were deemed unrealistic and terminated. Early terminations had no impact in determining MQE or NZPV.

3. Results from simulations
For the first series of simulations, an outer sheath of Cu with a resistivity ratio (RR$_{273/20}$K) of 10 was used to simulate an isolated Cu-Nb-MgB$_2$ filament with the interfilamentary region of a low AC-loss MgB$_2$
composite. With the thermal perturbation parameters and thermal boundaries chosen, it was not possible to generate enough Ohmic losses to nucleate a critical sized normal zone even with current densities in the MgB$_2$ filament reaching $\sim 1.8 \times 10^5$ A/mm$^2$ or 90 A in the single filamentary composite. Experiments with more aggressive thermal perturbation parameters still resulted in recovery, even when peak normal zone temperatures reached 1500 K. Because the baseline situation resulted in excess cooling and an accompanying unrealistic, almost unquenchable stability condition, it was deemed that these simulations should be used qualitatively instead of quantitatively in describing changes in stability between different composite filaments.

The CsI-Nb-MgB$_2$ composite filament was simulated next. After generating multiple recoverable normal zones, it was possible to find the approximate current density in which (for the fixed thermal perturbation parameters listed previously) unrecoverable NZP started to occur. Unrecoverable NZP started to occur at $\sim 3 \times 10^4$ A/mm$^2$ in the MgB$_2$ or 15 A in the filamentary CsI-Nb-MgB$_2$ composite. Figure 3 shows the temperature gradients and current sharing during the thermal perturbation for the 12.5 A recoverable normal zone situation. Figure 4 shows the temperature gradients and current sharing that occurs after the thermal perturbation for the 15 A propagating normal zone situation. From the 15 A results, the NZPV was $\sim 70$ cm/s, which is on par with strand level NZPV experimental data [12]. The peak temperatures of the generated normal zone, close to 1500 K, are above the melting point of CsI and Cu, and again support the opinion the results of this study examining stability should be kept qualitative and not quantitative.

Lastly, the V$_2$O$_3$-Nb-MgB$_2$ composite filament was simulated. Again, the switch from recoverable to unrecoverable NZP was monitored and images of the results are shown in figure 5. The V$_2$O$_3$-Nb-MgB$_2$ composite became unstable to the thermal perturbation at 12.5 A and had a NZPV of $\sim 50$ cm/s. The peak temperatures of the generated normal zone were less than 400 K.
Figure 3. (Left) Temperature (scale in Kelvin) around recoverable normal zone for composite with a CsI high thermal conductivity, electrically insulating outer sheath. (Right) Current sharing (scale in A/m²) around a recoverable normal zone (~0.15 mm long) for a composite with a CsI outer sheath, it is clear the Nb barrier performs some role in stabilization and CsI does not carry any current.

Figure 4. (Top left) Temperature (scale in Kelvin) around the propagating normal zone for the composite with a CsI high thermal conductivity, electrically insulating outer sheath. (Top right, bottom left, and bottom right) current sharing, scale in A/m², around a propagating normal zone at 3 different times 122 µs, 202 µs, and 334 µs after the beginning of the heat pulse. The NZPV was determined to be ~70 cm/s.
4. Discussion of results
Replacing the metal matrix of simulated filaments into a material with poorer thermal and electrical conductivity greatly reduced stability as measured by relative ease of a fixed thermal perturbation creating an irrecoverable normal zone at different current densities. The importance of current sharing for normal state recovery was clearly highlighted. However, the stability of CsI and V$_2$O$_3$ composites may not be as poor at lower temperatures where CsI becomes much more thermally conductive and with a metal-to-insulator transition material with a higher conductivity metallic state respectively. In the case of the V$_2$O$_3$ composite simulation, it would be ideal to only have a thin (not thick) layer of V$_2$O$_3$ sandwiched between the Nb barrier and a Cu outer sheath. These possibilities are the motivation for future investigations.

By separation of filaments with CsI or insulating V$_2$O$_3$, equation 2 would change to the eddy current losses of something more familiar, that of a Litz wire. It may be application dependent whether the reduction in stability is acceptable when continuous thermal loads from AC-loss are rampant.

5. Conclusion
The demand to have higher operational frequencies for superconducting composites has called for novel methods because composites with resistive metal matrices are still too lossy, driven strongly by coupling losses at high frequencies. This computational investigation shows while it may be possible to remove coupling currents, the stability from transient thermal disturbances will be greatly reduced. At a simulated temperature of 20 K, a CsI high thermal conductivity, electrically insulating matrix may

![Image](image_url)

**Figure 5.** (Top left) Temperature (scale in Kelvin) around the propagating normal zone for the composite with a V$_2$O$_3$ metal-to-insulating transitioning outer sheath. (Top right, bottom left, and bottom right) current sharing, scale in A/m$^2$, around a propagating normal zone at 3 different times 122 µs, 202 µs, and 334 µs after the beginning of the heat pulse. The NZPV was determined to be ~50 cm/s.
outperform a V$_2$O$_3$ metal-to-insulator transitioning matrix. Future simulations will investigate the performance of these novel matrices under more idealized conditions and more optimized geometry.

6. Appendix

Figure 6. Electrical conductivity data for the materials used. CsI was assumed to be a perfect insulator [23,27,28,34].
Figure 7. Thermal conductivity data for the materials used [17,22,26,28,30,31,33].

Figure 8. Heat capacity data for the materials used [21,24,25,28,29,32].
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