Feasibility of 2G HTS (YBCO) Roebel cable MRI gradient coils

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Introduction

The potential benefits of utilizing 2G HTS (YBCO) Roebel cable for gradient coils in MRI have been theoretically assessed. The requirement for fast slew rate and high gradient strength necessitates coils with minimum stored energy and high peak current. Hysteretic AC losses in HTS rise rapidly as transport current I_t approaches critical current I_c (as described by the Norris ellipse model[1]); this favours the use of high current capability Roebel cable, particularly in applications for larger subjects (since the required amp turns for fixed gradient strength rise with the square of coil radius). Efficient designs which achieve suitable gradient linearity have complex conductor patterns, particularly in cylindrical geometry. Planar coils (Figure 1) were identified as a more suitable candidate for winding from Roebel cable, which is constructed from continuously transposed strands cut from 2G tape (Figure 2). Furthermore, in this geometry the static imaging field is parallel to the HTS conductor plane, minimising AC losses. Such coils could be used as a high-performance insert gradient set, in their own cryostat, or alternatively could be integrated with the cryostat of a 2G HTS split-pair magnet (Figure 3).

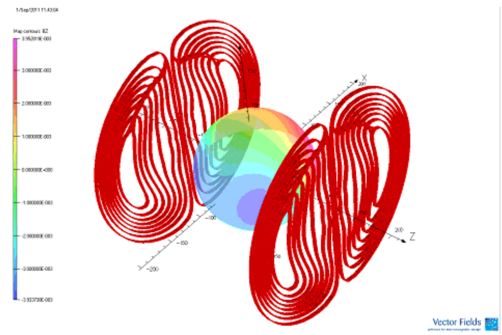

Figure 1: Planar unshielded X/Y gradient coils

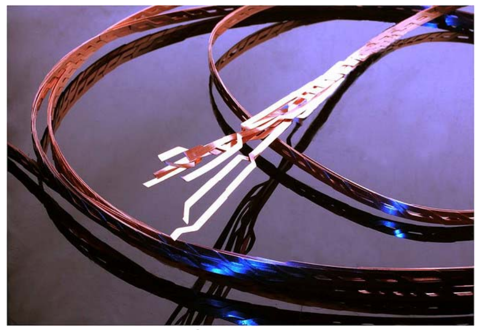

Figure 2: 2G Roebel cable

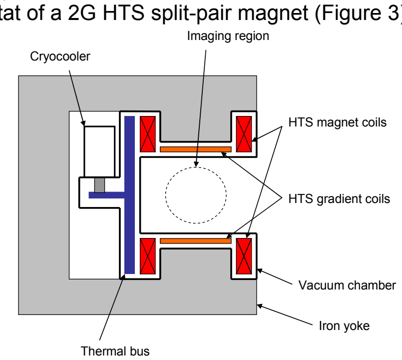

Figure 3: HTS C-magnet with integrated HTS gradient coils (schematic only).

Analysis

Previous studies[2,3] have demonstrated encouragingly small AC losses in BSCCO and Nb_3Sn gradient coils driven with audio frequency pulses; however tests were restricted to small coils and scaling issues were not addressed. More recently, measurements at 77K and self-field on circular pancake coils wound from 2G HTS Roebel cable with spaced turns[4] have demonstrated ~40% reduction in AC losses compared to coils wound with spaced parallel tapes. Losses were predominantly hysteretic up to several kHz. To facilitate translation of these results to realistic coil designs for various applications a phenomenological model of Roebel coil losses was developed. The losses observed at 77K and self field were scaled to the desired operating point (T_{op}, B_{op}) using a-priori knowledge of the cable's $I_c(T_{op},B_{op})$ and the Norris ellipse model. The refrigerator input power required to balance these losses and maintain the coil at T_{op} was then estimated based on Carnot efficiency. Minimum power consumption occurs between 20K and 50K, because AC losses reduce as the temperature of the coils is lowered, but refrigerator power requirements rise sharply at lower temperatures. This is conveniently the temperature range that would be chosen for a 2G magnet to provide the static field. Clearly the heat-load depends on the pulse sequence, and is highest for sequences with repeated gradient reversals, such as EPI. The I^2R dissipation in copper coils is also high for EPI due to ~100% duty cycle of the read-out gradient. For a typical EPI sequence with 15mT/m readout gradient, the ratio of copper losses to additional cooling power required by a Roebel transverse gradient coil (using 9 x 2mm wide strand cable with I_c of 319A at 77K, self field), falls from 100 for ∅15cm coils, to 10 for ∅42cm coils, and approaches parity for whole body coils. A Roebel cable with more stands would therefore be required for whole body use. It should be noted that dissipation in the power amplifier (GPA) is largely unaffected by conductor type, because the majority of dissipation occurs during current slewing, when the load presents an inductive impedance.

Discussion/Conclusions

Planar gradient coils wound from 2G Roebel cable potentially offer power reduction advantages, particularly in sequences which have high duty cycle and fewer switching cycles (possibly DWI). However, the power rating/cost of the GPA is unaffected and the integration of HTS gradient coils with the magnet cryogenics presents significant cryogenic engineering challenges: the additional heat leak of conductors penetrating the cryostat; time variable heat load and localized heating at cable joints, leading to hot-spots; variable heat-load to the static field magnet (both conducted and eddy current) and, most significantly, designing HTS coils and cryostat suspension with sufficient rigidity to withstand the vibration caused by Lorentz forces. A specialized application driven by the need for long-duration, high-strength gradients is required to justify further development

References

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