Which is the impact of the coil track width and frequency over a split gradient coil performance?

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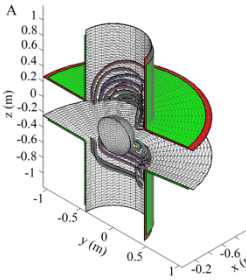
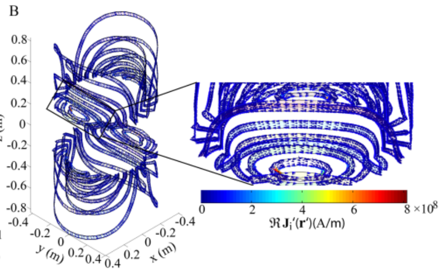
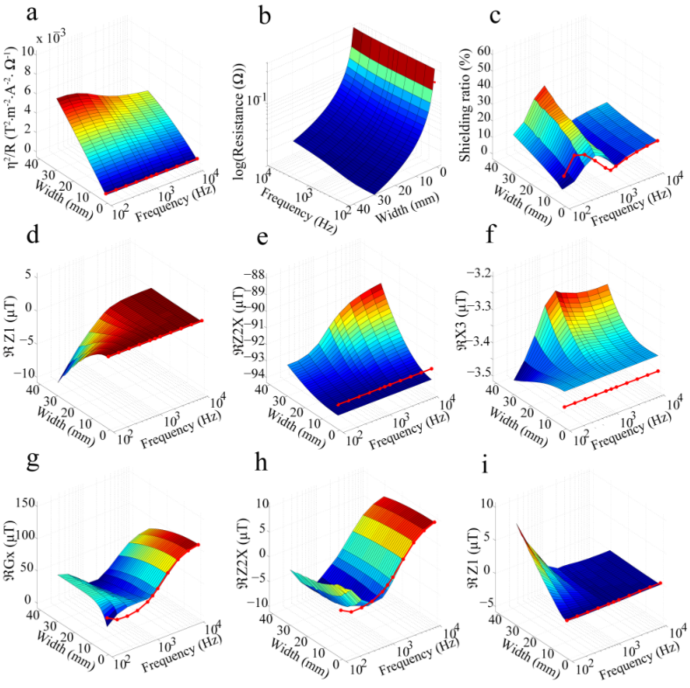
Introduction: In MRI applications, eddy currents will cause energy loss, mechanical vibration and power heating in the radiofrequency (RF) shield; moreover, it causes magnetic field asymmetries, leading to imaging artifacts [1]. To the best of the author's knowledge, there is no or insufficient attention in the literature to study proximity effects between tracks in gradient coils and its implications to those key characteristic parameters of gradient coils, such as gradient induced power loss in the cryostat, coil inductance and eddy currents, that usually are evaluated using an infinitely thin wire approximation. Kroot [2] developed a mathematical method to explain the current distribution in simple coil tracks, but the method is applicable to simple geometries only. Moreover, there is a lack of analysis to realistic and general geometry coils. In this work, the impacts of the wire track width and the frequency over essentials coil parameters such as resistance, inductance, power loss in the coil pattern and cryostat, spherical harmonics produced by the coil and by the cryostat, shielding ratio and figure of merit (FoM η^2/R; (coil efficiency/resistance)) were analyzed using an extended MIM method[3]. This study provides very valuable information which will guide coil engineers to choose the optimal wire track on regards the MRI coil applications.





Method: In order to study the influence on gradient coils of different track widths and frequencies, 30 split and shielded, whole-body *x*-gradient coils were designed using an equivalent magnetization current method (EMC) [4]. The track width was set from 1mm to 30mm with an increment of 1mm and the minimum gap between wires was 2.8mm. All the 30 *x*-split coils were designed to keep same field linearity 5% within the DSV and constant target gradient strength of G_0=10mT/m. Each coil was designed with uniform conductor width. The current pattern was discretized using 24 turns. The inner and outer radius of the coil envelope was 31.3cm and 40.4cm, respectively. A cryostat formed by a warm bore (non-magnetic steel) and cold shield (aluminum) was included in the eddy current analysis. Figure A) shows one of the designed split gradient coils, DSV and the cryostat.

The 30 designed split *x*-gradient coils were analyzed using the extended multi-layer integral method (MIM) [1] to study the interaction between the coils and the metallic surroundings, which took into account the skin and proximity effects. In order to study the influence of the frequency variation over the system parameters, a frequency sweep analysis in the range of 100 Hz to 10 kHz was performed using the extended MIM. The parameters here are defined as resistance, shielding ratio, FoM, field harmonics produced by the coils and surrounding conductors. The shielding ratio was measured as $\max(|B_z^{eddy}|)/\max(|B_z^{coil}|)_{DSV}\cdot 100\%$, where B_z^{eddy} is the field produced by the eddy current and B_z^{coil} is the field produced by the coil. The coils were also simulated as filamentary thin wires in order to compare aforementioned parameters to that evaluated assuming non uniform current density.



Results and Discussions: Figure B) shows the current density profile in one of the investigated gradient coils with track width of 30mm. The current density distribution is higher in rapid current path than the smooth path. Figure a) illustrates that the FoM increases with the track width as the resistance decreases with the increment of the track width (see Figure b)). However, the FoM tends to decrease with the increment frequency especially for wider tracks. The current density distribution is more uniform along the track width at low frequency, therefore coil the efficiency is larger than that at high frequency where current density is distributed in small sections near the track edges. Figure b) presents that the increment of resistance with the frequency is more accentuated for wider tracks than that of narrow tracks. Therefore that smaller track mitigates the deleterious consequence of the skin and proximity effects over the coil power loss. Figure c) shows that the shielding ratio reaches a minimum value at 1 kHz because the shielding ratio was controlled at the same frequency when the coil was designed. Figure d)-f) presents the most significant spherical harmonics amplitude produced by the designed *x*-coil when the coil track increases from 1mm to 30mm and frequency changes from 100 Hz to 10 kHz. Figure d) presents that the real part of the magnetic field harmonic Z1 decrease for high frequency and narrow track; it tends to disappear at high frequency. Figures e) and f) depict that the real part of field harmonics Z2X and X3 in the DSV tends to reduce for wide track and high frequencies due to the skin and proximity effects. Narrow tracks produce stable harmonic amplitudes in frequency and predicable field harmonics in the DSV. Figures g)-i) show the tendency of the real part of spherical harmonics amplitude produced by eddy currents induced in the cryostat when the coil track and frequency changes. Figures g) and h) describe that the spherical harmonics amplitude Gx and Z2X produced by the split cryostat reach to a minimum value around frequency of 1 kHz. This validates the fact that the coil was designed to produce a minimal and equal spatial field shape to that of the primary field at the target frequency of 1 kHz. Figure i) shows that the harmonic Z1 tends to disappear at higher frequency regardless the track width. The dotted line in Figure a)-i) illustrates the variation of the corresponding parameters with filamentary approximation. It shows that the parameters FoM, resistance, shielding ratio, field harmonics produced by the coils and surrounding conductors approximately agrees with those parameters calculated with narrow tracks. However, with the increment of the coil track, the difference between the parameters calculated using filamentary coils and those obtained when the coil was simulated using track tends to be significant.

Conclusions: We concluded that rapidly changing current paths should be avoided, otherwise an asymmetric current distribution along the track may be produced. It is recommended to use narrow tracks for mitigating zonal harmonics produced by the coil and cryostat, as zonal harmonics tend to disappear at high frequencies. Parameter related to shielding and eddy currents induced in the cryostat strongly depends on the target frequency for coil design. The increment in the resistance with the frequency is more significant in wider tracks than in narrow tracks, however a full temperature analysis should be performed in order to investigate a possible trade-off between the thermodynamic of the coil and the mitigation of possible deleterious effects, that need to be avoided when using wider tracks.

References: [1] C. Boesch, R. Gruetter, and E. Martin, Magnetic resonance in medicine, vol. 20, pp. 268-284, 1991.[2]J. Kroot, S. van Eijndhoven, and A. van de Ven, Journal of Engineering Mathematics, vol. 62, pp. 315-331, 2008. [3] Fangfang Tang .et al, submitted to ISMRM 2014. [4] H. S. Lopez, F. Liu, M. Poole, and S. Crozier, Magnetics, IEEE Transactions on, vol. 45, pp. 767-775, 2009.