Shielding requirements for a complete 3rd order shim set for a 31cm bore 9.4T system

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Introduction: MRI and in-vivo spectroscopy in preclinical applications at very high field (9.4T and above) require improved shimming capabilities. Our goal is to develop and optimize high-strength, dynamic shim systems for our 31cm bore 9.4T MR system. It is clear that dynamic shim systems will need to be actively shielded [1], especially higher order shims, yet no attempts have been made to address this. We are interested in investigating how performance of shielded shim coils changes as a function of shim order. In this abstract, we report on overall performance and shielding requirements for all shim coils up to third order, designed using a realistic constrained length minimum inductance algorithm.

Methods: A Fourier series method [2] was used to design shim coils of various orders with predetermined fixed length. This method expands the current density as a Fourier series over a specified interval, parameterizes magnetic field and resistance in terms of current density, and minimizes a functional that reflects these parameters. This algorithm was used to design shim coils up to third order: Z^0, Y^1, Z^1, Z^2, YZ, XY, Z^3, XYZ, YZ^2, and X^3. The X, X^2-Y^2, XZ, XZ^2, and Y^3 shims are merely rotations of other shim axes and were omitted to avoid redundancy. Each primary had radius 10cm, and length 50cm. To ensure all coils had the same field uniformity over a 10cm DSV, identical field targets and seven terms were used in the Fourier expansion for each design. Realistic discrete wire patterns were generated via the stream-function. This allowed for the evaluation of field efficiency and inductance for all coils. Shielding coils for each shim were obtained using the relationship shown by Turner et al. [3]. The shield radius was set to 14cm, compatible with our Varian 9.4T 31cm bore system. The final current density profiles were sampled with a finite number of windings such that each shielded and unshielded shim had a final inductance of 200 µH. The YZ shim coil and the Z^3 shim coil, along with their shielding counterparts, are shown in Figures 1 and 2 as examples. The field efficiency of each shim coil was determined by fitting the calculated field profile over the imaging region to a polynomial. The units of shim coil efficiency expressed this way depend on the order of the coil, and in general they are $mT/m^N/A$, where N is the order of the shim. When shim efficiency is expressed in this way, the efficiency of high order shims is typically numerically higher than for lower order shims. The efficiencies can be converted to absolute field efficiencies at the outer edge of the 10 cm DSV simply by multiplying by $(0.05\ m)^N$.

Results and Discussion: The coil efficiencies for the unshielded and shielded versions of each shim design are presented in Table 1. The efficiency of unshielded shim coils is better than that of shielded shim coils in all cases, as expected. However, the difference decreases considerably with increasing shim order. This is due to the fact that magnetic fields decrease more quickly as the complexity of the current density increases, and therefore, high order shims should require less shield current density in order to shield effectively. This result suggests that we will have more freedom with higher order shields than lower orders. Different shim axes will in general have different active shielding requirements. Of particular interest are even-order zonal shims, which will require active shielding, or at least some form of net flux cancellation because of strong coupling to the windings of the main magnet. We are in the process of constructing a complete shielded shim set based on these designs for evaluation on our 9.4T system.

References:

[1] Koch K M et al. J. Magn. Reson. 180 (2006) 286-296
[2] Carlson J W et al. 1992 Magn. Reson. Med. **26** 191-206
[3] Turner R et al. 1986 J. Phys. E: Sci. Instrum. **19** 876-879

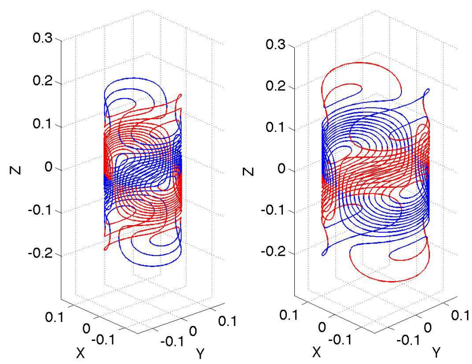

Figure 1. YZ Shim coil (left) and corresponding shielding coil (right).

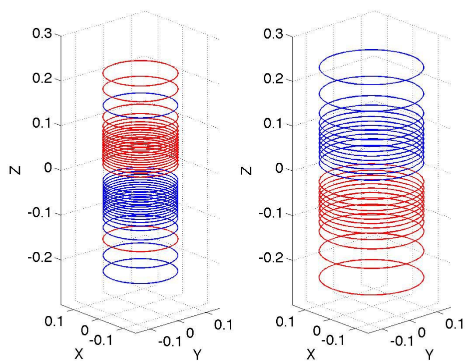

Figure 2. Z^3 Shim coil (left) and corresponding shielding coil (right).

Coil Efficiency [$mT/m^N/A$]			
Shim Order	Unshielded	Shielded	Efficiency Ratio
Z0	0.156	0.091	0.586
Z	1.831	1.396	0.762
Y	1.443	1.136	0.788
Z2	16.14	14.31	0.887
XY	38.18	33.89	0.888
YZ	34.04	29.29	0.860
Z3	172.1	150.7	0.876
XYZ	820.3	749.9	0.914
X3	437.5	402.5	0.920
YZ2	275.5	266.7	0.968

Table 1. Coil efficiencies and efficiency ratio for all shim axes. The units of efficiency are $mT/m^N/A$ where N denotes shim order.