A Multi-nuclear Volume Coil for H/X Pre-clinical MR at Ultra High Magnetic Fields

F. D. Doty[1], G. Doty[1], M. Skolozub[2], T. Harris[2], E. Montrazi[2], D. Arcos[1], J. Doty[1], L. Holte[1], and L. Frydman[2]
[1]Doty Scientific, Columbia, SC, USA, [2]Weizmann Institute of Science, Rehovot, Israel

INTRO There has been growing appreciation of the value of H/X multi-nuclear MRI, but the S/N from low-gamma nuclides is often insufficient except at **U**ltra-**H**igh **F**ields (**UHF**). UHF magnets usually have relatively small gradient bores, exacerbating the challenges in H/X volume coil MRI. The insulated cross-overs in the foil patterns of prior linear "Litz-foil" coils ensured highly optimized surface current distribution and thus higher B_1 homogeneity and sensitivity than those of classic saddle coils, but those coil simulations only optimized each coil independently.

METHODS The foil and cross-over patterns in Litz-foil coil designs were optimized using **CST** and detailed 3D models of the complete module, including both coils, their substrates and support structure, the tune/match networks, the sample, and rf shield (here, 58 mm). The outer ^{1}H-^{19}F **SQT** (**S**ymmetric **Q**uarter **T**urn) Litz coil, the leads to it, and the inner **C**enter-**F**ed **2**-turn **b**alanced (**CF2b**) orthogonal inner Litz coil for the multi-X channel can be seen in **Figure 1** below. The insulated cross-overs in the outer coil pattern establish the current distribution needed to achieve high ^{1}H B_1 homogeneity. The segmenting capacitors at its top, bottom, and sides are hidden here. The z-component of the current density I_z on the surfaces of the coils is shown when the SQT coil is tuned, matched, and driven at 650 MHz.

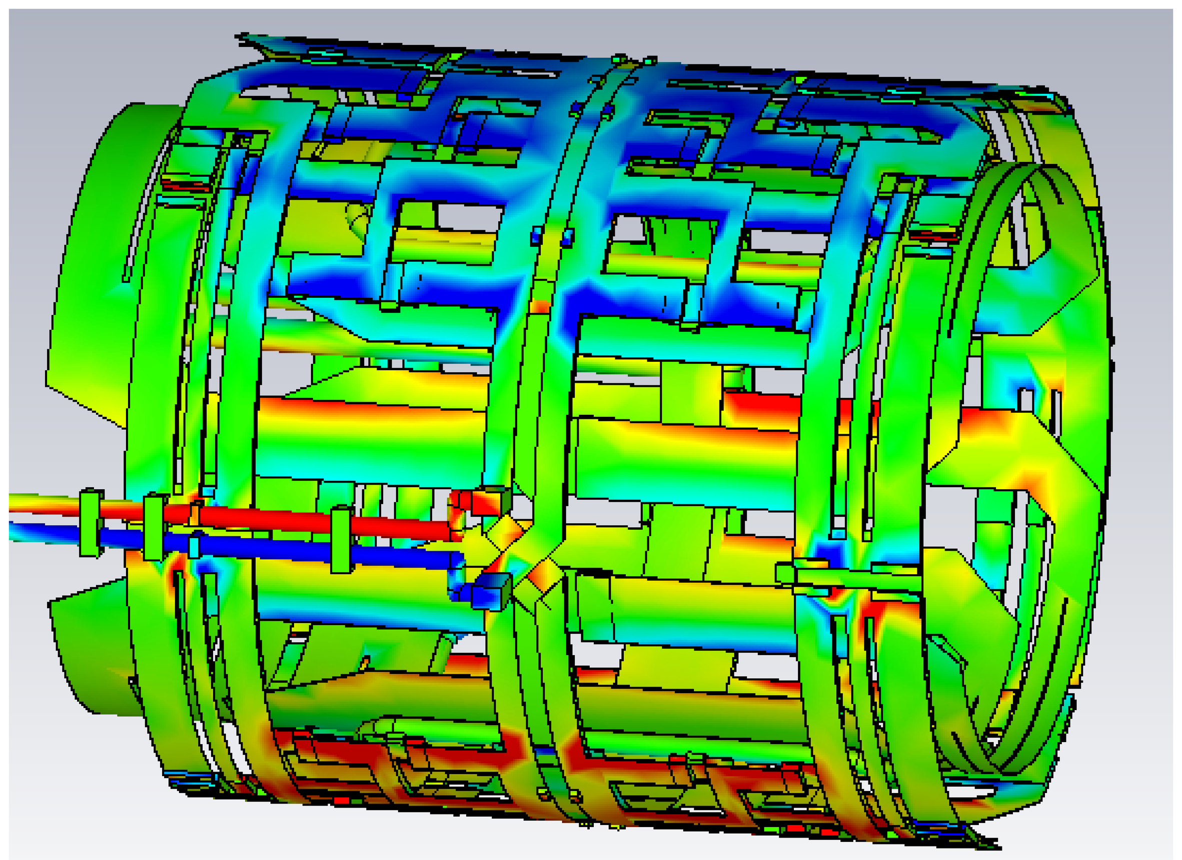

Fig 1. Foil patterns showing I_z on the coil surfaces when the outer coil is driven at 650 MHz.

The primary objective for both coils was a balance between maximizing sensitivity ($B_1/P^{0.5}$) over a large homogeneous volume – enabling pregnant mouse whole body studies – and minimizing the distance from the access end to the region of high B_1 – for rat head studies. Additional objectives included high homogeneity at both frequencies, high isolation between the two coils, minimizing E fields in the sample, clean tuning, and the ability to easily tune and match the X channel to any frequency of interest from ^{23}Na to ^{14}N by simply changing plug-in capacitors or small coils (located to the left of the above view).

A perspective view of the inner multi-X CF2b coil (with other parts hidden) from a CST simulation is seen below in **Figure 2** with z-component of the current density I_z on the surfaces for the case where the LF is tuned and driven at 100 MHz for ^{2}H. The paralleled turns on each side make effectively one turn on each side, and the two sides are connected in series so the inductance (~80 nH) is appropriate for tuning up to ~180 MHz. Without the insulated cross-overs (on the far side of this view, so hardly visible here) the current in the outer bands would be about half that in the inner bands, and high homogeneity could not be achieved. The widths of the arcs at the access end in this novel coil are much less than at the distal (tuning) end, thereby moving the rf field nearer to the access end for better coverage of the head of a rat.

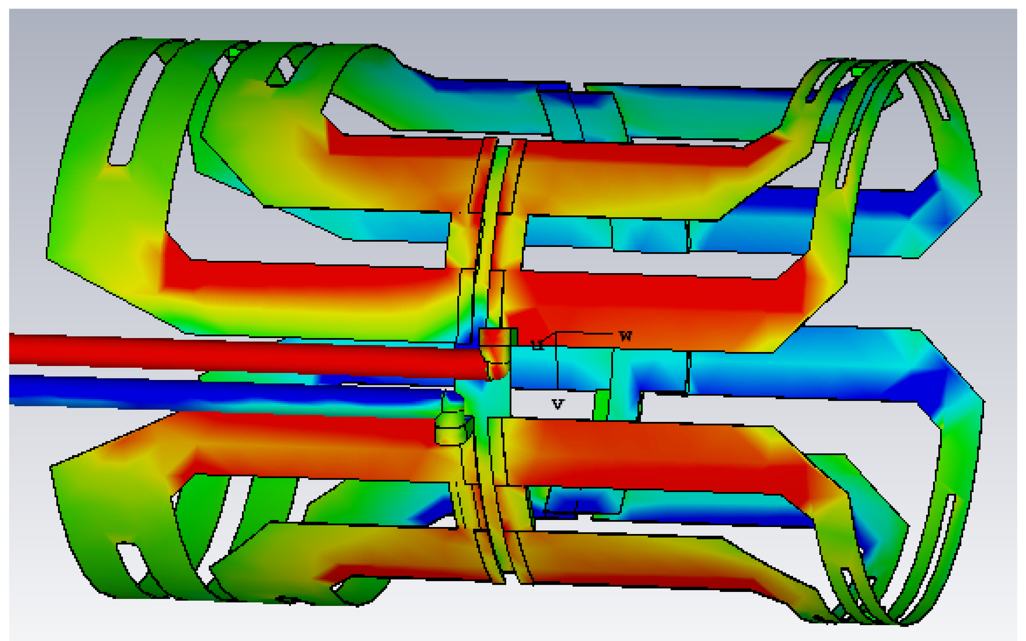

Fig 2. A perspective view of the inner CF2b multi-X coil showing I_z at 100 MHz.

For the 15.2-T 38-mm coil here examined, CST predicted the following pulse lengths for hard π/2 nutations with full loads (obese mouse body):
50 μs at 450 W for ^{1}H at 650 MHz;
70 μs at 400 W for ^{19}F at 612 MHz;
150 μs at 160 W for ^{23}Na at 172 MHz;
150 μs at 210 W for ^{2}H at 99.3 MHz;
150 μs at 260 W for ^{17}O at 87.7 MHz;
200 μs at 1100 W for ^{14}N at 46.7 MHz.

B_1 magnitudes at z=10mm (nearer the access end than the tune end) are seen in Figures 3 and 4 below with a large 30mM saline cylindrical sample.

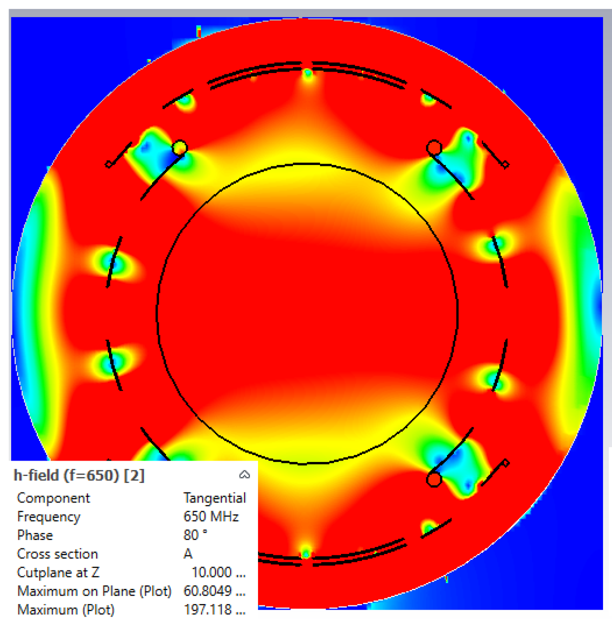

Fig 3. ^{1}H B_1 magnitude.

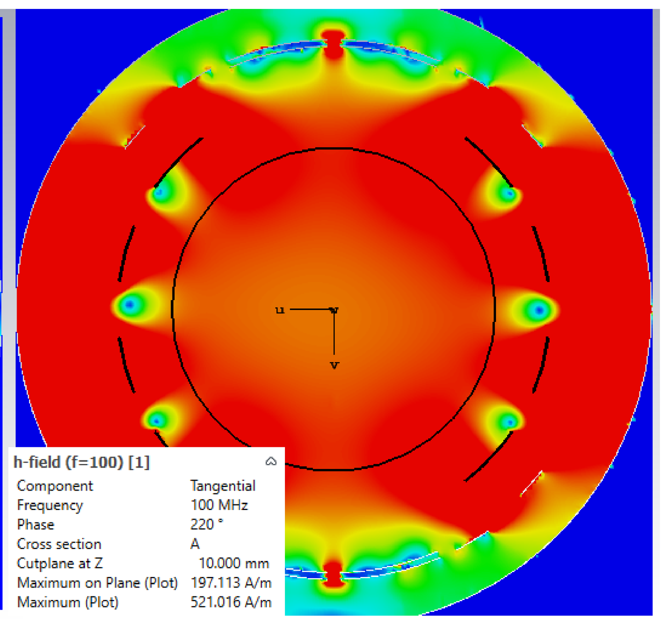

Fig 4. ^{2}H B_1 magnitude.

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RESULTS The simulations accurately predicted this H/X module would perform well to at least 15.2 T with a 36-mm inside diameter (ID), and possibly to 21.1 T (900 MHz) in H/X modules with 25-mm ID.

MRI ^{1}H and ^{2}H results from the 36 x 35 mm (ID x window) at 15.2 T are shown below. Images from a a pregnant mouse (E16.5) were recorded in ~2 minute intervals following injection of saline D_2O, providing water transport information across the placentas and into individual fetal organs at a level never before seen. The coronal ^{1}H and ^{2}H images in Figures 5 and 6 show fetuses and organs in a pregnant mouse 18 minutes after D_2O injection, when D_2O signals in the various regions have reached 70-90% of final values.

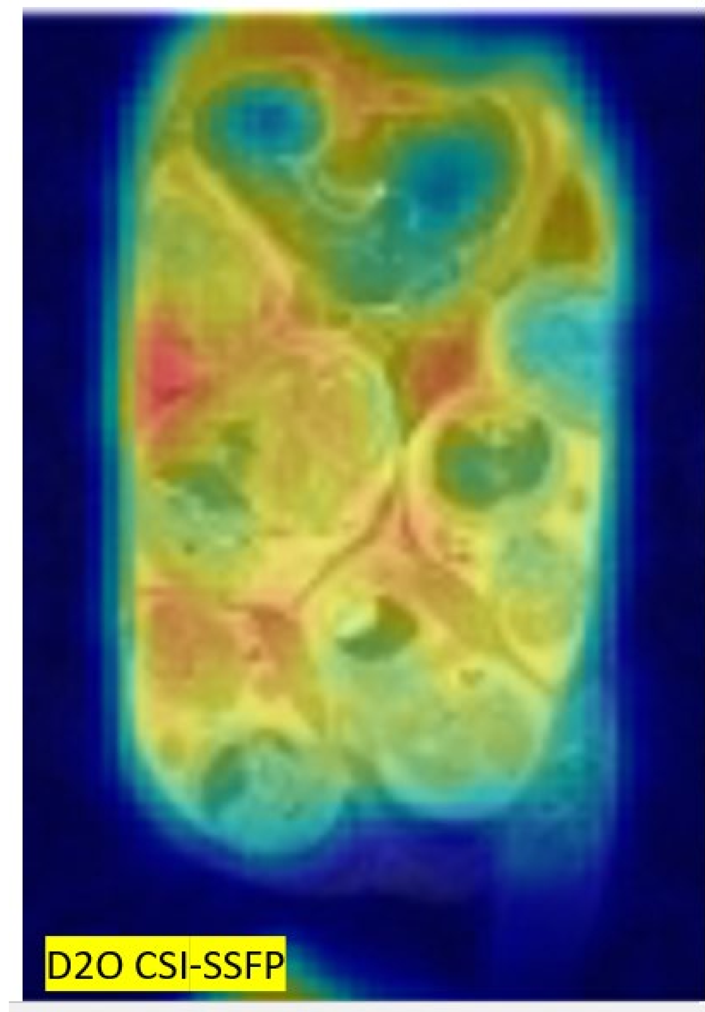

Fig 5. ^{2}H MRI showing differential uptakes in a pregnant mouse ~18 minutes after D_2O injection. 3D-bSSFP; TR: 2.206 ms; Matrix: 32x32x16.

Fig 6. ^{1}H MRI of the ROI in Figure 5. RARE acquisition, Matrix: 256x256. Thick: 1 mm. Circled in blue and yellow are two fetuses; orange and purple indicate placentas.

CONCLUSION Efficient volume coils make experiments much easier than working with surface coils by capturing multiple large clear slices throughout multiple organs over large regions at the same time. H/X rf modules utilizing orthogonal optimized Litz-foil coils promise to make fully multi-nuclear pre-clinical MRI more practical.

References: FD Doty, G Entzminger, and CD Hauck, Error-Tolerant Litz Coils for NMR/MRI, JMR, 140:17-31 (1999).
G Wang, H Yang, J Li, J Wen K Zhong, C Tain, Overview and progress of X-nuclei MRI in biomedical studies, Magn. Reson. Letters 2 (2023) 327-343.