# Optimization of Homogeneity and S/N in an 18 mm Micro-Imaging Coil at 750 MHz

David Doty[1], George Entzminger[1], John Staab[1], James Gravel[1], Laura Holte[1], Daniel Plant[2], and Samuel Grant[2]
Doty Scientific[1], Columbia, SC; and McKnight Brain Institute[2], U. of Florida, Gainesville, FL

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**Abstract:** We report the first results from a circularly polarized (CP) rf MRI volume coil at 750 MHz using a novel rf coil topology and balancing circuit that demonstrate simplified tuning procedures and improved $B_1$ homogeneity. We denote these coils "**litzcages**", as they embody both paralleled conductor elements with insulated crossovers, similar to that in prior linear "litz coils", and the capacitively segmented phase shifts common to birdcages. Several 4-point-drive balancing circuits were tested that efficiently symmetrize perturbed coils and greatly improve the tuning range.

A high-pass litzcage of 21 mm diameter and 18 mm internal length was constructed for use inside a thin-walled brass shield tube of 40 mm OD for compatibility with Bruker gradients in the vertical WB magnet. The 4-point-drive circuit was found to reduce worst-case rung-current errors by a factor of four and improve channel isolation by at least 5 dB compared to 2-point drive circuits. Half-lambda coax lines between nodes $180^0$ apart maintain precise symmetry. The combination of three novel features: 1) 4-point balanced drive with orthogonal symmetrization, 2) the 8-section litzcage, and 3) tuned variable capacitors appears to increase the useful tuning range of homogeneous CP MRI coils by an order of magnitude compared to standard CP methods.

The coils and balancing circuits are demonstrated on human spinal cord, mouse brain, and baby shark. S/N, $B_0$, and $B_1$ homogeneity were found to be significantly better than that of other available coils of similar size.

**Introduction: The CP RF Litzcage.** Field simulations show that even with perfect symmetry, at least 12 rungs are generally required for adequate $B_1$ homogeneity in a closely shielded conventional birdcage with a relatively large ROI (>0.7*d*) [*1*]. Such coils typically have a quick tuning range of less than 0.7% with good homogeneity and channel separation. However, our circuit simulations and experiments show that the 8-section birdcage is about twice as robust (tunable and correctable) as the 12-section birdcage because it is possible to attach two adjustment variables to nodes at $45^0$ with respect to the feed planes, which simplifies the symmetrization problem when tuning to different loads. While the $45^0$ nodes are available in the 16-section birdcage, it has twice as many distinct capacitors and hence half the tuning range. Corrections in the 12-rung birdcage, on the other hand, tend to mix asymmetrically with all tune and match adjustments, which complicates the process.

Our basic "litz" concept of using parallel conductors with judiciously placed insulated crossovers may be applied to the conventional 8-rung CP birdcage to make it much easier to obtain high $B_1$ homogeneity and greatly increased tuning range [2], as will become clear in the following sections. The resulting coil has homogeneity and S/N comparable to that of the ideal 16-rung birdcage (supporting simulations have been presented elsewhere) while retaining the tuning robustness of the 8-rung birdcage. The complete solution requires a 4-point-drive network as well.

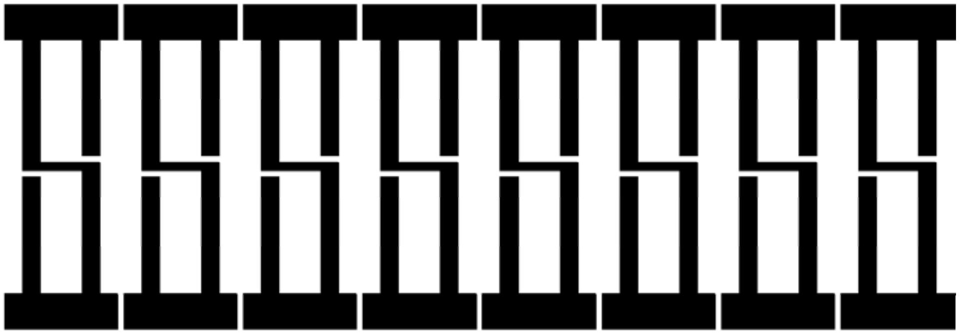
Figure 1. One surface of the High-pass Litzcage foil pattern. The other surface (not shown) completes the central crossovers.

**Figure 1** illustrates the primary surface of our standard 8-section high-pass litzcage pattern, laid out flat. Each rung in the 8-section birdcage has been replaced by two parallel rungs with an insulated crossover at the center; so it has 16 rungs, but only 8 sections. From the axial symmetry, each of the two parallel rungs per section must carry equal current, irrespective of the section's relative phase. From an rf circuit perspective, the homogeneous mode is almost indistinguishable from that of Crozier's parallel-rung 8-section birdcage [*3*], which is of course quite similar to the conventional birdcage from an rf perspective. However, the addition of the insulated crossovers in each section gives a dramatic improvement in $B_1$ homogeneity. Moreover, the 30% reduction in stray capacitance in the litzcage allows it to tune ~20% higher than the 8-rung birdcage.

More than 8 rungs have been used (even 24) in birdcages for reasons other than to improve homogeneity near the edges in the central plane – it has made it easier to tune reliably to higher frequencies, partially because accurate models for the hybrid birdcage have not been reported. It appears that with our litzcage there is no longer a need for more than eight azimuthal sections, even at the highest fields.

**Tuning Robustness, Symmetry, and $B_1$ Homogeneity.** Several factors conspire to make it difficult to achieve high $B_1$ homogeneity in small-animal coils for vertical-bore magnets at high fields. First of all, the tight space constraints require the sample diameter generally to exceed 82% of the rf coil diameter, compared to the typical ratio of 60-70% for human-head coils, for example. The proximity of the sample to the coil and the high variability of this spacing make it difficult to symmetrize the small high-field birdcage.

Serious difficulties in obtaining high $B_1$ homogeneity and channel isolation are *not* generally encountered in moderate-sized birdcages of moderate *fd* product (5-30 MHz-m) up to ~200 MHz when $Q_L$ is low, so the difficulties of symmetrizing birdcages at very high fields have not always been well appreciated. Our simulations suggest these difficulties are roughly proportional to $f^2d$, at least when $f(d\,l)^{0.5}$ (where $l$ is the sample length) is in the range of 10-40 MHz-m. Hence, an 800 MHz birdcage of 20 mm diameter is expected to be as challenging as a 200 MHz, 32 cm coil (which most would admit to being quite difficult, especially with a high filling factor, $\eta_F$).

Even though birdcages and related CP coils of many varieties have been in wide usage for eighteen years, most published circuit models leave much to be desired. Part of the problem is that to make the models analytically tractable, it has been customary to either ignore or use highly simplified expressions for most of the couplings (electric and magnetic), circuit losses, and propagation effects.

The standard theoretical model (which ignores all mutual inductances and stray capacitances) gives the following for the modes of the balanced high-pass birdcage:

$$\omega_m = \left[ C \left( L_E + 2L_{trl} \sin^2 \frac{\pi m}{N} \right) \right]^{-1/2} \qquad (1)$$

where $L_E$ is the end ring (section) inductance and $L_{TRL}$ is the rung inductance.

The next-highest mode, m=1, is the homogeneous (NMR/MRI-useful) mode. The above equation is often off by more than 15% for the homogeneous mode and even more for the other modes. In practice, other modes generally appear that are not predicted by either eq. (1) or the more complex published models, but are generally captured by our circuit models.

For the high-range band-pass birdcage, stray capacitance, propagation effects, and electromagnetic couplings become very significant; and errors in the above equation may be over 20%.

The capacitor accuracy required to place the resonance within the tuning range (the range which keeps the loaded peak-to-peak relative rung current errors below 15%) is extremely tight for two-point quadrature drive. For an 8-rung (balanced) high-pass birdcage, mean-capacitor-value accuracy must be within 1.5%. But a short 18 mm coil of this type (for mouse-brain studies) at 750 MHz requires tuning capacitors of ~3.9 pF – including stray, which varies from 0.2-0.5 pF, depending on the sample. Hence, the stray variability exceeds the required tolerance by a factor of two, which makes this coil and tuning method (2-point-drive) impractical. Moreover, even if ideally tuned, the 8-rung birdcage has inadequate $B_1$ homogeneity for most purposes, and the tolerance requirements on the 16-rung birdcage are nearly twice as stringent.

**Figure 2** illustrates the simplest circuit model that seems to give the accuracy needed for the 8 rung Balanced High Pass (**BHP**) birdcage or litzcage. To represent the nearest-rung couplings ($L_C$), each rung includes two ideal transformers, one on either side of the central plane – e.g., rung 2 includes {2,12,3,13} and {13,23,14,24}]. A transmission line (TRL) at each end of each rung completes its self-inductance and furnishes most of the significant stray capacitance per rung (e.g., {11,12} and {14,15} in rung 2).

We have developed methods of determining appropriate values for the characteristics of the TRLs and the rung-coupling transformers.

In our model, all of the major parasitics are included, and their effects have been simulated for several 2-point and 4-point drive schemes for various loadings, detunings, and random errors. We should note that our previous method [*1*] of representing all sample losses as stray capacitors $C_S$ in series with resistors $R_S$ leads to problems if $R_S > 1/\omega C_S$ and if the rungs are represented by inductors with coupling coefficients rather than transmission lines with coupling coefficients. Most of the losses now appear as corrected attenuation coefficients in the TRLs representing the rungs.

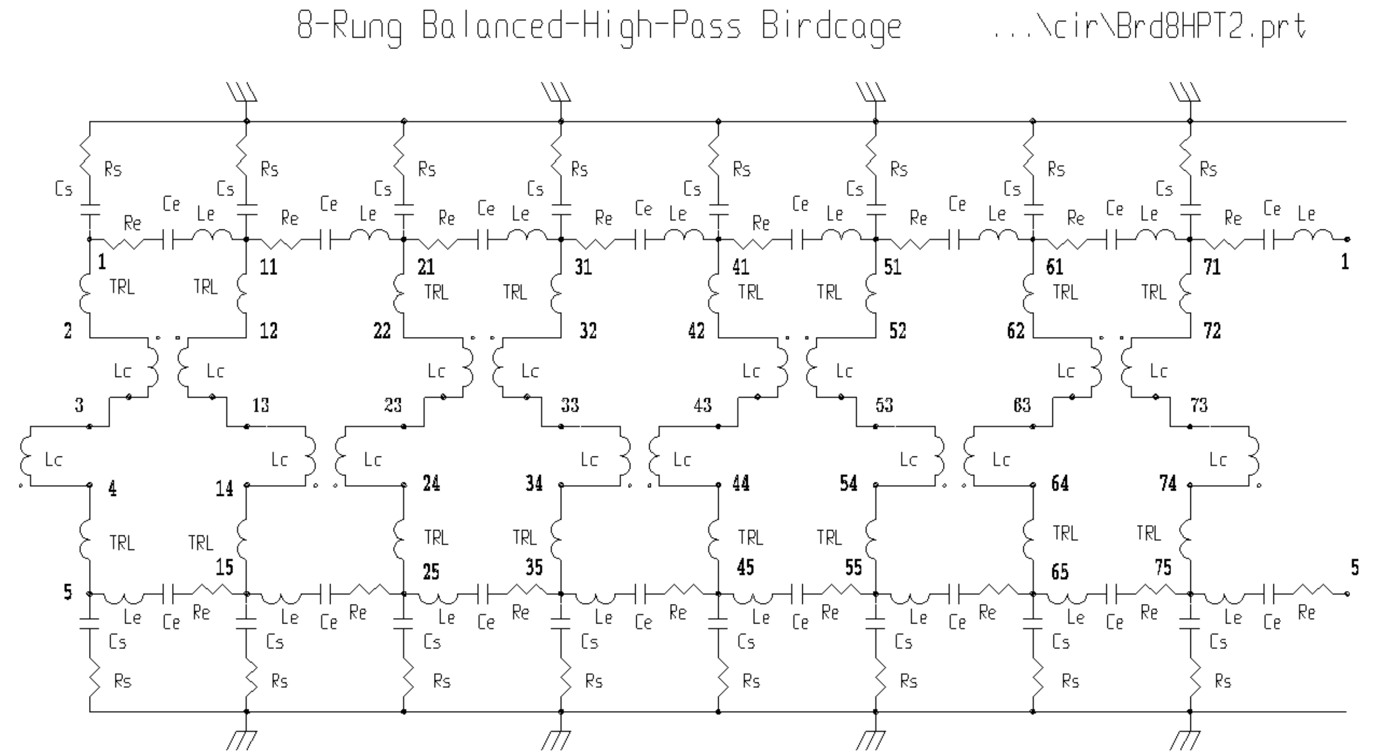

Figure 2. A useful rf model for the 8-section small-animal BHP birdcage or litzcage.

It has recently been shown that the inhomogeneity of a perturbed coil improves as the separation from the nearest inhomogeneous mode increases; but the mode structure is known to depend on the mutual coupling coefficients, which are ignored in some perturbation theory. Our experiments and models show that perturbations along a feed plane have almost no effect on cross-talk (as long as the two modes are at the same frequency) *but still perturb homogeneity* almost as severely as the perturbations in planes $45^0$ with respect to the feed planes, contrary to the predictions based on perturbation theory.

We find the inhomogeneity of a perturbed CP coil cannot be assessed simply from cross-talk or the relative magnitude of a single perturbation, and better methods are required to insure symmetry.

Our experience agrees with published discussions that the maximum useful tuning range for a low-field 8-section BHP birdcage with 2-point-drive is 1.3%. The sample-induced tuning shift for a high-field small-animal coil can exceed 8% – 15 times the tuning range of a 12-rung hybrid birdcage with 2-point-drive.

We have developed several highly effective 4-point-drive tune/balance/match circuits which provide an order-of-magnitude increase in tuning range for birdcages without spoiling $B_1$ homogeneity or isolation. When combined with our 8-section litzcage, one then has $B_1$ homogeneity comparable

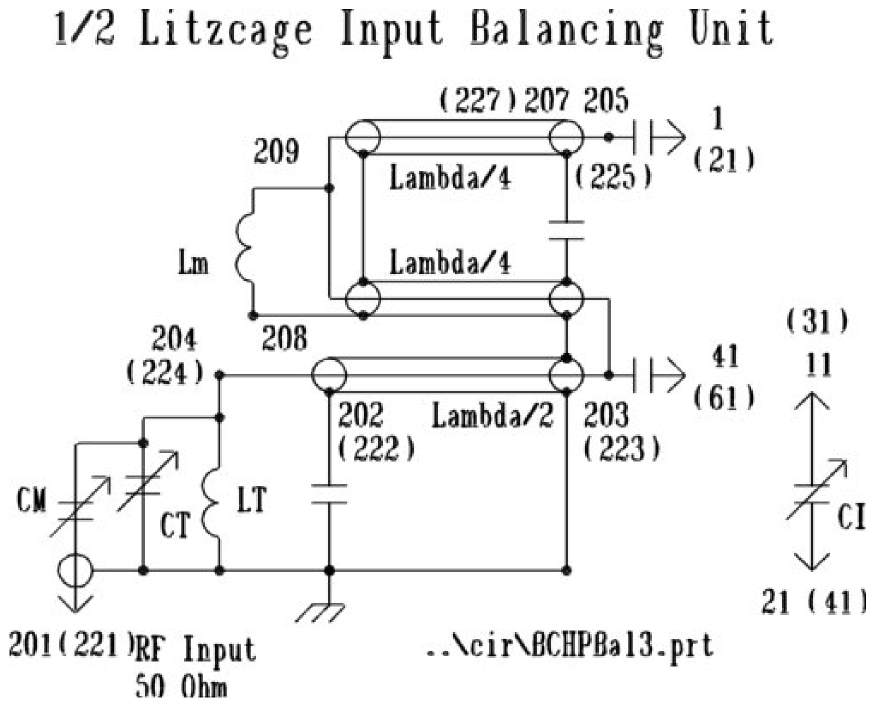

Figure 3. One channel of 4-point-drive network.

to that of an *ideal* 16-rung birdcage (i.e., perfect precision and no variability in strays) with well over an order of magnitude greater tuning range, as needed for practical small-animal applications. One-channel of our currently preferred quad-balance network is shown in **Figure 3**. The two series quarter-lambda's force the needed symmetry; the unlabeled capacitors are simply eddy-current-blocking capacitors (rf shorts); $L_M$ is used to move the common mode well away from the differential mode; and $L_T$ tunes out half of the sum of the tuning variable $C_T$ and the mean match variable $C_M$, thereby doubling the useful tuning range. The half-lambda feed line allows convenient placement of the variable capacitors well away from the coil. With low-loss coax lines (e.g., Belden type 1855A, which is only 4 mm in diameter), the total signal loss added by the balancing network is under 5% for typical 750 MHz small-animal coils.

Earlier small-animal MR research in horizontal-bore magnets often utilized surface receive coils inside large transmit coils. However, with the recent availability of our high-performance volume coils, the trend is clearly toward increased use of volume coils customized for the ROI. The experimental difficulties associated with rf decoupling between the transmit and receive coils are now seldom justified by the small increase in S/N over a very small fraction of the ROI, even in horizontal bores. In vertical bores, the problems with surface coils are exacerbated, and the benefits usually less. Hence, while we have successfully implemented PIN-diode detuning of our volume coils for use with surface coils in VB magnets, it is not included in this 750 MHz demo.

**Results: Maximizing SNR.** In large coils, where coil and capacitor losses are very small compared to sample losses, the losses associated with the rf field outside the sample are relatively small. Hence, the magnetic filling factor (the integral of the square of the transverse $B_1$ in the sample divided by the integral of the square of the rf magnetic field over all space) is relatively unimportant as long as the rf field within the sample is mostly transverse and largely confined to the region of interest (ROI), as $Q_L$ is then nearly inversely proportional to $\eta_F$. For small coils, on the other hand, detailed numerical simulations, showing where losses in both $Q_L$ and $\eta_F$ are originating, are essential for effective S/N optimization. Filling factor can easily be degraded by inattention to proper optimization of conductor widths or even improper capacitor placement.

The dependence of the SNR on the probe and NMR parameters may be expressed in a number of ways. The following is often useful, as it separates coil, tuning circuit, and NMR parameters [4]:

$$S/N = \left[\frac{\hbar^2 \sqrt{\pi \mu_0}}{12\, k_B^{3/2}}\right]\left[\frac{n_s\, \gamma I_x \left(I_x + 1\right)\sqrt{T_2}}{T_S \sqrt{T_R + T_P}}\right]\left(\eta_e\, \eta_f\, Q_L V_S\right)^{1/2} \omega^{3/2} \qquad (2)$$

where $\hbar$ is Plank's constant divided by $2\pi$, $\mu_0$ is the permeability of free space, $k_B$ is Boltzmann's constant, $n_s$ is the number of spins at resonance per unit volume, $\gamma$ is the magnetogyric ratio, $I_x$ is the spin quantum number, $T_2$ is the spin-spin relaxation time, $T_S$ is the sample temperature, $T_R$ is the temperature of the circuit resistance (coil and capacitors), $T_P$ is the effective preamp noise temperature, $\eta_E$ is the rf efficiency, $\eta_F$ is the magnetic filling factor, $Q_L$ is the loaded circuit quality factor, $V_S$ is the sample (voxel) volume, and $\omega$ is the Larmour precession frequency, $\gamma B_0$. The rf circuit matching efficiency $\eta_E$ depends largely on the losses in the tune/balance/match network, which are easily quantified (and then minimized) using standard circuit analysis tools. While $\eta_E$ is often below 40% in small double-resonant circuits at high fields, it is not difficult to exceed 90% in single-tuned coils at low fields. In this first 4-point-drive Litzcage tuned to 750 MHz, we were able to achieve an rf efficiency (percent of power delivered to the rf sample coil) of ~80%.

It is also straightforward to show that S/N is proportional to $B_1/P_i^{1/2}$, where $B_1$ is the magnitude of the circularly polarized transverse component of the rf magnetic field in the sample that is generated by a pulse of power $P_i$ [*3*]. We find this relationship (a more precise restatement of the classic principle of reciprocity) to be the best method of quantifying coil performance on the bench if sufficient care is taken in accurately measuring $B_1$ [*1*]. This also is one of the best methods of evaluating the utility of MRI RF coil simulation software.

In small coils, $Q_L$ is highly dependent on numerous details that are immaterial in large coils, including foil edge and corner profiles, rf shield losses, capacitor quality, and current distribution over the conductor surface. It is fortunate that these factors are usually of relatively little importance in large coils, as they are extremely difficult to quantify, either with analytical approximations or available software.

**Full-wave, Complete, Numerical Simulations.** We have evaluated three commercial full-wave EM software packages recently. We found REMCOM's XFDTD to be useless for evaluating $Q_L$ and $\eta_F$ or $B_1/P_i^{1/2}$ in complete, small-animal, coil systems. Ansoft's HFSS 8.5 is of some utility for these problems, and perhaps version 9.0 (coming in a few months) will be quite useful.

Some very recent runs by CST Microwave on their next version, CST MWS 4.2, to be released in a few weeks, show some promise – the calculated unloaded and loaded Q's of a 10 cm 200 MHz semi-shielded litzcage agreed with experimental data within ~15%, and all modes were predicted with excellent accuracy. However, it is difficult to combine the balancing networks with the coil structures, and the sequence of runs needed for accurate field data requires 4-10 hours on the fastest 4 GHz PC. We have heard that FEKO and perhaps IES can be useful, but we have not yet evaluated either.

The external, gradient-transparent, rf shielding is seldom perceived to be a significant source of signal loss, but in fact that can be the case for small-animal coils with closely spaced external shields. We have found that the standard method (overlapping slotted shields on double-clad Duroid laminate) adds very high losses under these conditions. Much lower losses may be obtained using single-layer gapped foil with discrete chip capacitors across the gaps in the regions where the azimuthal-rf-current densities are high.

Measurements yielded a $90^0$ pulse length of 22 $\mu$s for a square 50 W pulse on a pure water sample in an 18 mm diameter NMR tube.

**$B_0$ Homogeneity.** Achieving satisfactory $B_0$ homogeneity in small coils requires extra attention to effects that are safely ignored in larger coils. For example, small holes in the coilform (irrespective of what material is used) in the coil region may cause unacceptable artifacts. The most "non-magnetic" chip capacitors available may be too magnetic without magnetic compensation, which, for example, might entail soldering a small chip of silver (typically, of volume ~0.12 that of the chip) to each of its terminations.

While the analytical calculation of the $B_0$ field perturbations generated by complex geometries is intractable, there are a number of viable options here for numerical solutions. The approach we have found most efficient and satisfactory is to represent the magnetic effects of the various materials by currents distributed over their surfaces. The general solution for the effective surface current density $\mathbf{J}(\boldsymbol{r})$ at the boundary between two regions of uniform magnetization $\mathbf{M}_1$, $\mathbf{M}_2$ can be shown to be

$$\mathbf{J} = \mathbf{n} \times (\mathbf{M}_1 - \mathbf{M}_2) \qquad (3)$$

where $\mathbf{n}$ is the unit normal to the surface and directed from region 1 to region 2. The 3D software, *COILS*, we have developed based on this approach allows us to readily determine the effects of primary sources and take appropriate mitigating measures. The coax used for the phasing and feed lines must have a foam dielectric, and the protective plastic jacket must be removed near the coil (its susceptibility is too large). Of course, the requirements for an 18 mm MRI coil are several orders of magnitude less stringent than for a 5 mm high-resolution spectroscopy probe, so zero-susceptibility palladium-plated copper foils and copper-clad aluminum wires are not required.

**Images at 750 MHz. Figures 4 and 5** show some results from a Doty probe for 18 mm sample tubes for use inside Bruker gradients of 40 mm ID in a 750 MHz WB magnet. The CP litzcage dimensions were 21 mm diameter by 20 mm window length. In both cases, in-plane resolution was 50 microns with a 300 micron slice thickness.

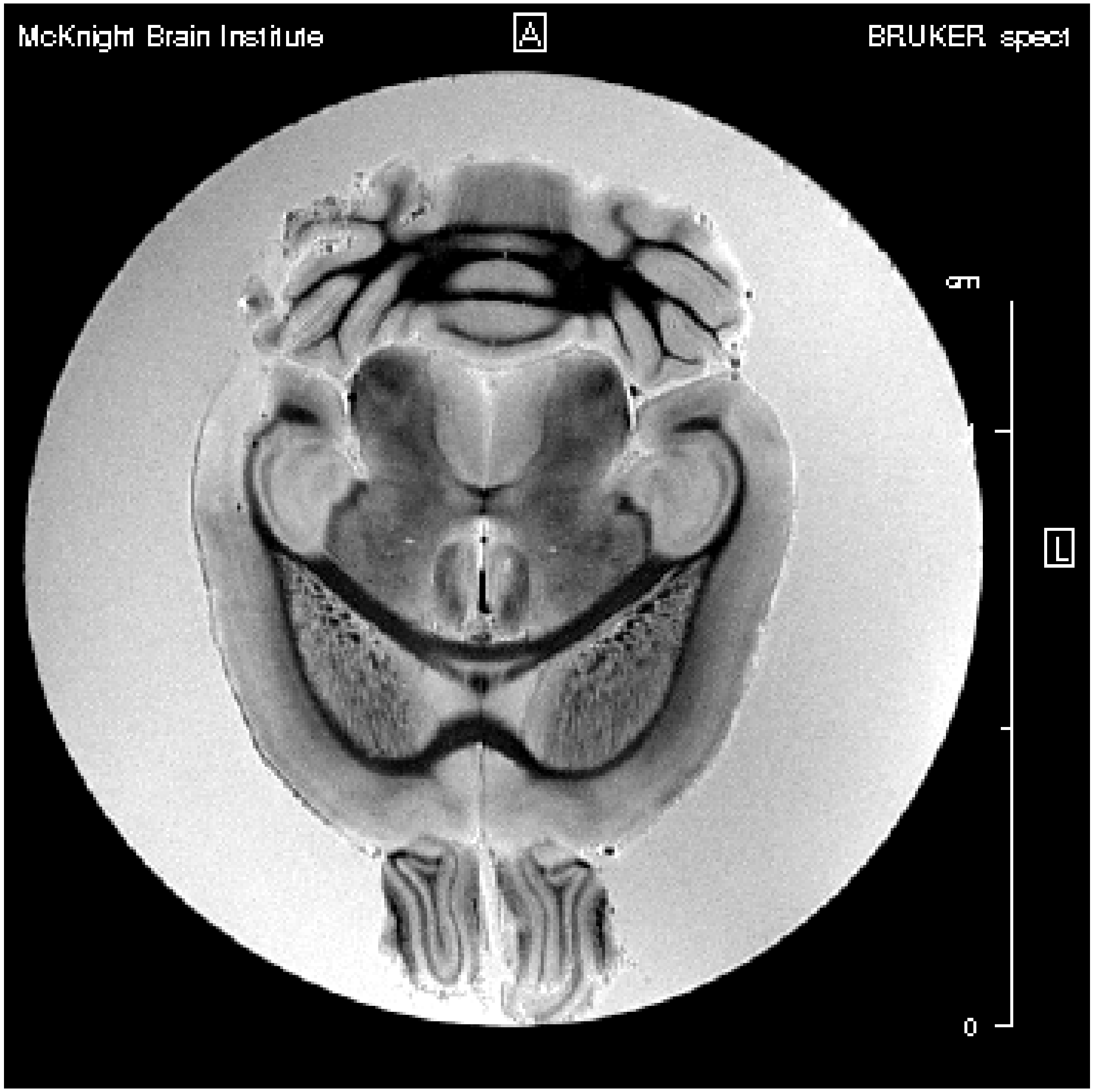

Figure 4. Mouse brain using CP litzcage at 750 MHz.

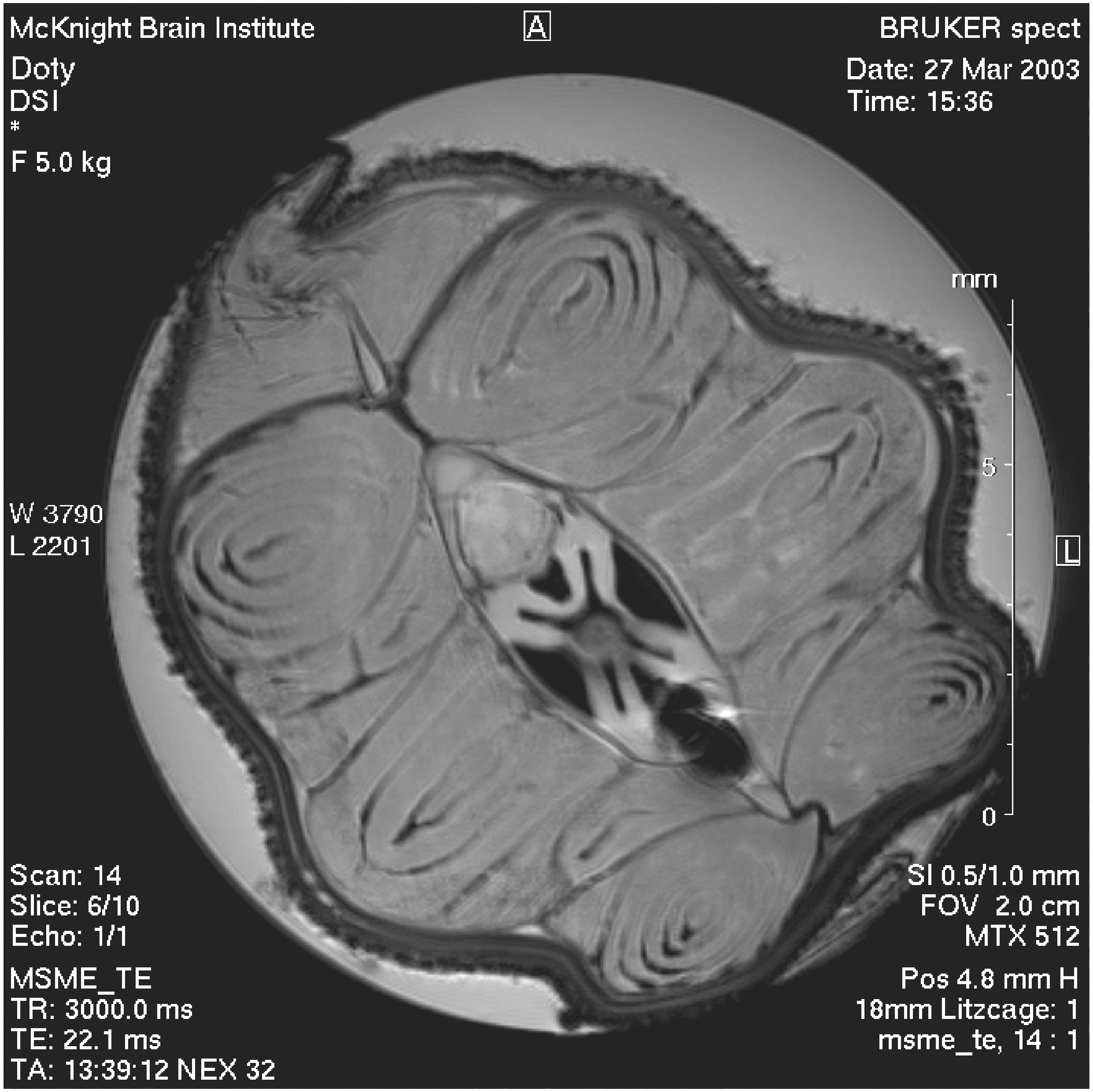

Figure 5. Baby Atlantic Sharpnose Shark, 50-micron resolution, using 21 mm Doty CP Litzcage at 750 MHz.

## Discussion and Conclusions:

We have shown strong advantages of the Circular Polarization 4-point-drive Doty Litzcage for MRI in an 18 mm sample at 750 MHz. To our knowledge, prior CP coils have not been successful above 600 MHz with sample sizes larger than 5 mm. (This tends to support our analysis, which suggests practical difficulties in CP coils increase quadratically with frequency.) The circuit simulations indicate overall rf efficiency exceeded 85%, which is roughly consistent with obtaining a 22 μs π/2 with under 50 W for a pure water sample (lightly loaded coil). Both $B_1$ and $B_0$ homogeneity appear excellent. The very minor shading that can be detected in the image is believed due to a small error in the coil etching that can easily be corrected. This error also contributed to somewhat more difficulty in re-tuning to widely differing loads than normally seen for the litzcage under similarly challenging conditions. It appears quite feasible to extend this coil design to enough to easily accommodate the adult mouse or small rat at 800 MHz.

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