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Trap Design and Construction for High-Power Multinuclear Magnetic Resonance Experiments

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Abstract

Performing multinuclear experiments requires one or more radiofrequency (RF) coils operating at both the proton and second-nucleus frequencies; however, inductive coupling between coils must be mitigated to retain proton sensitivity and coil tuning stability. The inclusion of trap circuits simplifies placement of multinuclear RF coils while maintaining inter-element isolation. Of the commonly investigated non-proton nuclei, perhaps the most technically demanding is carbon-13, particularly when applying a proton decoupling scheme to improve the resulting spectra. This work presents experimental data for trap circuits withstanding high-power broadband proton decoupling of carbon-13 at 7 T. The advantages and challenges of building trap circuits with various inductor and capacitor components are discussed. Multiple trap designs are evaluated on the bench and utilized on an RF coil at 7 T to detect broadband proton-decoupled carbon-13 spectra from a lipid phantom. A particular trap design, built from a coaxial stub inductor and high-voltage ceramic chip capacitors, is highlighted owing to both its performance and adaptability for planar array coil elements with diverse spatial orientations.

Keywords

multinuclear MRS; MRI; trap circuit; proton decoupling; carbon-13

INTRODUCTION

Performing multinuclear experiments requires radiofrequency (RF) coils operating at both the proton (^1H) and second-nucleus (X) Larmor frequencies. The use of two separate coils for this purpose allows optimization of each individual coil for its respective frequency, but the coils must be electromagnetically decoupled to prevent the induction of currents on the X coil by the ^1H coil and vice-versa. Insufficient isolation of the two coils can lead to significant proton sensitivity reduction and coil detuning. While inter-element interactions are often addressed by geometric orthogonality, this approach restricts the overall available coil configurations. The inclusion of blocking trap circuits provides the flexibility to position coils based on required anatomical coverage. The rudimentary trap circuit is a parallel LC tank tuned to the (higher) proton frequency and inserted serially on the X coil, often immediately adjacent to a separate series capacitor; this design is a long-established technique for dual-tuning coils (1,2) and has been utilized extensively for trap design in multinuclear imaging and spectroscopy (1-10). One disadvantage of this approach is that the reactance of the LC circuit is positive at the (lower) X frequency, introducing an inductive component that potentially reduces X coil symmetry. To address this problem, a second capacitor may be added in series with the inductor, forming an LCC trap (2); as described by Webb, this improved trap circuit blocks currents at the proton frequency while presenting the intended capacitance at the X frequency (11). Moreover, an analysis by Meyerspeer comparing LC and LCC traps elegantly proved the latter results in greater X coil Q -factor and signal-to-noise ratio (SNR) (12).

Of the nuclei commonly investigated in multinuclear studies, one of the most technically demanding is carbon-13 (^{13}C) on account of its low natural abundance and strong ^1H - ^{13}C J-couplings, both of which result in low SNR. Nevertheless, ^{13}C MRS draws considerable interest given its metabolism-rich informational content which is spread over an extended chemical shift range resulting in reduced spectral overlap of organic compounds and their unambiguous classification. For example, as compared to ^1H resonances, which are concentrated within 10 parts per million (ppm), the corresponding ^{13}C resonances are distributed across 200 ppm (13-15). To mitigate the reduction in SNR due to J-couplings and to simplify spectra, proton-decoupling (B_2) pulses are typically transmitted during ^{13}C signal acquisition. The power required for B_2 is substantial and increases both with decoupling bandwidth and with static magnetic field (B_0) strength (thus, overall $\gamma B_2 \propto (\gamma B_0)^2$), presenting challenges for both broadband and high-field decoupling (16). For example, a broadband-decoupled ^{13}C spectrum of all metabolites necessitates B_2 excitation across the proton chemical shift range of 10 ppm which equates to 3 kHz at 7 T. Achieving this would require $\gamma B_2 > 1$ kHz for most of the typical decoupling schemes (17). Thus, in practice, bandwidth is often limited by the RF amplifier power output and specific absorption rate (SAR) safety guidelines, placing great importance on the ^1H coil transmit efficiency and the ability of ^{13}C coils to electromagnetically decouple from the high-power ^1H irradiation. To date, a majority of *in vivo* studies at 7 T have relied on geometric decoupling to isolate the ^{13}C coil, circumventing the need for traps. Adriany and Gruetter achieved 700 Hz of WALTZ-16 decoupling in the head (18) with a 7T implementation of their widely-adopted, geometrically-decoupled quadrature half-volume coil (19). Chen et al.

used the same coil design to apply $B_{2\max} = 18 \mu\text{T}$ (766 Hz) in the leg (20). Our group also has previously applied $B_{2\max} = 18 \mu\text{T}$ in the breast using a geometrically-decoupled volume coil optimized for homogeneity at 7 T (21). The initial reported use of an *LCC* trap for ^{13}C at 7 T was for on-resonance continuous wave decoupling to examine one spectral peak (12). Serés Roig et al. subsequently added shielded *LCC* traps to two ^{13}C loops in a double-quadrature modification of the Adriany-Gruetter coil and decoupled across 700 Hz in the leg (22,23). Even at these limited bandwidths, ^{13}C coil coupling to B_2 has been shown to generate voltage spikes from corona or arcing events (23). Considering that transient spikes degrade the resulting spectrum by uniformly distributing noise below the reciprocal of the spike width (24), the construction and performance of lumped element components in this environment must be considered. This work presents observational data for various inductor and capacitor components in *LCC* trap configurations under the most demanding of conditions: high-power broadband proton decoupling of ^{13}C MRS at 7 T.

THEORY

Component selection is often a tradeoff between loss, quantified by R (or inversely Q), and power handling capability, rated as $V_{\max}$ or $I_{\max}$. Unfortunately, ratings for working AC voltage are rarely provided by manufacturers of multilayer ceramic capacitors, which are the mainstay of RF coil design. Limits for temperature-dependent breakdown owing to thermal runaway are typically listed; however, the temperature-independent dielectric voltage breakdown is far more difficult to categorize as it is contingent on multiple factors including capacitance, frequency, and electrode materials (25). The latter failure mode is of greater concern with low duty cycle pulses shorter than the capacitor's thermal time constant; indeed, capacitor dielectric breakdown failures usually occur at peak RF voltages far below the rated DC working voltages (26). Clearly, components must withstand expected operating conditions, but excessively conservative selections (with respect to higher voltage ratings) of available non-magnetic ceramic capacitors lower coil Q and SNR while constraining coil design with bulky component footprints. For example, in a receive array application small components are preferred to minimize the coil size, copper loading of the transmit coil, and B_1^+ flux blockage.

One of the integral components of the *LCC* trap is a solenoid inductor. Solenoids are typically rated for maximum current (based on wire gauge) or insulator breakdown voltage. While solenoids are relatively straightforward to construct and fine-tune, their use in trap circuits presents several challenges; sharp wire bends on leads are prone to cause failures under high power, and the lack of inherent shielding permits interaction with transmit fields. To mitigate coupling between the trap and B_2 field, solenoids may be oriented along the B_0 direction (5), while circumferential shielding may be added to reduce electric field interactions (6,22).

Semi-rigid transmission line stubs present an appealing alternative to solenoid inductors (27). By precisely specifying the length l , a short-circuited (sc) segment of coaxial cable is transformed to a desired impedance [in Ω] of

$$Z_{sc} = jZ_0 \tan\left(\frac{2\pi l}{\lambda}\right), \quad [1]$$

with characteristic line impedance Z_0 and wavelength in the transmission line λ . The resulting inductance [in H] at angular frequency ω is given by

$$L = \frac{Z_0}{\omega} \tan\left(\frac{2\pi l}{\lambda}\right). \quad [2]$$

Parasitic reactance is innately diminished by using a stub topology, and electric field effects may be mitigated further by capping the short-circuited terminal with copper foil as well as conforming and soldering the stub to the coil. Note that the latter step may present a design constraint if the coil segment is shorter than the stub length; in particular at higher frequencies, increased segmentation of lumped-element coil conductors with capacitors is often employed to reduce current phase shifts and voltage potentials across breaks. Here, the only degree of freedom may be the transmission line impedance, Z_0 . It is worth noting from the Z_0 term in Eq. 2 that a desired inductance may be achieved by employing a shorter length of higher-impedance transmission line, as shown in the implementation described below.

METHODS

To test different trap configurations, six identical ^{13}C loop coils were constructed and five different traps installed; they were tested by obtaining a FID with the same pulse sequence in order to observe SNR and noise potentially caused by breakdown of the trap. Additionally, one coil was tested with no trap for reference.

Hardware

The six loops, with inner and outer diameters of 70 and 76 mm, respectively, were milled from one-ounce copper-clad FR-4 circuit boards and fabricated into coils tuned to 74.9 MHz for ^{13}C at 7 T. As illustrated in Fig. 1a, a basic ^{13}C loop coil was constructed without a trap circuit and included a 100-pF capacitor placed opposite the feed. Each of the remaining five loops incorporated an *LCC* trap circuit, as drawn in Fig. 1b, tuned to 298 MHz for blocking ^1H at 7 T. To preserve current uniformity on the trapped coils, *LCC* component values were established to collectively maintain the reactance of the 100-pF capacitor at 74.9 MHz. Per Eqs. 2 and 3 in (12), the minimum possible trap series inductor value was 12.2 nH; a practical value of $L_s = 40$ nH was chosen as a suitable balance of trap efficiency while limiting the reduction of ^{13}C coil sensitivity. Of the two possible capacitance arrangements, we selected the solution that resulted in lower maximum voltages across components, with series trap capacitor $C_s = 51$ pF and parallel trap capacitor $C_p = 8.2$ pF. The coils were balanced matched and tuned to 74.9 MHz with variable capacitors (Voltronics, Salisbury, Maryland, USA), visible in Fig. 2a. A single feed cable with an integrated 74.9-MHz balun

and a 298-MHz cable trap was attached to each individual coil through an SMA connection. The balun and the trap were both a shielded LC tank design.

Trap Components

Several inductor configurations were examined, as listed in Table 1. We constructed nominal 40-nH inductors using 18-AWG ($d = 1$ mm) copper magnet wire (8075, Belden, St. Louis, Missouri, USA) on a 2.3-mm radius with an approximate 2-mm pitch. An unshielded solenoid was fabricated with three wire turns, while a second solenoid with four wire turns was circumferentially shielded with insulated copper foil. These hand-wound solenoids were oriented along the B_0 direction. In addition, we evaluated off-the-shelf tunable inductors (165 series, Coilcraft, Cary, Illinois, USA), a potentially attractive solution for simplifying coil construction and trap tuning. Transmission line stubs inductors were constructed from semi-rigid coaxial cable and conformed to underlying coil traces, as shown in Fig. 2a. Recalling from Eq. 2 that a higher Z_0 term facilitates a shorter stub length l for a given inductance L , we found it advantageous to employ 75- Ω semi-rigid coaxial cable (EZ 141-75-Cu, EZ Form Cable, Hamden, Connecticut, USA). Owing to the steep slope of the tangent term in Eq. 2, fine-tuning the inductance by shortening the stub was an arduous task; however, replication became straightforward once the precise length was verified empirically.

Multi-layer ceramic capacitors with DC voltage ratings of 7.2 kV (American Technical Ceramics, Huntington Station, New York, USA; Passive Plus, Huntington, New York, USA) were employed with the four different inductor types in Traps 1-4. In order to gauge the influence of capacitor selection while keeping the same inductor, Trap 5 utilized capacitors with lower DC voltage ratings of 2.5 (C_s) and 3.6 kV (C_p) with the same stub inductor as Trap 4, which used 7.2-kV capacitors. Photographs of the coils and trap circuits are shown in Fig. 2.

Bench Measurements and Modeling

All traps and coils were characterized on the bench with a network analyzer (E5071C, Keysight Technologies, Santa Rosa, California, USA). All coils were loaded with a cylindrical phantom of 5-cm diameter and 5-cm height filled with canola oil, selected for its similar loading to the breast and suitability for ^{13}C MRS detection. Coil Q -factors were calculated while matched and tuned to 74.9 MHz with the -7 dB S_{11} bandwidth method (24). Trap Q -factors were calculated from the S_{21} peaks at 298 MHz by weakly coupling to the isolated LCC structure with two decoupled 3-mm probes.

To model the traps under expected operating conditions, the electromotive force (EMF) induced on the ^{13}C coil was estimated with Faraday's law of induction. Thus, as a worst-case scenario, in the presence of a uniform circularly-polarized proton decoupling field $B_2 = 20$ μT , an open-circuited linear loop coil with mean diameter of 73 mm induces 110 V across the terminals. The coils and trap circuits were then simulated numerically in SPICE, excited by a 110-V, 298-MHz voltage source. Capacitor equivalent series resistance values were identified from manufacturer data sheets, and coil and trap inductor losses were calculated

from Q measurements. Note this simulation assumes the EMF arises solely from the decoupling B_2 without considering additional factors such as concentrated E -field regions.

Magnetic Resonance Spectroscopy

Carbon-13 spectra were acquired with a 7T Philips Achieva scanner, with the WALTZ-16 proton decoupling scheme (28) driven by the integrated 4-kW proton RF amplifier. Given the limited efficacy of WALTZ-16 with inhomogeneous RF transmit coils (17), a previously-reported quadrature ^1H volume coil exhibiting 0.6-dB uniformity over the sensitivity region of the 7-cm ^{13}C loop coil was employed for scout imaging and proton decoupling (21,29). In order to highlight differences in component performance, supplemental low pass filtering before the preamplifier was not employed. Individually, the ^{13}C coils were placed in the homogeneous region of the proton volume coil and loaded with the 5-cm cylindrical canola oil phantom. Pulse-and-acquire ^{13}C spectra were averaged from eight acquisitions of 4096 samples over 16 kHz, with $\text{TR} = 8$ s, $\text{TE} = 150$ μs , 70° flip angle, without NOE enhancement. For proton decoupling, WALTZ-16 was centered at 2.3 ppm with $B_2 = 20$ μT applied during the initial 20% (51 ms) of the 256 ms readout; with homogeneous $B_{2\text{max}} = 20$ μT , WALTZ-16 is expected to recover 90% of the perfectly-decoupled peak height across 2 kHz (17). J-coupled spectra (without WALTZ-16) were also acquired to illustrate decoupling effectiveness as well as quantify the increase in noise during decoupling pulses.

All spectra were processed in MATLAB[®] (MathWorks, Natick, Massachusetts, USA) using an in-house code library. Zero- and first-order phase corrections were applied to obtain absorption mode spectra, and baselines were corrected by piecewise cubic interpolation to simplify peak integration. No line broadening was applied. Peaks were identified from a previously published canola oil ^{13}C NMR spectrum (30). SNR was calculated by dividing the integral of the methyl peak (quartet for coupled spectra), well-segregated at 15 ppm, by the standard deviation of the baseline noise in a signal-free 500-sample region. To quantify noise breakthrough during decoupling, the ratio of proton-decoupled SNR to J-coupled SNR was calculated. In this way, a higher ratio of decoupled to coupled SNR (hereafter referred to as the SNR Ratio) suggests superior noise rejection.

RESULTS

Trap and loaded coil Q -factors, proton-decoupled and J-coupled SNR values, and SNR Ratios are listed in Table 2. The proton-decoupled spectra acquired by the various coils are displayed in Fig. 3a. All trap configurations mitigated, to some degree, the detrimental noise breakthrough from WALTZ-16 transmission observed with the untrapped coil throughout the decoupling duty cycle, as shown in Fig. 3b. Trap 4, with a coaxial stub inductor, led to the highest coil SNR, slightly higher than the unshielded hand-wound solenoid of Trap 3. The FIDs from other trap configurations acquired more appreciable noise during the WALTZ-16 decoupling scheme, with spectral SNR suffering as a result.

Notably, capacitors rated for 7.2 kV DC demonstrated superior ability to avoid intermittent noise spikes compared to alternatives rated for lower voltages. This observation is highlighted by comparing Traps 4 and 5, for which the only design difference was the capacitors; while their performance was equivalent in the J-coupled case, results from Trap

4, with the higher-voltage capacitor, were significantly superior when applying proton decoupling. The actual AC voltage present across each capacitor was estimated in the SPICE model of the coil and *LCC* circuit. With the coil *Q* set to 200, the resulting AC current amplitude exceeded 3 A with voltage surpassing 200 V across both the inductor and the 8.2-pF capacitor. Recalling dielectric breakdown failures usually occur at RF voltages far below rated DC working voltages, breakdown from 200 V at 298 MHz is plausible for lower DC-rated capacitors.

As seen in Fig. 3a, the largest ^{13}C peak was from bulk methylene resonances at 30 ppm, with other resolved peaks from methyl (15 ppm), glycerol (62 ppm), and olefin (130 ppm) resonances. The two traps resulting in the highest SNR, Traps 3 and 4, were also tested with $B_{2\text{max}} = 20 \mu\text{T}$ applied during the initial 70 ms of sampling, a 50% increase in WALTZ-16 duty cycle which should allow for proper decoupling of the entire FID *in vivo*, before it has decayed to zero. The FIDs acquired from these two cases showed no discernable noise breakthrough or voltage spikes; the acquisition from the coil with Trap 4 is shown in Fig. 3c.

DISCUSSION AND CONCLUSIONS

This study presented considerations for constructing trap circuits and a comparison of performance observed under stringent testing conditions. As the results were acquired at an extreme of power demands for decoupling (^{13}C at 7 T), this work should generalize to guide trap design for lower field strengths and MRS of other nuclei.

Noise propagation and spikes throughout a spectrum may occur from insufficient trap performance and may be confounded by pre-amplifier saturation (31). A worst-case scenario noise spike from the untrapped coil is shown in Fig. 3b. The coil with Trap 1 was an outlier with low SNR in comparison to all other cases, including the untrapped coil. This discrepancy could be due to the small 25-AWG wire of the variable inductor; furthermore, owing to the surface-mount package as shown in Fig. 2b, the solenoid aligned with the y-axis (and not along the z-axis/ B_0 direction as with the other trap solenoids), permitting coupling to the B_2 field and underlining another design consideration for trap construction.

Considering the low physical profile that facilitates planar configurations, as well as the confined region for magnetic energy storage, the stub inductor may be preferred for *LCC* trap design when the geometry is appropriate. It is worth noting we previously found the inductor stub to be problematic if not conformed and soldered to the coil trace, with unacceptable noise introduced when B_2 reached 15 μT .

While this study tested for noise propagation using the WALTZ-16 decoupling scheme, performance may be improved with alternate decoupling schemes. Adiabatic pulses have been shown to improve decoupling bandwidth over WALTZ-16 by 30% using the same amount of RF power (18), and frequency-modulated rectangular pulses may prove to be more beneficial for high-bandwidth applications (17). As such, the requirements for trap design and construction may prove to be less stringent, with additional attention being paid to the ease of construction, especially when planar multi-coil arrays are constructed.

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Figure 1.

Circuit diagrams for untrapped and LCC-trapped multinuclear loop coils. (a) An untrapped loop coil with segmentation capacitor $C = 100$ pF, and (b) a loop coil with an LCC trap, composed of series capacitor $C_s = 51$ pF, series inductor $L_s = 40$ nH, and parallel capacitor $C_p = 8.2$ pF. At the X frequency, the combined LCC reactance should equal that of C in (a).

Figure 2.

Photographs illustrating various trap inductor types, all utilized in conjunction with identical 7.2-kV DC-rated ceramic capacitors. (a) Carbon-13 coil incorporating Trap 4, with a short-circuited coaxial stub inductor conformed and soldered to the coil trace, (b) Trap 1 with a shielded commercial variable inductor, and (c) Trap 3 with an unshielded hand-wound solenoid. Note in all cases the parallel trap capacitor is obscured on the bottom side of the circuit board.

Figure 3.

Spectra and Free Induction Decays (FIDs) from MRS experiments. (a) An example J-coupled spectrum from the coil with Trap 4, followed by carbon-13 spectra from individual coils using WALTZ-16 decoupling $B_{2\max} = 20 \mu\text{T}$ with 20% duty cycle (on during the first 51 ms of acquisition). The coils incorporating Trap 3 (unshielded solenoid and 7.2-kV DC-rated capacitors) and Trap 4 (coaxial stub and 7.2-kV DC-rated capacitors) detected spectra with the largest ^{13}C peaks and greatest SNR. Other configurations resulted in lower SNR owing to reduced peak height, including Trap 1 (variable commercial solenoid) and Trap 2 (shielded solenoid), and baseline oscillations owing to intermittent noise spikes during FID acquisition observed with coils utilizing 2.5 and 3.6-kV DC-rated capacitors, including the untrapped coil and Trap 5 (coaxial stub). Insets highlight the methyl peak and baseline noise for each case. (b) A FID detected from the untrapped coil illustrates an intermittent noise spike; this FID clearly exhibits noise breakthrough during WALTZ-16 transmission. (c) A FID detected from the coil with Trap 4 demonstrates its ability to withstand noise breakthrough under more demanding conditions: $B_{2\max} = 20 \mu\text{T}$ with an extended 30% duty cycle.

Table 1

Trap components and manufacturer ratings for series inductor L_s , series capacitor C_s , and parallel capacitor C_p .

Coil	Inductor Type	L_s			C_s		C_p	
		Part	AWG	Rating ^b	Part	Rating ^c	Part	Rating ^c
Untrapped ^a	N/A	N/A	N/A	N/A	PPI 2225C101JP252X	2.5 kV	N/A	N/A
Trap 1	Variable solenoid, shielded	Coilcraft 165-02A06L	25	4.9 A	PPI 3838C470JP722X	7.2 kV	ATC 100E8R2BMN7200X	7.2 kV
Trap 2	Hand-wound solenoid, shielded	Belden 8075	18	5.7 kV	PPI 3838C470JP722X	7.2 kV	ATC 100E8R2BMN7200X	7.2 kV
Trap 3	Hand-wound solenoid, unshielded	Belden 8075	18	5.7 kV	PPI 3838C470JP722X	7.2 kV	ATC 100E8R2BMN7200X	7.2 kV
Trap 4	Transmission line stub	EZ Form EZ 141-75-Cu	19	5 kV	PPI 3838C470JP722X	7.2 kV	ATC 100E8R2BMN7200X	7.2 kV
Trap 5	Transmission line stub	EZ Form EZ 141-75-Cu	19	5 kV	PPI 2225C470JP252X	2.5 kV	PPI 2225C8R2CP362X	3.6 kV

^aThe untrapped coil's segmentation capacitor is listed as C_s .

^bVariable solenoid is rated for RMS (DC) current causing 15°C rise from ambient; hand-wound solenoid wire is rated for minimum insulator breakdown voltage; stub is rated for RMS withstanding voltage at 60 Hz.

^cCapacitors are rated for working DC voltage.

Table 2

Bench measurement and MRS results, all presented in arbitrary units.

Coil	Trap Q	Coil Q	Proton-Decoupled SNR	J-Coupled SNR	SNR Ratio (Decoupled / J-Coupled)
Untrapped	N/A	267	228	650	0.35
Trap 1 variable shielded solenoid	113	206	144	326	0.44
Trap 2 hand-wound shielded solenoid	122	199	548	823	0.67
Trap 3 hand-wound unshielded solenoid	168	239	867	1030	0.84
Trap 4 t-line stub	108	221	910	1070	0.85
Trap 5 t-line stub, low-V caps	117	228	481	1070	0.45