Novel transmitter designs for magnetic resonance imaging

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Evaluation of plasma-based transmit coils for magnetic resonance

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In this work a new concept for designing transmit coils for magnetic resonance using a plasma is introduced. Unlike conventional coils, a plasma can be turned on and off, eliminating electrical interactions between coils, and enabling radiofrequency-invisibility when desired. A surfatron has been designed to produce a surface-mode wave which propagates along the inner surface of a commercial fluorescent lighting tube. NMR spectra and images have been produced using the plasma as the transmit coil and a copper-based monopole to receive the signal. The transmit efficiency of the plasma tube was estimated, and is currently much lower than that of an equivalently-sized metal-based structure: however, there are many potential methods for increasing the efficiency using a custom-built plasma tube.

5.1. INTRODUCTION

NUCLEAR magnetic resonance (NMR) spectroscopy and magnetic resonance imaging (MRI) both use radiofrequency (RF) coils which are constructed from conductive metallic elements. Although there are a large number of different coil geometries used for various NMR and MRI applications [2], the use of metallic elements is almost universal (a few publications have used high permittivity ceramic dielectric resonators [3]). In this paper, a new concept for an MR transmit coil is introduced, which uses a reconfigurable conducting plasma rather than a fixed-geometry metallic conductor. A plasma consists of an electrically neutral medium of positive and negative particles, and is used in applications as diverse as non-invasive surgery and nuclear fusion. A plasma can be characterized in terms of its plasma frequency, ω_p, given in Anderson (p32) [4]:

$$\omega_p = \sqrt{\frac{n_e q_e^2}{\epsilon_0 m_e}} \tag{5.1}$$

where n_e is the electron number density (measured in m^{-3}), m_e the electron mass, ϵ_0 the permittivity of free space, and q_e the electron charge. Evaluating the fundamental constants this gives:

$$\omega_p \approx 56.4\sqrt{n_e} \tag{5.2}$$

A plasma can be conveniently created within a dielectric (usually glass, quartz or plastic) tube. The plasma is typically created at one end of the tube and propagates very rapidly along the tube via a surface-mode wave between the plasma and dielectric. The propagation vector of this surface-mode wave is real along the plasma/dielectric boundary and imaginary in the direction perpendicular to the boundary, which corresponds to the condition that the real part of the relative permittivity of the plasma is less than –1 [5, 6]. The frequency-dependent permittivity of the plasma is given by:

$$\epsilon(\omega) = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2} - j\frac{\omega_p^2}{\omega v_{cc}}\right) \tag{5.3}$$

where v_{cc} is the electron-neutral collision frequency of the plasma. The condition that

$\epsilon < -1$ means that $\omega_p > \omega\sqrt{2}$. In practice, as described in Anderson (p46) [4], a general rule-of-thumb is that the plasma frequency must be at least twice the operational frequency for the plasma to act similarly to a metal antenna.

The feasibility of using a plasma as a transmitter in MR experiments was investigated using a commercial fluorescent lighting tube. For this type of fluorescent tube $n_e \sim 10^{17} m^{-3}$, which gives a plasma frequency of ~2.8 GHz from Eq. 5.2, which is much higher than the Larmor frequencies in NMR and MRI, thus satisfying the conditions in Eq. 5.3. Experiments have been performed to characterize the plasma performance in terms of transmit efficiency compared to a conventional metallic conductor, and plasma relaxation times.

5.2. PRODUCTION OF THE PLASMA

INITIAL experiments were performed using a simple commercially-available fluorescent tube (Master TL 8W/827, 14 mm diameter, 30 cm length, Osram) to generate the plasma. The glass tube is filled with Argon at a pressure of ~2.5 Torr, with a mercury vapor pressure of 6–10 mTorr. Experiments were performed on a 7 T human MRI system (Philips Achieva). Lower clinical field strengths of 3 T and 1.5 T could equally well have been used: the 7 T was chosen due to the ease of interfacing custom built hardware to the scanner.

There are many ways to create a plasma within the tube. For example, the normal lighting mode uses an external DC source (via rectification of the AC mains) to heat the internal tungsten electrodes which emit free electrons via thermionic emission: these electrons ionize the argon gas atoms close to the filament to form a plasma via impact ionization. In this study the RF pulse used for MR excitation was used to create a non-ionizing surface wave which propagates along the interface between the glass tube and the plasma column. This wave can be produced most easily using a "surfatron", a device to create a strong electric field (on the order of several kV/m) which passes through the plasma tube to a ground plane. Different surfatron devices for various frequency bands have been reviewed by Moisan and Zakrzewski [7]. The particular surfatron design for these feasibility experiments consisted of a single wide copper band, impedance-matched to 50 Ω at 298.1 MHz (i.e. a design essentially identical to a loop gap resonator [8]), with a ground plane in close proximity, as shown in Fig. 5.1. The RF pulse from the amplifier establishes the plasma effectively instantaneously (typical plasma rise times are less than 1 μs.

A copper tube with the same length as the plasma tube and similarly-sized ground plane was used as a monopole element in order to compare the relative transmit sensitivity of the plasma and metal conductor, as well as being used as the receive element for spectroscopy experiments using the plasma as the transmitting source.

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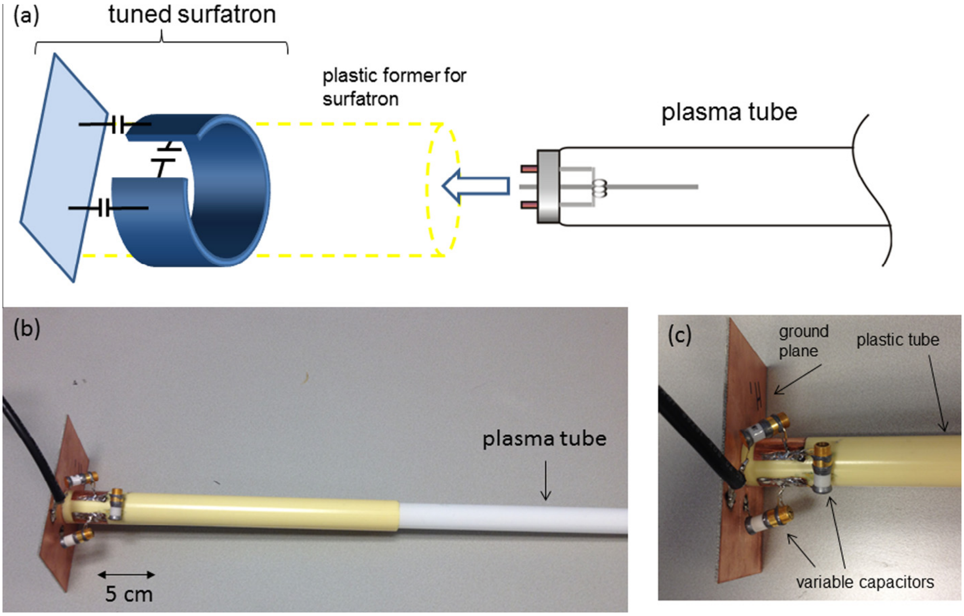

Figure 5.1: (a) Schematic of the surfatron used to produce the plasma. The circuit formed by the copper band and ground plane is resonated and impedance matched to 50 Ω at 298.1 MHz using three capacitors in a π-configuration. The surfatron is constructed on a thin plastic tube for mechanical support (yellow dotted line), and the tube is also used to center the plasma tube within the surfatron. The plasma tube is inserted through the copper band. The strong electric field (~2 kV/m) produced between the copper band and the ground plane passes through the tube and creates the plasma via a traveling surface wave. (b) Photograph of the assembled surfatron on the plastic former (yellow tube), and the plasma tube inserted into the plastic former. (c) Expanded view of the constructed surfatron showing the three variable capacitors (1–30 pF, Voltronics) used for impedance matching. The copper band has a width of 2 cm.

5.3. RESULTS

IN order to determine whether the idea of a plasma-based coil is feasible a small sample (1 × 1 × 1 cm) of paraffin oil was placed next to the axial mid-point of the plasma tube. Fig. 5.2a shows the free induction decay measured using the plasma to transmit and receive the signal. The signal decays very rapidly, effectively providing a measure of the plasma decay time after the RF pulse has been turned off. The signal decays with a time constant of ~4 ms, the primary relaxation mechanism being ambipolar diffusion to the lamp walls. The fact that the rapid signal decay is indeed caused by this relaxation was tested by using the plasma to transmit the RF pulse and the monopole (placed ~10 cm away from the plasma tube and sample to ensure that there is no coupling between the two elements) to receive the signal: the resulting FID is shown in Fig. 5.2b, clearly indicating that the very rapid signal decay shown in Fig. 5.2a is due to decay of the plasma. These results indicate that, in this particular configuration the plasma would only be suitable for signal detection in experiments in which the acquisition bandwidth is extremely large, e.g. for solid samples or for short echo time high-readout-bandwidth imaging.

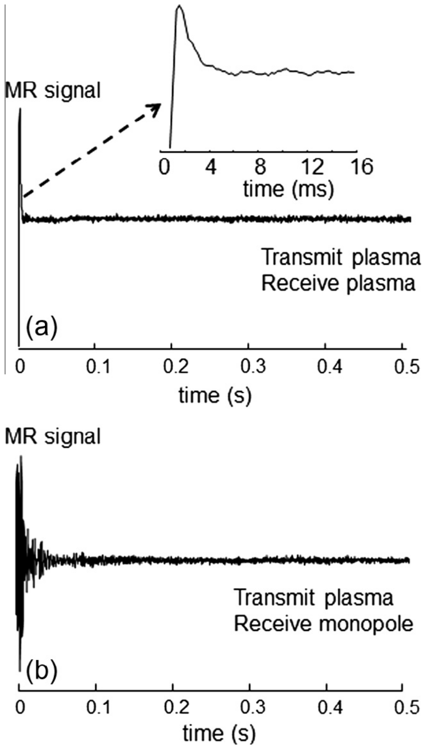

Figure 5.2: Experiments using a plasma tube and copper monopole in different transmit/receive configurations. (a) If the plasma tube is used both to transmit the RF pulse and receive the signal, then the time-domain MR signal is strongly damped since the plasma relaxes with a time constant on the order of 4 ms. (b) When the plasma is used to transmit the RF pulse, and a conventional conductor-based coil is used to receive the MR signal, the free induction decay lasts much longer, determined by the T_2/relaxation time.

The second experiment was performed in order to determine whether any component of the signal shown in Fig. 2 arises from the surfatron itself rather than the plasma, since it is well-established that traveling-wave effects [9, 10] can occur on human magnets at 7 and 9.4 T. A thin tube of water (diameter 2 cm, length 20 cm) was placed next to the plasma tube. Fig. 5.3 shows the results from a low tip angle 3D gradient echo imaging experiment (TR 25 ms, TE 1.1 ms, data matrix 132 × 136 × 20, field-of-view 10 × 40 × 10 cm). Fig. 5.3a shows one slice through the center of the water sample. Fig. 5.3b shows the corresponding experiment under identical conditions except with the plasma tube removed. These results indeed indicate that there is no measurable travelling wave component, and that the entire spectroscopic and imaging signal intensities shown in Figs. 5.2 and 5.3 arises from the magnetic field created by current flowing in the plasma. A similar experiment was performed in which the gas was removed from the plasma tube: again no signal was detected.

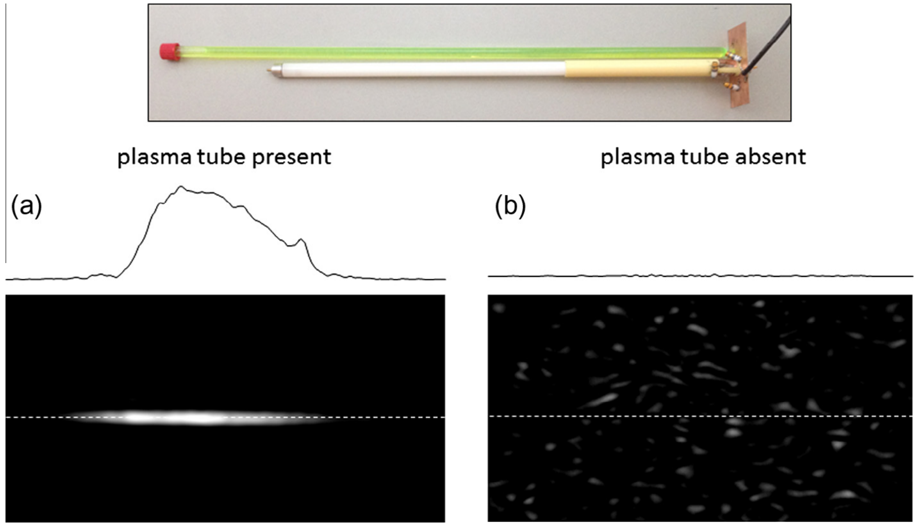

Figure 5.3: Top – physical arrangement of a long glass tube filled with water (and a dye for visibility purposes only) placed next to the plasma tube. Gradient echo images acquired (a) with and (b) without the plasma tube positioned in the surfatron. A line plot along the dotted line is shown above each image. The lack of signal in (b) shows that there is no traveling wave component to the signal detected in (a).

Fig. 5.4a shows the results of a pulse width calibration to measure the transmit efficiency of the plasma using the small paraffin oil sample described earlier. The signal intensity was measured as a function of input power to the surfatron: a block pulse with duration 2.6 ms was used. The input power (measured at the input to the plasma coil) required for the maximum signal intensity was 700 W. Since a small sample was used, one can approximate the maximum signal intensity as corresponding to a 90° pulse (despite the intrinsically inhomogeneous B_1^+ field produced by a rod-like structure) which translates to a transmit coil efficiency, defined as B_1^+ (Watt)$^{1/2}$, of 0.09 μT/$\sqrt{W}$. A similar experiment was performed using the monopole, with the sample positioned identically to that using the plasma tube, with the results plotted on the same power scale in Fig. 5.4b. In this case a transmit coil efficiency of 0.75 μT/$\sqrt{W}$ was measured, a factor of 8.3 greater than the plasma.

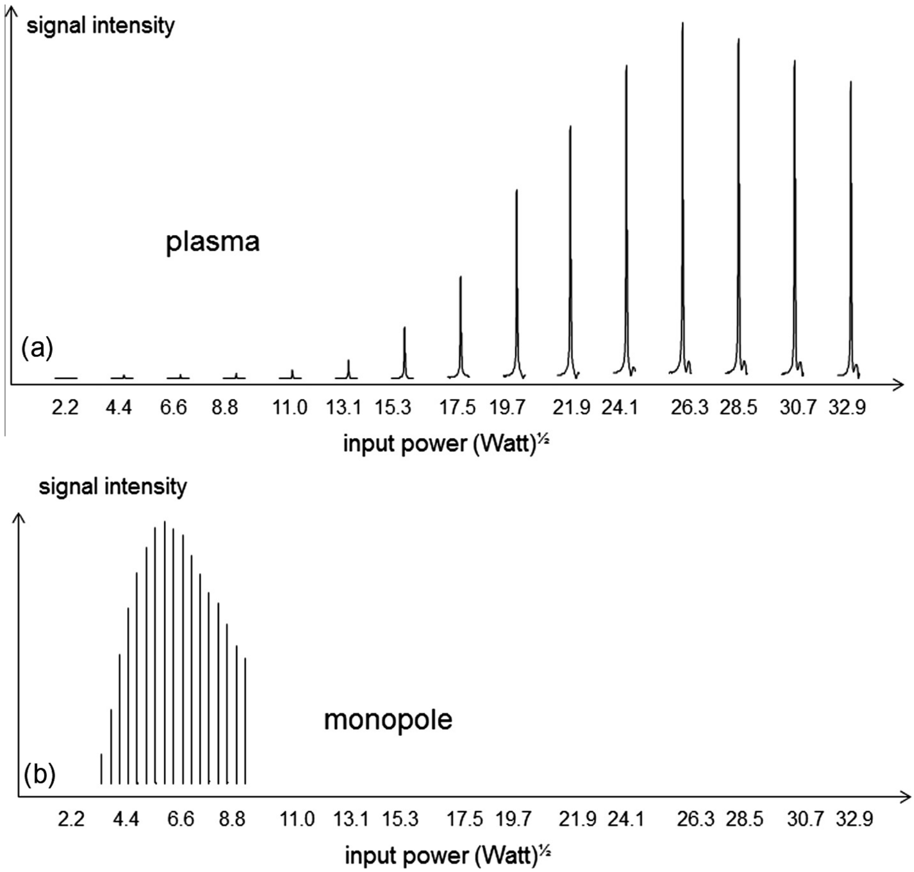

Figure 5.4: Pulse width calibrations used to measure the coil transmit efficiency by plotting signal intensity vs. the square root of input power. A 2.6 ms long hard pulse was used. (a) Plasma transmit, monopole receive. The maximum signal intensity occurs at an input power of ~700 W. (b) Monopole transmit, monopole receive, plotted on the same power scale for ease of comparison. The maximum signal intensity occurs at an input power of ~40 W.

5.4. DISCUSSION

INITIAL experiments outlined in this work illustrate the feasibility of using plasmas for magnetic resonance, even with very simple fluorescent tubes. The efficiency of the current plasma setup is much lower than that of an equivalently-sized copper conductor element. However, this is unsurprising given that an off-the-shelf lighting tube has been used as the plasma element. Significant improvements in the plasma performance can be anticipated if a custom-built tube is manufactured. The diameter of the tube can be reduced substantially reducing the power required to ionize the gas, and the gas pressure can also be adjusted. If the plasma pressure and electron density are increased then the plasma current increases, but the collision frequency increases which increases losses in the plasma, and so a compromise would have to be determined. Alternative plasma sources such as cold cathode fluorescent lamps (CCFLs) may be more appropriate since they do not require electrode heating to form the plasma. The geometry of the tube can also be improved: in the current implementation the plasma tube is fed from one end, effectively producing an electrical monopole. Symmetric central feeding of a two-tube element in a “dipole would produce a field more suitable for MRI. Finally, a more efficient surfatron can certainly be designed, since in the current configuration only a small fraction of the electric field passes through the plasma: for example Fig. 5.4a shows that at input powers up to ∼100 W, the plasma is not fully ignited.

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The current implementation uses the plasma as the transmit coil and a conventional conductor-based device to receive the MR signal. However, it may also be possible in the future to design a system in which the plasma is used for both transmission and reception, if desired. This would involve having two inputs to the plasma tube: one continuous low-frequency plasma excitation signal to maintain the plasma during signal detection by exciting the $m = 0$ surface wave [11, 12], and the other the high frequency input for producing RF pulses at the MR operating frequency. Since these signals are well-separated in frequency there would be negligible cross-talk. Alternatively, it may be feasible to alter the gas composition and/or pressure such that the plasma relaxation rate is decreased significantly. If the plasma were to be used as a receiver it is also important to consider the relevant noise characteristics and noise sources. These have been reported in several publications [13, 14], and are summarized in Chapter 12 of Ref. [4]. The noise spectrum of a plasma is given by

$$H(v) = 4RkT\left(\frac{1}{1+\frac{(2\pi v)^2}{v_{cc}^2}}\right) \tag{5.4}$$

where υ is the frequency of the transmitter in Hertz and υ_{cc} is the electron-gas atom collision frequency. Comparing this to the standard equation for Johnson noise for a conductor, one can see that whether the plasma has a higher or lower noise level than a conductor depends upon the relationship between the Larmor frequency and the collision frequency, the latter of which can be manipulated via the gas pressure in the plasma.

It should be emphasized that there are several important differences between the operation of a plasma and a conductor-based coil for MR applications. For example, under the pure travelling wave conditions of the propagating surface-mode wave, the electron density decreases as a function of distance from the surfatron, which means that the conductivity along the plasma tube also decreases. Below a certain critical value of plasma density, $n_{critical}$, the conductivity becomes zero:

$$n_{critical} = \frac{4\pi\epsilon_0 m_e}{e^2} f^2 (1+\epsilon_d) \tag{5.5}$$

The higher the applied power the higher the plasma density, and so the effective length of the plasma column depends on the input power: one can either view this as an extra degree-of-freedom in designing new types of experiments in which the spatial distribution of B_1^+ can be controlled by effectively altering the length of the RF coil, or alternatively as an inconvenient nuisance in that the peak input impedance is no longer a fixed value. As with conventional conductor-based RF coils it is important that the plasma tube not come into direct contact with the object/subject being studied, since this may alter the plasma distribution slightly. If the transmit efficiency of the plasma can be increased, one of the major advantages of using this approach would be that there would be no interaction between a plasma transmit coil and a conductor or plasma receive coil, which means that electrical isolation circuits could be eliminated. Other potential advantages include the increased radiation transparency of plasmas versus metals for hybrid imaging systems such as PET/MRI and SPECT/MRI.

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