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Communication

# Evaluation of plasma-based transmit coils for magnetic resonance

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ABSTRACT

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.



## 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 [1], the use of metallic elements is almost universal (a few publications have used high permittivity ceramic dielectric resonators [2]). 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, $\omega_p$, given in Anderson (p32) [3]:

$$\omega_p = \sqrt{\frac{n_e q_e^2}{\varepsilon_0 m_e}} \tag{1}$$

where $n_e$ is the electron number density (measured in $m^{-3}$), $m_e$ the electron mass, $\varepsilon_0$ the permittivity of free space, and $q_e$ the electron charge. Evaluating the fundamental constants this gives:

$$\omega_p \approx 56.4\sqrt{n_e} \tag{2}$$

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 $-1$ [4,5]. The frequency-dependent permittivity of the plasma is given by:

$$\varepsilon(\omega) = \varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2} - j\frac{\omega_p^2}{\omega v_{cc}}\right) \tag{3}$$

where $v_{cc}$ is the electron-neutral collision frequency of the plasma. The condition that $\varepsilon < -1$ means that $\omega_p > \omega\sqrt{2}$. In practice, as described in Anderson (p46) [3], 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. (2), which is much higher than the Larmor frequencies in NMR and MRI, thus satisfying the conditions in Eq. (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.

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## 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 [6]. 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 [7]), with a ground plane in close proximity, as shown in Fig. 1. The RF pulse from the amplifier establishes the plasma effectively instantaneously (typical plasma risetimes 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.

## 3. Results

In order to determine whether the idea of a plasma-based coil is feasible a small sample ($1 \times 1 \times 1$ cm) of paraffin oil was placed next to the axial mid-point of the plasma tube. Fig. 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. 2b, clearly indicating that the very rapid signal decay shown in Fig. 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.

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 [8,9] 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. 3 shows the results from a low tip angle 3D gradient echo imaging experiment (TR 25 ms, TE 1.1 ms, data matrix $132 \times 136 \times 20$, field-of-view $10 \times 40 \times 10$ cm). Fig. 3a shows one slice through the center of the water sample. Fig. 3b shows the corresponding experiment under identical conditions except with the plasma tube removed. These results indeed indicate that there is no measurable traveling wave component, and that the entire spectroscopic and imaging signal intensities shown in Figs. 2 and 3 arises from the magnetic field created by current flowing in the plasma. A similar

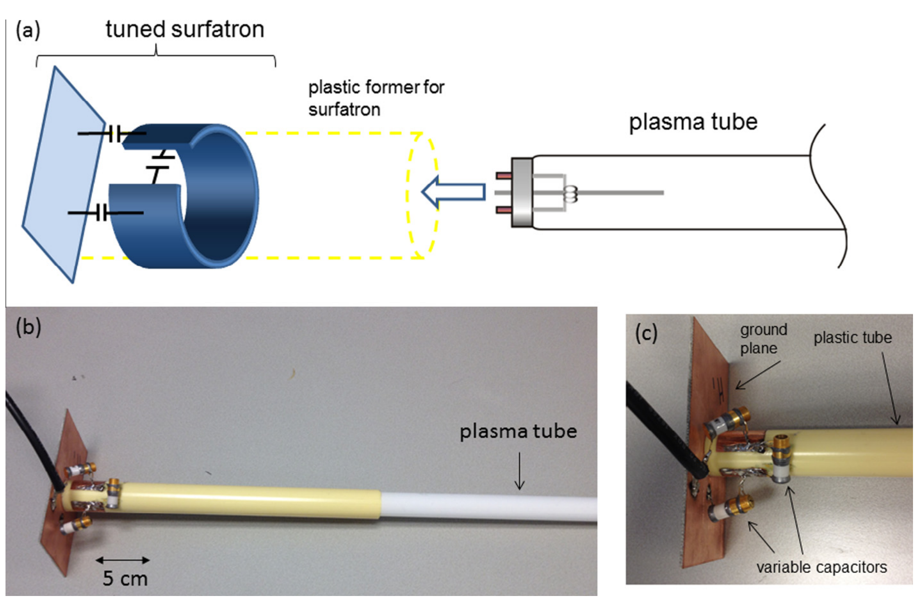


**Fig. 1.** (a) Schematic of the surfatron used to produce the plasma. The circuit formed by the copper band and ground plane is resonated and impedance matched to 50 Ω at 298.1 MHz using three capacitors in a π-configuration. The surfatron is constructed on a thin plastic tube for mechanical support (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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)