# Experimental Characterization of the Innovative Thermo-Brachytherapy Seed for Treatment of Prostate Cancer

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## INTRODUCTION

Low-dose-rate (LDR) brachytherapy seed implant is presently one of the commonly utilized treatments for early stage prostate cancer. Although a highly effective modality, brachytherapy alone is not suitable for patients with locally advanced disease. Extensive clinical data demonstrates that adjuvant administration of hyperthermia (heating tissues to sustained temperatures in the range of 40-45ºC) offers one of the most efficient enhancements of local and regional cancer control, acting both as a radiation sensitizer and a complementary treatment, especially when both are administered simultaneously.

We have recently proposed a new Thermo-Brachy (TB) seed that combines a sealed radioactive source with a ceramic ferrite core. The latter serves as a source of self-regulated hyperthermia due to loss of its magnetic properties once its temperature goes above the Curie temperature the ferrite material. The ferrite material possesses high relative permeability ($\mu_r$), enhancing magnetic flux, and inducing eddy currents in the surrounding conductive sheath. We characterize ferrite seeds based on their permeability as a function of temperature, Curie temperature and steepness of the Curie transition experimentally for a specific formulation of the ferrite material to assess its suitability for use in TB seeds. According to previous studies, Curie temperature of 42-46 ˚C and $\mu_r \sim 3000$ is desirable for hyperthermia properties.

## AIM

- Identification of the seed formulation with the desired properties
- Detailed experimental determination of the magnetic and material properties of the finalized ferrite, to inform dependent studies.

## METHOD

We begin our measurement with a toroidal shaped ferrite sample to avoid the complexity of the calculations and non-linear effects usually present in the case of small cylindrical samples. For this purpose we follow the steps below

- Measurement the intrinsic capacitance as a function of frequency using oscilloscope
- Set up an R-L circuit
- Obtain input voltage and the voltage difference across the inductor from oscilloscope at various temperatures
- Fit oscilloscope channel outputs to obtain amplitude and phase shift
- Calculate the inductance and relative permeability
- Compare the results to Pspice modelling results

## RESULTS

The relative permeability of toroid shaped sample at different frequencies can be calculated from the measured inductance at different temperatures. We assume that a toroid of rectangular cross-section is wound uniformly with n turns of wire as shown in Figure 1.

| Sample specification | |
|---|---|
| $h$ (mm) | 0.55 |
| $a$ (mm) | 0.35 |
| $b$ (mm) | 0.575 |

Table 1: Ferrite sample specification

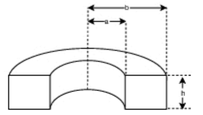

Figure 1: A typical toroid specimen with square cross-section

In a typical R-L circuit (Fig. 2), the intrinsic capacitance of the oscilloscope and parasitic capacitance of the inductor can cause some complications, hence they should be included in our calculations. Parasitic capacitance could be controlled by the density of the winding and reducing the number of turns at higher frequencies. Figure 3 shows how the resonance peak (and inductive and capacitive regions) shifts for different parasitic capacitance. The oscilloscope capacitance is always present but the contribution is more significant at higher frequencies.

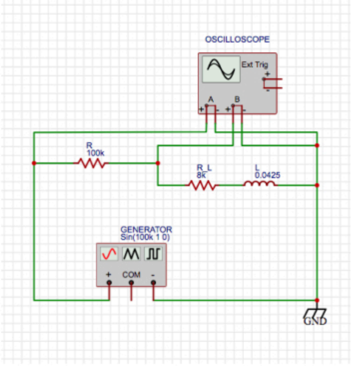


Figure 2: Schematic diagram of electrical circuit for inductance measurement

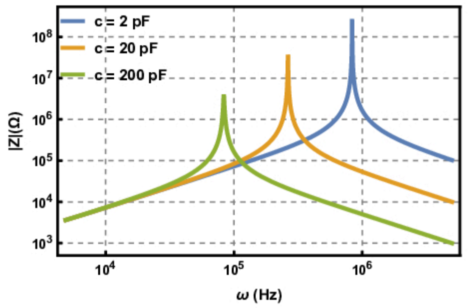


*Figure 3: Characteristic impedance of an inductor with parasitic capacitance $c$ and parasitic resistance $R \approx 900\,\Omega$*

Inductance is calculated from the imaginary part of the inductor impedance and from the below equations.

$$Z_{osc} = \frac{1 + i\,\omega\, C_{osc} R_{osc}}{R_{osc}},$$

$$V_r = \frac{V_L}{V_{in}} = \frac{|V_L|}{|V_{in}|}(\cos(\Delta\phi) + i\,\sin(\Delta\phi)),$$

$$Z_L = R_L + i\omega L,$$

$$Z_1 = \frac{1}{\left(\frac{1}{R_{osc}} + j\omega C_{osc} + \frac{1}{(R_L + j\omega L)}\right)},$$

$$V_r = \frac{Z_1}{Z_1 + R}.$$

- $C_{osc}, R_{osc}, Z_{osc}$ are intrinsic oscilloscope capacitance, resistance and impedance respectively
- $V_L, Vin$ are input, output voltage across the inductor and generator respectively
- $\Delta\phi$is the phase shift of $V_L$ with respect to $V_{in}$
- $R$ is the resistance in the circuit
- $R_L, Z_L$ are intrinsic resistance and impedance of the inductor

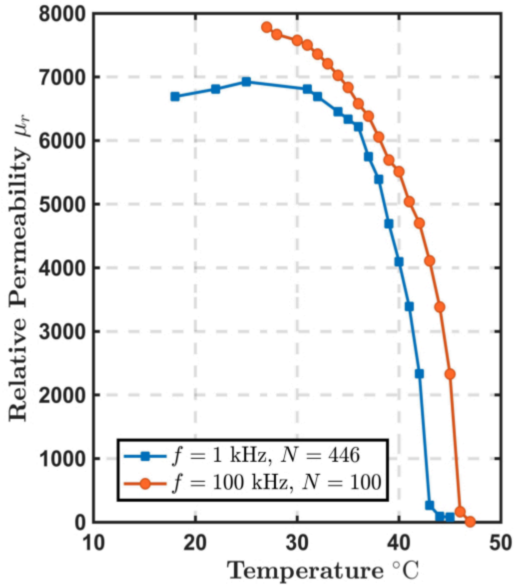


*Figure 4: Relative permeability versus temperature for toroidal-shaped ferrite sample at 1kHz and 100kHz frequency.*

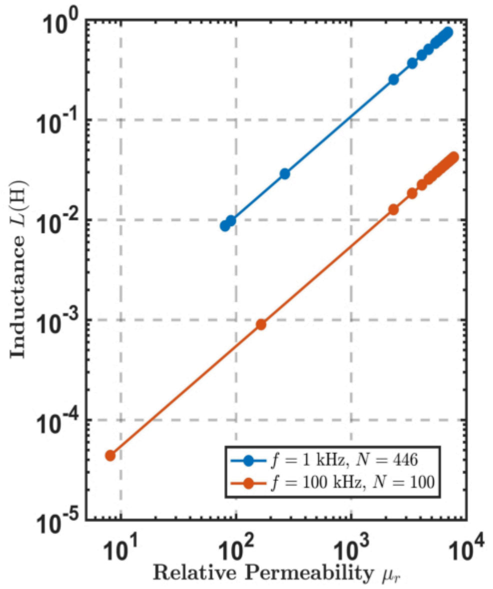


*Figure 5: inductance versus relative permeability.*

Where we obtained the phase shift $\Delta\phi$ and the voltage amplitude ratio $|V_L|/|V_{in}|$ by fitting the oscilloscope output using nonlinear least square method. To calculate the inductance and intrinsic resistance of the inductor we need to solve two coupled nonlinear algebraic equations. Finally, the relative permeability can be obtained from

$$\mu_r = \frac{2\pi L}{\mu_0 N^2 h \ln(\frac{b}{a})}.$$

It is important to note that in the above formula we have neglected the conductivity of the toroid, thereby neglected the skin-depth effect as we have proven them to be insignificant for our case.

Figure 4, shows how the permeability changes with frequency and temperature. The clear sharp drop indicates the Curie temperature where the ferrite loses its magnetic properties. The relative permeability of the ferrite ceramics was determined to be ~ 8000 at room temperature and temperature-dependent measurements established a drop in the relative permeability of the sample at the Curie temperature of 43°C. This result is in alignment with our theoretical modeling of magnetically-mediated hyperthermia in which we established that ferromagnetic material should have a relative permeability in the range of thousands at ~100 kHz frequency, and Curie temperature ~50°C. Figure 5 indicates the change of inductance with relative permeability.

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## CONCLUSIONS

We have described the procedure for measuring the relative permeabilities of toroid at two different frequencies versus temperature. Using measurements of the inductance of a toroid of rectangular cross-section, we calculate the relative permeability of the ferrite material.
We developed a method for reliable measurements of temperature-dependent relative permeability and obtained promising results. Since permeability is an intrinsic material property we will use these results to characterize TB seed prototypes. Finding ferrite material with suitable properties will bring a TB seed implant closer to clinical implementation.
All our results and calculations are consistent with simulations in PSpice up to ~1% relative error, validating our approach and experimental assumptions.
Curie temperature and relative permeability of the current sample is close to the acceptable range according to previous studies.
Experimentally obtained values of the magnetic and thermal properties of the seed, combined with simulations of thermal distributions that may be obtained in realistic patient-specific scenarios, can be used to inform thermal treatment planning in the pre-clinical and clinical phases of the project.

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