Electrical considerations for RIT engines based on 3D fullwave field simulation of electromagnetic scattering of their RF coils

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Abstract: Field simulations of the induction coils of RIT engines were performed. A virtual engine model was used to compare a conventional and a novel coil geometry. Impedance curves are derived from the port scattering parameters, which allow statements to be made about the electrical parameters like inductance and capacity.

Nomenclature

Z	= impedance
Y	= admittance
Z_0	= reference impedance
$\mathbf{I}$	= unity matrix
S	= scattering parameter
μ_0	= magnetic field constant
N	= windings
A	= area
l	= length
R	= radius or resistance
L	= inductance
i	= current
u	= voltage
ω	= radiant frequency
f	= frequency
ω_0	= resonant frequency
C	= capacity

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I. Introduction

An essential component of a RIT engine is the induction coil, which is used to feed energy into the plasma. A RFG supplies the voltage for the ionization of the supplied noble gas, usually xenon. In combination with an extraction system, this enables the acceleration of the particles, which generates thrust.

There have been studies on how this induction coil can be constructed, where it has been shown that alternative geometries can lead to an increase in the efficiency of the engine. This paper discusses the electrical properties of a bifilar wound coil using simulative investigations as a starting point.

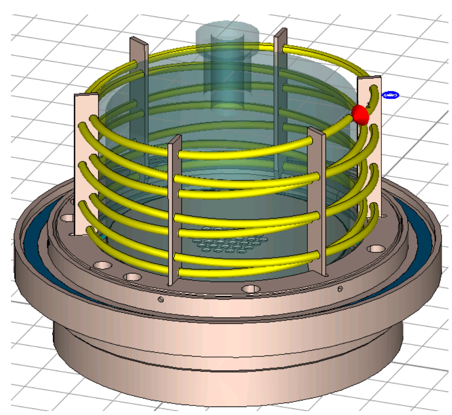
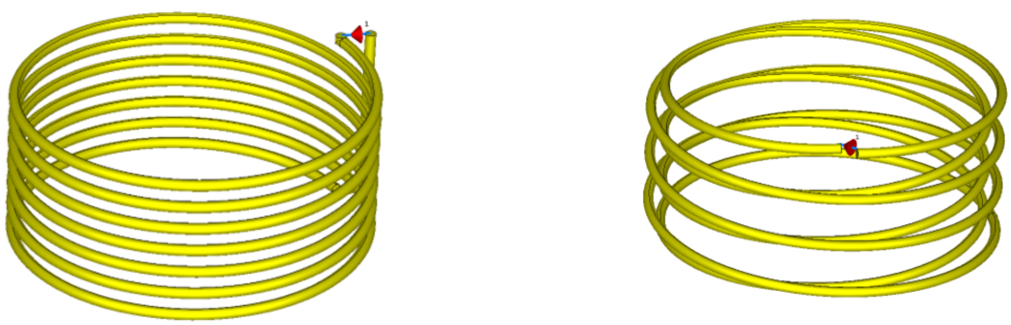


Figure 1: Mounted bifilar coil w/ grids

The simulated induction coils are, on the one hand, a conventional solenoid coil and, on the other hand, the bifilar wound coil presented in [1]. The geometries are shown in figure 2. The bifilar coil has the property that a strong damping of the axially induced field takes place. Investigations have shown that this arrangement can improve engine efficiency of the thruster.

The purpose of the simulative investigation is to determine the behavior of the coil in the electrical network of the series resonant circuit. The primary characteristic of the inductance is superimposed by undesired capacitive effects in the higher frequency range. The simulation should contribute to qualitative statements about the degree of these effects. In order to enable the results to be included in calculations, a substitute circuit diagram is drawn up which can take these effects into account.



(a) Conventional coil

(b) Bifilar coil

Figure 2: Coil examples

II. Impedance considerations

First, the geometry of the induction coils is reconstructed in a 3D field simulation tool. From there, it is possible to simulate the transmission properties of the component. For this purpose, specific signal feeds are possible on the one hand, and a general system theoretical consideration (s-parameter extraction) on the other. The latter serves as a starting point for modeling the coil as an RF component. The impedance curve for a frequency range can be extracted from the s-parameters with the equation

$$\mathbf{Z} = Z_0 \left(\mathbf{I} - \mathbf{S}\right)^{-1} \cdot \left(\mathbf{I} + \mathbf{S}\right) . \tag{1}$$

Typically, s-parameters are given in matrix form. In multiport systems, these describe all the transmission properties present in the system. The relationship applies both to discrete data values and to mathematical functions that describe these s-parameters. In the case of the induction coil, it is a two-terminal component. This can be fully described by the port wave reflection behavior. Analogously, in the voltage-current domain the current is measured by an applied harmonic voltage and the complex division is plotted as complex impedance. The reference impedance Z_0 is defined as 50 Ohm.

The simulation in the frequency domain initially only simulates the properties of harmonic excitation of a fixed frequency, i.e. impedances and inductance values of discrete frequency points are determined. By adaptive selection of the interpolation points and an s-parameter convergence criterion, interpolation makes it possible to generate a corresponding continuous curve.

A. Resulting impedance curves

After converting the s-paramters to z-parameters (z_{11}), the results are shown in figure 3. In the operating

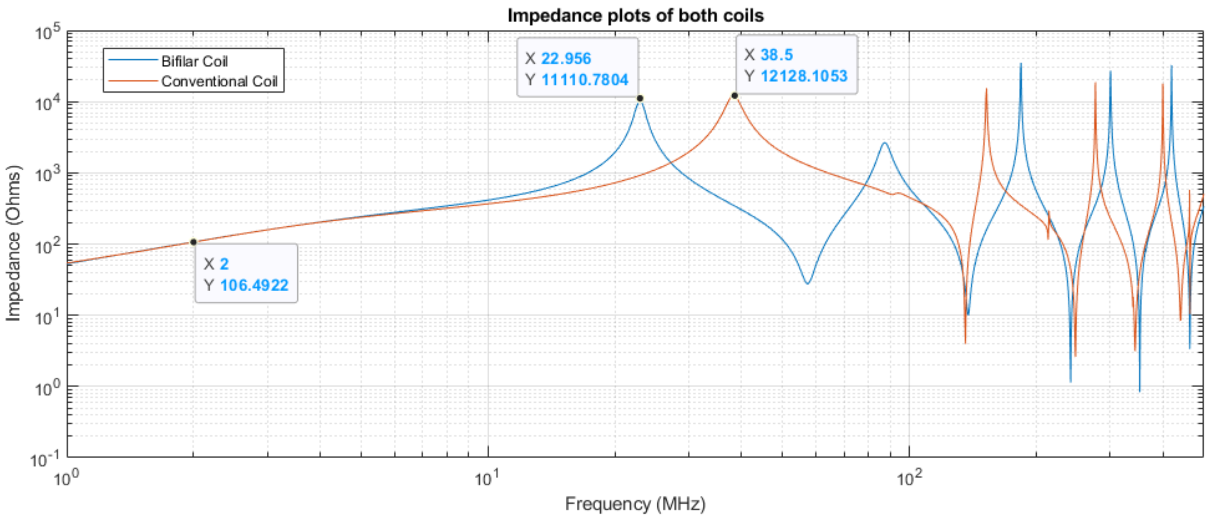


Figure 3: Resulting impedance curves of the coil

frequency range, the curves are almost congruent, so the inductance there is identical. The displacement of the resonance peaks indicates that the capacitive properties of the coils differ, which is determined later.

The conventional coil can be used up to about 20 MHz, the bifilar coil up to 15 MHz inductively at nominal inductance. At higher frequencies, the inductance rises sharply and changes to capacitive behavior at a certain point.

B. Inductance determination

There is an approximation formula [2] for reference for short air solenoid coils, which leads for an example coil of $N = 7$ turns, a radius $R = 57\,\text{mm}$ and length $l = 54\,\text{mm}$ to

$$L \approx \frac{\mu_0 N^2 A}{l + 0.9R} = \frac{\mu_0 N^2 R^2 \pi}{l + 0.9R} = \frac{4\pi \cdot 10^{-7}\,\frac{\text{N}}{\text{A}^2}\, 7^2 (57 \cdot 10^{-3}\text{m})^2 \pi}{54 \cdot 10^{-3}\text{m} + 0.9 \cdot 57 \cdot 10^{-3}\text{m}} \approx 6\,\mu\text{H}\,.$$

Since the z-parameters are known, the inductance values can be calculated from them for each frequency. By the definition of

$$u = L \frac{\mathrm{d}i}{\mathrm{d}t}\,,$$

the frequency response of an inductor is given by its fourier transformation

$$u = Lj\omega i = Lj2\pi f\,.$$

By using the impedance parameter z_{11} we can calculate the inductance

$$L = \frac{\text{Im}(z_{11})}{2\pi f}$$

for each z_{11}. The simulation of the coil delivered z-parameters for each frequency in a defined range. Because of the frequency dependence of L , samples in the in the lower frequency range near the operation frequency are chosen. In this range, the inductance is approximately constant. The conventional coil resulted in $\mathrm{Im}(z_{11}(f = 2\,\mathrm{MHz})) = 106.49\,\Omega$, which leads to

$$L = \frac{106.49\,\Omega}{2\pi \cdot 2 \cdot 10^6\,\mathrm{Hz}} \approx 8.41\,\mu\mathrm{H}$$

and for the bifilar coil a simulation results in $\mathrm{Im}(z_{11}(f = 2\,\mathrm{MHz})) = 107.28\,\Omega$. The result is

$$L = \frac{107.28\,\Omega}{2\pi \cdot 2 \cdot 10^6\,\mathrm{Hz}} \approx 8.47\,\mu H$$

The minimal higher inductance is caused by the offset of the outer coil windings resulting in an long cross-sectional area.

The bifilar coil differs in its impedance characteristics. Its first resonance peak occurs at a slightly lower frequency ($f_0 \approx 23\,\mathrm{Mhz}$) which are followed by additional similar peaks. In figure 4, the resulting inductance curve is shown.

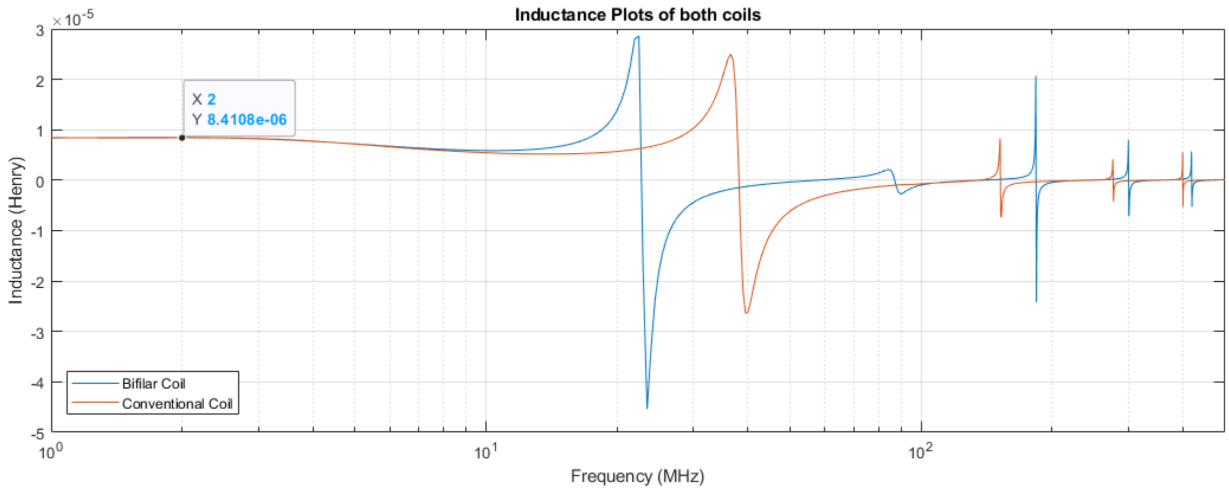


Figure 4: Resulting inductance curves of the coil

C. Equivalent Circuit and capacitance determination

Although it is possible to take the entire impedance curve as the starting point for a simulation, it functions as a black box and a corresponding replacement model would become arbitrarily complex. Therefore the decision was made to use a simple model which describes the capacitive effect in addition to the inductive effect. This increases the order of the series resonant circuit by 1. The transfer function allows frequency response and time domain analysis to be performed analytically. The impedance of this circuit is

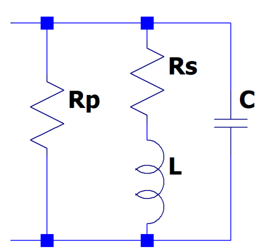


Figure 5: Equivalent circuit of coils

$$Y = \frac{1}{R_p} + \frac{1}{R_s + j\omega L} + j\omega C$$

$$Z = \left(\frac{1}{R_p} + \frac{1}{R_s + j\omega L} + j\omega C\right)^{-1} = \frac{\frac{R_s}{(\omega L)^2+R_s^2} + \frac{1}{R_p} + j\omega\left(C - \frac{L}{(\omega L)^2+R_s^2}\right)}{\left(\omega C - \frac{\omega L}{(\omega L)^2+R_s^2}\right)^2 + \left(\frac{R_s}{(\omega L)^2+R_s^2} + \frac{1}{R_p}\right)^2}$$

$$= \frac{\alpha}{\gamma} + j\frac{\beta}{\gamma}$$

$$|Z| = \sqrt{\left(\frac{\alpha}{\gamma}\right)^2 + \left(\frac{\beta}{\gamma}\right)^2}$$

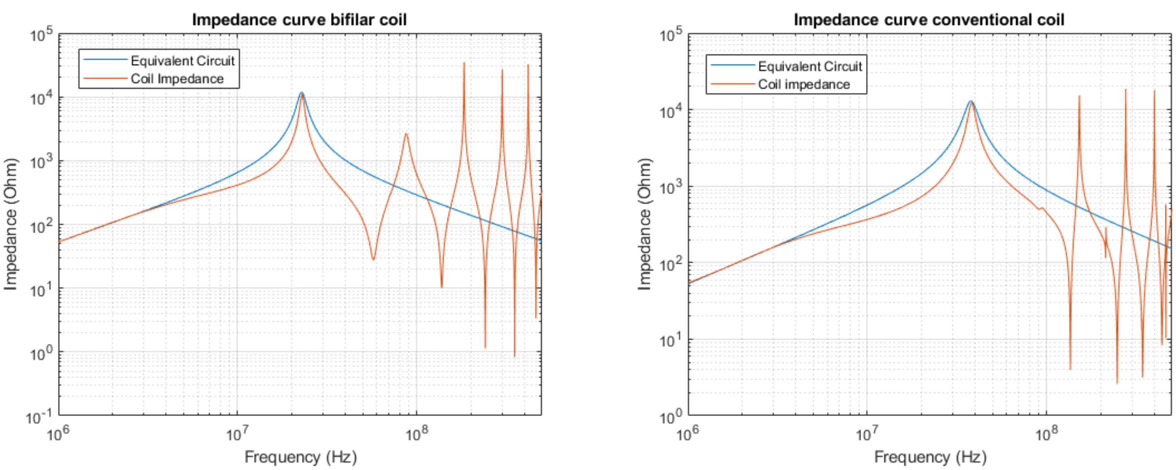
for $R_s = 0, R_p = \infty$ it simplifies to

$$Z = \frac{j\omega L}{\omega^2 LC - 1} \tag{2}$$

Resonance occurs when $u_L + u_C = 0$ for every t. This is satisfied for $\mathrm{Im}(Y) = \mathrm{Im}(Z^{-1}) \overset{!}{=} 0$, thus the resonance frequency is

$$\omega_0 = \sqrt{\frac{1}{LC} - \left(\frac{R_s}{L}\right)^2} \tag{3}$$

To determine the capacitance, the calculated inductance value is used and the first resonance peak is fitted by selecting a suitable capacitance.



(a) Bifilar coil

(b) Conventional coil

Figure 6: Coil examples

Because the lower frequency range inductance obtained by the z-parameters is almost identical, the parameter C has to be variied to move the resonance frequency through the frequency spectrum. The position of the peak is matched by setting $C = 2.1\,\mathrm{pF}$ for the conventional coil and $C = 5.8\,\mathrm{pF}$ for the bifilar coil, so there is a factor about 3 between the coil capacities.

In a visual way, this makes sense because there is a superposition of the coil capacities caused by the inner and the outer winding, so there are multiple wires where capacitive coupling happens.

D. Mounted state

It must be noted that the values differ significantly in the installed condition. In qualitative terms, however, it can also be said that the capacity of the bifilar coil is greater than that of the conventional coil. Figure 7 shows that when the coil is excited, the field distribution is influenced by the housing. A higher magnetic resistance leads to a decrease in the magnetic flux and thus also inductance. In the model used, the inductance drops to 4 μH.

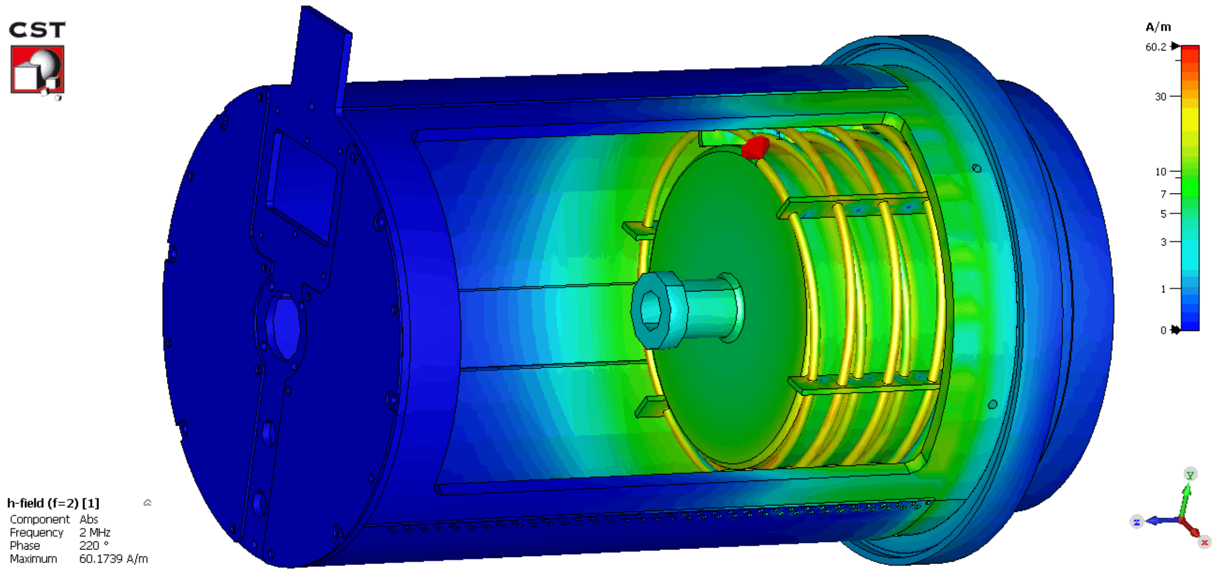


Figure 7: Example field distribution

III. Conclusion

It has been shown that the novel bifilar coil has slight differences in high frequency response, as shown by a different shape of the impedance curve. Nevertheless, the inductive behaviour is identical in the useful frequency range. Due to its other capacitance, a resonance shift of the series resonant circuit is to be expected, which, however, is kept very low, whereby the coil can be used without hesitation without major modifications of the electronics.

References

[1]Volkmar, *Self-Consistent Numerical 1D/3D Hybrid Modeling of Radio-Frequency Ion Thrusters*, 2015, Dissertation, Justus-Liebig-University Gießen.

[2]Wheeler, Simple Inductance Formulas for Radio Coils, *Proceedings of the Institute of Radio Engineers*, Vol. 16 , Issue: 10 , Oct. 1928