

Examination of the External Magnetic Field generated by a Radio-Frequency Ion Thruster (RIT)

IEPC-2013-196

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University, Washington, D.C., USA
October 6–10, 2013*

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Abstract: For the characterization of Radio-Frequency Ion Thrusters, in terms of EMC, numerical methods are required to make predictions and optimizations for new thruster designs. For this purpose the 3D EM field simulation tool *CST Studio Suite 2013* as well as *MATLAB* were used here. A simplified CAD model of a coil which is used in Radio-Frequency Ion Thrusters was created to keep the simulation duration acceptably low. The magnetic field generated by the thruster coil was simulated with *CST Studio Suite* and verified by a numerical model based on Biot-Savarts Law. After verification of the results, the model of the coil was extended to a simplified model of a RIT. The resulting magnetic field distribution was converted into a near-field source such that the contents of the thruster CAD model need no longer be taken into account in further simulations on a larger scale. The magnetic field strength was analyzed and compared with analytical methods.

I. Introduction

Electric propulsion systems have to fulfill all requirements concerning electromagnetic compatibility in order to work infallibly during mission and not to harm other electronic subsystems of the satellite.¹ Tethered interferences can be controlled by filter technology, whereas countermeasures against field-bound radiation are more difficult to implement. Therefore, common standards like *MIL-STD-461* or *E-ST-20-07C* provide limits for electromagnetic emission and susceptibility. To ensure that those limits are not exceeded, measurements and tests in special environments have to be performed which causes high effort and cost.

A precise knowledge of the emitted fields in terms of the frequency spectrum and magnitude are particularly important. With aid of simulation tools coupling mechanisms and interferences can be investigated during development to optimize the systems behavior in terms of electromagnetic compatibility. To achieve this aim, the main components, i.e. induction coil, cables or acceleration grids, have to be modeled and simulated taking their electrical properties into account. The impact of electrical parameters, such as voltage, current, frequency, and rising times have to be reviewed. The simulation results of all components can be preferably combined at the end resulting in a complete description of a RIT concerning EMC.

To perform simulations of complex geometries, software packages based on the finite difference or finite integral method are well suited. At this point, the software *CST Studio Suite 2013*⁵ was used to calculate the distribution of the magnetic fields. To avoid the risk of inaccurate results, simulations should always be verified. These may include, for example, measurements or analytical methods to be used.

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II. The Magnetic Field induced by a Coil

In order to examine the magnetic field generated by a RIT with numerical tools, a source must be modeled first. The RF coil can be assumed to be the main source of the magnetic field in this case. Representing a large spectrum of RITs a coil geometry with height $H = 40$ mm, radius $R = 25$ mm and number of windings $N = 8$ was adopted here. The current is defined as $I = 1$ A in each simulation case.

To obtain an indication of the result's accuracy produced by CST, a numerical model based on the Biot-Savart Law was programmed in *MATLAB*⁵.

A. Numeric Model based on Biot-Savarts Law

The numerical model computes the magnetic field strength of a arbitrarily shaped coil for a given current I through the coil, represented by the discretized elements $d\mathbf{s}$ in the integral, assuming homogenous current distribution because of $l_{coil} \ll \lambda_{2MHz}$ as well as constant current due to a infinitely thin wire. The model first computes the vector potential at the given point $|\mathbf{r} - \mathbf{r}'|$ taking all elements of the coil into account, followed by calculation of the curl given by

$$\mathbf{A}(\mathbf{r}) = \frac{I}{4\pi} \int_C \frac{d\mathbf{s}}{|\mathbf{r} - \mathbf{r}'|} \quad (a), \quad \mathbf{H}(\mathbf{r}) = \nabla \times \mathbf{A}(\mathbf{r}) \quad (b) \quad (1)$$

to obtain the magnetic field distribution. More detailed information of the implementation can be found elsewhere⁴.

Figure 1 shows the calculated values of the magnetic field strength along three virtual lines in the xz plane of the 3-dimensional coil, which contour is seen from a position on the y -axis in the figure, arranged at different positions in z -direction.

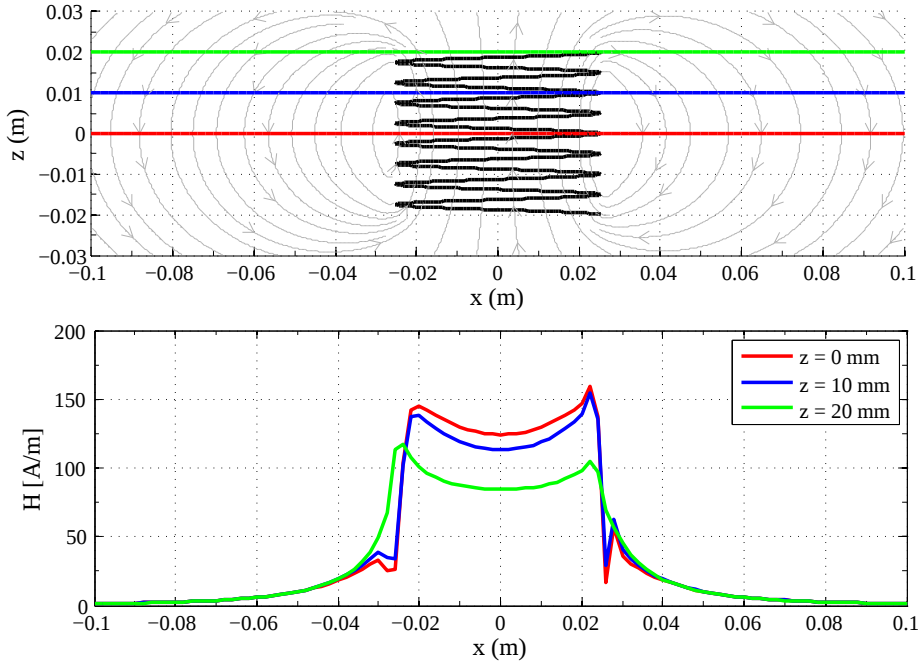


Figure 1. Magnetic field strength computed by the numeric model based on Biot-Savarts Law along three virtual lines in the xz -plane of the coil differing in z -direction.

As can be seen, the field strength reaches its maximum in the region of the coil geometry. Inside, it remains almost constant and, as expected, the field strength outside the coil drops off sharply.

B. 3-dimensional Model for CST Simulations

For the simulation with *CST Studio Suite* the coil model was created with a similar geometry as for the numerical model. The models differ in another line item, which can be found in the CST geometry. This is needed in order to define the port to excite the coil (Figure 2(a)). The simulation yields the values shown in Figure 2(b) and Figure 3 for the absolute value of the magnetic field strength whereby the center of the coil is defined as the coordinate origin.

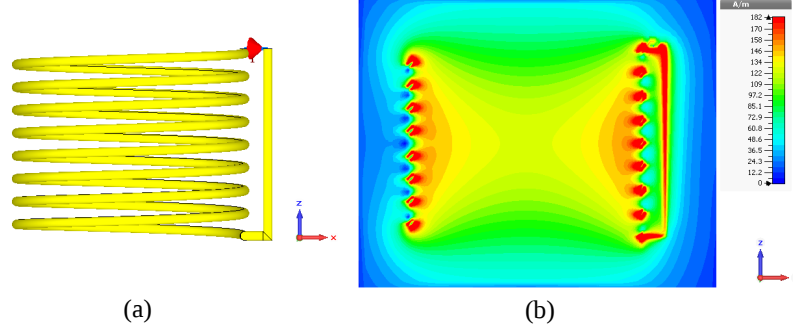


Figure 2. (a) Coil geometry with line item for CST simulations. (b) Magnetic field strength computed by CST in the xz-plane of the coil.

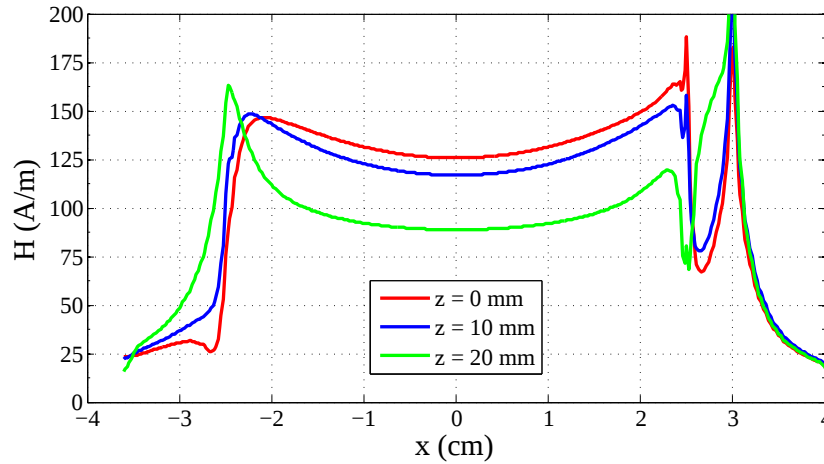


Figure 3. Magnetic field strength computed by CST along three virtual lines in the xz-plane of the coil differing in z-direction.

Compared with the numerical simulation based on Biot-Savarts Law the results show the same qualitative characteristic of the field strength values. Due to the slightly different geometry the field around the coil behaves differently. The field strength along the z-axis shows comparable values at the intersections with the virtual lines also.

III. Simulation - Thruster Model

Since the comparison of the numerical model and the CST simulation has shown that only minor deviations exist, the CST model has been extended from the simple coil to a simple Radio-Frequency Ion Thruster for further examinations.

A Radiofrequency Ion Thruster is assembled from different components, each of which performs certain tasks. From an EMC perspective, however, not every component is equally important. If a component behaves to a first approximation electromagnetically neutral or is sufficiently small compared to other components, it can be neglected for a simulation. This not only saves computing time due to a decrease of meshcells but also

simplifies the understanding of the circumstances and components leading to radiation. The components which are considered important for the behavior of the magnetic field generated by the RITs coil are mainly the grids, housing but also the beam (which is not taken into account in this work). This model includes a vessel, too. When modeling care was taken to avoid refinements in the geometry, such as notches to reduce the amount of meshcells and thus to save simulation time. A sectional view of the simplified RIT model, which is used for the simulations, is shown in Fig. 4(a) as well as the generated magnetic field in Fig. 4(b).

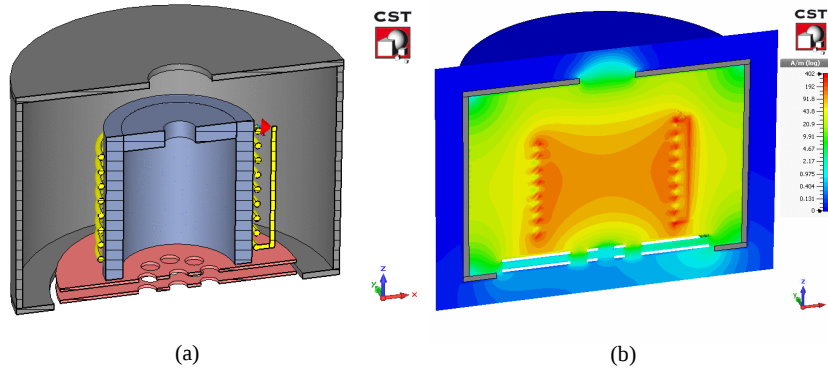


Figure 4. (a) Simplified CAD Model of a RIT. (b) Magnetic Field generated by the simplified RIT.

The model is designed with alumina for the housing, copper for the coil, silica glass for the vessel and molybdenum for the grids.

In Figure 5, the magnetic fields along the same three virtual lines, as shown in Figure 3 are plotted for the simplified CAD model of a RIT. At the positions where the housing can be found (indicated with arrows), a sharp drop of the values can be seen. This is due to eddy currents the magnetic field induces in the housing.

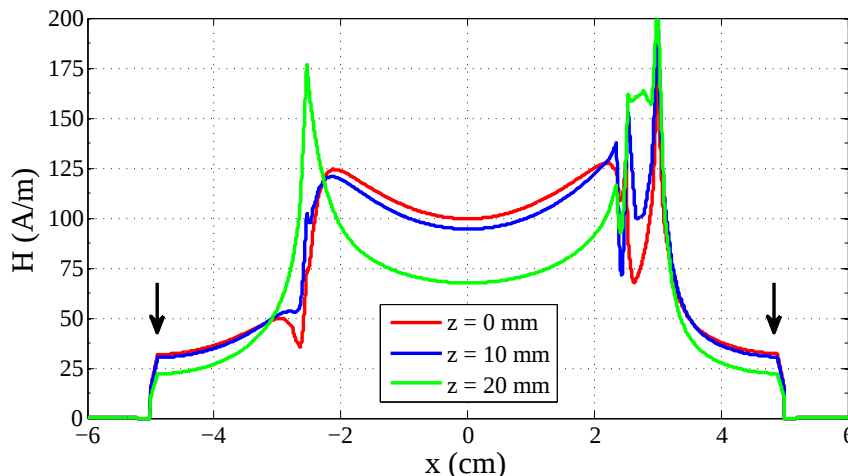


Figure 5. Magnetic field strength computed by CST along three virtual lines in the xz -plane of the coil differing in z -direction. The arrows indicate the position of the enclosure.

IV. External Magnetic Fields

Since one is interested in the fields outside the thruster, this area must be considered preferentially. Basically, the procedure comprises to determine the magnetic fields of the model in CST and to correlate as a near-field source. The near-field source can be used to perform further simulations on a larger scale. More information about near-field sources in CST can be found in the documentation of *CST Studio Suite 2013*⁵. The workflow is schematically described in Figure 6.

The advantage of this approach is the separation of the simulation domains. To simulate the domain

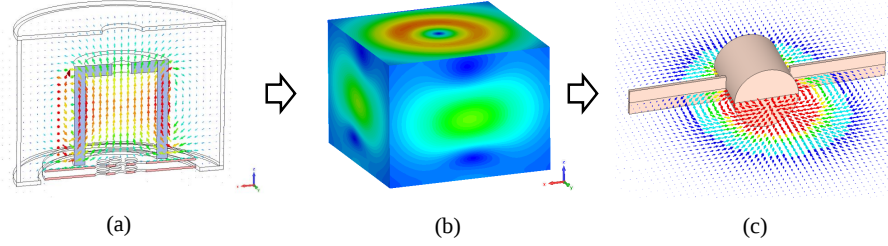


Figure 6. (a) Compute the magnetic fields of the model. (b) Correlate a Nearfield-Source. (c) Use the Nearfield-Source for further simulations, e.g. interaction with (fictitious) satellite.

outside the thruster with the same meshgrid resolution as inside would lead to very long simulation times caused by the high amount of meshcells needed.

As one can assume $\lambda_0/2\pi$ to be a criterion for differentiation between near field and far field², with a RF operating frequency of 2 MHz and $c_0 = 3 \cdot 10^8 m/s$ is the speed of light, one can define

$$R \ll \frac{c_0}{2\pi \cdot 2MHz} \approx 23.87m \quad (2)$$

as a near field region. This boundary is not meant to be a precise criterion, but is only intended to indicate a general region². Therefore and also assuming a homogenous as well as constant current distribution I the accurate calculation of the magnetic field radial and tangential components of a current loop given by³

$$\underline{H}_r = 2Z_0^{-1}j\pi I_M \frac{l}{\lambda_0^2} \cos \vartheta \frac{e^{-jk_0r}}{k_0r} \left(\frac{1}{jk_0r} + \frac{1}{(jk_0r)^2} \right) \quad (3)$$

$$\underline{H}_\vartheta = Z_0^{-1}j\pi I_M \frac{l}{\lambda_0^2} \sin \vartheta \frac{e^{-jk_0r}}{k_0r} \left(1 + \frac{1}{jk_0r} + \frac{1}{(jk_0r)^2} \right) \quad (4)$$

can be simplified, i.e. in the very near field the magnetic field is proportional to $1/r^3$:

$$H_r = \frac{I \cdot N \cdot A}{2\pi r^3} \cos \vartheta \quad (5)$$

$$H_\vartheta = \frac{I \cdot N \cdot A}{4\pi r^3} \sin \vartheta \quad (6)$$

where N is the number of windings, r the distance from origin, ϑ the polar angle and A the area cross-section of the coil².

In Figure 7 the results of the external magnetic field, in a range up to 2 meters along the x- & z-axis are shown for the near-field source simulation. The blue line in each case describes the results obtained with the simple thruster model while the red line in each case shows the results obtained with the simple coil model. Each (black) curve for H_ϑ and H_r shows the $1/r^3$ -dependence of the simplified analytical solutions Eq. (5) and Eq. (6).

For the calculation of $H_{\vartheta,Coil}$ and $H_{\vartheta,RIT}$ the polar angle ϑ is set to $\pi/2$ as well as for $H_{r,Coil}$ and $H_{r,RIT}$ ϑ is set to 0. With this choice, Eq. (5) and Eq. (6) each disclose either the axial or radial field strength, wherein the other component becomes zero. It follows that H_ϑ describes the absolute value of the magnetic field strength on the x-axis whereas H_r describes the absolute value of the magnetic field strength on the z-axis. This is required in order to make a comparison with the simulation results, as they are also available as absolute values.

Evaluating the characteristics of the field distributions it is noticed that the simulated models differ from each other. The simple model of the coil matches in good approximation with the analytical model of a current loop. In contrast, the simple model of a RIT differs especially in the range up to 1 Meter distance before the values approach each other again. This is due to the differences in the coil geometry. An attenuation of the values from the simulation of the simple coil model and the simple thruster model should be mentioned. This is due to inducing eddy currents in the enclosure of the thruster.

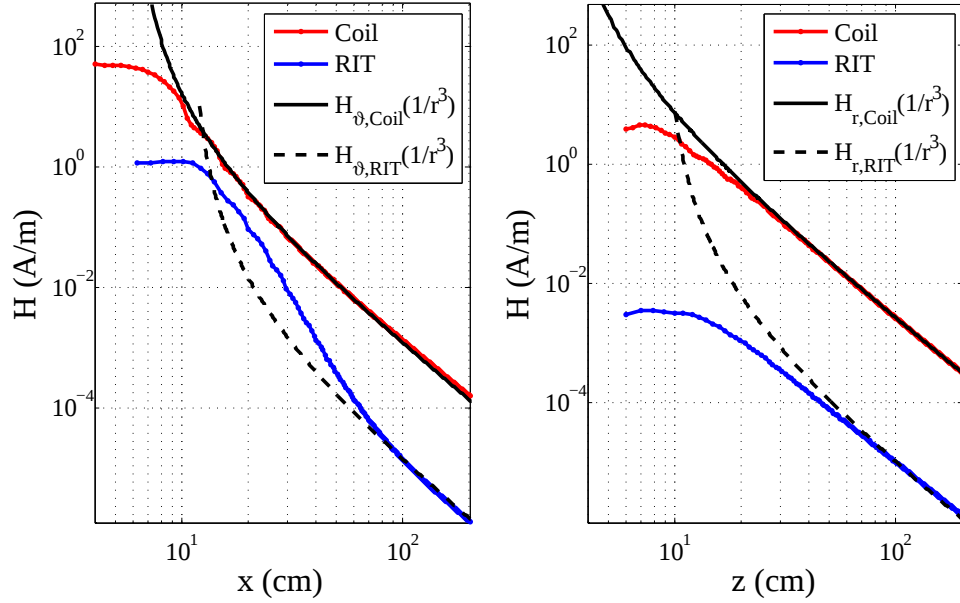


Figure 7. Magnitude of the magnetic field along the x- & z-axis calculated with the simple CST RIT model (blue) and simple CST Coil model (red) as well as the simplified analytical terms for the $1/r^3$ -dependence of H_r on the z-axis and H_ϑ on the x-axis (black).

V. Conclusion and Outlook

A simple CAD model of a RIT was created and simulated with respect to the magnetic field strength in the near field. The field strength generated within the coil could be verified using a numerical model. By the correlation into a Nearfield-Source the characteristic in the range up to 2 meters could be determined exemplary on the coordinate axes.

As shown in this work, components of a RIT can be characterized for their properties as electric or magnetic source by the use of *CST Studio Suite 2013*. In the future other parts of the thruster, e.g. grids, and the ion beam itself need to be included in the model. We are also planning to compare our theoretical results with experiments in order to fully verify the model and its predictive power.

Acknowledgments

We would like to thank Peter J. Klar and Bruno Meyer from the Giessen University for their cooperation. This project is funded by the Hessian State Ministry of Higher Education, Research and the Arts.

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