Study of The Effects of The Magnetic Field Topology on The Design of a Prototype ECR Microwave Ion Thruster and Neutralizer

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***Abstract*— This study examines the phenomenon of electron cyclotron resonance which is utilized in microwave discharge ion thrusters and neutralizers, and the effects of magnetic field topology on plasma and thruster parameters. Various designs from the literature that use permanent magnets to create a static magnetic field are investigated, their magnetic field topologies are solved and compared. ECR regions with respect to different microwave frequencies are plotted. Further study regarding the numerical plasma modeling based on the topology is explained, the numerical technique behind is described.**

Keywords*— *space propulsion, electron cyclotron resonance, magnetic field modeling.

I. INTRODUCTION

In ECR microwave ion thrusters which is the main concept studied in this paper, plasma coupling is achieved by the interaction of microwaves and static magnetic field. Electromagnetic waves whose frequencies lie in the range of 0.3-300 GHz are defined as microwaves. In an ECR microwave ion thruster assembly, electromagnetic waves are steered through waveguides and in the ionization chamber, where static magnetic field is present via permanent magnets or magnetic coils, electron cyclotron resonance phenomenon takes place. In static magnetic field, the cyclotron frequency of an electron is given by

$$\omega_{cyclotron} = \frac{eB}{m_e} \quad (1)$$

where e is the elementary charge, B is the applied magnetic field flux density and m_e is the mass of an electron.

For a given magnitude of magnetic flux density, there is a corresponding value of cyclotron frequency. Electron cyclotron resonance, hence the name, relies on the effect of resonance when coupling to a plasma. If the microwave's frequency coincide with the cyclotron frequency for a given magnetic field norm, then the energy of the electromagnetic wave is absorbed by the electrons, these energized electrons in turn cause the ionization of the propellant atoms.

For a given input power, ECR ion thrusters have been proven to deliver much higher plasma densities. The µ10 neutralizer on HAYABUSA spacecraft has delivered 140 mA of beam current when operating with 0.5 sccm xenon gas flow with a discharge voltage of -48 V, relative to the space potential of the ion beam. Absorbed microwave power was 8 W at a frequency of 4.2 GHz. The total electron production cost in terms of the power consumption is 105 W/A, taking the microwave power and the beam extraction power into account [1].

Another ECR plasma cathode that was used as a neutralizer was demonstrated in [2]. This cathode which was studied at the University of Michigan in Ann Arbor, was investigated in terms of plasma diagnostics and electron extraction properties. The maximum electron current that can be extracted was on the order of 0.6 A, with a discharge voltage difference of 40 V and 200 W of microwave power.

NASA's ECR cathode which had been considered as a neutralizer for the High Power Electric Propulsion (HiPEP) thruster was excited at a lower frequency, 2.45 GHz; at a xenon gas flow rate of 3.5 sccm, and delivered microwave power of 125 W, extractable electron current was in the order of 2.45 A at a bias voltage of 70 V [3]. NASA's Evolutionary Xenon Thruster (NEXT) which uses a hollow cathode assembly as a neutralizing device, has 10 W/A electron production cost [4]. Operational characteristics of these ECR cathodes from the literature are summarized in Table I.

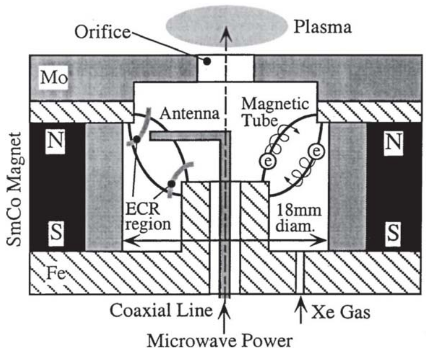

Fig. 1. Representative drawing of 4.2 GHz µ10 neutralizer cathode [1]

One can conclude that the cost of electron extraction in ECR is significantly higher than that of hollow cathode. The difference is mainly because of the confinement of electrons in the ECR zone. Even though ECR cathodes provide a much higher plasma density than hollow cathodes, the strong magnetic field also results in a difficulty of diffusing the electrons out of the ECR zone. The tradeoff is such that ECR neutralizers are much less-energy efficient, but have a much longer lifetime when compared to hollow cathodes as they do not have emitters which strongly limit the lifetime of the device [5]. Therefore, it serves as a key design parameter that the confinement of the electrons by the static magnetic field must be optimized so that the power consumed to extract electrons from the ECR zone is feasible.

The μ10 ion thruster, that was utilized on HAYABUSA spacecraft for the asteroid mission described in [6], was developed to a further stage with a 20 cm diameter thruster μ20, whose operational characteristics were presented in [7]. The 20 cm thruster had a 500 mA of ion beam current with a production cost of 200 W/A. 100 W of microwave power was supplied to the antenna of the ion source. While the μ10 ion thruster had developed an average thrust of 8 mN, the μ20 thruster operate with an average thrust of 27 mN, which is mainly caused by the enlargement of the discharge chamber. The neutralizer for the μ20 was designed to be the same as μ10's, with higher gas flow rate and microwave power in order to extract the necessary electron current which is on the order of 500 mA [7].

II. THEORY

For the wave propagating along a magnetic field line, E-field will have polarization components which also give rise to the polarization of B-field. The solution of the momentum equation, Ampere's Law and Faraday's Law therefore will yield the following wave dispersion relation:

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega(\omega - \omega_{cyclotron})} \tag{2}$$

where c is the speed of light, k is the wave propagation number and ω_p is the plasma frequency.

TABLE I. OPERATIONAL CHARACTERISTICS OF THE ECR CATHODES FROM THE LITERATURE

	Delivered Microwave Power [W]	Gas Flow Rate [sccm]	Bias Voltage [V]	Extracted Electron Current [A]	Electron Production Cost [W/A]
μ10	8	0.5 (Xe)	48	0.14	105
UofM	200	5.6 (Ar)	40	0.7	320
HiPEP	125	3.5 (Xe)	70	2.45	120

The left hand side of the equation is the square of the index of refraction (N). N=0 will denote the condition that the wave no longer propagates. N→∞ is the condition at which the wave is resonantly absorbed. This deduction mathematically shows that $\omega_{cyclotron} \to \omega^+$, which means that the wave should be launched in the direction of a decreasing magnetic field.

III. NUMERICAL METHOD

The magnetic field topology of ECR thrusters and neutralizers are modeled using COMSOL, a finite element software. Since a large proportion of the thrusters and neutralizers have axial symmetry, the models were built on 2D axisymmetric domain using cylindrical coordinates. The magnetic field contours denote the φ-component of the magnetic vector potential, **A**, that can be derived from Gauss's Law for the magnetic field:

$$\nabla \cdot \vec{B} = 0 \tag{3}$$

To obtain a 3D model, it is best to take advantage of the axial symmetry and revolve the 2D model about the symmetry axis rather than solving the model over a 3D Cartesian domain. A comparative study was carried out to underline the difference in these two ways for a series of ring magnets.

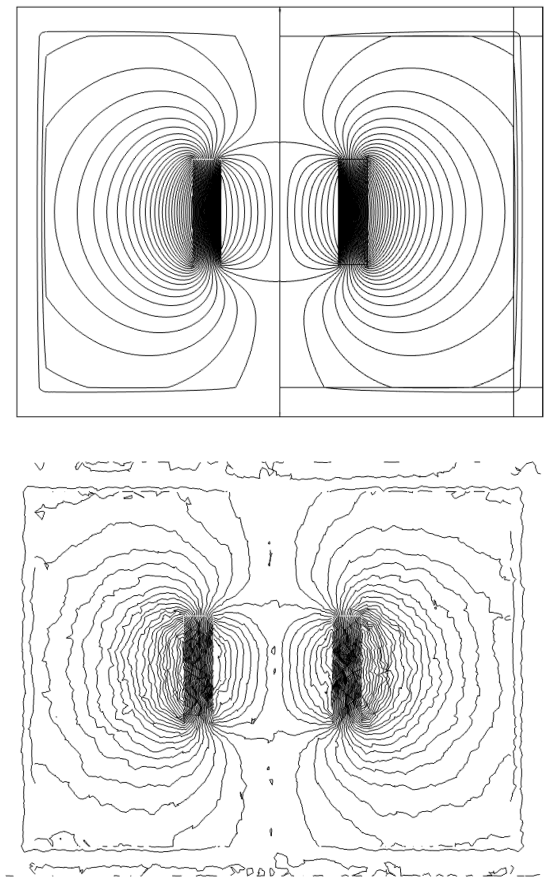

Fig. 2. 2D-axisymmetric domain solution (top), 3D Cartesian solution (bottom) for the φ-component of the magnetic vector potential

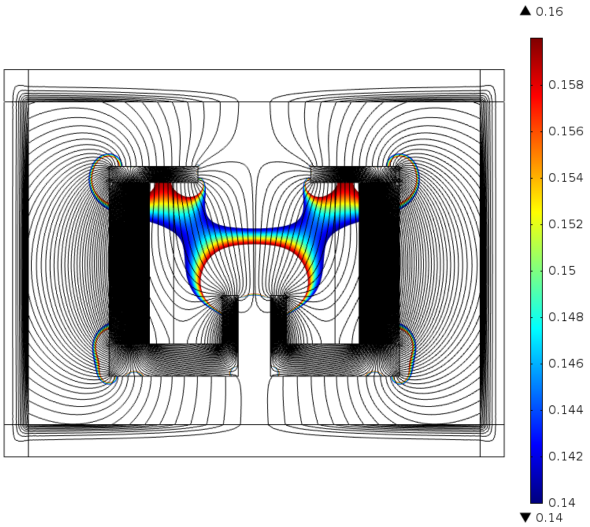

Fig. 3. Magnetic field topology and the ECR region of the neutralizer cathode of µ10

In Fig. 2 coordinate transformation was used to obtain the magnetic field lines for the Cartesian case. It can be deduced that it is both computationally expensive and less precise and reliable when the model is solved over Cartesian domain.

IV. Results and Discussion

The magnetic topology of the neutralizer shown in Fig. 1 with the dimensions drawn qualitatively is solved using COMSOL. The static magnetic field of µ10 was supplied using Samarium Cobalt permanent magnets.

For 4.2 GHz microwave source, the corresponding critical magnitude of magnetic field can be calculated using Eq'n 1. For a microwave frequency of 4.2 GHz, the critical magnetic field is approximately 0.152 T. The ECR region for the µ10 neutralizer is modeled and shown in colored regions in Fig. 3.

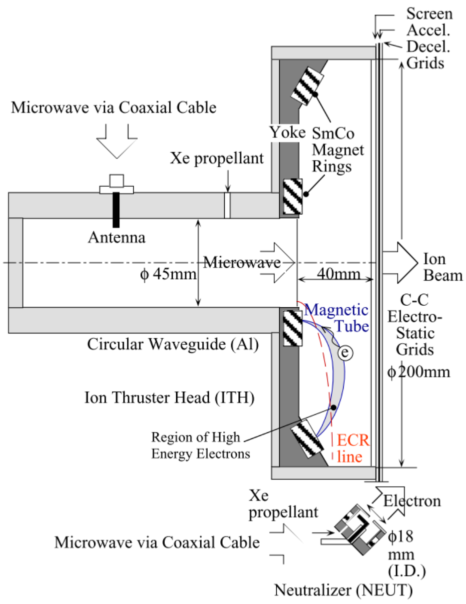

Fig. 4. Schematic of the ion thruster head of the 20mN class ECR thruster [8]

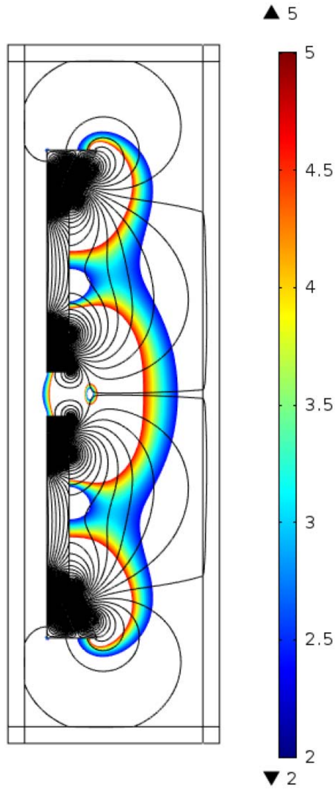

Fig. 5. The magnetic field topology and the ECR layer for different microwave frequencies of 20mN-class ECR ion thruster shown in Fig. 4

Another model that shows the magnetic field topology and the ECR layer thickness is done on the 20mN-class ECR ion thruster head shown in Fig. 4. This time the magnetic field was held constant to see the range and the region of different microwave frequencies that will result in electron cyclotron resonance. The plot in Fig. 5 shows the ECR layer for frequencies ranging from 2 GHz to 5 GHz. The yoke plate which was made out of iron [4], [8] guides the magnetic field lines and acts as a confining structure.

Such analysis of magnetic field characteristics is essential when modeling the plasma properties inside the discharge chamber. To obtain a reliable model of plasma properties the mesh has to be refined after solving for the magnetic field, to be finer near the ECR region, using the solution from the magnetic field model. Eq'n. 4 shows the function from which the adaptive mesh is developed.

$$N_{element}(|\vec{B}|) = \frac{1}{\left| |\vec{B}| - \frac{\omega_{cyclotron} m_e}{e} \right| + \varepsilon} \quad (4)$$

where N represents the number of elements as a function of the magnetic field magnitude and ε is an arbitrary small number to prevent division by zero. A comparison of how the mesh is altered can be seen in Fig. 6, which was applied on the µ10 neutralizer shown in Fig. 3.

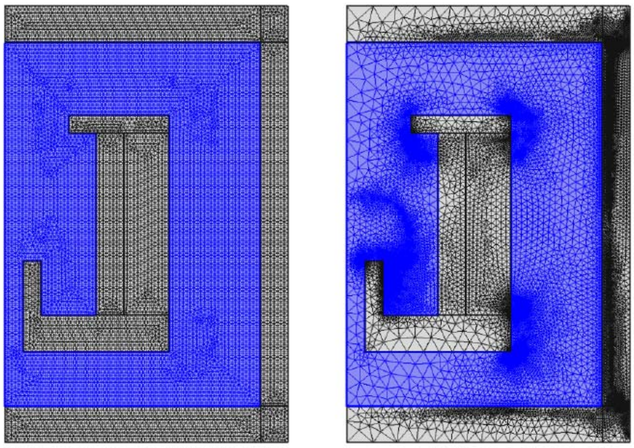

Fig. 6. Initial mesh to solve magnetic field (left), adapted mesh to solve plasma properties more accurately along the ECR region (right)

V. CONCLUSION

Electron cyclotron resonance in microwave discharge ion thrusters and neutralizers are being examined in a wider sense gradually. This study summarizes the operating characteristics of the ECR neutralizer that can be come across throughout the literature and compares it with other types of neutralizer cathodes. A brief theoretical background on the ionization mechanism was provided in order to explain the numerical technique for visual modeling. Some of the ECR mechanisms from the literature were modeled in terms of their magnetic field topologies and were discussed. Background for further study regarding the model of plasma inside the discharge chamber was introduced.

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