Lifetime Evaluation of Microwave Discharge Neutralizer using Numerical Analysis

IEPC-2019-309

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: Lifetime of microwave discharge neutralizer is related to sputtering phenomena inside the discharge chamber. In order to investigate sputtering phenomena inside a microwave discharge neutralizer, we investigated plasma inside discharge chamber using numerical analysis. This numerical analysis required analysis of the electromagnetic field and particle motion since calculation model is a microwave discharge neutralizer. Calculation results shows averaged value of electron temperature was 3 eV at 500 nsec. There were no electrons that exceed the ionization energy. However, in earlier experimental work, electron current was extracted continuously. Thus electron temperature seems to be underestimated.

I.Introduction

One failure mode of electric propulsion devices is that the neutralizer ceases to function.[1] The process is thought to have been as follows. 1) Ions in the discharge chamber sputter on the walls. 2) Sputtered particles deposit on the walls. Some portion of the sputtered particles are deposited on an insulator around an antenna. 3) Propagation performance is decreased with decrease of insulation performance. 4) Electrons cannot be received energy, so the density of the plasma is decreased. Thus, the lifetime of neutralizers is related to sputtering phenomena inside the discharge chamber.

It is important for reducing the cost of developing electric propulsion to estimate device lifetime in the preparation phase, so as to reduce prototyping and testing requirements. Numerical analysis is one method to estimate lifetime early in the design process. The lifetime of a microwave discharge neutralizer can be estimated by taking into account the degradation of microwave propagation performance by the deposition of sputtered particles on components, as described above. In this paper, we focus on the simulation of the ions and the electrons inside chamber. Device lifetime will be estimated in future work, using by results obtained here.

II.Calculation Procedure

A miniature microwave discharge neutralizer has been developed in Kyushu University.[2] The present authors conducted several experiments to investigate the behavior of the discharge chamber, and we measured physical quantities such as electron density and temperature. Here, we use the miniature microwave discharge neutralizer developed at Kyushu University as a calculation model to compare with the values obtained by experimental measurement.

The structure of the neutralizer is shown in Fig. 1. The neutralizer consists of an aluminum discharge chamber sandwiched between soft iron yokes. The discharge chamber is surrounded by six magnets, and has three magnets inside. Figure 2 shows the distribution of magnetic lines in the discharge chamber. The magnetic field is used for electron confinement. The electrons are reflected by the magnetic mirror and heated by reciprocating near the antenna. This confinement area is called the magnetic

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tube.[3] As an additional effect of applying a magnetic field, electron cyclotron resonance (ECR) is expected. Electrons efficiently absorb microwave energy in a magnetic field where the microwave and cyclotron frequencies coincide. Electrons resonate at 87.5 mT since microwave frequency is 2.45 GHz.

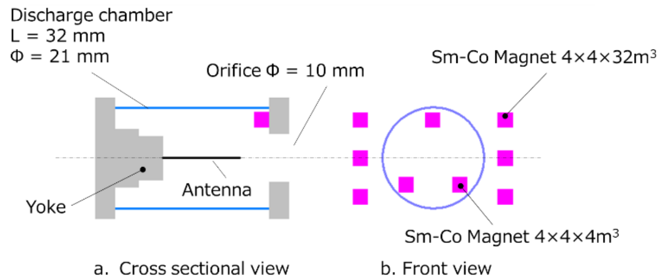

Figure 1. Structure of the neutralizer used in the experiment.

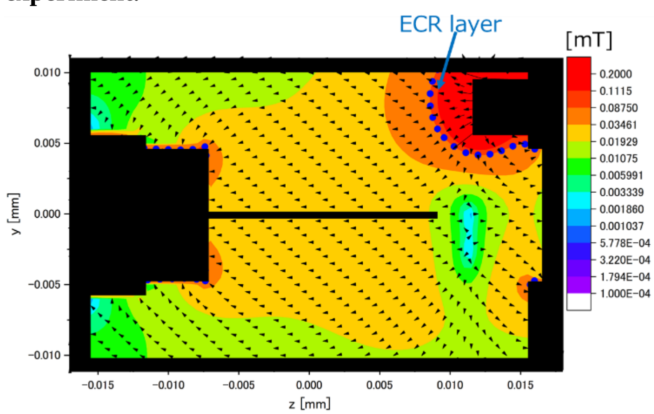

Figure 2. The magnetic field lines distribution.

1. Numerical Analysis

This calculation requires analysis of the electromagnetic field and particle motion, since the model is a microwave discharge neutralizer. Thus it is necessary to simultaneously solve ions, electrons and microwave.

2. Microwave Propagation Analysis

The microwave discharge was modeled using the FDTD (Finite Difference Time Domain) method.[4,5,6] The fundamental equations are:

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \tag{1}$$

$$\nabla \times H = \varepsilon_0 \frac{\partial E}{\partial t} + J \tag{2}$$

Here, E is the electric field, μ0 is the permeability in vacuum, t is the time, H is the magnetic field, ε0 is the dielectric constant, J is electron current.

3. Particle Motion Analysis

The PIC (Particle in Cell) method was used to solve the motion of the ions and the electrons. The particles feel the linearly interpolated electromagnetic field from each grid point. The fundamental equation for this method is the motion equation for the ions and electrons, as follows.

$$m \frac{dv}{dt} = q(E + v \times B) \tag{3}$$

Here, m is the mass, v is the velocity of the particle, q is the charge, B is the magnetic flux density. The equation was time integrated using the leap-frog method.

Collisions were reproduced using the null-collision method,[7] with elastic, excitation, and ionization collisions. In this calculation, multivalent ions were not considered. As the neutral particle density is higher than the electron and ion densities, collisions occurred only from the electrons to neutral particles.

4. Static Electric Field Analysis

The static electric field was solved using an iterative method. The fundamental equation is as follows.

$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \tag{4}$$

Here, Φ is the electric potential, ρ is the charge density. We adopted A flexible version of the BiCGStab method by benchmarking test as iterative method.[7] This method has provided by PETS library.

5. Calculation Conditions

Table 1 shows main calculation parameters. The time step was chosen based on the Courant-Friedrichs-Lewy Condition.

6. Calculation Flow

Figure 3 shows the calculation flow.[9,10] This calculation treated phenomena at several different timescales; the microwave, the electrons and the ions. The timescale of the microwave is much smaller than that of the ions, and so the microwave propagation was solved for only a few nanoseconds to reduce calculation costs. The output of the microwave propagation analysis was a probability function of the electron energy imparted by microwave per unit time. In the PIC method and Poisson solver, each electron was given energy determined by the probability function.

The microwave propagation analysis had 3 dimensions x, y, z and 3 velocities vx, vy, vz. The PIC method and Poisson solver had cylindrical coordinate. They had 2 dimensions r,z and 3 velocities vr, vθ, vz to reduce computational cost. Here, r is distance from antenna center axis. Θ is azimuthal component, but it can be ignored by axis symmetry.

Table 2 Calculation Parameters.

Parameter	Value
Time step width (FDTD)	2.5×10^{-13} sec
Mesh size (x, y and z direction in FDTD)	0.25 mm
Microwave frequency	2.45 GHz
Microwave incident power	8 W
Time step (PIC)	1×10^{-10} sec
Calculation time (PIC)	500 nsec
Mesh size (z direction in PIC)	0.011 mm
Mesh size (r direction in PIC)	0.0105 mm
Propellant flow rate	0.02 mg/sec
Propellant	Xenon

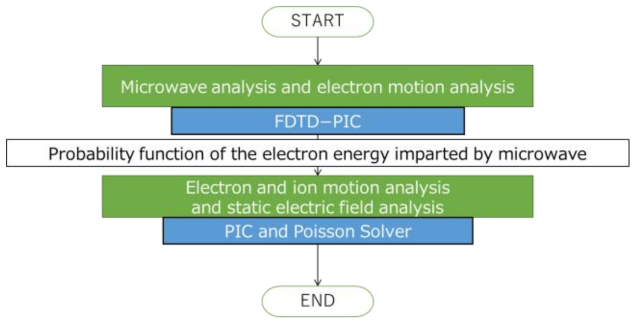

Figure 3. Calculation flow.

7. Boundary Conditions for FDTD - PIC

Figure 4 shows the model geometry. The calculation region was composed of three areas: the blue area is a conductor, the red area is the antenna, and the green area is the dielectric (polytetrafluoroethylene). The white space represents vacuum. The PEC (Perfect Electric Conductor) condition was applied to the conductor wall and the antenna to reflect electromagnetic waves. The electromagnetic field is zero inside and on the surface of the conductor wall. Mur's absorbing condition was applied to the root of the antenna.[11]

A boundary condition for particles was introduced, simulating a sheath potential. In this calculation, ions were not calculated, but a sheath that reflects electrons is formed on the wall surface since there are ions in the actual discharge chamber. A boundary condition that reflected electrons was introduced at the conductor wall surface to consider the effect. The electrons were reflected when their energy was lower than the sheath potential. The electrons were lost when their energy was higher than the sheath potential. In this calculation, the sheath potential was 20 eV, as reported in experimental data.[12]

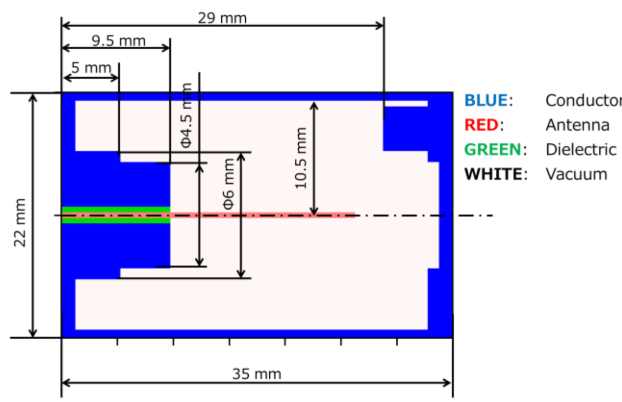

Figure 4. Model geometry.

8. Boundary conditions for Poisson solver - PIC

The electric potential of the whole wall surface of Fig. 5 was set to zero. The ions and electrons that reach the wall were eliminated, since they were considered to become neutral particles or current into the wall when they collide with the wall.

9. Initial particle condition

Initial particle positions were uniformly distributed. The initial particle density was 2.1×10^{17} m^{-3}. Initial particle velocity was distributed as a Maxwell distribution. Initial temperature was 2 eV.

III. Results and Discussions

1. Electron Energy Distribution

Figure 5 shows space distribution of electron energy at 500 nsec. The temperature was almost uniformly distributed. Average electron temperature was 3.0 eV. Figure 6 shows frequency distribution of the electron energy. Most electrons had no energy exceeding the ionization energy (= 12.13 eV). However, in earlier experimental work, electron current was extracted continuously. This means that ionization had occurred frequently. Thus electron temperature seems to be underestimated. The cause seems to be the time step difference between the FDTD-PIC solver and the PIC-Poisson solver. Although these time steps were approximately 100 times different, PIC-Poisson solver gave energy calculated by FDTD-PIC each time steps. We will change the algorithm so that the energy of the particles increases each time steps of FDTD-PIC.

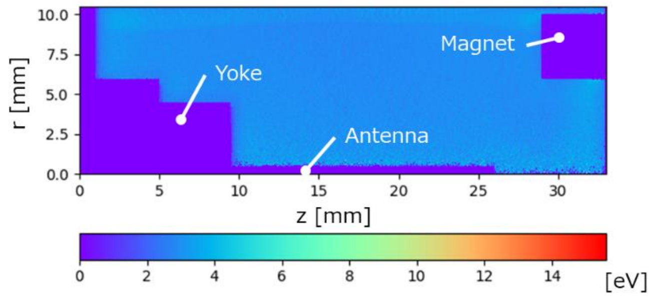

Figure 5. Space distribution of the electron energy.

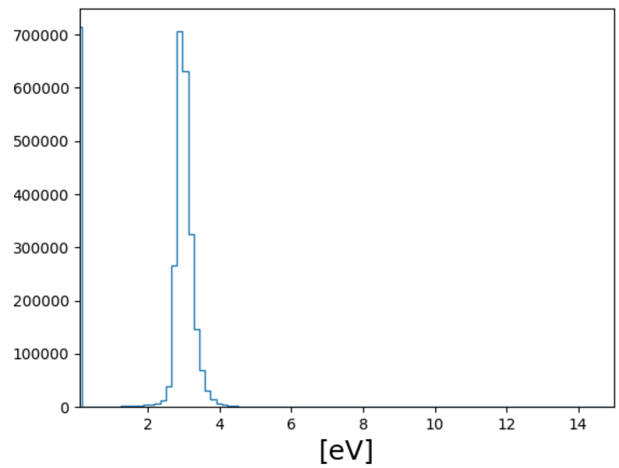

Figure 6. Frequency distribution of the electron energy.

IV. Conclusion

Numerical analysis in the discharge chamber using FDTD-PIC solver and PIC-Poisson solver produced the following results.

1) Microwave heating did not occur in the numerical analysis. This cause is the time step between the coupled codes was not considered. We will change the algorithm so that the energy of the particles increases appropriately.

Acknowledgments

This study was completed with support from a Kyushu University Doctoral Program Scholarship, by the Doctoral Student Support Program of the Kyushu University platform for inter transdisciplinary energy research, and by the 2016-2018 and 2019 JAXA Strategic Development Program and JSPS KAKENHI Grants Numbers JP16H04595, JP16K14506 and JP18H03815.

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