PARTICLE-IN-CELL SIMULATIONS ON ANTENNA CHARACTERISTICS IN MAGNETIZED PLASMA

Hideyuki Usui
Radio Science Center for Space and Atmosphere, Kyoto University
Gokasho Uji, Kyoto 611-0011, Japan
Phone: +81-774-38-3817
Fax: +81-774-38-3817
E-mail: usui@kurasc.kyoto-u.ac.jp

N. Nakamura
H. Kojima
H. Matsumoto
Y. Omura
Radio Science Center for Space and Atmosphere, Kyoto University

Abstract

We for the first time applied electromagnetic PIC (Particle-In-Cell) computer simulations to analyze the antenna characteristics in magnetized plasma. In a three-dimensional simulation space, we placed a dipole antenna which is a conducting current line in a magnetized plasma. By providing a Gaussian pulse as an input power to the center of the antenna and observing the current induced at the power feeding point, we obtain the input impedance of the antenna as a function of frequency. We particularly examined the electron kinetic effects on the antenna impedance such as electron temperature and electron evacuated region (ion sheath) formed around the antenna. It is confirmed that the most obvious resonance point is the local Upper Hybrid Resonance frequency. As the electron temperature increases, the resonance frequency also increases in accordance with the modification of dispersion relation for the UHR branch. We also examined the antenna impedance variation by changing the size of the electron evacuated region or ion sheath created around the antenna. We could confirm that the antenna resonance near the local UHR frequency is sharp for the small sheath while the profiles of the impedance approach to those of vacuum case as the sheath becomes large. The resonance frequency also decreases because the plasma density also decreases in the vicinity of the antenna.

Introduction

Antenna characteristics in plasma have been investigated by many scientists (e. g. Balmain, 1964, Adachi et al., 1977, Sawaya et al., 1976). However, the analysis of the antenna characteristics such input impedance is very complex because plasma is dispersive and anisotropic medium. In the previous theories with an assumption of cold plasma, approximations in the current distribution along the antenna or the sheath structure around the antenna were hired. Antenna analysis with warm plasma approximation was also done for some limited models (e.g. Kuehl, 1966). Meanwhile, recent progress of computer facilities enables us to analyze the antenna properties in vacuum with the FDTD (Finite Difference Time Domain) method which solves the Maxwell equations with spatial and temporal grid points. By using the FDTD method with a dielectric tensor obtained under the cold plasma approximation, we can basically analyze the antenna impedance in plasmas. However, in order to include the plasma kinetic effects in the antenna impedance such as electron temperature and sheath around the antenna, we need to treat the plasma as particles in the simulations. To treat the plasma dynamics, we apply the PIC (Particle-In-Cell) method to the conventional FDTD field solving simulations. In the PIC method, we solve the equation of motion for each particle with the field components obtained at grid points with the FDTD method. To obtain the plasma density and current at each grid point, we use the area sharing method. In the present paper, we will report preliminary results of the antenna impedance obtained in the PIC simulations. We particularly focus on the dependence of antenna resonance on the electron temperature and sheath size around the antenna.

Simulation Model

In the current simulation studies, we use a three-dimensional full electromagnetic particle code called KEMPO (Matsumoto and Omura, 1985). In KEMPO, we solve Maxwell's equations and equations of motion of electrons and ions. To advance the electromagnetic field with Maxwell's equations in the simulation space, we adopted the FDTD (Finite-Difference Time-Domain) method. Plasma dynamics and the associated plasma current are solved by adopting the PIC (Particle-In-Cell) method (Birdsall and Langdon, 1985).

Three-dimensional simulation model is shown in Figure 1. In the simulation space with $64 \times 64 \times 64$ grid points a number of electrons is uniformly distributed. In the center, a dipole antenna with the length of 32 grid points is set. We assume that the antenna is a pure conductor, which implies that the electric field inside the antenna is assumed to be zero. To feed the power to the antenna, we adopted the delta gap feeding method. At one grid point located in the middle of the antenna, we provide voltage as a function of time. To obtain the wide-band characteristics of frequency with one simulation run, we utilize a Gaussian-type pulse for the voltage at the feed point. The induced current is obtained with the rotational field around the feed point. The antenna impedance is calculated as the ratio of the voltage to

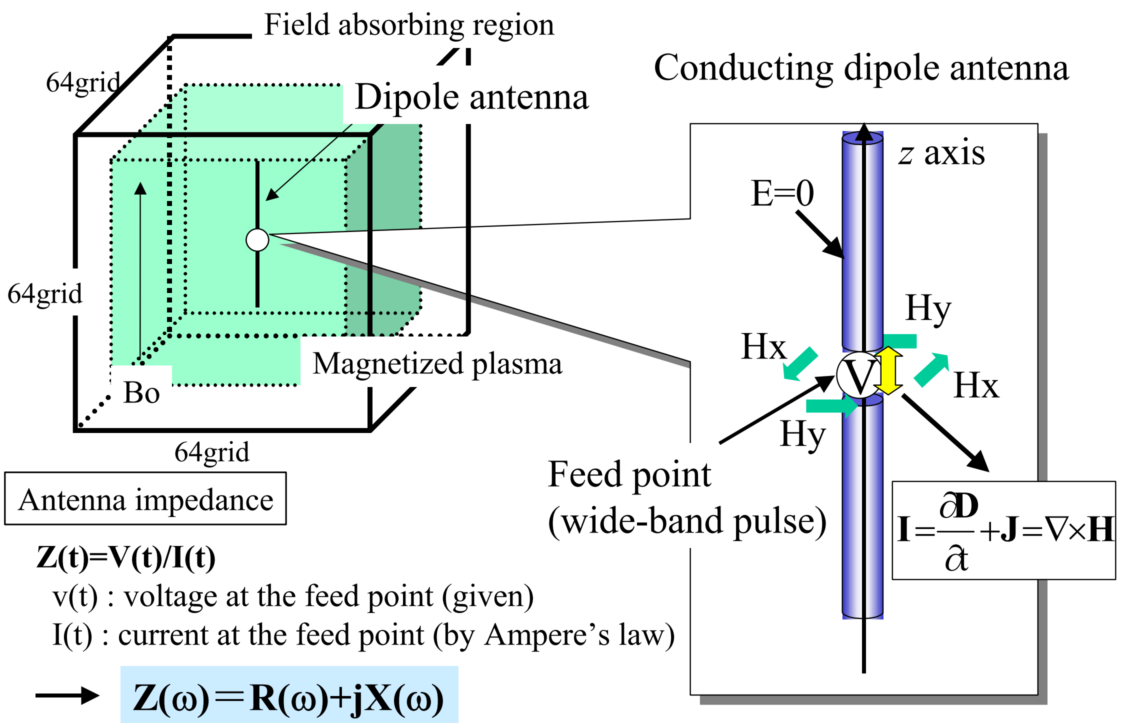

Figure 1. Simulation model

the current. By taking its Fourier transformation, we obtain the antenna impedance in frequency domain.

Dependence of Antenna Impedance on Plasma Temperature

Figure 2 shows the antenna impedance obtained in the simulations with different plasma temperature. The upper and lower panels indicate the real and imaginary parts of the impedance, respectively. The dashed lines correspond to the impedance for the vacuum case. As clearly shown, there is a large change of impedance at the Upper-Hybrid Resonance frequency ω_{UHR}. The real part of the impedance takes large values at peaks in comparison with the vacuum case, which implies that the minimum power is radiated in plasma from the antenna at ω_{UHR}. The interesting feature we should mention is that the peaks found in the real part of the impedance shift toward higher frequency as the plasma temperature increases. This tendency is not observed when no external magnetic field is included in the simulation model. Therefore, we speculate that specific plasma wave mode is closely related to the shift of the impedance resonance.

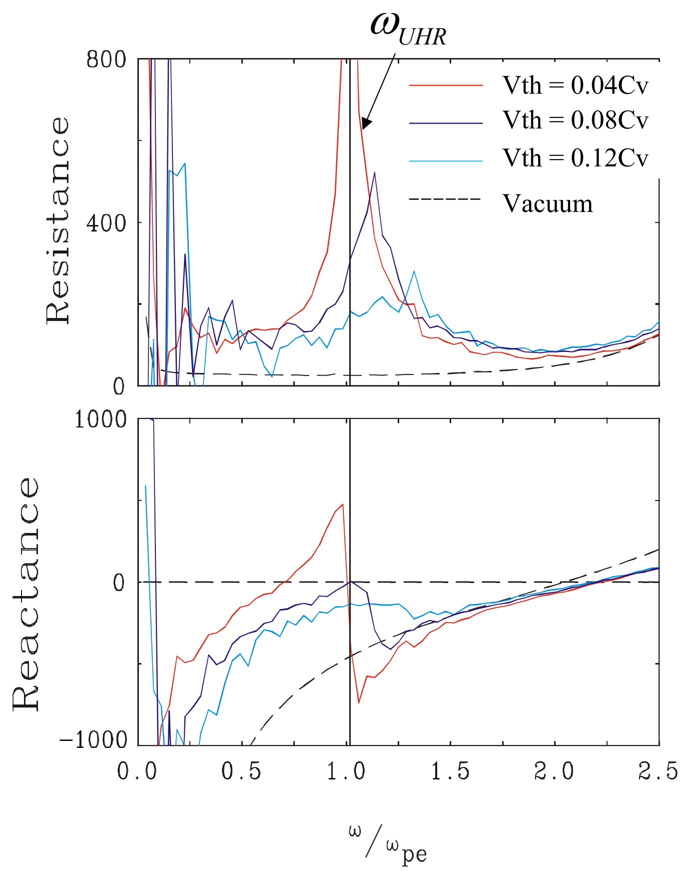

Figure 2. Antenna impedance with different plasma temperature.

Figure 3 shows the dispersion curves of the slow-X mode with different temperature. At the wavenumber corresponding to the wave length which resonates with the present antenna, we can find the resonance frequency for each wave branch. As easily found, the resonance frequency on the slow-X mode also increases as the plasma temperature becomes high. This can explain the shift of the resonance frequency as shown in Figure 2.

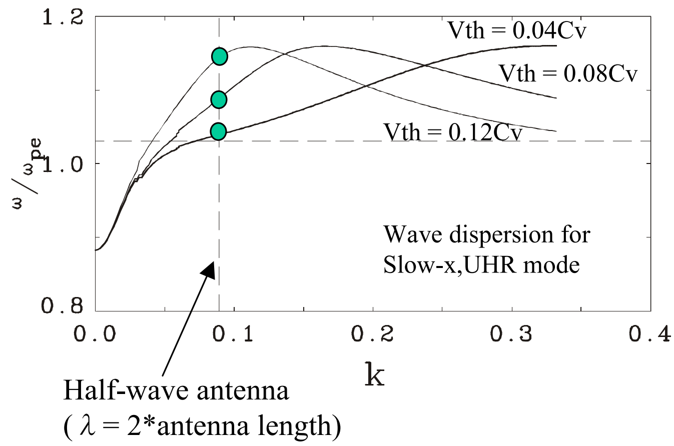

Figure 3. Slow-x mode with different temperature and the corresponding resonance frequencies.

Sheath Effect on the Antenna Impedance

Figure 4 shows the dependence of the antenna impedance at frequency around ω_{UHR} on the sheath size created around the antenna. The right panels depict the profiles of the sheath around the antenna. By changing the simulation parameters, we varied the size of the region where electrons are evacuated around the antenna. We regard the electron evacuated region as sheath. At each case, we examined the antenna impedance as shown in the left panels. It is obviously shown that the resonance at ω_{UHR} is sharp for the small sheath while the profiles of the impedance approach to those of vacuum case as the sheath becomes large. It is because the vacuum region around the antenna expands for the larger sheath. The resonance frequency also decreases because the plasma density also decreases in the vicinity of the antenna. It is theoretically examined that the impedance will be affected by the sheath resonance, which we could not confirm in the present simulations. It is also reported that sheath waves which propagate along the antenna surface may affect the antenna impedance. Currently we have been working on the properties of the sheath waves. We will examine the effect of the sheath waves on the antenna impedance with the larger scale of simulation model, which is left as a future work.

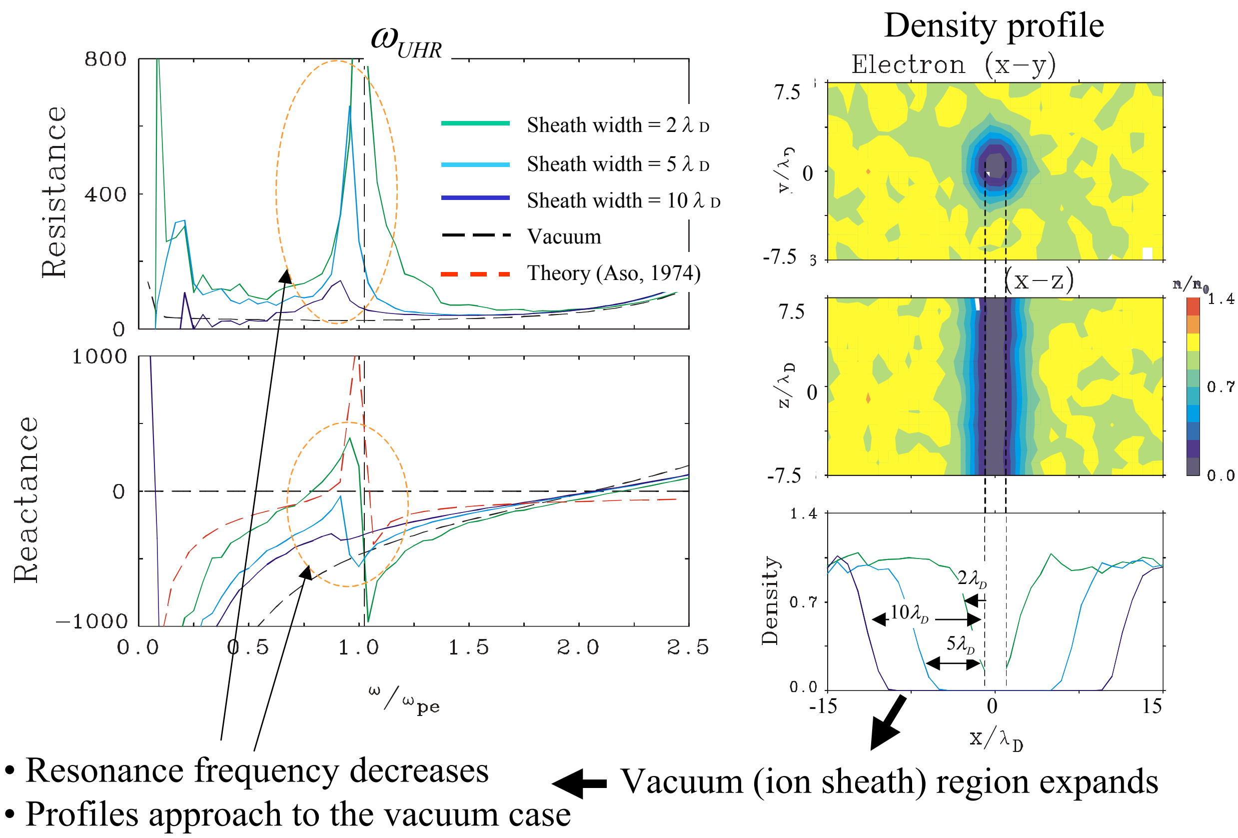

Figure 4. Sheath profiles (right panels) and corresponding antenna impedance (left panels).

Conclusions

We for the first time applied three-dimensional electromagnetic PIC computer simulations to study the antenna impedance characteristics. We particularly focused on the electron kinetic effects on the antenna impedance such as electron temperature and electron evacuated region (ion sheath) formed around the antenna. We confirmed that a dipole antenna immersed in magnetized plasma has a resonance at the local Upper Hybrid Resonance frequency. As the electron temperature increases, the resonance frequency also increases in accordance with the modification of dispersion relation of the UHR branch. We also examined the antenna impedance variation by changing the size of sheath where electrons are evacuated around the antenna. We could confirm that the resonance at ω_{UHR} is sharp for the small sheath while the profiles of the impedance approach to those of vacuum case as the sheath becomes large. The resonance frequency also decreases because the plasma density also decreases in the vicinity of the antenna. Although the simulations performed in the current study are preliminary and the simulation results are rather conventional, it should be noted that antenna analysis by performing electromagnetic PIC simulations basically works and we will be able to apply this method to examine the antenna characteristics in various plasma situations such as the existence of photo-electrons, which is left as a future work.

Acknowledgments

Computation in the present study was performed with the KDK system of Radio Science Center for Space and Atmosphere (RASC) at Kyoto University as a collaborative research project. The present work was supported by the Grant-in-Aid for Scientific Research 12440131.

References

1. Adachi, S., T. Ishizone, and Y. Mushiake, Transmission line theory of antenna impedance in a magnetoplasma, Radio. Science, 12-1, 23-31, 1977.

2. Balmain, K. G.,The Imedance of a Short Dipole Antenna, IEEE. Trans. Antennas Propag., AP-12, 605, 1964.

3. Birdsall, C.K. and A.B. Langdon, Plasma Physics via Computer Simulation, McGraw-Hill Inc., New-York, 1985.

4. Kuehl, H. H., Resistance of a Short Antenna in a Warm Plasma, Radio Science, 1-8, 971-976, 1966.

5. Matsumoto, H. and Y. Omura, Particle simulation of electromagnetic waves and its application to space plasmas, Computer simulation of space plasma, ed. By H. Matsumoto and T. Sato, Terra Sci. Pub., 43, 1985.

6. Sawaya, K., H. Mizuno, T. Isizone, and Y. Mushiake, Characteristics of a Linear Antenna in a Uniaxially Anisotropic Plasma, Trans. Inst. Electron. Commun. Eng. Jpn., 59, 254, 1976.