COMMUNICATIONS IN COMPUTATIONAL PHYSICS
Vol. 1, No. 4, pp. 677-700

Commun. Comput. Phys.
August 2006

Simulating Microwave Radiation of Pyramidal Horn Antenna for Plasma Diagnostics

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Recevied 13 September 2005; Accepted (in revised version) 5 December 2005

Communicated by Wei Cai

Abstract. Computational simulation of the radiating structure of a microwave from a pyramidal horn has been successfully accomplished. This simulation capability is developed for plasma diagnostics based on a combination of three-dimensional Maxwell equations in the time domain and the generalized Ohm's law. The transverse electrical electromagnetic wave of the $\mathrm{TE}_{1,0}$ mode propagating through a plasma medium and transmitting from antenna is simulated by solving these governing equations. Numerical results were obtained for a range of plasma transport properties including electrical conductivity, permittivity, and plasma frequency. As a guided microwave passing through plasma of finite thickness, the reflections at the media interfaces exhibit substantial distortion of the electromagnetic field within the thin sheet. In radiating simulation, the edge diffraction at the antenna aperture is consistently captured by numerical solutions and reveals significant perturbation to the emitting microwave. The numerical solution reaffirms the observation that the depth of the plasma is a critical parameter for diagnostics measurement.

Key words: Plasma diagnostics; microwave simulation; antenna.

1 Introduction

Recently magneto-fluid-dynamics has become the most vibrant research topic in the aerospace science community through an added physical dimension for enhancing aerodynamic performance of flight vehicles. In this aspect, magneto-fluid-dynamics reemerges as one of the few last frontiers for fluid dynamic research [1, 2]. Magneto-aerodynamic interactions have been widely applied and have demonstrated impressive application potential

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for flow control [3–7], MHD scramjet bypass [8], innovative radiatively drive hypersonic wind tunnel [9] and combustion or ignition enhancement [10]. To accurately assess the relative magnitude of electromagnetic and aerodynamic forces in an interaction, an accurate evaluation of the plasma transport properties such as the charge particle number density, temperatures and electric conductivity become necessary.

Partially ionized plasma or weakly ionized air in aerospace applications has a distinctive oscillatory and instability feature. Therefore, all experimental measurement techniques must be able to determine the characteristics of these oscillations and to provide sufficient resolution to this important aspect of the experiment [11–13]. Plasma exhibits outstanding attributes at different thermodynamic states. The high-temperature plasma radiates electromagnetic waves over a broad frequency spectrum ranging from microwaves to the infrared, ultraviolet, and X-ray regions. These radiations result from the bound-bound (atoms or ions), free-bound (electron-ion recombination), free-free transitions (elastic collisions of charged particles with atoms, bremsstrahlung), and in the presence of a strong magnetic field the radiation even emits from electrons spinning [14]. For plasma diagnostics using radiation, spectral line intensity measurements have been extensively used by most traditional methods. The comparative measurements of spectral line intensities have also been used to determine the electron temperature in low-temperature plasma [15, 16].

A widely used non-intrusive plasma diagnostic tool is microwave probing. The microwave system is adopted both for plasma diagnostics and in deep-space communication. For plasma diagnostics, the number density of the charge particles and its collision frequency with the neutral particles are measured based on the microwave attenuation phenomenon [17–20]. This unique microwave behavior in weakly ionized air is also known for the famous communication blackout phenomenon in the reentry phase either for an aerospace vehicle or for an inter-planet flight [21, 22]. Communication blackout is the consequence of an incident microwave propagating at a frequency lower than the cut-off frequency [23]. When the two frequencies equal, the propagating wave starts to become evanescent and the transmission of the electromagnetic energy ceases. When the transmission bandwidth is greater than that of the plasma, the microwave will attenuate as it propagates through the plasma. The dissipated energy along the wave path is proportional to the electrical conductivity of the medium.

An electromagnetic wave propagating in an electrically conducting medium depends strongly on its electrical conductivity and the transmission frequency. For a linear polarized plane wave traveling in a conducting medium, the current density consists of the conductive and displacement components. For an electrically neutral medium, the electric conductivity σ and the conductive current vanish, and the wave may travel without any impedance. Otherwise, the relative magnitude of σ and the product of wave frequency and electrical permittivity $\omega\varepsilon$ will dominate the behavior of the propagating wave [23]. In the absence of an external magnetic field, the partially ionized gas can be studied as an isotropic medium. The plasma behaves as a simple quasi conductor and will support high frequency wave motion through the response of electrons.

This salient feature of microwave attenuation in plasma has been used to measure the