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Hybrid Simulation of RF Plasma Production Using FEM

有限要素法を用いた高周波プラズマ生成のハイブリッドシミュレーション

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In order to simulate a processing plasma with an arbitrary boundary shape, we are developing an integrated code PAF based on the finite element method. We here describe the PAF code and the results of newly-developed three-dimensional wave module WF. The hybrid simulation using the plasma transport module TF and the particle-in-cell module PF is also discussed.

1. Introduction

In order to describe production of processing plasmas, we are developing an adaptive integrated simulation code, PAF (Plasma Analysis by FEM), which was originally developed for a two-dimensional fluid plasma model [1]. This code is composed of several modules to describe the wave propagation in a plasma and the time evolution of plasma production. Recently the wave analysis was extended to the three dimensional plasma using the edge elements to suppress unphysical spurious modes. We are also developing hybrid simulation which couples the fluid plasma model and the particle plasma model.

2. PAF Code

The PAF code is an integrated plasma simulation code with modular structure. The main purpose is to quantitatively describe various kinds of interactions between the electromagnetic fields and the laboratory plasmas. Though it is still under development, it will be composed of three electromagnetic modules (WF, EM, ES), three plasma modules (TF, FF, PF), utilities (MG, GR) and common libraries. All the solvers are based on the finite element method so that the boundary shape is rather flexible and the spatial resolution can be increased locally. The modules are briefly described as follows:

WF: Stationary propagation of electromagnetic waves is analyzed by solving Maxwell's equation as a boundary-value problem. The plasma is represented by a dielectric tensor with the cold plasma approximation. This module is appropriate for describing high-frequency waves such as electron cyclotron waves.

EM: Time evolution of electromagnetic field is described by solving Maxwell's equation as an initial-value problem. The induced current in a plasma is calculated by the plasma modules.

ES: Electrostatic field is calculated by solving Poisson's equation with the electric charge density given by the plasma modules.

TF: Time evolution of fluid plasma is described by a set of diffusive transport equations for multi species. Several models of the diffusivity and mobility tensors can be employed. Atomic processes are also included as particle and momentum sources. This module is appropriate for describing various phenomena slower than the collision frequency.

FF: Time evolution of fluid plasma is calculated form a set of dynamic multi-fluid equations. Since the equation of motion is solved in this module, high frequency phenomena can be well described.

PF: Time evolution of plasma is described by the particle-in-cell model[2]. This module[3] implements the algorithm to push particles in triangular elements and various kinds of collision models.

MG: This module generates two-dimensional and three-dimensional meshes necessary for computation. It also reads a kind of files in a general-purpose unstructured mesh file format.

GR: This module includes 2D and 3D graphic routines to illustrate computation results. They are based on our original graphic libraries GSAF and GSGL using OpenGL.

3. Three Dimensional Wave Analysis

Though most of modules in PAF are two-dimensional at present, we have extended the wave module WF to the three-dimensional inhomogeneity. We have also introduced edge elements to eliminate unwanted spurious modes which often pollutes the solutions in node-based codes. In this code, the wave electric field is defined on the edge of a triangular element as a parallel component along the edge.

As a typical example of computation, the wave field and the power deposition are calculated in a ICP plasma with a spiral antenna. Figure 1 illustrates the configuration and the shape of top elements. The diameter of the cylindrical plasma is 0.24m, the heights of the plasma and the vessel are 0.16m and 0.3m, respectively. The antenna is excited by a uniform current with 13.56MHz and the plasma density is 5×10^{17} m^3. The vertical structure of wave field is shown in Fig. 2. The imaginary components of the electric field, (a,c,e), are out of phase with the antenna current and related to the antenna inductance. The real components, (b,d,f), are related to the antenna resistance and penetrate into the plasma. The power deposition profile shown in Fig. 3 strongly localized near the upper plasma surface.

4. Hybrid Simulation

The energy distribution function of charged particles has a very important role in plasma processing. In order to evaluate the particle distribution function, we have calculated the wave field by fluid plasma models, WF or TF, and followed the particle trajectories by PF with given electromagnetic field. This is a first step for fluid-particle hybrid simulation with reduced computer resources. Simulation results will be presented in the poster.

Acknowledgments

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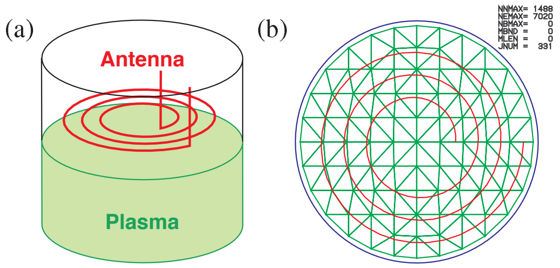

Fig. 1. (a) Schematic view of the configuration; a spiral antenna and a cylindrical plasma. (b) Top view of the finite elements and the spiral antenna.

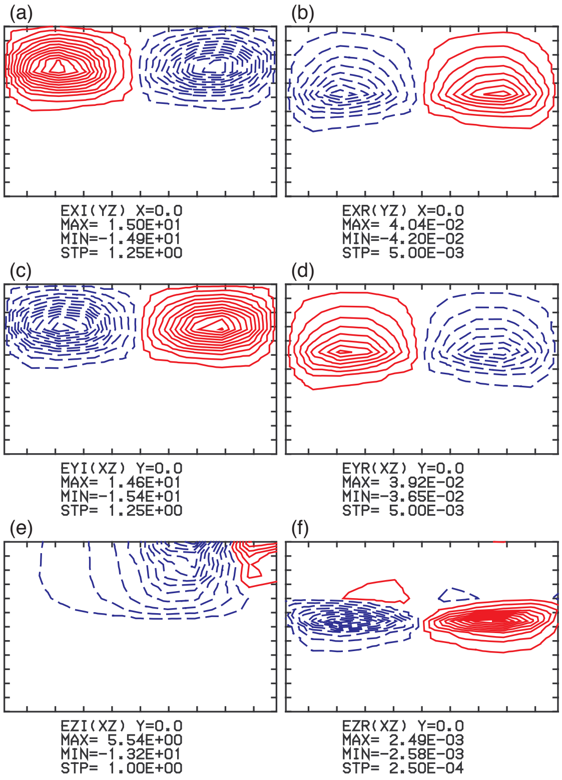

Fig. 2. Horizontal view of the contours of the wave electric field: (a) $\Im E_x$ and (b) $\Re E_x$ on the $x = 0$ plane. (c) $\Im E_y$ and (d) $\Re E_y$ on the $y = 0$ plane. (e) $\Im E_x$ and (f) $\Re E_z$ on the $y = 0$ plane.

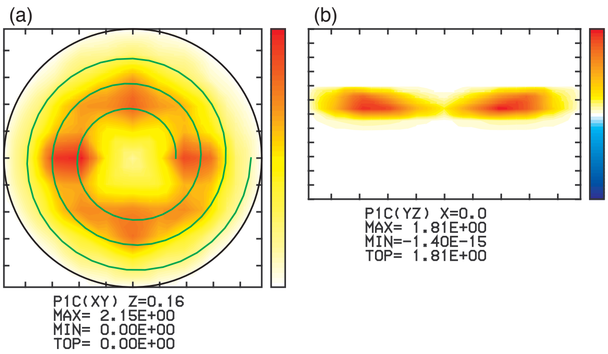

Fig. 4. Power deposition profile; (a) on the $z = 0.16$ m plane and (b) on the $x = 0$ plane.