FDTD SIMULATION OF THE PROPAGATION CHARACTERISTICS OF MILLIMETER-WAVE VORTEX IN MAGNETIZED PLASMA

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This study investigates the propagation characteristics of millimeter-wave vortex fields in the magnetized plasma using three-dimensional numerical simulations based on the Finite-Difference Time-Domain (FDTD) method. The findings demonstrate that the hybrid mode of millimeter-wave vortex can propagate in high-density plasma, where normal plane wave cannot propagate due to plasma cut-off condition. Additionally, it was also found that the propagation power in the magnetized plasma is highly dependent on the topological charge *l*. These findings provide a high potential for functional plasma heating.

The phenomena of optical vortex, recognized for their unique helical wavefronts and orbital angular momentum (OAM), has been widely investigated in various scientific fields, including manipulation of particles and advanced imaging techniques [1]. As a new application, it was pointed out in 2021 by Tsujimura et al [2] that the millimeter-wave vortex of Laguerre-Gaussian (L-G) mode can propagate in the magnetized plasma even in conditions where the normal plane wave is cut-off. This means that Electron Cyclotron Resonance Heating (ECRH) in high electron density region, in which plane wave cannot transfer its energy, can be provided by millimeter-wave vortex. On the other hand, it is known that the hybrid mode of millimeter-wave vortex can propagate stably in the cylindrical corrugated waveguide, which carries well-defined OAM [3]. Accordingly, we utilized the hybrid-mode vortex in the cylindrical corrugated waveguide to investigate millimeter-wave plasma heating. The whole configuration of plasma heating by hybrid mode of millimeter-wave vortex is shown in Fig.1. The hybrid mode of millimeter-wave vortex is excited in the corrugated waveguide and travels to the vacuum and then incident to the magnetized plasma. Several examples of the distribution of electric field intensity of the hybrid-mode vortex in the vacuum at an *x*-*y* vertical cross-section for cases of *l*=0, *l*=1, *l*=10 and *l*=20 are depicted in Fig.1. It was confirmed that the hybrid-mode vortex can propagate stably in the cylindrical corrugated waveguide. Based on the stable propagation of hybrid mode of millimeter-wave vortex, we further discussed the propagation characteristics of hybrid-mode millimeter-wave vortex fields in magnetized plasma using FDTD method [4].

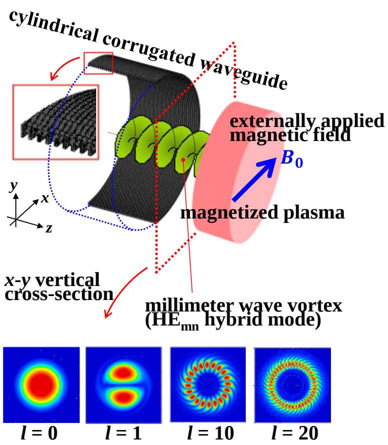

Fig. 1. The whole configuration of plasma heating by hybrid mode of millimeter-wave vortex, where *l* is topological charge.

A full 3D FDTD simulation, coupling with a macro-model of dispersive material, was employed to analyze the hybrid mode of millimeter-wave vortex fields in magnetized plasma. The behavior of millimeter-wave can be described by the following Maxwell's equations,

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \ , \tag{1}$$

$$\nabla \times \boldsymbol{B} = \mu_0(\boldsymbol{J} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}), \tag{2}$$

and we adopt the following Drude-Lorentz macro-model to describe the electron displacement density vector $\boldsymbol{P}$ and plasma current density vector, given by $\boldsymbol{J} = d\boldsymbol{P}/dt$,

$$\frac{d\boldsymbol{J}}{dt} + \gamma \boldsymbol{J} + \omega_0^2 \boldsymbol{P} = \varepsilon_0 \omega_p^2 (\boldsymbol{E} + \frac{1}{n_e q_e} \boldsymbol{J} \times \boldsymbol{B}_0), \tag{3}$$

where γ, n_e, q_e and $\boldsymbol{B}_0$ are the dumping coefficient, the electron density, elementary charge and externally applied magnetic field, respectively. Then the FDTD analysis of millimeter-wave vortex fields in magnetized plasma is conducted within a 3D grid space for the field components ***E***, ***H, P*** and ***J***. In this scheme, ***E*** and ***P*** are assigned to integer time steps *n*, while ***H*** and ***J*** are assigned to half-integer time steps (*n*+1)/2, ensuring that ***E*** and ***P***, as well as ***H*** and ***J*** are computed simultaneously.

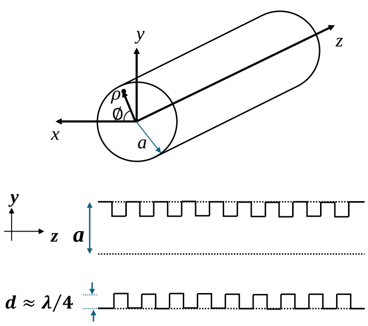

Fig.2 (a)

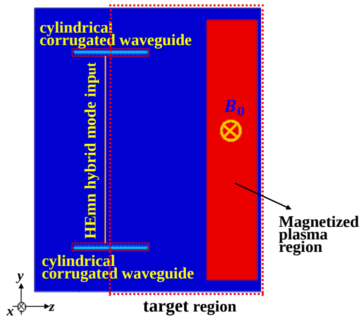

Fig.2 (b)

Fig. 2 (a). Cylindrical corrugated waveguide with 40 mm radius. Fig.2 (b). FDTD simulation of numerical model (*y-z* vertical cross-section) for the propagation of millimeter-wave vortex in magnetized plasma.

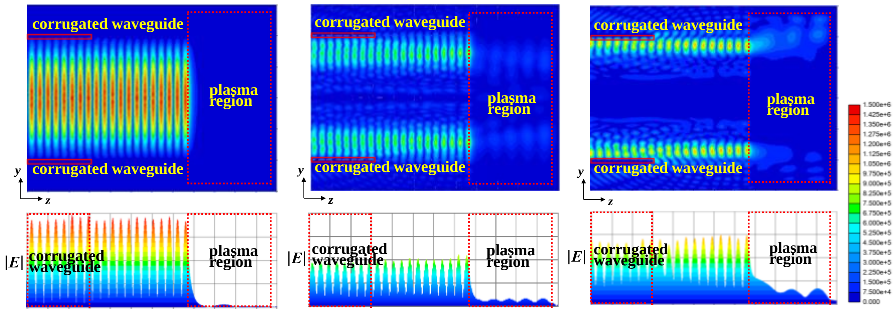

Fig.3 (a) Fig.3 (b) Fig.3 (c)

Fig.3. The electric field intensity distributions in *y-z* plane for cases of *l*=0 (plane wave) (Fig.3 (a)), *l*=5 (Fig.3 (b)), and *l*=20 (Fig.3 (c)), respectively [4].

The hybrid mode of millimeter-wave vortex is the solution to Helmholtz equation in a cylindrical corrugated waveguide (Fig.2 (a)), where the waveguide radius is assumed to be 40 mm. The numerical model for the FDTD simulation of propagation of the hybrid-mode millimeter-wave vortex in the magnetized plasma is depicted in Fig.2 (b). The entire computational grid consists of 800 $\times$ 800 $\times$ 600 cells, with a unit grid size of 0.15 mm. In this simulation, the hybrid mode of millimeter-wave vortex is assumed to be excited at a position two wavelengths upstream from the edge of the cylindrical corrugated waveguide. The wave then propagates downstream into the vacuum before illuminating the magnetized plasma. Additionally, the frequency and power of the excited millimeter-wave vortex are assumed to be 84 GHz and 1 MW, respectively, with the vortex field linearly polarized along the *x*-axis. The distribution of the absolute value of the instantaneous electric field intensity for cases of *l*=0 (plane wave), *l*=5 and *l*=20, is depicted in Fig.3(a), (b) and (c), respectively. In Fig.3 (a), (b) and (c), the upper figure shows the electric field intensity distribution in the *y-z* plane, while the lower figure provides a side view. It can be seen from the simulation results in the plasma region that the hybrid mode of millimeter-wave vortices can propagate in the magnetized plasma region, whereas the normal plane wave (*l*=0) cannot propagate due to the cut-off condition. Furthermore, as demonstrated in Fig.3(b) and (c), the propagation characteristics of millimeter-wave vortices are highly dependent on the value of topological charge *l*. Moving forward, we aim to further investigate the propagation characteristics of millimeter-wave vortex in magnetized plasma with non-uniform density distributions.

To further explore the practical implications, ongoing experimental studies are being conducted to investigate the feasibility of utilizing optical vortices for plasma heating. Currently, ECRH experiments using Gaussian beams (GB) for plasma heating are being conducted in almost all major magnetic fusion devices. Research on the propagation of HE_{11} mode waves in waveguides and the generation of GB in vacuum has already been carried out in these experiments. To further enhance the functionality of plasma heating, plasma heating experiments utilizing optical vortices are ongoing. These preliminary experiments are performed by replacing one of miter bend mirrors in the transmission line by a spiral plate mirror to excite topological charge. So far, any appreciable effects are not observed may be due to insufficient topological charge and / or low conversion efficiency from HE_{11} mode to Laguerre-Gaussian (LG) beam. A new basic experiment is planned to study the propagation characteristics of microwave optical vortex in the HYPER-I device.

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