9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Numerical Investigations on Propagation Characteristics of Millimeter—wave Vortex in Magnetized Plasma

Chenxu Wang[1], Hiroaki Nakamura[1,2], Hideki Kawaguchi[3], Shin Kubo[4]
[1] National Institute for Fusion Science, [2] Nagoya University,
[3] Muroran Institute of Technology, [4] Chubu University
e-mail (speaker): wang.chenxu@nifs.ac.jp

Optical vortices carrying orbital angular momentum (OAM), such as Laguerre-Gaussian (LG) modes, have attracted increasing attention due to their potential applications in plasma heating and diagnostics. Vortex beams possess a helical phase structure and due to the presence of OAM, exhibit unique propagation behaviors in dispersive media, which differ significantly from those of conventional plane waves. Previous studies have shown that millimeter-wave vortex beams can propagate into magnetized plasma regions even when normal plane wave cannot propagate due to cut-off condition. In this research, we investigate the propagation characteristics of millimeter-wave vortex beams in magnetized plasma using full three-dimensional finite-difference time-domain (FDTD) simulations.

The study 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 optical techniques. As a new application, it was pointed out in 2021 by Tsujimura, et al [1], the millimeter-wave vortex can propagate in the magnetized even in which the normal plane wave is cut-off condition. In our previous work, we investigated the propagation characteristics of hybrid mode of millimeter-wave vortex generated in the cylindrical corrugated waveguide in the magnetized plasma [2]. Our simulations confirmed that the hybrid mode of millimeter-wave vortex can propagate in the magnetized plasma in which the normal plane wave is in cut-off condition and revealed a strong dependence of the penetrated power in the magnetized plasma on the topological charge *l*. Furthermore, we found that this dependence is significantly influenced by the radius of waveguide [3]. To more precisely investigate the propagation characteristics of optical vortices in magnetized plasma, it is desirable to eliminate the structural effects introduced by waveguide boundaries. In this work, we therefore consider to discussing the propagation characteristics of the Laguerre-Gaussian modes of millimeter-wave vortex fields in the magnetized plasma by using FDTD method.

A full 3D FDTD simulation, coupling with a macro-model for dispersive magnetized plasma, was employed to analyze the propagation characteristics of L-G mode of millimeter-wave vortex fields in magnetized plasma. The L-G mode is a solution to the paraxial approximation of the Helmholtz equation in cylindrical coordinates (Fig.1).

$$u(r,\emptyset,z)=\frac{C}{\left(1+\frac{z^2}{z_R^2}\right)^{\frac{1}{2}}}\left(\frac{\sqrt{2}r}{w(z)}\right)^{l}L_p^l\left(\frac{2r^2}{w^2(z)}\right)\exp\frac{-r^2}{w^2(z)}\cdot\exp\frac{-ikr^2z}{2(z^2+z_R^2)}\exp\left(-il\emptyset\right)\exp\left(i(2p+l+1)\tan^{-1}\frac{z}{z_R}\right)\quad(1)$$

where L_p^l is Laguerre polynomial, $w(z)$ is beam radius, z_R is Rayleigh range. And here we adopt the following Drude-Lorentz macro-model for the full simulation of plasma particles by using electron displacement density vector $\boldsymbol{P}$ and current density vector $\boldsymbol{J}=d\boldsymbol{P}/dt$,

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

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 the millimeter-wave vortex in magnetized plasma in 3D grid space for ***E***, ***H***, ***P*** and ***J***, where ***E*** and ***P*** are assigned to integer time step, ***H*** and ***J*** are assigned to half integer time step, that is, ***E*** and ***P*** or ***H*** and ***J*** are calculated simultaneously.

We assumed the L-G mode of millimeter-wave vortex is illuminated into the magnetized plasma (Fig.2). We will further investigate the dependence of penetrated power in the magnetized plasma on topological charge without the influence of waveguide boundaries and explore the efficiency of absorption power in the magnetized plasma.

References
[1] T. Tsujimura, et al: Phys. Plasmas 28, 012502 (2021).
[2] C. Wang, et al: Jpn. J. Appl. Phys. 63, 09SP08(2024).
[3] C. Wang, et al: JASSE. 12, pp.145-151(2025).

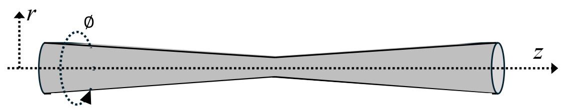

Fig.1 Laguerre-Gaussian beam

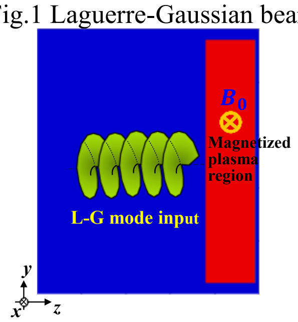

Fig.2 Numerical model