Propagation properties of an optical vortex in an electron cyclotron range of frequencies in magnetized plasmas

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Radiofrequency (RF) waves are widely employed for heating, current drive, and diagnostics in magnetic fusion plasmas. Knowledge of the propagation properties of RF waves in magnetized plasmas is fundamental to designs of RF systems such as launching antennas. The propagation properties of RF waves conventionally originate from a plane wave, where the phase of the wave fields is assumed to be $\boldsymbol{k} \cdot \boldsymbol{r} - \omega t$, where $\boldsymbol{k}$, $\boldsymbol{r}$, ω, and t denote a wave vector, a position vector, an angular frequency, and time. Recently, it is theoretically and experimentally demonstrated that a single free electron in circular or spiral motion emits twisted photons carrying orbital angular momentum (OAM) along the axis of the electron circulation in addition to spin angular momentum.[1,2] It is found that the radiated wave field has a phase term represented by $l\varphi + k_z z - \omega t$, where l is the topological charge, and φ is the azimuthal angle around the optical axis z. The wave with a helical wavefront is commonly called an optical vortex. Figure 1 shows a schematic diagram of the propagation of an optical vortex. An optical vortex was originally discussed regarding a special mode of electromagnetic waves called the Laguerre-Gaussian (LG) mode and was conventionally considered to be produced artificially with optical elements. However, twisted photons are naturally emitted by the cyclotron motion of electrons and are more ubiquitous in laboratories and nature. Naturally, questions arise as to how an optical vortex propagates in magnetized plasmas as anisotropic media and whether the unique property of the helical wavefront is beneficial to heating, current drive, or diagnostics in magnetic fusion plasma.

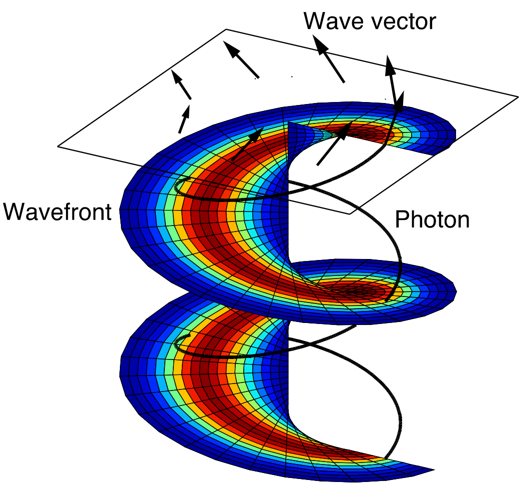

Figure 1. Schematic diagram of propagation of an optical vortex with a helical wavefront along with a twisted photon with OAM.

In this work,[3] propagation properties of an optical vortex with a helical wavefront in cold uniform magnetized plasma are theoretically investigated in an electron cyclotron (EC) range of frequencies. The effects of the helical wavefront of the optical vortex on the wave fields in magnetized plasma are described. Detailed descriptions of the theory will be presented at the conference. It is found that these effects are significant as the topological charge of the optical vortex increases or the distance from the phase singularity becomes small. The different propagation properties are also confirmed in the propagation of Laguerre-Gaussian beams in three-dimensional simulations with commercial software COMSOL Multiphysics by the finite element method. It is found that a part of the ordinary-mode LG beam with the topological charge l excited at the lower electron-density region is converted into the high-wavenumber extraordinary-mode LG beam with $l - 1$ at the upper hybrid resonance layer. Then, the beam can propagate into the higher electron-density region.

In order to demonstrate the new propagation properties of vortex EC waves in heating and current-drive experiments, an optical vortex with desired l must be generated in the millimeter-wave transmission system and launched into magnetic fusion plasma. A spiral-shaped mirror has been developed to generate an optical vortex with designed l in a frequency range of millimeter waves.[4] Thus, an optical vortex can be generated by installing the spiral-shaped mirror between a gyrotron and launching antenna mirrors in the existing transmission line for EC heating and current drive. This modified system enables verification of whether an optical vortex can be a tool to heat high-density plasma efficiently.

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