Formation and microfilamentation of spiral density waves in plasmas induced by circularly polarized field ionization

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Optical-field ionization (OFI) is a fundamental process that serves as the basis for a wide range of applications in plasma and atomic physics. It is well established that the properties of electrons produced by OFI depend strongly on the laser parameters and the target gas species. Studies have shown that the electron velocity distribution in OFI plasmas can be predictably initialized using ultrashort laser pulses [1], providing a platform for investigating the growth of various kinetic instabilities [2] and the generation of Weibel magnetic fields [3, 4].

In this work, we examine a novel kinetic effect that arises from the spatial and temporal intensity profile of an ultrashort laser pulse when it induces OFI in gas atoms and molecules. This process results in an inhomogeneous initial plasma and the formation of complex coherent patterns, which depend on the laser parameters (such as polarization, frequency, and temporal pulse shape) and the gas species (the ionization potential of the atom or ion) [5]. By incorporating well-defined spatial and temporal structures of the laser pulse together with initial drift motion of tunnel-ionized electrons, we derive an analytical expression describing a spiral density modulation induced by a circularly polarized laser, as shown in Fig. 1(a). Due to the inhomogeneous and anisotropic electron drift, the plasma becomes susceptible to streaming instabilities that lead to the growth of microfilaments within the density wave. Particle-in-cell simulations are carried out to verify these findings and study the later stages of plasma evolution, as shown in Fig. 1(b).

The induced spiral density structure can be attributed to a fundamental property of circularly polarized light, as its photons carry optical angular momentum. In a confined system, spiral patterns are known to correspond to bound states with nonzero angular momentum. During the ionization process, optical angular momentum can be transferred to the plasma, leading to the observed spiral patterns under circular polarization.

References

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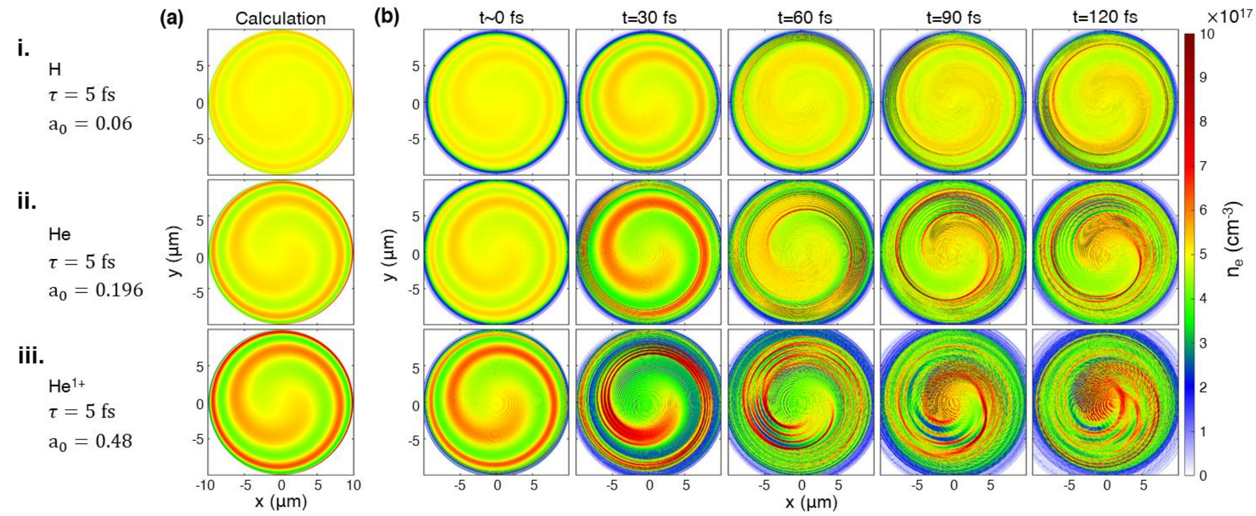

Figure 1. Calculations and simulations of the electron density pattern formation from atoms or ions with a uniform density $n_0=5\times10^{17}$ cm^{-3} singly ionized by an 800-nm, 5-fs circularly polarized laser pulse with a focal spot size of 7 μm. (a) Calculated electron spatial distributions. (b) Simulated electron distributions using code OSIRIS are shown at various time delays. Each row represents a case of different species: (i) hydrogen atom, (ii) helium atom, and (iii) He^{1+} ion. a_0 in each case is chosen to fix the size of the plasma.