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Relativistic Electromagnetically Induced Transparency Effect in Laser-plasma Interaction

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Efficient laser beam transport through over-dense plasmas is essential for applications like fast ignition in inertial confinement fusion, relativistic electron generation, and the production of intense electromagnetic emissions. However, achieving stable beam transport in over-dense plasmas has been a longstanding challenge.

In 1996, Harris introduced the concept of electromagnetically induced transparency (EIT), inspired by atomic physics, to enable the transparency of low-frequency (LF) lasers through over-dense plasmas using a high-frequency pump laser [1]. However, later studies showed that there are strict restrictions for EIT happening, such as a narrow passband of the LF wave frequency or a strongly magnetized plasma background. In 2000, after systematic research on EIT in weakly relativistic regime, Gordon and his colleagues announced that EIT could not occur in real plasmas with boundaries [2, 3].

In this study, we utilize particle-in-cell simulations to demonstrate that EIT can occur in a strongly relativistic regime [4]. Here, the induced current of LF wave tends to be cancelled by the beat current of pump and plasma wave, allowing stable LF laser propagation through bounded plasmas with densities close to tens of times their critical value (Fig. 1).

We also developed a relativistic three-wave coupling model to clarify the conditions and frequency passband required for EIT. Our results indicate that in the strongly relativistic regime, the passband is sufficiently wide to support the sustained operation of EIT. In contrast, in the weakly relativistic regime, the passband narrows dramatically, nearly collapsing to a single point, which explains the suppression of EIT observed in previous studies involving bounded plasmas.

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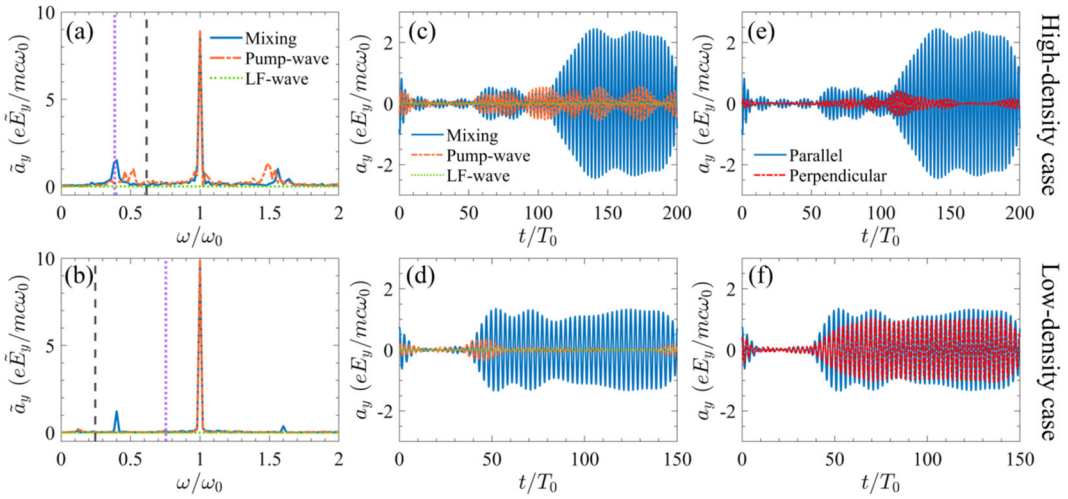

Figure 1. Spectra and filtered laser fields at the right vacuum. The transparency of the LF wave is polarizing-dependent, which indicates EIT happening. [(a),(b)] Spectra of the laser fields collected in the right vacuum and [(c),(d)] laser field waveforms filtered with the frequency range $\omega/\omega_0 \in [0.35,0.42]$, where different curves correspond to the mixing-wave, pump-wave, and LF-wave incidence cases. [(e),(f)] Laser field waveforms filtered with $\omega/\omega_0 \in [0.35,0.42]$, where the mixing waves are incident with the p-polarized LF wave and the pump wave of *p*-polarization (blue-solid line) and s polarization (red-dashed line), respectively. The upper and lower rows correspond to high-density and low-density cases.