Particle-in-Cell Simulation of Phase-Matched High Harmonics Generation in Highly Ionized Plasmas

Ying-Shan, Chen Yao-Li, Liu Shih-Hung, Chen
Department of Physics, National Central University

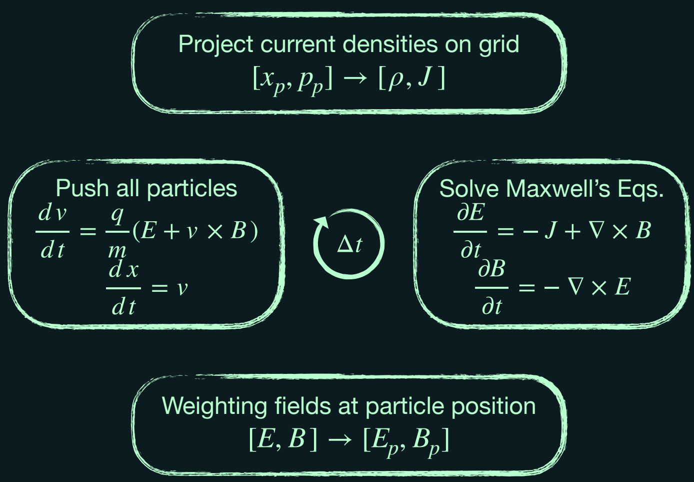
Introduction

High harmonic generation is an important method to generate short-wavelength electromagnetic waves in laser-plasma interactions. However, the conversion efficiency of this approach is low. The phase matching method, which is achieved by balancing the wave dispersion, can be adopted to enhance the HHG efficiency. Based on the scheme, realization of a stable short-wavelength source becomes possible.

Goal

In the lab of NCU, we can use 100 TW laser to ionize neutral gas to produce plasmas and generate high harmonic fields by balancing the wave dispersion induced by dipoles and plasmas, respectively. In addition, the PIC simulation is used to find the operating ranges of phase matching conditions, such as energy of laser E, laser focus position x_f, beam width of driving laser w and gas density N_{gas}.

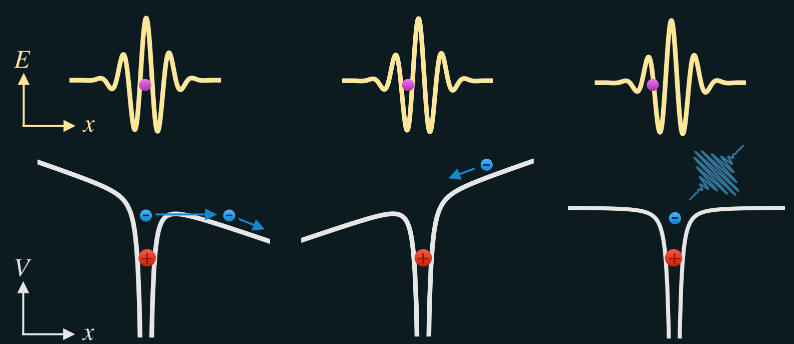
PIC (Particle-In-Cell)



We use two PIC code, i.e. EPOCH (three-dimensional and two-dimensional) and Smilei (two-dimensional and Cylindrical coordinates) to simulate laser-plasma high harmonic generation.

High Harmonic Generation (HHG)

The figure shows the three-step model of HHG. First, the laser pulse is focused onto gas targets to produce electron plasmas. Second, the electrons are accelerated by laser fields. Then, the phase of laser fields change so that the electrons return and recombine with ions. Lastly, high energy photons with multiples of laser frequency are emitted.



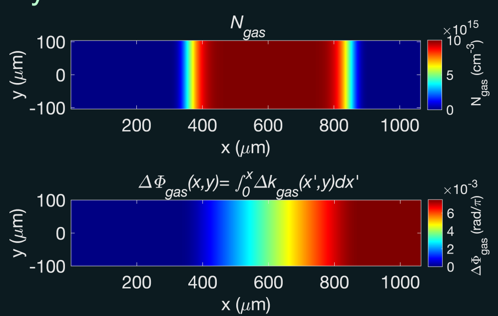
Phase Matching Condition

The phase matching condition is $|\Delta\Phi| = |\Delta k L| < \pi$, where $\Delta k = qk_0 - k_q$ is the wavenumber mismatch. The definition of dephasing length is $L_d = \frac{\pi}{\Delta k}$. Therefore, the destructive interference would occur when $L > L_d$, and let the conversion efficiency of HHG decrease. Δk depends on four effects: neutral gas dispersion Δk_{gas}, plasma dispersion Δk_{plasma}, geometrical phase shift Δk_{geo} (Gouy phase shift), and intrinsic dipole phase variation Δk_{dipole}. The operating parameters of following figures are $E = 0.04mJ$, $x_f = 150\mu m$, $w = 20\mu m$, $N_{gas} = 10^{22} m^{-3}$ Argon in 3D PIC.

Neutral gas dispersion:

$$\Delta k_{gas} = \frac{q\omega_0}{c}[n(N_{gas}, \omega_0) - n(N_{gas}, \omega_q)]$$

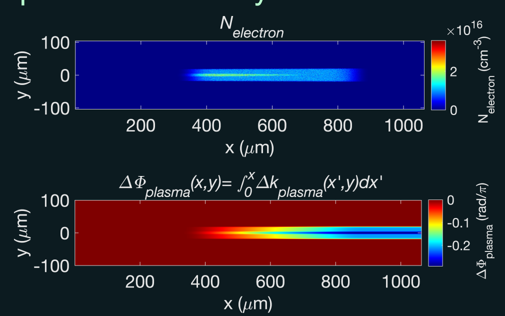
Generate by neutral gas in the system.



Plasma dispersion:

$$\Delta k_{plasma} = -\frac{\mu_0 e^2 N_e}{4\pi m_e}\lambda_0(q - \frac{1}{q})$$

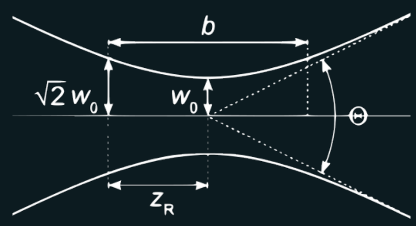
Generate by the charged particles in the system.



Geometrical phase shift:

$$\Delta k_{geo} = -\frac{1}{z_R}(q - \frac{1}{q}),\ \text{where } z_R = \frac{\pi w_0^2}{\lambda_0}$$

The laser intensity in z_R can be viewed as changeless.

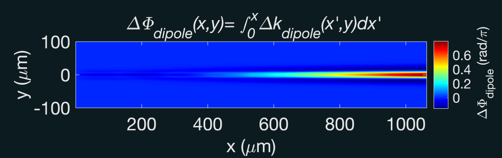


Intrinsic dipole phase variation:

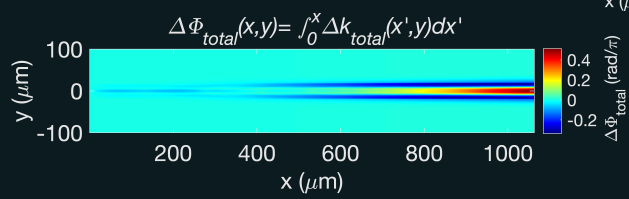
$$\Delta k_{dipole} = \alpha(q, I_d)\frac{\partial I_d}{\partial x}$$

$$\alpha(q, I_d) \equiv \frac{\partial \phi}{\partial I_d},\ \text{where } \phi = q\omega_0 t_f - \frac{S}{\hbar}$$

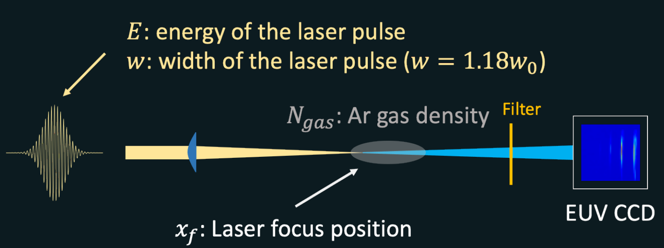
Generate by the interaction between laser and plasma.

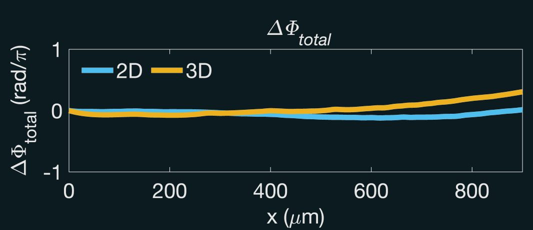


$$\Delta\Phi_{total} = \Delta\Phi_{gas} + \Delta\Phi_{plasma} + \Delta\Phi_{geo} + \Delta\Phi_{dipole} \longrightarrow$$



Experimental Setup & Experimental result





The 3D and 2D simulation is roughly the same. Therefore, we use 2D to find the operating range.

The parametric study is performed using 2D PIC simulation. The operating range with phase matching conditions can be obtained.

$x_f = 150\mu m$, $w = 20\mu m$, $N_{gas} = 10^{22} m^{-3}$
$\rightarrow 0.02mJ < E < 0.05mJ$

$x_f = 150\mu m$, $w = 20\mu m$, $E = 0.04mJ$
$\rightarrow 1 \times 10^{22} m^{-3} \le N_{gas} \le 4 \times 10^{22} m^{-3}$

Conclusion

1. In highly ionized plasmas, the efficiency of HHG can be enhanced by balancing the wave dispersion to achieve phase matching condition.
2. The 2D PIC simulation is used for parametric study to reduce the data storage and computing time.
3. Operating ranges for phase matching conditions can be obtained by varying the gas density and laser energy.

References

[1] J. Phys. B: At. Mol. Opt. Phys. **45** (2012) 074020 (9pp)
[2] Trans. R. Soc. A **377**: 20170468.
[3] E. A. Gibson, Quasi-Phase Matching of Soft X-ray Light from High-Order Harmonic Generation using Waveguide Structures, Ph.D. thesis, University of Colorado (2004).

q: harmonic order k_0: wavenumber of driving laser field k_q: wavenumber of q^{th} harmonic field L: interaction length ω_0: driving laser frequency ω_q: harmonic frequency ($\omega_q = q\omega_0$)
$n(N_{gas}, \omega_0)$: refractive index of driving laser field $n(N_{gas}, \omega_q)$: refractive index of q^{th} harmonic field η: ionization ratio N_e: electron density ($N_e = \eta N_{gas}$) e: elementary charge m_e: electron mass
λ_0: driving laser wavelength in vacuum w_0: waist radius of driving laser beam z_R: Rayleigh range I_d: driving laser intensity S: action ϕ: phase of electron t_f: return time