# Extension of the bright high-harmonic photon energy range via nonadiabatic critical phase matching


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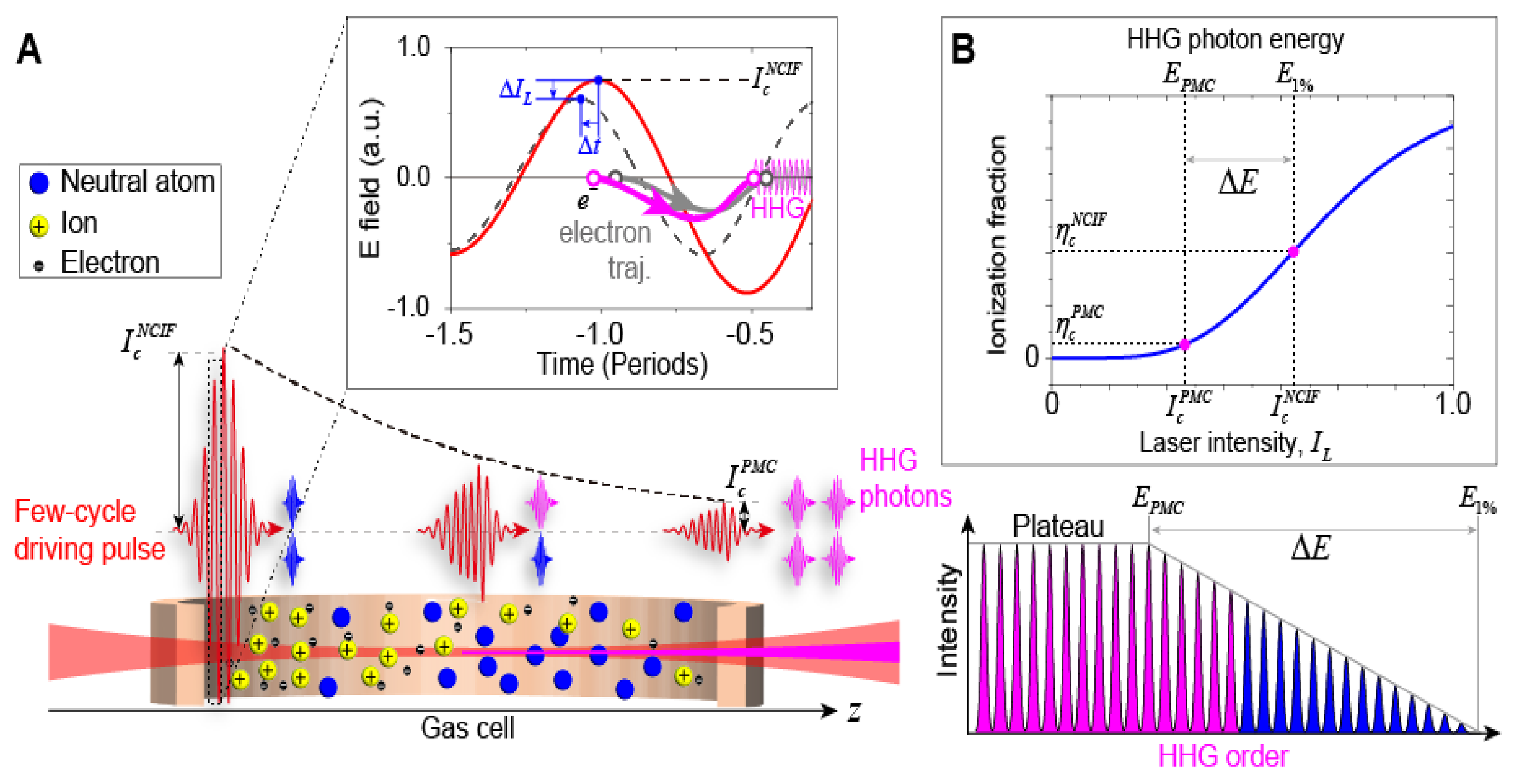
## 1. Introduction

Extending the photon energy range of bright HHG to cover the entire soft X-ray region is important for many applications in science and technology. In this work, we reveal a second, nonadiabatic critical ionization fraction that can substantially extend the maximum phase-matched high-harmonic photon energy, arising due to strong reshaping of the intense driving laser field in a gas plasma. We also present an analytical model that predicts the spectral extension that can be achieved for different driving lasers. These findings are important for the development of high-brightness soft X-ray sources for applications in spectroscopy and imaging.

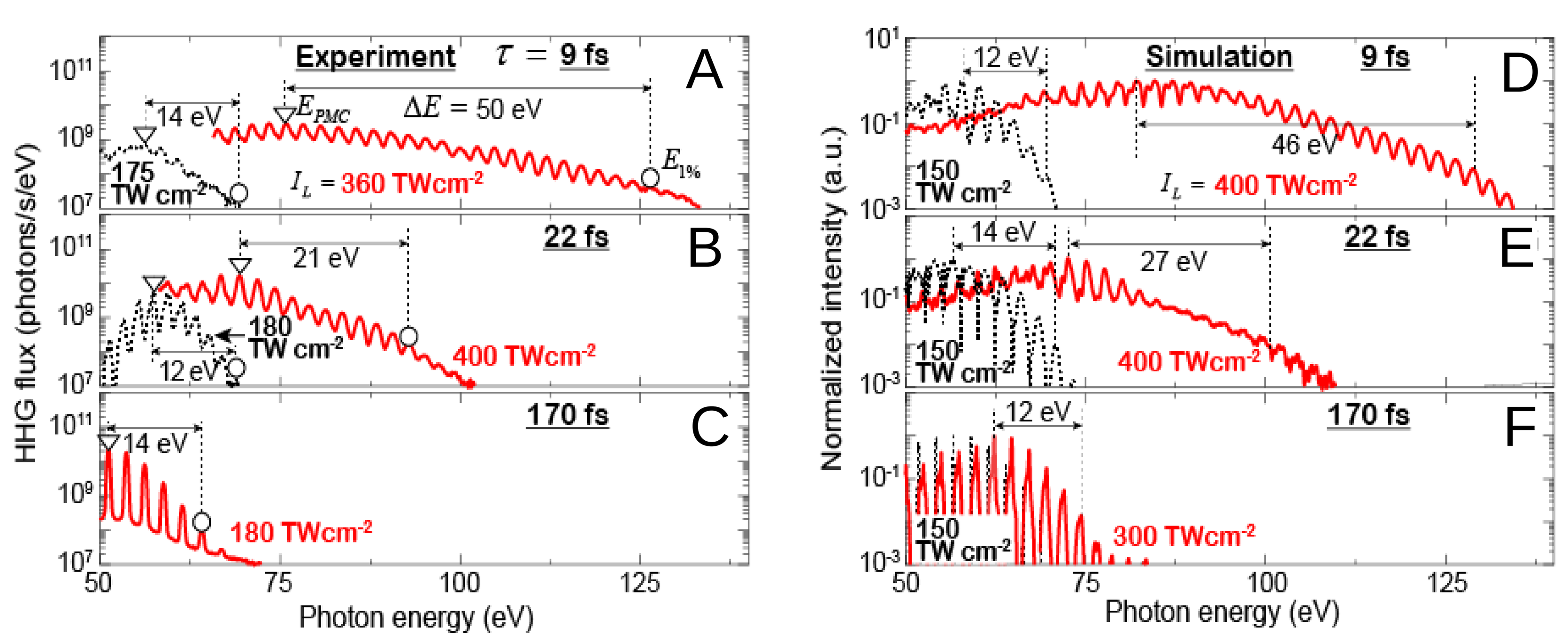
### Illustration of the concept of nonadiabatic HHG




- (A) Plasma induced laser intensity decay, temporal pulse reshaping affecting the electron trajectories and phase matching.
- (B) Illustration of that nonadiabatic critical ionization fraction can substantially extend the maximum phase-matched HHG photon energy.

## 2. Results

### Harmonic spectrum roll-offs under different driving conditions




- (A)-(C) The HHG spectrum driven by pulse durations of τ=9 fs, 22 fs and 170 fs, respectively, under different laser intensities ($I_L$).
- (D)-(F) The results of numerical simulations under similar conditions as in (A)-(C).
- As shown in Fig. A, ΔE can be as large as ~50 eV, which is comparable to the corresponding $E_{PMC}$ (~75 eV), delivering a great amount of usable high-energy XUV photons beyond the PMC.

### The NCIF model

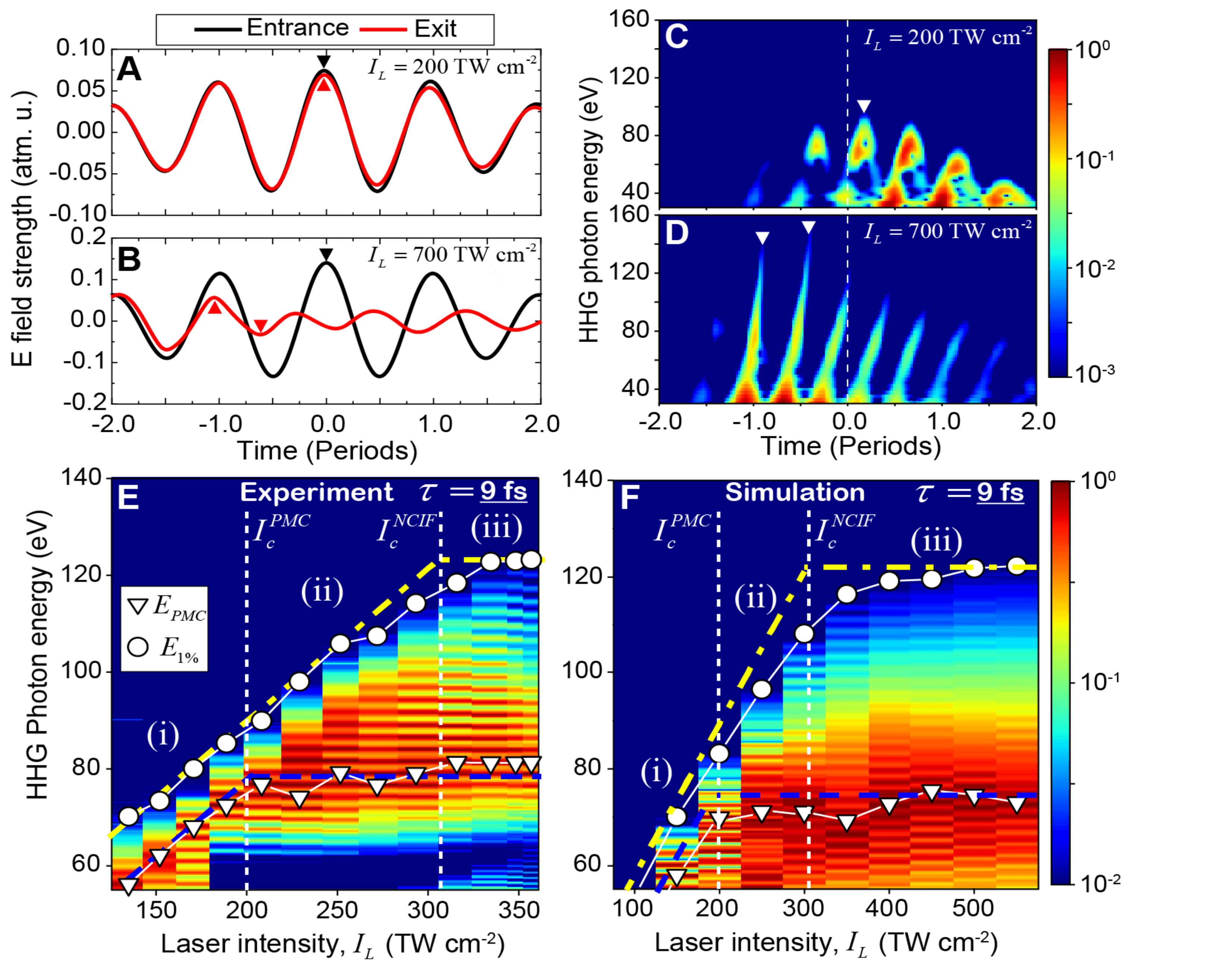
The wavevector mismatch for HHG:

$$\Delta k_q = \Delta k_g + \Delta k_n + \Delta k_p + \Delta \boldsymbol{k_d}.$$

A critical ionization fraction including the nonadiabatic effects can be derived:

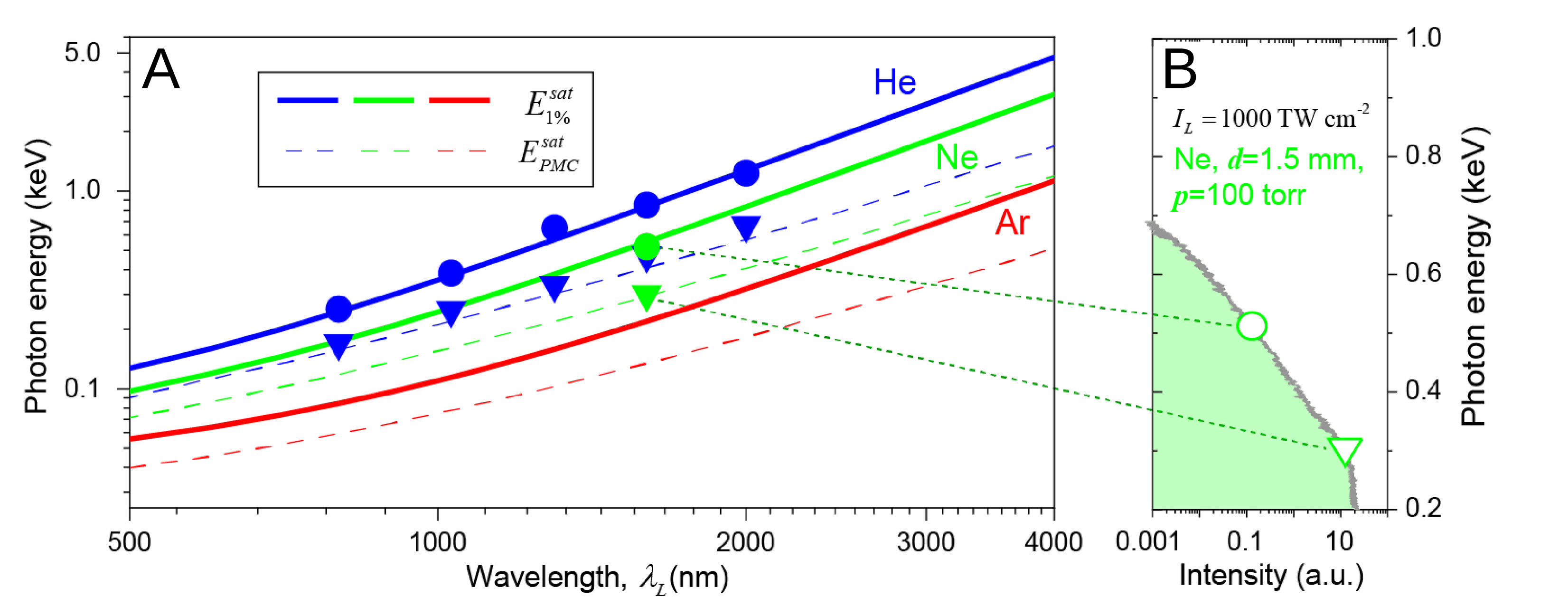
$$\eta_c(I_L) \approx \frac{\frac{2\pi}{\lambda_L}\Delta\delta + C_d \overbrace{\frac{\alpha_j}{2\pi c}\frac{3U_p}{I_p+3.17U_p}\lambda_L^2 r_e N_{atm}\frac{\partial \eta(I_L,t)}{\partial t}\Big|_{t=0}}^{\text{Nonadiabatic term}}}{\frac{2\pi}{\lambda_L}\Delta\delta + r_e N_{atm}\lambda_L}$$

### Influence of nonadiabatic effects on harmonic spectrum




- (A)-(B) The temporal field reshape obtained from the numerical simulations at the entrance and the exit of a gas cell under laser intensity of $I_L$=200 TW cm-2 and $I_L$=700 TW cm-2.
- (C)-(D) The time-frequency analysis of HHG generated under the same conditions in (A) and (B).
- (E)-(F) The experimental and simulation HHG spectrum in argon driven by different laser intensity.

### Extension to mid-infrared few-cycle lasers




- (A) The NCIF model results under different wavelengths (λL) in argon, neon and helium. The symbols represent the results obtained from the numerical simulations.
- (E) A typical numerical spectrum of HHG in neon. The $E_{PMC}$ and E1% are labeled. The gas pressure is 100 torr, cell length is 1.5 mm and the driving intensity is 1000 TW cm-2.

## 3. Conclusion

- We develop a NICF model taking the nonadiabatic effects on the HHG phase matching into account. The model can precisely predict the reshaping and extension of a harmonic spectrum. Our results have potential for great impact and widespread use considering the recent great advances in high-energy few-cycle mid-infrared lasers as the driving sources of HHG.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