Carrier-envelope-phase-stabilized sub-10-fs lasers and their application to laser-based electron acceleration

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Outline

• Carrier-Envelop Phase (CEP)
• CEP-stabilized amplifier in Vienna
• General application of a CEP-stabilized laser:
  High Harmonic and Attosecond Pulse Generation
• Electron acceleration with sub-10-fs, CEP stabilized lasers
• One stage electron acceleration in plasma
• Cascaded electron acceleration in plasma and in vacuum
• Summary
Carrier-Envelope Phase (CEP)

\[ \omega_n = n \omega_r + \omega_0 \]
\[ \Delta \phi = 2\pi \frac{\omega_0}{\omega_r} \]
\[ \omega_r/2\pi = c/2L \quad \text{repetition rate} \]

\[ \omega_0 = 2(n\omega_r + \omega_0) - (2n\omega_r + \omega_0) \]

H.R. Telle et al., Appl. Phys. B 69, 327 (1999);
Pulse Parameters

-15 -10 -5 0 5 10
-1
0
1
-20 -10 0 10 20

$A(t) = \frac{p}{2}$

Electric field strength (a.u.)

Delay (fs)

Intensity

Time (fs)

Intensity

Photon energy (eV)

Wavelength (nm)

1000 800 600

Intensity

1.5 2.0

Wavelength (nm)

1000 800 600

Photon energy (eV)
Double Phase-Lock Loop

Unlocked

Combined phase-lock (with fast+slow feedback)

Simple phase-lock (oscillator only)

CEP stability with 2 loops: $\pi/6 \rightarrow 200$ attosecond accuracy !!!
Application and a Quick and Easy Check: High Harmonic and Attosecond Pulse Generation

**Step 1**
Optical field ionization

**Step 2**
e⁻ acceleration

**Step 3**
XUV emission on recollision

**Temporal manifestation**

- \( \phi = 0 \)
- \( \phi = \pi/2 \)

**Spectral manifestation**

(Highest energy photons)
Experimental Results with 5.4-fs pulses

- 5-fs
- 0.5-mJ
- 1-kHz phase-locked pulses

How to Use These Lasers for Electron Acceleration?

Laser-based electron acceleration

In plasma

Bubble regime of electron acceleration or Laser wake field acceleration

Sub-10-fs pulses

Advantage: less sensitive to synchronization
Disadvantage: requires plasma

In vacuum

Capture and Acceleration Scenario (CAS)

Sub-10-fs pulses + Carrier-envelope phase stabilization

Advantage: simple setup
Disadvantage: sensitive to synchronization
One Stage Bubble Acceleration

• High efficiency ~ 10%
• Nonthermal spectrum
• $\tau_L \sim 1/(2\omega_p)$

Criterion for electron acceleration: Wavebreaking

Wavebreaking field $E_{wb}/E_0 = [2(\gamma_p - 1)]^{1/2}$

$\gamma_p = 1/(1 - v_g^2/c^2) = \omega_0/\omega_p \sim 1/n_e^{1/2}$

$n_e \sim \omega_p^2 \sim \tau_L^{-2}$
Scaling of the Electron Energy with the Laser Energy

Sublinear scaling of the electron energy with laser energy

Multi-stage (or cascaded) electron acceleration is practical

VLPL 3D PIC Simulations by A. Pukhov
Cascaded electron acceleration in plasmas
High Electron Energies

Stage 1.) Bubble accelerator (injector) \(\rightarrow\) Large laser energy requirements!
Stage 2.) Laser wake field accelerator (booster) \(\rightarrow\) No special requirements

Electron bunch length \(\sim\) Laser Pulse Duration \(\rightarrow\) Synchronization is not critical
Cascaded Electron Acceleration
Short Electron Bunches

Phase velocity smaller than light velocity c
CEP stabilization is important
Short electron bunch for 5fs laser pulse at selected electron angle
Summary

**Ti:sapphire CEP-controlled amplifier:**
- Phase-stabilization of amplified 1 kHz 5-fs pulses has been demonstrated.
- Achieved accuracy: 200 attosecond
- Typical applications: HHG and Attosecond pulse generation

**Laser Based Electron Acceleration:**
- Bubble acceleration
- 2 stage acceleration:
  - LWFA
  - Laser vacuum acceleration
Cooperations

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