Generation of intense subcycle pulses using laser-driven wakes

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or... How Smilei changed my life... before I even managed to compile it!

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How to do that?

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### Smilei users in Chalmers/GU

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<td>I. Thiele, J. Ferri</td>
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Overview

• Motivation
• Laser-wakefield acceleration
• Relativistic mirrors
• Electron beam driven amplification (EBDA)

• Laser-wakefield driven amplification (LWDA)
Subcycle pulses

- Intense subcycle pulses: isolate electron dynamics
- Several methods
  - Optical parametric amplification
  - Difference-frequency generation
- Mid-IR regime:
  - 2-20 μm
  - Interesting for applications
  - Hard to attain intense mid-IR pulses
- How to scale to mJ energy?
- Intensity limit: material damage thresholds

- From Liang et al, Nat. Comm. 2017
- Coherent pulse synthesis
- 0.88 cycle, 4.2 μm, 33 μJ pulse
- Use it to drive HHG in silicon
Secondary light sources from intense laser-plasma interaction

- Parametric amplification in plasma
- High harmonic generation from laser-solid interaction
- Relativistic mirrors
- Scattering of laser pulses by (laser-plasma accelerated) electron beams
- ... and much more...
- *No method so far for isolated subcycle pulses*
Laser-wakefield acceleration

- Laser-plasma driven electron acceleration
- Uses intense ($I > 10^{18} \text{ W/cm}^2$), of few (~10) cycles duration
- Electron bunch duration < 10 fs
- MeV to few GeV energy
- Up to 0.5nC charge

Relativistic Mirrors

- **Relativistic (double) Doppler effect**
- **Frequency up/down shift in counter-/co-propagation:**
  \[ \omega' \approx 4 \gamma^2 \omega, \text{where } \gamma = 1/\sqrt{1 - v^2/c^2} \]
- **Energy gain/loss by factor** \( 4 \gamma^2 \)
- **In counter-propagation: amplification**

Einstein, Annalen der Physik **322**, 891 (1905)
Landecker, Phys. Rev. **86**, 852 (1952)
Bulanov et al, Plasma Sources Science and Technology **25**, 053001 (2016)
Relativistic Mirrors

- High reflectivity required
- Conservation of number of cycles:
  No subcycle generation

Einstein, Annalen der Physik 322, 891 (1905)
Landecker, Phys. Rev. 86, 852 (1952)
Bulanov et al, Plasma Sources Science and Technology 25, 053001 (2016)
EBDA:
Electron beam driven amplification

- Introduce a standing mirror (foil)
- Limit interaction time: subcycle pulse

EBDA: Electron beam driven amplification

- Limit interaction time: subcycle pulse
EBDA: 2D simulation

- **2D Smilei simulation**
- **Single cycle THz seed** [inspired by Vicario et al, Phys. Rev. Lett 112, 213901 (2014)]
  - $f=3\text{THz}$ ($\lambda=100\mu\text{m}$), $1/e$-duration $t_0=0.2T_0$, $a_0=1$, $(E_0=cm_e\omega_0/q_e)$.
- **Short electron bunch**
  - $1/e$-duration $t_e = 0.016T_0$, peak density $n_e = 30\ n_c$ and 10 MeV energy
- **Generation of Mid-IR subcycle pulse**, $\lambda=14\ \mu\text{m}$
EBDA: Fluid model

- 1D model
- Electron beam as cold, relativistic fluid
- Transverse fluid momentum equation
  \[ \partial_t p_\perp = q_e E_\perp , \]
- Conservation of transverse canonical momentum
  \[ p_\perp = -q_e A_\perp / c , \quad \text{where} \quad A_\perp = -\partial_t E_\perp \]
- Wave equation
  \[ \frac{\partial^2 A_\perp}{\partial t^2} - c^2 \frac{\partial^2 A_\perp}{\partial x^2} = -\frac{q_e^2 n_e}{m_e \gamma_e} A_\perp \]
  where \( \gamma_e = \sqrt{1 + \frac{|p|^2}{(m_e c)^2}} \) and we assume
  \[ \gamma_e \approx p_x / (m_e c) \]
- Undepleted electron pump approximation
EBDA: Benchmarking the model

- PIC vs Fluid model
EBDA: Energy gain

- Energy gained by the reflected electromagnetic field

\[ U_{\text{gain}}(t) = -U_e(t) = \frac{q_e^2}{2m_e c^2} \int_{-\infty}^{t} |A_\perp|^2 \frac{\partial}{\partial \tau} \left( \frac{n_e}{\gamma_e} \right) d\tau \]

- Short electron-bunch limit:

\[ U_{\text{gain}}(+\infty) = -\frac{q_e^2}{2m_e c^2} \frac{\partial}{\partial t} |A_\perp(t_d)|^2 \int_{-\infty}^{+\infty} n_e/\gamma_e dt \]

- Gain if we introduce the electron beam at appropriate delay!
EBDA: Scalability

- Vary seed amplitude

- Vary seed frequency

<table>
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<tr>
<th>Seed</th>
<th>Frequency</th>
<th>Output</th>
<th>Wavelength</th>
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<tr>
<td>THz</td>
<td>1 – 10 THz</td>
<td>(Mid)-IR</td>
<td>3 – 30 μm</td>
</tr>
<tr>
<td>(Mid)-IR</td>
<td>10 – 100 THz</td>
<td>Optical</td>
<td>300 nm – 3 μm</td>
</tr>
<tr>
<td>Optical</td>
<td>100 – 1000 THz</td>
<td>EUV</td>
<td>30 nm – 300 nm</td>
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EBDA: Few cycle seeds / low density beams

- Sub-cycle pulse generation still works even for few cycle seeds and low density electron beams
EBDA: Summary

- Amplification, frequency conversion and spectral broadening of long-wavelength pulses
- Robust with respect to seed duration (and delay), beam density (and thermal spread)
- Downside: Carrier envelope phase (CEP) not tunable
Carrier envelope phase (CEP)

- Phase between maximum of the envelope and of the oscillation field
- Becomes important for short pulses
- Important for applications, e.g. high-harmonic generation [Corkum and Krausz, Nature Phys. 3, 381 (2007)]
- EBDA is not CEP-tunable
LWDA: Laser-wakefield driven amplification

- Can we directly leverage e⁻ in a wake?
- Counter-propagation: limited by density
- Laser-wakefield driven amplification (LWDA)
- Long wavelength seed in co-propagation with pump laser
LWDA - concept

- 2D Smilei simulations
- Intense y-polarized laser ($a_0=2.5$, $\lambda_0=0.8\mu m$)
- Low intensity z-polarized seed ($a_{0,s}=0.001$, $\lambda_s=4\mu m$)
- Underdense plasma ($n_0=4.5 \cdot 10^{-19} cm^{-3}$)
LWDA – CEP tunability

- Vary CEP of seed
- Control CEP of amplified pulse
LWDA – spectral tunability

- Vary plasma density to control central frequency
- We can have intense mid-IR, CEP-tunable, subcycle pulses
LWDA – scaling with seed intensity

- Vary seed amplitude
- Linear effect up to weakly relativistic seed
LWDA – 3D Smilei simulation

• Same parameters but with $a_{0,s}=0.1$
• Weakly relativistic sub-cycle pulse
Conclusions

- We propose two methods for the generation of intense subcycle pulses
- Electron beam driven / Laser wakefield driven
- Generation of mid-IR subcycle pulses through amplification of long-wavelength pulses
- LWFA: spectrally and CEP tunable
- Could allow to reach relativistic intensities

For more details:

I. Thiele and E. Siminos, arXiv:1902.05014
Acknowledgments

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- Mickael Grech and the Smilei team

For more details:

I. Thiele and E. Siminos, arXiv:1902.05014

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Energy gain

- Assume density profile
  \[ n_e(x, t) = n_e^{\text{max}} \exp \left[ -(t - t_d - x/v_b)^2/t_e^2 \right] \]

- Decompose fields to incident and reflected
  \[ E^\pm_z(t) = \mp E_z^{\text{max}} \sin(\omega_0 t) \exp \left( -t/t_0^2 \right) \]

- Energy gained by the field
  \[ U_{\text{gain}}(t) = -U_e(t) = \frac{q_e^2}{2m_e c^2} \int_{-\infty}^{t} |\mathbf{A}_\perp|^2 \frac{\partial}{\partial \tau} \left( \frac{n_e}{\gamma_e} \right) d\tau \]

- Short electron-bunch limit:
  \[ U_{\text{gain}}(+\infty) = -\frac{q_e^2}{2m_e c^2} \frac{\partial}{\partial t} |\mathbf{A}_\perp(t_d)|^2 \int_{-\infty}^{+\infty} n_e/\gamma_e dt \]

- Gain if we introduce the electron beam at appropriate delay!