Interaction of plasmas with intense laser pulses carrying orbital angular momentum

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John Adams Institute for Accelerator Science Lecture Series
Content

- Introduction, motivation

- Circularly polarized (CP) intense pulse interacting with solid density targets
  - Laser induced Coherent Synchrotron Emission (CSE)
  - Attopulse and attospiral generation

- Screw-shaped pulses interacting with underdense plasmas
  - Generation of GigaGauss axial magnetic fields
  - Possible applications in LWFA
Orbital Angular Momentum (OAM)

Particles

\[ r = \sqrt{y^2 + z^2} \]

\[ L_{ix}(t_0) = \sum_j (r_j \times p_j)_x, \]

EM Waves

\[ \vec{S} = \frac{(\vec{E} \times \vec{B})}{\mu_0} \]

\[ L_{Lx}(x_0, x_1) = \frac{1}{c^2} \int_{x_0}^{x_1} \int_0^{2y_0} \int_0^{2z_0} (r \times \vec{S})_x dz \ dy \ dx, \]
Synchrotron radiation

\[
I(\omega) \sim \left| \int dt \, \hat{\epsilon} \times [\hat{\epsilon} \times \mathbf{J}(\hat{r},t)] \exp[i \omega (t - \hat{\epsilon} \cdot \hat{r} / c)] \right|^2 \quad \Rightarrow \quad I(\omega) \sim \left| J_\perp(x,t) \exp[i \omega (t - x(t) / c)] \right|^2
\]

\[
\vec{v}_\perp \ll c \\
\vec{v} \\
\vec{r} \\
\epsilon \\
\vec{V}_x \approx c
\]

Observer
Synchrotron radiation

\[ I(\omega) \sim \left| \int dt \vec{\epsilon} \times [\vec{\epsilon} \times J(\vec{r}, t)] \exp[i \omega (t - \vec{\epsilon} \cdot \vec{r} / c)] \right|^2 \]

\[ I(\omega) \sim \left| J_\perp(x, t) \exp[i \omega (t - x(t)/c)] \right|^2 \]

\[ x(t) = r(t) = ? \]

\[ \gamma = \left(1 - \dot{x}(t)^2/c^2\right)^{-1/2} \]

\[ \ddot{x}(t) \sim t^{2n-1} \Rightarrow \omega_r \sim \gamma^{\frac{2n+1}{n}} \]

\[ I(\omega) \sim \omega^{\frac{2n+1}{2n+2}} \]

D. an der Brügge and A. Pukhov, arxiv:1111.4133 (2011)
Twisted pulses (using electron beams)

Erik Hemsing et al., Nature Physics 9, 549 (2013)

Electron gamma:
100-1000
Undulator length:
~cm-m

Simulation setup: Solid density target, CP pulse

Codes:
✓ Vsim (VORPAL), Tech-X Corp.
✓ EPOCH

Collissionless, relativistic particle-in-cell plasma simulations.

Normalized laser amplitude

\[ a_0 = \sqrt{\frac{I[W/cm^2] \lambda_L^2[\mu m]}{1.4 \times 10^{18}}} \]
CP pulse vs. flat foil

Simulation parameters:

\[ I_L = 10^{20} \text{ W/cm}^2 \]
\[ t_L = 20 \text{ fs} \]
\[ w_L = 2 \mu\text{m} \]
\[ h = 0.2 \mu\text{m} \]
\[ n_0 = 28n_{cr} \]

solid hydrogen foil
Attopulse generation

Relativistic electrons near the plasma surface emit coherent radiation.

\[ v_{\parallel} \approx c \]
\[ v_{\perp} \approx 0 \]

\[ a_{\perp} \approx \frac{eA_0}{m_e \omega_0} \]
Rotation symmetric interaction: 
CP pulse vs. cone-like targets

Cylinder target
Energetic electrons move on a spiral path

Cone target
Focusing of attospiral near the exit hole
Movie
OAM in attopulse

Transversal poynting vector

Incident pulse

Max : $10^{24} \frac{W}{m^2}$

1 $\mu$m

Attospiral

Max : $1.4 \times 10^{25} \frac{W}{m^2}$

0.4 $\mu$m
Coherent Synchrotron Emission

\[ E_y < 0 \]
Coherent Synchrotron Emission

Schematic view:

Acceleration: $a_y(t) \sim \exp(-t^2)$

$v_y \ll c$

$E_y(t) = -\frac{N e}{c^2 R} \frac{a_y(t')}{(1 - v_x(t')/c)^2}$

$= -CA_y(t') \frac{4 \gamma^4}{(1 + \alpha_1 \gamma^2 t'^{2n})^2}$

$x' = x - c(t - t')$

$v_x(t') = v_0 (1 - \alpha_1 t'^{2n})$

J.M. Mikhailova et al., PRL 109, 245005 (2012)
Harmonic spectrum

Zs. Lécz and A. Andreev, PRE 93, 013207 (2015)

\[ N_{dr} = \frac{\omega_{dr}}{\omega_L} \approx \left( \frac{3}{2} \right) a_0^2 \]

\[ t_{atto} = 0.21 N_{dr}^{-1} t_L, \quad I_{atto} = \left( N_{dr}/2 \right)^2 I_{\omega_0} \]

\[ I_{\omega_0} = ? \]
Screw-shaped laser pulse

The laser pulse is represented by the envelope function of the intensity distribution.

http://arxiv.org/abs/1604.01259

Front View:

The ponderomotive force has an azimuthal component as well!

\[ F_p \sim \nabla I_L \lambda_L^2 \sim \left( \frac{I_L}{\lambda_{sp}} \right) \lambda_L^2 \]
**Envelope model**

\[ F_p = e \mathbf{v} \times \mathbf{B} \sim \mathbf{E} \times \mathbf{B} \]
\[ \sim E \partial E / \partial x \sim \nabla E_{env}^2 \cdot [1 + \cos(2kx)] \]

If the electron plasma period is much larger than the laser period:
\[ F_p \sim \nabla I_L \]
Electron dynamics

In the moving frame of the laser pulse!

In the back of the bubble.
Bubble solenoid

The plasma has to be underdense, otherwise the pulse depletion becomes significant.
Scaling of peak magnetic field

\[ B \sim (\gamma n_0)^{1/2} \]
\[ \gamma \sim I_L \lambda_L \]

\[ n_0 < 0.1 n_{cr} = \lambda_L^{-2} 1.12 \cdot 10^{14} m^{-1} \]

For larger B-field small wavelength and high intensity is required!!

\[ B = 1 \text{MT} \Rightarrow n_0 = 7 \cdot 10^{28} m^{-3}, \lambda_L = 20 \text{nm}, I_L = 8 \times 10^{23} W / cm^2 \]
\[ B = 50 \text{kT} \Rightarrow n_0 = 7 \cdot 10^{28} m^{-3}, \lambda_L = 800 \text{nm}, I_L = 2 \times 10^{22} W / cm^2 \]
Parameter map

\[ \lambda_L = 800 \text{ nm} \]

\[ \lambda_L = 100 \text{ nm} \]

\[ k = \frac{n_0}{n_{cr}} \]

\[ \lambda_p = 2\pi \frac{c}{\omega_p} = \text{plasma wavelength} \]
Electron collimation: Low emittance via synchrotron cooling?

04/14/16

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Steady solenoid

The plasma wavelength is smaller than the laser pulse length (or spiral step). In this regime bubble can not be formed, but rotational current is generated behind the pulse.

The length and lifetime of the uniform axial field depends on the depletion time and diffusion time respectively.

100 micrometers long for 100 fs
Future plans

Project 1

- Electron cooling via synchrotron emission
- Near the laser axis higher grid resolution is needed
- Improved beam emittance? New short wavelength source?

Project 2

- Generalize the driver beam: does it work with e-beam as well?
Multi-scale problem
Thank you for your attention!
Twisted pulses (using plasmas)

OAM conversion of Laguerre-Gaussian pulses
Attosecond UV vortex

In gas target:
Carlos Hernandez-Garcia et al.,


The wavefront of the incoming pulse is distorted by the tailored spiral-shaped surface.
Collimated electron and ion beams

**Electron trajectories**


**Axial magnetic field:**

N. Naseri et al., PHYSICS OF PLASMAS 17, 083109 (2010)

**Inertial Confinement Fusion:**