High Intensity Laser Plasma Cavitation: Second Harmonic, Electron Acceleration, and Nonlinear Conversion of Photon Spin to Orbital Angular Momentum *

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Introduction

• Intense laser pluses can drive plasma waves

• At high intensities blowout regime can be reached

• This is of great interest to advanced laser plasma based accelerators
Plasma Based Accelerators

• Electrical breakdown limits the accelerating gradients for electrons in conventional rf accelerators to $E_{acc} \sim 30 \, MV / m$

• To achieve a final energy of 1 TeV for future linear collider, $(10^{12} \, eV, \gamma = 2 \times 10^6)$, an acceleration distance of 30 km is needed.

• Lasers can produce laser pulses with focused intensities well above $10^{19} \, W/cm^2$

• Plasmas are fully ionized and can support extremely high fields.

• For example, $E_{acc} > 30 \, GV / m$

  the acceleration distance can be more than 1000 times smaller.
Laser Wakefield Acceleration (LWFA)

- Short pulse ($< 1$ psec), high power ($> 10^{12}$ W) laser
- Laser pulse length $\sim$ plasma wavelength
- Large amplitude plasma waves accelerate electrons (usually not from background)
- Accelerating gradients can be large, $E_{\text{acc}} > 10$ GV/m
  ($10^3$ greater than conventional RF accelerators $\Rightarrow$ compactness)

Marque et al., PRL, 76, 3566 (1996); Siders et al., PRL, 76, 3570 (1996)
Self-Modulated Laser Wakefield Acceleration

- Long laser pulse undergoes Raman and self focusing instabilities
- Very large amplitude plasma waves are generated, $E_{\text{acc}} > 100 \text{ GV/m}$
- Plasma waves trap and accelerates background electrons

J. Krall et al., PRE 48, 2157 (1993)
Ting et al., PRL 77, 5377 (1996); Le Blanc et al., PRL 77, 5381 (1996)
D. Gordon et al., PRL 80, 2133 (1998), and many others
Motivation

- Laser driven plasma accelerators have demonstrated large accelerating gradients (~100 GeV/meter) and final energies of few hundred MeV’s
- Self-injection has led to quasi-monoenergetic acceleration – rich in physics, but unstable by nature.
- External optical injection could lead to stable, compact, high-quality laser plasma accelerators.

It is time for the long awaited transition of laser plasma accelerator

Novel advanced concept ⇒ State-of-the-art compact accelerator
**Strategy**

- To produce high quality high energy electron beams
  - Operation in **standard** LWFA regime \((c \tau_L \sim \lambda_p/2)\) - stable propagation
  - Plasma channel for optical guiding - overcome laser diffraction
  - Precisely phased injection with ultrashort, monoenergetic electron beam bunch \((c \tau_b \ll \lambda_p)\) - produce small energy spread, low emittance
  - Plasma density tapering or staging: **optimize energy gain**
  - Channel-guided LWFA: **high final energy**

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P. Sprangle, AAC Workshop, 2002.
Motivation

• Optical signatures of plasma bubble -- ultra-fast harmonic generation

• To create quasi-monenergetic electrons using minimum laser power.

• Off-axis electrons are easier to couple into acceleration stages.

Nature 9/30/04 cover – 3 papers on LWFA experiments
Blowout Regime

- Plasma electrons are ejected from the laser path by the pondermotive force ($\propto \nabla I$)
- “Plasma bubble” is created when electrons are completely blown out of wake
- A thin electron sheath surrounds ionic core
Electro-optic shock second harmonic radiation

- Second harmonic light is generated within the electron sheath and emitted at a defined angle

Electro-Optic Shock

Cylindrical electron sheath

\[ n^{(0)} = n_0 \Delta \rho \delta(\rho - \rho_0) g(z - v_b t) h(z) \]

\( \Delta \rho \) is the sheath thickness

2\(^{nd}\) order current perturbation on sheath by pump laser

\[ j_2 = \frac{e c^2 n^{(0)} \partial a_1^2}{8 i \omega_0 \partial \rho} (3 \hat{x} \cos \phi - \hat{y} \sin \phi) + j_2 \hat{z} \]

\( k_0/|\partial_z g| \to \infty \) and \( \omega_0/\omega_p \to \infty \)

2\(^{nd}\) harmonic radiation (F.T.)

\[ \hat{A}_2 = -4 \pi^2 i S_0 J_1(k \rho_0 \sin \theta) \hat{g}(-\delta \omega/v_b) \hat{h}(K) \frac{e^{i kr}}{r/\rho_0} \]

where \( S_0 = -\frac{e c^2 n_0 \Delta \rho \partial a_1^2}{8 i \omega_0 c v_b \partial \rho} (3 \hat{x} \cos \phi - \hat{y} \sin \phi) \), \( K = \frac{\delta \omega}{v_b} + 2 k_0 - k \cos \theta \)

Neglecting bubble evolution

\[ \tilde{\theta}_c(\omega) = \cos^{-1}\left( \frac{c}{v_b} \frac{\delta \omega + 2 k_0 v_b}{\sqrt{\omega^2 - \omega_p^2}} \right) \]

\[ \theta_c = \tilde{\theta}_c(2 \omega_0) = \cos^{-1} \sqrt{\frac{e(\omega_0)}{e(2 \omega_0)}} \]
Conical Emission Angle

• Conical emission is not due to phase matching
• It is determined by a Cherenkov type angle
• It is similar to an electro-optic shock in a crystal*

\[
\cos \theta = \frac{v_\phi(2\omega_0)}{v_{\phi,s}} \approx \frac{v_\phi(2\omega_0)}{v_\phi(\omega_0)}
\]

Agrees with high-res 2D run to within 4%

FIG. 2 (color). 3D ray tracing image of the charge density in the $2 \times 10^{19}$ cm$^{-3}$ case. The laser pulse propagates to the right and slightly down. Red corresponds to $n_e = 0$, while blue corresponds to $n_e \approx 10^{20}$ cm$^{-3}$. The blue area furthest to the right is the electron sheath which emits the electro-optic shock.

\[ r_L = 5 \, \mu m \]
\[ \rho_0 = 2.9 \, \mu m \]
\[ \Delta \rho = 0.25 \, \mu m \]
Second Harmonic and Wake

Conical Wavefronts of 2nd harmonic

Laser polarization is out of the plane (in x-direction)

\[ E_{\perp}^2 (\omega_0 \text{ is filtered out}) \]
Miniworkshop on Extreme Intensity Laser and Science, National Taiwan University, Taipei, Taiwan, Dec. 17-19, 2009

NRL
Plasma Physics Division

Setup: TFL Laser System

![TFL Laser System Image]

**Ti:Sapphire Femtosecond Laser Parameters:**

- Wavelength: 800 nm
- Pulse length: 50 fs compressed
- Rep. Rate: 10 Hz
- Energy \( \leq \) 600 mJ/pulse
Setup: Experimental Chamber

- Interaction chamber
- Gas jet and plasma capillary
Experimental Setup

Laser Parameters:
- Center Wavelength: 800 nm
- Pulse Length: 50 fs compressed
- Energy: ~0.5 J/pulse
- Focusing Optics: ~f/10

*Screen was placed at focal/fourier plane to resolve angular distribution
• Spectrum from imaging spectrometer shows that second harmonic is being produced off-axis.
Azimuthal Distribution

- Intensity distribution as a function of azimuthal angle, $\phi$, for linearly polarized light.

[*D. F. Gordon, B. Hafizi, D. Kaganovich, and A. Ting, PRL 101, 045004 (2008).]
2nd Harmonic Distribution for High Plasma Density

Theoretical Prediction*

Experimental Results

Low Plasma Density

High Plasma Density

Second Harmonic Density Dependence

- Diameter (Cherenkov angle) increases as function of plasma density, until a certain point where the feature starts to break up.
Corresponding Density

- Combining dispersion relation with Cherenkov condition

\[ \theta = \cos^{-1}\left(\sqrt{4(\omega_o^2 - \omega_p^2)/(4\omega_o^2 - \omega_p^2)}\right) \]

- For range of \(6^\circ \leq \theta \leq 9^\circ\), plasma density is

\[2\times10^{19} \text{ cm}^{-3} \leq n_e \leq 6\times10^{19} \text{ cm}^{-3}\]

- This range is consistent with interferometric density measurements
• Plotting as a function of plasma density shows Cherenkov relation.
Linearly vs Circularly Polarized

- A circularly polarized pump produces a ring which carries orbital angular momentum*.

Multiple Rings

2.09E+19

3.17E+19

3.2E+19

4.41E+19
Optical Injection and Acceleration

Injector Laser

Accelerator Laser

Injector Electrons

Accelerated Electrons
Volumetric rendering of charge density behind the laser pulse as computed by turboWAVE. Orange is positive and blue-green is negative. The propagation direction is down and to the right. The orange “bubble” in the lower right is the ion-rich cavitation region, and the blue-green sheath surrounding it is a dense shell of electrons.
Experimental Setup

Angle scan: 0-50 degree

Laser power: 1-10 TW

Gas density: $2 \times 10^{18} - 3 \times 10^{19} \text{ cm}^{-3}$ (N$_2$ or He)

Electron spectrometer resolution 10% for 2 MeV electrons at 40°

Collimator F#30

Total electron charge around 40 degrees $> 1.5 \text{ nC}$
He gas density $4-6 \times 10^{18} \text{ cm}^{-3}$
Laser power 2.5 – 3 TW
No off-axis effects for N$_2$ gas, other gas densities, or higher laser power.
Electron Energy Distribution at 40°

- Background level
- Laser beam direction
- 1.5 MeV
Trajectory of a test electron superimposed on the wakefields produced in the $2 \times 10^{19}$ cm$^{-3}$ plasma: The laser fields have been suppressed using a Fourier filter, though their effect is visible on the particle trajectory.
Pre-Ionized vs. non-Pre-Ionized

Electrons transverse phase space for pre-ionized plasma. No polarization dependence.

Transverse phase space for the 2nd He electron, ionization included. Laser is horizontally polarized.
Second Harmonic and Electron Generation

- The first appearance of second harmonic coincided with the observation of off-axis monoenergetic electrons*. As the structure dissipated, on-axis electrons were detected.

Spectra of Multiple Rings

- Single shot wide band spectra using an imaging prism spectrograph
Spectra of Multiple Rings (Experiment and Theory)

- Self-modulated LWFA: two bubbles, 2 μm long separated by 6 μm
Angular Momentum of Photons

• The angular momentum of light has significance as a fundamental physical concept and in terms of applications such as rotating micromachines, trapping of particles, and others.

• The total angular momentum of free photons can be expressed as

\[ J = \frac{1}{2\pi c} \int d^3r \left[ \mathbf{E} \times \mathbf{A} + \sum_i E_i (\mathbf{r} \times \nabla) A_i \right] \]

The first term is sometimes identified with a spin contribution and the second with an orbital contribution.

• A nonlinear laser-plasma interaction can convert incident photons with purely spin angular momentum into frequency-doubled photons with equal parts spin and orbital angular momentum.
Nonlinear Conversion of Spin to Orbital Angular Momentum

- Diagram for the nonlinear conversion of spin to orbital angular momentum.

- Incoming photons $|k_0, 1\rangle$ interact with the virtual plasmon $|k_0 + k_p, 1\rangle$ which represents the perturbation $n_1$. The outgoing photon $|2k_0 + k_p, 2\rangle$ must have at least $\hbar$ units of orbital angular momentum, since photon spin can take only the values $\pm \hbar$. 

Wavy lines represent photons and braided lines represent plasmons.

Time increases upward.
Gaussian Modes with Orbital Angular Momentum

- A Laguerre–Gaussian beam with azimuthal mode number $\ell$ has an orbital angular momentum of $\ell \hbar$ per photon.

- To generate such a mode, the current density must also have an $e^{i\ell \varphi}$ dependence. In the case $\ell=1$, this means the source phase must rotate about the z axis once per optical cycle.

- The perturbed current on the thin sheath of the plasma bubble is

\[
j_2 = \frac{ec^2 n^{(0)}}{4i\omega_0} \partial_\rho a_0^2 (\hat{x} + i\hat{y}) e^{is\varphi}
\]

Density wave on a cylindrical shell of electrons, corresponding to the virtual plasmon in the Feynman diagram
Second Harmonic Electro-optical Shock with Orbital Angular Momentum

- Second-order scattered vector potential for the second harmonic in the Lorentz gauge

\[ A^{(2)} = \frac{mc^2}{e} h \left( \frac{c \tau}{\theta_c^2} \right) (\hat{x} + is\hat{y}) e^{is\varphi} a_2 e^{i\psi_2} + \text{c.c.} \quad s = \pm 1 \]
Conclusion

• Conical emission of second harmonic radiation into a Cherenkov angle has been experimentally established.
• This effect has been confirmed for both linearly and circularly polarized light.
• Off-axis electrons were observed when second harmonic radiation was generated. While on-axis were not observed until the structure had significantly broken up.
• This leads us to believe that it is the breaking of the bubble that initiates trapping and acceleration of on-axis electrons.
• For circularly polarized pump radiation, the second harmonic carries orbital angular momentum that is converted from the spin momenta.
• Experiments are currently underway to further study second harmonic dynamics, the properties of different gas species, Raman effects, and the observation of orbital angular momentum.