Plasma-Based Photonic Devices: Wave Plates, Polarizers, and Amplifiers

\[ G_I = -2k_0 \Im(\delta \eta)L/\eta_0 \]
\[ \Delta \phi = k_0 \Re(\delta \eta)L/\eta_0 \]

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Summary

Laser-plasma systems can be used as high-power, tunable photonic devices (e.g., wave plates, polarizers, and amplifiers)

- Recent experiments at Jupiter Laser Facility (JLF) have validated the linear theory* used to calculate cross-beam energy transfer (CBET) in direct- and indirect-drive inertial confinement fusion (ICF)

- Ultrafast, high-power, tunable laser-plasma wave plates** and polarizers† were also demonstrated using this stimulated Brillouin scattering (SBS)-based system

- Simulations illustrate how a new scheme (called “flying focus”) offers many advantages for stimulated Raman scattering (SRS)-based amplifiers

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Collaborators

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University of York
York Plasma Institute
CBET affects energy coupling and implosion symmetry in direct- and indirect-drive ICF.

Validating CBET models is an important component of simulating ICF implosions.
CBET theory* can be formulated as a laser-plasma system with a complex refractive-index perturbation operating on a probe beam.

Optical system = [plasma \((n_e, T_e, T_i, v_f, Z)\) + pump laser \((I_0, \alpha_{cr}) \to \delta \eta\)]

\[ I_{\text{beat}} = |E_0 + E_1|^2 \]

\[ \lambda_B = \frac{2\pi}{|k_0 - k_1|} \]

\[ \eta = (1 - n_e/n_c)^{1/2} \]

Interaction is anisotropic

\[ E_{1,\perp}' = E_{1,\perp} \]

\[ E_{1,\parallel}' = E_{1,\parallel}e^{ik_0\delta \eta L/\eta_0} \]

\[ \text{Im} (\delta \eta) \to \text{energy transfer} \]

\[ \text{Re} (\delta \eta) \to \text{phase delay} \]

 Beat wave

Refractive-index modulation

Such a system can modify the amplitude and/or polarization of the probe beam.

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A pump-probe experiment with wavelength tuning was carried out to measure $\delta \eta$ as a function of $\Delta \lambda$ (a new capability at JLF)

Polarization is generally elliptical because of induced phase delay.

\[
\Delta \varphi = \cos^{-1} \left[ \frac{(U_{45^\circ} - U_{135^\circ})/(U_{45^\circ} + U_{135^\circ})}{2 \sqrt{U_0^\circ U_{90^\circ}}/U_0^\circ + U_{90^\circ}}} \right]
\]

*TCC: target chamber center
$\delta \eta$ is in good agreement with linear theory using inputs from measurements and HYDRA*

This is the first time that the gain curve is resolved this accurately and found to be in good agreement with linear theory; the first measurement of $\text{Re} (\delta \eta)$ versus $\Delta \lambda$.

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$G_I = -2k_0 \mathcal{J}(\delta \eta) L/\eta_0$

$\Delta \phi = k_0 \mathcal{R}(\delta \eta) L/\eta_0$

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<tr>
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<th>HYDRA simulation</th>
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**Measurement did not include transport optic losses, inverse bremsstrahlung absorption, or the possibility of nonideal pump spot.

†Implies depletion of H from the interaction region.
Summary

Laser-plasma systems can be used as high-power, tunable photonic devices (e.g., wave plates, polarizers, and amplifiers)

- Recent experiments at Jupiter Laser Facility (JLF) have validated the linear theory used to calculate cross-beam energy transfer (CBET) in direct- and indirect-drive inertial confinement fusion (ICF)

- Ultrafast, high-power, tunable laser-plasma wave plates and polarizers were also demonstrated using this stimulated Brillouin scattering (SBS)-based system

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The system can act as a “plasma polarizer” with 85% to 87% extinction for these laser and plasma parameters.

\[ E_0, \lambda_0 \]

\[ E_1, \lambda_1 \]

\[ E_1, \perp \]

\[ \omega_1 - \omega_2 = -\omega_{\text{IAW}} \]: pure polarizer

\[ \frac{\Delta \lambda (\text{Å})}{G_I = -2k_0 \Im(\delta \eta) L/\eta_0} \]

\[ \Delta \phi = k_0 \Re(\delta \eta) L/\eta_0 \]

Counts

8000

6000

4000

2000

\(~85\% \text{ to } 87\% \text{ extinction}~

P. Michel et al., Phys. Rev. Lett. 113, 205001 (2014);
The system can also act as a pure tunable "plasma wave plate," which was demonstrated in the previous year’s campaign.

P. Michel et al., Phys. Rev. Lett. 113, 205001 (2014);
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A grating lens longitudinally disperses the focal positions of different colors within the pump bandwidth.

Typically used to correct chromatic aberration, here we propose using it to deliberately introduce chromatic aberration.

Variable line spacing

\[ G(r) = \frac{r \Delta \lambda}{L \lambda^2} \]
“Flying focus” refers to control over the propagation of high intensity within a laser focusing region.

With positive chirp and $Tc/L = 2$, high intensity travels at $c/3$. 

Positive chirp (red to blue)

Pulse length ($Tc/L = 2$)
It is advantageous for laser-plasma amplifiers that high intensity propagate at \(-c\)

With negative chirp and \(Tc/L = 2\), high intensity travels at \(-c\).
Chirp plus grating lens provides spatiotemporal control over propagation of high intensity

\[ \frac{v_f}{v_g} = \frac{1}{1 + TV_g/L} \]


*LWFA: laser wakefield accelerator*
Amplifiers based on stimulated Raman scattering* can also be used to create ultraintense laser beams

• Typically, the goal is to transfer most of the energy from a tens of picoseconds “long”-pulse beam to a frequency-downshifted ~100-fs beam

• Energy transfer is mediated by an electron plasma wave (EPW)

• Experiments have been limited by:
  – thermal effects
  – spontaneous SRS

Three-wave coupled equations, plus ionization model, are solved numerically* to investigate flying-focus Raman amplification (FFRA)

\[
\begin{align*}
(\partial_t - v_1 \partial_x + v_1) a_1 &= K a_2 a_3 \\
(\partial_t - v_2 \partial_x + v_2) a_2 &= -K a_2 a_3^* \\
(\partial_t - v_3 \partial_x + v_3 + i \delta \omega) a_3 &= -K a_1 a_2^* + s_3
\end{align*}
\]

\[
\begin{align*}
\partial_t n_e &= n_n w(a_1) \\
\partial_t n_n &= -n_n w(a_1)
\end{align*}
\]

\(v_{1,2}\): collisional damping  
\(v_3\): collisional/Landau damping  
\(v_3 \approx 0\): neglect EPW advection  
\(\delta \omega = 0\): neglect detuning  
\(S_3 \sim v_3 T_e\): tunable noise source

\(w(a)\) is ionization rate  
(Keldysh formula)

Flying focus is included via the time-varying boundary condition and intensification of pump as it propagates across interaction region.

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* D. S. Clark and N. J. Fisch, Phys. Plasmas 9, 2772 (2002);  
FFRA forms an ionization wave that travels at $-c$

Flying focus

$n_e = 6 \times 10^{18} / \text{cm}^3$

$I_p = 1.4 \times 10^{14} \text{ W/cm}^2$

4-mm length

26.7-ps pump

$\lambda_p = 1 \mu\text{m}$

f/5 pump
With an injected seed pulse, ideal plasma amplifier behavior is observed.

Flying focus

\[ n_e = 6 \times 10^{18}/\text{cm}^3 \]
\[ I_p = 1.4 \times 10^{14} \text{ W/cm}^2 \]
4-mm length
26.7-ps pump
\[ \lambda_p = 1 \mu\text{m} \]
f/5 pump
\[ \tau_{\text{seed}} = 500 \text{ fs} \]
\[ T_e \text{ controlled by IB}^* \]
\[ S_3 = 0.05v_3T_e \]

*IB: inverse bremsstrahlung
With a collimated pump, plasma is ionized earlier, growth is slower, and pump depletion does not occur.

**Standard focus**

- $n_e = 6 \times 10^{18}/\text{cm}^3$
- $I_p = 1.4 \times 10^{14} \text{ W/cm}^2$
- 4-mm length
- 26.7-ps pump
- $\lambda_p = 1 \mu\text{m}$
- $f/\infty$ pump
- $\tau_{\text{seed}} = 500 \text{ fs}$
- $T_e$ controlled by IB
- $S_3 = 0.05v_3T_e$
Temperature (approximately constant and tunable in FFRA) accounts for the difference between the previous two cases

- Duration of plasma heating prior to seed arrival is approximately constant in FFRA
- $T_e$ can be tuned by adjusting the delay between ionization and seed arrival

$T_e$ tunability can minimize damping, mitigate thermal detuning, prevent wave breaking, and preclude kinetic effects.
With $T_e$ fixed to look at nonthermal differences, spontaneous SRS grows and degrades the interaction.

Standard focus:
- $n_e = 6 \times 10^{18}$/cm$^3$
- $I_p = 1.4 \times 10^{14}$ W/cm$^2$
- 4-mm length
- 26.7-ps pump
- $\lambda_p = 1$ μm
- $f/\infty$ pump
- $\tau_{seed} = 500$ fs
- $T_e = 45$ eV
- $S_3 = 0.05v_3T_e$

FFRA also mitigates spontaneous SRS.
FFRA has many advantages over conventional schemes

- Interaction intensity follows the seed, without high f/# or a waveguide
- Can produce an ionization wave that immediately precedes seed
  - mitigates spontaneous SRS
  - eliminates thermal detuning
  - enables temperature optimization
  - enables a zero detuning amplifier without adverse side effects

*D. Turnbull et al., “Raman Amplification with a Flying Focus,” in preparation.*
Summary/Conclusions

Laser-plasma systems can be used as high-power, tunable photonic devices (e.g., wave plates, polarizers, and amplifiers)

- Recent experiments at Jupiter Laser Facility (JLF) have validated the linear theory* used to calculate cross-beam energy transfer (CBET) in direct- and indirect-drive inertial confinement fusion (ICF)

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The ion-acoustic wave (IAW) resonance peak location suggests an impact of ion-species separation

30% C matches the peak location

20% C (initial methane composition)

Most inputs are consistent with experimental measurements and/or a 3-D HYDRA simulation, but it is also necessary to invoke species separation to match the peak.

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*Measurement did not include transport optic losses, inverse bremsstrahlung absorption, or the possibility of nonideal pump spot.

**Implies depletion of H from the interaction region.
Recreating these conditions, ion-feature Thomson scattering will provide a more-direct measurement.

The idea is to probe the center of the channel to see if the Ar fraction increases because of the channel expansion dominated by H.

*All curves fix $T_e = 250$ eV, $T_i/T_e = 0.15$, $Z_{Ar} = 13$, $n_e = 10^{19}$ cm$^{-3}$
The refractive-index variation associated with the optical resonance also creates “slow” and “fast” light*

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Group velocity \( v_g = \frac{c}{\eta_g} = \frac{c}{\eta - \lambda \frac{\partial \eta}{\partial \lambda}} \), so \( \eta_g \) can be large near optical resonance.

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Slow and fast light have been demonstrated in other media, but not yet in plasma.

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The group index scales like gain over the resonance bandwidth

- Group velocity slows to $\sim c/25$ by increasing $n_e$ and $I_p$ by factors of $\sim 3$
- Now it takes $\sim 80$ ps to propagate across the 1-mm interaction length (as opposed to $\sim 3$)

From the existing literature on slow light, the implications for such dramatic changes to group velocity are not clear.
We will exploit the anisotropic system again to directly measure the delays between polarization components.

We aim to better understand and help clarify the nature of SBS-based slow/fast light.
The tunable OMEGA P9 beam (TOP9) will be used to develop a CBET platform at the Omega Laser Facility.

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<td>λ range</td>
<td>350.2 to 353.4 nm</td>
</tr>
<tr>
<td>λ step size</td>
<td>0.01 nm</td>
</tr>
<tr>
<td>Power on target</td>
<td>0.1 TW (351 nm to 352.6 nm) 0.01 TW (350.2 nm to 353.4 nm)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear (20:1 contrast), ±90° range</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>90 min</td>
</tr>
<tr>
<td>Spot size</td>
<td>Compatible with existing OMEGA distributed phase plates</td>
</tr>
<tr>
<td>Additional</td>
<td>FABS* and TBD** diagnostics</td>
</tr>
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*FABS: full-aperture backscatter
**TBD: transmitted-beam diagnostic
Initial experiments will test CBET in ICF-relevant conditions and investigate the onset of nonlinearities.

The previous two-beam experiments can be repeated with $T_e$ and $n_e$ closer to ICF, then seed intensity will be increased to probe the nonlinear regime.
OMEGA will facilitate the study of multiple IAW’s coexisting in the same volume

Three- to six-beam measurement

This tests CBET under conditions that are relevant to both direct and indirect drive.
CBET beamlets* experiments using TOP9 will demonstrate CBET mitigation via wavelength detuning.

This configuration will be a robust test of our integrated CBET hydrodynamic models and demonstrate CBET mitigation using wavelength shifting.

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