Flying Focus: Spatiotemporal Control of Intensity for Laser-Based Applications

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A chirped laser pulse focused by a chromatic lens exhibits a dynamic, or “flying,” focus*

- The flying focus provides unprecedented spatiotemporal control over laser-plasma interactions by decoupling
  - the spot size of the pulse from the focal range
  - the velocity of the peak intensity from the group velocity
- Experiments have demonstrated the flying focus and the ability to generate ionization waves at any velocity (IWAV)
- Flying focus was applied to several applications
  - photon accelerator: IWAV’s can shift visible laser light to the XUV
  - Raman amplification: flying focus could overcome several challenges of laser-plasma amplifiers
  - Cherenkov radiation: flying focus allows new radiation sources
  - vacuum electron acceleration: flying focus enables vacuum acceleration

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XUV: extreme ultraviolet
We have an outstanding research team working on the flying focus and its applications


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Ideal lenses limit the region of high intensity to the Rayleigh range.

For fixed pulse power ($P$), increasing the Rayleigh range necessarily decreases the intensity, $I \sim \frac{P}{\omega_0^2} \sim \frac{P}{L_R}$. 

$\omega_0 = \frac{2f\lambda}{\pi D}$

$L_R = \frac{\pi\omega_0^2}{\lambda}$
A diffractive lens has a different focal length for each color

\[ L_f = \frac{(\Delta \lambda/\lambda)f}{\lambda} \]

With only 10 nm of bandwidth, the distance separating focused colors can be \(~100\times\) greater than the Rayleigh length, extending the range of high intensity.
Combining a diffractive lens with a chirped laser pulse provides spatiotemporal control over the focus.

The spectral phase of the pulse determines the time at which color reaches focus, resulting in a peak intensity with a dynamic trajectory.
The dynamic focus can propagate over $100 \times$ the Rayleigh length of the system.

$$L = \frac{\Delta \lambda}{\lambda} f_0 \approx 4.5 \text{ mm}$$

$\lambda_0 = 1054 \text{ nm}$

$\Delta \lambda = 9.2 \text{ nm}$

$f_0 = 511 \text{ mm}$

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By varying the pulse duration (chirp) of the laser ($T$), the velocity of the focus can be controlled.

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By changing the direction of the chirp (blue to red) the focus can be made to counter-propagate.
Reducing the pulse duration of the negatively chirped beam (blue to red) produces a focal velocity faster than the speed of light.
Setting the pulse duration equal to the focal range \((L/c)\) results in an “infinitely” fast focal velocity (line focus).
A simulation of the focal region shows that the peak intensity of the flying focus propagates with a self-similar form.

The longitudinal profile of the intensity peak depends only on space and time in the combination

\[
\left[1 - \frac{\Delta \lambda (z - ct)}{\lambda c T}\right]^{-1} z
\]

Outline

• Description of the flying focus
• **Experimental demonstration of the flying focus**
  • Ionization waves of arbitrary velocity (IWAV’s)
  • Applications of the flying focus
The Multi-Terawatt (MTW) laser at the University of Rochester’s Laboratory for Laser Energetics (LLE) was used to demonstrate the flying focus.

- OPCPA front end and Nd:glass amplifiers (1053-nm, 10-nm bandwidth)
- 0.7 ps to 300 ps up to 50 J

OPCPA: optical parametric chirped-pulse amplifier
SHG: second-harmonic generation
A picosecond optical streak camera imaged the intensity profile of the flying focus

Several locations in the focal region were imaged onto a streak camera, providing the spatiotemporal profile of the flying focus pulse.
The measurements show excellent agreement with the analytic calculations

Focal velocity:

\[
\frac{v_f}{c} = \left(1 \pm \frac{cT}{L}\right)^{-1}
\]

\(T\): stretched pulse duration

\(L = f_0 \frac{\Delta \lambda}{\lambda_0} \approx 4.5\) mm

\(\lambda_0 = 1054\) nm

\(\Delta \lambda = 9.2\) nm

\(f_0 = 511\) mm

The measured images provided space and time information that were reconstructed to generate the focal intensity in space.
The images form a movie of the flying focus (~3 ps/frame)

Positive chirp (65 ps)

Negative chirp (55 ps)
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Positive chirp (65 ps)

Negative chirp (55 ps)
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The flying focus pulse can be used to generate an ionization wave of arbitrary velocity (IWAV).

Counter-propagating flying focus mitigates ionization-induced refraction.

The flying focus pulse can be used to generate an IWAV

A counter-propagating flying focus mitigates plasma refraction and produces a sharp ionization front.
To study IWAV’s in the laboratory, a spectrally resolved schlieren diagnostic was used.

Chirped probe (1$\omega$)

Chirped probe (2$\omega$)

Spectrally (time) resolved schlieren

$\Delta \lambda \propto \Delta t$

$\frac{\Delta z}{\Delta \lambda} \propto \frac{\Delta z}{\Delta t}$

P. Franke, UP11.00093 this conference.
CCD: charge-coupled device
The analytic calculations and simulations are in excellent agreement with the measurements.

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- Description of the flying focus
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The flying focus could be used extend the interaction length in a photon accelerator

A photon accelerator uses a time-varying refractive index to increase the group velocity of light

Density scale length ($L_s$)

Laser pulse

$\xi = z - v_i t$

Index of refraction

$$n = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \quad \omega_p \propto \sqrt{n_e}$$

Frequency shift

$$\frac{\Delta \omega}{\omega} = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \frac{Z_{\text{effective}}}{L_s}$$
The flying focus could be used to extend the interaction length in a photon accelerator.

A photon accelerator uses a time-varying refractive index to increase the group velocity of light.

\[ v_g = z - v_i t \]

Density scale length \( (L_s) \)

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\[ n = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \quad \omega_p \propto \sqrt{n_e} \]

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Density scale length ($L_s$)

- $n_e$
- $v_i$
- $v_g$

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As the photons accelerate, they eventually outrun the ionization front in a “conventional” photon accelerator.
By using the flying focus to generate ionization waves propagating at the speed of light, optical light can be frequency converted to the extreme ultraviolet.

The photon accelerator driven by a flying focus could convert optical light to the extreme ultraviolet (100 nm).

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The photon accelerator driven by a flying focus could convert optical light to the extreme ultraviolet (100 nm).

A counter-propagating ionization wave could overcome several challenges of Raman amplification

- **Constant longitudinal intensity**: the seed pulse experiences a constant pump intensity over the entire amplifier length
- **Counter-propagating ionization wave**: the pump will propagate through gas-eliminating parasitic instabilities
- **Plasma conditions**: the plasma conditions observed by the seed will be constant and controllable

EPW: electron plasma wave
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The flying focus could enable new sources by decoupling the group velocity of light from the driver velocity.

Cherenkov radiation (THz source*)

Cherenkov radiation requires: \( v_{\text{driver}} > v_{\phi} \)

\[ v_{ff} = v_{\phi}^{\text{THz}} \]

Cherenkov radiation is typically prohibited in a non-magnitized plasma (\( v_{gr} < v_{\phi} \)).

The flying focus can generate Cherenkov radiation in a plasma.

Magnitude of Poynting flux

The flying focus enables Cherenkov radiation in a plasma by propagating the driver faster than the phase velocity of the radiation.

The flying focus can be used to phase match THz radiation in a crystal and extend the frequency-conversion process by orders of magnitude.

Simulations show on-axis phase matching in crystals over 1 cm,* otherwise constrained to off-axis phase matching.

A zoom lens system enables the flying focus velocity to be tuned for a given chirp.

The flying focus enables a novel mechanism for direct vacuum electron acceleration*  

Dillon Ramsey  
PAS  
Grad student

Lawson–Woodward Theorem: the net energy gain for an electron in a laser pulse is zero.  

In a flying focus pulse, electrons that overtake the laser pulse will exit with a longitudinal momentum.

Flying focus overcomes the Lawson–Woodward Theorem: electrons can extract energy from the laser pulse.
Summary/Conclusions

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This decoupling has the potential to enable or improve several laser-based applications.

Thank you for your attention

3-D calculations  
(counter-propagating flying focus)

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Time</th>
</tr>
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<tbody>
<tr>
<td>D. Turnbull</td>
<td>Ionization Waves of Arbitrary Velocity</td>
<td>4:12 pm, Monday, Nov. 5</td>
</tr>
<tr>
<td>J. Palastro</td>
<td>Cherenkov Radiation from a Plasma</td>
<td>3:24 pm, Tuesday, Nov. 6</td>
</tr>
<tr>
<td>A. Howard</td>
<td>Photon Acceleration in the Ionization Front of a Flying Focus</td>
<td>4:48 pm, Tuesday, Nov. 6</td>
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<tr>
<td>P. Franke</td>
<td>Ionization Waves of Arbitrary Velocity</td>
<td>2:00 pm, Thursday, Nov. 8</td>
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