Nonlinear Spatiotemporal Control of Laser Intensity

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Summary

A novel technique called the ‘self-flying focus’ has been developed, enabling control of a laser intensity peak for distances comparable to a lens focal length.

- The self-flying focus combines temporal pulse shaping in the near field with nonlinear self-focusing in the far field to provide spatiotemporal control of laser intensity.
- The technique does not require advanced focusing optics: the instantaneous power controls the intensity peak location and the shape (slope) controls the velocity.
- The self-flying focus can utilize long, low power pulses where short, high power pulses are conventionally required.
- The self-flying focus can produce a meter long, highly uniform plasma for advanced accelerator concepts, particularly the dephasingless laser wakefield accelerator.

*Simpson et al. submitted (2020)  **Palastro et al. PRL (2020)
For a focused laser beam, the region of high intensity is limited to the Rayleigh range, while the intensity peak moves at the group velocity.

Many applications benefit from a sustained intensity or a more tunable intensity peak trajectory.
Spatiotemporal couplings can structure a pulse to control the intensity peak velocity; more advanced schemes can also extend the region of high intensity.

Current techniques achieve spatiotemporal control with linear optics, but couplings from nonlinear optics can also modify pulse propagation.

Self-focusing will affect a laser pulse differently depending on its power relative to the critical power, $P_c$

Within a pulse, the instantaneous power controls the amount of self-focusing, while the shape controls the timing between adjacent foci.

\[ v_c \propto \frac{P_1 - P_2}{\Delta t} \]
Each temporal slice composing a laser pulse will experience a focusing effect dependent on its power.

A shaped pulse, like those developed for inertial fusion, can drive an intensity peak at any velocity.
An arrest mechanism (e.g., ionization) halts self-focusing near the collapse point and ensures a nearly constant on-axis intensity.

As each slice reaches arrest at a different location, the intensity peak duration is much shorter than the overall pulse duration.

$$\frac{P(t)}{P_c} = \left[ \left( \frac{w_i}{w_f} \right) \left( \frac{1}{Z_c(t)/f} - 1 \right) \right]^2 + 1$$
A large spot size ratio creates a steeper power profile, greater energy expenditure, and larger arrested spot size for the same $L_c/f$. 

The power and energy can be tuned to meet a wide range of laser requirements by adjusting the focal geometry.
The self-flying focus can drive an intensity peak over large distances, making it an obvious choice for producing long plasma channels.

\[
\left(\nabla^2_\perp + 2ik_0 \frac{\partial}{\partial z}\right)E_\perp(r, \xi) = \left(-2k_0^2n_2l + k_p^2\right)E_\perp(r, \xi) - Q_{FI} - Q_{IB}
\]

Parameters are chosen to minimize the accelerator length of the recently proposed dephasingless laser wakefield accelerator.*

*Palastro et al. PRL (2020)
The self-flying focus mitigates ionization refraction by propagating backwards and can create a plasma at the velocity of relativistic accelerated electrons.
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