Nonlinear Spatiotemporal Control of Laser Intensity

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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.

Tilted pulse front method for THz generation

Original ‘Flying focus’ using chromatic aberration and temporal chirp

\[ \tau = \frac{2l}{c} \]

Figure from Franz Kartner website

*Hebling et al. Opt. Express (2002)  **Froula et al. Nat. Photonics (2018)
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.

\[
\frac{P(t)}{P_c} = \left[ \left( \frac{w_i}{w_f} \right) \left( \frac{1}{Z_c(t)/f} - 1 \right) \right]^2 + 1
\]
The power and energy can be tuned to meet a wide range of laser requirements by adjusting the focal geometry.

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 self-flying focus can drive an intensity peak over large distances, making it an obvious choice for producing long plasma channels.

\[ \left( \nabla_\perp^2 + 2ik_0 \frac{\partial}{\partial z} \right) E_\perp (r, \xi) = (-2k_0^2n_2 I + k_p^2) E_\perp (r, \xi) - Q_{FI} - Q_{IB} \]

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.
Summary

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