Spatiotemporal control of laser intensity through cross-phase modulation

\[ \nu_f > c \]

\[ L_f \approx 33Z_R \]

\( \nu_f = 1.01c \)

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A new method for spatiotemporal control of laser intensity can create pulses with arbitrary velocity, transverse profile, duration, or orbital angular momentum.

Spatiotemporal pulse shaping provides control over the velocity and range of a laser intensity peak, but existing techniques constrain the duration, profile, or orbital angular momentum.

In a nonlinear medium, a temporally shaped, high intensity “stencil” pulse can impart a time-dependent focusing phase onto a second, “primary” pulse through cross-phase modulation (XPM).

This offloads the constraints of spatiotemporal control onto the copropagating “stencil” pulse.

This technique, the “flying focus X”, can create an ultrashort, arbitrary trajectory intensity peak over distances much longer than a Rayleigh range.

*Simpson et al. (in review) 2021*
Spatiotemporal control of laser intensity provides an arbitrary velocity intensity peak over distances much larger than a Rayleigh range.

Conventional optics

- The region of high intensity is limited to the Rayleigh range, $Z_R$
- The peak intensity travels at the group velocity, $v_g$

A tunable velocity and extended region of high intensity can enable or enhance several laser-based applications*

*See presentations by Franke, Palastro, and Ramsey, this session
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**Spatiotemporal control**

- Chromatic aberration and chirp control the time and location of the focus

*See presentations by Franke, Palastro, and Ramsey, this session*
Existing techniques for spatiotemporal control constrain properties, such as the transverse profile, duration, or orbital angular momentum.

Chromatic focusing of a chirped laser pulse*

\[ \tau = \frac{4l}{c} \]

Spherical aberration and a radial delay**

Tunable velocity and transverse profile, but intensity peak durations longer than ~1ps

Near transform-limited duration, but limits focal velocity and profile

*Froula et al. (2018) **Palastro et al. (2020)
The constraints of spatiotemporal control can be mitigated by using the interaction of two pulses in a nonlinear medium.

Through cross-phase modulation, a “stencil” pulse can modify the phase of a “primary” pulse in a nonlinear medium with $n_2 > 0$. 
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Nonlinear medium

Filter

$\text{Primary Pulse}$

$n_2 > 0$

$\text{Stencil Pulse}$
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Through cross-phase modulation, a “stencil” pulse can modify the phase of a “primary” pulse.

Refractive index assuming $I_S \gg I_P$

$$n = n_0 + 2n_2I_S$$

$n_2 > 0$
By shaping the nonlinear medium, the stencil can apply an intensity-dependent focusing phase to the primary

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\[ f_k = \frac{R}{2n_2I_s} \]

Radius of curvature

Far field

Primary pulse

Stencil pulse

Kerr lens

Filter

\[ n_2 > 0 \]
The temporal profile of the stencil pulse determines the time-dependent focusing of the primary pulse.

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Time-dependent focal length

\[ f_k(t) = \frac{R}{2n_2 I_s(t)} \]
The focal velocity can be tuned for a given focal range by adjusting the pulse duration.

A ramp-down stencil produces positive, subluminal focal velocities.
The focal velocity can be tuned for a given focal range by adjusting the pulse duration.

A long ramp-up stencil produces negative focal velocities.
The focal velocity can be tuned for a given focal range by adjusting the pulse duration.

A short ramp-up stencil produces positive, superluminal focal velocities.
The flying focus X produces a focus with ideal wavefront curvature, enabling spatiotemporal control for an arbitrary transverse profile.

The transverse structure of any Laguerre-Gauss mode (including those with OAM) is preserved.

The focus is nearly diffraction limited and the intensity peak can be ultrashort.

Photon accelerator using a structured flying focus*

Dephasingless laser wakefield accelerator with an ultrashort pulse**

*Franke (this session) **Palastro et al. (2020)
Simulations verify that the flying focus X can create an ultrashort duration orbital angular momentum pulse with a superluminal focal velocity.

### Optical configuration

| Parameter                  | Value       |
|----------------------------|-------------|
| $n_2$ (cm$^2$/W)           | $8.5 \times 10^{-15}$ |
| $I_S^{max}$ (W/cm$^2$)     | $1.7 \times 10^{10}$ |
| Focal length (cm)          | 60          |
| Initial spot size (cm)     | 2           |
| $\tau_s$ (fs)              | 330         |

### Far field

| Parameter                  | Value |
|----------------------------|-------|
| Focal spot size (μm)       | 10    |
| $L_f$ (cm)                 | 1     |
| $v_f/c$                    | 1.01  |
| $\tau_f$ (fs)              | 20    |
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$v_f = 1.01c$  
$L_f = 33Z_R$
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