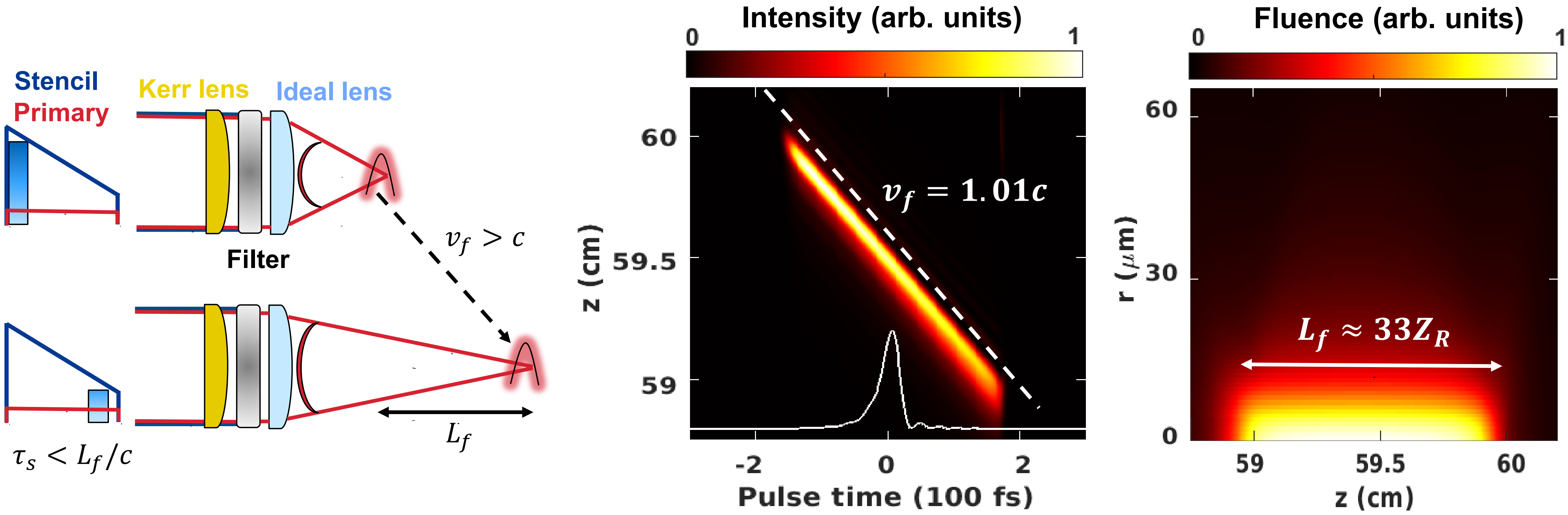
Spatiotemporal control of laser intensity through cross-phase modulation



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K. Weichman, D. Turnbull, D.H. Froula, and J.P. Palastro
Laboratory for Laser Energetics
University of Rochester

63rd Annual APS DPP Meeting
Pittsburgh, PA
November 9th-13th, 2021

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)

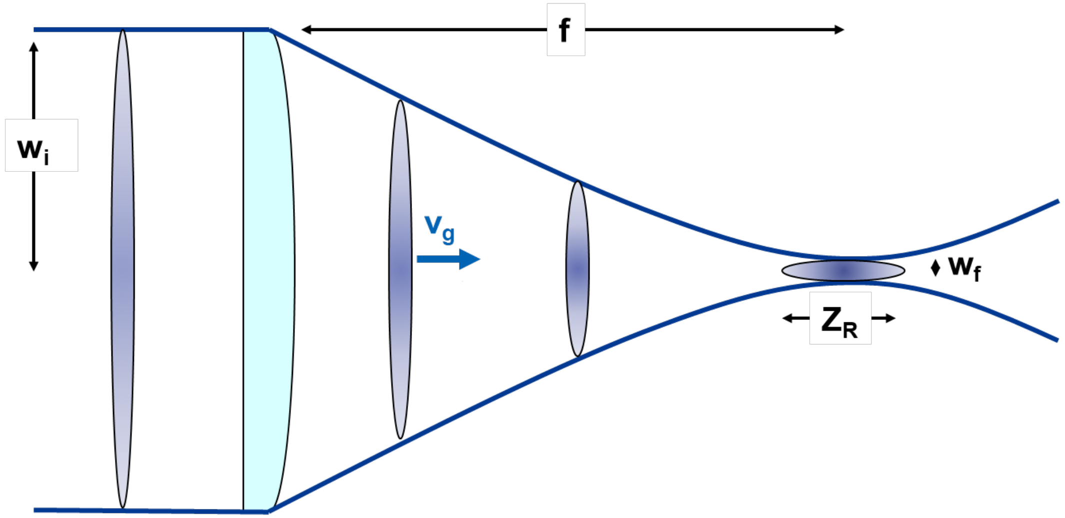
This offloads the constraints of spatiotemporal control onto the copropagating “stencil” pulse

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

Spatiotemporal control

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

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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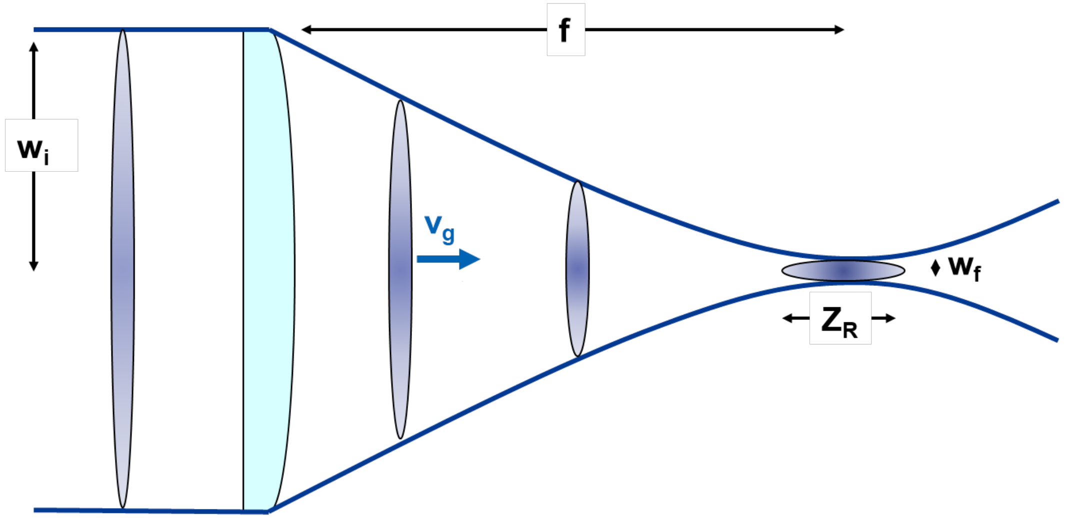

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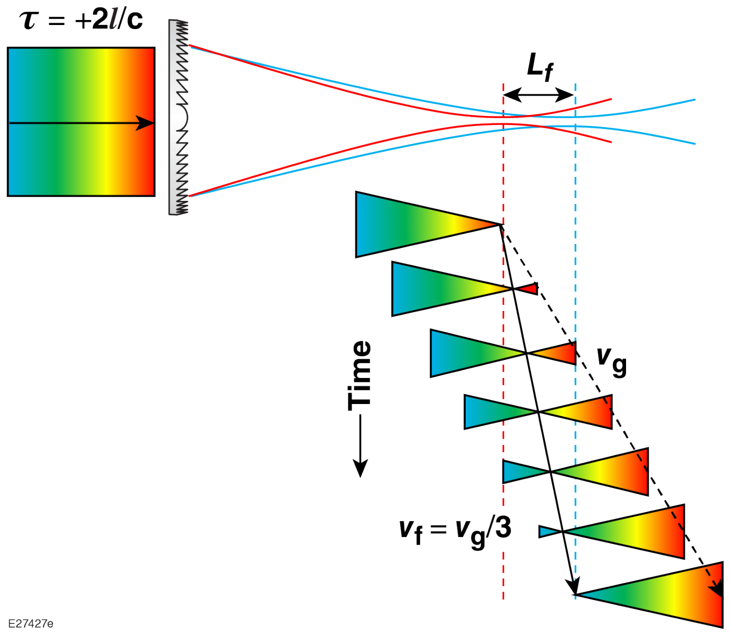
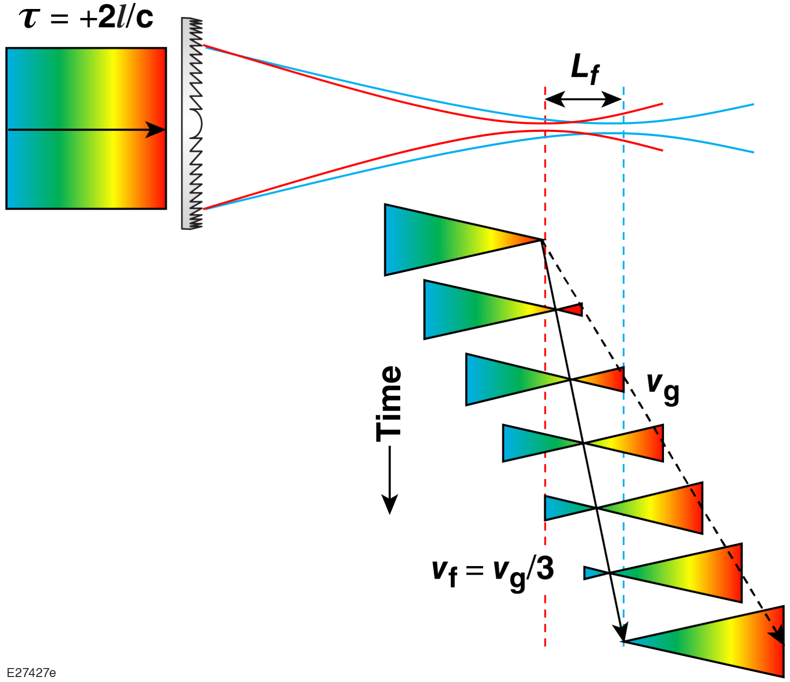


- Chromatic aberration and chirp control the time and location of the focus

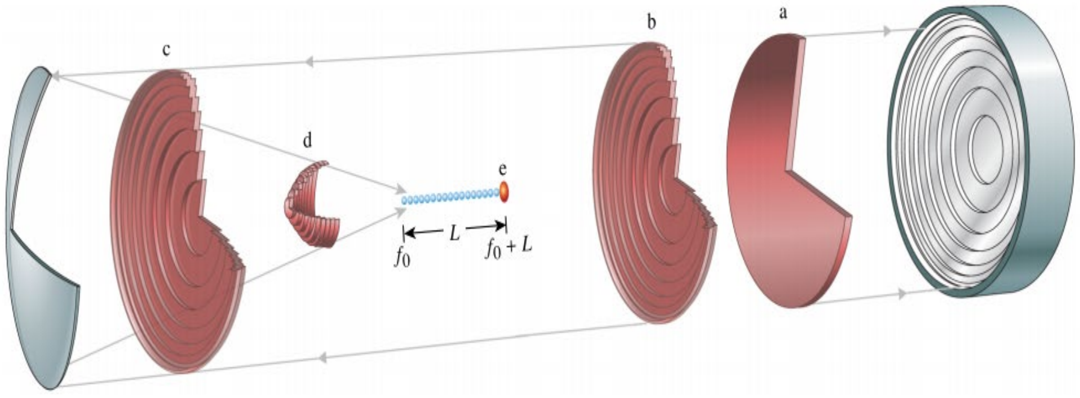
A tunable velocity and extended region of high intensity can enable or enhance several laser-based applications*

Existing techniques for spatiotemporal control constrain properties, such as the transverse profile, duration, or orbital angular momentum

Chromatic focusing of a chirped laser pulse*



Spherical aberration and a radial delay**



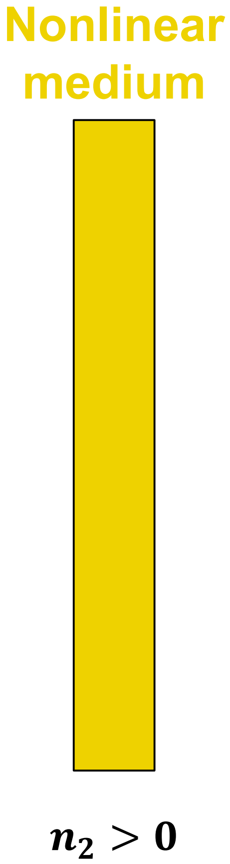
Tunable velocity and transverse profile, but intensity peak durations longer than ~1ps

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



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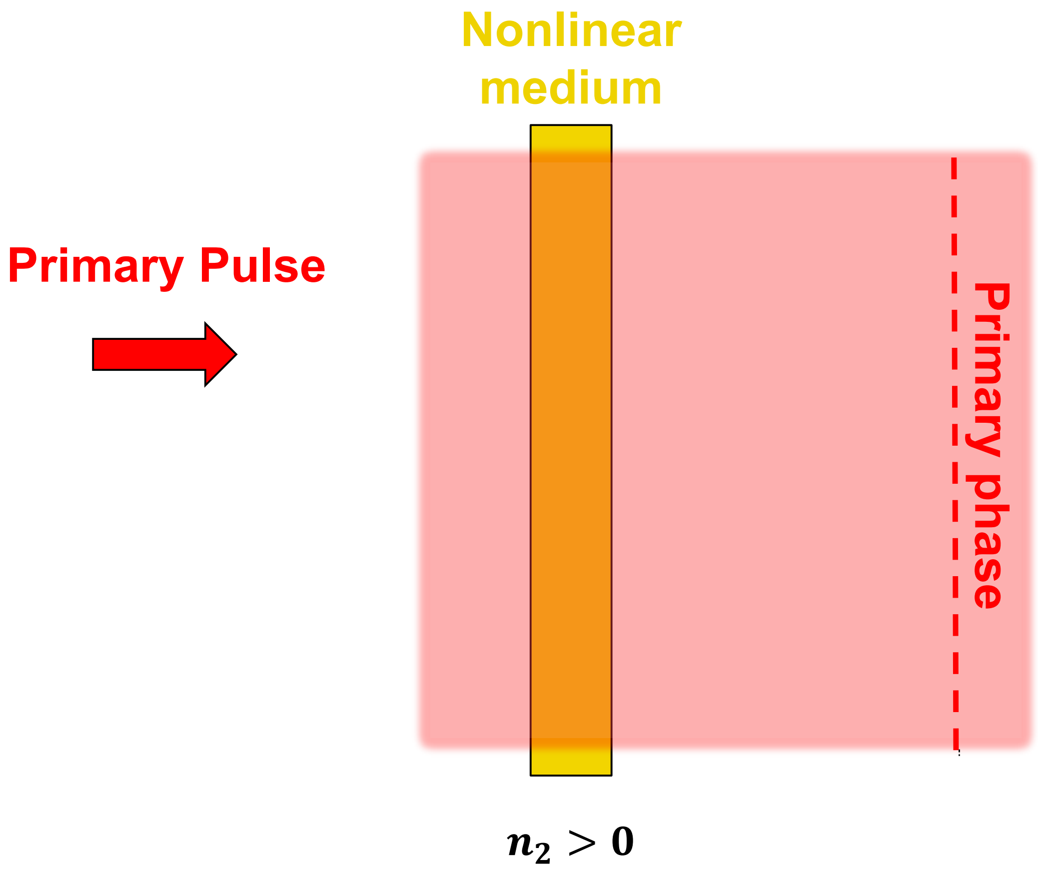

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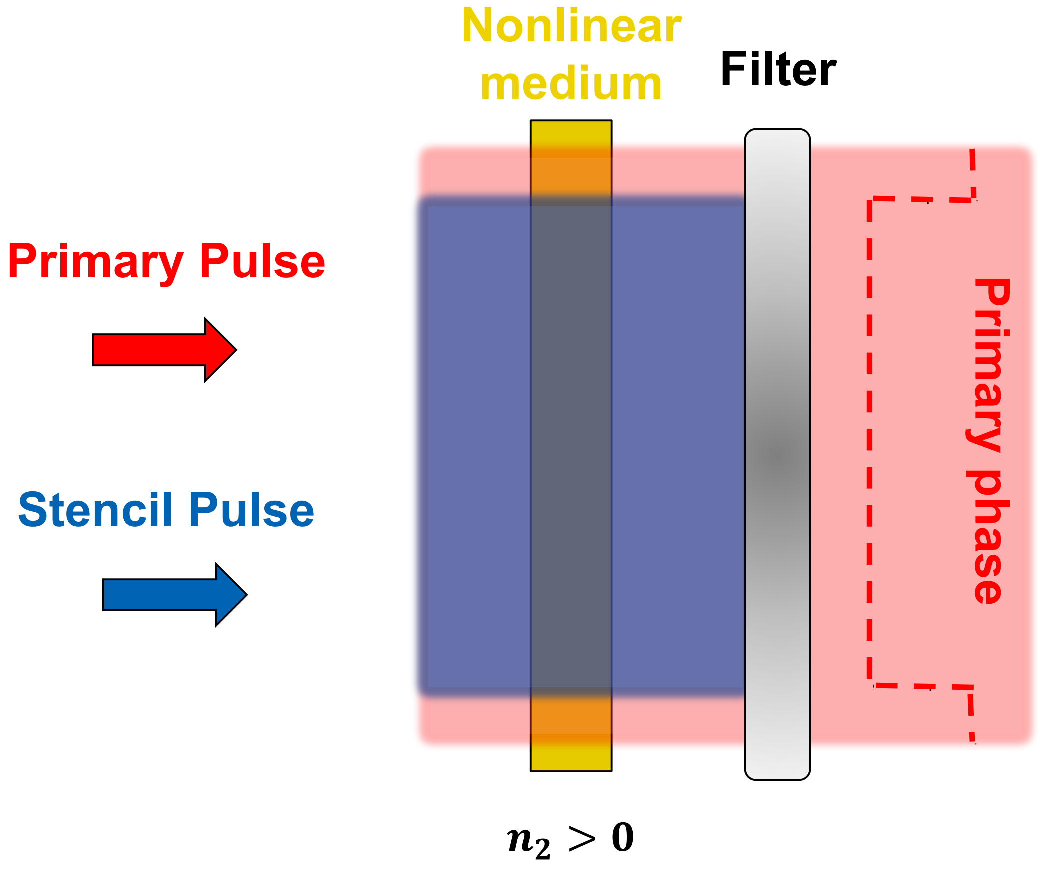

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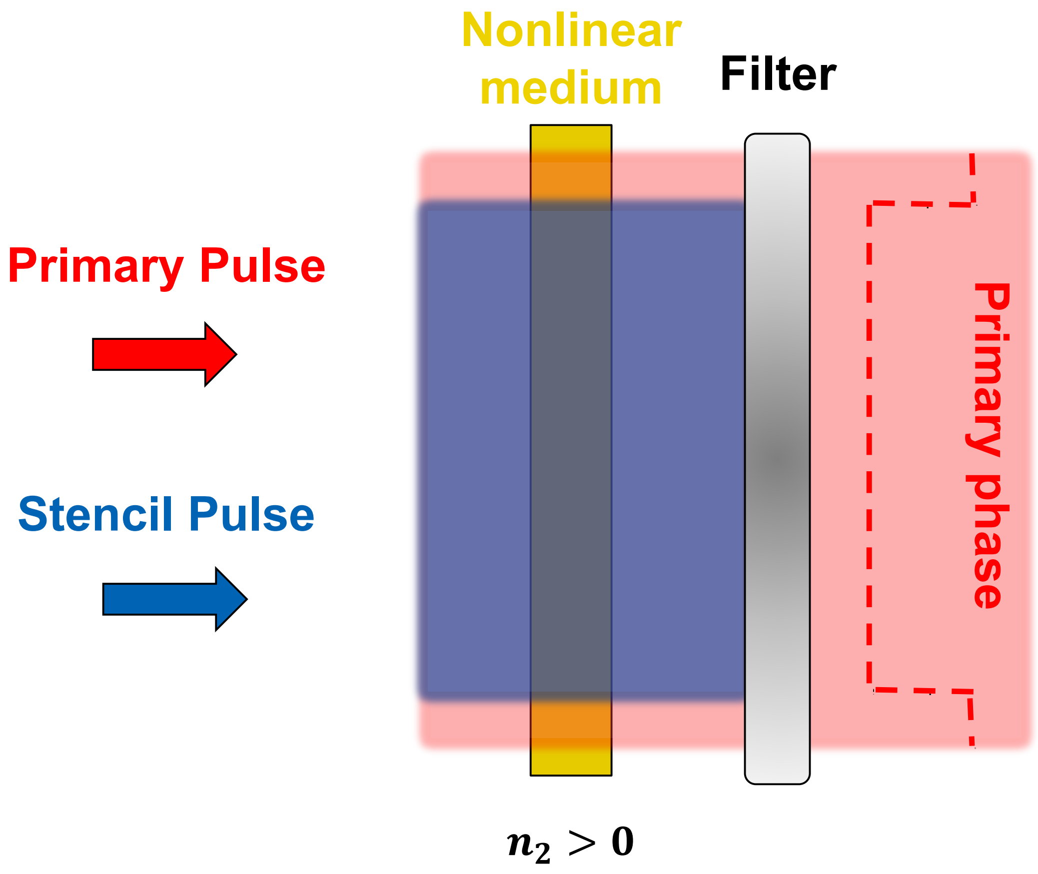

Refractive index assuming $I_S >> I_P$

$$n = n_0 + 2n_2 I_S$$

Linear refraction

Nonlinear refraction

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

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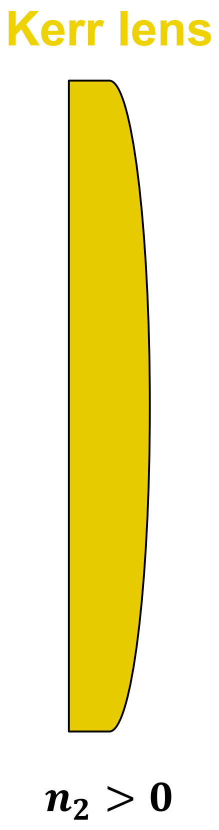

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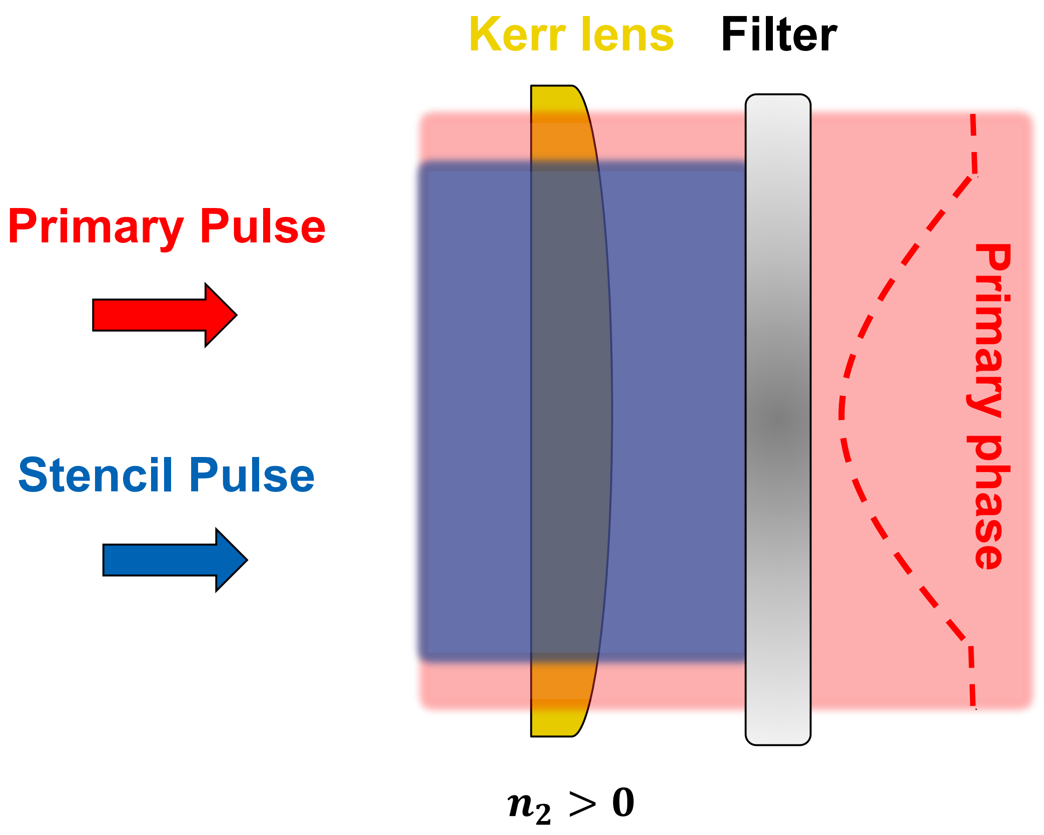

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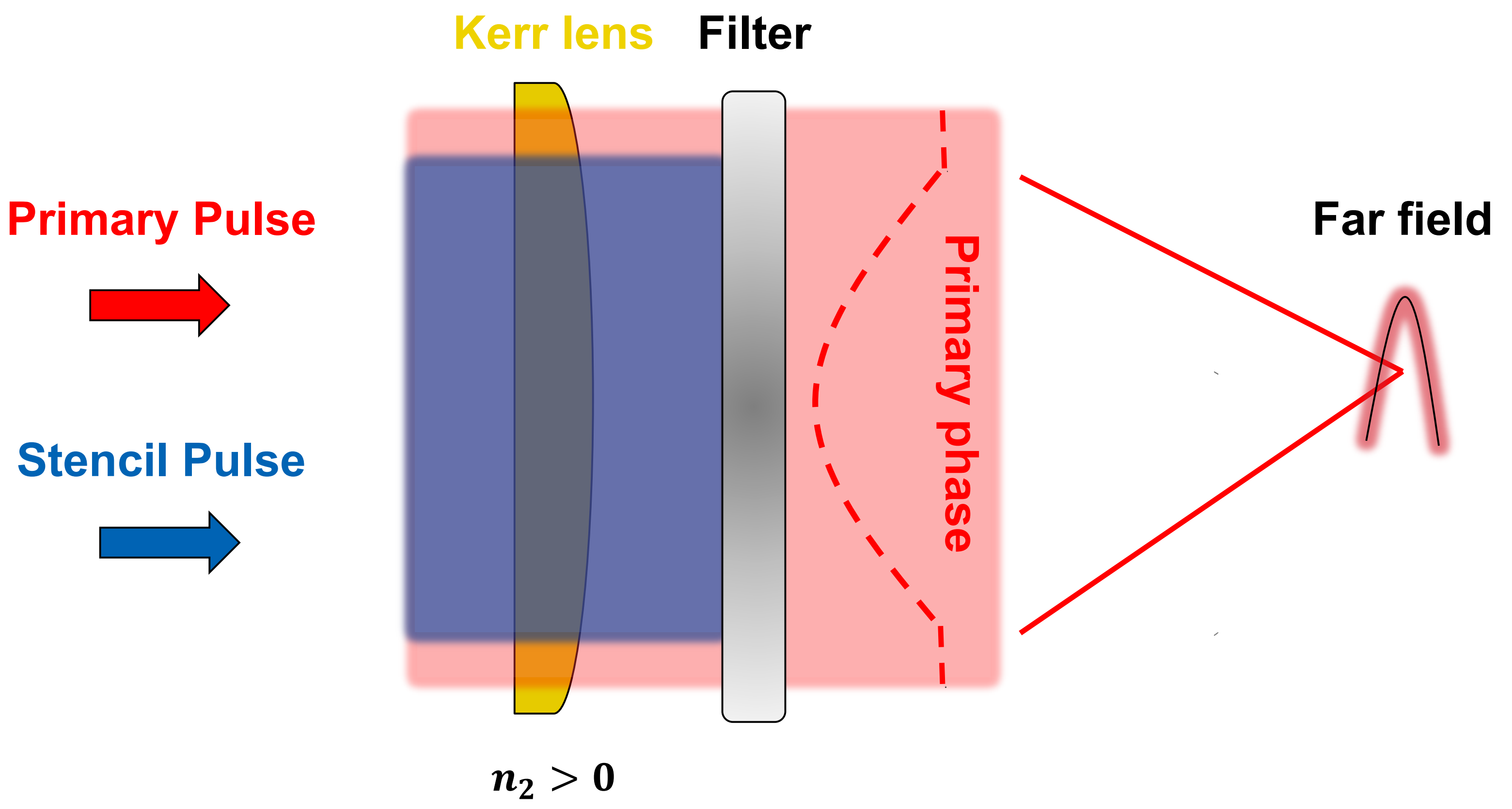

Focal length assuming $I_S >> I_P$

$$f_k = \mathrm{R}/2\mathrm{n}_2\mathrm{I}_s$$

Radius of curvature

The temporal profile of the stencil pulse determines the time-dependent focusing of the primary

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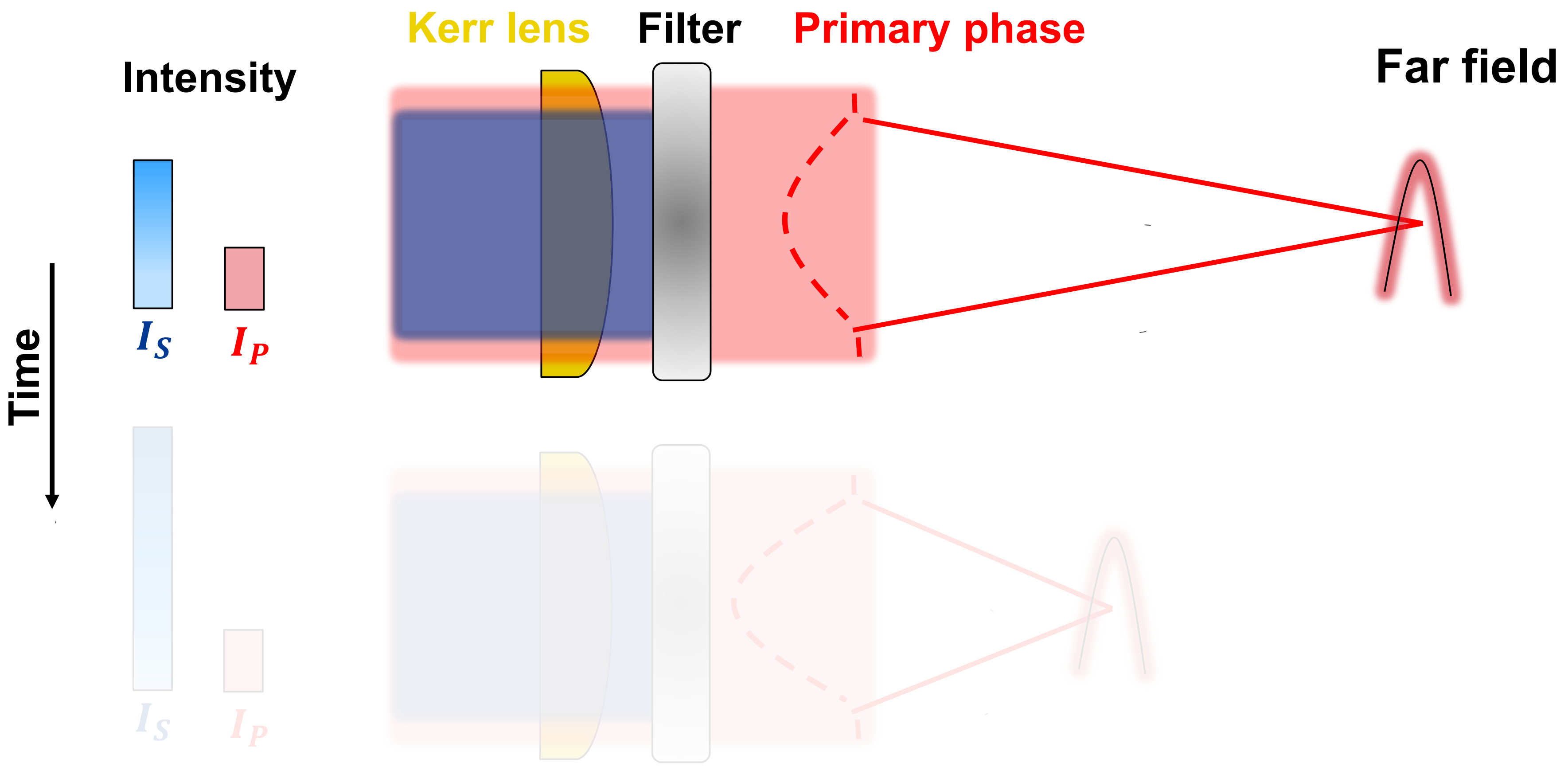

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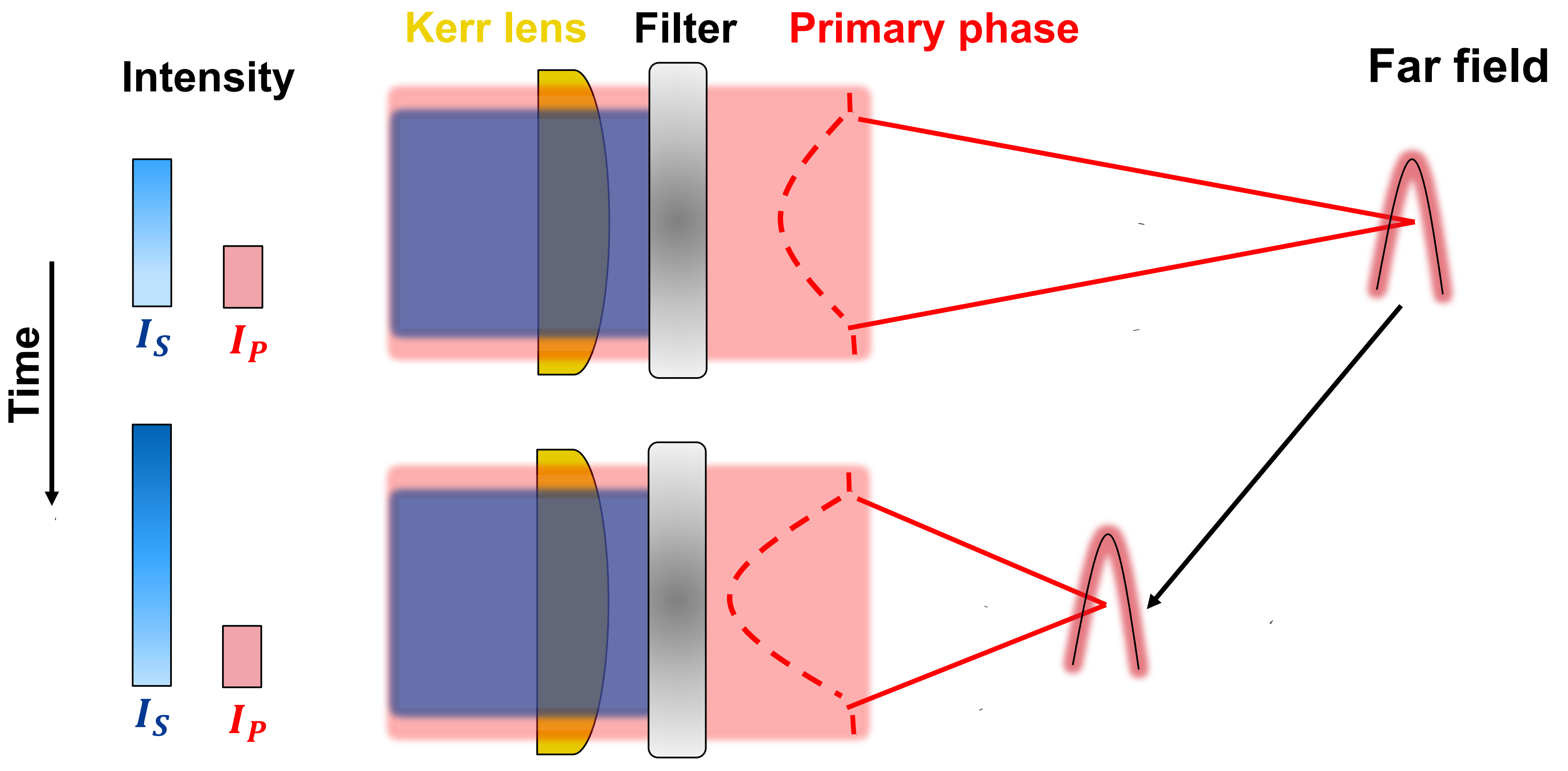

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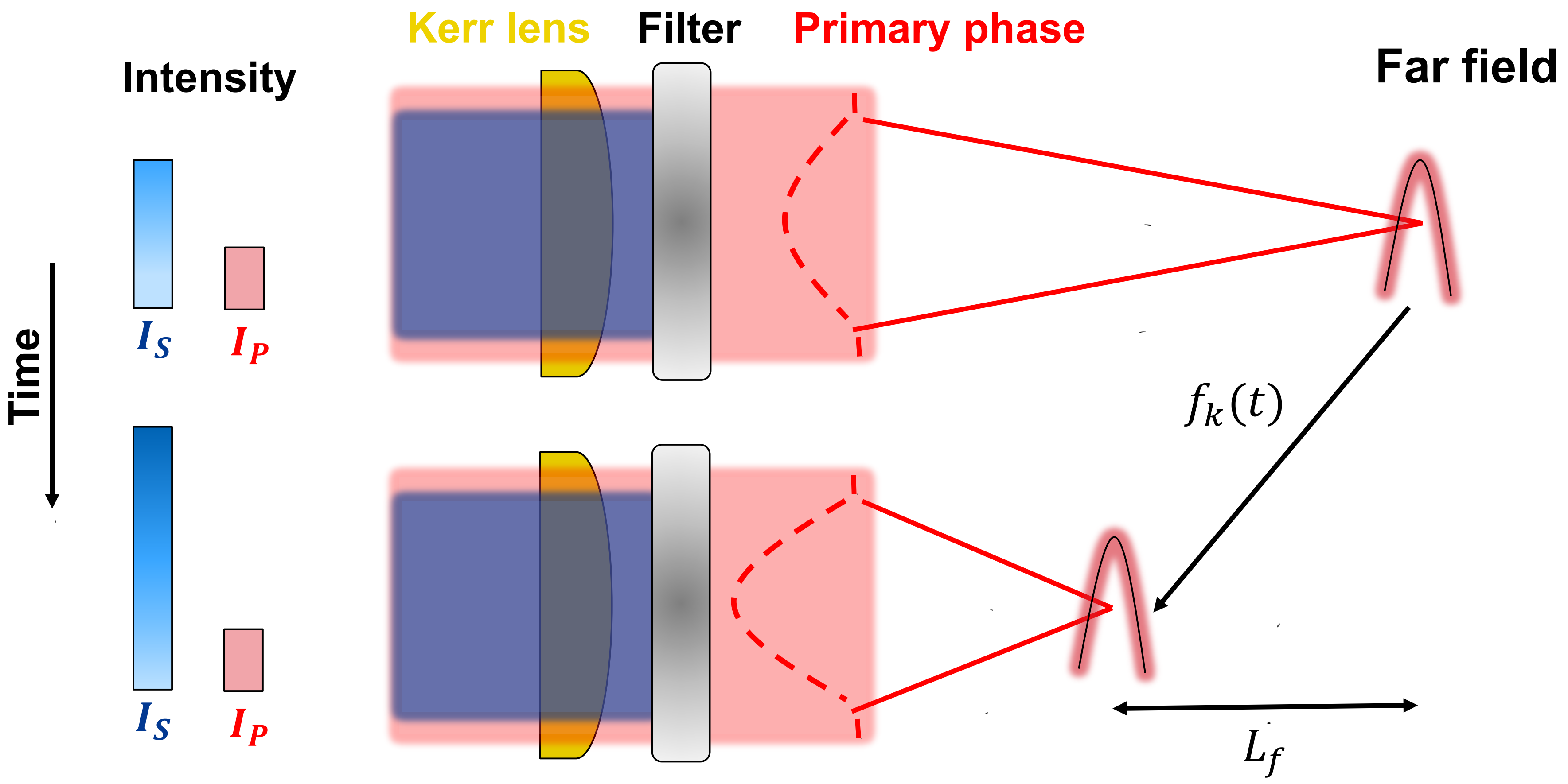
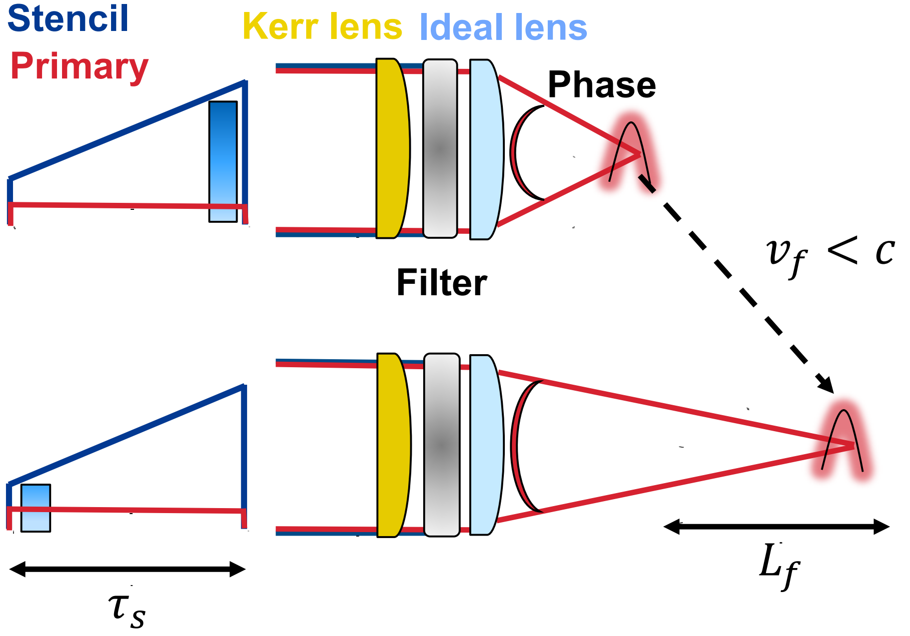


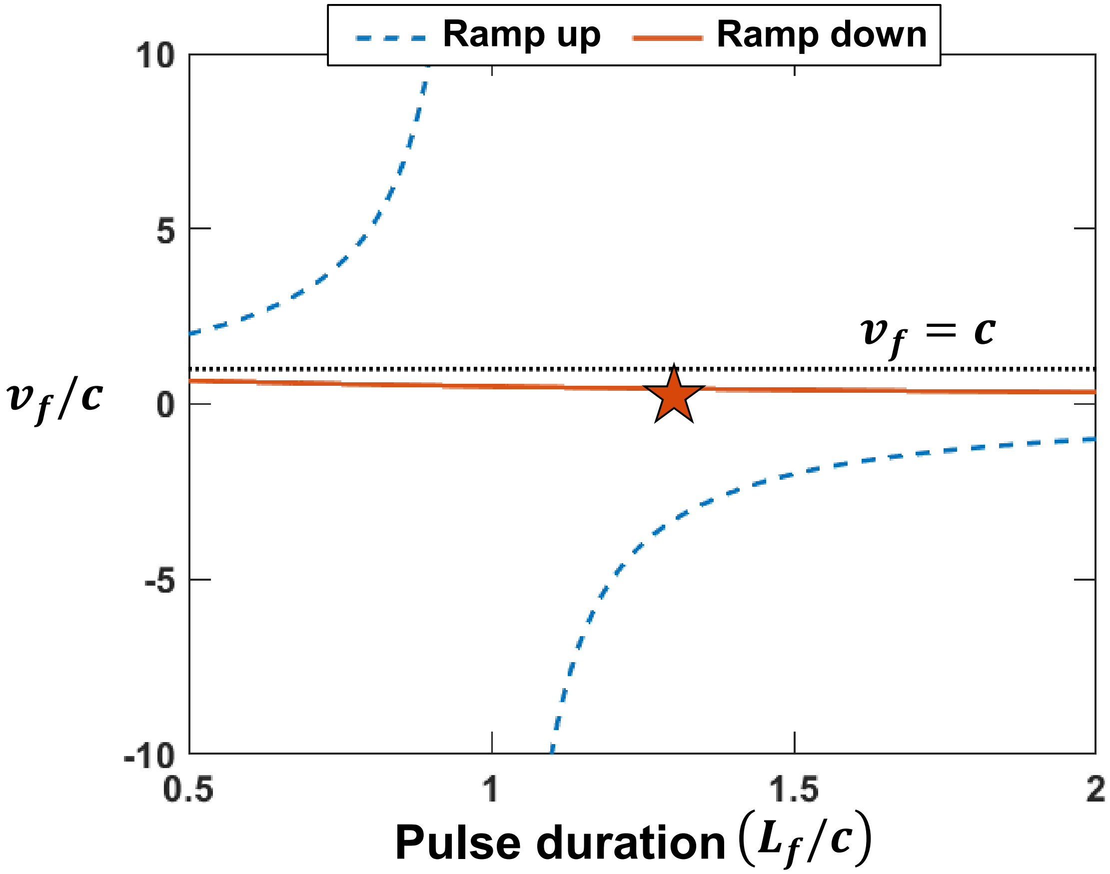
Time-dependent focal length

$$f_k(t) = \mathrm{R}/2\mathrm{n}_2\mathrm{I}_\mathrm{s}(t)$$

Radius of curvature

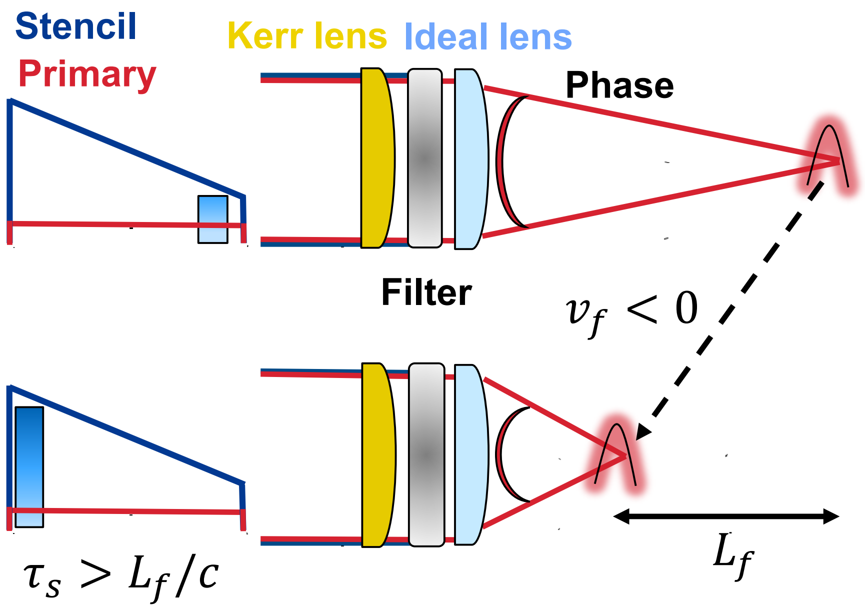
The focal velocity can be tuned for a given focal range by adjusting the pulse duration

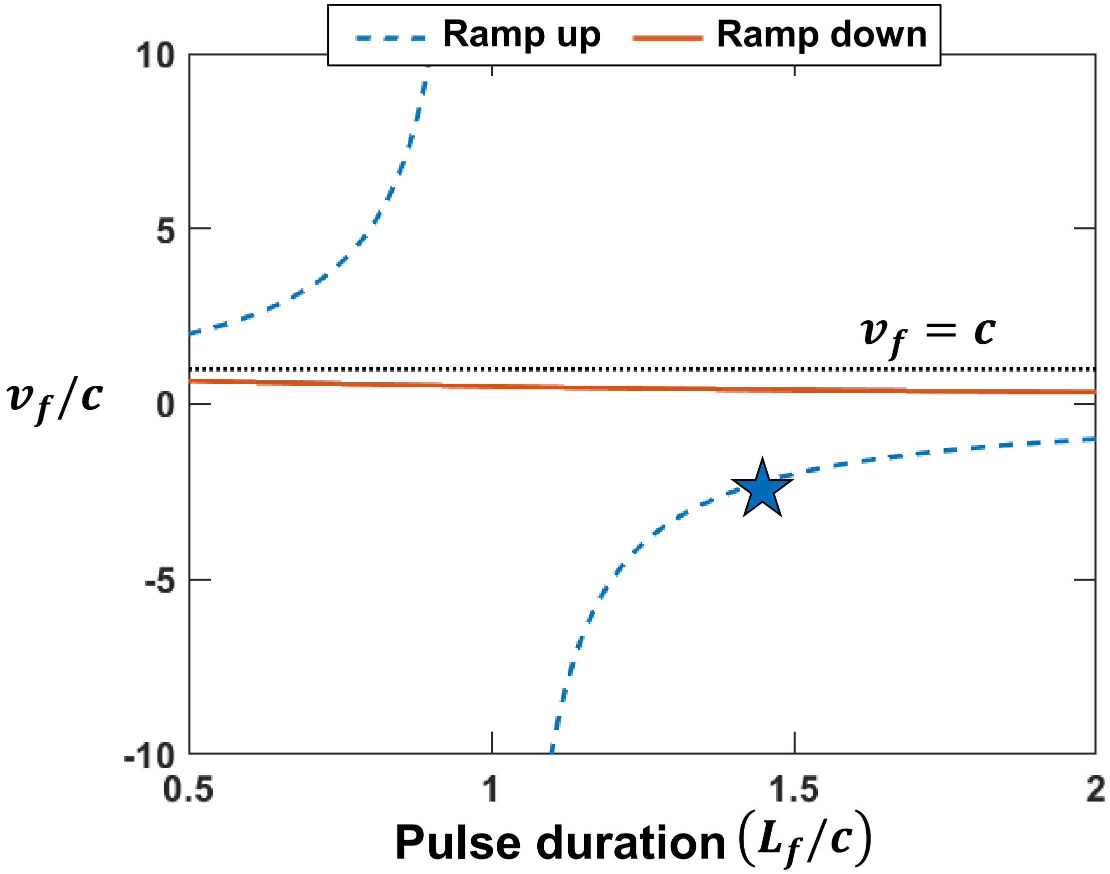




A ramp-down stencil produces positive, subluminal focal velocities

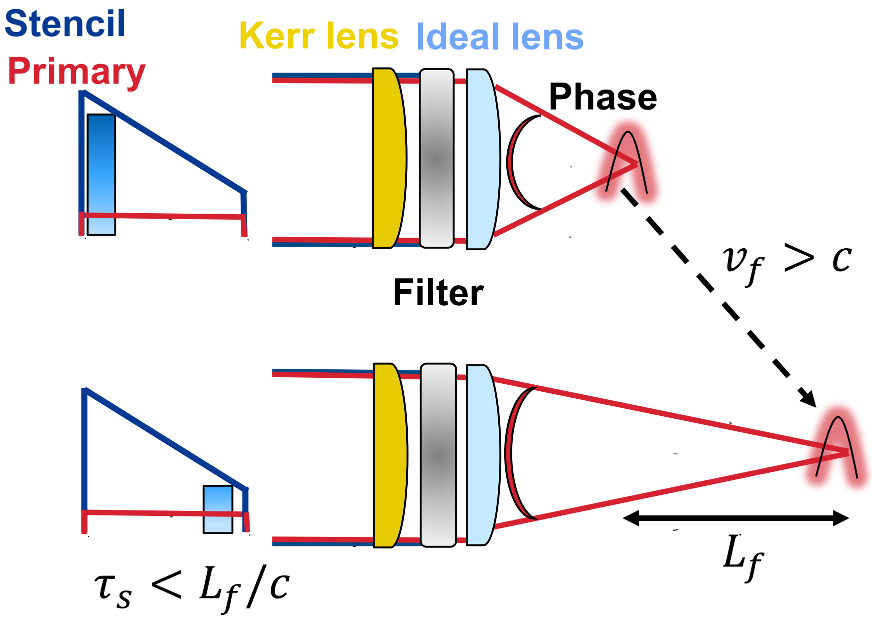
The focal velocity can be tuned for a given focal range by adjusting the pulse duration

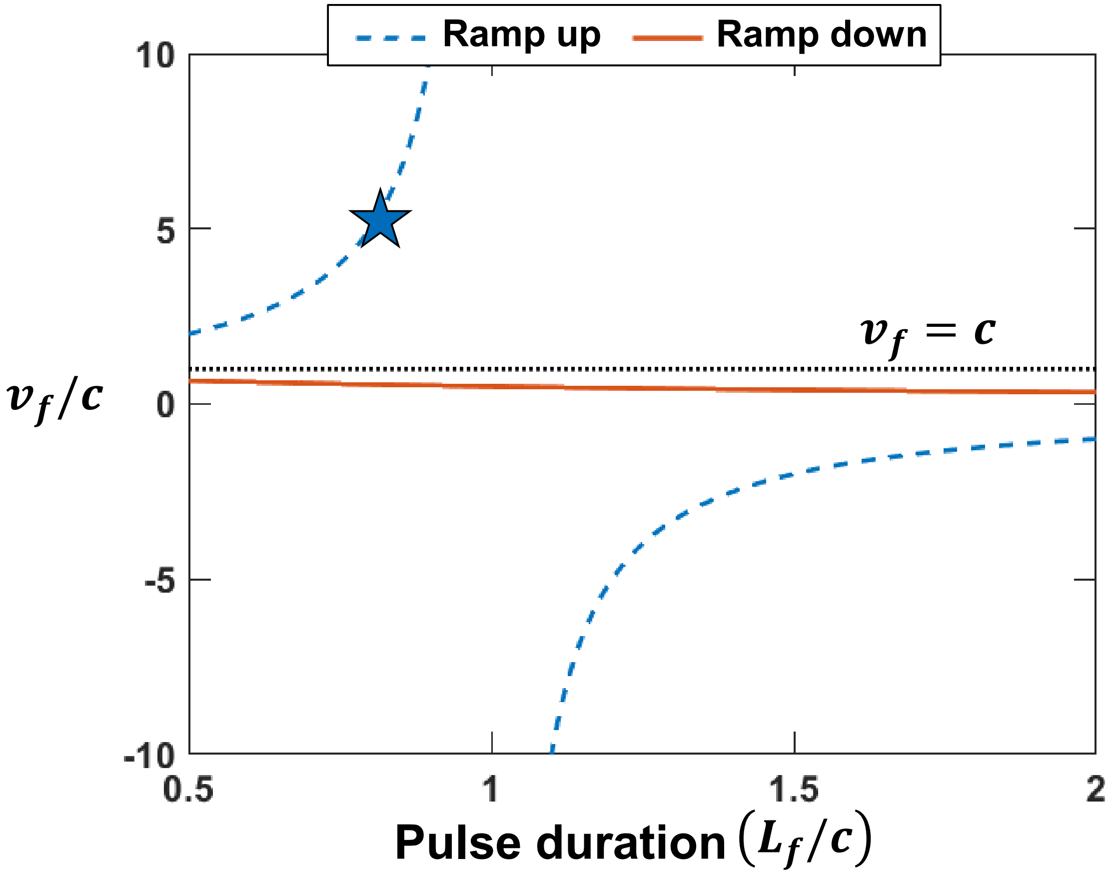




A long ramp-up stencil produces negative focal velocities

The focal velocity can be tuned for a given focal range by adjusting the pulse duration

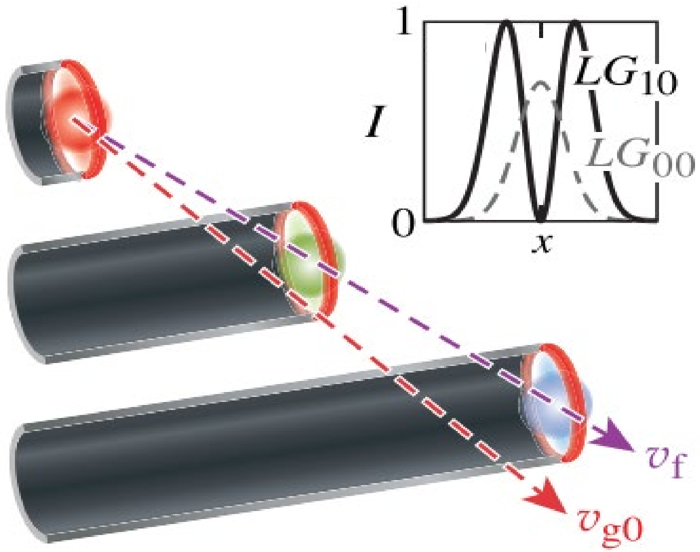




A short ramp-up stencil produces positive, superluminal focal velocities

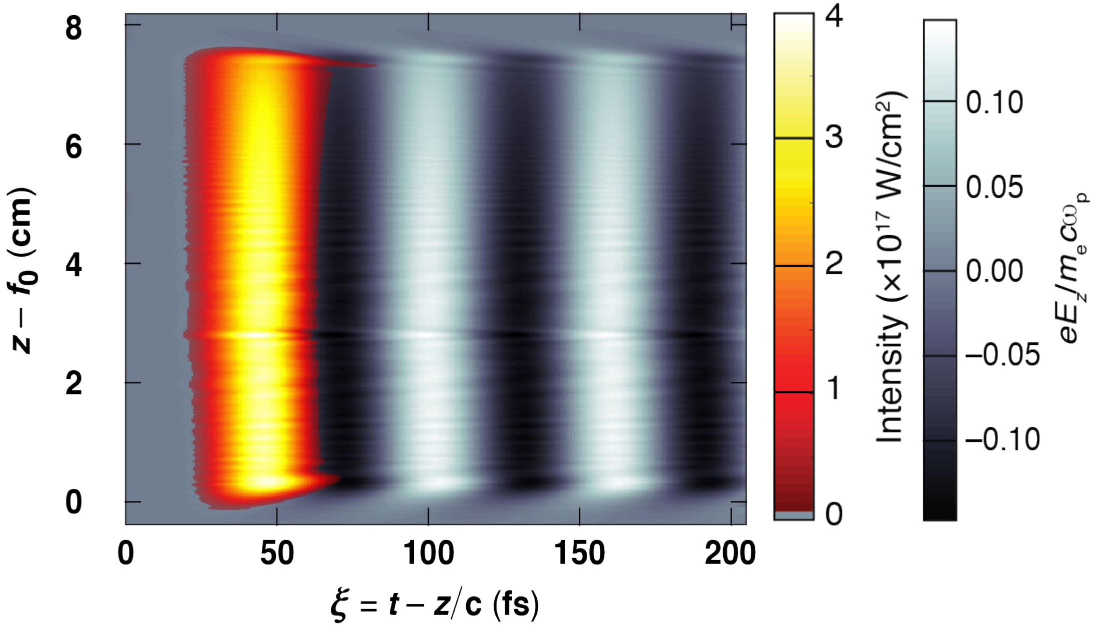
The flying focus X produces a focus with ideal wavefront curvature, enabling spatiotemporal control for an arbitrary transverse profile

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



Photon accelerator using a structured flying focus*

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



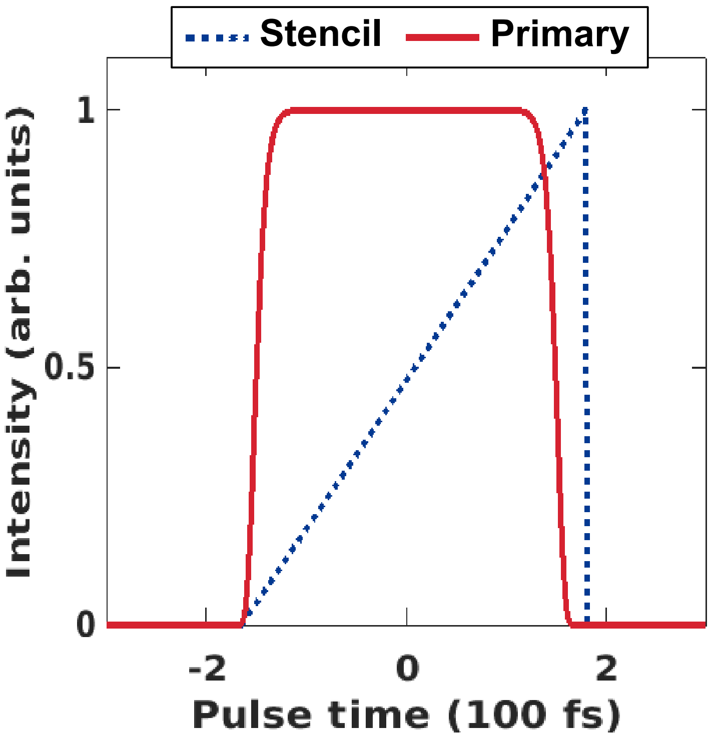
Dephasingless laser wakefield accelerator with an ultrashort pulse**

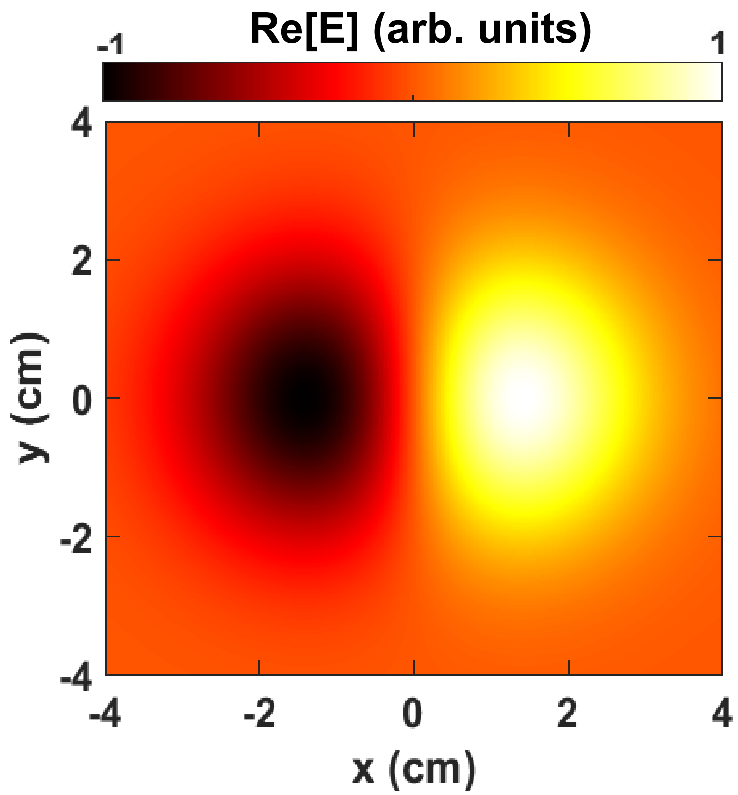
Simulations verify that the flying focus X can create an ultrashort duration orbital angular momentum pulse with a superluminal focal velocity

Optical configuration	
n_2 (cm²/W)	8.5×10^{-15}
I_S^{max} (W/cm²)	1.7×10^{10}
Focal length (cm)	60
Initial spot size (cm)	2
τ_s (fs)	330

Far field	
Focal spot size (µm)	10
L_f (cm)	1
v_f/c	1.01
τ_f (fs)	20

Near field





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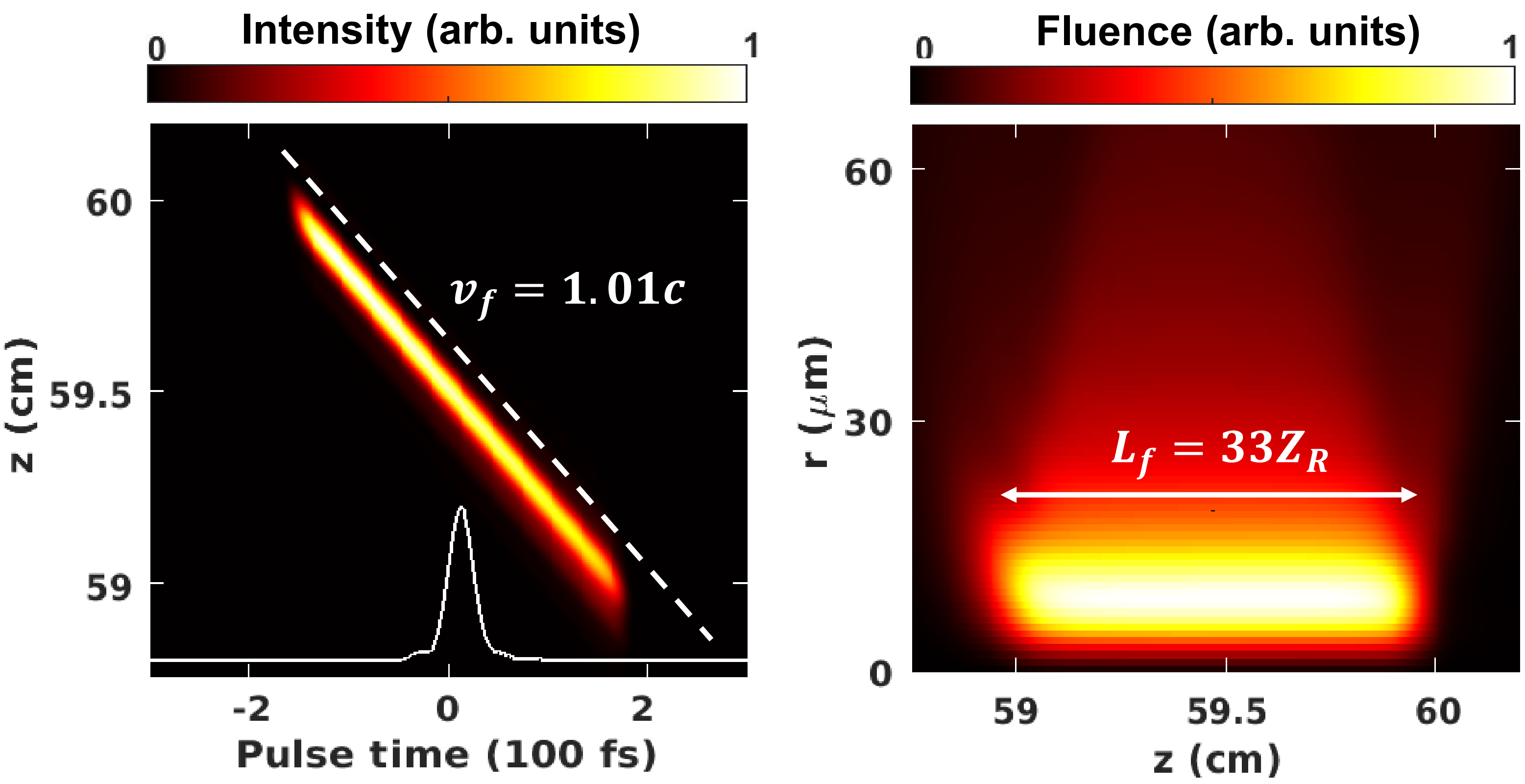

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