Photon Acceleration in a Flying Focus

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Summary

A *flying focus* triggers an ionization front that upshifts an ultrafast pulse from the optical to the extreme ultraviolet (XUV)

- The theory of photon acceleration predicts impressive frequency upshifts but experiments are ultimately limited by two effects
- Use of the flying focus effectively eliminates both of these effects
- For short pulses (<100 fs), simulations of photon acceleration in a flying focus demonstrate upshifts from the optical to the XUV
- The energy efficiency of this process compares favorably with prior experiments
- This scheme can be scaled to produce a novel tabletop source of x rays

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Motivations and Background

Photon acceleration offers a method of tunable XUV production

XUV (λ < 120 nm) sources provide

- High-resolution imaging for HED physics and nanotechnology
- Fine-scale material ablation for nanomachining, spectrometry, and photolithography
- Ultrafast pump/probe techniques for fundamental atomic physics

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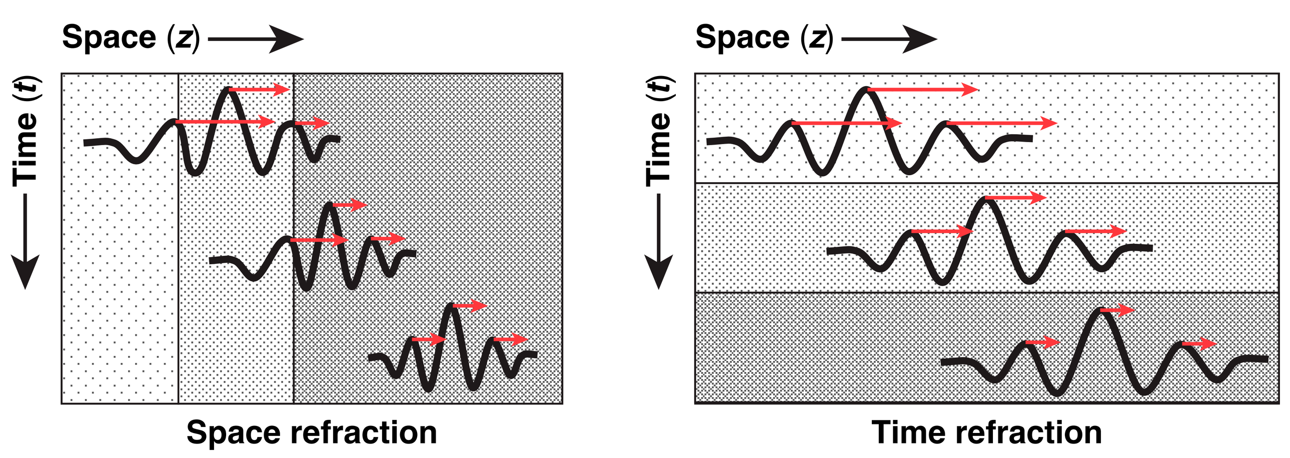
***Time refraction*, the temporal analogue to spatial refraction, is the underlying phenomenon that permits photon acceleration**

Dispersion relation for a photon: $\omega = ck/n$

- A spatially varying index will cause a shift in k
- A temporally varying index will cause a shift in ω



In a plasma: $n = \sqrt{1 - \omega_p^2/\omega^2}$

- $\omega_p^2 = e^2 n_e / \varepsilon_0 m_e \propto$ free-electron density, increased via ionization

Photons propagating within the ionization front of a plasma will undergo a frequency upshift.

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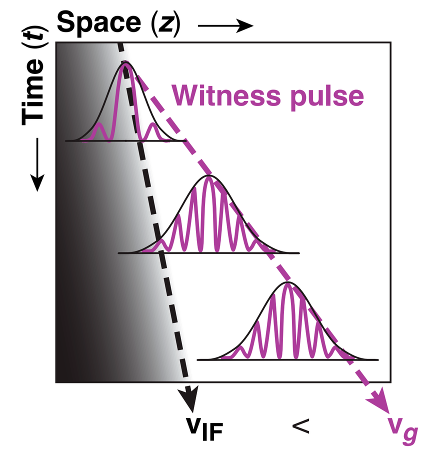
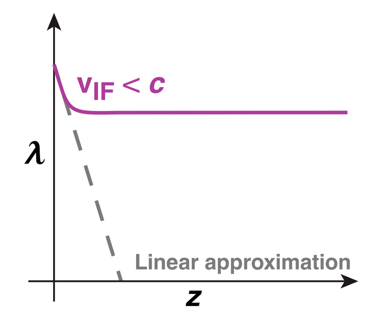
Proposed Scheme

A prototypical scheme for photon acceleration: a witness pulse co-propagating with a laser-driven ionization front (IF)





If v_{IF} < c, then accelerated photons outpace the ionization front.

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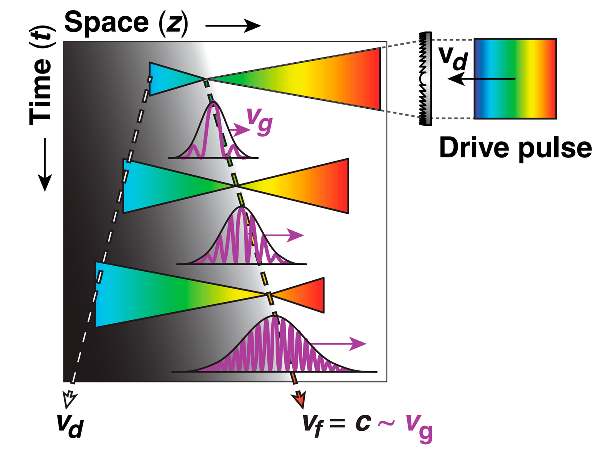
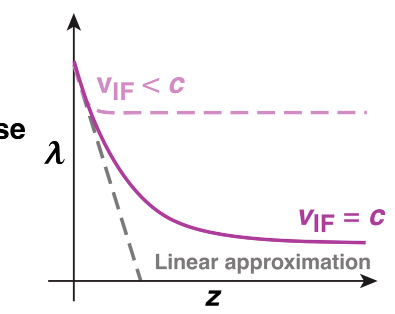
The *flying focus*, a focal spot that moves in time, can produce an ionization front traveling at *c* that *counter*-propagates with respect to the drive pulse





When v_{IF} = c, then photons upshift to significantly higher frequencies.

A chirped pulse sent through a chromatic lens creates a moving or "flying" focus

- A negative chirp can create a focus that counter-propagates with respect to the drive pulse at *c*
- If the drive pulse has sufficient intensity, the flying focus will create an ionization front traveling at *c*

1. Ensures accelerated photons cannot outrun the ionization front
2. Mitigates ionization refraction of the drive pulse

By eliminating these two effects, the interaction distance is extended long past the Rayleigh range of the drive pulse

Simulation and Modeling

Drive-pulse propagation equation ($\xi = ct - z$):

$$\left[2\left(ik_0 - \frac{\partial}{\partial \xi}\right)\frac{\partial}{\partial z} + \nabla_\perp^2\right]E_\perp = \frac{\omega_p^2}{c^2}E_\perp - \eta E_\perp$$

Spatiotemporal modifications; Diffraction; Plasma refraction; Ionization and inverse bremsstrahlung energy losses

Electron density profile:

$$c\frac{\partial}{\partial \xi} n_e = v_{FI}\, n_g + \alpha_{CI}\, n_e n_g - \alpha_R\, n_e^2 - \beta_{3B}\, n_e^3$$

Field ionization; Collisional ionization; Radiative recombination; 3-body recombination

Laser: 2ω Ti:sapphire

Parameter	Value
λ_c	400 nm
$\Delta\lambda$	6.0 nm
T_0	87 fs
T	54 ps
ε	5.6 J
I (t)	SG-8
I (r)	SG-10
f	1.02 m
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Medium: H_2 gas jet

Parameter	Value
Species	H_2
n_g	1.75×10^{21} cm^{-3}
U_I	13.6 eV

The dispersion relation $\omega = \left(\omega_p^2 + c^2k^2\right)^{\frac{1}{2}}$ provides equations of motion for:

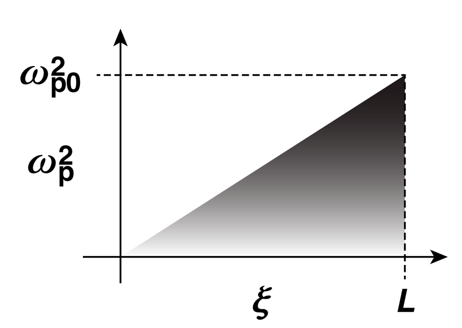
I. Spatial refraction, $\frac{dk}{dt} = -\nabla\omega$

II. Group velocity, $\frac{dr}{dt} = \frac{\partial \omega}{\partial k}$

III. Time refraction, $\frac{d\omega}{dt} = \frac{1}{2\omega}\frac{\partial}{\partial t}\omega_p^2$

$$\frac{d\omega}{dz} = \frac{1}{2ck_z}\frac{\partial}{\partial \xi}\omega_p^2$$

A simple analytic model reveals multiple paths to shorter wavelengths:



$$\frac{\Delta\omega}{\omega_0} = \sqrt{\left(\frac{\omega_{p0}^2}{\omega_0^2}\right)\frac{z}{L}}$$

$\Delta\omega$ scales with

- the length of the focal region ($\uparrow z$)
- the density of medium ($\uparrow \omega_{p0}^2$)
- the intensity of the drive pulse ($\uparrow \omega_{p0}^2$, $\downarrow L$)

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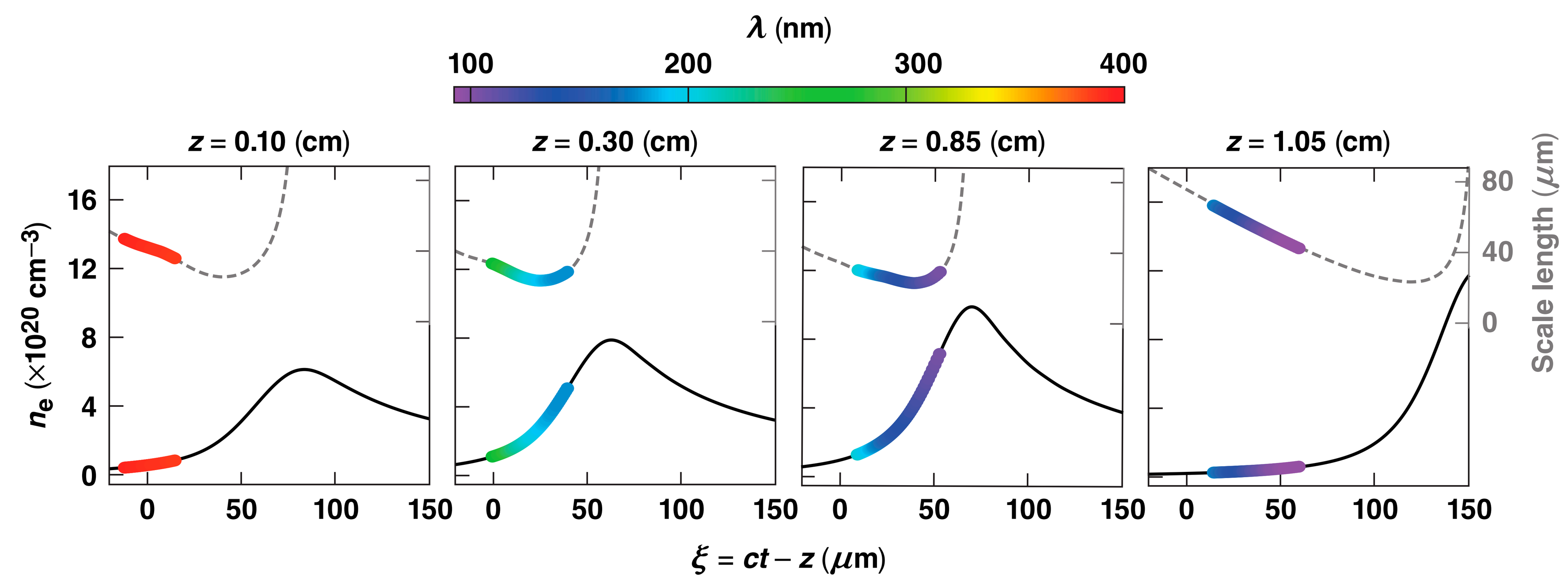
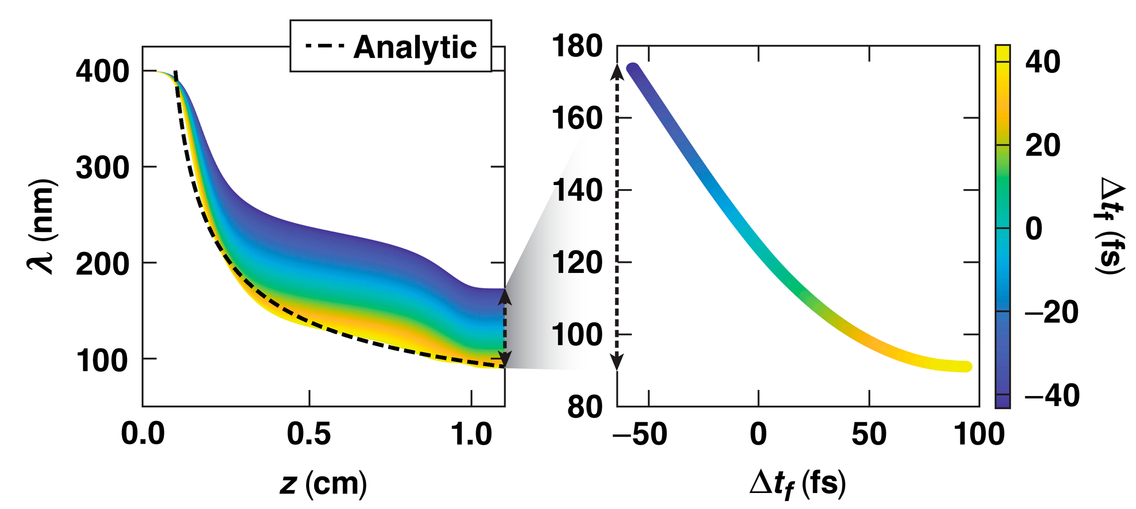
Simulation Results

A *flying focus* photon accelerator overcomes prior limitations to upshift an ultrafast optical pulse to the XUV over 1 cm of propagation





$\lambda_{min} \cong$ 91 nm

$\Delta\lambda \cong$ 83 nm

$T \cong$ 150 fs

Energy efficiency:

ε_d = 5.6 J

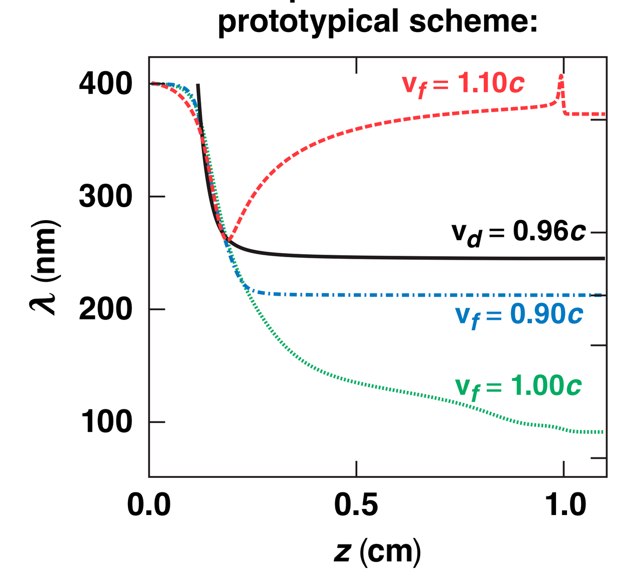
$(\varepsilon_w)_{in}$ = 170 mJ

$(\varepsilon_w)_{out}$ = 43 mJ

~25%

~10^{-5}

Compared to the prototypical scheme:



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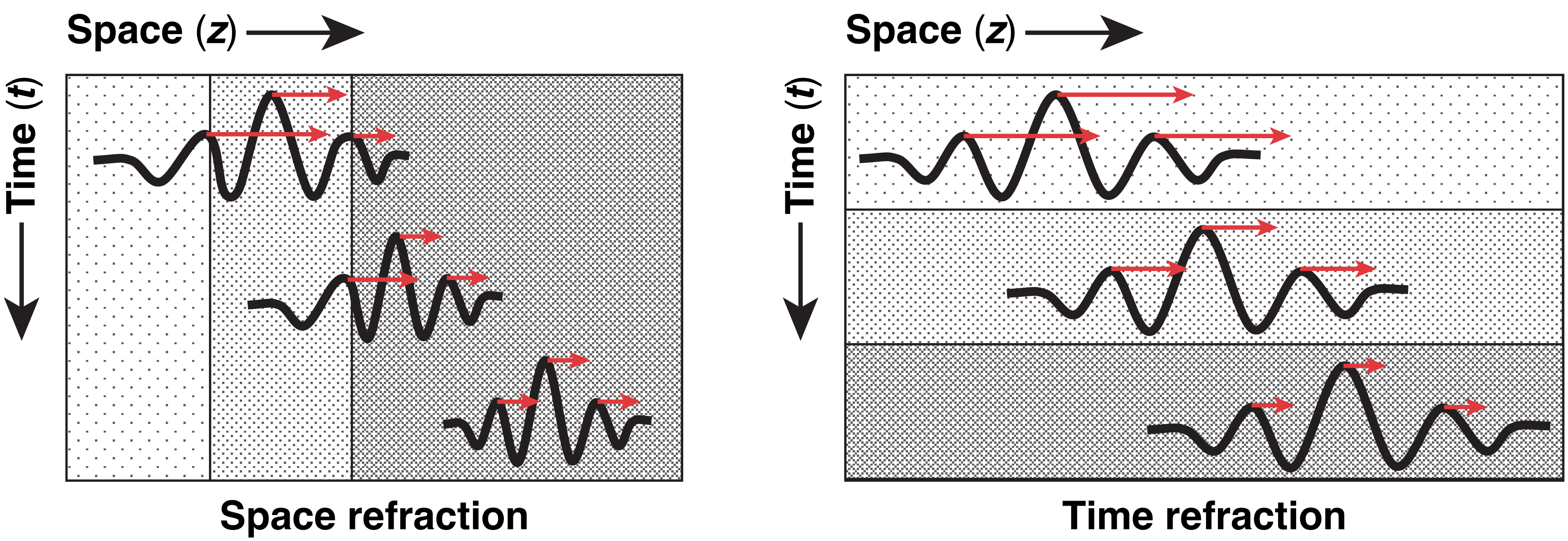

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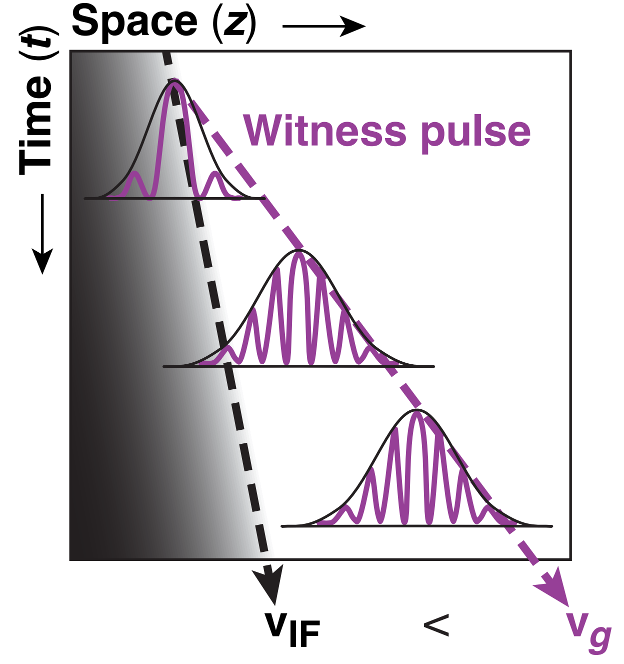

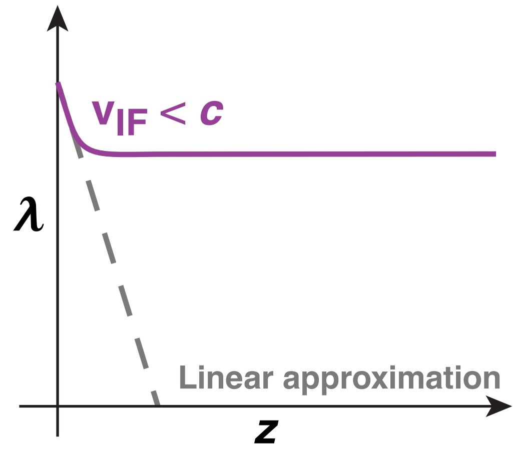

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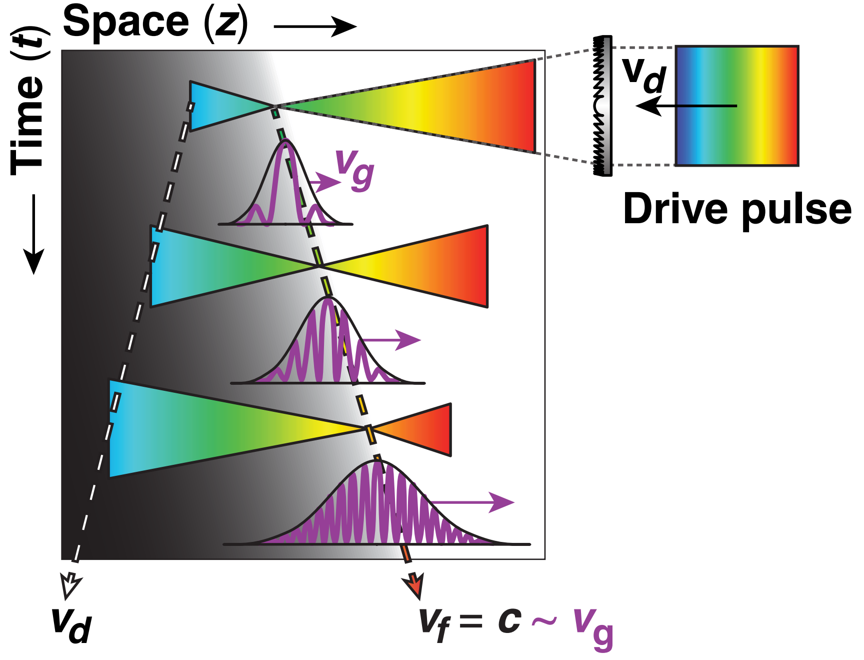

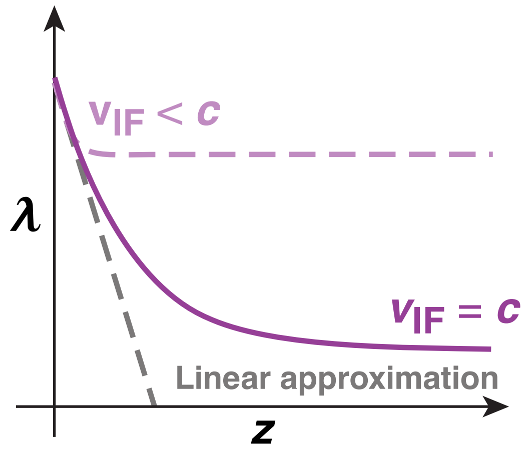

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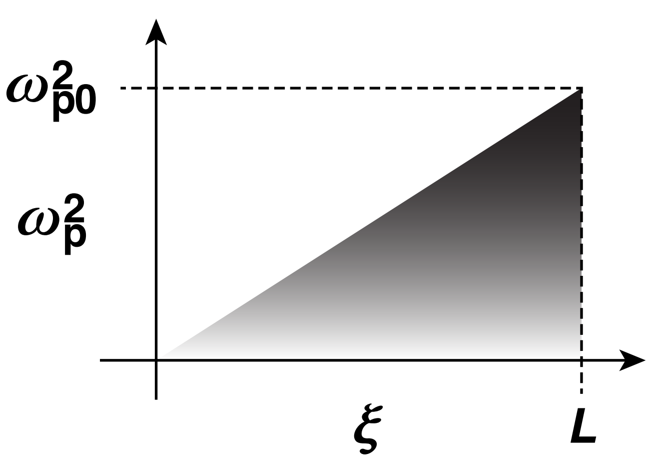

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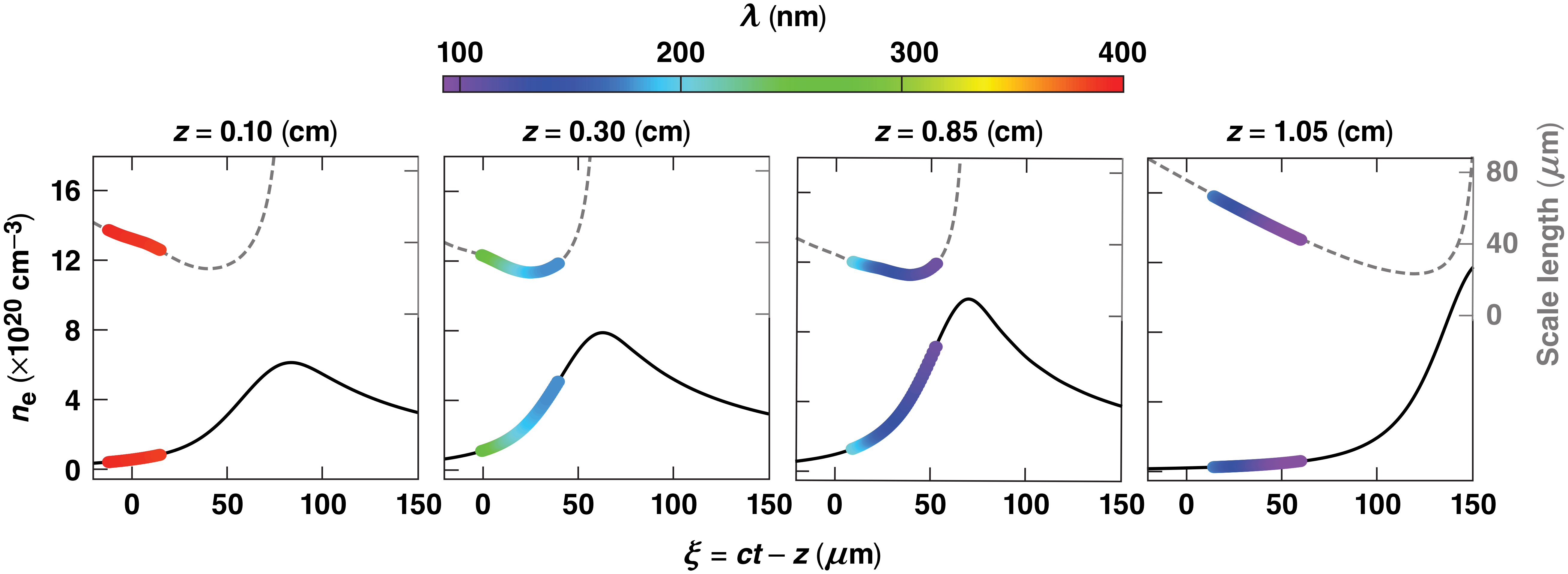

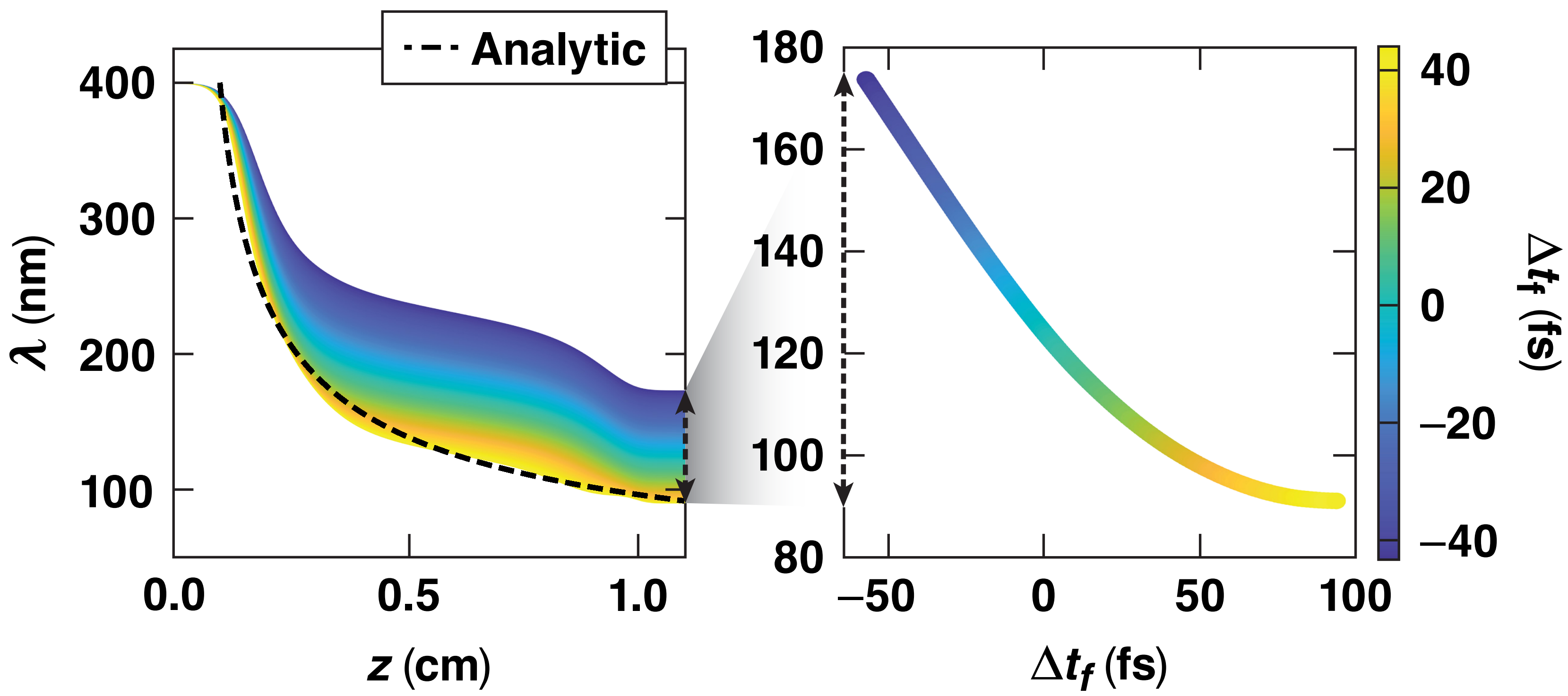

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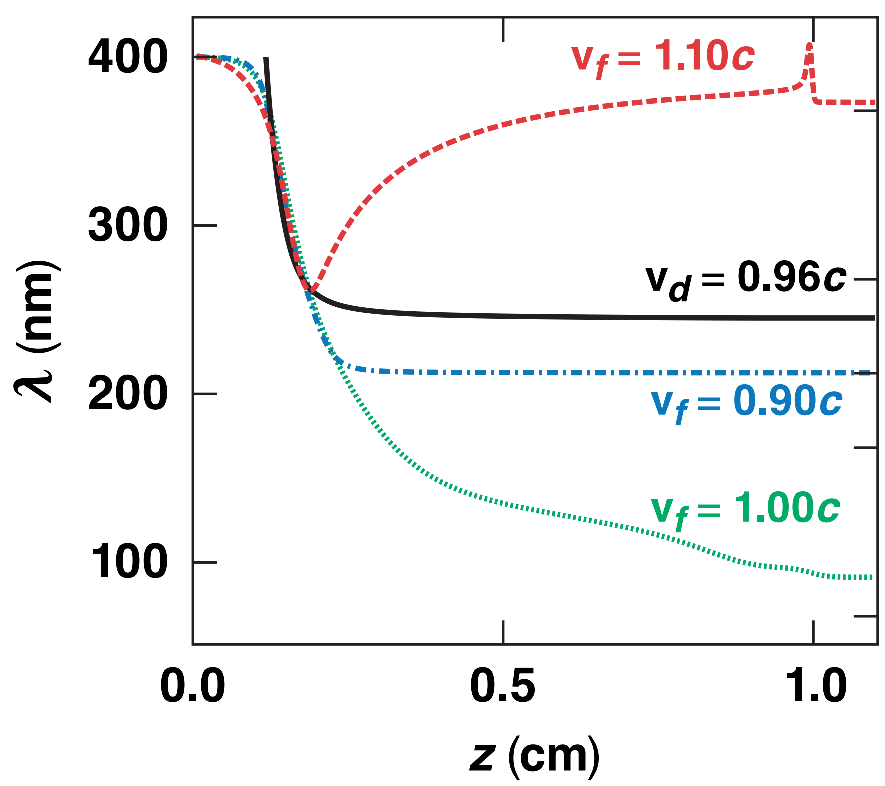

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