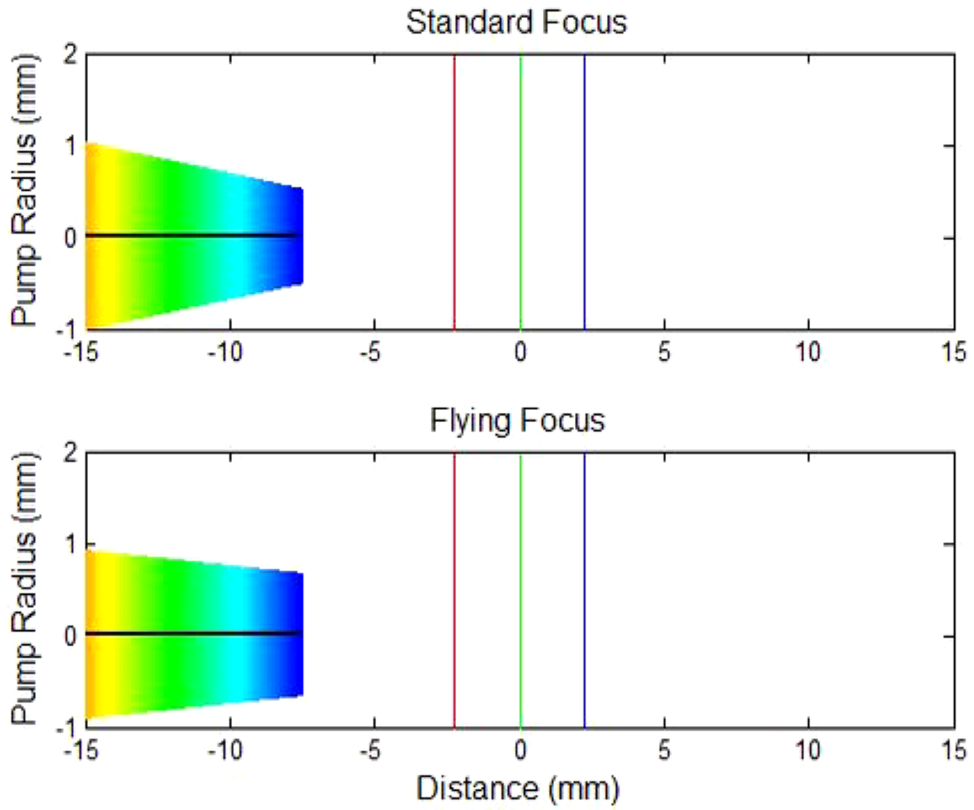
Frequency Conversion of Laser Pulses Reflected from Ionization Waves of Arbitrary Velocity



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61st APS DPP
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21-25 October 2019

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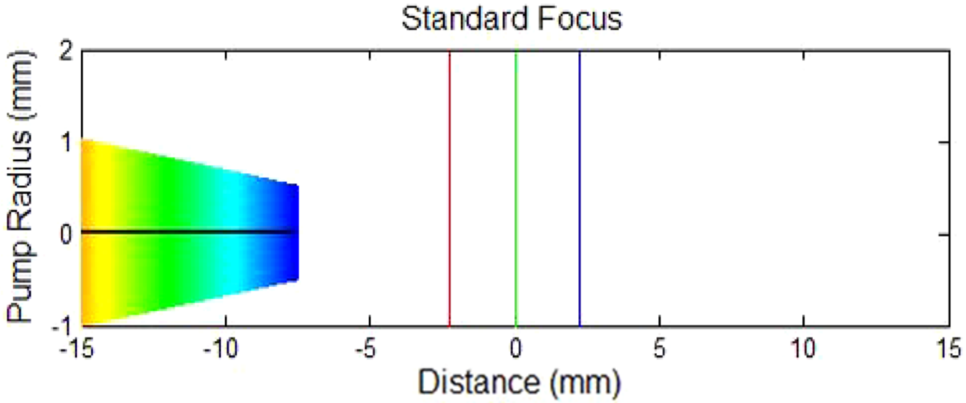

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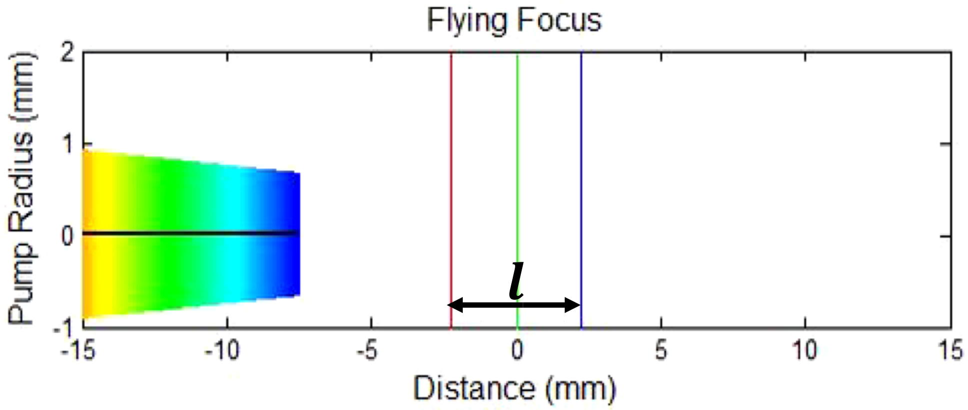
T07:12 (T. T. Simpson)
T07:13 (D. W. Ramsey)



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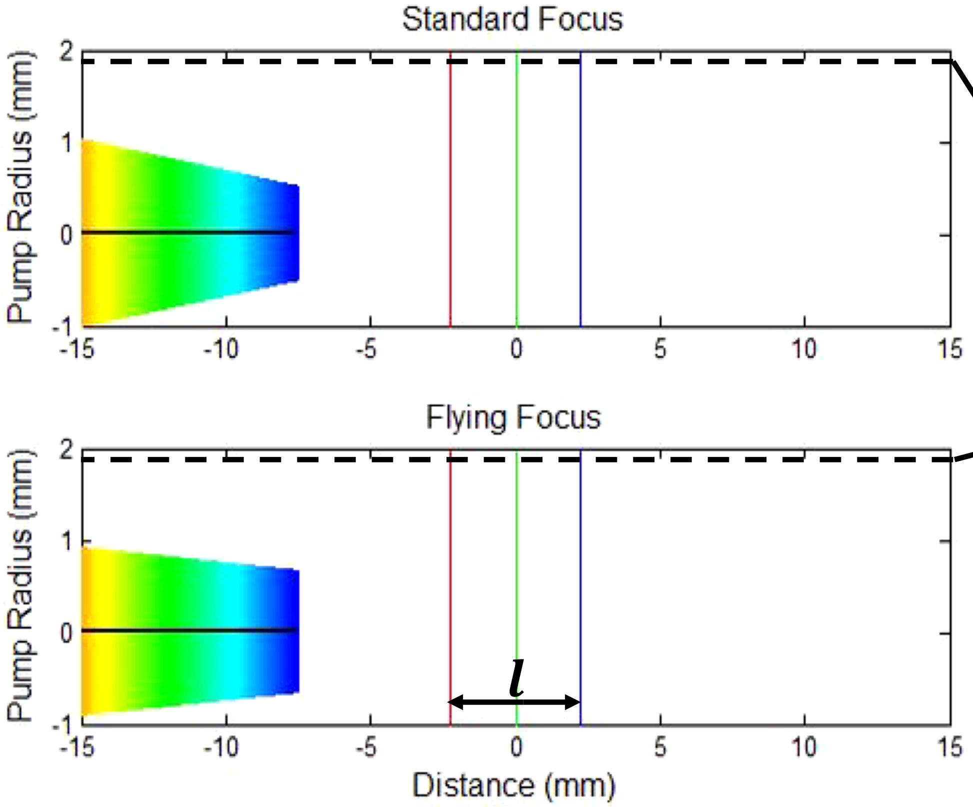

Ionization intensity threshold of background material

T07:12 (T. T. Simpson)
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Summary

Laser pulses reflected from flying focus-driven ionization fronts can undergo extreme frequency upshifts

- High density ionization fronts can be driven over long distances at any velocity with the flying focus
- Reflected pulses can be shifted to high frequencies, while retaining desirable characteristics such as spatial coherence, low divergence, and ultrashort duration
- Output frequency is easily tuned over a broad range by changing the front velocity

Experiments have demonstrated that the flying focus can create predictable and tunable ionization waves of arbitrary velocity (IWAV's)

$$v_{focus}/v_g = \left(1 \pm \frac{\tau\, v_g}{l}\right)^{-1} = v_{IWAV}/v_g$$

v_{focus}: velocity of flying focus intensity peak

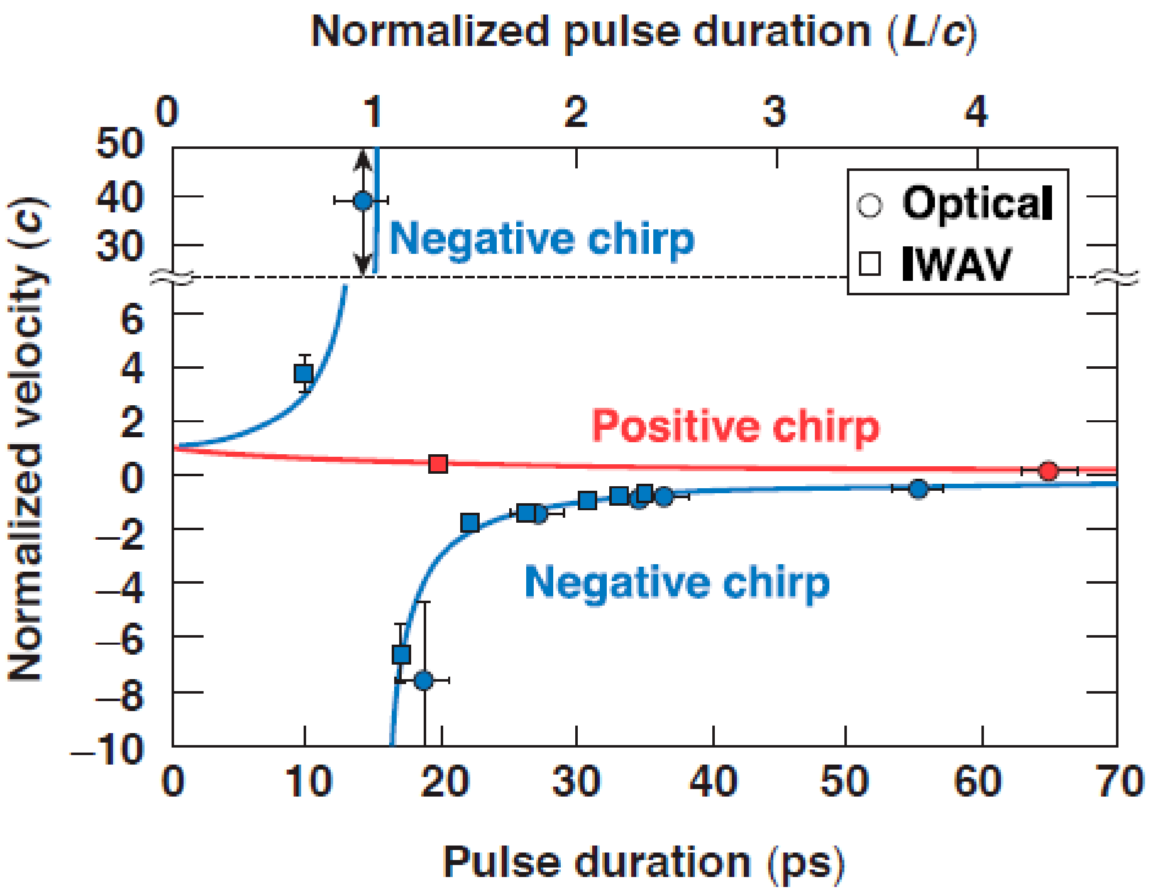
v_g: laser group velocity

τ: pulse duration

l: longitudinal focal shift across bandwidth

$\pm$: sign of chirp

v_{IWAV}: IWAV velocity



IWAV velocity is decoupled from the laser group velocity

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[*] D. Turnbull *et al.*, Phys. Rev. Lett. 120,225001 (2018).

[**] D. Froula *et al.*, Nature Photonics 12, 262+ (2018).

[†] D. Froula et al., Phys. Plasmas 26, 032109 (2019).

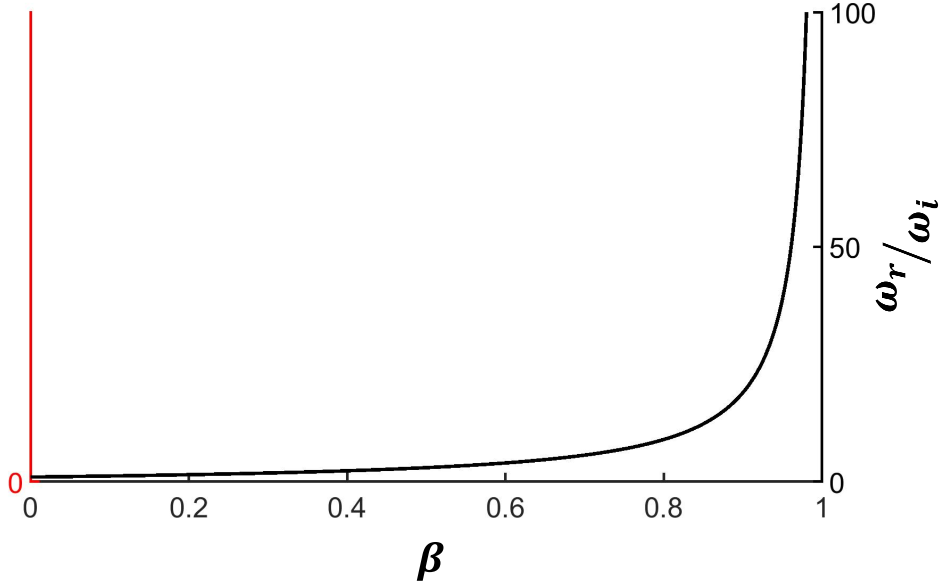
[‡] J. P. Palastro *et al.*, Phys. Rev. A 97, 033835 (2018).

[*‡] P. Franke *et al.*, Opt. Express 27, 31978-31988 (2019).

High density IWAV's can reflect a counter-propagating laser pulse and cause extreme frequency up-shifts and pulse compression

- **Frequency shift:**

$$\frac{\omega_r}{\omega_i} = \frac{1+\beta}{1-\beta}$$



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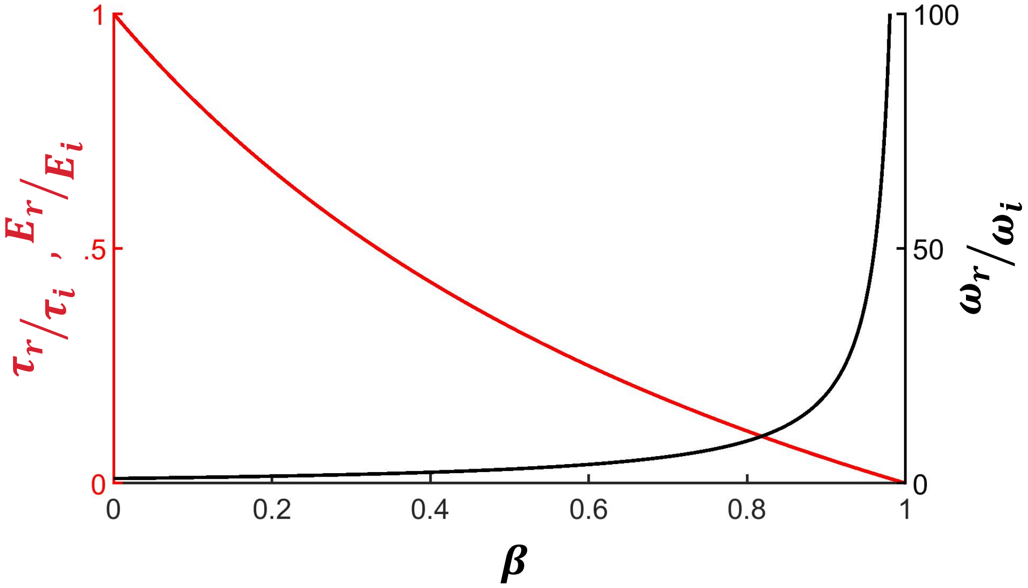

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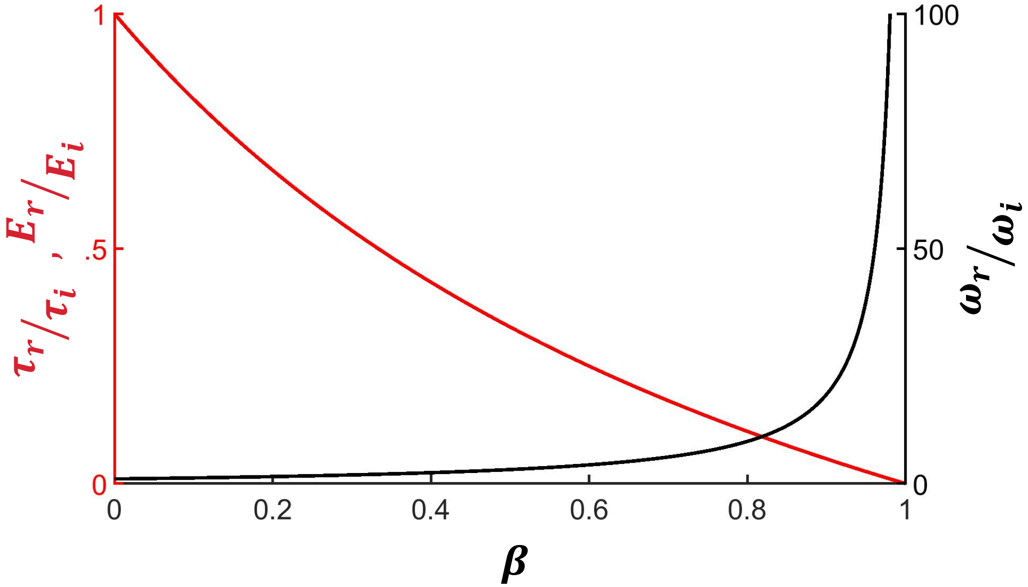
$$\frac{\omega_p}{\omega_i} > \left[\frac{1+\beta}{1-\beta}\right]^{1/2}$$



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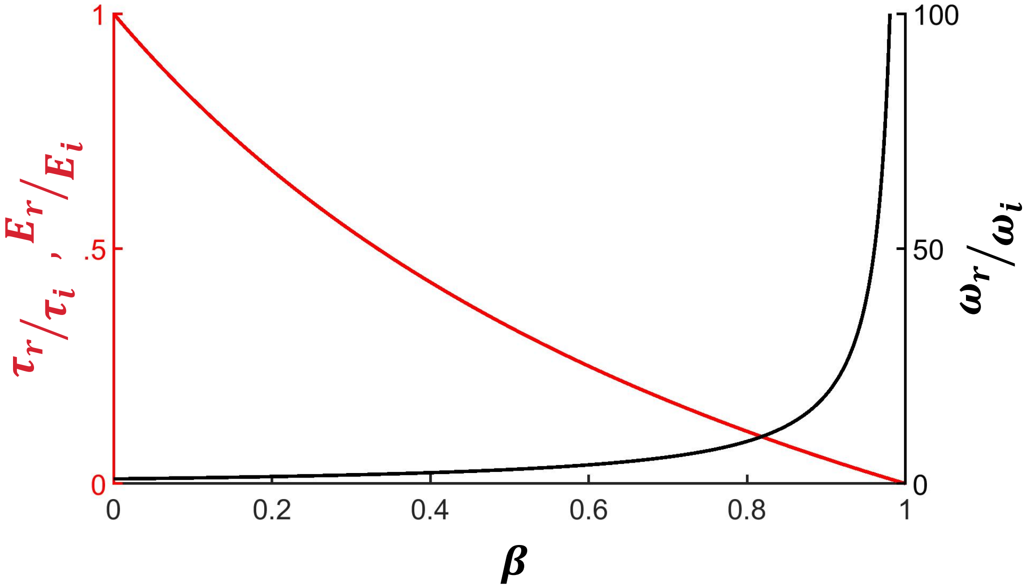

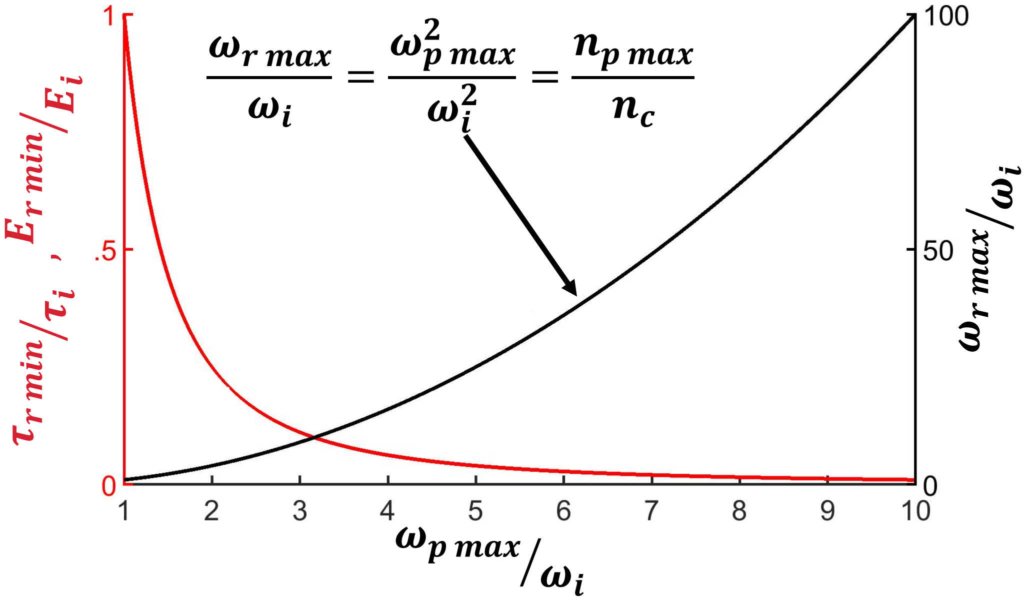

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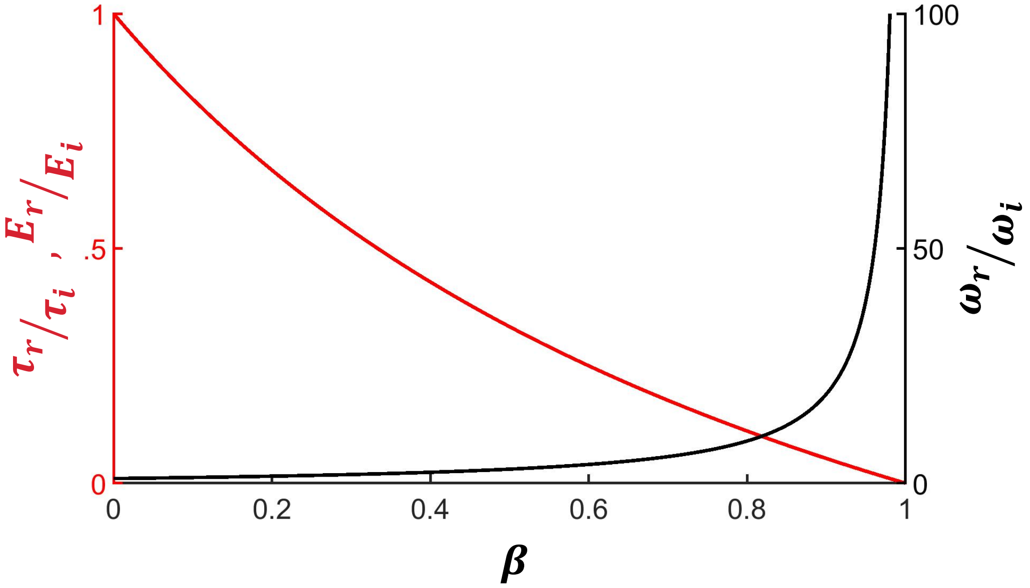

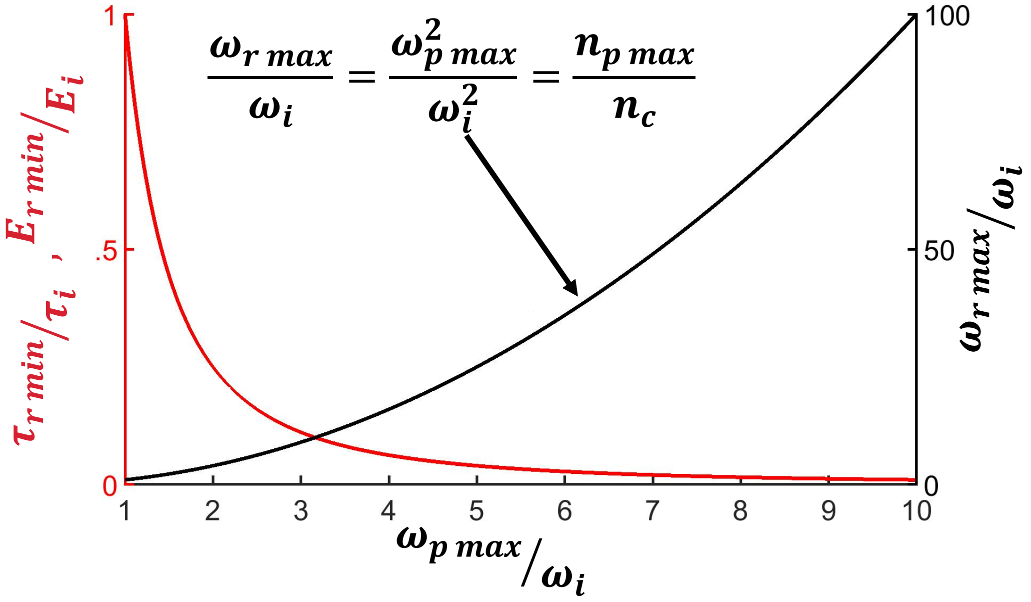

$$\omega_{r\,max} = \frac{\boxed{\omega^2_{p\,max}}}{\boxed{\omega_i}}$$

Increase Maximum Density

Decrease Initial Frequency

---

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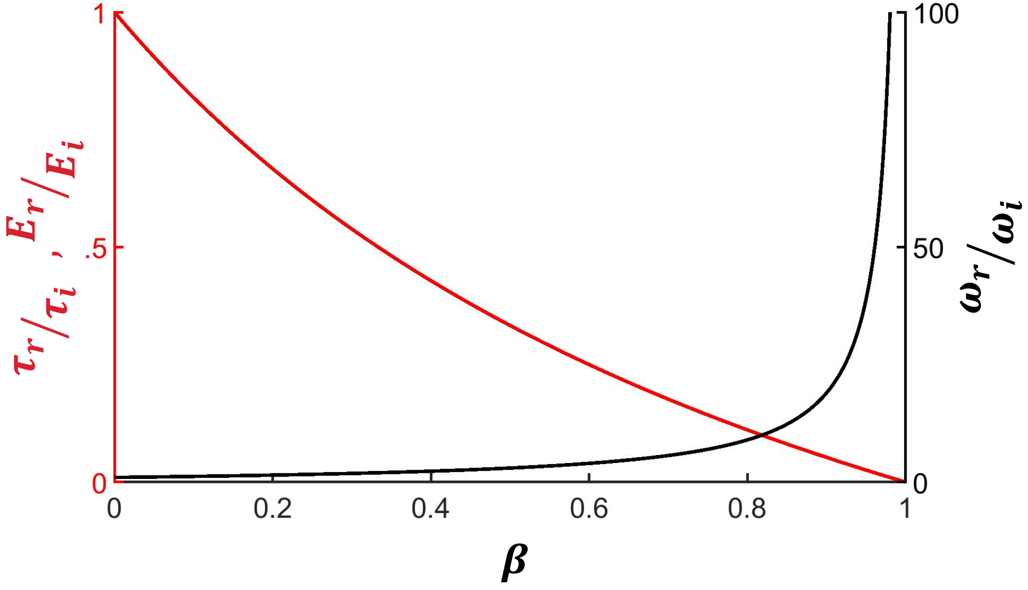

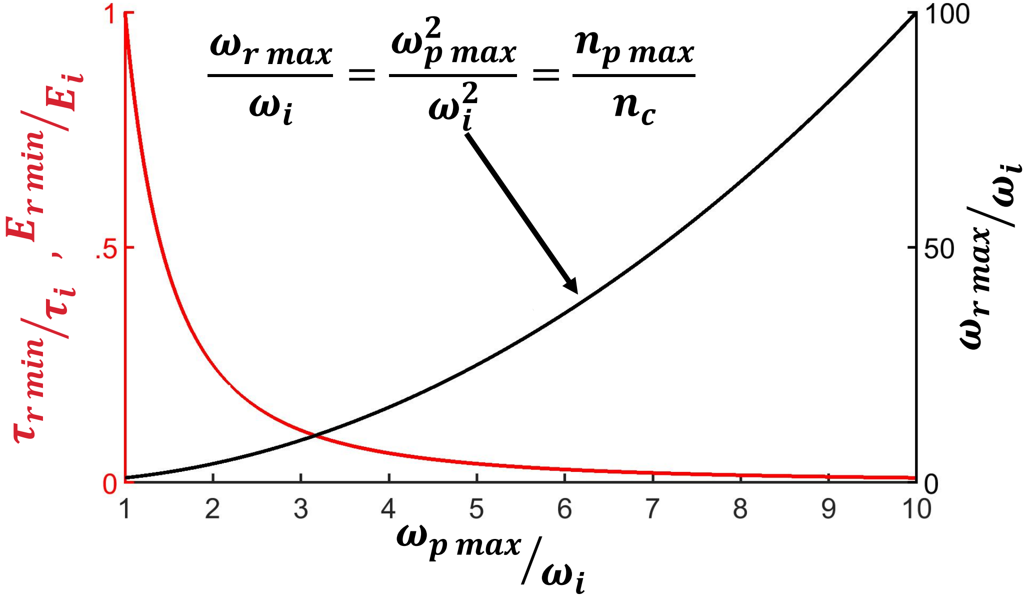

$Nd{:}YLF\ (3\omega)$

$$\omega_{r\,max} = \frac{\omega^2_{p\,max}}{\omega_i} = \frac{\omega_c^2\,(351nm)}{\omega_i(10\mu m)}$$

$CO_2\ (1\omega)$

---

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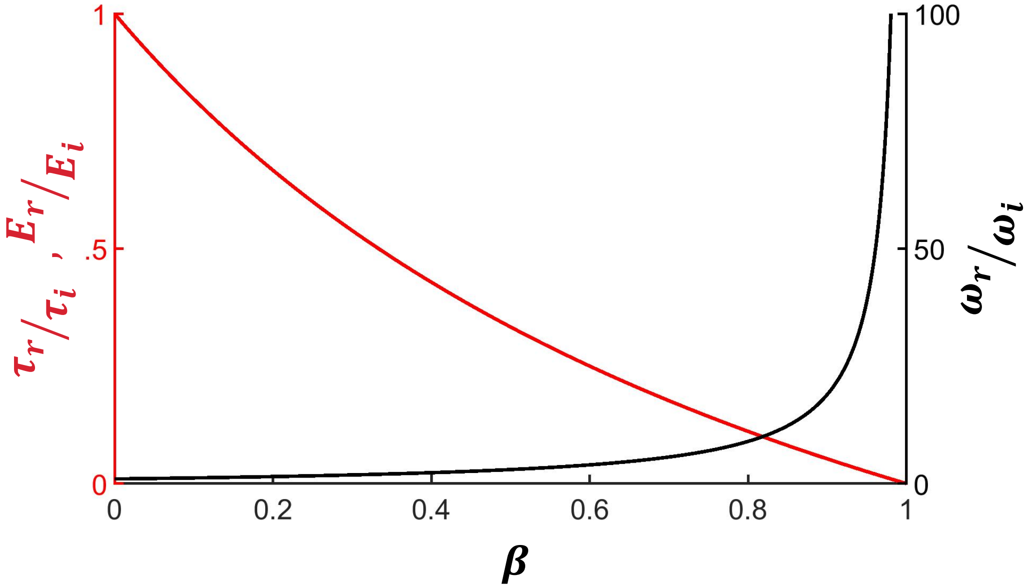

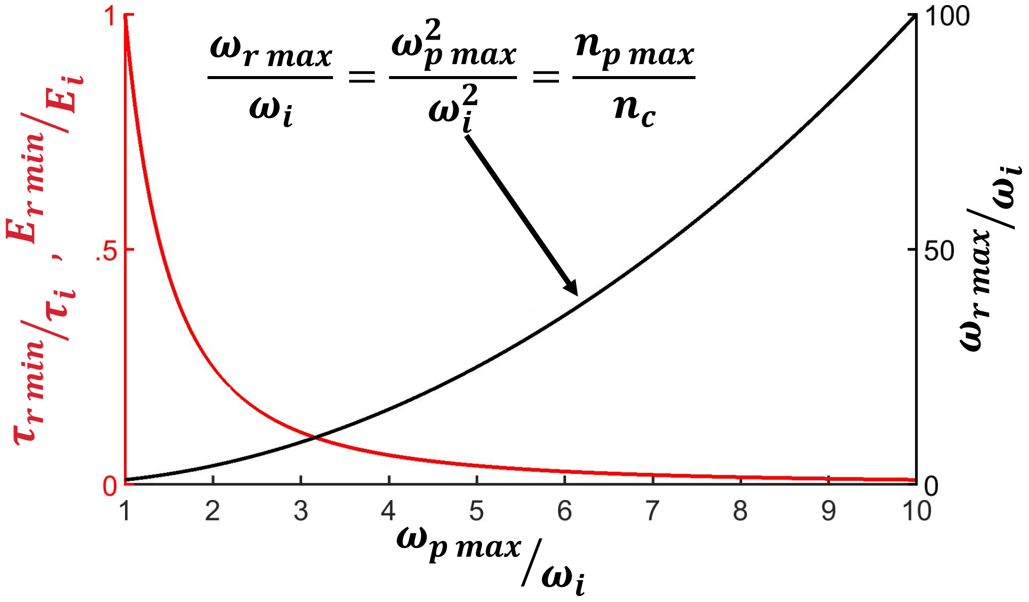

$Nd{:}YLF\ (3\omega)$

$$\omega_{r\,max} = \frac{\omega^2_{p\,max}}{\omega_i} = \frac{\omega_c^2\,(351nm)}{\omega_i(10\mu m)} = \omega_{r\,max}(12nm)$$

$CO_2\ (1\omega)$

IWAV frequency conversion could enable a tunable, table-top source of coherent, ultrashort, high frequency radiation

---

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1D FDTD simulations provide a simple model of laser pulse dynamics in an ideal IWAV

- **Curl equations + linear current model:**

$$\nabla \times E = -\mu_0 \partial_t H \qquad \nabla \times H = -\varepsilon_0 \partial_t E + J$$

$$\partial_t J = \varepsilon_0 \omega_p^2 E$$

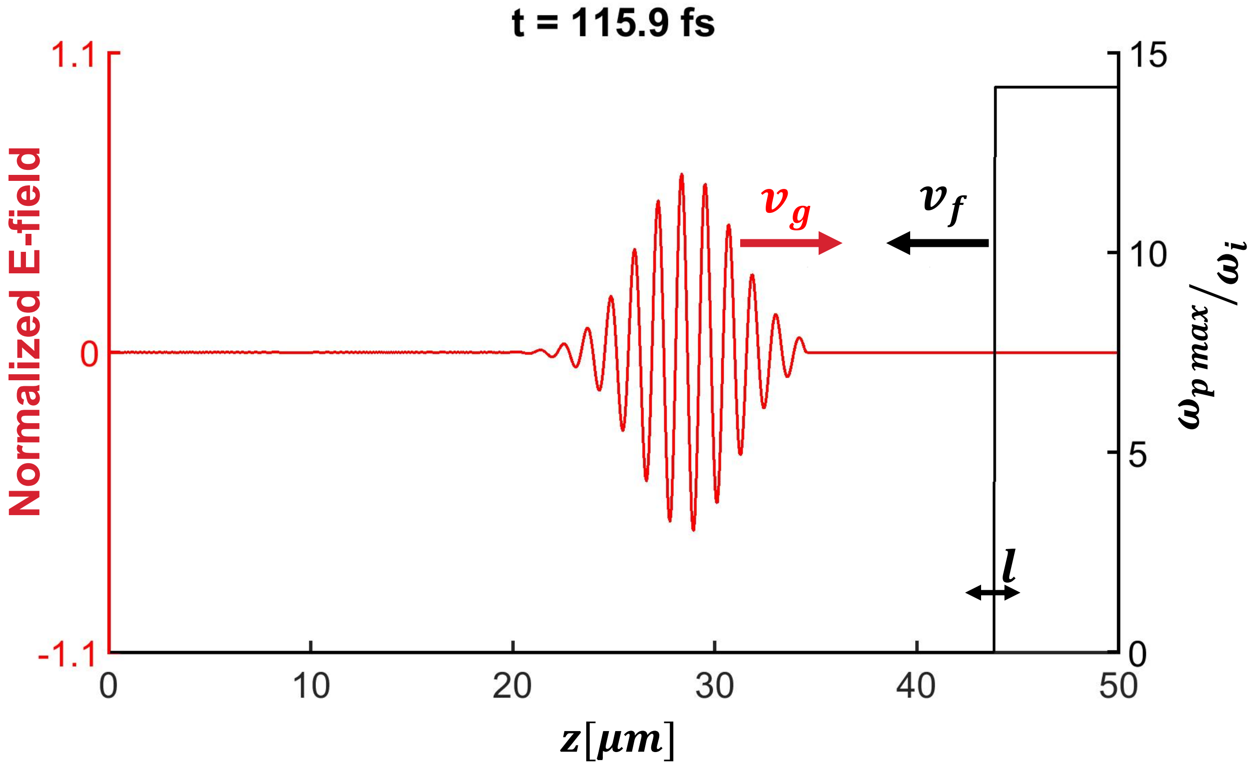
- **Specify density profile:**

$$\omega_p(z,t) = \frac{\omega_{p\max}}{2}\left\{1 + \tanh\left[l^{-1}\left(z - v_f t\right)\right]\right\}$$

Vary: $\omega_{p\,max}, l\,, v_f$

- **Specify (Gaussian) source parameters:**

Vary: $\lambda_0, \delta\lambda\ (\tau_{T.L.})$, chirp



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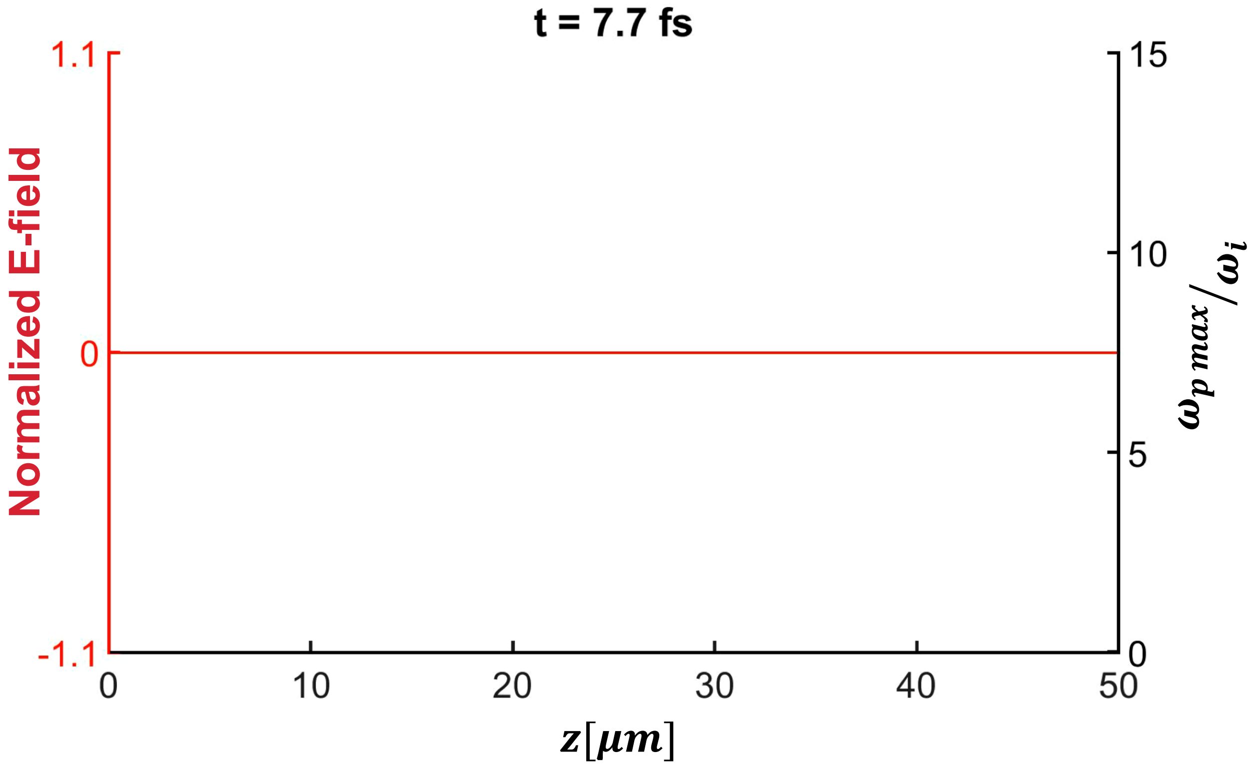
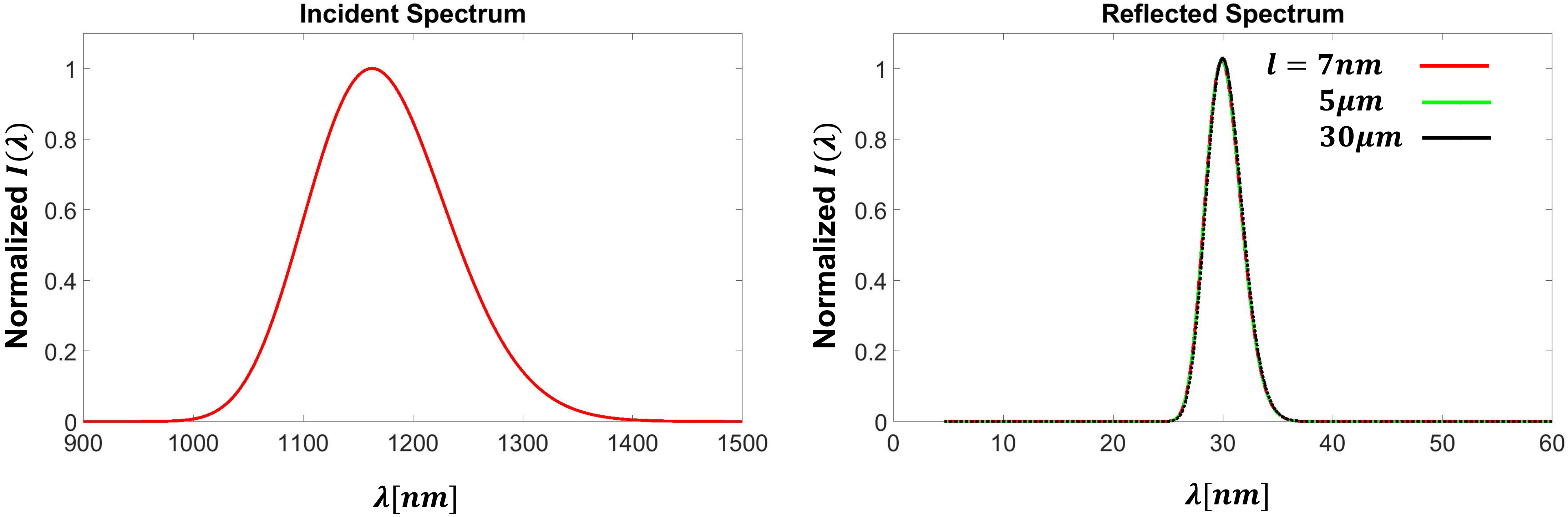


Reflected spectra and energies are consistent with the simple analytic theory for all ionization front density scale lengths

$$\lambda_i = 1170\text{nm}$$
$$\delta\lambda_i = 150\text{nm}$$
$$\tau_i = 13fs$$

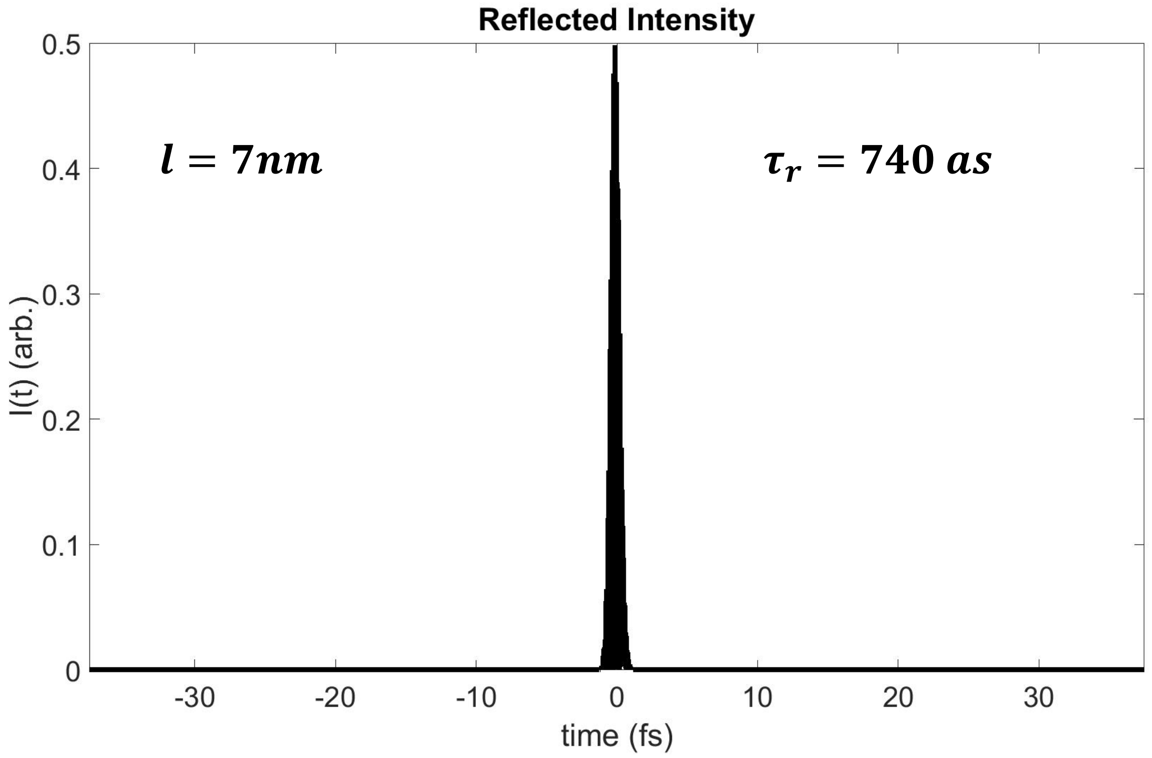
$$\beta = .95$$
$$l = 7nm - 30\mu m$$

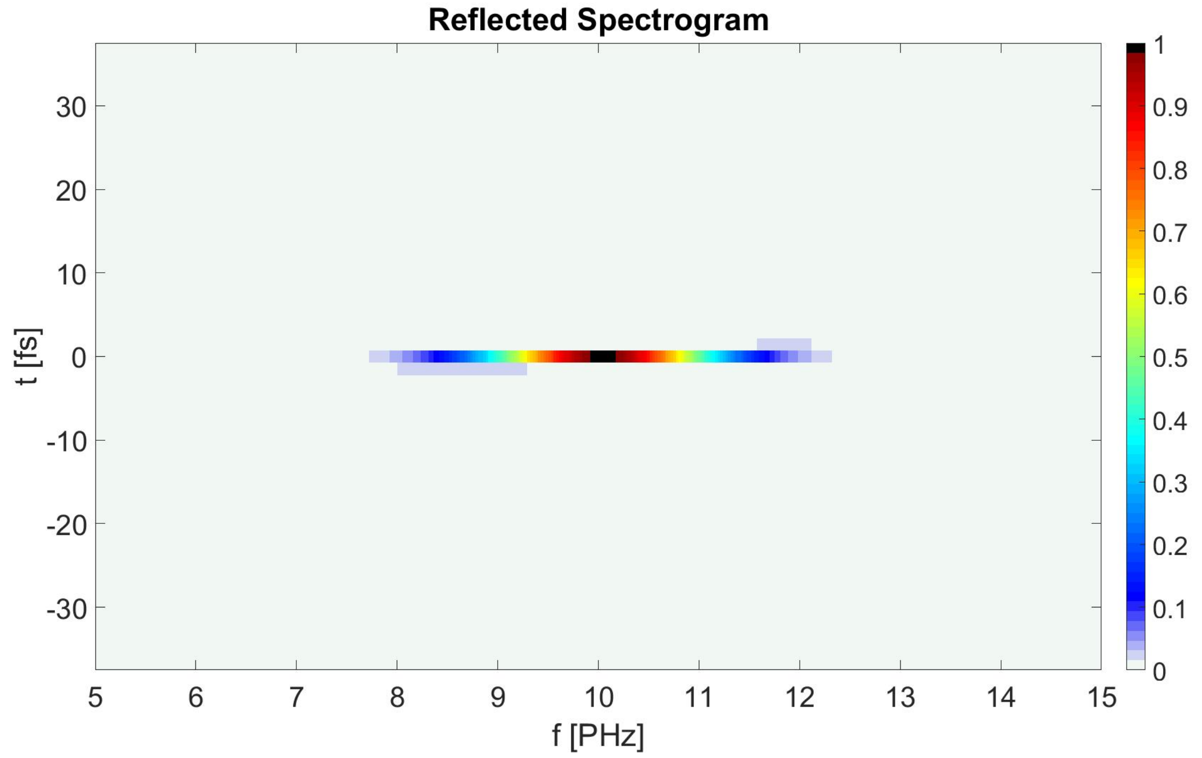
$$\lambda_r = \frac{1-\beta}{1+\beta}\lambda_i = 30nm$$
$$\delta\lambda_r = \frac{\lambda_r}{\lambda_i}\delta\lambda_i = 3.8nm$$



Reflected pulses remain coherent and ultrashort, but finite scale lengths and bandwidths contribute to temporal broadening

$$\tau_r = \frac{\lambda_r}{\lambda_i} 13\ fs = 333\ as$$





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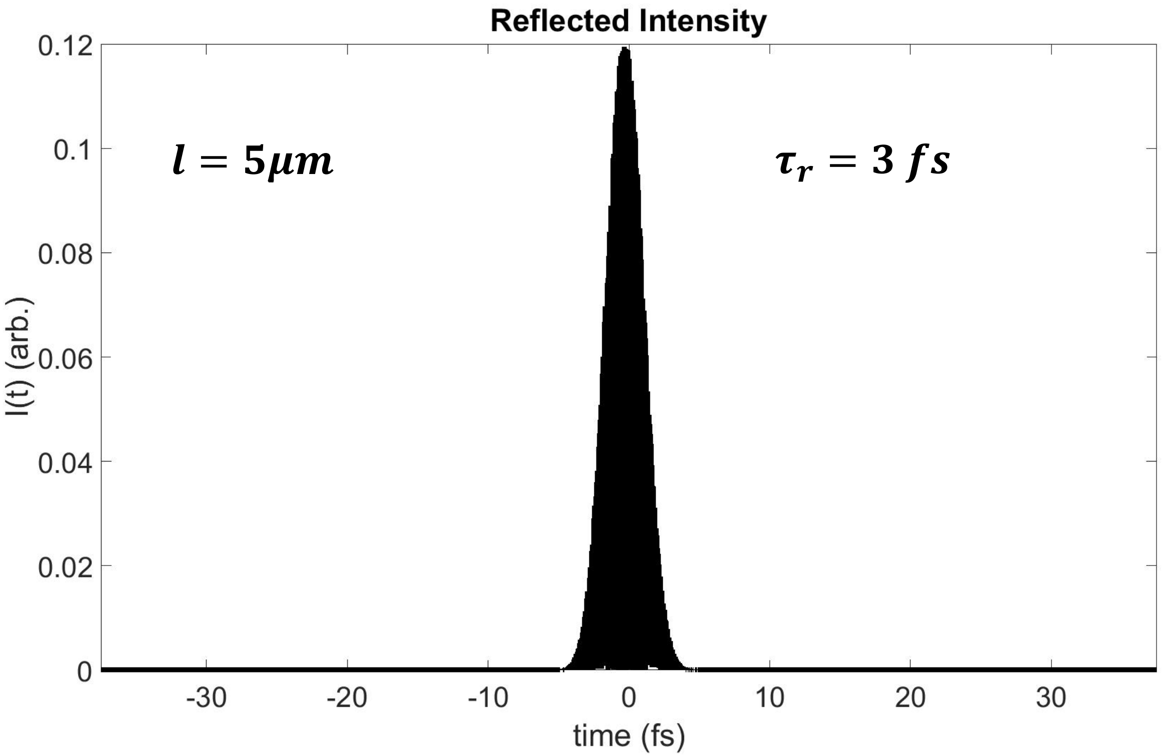

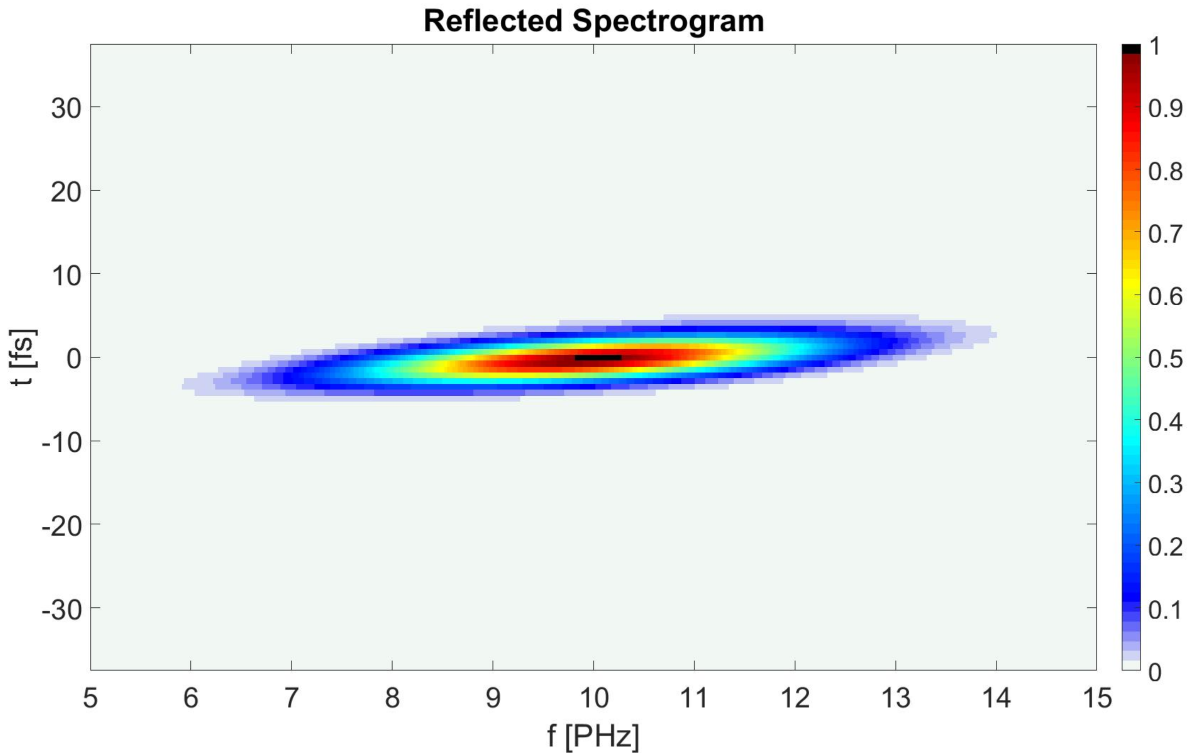

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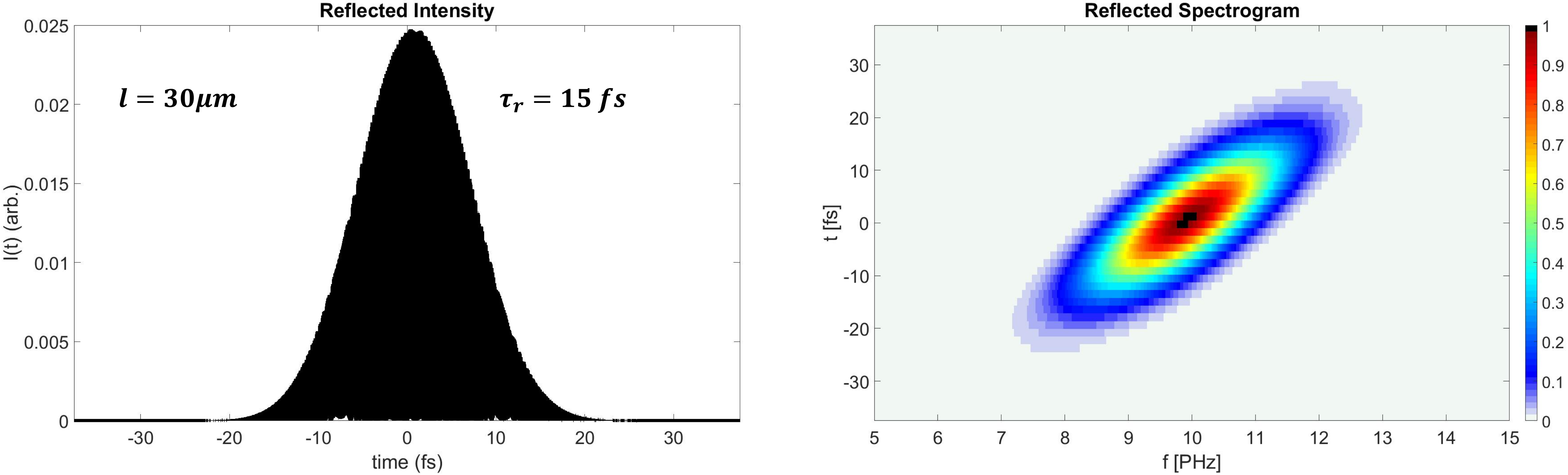


Dispersion can be mitigated by pre-chirping the incident pulse

Summary/Conclusions

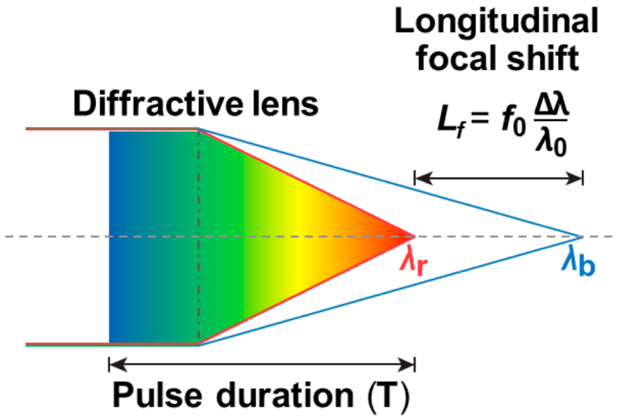
Laser pulses reflected from flying focus-driven ionization fronts can undergo extreme frequency upshifts

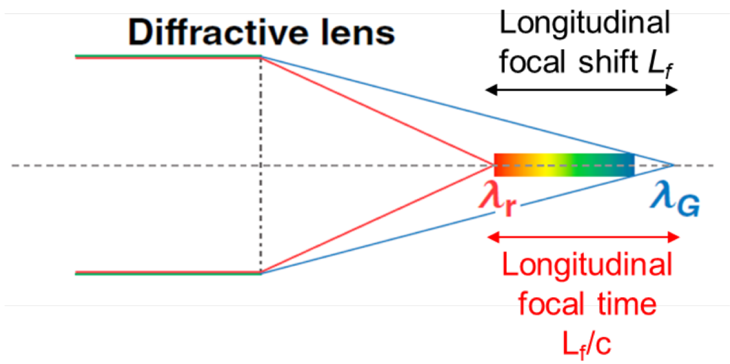
- High density ionization fronts can be driven over long distances at any velocity with the flying focus
- Reflected pulses can be shifted to high frequencies, while retaining desirable characteristics such as spatial coherence, low divergence, and ultrashort duration
- Output frequency is easily tuned over a broad range by changing the front velocity

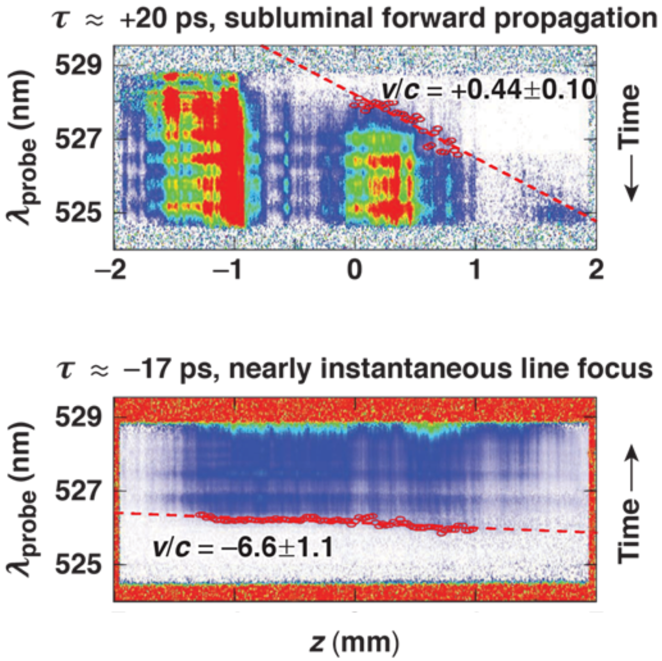
The details of high density IWAV generation are being studied computationally

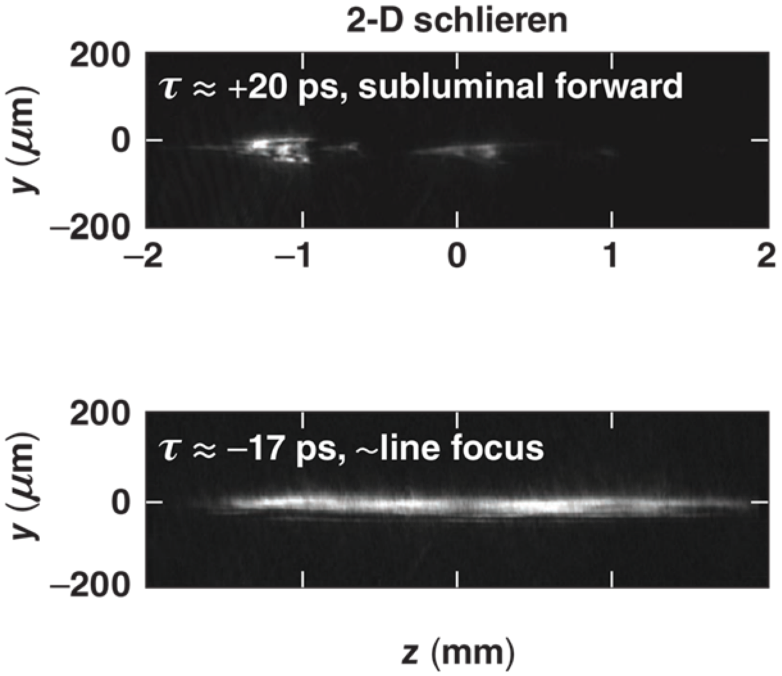
Backup

Backward and/or superluminal focal velocities eliminate the effects of ionization refraction on the IWAV propagation

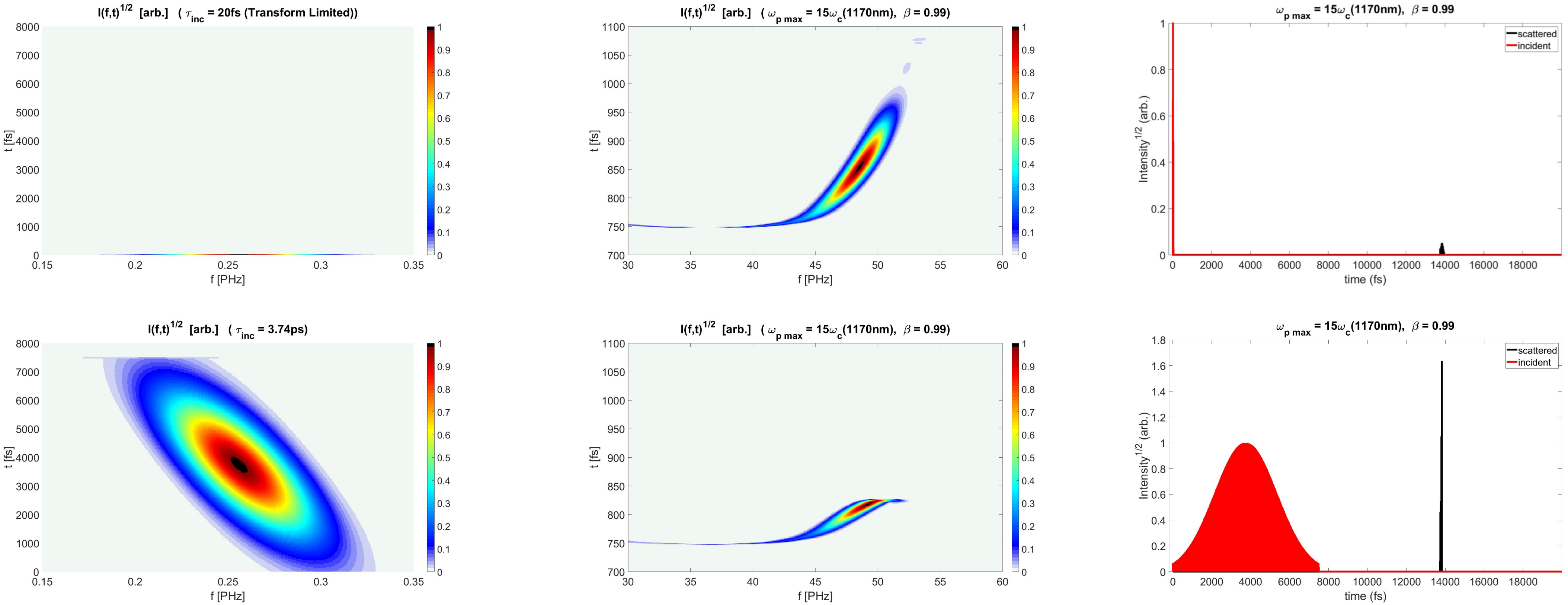




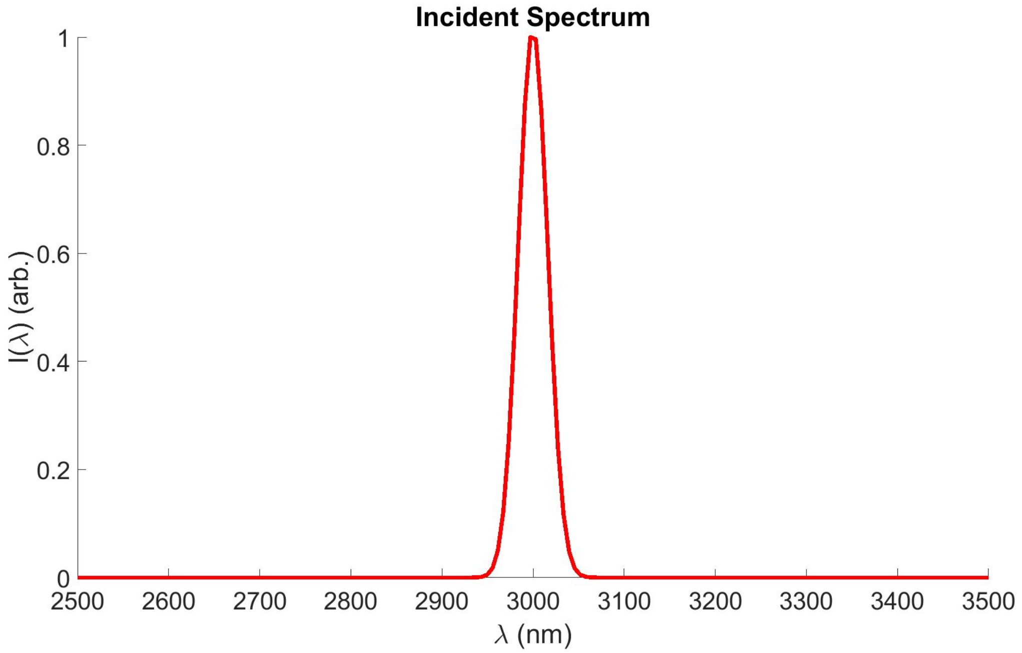


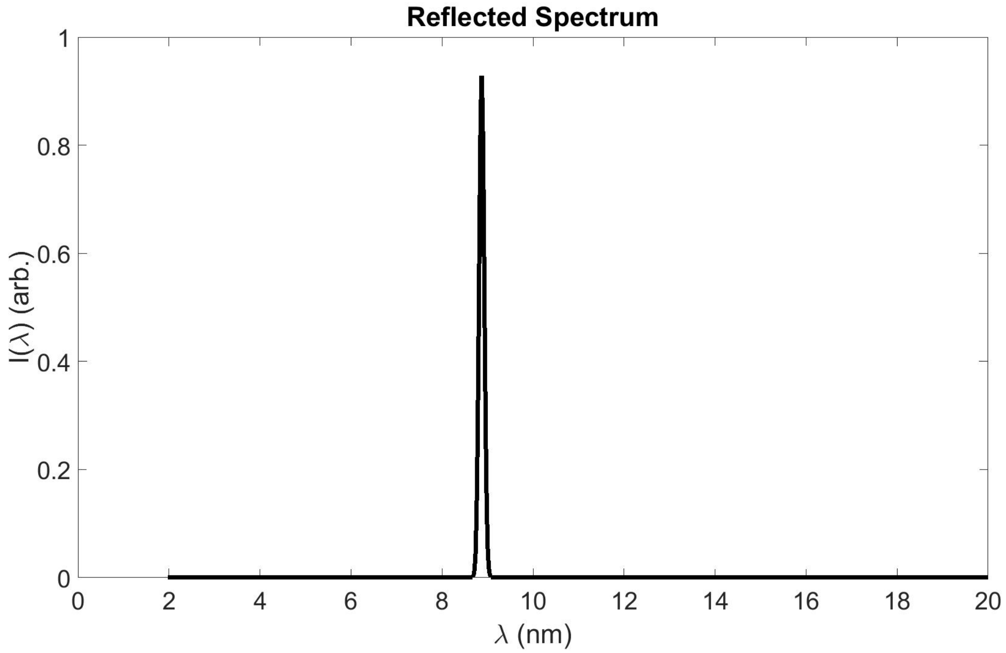


Introducing a negative chirp to the incident pulse mitigates temporal broadening in the reflected pulse

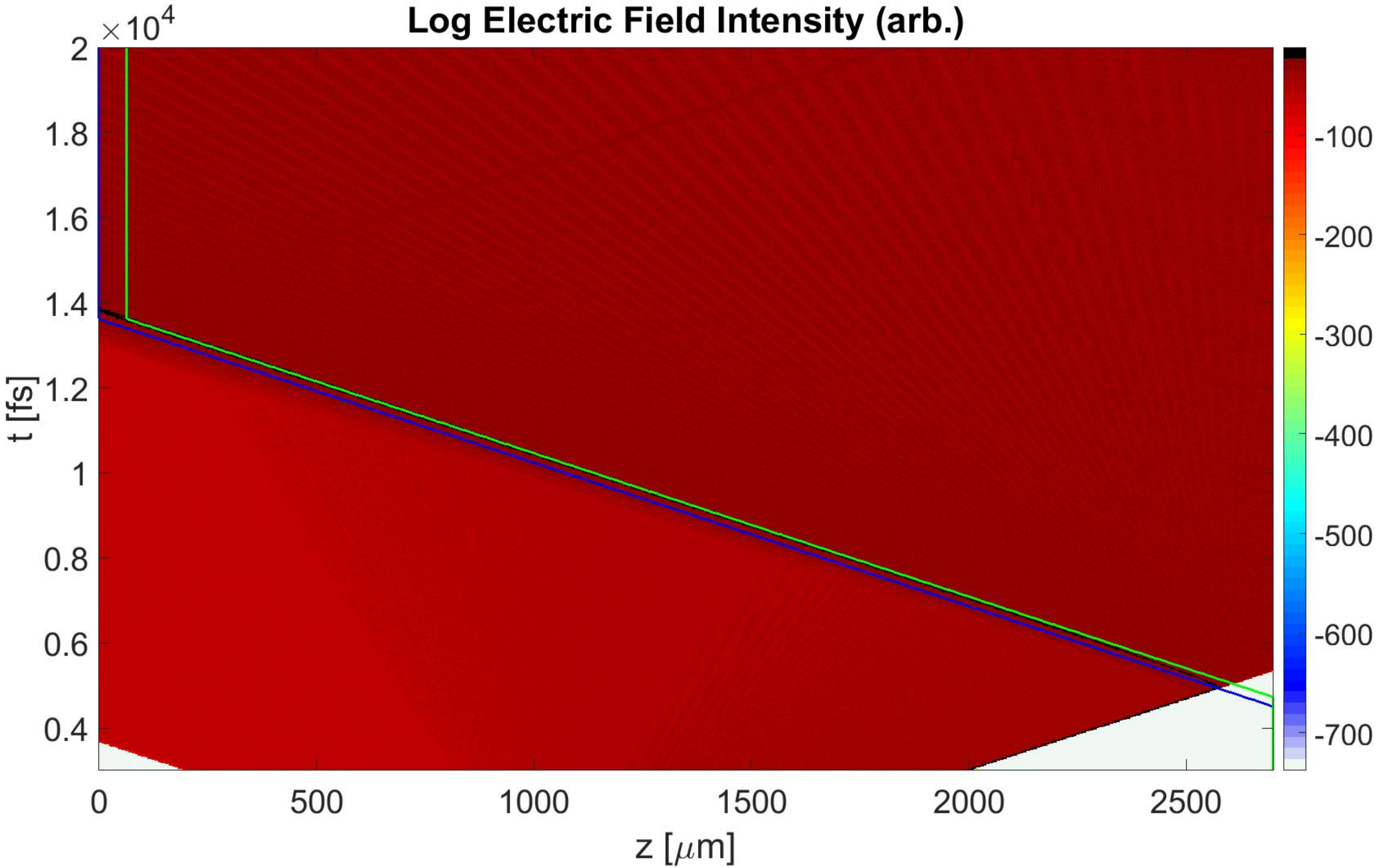


Smaller initial frequency and bandwidth permits higher frequency reflected light with the same plasma density





Fronts of finite width can interact with the test pulse over long distances and durations



High quality XUV and X-ray sources have broad applicability

- HEDP diagnostics
  - Spectroscopy, radiography, interferometry, scattering
- Materials science, AMO physics, chemistry and biology
  - All of the above plus others
- Industrial applications
  - Small feature sizes in etching and lithography

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* Pierre Jaeglé, *Coherent Sources of XUV Radiation: Soft X-Ray Lasers and High-Order Harmonic Generation* (Springer, 2006).

Collaborators

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