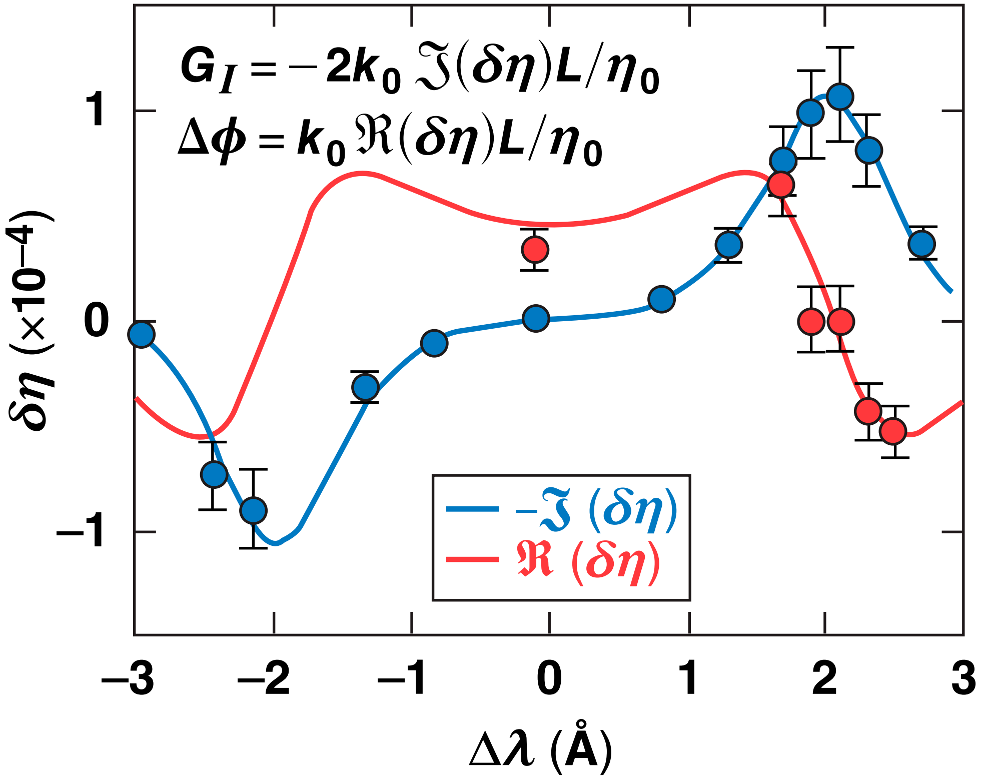
Plasma-Based Photonic Devices: Wave Plates, Polarizers, and Amplifiers



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Summary

Laser-plasma systems can be used as high-power, tunable photonic devices (e.g., wave plates, polarizers, and amplifiers)

- **Recent experiments at Jupiter Laser Facility (JLF) have validated the linear theory* used to calculate cross-beam energy transfer (CBET) in direct- and indirect-drive inertial confinement fusion (ICF)**
- **Ultrafast, high-power, tunable laser-plasma wave plates** and polarizers† were also demonstrated using this stimulated Brillouin scattering (SBS)-based system**
- **Simulations illustrate how a new scheme (called "flying focus") offers many advantages for stimulated Raman scattering (SRS)-based amplifiers**

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* P. Michel *et al.*, Phys. Rev. Lett. 113, 205001 (2014).

** D. Turnbull *et al.*, Phys. Rev. Lett. 116, 205001 (2016).

† D. Turnbull *et al.*, Phys. Rev. Lett. 118, 015001 (2017).

Collaborators

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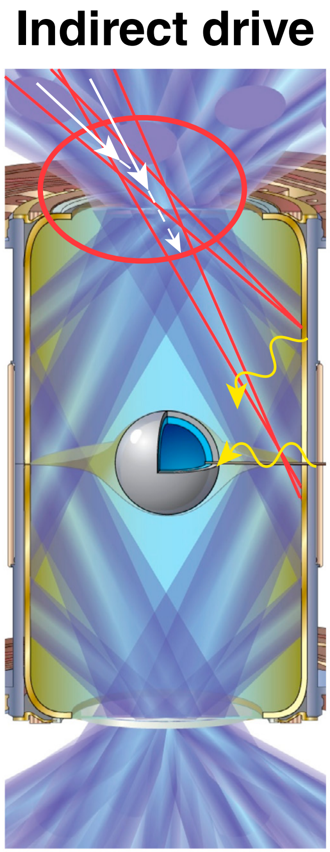
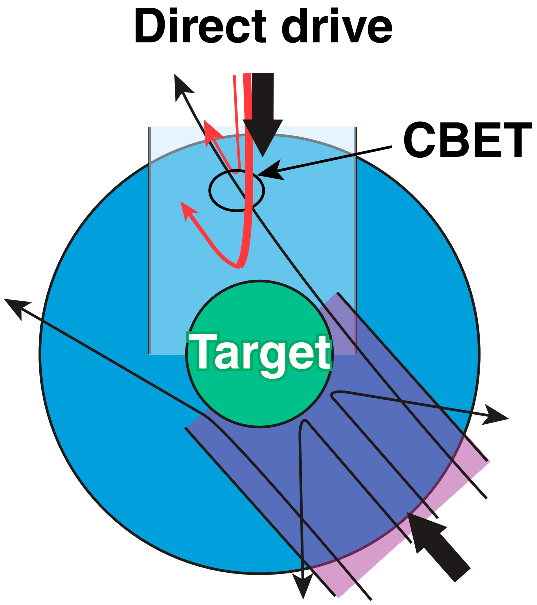
York Plasma Institute

CBET affects energy coupling and implosion symmetry in direct- and indirect-drive ICF

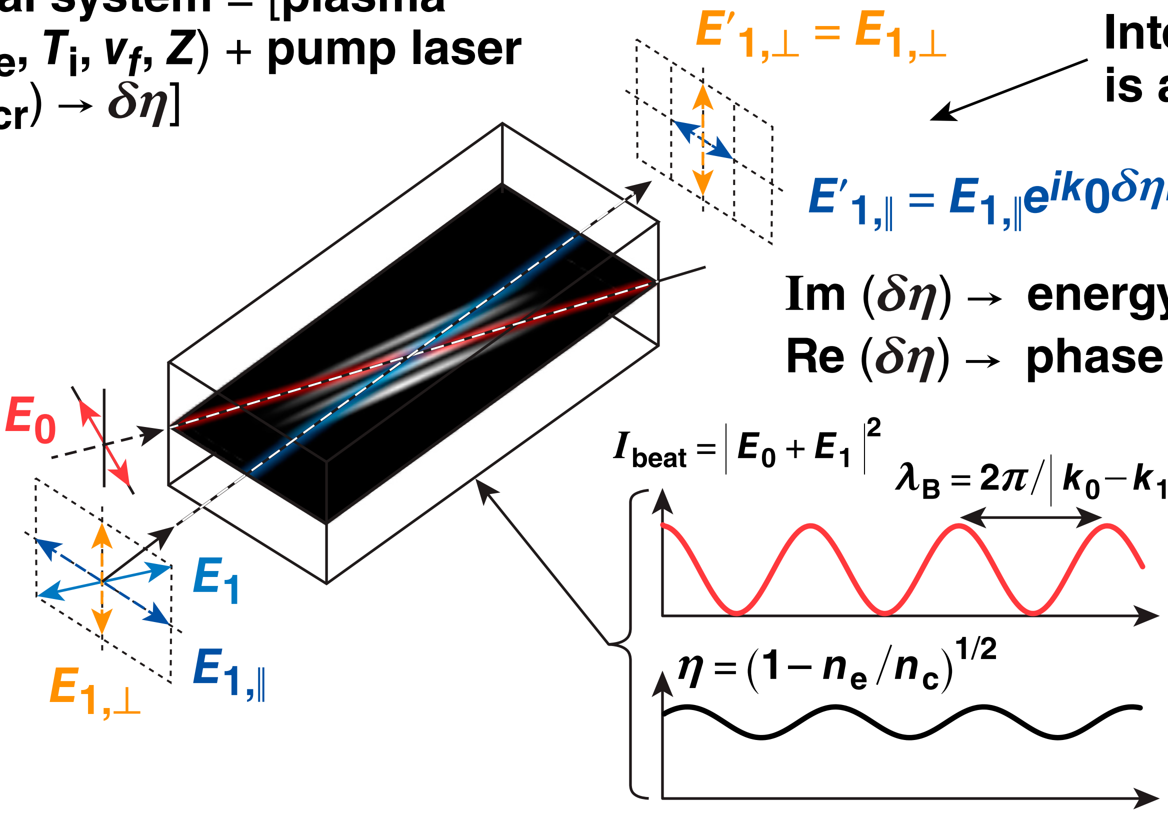




Validating CBET models is an important component of simulating ICF implosions.

CBET theory* can be formulated as a laser-plasma system with a complex refractive-index perturbation operating on a probe beam

Optical system = [**plasma** (n_e, T_e, T_i, v_f, Z) + **pump laser** (I_0, α_{cr}) → $\delta\eta$]



$E'_{1,\perp} = E_{1,\perp}$

Interaction is anisotropic

$E'_{1,\parallel} = E_{1,\parallel} e^{ik_0 \delta\eta L/\eta_0}$

Im ($\delta\eta$) → **energy transfer**

Re ($\delta\eta$) → **phase delay**

$I_{\text{beat}} = |E_0 + E_1|^2$

$\lambda_B = 2\pi/|k_0 - k_1|$

Beat wave

$\eta = (1 - n_e/n_c)^{1/2}$

Refractive-index modulation

Such a system can modify the amplitude and/or polarization of the probe beam.

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- Ultrafast, high-power, tunable laser-plasma wave plates** and polarizers† were also demonstrated using this stimulated Brillouin scattering (SBS)-based system
- Simulations illustrate how a new scheme (called "flying focus") offers many advantages for stimulated Raman scattering (SRS)-based amplifiers

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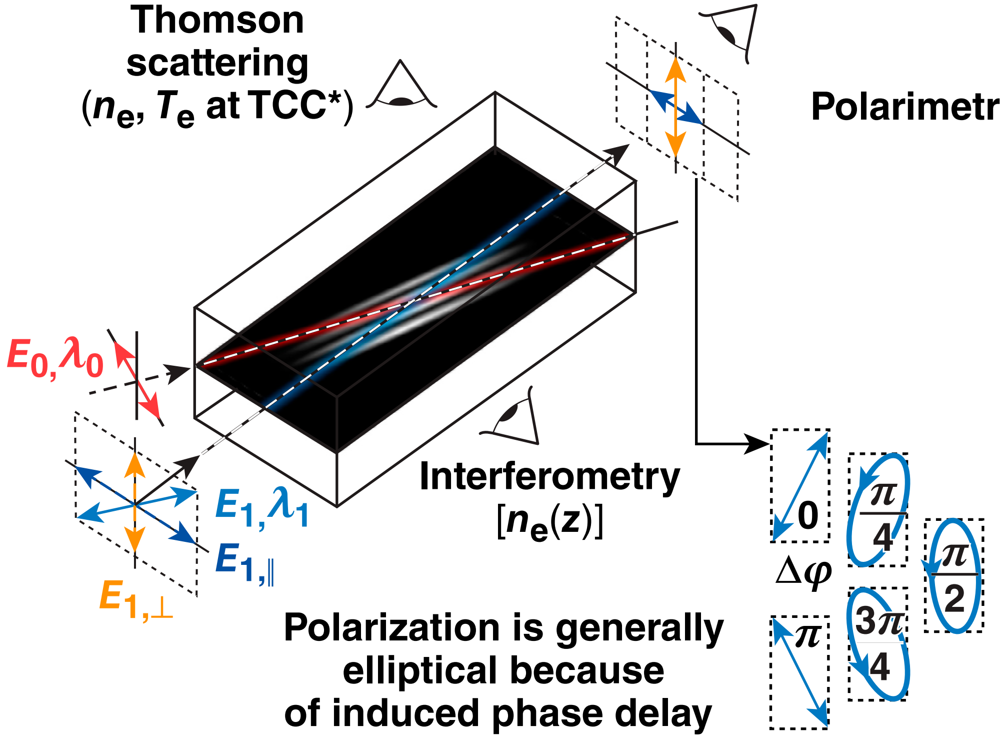
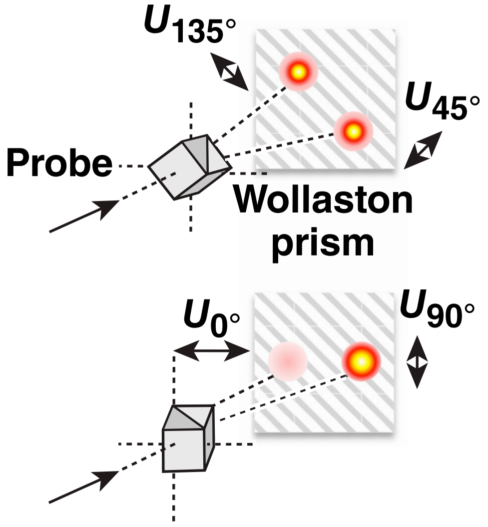
A pump-probe experiment with wavelength tuning was carried out to measure $\delta\eta$ as a function of $\Delta\lambda$ (a new capability at JLF)



Polarization is generally elliptical because of induced phase delay



Amplification

$$G_I = \ln(U_{0^\circ}/U_{90^\circ})$$

Phase delay

$$\Delta\varphi = \cos^{-1}\left[\frac{(U_{45^\circ} - U_{135^\circ})/(U_{45^\circ} + U_{135^\circ})}{2\sqrt{U_{0^\circ}U_{90^\circ}/U_{0^\circ} + U_{90^\circ}}}\right]$$

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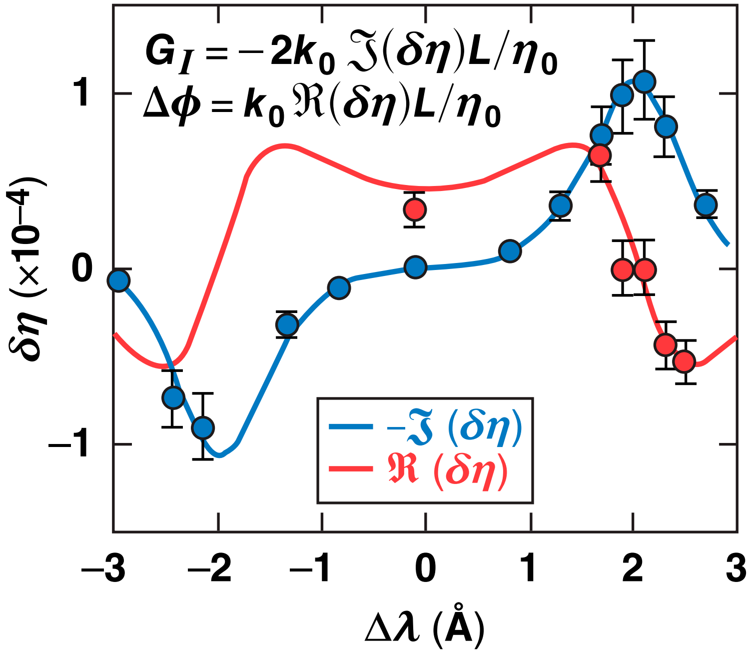
*TCC: target chamber center

$\delta\eta$ is in good agreement with linear theory using inputs from measurements and *HYDRA**



Parameter	Theory input	Measured value	*HYDRA* simulation
n_e/n_c	0.0104	0.011 ± 0.001	~ 0.009
T_e (eV)	220	224 ± 24	~ 231
T_i/T_e	0.1200	—	~ 0.090
$\overline{\lvert v_{\text{flow}}\rvert}$ (m/s)	$\sim 1.4\times10^{4}$	—	$\sim 1.4\times10^{4}$
I_0	$\sim 2.9\times10^{13}$	$\sim 3.6\times10^{13}$**	$\sim 3.6\times10^{13}$
$\bar{Z}$	2.5†	—	2

This is the first time that the gain curve is resolved this accurately and found to be in good agreement with linear theory; the first measurement of Re $(\delta\eta)$ versus $\Delta\lambda$.

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*D. Turnbull *et al.*, Phys. Rev. Lett. 118, 015001 (2017).

**Measurement did not include transport optic losses, inverse bremsstrahlung absorption, or the possibility of nonideal pump spot.

†Implies depletion of H from the interaction region.

Summary

Laser-plasma systems can be used as high-power, tunable photonic devices (e.g., wave plates, polarizers, and amplifiers)

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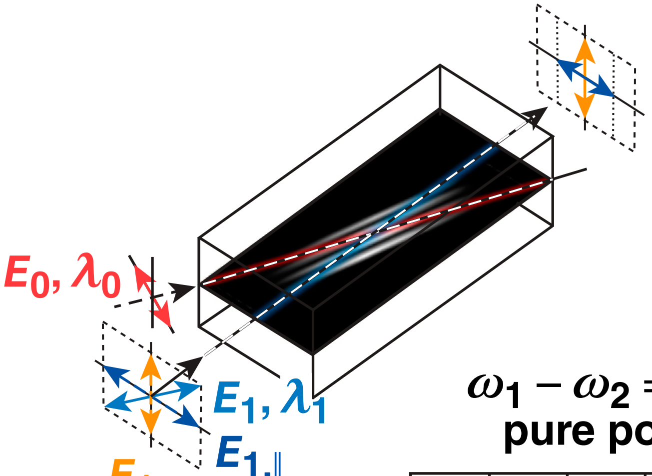
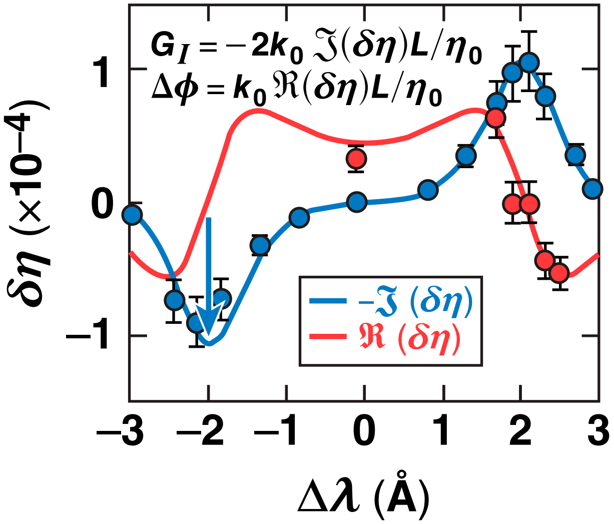
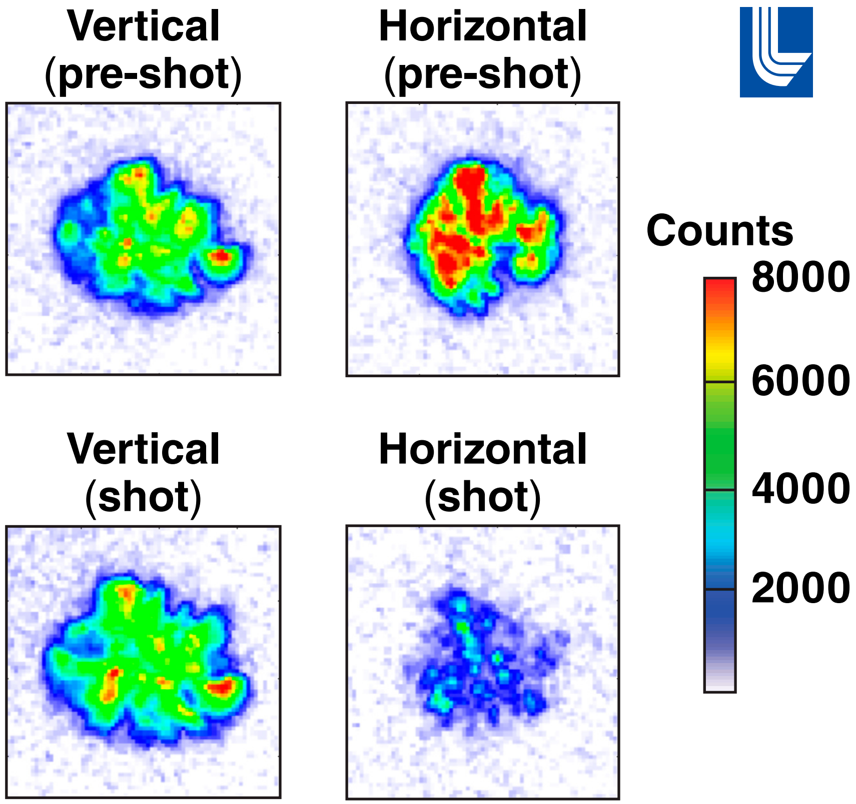
The system can act as a "plasma polarizer" with 85% to 87% extinction for these laser and plasma parameters



$\omega_1 - \omega_2 = -\omega_{IAW}$:
pure polarizer





~85% to 87% extinction

P. Michel *et al.*, Phys. Rev. Lett. 113, 205001 (2014);
D. Turnbull *et al.*, Phys. Rev. Lett. 118, 015001 (2017).

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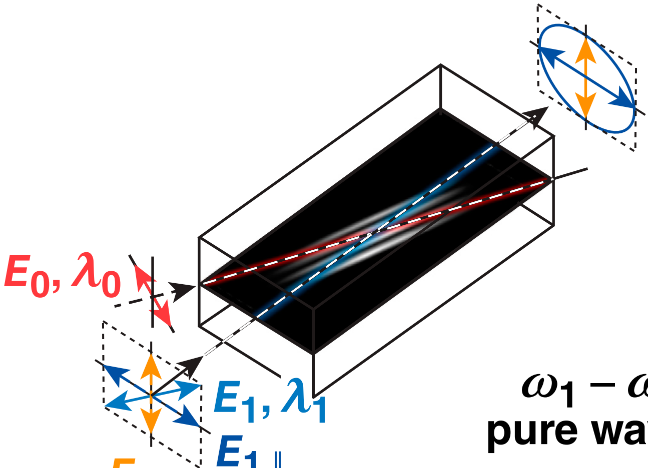
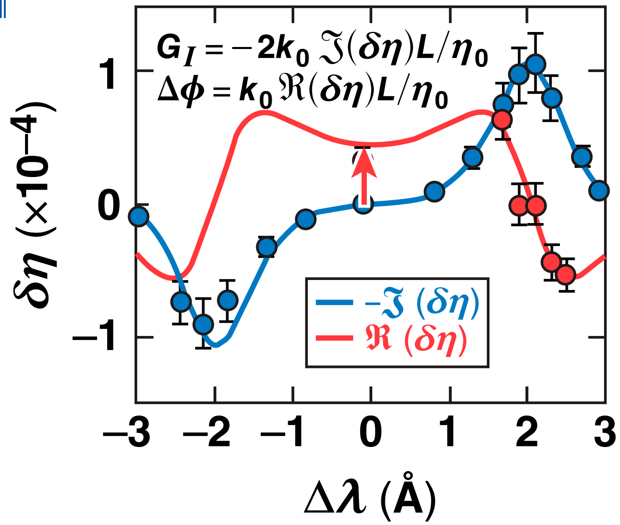
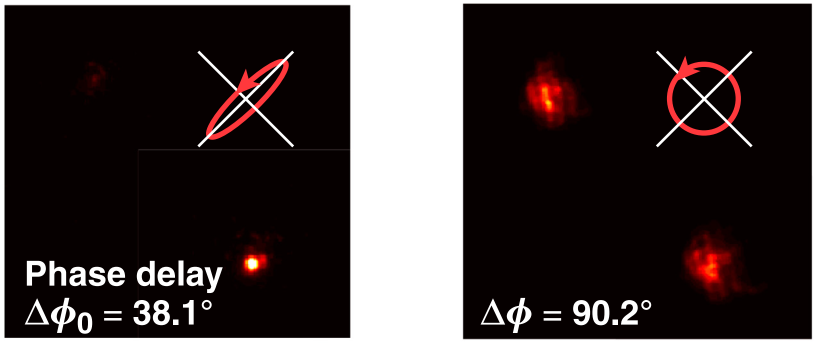
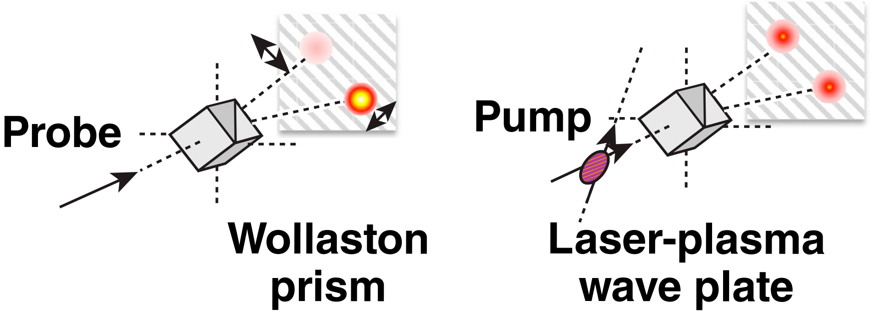
The system can also act as a pure tunable “plasma wave plate,” which was demonstrated in the previous year’s campaign



$\omega_1 - \omega_2 = 0$:
pure wave plate







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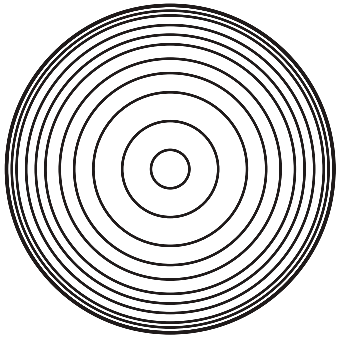
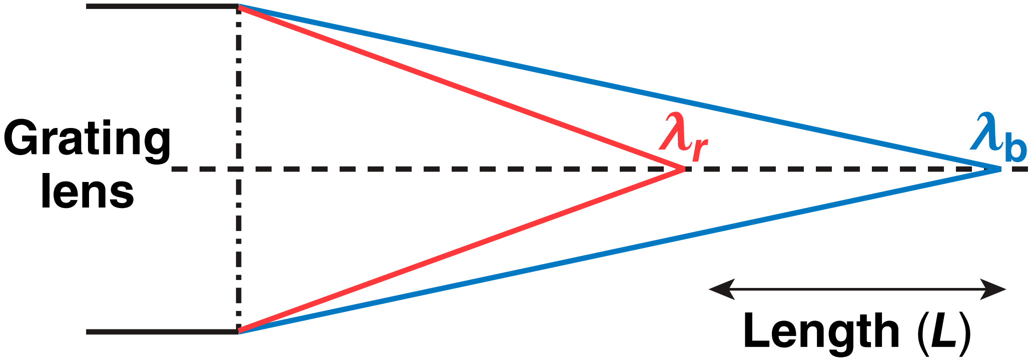
A grating lens longitudinally disperses the focal positions of different colors within the pump bandwidth

Variable line spacing

$$G(r) = \frac{r\Delta\lambda}{L\lambda^2}$$

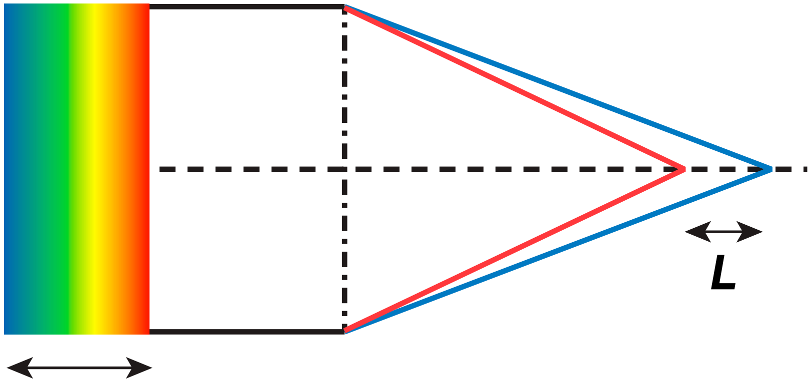




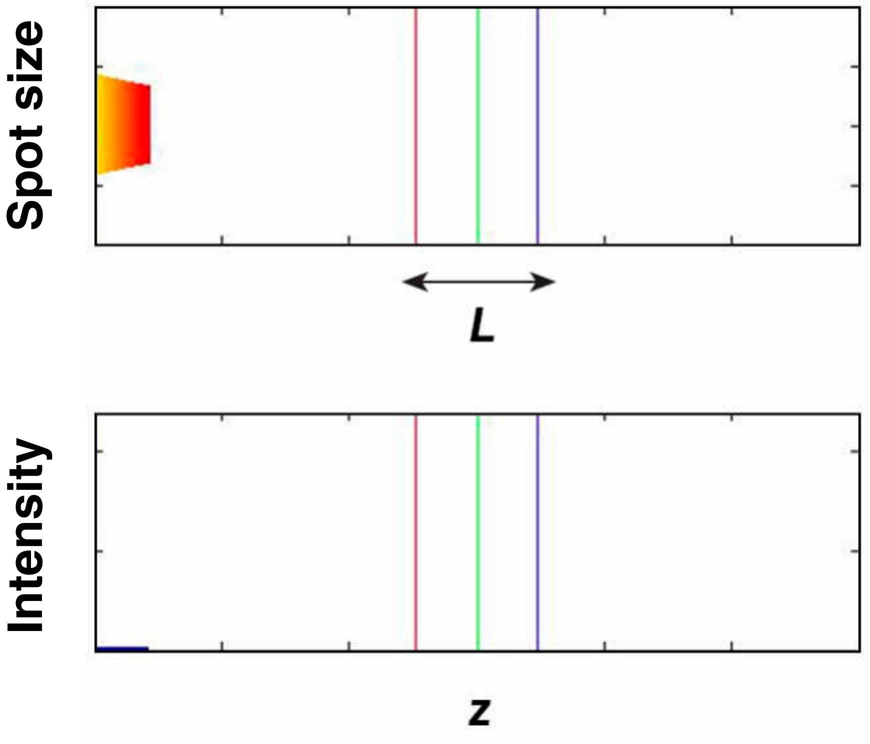
Typically used to correct chromatic aberration, here we propose using it to deliberately introduce chromatic aberration.

"Flying focus" refers to control over the propagation of high intensity within a laser focusing region

Positive chirp (red to blue)

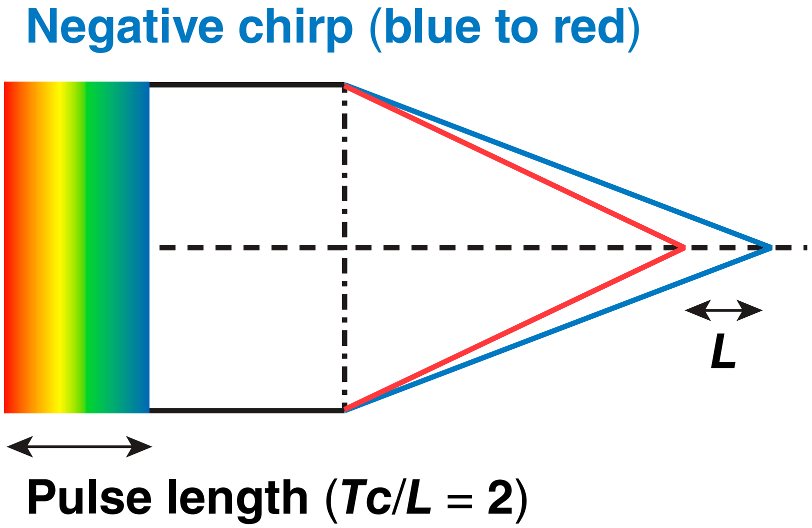


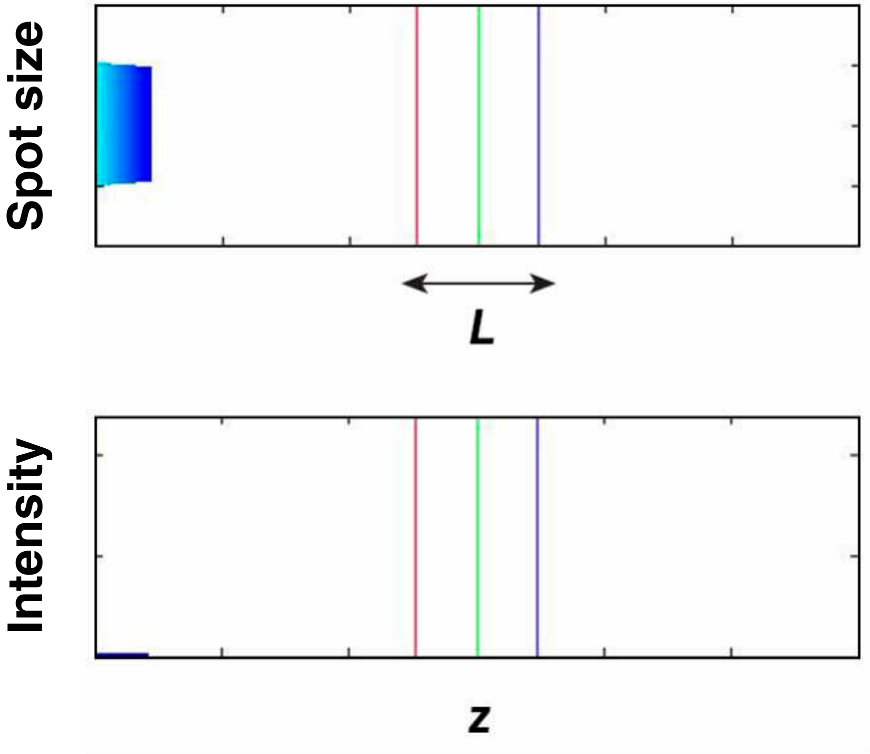
Pulse length ($Tc/L = 2$)



With positive chirp and $Tc/L = 2$, high intensity travels at $c/3$.

It is advantageous for laser-plasma amplifiers that high intensity propagate at –c





With negative chirp and *Tc*/*L* = 2, high intensity travels at –c.

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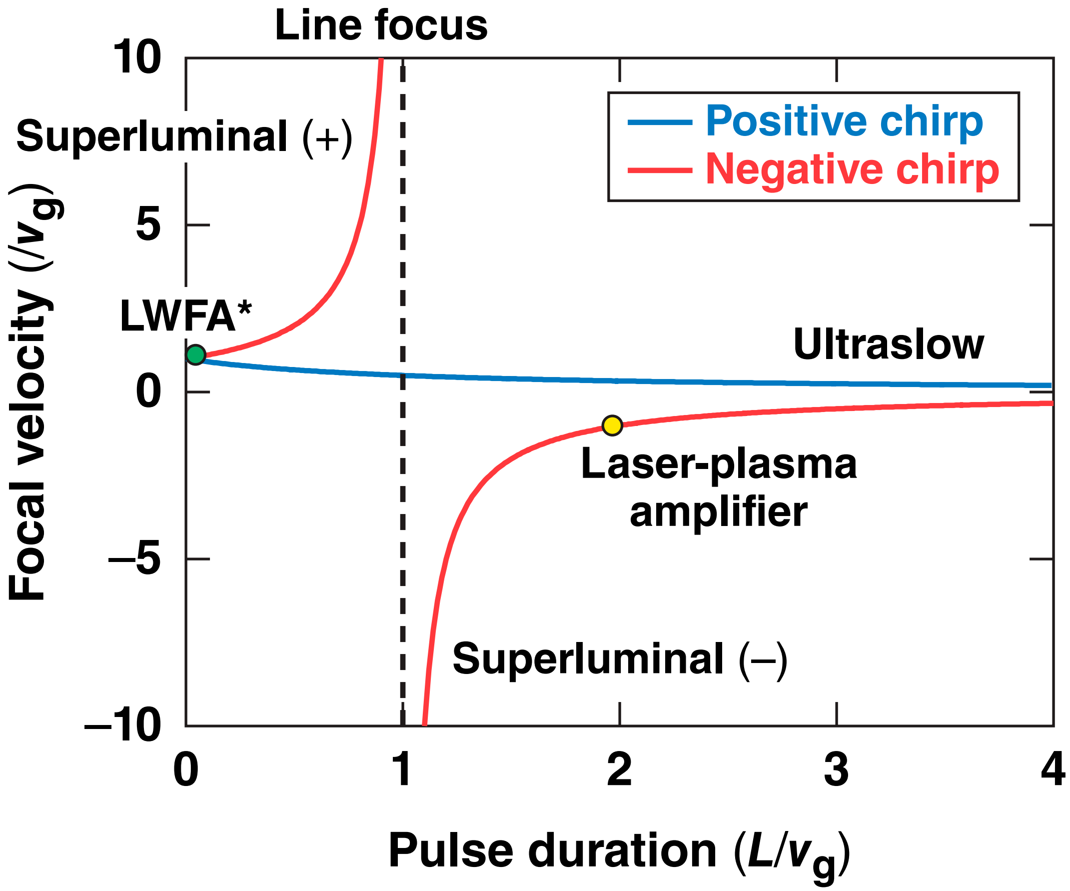
Chirp plus grating lens provides spatiotemporal control over propagation of high intensity



$$\frac{v_f}{v_g} = \frac{1}{1 + Tv_g/L}$$

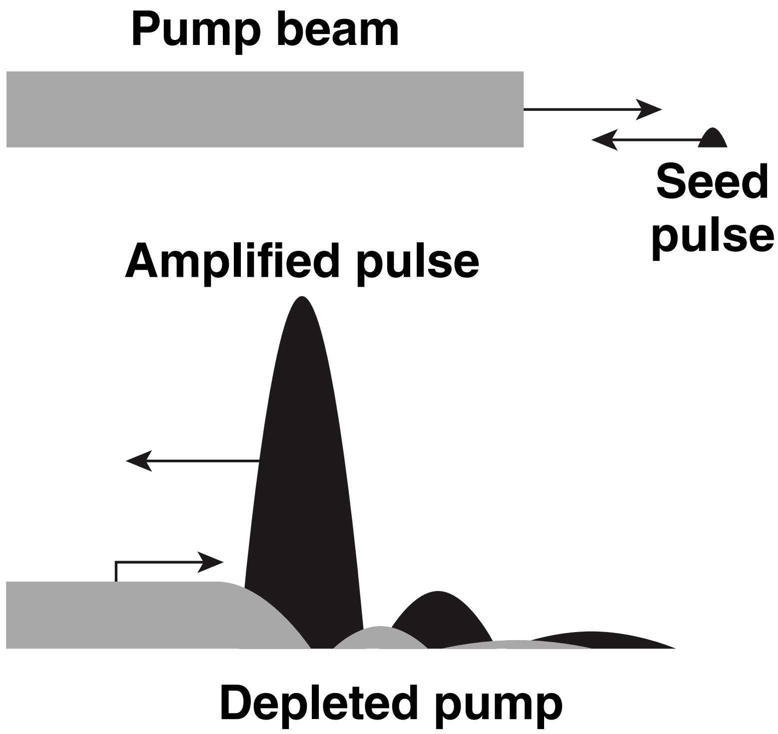
D. H. Froula *et al.*, "Flying Focus: Spatiotemporal Control of the Longitudinal Laser Beam Intensity," in preparation.

*LWFA: laser wakefield accelerator

E26267

Amplifiers based on stimulated Raman scattering* can also be used to create ultraintense laser beams

- Typically, the goal is to transfer most of the energy from a tens of picoseconds "long"-pulse beam to a frequency-downshifted ~100-fs beam
- Energy transfer is mediated by an electron plasma wave (EPW)
- Experiments have been limited by:
  - – thermal effects
  - – spontaneous SRS



E26268

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*V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. 82, 4448 (1999).

Three-wave coupled equations, plus ionization model, are solved numerically* to investigate flying-focus Raman amplification (FFRA)

$$
\begin{aligned}
(\partial_t - v_1\partial_x + \nu_1)a_1 &= Ka_2a_3\\
(\partial_t - v_2\partial_x + \nu_2)a_2 &= -Ka_2a_3^*\\
(\partial_t - v_3\partial_x + \nu_3 + i\delta\omega)a_3 &= -Ka_1a_2^* + s_3
\end{aligned}
$$

$\nu_{1,2}$: collisional damping
ν_3: collisional/Landau damping
$v_3 \approx 0$: neglect EPW advection
$\delta\omega = 0$: neglect detuning
$S_3 \sim \nu_3 T_e$: tunable noise source

$$
\begin{aligned}
\partial_t n_e &= n_n w(a_1)\\
\partial_t n_n &= -n_n w(a_1)
\end{aligned}
$$

$w(a)$ is ionization rate
(Keldysh formula)

Flying focus is included via the time-varying boundary condition and intensification of pump as it propagates across interaction region.

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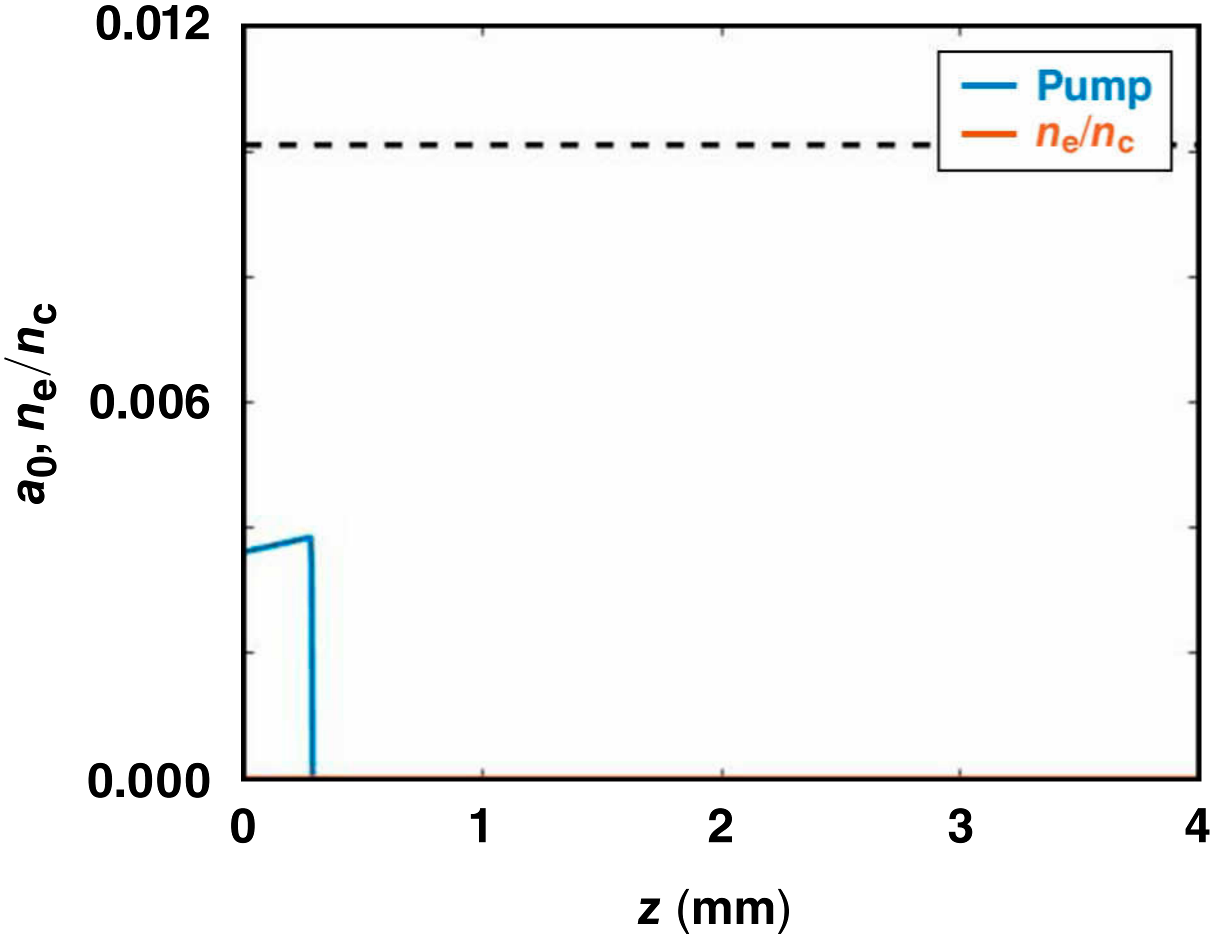
*D. S. Clark and N. J. Fisch, Phys. Plasmas 9, 2772 (2002);
D. S. Clark and N. J. Fisch, Phys. Plasmas 10, 3363 (2003).

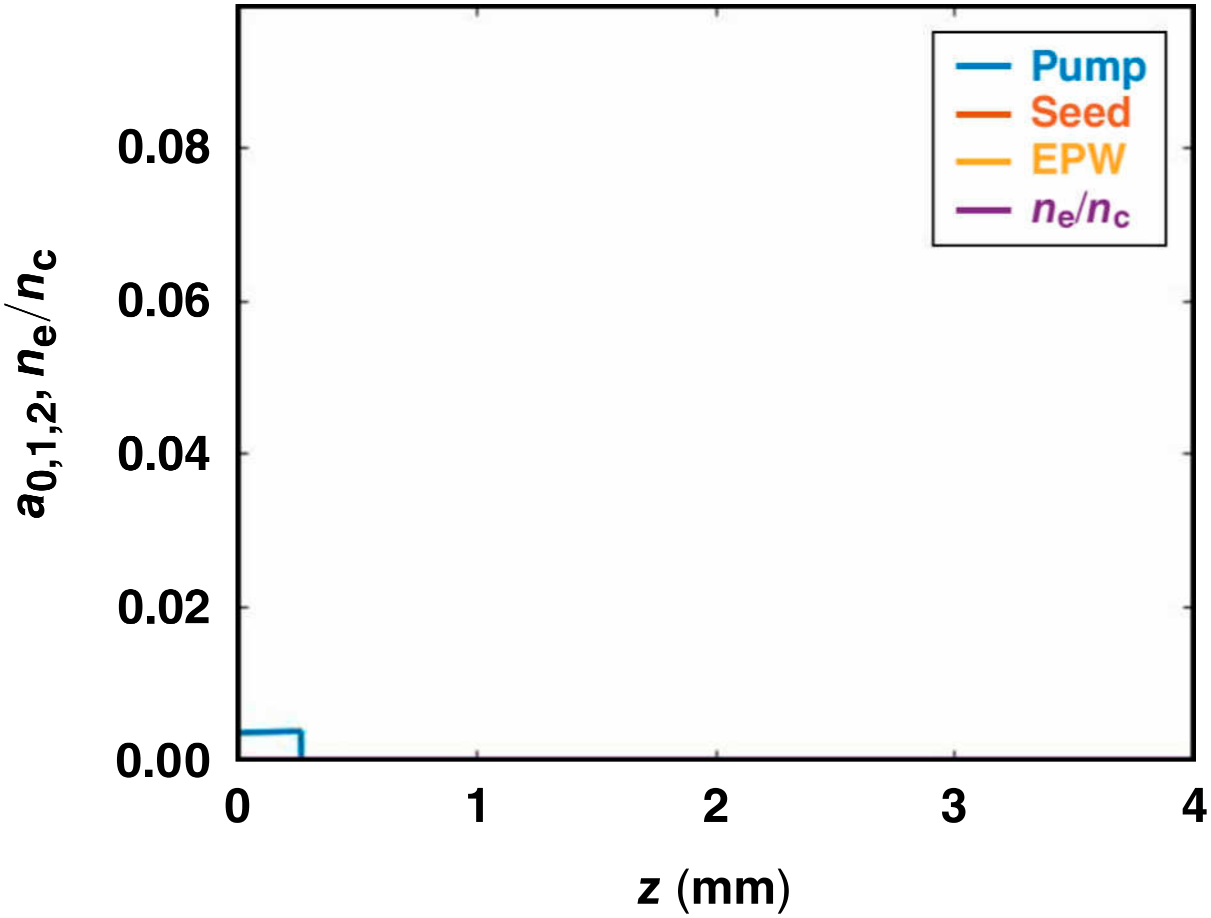
FFRA forms an ionization wave that travels at –c



Flying focus
$n_e = 6 \times 10^{18}/\text{cm}^3$
$I_p = 1.4 \times 10^{14}\ \text{W}/\text{cm}^2$
4-mm length
26.7-ps pump
$\lambda_p = 1\ \mu\text{m}$
***f*/5 pump**

E26270

With an injected seed pulse, ideal plasma amplifier behavior is observed



Flying focus
$n_e = 6 \times 10^{18}/\text{cm}^3$
$I_p = 1.4 \times 10^{14}\ \text{W}/\text{cm}^2$
4-mm length
26.7-ps pump
$\lambda_p = 1\ \mu\text{m}$
f/5 pump
$\tau_{\text{seed}} = 500$ fs
T_e controlled by IB*
$S_3 = 0.05 v_3 T_e$

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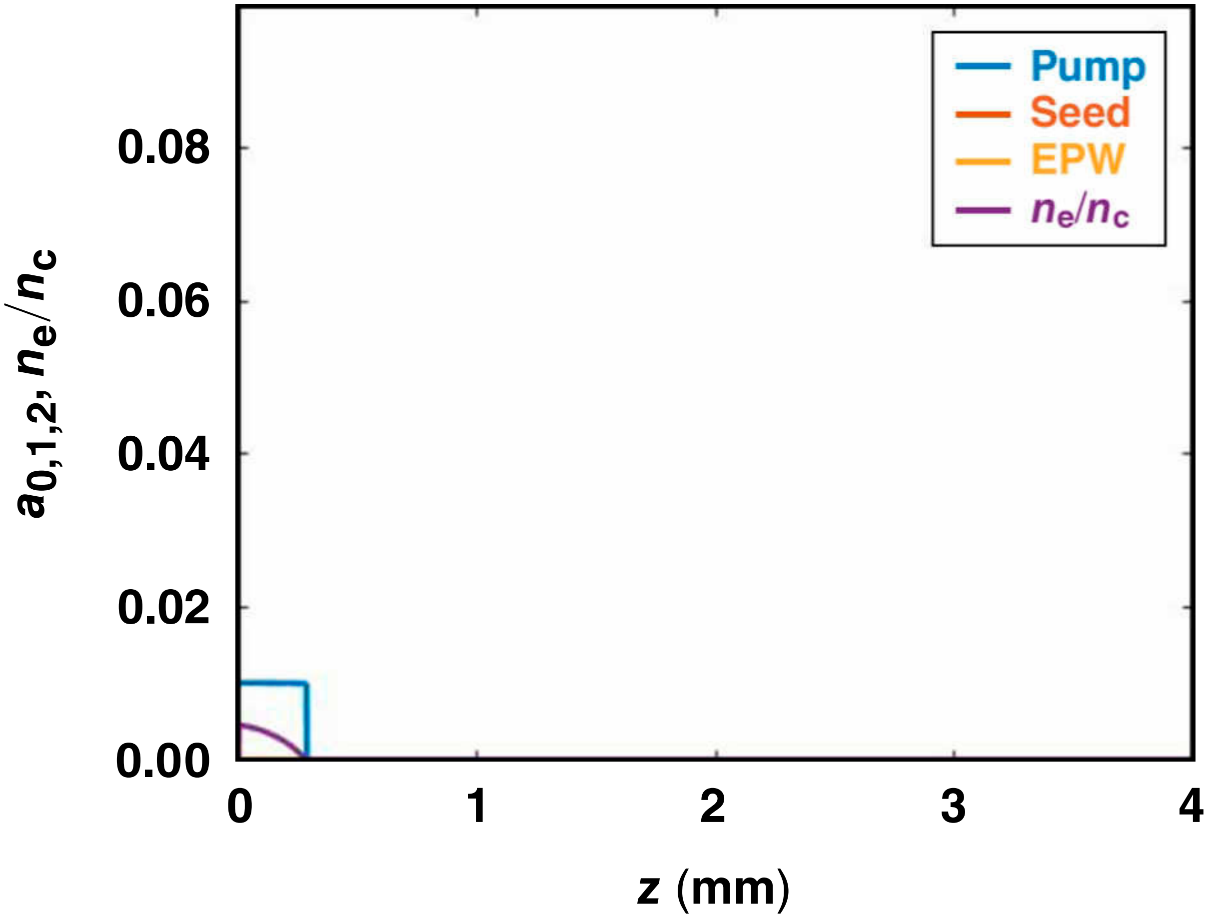
*IB: inverse bremsstrahlung

With a collimated pump, plasma is ionized earlier, growth is slower, and pump depletion does not occur



Standard focus

$n_e = 6 \times 10^{18}/\text{cm}^3$

$I_p = 1.4 \times 10^{14}\ \text{W}/\text{cm}^2$

4-mm length

26.7-ps pump

$\lambda_p = 1\ \mu\text{m}$

f/∞ pump

$\tau_{\text{seed}} = 500$ fs

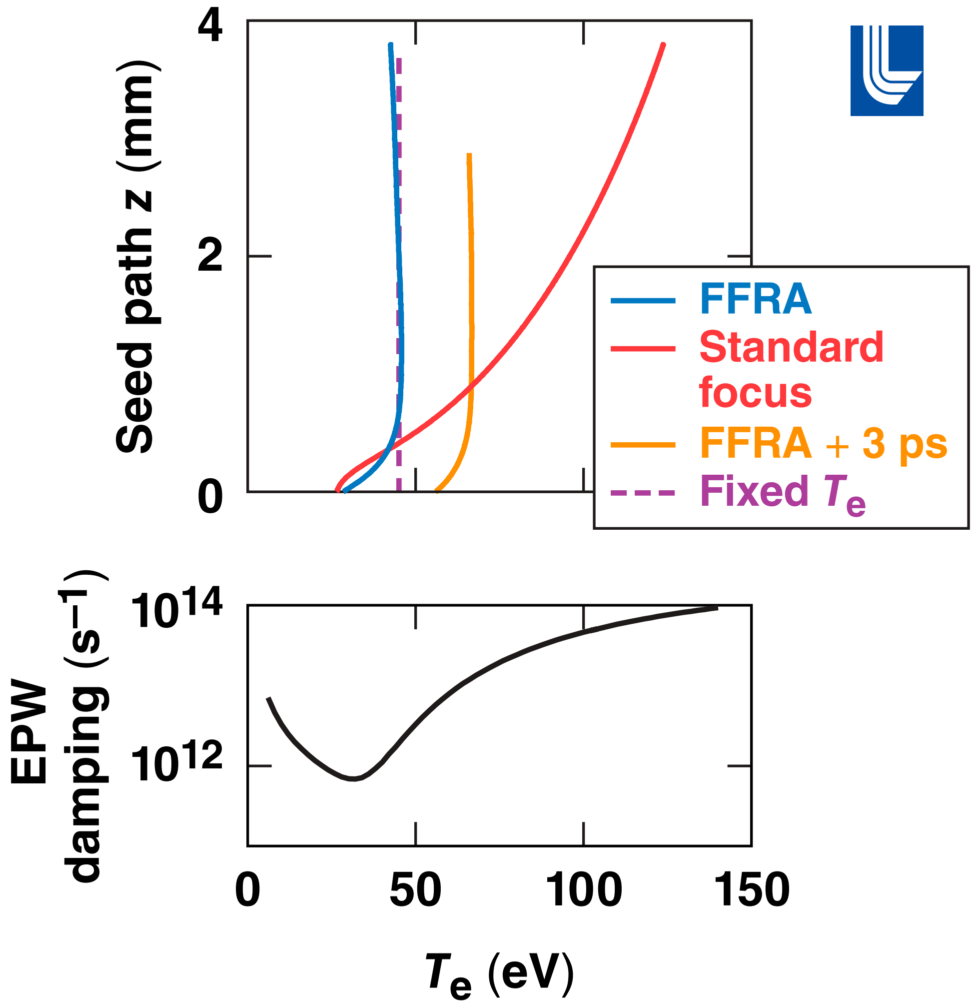
T_e controlled by IB

$S_3 = 0.05 v_3 T_e$

E26272

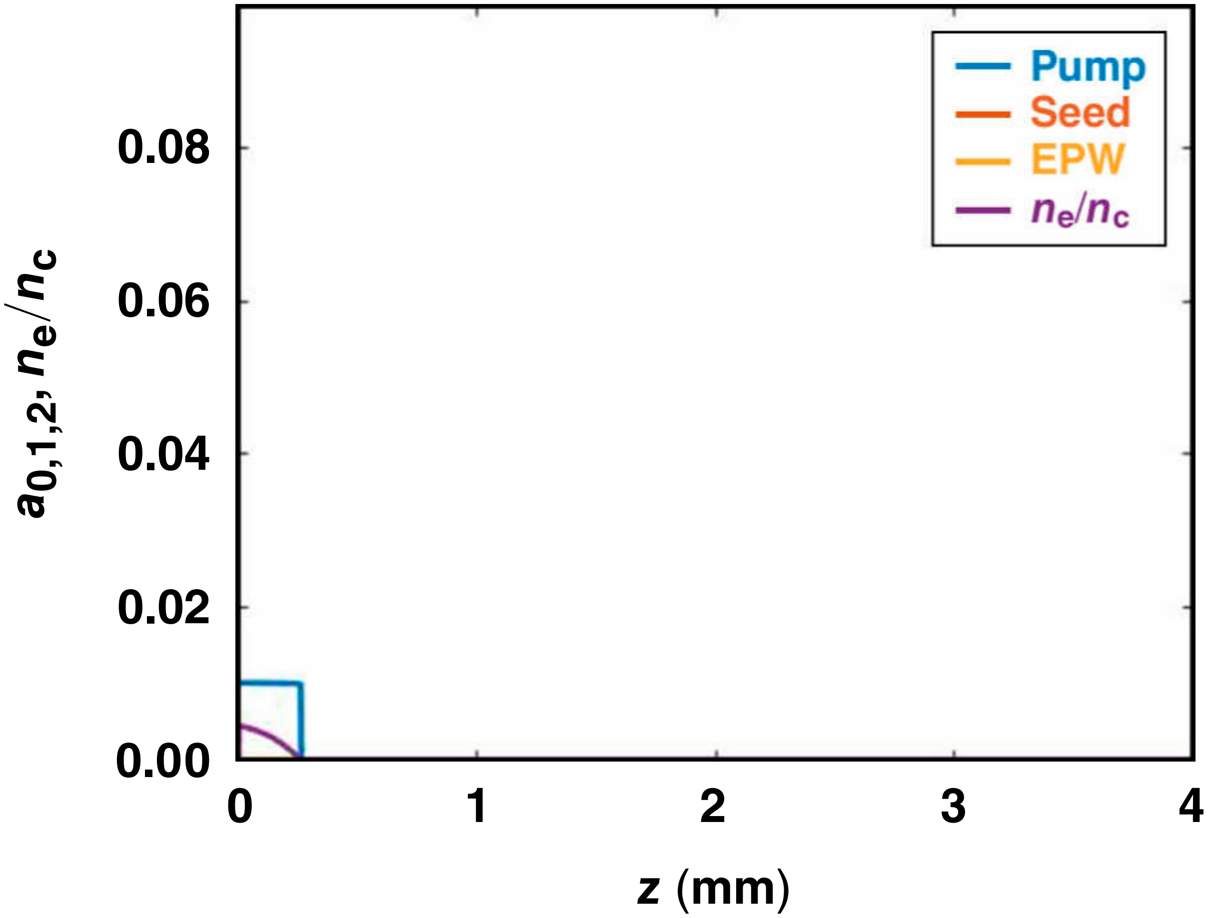
Temperature (approximately constant and tunable in FFRA) accounts for the difference between the previous two cases

- **Duration of plasma heating prior to seed arrival is approximately constant in FFRA**
- **T_e can be tuned by adjusting the delay between ionization and seed arrival**



T_e tunability can minimize damping, mitigate thermal detuning, prevent wave breaking, and preclude kinetic effects.

With T_e fixed to look at nonthermal differences, spontaneous SRS grows and degrades the interaction



Standard focus

$n_e = 6 \times 10^{18}/\text{cm}^3$

$I_p = 1.4 \times 10^{14}$ W/cm^2

4-mm length

26.7-ps pump

$\lambda_p = 1\ \mu\text{m}$

f/∞ pump

$\tau_{\text{seed}} = 500$ fs

$T_e = 45$ eV

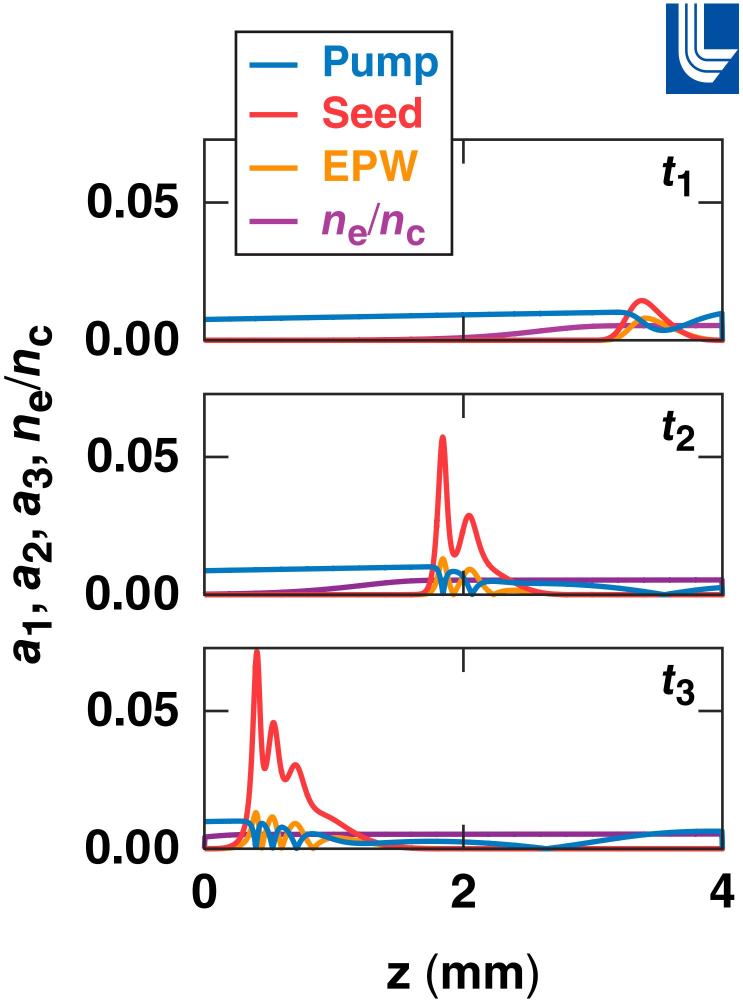
$S_3 = 0.05 v_3 T_e$

FFRA also mitigates spontaneous SRS.

E26274

FFRA has many advantages over conventional schemes

- **Interaction intensity follows the seed, without high *f*/# or a waveguide**
- **Can produce an ionization wave that immediately precedes seed**
  - **mitigates spontaneous SRS**
  - **eliminates thermal detuning**
  - **enables temperature optimization**
  - **enables a zero detuning amplifier without adverse side effects**



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*D. Turnbull *et al.*, "Raman Amplification with a Flying Focus," in preparation.

Summary/Conclusions

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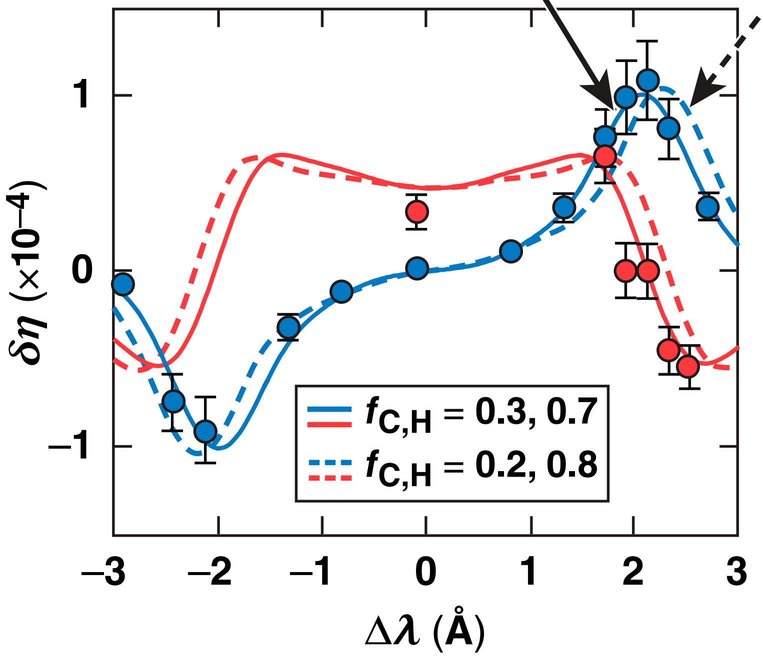
The ion-acoustic wave (IAW) resonance peak location suggests an impact of ion-species separation



30% C matches the peak location

20% C (initial methane composition)

Parameter	Theory input	Measured value	3-D *HYDRA* simulation
n_e/n_c	0.0104	0.011±0.001	~0.009
T_e (eV)	220	224±24	~231
T_i/T_e	0.1200	—	~0.090
$\overline{\lvert v_{flow} \rvert}$ (m/s)	~1.4 × 10^4	—	~1.4 × 10^4
I_0	~2.9 × 10^{13}	~3.6 × 10^{13}*	~3.6 × 10^{13}
$\overline{Z}$	2.5**	—	2

Most inputs are consistent with experimental measurements and/or a 3-D *HYDRA* simulation, but it is also necessary to invoke species separation to match the peak.

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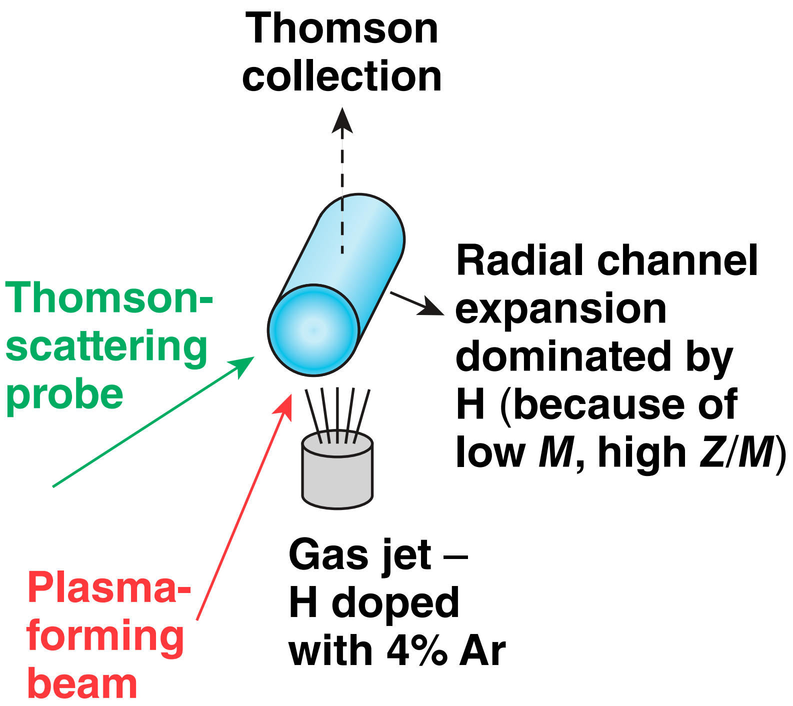
*Measurement did not include transport optic losses, inverse bremsstrahlung absorption, or the possibility of nonideal pump spot.

**Implies depletion of H from the interaction region.

Recreating these conditions, ion-feature Thomson scattering will provide a more-direct measurement



Thomson collection

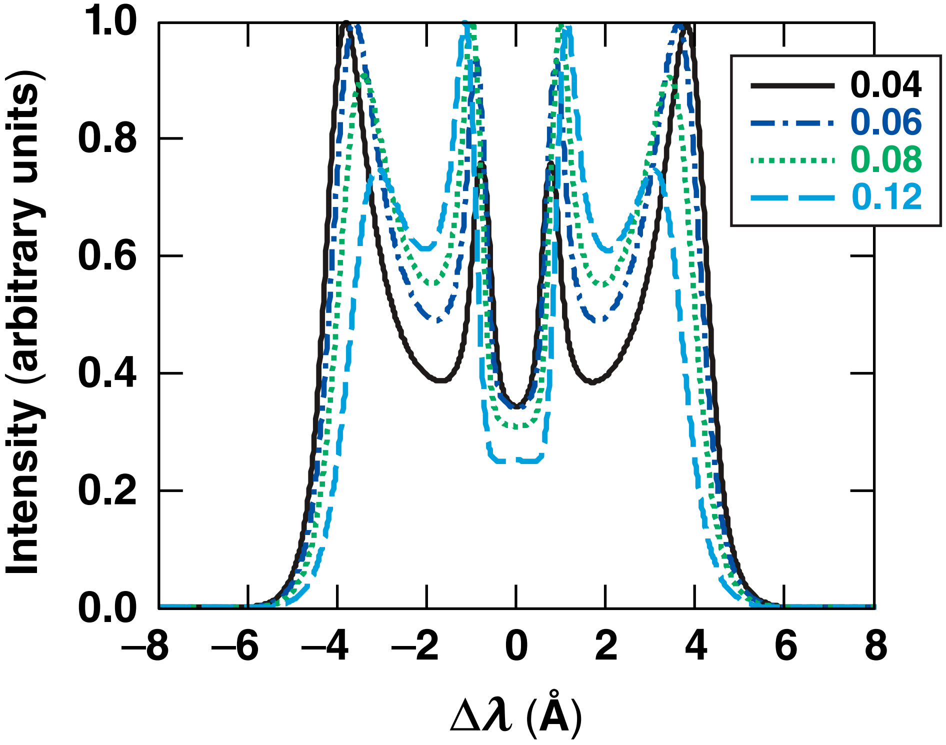
Thomson-scattering probe

Plasma-forming beam

Radial channel expansion dominated by H (because of low *M*, high *Z*/*M*)

Gas jet – H doped with 4% Ar

IAW feature versus Ar fraction*



The idea is to probe the center of the channel to see if the Ar fraction increases because of the channel expansion dominated by H.

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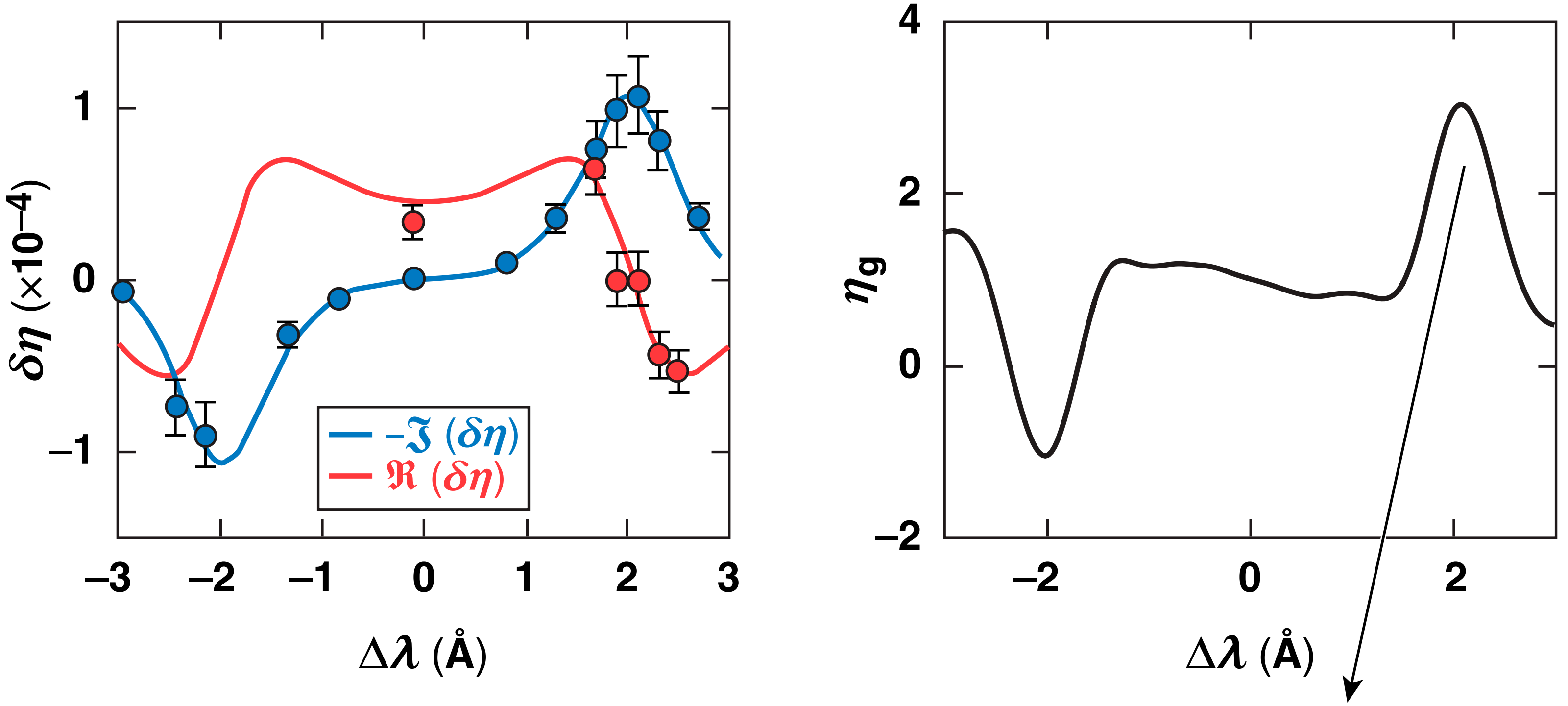
*All curves fix T_e = 250 eV, T_i/T_e = 0.15, Z_{Ar} = 13, n_e = 10^{19} cm^{-3}

The refractive-index variation associated with the optical resonance also creates "slow" and "fast" light*



Group velocity $v_g = \frac{c}{\eta_g} = \frac{c}{\eta - \lambda\frac{\partial\eta}{\partial\lambda}}$,

so η_g can be large near optical resonance

Slow and fast light have been demonstrated in other media, but not yet in plasma.

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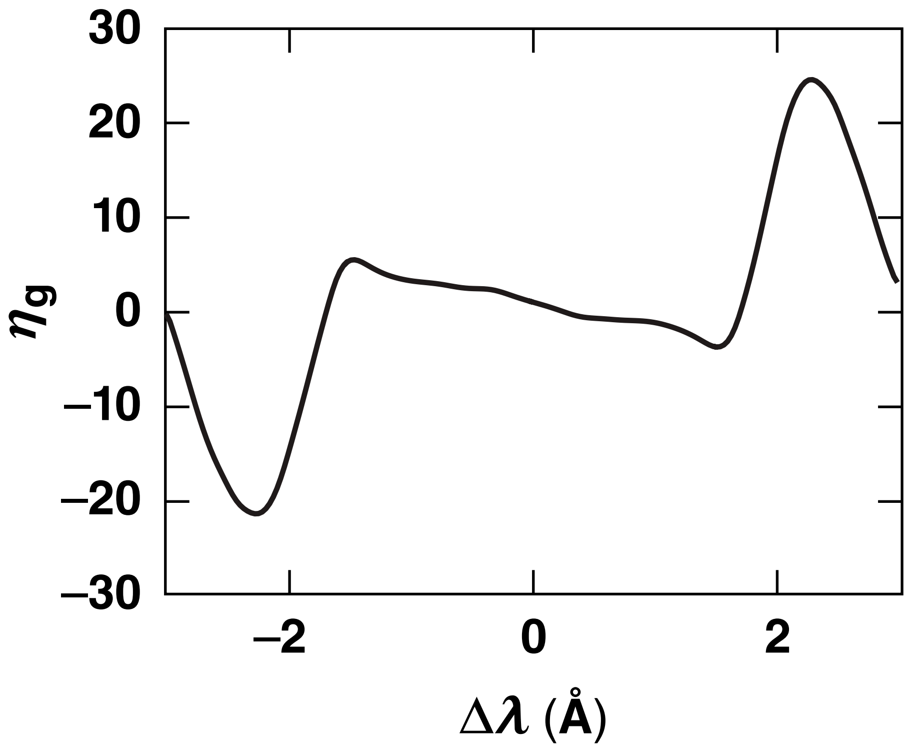
*P. A. Michel and G. Goyon, Lawrence Livermore National Laboratory, private communication (2017).

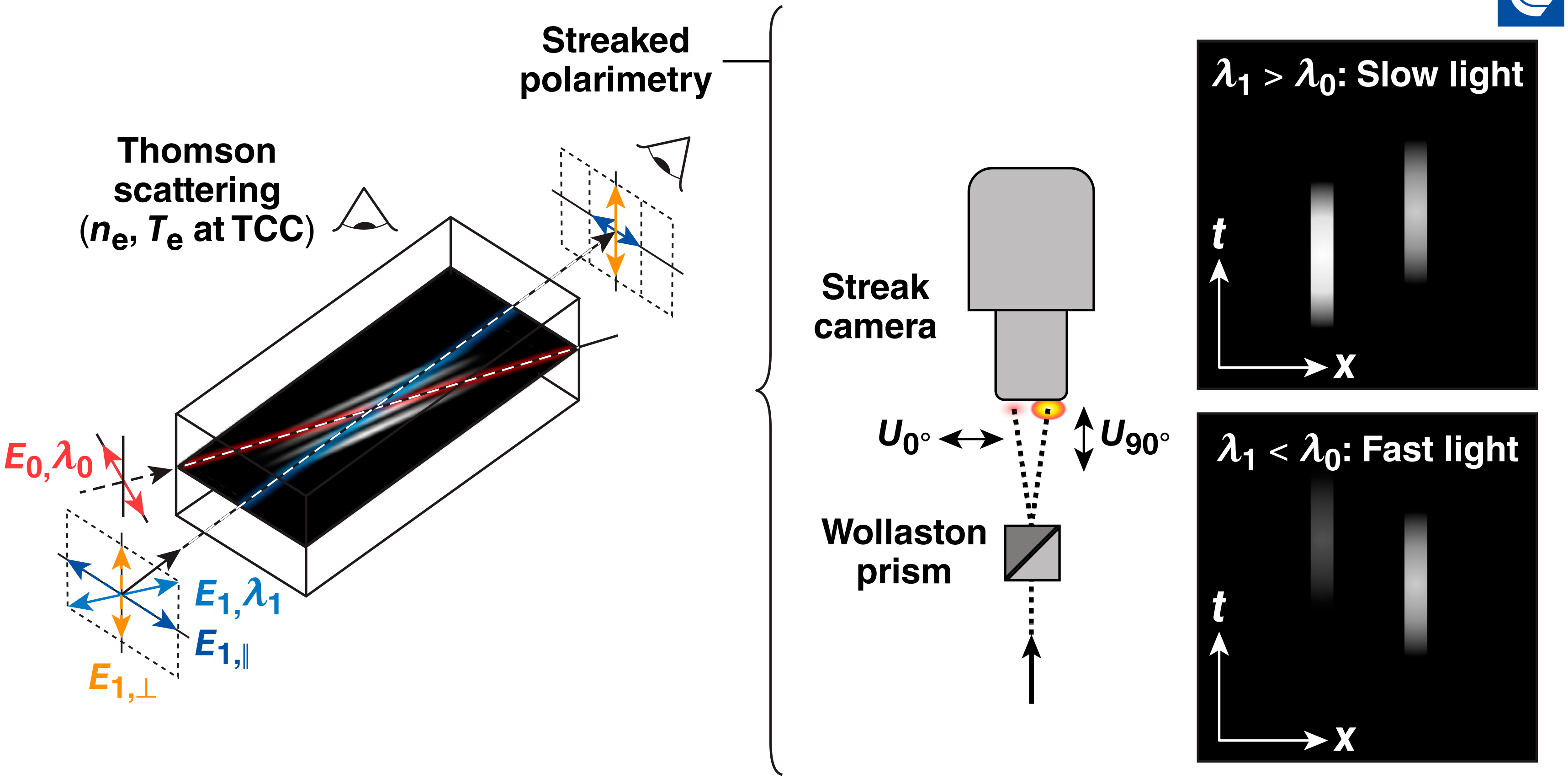
The group index scales like gain over the resonance bandwidth



- Group velocity slows to ~c/25 by increasing n_e and I_p by factors of ~3
- Now it takes ~80 ps to propagate across the 1-mm interaction length (as opposed to ~3)!

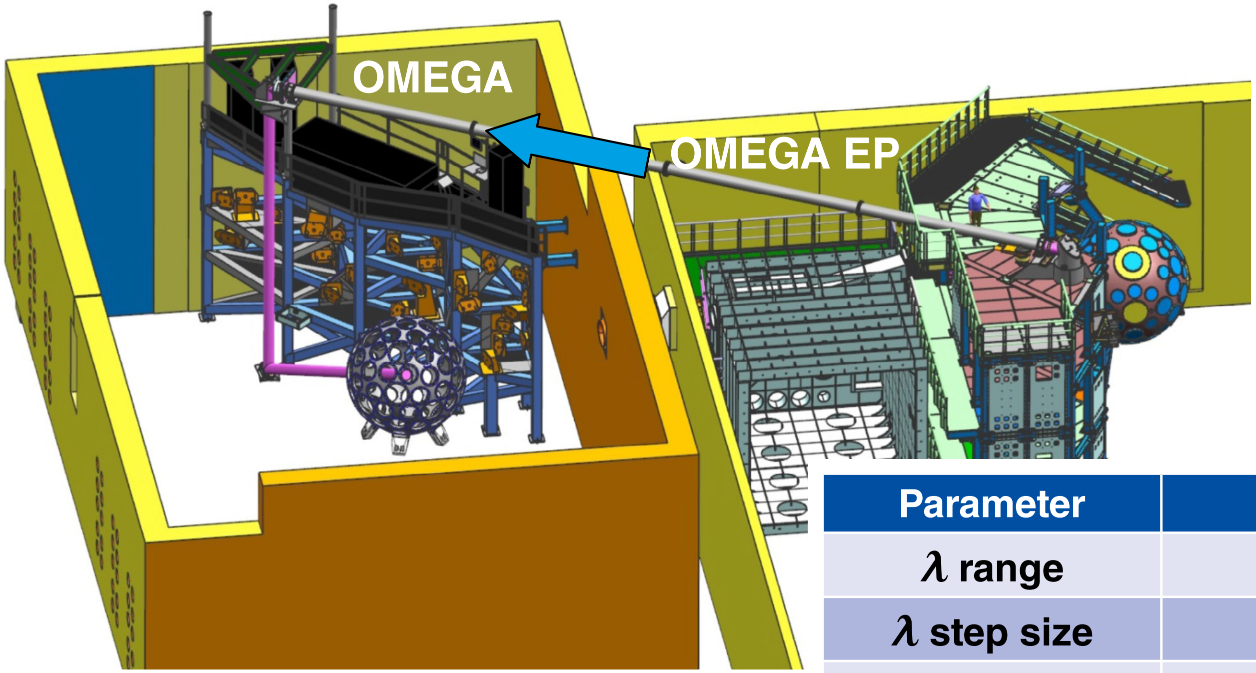
From the existing literature on slow light, the implications for such dramatic changes to group velocity are not clear.

We will exploit the anisotropic system again to directly measure the delays between polarization components



We aim to better understand and help clarify the nature of SBS-based slow/fast light.

The tunable OMEGA P9 beam (TOP9) will be used to develop a CBET platform at the Omega Laser Facility



Parameter	Minimum requirement
λ range	350.2 to 353.4 nm
λ step size	0.01 nm
Power on target	0.1 TW (351 nm to 352.6 nm) 0.01 TW (350.2 nm to 353.4 nm)
Polarization	Linear (20:1 contrast), ±90° range
Repetition rate	90 min
Spot size	Compatible with existing OMEGA distributed phase plates
Additional	FABS* and TBD** diagnostics

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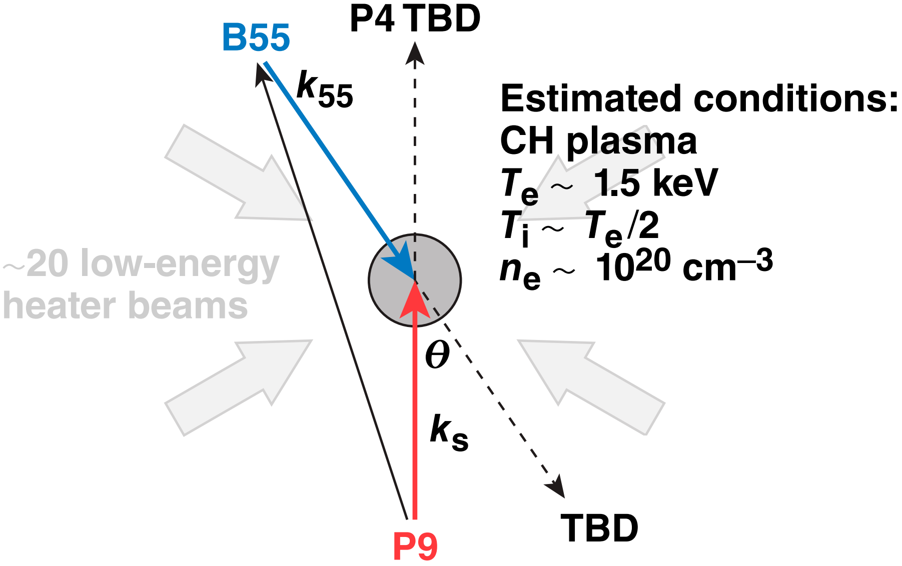
*FABS: full-aperture backscatter
**TBD: transmitted-beam diagnostic

Initial experiments will test CBET in ICF-relevant conditions and investigate the onset of nonlinearities

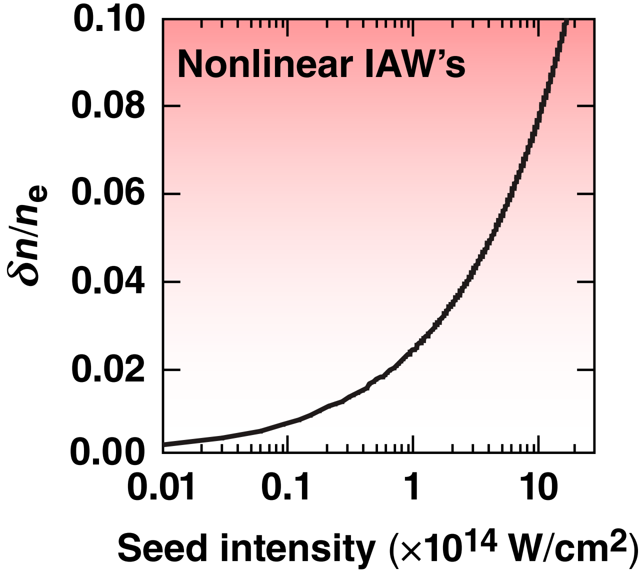
Pump: 250 μm diam
I_p = 500 J/1 ns = 10^{15} W/cm^2



Estimated conditions:
CH plasma
$T_e \sim$ 1.5 keV
$T_i \sim T_e/2$
$n_e \sim 10^{20}$ cm^{-3}

Seed: 250 μm diam
I_p = 5 J/1 ns = 10^{13} W/cm^2

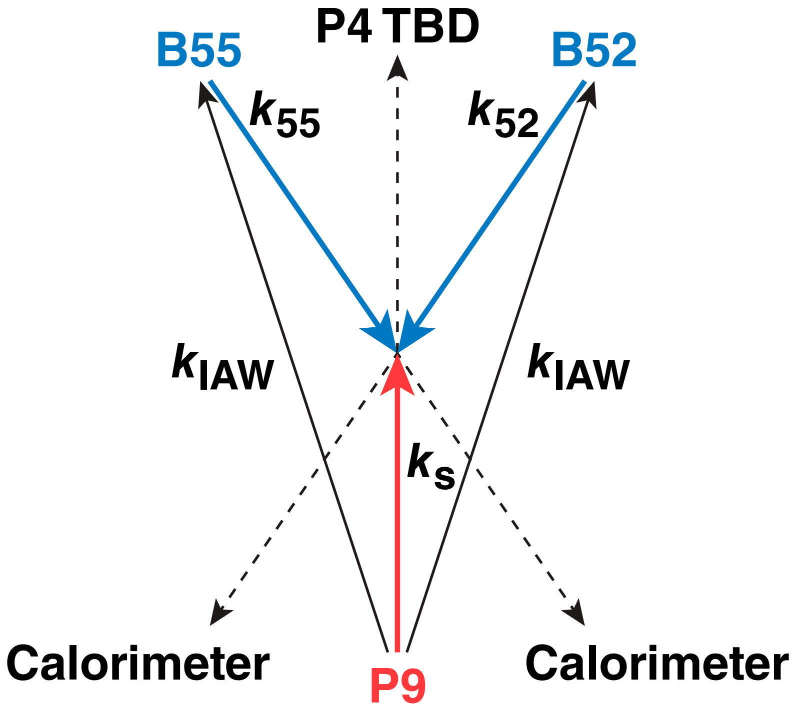
IAW amplitude (center of the plasma)



The previous two-beam experiments can be repeated with T_e and n_e closer to ICF, then seed intensity will be increased to probe the nonlinear regime.

OMEGA will facilitate the study of multiple IAW's coexisting in the same volume

Three- to six-beam measurement



This tests CBET under conditions that are relevant to both direct and indirect drive.

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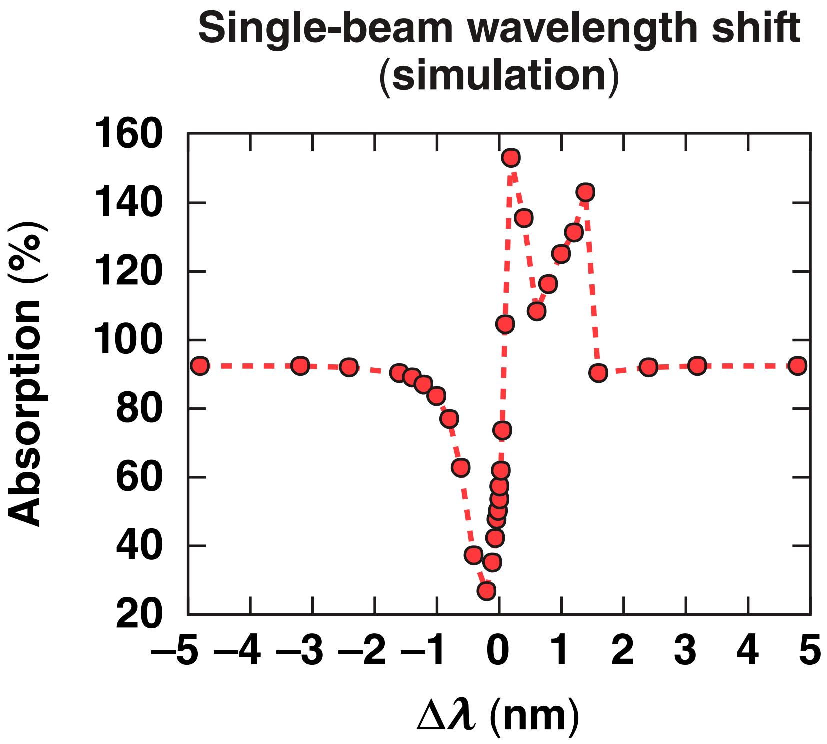
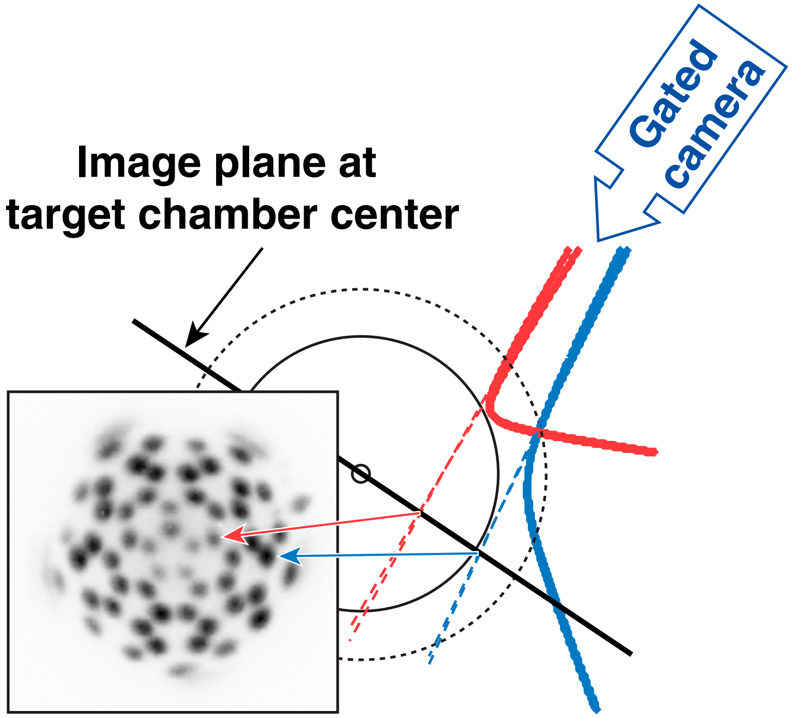
CBET beamlets* experiments using TOP9 will demonstrate CBET mitigation via wavelength detuning





This configuration will be a robust test of our integrated CBET hydrodynamic models and demonstrate CBET mitigation using wavelength shifting.

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*D. H. Edgell and D. H. Froula, Laboratory for Laser Energetics, private communication (2017).