Measuring the Ponderomotive Filamentation Instability Growth Rate in Short-Pulse Laser Beams

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Filamentation in Raman Amplification

Most simulations and experimental work investigating the amplification of a seed pulse via backwards Raman scattering have been in a cold plasma (< 100 eV).

- The analysis of said works neglects to consider the filamentation of the pump which can have a large growth rate in these cold plasmas.
- For typical plasma conditions seen in Raman amplification, filamentation is expected to be present as seen in FIG. 1.
- Filamentation of the pump can significantly affect the Raman interaction by diffracting the pump intensity, detuning the resonant interaction, and creating density perturbations that refract the seed beam [1].

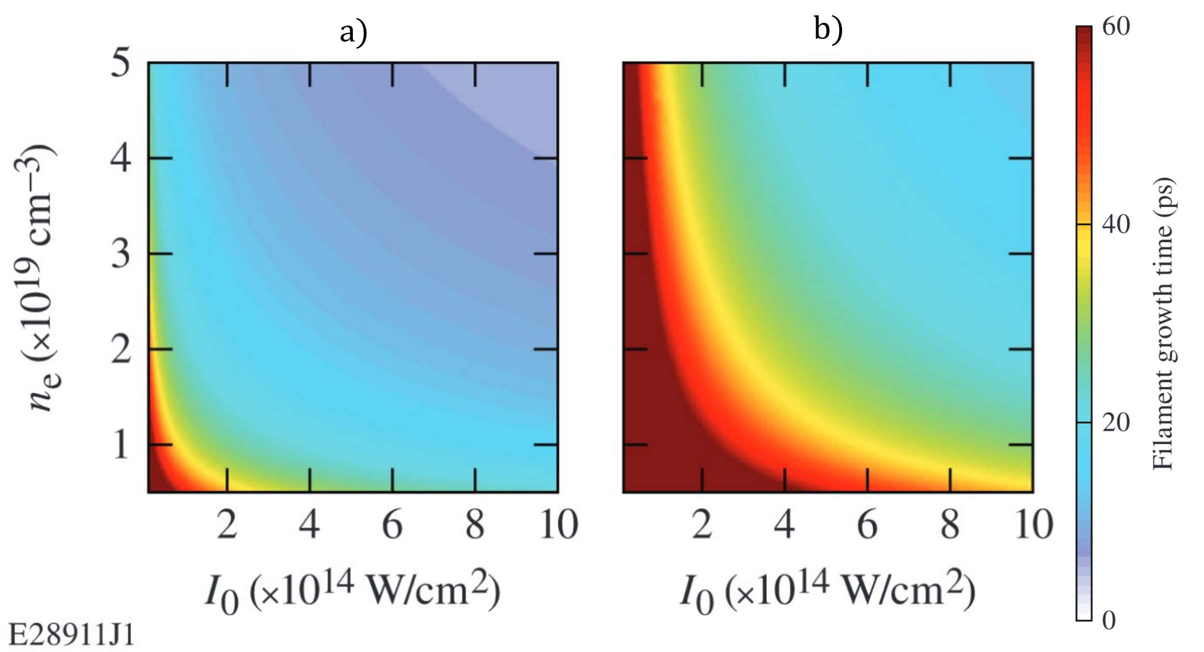

FIG. 1: Filamentation growth times are plotted in picoseconds for (a) thermal and (b) ponderomotive mechanisms [3]. Here $T_e = 50$ eV, $\lambda_0 = 1$ μm, and $Z = 1$. Figure from [1].

Preliminary experiments investigate the filamentation of the pump pulse in Raman-amplification-relevant plasmas.

- In FIG. 2b, an 8 × 10^{15} W/cm^2, ~ 35 ps, 1053-nm laser pulse is incident upon a plasma and sprays into an f/12.3 vertical field of view. This indicates the beam underwent filamentation consistent with filamentation theory [2] which predicts the onset of ponderomotive and thermal filamentation to occur at 28 ps and 15 ps respectively.

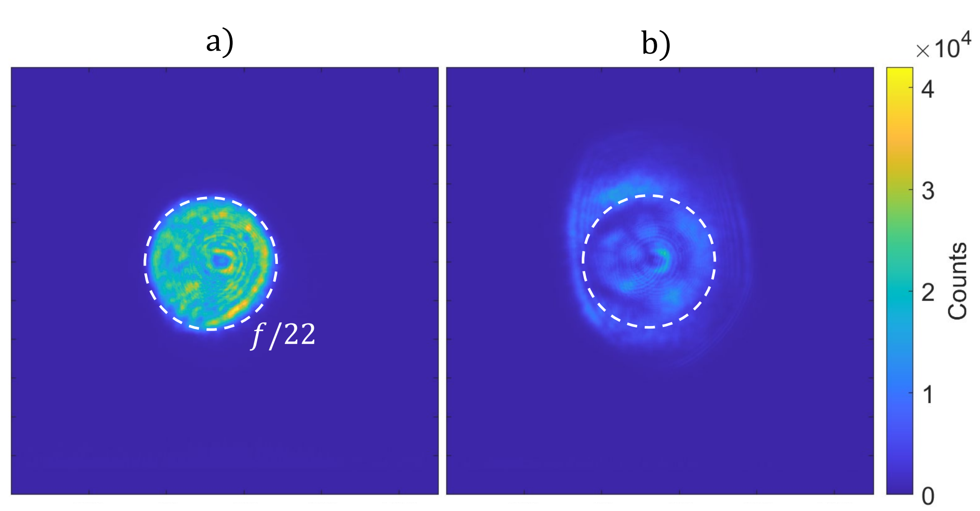

FIG. 2: (a) Nearfield of the pump beam when no plasma is present. White circle delineates the $f/22$ focal geometry of the beam. (b) Beam spray of the pump beam into an $f/12.3$ cone after propagating through a 1.3×10^{19} cm^{-3} plasma at ~ 25 eV.

Filamentation Theory

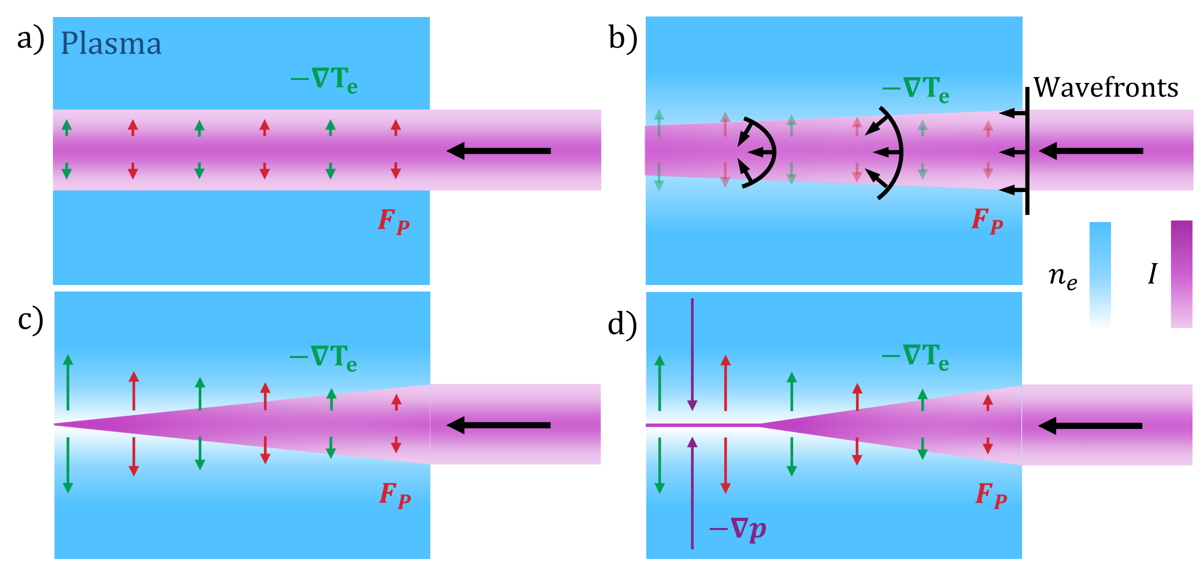

FIG. 3: In the filamentation instability, (a) an incident laser pulse ponderomotively or thermally ejects electrons from regions of the highest intensity. (b) Due to the corresponding change in the refractive index, these high-intensity regions are slightly focused and intensified. (c) This amplified intensity exacerbates the density depression providing feedback for the instability. As this process repeats, the light is focused to the point of diffraction, or, (d) if the surrounding plasma pressure balances the pressures generated by the light, a steady-state filament forms.

Assuming a steady state density profile and a constant intensity over time, one obtains the dispersion relation for filamentation [3],

$$\kappa = \frac{k}{2\sqrt{\varepsilon}}\left\{2\frac{n_e}{n_{cr}}\left[\gamma_P + \gamma_T\left[1 + (30k\lambda_e)^{4/3}\right]\frac{\omega^2}{k^2c^2}\right] - \frac{k^2c^2}{\omega^2}\right\}^{1/2}$$

where the ponderomotive and thermal coefficients are

$$\gamma_P = \frac{1}{4}\left(\frac{Z}{Z+1}\right)\frac{v_{osc}^2}{v_T^2}$$

and

$$\gamma_T = \frac{c^2 S}{\omega^2 \kappa_{SH} T_e}$$

respectively. Here λ_e is the electron mean free path, S is the inverse Bremsstrahlung heating rate, and κ_{SH} is the Spitzer-Harm conductivity.

Taking $\gamma_T = 0$, we can isolate and find the maximum ponderomotive filamentation growth rate,

$$\kappa_{\max}^{\mathrm{P}} = \frac{1}{2}\frac{\omega}{c}\frac{n_e}{n_{cr}}\frac{\gamma_P}{\sqrt{\varepsilon}},$$

and taking $\gamma_P = 0$, we find the maximum thermal filamentation growth rate,

$$\kappa_{\max}^{\mathrm{T}} = \frac{\omega}{c\sqrt{2\varepsilon}}\left[30\lambda_e\frac{\omega}{c}\left(\frac{2}{3}\frac{n_e}{n_{cr}}\gamma_T\right)^{3/4}\right],$$

for perturbation wavenumbers

$$k_{\max}^{\mathrm{p}} = \frac{\omega}{c}\left(\frac{n_e}{n_{cr}}\gamma_p\right)^{1/2}$$

and

$$k_{\max}^{\mathrm{T}} = \frac{\omega}{c}\left[\frac{2}{3}\frac{n_e}{n_{cr}}\gamma_{\mathrm{T}}\left(30\lambda_e\frac{\omega}{c}\right)^{4/3}\right]^{3/8}$$

respectively.

These wavenumbers also lend themselves to filamentation growth times given by [4]

$$\tau_{fil} \sim \lambda_{fil}/c_s \sim (2\pi/k_{\max})/c_s,$$

which is the time it takes ions to leave the filament.

Experimental Design

Motivated by a need to validate the existing theory and to understand the role filamentation plays in Raman amplification we are planning an experiment to isolate and measure the growth rate of ponderomotive filamentation.

- In our experiment, a short-pulse laser beam from OMEGA EP is coupled into a preheated plasma, (≥ 500 eV, 1 × 10^{19} cm^{-3}) on the OMEGA 60 platform.
- With an incident intensity of 1 × 10^{14} W/cm^2, these parameters allow us to minimize the effect of thermal filamentation and maintain a ponderomotive filamentation growth time of ~ 90 ps.

After propagation through the plasma, the spatial profile of the beam is imaged on a diffuser by a CCD allowing us to infer the filamentation growth rate by relating the beam spray to the filament size via,

$$\tau_{fil} \sim \lambda_0(f/\#) = \lambda_0\left(\frac{L}{2R_{spray}}\right)$$

where L is the distance from TCC to the diffuser and R_{spray} is the radius of the beam spray.

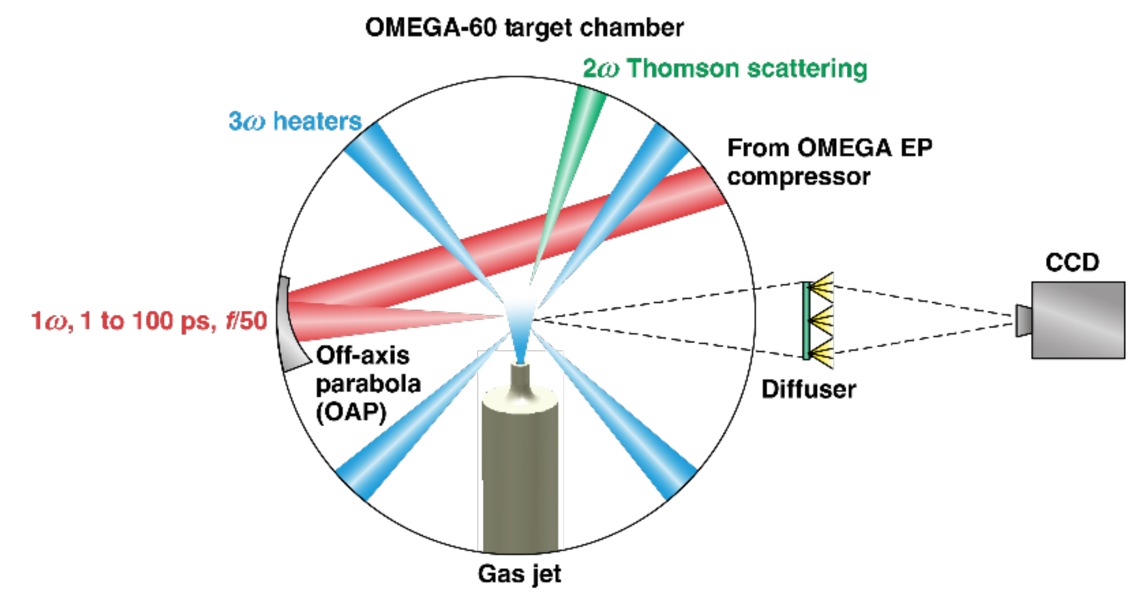

FIG. 4: Experimental layout

Conclusions

In the filamentation instability, the ponderomotive and thermal ejection of electrons from the high-intensity regions of a laser beam causes modulations to the plasma density and refractive index, which lead to self-focusing and filamentation. This instability leads to deleterious effects in laser-plasma interactions such as Raman amplification where the pump beam can be diffracted, the interaction detuned, and the seed beam refracted. We present an experiment that utilizes the joint operation of the OMEGA 60 and OMEGA EP Laser Systems at the University of Rochester's Laboratory for Laser Energetics to investigate the growth rate of the ponderomotive filamentation instability on the picosecond timescale.

References

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Acknowledgements

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