Hot Raman Amplification

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From its conception at the turn of the 21st century,[1,2] Raman amplification in a plasma has attracted attention from the laser-plasma community for its application to the production of extremely high power laser pulses. While optical parametric chirped-pulse–amplification (OPCPA) technologies have revolutionized high-power laser physics by allowing for a many-orders-of-magnitude increase to the maximum achievable power, another plateau has slowly emerged around the 30-PW level for single beams. Increasing the energy or decreasing the pulse width of these ultrahigh-power lasers requires unfeasibly large compression gratings to avoid damage.[3] As a result, many envisioned applications of high-power lasers remain beyond the intensity frontier.[4] A laser-plasma power amplifier can sustain orders-of-magnitude higher fluences and intensities than solid-state compressor gratings and could provide the technology to expand this frontier. While this promise has sustained interest over the past two decades, experiments have failed to produce a proof-of-principle amplifier scalable to its main application.

The Raman amplification process utilizes a three-wave instability, stimulated Raman scattering (SRS), whereby a short seed pulse at a frequency ω_s counter-propagates with respect to a long energetic pump pulse at a frequency ω_0 in a plasma. The ponderomotive beat wave created by the pump and seed pulses drives an electron plasma wave (EPW) at approximately the plasma frequency $\omega_{pe} = \omega_0 - \omega_s$, where $\omega_{pe} = \sqrt{n_e e^2 / m_e \varepsilon_0}$, n_e is the electron plasma density, e is the electron charge, m_e is the electron mass, and ε_0 is the permittivity of free space. Under optimal conditions, the pump can transfer a large fraction of its energy to the seed (up to the Manley–Rowe limit ω_s / ω_0), thereby amplifying it; however, several phenomena can interrupt this process, depending on where one operates in the vast parameter space that spans pump and seed pulse intensities, seed pulse width, pump wavelength, plasma temperature, and plasma density. Navigating this parameter space is complicated by the lack of a defining metric for scaling a proof-of-principle amplifier to the multi-PW level.

While the signatures of many limiting phenomena have been studied in simulations, the complexities of Raman amplification experiments have inhibited reaching a consensus on how many of, and the extent to which, these phenomena are limiting the performance. This is evidenced by the modest advancement in experiments over two decades, despite many detailed theoretical and simulation studies. Much of the simulation work and all past experiments have focused on amplification in a cold plasma (≤100 eV), where low damping of the SRS instability allows for exponential growth of a weak seed pulse to rapidly reach the efficient pump-depletion regime (Fig. 1, gray-shaded region). In this regime, SRS growing from thermal noise ahead of the seed is often identified as a limiting mechanism,[5,6] but it is typically assumed that it can be detuned with an appropriate amount of pump chirp or plasma density gradient. However, experiments with highly chirped pumps ($\Delta t_{stretch} = \Delta t_{compressed} > 100$) have yet to surpass an ~3.5% single-stage efficiency.[7] Furthermore, thermal filamentation of the pump has a high gain rate in cold plasmas.[8] While a discussion on filamentation is mostly absent from Raman amplification literature,[9] it can deplete the pump-beam intensity through diffraction and create density perturbations that refract the seed beam, detune the resonant interaction, and imprint modulations on the amplified seed phase front, thereby limiting its focusability.[10]

Here we present a novel high-temperature, efficient Raman amplifier, where deleterious laser instabilities are mitigated. The high temperature increases the intensity threshold for thermal filamentation and generates strong Landau damping of the EPW's, which suppresses SRS growth from thermal noise. The regime takes advantage of quasi-transient amplification,[11] where a sufficiently intense seed pulse allows for amplification, even in conditions where Landau damping exceeds the linear SRS gain. Vlasov simulations were used to demonstrate and define a new regime for proof-of-principle experiments scalable to PW-class amplifiers, where the (1) intensity gains are ≥10, (2) energy transfer efficiencies are ≥30%, and (3) amplified output intensities are ≥100× the pump intensity (Fig. 1, blue-shaded area).

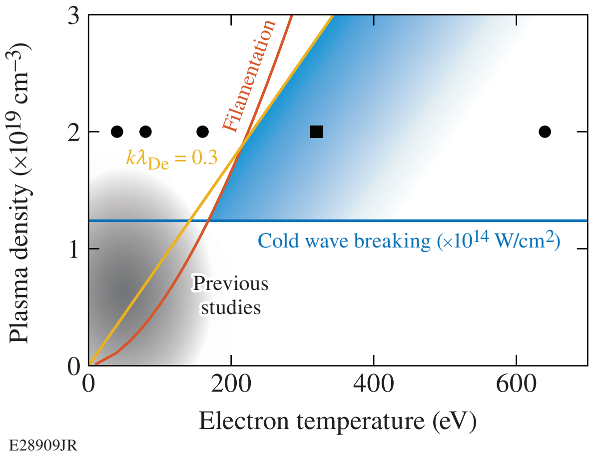

Figure 1
The optimal parameter regime for Raman amplification is shown to be at high temperatures.

At a plasma density of 2×10^{19} cm^{-3}, 1-D Vlasov simulations (ARGOS[12]) at temperatures below 200 eV (black circles in Fig. 1) show strong growth of SRS from noise that depletes the pump pulse before crossing the seed, leaving behind a turbulent EPW spectrum. The square indicates efficient amplification with sufficient gain. Increasing the temperature to 320 eV damps SRS growth from noise driving the interaction into the kinetic regime [$k\lambda_{De} \geq 0.3$ (Ref. 13), where k is the EPW wave vector and λ_{De} is the Debye length], where a peak efficiency of 55% and intensity amplification factor of 13 were obtained, which is nearly ideal for a next-generation power amplifier. Further increase in the temperature to 650 eV showed a decrease in performance as strong Landau damping and particle trapping inhibit EPW growth. The optimal regime is also shown to be at a plasma temperature above the threshold for thermal filamentation[8] for a pump intensity of 10^{14} W/cm^2. The plasma density resides above the cold wave-breaking limit but not too high so as to not partition a large fraction of the pump energy into the driven EPW. The previous experimental studies on Raman amplification are shown to be plagued with all three limitations described here: wave breaking, SRS growth from noise, and filamentation.

The ultimate goal of Raman amplification is to provide an amplifier for petawatt-scale laser systems; therefore, modest intensity gains ≥10, far below what is often the objective in experiments,[14] are sufficient. Presumably, the seed pulse is created by a state-of-the-art OPCPA system and has a compressed power of the order of 10 PW (Ref. 3) with a pulse width of the order of 10 to 100 fs. The pump pulse, which is of the order of tens of picoseconds, would necessarily have an intensity less than that of the input seed; therefore, a plasma amplifier should require that the amplified seed intensity be a factor of ≥100× larger than the pump intensity. Limiting the energy in the pump to a level attainable in state-of-the-art, solid-state picosecond chirped-pulse–amplification systems requires an energy transfer efficiency of ≥30%. This final criterion is potentially the most difficult to satisfy since it relies on uninhibited pump-beam propagation, no pre-seed depletion of the pump from thermal SRS, and the seed entering the amplifier being intense enough to achieve high-energy transfer—all of which detrimentally affect high-gain amplifiers relying on exponential gain at low temperatures. Here, we have shown through calculations and kinetic simulations that at high temperatures it is expected that all fluid-like limitations are suppressed, while amplification continues in the presence of kinetic limitations such as Landau damping, particle trapping, and warm wave breaking, which are modeled accurately in the Vlasov simulations. The high-power amplifier metrics were satisfied in a 2-mm plasma preheated to 320 eV and seeded strongly at 10^{15} W/cm^2—all experimentally achievable parameters.

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1. G. Shvets *et al*., Phys. Rev. Lett. **81**, 4879 (1998).
2. V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. **82**, 4448 (1999).
3. C. N. Danson *et al*., High Power Laser Sci. Eng. **7**, e54 (2019).
4. G. Mourou, Rev. Mod. Phys. **91**, 030501 (2019).
5. V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. **84**, 1208 (2000).
6. D. S. Clark and N. J. Fisch, Phys. Plasmas **10**, 3363 (2003).
7. J. Ren *et al*., Nat. Phys. **3**, 732 (2007).
8. W. L. Kruer, Comments Plasma Phys. Control. Fusion **9**, 63 (1985).
9. D. Turnbull *et al*., Phys. Plasmas **19**, 073103 (2012).
10. A. A. Solodov, V. M. Malkin, and N. J. Fisch, Phys. Plasmas **10**, 2540 (2003).
11. V. M. Malkin and N. J. Fisch, Phys. Rev. E **80**, 046409 (2009).
12. R. K. Follett *et al*., Phys. Plasmas **26**, 062111 (2019).
13. J. L. Kline *et al*., Phys. Rev. Lett. **94**, 175003 (2005).
14. G. Vieux *et al*., Sci. Rep. **7**, 2399 (2017).