High Energy Density Physics 23 (2017) 212–216

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Robustness of raman plasma amplifiers and their potential for attosecond pulse generation

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ARTICLE INFO

Article History:
Received 11 May 2017
Accepted 14 May 2017
Available online 15 May 2017

Keywords:
Raman scattering
Laser plasma interactions

ABSTRACT

Raman back-scatter from an under-dense plasma can be used to compress laser pulses, as shown by several previous experiments in the optical regime. A short seed pulse counter-propagates with a longer pump pulse and energy is transferred to the shorter pulse via stimulated Raman scattering. The robustness of the scheme to non-ideal plasma density conditions is demonstrated through particle-in-cell simulations. The scale invariance of the scheme ensures that compression of XUV pulses from a free electron laser is also possible, as demonstrated by further simulations. The output is as short as 300 as, with energy typical of fourth generation sources.

1. Introduction

Reaching high power and high brightness laser pulses is a primary goal for high energy density science, both for producing and diagnosing extreme plasma conditions. High power pulses across a wide spectral range have a myriad of applications in inertial confinement fusion [1], atomic physics [2], laser particle acceleration [3] and generating matter-antimatter plasmas [4]. Currently chirped pulse amplification using solid state grating compressors is the highest power method in the near optical range, however free electron lasers have also reached unprecedented brightness deep in to the X-ray spectrum. Both suffer the drawback of requiring large scale infrastructure with continuing replacement, limiting the proliferation and maximal power of such sources.

Non-linear optics effects in crystals can also be used to amplify ultra-short pulses, however these are still subject to the same intensity and fluence limitations and still require a grating compressor. Plasma amplifiers circumvent this problem by utilising parametric instabilities in a plasma, a medium that is both compact and cheap. If conditions can be sufficiently controlled, the Raman backscatter instability can be used to compress a long laser pulse (frequency ω), while minimising the growth of other detrimental instabilities [5,6].

To stimulate Raman scattering an electron plasma wave must be resonantly excited, requiring two separate laser pulses differing in frequency by the plasma frequency $\omega_p = \omega\sqrt{n/n_{crit}}$, where n is the electron number density and $n_{crit} = \frac{1.1\times10^{21}}{\lambda_{\mu m}^2}$ /cm^3 is the critical density. The beating of these pulses ponderomotively excites a highly nonlinear plasma wave, and the growth rate is maximised for counter-propagation. The higher frequency long pulse is then scattered by the density perturbation to amplify the shorter, lower frequency pulse. Providing the electron plasma wave is not heavily damped or turbulent, this mechanism can fully deplete the long pump pulse and transfer energy to the shorter pulse at high efficiency. Large scale particle-in-cell and Vlasov simulations [7–10] agree with the analytical result in the non-linear regime, predicting energy transfer from the long to the short pulse greater than 50%.

However, several conditions must be met to preserve the plasma wave fidelity; its small wavelength of approximately half that of the pump pulse makes it delicate [11]. Firstly, it must not be excessively Landau damped, requiring $k\lambda_D < 1$ where $k \simeq (2\omega-\omega_p)/c$ is the wave-number of the Langmuir wave and λ_D is the Debye length [12].

A further problem is breaking of the plasma wave, subsequently becoming turbulent and losing coherence. This is a problem due to the low phase velocity of the wave. If the wave amplitude is

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http://dx.doi.org/10.1016/j.hedp.2017.05.007
1574-1818/

ponderomotively over-driven, electrons will exceed the phase velocity and become trapped. For a cold plasma this occurs for pump pulse dimensionless amplitudes above $0.35(n/n_{crit})^{0.75}$ and worsens for hotter plasmas [9,13–15].

In denser plasmas, collisional damping also plays a significant role if the electron ion collision time is of the order ω_p. Unfortunately the conditions to minimise this problem, low density and high temperature, are the opposite to those minimising Landau damping.

The scheme is also reliant on the three wave resonance, indicating that a chirp in the long pulse or plasma density gradients may decrease performance. Here we show, using particle-in-cell simulations, that the scheme is robust to typical variations.

2. Robustness of raman amplifiers to experimental perturbations

Many previous simulations of plasma amplifiers have used uniform plasma density, transform limited Gaussian laser pulses and sometimes even cold, fully ionised plasma. Because Raman backscatter is a resonant process, deviations from these ideal conditions may lead to efficiency losses due to loss of resonance [16], increased kinetic effects or enhanced seeding of competing instabilities [17]. It is an important consideration for any experimental design to know the relevant tolerance for each deviation from these ideal conditions [18–22]. We show here that the non-linear stage (and to a certain extent the linear stage) of the amplification is tolerant to variations in plasma density.

Variation of Electron Density

For near optical laser pulses, a typical electron density of $n/n_{crit} \simeq 0.01$ requires a gas target of approximately atmospheric pressure for hydrogen. A typical experimental target will use a room temperature gas system, requiring a gas burst in to the vacuum chamber shortly before the laser pulse arrival. This means the neutral gas is often in a transient hydrodynamic state before the interaction and therefore the electron number density n_e is hard to predict or control, and may not be spatially uniform. This can be countered, with considerable complexity, by using low density solid targets or cryogenic liquefied gasses.

However, a gaseous target may be sufficient if the Raman amplification is robust to density variations in the target. Changes in plasma density could cause a loss of resonance with the plasma wave. However, theory indicates that the amplification has a wide bandwidth in the non-linear stage and may withstand the slight deviation from perfect resonance.

The high efficiency non-linear stage requires that the seed pulse meets the condition [23]

$$a_{seed} T \sqrt{\omega\omega_p} = 5, \tag{1}$$

where a_{seed} and T are the seed pulse peak dimensionless amplitude and full width at half maximum duration of the seed intensity envelope. For linear polarisation, the amplitude is related to the pulse intensity and wavelength through $I = 1.4 \times 10^{18} a_{seed}^2/\lambda_{\mu m}^2$, with units W/cm^2 and microns. The pump pulse amplitude can also be found in this way. This is an attractive solution, so it continues to hold throughout the non-linear amplification stage.

Assuming this condition is met, we may estimate the maximum tolerable plasma density variations by first evaluating the seed pulse bandwidth in the non-linear stage. Assuming the seed is a transform limited Gaussian with duration given by (1), we find the full width at half maximum bandwidth of the spectral power is

$$\Delta\omega_{seed}/\omega = \frac{4\ln(2) a_{seed}}{5}\sqrt{\frac{\omega_p}{\omega}}. \tag{2}$$

As a basic model, any changes in plasma density must not move the resonance outside of the bandwidth of the seed pulse, therefore the maximum tolerable density variation in the non-linear stage is

$$\frac{\delta n}{n} = 2\frac{\delta\omega_p}{\omega_p} = -2\frac{\delta\omega}{\omega_p} = -2\frac{\delta\omega_{seed}}{\omega}\frac{\omega}{\omega_p} = \frac{a_{seed}}{2}\sqrt{\frac{\omega}{\omega_p}}. \tag{3}$$

Where we have used the result (2) and assumed the seed pulse satisfies the non-linear solution (1). For a seed amplitude of 0.1 in the nonlinear stage and density $n_0/n_{crit} = 0.01$, as simulated, this gives a density tolerance of 16%. This is a large value and easily achievable experimentally. The tolerance increases as the pulse amplifies through the nonlinear stage.

To verify the expression (3), we conducted a series of one-dimensional Particle-in-Cell simulations where the transform limited seed pulse is initialised on the non-linear solution (1) with central frequency $\omega_{seed} = 0.9\omega$. The pump amplitude was constant at 0.01, with a uniform plasma of variable density. The electron temperature was 50 eV. The seed was initialised on the nonlinear trajectory (Eq. 1) with dimensionless amplitude 0.1. The energy transfer efficiency after a 300 wavelength propagation is shown in Fig. 1. The box length was $200\lambda_0$ and it moved with the amplified pulse. There were 128 particles per cell and 120 cells per pump wavelength. Efficiency was calculated by first subtracting the pump pulse, finding the change in fluence from the initial seed, then dividing by the total fluence of the pump pulse.

There is clearly great resilience to de-tuning for the pulse in the nonlinear stage, so experimental density variations will be of little concern. The tolerance to density de-tuning agrees with the estimate of 16%. The expected resonant density is $n/n_{crit} = (1-\omega_{seed}/\omega)^2 = 0.01$. The maximal efficiency is found for a density slightly higher than this. This is due increased kinetic effects at lower densities.

The growth in the linear stage is likely to be more susceptible to de-tuning as the linear Raman instability has a narrow bandwidth. However, if the seed pulse bandwidth is greater than this then there will still be a good tolerance. The simulations were repeated for an identical transform limited seed pulse but with peak amplitude 0.01, far below the non-linear stage. The tolerance, also shown in Fig. 1a, is similar to the previous case because the seed bandwidth is the same. A wide bandwidth seed pulse is therefore an effective strategy to increase the tolerance to plasma variations.

The maximal efficiency occurs for a density slightly less than $0.01 n_{crit}$. This is because kinetic effects are less important for this lower seed intensity and the plasma wave frequency is slightly increased by its temperature dependence.

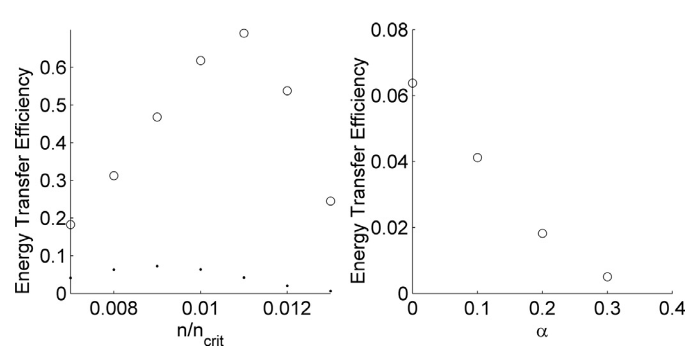

Fig. 1. Investigation of the effects of density variations. (a) Energy transfer efficiency after a 300 wavelength propagation is shown versus the uniform plasma density. The open circles are for $a_{seed} = 0.1$ and the dots for $a_{seed} = 0.01$, both with transform limited duration 22λ. The seed frequency was 0.9 of the pump frequency. The amplifier is largely unaffected by variations up to 20%, due to the wide bandwidth of the seed pulse. (b) Effects of a linear density gradient for the $a_{seed} = 0.01$ case. α is the density change, as a fraction of the starting density, over the 300 wavelength propagation.