On the effects of multi-pump Raman amplification of short laser pulses

K. V. Lezhnin, K. Qu, N. J. Fisch, Princeton University

Abstract

- Experiments on combining multiple laser beams using plasma medium, known as "beam combining", is an ongoing experimental campaign at National Ignition Facility [1]
- Detailed understanding of both fluid and kinetic effects involved in beam combining is crucial for rigorous control of the output laser beam
- The beam combining mechanism may leave its imprints on the seed pulse envelope and phase fronts [2], impeding its applicability
- In our work, we use coupled nonlinear Schrödinger equations (NSE) simulations with the self-developed code CNSE [3] and 2D Particle-In-Cell (PIC) simulations with the code EPOCH [4] to reveal the effects of the resonant multi-pump amplification via near-forward Raman scattering (nFRS) on the amplified seed.

Coupled NSE model

Following [5] and using envelope approximation, we formulate the following set of equations for the coevolution of seed, pumps, and plasma wave beating:

$$\left[\frac{\partial}{\partial t} + v_{gs}\cdot\nabla - \frac{ic^2}{2\omega_s}\nabla^2 - \frac{3i\omega_{\rm pe}^2}{16\omega_s}\left(|\hat{a}|^2 + \sum_{i=1}^{N}|\hat{b}_i|^2\right)\right]\hat{a} = V n_f^* \sum_{i=1}^{N}\hat{b}_i, \quad (1)$$

$$\left[\frac{\partial}{\partial t} + v_{gp,i}\cdot\nabla - \frac{ic^2}{2\omega_p}\nabla^2 - \frac{3i\omega_{\rm pe}^2}{16\omega_p}\left(|\hat{a}|^2 + \sum_{i=1}^{N}|\hat{b}_i|^2\right)\right]\hat{b}_i = -V\hat{a}n_f, \quad (2)$$

$$\frac{\partial}{\partial t}n_f = \hat{a}^*\sum_{i=1}^{N}W_i\hat{b}_i, \quad (3)$$

$$V = \frac{\omega_{\rm pe}^2}{4\omega_s}, \quad (4)$$

$$W_i = \frac{c^2|k_s - k_{p,i}|^2}{\omega_{\rm pe}}. \quad (5)$$

Here, $\hat{a}$, $\hat{b}_i$, and n_f are dimensionless seed/pump envelopes normalized to $E_0 = m_e\omega_0 c/e$ and plasma wave envelope normalized to ambient plasma density n_0. $\omega_{s,p,\rm pe}$ are the seed, pump, and plasma wave frequencies ($\omega_p = \omega_s + \omega_{\rm pe}$), $k_{s,\ p,i}$ are the seed and $i^{\rm th}$ pump wavenumbers ($k_{p,i} = k_s + k_{\rm pe}$), and c is the speed of light.
Ignoring all quadratic terms (assuming $|a|^2, |b|^2 \ll 1$), normalizing time/space with $\tau \equiv \omega_s t$ and $\nabla := c\nabla/\omega_s$, and normalizing temporal rates V and W, we get the following dimensionless system we are going to solve numerically:

$$\left[\frac{\partial}{\partial\tau} + v_{gs}\cdot\nabla - \frac{i}{2}\nabla^2\right]\hat{a} = n_f^*\sum_{i=1}^{N}\hat{b}_i, \quad (6)$$

$$\left[\frac{\partial}{\partial\tau} + v_{gp,i}\cdot\nabla - \frac{i\omega_s}{2\omega_p}\nabla^2\right]\hat{b}_i = -\hat{a}n_f, \quad (7)$$

$$\frac{\partial}{\partial\tau}n_f = V\hat{a}^*\sum_{i=1}^{N}W_i\hat{b}_i, \quad (8)$$

$$V = \frac{\omega_{\rm pe}^2}{4\omega_s^2}, \quad (9)$$

$$W_i = \frac{c^2|k_s - k_{p,i}|^2}{\omega_{\rm pe}\omega_s}. \quad (10)$$

NSE simulation setup

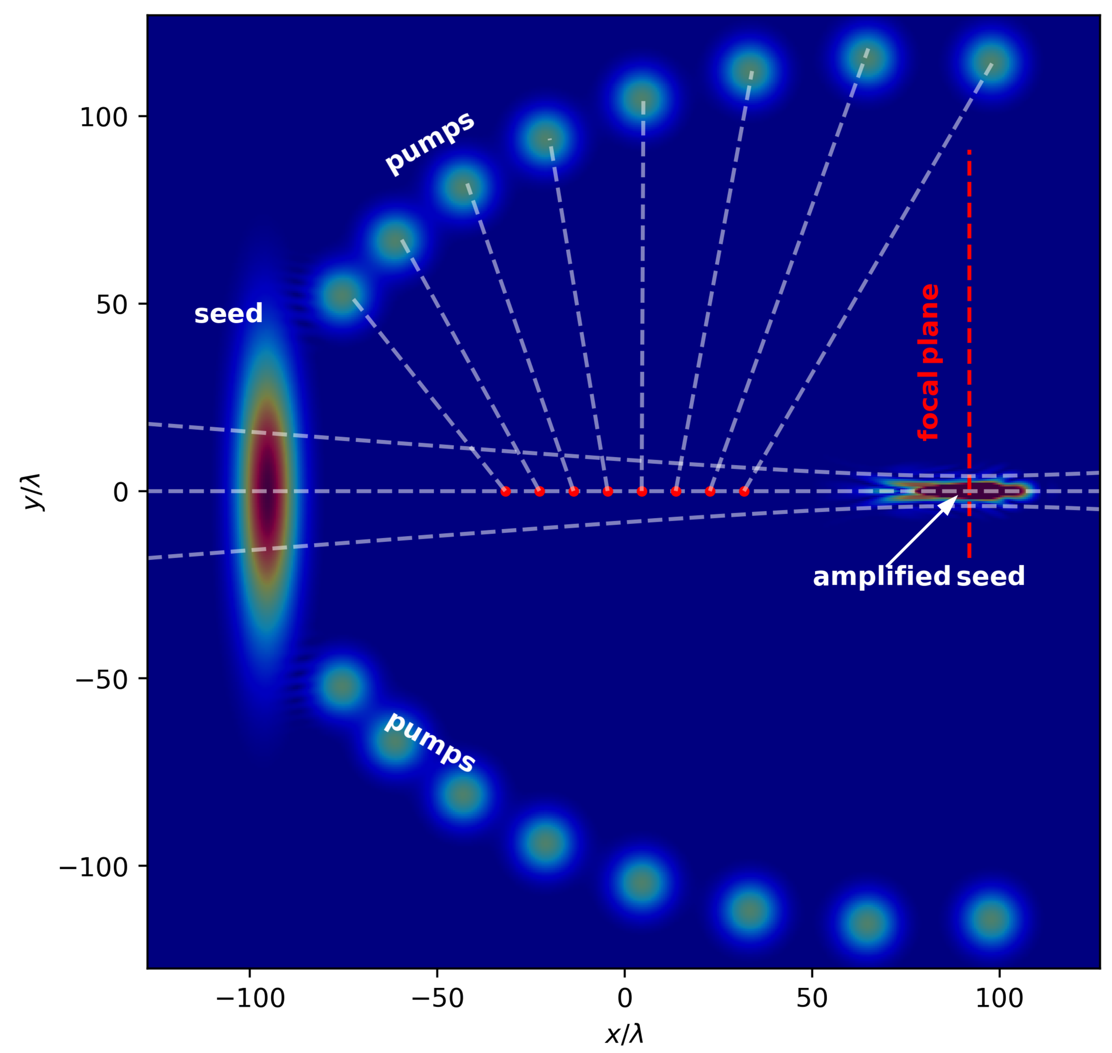
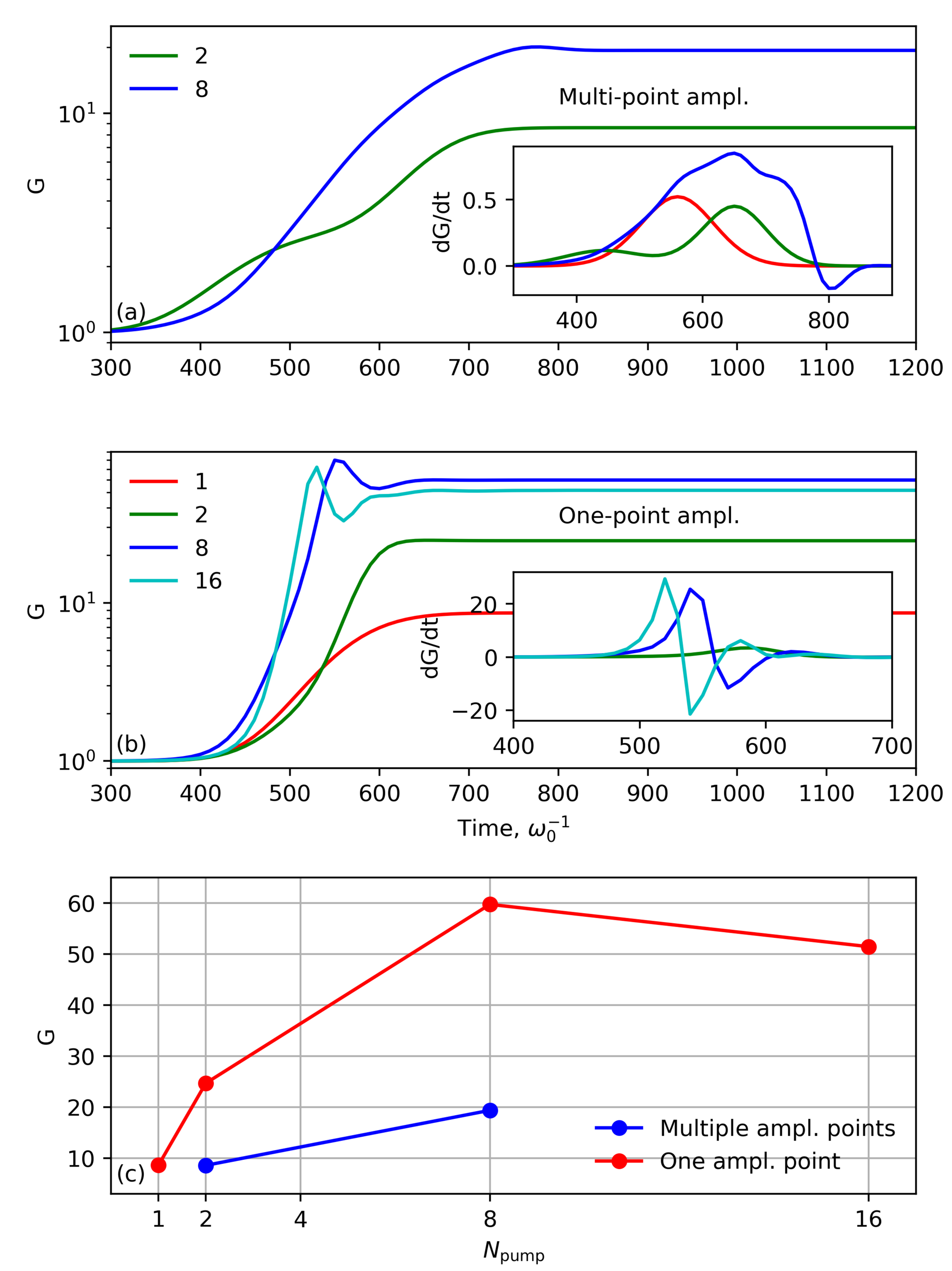


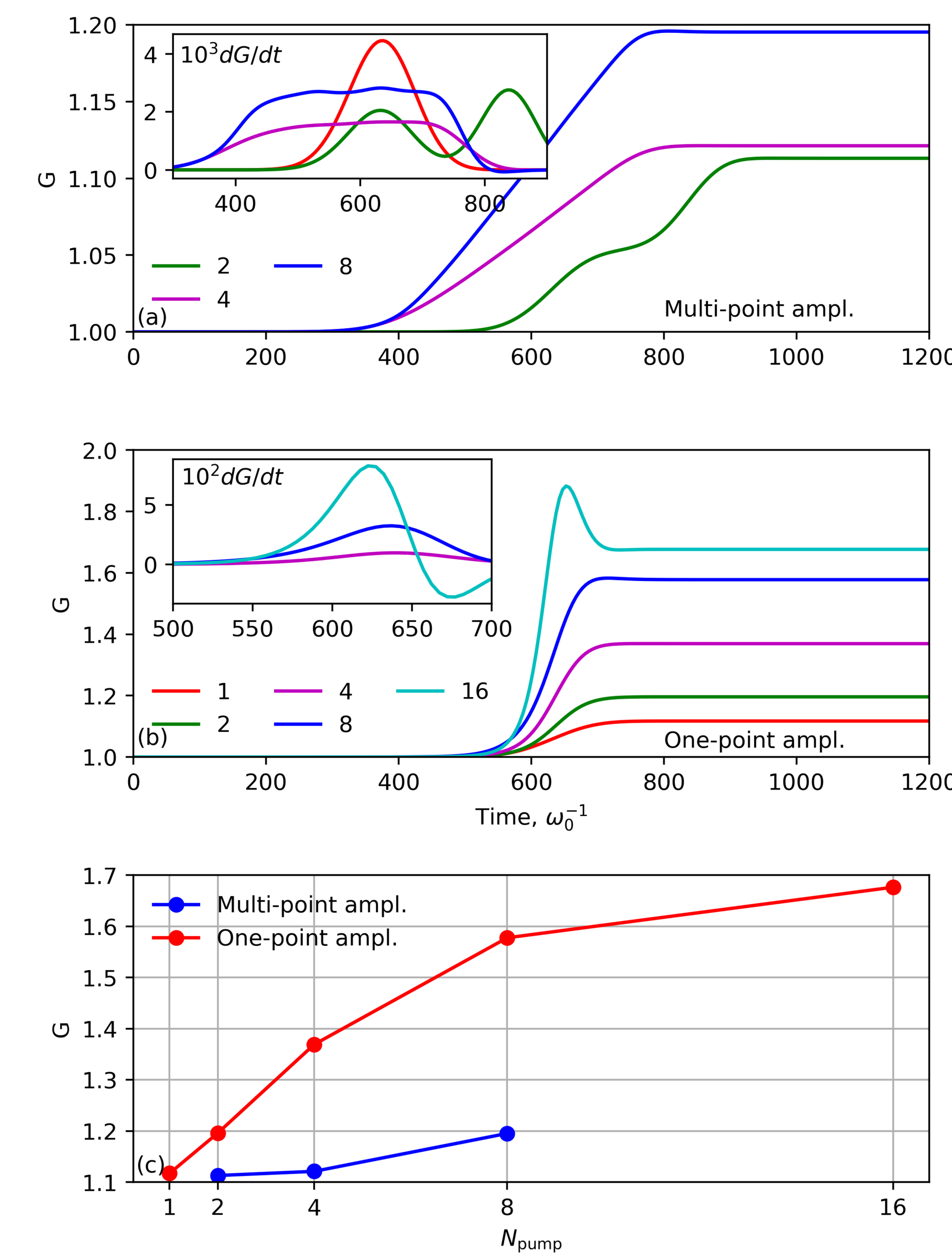
Illustration of the multi-pump seed amplification setup. Seed pulse propagates along the x axis and focuses onto a tight spot at the focal plane (dashed red line) while being amplified by 16 pumps coming from 40° to 120° angles and amplifying the seed at $y = 0$ axis at specific locations (denoted by red points). We consider both the case of multi-point amplification (as shown in the figure) and one-point amplification, where the locations of all red circles coincide.

Weak seed regime



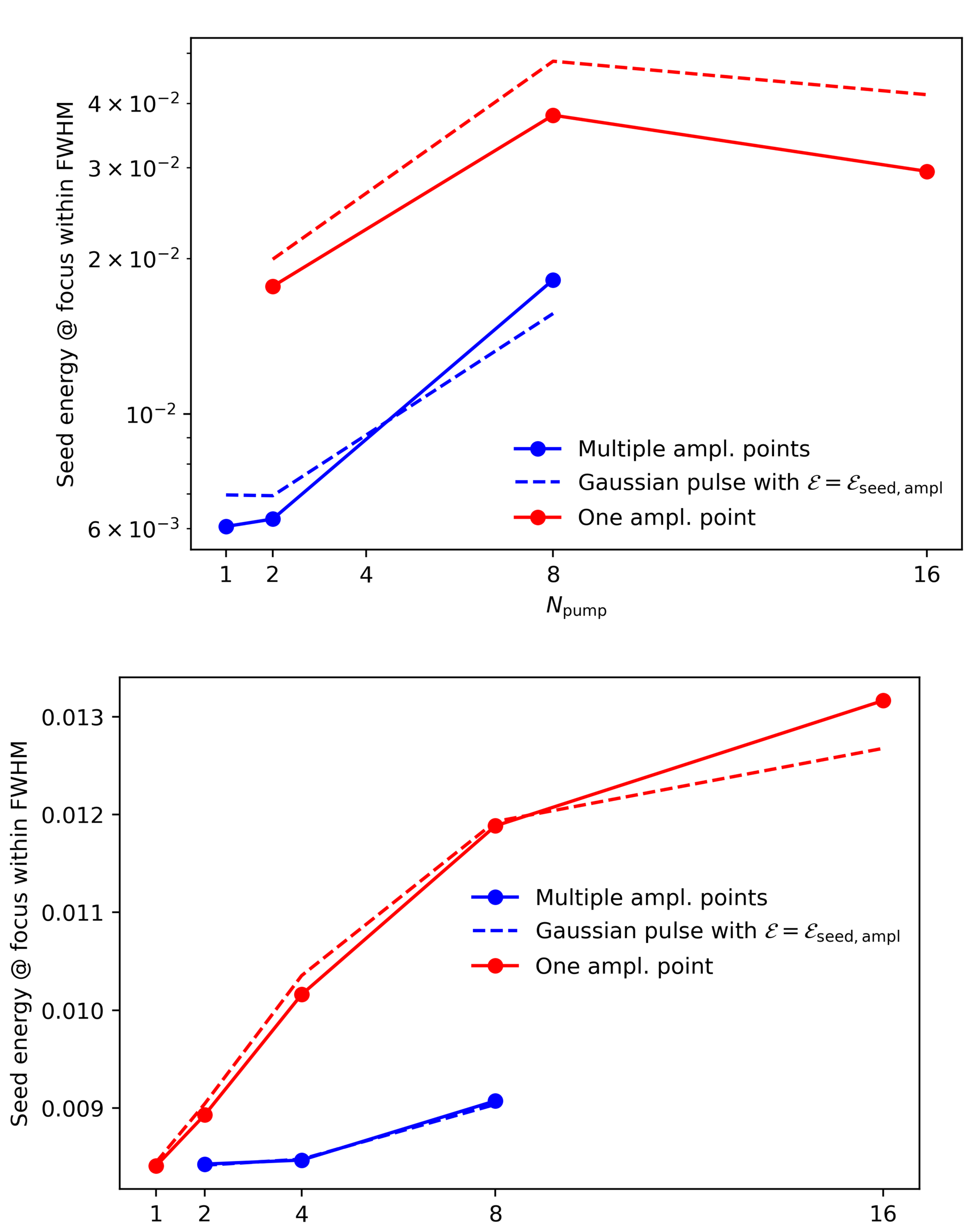
(a)Evolution of seed pulse energy gain for multi-point amplification, (b) one-point amplification, and (c) dependence of seed pulse energy gain on number of pumps and interaction point arrangement for the weak seed regime (Measured in terms of initial seed and pump energies, $r \equiv \mathcal{E}_{\rm seed,0}/\mathcal{E}_{\rm pump,0} = 0.01$). The trend towards higher seed energy gain G for larger $N_{\rm pump}$ is seen. One-point amplification seems to be preferrable in comparison to multi-point amplification due to higher value of plasma beating $\propto \Sigma_{i=1\ {\rm pump}}^{N} W_i\hat{b}_i \propto N_{\rm pump}^{1/2}$. Seed-pump energy oscillation for higher $N_{\rm pump}$ is observed.

Strong seed regime



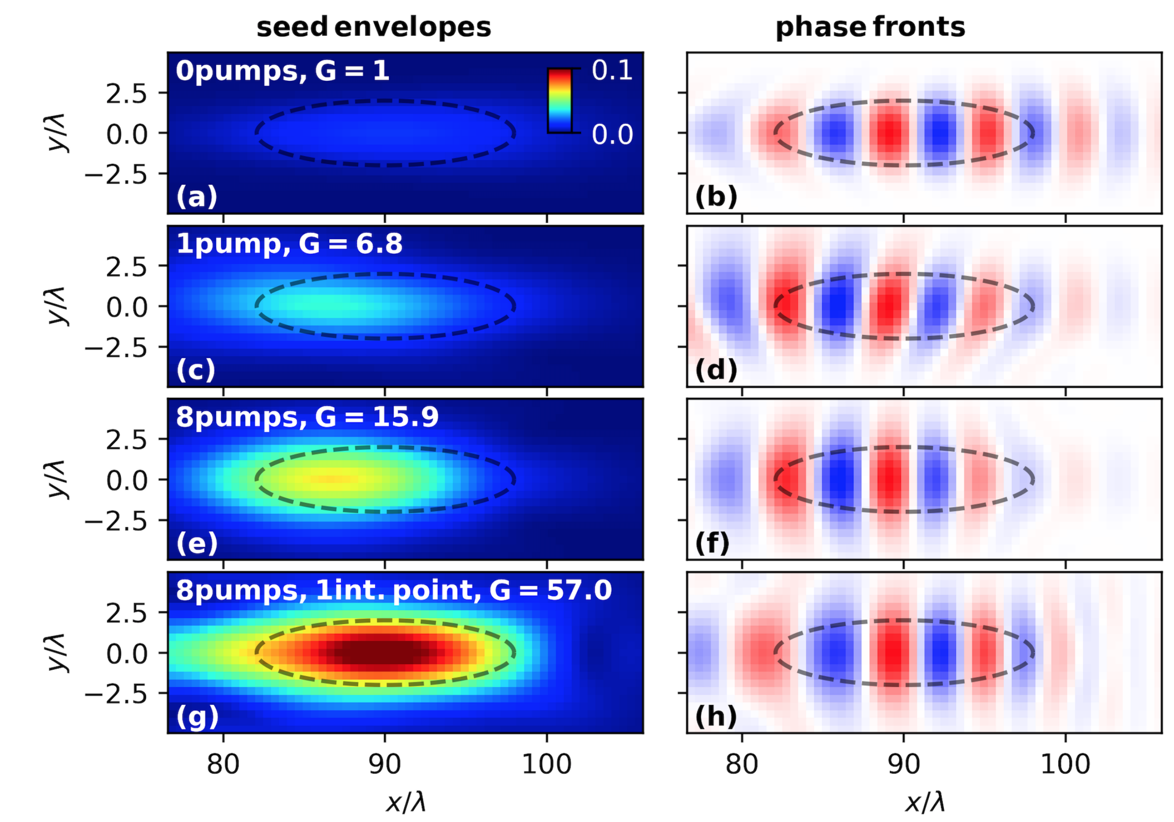
(a)Evolution of seed pulse energy gain for multi-point amplification, (b) one-point amplification, and (c) dependence of seed pulse energy gain on number of pumps and interaction point arrangement for the strong seed regime ($r = 1$). Larger $N_{\rm pump}$ and one-point amplification are preferrable as well.

Amplified seed intensity at the focal plane within FWHM



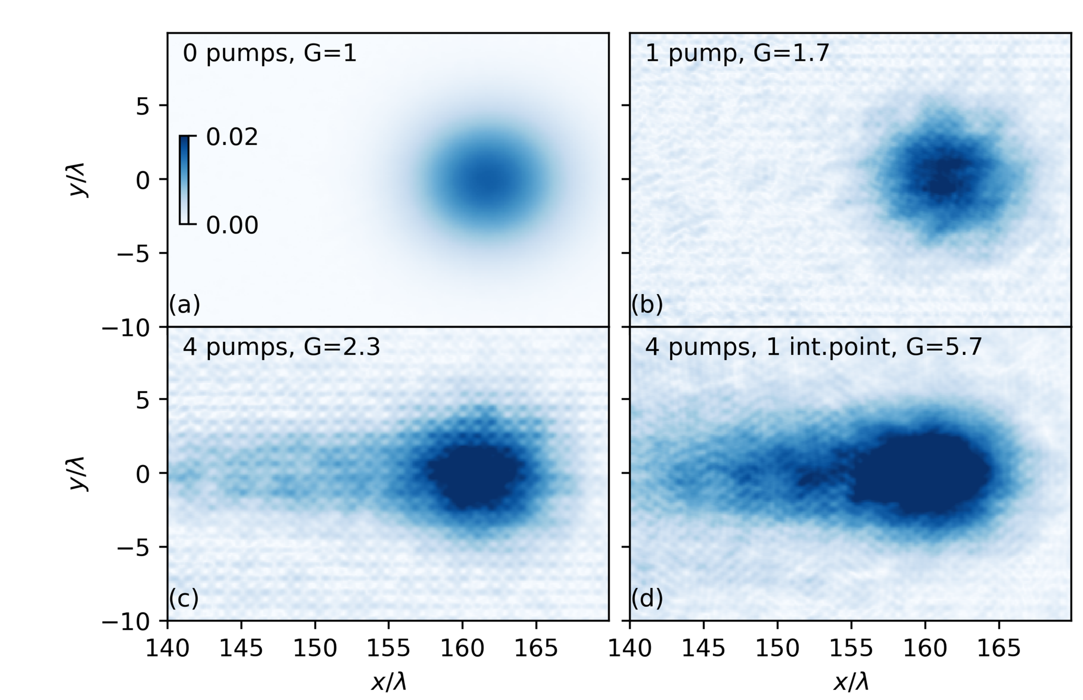
Energy of the amplified seed within the FWHM at the focal plane ('intensity') as the function of number of pumps, $N_{\rm pump}$, for weak (top, $r = 0.01$) and strong (bottom, $r = 1$) seed regimes. Higher seed intensity at focus for larger $N_{\rm pump}$ (solid lines) and fair performance in comparison to idealized case of Gaussian envelope (dashed lines) is seen.

Tightly focused amplified seed envelopes & phase fronts



Envelopes and phase fronts of the seed pulses for various levels of amplification in the weak seed regime ($r = 0.01$): (a),(b) no amplification, (c),(d) amplification by a single pump pulse, (e),(f) amplification by 8 pumps, and (g),(h) 8 pumps intersected in one point. Single-point multi-pump amplification is preferrable.

Tentative 2D PIC simulation result



In analogy with NSE simulations, we set up 2D PIC simulations using EPOCH code. The main difference in PIC is that we consider semi-infinite pump pulses and keep total pump power fixed while changing $N_{\rm pump}$, rather than keeping the total pump energy fixed, as was done for NSE runs. Seed envelopes for various levels of amplification in 2D PIC simulations: (a) no amplification, (b) amplification by a single pump pulse, (c) amplification by 4 pumps, and (d) 4 pumps intersected in one point. Seed energy gain grows with

Conclusions

- We present a progress report on the project on multi-pump Raman amplification of short laser pulses
- The effects of the resonant amplification on pulse envelope & phase fronts may be significant in the weak seed regime
- There is a trend towards higher seed energy gain and amplified seed intensity at the focal plane for larger $N_{\rm pump}$ for the fixed pump energy
- 2D PIC runs confirm this trend, but further analysis is required to understand the discrepancy in energy gains

References

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[5] Z. Li et al., Phys. Plasmas 25, 043109 (2018)