There are many phenomena that can interrupt the Raman amplification process:

- Pump depletion: limited energy amplification
- Pumpout: seed/efficient Raman gain
- Ionization: affects ionization density and the plasma velocity carrying the wave
- Landau damping: reduces the plasma's velocity carrying the wave
- Electron temperature: affects the plasma's velocity carrying the wave
- Nonresonant interaction: affects the plasma's velocity carrying the wave
- Forward pumping: affects the plasma's velocity carrying the wave
- Backward pumping: affects the plasma's velocity carrying the wave
- Relativistic filamentation: affects the plasma's velocity carrying the wave
- Resonance detuning: affects the plasma's velocity carrying the wave
- Landau damping: affects the plasma's velocity carrying the wave
- Ionization: affects the plasma's velocity carrying the wave

The LLE experimental setup is designed to be flexible to allow changing of parameters to follow feedback from experimental results.

The high-energy regime aims to produce the highest energy amplifier using the maximum energy of the pump: 50 J.

The seed-ionization regime takes advantage of our intense seed to produce the plasma, thereby avoiding the pump limitations.

The pump-depletion (PD) regime aims to produce the highest-efficiency amplifier possible by depleting the pump from the beginning.

Advantages:
- Highest possible efficiency, no linear gain
- Test of pump-depletion theory

Disadvantages:
- Requires a small spot size, therefore little energy in the pump
Plans for a tunable Raman amplifier at the Laboratory for Laser Energetics

Resonance condition: $\omega_{\text{pump}} = \omega_{\text{seed}} + \omega_{\text{plasma}}$

Technological novelty

- Energetic lasers: picoseconds
  - narrowband gratings
  - multilayer dielectric coated
  - $\sim2.5\text{-J/cm}^2$ damage threshold
- Powerful lasers: femtoseconds
  - broadband gratings
  - gold gratings
  - $\sim0.15\text{-J/cm}^2$ damage threshold
The capabilities afforded by the lasers and diagnostics at LLE will allow for multiple areas of new exploration into the field of Raman amplification.

- The promise of Raman amplification to amplify and compress short pulses to high peak powers in a plasma has largely been contained within theory and simulations.

- Experiments are hindered by many plasma-physics phenomena that are difficult to predict and therefore require careful measurement.

- The characteristics of the pump and seed lasers at LLE make it possible to access regimes that were not possible in past experiments, where much of the limitations of Raman amplification are avoided.
The primary application of Raman amplification is to produce PW-scale laser pulses not limited by the damage thresholds of grating compressors

**Physics milestones**

**Amplification of seed**
- Strong coupling between pump and seed mediated by an electron plasma wave (EPW)

**Reach pump depletion**
- Demonstrate that the slice efficiency of a Raman amplifier can be high (>30%)

**Efficient amplifier**
- Demonstrate pump depletion across the entire amplifier such that the overall efficiency is high (>30%)

**High-fidelity seed**
- Demonstrate that the amplified seed has good wavefront and temporal characteristics required for experiments (focusability, contrast, etc…)

**LLE objectives**

- Develop advanced diagnostics to identify limiting phenomena
- Develop mitigation strategies
- Identify an empirical optimal parameter regime for efficient Raman amplification
- Elucidate the road map to scaling to large laser systems based on these results
There are many phenomena that can interrupt the Raman amplification process

<table>
<thead>
<tr>
<th>Pump: Amplification</th>
<th>EPW: Pump depletion</th>
<th>Seed: Amplification limits</th>
</tr>
</thead>
</table>
| Thermal stimulated Raman scattering (SRS)  
  - SRS growing from thermal noise can deplete the pump and degrade amplified seed contrast | Wavebreaking  
  - Nonlinear effect where electrons dephase from the EPW, destroying the coherence of the structure | Thermal forward raman scattering  
  - Intense seed can decay into a forward-propagating photon and backward-propagating EPW |
| Filamentation  
  - Thermal or ponderomotive filamentation degrades the pump pulse wavefront | Resonance detuning  
  - Resonance condition not satisfied over the whole interaction (pump chirp, density gradients, temperature gradients...) | Relativistic filamentation/focusing  
  - Wavefront degradation caused by filamentation driven by a relativistic mass increase of electron |
| Landau damping  
  - Collisionless damping of the EPW | | Wakefield generation  
  - An intense seed expels electrons, changes density, destroys resonance, and loses energy |
The best experiments to date have only reached energy-transfer efficiencies of $<10\%$.

| Year | Author | Facility     | Pump Laser | $E_{\text{pump}}$ (mJ) | $\Delta t_{\text{pump}}$ (ps) | $I_{\text{pump}}$ ($10^{14}$ W/cm$^2$) | $E_{\text{seed}}$ ($\mu$J) | $\Delta T_{\text{seed}}$ (fs) | $n_e$ ($10^{18}$ cm$^{-3}$) | $\omega_{\text{pump}}/\omega_{\text{pe}}$ | Efficiency (overlap) (%) |
|------|--------|--------------|------------|-----------------|-----------------|---------------------------------|-----------------|-------------------|----------------|------------------|----------------|----------------------|
| 2004 | M. Dreher | Max Plank | Ti:Sa | 140 | 3.5 | 57 | 60 | 80 | 3 | 24 | 0.67 |
| 2005 | W. Cheng | Princeton | Ti:Sa | 40 | 10 | 2 | 7.5 | 550 | 11 | 13 | 1.1 |
| 2007 | J. Ren | Princeton | Ti:Sa | 82 | 20 | 2 | 16 | 500 | 13 | 12 | 3.9 (7.8) |
| 2007 | J. Ren | Princeton | Ti:Sa | 56 | 20 | 1.4 | 3300 | 90 | 13 | 12 | 4.1 (5.9) |
| 2012 | D. Turnbull | Princeton | Ti:Sa | 300 | 25 | 1.5 | 100 | 200 | 15 | 11 | 4.0 |
| 2015 | X. Yang | University of Strathclyde | Ti:Sa | 880 | 250 | 1.2 | 560 | 270 | 1 | 42 | 0.4 |

---

Pump Limitation

Stimulated Raman backscatter from thermal noise can deplete the pump energy before reaching the seed pulse

\[ \gamma_{SRS} = a_{pump} \left( \omega_{pump} \omega_{pe} \right)^{1/2} \]

General SRS

\[ a_0 = \left( \frac{I \times \lambda_{\mu m}^2}{1.3 \times 10^{18}} \right)^{1/2} \]

\[ \omega_{pe} = \left( \frac{e^2 n_e}{m_e \epsilon_0} \right)^{1/2} \]

Effect of chirp

\[ \Delta v_{SRS} = \gamma_{SRS} / 2\pi \]

\[ G = \exp \left( \Delta v_{SRS} t_{\text{lim}} \right) \]

\[ t_{\text{lim}} = \Delta t_{pump} \frac{\Delta v_{SRS}}{\Delta v_{pump}} \]

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Name} & \Delta \lambda_{SRS} \text{ (nm)} & \Delta \lambda_{pump} \text{ (nm)} & G \\
\hline
\text{M. Dreher} & 4.5 & 8 & 41 \\
\text{W. Cheng} & 1.7 & 11 & 2 \\
\text{J. Ren} & 1.4 & 10 & 4 \\
\text{J. Ren} & 1.2 & 10 & 2 \\
\text{D. Turnbull} & 1.3 & 10 & 4 \\
\text{X. Yang} & 0.5 & 35 & 2 \\
\hline
\end{array}
\]
The pump chirp detunes the resonant interaction, which can reduce the efficiency of energy transfer in the pump-depletion regime.

\[ q \approx \frac{613}{\Delta t \, (\text{ps})} \frac{\Delta \lambda}{\lambda} \left( \frac{10^{19} \, \text{cm}^{-3}}{n_e} \right)^{1/2} \frac{10^{14} \, \text{W/cm}^2}{I \lambda^2 \, (\mu\text{m})} \]

\[ E_{\text{max}} < 1 - q \]

<table>
<thead>
<tr>
<th></th>
<th>( q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Dreher</td>
<td>0.09</td>
</tr>
<tr>
<td>W. Cheng</td>
<td>0.4</td>
</tr>
<tr>
<td>J. Ren</td>
<td>0.26</td>
</tr>
<tr>
<td>J. Ren</td>
<td>0.38</td>
</tr>
<tr>
<td>D. Turnbull</td>
<td>0.25</td>
</tr>
<tr>
<td>X. Yang</td>
<td>0.43</td>
</tr>
<tr>
<td>LLE</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Landau damping (LD) is a wave–particle interaction that transfers energy from a plasma wave to particles that are traveling near the phase velocity of the wave.

\[
f(v) \quad \quad \quad k_{\text{EPW}} \lambda_{\text{De}} \leq 0.29
\]

\[
\lambda_{\text{De}} \propto \sqrt{\frac{T_e}{n_e}}
\]

- Weak seed (noise): LD damps the wave amplitude to zero
- Strong seed: LD reduces growth rate, increasing the time in the linear regime
- Pump depletion: LD is too slow to damp the wave

<table>
<thead>
<tr>
<th>Name</th>
<th>(k\lambda_{\text{De}}) (50 eV)</th>
<th>(k\lambda_{\text{De}}) (150 eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Dreher</td>
<td>0.48</td>
<td>0.83</td>
</tr>
<tr>
<td>W. Cheng</td>
<td>0.25</td>
<td>0.43</td>
</tr>
<tr>
<td>J. Ren</td>
<td>0.23</td>
<td>0.40</td>
</tr>
<tr>
<td>X. Yang</td>
<td>0.83</td>
<td>1.43</td>
</tr>
</tbody>
</table>
At high amplitudes, the EPW can break if the particle velocity carrying the wave approaches the wave’s phase velocity.

Particle longitudinal velocity versus space:

\[ V_{ph} \]

\[ t_1 \rightarrow t_2 \rightarrow t_3 \]

Finite temperature affect on wave breaking:

\[
\frac{E_{\text{warm}}}{E_{\text{cold}}} = \left( 1 - \frac{1}{3} B - \frac{8}{3} B^{1/4} + 2B^{1/2} \right)^{1/2}
\]

Prevention:

\[ v_{osc} < v_{ph} \]

\[
\frac{n_e}{n_c} > 2.5 (a_{pump})^{4/3}
\]

D. S. Clark and N. J. Fisch, Phys. Plasmas 10, 3363 (2003);
A large parameter scan over pump intensities and densities has been run in particle-in-cell (PIC) to study the effect of wave breaking.
Temperature is an extremely important parameter to Raman amplification and has been the least diagnosed in experiments so far.

- Increasing temperature
  - decreases gain for SRS (good for thermal SRS, bad for seed in linear regime)
  - strongly reduces the threshold for thermal and ponderomotive filamentation
  - increases the effect of Landau damping
  - grossly changes the optimal regime avoiding wave breaking

- Changing temperature as the pump heats the plasma can detune a resonance in the linear regime

- In literature
  - no mention of temperature
  - analytic estimate based on inverse bremsstrahlung heating (many different models)

- At LLE we plan to build a time resolved Thompson scattering diagnostic (~2 ps resolution)*

*Absolute temperature measurements versus time are extremely important for the interpretation of results.

*A. Davies et al., UO6.00003, this conference.
The LLE experimental setup is designed to be flexible to allow changing of parameters to follow feedback from experimental results.

### Target/geometry
- **Gas cell**
  - long homogeneous plasma density
  - $5 \times 10^{18}$ to $1.5 \times 10^{19}$ cm$^{-3}$
  - $\omega_{\text{pump}}/\omega_{\text{pe}} = 8$ to 13
- **Nonlinear interaction**
  - isolate scattering sources

---

### Interaction drawn to scale
- $f/26$ focus, $f = 120$ cm
- $4^\circ$ angle between beams

### Beam Parameters

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_{\text{cen}}$</th>
<th>$\Delta \lambda$</th>
<th>$E_{\text{max}}$</th>
<th>$\Delta t$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pump</strong></td>
<td>1053 nm</td>
<td>8 nm</td>
<td>50 J</td>
<td>1 to 100 ps</td>
</tr>
<tr>
<td><strong>Seed</strong></td>
<td>1140 to 1200 nm</td>
<td>60 to 120 nm</td>
<td>75 mJ</td>
<td>75 to 100’s fs</td>
</tr>
</tbody>
</table>

E23504d

S. Bucht et al., GP10.00050, this conference.
There are three parameter regimes of interest where potentially new experimental progress can be achieved in the field of Raman amplification:

1. Avoids pump limitations
2. Produces a very cold plasma (<10 eV)

The seed-ionization and pump-depletion regimes will be realized at LLE for the first time because of our high-power seed pulses.
The high-energy regime aims to produce the highest energy amplifier using the maximum energy of the pump: 50 J

### Advantages
- Most-energetic amplifier
- Possibility of producing a medium-range Raman amplifier (first)

### Disadvantages
- Fighting all previously mentioned limitations

<table>
<thead>
<tr>
<th>Regime</th>
<th>$E_{\text{pump}}$ (mJ)</th>
<th>Diameter (µm)</th>
<th>$\Delta t_{\text{pump}}$ (ps)</th>
<th>$I_{\text{pump}}$ ((10^{14} \text{ W/cm}^2))</th>
<th>$E_{\text{seed}}$ (mJ)</th>
<th>$\Delta t_{\text{seed}}$ (fs)</th>
<th>$I_{\text{seed}}$ ((10^{14} \text{ W/cm}^2))</th>
<th>$n_e$ ((10^{18} \text{ cm}^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy</td>
<td>50000</td>
<td>800</td>
<td>25</td>
<td>4</td>
<td>75</td>
<td>75</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

### SRS

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \lambda_{\text{SRS}}$ (nm)</th>
<th>$\Delta \lambda_{\text{pump}}$ (nm)</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.4</td>
<td>8</td>
<td>1620</td>
</tr>
</tbody>
</table>

### Detune

<table>
<thead>
<tr>
<th></th>
<th>q</th>
<th>$k\lambda_{De}$ (50 eV)</th>
<th>$k\lambda_{De}$ (150 eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.03</td>
<td>0.16</td>
<td>0.28</td>
</tr>
</tbody>
</table>
The seed-ionization regime takes advantage of our intense seed to produce the plasma, thereby avoiding the pump limitations

<table>
<thead>
<tr>
<th>Regime</th>
<th>$I_{\text{seed}}$ (10^{14} \text{ W/cm}^2)</th>
<th>$E_{\text{pump}}$ (mJ)</th>
<th>Diameter (\mu m)</th>
<th>$I_{\text{pump}}$ (10^{14} \text{ W/cm}^2)</th>
<th>$\Delta t_{\text{pump}}$ (ps)</th>
<th>$E_{\text{pump}}$ (mJ)</th>
<th>$n_e$ (10^{18} \text{ cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed ionization</td>
<td>2.6</td>
<td>75</td>
<td>700</td>
<td>0.8</td>
<td>50</td>
<td>16000</td>
<td>10</td>
</tr>
</tbody>
</table>

**Advantages**

- Avoid pump limitations
- Test of seed ionization *(first)*
- Possibility of producing a medium range-raman amplifier *(first)*

**Disadvantages**

- Fighting all previously mentioned limitations
The pump-depletion (PD) regime aims to produce the highest-efficiency amplifier possible by depleting the pump from the beginning.

<table>
<thead>
<tr>
<th>Regime</th>
<th>$\Delta t_{\text{seed}}$ (fs)</th>
<th>$E_{\text{seed}}$ (mJ)</th>
<th>Diameter ($\mu$m)</th>
<th>$I_{\text{seed}}$ ($10^{14}$ W/cm$^2$)</th>
<th>$n_e$ ($10^{18}$ cm$^{-3}$)</th>
<th>$I_{\text{pump}}$ ($10^{14}$ W/cm$^2$)</th>
<th>$\Delta t_{\text{pump}}$ (ps)</th>
<th>$E_{\text{pump}}$ (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Depletion</td>
<td>200</td>
<td>75</td>
<td>150</td>
<td>21</td>
<td>10</td>
<td>0.9</td>
<td>50</td>
<td>800</td>
</tr>
</tbody>
</table>

$$a_{\text{seed}} \Delta t_{\text{seed}} \sqrt{\omega_{\text{seed}} \omega_{\text{pe}}} \sim 5$$

**Advantages**
- Highest possible efficiency, no linear gain *(first)*
- Test of pump-depletion theory *(first)*

**Disadvantages**
- Requires a small spot size, therefore little energy in the pump

M. Dreher | PD | 0.31  
W. Cheng  | 0.28 
J. Ren    | 0.32  
J. Ren    | 2.0   
D. Turnbull| 0.27  
X. Yang   | 0.60  
LLE-PD    | 5.07  

E25533a