Modeling of Laser–Plasma Interaction in the Shock-Ignition Regime with *LPSE*: Comparison with Particle-in-Cell Simulations and Experiments

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Shock ignition

- **Shock ignition (SI) [1]:** an initial low-intensity drive compresses the target with a low-implosion velocity to avoid hydrodynamic instabilities, followed by a high-intensity spike that ignites the target
- **Laser–plasma instabilities (LPI's) [2] in the SI regime:** the high-intensity spike ($I \approx 10^{16}$ W/cm^2) strongly drives LPI's in the coronal plasma, potentially generating a large amount of hot electrons
  - **stimulated Raman scattering (SRS):** coupling between the pump wave (frequency ω_0) and electron density perturbation (frequency ω_{pe}), generating backscattered light (Raman frequency $\omega_1 = \omega_0 \pm \omega_{pe}$); its saturation can cause hot-electron production
  - **stimulated Brillouin scattering (SBS):** coupling between the pump wave and ion-density perturbation (frequency ω_{IAW}), creating backscattered light (Brillouin frequency $\omega_B = \omega_0 \pm \omega_{IAW}$)
- **AIM:** modeling of SRS and SBS in 1-D with *LPSE* under plasma and laser conditions relevant for SI; comparison to particle-in-cell (PIC) simulations and experimental results

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LPSE

- ***LPSE* [3,4]:** a time-enveloped, non-paraxial code for studying parametric instabilities and electron acceleration at scales intermediate to hydrodynamic and kinetic codes; linear fluid–plasma description; lower numerical noise than PIC codes; *LPSE* includes the following equations
  - **Pump electric field:** time enveloped around the laser frequency ω_0: accounts for collisional laser absorption, diffraction, and self-focusing and absorption as a result of SRS and two-plasmon decay (TPD is not modeled in 1-D)
  - **Langmuir waves (LW's):** a Zakharov-like equation, enveloped at frequency ω_{LW} given from input; the Langmuir wave is seeded by a small noise term and accounts for collisional absorption and Landau damping
  - **Raman field:** time enveloped around the Raman frequency $\omega_1 = \omega_0 - \omega_{LW}$; excitation of the Raman light via coupling between the pump field and the LW; accounts for collisional absorption
  - **Ion-acoustic fluctuation:** fluid–plasma equations for linear ion perturbation: there is one equation for particle conservation and another for momentum conservation; the plasma response is coupled to fields through ponderomotive terms; accounts for ion wave damping
  - **hybrid particle evolution:** test particles package; switched off throughout this work

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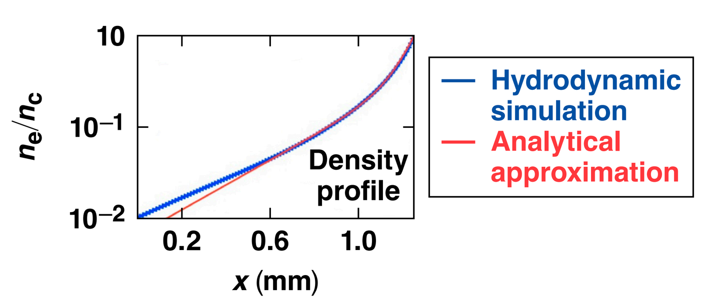
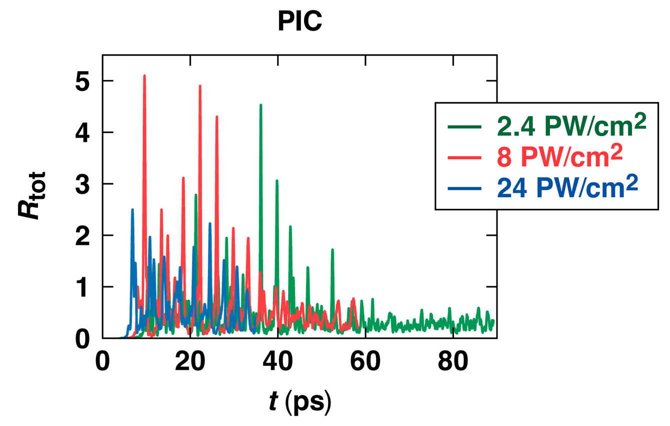
Comparison to PIC results

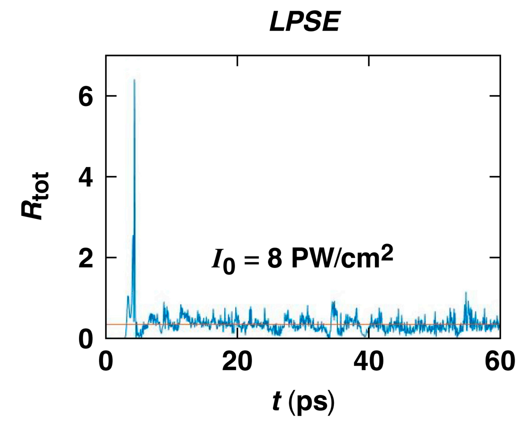
- *LPSE* accuracy is tested in the SI regime against long spatial and time-scale PIC simulations [5]
  Goal: compare measurable quantities such as the total reflectivity and SRS spectra



- Initial parameters
  - plastic (CH) plasma: $Z_{eff} = 5.3$
  - electron and ion temperatures: $T_e = 2.2$ keV, $T_i = 1.2$ keV
  - laser intensity $I_0 = 8$ PW/cm^2
  - wavelength $\lambda = 0.35\ \mu$m
  - *LPSE*: linearized profile

Instantaneous SRS and SBS reflectivity as functions of time

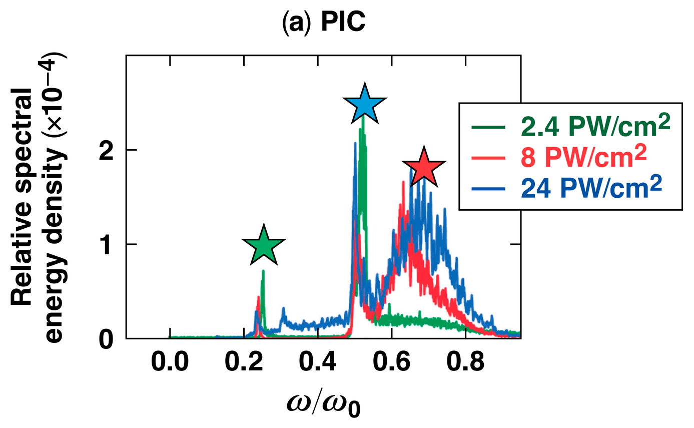


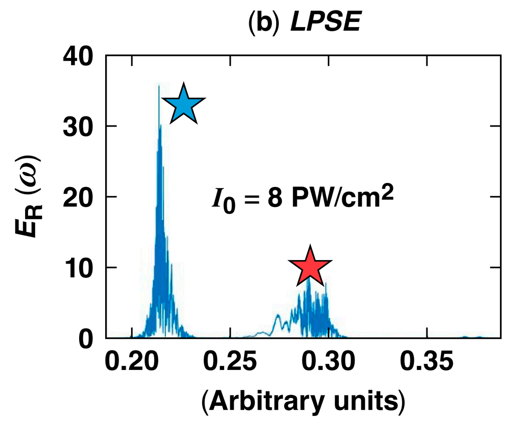


Red curve: peaks are a result of SBS behavior of (transient stage—up to 35 ps), followed by saturation at ≈35% to 40% caused by absolute SRS and cavitation

Reflectivity saturation around 37% is caused by Langmuir decay instability; the initial spike results are from SBS, then suppressed by SRS

Raman spectra





- (a) relative spectral energy density of Raman light for PIC and (b) Raman signal for *LPSE* simulations as a function of frequency
  - **Blue stars:** evidences of absolute SRS at quarter critical
  - **Red stars:** evidences of convective SRS at lower densities in (a) there is a weaker signal at n/n_c=1/16 (green star) that is not observed in *LPSE* results
- **Conclusion:** *LPSE* results agree with PIC results for what concerns averaged SRS + SBS reflectivity and the Raman spectrum; discrepancies on saturation SBS time scales; no absolute SRS instability at n/n_c = 1/16 in *LPSE* results; furthermore, electron acceleration is neglected in *LPSE*

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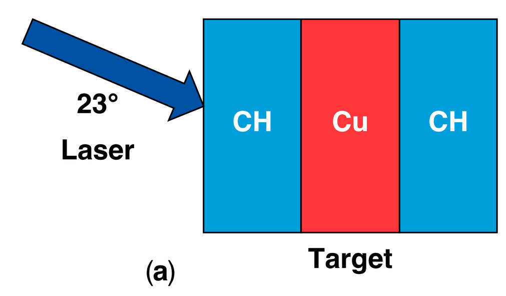
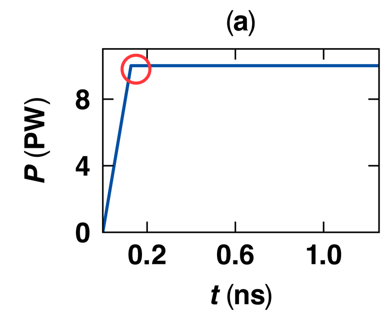
Modeling of an OMEGA EP experiment

The aim of the experiment on OMEGA EP is to study the influence of hot electrons on the shock front in planar geometry ($\lambda = 0.35\ \mu$m).



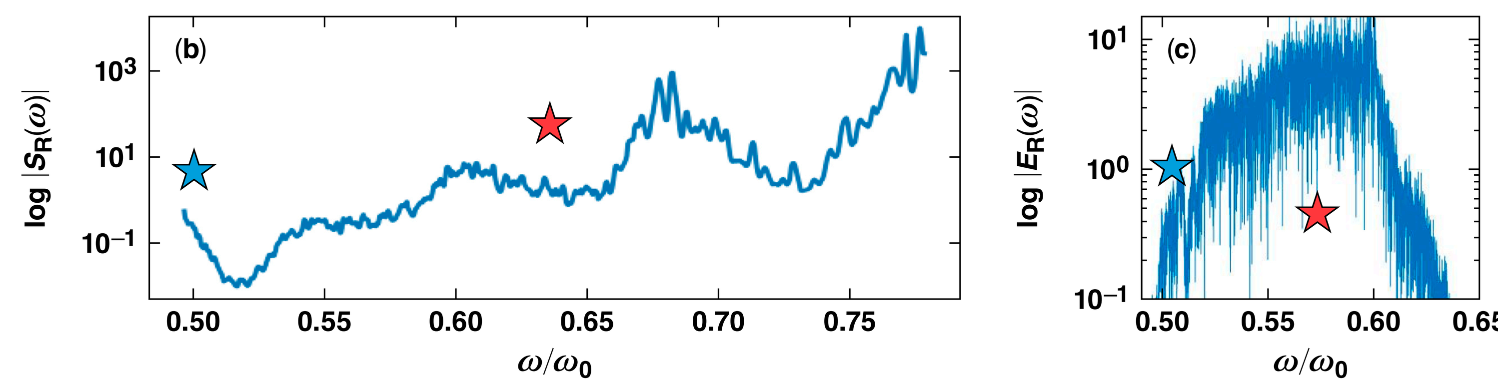


Temporal laser shape in the experiment

LPSE parameters from hydro simulations at the **beginning** of the pulse [red circle in (a)]

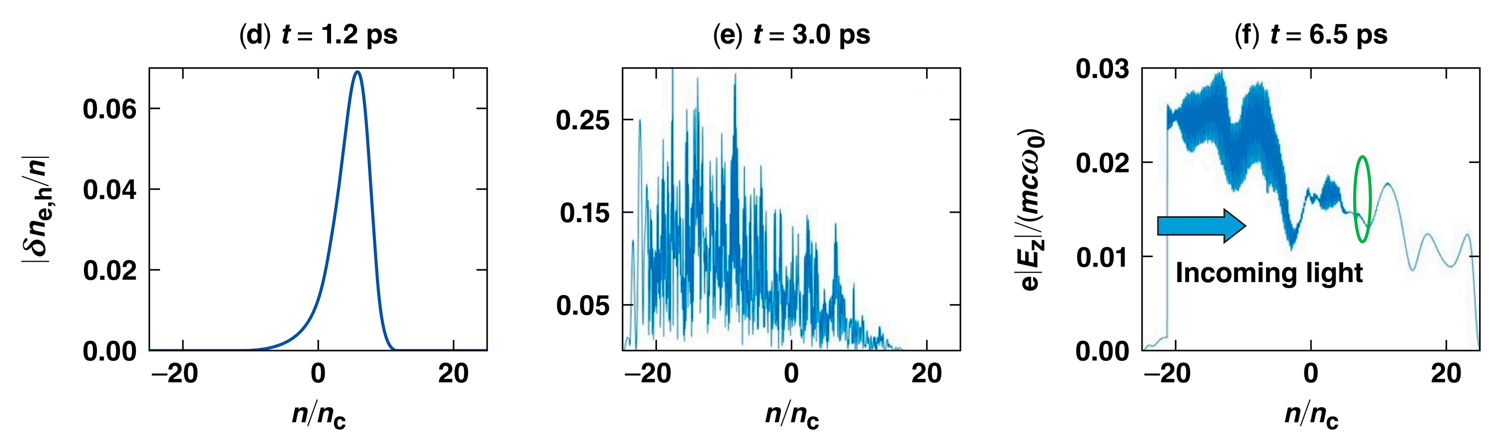
- plastic (CH) plasma: $Z_{eff} = 5.3$
- Electron and ion temperatures
  - $T_e = 3.5$ keV, $T_i = 0.3$ keV
- Laser intensity $I_0 = 6 \times 10^{15}$ W/cm^2
- Wavelength $\lambda = 0.35\ \mu$m
- *LPSE*: linearized profile
- High ion damping: $\nu_i/\omega_i = 0.4$
- Short plasma profile
  - $L_{n_c/4} = 48\ \mu$m for $0.18 < n/n_c < 0.28$
  - $L_{tot} = 100\ \mu$m for $0.05 < n/n_c < 0.3$
- No test particle package

Entire linearized plasma profile ($L = L_{tot}$): Raman spectrum



Raman signal from experimental data and (c) Raman spectrum from *LPSE* simulations. Both axes are on the logarithmic scale. The broad convective SRS (red stars) is stronger than the absolute SRS at quarter critical (blue stars) in both images. In (c), the *LPSE* spectrum cannot detect a spectrum as large as in (b) because of limitation of the envelope model. Furthermore, *LPSE* cannot reproduce the typical Raman gap between $0.5 < \omega/\omega_0 < 0.55$ detected in the experiments since the limitation on the hydrodynamics model does not consider more complex phenomena (profile steepening for example).

- Shorter linearized profile ($L = L_{n_c/4}$). Behavior of the absolute SRS



[(d),(e)] normalized high-frequency plasma perturbation and (f) normalized pump field as a function of the density profile: (d) excitation of LW at quarter critical; (e) shift in oscillation location of LW toward lower densities; peaked feature: short-scale perturbations as a consequence of Langmuir decay instability; (f) pump depletion caused by absolute SRS (around quarter-critical density—green circle); oscillation in the pump caused by interference of backscattered light caused by Langmuir decay instability (LDI) and incoming pump

Conclusion

- Broad spectrum in Raman light found in *LPSE*, as in data; cut off on the maximum frequency of the convective SRS spectrum for *LPSE* caused by the envelope limit
- Simulations around quarter critical: shift in the LW oscillation position as a result of strong pump depletion; gives a lower absolute SRS signal, as seen in the spectrum.

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Conclusion and perspectives

- Laser–plasma instabilitites within the shock-ignition regime are studied with the code *LPSE*. Electron acceleration is neglected here
- *LPSE* results concerning experimentally measurable quantities, such as light reflectivity and Raman spectrum, are in agreement with PIC results
- Simulations of experimental results: the early laser–plasma interaction shows a strong pump depletion for simulations around quarter critical. A shift in the Langmuir wave oscillation position may be associated with a weaker signal from quarter critical. The spectrum from *LPSE* results qualitatively agrees with the Raman spectrum measured at the early stage of the laser propagation
- Future studies
  - simulations with test particles package: fraction of hot electrons generated, hot-electron temperature
  - simulations at later time of the laser pulse: longer plasma scale
  - effect on Raman absorption, Raman spectrum, and hot-electron generation

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