Nanosecond Raman scattering computation in large plasmas

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Abstract. We present some numerical studies about stimulated Raman scattering (SRS) in
millimeter scale plasmas and in nanosecond regime. A software has been developed for computing
SRS in nonlinearly saturated regime. We aim to deal both with fine saturating processes, and
with realistic profiles for plasma hydrodynamic data. We thus present some results of simulations
which have been carried out with this code, in the context of a recent laser-plasma-interaction
experiment on the LIL facility.

1. Introduction
Laser-plasma interaction (LPI) might be one of the main limiting processes involved in the
operating of high power laser facilities such as the ligne d’intégration laser (LIL) or the future
laser Mégajoule (LMJ) \([1]\). Among the various LPI physical effects, Raman backscattering in
nanosecond regime is probably the most complicated to understand and to predict. There are
many difficulties involved by Raman scattering, such as the large number of physical regimes,
as well as the general multi-scale behavior of this instability. More precisely, kinetic phenomena
in saturation regime have to be dealt with, together with space and time large scale variations
of hydrodynamic parameters. Other difficulties come from the possibly incoherent character
of the backscattered light, specially in case of inhomogeneous plasmas. We furthermore note
that LMJ-relevant regimes (eg. \(k_{Lm}\lambda_{De} > 0.2\), \(k_{Lm}\) being the Langmuir wave wavenumber and
\(\lambda_{De}\) the Debye length) are, for a given electron density, difficult to achieve on smaller laser
experiments.

Let us first note that our goal of simulating full LMJ (centimeter sized) cavities is hardly
achievable. We thus for now restrict ourselves to LPI devoted millimeter-sized experiments,
such as being recently carried out on the LIL facility \([2]\). As we already presented in a previous
conference \([3]\), we first use a 2D Lagrangian and ray-tracing code (FCI2) to compute the plasma
parameters profile within the whole geometry of the experiment. Then a LPI post-processor
(Piranah) is used to compute Raman and Brillouin linear gains, and thus to know where and
when the LPI instabilities may occur. We finally carry out specific nonlinear LPI calculation
within a few space and time areas of the experiment (mesoscopic scale), those being deduced
from the Piranah calculation. These nonlinear calculations use FCI2 results as initial conditions.
2. Nonlinear Raman scattering calculation

We use a full envelope (paraxial) model, as e.g. in references [4; 5]. Saturation of SRS by pump depletion as well as Langmuir decay instability (LDI) are dealt with. Propagation of each of the involved electromagnetic, Langmuir, and acoustic waves, is computed independently, within the envelope approximation always. Various nonlinear three-wave coupling terms (for the Raman process itself and for the LDI at first and second order) are then added through a splitting method. This allows us to deal with the beginning of the LDI cascade phenomenon, provided that one does not reach the collapse regime.

Dealing with nonlinear kinetic saturation cannot been carried out rigourously within a mesoscopic code. For that reason, we implemented the Rose and Russell [6] adiabatic nonlinear relation of dispersion, from which one can deduce a nonlinear frequency shift for the Langmuir waves, this shift being known analytically. Note that a consequence of this model is that no SRS occur for \( k_{\text{Lm}} \lambda_{\text{De}} > 0.53 \), which may have relevant consequences on backscattered light temporal shape and spectrum. Another limitation comes from the monochromatic waves assumption in Rose and Russell. Saturation e.g. due to beam acoustic modes [7] cannot thus be dealt with.

All this modeling has been implanted within the CEA’s hydrodynamic platform \( H\rho\alpha \) (Héra) [8], which also contains Eulerian hydrodynamic capabilities as well as a stimulated Brillouin scattering module [9]. This would allow in the future to carry out SRS calculations dealing with ponderomotive effects, and possibly with Raman/Brillouin competition.

3. Comparison between \( H\rho\alpha \) SRS calculation and the CALDER PIC code

Since no experimental results are for now available to validate our modeling, we attempted to carry out cross-validations between different codes. We compared e.g. our \( H\rho\alpha \) results with data produced by the CALDER particle-in-cell (PIC) code. We considered for that purpose (fig. 1) a “school case” (small-sized 1D homogeneous plasma: see parameters on the figure caption) so that PIC results where achievable in a reasonable delay. It appears that ion density spectra, as well as electron distribution function (as deduced from the Rose & Russell model in the \( H\rho\alpha \) case) are comparable. Although reflectivity rates are not the same in both codes, one can notice that the general behaviour of the plasma respose (e.g. importance or not of the LDI effect vs \( k_{\text{Lm}}\lambda_{\text{De}} \)) exhibits strong similarities.

![Figure 1](image-url)
4. LPI-devoted experiment on the LIL facility

A couple of experiments devoted to LPI have recently been carried out on the LIL facility [2]. Since some experimental data were still unavailable when we wrote this paper, we limited our study to testing the capabilities of our chain of softwares, using the parameters of one of these experiments. Scheme of the experiment and corresponding hydrodynamic simulations results are presented on figure 2. The setup is constituted by a 4 mm length and 1.4 mm diameter gold tube, filled with pentane gas and closed by two plastic windows. The laser (14 kJ, 6 ns at $\lambda = 351$ nm) first destroys the windows, then heats the pentane, and a density plateau at about $n_e/N_c = 0.15$ with a 3 keV electron temperature is obtained after 4.1 ns [10]. This instant maximises the Raman linear gain value, as predicted by Piranah (relevant SRS for $G > 20$).

5. Attempt to manage the light bandwidth within H$\alpha$

Carrying out $H\alpha$ computation of SRS within the former calculated plasma, leads to consequent problems coming from the density inhomogeneity and thus the backscattered light bandwidth. To attempt to overcome these problems, we replaced the initially quasi-monochromatic modeling by a new one, in which both the wavenumbers and the wave frequencies may depend on the point of space. The envelope for one wave $\ell$ is then defined as: $A_\ell = A_\ell\exp\left(\pm i\int_{-\infty}^{z} k_\ell(z')dz' - i\omega_\ell(z)t \right) + c.c.$, and the propagation equation becomes:

$$
\partial_t A_\ell + v_{g,\ell} \partial_z A_\ell - v_{g,\ell} \frac{\omega'_\ell t}{k_\ell} \partial_z A_\ell + \frac{i v_{g,\ell}}{2k_\ell} \left[ \left( 1 - \frac{t}{k_\ell \omega'_\ell} \right)^2 - 1 \right] A_\ell + \frac{v_{g,\ell}}{2k_\ell} \left( k'_\ell - \omega'_\ell t \right) A_\ell + i \delta_\ell A_\ell + \nu_\ell A_\ell + \frac{1}{2} \left( \partial_z v_{g,\ell} \right) A_\ell = [NL] \text{ coupling term.}
$$

Figure 2. Hydrodynamic simulation of a LPI-devoted experiment on the LIL facility. Upper left is the experiment scheme, upper right the time evolution of the laser power and the mean plasma temperatures. Lower left is the plasma density profile after 4.1 ns. Lower right is the SRS linear gain at the same instant, as predicted by Piranah (relevant SRS for $G > 20$).
Let us notice that this model differs from [4] by the fact that $\omega$ is not constant. As the light propagates its frequency becomes thus off-resonant. We then introduced an additive absorption term $\eta$ to progressively remove this off-resonant light from the (coherent) envelope modeling. Removed light is then considered as incoherent and modeled in that way. We checked that the simulation results are weakly sensitive on the $\eta$ value.

6. 1D $H\rho\alpha$ SRS computation of LIL experiment

We then used model of section 5 to carry out a SRS simulation from plasma computed in section 4 (hydrodynamics is frozen during this simulation). Figure 3 presents the results in term

![Figure 3. 1D SRS $H\rho\alpha$ simulation within plasma of figure 2. On the left, reflectivity vs time. On the right, time-resolved spectrum of the backscattered light.](image)

of reflectivity and spectrum. Bursts on reflectivity as well as variation of the backscattered light wavelength can be related to SRS saturation by pump depletion. Note that this simulation does not take into account the $k_{Lm}\lambda_{De} < 0.53$ limitation. Dealing with it would slightly change the burst periodicity as well as the reflected light bandwidth.

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