Laser plasma interaction studies in the context of shock ignition

O. Klimo, J. Limpouch
Czech Technical University in Prague, FNSPE, Czech Republic

V. T. Tikhonchuk, M. Lafon, X. Ribeyre, G. Schurtz, S. Weber
CELIA, University Bordeaux 1-CEA-CNRS, France

C. Riconda
LULI, CNRS-CEA-Ecole Polytechnique-Universite Paris 6, France

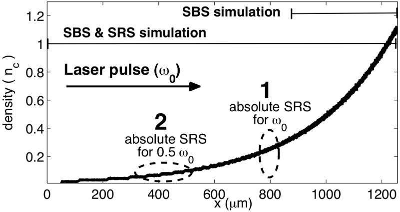
A. Casner
CEA/CESTA, Le Barp, France

International Workshop on ICF Shock Ignition, March, 2011

Laser-plasma interaction and shock-ignition in full scale ICF

- high intensity $I_0\lambda^2 = 10^{15-16}\ \mathrm{W}\mu\mathrm{m}^2/\mathrm{cm}^2$ → strongly nonlinear regime
- high plasma temperatures $3 - 5\ \mathrm{keV}$ → suppression of SRS
- greater role of SBS expected, although regime of inflationary SRS predicted

UNEXPECTED FINDINGS ! [PPCF **52** 055013 (2010)]



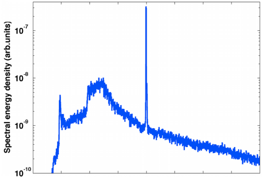
- ○ after initial phase SRS dominates
- ○ SBS is suppressed by absolute SRS at $n_c/4$ and subsequent cascade at $n_c/16$
- ○ all laser absorption is by collective effects
- ○ cavitation is a dominant mechanism for laser-plasma interaction in SI

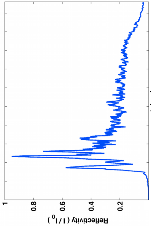
- Original analysis done in 1D for HiPER relevant parameters.
- Extended to 2D and scaled to parameters of OMEGA experiments.

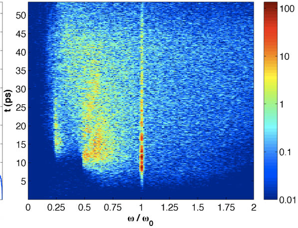
Temporal evolution of SBS and SRS, reflectivity

- SBS comes up first due to strong Landau damping of SRS
- SRS excited at resonance point $n_c/4$ (as absolute instability) and producing $\omega_0/2$ backscattered light
- Convective SRS below $n_c/4$ is probably responsible for the signal $0.5 - 0.7\omega_0$
- SRS excited at resonance point $n_c/16$ producing $\omega_0/4$ forward-scattered light (down the density gradient)
- Raman cascade could continue if scattered light overcomes threshold condition $(k_0 L_n)^{4/3}\ (v_{osc}/c)^2 > 1$
- Density perturbations & pump depletion saturate SBS

Reflected light - spectrum vs. time

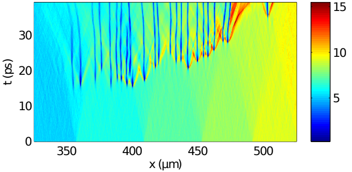




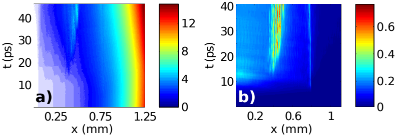


Cavitation, laser absorption and energy transport

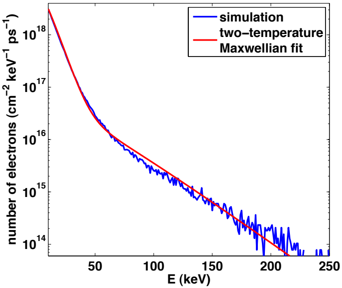
Ion density near 1/16th n_c - temp. evol.



Kinetic & EM field energy density



Distribution of elns. moving into target

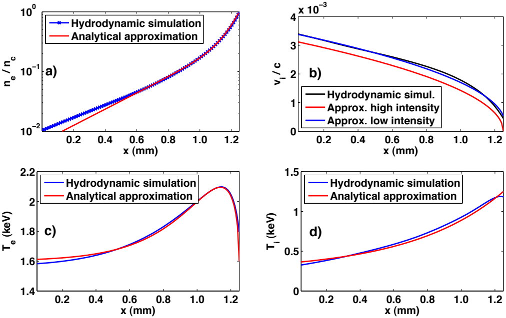


$T_{hot} \approx 30$ keV

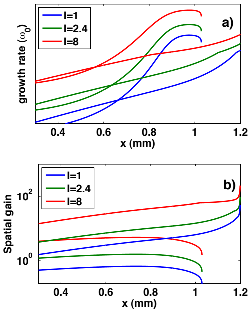
- Absolute instability grows locally in time - pond. force expels electrons - ions undergo Coulomb explosion - cavitation - trapped em. field in cavity
- Cavitation at $n_c/4$ and $n_c/16$ converts em. field energy into kinetic energy
- **Absorption due to collective effects, rather than iB at high intensities**

OMEGA relevant simulations

Hydrodynamic profiles as initial conditions for PIC



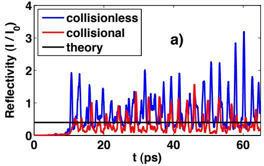
Growth rate & linear gain



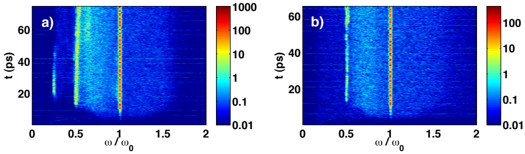
- Initial conditions taken from hydro. simulations, other parameters: $I = 1, 2.4, 8 \times 10^{15}$ W/cm^2, $\lambda = 0.35$ μm, with and without Coulomb collisions
- SRS gain low but growth rate below $n_c/4$ high - ¿absolute instability?
- SBS (high gain close to n_c) may dominate unless limited by e.g. cavities or pump depletion

Low intensity (10^{15} W/cm^2) - collisional vs. collisionless absorption

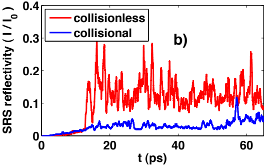
Total reflectivity



Spectra of the reflected light



SRS reflectivity

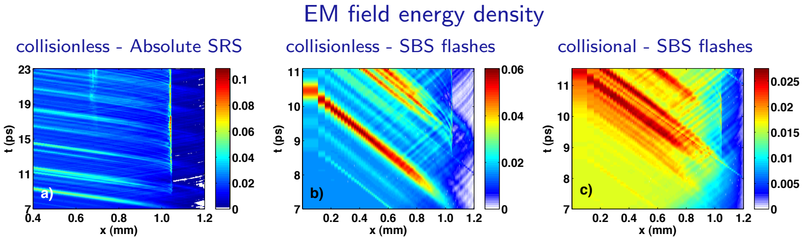


- The LPI regime changes at lower intensities.
- Collisional absorption important - strong reduction of the reflectivity from 70% to less than 40%.
- Absoprtion corresponding to the theoretical one

$$\alpha_{abs} = 1-\exp\left(-\int \frac{\nu_{ei}(n_c)}{c}\left(\frac{n_e}{n_c}\right)^2\left(1-\frac{n_e}{n_c}\right)^{-1/2}\mathrm{dx}\right)$$

- SBS dominates, SRS plays secondary role ($< 5\%$ in the collisional case).
- SRS strongest at quarter critical density corresponding to absolute instability.
- Raman cascade only in the collisionless case - close to the threshold.

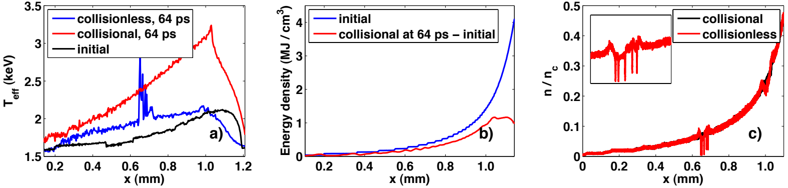
Absolute SRS and convective amplification of SBS



- Local increase of EM field confirms absolute SRS in the collisionless case
- Absolute SRS is weaker in the collisional case due to efficient damping
- SBS is seeded in denser plasma ($n \gtrsim n_c/4$) deeper in the target (1.1 mm)
- Convective amplification during about the first 0.3 mm of propagation
- Collisionless case - SBS takes all the pump energy - depletion & pulsation
- Collisional case - SBS weaker due to collisional damping of the incident and the scattered light wave (comparable with SBS growth rate)
- Collisional case - SBS amplification zone shifts in a less dense plasma

Where does absorption take place

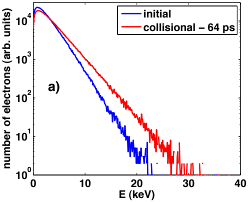
Effective temperature — Kinetic energy dens. increase — Cavitation - ion density



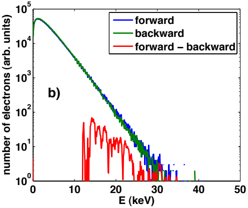
- Electrons along the whole profile are significantly heated in the collisional simulation with sharp maximum close to $n_c/4$.
- Mild increase in the effective electron temperature in the low density plasma with sharp maximum at 0.7 mm in the collisionless case - cavities.
- Initial energy density of plasma, $W_0 = 3/2 n_0 T_0$ and its increase at time 64 ps $(W(t) - W_0)$ - significant absorption, which peaks in a higher density plasma.
- Cavities develop only in the collisionless simulation, where absolute SRS is enough strong.

Where does the absorbed energy go - collisional case

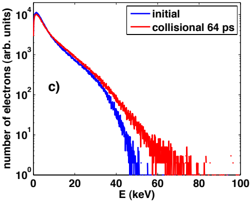
Electron energy dist. inst.



Elns. into the target from $n_c/4$



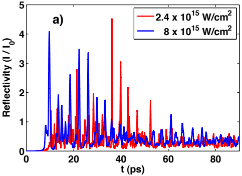
Ion energy dist. inst.



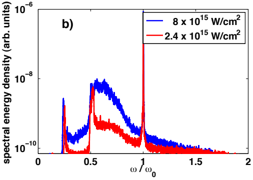
- Absorption in the collisional case is 66% (28% collisionless case).
- The energy distribution of bulk electrons at 64 ps shows temperature increase from 2 to 2.5 keV - this contains about 60% of the absorbed energy.
- Higher energy electrons (20 keV) may quickly leave the box - not observed in the instantaneous distribution. Their flux recorded $40\ \mu\mathrm{m}$ behind $n_c/4$ - contains about 20% of the absorbed energy.
- About 20% of the absorbed energy is used for plasma expansion and ion acceleration $\int_0^L \partial_t(n_i m_i v^2)/2\ \mathrm{d}x \approx \int_0^L v\partial_x P_e \mathrm{d}x$

Transition to collisionless absorption (collisional simulations)

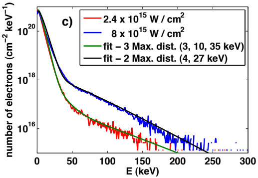
Reflectivity



Spectrum of reflected light



Elns. going into the target

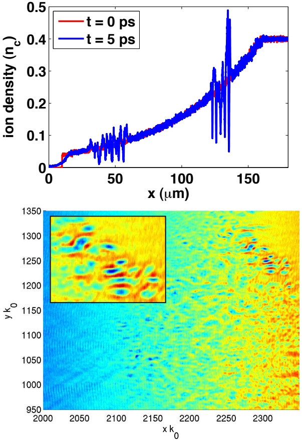


- After transient stage, reflectivity saturates 38, 36% - almost independent of I.
- Spectra of temp. integrated light similar like for $10^{15}\ \mathrm{W/cm^2}$ - same physics but different repartition between the collisional and collisionless processes.
- At highest intensity, even convective SRS below $n_c/4$ is significant.
- Collisional absorption leads to heating of thermal electrons from 2.5 keV at the lowest intensity to 3 keV and to 4 keV for higher intensities.
- With increasing laser intensity - 70% and 93% of absorbed energy is contained in hot electrons.
- Hot electron temperature does not strongly depend on I - $20 - 40$ keV

2D reduced simulations - cavities

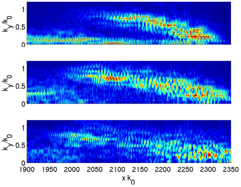
- CPU-time limitations require reduced set-up (shorter L_n, higher I & SRS part of profile)
- 2D simulation set-up:
  - plasma: $160\ \mu\mathrm{m} \times 103\ \mu\mathrm{m}$; $T_e = 5\ \mathrm{keV}$, $T_i = 2\ \mathrm{keV}$; exp. profile scale length $L_n \approx 60\ \mu\mathrm{m}$
  - laser: $I_0\lambda_0^2 = 5 \times 10^{15}\ \mathrm{W}\mu\mathrm{m}^2/\mathrm{cm}^2$
  - time $\approx 5\ \mathrm{ps}$, plane wave versus full-speckle
- Cavity creation and disappearance is a continuous process in the vicinity of $n_c/4$, cavities are not stable like in 1D.
- Disruption of plasma homogeneity on small scale prevents SBS activity, where cavities are.
- The simulations are too short to reach quasi-stationary state and predict the result of competition SRS vs. SBS.

Ion density

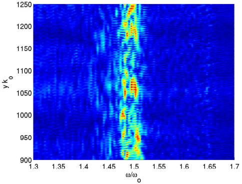


SRS and 2-plasmon decay

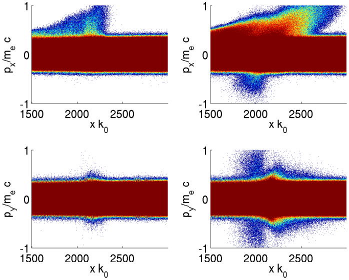
Spectrum of ES field



Spectrum transmit. light



Electron phase space



- Clear observation of 2PD
- SRS sidescattering with small angle
- Electron heating due to:
  - bursts of SRS - forward direction
  - cavities localized around $n_c/4$ - isotropic heating not too hot
  - two plasmon decay - only transient and lasts short times
- At $n_c/4$ SRS wins because 2PD has somewhat lower growth rate.
- 2D studies done so far do not contradict 1D results :
  electron heating (not "too" hot, $T_{hot} \approx 30 - 50\ \mathrm{keV}$) in low density ramp & "long time" saturation of backscattering instabilities.

Comparison with experimental findings

- **General agreement with experiments in:**
  - Appearance of hot electrons at the intensity $1 - 2.4 \times 10^{15}\ \mathrm{W/cm^2}$
  - Time integrated reflectivity of less than 35%
  - SRS reflectivity at lower intensity $10^{15}\ \mathrm{W/cm^2}$ is less than 5%
  - Hot electrons are "not too hot", $T_{hot} \approx 20 - 40\ \mathrm{keV}$
- **What can be measured to confirm or refute our findings:**
  - The spectrum of reflected light around the wavelength $0.7\ \mu\mathrm{m}$ may provide important indication on absolute Raman scattering.
  - Measurement of strong EM fields (via X-ray line from some higher Z tracer) may give indications about the presence of absolute instabilities and the cavitation process.
  - Reflectivity measurements with temporal resolution ($\approx 100\ \mathrm{ps}$) may give indications about the transient stage with large reflectivity and the subsequent quasi-steady stage with large absorption, which is observed at higher intensities.
  - Importance of high electron temperature: progressive shift of the SRS spectrum toward $\omega_0/2$

Summary & Conclusions

- **1D kinetic laser plasma interaction studies predict up to 70% absorption of the spike almost independent of intensity.**
- **High intensities**
  - Suppression of the SBS by strong SRS accompanied by cavitation.
  - Absorption goes into hot electrons with temperature of about 30 keV
- **Low intensities**
  - Suppression of the SBS by collisions.
  - Efficient collisional heating of electrons.
- **2D simulations**
  - Confirm cavitation around $n_c/4$.
  - Early saturation of two plasmon decay due density disruption by cavities.
  - Collisionless absorption by two plasmon decay, SRS and cavities - similar electron temperature like in 1D.
  - The most weak part is the short simulation time, we cannot be sure that the asymptotic regime is attained.