Laser interaction with a coronal plasma in the conditions relevant to shock ignition

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Shock ignition in a nutshell

Conventional drive:
- does double duty
  - compress
  - ignite

Low velocity drive:
- safer implosion
- higher fuel mass
- higher gain

Time

Laser Power

Ignition of the fuel from a converging shock launched from a short intense laser pulse

Requires ~200 TW spike to launch the ignitor shock

The physics of laser plasma interaction is not understood and controlled
Laser plasma interaction physics in Omega experiments

Spike irradiation

Omega experiments under the conditions relevant to shock ignition

Power per beam

W. Theobald 2009
X. Ribeyre 2011
Interaction conditions are defined by hydro simulations

The plasma corona is hot and it extends over a mm scale

Electron density

2D

1D

Electron temperature

2D

1D

Velocity

10^{-3}

2D

1D

Ion temperature

W
Parametric instabilities in the corona: SBS, FI, SRS, TPD

Parametric instabilities decrease the coupling efficiency but we have to learn how to live with

SBS and filamentation operate at \( n_e < n_c \)

SBS – convective amplification of the backscattered signal \( \omega_s = \omega_0 - 2k_0cs \)

Laser beam filamentation leads to focalization and spreading

SRS operates at \( n_e < \frac{1}{4} n_c \)

convective amplification of the backscattered signal \( \omega_s = \omega_0 - \omega_p \) and production of hot electrons

1/4 \( n_c \) – a dangerous zone of coexistence of absolute instabilities SRS and the two plasmon decay

\( \omega_0 \rightarrow 2\omega_p \) hot electron generation

Emerging subject: energy exchange in the crossing beams
SBS and SRS gains for intensities $\times 10^{15} \text{ W/cm}^2$ for $3\omega$

Convective instabilities: stationary spatial gain $R = R_{th} \exp (1-R)G$

Although the gains are relatively low, the instability may be excited either in hot spots (speckles) or due to the kinetic effects (particle trapping)

Pulse amplification goes well above the stationary level
SBS: generation of giant reflected pulses

Danger of SBS in periodic generation of intense pulses that are amplified on their way down the density profile

1D×3V simulation: $10^{15}$ W/cm$^2$

A.Andreev et al PoP 2006
O.Klimo et al PPCF 2011
**SBS: laser energy absorption in density cavities**

Energy absorption starts in the cavities created by the backscattered pulse at higher laser intensities $I\lambda^2 = 10^{16} \text{ W/cm}^2$

1D×3V simulation: cavity assisted laser absorption

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**Diagram**

- **Laser**
- **Density**
- **Reflectivity**

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S. Weber et al PRL & PoP 2005

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SBS: density cavities & electron acceleration

Laser energy absorption in the cavities results in electron and ion heating and acceleration to 100 keV. 2Dx3V simulations in a homogeneous plasma layer.

Electron density

Electrons

Ions

Electron phase space

Ion density

Laser

S. Weber et al. PRL & PoP 2005
Forward SBS and plasma smoothing effect

Multispeckle laser beam experiences angular and frequency spreading in plasma. This effect is due to the speckle instability and the forward SBS

Criterion for the laser beam smoothing is defined by the average speckle power

\[ C = \sqrt{\frac{\pi}{2}} \frac{\gamma_T}{\nu_{I\!A\!W}} \frac{\langle P \rangle / P_c}{\omega_{I\!A\!W}} \]

This effect is observed in a foam produced plasma

S. Depieurreux et al PRL 2009

M. Grech et al PRL 2009
TPD & SRS instabilities near the quarter critical density

Two plasmon decay instability is excited near $1/4$ $n_c$, it develops as an absolute instability as slow plasma waves do not escape the resonance

\[ k_{1y} = -k_{2y} = k_y, \quad k_{1,2x} = \frac{1}{2}k_0 \pm \Delta k, \quad \text{and} \quad \Delta k^2 = \frac{1}{4}k_0^2 + k_y^2. \]

\[ k_0 \]

\[ k_1 \]

\[ k_2 \]

A.Simon et al PF 1983

TPD be easily excited above $3-5 \times 10^{14}$ W/cm$^2$

S.P.Regan et al PoP 2010

Omega experiments are confirming the TPD excitation threshold, but they also show a competition with SRS
SRS – TPD competition → hybrid instability HFHI

SRS and TPD are in competition as their thresholds are comparable

B. Afeyan & E. Williams
PRL 1995 & PoP 1997

Angular dependence of the high field hybrid instability (HFHI) growth rate

Recent 2D simulations in the zone near 1/4 nc show rather fast excitation of the SRS and TPD instabilities associated with the hot electron generation

R. Yan et al PRL 2012
Destabilization of the SRS in the hot spots

SRS in a low density plasma can be destabilized due to presence of the laser speckles and the electron trapping – inflationary regime

\[
\frac{n_e}{n_c} = 0.12 \\
T_e = 2.6 \text{ keV} \\
F/8 \text{ speckles}
\]

Linear theory predicts higher onset intensity than the multi-speckle simulations and experiments – strong speckles destabilize the weaker ones

L. Yin et al PoP 2009 & 2012
SBS – SRS interaction in inhomogeneous plasma

Numerical simulations in an inhomogeneous plasma at \(10^{16}\) W/cm\(^2\): SBS is suppressed by SRS

**short profile: SBS dominated**

\(L = 3000\) laser wavelengths
\(T_e = 5\) keV

**long profile: SRS dominated \(\rightarrow\) better absorption**

Time integrated spectrum for the short and long density profiles

Time-resolved spectrum of reflected light – long profile

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O.Klimo et al PPCF2010
Energy absorption starts in the quarter critical density where SRS develops as an absolute parametric instability. Nonlinear saturation is accompanied by cavity development.

Backscattered electromagnetic wave produces secondary absolute SRS in the 1/16 of the critical density where multiple cavities are produced.

Major absorption takes place between 1/4 and 1/16 of $n_c$ and produces hot electrons.

$T_c = 6$ kev
$T_H = 29$ kev
Energy flux transported by fast electrons

Energy balance between the forward and backward fluxes agrees with the absorbed energy: $n_{\text{hot}} \approx 0.022 \ n_c$

Kinetic simulations demonstrate feasibility of the shock ignition scenario
Nonlinear effects dominate the absorption and the hot electrons are supposed to transport energy to the ablation zone
Fast electron stopping length

The stopping length of 30 keV electrons is smaller than the shell thickness at the time when the shock is launched.

Fast electrons may provide a better hydrodynamic efficiency for the shock.
Transition from collisional to collisionless absorption

The quality of absorption changes in the intensity range \(10^{15} \text{ – } 10^{16} \text{ W/cm}^2\)

Reflectivity saturates at the level 36 – 38\% independently on the laser intensity

The number of energetic electron increases while their temperature remains at the same level of 30 keV

Hot electrons transport up to 90\% of the absorbed energy

The spectral lines in the backscattered light at \(1/2 \omega_0\) and \(1/4 \omega_0\) indicate the increasing role of the cavitation process

O.Klimo et al PoP2011
2D simulations of LPI in inhomogeneous plasmas

Issues for 2D:
1. Is absorption affected?
2. How does electron DF change?
3. Role of 2D-effects: filamentation, self-focusing & 2PD
4. Inflationary SRS?

2D simulation set-up

- Plasma: $160 \, \mu m \times 103 \, \mu m$; $T_e = 5 \, keV$, $T_i = 1 \, keV$; exp. profile scale length $L_n = 186 \lambda_o \approx 60 \, \mu m$
- Laser: $I_0 \lambda_o^2 = 1.2 - 4.9 \times 10^{15} \, W/\mu m^2/cm^2 \quad @ \quad 3\omega$
- Simulation time: $\approx 2.5 \times 10^4 \omega_o^{-1} \Rightarrow \approx 5 \, ps$
- Full-speckle (FWHM $\approx 29 \, \mu m$)

2D full scale one speckle collisionless simulation requires 320,000 h CPU time on 600 proc.
Total reflectivity in 2D simulations

Instability develops in the time scale of 0.2 – 0.3 ps
Reflection increases strongly with the laser intensity
Large reflectivity bursts – filamentation
Very low transmission
SBS – SRS competition in 2D simulations

central point of speckle, $I\lambda_0^2 = 4.9 \times 10^{15}$ W μm²/cm²

- contribution to reflectivity from SBS ($0.9 - 1.1 \omega_o^{-1}$) and SRS ($0.0 - 0.9 \omega_o^{-1}$)
- SRS activity strong initially and reappears later on in a different location (more later)
- compared to 1D spectrum much broader (2PD ?!)
- spectra of center and wings differ considerably

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Inflationary SRS development: single event

Each SRS pulse contains a broad frequency spectrum
Larger the scattered frequency – broader the pulse (coupling to strongly damped modes)
Low density plasma dominates the response

C.Riconda et al PoP2011
Electron distribution function induced by the SRS

SRS reflectivity is associated with the hot electron generation
Electrons generated from the zone $1/4nc$ are more energetic

Electron distribution function averaged over the speckle cross section time interval from 0 to 2 ps

Electron distribution function at $t = 0$ and at the time instant of 0.9 ps
Two-plasmon decay instability excitation

- Transmitted light
- Electrostatic waves
- Momentum matching for the TPD
- Harmonic 3/2 generation due to the TPD

- 2PD driven far above absolute threshold, $I_{14}\lambda_0^2 > 51 \frac{T_e [keV]}{(L/\lambda_0)}$,
  $\Rightarrow$ rapid nonlinear saturation as shown for $3/2\omega_0$-signature in transmitted light (turbulent structure, cascading?)
- No hot electrons and limited in time
- Negligible energy contribution
TPD and SRS competition

Spectra of electric fields provide information about the TPD – SRS competition

TPD and SRS are excited almost at the same time
The instability zone is shrunk and the wave activity is reduced due to the cavity formation
No signatures of TPD after 1.5 ps
Cavitation scenario in 2D simulations

The plasma cavitation in the quarter critical density is enhanced due to TPD activity.

Beating of plasma waves excited by TPD creates quasistationary density modulations that are transforming later in cavities.
Cavitation scenario in 2D simulations

The plasma cavities have much smaller size than the laser speckle. They are quenching the SRS and TPD in the region near 1/4 nc.

There is no profile steepening as it was supposed in smaller size simulations.

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Electron heating due to the SRS and TPD

The SRS and TPD create the electrons with different energy distributions

Asymmetric evolution of the electron distribution function

A : SRS and 2PD
B : 2PD
C : 2PD
D : 2PD & cavitation
Large scale filamentation of the laser beam

Poynting vector shows three distinct zones

Low density zone $n_e < 1/4 \, n_c$ – large scale filamentation

Near quarter critical zone – cavitaiton

High density zone $n_e > 1/4 \, n_c$ – small scale filamentation and beam spreading

Later time the SBS activity moves down over the density profile
Conclusions

Laser plasma interaction studies predict 70% absorption of the spike:

- high intensities/high temperatures: suppression of the SBS by a strong SRS, cavitation absorption, hot electrons at 30 keV
- low intensities collisional suppression of the SBS, efficient electron heating
- 2D simulations show early saturation of the two plasmon decay, SBS-SRS competition