Kinetic simulations of intense light pulses generated by Brillouin backscattering in laser-plasma interaction

C. Riconda
LULI, Université Pierre et Marie Curie,
Paris, FRANCE
Collaborations

J.-R. Marquès, M. Chiaramello, A. Castan
A. Chatelain, T. Gangolf, J. Fuchs

Sapienza University of Rome

M. Quinn, G. Mourou

GSI

S. Weber
High-intensity laser in time and space

- since invention of laser: constant push towards increasing focused intensity of the light pulses

UHI light infrastructures in the world from ICUIL 2011
The problem of damage threshold for optical materials

Laser-induced damage of optical coatings

Chirped pulse amplification
D. Strickland, G. Mourou, Optics Comm. 55, 219 (1985)

⇒ ionisation intensity-limit: $I \leq 10^{12} \text{ W/cm}^2$
⇒ damage threshold of gratings: $\leq 1 \text{ J/cm}^2$
⇒ $1 \text{ EW} \& 10 \text{ fs} \rightarrow 10 \text{ kJ}$
⇒ surface areas of order $10^4 \text{ cm}^2 = 1\text{m} \times 1\text{m}$
⇒ difficult to produce and very expensive

PLASMA OPTICS

BUT : Laser Propagation in a Plasma?
Natural modes in a non-magnetized plasma

Electromagnetic wave (EMW)

$$\omega^2 = \omega_p^2 + k^2 c^2 \rightarrow \text{limiting frequency } \omega = \omega_p$$

plasma behaves as ‘transparent’ dielectric

Electron plasma wave (Langmuir wave, EPW)

$$\omega_{epw}^2 \approx \omega_p^2 + 3 k_{epw}^2 v_{Te}^2 \approx \omega_p^2 (1 + 3 k_{epw}^2 \lambda_D^2)$$

Ion-acoustic wave (IAW)

$$\omega_{iaw} \approx c_s k_{iaw}$$
$$\omega_p = (4\pi n_e e^2/m_e)^{1/2} ; \ v_e = (k_B T_e/m_e)^{1/2} ;$$
$$\lambda_D = v_e/\omega_p ; \ c_s = (k_B T_e/m_i)^{1/2}$$

⇒ „Un“-natural modes are of great interest (see later)!
Wave coupling in a plasma

Waves in a plasma can couple:

*intensity of one or two waves can grow in an uncontrolled way at the expense of the intensity of another wave if a resonance condition is fulfilled:*

\[
\omega_0 = \omega_1 + \omega_2 \quad \text{(energy)}
\]

\[
k_0 = k_1 + k_2 \quad \text{(momentum)}
\]

⇒ 3-wave coupling due to conservation of energy and momentum

A classic exemple of Laser-Plasma Interaction (LPI): Parametric Instabilities (PI), energy transfer among waves
Parametric Instability growth: from noise to coherent motion

Laser into plasma

Plasma oscillations radiate scattered light

Beating of 2 em. Waves → ponderomotive force → particles into troughs

Bunching matches electrostatic mode → 3 waves resonant → growth of instability

How to control it?
The basic principle of plasma amplification

"NO" damage threshold in plasmas

- high-energy long pump
- low-intensity short seed

Standard parametric instabilities:
3 wave coupling where the plasma response is taken up by
- electron plasma wave $\rightarrow$ Raman
- ion-acoustic wave $\rightarrow$ Brillouin

Conservation equations:
- $\omega_{\text{pump}} = \omega_{\text{seed}} + \omega_{\text{plasma}}$
- $k_{\text{pump}} = k_{\text{seed}} + k_{\text{plasma}}$

Time scales:
- Brillouin $\tau_s \geq \omega_{cs}^{-1} \sim 1 - 10$ ps
- Raman $\tau_s \geq \omega_{pe}^{-1} \sim 5 - 10$ fs

Raman allows higher intensity since contraction to shorter scales
Brillouin in the strong-coupling regime (sc-SBS)

- in contrast to before: sc-SBS is a non-resonant mode (not an eigen-mode)

When the laser intensity is above a threshold that depends on the plasma temperature, transition from eigen-mode regime $\rightarrow$ quasi-mode regime characterized by:

$$\omega_{sc} = (1 + i \sqrt{3}) 3.6 \times 10^{-2} (I_{14} \lambda_0^2)^{1/3} (Zm_e/m_i)^{1/3} (n_e/n_c)^{1/3}$$

i.e. pump wave (laser) determines the properties of the electrostatic wave!

- instability growth rate: $\gamma_{sc} = \text{Im}(\omega_{sc})$

- New characteristic time scale for IAW: $\sim 1/\gamma_{sc}$ $\rightarrow$ can be a few 10s of fs!!

- More compression = higher intensity, and some advantages with respect to Raman
Particle-in-cell approach

Idea: initial condition is a large number of particles with a given temperature distribution - they then evolve according to the following equations (Maxwell + Newton)

**Electromagnetic field**

\[
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0
\]

\[
\nabla \times \mathbf{B} - (1/c^2) \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}
\]

\[
\nabla \cdot \mathbf{E} = \rho/\varepsilon_0
\]

\[
\nabla \cdot \mathbf{B} = 0
\]

**Characteristics of Vlasov-eqn.**

\[
\frac{dx_p}{dt} = u_p/\gamma_p
\]

\[
\frac{du_p}{dt} = q_p (\mathbf{E}_p + u_p \times \mathbf{B}_p/\gamma_p)
\]

\[
\gamma_p = (1 + p^2/(mc)^2)^{1/2}
\]

**Constituent relations for each cell**

\[
\rho = \Sigma q_p
\]

\[
\mathbf{J} = \Sigma q_p \frac{u_p}{\gamma_p}
\]

**Reality versus simulation**

\[
L \gg \lambda_D, \quad N_D = O(10^2...10^6)
\]

⇒ millions of billions of particle impossible!

BUT: simulation same for 10 and 10.000 since collective motion, particles ‘enslaved’
Computational aspects: laser propagation in a density ramp

→ Need to resolve: $1/\omega_{pe}$, $1/\omega_o$ & $1/k_o$

→ Particular case: $\Delta x = \Delta y = 0.18 \ k_o^{-1}$
  and $\Delta t = 0.18 \ \omega_o^{-1}$ ; CFL: $c \ \Delta x \leq \Delta t$

→ $2.4 \times 10^8$ computational cells
→ $1.4 \times 10^5$ time steps
→ $10^8...9$ macro-particles
  (a small fraction of real number!)

→ Order of 500‘000 CPU-hours !! (~1 month running on 600 cores-57 yrs on 1 core)

→ Producing hundreds of GB data

→ Multidimensional kinetic equations require VERY BIG computers !!!
Competing instabilities

- amplification process has to be optimised in concurrence with other plasma instabilities!

1) avoid filamentation for pump and seed: \( \tau_{p,s}/(1/\gamma_{fil}) < 1 \) with \( \gamma_{fil}/\omega_o \approx 10^{-5} l_{14} \lambda^2 [\mu m] (n_e/n_c) \)

\( \tau_{pump} = O(10ps) \) too long for the given density

\( \tau_{pump} = 300 \text{ fs} \) ok for instability

But not much energy transfert
Competing instabilities cont’d

2) avoid SRS if possible: \( \tau_p/(1/\gamma_{srs}) < 1 \) with \( \gamma_{srs}/\omega_o \approx 4.3 \times 10^{-3} \sqrt{(l_{14} \lambda^2[\mu m]) (ne/nc)^{1/4}} \)

\[ \Rightarrow 1/\gamma_{srs} \approx 25 \text{ fs} \]

BUT can be controlled by plasma profile and temperature, associated energy losses small

\[ \Rightarrow \text{Other limit related to efficiency of energy transfer: } (1/\gamma_{sc}) \sim \tau_{wb} \Rightarrow a_{\text{max}} = v_{osc}/c \approx \sqrt{(m_i/Zm_e)} \ (n_e/n_c) \]

\[ \Rightarrow \text{for } n_e = 0.05 \ n_c \text{ get } I_{\text{max}} \approx 10^{18} \text{ W/cm}^2 \]

- high density \( \Rightarrow \) filamentation
- low density \( \Rightarrow \) weak coupling
- short pulse \( \Rightarrow \) low efficiency
- long pulse \( \Rightarrow \) wavebreaking

\[ \Rightarrow \] From these considerations one obtains a parameter space of operation

\[ \Rightarrow \] Optimization is required wrt

\[ \Rightarrow \] to plasma profile, seed duration, pump intensities
1D sc-SBS plasma amplification simulations

Density profile motivated by gas-jet experiments
2D sc-SBS plasma amplification results

- pump depletion obtained w/o problem (210 fs seed)
- close to actual experimental regime
A first proof-of-principle experiment @ LULI 100 TW

$E_p = 2 \, J, \quad I_p = 6.5 \times 10^{16} \, W/cm^2$

$\tau_p = 3.5 \, ps$

$E_s = 15 \, mJ, \quad I_s = 5 \times 10^{15} \, W/cm^2$

$\tau_s = 400 \, fs$

- Pump & seed cross under angle interaction length: $\approx 100 \, \mu m$
- Energy uptake of seed 45 mJ
- Relative amplification factor of 35 ($I_s/I_{s0}$) achieved
- Pump depletion achieved! (100% on trajectory)
- Crossed polarization $\Rightarrow$ NO amplification

$\Rightarrow$ L. Lancia et al. PRL (2010)
**Experimental set-up**

**IONIZATION BEAM**

- 15 mJ
- 400 fs
- $\lambda_0 = 1057$ nm
- $5-8 \times 10^{15}$ W/cm$^2$

**SEED BEAM**

- $\sim 20^\circ$
- 1 mm

**PUMP BEAM**

- 4-5 J
- 3.5 ps
- $\lambda_0 = 1057$ nm
- $2-6 \times 10^{16}$ W/cm$^2$

**Limitations:**
- Inhomogeneous plasma $\rightarrow$ refraction
- Limited overlapping region
- Relative amplification

**Novelties:**
- Counter-propagating setup to exploit whole plasma length
- More homogeneous plasma ionization
- Very low seed intensity!

**Path for improvements:**
- Plasma quality and characteristics
- More energy available for transfer
Recent experiment @ LULI 100 TW

4 - 8 mJ
700 fs
~3 x 10^{13} W/cm^2

6 - 8 J
2 - 4 ps
~ 10^{15} W/cm^2

45 J
0.5 ns
3 x 10^{12} W/cm^2

SEED beam IN

PUMP beam IN

IONIZATION beam

GAS JET

AMPLIFIED SEED beam OUT

probe for interferometry and filamentation monitoring

- calorimetry
- spectrometry
- autocorrelation
Absolute amplification obtained

Spectral amplification for different delays

- A narrow range of frequencies favoured,
- More efficient amplification corresponds to a wider range

Spectrally resolved signal of the amplified seed for different delays

- The more efficient amplification is the more spectrum is shifted to lower frequencies
• **80 fs** seed pulse at $10^{17}$ W/cm$^2$ is amplified down a plasma ramp
• high energy extraction efficiency of 53%, final intensity $\sim 4 \times 10^{17}$W/cm$^2$
• ramp profile: reduces thermal SRS on pump, but SBS coupling robust
• pump & seed meet at high-density edge of ramp where coupling is strong from beginning
• such profiles can be easily generated from gas jets
• increase final intensity by optimizing plasma profile

2D plasma based amplification: ‘large’ transverse spot

Simulations of Raman and strong coupling Brillouin have shown the possibility of amplifying wide spots to relativistic intensities.

$I \sim 10^{17}-10^{18} \text{ W/cm}^2$

10 µm
-1 mm

R. M. G. M. Trines et al. PRL 107, 105002 (2011)
Plasma focusing mirror – plasma lens

- The amplified pulse needs to be focused somehow

- plasma lens based on relativistic self-focusing: another controlled instability usage
Plasma amplification: a long-term perspective

The future of UHI light pulse generation ?!
Conclusions and work in progress

- **sc-SBS (regime of today experiments)** very robust
- As seed pulse shortens, and intensity grows, transition to mixed SBS/SRS regime → needs further study
- **Possibility of amplifying large spots**
- What is the best strategy to focus the amplified seed?
Comparison SBS-mixed mode/SRS: wavefront

Deformation of the wavefront for SRS-amplification
Transverse size and wavefront (seed 80 fs)

TRANSVERSE SIZE SLIGHTLY REDUCED (2/3), PHASE FRONT PRESERVED
COUPLING WITH PLASMA MIRROR WOULD ALLOW FOCUSING AND
FURTHER INTENSITY ENHANCEMENT
Transverse size and wavefront (seed 30 fs)

$I_p = 10^{16}$

Short seed: the center tends to be amplified.

$I_p = 5 \times 10^{15}$

↓ pump strength to preserve size and wavefront, but ↓ amplification
Comparison of mixed mode/SRS amplification (downshifted seed)

- SRS amplification starts earlier, but saturates earlier as well!
- Mixed mode starts more slowly but then grows to much larger amplitude
- Upshifted signal does not grow.

\[
\begin{align*}
\omega_1 &= \omega_0 \text{ Mixed mode} \\
\omega_1 &= 0.8 \omega_0 \text{ SRS} \\
\omega_1 &= 1.2 \omega_0 \\
\tau_s &= 13 \text{ fs} \\
\text{Plateau, no ramps}
\end{align*}
\]
1D sc-SBS plasma amplification simulations

Density profile motivated by gas-jet experiments