INERTIAL CONFINEMENT PROGRAMME
INTRODUCTION

In the context of inertial confinement fusion (ICF) by lasers, “laser fusion”, the control of instabilities occurring during the interaction between the laser beams with the underdense plasmas corona is of crucial importance for the coupling efficiency. Parametric instabilities which arise due to the coupling between the laser light waves and plasma waves can lead to considerable losses due to light scattering and fast electron generation which avoid an efficient thermal coupling in the vicinity of the critical density. Most recently, under fusion-relevant conditions, losses originating from parametric scattering instabilities of the order of 30% and higher, reducing eventually the radiation temperature in indirect drive targets, have been measured [1], [2]. These measurement underline the importance of fundamental research on the subject of parametric instabilities, in particular on the understanding of the nonlinear saturation mechanisms of the scattering instabilities “stimulated Brillouin scattering” (SBS) and “stimulated Raman scattering” (SRS).

SBS and SRS are particularly important, and they both involve the excitation of large-amplitude longitudinal waves. The electron plasma waves in the case of SRS, and the ion acoustic waves in the case of SBS, are easily subject to nonlinear saturation processes for the laser and plasma parameters corresponding to fusion-relevant conditions.

Numerical predictions of SBS and SRS, based merely on fluid-type simulations, have so far been unable to reliably reproduce experimental results. However considerable progress has been made in the capability to model SBS in large-scale plasmas [3].

Kinetic simulations, due to high numerical resolution required, can be carried out only on a limited spatial scale. The goal of our fundamental studies is to elaborate a profound understanding of nonlinear saturation processes of SRS and SBS in order to develop a modelling which eventually can be included in long-scale-length hydro models.

The current task is focused on the nonlinear evolution of the electron plasma waves, excited in the SRS process, and ion acoustic wave (IAW), involved both in the SBS process as well as in the SRS process via a secondary instability. Particular interest has been given to kinetic effects.

2006 ACTIVITIES

In the past, our efforts were focused on kinetic effects in the SBS process, disregarding SRS, where the role of ion and electron kinetic effects as well as of the decay of the SBS driven IAW into subharmonics has been studied in the context of the nonlinear saturation of Ion Acoustic Waves. We have performed numerical studies using two different types of particle-in-cell (PIC) simulation codes, first with a ‘full-PIC’ code, simulating the motion of both electrons and ions, and, secondly, a ‘hybrid-PIC’ code (see our previous reports), in which only the ion motion is described, the electrons being then considered as a fluid within the Boltzmann law. Whereas the hybrid-PIC code enables to study SBS in any (underdense) density regime without the onset of SRS (due to the missing electron inertia), in the full-PIC code SRS should occur at densities below 0.25 \( n_c \) (quarter critical density). Therefore, we decided in the past to consider densities above this limit in order to clearly investigate SBS effects without the onset of SRS. However, in order to be closer to the MegaJoule-laser conditions, we have decided to simulate laser-plasma interaction with plasma densities of the order of 0.1-0.4 \( n_c \) [4]. This requires to include the nonlinear saturation process of SRS in our investigations. While SBS is occurring on a picosecond time scale, the more rapid onset of SRS gives rise to a nonstationary behaviour of the backscattered light and hence a low average level in the SRS reflectivity [5].

Figure 1: upper subplot: Light reflectivity as a function of time for a typical full-PIC simulation (electron and ion particles), showing the onset of nonstationary SRS followed, later, by the onset of SBS which becomes dominating for times \( \omega_0 t > 10^7 \). Lower subplot: Spectrum of electron density perturbations in wave-number space \( k/k_0 \) (\( k_0 \) being the laser wave number) as a function of time in the interval \( 0 < \omega_0 t < 6000 \). The different spectral components are associated with SRS, SBS, LDI and its cascade, and kinetic effects. Simulation parameters: light intensity \( I_0 = 10^{15} \text{W/cm}^2 \) at 1\( \mu \text{m} \) laser wavelength, \( k_{BPM} \lambda_D = 0.2 \).
**SIMULATION RESULTS**

Two principal processes have been identified to explain this low-level saturation:

- On the one hand, the SRS-generated electron-plasma waves undergo a decay, called Langmuir decay instability (LDI), into a counter-propagating electron-plasma wave (EPW) and an ion acoustic wave, weakening the SRS process;
- On the other hand, EPWs easily exhibit kinetic effects such as particle trapping or wave breaking, once their amplitude exceeds a few percent of the average electron density. The kinetic effects modify the electron phase space and hence modify the resonance coupling conditions for SRS.

We extensively studied, based on fluid-type equations, the LDI process [6], which can give rise to an instability cascade, and further on to the 'cavitation' process, where EPWs are trapped in localized ion-density depressions leading to a strong incoherence in the Raman backscattering.

In parallel, we performed kinetic simulations with a PIC code in order to identify the regime where LDI occurs and persists as saturation process. Depending on the ratio between the Debye-length and EPW-length, kEPW λD, LDI seems to persist only in a small parameter window before kinetic effects dominate and wash out the LDI signatures in the electron and ion wave spectra.

This is illustrated in Fig. 1, where one can observe signatures of LDI in the spectrum ne(k,t) of the electron plasma waves shortly after the onset of the SRS instability, followed by signatures of the LDI cascade. The spectrum, very early, exhibits the importance of kinetic effects occurring via the onset broadband long-wavelength (k-values smaller than k0) components.

**CONCLUSIONS**

While the LDI effects can be described via fluid-type equations and hence be integrated in a large-scale modelling [3], kinetic effects have to be modelled, if ever, phenomenologically, and perhaps only in a limited parameter regime. Our current and future efforts aim in finding such a modelling for kinetic effects for SRS and SBS [7], by involving simulations in more than one spatial dimension.

**REFERENCES**


**REPORTS AND PUBLICATIONS**


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INTRODUCTION

The main objective of this subtask in 2006 has been the development of theoretical and numerical tools to study radiative properties and transport coefficients (opacities, resistivities...) as well as the equation of state (EOS) for IFE plasma modeling. The subtask has been divided into three parts. The first one (D1) is related to new methods and code development for opacities and resistivities. The second (D2) is the work on a new fully quantum-mechanical approach to atoms and ions in plasmas; the third (D3) – related to D1 – is focused on experiments and comparisons to results from numerical codes.

2006 ACTIVITIES

D1: THEORETICAL METHODS AND CODE DEVELOPMENT IN CASE OF RADIATIVE PROPERTIES

a) We have derived a system of equations for the linear response of a quantum Average Atom in plasma to a frequency-dependent perturbing dipole potential [1]. Both bound and free states are treated quantum-mechanically. In our approach the energy extinction cross-section per AA is calculated from the imaginary part of the induced dipole. We have derived a sum rule in which the induced dipole is localized using two equilibrium AA quantities: the gradient of the equilibrium potential and the gradient of the equilibrium electron density. The new sum rule is a generalization of the known relation between different forms of dipole matrix element. It also opens a way to practical calculation of the induced dipole. We have further shown how the homogeneous plasma contribution to the induced potential leads to a renormalization in the form of the cold plasma dielectric function. Radial equations have been derived for the frequency-dependent response. The simplifications proposed and the new sum rule may be a good starting point for various approximate methods.

b) In order to check the statistical treatment of terms and configurations in the SCO code we have performed some comparisons of the results from the code to available X-ray and XUV absorption measurements in some Aluminium and Germanium plasmas [3]. Especially interesting have been the modifications in the theoretical spectra due to the assumed experimental width. For the low and medium Z elements considered, the statistical term treatment essential in the superconfiguration method is less physically sound than a detailed line-by-line treatment. Nevertheless, comparisons with recent spectroscopic measurements at near solid density suggest a larger domain of validity for statistical approximation than previously thought. Physical line broadening, especially due to pressure ionization of the 3p bound level of electron impact, may be responsible for line overlapping at higher density. Statistical term treatment could become a reliable approximation in such circumstances. We have also addressed some specific theoretical issues that affect the absorption structures such as orbital relaxation in the final state of optical transitions and the broadening of spectral lines by collisions with electrons. It follows from this study that better modeling of physical line broadening is needed and that new experiments with enhanced spectral resolution and possibly absolute measurement of the absorbed radiation are required. New experiments can explore the domain of validity of the statistical term treatment by comparing the DTA and UTA approaches.

c) The work on the radiative collisional code SCRIC [3] based on the HULLAC code system has been continued. A new detailed version of the SCRIC code has been prepared. In this version the collisional-radiative calculations involve the detailed levels. Comparisons between the detailed and configuration-averaged versions have been performed in order to check the validity of the latter version that is practically always used in atomic physics codes for hot dense plasma applications.

D2: EQUATION OF STATE WITH QUANTUM FREE ELECTRONS, RESISTIVITY MODELING

The work in collaboration with P. Arnault, G. Dejonghe and J.-Ch. Pain to improve the thermodynamics of the SCO code has been continued. Recent studies have been focused on the quantum-mechanical description of all electrons. The motivation of these studies is directly connected to higher density plasmas in which pressure ionization can occur. The superconfiguration approximation enables one to perform rapid calculation of averages over all possible configurations representing excited states of bound electrons. We have developed a thermodynamically consistent model involving detailed screened ions (described by superconfigurations) in plasmas. We have implemented a version of the code in which all electrons (bound and free) are treated quantum mechanically. The model provides main thermodynamic quantities, together with a treatment of pressure ionization, and gives a better insight into the electronic properties of hot dense plasmas. The model enables one to perform simultaneous calculations of photoabsorption and equation of state. At present, the ions are still confined in the spherical cell, but all the electrons are described quantum mechanically. Example of this that can be observed performing the self-consistent calculations with the quantum free electrons (figure 1) Resonances are carefully taken into account in the self-consistent calculation of the electronic structure of each superconfiguration. In the figure 1 we see an example of a pressure ionization that does not lead to discontinuities in thermodynamic quantities: the sudden increase of the free-electron number due to pressure ionization of the 3p bound level of...
potassium at 3 eV is absorbed by an increase of continuum density of states. The abrupt change of the bound-electron pressure is compensated by an abrupt change of the free-electron pressure, leading to a continuous total pressure. The corresponding numerical code enables one to calculate the thermodynamic functions over a wide range of densities and temperatures, and, thanks to the superconfiguration averaging process, for mid-Z elements. In the future, it would be interesting to calculate the ionic structure factor and therefore to evaluate electrical static resistivities, using the extended Ziman formula [2].

Figure 1: Bound-electron pressure, free-electron pressure and total pressure for a potassium (K) plasma at \( T = 3 \text{ eV} \) and different values of density.

D3: COMPARISON THEORY-EXPERIMENT IN THE FIELD OF PLASMA RADIATIVE PROPERTIES

a) Theoretical line strengths and positions of satellite lines of xenon and tin ions have been computed in the EUV region (transitions from doubly excited configurations or between singly excited configurations). Calculations were conducted with HULLAC parametric multi-configuration relativistic code. Influence of configuration interaction has been investigated for doubly excited configurations of ions from Pd- to Rb-like. The emission in the 100 -150 Å region interesting for plasmas at the temperature of the order of 20-40 eV (typical for laboratory plasmas) has been investigated. A strong narrowing of 4d–4f/4d–4p group of satellite lines was observed, compared to the calculation without configuration interaction. The emissivity is strongly enhanced in the centre of this group of lines. This strongly increases the EUV emission at about 130 Å for tin at moderate to high densities. The EUV emission of xenon at the same wavelength is enhanced by 4d–5p satellite lines of \( \text{Xe} \ 9^+ \) and \( 10^+ \). Radiative transitions between singly excited configurations and between doubly excited configurations also enhance the emission at these wavelengths, especially 6g–4f transitions of \( \text{Xe} \ 9^+ \), \( 10^+ \) and 5g–4f transitions of \( \text{Xe} \ 11^+ \).

b) Time-resolved absorption of zinc sulfide (ZnS) and aluminum in the XUV-range has been measured at the LULI2000 laser. Thin foils in conditions close to local thermodynamic equilibrium were heated by radiation from laser-irradiated gold spherical cavities. Analysis of the aluminum foil radiative hydrodynamic expansion, based on the detailed atomic calculations of its absorption spectra, showed that the cavity emitted flux that heated the absorption foils corresponds to a radiation temperature in the range 55 – 60 eV (figure 2). Comparison of the ZnS absorption spectra with calculations based on a superconfiguration approach (SCO code) identified the presence of species \( \text{Zn}^{9+} - \text{Zn}^{10^+} \) and \( \text{S}^{9+} - \text{S}^{10^+} \). Based on the validation of the radiative source simulations, experimental spectra were then compared to calculations performed by post-processing the radiative hydrodynamic simulations of ZnS (figure 3). Better agreement is found when temperature gradients are accounted for.

Figure 2: Comparison of the experimental transmission (thin dashed line) with the averaged transmission calculated with HULLAC code (thick full line) in case of the Aluminium plasmas. The density and the electron temperature are calculated with a 1-dim hydrocode MULTI. The time evolution gradients are included calculating separately the transmissions given by the spatial gradients distributions at three times and taking their average.

Figure 3: Comparison of the experimental transmission (thin dashed line) with the averaged transmission calculated with the SCO code (thick full line). The density and the electron temperature are calculated with the MULTI code. The time evolution gradients are included calculating separately the transmissions given by the spatial gradients distributions at three times and taking their average (Pain J.-C., Dejonghe G., Blenski T. «Journal of Quantitative Spectroscopy and Radiative Transfer, 99, (2006) 451-468).
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INTRODUCTION

This part of our Association’s research activity related to inertial fusion is focused on Heavy Ion Inertial Fusion (HIIF) and to the physics of the fast ignitor scenario (FIS). The 2006 results concern the development of a new model to describe atomic collision for heavy ions in relation with HIIF and new theoretical and numerical investigations of the electron transport for fast ignition application.

2006 ACTIVITIES

ATOMIC PHYSICS FOR HEAVY ION COLLISIONS IN HIIF [1], [2], [3]

Atomic collisions related to the transport of heavy ion beam inside the target chamber of a HIIF reactor pertain to a rather specific domain of collision involving ions at high energies and very low ionization state for which there are presently no experimental results; therefore data can only be derived from theoretical investigations. In [1] we have shown that dynamic screening by the electrons inside the reactor chamber plays a central role in the final radius at the DT target. Ionisation of the beam ions will influence the dynamic of the beam first by producing new plasma electrons that will participate to the screening and also by increasing the charge of the beam ions.

The problem of describing the atomic collisions at high energies between two heavy atoms consist of describing the dynamics of N electrons interacting with a time dependent strong field, which in the case of ions is produced by the nucleus. This problem has a strong relation with the interaction of a short laser pulse at high intensity with a high-Z atom, a cluster or a dense target, it has thus a large domain of applications in particular considering the physics of ICF.

Concerning this work, our objective is to construct a general framework, which can be efficiently applied in a broad domain including both atomic collisions (and/or molecules and clusters) and laser-atom interaction at high intensity but for low density targets. It is expected also that our formalism will be applied to calculate the dynamical properties of dense plasmas.

A new method has been developed in which the dynamics of the atomic electrons is described using Hermite-Gaussian Wave Packet Molecular Dynamic (HGWP-MD) [2], [3]. To check the relevance of HGWP-MD for atomic collision calculations, we have used as a benchmark, the collision of ions with an atomic hydrogen. A summary of our results is reported on figure 1.

THEORETICAL MODELING OF ELECTRON TRANSPORT FOR FAST IGNITION [4], [5], [6], [7], [8], [9]

The fast ignition scenario for inertial confinement fusion imparts a very important role to beam-plasma interaction physics, since a laser generated relativistic electron beam is supposed to ignite the pre compressed target.

Figure 1: Stopping number for a 100 keV/n ion with charge Z and velocity V, interacting with a hydrogen atom, in terms of the perturbation parameter \( \eta = Z/V \) (V in atomic units).

Yellow triangle: CTMC results;
Green triangle: GWP-MD results;
Blue stars: static HGWP;
Red circles: our HGWP-MD results

In Figure 1 we have reported the CTMC results which serve as reference, the Gaussian Wave Packet MD (GWP-MD) calculation results, the HGWP ones with a static basis and the full HGWP-MD calculations results. For the HGWP-MD and the static HGWP, we used the same basis, the dimension of which is determined for getting the right limit at small \( \eta \).

We can observe on the figure 1 that the GWP-MD can reproduce the right limit at strong coupling \( \eta >> 1 \) but does not yields accurate results at small coupling, whereas the static HGWP is valid only in the regime of small perturbation. On the other hand, our new HGWP-MD calculations provide accurate results in the whole perturbation domain. Therefore our calculations demonstrate that the HGWP-MD model is well adapted to describe the dynamics of atomic electrons in a strong external field. In particular the size of the basis can be significantly reduced compare to the static case. It opens the way to consider the dynamics of several electrons for analyzing the influence of dynamical correlation in the strong perturbation domain.
The basic physics underlying the phenomena has been investigated for decades. Nevertheless, new lights have been recently shed on the subject, mainly emphasizing the transverse instabilities undergone by the relativistic electron beam as well as the way temperature may affect them.

When the beam enters the plasma, a return current neutralizes it and the resulting system is the well known two-stream configuration. The instabilities undergone by such a system can be classified in terms of their “polarization” (transverse or longitudinal), the orientation of their wave vector with respect to the beam and finally, their origin. By “origin” we mean that some instabilities depend only on the beam density while others only depend on the plasma temperature anisotropy. Although the whole space vector is unstable [4] and [6], it is commonplace to single out three main instabilities, namely the two-stream, the filamentation and the Weibel instabilities. Two-stream and filamentation instabilities both depend on the beam, but the first one is longitudinal with a wave vector parallel to the beam while the second one is transverse with a wave vector normal to the beam. On the contrary, the Weibel instability is also transverse but simply relies on a plasma temperature.

A full algebraic analysis of the system stability unravels the whole unstable spectrum, including the unstable modes we just mentioned. From the performed analysis some points need to be emphasized:

1. The two-stream and the filamentation instabilities are found on the same branch of the dispersion equation. The same root of the dispersion equation yields the two-stream instability when the wave vector is aligned with the beam, and the filamentation instability when the wave vector is normal to the beam.

2. It can be checked that two-stream and filamentation growth rates vanishes with the beam energy whereas Weibel growth rate is independent of the beam.

3. As soon as the beam is relativistic (see for non-relativistic case), the largest growth rate over the whole wave vector space is found on the two-stream/filamentation branch. Interestingly, it is found for an intermediate orientation of the wave vector. We have denoted this intermediate mode as TSF mode, where “TSF” stands for Two-Stream/Filamentation.

4. This TSF mode which yields the largest growth rate is quasi longitudinal.

For a strong non-linear problem as the one considered here, the connection between analytical linear theory and numerical simulation should be addressed. This has been done by making a direct comparison between our analytical model and 2D PIC simulation. The comparison, in particular concerning the map of growth rates in the wave vector plane, shows a clear correspondence between the numerical results and the linear theory ones, reinforcing the physical grounds of the linear theory approach.

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INTRODUCTION

Producing, in a controlled way, matter at moderate temperature (1-25 eV) while maintaining it at solid density (1-10 g/cm$^3$) is of prime interest; it would actually allow studying matter under conditions relevant to a number of topics, from fundamental plasma physics to classical inertial confinement fusion or fast ignition. Such a warm and dense state can of course be achieved in laser-irradiated samples but, due to the skin-depth penetration of visible or infra-red light in solids, only in volumes too small to allow an accurate characterization.

Some recently carried out experiments have then shown the usefulness of laser-accelerated proton beams since they deposit their energy volumetrically (the so-called “Bragg peak”). Furthermore, they are produced in a very short bunch (less than 1 ps when exiting the source) and then can heat samples before they start to expand.

Such an experiment has been conducted at LULI under the 2004 EFDA technology work programme and encouraging results have been obtained [1]. The current task is focused on improving the characterization of the states of matter that can be achieved and varying the range of temperatures that can be obtained, optimizing the proton energy deposition by enhancing the low-energy part of the proton spectrum and, at least, measuring the stopping power of the protons in the dense warm matter.

2006 ACTIVITIES

The experimental campaign has been conducted on the LULI 100TW laser facility in March and November 2006 involving various participants from European countries (Italy, United Kingdom and Serbia) and abroad (USA and Japan). It is still under analysis but preliminary results look promising.

Characterizing the complete proton spectrum, in particular its low-energy component is a crucial part of aiming towards a useful and quantitative measurement of the hydrodynamic conditions (temperature and density) reached in proton-heated matter, for application purposes. Indeed, up to now, only the high-energy tail of the proton spectrum has been investigated, as experimentalists have mainly focused their attention on the few MeV range in view of enhancing the ability of probing dense matter by high-energy protons. However, heating is mostly due to the low-energy protons, and they may present a quite different energy distribution as the rear-surface acceleration mechanism, that drives acceleration of the high-energy part of the spectrum, is associated with other mechanisms yielding lower energy protons.

Proton spectra measured, using a magnetic spectrometer, during the experimental campaign under various conditions are shown in figure 1.

As we are currently performing absolute calibration of our detector, the ordinates are still in arbitrary units. However, it can be clearly seen that there are ways to enhance the numbers of protons contained in the low-energy part of the spectrum (below 1 MeV) by varying the target composition and the focusing conditions. We have also tried using a circular laser polarization, as was proposed by recent theoretical works, but no significant difference with the linear polarization case has been observed.

In order to improve the measurement of the proton-induced energy deposition, two main diagnostics have been used: (i) a space sampling technique coupled to a streak camera (HISAC) providing a 2D time-resolved image of the heated plasma self-emission at two different wavelengths (in the visible) and (ii) time- and space-resolved frequency-domain interferometry (FDI).

Figure 1: Proton spectrum as measured at LULI in various target and laser conditions.

Figure 2: Schematic of the emissivity measurement diagnostic using two distinct colour channels.
By using 2 colour channels, (see figure 2) an absolute measurement of the temperature can be obtained, through the ratio of the recorded emissivities, without having to rely on any “absolute” calculation, while using a sample technique allows measuring emissivities with good spatial (~ 40 µm) and temporal resolutions (~30 ps) (figure 3).

Figure 3: 2D time-resolved image of the target “red” self-emission (output of the streak camera)

Reflectivity of an auxiliary chirped beam on the rear side of the heated foil is measured with the help of the FDI technique (see set-up figure 4). It gives useful time-resolved information on the plasma expansion and on its temperature. In fact, from the phase information of the reflected probe beam, we can infer the expansion velocity from which we can deduce the temperature of the heated sample on the rear surface and cross-checked it with the emissivity measurements.

CONCLUSIONS

Promising results have been obtained. This task will then continue: foam targets (instead of solid ones) will be used to increase the temperature of the heated medium as well as recently demonstrated ps x-ray backlighting technique to diagnose it.

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Figure 4: Set-up of the FDI experiment
INERTIAL CONFINEMENT FUSION

INTERACTION OF SMOOTHED LASER BEAMS WITH HOT PLASMAS IN THE CONTEXT OF INERTIAL CONFINEMENT FUSION

INTRODUCTION

The objective of this work is to improve our understanding of the laser plasma interaction for the parameters previewed for the future fusion-scale experiments and to develop reduced models of key physical processes, which could be suited for implementation in large-scale numerical codes with predictive capabilities. In particular, three problems have been advanced in 2006: (i) the development of the model for the forward stimulated Brillouin scattering (SBS) driven by the smoothed laser beam and validation of the recently developed laser smoothing methods in the experiment, (ii) interpretation of the experiment on the energy transport and validation of the correspondent module in the hydrodynamic code; (iii) studies of the nonlinear and kinetic processes produced on the nonlinear stage of the SBS in the strongly driven regime. A short review of the principal results obtained in 2006 is presented below.

2006 ACTIVITIES

DEVELOPMENT OF A RELIABLE METHOD OF THE TEMPORAL SMOOTHING OF A SPATIALLY RANDOMIZED LASER BEAM IN PLASMA

In previous years we have identified the process of laser beam smoothing in plasmas at powers below the filamentation threshold and conducted the numerical simulations and a first experimental campaign on the laser ALISÉ at CEA/CERTA.

Statistical approach to the laser plasma smoothing

This year we developed a statistical approach for the laser field interaction with underdense plasmas and modification of the laser beam temporal coherence in plasma at powers well below the filamentation threshold [1]. The main properties of the plasma density perturbations driven by a randomized laser beam are derived from a stochastic wave equation for the electric field correlation function \( \langle E E^* \rangle \). The laser spectral and angular broadening is shown to occur on a distance that depends essentially on the ratio of the average power in a speckle to the critical power for filamentation. The coherence time of the transmitted light is reduced to the plasma acoustic time of response to the laser. It is typically a few picoseconds.

Dedicated diagnostics have been developed for the laser plasma interaction code PARAX in order to analyse the laser and plasma statistical properties [2]. The effect of the plasma length on the transmitted light coherence is found to be in good agreement with theoretical predictions. An example of calculations of the plasma smoothing effect is shown below.

The figure 1 shows the time resolved intensity distribution in a transverse direction after propagating through 2 mm long plasma with the density 5% of the critical density. A comparison between the time integrated intensity in vacuum (dashed curve) and after propagation through the plasma (solid curve) shows a strong reduction of the contrast. The forward SBS is shown to play a key role in the laser coherence loss in this low intensity regime. The transmitted wave spectrum in the \( \omega-k \) plane shows a characteristic red shift. The figure 2 demonstrates this effect after the 2 mm long plasma.

The limitations of the analytical model are discussed in terms of the deviation of the electric field distribution from the Gaussian statistics and creation of density-electric field correlations.
Statistical model of the forward SBS

We studied the linear evolution of the forward SBS of a spatially incoherent pump wave with given statistical properties. The governing equations for the field correlation functions are obtained from a three-wave paraxial model assuming a resonant coupling between the incident wave with frequency \( \omega_1 \) and transverse wave vector \( \mathbf{k}_1 \) and the scattered electromagnetic wave with the transverse wave vector \( \mathbf{k}_2 \) and frequency \( \omega_2 < \omega_1 \) via the ion acoustic wave, propagating in the transverse plane with wave vector \( \mathbf{k}_s = \mathbf{k}_1 - \mathbf{k}_2 \) and frequency \( \omega_s = \mathbf{k}_s c_s \), where \( c_s \) is the ion acoustic velocity. An equation for the electric field correlation function \( \langle E_1^*(\mathbf{k}_1)E_2(\mathbf{k}_2) \rangle \) is derived beyond the standard random phase approximation (RPA) and accounts for coupling of different electromagnetic pairs to the same acoustic wave. It is shown that the spatial growth rate of the instability is much larger than the one obtained using the standard RPA technique. It is of the same order as in the plane pump wave case.

Experiment on the laser plasma smoothing

This regime of low intensity laser induced incoherence is especially interesting in that the associated angular broadening is not as deleterious as observed for higher intensities. Moreover, beam smoothing can be achieved in low density plasmas where energy losses due to absorption and backscattering are not too important. This year we conducted an experimental campaign on the laser beam smoothing on the laser ALISE.

The interaction between a low density, mm-size plasma created in a He gas jet and a spatially incoherent laser beam has been studied with several dedicated diagnostics. We characterized the spatial and temporal coherence loss of the transmitted light in both regimes, above and below the filamentation threshold. The plasma induced smoothing has been obtained without important angular spreading of the transmitted light. The backscattering instabilities are shown to be negligible.

NONLOCAL ELECTRON ENERGY TRANSPORT IN INERTIAL FUSION CONDITIONS

Correct modelling of the electron energy transport is essential for Inertial Confinement Fusion (ICF) target design. We have carried out new experiments designed to be highly sensitive to the modelling of the heat flow on the Ligne d’Intégration Laser (LIL) facility, the prototype of the Laser Megajoule. We show that two-dimensional hydrodynamic simulations correctly reproduce the experimental results only if they include both the nonlocal transport and magnetic fields [3].

Experimental results

We have used four beams of the LMJ prototype, the LIL laser, which laser wavelength (0.35 \( \mu \)m), energy (multi-kJ) and pulse duration (several ns) are relevant to direct drive ICF.

The laser smoothing is achieved by combining longitudinal spectral dispersion and continuous-phase plates. These features allow the observation of laser driven flows on long durations and with a good temporal resolution for the plasma parameters similar to future LMJ implosion experiments.

The purpose of the experiment is to measure the velocity of the heat wave induced in a planar target for different laser intensities. Seven successful shots were performed with a laser energy varying from 4 to 10 kJ pulse duration of 3 ns, corresponding to intensities from \( 8 \times 10^{14} \) up to \( 2 \times 10^{15} \) W/cm\(^2\).

In order to obtain the heat wave velocity, we observe the time dependent He-like emission of two thin metallic markers buried in a flat plastic disk (see figure 4).

The target disk is chosen thick enough, so that the rarefaction wave originating from the rear side of the target does not interact with the ablation front: the target is not accelerated and is therefore stable.

The markers are V and Ti layers, buried either at 5 or 10 \( \mu \)m (V) and 15 or 30 \( \mu \)m (Ti) from the target surface: they produce He-like resonance lines at 5.2 keV and 4.7 keV, respectively. The 2D geometry related to the finite size of the focal spot launches naturally the competition between the nonlocal and magnetic field effects in the electron energy transport.

The markers thickness is constrained by two opposite trends: on the one hand, the markers should be thick enough to radiate a measurable signal on our detectors; on the other hand, the markers should be as thin as possible in order not to alter the heat flow.

![Figure 3](image1.png)

Figure 3 shows a shadowgraphy image of the plasma created by the laser pulse. The laser arrives from the left. The dark part in the left part of the plasma indicates a turbulent zone where the smoothing takes place.

![Figure 4](image2.png)
For this experiment, we used two series of thicknesses: 0.05 and 0.2 µm. The electron temperature and density in the V layer was inferred by high resolution emission spectroscopy.

The main diagnostic, located at 50° to the laser beam direction, is a cylindrically-bent Highly Oriented Pyrolytic Graphite (HOPG) crystal spectrometer. Due to its high efficiency in the 4.5 – 5.5 keV spectral region of interest, we were able to couple it with a streak camera and detect a time-resolved spectrum of the V and Ti He-like emission lines, filtered by a 5 µm Cu foil, even for the thinnest 50 nm Ti and V layers. For each shot the time range was about 7 ns with a 100 ps resolution. Figure 5 shows raw experimental data at the laser energy of 10 kJ (left) and the results of the numerical simulation of the experiment (right).

**Numerical simulations**

We have used the 2D hydrodynamic code CHIC to simulate the laser-plasma interaction and the time resolved tracer diagnostics. CHIC is a two-temperature code devoted to the design of direct drive ICF targets. The code solves the standard conservation equations for mass, momentum, and energy of the fluid in the Lagrangian formalism. The radiative transport is calculated assuming that the radiation field is quasi stationary and weakly anisotropic (multigroup diffusion). The propagation and absorption of laser energy is calculated in the geometrical optics approximation with a 3D ray tracing package. CHIC includes a flux limited Spitzer-Harm (SH) heat transport package and a new two-dimensional kinetic model for nonlocal transport including the effect of azimuthal magnetic fields [4], [5].

A set of performed calculations can be summarized as follows. The flux limited SH model does not succeed at restituting the time-resolved measurements at the three energies with the same limiter. Nonlocal heat transport fails dramatically in the 7.2 kJ case and was not run at other energies. This is the clear indication of the magnetic field effects. Figure 6 below displays lateral electron temperature profiles obtained at 1 ns after the onset of the laser pulse in CHIC calculations using either the SH, Braginskii or the nonlocal model with magnetic fields included.

The nonlocal model without magnetic fields produces a much warmer axial spot. This is related to a very strong inhibition of lateral heat transport. The temperature in the absorption region is about 3 keV and the heat is mainly carried by electrons with the energies of 8–10 keV. The mean free path of these electrons in the corona is close to 1 cm and their distribution is therefore nearly uniform in this region of the target, not producing any transverse heat flux any more.

Our simulations indicate that azimuthal magnetic fields of several hundreds of kG are generated on the edges of the focal spot. The corresponding Hall parameter \( \omega_b \tau \) (the ratio of the electron gyrofrequency to the collision frequency) lies in the 0.1 – 0.5 range. A Hall parameter of 0.2 causes a 25% reduction of the heat flux magnitude, but also a rotation by 40° of its direction through the Righi-Leduc effect. In the geometry of the experiment, this rotation is clockwise, which enhances the lateral flux and slows the longitudinal heat wave. The calculations including the Righi-Leduc effect are compatible with the measurements, thus indicating that the main cause for flux inhibition in our experiment lies in the presence of self-generated magnetic fields. Nonlocal and magnetic field effects obviously compete as they predict opposite modifications of the lateral heat flux. Moreover, magnetic fields improve the validity of the linear transport theory and moderate the nonlocal effects by reducing the effective range of high energy electrons to their gyroradius. This range scales as \( v^4 \) in plasma without magnetic fields, where \( v \) is the electron velocity, whereas the electron gyroradius is proportional to \( v \). Only the calculations that are taking into account both effects reproduce the experimental chronometry at three energies.

In conclusion, our experiments proved to be highly sensitive to the modelling of the heat flow and to discriminate the heat inhibition effects. Analysis of the experimental data allows us to isolate the effects of heat flux modification both due to nonlocal effects and magnetic fields for the typical ICF conditions. The nonlocal heat transport alone is inadequate because it strongly inhibits lateral fluxes thereby producing a faster longitudinal heat wave than in the experiment. The dominant effect identified in our simulations is the presence of magnetic fields. We show that the model including both nonlocal transport and magnetic fields correctly reproduces the experimental results and confirms the role of the magnetic fields on electron thermal transport in direct-drive ICF conditions.
NONLINEAR AND NONSTATIONARY EFFECTS IN THE STIMULATED BRILLOUIN SCATTERING AT HIGH LASER INTENSITIES

One of the important results in the years 2004 and 2005 was a discovery of a very strong suppression of the SBS backscattering at high laser intensities due to the formation of density cavities. The latter were identified as stationary electromagnetic solitons, which are an excellent agreement with the theoretical model. The most important result of this year is the confirmation of this scenario with more complete 2D simulations [6]. The transient behavior of the SBS reflectivity and the formation of density cavities have been confirmed. In difference from previous one-dimensional simulations, the plasma cavities have a shorter life time, but they playing an important role in suppression of the SBS reflectivity and in efficient electron heating.

Simulations of cavity formation

The numerical simulations were performed with the relativistic PIC-code emi2d13. The code is 2D in space and solves Maxwell's equations for the fields \( E_x, E_y, \) and \( B_z \). The simulation parameters were motivated by the original one-dimensional configurations. In order to avoid the Raman backscattering, the density was fixed above the quarter-critical density at 0.3 \( n_e \), for a plateau of width of 10 \( \lambda_0 \) and length of 55 \( \lambda_0 \) (parallel to the propagation direction of the laser). In parallel direction the plasma is surrounded by a vacuum region of 24 \( \lambda_0 \) extension. The mass ratio was set to 1836 and the temperature ratio was fixed at 50. Laser intensity and electron temperature were varied but have values of a few times \( 10^{16} \) W/cm\(^2\) and a few hundred eV, respectively. The laser beam is presented by a plane wave of constant intensity, which is switched on instantaneously. The interaction process was simulated for a time period of the order of 14,000 \( \omega_0^{-1} \).

Figure 7 shows the plasma profile with several cavities. They were produced in the three dominant filaments which were created at the beginning of the interaction process. The intensity in the filaments varied and correspondingly the cavitation process is not exactly the same for each filament.

The cavitation process destroys locally the backscattering process and the reflectivity is reduced. Analysis of the density figures shows that behind the cavities no new ion acoustic waves are excited as long as the cavity remains in place. Due to refraction of the subsequent laser the transmitted as well as the backscattered light have a non-negligible perpendicular component, which renders the reflectivity more complicated.

Electron heating

The creation of the cavities goes along with a strong increase in the electron energy content. Each time a cavity is created the energy content shows a jump due to the Coulomb explosion mechanism and the plasma waves excited (see the figure 8). At later times the energy content starts to level off and correspondingly transmission strongly increases.

The 2D simulations in the strong coupling regime reproduce the characteristic oscillatory behavior of the reflectivity found in the 1D simulations at initial time before the cavity formation. At the end of simulation the average value of the reflectivity is reduced to approximately 1% (mean value). The 2D simulations therefore reproduce the 1D results as far as the reflectivity is concerned. Analysis of the transverse dependence shows that the averaged global reflectivity and the local one agree starting from \( t = 8000 \omega_0^{-1} \). The averaging procedure does not smooth out any possible local high-intensity peak in the reflectivity.

The scenario for cavity formation is supported by an electron and ion phase space analysis. One observes at the cavity location the phase space structures characteristic for electron trapping by the electron plasma wave, which has its origin in the three wave coupling process. Although the incident laser wave has a dimensionless amplitude \( a = eE/mc_0 = 0.1 \), the field in the cavities is strongly enhanced and electrons are gaining an energy corresponding to a relativistic factor \( \gamma \sim 2 \).

These findings are confirming the results found previously in the 1D simulations. However, the 2D simulations also showed that the global, averaged reflectivity can differ strongly from the local reflectivity originating from a single speckle/filament or a small collection of them, in agreement with recent experimental findings.

CONCLUSIONS

The studies previewed for the year 2006 are fully completed according the plan. We obtained new results concerning the modelling the laser plasma interactions for the ICF conditions. Formation of young scientists make an important part of this work: three graduate students are working in this project, and one of the M. Grech will defend his thesis shortly, in the first semester of 2007.
REPORTS AND PUBLICATIONS


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INTRODUCTION

Among the large variety of plasmas created in the conditions relevant to ICF, one of particular interest is dense and transient ones. Actually, they can be generated by irradiation of solid target by intense laser pulses at high temporal contrast. In these particular conditions, the interaction allows to produce efficient secondary particle sources, of interest for the diagnostic of the interaction itself as well as for various applications. As these media are opaque for visible probes, it’s difficult to directly characterise them. One of the possibilities to get access to the “density-temperature” parameter couple is to probe them in the XUV domain.

Our task is to diagnose near transient solid-density plasmas using High Order Harmonics (HHG) generated by frequency conversion in a pulsed gas jet as XUV probe beam. We have already diagnosed near solid-density plasma by HHG transmission measurements, with a femtosecond range temporal resolution [1].

Our goal, now, is to get 2D informations of plasma temporal evolution by another diagnostic: spatial interferometry at 32nm. First, we focus on the main characteristics of the diagnostic and secondly, we report on the temporal evolution of a plasma created by intense laser irradiation of Aluminium solid target. In the last part, we compare numerical simulations to experimental results.

2006 ACTIVITIES

2D-IMAGING XUV INTERFEROMETER

Since 2004, we have developed a new 2D-imaging XUV interferometer using H$_{25}$ of a Ti:Sa laser ($\lambda$=32nm), in collaboration with ATTO group (CEA-Saclay) and Laboratoire Charles Fabry – Institut d’Optique (France). The diagnostic has been detailed in the last year report. In summary, we use the property of mutual coherence of HHG generated in gas to design a Mach Zehnder type XUV interferometer. One of the originalities lies in the amplitude division performed in the IR domain, the XUV frequency conversion taking place inside the interferometer, like is reported on figure 1.

One XUV beam is the reference beam and the second one is the probe beam, perturbed by the plasma passing through. The two XUV beams are recombined via a prism. The second originality of this diagnostic is the collecting optic (ellipsoidal mirror) which images the interferograms from the virtual object plane to the real image plane with a magnification of 10.

The wavelength (H$_{25}$ of Ti:Sa, $\lambda$=32nm) is selected via multilayer coating deposited on the ellipsoidal mirror and on the folding mirror (used to compact the system, while maintaining a large magnification). This tool has been designed to combine micrometric spatial resolution to femtosecond temporal resolution.

The interferometer has been characterised and the original concepts validated in 2005. The fringe spacing can be varied from 5 to 13µm, the interference field is 200x100µm and the maximum contrast is close to 30%, allowing performing interferometric measurements.

TEMPORAL EVOLUTION OF ELECTRONIC DENSITY FOR A PLASMA CREATED BY INTENSE IRRADIATION OF ALUMINIUM TARGET

Experimental results:

This diagnostic has been first used to diagnose the temporal evolution of a plasma created by intense irradiation ($I_{\text{max}}=7\times10^{15}$W/cm$^2$) of solid aluminium. A temporal delay line has been inserted between the pump and the XUV probe beams allowing to record the plasma evolution up to $\Delta t=1.1$ns after the interaction of the IR pulse with the target.

2D electronic density maps are reported on figure 2, for $\Delta t=700$ps (a) and 1.1ns (b). We extract the electronic density information using a numerical treatment based on rapid Fourier transform of the interferogram. This is followed by a filtering around the spatial frequency of the reference fringe (without plasma) for reducing the noise (contrast of 30% without plasma), and finally, we perform an inverse Fourier transform to obtain a 2D-phase map. Due to the cylindrical symmetry of the interaction, an Abel inversion of the 2D-phase map is performed to obtain the 2D electronic density map. Due to the cylindrical symmetry of the interaction, an Abel inversion of the 2D-phase map is performed to obtain the 2D electronic density map. We can note that, in our experimental conditions, it was not possible to probe plasmas at delays shorter than 700ps because of the ultimate spatial resolution (5µm) of our interferometer lowered by filtering process necessary to get phase information due to the plasma presence.
Inertial Confinement Fusion

Figure 2: Interferograms at $\lambda=32\text{nm}$ with plasma created by irradiation $(I_{\text{max}}=7\times10^{15}\text{W/cm}^2)$ of Aluminium solid target, for a pump-probe delay of $\Delta t=700\text{ps}$ (a) and $\Delta t=1.1\text{ns}$ (b)

From these two electronic density maps, we succeed to measure an electronic density of $10^{20}\text{cm}^{-3}$ at $15\mu\text{m}$ from the initial target surface. The maximum electronic density decreases from $7\times10^{20}\text{cm}^{-3}$ at $\Delta t=700\text{ps}$ up to $3\times10^{20}\text{cm}^{-3}$ at $\Delta t=1.1\text{ns}$.

1D-hydrodynamic simulations:

We have performed numerical simulations using a 1D-hydrodynamic code named MULTI-fs [2] to validate our experimental results. The spatial variations of electronic density and temperature are reported in figure 3(a) for $\Delta t=700\text{ps}$ and in figure 3(b) for $\Delta t=1.1\text{ns}$. The maximum electronic density reaches $3\times10^{20}\text{cm}^{-3}$ for $\Delta t=700\text{ps}$, decreasing to $2\times10^{20}\text{cm}^{-3}$ for $\Delta t=1.1\text{ns}$. The temporal behaviour of the maximum electronic density is in good agreement with experimental results. Simulations have to be completed by 2D simulations for explaining temporal behaviour of plasma spatial extension for time delays between $\Delta t=700\text{ps}$ and $\Delta t=1.1\text{ns}$.

CONCLUSIONS

We have presented temporal evolution of an Al plasma characterised by a 2D imaging XUV interferometer and shown that the mutual coherence of HHG generated in gas can be used to diagnose dense and transient plasmas. A maximum electronic density of $7\times10^{20}\text{cm}^{-3}$, 700ps after the interaction of the pump with the target, has been inferred from single shot interferograms and directly compared to one dimensional-hydrodynamic code simulations exhibiting a quite reasonable agreement. The advantage of this new diagnostic is the possibility to extend considerably the size of the object under study. These encouraging results open large perspectives for bright XUV compact ultra-short sources (as HHG from solid target) usable to diagnose dense transient plasmas, a perspective particularly crucial in the context of the fast ignition for energy production route.

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REPORTS AND PUBLICATIONS

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