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# Physics of laser plasma interaction and particle transport in the context of inertial confinement fusion

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## Abstract

Lasers are unique tools for transporting extremely high powers over large distances, but transfer of such a power from photons to matter in small volumes is a very complicated problem. First of all, the interaction proceeds very far from equilibrium, as with photons having energy of a few electron-volts one would like to heat plasma to temperatures thousand times higher. Second, these processes are strongly nonlinear, as they correspond to transfer energies of a large number of photons to a much smaller number of charged particles in extremely small volumes and in very short time scales. Research in inertial confinement fusion (ICF) gave a strong push for studying all these processes in detail, and now, although many issues remain to be resolved, we have quite a good understanding of how they operate in ICF conditions and what limitations and advantages they offer.

In this short review, I share my personal recollections of almost 50 years history of the physics of laser plasma interaction. Understanding of highly nonlinear microscopic processes allowed us to improve the hydrodynamic performance of ICF targets and to foresee future developments. The key point is that multiscale modeling allowed for the retainment of major elements of microscopic physics in macroscopic hydrodynamic codes and make them more accurate and predictive.

Keywords: inertial confinement fusion, laser plasma interaction, parametric instabilities, nonlocal electron transport

(Some figures may appear in colour only in the online journal)

## 1. Introduction: historical outlook

The processes of laser plasma interaction and particle transport operate on the micrometric and picosecond time scales, which are two-three orders of magnitude smaller than the scales of inertial confinement fusion (ICF) targets. This disparity of scales makes communication difficult between the world of hydrodynamics and the world of these ‘anomalous’ processes. Although the physics of parametric instabilities

and kinetic particle transport has developed rather rapidly, its implementation in the ICF phenomenology is still under way. We still have serious problems with the development of multiscale physics models and understanding of intricate interactions between the microscopic and mesoscopic levels. In this paper, based on my personal experience, I give several examples of the phenomena where such an interaction was successful and allowed to improve the target hydrodynamic performance by controlling the microscopic processes; I also provide examples where mother nature did not allow us to access the performances we wished for.

I had a chance to start my PhD thesis on parametric instabilities in plasmas in 1971, just a year before the ICF studies



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were declassified by Edward Teller at the 7th Quantum Electronics Conference in Montreal and Nikolai Basov at the 2nd Workshop ‘Laser Interaction and related Plasma Phenomena’ in Hartford [1]. The detailed numerical simulations were published by John Nuckolls and his colleagues in the famous Nature paper [2]. The ideas of using lasers for igniting fusion reactions were already circulating for about 10 years in Russia [3], USA [4], and France [5] after Maiman’s demonstration of the ruby laser [6], but clear understanding of the necessity of laser-driven target implosion for ignition of fusion reactions came only with the paper published by Nuckolls *et al* [2]. At that time, the problem of efficient laser absorption has been identified, but no solution has been proposed. Ray Kidder in his analysis of the laser absorption wrote [7]: ‘The absorption coefficient of a plasma for visible light is too small to permit laser light to be an effective means of heating a plasma unless ... it has an electron concentration of the order of  $10^{20} \text{ cm}^{-3}$  or greater’. John Nuckolls was even more definitive [2]: ‘Calculations with non-Maxwellian electron and linear electron coupling show that suprathermal electrons generated by laser plasma instabilities preheat the fuel ... and effectively decouple from the atmosphere’. This last phrase in fact stimulated the interest to the parametric instabilities in Russia and was a turning point in my scientific life.

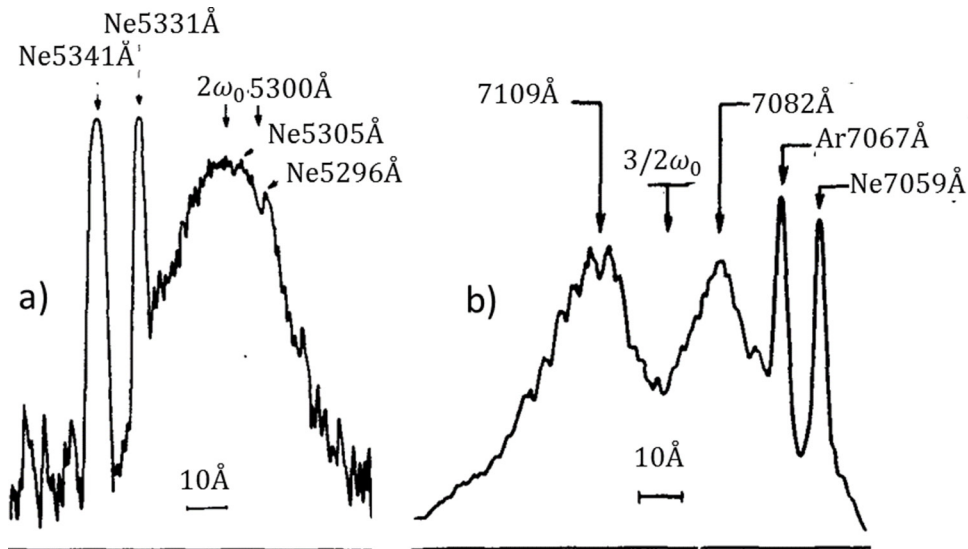
The relations between the nonlinear laser plasma interactions (LPI) and ICF were never simple. The attempts to circumvent the nonlinear effects are still continuing nowadays. The known example is the transition to the third harmonic of Nd laser in 1990s. This is certainly one of efficient methods to avoid nonlinear effects, but it is evidently insufficient and the need to domesticate LPIs is still the actuality. The studies of parametric instabilities in plasmas and stimulated laser scattering in solids and liquids have started in the 1960s almost simultaneously. The stimulated Raman (SRS) [8] and Brillouin (SBS) [9] scattering were observed immediately after the invention of lasers. These processes have been described theoretically as spatial amplification of spontaneous fluctuations in a homogeneous media of a finite length. The theory of parametric instabilities in plasmas has started by Silin [10] and DuBois and Goldman [11] with analysis of the temporal growth rates and threshold conditions for the external electromagnetic field with frequencies close to the plasma frequency. The decay instability of an electron (Langmuir) plasma wave was predicted by Oraevskii and Sagdeev [12] three years earlier. Experimental observations of the parametric decay instability in the microwave domain has been reported by Stern and Tsoar in 1966 [13], while the linear theory of parametric instabilities has been consolidated by Kyoji Nishikawa two years later [14].

The role of parametric instabilities in laser plasma heating has been studied by John Dawson and his colleagues. In his paper with Predhiman Kaw [15] the threshold of nonlinear plasma heating due to the parametric instabilities has been estimated at the level of  $\sim 10^{14} \text{ W cm}^{-2}$  and the concept of ‘anomalous absorption’ has been introduced. First numerical simulations demonstrating an enhanced absorption of a large amplitude electric field oscillating near the plasma frequency have been published by Kruer *et al* [16, 17].

Thus, in the beginning of the 1970s, the parametric instabilities in a homogeneous plasma were already known and the theory has been partially compared with experiments. However, there was another important point—accounting for the plasma spatial inhomogeneity. This issue has been raised by Perkins and Flick [18] and put in the laser plasma interaction context by Rosenbluth [19] and Pilya [20, 21]. Two representative cases have been identified: the first one is a plasma with a monotonously evolving density near the resonance point where the daughter waves are amplified spatially (similarly to an open resonator in nonlinear optics). Here, the instability is convective, that is, the daughter waves are amplified in space. The second case corresponds to plasma profiles with an extremal point where the unstable daughter waves are trapped between two turning points (similarly to a lasing media between two mirrors) and are growing exponentially in time. Here, the instability is absolute. The theory of parametric instabilities in an inhomogeneous plasma with application to laser plasma interactions has been developed in the joint Russian-French-US publication [22] followed by a mode detailed analysis [23]. With these seminal papers the general background of the theory of parametric instabilities has been laid. However, a lot more work was needed to bring it to realistic laser plasma interaction conditions.

## 2. Parametric instabilities in laser produced plasmas

My contribution to that competitive and fast developing field of laser plasma interaction was two-fold: development of the nonlinear theory of saturation of parametric instabilities and interpretation of experimental data. Both of them strongly benefited from the first multibeam laser installation constructed in 1972 in the Basov’s laboratory in the Lebedev Physical Institute of the Russian Academy of Sciences in Moscow [1, 24]. Its nine beams delivered a record energy up to 1 kJ in a 2–4 ns pulse at the wavelength of  $1.054 \mu\text{m}$  in a planar and spherical geometry. The observations of reflected light at the fundamental and at the harmonics of the laser frequency  $2\omega_0$  and  $\frac{3}{2}\omega_0$  have been related to the parametric instabilities: SBS, parametric decay and two plasmon decay (TPD) [25, 26]. Figure 1 shows examples of the spectra of reflected light at  $2\omega_0$  and  $\frac{3}{2}\omega_0$ . The laser spectrum was too broad for seeing a shift related to scattering on the acoustic wave at the second harmonic, but the specific two-peak feature at the harmonic  $\frac{3}{2}\omega_0$  was well resolved. It has been related to the TPD followed by coupling of the daughter plasma waves to the reflected laser light. Theoretical analysis of TPD convective amplification and subsequent wave coupling in [27, 28] provided a relation between the frequency splitting  $\delta\omega_{3/2}$ , the scattering angle  $\theta$  and the electron plasma temperature  $\delta\omega_{3/2} \approx 2.25 \omega_0 T_e / m_e c^2 \sqrt{1 + 12 \sin^2 \theta}$  (here,  $m_e$  is the electron mass and  $c$  is the light velocity). This expression turned out to be quite useful for estimates of the local electron temperature near the quarter-critical density [29].



**Figure 1.** Spectra of the reflected light  $2\omega$  (a) and  $\frac{3}{2}\omega$  (b) observed in experiments at the installation KAL'MAR at the laser intensities  $\sim 10^{14}$  W cm $^{-2}$ . Reproduced from [25, 26], respectively, with the permission of AIP Publishing.

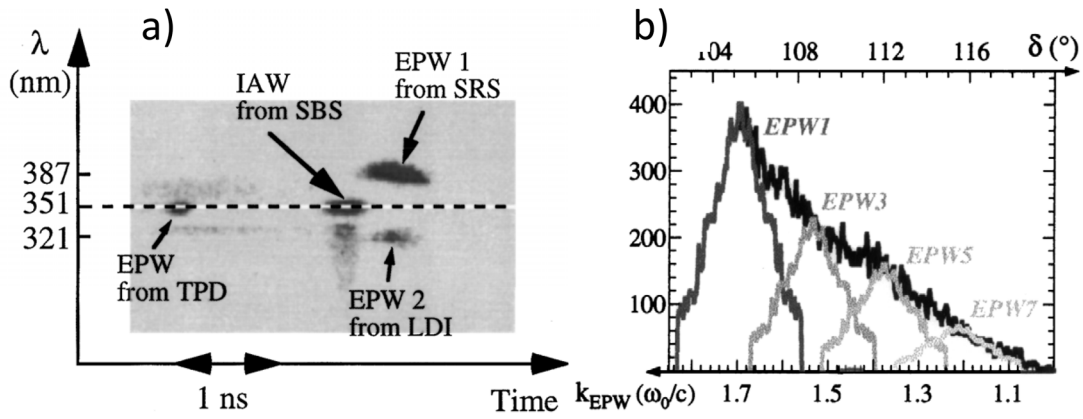
My theoretical studies of the nonlinear saturation of parametric instabilities have been first directed to the analysis of secondary parametric decays of plasma waves. The idea was rather simple, if the primary parametric instability produces a large amplitude daughter plasma wave, this wave can also be unstable and produce a tertiary plasma wave via the Langmuir decay instability (LDI) [12] and so on. The cascade of LDIs stops as the plasma wave amplitude in subsequent cascades decreases and eventually goes below the threshold of the next decay. The absorption rate of such a broad spectrum of plasma waves is proportional to the number of cascades and results in an enhanced absorption of the driver field. By equating the rate of the primary decay to the damping rate of all daughter waves one can estimate the effective (anomalous) absorption rate. For example, in the case of TPD, the effective collision frequency scales as  $\nu_{\text{eff}} = \omega_0(T_e/m_e c^2)\gamma_{\text{TPD}}/\omega_s$  [30], where  $\gamma_{\text{TPD}}$  is the TPD growth rate and  $\omega_s$  is the ion acoustic frequency. The theory of nonlinear absorption of the laser radiation has been further extended to an inhomogeneous plasma including the spectra of plasma waves and modification of the electron distribution function [31].

Although such an analytical approach provided an interesting insight in the physics of nonlinear laser plasma interaction, many effects were not considered at that time, including the collapse of plasma waves [32] and particle trapping. At that time in Russia, we did not yet have appropriate computational resources and kinetic codes for evaluation of various nonlinear processes. In the application to TPD, effects of the plasma wave collapse were analyzed by DuBois *et al* [33] and electron acceleration was included later on by Vu *et al* [34]. At the same time, we progressed with understanding of saturation mechanisms of the SRS and SBS. A numerical code describing nonlinear coupling the SBS and SRS and secondary LDIs [35] has been developed in collaboration with Rozmus and his colleagues at the university of Alberta. It provided us with detailed understanding of the nonlinear saturation of SRS and the important role of the LDI cascade. This

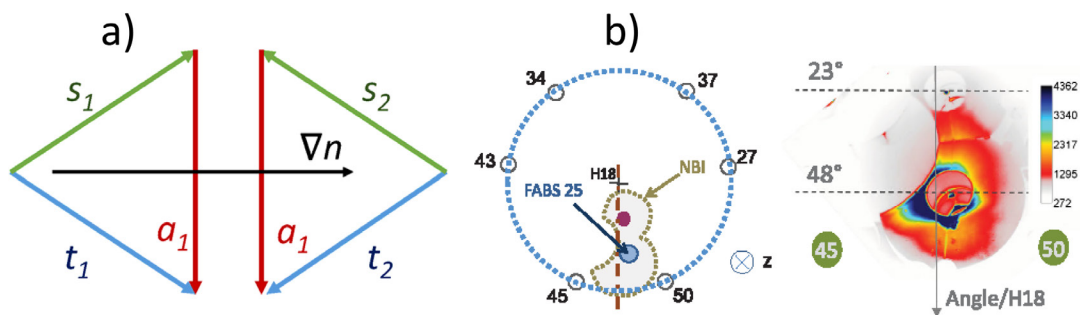
has been confirmed in the experiment conducted by Christine Labaune and her colleagues [36] by using sophisticated techniques—creation of a relatively large, hot and homogeneous plasma and diagnostic of plasma waves with Thomson scattering (TS). Figure 2(a) shows an example of TS signal presenting Langmuir wave SRS satellites along with the TPD and SBS features from the original experiment [36]. More detailed measurements performed a few years later [37] allowed to reconstruct the spectrum of plasma wave produced by 7 LDI steps, figure 2(b).

Kinetic effects contribute to the saturation of parametric instabilities in the domain of short plasma wavelengths, where particle trapping in the ion acoustic or electron plasma wave leads to the resonance detuning and modification of Landau damping. In application to SBS these effects have been studied in our paper [38]. In applications to SRS, the kinetic effect leading to a rapid increase of backscattering was called inflation [39–41]. More recently we conducted SRS studies in application to the shock ignition scheme [42] for higher laser intensities where stronger nonlinear effects related to the plasma cavitation and electron acceleration take place [43]. It is, however, very difficult to measure the kinetic effects in experiments because they take place on a short, picosecond time scale. The effects of electron trapping and coupling of multiple laser beams on SRS saturation have been demonstrated only recently [44] in dedicated experiments with high spatial and temporal resolution.

Analysis of parametric instabilities in an inhomogeneous laser produced plasma lead us to the idea of double stimulated scattering process where two wave triplets are coupled together either by a structure of the pump wave or by boundary conditions. Let us demonstrate that in a simple case of a plain wave incident obliquely on an inhomogeneous plasma. This wave  $t_1$  undergoes a near-forward SBS on an acoustic wave  $a_1$  propagating perpendicularly to the density gradient as it is shown in figure 3(a). The scattered wave  $s_1$  propagates further in plasma and transforms into the reflected wave  $s_2$ . It



**Figure 2.** (a) Thomson scattering time-resolved spectra from a near quarter-critical density plasma. (b) Cascade of 7 consecutive LDIs measured by Thomson scattering technique in a low-density plasma. (a) Reproduced from [36] with the permission of AIP Publishing. (b) Reprinted figure with permission from [37], Copyright 2002 by the American Physical Society.



**Figure 3.** (a) Scheme of two coupled SBS processes with a common acoustic wave [46]. (b) Scattering diagram and near-field image of the amplified emission of a common SRS wave. (b) Reprinted figure with permission from [49], Copyright 2016 by the American Physical Society.

is evident that this scattered wave together with the reflected pump wave  $t_2$  interact with the same acoustic wave  $a_1$ . Thus, two triplets  $t_1, s_1, a_1$  and  $t_2, s_2, a_1$  are coupled through the common daughter wave  $a_1$  and are mutually enhanced. In the case shown in figure 3(a), SRS becomes an absolute instability [45, 46]. The considered scheme is quite general. It could be applied to the Raman instability [47], TPD [48] and depending on the interaction geometry it may provoke a strong scattering in certain particular directions. Figure 3(b) shows the result of recent experiment on OMEGA in the multibeam geometry where the common scattered wave is enhanced in the bi-sectional direction as a result of two coupled SRS processes [49].

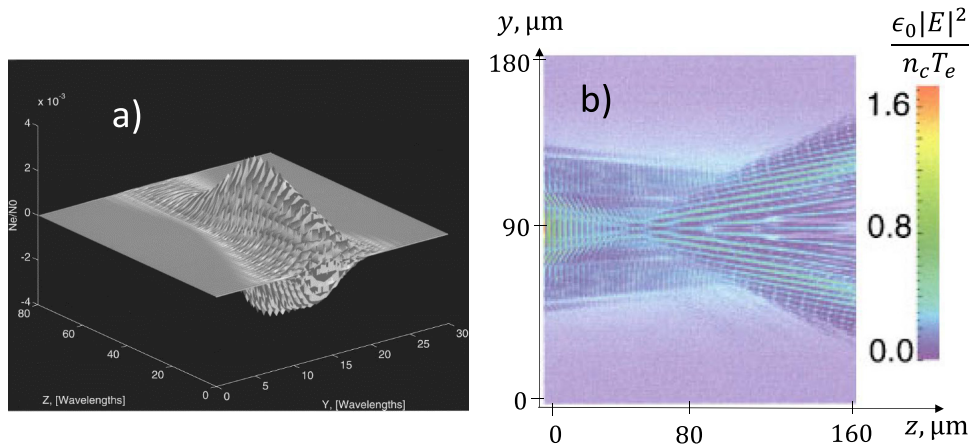
Coupling several parametric processes together via a common plasma or electromagnetic wave is a very general phenomenon, which takes different forms depending on the nature of interacting waves. One can recognize in figure 3(a) the cross beam energy transfer (CBET) if  $t_1$  and  $s_1$  are considered as two pump waves. It gives rise to nonlocal coupling between different zones of plasma (for example, critical and quarter critical densities), which are often neglected in simulations.

In close collaboration with Canadian and French colleagues, we contributed to understanding of the stimulated scattering processes in the laser plasma interaction context. We have developed one of the first non-paraxial electromagnetic codes, which gave us access to a number of interesting effects related to competition of the beam self-focusing, CBET and SRS in two- and three-dimensional geometry. Figure 4(a)

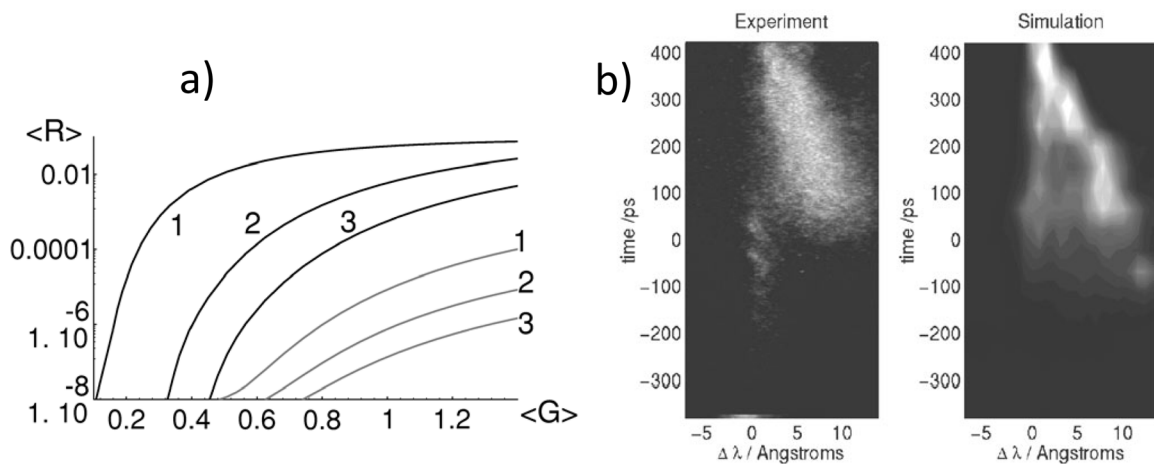
shows an example of the ion acoustic wave excited in a tightly focused laser beam [50]. Its narrow localization in the transverse direction is responsible for the angular broadening of the transmitted and backscattered laser light (panel b).

Such simulations allowed us to analyze CBET, taking into account the temporal evolution of transmitted beams [52], modification of their spatial structure [53], and to propose estimates and simplified expressions, which can be used for accounting for nonlinear interaction processes in hydrodynamic codes. These works helped us much later in the development of a quasistationary CBET model and its implementation in our radiation hydrodynamic code CHIC [54].

An important development that took place in the 1990s was the implementation of the spatial and temporal laser beam smoothing techniques in LPI experiments [55, 56]. Laser smoothing was initially thought as a method for improving homogeneity of laser irradiation of targets, but it also significantly changed the physics of nonlinear LPI and allowed, for the first time, reproducible experiments and a robust comparison with the theory. The LPI physics with smoothed laser beams was described in the seminal paper by Rose and DuBois [57] demonstrating the role of intense laser speckles in the excitation of parametric instabilities; in particular, SRS and SRS. The idea is quite clear: although the number of high intensity speckles in plasma is exponentially small, the amplification factor is an exponential function of intensity. Therefore, even a small number of intense speckles may produce a dominant effect: reducing the threshold and increasing reflectivity. This



**Figure 4.** (a) Distribution of the ion acoustic wave amplitude in a tightly focused laser beam [50]. (b) Near field intensity distribution in a focused laser beam at the intensity  $1.7 \times 10^{15} \text{ W cm}^{-2}$  [51]. Laser propagates in the positive  $z$  direction. Reproduced from [50, 51], respectively, with the permission of AIP Publishing.



**Figure 5.** (a) Dependence of the average SBS reflectivity from a speckled laser beam in an inhomogeneous plasma in function of the average spatial gain [59]. Black (gray) lines correspond to the case with (without) accounting for self-focusing. Numbers near the curves correspond to three different ratios of the plasma velocity scale length to the speckle Rayleigh length. (b) Experimental observation and numerical simulation of the filament instability in an underdense plasma [60]. (a) Reprinted from [59], with the permission of AIP Publishing. (b) Reproduced from [60]. © IOP Publishing Ltd. All rights reserved.

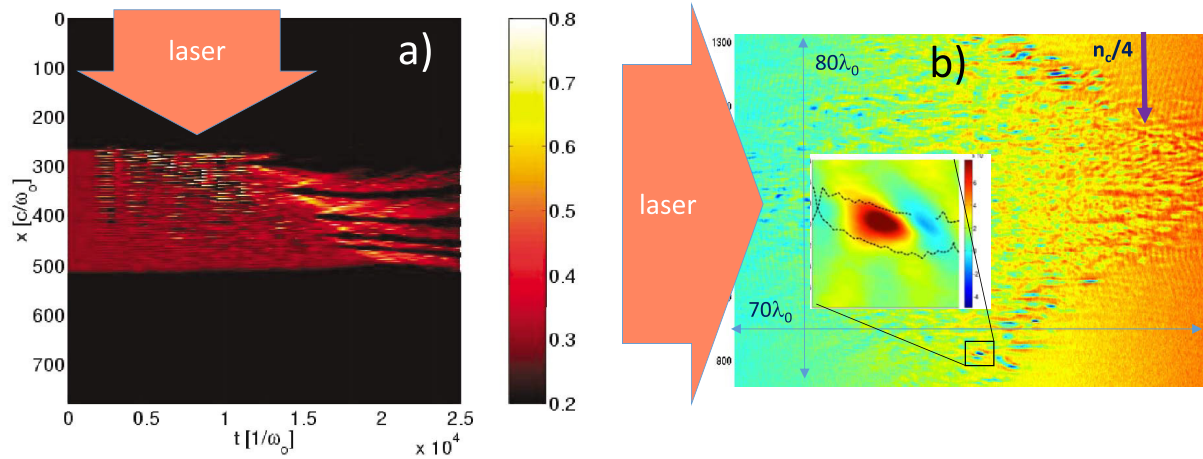
idea of modification of the SBS features from an ensemble of stochastically distributed speckles was applied to the analysis of experiments performed at LULI with laser beams smoothed with random phase plates [58]. We succeeded to obtain good agreement with theoretical predictions of the measured SBS reflectivity and spatial and temporal profiles of the Thomson scattered light from ion acoustic fluctuations.

This first indication of the relevance of the statistical LPI approach motivated us for further work in this direction. Two effects have to be mentioned in this context: self-focusing of intense speckles and their stability. It is intuitively understandable that highest intensity speckles are prone for self-focusing. This leads to even higher intensities thus provoking secondary instabilities and changing the speckle statistics. However, as the speckle self-focuses, its size decreases leading to a shorter interaction length for secondary instabilities. So, the overall result is not so evident. Figure 5(a) shows our predictions [59] for the averaged SBS reflectivity in function of the average SBS gain. The presence of self-focusing significantly reduces

the threshold and enhances the reflectivity, but it also leads to quick saturation of the reflectivity at higher gains because of a limited number of available speckles.

Another important effect is the instability of a self-focused speckle. This has been demonstrated theoretically in our paper [61], which followed numerical simulations of ‘dancing filaments’ performed by Schmitt and Afeyan [62]. Figure 5(b) shows the experimental observation of the time evolving filament and the corresponding simulation with a paraxial electromagnetic code [60].

The effects of the speckle self-focusing and subsequent strong enhancement of the parametric instabilities led us to a more detailed analysis of nonlinear effects at high laser intensities above  $10^{15} \text{ W cm}^{-2}$  for the blue light (third harmonic of the Nd laser). At that time, 10–15 years ago, the performance of computers allowed us to model parametric instabilities with good precision and for a relatively long time by using particle-in-cell (PIC) codes. (By using very high number of macro-particles it became possible to maintain numerical



**Figure 6.** (a) Plasma density evolution and cavity formation driven by SBS in a layer of homogeneous underdense plasma. (b) Numerical simulation of the cavitation near quarter critical density driven by the TPD instability [65]. (a) Reprinted figure with permission from [63], Copyright 2005 by the American Physical Society.

noise at a sufficiently low level and to resolve subtle kinetic effects.) Although these intensities are higher than expected in the standard ICF scenarios, they can be easily achieved in speckles and are also of interest for advanced schemes such as shock ignition [42]. While weak nonlinearities such as secondary LDIs, generation of higher harmonics of ion acoustic waves and particle trapping operate in near threshold conditions, we found quite different scenario at higher intensities. SBS was evolving in strong bursts ended up with formation of a series of cavities with electromagnetic waves trapped inside [63]. That process resulted in suppression of the scattered field, electron heating and acceleration. Figure 6(a) shows the formation of density cavities in a simple one-dimensional case of excitation SBS in a homogeneous plasma layer [63]. This first observation was confirmed in an extended two-dimensional SBS simulations [64] and later the similar scenario was found in SRS and TPD modeling for the shock ignition conditions [43, 65]. In particular, the plasma cavitation near quarter critical density leads to quenching of the TPD instability at a relatively low level. These cavities shown in figure 6(b) are not yet observed experimentally because of their micrometric size, but the TPD suppression has been reported in many experiments at high laser intensities.

The first observation of cavity formation in the laser plasma interaction was reported much earlier by Bruce Langdon and Barbara Lasinski [66], but this paper did not attract the attention it deserved. In an elegant numerical study with the PIC code ZOHAR they identified the modulational instability as the origin of cavitation and demonstrated a strong frequency shift of the trapped light. The plasma cavitation is a rather important process in ICF conditions and it merits further detailed studies. It affects important features, such as the level of reflectivity, spectrum of reflected and transmitted light and hot electron production.

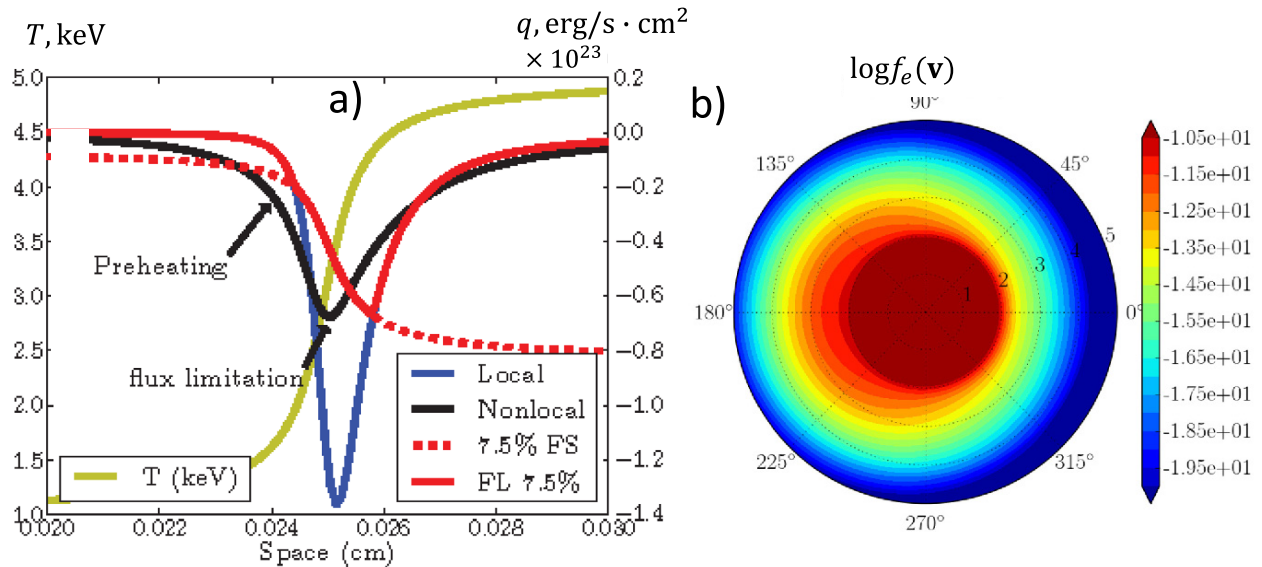
### 3. Nonlocal electron transport

Another important issue that is hanging on ICF research from the beginning is the nonlocal electron transport. It was noted

first by Malone *et al* [67] that the classical diffusion model of electron energy transport developed by Spitzer, Härm and Braginskii is incompatible with observations of x-ray plasma emissions. The flux limiter technique used since that time in all radiation hydrodynamic codes improves the overall situation but it is certainly insufficient and leads to large errors in prediction of laser absorption, plasma temperature in the corona, etc. Although in each particular case it is possible to adjust the simulation results by an appropriate choice of the flux limiter, this procedure undermines the codes' predictive capabilities. The kinetic studies conducted in 1980s with Fokker–Planck codes [67, 68] identified the major reason of heat flux inhibition, that is, modification of the tail of electron distribution function. The approach proposed by Luciani *et al* [69] consisted in a nonlocal expression for the heat flux  $q(x) = \int dx' q_{SH}(x') w(x, x')$  corresponding to a convolution of the local (Spitzer–Härm, SH) heat flux,  $q_{SH} = -\kappa_{SH} \nabla T_e$ , over distances on the order of a few electron mean free paths. The Gaussian-like kernel  $w$  proposed in [69] was improved by Epperlein and Short [70] by using the Fourier representation. This approach was further developed and extended to other nonlocal processes in our paper [71]. It turned out to be quite useful for analysis of parametric instabilities in the plasma corona where the electron mean free path is comparable to the plasma size [72].

However, such an integral representation of the heat flux has significant drawbacks preventing its utilization in hydrodynamic codes. First, this form is one-dimensional, and its extension to two- or three dimensions is not evident. Second, the integral representation is very impractical for implementation in hydrodynamics, which describes plasma evolution with differential equations evolving in time and in space. Third, the kinetic background of the nonlocal transport is hidden in the spatial convolution integral. Another version of the nonlocal transport formulation has been proposed by Schurtz, Nicolai and Busquet (SNB) [73] based on the multigroup approach. The first two authors of that paper joined our group in CELIA shortly after this publication, and we developed this model further together. A big advantage of the SNB model is that it





**Figure 7.** (a) Spatial dependence of the electron heat flux in the case where the electron mean free path is 30 times smaller than the temperature scale length. Blue line—SH heat flux, black—nonlocal flux, red—flux limited (right axis). Yellow line—electron temperature profile (left axis). (b) Electron distribution function in the cold plasma region showing presence of energetic electrons obtained in the same simulation. (b) Reprinted from [75], with the permission of AIP Publishing.

is local in space: the convolution integral in the expression by Luciani *et al* is replaced by a differential diffusion operator in space for each energy group of hot electrons. The total heat flux is then calculated as a sum over all energy groups similarly as it is done for the radiation transport. This approach is certainly advantageous for numerical implementation as it is compatible with the overall structure of hydrodynamic equations. Moreover, it is naturally three-dimensional, computationally efficient, and accounts for the energy dependence of the electron collision length. It was extended to the case of external magnetic field [74] following the scheme by Braginskii. This model is implemented in many radiation hydrodynamic codes and shows much better results than the flux limiter approach.

Figure 7(a) demonstrates the performance of the SNB heat transport model in the case of a strong temperature gradient [75]. Although the electron mean free path in this example is 30 times smaller than the temperature scale length, the maximum electron heat flux is already two times smaller than the SH model predicts. The flux limiter can be adjusted (it is 7.5% in this case) to fit the nonlocal result, but the heat flux spatial distribution is quite different. The flux limiter overestimates the heat flux in the hot zone to the right from the maximum, and it underestimates it in the cold zone. This kinetic preheating effect could be rather important. It presents the population of the streaming hot electrons in the cold zone as it is shown in figure 7(b). The SNB model has been compared with kinetic Fokker–Planck simulations showing rather good agreement in certain cases [76]. It does not however cover the whole zone of parameters interesting for ICF, and we now conducting a more thorough set of comparisons in collaboration with our UK colleagues [77].

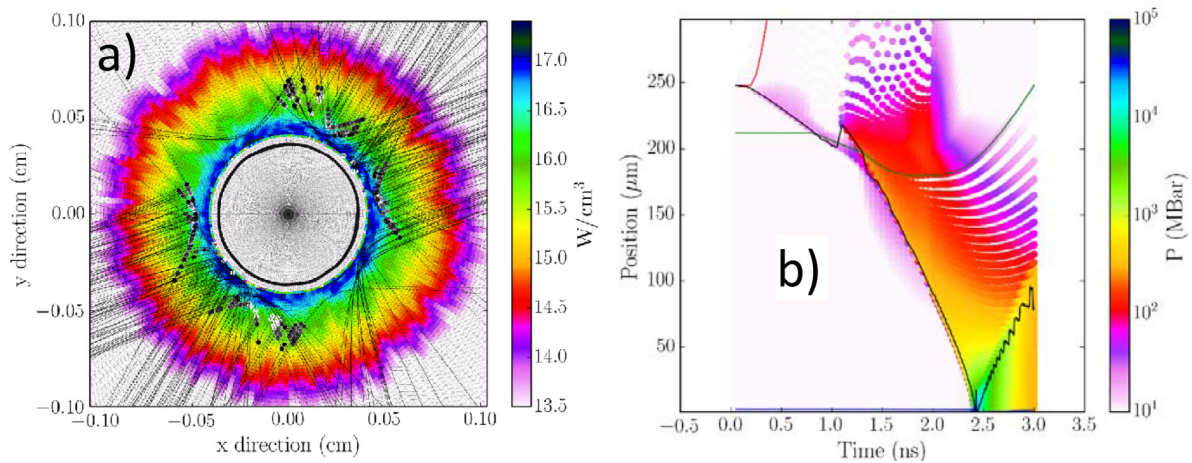
While the SNB model turned out to be quite successful in applications, it remains largely empirical, based on a simplified BGK collision integral, and accounts for the self-consistent electric field in the local SH approximation by using

correction factors. These issues are limiting predictive capabilities of the model and prevent from using it for description of the energy transport with hot electrons produced by other sources than the temperature gradient. In particular, hot electrons generated by parametric instabilities may also contribute to the energy transport in dense plasmas, but their energy distribution is in general non-Maxwellian and they do not follow the diffusion approximation even in the multigroup approximation. As an example, I mention the shock ignition experiment in OMEGA, which shows in average 9% of the incident laser energy been transformed into fast electrons due to SRS instability [78]. The presence of hot electrons allowed to double the shock pressure in this experiment. This number is in good agreement with our theoretical estimate for the shock pressure amplification in the case the electrons depositing their energy downstream the shock front [79].

#### 4. Conclusion: towards a new, integrated model of laser plasma interaction and hot electron transport

This example of strong shock excitation shows the necessity to upgrade the electron transport model in hydrodynamic codes, to make it compatible with multiple hot electron sources and arbitrary electron distribution functions. Such a prospective model is based on two key elements: (i) a fast electron kinetic model capable to describe evolution of the hot electron distribution function and the electron energy deposition in plasma at hydrodynamic time scales and (ii) a laser energy deposition model accounting for the nonlinear effects and capable to define dynamically hot electron sources in plasma corona. That is the major goal of our group in CELIA: to create such a new integrated model of LPI and hot electron transport and to implement it in the radiation hydrodynamic code CHIC [80].

The kinetic model of our choice is M1 [81, 82]. Similarly to the well-known P1 model used by Spitzer, Härm and



**Figure 8.** (a) Energy deposition in a CH cylindrical target imploded with 18 laser beams. Thin lines show centroids of beamlets representing 4 laser beams. Black dots show the CBET zones. (b) Numerical simulation of the pressure evolution in a spherical target in the strong shock experiment on OMEGA laser facility. (a) Reprinted figure with permission from [86], Copyright 2015 by the American Physical Society. (b) Reproduced from [87], with the permission of AIP Publishing.

Braginskii, it considers the development of the electron distribution function in two Legendre polynomials around one preferential direction, but this direction can be chosen separately for each energy group. Moreover, thanks to the special ‘entropic’ closure [83] it operates for an arbitrary anisotropy always preserving the positivity of the electron distribution function. We tested it extensively by comparison with Monte Carlo codes in cold material [84]. It provides an accuracy better than a few per cent. It is also compared with the SNB model showing a very good agreement for the heat fluxes and in addition, providing a detailed electron distribution in energy and angles [75]. An example of an electron distribution calculated with the M1 model is shown in figure 7(b). Our actual plans are to extend it to the case of external magnetic fields and to test it by detailed comparison with large scale Fokker–Planck and PIC simulations for a set of representative cases.

Another key component of our multiscale approach is a nonlinear LPI model based on the paraxial complex geometrical optics (PCGO) [85]. In contrast with the conventional ray tracing technique, where laser beams are represented as bunches of thousands thin rays each following the laws of geometrical optics in plasma, our thick rays are Gaussian beamlets. In addition to the ray coordinates, each beamlet is characterized by its width and wave front curvature, so we know the beamlet intensity all along its trajectory. It is possible, therefore, to define the laser intensity everywhere in plasma as a sum of local beamlet’s intensities in each hydrodynamic cell. This approach opens way for accounting not only the collisional absorption, as it is done with thin rays, but to all other nonlinear processes as soon as they related to the local plasma parameters and laser intensity. Certainly, this is a strongly simplified treatment of nonlinear LPI processes as all of them are treated locally and instantaneously (on the hydrodynamic scales). However, it provides a rather general framework for self-consistent coupling of micro- and macroscopic processes in the same numerical tool, which is convenient for planning and analyzing experiments and the target design.

Not all possibilities of such a multiscale approach are explored for the moment. We succeeded to model speckled laser beams and their temporal smoothing, cross beam energy transfer (CBET) and hot electron generation due to the resonance absorption, SRS and TPD. Figure 8 shows two examples of CHIC simulations with the nonlinear LPI package. The left panel shows the CBET effect on the implosion of a plasma cylinder with 18 laser beams smoothed with random phase plates. Each beam is modeled with 60 Gaussian beamlets focused randomly near the focal plane. A significant azimuthal inhomogeneity of the laser energy deposition is introduced by statistical distribution of laser speckles and further enhanced by CBET between the beamlets coming from adjacent laser beams. The zones of energy exchange are shown with black points in the figure. Figure 8(b) shows the pressure evolution in an experiment where a solid plastic sphere was irradiated with 60 OMEGA beams calculated with the CHIC multi-scale package [87]. A thin dark line shows the shock trajectory, which converges to the center at time of  $\sim 2.5$  ns. It was launched with a prepulse during the first nanosecond and further amplified with the main pulse during the second nanosecond. The main pulse was sufficiently intense to generate a large number of hot electrons due to the SRS and TPD instabilities, which contributed to the shock pressure by depositing their energy downstream the shock. However, the most energetic electrons penetrate upstream the shock front and deposit their energy there (the pink zone in the time interval between 1 and 2 ns). Accounting for the energy deposition of hot electrons was necessary for explaining the observed shock collapse time and thus for evaluating of the shock pressure.

The multiscale hydrodynamic modeling is a promising approach for the planning and interpretation of laser plasma interaction experiments and future target designs. The presented examples are encouraging but the model needs further developments and fine tuning in specially designed experiments. It will be helpful also for studying other problems in high energy density physics.

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