REPORT

on the dissertation of

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on the topic:

Nonlinear laser absorption under high-energy-density conditions

The dissertation focusses, via a theoretical and numerical research work, on the scenario of shock ignition, within the context of inertial confinement fusion (ICF) induced by impinging a nanosecond high-power laser pulse on a millimetre-size deuterium-tritium-filled capsule. In this scenario dating back to 2009, two different topics are addresses: (i) the nonlinear processes which scatter the incident laser light, namely the stimulated Brillouin (SBS) and Raman (SRS) scatterings, which contribute to reduce the amount of laser light deposited into the capsule and (ii) the creation of a long quasi-homogeneous plasma from a porous foam, used to smooth the laser-beam homogeneity flaws, a heterogeneous material made of 1 μm-scale solid plastic/gas cells. Coherently with the present ICF programs, a 0.35 μm laser wavelength (denoted henceforward λ_0) has been used along this work. The work has been carried out within a collaboration framework between the Czech Technical University in Prague and University of Bordeaux. The dissertation entails 141 pages of text including the bibliography. The results are already reported in 4 papers published in peer-reviewed journals with the candidate as the first author. Herebelow, the main points found in the six parts of the dissertation are detailed, chapter per chapter and the issues raised by the results are collected at the end of this report.

The introduction (11 pages) gives an overview of the context of researches on laser-driven ICF, on both pathways, indirect drive, with better homogeneity of the capsule irradiation but lower efficiency, and direct drive, with lower complexity but higher sensitivity to the laser beam quality which furthermore features alternative scenarii. In the latter, the shock ignition consists in launching, in addition to a main laser pulse used to highly compress the capsule core, a short laser pulse able to send a strong shock going inward to the capsule core in order to heat it up to trigger the nuclear fusion reactions.

Part I (34 pages) gathers the knowledge on the various laser-plasma interaction processes at stake: (i) laser absorption induced by electron-ion collisions within the linear response of the plasma; it is strengthened nearby the so-called critical density n_c beyond which the laser light cannot penetrate. (ii) SBS growth rate and spatial gain for inhomogeneous plasma and its dependence on plasma flow, laser bandwidth and multiple ion species; C and H ions show a 6-fold increase of the ion-acoustic wave damping induced by a kinetic effect of the light protons and a spatial gain reduced by a factor three. (iii) SRS with generated hot electrons; non monotonic density profile induced by the ponderomotive pressure below the scatter-wave cut-off density $n_c/4$ has a large impact on the SRS-induced absorption. A kinetic model of a plane wave obliquely incident on a plasma surface is described together with a bottom and top density cavity model. The real and imaginary parts of the dielectric constant and the collisionless absorption by mode damping on the wall of the cavity are calculated as a function of the electron temperature and the cavity width. 1 %-absorption is observed. 2 λ_0 width is a critical cavity size below which the mode frequency grows rapidly towards 0.5 ω_0 and beyond which SRS behaves as in the bottom density plasma. This analytical model is appealing but the context of the presence of these cavities with the numerous previous works of the 80's to explain the specificities of the SRS backscattered light spectrum is lacking. The chapter ends with the preheating of the capsule core by the hot electrons generated by essentially SRS at typical 50 keV temperature. The wave-particle interaction processes are reviewed: Landau damping, particle trapping and wavebreaking. It should be noted that SI units are used in the text (with dielectric permittivity in vacuum explicitly written) but CGS units are used for Maxwell equations and in Chapter II as well.

Chapter II (25 pages) reports on numerical simulations carried out with a kinetic plasma model, centred on Vlasov equation coupled to Maxwell equations solved by a particle-in-cell (PIC) code. The chapter starts with the basic principles of a PIC code and some features of the new open-access code used. The time/space scales resolved in PIC codes, namely the electron plasma period/Debye length, limits dramatically to 5-10 picoseconds the physical duration of a PIC simulation. As a usual laser pulse is in the range 10^{3-4} picosecond, PIC simulations need to use plasma conditions specific to one time within the laser pulse. The features of the plasma (ionization level, density, flow, temperature profiles) are consequently provided by a one-fluid model coupled to a reduced model for the electromagnetic field. A well-known 2D code from CEA and University of Bordeaux has been used. Six 1D simulations have been carried-out over 8 ps with different parameters (1) reference case with no collisions, no flow, one ion species, (2) with collisions, (3) with linear flow ramp, (4) with both collisions and flow, (5) H and ion species, (6) H and ion species and a laser bandwidth. The macroscopic parameters are: constant laser irradiance 6 10^{15} W/cm^2, simulated density range [0.05,0.28] over 286 λ_0 length framed by 14 λ_0 vacuum area. Particle boundary conditions model a canonical system with a plasma tank on both sides at constant temperature. First, results on the time influence on temperature, on reflexion, transmission and absorption are given. Time-space display of the back-scattered light and the longitudinal electric field conditions show scenario where after 4 ps SBS backscatter strongly the incoming light. With plasma flow, the inhomogeneous flow kills SBS and let SRS grow. Second, hot electron generation is presented. 10 % of the electron are seen as hot ones, with 35 keV temperature at maximum reduced to 10 keV when SRS is inhibited by strong SBS or laser bandwidth. At last, results on ion heating driven by both SBS and expansion of the SRS-generated cavities are reported. The next part reports on 2D simulations. No detailed information is given as to the conditions of simulations: collisionless, no bandwidth, no expansion are indicated only in the concluding part of the chapter. As major results: weak SRS backscatter (4 %), high SBS level (10 to 40 %) and hot electron observed at 90 keV-temperature at the pulse intensity peak and in a large 50° half-aperture cone. As a difference with 1D simulations, sidescatter plays a large role and the driven-EPW is claimed to trigger Langmuir decay instability.

Chapter III (19 pages) concentrates on the behaviour of a foam, from a rigid set of plastic-made solid bits surrounded by atmosphere gas, toward a homogeneous plasma. The involved processes of ionization and subsequent heating and fluid expansion and mixing with neighbour solid sites are made intricate because of the large density and material gradient on micrometre scale. This topic had a burst activity around 2010 in US and France in connexion with megajoule laser programs. One difficulty comes from the size for the solid element comparable to the laser wavelength. A 2D analytic model of the interaction is proposed assuming the plastic part is a solid-density disk (infinitely-long cylinder) instantaneously ionized such that the resulting free electron density make the plastic bit opaque. This disc is on the centre of a much larger square cell, such that at last when homogenized the cell is characterized by an underdense transparent homogenised plasma. Following the Mie theory, the electric field expanded on a set of Bessel functions lets find the scattered field and the absorbed one (collisional or collisionless) in the disc as a function of the radius and the angle for two density profiles: uniform or bell-shaped. The latter make the two polarisations largely differentiate, due to resonant absorption induced when the incident electric field is within the disc plane. Clear influence of this process is observed by comparing the radial distribution of laser energy deposition as a function of the density ramp. The field polarization perpendicular to the disk shows a bell shape associated to the collisions whereas the polarization in the disk plane exhibits in addition a resonance at critical density, which with 90 % of the total absorption largely dominates the total absorption. Two hydro codes, one at University of Prague and another open-access, have been used with multiscale model featuring the discussed cold-to-hot foam homogenization model.

Chapter IV (21 pages) reports on 2D PIC simulations of a laser wave impinged upon a series of discs representing a porous material, with similar geometry as discussed in the analytical previous chapter. Somehow low irradiance 10^{14} W/cm^2 has been used with plastic disc with density 35 n_c, 1 eV temperature and radius 0.1 μm within a 2.7 μm size square. The density profile shows that a rarefaction wave converges towards the disc centre preserving a radial symmetry and after 8 ps an outward motion is associated to the expansion causing the decrease of the peak density. Electron and ion energies are then analysed: referred to the cylinder axis, parallel polarization (P) lets see 0.02 and 0.3 keV e/ion temperatures whereas normal polarization (S; electric field within the disc plane) shows much larger energies 0.7 and 25 keV respectively. In the latter case, the cell is filled with the expanded plasma at 4 ps. perpendicular polarization shows a larger laser absorption, because of strong resonant absorption. The text reports a detailed analysis of the simulation and comparison with the analytical results based on a hyper-Gaussian density profile separating the ablation velocity associated to the disc mass variation and the expansion velocity attached to the variation of the central density and the profile stiffness (negative when rarefaction wave). For S (resp. P) polarization, ablation (resp. expansion) dominates and the homogenization time is roughly 1/3 of the second case, i.e. 30 ps. A singular feature of this kind of interaction is the ions are hotter than the electrons (3.8/1.4 keV) and the large role of ion-ion collisions inducing a smaller collision mean free path for ions compared to the electron one. From this analysis preformed with a kinetic model, a so-called macroscale fluid model has been implemented in two radial geometry codes, playing with a unique plasma density and flow and two different electron and ion energies $\varepsilon_{e,i}$: one local code in Prague University and one open-source code. Three different kinds of state of matter have been modelled: piece of solid surrounded by vacuum, intermediate state and plasma state. For the first cases, the cylinder-plane wave model discussed before is solved together with the laser and heat transport in the fluid (microscale model). In case when the cell density becomes equal to the surrounding density, the plasma is considered dominating and the full 4-equation fluid model (macroscale) is solved. The incoming light is modelled by a set of rays which suffer refraction and absorption by each traversed cell. As a paramount result of this work, the model shows a better agreement to the models proposed since 2018 by Gu'skov et al (absorption underestimate) and Belyaev (absorption overestimate).

The conclusion (3 pages) summarizes the two different parts of this work: (i) via plasma kinetic-Maxwell coupled equation simulation, the mitigation of SBS and the important absorption at quarter-critical density SRS in density cavities, (ii) the Mie theory-based model, its validation by 2D kinetic simulations and implementation into a fluid model code. This is followed by a short list of prospects, multi-parameter analysis where multi-ion species, laser bandwidth and fluid expansion variation are joined together and the influence of the pore size in the foams. The list of conferences and published papers is then given and the dissertation is ended as usual with a large bibliography, gathering pioneer papers and recent papers associated to a very active area of physics.

As conclusive remarks, the dissertation reports on original results collected during a 5-year research activity, which show a high scientific value with the context of an alternative scenario of the direct drive for ICF. Each studied process is introduced by a short list of previous works with their main input, so explicating the chaining with other researches over the world on this challenging topic. The text is well written (only a few misprints have been noted), easy to read, to understand; the summary which ends each chapter has been greatly appreciated. Even though the details of numerical simulations and the computing aspects are far to be given, i.e. simulation time, diagnostics to adapt, the PhD student was involved in running the simulations and developing diagnostics and new models within the codes and this is well known to be very time-consuming, to require deep investment and effort to be able to extract interesting results from the mass of data provided by these multiple different numerical tools. Aware of all the positive arguments pointed out on the physics gathered in this dissertation, I acknowledge the quality of the research work conducted by the candidate, who fulfils the requirements to be awarded Doctor of Philosophy and I recommend S. Shekhanov to defence his PhD thesis.

The reading induced me several questions which are listed below, with reference to the typescript page:

Chapter I:

- P. 22 : why is $\vec{\nabla}T$ disregarded?
- P. 22 : is the bandwidth used for a unique ion species?

Chapter II:

- About the boundary conditions, symmetry chosen would be discussed, since on the vacuum side, a sticky condition is expected to be more appropriate than a reflective condition.
- P. 54: how is the electron bulk temperature T_e inferred with no account of the hot electrons would be commented. Its growth associated the $n_c/4$ density SRS needs to be clarified.
- P. 58: SRS is claimed to be convective. What about the presence of IAW generated by SBS which can destabilize into absolute instability?
- P. 59: the cavity-induced absorption (0.1 %) is well below the observed absorption (10 %). How can it be claimed so important?
- P. 66: no geometrical aspect for the 2D runs is given. What about the transverse conditions? The transverse size?
- P. 68: the definition behind the plasma wave turbulence should be given?
- 2D simulations report on existence of Langmuir-decay-instability (LDI) of the SRS-driven plasma wave only for sidescatter. Why is this instability invisible for 1D simulations?
- As no information is provided on the runtime, it is unclear why only 6 1D simulations and 1 2D simulation have been carried out and not a larger parametric study

Chapter III:

- P. 81: how many harmonics are required to get physical results?
- P. 84: numerical solving is carried out via a Wolfram Mathematica package. The kind of solving and procedure would be detailed?

Chapter IV:

- p. 92 (fig. (d): why is there a hole, visible only for P polarisation? Why does the plasma expand with a monotonic profile?
- The model disregards the low intensity solid-laser interaction. What about the possible destruction of the foam pattern by a shock induced by laser irradiances as low as 10^8 W/cm^2 ?

Conclusion:

- With the benefit of the hindsight brought by these reported results, which credit could be bring to the shock ignition scenario within short term?

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