Title : **Laser-Plasma Interaction and confinement inertial fusion**

Acronym : O8

EU Coordinator : Sylvie DEPIERREUX, Benoit CANAUD (CEA/DAM)

Teaching staff : Sylvie DEPIERREUX, Benoit CANAUD, Frédéric PEREZ

Pre-requisites : First year of MSc in Physics or Engineering Schools.

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This module consists of two parts. The first one is devoted to laser-plasma interaction. It discusses the non-linear wave mixing mechanisms inherent in the propagation of a large wave in a plasma and the resulting resonant couplings. The ponderomotive force is described as well as its effects on plasma as self-focalization. Thomson scattering is also presented as a powerful method for plasma diagnosis and various parametric instabilities such as stimulated Raman scattering. Finally various applications are presented.

The second part outlines the general concepts of inertial confinement fusion: compression, heating, ignition, gain. The fundamental concepts of nuclear physics, thermonuclear fusion and the principle of confinement are recalled. Post's temperature concepts and Lawson's criteria are introduced. Various gain fusion schemes are presented, such as isobaric ignition, fast ignition and shock ignition. The hydrodynamics of laser-created plasmas provide an opportunity to address the notions of self-similar flow or shocks. The modes of transport of thermal energy within the target are detailed.

Interaction laser-plasma

We study the non-linear mechanisms that develop when an intense laser electromagnetic wave is propagating in a plasma. For such wave, a development of the equations of propagation of the laser wave and ion and electronic plasma acoustic waves up to the second order is necessary. New mechanisms of non-linear coupling between these modes appear.

A first effect, called a ponderomotive force, leads to the expulsion of electrons from areas of higher intensity. For a beam of finite transverse dimension, the ponderomotive force leads to a modification of the optical index in the direction transverse to propagation, producing the effect of a plasma lens that concentrates beam energy on a small size (Fig. 1a). For very short-duration beams, of the order of a few femtoseconds, the finite size of the laser pulse causes the electrons propagating forward the direction of the pulse regarding the beginning of the pulse and backward for the pulse end (Fig. 1b).

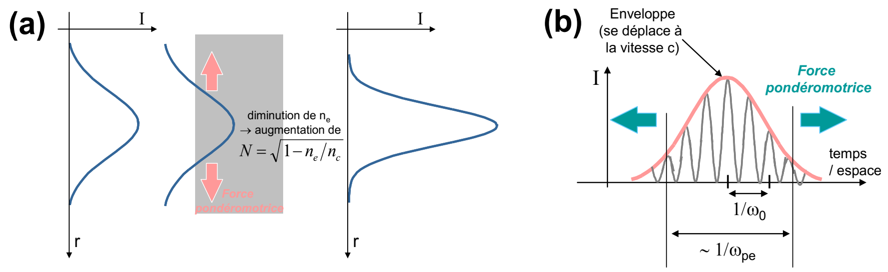

Fig. 1 : two effects of the ponderomotive force :(a) self-focusing of a Gaussian beam; (b) excitation of an electron plasma wave by a short pulse.

A second non-linear effect generated by any incident electromagnetic wave in a plasma regards the resulting current from the oscillation of electrons in the electric field of the incident electromagnetic wave. This current is the source of a diffused electromagnetic wave. For low-intensity, it results in the probe spreading about density fluctuations in the plasma, which is still known as the Thomson scattering. It is a powerful method of characterizing plasmas. Beyond an intensity threshold for the incident beam, these two non-linear terms (ponderomotive force and non-linear current) lead to the unstable coupling of the incident electromagnetic wave with a plasma wave and a scattered electromagnetic wave. This three-wave coupling is schematically represented in Fig. 2. The energy of the incident laser wave maintains the instability that amplifies both the scattered and the plasma waves. These instabilities are called "stimulated Raman scattering" or "stimulated Brillouin scattering" depending on whether they involve an electronic plasma wave or an ion acoustic wave.

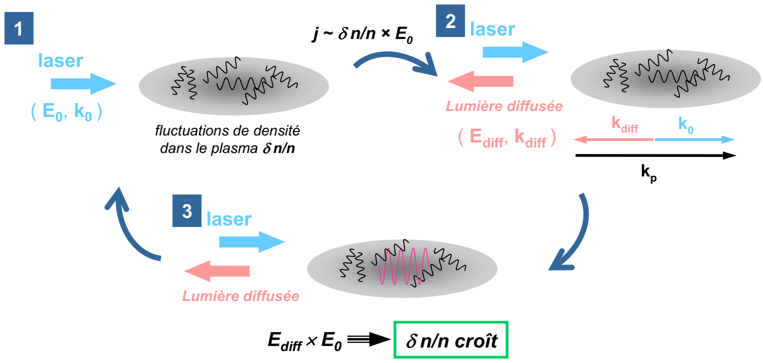

Fig. 2: Schematic representation of scattering instabilities (three-wave coupling).

These mechanisms were first studied in the context of thermonuclear fusion controlled by laser inertial confinement (ICF). Laser-plasma interaction is one of the first themes to master as it aims to optimize the efficiency and quality of laser energy deposition. In this context, self-focalization interferes with the proper spread of the laser, while stimulated scattering instabilities lead to significant losses of laser energy in the form of backscattering. In the multi-beam configurations of direct and indirect drive in ICF, the beating between the incident laser waves themselves profoundly alters the laser-plasma interaction in the crossover regions of the laser beams. This aspect of the laser-plasma interaction will also be dealt in the course. Others applications concern the stimulated Raman and Brillouin scattering instabilities that are studied today as new technique for the amplification of short pulses. These patterns of amplification of short pulses in plasmas aim to push the limits towards ultra-high intensities beyond the technological limit of damaging optics inherent in the traditional method of amplification of pulses by drifting frequency.

Thermonuclear inertial Fusion

The second part outlines the general concepts of inertial confinement fusion as well as the main plasma physics problems associated with it. After a detailed recall of the nuclear reactions involved, the concepts of nuclear physics and the different pathways of nuclear fusion, the fundamental elements of thermonuclear fusion such as thermal reactivity and the notion of confinement that leads to the definition of Post's temperature or the Lawson criterion are introduced. Next, we discuss inertial confinement and the concept of hot spot ignition and its various variants (isobaric self-ignition, non-isobaric shock ignition, fast ignition) to look at the implosion of a target and its compression. This introduces the concept of minimal isobaric ignition kinetic energy and the different pathways of inertial confinement fusion (direct drive of the target by laser radiation or indirect drive after conversion of laser radiation into X-ray). The description of hydrodynamics of laser-created plasmas such as the flow triggered by laser-matter interaction, shocks, which play an important role in the acceleration of the internal layers, or the conduction of thermal energy, especially between the energy absorption zone and the more internal parts of the target. For the latter, we discuss the conduction of Spitzer-Herm which, in the extreme situations encountered in ICF, is no longer correct and must evolve towards a non-linear and non-local theory. Finally, we present the deleterious mechanisms of implosion that are hydrodynamic instabilities that degrade the symmetry that one would like perfectly spherical.

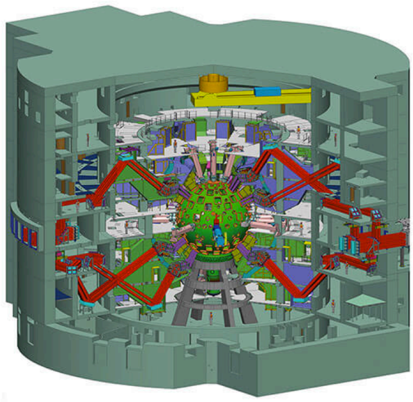

Fig3. : Inertial Fusion experiment