Study of low-frequency radiation produced by particle acceleration at ultra-high laser intensity in relativistic plasmas

Context: Laser-matter interaction – Laser-induced low-frequency radiation

Thesis objective: Today, petawatt laser sources deliver optical pulses lasting a few tens of femtoseconds with an intensity larger than 10^{20} W/cm^2. When such a light beam interacts with a gas or a solid target, the electrons accelerated by the laser ponderomotive force become relativistic and acquire high energies, in excess of the GeV. These laser systems also produce various radiations such as hard X photons or electron-positron pairs by quantum conversion of gamma photons. As laser technology is advancing rapidly, these light sources have increasingly compact dimensions and they nowadays complement many international laboratories hosting synchrotrons or conventional particle accelerators.
If this extreme light makes it possible to generate radiation in the highest frequency regions of the electromagnetic spectrum, it also fosters, through the production mechanisms of plasma waves and particle acceleration, conversion processes towards much lower frequencies belonging to the gigahertz and terahertz (THz) ranges.

Having high-power transmitters operating in this frequency band is attracting more and more interest in Europe, overseas and in Asia. On the one hand, the generation of intense electromagnetic pulses with GHz-THz frequencies is harmful for any electronic device close to the laser-plasma interaction zone and the diagnostics used in large-scale laser facilities like, e.g., the PETAL/LMJ laser in the Aquitaine region. It is therefore necessary to understand their nature to better circumvent them. On the other hand, the waves operating in this field not only make it possible to probe the molecular motions of complex chemical species, but they also offer new perspectives in medical imaging for cancer detection, in astrophysics for the evaluation of ages of the universe, in security as well as environmental monitoring. The processes responsible for this violent electromagnetic field emission, if properly controlled, can lead to the production of enormous magnetic fields in excess of 1000 Tesla, which presents exciting new opportunities for many applications such as particle guiding, atomic physics, magnetohydrodynamics, or modifying properties of condensed matter in strong field.

The objective of this thesis is to study the physics of the generation of such giant electromagnetic pulses by ultrashort laser pulses interacting with dense media, to build a model based on the different THz/GHz laser-pulse conversion mechanisms, and validate this model by using dedicated experimental data. The proposed work is mainly oriented towards an activity of analytical modeling and numerical simulation.

The doctoral student will be invited to deal with this problem theoretically and numerically using a particle code whose Maxwell solver will be adapted to describe radiation coming from different energy groups of electron/ion populations. A module calculating online the field radiated by each particle population in the far field will be implemented. Particular attention will be given to the radiation associated with the acceleration of electrons and ions on femto- and picosecond time scales by dense relativistic plasmas and their respective roles in target charging models available in the literature. This field of physics requires a new theoretical and numerical modeling work, at the crossroads of extreme nonlinear optics and the physics of relativistic plasmas. Theory-experiment confrontations are planned within the framework of experiments carried out on site at CELIA facilities and experiments carried out in collaboration with US laboratories (LLE/Rochester).

Progress of the thesis: Thesis's first year will consist in acquiring the bibliographical knowledge necessary for the proposed work. The student will be invited to familiarize him/herself with the physics of relativistic plasmas, particle acceleration by ultrahigh intensity lasers and the production of electromagnetic radiation by a beam of particles accelerated in a plasma. Original scenarios and devices optimizing the production of radiation will be proposed. The student will invest in the kinetic, "particle-in-cell" code SMILEI available at CELIA and will be guided to adapt routines to map and manipulate populations of electrons and accelerated ions according to their energy range. The second year of the thesis will aim to test the interaction schemes proposed by the student from simulations using this code on the massively parallel supercomputers of the TGCC and the CINES. The third year of the thesis may be devoted to comparing the theoretical and numerical results acquired by the student with experimental data already published or obtained within the framework of collaborations. This last year will also be that of writing the thesis.

The candidate must have advanced training in plasma physics and/or scientific computing, with an ability to handle simulation codes or for programming (Python, Fortran, C++).

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