Laboratory astrophysics studies : from collisionless shocks to quantum effects

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Laboratory astrophysical studies are approaching astrophysical conditions, at least in terms of dimensionless ruling parameters. Terawatt-class lasers along with efficient magnetic pulsers allow to study physics related to collisionless shocks in supernovae remnants (SNRs), at the stage of the interaction with an ambient magnetized interstellar medium. Such studies aim to give a deeper understanding of the formation of magnetized collisionless shocks and their structure, interaction of a plasma flow with the magnetized medium, including collisionless magnetization, particle acceleration and energy redistribution.

Moreover, the development of multi-Petawatt laser facilities such as ELI or Apollon will offer the possibility to study novel regimes of relativitic laser-matter interaction, in which the quantum electrodynamics (QED) effects play an important role. These effects include synchrotron-like emission of X and gamma photons, and their subsequent decay into electron-positron pairs. They are expected to largely influence the laser-driven acceleration of charged particles and, as a result, the overall energy balance of the laser-target interaction. Furthermore, the successive emission of hard photons and their decay into newly emitting particles may result in pair-creation cascades, of great interest for the experimental generation of high-temperature and high-density quantum plasmas.

Finaly, high energy photon sources allow to study e^+, e^- pair creation. The generation of electron-position pairs in photon collisions is one of the basic processes in the Universe. The electron-positron production $\gamma + \gamma$ to $e^+ + e^-$ (linear Breit-Wheeler process) is the lowest threshold process in photon-photon interaction, controlling the energy release in Gamma Ray Bursts, Active Galactic Nuclei, black holes and other explosive phenomena. It is also responsible for the TeV cutoff in the photon energy spectrum of extra-galactic sources.

In this communication, concerning the collisionless chocks we consider the interaction of two couter-propagating homogeneous sub-relativistic plasma beams. Two different situations are studied: with the presence or not of an external magnetic field. The numerical simulations are performed with the PIC (particle-in-cell) codes PICLS and CALDER.

Our results show that without magnetic fields: the shock formation is initiated with development of electron-ion Weibel-like micro-instabilities, followed by fast electron heating and ion de-acceleration and heating. We present a theoretical analysis of the instabilities development and nonlinear saturation to explore the origins of the heating and the magnetic field generation.

However, concerning the case with a strong external magnetic field, two stages are reported. A magnetic field compression stage develops in our studies along with the charge separation effect, at a time scale much shorter than a collisionless shock formation time. The next stage

is a magneto-electrostatic instability which develops in the interpenetration region [1]. After this fast instability development, slow collisionless magnetization of the interpenetrating plasma flows takes place. This latest stage is clearly seen in the experimental data obtained on the JLF-Titan laser (USA), which we compare with transparent physical models and with PIC simulations.

Another interseting physics concerns the quantum effect during high intensity laser plasma interaction [2, 3]. The newly upgraded PIC code CALDER is used to simulate a number of ultra-high intensity laser-plasma scenarii, further demonstrating the robustness of the chosen numerical schemes. We first focus on the interaction of a laser pulse with thin aluminum foils in the hole boring regime. The consequence of the radiation losses on the electron heating and the ion acceleration is studied for different intensities. Using a laser pulse of intensity $I > 10^{23}$ W/cm^2 leads to the generation of a dense $e^+ e^-$ pair plasma accelerated backward to relativistic energies. Using a setup with two lasers, it is possible to study the developpement of a collisionless shock in the collision of $e^+ e^-$ plasmas.

Finally, concerning the QED process, we proposed to study the linear Breit-Wheeler (BW) process [4]. The electron-positron pairs creation by photon-photon collision has never been clearly observed in laboratory with important probability of matter creation. We propose a new experimental approach for the observation of this process. This scheme offers a possibility of conducting a multi-shot experiment with a reliable statistics on laser systems with pulse energies on the level of a few joules and in a low noise environment without heavy elements. This scheme relies on a collision of relatively low energy (few MeV), intense photon beams. Such beams can be created in interaction of intense laser pulses with thin plastic targets. By colliding two of them in vacuum, one would be able to produce a significant number of electron-positron pairs in a controllable way. We provide details of the experimental setup, estimates of the expected yield of reactions and possible ways of creation of a photon source with requested parameters [5].

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