FINAL PUBLISHABLE SUMMARY REPORT

Interaction of ultra-intense laser pulses with plasmas

The goal of this project is to coordinate the activities of four partner laboratories in the domain of high energy density physics and laser plasma interaction and to build more close and efficient relations between the theoretical developments, numerical simulations and experiments. The project is divided in four work packages. The major outcomes are presented below.

Work package 1: Electron and ion acceleration by the ultra-relativistic laser pulses

For practical applications of laser acceleration of ions, in particular for the hadron therapy, it is very important to produce quasi-mono-energetic ion beams. In our work on laser acceleration of ions from solid targets, a special attention is focused on targets with two ion species (light and heavy) distributed homogeneously or heterogeneously. Such targets are very thin, less than 1 μm, with optimum thickness subject to finding from computer simulations. They can provide higher quality ion beams as compared to the single species targets. The heavier atoms serve as a source of electrons leaving a target and creating a strong electric field, which accelerates light ions. Heavy ions behind them are acting as a Coulomb piston and provide a mono-energetic feature of the light ions. Self-repulsion between light ions can significantly worsen their spectral characteristics. Therefore, for best quality of a bunch of light ions their total charge should be rather small.

By varying structuring of two component targets one can make practical use of more effective laser acceleration and achieve better ion characteristics: lower energy spread, higher energy and increased number of particles in a given energy range [A V Brantov et al., Proc 7th Conf Inertial Fusion Science and Applications, p.93 (2011)]. The target with an optimum thickness is nearly transparent for the laser pulse, which removes significant part of electrons from the focal sport. Strong charge separation field push out all the protons from the focal spot. Together with radiation pressure, non-instantaneous electron acceleration in forward direction makes ion explosion asymmetrical, called directed Coulomb explosion. As a result, a mono-energetic proton beam with energy of hundreds mega-electron-volts was generated by the laser pulses with energy of the order of few tens joules.

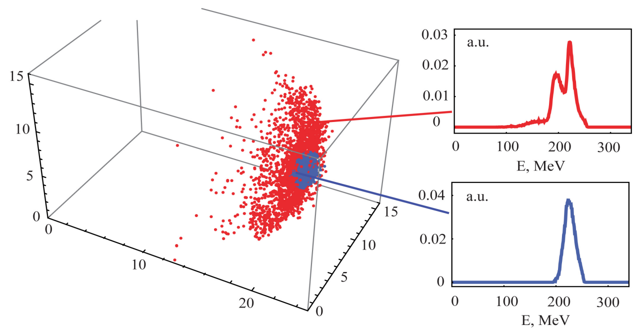

Figure 1: Spatial distribution of protons accelerated with a 20 J 15 fs laser pulse tightly focused on a 100 nm flat target. Inserts show the energy distributions of protons.

Work package 2: Effects of electron ion collisions in a strong laser field

Traditionally, the theoretical study of electron-ion collisions in strong electromagnetic fields is carried out based on models that are based on the approximation of binary collisions. It is assumed that the probability of a simultaneous collision of three particles in the same point in space is negligible. The characteristics of the collision integral for the particle distribution function can be found by considering the scattering of a beam of noninteracting (test) electrons on one ion. All studies were based on the assumption of uncorrelated collisions. Only recenty, in our publications [G M Fraiman et al., Phys. Plasmas **8,** 2502 (2001), H-J Kull and V Tikhonchuk, Phys Plasmas **12,** 063301 (2005)] it was demonstrated that in strong laser fields multiple electron-ion correlated collisions may have a significant effect on the energy exchange. An electron that is initially far from the scattering centre (an ion) may experience several returns and finally obtain a big amount of energy in a last “hard” collision. However, this effect was demonstrated in a classical approach, even if the de-Broglie length of the incident electron can be compared with the impact parameter. In the present work the classical scattering problem of an electron by an ion in nonrelativistic laser field is compared with the quantum scattering problem by using the numerical solution to the Schrodinger equation. Comparison of the quantum and classical distribution functions of scattered electrons on energy demonstrate that the classical solution reproduces the quantum result with a good accuracy.

A microscopic effect of correlated electron-ion collisions in strong laser fields manifests itself in the kinetic, many-particle approach in the specific collision integral. We developed a new electron-ion collisional operator in the Boltzmann form where the effective collision frequency is averaged over the laser period [A A Balakin and G M Fraiman, Europ Phys Lett **93**, 35001 (2011)]. In difference from a standard diffusion in the momentum space, the new collision integral contains a source term describing generation of energetic electrons. It is demonstrated that such representation gives correct values for the plasma heating rate and for the distribution of hot electrons.

Work package 3: Interaction of intense laser pulses with low density structured targets

Under-critical plasma can significantly improve uniformity of laser beams and homogeneity of laser energy deposition in inertial fusion targets. This is especially important at the initial phase of the laser pulse when the optical smoothing methods are not yet operational. A physical model of energy transfer in the plasma produced from an under-critical foam is developed [S Yu Gus'kov et al., Phys Plasmas **18**, 103114 (2011)]. The laser-supported ionization wave in a foam has a significantly smaller velocity than in a homogeneous material with the same average density. Such a delay is due to the process of homogenization of pores on the wave front. Our model is in good agreement with the measurements of ionization wave velocity (500 km/s) and plasma temperature behind the ionization front (1.7 keV) in the experiments conducted on the LIL facility in France [S Depierreux et al, Phys Rev Lett **102**, 195005 (2009)].

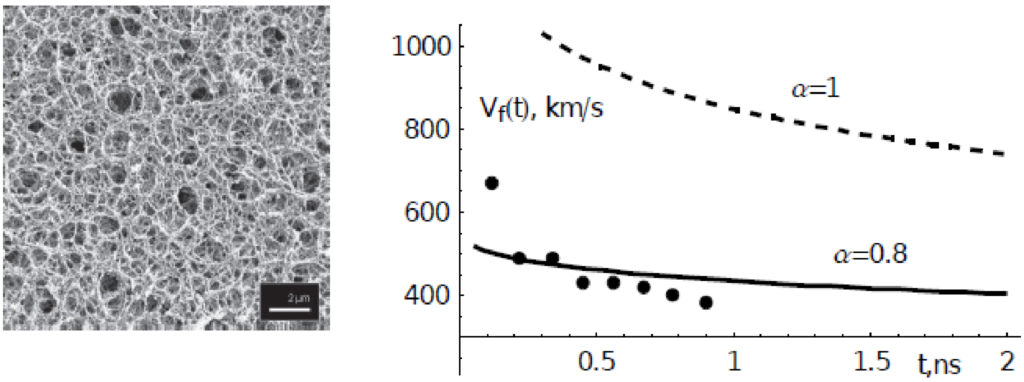

Figure 2: Left: fractal structure of the foam. Right: temporal dependence of the ionization front velocity for the parameters of LIL experiment. for two values of the fractal parameter $\alpha = 0.8$ (solid line) and 1 (dashed line). The points present the measurements of the ionization front velocity.

We have developed a new criterion of the efficient plasma smoothing based on the process of near forward stimulated Brillouin scattering that can be realized with foams. That theoretical idea has been tested in several large scale experiments on the LIL laser facility [S Depierreux et al., Plasma Phys Control Fusion **53**, 124034 (2011)]. A specially prepared target with a foam of the density ~ 10 mg/cm^3 was ionized with a 12 kJ with millimetre-size laser beam, reproducing the conditions of the initial interaction phase in the direct-drive scheme. Generation of a supersonic ionization wave in the foam and the reduction of initial laser fluctuations with limited levels of stimulated Brillouin and Raman scattering were measured. The smoothing mechanisms are found to be in agreement with the theoretical expectations.

The analysis of the influence of irradiation symmetry on the baseline HiPER target compression was carried out on the base of method of the maps and histograms of irradiation by using the one- and two-dimensional hydrodynamics simulations. The irradiation symmetry was calculated at the number of laser beams 8, 12, 20 and 48. The dependence of the areal density of the compressed HiPER target on the number of irradiating laser beams was found.

Work package 4: Generation of directed THz pulses from plasma channels

Considerable attention has been focused recently on the plasma mechanisms of terahertz radiation generation involving atmospheric air breakdown induced by focused femtosecond laser pulses. This generation technique offers certain advantages over nonlinear rectification in solids: the absence of a damage threshold, allowing use of higher intensities of laser radiation; absence of clearly defined resonances, which may cut off appreciable portions from the spectrum of generated terahertz radiation; and a high generation efficiency of several schemes. Furthermore, in remote monitoring systems, it is possible to bring the plasma source and the terahertz radiation detector quite close to the object under inspection.

Extensive experimental research into the generation of terahertz radiation in a laser-induced spark was carried out in the framework of this project. It was shown, in particular, that the application of an electric field of about 10 kV/cm (close to the threshold of air breakdown at atmospheric pressure) increases the generation efficiency by more than a factor of 200 and that the addition of the second harmonic to the optical radiation at a 10% level (with the appropriate phasing of the 1st and 2nd harmonic fields) results in an efficiency increase by more than four orders of magnitude. Furthermore, the measurement of the radiation pattern and polarization of the terahertz emission from the laser-induced spark demonstrated insufficiency the existing model [C D'Amico et al., Phys. Rev. Lett. **98**, 235002 (2007)] that supposes an axially symmetric distribution of low-frequency currents in a laser-induced spark, which are responsible for this radiation.

A new theoretical model was elaborated [N A Zharova et al., Phys Rev E **82**, 056409 (2010)] that accounts for the specific character of the electron distribution function created under tunnel ionization in the laser field. The current excitation efficiency was analyzed for a bi-chromatic breakdown scheme depending on the laser radiation parameters (the relative phase difference, the polarization, the amplitudes of harmonics). Qualitative agreement was obtained between theoretical results and experimental data. This new mechanism of low-frequency current formation in the laser-induced spark accounts for an anisotropy of the electron pressure with respect to the direction of laser polarization. In the relaxation of the anisotropy, low-frequency currents are also excited in the direction perpendicular to the optical field, which appreciably changes the radiation pattern and polarization of the terahertz radiation.

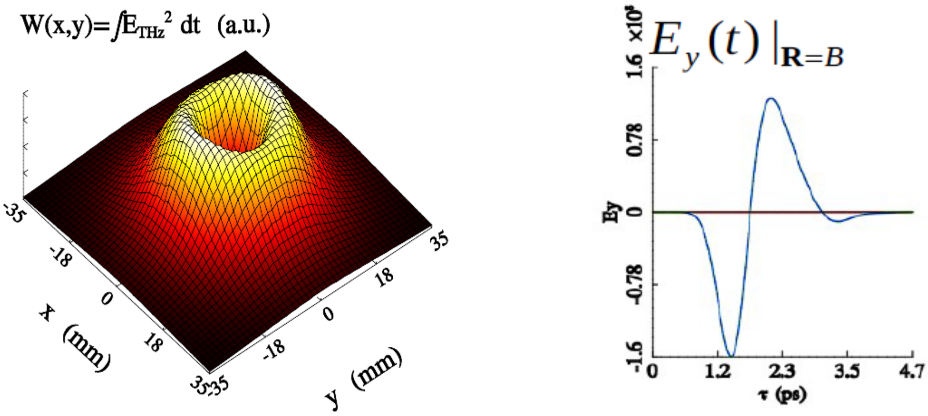

Figure 3. Left: near field distribution of the THz emission from the air irradiated by a linearly polarized laser beam of the amplitude 2×10^{11} V/m and a radius of 50 μm. Right: wave form of the emitted signal.

List of keywords

laser plasma interaction, inertial confinement fusion, electron-ion collisions, laser particle acceleration, electromagnetic emission from laser-produced plasmas

Websites where additional information may be found