Relativistic Mirrors in Laser Plasmas

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Relativistic mirror concept is based on the property of electromagnetic waves to change the frequency and energy in nonlinear interaction with plasmas. This concept paves a way towards developing a compact tuneable source generating coherent ultra-short x-ray pulses. It also covers the case of high efficiency ion acceleration by the radiation pressure, with the laser energy almost totally transferrable to the ions in the relativistic regime.

The review talk is devoted to relativistic mirrors, their properties and applications. High importance of the concept of relativistic mirrors can be seen from the fact that the problem on the electromagnetic wave reflection from a mirror moving at the velocity close to speed of light in vacuum has been mentioned in the first article by A. Einstein on the special theory of relativity. The theory of relativity explains why and how this process leads to an increase in the energy of the photon and the electromagnetic pulse compression. This may open a way for developing a compact source of coherent hard electromagnetic radiation. For applications such the compact device is of great interest: it will be a source of powerful ultra-short XUV and X-ray pulses, which is needed in a vast number of applications in biology, medicine, and materials science. Nowadays for these purposes the XFEL and synchrotron radiation sources have been built, which have large size because they use the beams of ultrarelativistic electrons generated by conventional accelerators. In Ref. [1] we have proposed as relativistic mirrors the nonlinear plasma waves, excited by laser radiation. Nonlinear plasma wave steepens and breaks, like the ocean waves. The plasma wave breaking leads to the formation of thin, dense shell of relativistic electrons, which can be used as a relativistic mirror. In the counter-propagation configuration, the frequency of the reflected electromagnetic wave is multiplied by the factor proportional to the electron gamma-factor squared. The counter crossing laser pulse reflection from the plasma wake wave accompanied by its frequency multiplication (with a factor from 50 to 114), corresponding to a reflected radiation wavelength from 7 to 15 nm, was detected in the experiment [2, 3]. The demonstrated flying mirror reflectivity is close to the theoretical estimate for the parameters of the experiment [4].

The source of powerful x-rays on the basis of relativistic mirrors will be in demand for a variety of applications, since it promises high brightness radiation and the relatively small size of the device. These, though very important applications, do not exhaust all the areas for which the concept of relativistic mirror is useful. In Refs. [1, 5, 6], it was drawn attention to the fact that the next generation of laser facilities can achieve the parameters, for which the reflected wave will become so strong that it will manifest such effects of nonlinear quantum electrodynamics as the vacuum polarization and the electron-positron pair creation from vacuum. This will make possible the experimental studies of non-perturbative processes, predicted by the quantum field theory (e. g. see [7] and review articles [8, 9]).

There are several other schemes to develop compact X-ray sources of high intensity based on the use of relativistic mirrors formed in the process of nonlinear interaction of laser radiation with plasma, whose implementation will create exciting opportunities for experiments on nonlinear electrodynamics of continuous media in the relativistic regime. Dense electron and electron ion layers accelerated to a relativistic velocity by laser radiation interacting with inhomogeneous plasmas [10, 11] and with a thin plasma foil are also considered as relativistic mirrors capable of generating beams of coherent X-ray and gamma radiation of high brightness [12–14].

Interaction of the electromagnetic radiation with an electron layer oscillating with relativistic velocity provides an underlining mechanism of the high order harmonics generation in relativistic collisionless plasma which is based on the oscillating relativistic mirror concept, [15] (e. g. see review articles [6, 16] and literature cited therein) and of generation of attosecond pulses of electromagnetic radiation.

Another process, where the concept of relativistic mirror helps to develop the adequate theory, is the ion acceleration by the radiation pressure of light [17], when in the co-propagating configuration, the energy of the electromagnetic wave is transferred to the ion energy, providing a highly efficient acceleration mechanism. The required theory for its description in the ultra-relativistic limit and the results of extensive computer simulations are presented in Refs. [18–23]. Currently there are the first experimental indications for the implementation of the radiation mechanism of particle acceleration in laser plasma (see references in the review articles [6, 24, 25]). It is believed that the particle acceleration by the laser light radiation pressure will be the main ion acceleration mechanism for the next generation lasers, which will find various applications, e.g. in nuclear physics, in laboratory astrophysics, in controlled thermonuclear fusion, and in hadron therapy [26–31].

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