ADVANCED ACCELERATION MECHANISMS FOR LASER DRIVEN IONS BY PW-LASERS

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Abstract

With the fast development of laser technology, the energy of laser accelerated proton beams rose up to almost 100 MeV. The PW-class laser facilities that are being built right now or are already in operation, such as the Berkeley Lab Laser Accelerator (BELLA) Center, will offer peak intensities approaching 10^{22} W/cm^2. This will allow the development of a new generation of laser ion accelerators for numerous applications. The integral part of this task is the investigation of the advanced accelerator mechanisms for laser driven ion beams that would allow for a high degree of control over the angular and energy distributions of ion beams, as well as the increase of the ion maximum energy.

We will present recent theoretical and simulation results on the three advanced acceleration mechanisms: (i) Directed Coulomb Explosion, (ii) Radiation Pressure Acceleration, and (iii) Magnetic Vortex acceleration.

INTRODUCTION

During the last century the conventional particle acceleration achieved a great progress from basic principles to enormous complicated machines able to study the fundamental laws of nature. However, as the complexity of particle accelerators increased so did their cost and size, which raised a question if there are other ways of accelerating particles. It is believed that laser-plasma interaction may provide such a way due to the fact that plasma is able to sustain electro-magnetic fields many orders of magnitude larger than it is possible in conventional accelerators. Thus it gives hope to significantly reduce the size and possibly the cost of future colliders.

In the case of electron acceleration in a number of proof-of-principle experiments it was shown that the interaction of laser pulses with gas targets can lead to the acceleration of electrons up to tens and hundreds of MeV [1]. The consequent experiments showed that scalability of the proposed acceleration concept yielding GeV-type e-beams with the highest energy achieved up to date of 4.2 GeV [2]. Moreover, it was predicted that staging of several plasma accelerators would address some of the fundamental limitations on the energy gain, such as laser depletion and dephasing between the laser and e-beam. Recently this concept was verified in a proof-of-principle experiment [3].

Thus, whereas the electron acceleration by lasers in plasma was already demonstrated as a viable path to next collider, the laser driven ion acceleration is still at the concept phase. Also it is believed that laser ion acceleration is more suitable not for fundamental studies of elementary particle properties but for such applications as hadron therapy, fusion ignition, radiography, and warm matter studies [4-6]. It is well understood that the interaction of intense laser pulses with a variety of targets, mainly solid density foils, produces energetic ion beams. The computer simulations of presently available laser systems predicted the ion energy in the range from hundreds of MeV to GeV. However, in order to reach these energies, the ion acceleration mechanisms different from the ones already studied experimentally are needed.

In principle, one can identify several basic acceleration mechanisms [4-6]: (i) target normal sheath acceleration (TNSA), (ii) coulomb explosion (CE), (iii) radiation pressure acceleration (RPA), and (iv) magnetic vortex acceleration (MVA). The TNSA is usually realized for rather low intensity, low contrast laser pulse and thick targets. In this case the laser heats up the electrons at the front of the target and then launches them through the target. When these electrons reach the back side of the target they establish charge separation electric field, which accelerates ion from the back side of the target. The the ion energy in TNSA scales as the square root of laser power. Most of the experimental results obtained up to date can be described in terms of the TNSA mechanism [7,8]. The CE requires high intensity, high contrast laser pulses and thin targets. Upon interaction of such laser pulses with such targets a significant part of the target electrons are expelled from the irradiated spot. Then the remaining ion core explodes due to the non-compensated positive charge. The ion energy in this case scales as laser power. The radiation pressure mechanism takes advantage of the fact that sufficiently intense laser pulses can push the foil as a whole. In this case the laser contrast is also an issue. However, this mechanism has high efficiency especially in the ultra-relativistic regime, where almost all laser energy can be transferred to the target. The MVA is different from the three above mentioned mechanisms, because it employs not thin solid density foils but near critical density slabs. When intense laser pulse interacts with such a target in makes a channel first in electron and then in ion density. After that the laser pulse propagates in this self-generated channel, accelerating electrons in its wake. These electrons generate magnetic field and also pinch background ions in a thin filament along the laser propagation axis. Upon exiting the target from the back the laser pulse and the electron current establish a quasi-stationary electric field, which accelerates the ions from

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the filament. In this case the ion energy scales as the laser power in the power of two thirds.

There are several mechanisms that are combination of some of the basic regimes, or their enhancement through some target engineering. For example, the Burn-out-Afterburner (BOA) [9], which employs both TNSA and volumetric ion acceleration, and Directed Coulomb Explosion (DCE) [10], which is an effective combination of RPA and CE, are such composite mechanisms.

As it was mentioned above most of the experimental results can be attributed to the TNSA, however, with the rapid increase in laser pulse quality, stability, and contrast, as well as the availability of plasma mirror technology, other acceleration mechanisms start to be explored experimentally [11-13]. These mechanisms are predicted to generate ion beams with the parameters needed for applications in terms of maximum energy, number of particles, relative energy spread. In what follows, we argue that three of the above mentioned mechanisms, the advanced acceleration mechanisms such as RPA, MVA, and DCE offer the way of generating ion beams with the required properties for applications.

RADIATION PRESSURE ACCELERATION

In the case of RPA (see Fig. 1), the motion of the foil is modeled by an interaction of an EM wave with a moving mirror. The laser pulse radiation pressure is taken into account as a force proportional to the EM wave momentum, which in turn is proportional to the EM wave Pointing vector. The equation of motion can be written in the following form

$$\frac{dp}{dt} = \frac{P}{n_e l}\vec{\nu}$$

where the force is directed along the normal to the surface element, denoted by unit vector $\vec{\nu}$. The light pressure is determined from balancing the fluxes of the incident, reflected, and transmitted EM waves in the reference frame, where the particular surface element is at rest. Taking into account the energy conservation, $|\rho|^2 + |\tau|^2 + |\alpha|^2 = 1$, where α is the absorption coefficient, ρis the reflection coefficient, and τ is the transmission coefficient, we obtain the following equation of foil motion

$$\frac{dp}{dt} = (2|\rho|^2 + |\alpha|^2)\frac{|E_L|^2}{4\pi n_e l}\frac{\gamma - p}{\gamma + p}$$

where γ is the Lorentz factor of the foil, and E_L is the laser field. The solution of this equation is [4]

$$\gamma = \frac{2 + 2W + W^2}{2(1 + W)}$$

where

$$W = \frac{2}{n_e l}\int_{-\infty}^{t-x}\frac{|\rho E_L|^2}{4\pi}d\eta$$

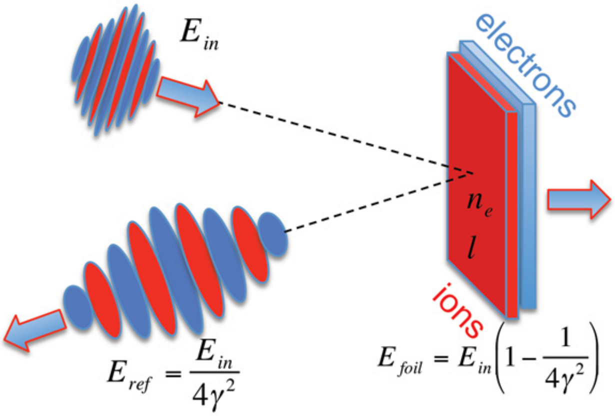

Figure 1: The principal scheme of RPA.

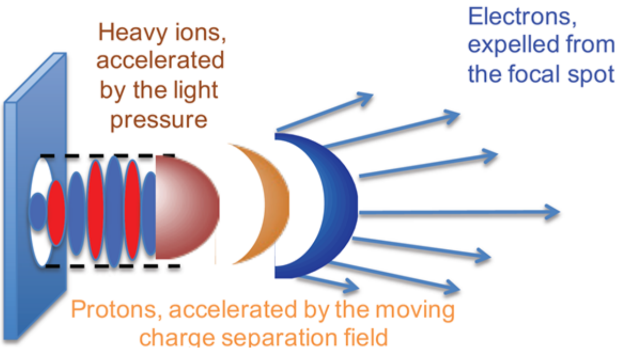

Figure 2: The principal scheme of DCE.

In the non-relativistic case the ion kinetic energy is proportional to W^2, in the relativistic case to W. A simple scaling can be derived from these equations

$$E_a = 8 \times (10^{11}/N_{tot})^2(m_p/m_a)(E_{las}/1\,J)\ MeV$$

Here N_{tot} is the total number of ions accelerated by the laser pulse, E_{las} is the laser pulse energy in joules, and subscript a denotes the species of ions. The estimate gives for a 1 PW laser pulse focused to a spot of 2 μm on a hydrogen foil with density of 200 n_{cr} and the thickness of 100 nm a 300 MeV proton beam.

DIRECTED COULOMB EXPLOSION

In most cases the interaction of an intense laser pulse with an ultra-thin foil leads to the foil experiencing the radiation pressure and the electrons being pushed out of the foil by the EM field of the laser. These two effects can be combined together to give rise to an efficient regime of laser ion acceleration, the Directed Coulomb Explosion (see Fig. 2). The most efficient realization of this regime is achieved with ultra-thin solid density two-layer (high Z/low Z) foils, which allows the production of quasi monoenergetic proton beams remarkable for various applications. The laser pulse forces the foil to move in the direction of the pulse propagation by the radiation pressure and also expels the electrons from the irradiated area. It leads to the transformation of the heavy ion core into an ion cloud expanding predominantly in the direction of the laser propagation. This ion cloud generates a longitudinal charge separation electric field moving ahead of it that efficiently accelerates protons from the second layer. Taking this into account we obtain the scaling of the ion energy in this regime [10]:

$$E_p = E_p' + (p_f/m_p)\sqrt{2m_pE_p'}$$

where E_p' is the energy gain from CE, and p_f is the momentum of the foil, which is due to RPA. The estimate gives for a 0.5 PW laser pulse focused to a spot of 2 µm on a two-layer (aluminum/hydrogen) foil with density of 400 n_{cr} and the thickness of 100 nm a 150 MeV proton beam.

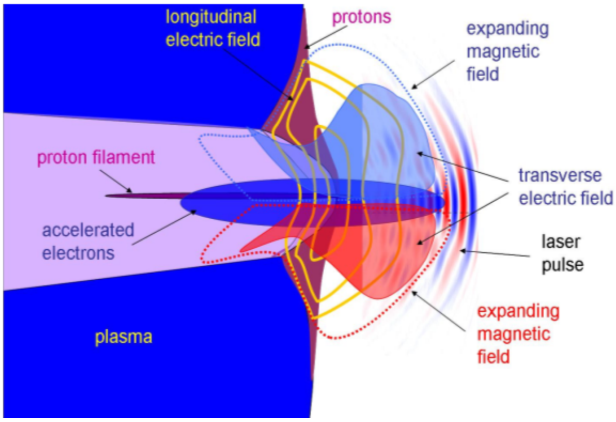

Figure 3: The principal scheme of MVA

MAGNETIC VORTEX ACCELERATION

In the MVA regime, the laser pulse propagates in near critical density (NCD) plasma, which is long compared to the laser pulse length. In course of the propagation the expels electrons and ions in the transverse direction. The time of ion response is much longer than that of electrons, which leads to a formation of a positively charged region just after the front of the laser pulse. Thus the electrons move under the action of the laser pulse EM field and the field of a remaining ion core. This results in the formation of a channel in electron density with high density walls and strong electron current flowing along the laser propagation axis. The acceleration is achieved by an electric field at the back of the target, which is generated by, and is of order of, the magnetic field of electrons, accelerated by the laser pulse in plasma in the forward direction, as they exit the target. This EM field associated with the electron current leaving the target expands along the back surface of the target, however the magnetic field flux is conserved. The maximum energy gain of a charged particle in such an expanding field is [14]

$$E_{He} = m_e 2\pi^2 Z_{He}\frac{n_e}{n_{cr}}\left(\frac{R_{ch}}{\lambda}\right)^4$$

The estimate gives for a 1 PW laser pulse and target density $n_e = 3n_{cr}$ maximum helium ion energy of 3 GeV.

CONCLUSIONS

We considered three advanced acceleration mechanisms for the laser driven ion acceleration: Radiation Pressure Acceleration, Directed Coulomb Explosion, and Magnetic Vortex Acceleration. These mechanisms are characterized by more favorable ion energy scaling with laser energy than TNSA and can provide ion beams with the energies required by applications using the PW-class laser systems.

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