Issues in Radiation Pressure Acceleration

A.Macchi[1,2], C.Benedetti[3], T.V.Liseykina[4], M.Tamburini[1], S.Veghini[1] and F.Pegoraro[1]

[1] *Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*

[2] *Istituto Nazionale di Ottica (INO), Consiglio Nazionale delle Ricerche (CNR), Italy*

[3] *Dipartimento di Fisica and INFN, Università di Bologna, Bologna, Italy*

[4] *Institute for Computational Technologies, SD-RAS, Novosibirsk, Russia*

E-mail: macchi@df.unipi.it

Abstract: Radiation Pressure Acceleration by circularly polarized laser pulses has been proposed and widely investigated theoretically as a promising scheme for efficient generation of ions. In particular, the use of ultrathin targets may allow to reach energies per nucleon beyond the GeV range. The first, recently reported experiments appear to confirm the basic mechanism and instantiate open challenges such as achieving a monoenergetic spectrum. In the present work we extend the "accelerating mirror" or "Light Sail" textbook model by including the effect of nonlinear "relativistic" transparency. The comparison with particle-in-cell simulations shows that the simple model gives meaningful predictions for the foil velocity and its "optimal" thickness for acceleration. At the same time, simulations show that the underlying dynamics is complex and involves a high degree of self-organization of the system. In particular, electron heating in the final stage of acceleration appears to be responsible for late broadening of the ion spectrum. We also report results on ion acceleration by extremely short pulses in liquid hydrogen jets to achieve high repetition rate in the "hole boring" regime. Finally, preliminary results on radiation friction effects are also reported.

1. Introduction

As higher and higher intensities are approached, radiation pressure effects are expected to play an increasing and eventually dominant role in laser interaction with dense matter, leading to the acceleration of large numbers of ions up to high energies [1,2]. In particular, radiation pressure dominance is enforced by the use of circularly polarized (CP) pulses at normal incidence because of the strong quenching of the generation of high-energy electrons [3,4]. The radiation pressure acceleration (RPA) of ultrathin (a few nm) targets by using high-contrast pulses is of particular interest since it may allow to reach relativistic (i.e. GeV) ion energies with "realistic" laser pulses. The first experimental results on such regime have been reported recently [5]. In this contribution we describe recent theoretical results on RPA with CP pulses, with the aim to point out open theoretical issues and challenges to obtain high-quality ion "beams".

2. Thin foil acceleration: "Light Sail" revisited

The RPA of ultrathin foils by CP pulses as a route to the generation of monoenergetic GeV ions has been proposed by several groups [6-8] and later studied in many theoretical papers (see references in recent work [9,10]). The basic features of this acceleration regime can be illustrated by the simple "Light Sail" (LS) model of an accelerating mirror, which provides compact formulas for the ion energy and conversion efficiency as a function of the energy of the laser pulse (in an one-dimensional plane-wave geometry). Recently we revisited the LS model [9,10] by including the effect of self-induced transparency of the foil which determines the "optimal" surface density of the foil as a function of the laser pulse parameters. The predictions of the improved analytical model are in good agreement with the results of parametric particle-in-cell (PIC) simulations in one spatial dimension (1D). At the same time the simulations reveal a quite complex and self-organized dynamics of thin foil RPA, so that the agreement with the LS model is actually less trivial than it may seem. It is observed that the balance between radiation and electrostatic pressures on electrons in the moving frame of the foil breaks down near the end of the laser pulse, causing heating of electrons and, as a consequence, a broadening of the ion spectrum after the acceleration stage, qualitatively similar to the first experimental observations [5].

Thin foil RPA has been also studied by multi-dimensional simulations and in particular in a 3D geometry where the issue of the conservation of the angular momentum of the CP pulse can be discussed [11].

3. "Hole boring" acceleration by few-cycle pulses

RPA using CP pulses also occurs in "thick" targets, i.e. targets whose thickness largely exceeds the laser penetration depth and thus, differently from ultrathin targets, are not accelerated as a whole. In this regime, also named as "Hole Boring" (HB), the scaling of the ion energy depends on the pulse intensity, rather than on the pulse energy, and is much less favorable than the LS scaling [3-4,12-13]. However, the HB regime may be less prone to prepulse effects and be more suitable for high repetition rate operation if a "flowing target" can be used. A liquid hydrogen jet might be a possible choice with the additional advantages of the pure proton content and of the modest plasma density (a few tens the "critical" density), so that proton energies exceeding 100 MeV may be reached with foreseeable laser intensities. To increase the efficiency and have an acceptable spectral width, few-cycle pulses would be preferred so that a single ion bunch is accelerated within the pulse duration. The above described set-up for HB acceleration of protons has been studied by 1D and 2D PIC simulations [13] for a laser pulse of two-cycle duration and intensity up to some 10^{22} W/cm^2.

4. Radiation reaction effects

At the extremely high intensities expected for experiments in the near future, electrons become ultrarelativistic and experience superstrong accelerations, so that radiation reaction (RR) effects become more and more important. In particular, recent simulation results suggest that RR plays an important role also in RPA both in the HB [14] and LS [15] regimes. We inserted RR effects in a PIC code using the Landau-Lifshitz approach, which allowed us a numerical testing based on exact solutions in a plane wave [16]. Preliminary simulation studies of RPA with RR included will be reported.

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