Simulations of proton beam characteristics for ELIMED Beamline

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Abstract. ELIMED Beamline should demonstrate the capability of laser-based particle accelerators for medical applications, mainly for proton radiotherapy of tumours which requires a sufficient number of accelerated protons with energy about 60 MeV at least. In this contribution, we study the acceleration of protons by laser pulse with parameters accessible for ELIMED Beamline (intensity $\sim 10^{22}$ W/cm^2, pulse length ~ 30 fs). In our two-dimensional particle-in-cell simulations, we observed higher energies of protons for linear than for circular polarization. Oblique incidence of the laser pulse on target does not seem to be favourable for proton acceleration at such high intensities as the accelerated protons are deflected from target normal axis and their energy and numbers are slightly decreased. The expected numbers of accelerated protons in the energy interval 60 MeV $\pm 5\%$ are calculated between 10^9 and 10^{10} per laser shot with estimated proton beam divergence about $20°$ (FWHM).

1. Introduction

With rapidly increasing laser pulse intensities in last decades, ion acceleration by femtosecond laser pulses is of great interest in the present research. Several mechanisms of ion acceleration by short laser pulses have been proposed [1]. The most studied one is target normal sheath acceleration (TNSA) based on laser energy transformation to energetic electrons that penetrate to vacuum and produce there a strong quasi-static electric field that accelerates ions from the target surface [2]. At higher laser intensities (above 10^{20} W/cm^2), radiation pressure acceleration (RPA) was proposed as an efficient mechanism for generation of quasimonoenergetic ion beams [**?**]. However, RPA requires to avoid electron heating which can be reduced by using circularly polarized laser beams, but it cannot be removed completely due to two-dimensional effects.

The ELIMED (MEDical applications at ELI) project aims to demonstrate the potential clinical applicability of optically accelerated proton beams [4]. Numerical study of laser-proton acceleration for expected parameters of generated laser pulse is one of important tasks in the preparatory phase of the ELIMED project. In this paper, we summarize the results obtained by means of two-dimensional particle-in-cell simulations. Our goal is to estimate maximum energies of accelerated protons, the number of high-energy protons, and their divergence. We have done computational study of the dependence of proton acceleration on the foil material and thickness, laser polarization, and the incidence angle.

2. Simulation method and parameters

Our relativistic colisionless particle-in-cell (PIC) code in two spatial directions and with three velocity components is described in Ref. [5]. In the simulations, we assumed two intensities of laser pulse. The pulse has $\sin^2$ temporal profile and full length about 40 fs (15 laser periods) focused to 3 μm (FWHM) diameter. In the first case, the pulse reaches maximum intensity equal to 1.4×10^{22} W/cm^2 (corresponding to 1 PW case in the following text). In the second case, the using of double-plasma mirror is assumed in order to improve the laser pulse contrast, which reduces the intensity of the focused laser beam to 7.2×10^{21} W/cm^2 (0.5 PW pulse). In most of simulations, the beam is incident normally on the polyethylene (CH$_2$) foil of thickness 200 nm or 1 μm. The foil is assumed to be ionized to C^{6+}H$_2^+$ plasma with electron density $n_e = 3.5 \times 10^{23}$ cm$^{-3} = 200$ n$_{ec}$, where n_{ec} is the electron critical density for laser of wavelength 800 nm.

3. Results and discussion

3.1. Dependence on laser polarization and target composition

Firstly, we calculated the interaction of 1 PW laser pulse, linearly and circularly polarized, with 200 nm thick foil composed of fully hydrogen plasma or CH$_2$ plasma. The proton energy distribution is plotted in Fig. 1 (at time instant 120 fs after the target interaction with maximum laser pulse amplitude). Linear p-polarization leads to higher energies and numbers of the most energetic protons compared with circular polarization, as the foil is too thick and focusing too tight for more efficient RPA in the light sail regime [3]. Therefore, we investigated further only the interaction with linearly polarized laser beams.
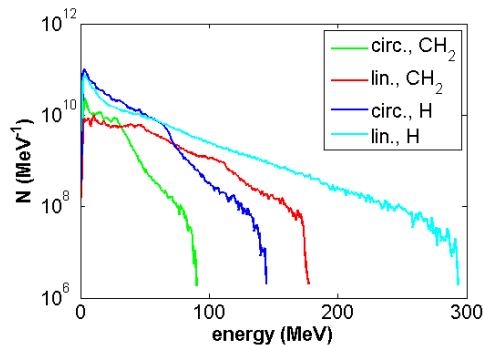

Figure 1. Energy spectra of accelerated protons for linear and circular polarization and polyethylene (CH$_2$) and hydrogen (H) foils of thickness 200 nm at laser intensity 1.4×10^{22} W/cm^2.

It is demonstrated that using pure hydrogen target in the simulations leads to an overestimation of the proton energies in comparison with plastic foils that can be used in experiments. We ascribe this difference to a slower deformation of the target front surface by the radiation pressure when the plasma contains heavier C^{6+} ions. Due to a slower surface deformation, the electrons in the target are heated in a smaller volume. Indeed, the total absorption of the laser pulse energy is about 36% for linear polarization and pure hydrogen target, whereas it is only 25% for polyethylene target. For circularly polarized laser beam, the calculated absorption drops to 21% (hydrogen) and 14% (polyethylene). Due to reduced electron heating and increased radiation pressure on target via ponderomotive force, circularly polarized laser beams can accelerate relatively higher number of protons to lower energies compared with linearly polarized beams for the same absorption rate.

3.2. Dependence on incidence angle and target thickness

In difference from lower intensities (below 10^{20} W/cm^2), oblique incidence (30°) is at intensity 7.2×10^{21} W/cm^2 less efficient than the normal incidence for ion acceleration (Fig. 2a) as at these intensities $\vec{j} \times \vec{B}$ heating dominates and the effective laser intensity is decreased for the oblique incidence. The other drawback of the oblique incidence is here preferential oblique direction of the accelerated ions (Fig. 2b). This observation is in agreement with the theoretical and PIC simulation results [6] that predicted the average deflection angle of approximately 5° for protons with kinetic energy 60 MeV. From Fig. 2b, one can also estimate the divergence of high-energy protons, which is about 20° at FWHM. Similar values of the divergence were observed for all simulation runs.
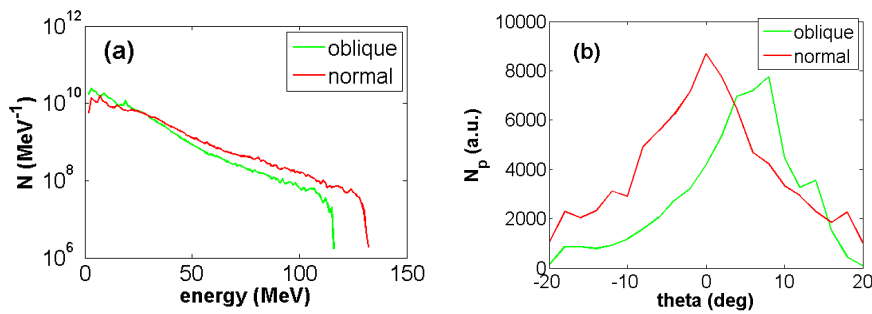
Figure 2. Proton spectra (a) and angular distribution of protons with energy >30 MeV (b) for 200 nm thick CH$_2$ foil and laser intensity 7.2×10^{21} W/cm^2 for the normal incidence and for the oblique incidence at angle 30°.

Maximum energies and numbers of protons accelerated from thinner (200 nm) and thicker (1 μm) CH$_2$ foils for normal and oblique incidence are shown in Table 1. Note that the absorption of laser pulse energy is similar for both foil thicknesses and the same incidence angle. It depends strongly on the front target surface (as shown further below) and partly on the incidence angle. The number of protons N_p with energy $57 - 63$ MeV, suitable for proton therapy, is estimated from energy transformation efficiency η_{Lp} of laser pulse energy to the protons with energy $\varepsilon_p \pm 5\%$

$$N_p = \eta_{Lp} \cdot \varepsilon_L / \varepsilon_p, \qquad (1)$$

where ε_L is laser pulse energy and $\varepsilon_p = 60$ MeV. The laser pulse energy is assumed to be 15 J for 0.5 PW pulse and 30 J for 1 PW pulse.

Table 1. Comparison of maximum energies and numbers of protons accelerated from thinner (200 nm) and thicker (1 μm) planar foils irradiated at normal (0°) and at oblique (30°) incidence by 0.5 PW laser pulse.

target thickness, angle of incidence	max. energy [MeV]	proton number (57; 63 MeV)
200 nm, 0°	130	4.8×10^9
1 μm, 0°	85	1.4×10^9
200 nm, 30°	115	3.1×10^9
1 μm, 30°	75	8.0×10^8

3.3. Enhanced proton acceleration by a microstructure on the front side

For the enhancement of proton energies and numbers due to increased laser pulse energy absorption, microstructures on the front side of thin plastic foils have been already successfully used in the experiments at lower laser intensities about 10^{20} W/cm^2 [7]. Therefore, we also tested the interaction with these targets at at higher intensities (near to 10^{22} W/cm^2 for 0.5 PW pulse) in the simulations. The results, described in detail in Ref. [8], are qualitatively similar to simulations and experiments at lower intensity - maximum proton energy is increased about several tens of per cent by using structured front foil surface, whereas the number of accelerated protons can be much higher (almost about one order of magnitude higher) compared with flat foils.

4. Conclusions & Perspectives

We have performed numerical simulations of laser-induced ion acceleration for laser intensities of order 10^{22} W/cm^2 that will be achievable at ELI-Beamlines facility. It is shown that simulations with pure hydrogen targets overestimate the proton energies in comparison with more realistic plasma containing heavier ions. In difference from lower laser intensities, oblique incidence is less efficient than the normal one for the proton acceleration. Linear polarization is preferred to the circular one for the foils of thicknesses $\geq$ 200 nm. Maximum energy of accelerated protons is estimated to be about 100 MeV, the number of high-energy (60 MeV $\pm$ 5%) protons suitable for proton therapy should exceed 10^9 per laser shot, and the calculated proton beam divergence is about 20° (FWHM). The number of high-energy protons can be substantially (several times) increased by introducing a microstructure (deposited nanospheres or grating) on the front surface of a thin foil. Although simulation parameters are chosen to be rather conservative (full pulse duration 40 fs, mostly 0.5 PW laser power instead of 1 PW), 3D simulations are planned for the future to check the validity of our numerical estimates from 2D PIC code.

References

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