Computer simulation of laser proton acceleration for hadron therapy

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Abstract. The LegoLPI code was used for simulation of laser-driven proton acceleration with the purpose to find an optimal conditions for the generation of proton beams with parameters required for hadron therapy. The 2D PIC simulations were done for various type of targets (double-layer foils, polyethylene foils, hydrogen jets) and target irradiation conditions (different intensities and polarizations, laser pulse wavelengths and durations, focal spot sizes). It is shown that efficiency of proton generation would be high enough for the optimal condition of target irradiation, but the spectrum of accelerated protons is rather broad for both linearly and circularly polarized laser pulses because of the two-dimensional effects arising when the proton acceleration length is comparable with the focal spot. As follows from the 2D LegoLPI calculations, the efficiency of formation of proton spectrum in energy range of 200-250 MeV and normalized to laser energy may reach values \((0.5-1)\times10^7\) protons\(\times\)MeV\(\times\)J\(^{-1}\) for the considered types of laser - targets systems. The performed calculations specify an opportunity of generation proton beams whose parameters meet proton therapy requirements with the use of a laser that would have a peak power of about 1 PW and average power up to 1 kW. The powerful ultra-short pulse lasers, which are under construction in some countries around the world, are very close to the facilities necessary for this purpose.

Introduction

The experimental and theoretical studies of laser-driven ion beams attract considerable attention due to their potential applications in medicine, science and technology [1-4]. The practical applications (proton radiography and therapy, laser ion sources for linear accelerators) require quasi-monoenergetic and even monoenergetic beams. Following from results of numerical simulations, it was proposed that ion beams with quasi-monoenergetic spectra can be generated if use a high-Z thin foil with hydrogen or water vapor present on its surface [3]. Circularly polarized laser pulses may be of special interest to the generation of monoenergetic proton beams. This problem is discussed in a number of interesting papers [5-7], however, feasibility of implementing the advantages of circularly polarized pulses for the generation of quasi-monoenergetic ions from thin foils is still to be studied out. Laser-driven acceleration of protons to high energies from thin foils irradiated by high-intensity laser pulses imposes rigid requirements for laser pulse contrast. Thus it is necessary more practicable laser-target systems for proton acceleration to high energies. The gas-jet targets seem quire realistic for this purpose. These targets have already been studed by multidimensional PIC-codes [8-9] and it used in experiments on laser-driven ion acceleration to high energies [10].

The 3D parallel relativistic PIC-code LegoLPI to simulate the high-intensity laser – plasma interaction, the electron and ion acceleration was developed by G V Baidin in RFNC-VNIITF [11].
The paper presents results of the 2D LegoLPI calculations performed with the purpose to find an optimal conditions for the generation of proton beams with parameters required for hadron therapy: the proton energy must be about 200 - 250 MeV with monochromism 1-2%, and proton beam intensity - above 10^{10} protons\cdot s^{-1} [2]. The calculations were done for different targets (double-layer foils of aluminum and polyethylene, polyethylene foils and hydrogen jets of different densities) and pulse parameters (intensity, duration and wavelength, linear and circular polarizations, focal spot size). The main criterion in their comparison was attaining the highest possible efficiency in the laser acceleration of protons to 200-300 MeV.

1. The simulation of protons acceleration at laser irradiation of double-layer foils

The target was the aluminum foil with thickness of 100 nm and the polyethylene disk with diameter of 6 \mu m and thickness 50 nm that was placed at the rear surface of Al-foil. Matter was assumed fully ionized, i.e. two plasma layers were initially present: the first layer had consisted of electrons and Al^{13+} - ions with number densities n_e=7.8\cdot10^{23}\text{cm}^{-3} and n_{Al}=6.0\cdot10^{22}\text{cm}^{-3}; the second one - electrons, protons and C^{6+} - ions with number densities n_e=3.4\cdot10^{23}\text{cm}^{-3}, n_p=8.5\cdot10^{22}\text{cm}^{-3}, and n_{C}=4.25\cdot10^{22}\text{cm}^{-3}, respectively. The laser pulse was characterized by Gaussian profiles in time and transverse space direction. It had p- polarization, wavelength =1 \mu m, focal spot size d_{fwhm} = 3 \mu m. The laser pulse had duration \tau_{fwhm} = 30 fs and maximum of intensity: <I>_{max} = 1.4\cdot10^{22} \text{Wcm}^{-2} ( <I>_{max} = c(a \cdot d_0)^2 \cdot (8\pi)^{-1} \cdot a =100, a_0 = 2\pi m_e c^2 (q_0 \lambda)^{-1}). The maximal intensity <I>_{max} was reached at the moment t_{max} = 2 \tau_{fwhm}. The computational domain was 40\times24 (\mu m \times \mu m). It was divided into square cells with side length of 0.01 \mu m. For the 2D case, the total laser pulse energy was E_{2D} = 14.3 J \mu m^{-1}.

The protons were accelerated mainly during time 100-150 fs, achieving for this time about 70% of energy that they obtained at last moment of this run (see figure 1).

![Figure 1. The proton spectrum for a moment of time 225 fs in calculation of double-layer foil.](image1.png)

![Figure 2. The proton spectrum for a moment of time 160 fs in calculation of CH_2 - foil irradiated by laser pulse with a linear (continuous line) and a circular (dashed line) polarization.](image2.png)

Our calculations show that the efficiency of laser energy conversion to protons with energies above 100 MeV is about 2-4%, the spectrum of accelerated protons is broad and the number of protons accelerated to energy of 200-250 MeV per unit of a proton energy and normalized to laser energy may reach (2-5)\cdot10^6 protons\cdot(MeV\cdotJ)^{-1}. 
2. The simulation of proton acceleration to 200-400 MeV from polyethylene foil irradiated by linearly and circularly polarized laser pulses

The figure 2 shows results of the 2D *LegolPI* calculations performed for polyethylene foils with thickness of 100 nm that irradiated by laser pulses with linear and circular polarization. The laser pulse was Gaussian in time and super-Gaussian (n=4) over the focal spot. It had follows parameters: wavelength $\lambda=0.8 \mu m$, focal spot size $d_{focal}=4 \mu m$. The maximum intensity $I_{max}$ was equal to $6.8 \times 10^{15} \text{W cm}^{-2}$ and reached at $t_{max}=30$ fs that was equal to the total pulse duration at half maximum ($t_{max}=r_{FWHM}$) the total laser pulse energy was $E_{tot}=8.5 \text{J} \mu \text{m}^{-1}$. 

The target was assumed to contain fully ionized polyethylene with number densities of electrons, protons and $^{4}$He- ions, respectively: $n_e=3.6 \times 10^{21} \text{cm}^{-3}$, $n_1=9 \times 10^{20} \text{cm}^{-3}$, and $n_{He}=4.5 \times 10^{20} \text{cm}^{-3}$. The computational domain was $50 \times 24 \mu m \times \mu m$ in size. grid was square with side length of 0.01 $\mu m$. The number of particles of each species in one cell was 100.

For the above mentioned parameters of laser pulse, the foil thickness was varied in the range of 50-200 nm to obtain the highest possible efficiency of laser energy conversion to 200-400 MeV protons. The 2D calculations performed by *LegolPI* code for the polyethylene foils irradiated by laser pulses with linear and circular polarization shown that the spectra of accelerated protons are rather broad for both polarizations. This is due to the fact that the foil significantly bends during acceleration: protons obtain the main part of their energy while passing distance of 2-4 $d_{focal}$. The efficiency of laser proton acceleration to energy of 200-250 MeV may reach value of $(0.5-1)$ MeV·J, as it follows from the 2D -calculations performed for the polyethylene foils irradiated by the 30 fs laser pulses at intensity of $7 \times 10^{19}$ W cm$^{-2}$. It should be noted that the circularly polarized pulses are more effective than the linearly polarized ones in 2-3-times (see figure 2).

3 The simulation of proton acceleration to 200-400 MeV from low-density hydrogen jets irradiated by laser pulses with wavelength of 3.3 $\mu m$

Since laser proton acceleration to high energies from thin foils irradiated by short laser pulses imposes rigid requirements for laser pulse contrast, it is necessary to seek for more practicable laser-target systems. Gas jet targets seem quite realistic for laser-driven ion acceleration.

Here we present results of 2D calculations performed by the *LegolPI* code for hydrogen jets irradiated by pulses from a PW-laser with wavelength of 3.3 $\mu m$. The diod-pumped laser LUCIA ( =3.3 $\mu m$, 400 TW, 10 Hz) being built on the OPCPA scheme [12] can be taken as a prototype.

The laser pulse was set to be Gaussian in time and super-Gaussian (n=4) over the focal spot. Its parameters were as follows: wavelength $\lambda=3.3 \mu m$ and the focal spot size $d_{focal}=24 \mu m$. The laser intensity maximum was equal to $3 \times 10^{19}$ W cm$^{-2}$ at time $t_{max}=200$ fs (18 laser periods) that was equal to pulse duration $r_{FWHM}$. The target was assumed to be a 60-$\mu m$-thick layer of fully ionized hydrogen. The initial number densities of electrons and protons were varied in the range $(0.25-10) n_1$, where $n_1=10^{20} \text{cm}^{-3}$. The computational domain had sizes $256 \times 96 \mu m \times \mu m$ and was divided into square cells with side of 0.125 $\mu m$. The number of particles of each species in one cell was 25.

The figure 3 and figure 4 show results of the 2D *LegolPI* code calculations performed for above mentioned parameters of laser pulse and initial number density equal to $3 \times 10^{20} \text{cm}^{-3}$ ($n_1=3 n_e$). The efficiency of laser-to-proton energy conversion was about 20% and the efficiency of proton spectrum formation in energy region of 200-250 MeV was about $(5-8) \times 10^{10}$ protons/(MeV·J)$^{-1}$ in this simulation. It is significant that these values close enough to results obtained in the 2D simulations of the double-layer foils and the polyethylene foils irradiated by linearly polarized pulses.

The efficiency of proton spectrum formation by laser pulses with different wavelengths is conserved under concurrently changing: laser intensity $I \sim t^{-2}$, pulse duration $t \sim L$, target and focal spot sizes $L, d \sim \tau$, electron number density in target $n_e \sim \tau^{-2}$. The 2D *LegolPI* code calculations confirmed these simple scaling laws that conserve all parameters of laser accelerated proton beams.
Figure 3. The proton spectrum at moment 890 fs according to the 2D Lego-LPI code calculation performed for the PW laser with wavelength of 3.3 µm and hydrogen jet with initial electron number density of $3 \times 10^{20}$ cm$^{-3}$

Figure 4. The spatial profile of proton number density at moment 890 fs according to the 2D Lego-LPI code calculation performed for the PW laser with wavelength of 3.3 µm and hydrogen jet with initial electron number density of $3 \times 10^{20}$ cm$^{-3}$

It should be noticed that the maximum of proton energy in these calculations is about two times more than energy needed for hadron therapy. So we hope that main results of the 2D Lego-LPI code simulations of laser proton acceleration for hadron therapy remain true and after the 3D-calculations performing.

A beam of protons with energies of 200-250 MeV and monochromism about 1-2% that required for proton therapy can be formed from broad spectrum of laser-accelerated protons with the help of electromagnetic systems and filters with high efficiency. It is known also that for proton therapy, the intensity of a proton beams to be about $10^{10}$ protons per second on average. So, performed calculations specify an opportunity of generation proton beams whose parameters meet proton therapy requirements with the use of lasers that would have a peak power of about 1 PW and average power up to 1 kW. The powerful ultra-short pulse lasers that are under construction in some countries are close to facilities necessary for this purpose.

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