

PACS numbers: 41.75.Jv; 42.65.Re; 52.38.-r
DOI: 10.1070/QE2010v040n01ABEH014101

Simulation of photon acceleration upon irradiation of a mylar target by femtosecond laser pulses

S.N. Andreev, A.A. Rukhadze, V.P. Tarakanov, B.P. Yakutov

***Abstract*. Acceleration of protons is simulated by the particle-in-cell (PIC) method upon irradiation of mylar targets of different thicknesses by femtosecond plane-polarised pulsed laser radiation and at different angles of radiation incidence on the target. The comparison of the results of calculations with the experimental data obtained in recent experiments shows their good agreement. The optimal angle of incidence (45°) at which the proton energy achieves its absolute maximum is obtained.**

Keywords: *laser acceleration of particles, PIC method, thin-film target.*

1. Introduction

The interaction of super-high intense laser radiation with matter is being widely studied both experimentally and theoretically (see for example, reviews [1 – 3]).

The most adequate method for investigating the processes proceeding during the interaction of femtosecond and picosecond laser pulses with different targets is the simulation by the particle-in-cell (PIC) method. To study numerically the relativistic laser-plasma processes, we used a two-dimensional plane version of the fully relativistic electrodynamic PIC code KARAT [4] whose advantages are the possibility to use the code on personal computers and the developed graphic interface making it possible to perform a preliminary analysis of the results during computation.

Despite the limited computational capabilities of personal computers, there exist a wide range of problems associated with the interaction of super-high intense laser radiation with matter. These problems can be studied by using the above code in its one-dimensional and two-dimensional modifications, and, as will be shown below, the results of simulations prove to be in good agreement with the experimental data.

S.N. Andreev, A.A. Rukhadze A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: andreevsn@ran.gpi.ru, rukh@fpl.gpi.ru;
V.P. Tarakanov Joint Institute for High Temperatures, Russian Academy of Sciences, Izhorskaya ul. 13/19, 125412 Moscow, Russia; e-mail: karat@tarak.msk.ru;
B.P. Yakutov Russian Federal Nuclear Center – The All-Russian Research Institute of Experimental Physics, prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia; Boris_Yakutov@mail.ru

Received 13 March 2009
Kvantovaya Elektronika **40** (1) 64 – 67 (2010)
Translated by I.A. Ulitkin

As a test problem, we chose recent paper [5], which studied experimentally the proton acceleration during the interaction of femtosecond laser pulses having a record-high contrast (more than 10^{10}) with the mylar films of different thicknesses. The authors of paper [5] demonstrated experimentally that in the absence of a pre-plasma on the front surface of the target, the proton acceleration both from the front and back surfaces of the target proceeds almost with the same efficiency.

The simulation of this problem by using the KARAT code performed in this paper confirmed the main conclusions [5] not only qualitatively but also quantitatively and allowed us to obtain additional information on the dependence of the parameters of accelerated protons on the angle of incidence of the laser pulse.

2. Brief description of the physical model of the KARAT code

The code is based on the three-dimensional electrodynamic model in which induced electric $\boldsymbol{E}$ and magnetic $\boldsymbol{B}$ fields are found from Maxwell's equations:

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}, \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \tag{2}$$

where $\boldsymbol{J}$ is the current density. The fields $\boldsymbol{E}$ and $\boldsymbol{B}$ satisfy different boundary conditions, depending on the types of the boundaries of the countable domain including the ideally conducting surfaces, surfaces with the finite conductivity, open boundaries. The external electromagnetic pulse, in particular, a laser pulse is introduced by realising the boundary conditions corresponding to the wave type. System (1), (2) is solved by the finite-difference time-domain (FDTD) method on a rectangular ьуыр with a shift in space and time.

In the present problem, the current density at each point of the system was determined within the framework of the PIC method:

$$\boldsymbol{J} = \frac{1}{\Delta V}\sum_s Q_s \boldsymbol{v}_s, \tag{3}$$

where $\boldsymbol{v}_s$ is the velocity of the macroparticle with the number s; Q_s is the part of the macroparticle charge with the number s in this elementary cell; ΔV is the volume of the elementary cell.

Because electrons can have relativistic velocities, the motion of macroparticles is described by the relativistic equation of motion for a charged particle in the electromagnetic field

$$\frac{\mathrm{d}\boldsymbol{p}_s}{\mathrm{d}t} = Q\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}_s \times \boldsymbol{B}\right). \quad (4)$$

Here, $\boldsymbol{p}_s$ is the momentum of the macroparticle; in this case,

$$\boldsymbol{p}_s = m_{\mathrm{p}}\boldsymbol{v}_s\gamma; \quad \gamma = \frac{1}{(1 - \boldsymbol{v}_s^2/c^2)^{1/2}}; \quad (5)$$

$m_{\mathrm{p}} = \eta m$ is the macroparticle mass; $Q = \eta q$ is its charge; m and q are the mass and charge of real plasma particles (electrons and ions); η is the enlargement parameter.

Equations (1)–(5) form a complete system making it possible to describe self-consistently the dynamics of the particles and electromagnetic fields generated by them.

The essence of the PIC method consists in the fact that the mass and the charge of the macroparticles can exceed by several orders the mass and the charge of real plasma particles (electrons and ions); nevertheless, when some conditions are fulfilled, the results of PIC simulation coincide with a high accuracy with the results of a real experiment and analytic solutions. Indeed, the macroparticle mass and the charge enter equation (4) in the form of a ratio. For this reason, the dynamics of macroparticles does not differ from the dynamics of real plasma particles. However, in determining the current density $\boldsymbol{J}$, the macroparticle charge enters expression (3) explicitly, and the quantity of the enlargement parameter η can affect the simulation results.

In PIC simulation of laser-plasma processes on a personal computer, the main restriction is the number of macroparticles used in calculations, which at present cannot exceed significantly 10^7. To achieve the maximum calculation accuracy (when the number of macroparticles is maximal), the enlargement parameter will vary depending on the initial configuration and the dimensions of the target. Below, we will study the influence of the enlargement parameter on the simulation results.

3. Formulation of the problem

Figure 1 shows an example of the simulation region of interaction of a 65-fs laser pulse with a thin mylar ($C_8H_{10}O_4$) film, corresponding to the experiment described in paper [5]. The dimension of the simulation region was 40×40 μm with a 57-nm mesh size along each axis. The calculation time was 900 fs.

The 790-nm laser pulses had a Gaussian profile both in time and space (in the xz plane) with the FWHM of 65 fs and 8 μm, respectively. The laser pulse peak intensity was $I_0 = 5 \times 10^{18}$ W cm^{-2}.

The target was simulated as plasma within the PIC model. The argument in favour of this assumption was the fact that the energy of the particle motion in the field of the simulated laser pulse exceeds by many orders of magnitude the bonding energy of the electrons in the target material.

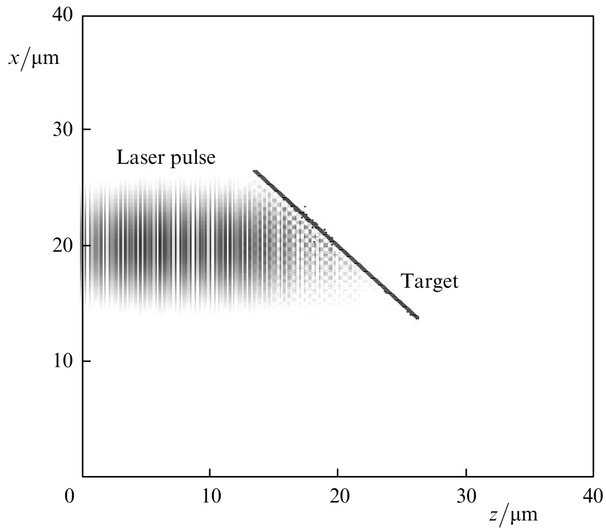

Figure 1. Simulation region of the interaction of a laser pulse (projection of the magnetic field to the y axis) with a film at the instant $t = 90$ fs.

The model design corresponds to that used in real experiments [5]. At the initial moment, the target represented a singly ionised plasma region of width 18 μm and thickness $h = 80 - 800$ nm, consisting of e^- electrons and ions of three types: p^+ protons with the concentration $n_{p^+} = 50 \times 10^{21}$ cm^{-3}, C^+ carbon ions with the concentration $n_{C^+} = 40 \times 10^{21}$ cm^{-3}, and O^+ oxygen ions with the concentration $n_{O^+} = 20 \times 10^{21}$ cm^{-3}, which corresponded to the mylar density $\rho = 1.4$ g cm^{-3}. The target was rotated by 45° with respect to the propagation direction of the laser pulse.

In the two-dimensional plane version of the KARAT code applied to this problem, which involves the Cartesian coordinate system xz (i.e. the dependence on y is absent), instead of the enlargement parameter η we used the merging factor $M = 0.33 \times 10^{-10}\eta$ proportional to it. The maximum number of macroparticles of each type could not exceed 1.2×10^6 in our case (the total number of particles is 7.2×10^6); therefore, the minimal value of M was determined by the concentration of ions of each type in the plasma region and by its area. In this research, the width of the plasma region was constant, while the thickness h was varied. Thus, for each value of h we chose the minimal value $M_{\min}(h)$ providing the maximally possible (for this h) calculation accuracy. Therefore, when h was varied from 80 nm to 0.8 μm, the quantity $M_{\min}(h)$ varied from 0.3 to 2.

4. Results of simulations

Let us discuss now the results of the simulation. Figure 2 presents the time dependence of the maximal kinetic energies of protons accelerated by a laser pulse and moving in the regions to the left from the front surface of the target and to the right from the back surface of the target (see Fig. 1). The target thickness was $h = 80$ nm, and the merging factor was $M_{\min}(h) = 0.3$. One can see from Fig. 2 that the energy accumulation by protons takes not less than 1 ps. Because the saturation of the proton energy is a rather long process, we terminated the calculations at the instant $t = 900$ fs to save the computation time; in this case, the change in the proton energy for the last 100 fs did

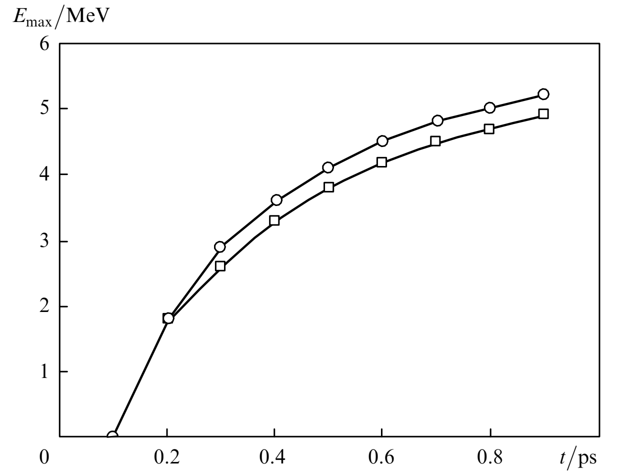

Figure 2. Time dependences of the maximal kinetic energies of the protons from the front (□) and back (○) surfaces of the target.

not exceed 5 %. The maximum energies of the protons moving from the front and back surfaces of the target were 4.9 and 5.2 MeV, respectively, in good agreement with the experimental results of paper [5].

The authors of paper [5] showed that the absence of the pre-plasma region due to the high laser pulse contrast leads to the fact that the protons from the front and back sides of the target accumulate approximately equal energies. This circumstance is confirmed by the present calculations in which the difference in the proton energies from two sides of the target at the instant $t = 900$ fs does not exceed 6 %. The acceleration dynamics of the protons during the interaction of laser pulses with thicker targets considered in this paper does not change qualitatively.

Figure 3 demonstrates the maximal kinetic energies of the protons from the front and back sides of the target as a function of its thickness h. The solid curve shows the experimental data presented in paper [5]. The calculations were performed at some values of M in order to study the influence of this parameter on the simulation results. One can see from Fig. 3 that these results coincide satisfactorily with the experimental results at $M \leqslant 0.75$, larger values of the energy at constant h corresponding to lower values of M. Note that this dependence tends to saturation. For example, Fig. 3a shows that in calculations with the target thickness $h = 0.1$ μm, when M was varied from 2 to 0.75, the proton energy increased from 3.4 to 4.4 MeV, and while M was varied from 0.4 to 0.3, it increased from 5 to 5.1 MeV. Thus, the influence of the enlargement parameter of the macro-particles on the results of the PIC simulation becomes weaker when their total number is increased.

Despite the differences in the kinetic proton energies calculated at different M, the shapes of the dependences of these energies on the target thickness prove similar: they have a maximum at the thickness $h \approx 0.2$ μm. The experimental dependences [5] also show the energy maximum but at $h \approx 0.1$ μm, which, taking into account the experimental error, can be treated as a good agreement between the calculations and the experiment.

To compare the dependences obtained at $M = 0.3$, 0.4, 0.75, and 2, the corresponding values of the kinetic proton energies from the front surface of the target were multiplied by the coefficients 0.86, 0.88, 1, and 1.3. As a result, the

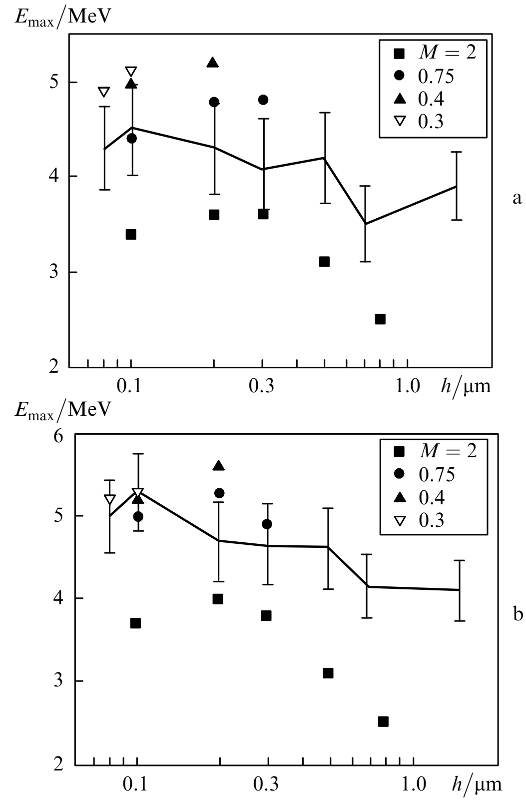

Figure 3. Dependences of the maximal proton energies from the front (a) and back (b) surfaces of the target on its thickness h at different values of the merging factor M; the solid curve is the results of the experiment [5].

values of the kinetic proton energies from the front surface of the 0.1-μm-thick target coincided with each other for all M (similarly for protons from the back side). The 'reduced' dependences obtained at $h = 0.1$ μm are shown in Fig. 4 for the kinetic proton energies from the front and back sides of the target. One can see that all the dependences fit one curve with a good degree of accuracy, which in turn, satisfactorily describes the experimental data in the studied range of the target thicknesses. Therefore, the proposed 'reduction' procedure allows one to obtain rather accurate quantitative results in a broad range of target thicknesses.

Consider now the dependence of the maximal kinetic energy of the protons on the angle of incidence θ of the laser pulse on the mylar target at $h = 0.1$ μm and $M = 0.75$. Figure 5 presents the maximal kinetic energies of the protons from the front and back sides of the target and the absolute value of their difference as a function of θ. One can see from Fig. 5 that the maximal proton energy is achieved at the angle of incidence close to $\theta = 45°$. When θ is decreased, the maximal energy noticeably decreases: at the normal incidence ($\theta = 0$), the proton energy from the front side is 1.9 MeV, while from the back side – 2.6 MeV, which is almost two-fold smaller than at $\theta = 45°$. In addition, when θ is decreased, the difference in the energies from the back and front sides is increased (reaching saturation), reaching 0.7 MeV at $\theta = 0$. Thus, at the normal incidence of the laser pulse, the proton energy from the back side of the target proves substantially higher than the proton energy from the front side, even despite the absence of pre-plasma.

Note finally, that the results of the two-dimensional PIC simulation by the CALDER code [6] presented in paper [5] also describe well the experimental data. However, to obtain

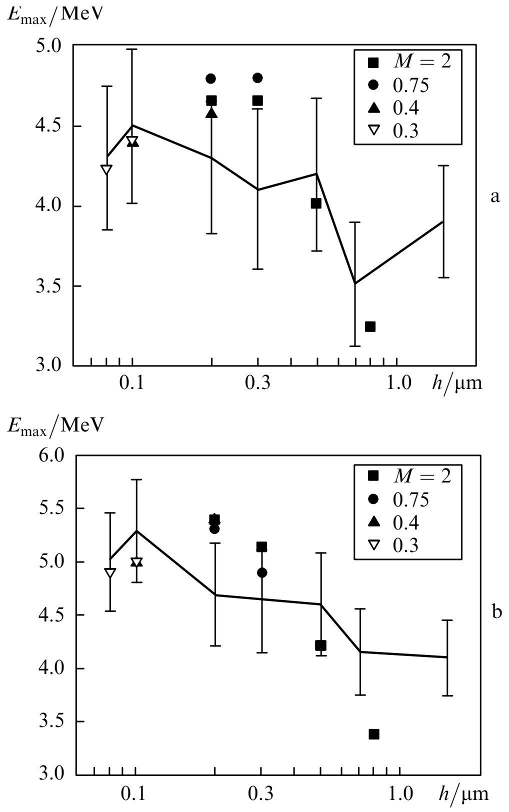

Figure 4. Dependences of the 'reduced' maximal energy of the protons from the front (a) and back (b) surfaces of the target on its thickness h at different values of the merging factor M; the solid curve is the results of the experiment [5].

this coincidence, the authors of paper [5] used in calculations a lower laser pulse intensity $I_0 = 3 \times 10^{18}$ W cm^{-2} and a higher particle concentration of the mylar target (150 critical densities), corresponding to the density $\rho = 1.9$ g cm^{-3}. These two circumstances point to the fact that the CALDER PIC code used in paper [5] yields overestimated results compared to the results obtained by using the KARAT code. To compare our results with those of [5], we performed calculations for a 100-nm-thick mylar target with $\rho = 1.9$ g cm^{-3}, $I_0 = 3 \times 10^{18}$ W cm^{-2}, $M = 0.75$. The obtained maximal proton energies from the front and back sides of the target proved equal to 3.3 and 3.6 MeV, which is more than 1 MeV lower than the corresponding experimental results (4.5 and 5.3 MeV).

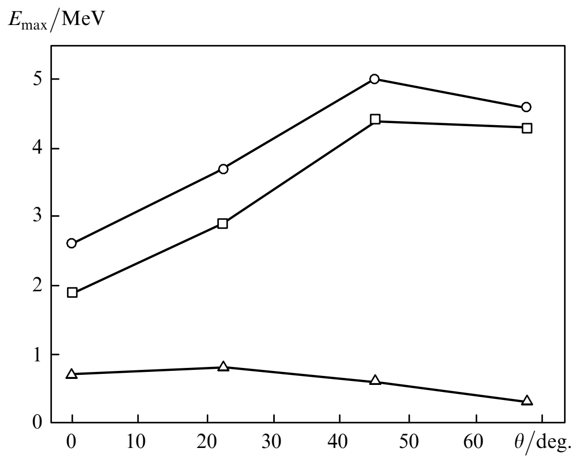

Figure 5. Dependences of the maximal energy of the protons from the front (□) and back (○) surfaces of the target and of the absolute value of their difference (△) on the angle of incidence θ of laser radiation.

5. Conclusions

The results of the KARAT PIC code simulation of interaction of femtosecond laser pulses with a mylar target well agree with the experimental data. The influence of the enlargement parameter of macroparticles on the simulation results has been studied, and this influence has been shown to decrease when the total number of macroparticles in the system increases. We have studied the dependence of the maximal kinetic energy of the protons on the angle of incidence of the laser pulse on the target and obtained that the proton energy reaches the absolute maximum at the angle of incidence equal to 45°. The results of the KARAT PIC code simulation with the results of the two-dimensional CALDER PIC code [5] have been compared. We have shown that the CALDER code significantly overestimates the maximal kinetic energy of the protons compared to the KARAT code.

Acknowledgements. The authors thank V.P. Makarov for his attention to this work and valuable remarks. This work was supported by the Russian Foundation for Basic Research (Grant No. 07-02-12060).

References

1. Umstadter D. *J. Phys. D: Appl. Phys.*, **36**, R151 (2003).
2. Pukhov A. *Rep. Prog. Phys.*, **66**, 47 (2003).
3. Belyaev V.S., Krainov V.P., Lisitsa V.S., Matafonov A.P. *Usp. Fiz. Nauk*, **178**, 823 (2008).
4. Tarakanov V.P. *User's Manual for Code KARAT* (Springfield VA, USA: Berkeley Research Associates, 1992).
5. Ceccotti T., Levy A., Popescu H., et al. *Phys. Rev. Lett.*, **99**, 185002 (2007).
6. D'Humieres E., Lefebvre E., Gremillet L., Malka V. *Phys. Plasmas*, **12**, 062704 (2005).