Mapping of induced electric field in FSA configuration

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Abstract

A recent method to produce accelerated protons and ions is the Front Surface Acceleration (FSA) realized by Laser Ion Source (LIS). We analyzed a LIS implemented to justify the ion acceleration. The plasma is reached by a KrF excimer laser operating at 248 nm. The beam was focused on a solid aluminum target mounted inside a vacuum chamber in order to obtain warm particles. The laser energy was varied from 28 to 56 mJ/pulse and focused onto the target by a 15 cm focal lens forming a spot of 0.05 cm in diameter. A high impedance resistive probe was utilized to detect the potential value inside the chamber, around the target. In order to avoid that the plasma particles invest the probe, a PVC shield containing the probe was placed perpendicularly to the main axis. Particles inevitably streaked the shield but their influence on the probe was irrelevant trivial. By the above consideration we detected potential values from 4.7 cm to 6.2 cm with respect to target axis, while the distance of the shield from the axis is about 3 cm. The electric field, determined by the potential measurement, can be very important to find the phenomenon responsible of the accelerating field creation. The behavior of the field on distance x assumes the dependence of $1/\mathrm{x}^{1.85}$ with 28 mJ laser energy, $1/\mathrm{x}^{1.83}$ with 49 mJ laser energy and $1/\mathrm{x}^{1.84}$ with 56 mJ laser energy. The power degree is between $1 \div 2$. So, it is possible to hypothesize that the electric strength is the contribution of an electrostatic and of an induced field The extension of the experimental behavior just to $x = 0.02\ cm$ the electric strength is of the order of tens kV/m which delivers ions up to 1keV. These values were justified by measurement performed with the electrostatic barrier. Considering exclusively the induced field and applying the Larmor formula the field strength results to be maximum at the center. For an electronic density of $\rho = 1 \times 10^{18}\ m^{-3}$, we estimated a field of $E = 1.97 * 10^{6}\ V/m$ at the center, and an filed of $E = 1.26 * 10^{6}\ V/m$ at beam borderline.

Introduction

The first experiment concerning the ejecting of energetic particles, proton or ions, by plasma-laser was performed in 1963[1], others in subsequent years [2,3]. The initial theory was referred to the self-generated magnetic fields generated during laser interaction insulate fast electrons from target surface, and the formation of a space charge electric field that acts on accelerating positive ions inside the evolution plasma. More deep theories are very nearly to the classic physic. They exploit the Coulomb force and the Maxwell-Boltzmann thermodynamic theory[4-6]. It is known that the Coulomb theory isn't sufficient to explain the matter constitution and as well the thermodynamic theory. This last is applicable for systems in equilibrium where it is possible to introduce the concept of temperature. Systems in transient state must be studied differently as the nature of matter is justified applying exclusively the quantum mechanics. The double layer of different charges give origin to electrostatic field which intensity is controlled by the charge density involved in the system. Instead, to reach high intensities, induced fields provoked from accelerated charges are exploited. In fact, Larmor formula gives the induced electric field for a charge *e* having acceleration *a*:

$$\vec{E} = -\frac{e}{4\pi\varepsilon_o x c^2}\vec{a}(t') \qquad (1)$$

where *r* is the radial distance from the charge *e* to field $\vec{E}$, *t* is the time and *t'* is the retarded time corresponding to *t-r/c*.

Apart from the scientific research, today, the acceleration of protons by compact devices is important for hadron therapy application, and other. The medical demand is to equip the oncological therapy centers with compact accelerators. To reach it is necessary to construct accelerators by small dimension and versatile. The threshold of interest for the therapy is more than 60 MeV [7].

Materials and methods

Let us suppose that during laser interaction with solid targets, electrons, initially lying inside the target, are instantaneously removed. The measurements of electric field inside the chamber have been performed modifying the Platone accelerator[8]. Transversally to main axis of the target, a high impedance antenna was placed. It was mobile and inserted in a PVC shield in order to protect the antenna from plasma charges. The antenna had an impedance of 10 MΩ and an attenuator factor of 10. It was delivered by the Le Croy company. To detector the electric field, we measure the electric potential in different point and because we are interested to the longitudinal electric field, we detected the potentials in two points space out horizontally of 1 cm. Fig. 1 shows experimental set up and the probe.

The accelerator consists of a vacuum chamber and an excimer laser. This last is a Compex 205 excimer laser operating in the UV range. Employing a gas mix to form the KrF excimer, its output beam was of 600 mJ maximum output energy, 248 nm wavelength, 25 ns pulse duration and a maximum repetition rate 50 Hz

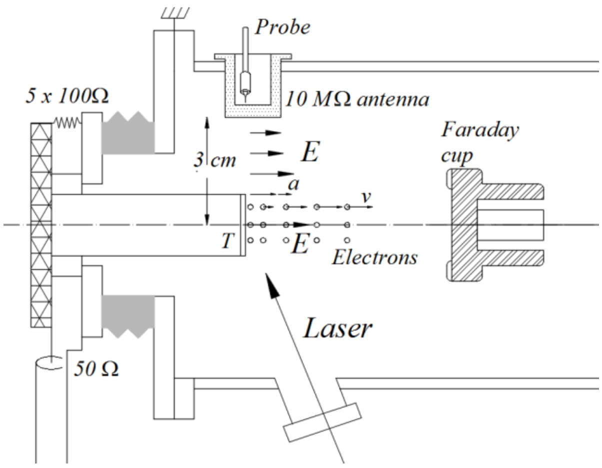

Fig. 1. Experimental set up. T: Al target; E: Electric field.

The accelerator consists of a vacuum chamber and an excimer laser. This last is a Compex 205 excimer laser operating in the UV range. Employing a gas mix to form the KrF excimer, its output beam was of 600 mJ maximum output energy, 248 nm wavelength, 25 ns pulse duration and a maximum repetition rate 50 Hz. The experiments were performed utilized as target a disk of pure *Al*. During our measurements the laser spot onto the target surface was 0.05 cm in diameter. The vacuum chamber was done by two turbo-molecular pumps reaching vacuum values down to 10^{-6} mbar. The laser beam enters into the chamber at an angle of 70° with respect to the normal to the target (T) surface, through a thin quartz window by a focusing lens.

Results

The diagnostic of electric field was performed at different distances orthogonally from main axis; from 4.7 to 6.2 cm, and with three laser energies: 28, 49 and 56 mJ.

The pulse of the antenna signals is approximately 50 ns wide, while its risetime in all measurements resulted of 25 ns, Fig. 2. This last value is coincident with the laser time duration and it points out that charges are accelerated during the laser beam action.

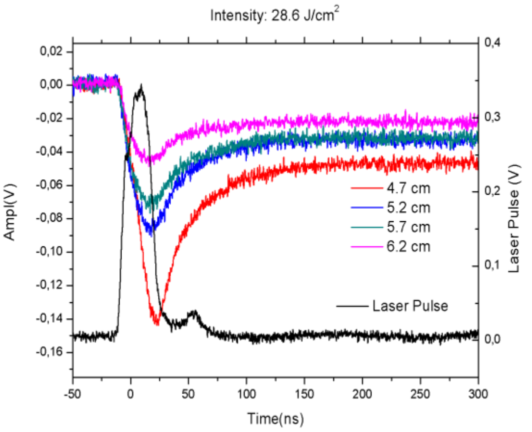

Fig. 2. Typical waveform at 28.6 J/cm^2 laser fluence.

Moreover, all potential pulses present a peak corresponding at the end of laser pulse. By the above observations, it seems that the difference of potential (between 1 cm) we observe grows with the laser fluence. Processing the experimental results, the electric field decreases as the axis distance increases and this behavior comes recorded at the three laser fluence we utilized. The experimental data are reported in Fig. 3.

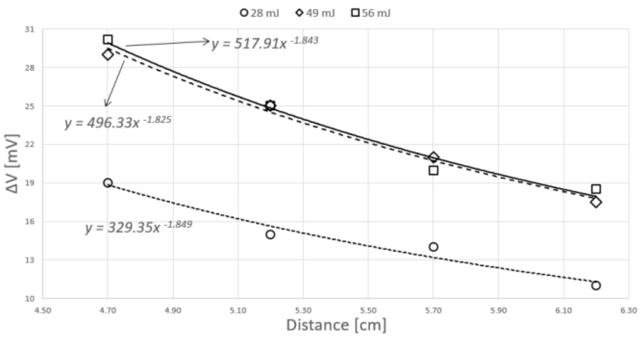

Fig. 3. Experimental values of ΔV, spaced out 1 cm, at 28, 49 and 56 mJ laser energy.

Analysis and mechanism

The results obtained are very interesting since the power of the fitting curves in Fig 3 lies between $1/\mathrm{x}$ and $1/\mathrm{x}^2$. Then, the result found suggests that a different kind of field with respect to the double-layer, should be responsible for acceleration of charges. Its action, indeed, would appear to our measures as a power like $1/\mathrm{x}^3$ for distances $\mathrm{x} \gg 0.05$ cm. It is possible to recover the situation if the presence of an induced field is supposed. This field should be ascribed to the acceleration of charges inside the plasma. The Larmor formula describes the electric field of an accelerated charge at distance r. The induced field, around the charge trajectory, perpendicularly to the main axis and at distance r is given in our case by:

$$E(r,t) = -1 \times 10^{-7} \frac{qa}{x} \tag{2}$$

with q the total charge and a its acceleration. Now, by fitting the results showed in Fig. 3, the accelerating field increases considerably near the target. Because the laser spot has been valuated to be 0.05 cm in diameter, we find the accelerating field on the borderline of laser beam but just inside it which imposes to consider the distance from the axis center about $\mathrm{x} = 0.02$ cm. At the three laser fluences utilized in this work, we have the following results:

Fluence [J/cm^2]	Accelerating field [kV/m]	Proton energy [keV]
14.3	46	2.3
25.0	63	3.1
28.5	69	3.5

Table 1: Accelerating field at different laser fluences

The found electric field has a direction perpendicular to the target surface and then it is able to accelerate positive charges. In the plasma-laser interaction it is known that an abundance of proton is present due to the impurities of target. Being the lightest positive charges, protons are the first to be accelerated. Initially lying into the target matrix, electrons absorb laser energy, escaping out. This give origin to the induced electric field. Furthermore, leaving the target, such electrons confers it a net positive charge that originate an electrostatic field. The latter could be responsible of the power of the experimental curves.

We don't measure the proton energy but let us consider the presence of the accelerating field near the target that persists for a distance equal to the laser beam diameter (0.05 cm). The proton energy we could measure would be these reported in Table 1. The final energy results to be more than 1 keV. These results are very near to the ones obtained at the LEAS laboratory utilizing an electrostatic barrier as probe [9].

To validate the results obtained, we applied the Larmor formula. Hypothesizing an electronic concentration less than $\rho = 1 \times 10^{18}\ m^{-3}$ which hits a volume equivalent to a cylinder of D=0.05 cm in diameter and h=0.05 cm in height in a time of 10 ns owing to the rise time of laser pulse, *Fig. 4.*

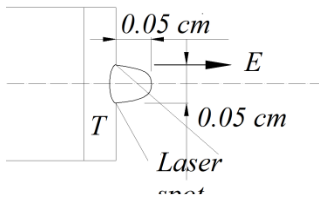

Fig. 4. Model of ejected electrons. T: target.

The accelerating electric field E at the borderline of the laser spot and as well as inside the spot surface can be obtained considering a surface charge density ρh uniformly distributed on the area $A = \pi r_o^2$:

$$E = 2 \cdot 10^{-7} \rho h\ a \int_0^{r_o} \int_0^{\pi} \frac{s}{l}\, ds\, d\vartheta \qquad (4)$$

where $l = \sqrt{(s \cdot sin\vartheta)^2 + (x - s \cdot cos\vartheta)^2}$ and *Fig. 5* shows the cross-section of the hypothetical cylinder.

The result of the integration is:

$$E(x) = 2\pi\,\rho h \left[(r_0 + x) E_e\left(\frac{4 r_0 x}{(r_0 + x)^2}\right) + (r_0 - x) K_e\left(\frac{4 r_0 x}{(r_0 + x)^2}\right) \right] \qquad (3)$$

where, $K_e(y)$ and $E_e(y)$ are the complete elliptic integrals of the first and second kind respectively.

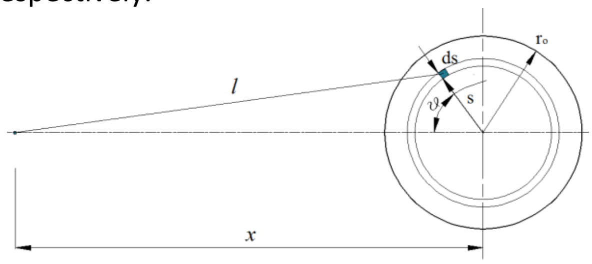

Fig. 5. Cross section of the hypothetical cylinder.

At the center of the beam we have $K(0) = E(0) = \frac{1}{2}\pi$ and the field strength corresponds to:

$$E = 1.97 * 10^6\ V/m \qquad (5)$$

while for $x = 0.025\ cm$, the it corresponds to:

$$E = 1.26 * 10^6\ \mathrm{V/m} \qquad (6)$$

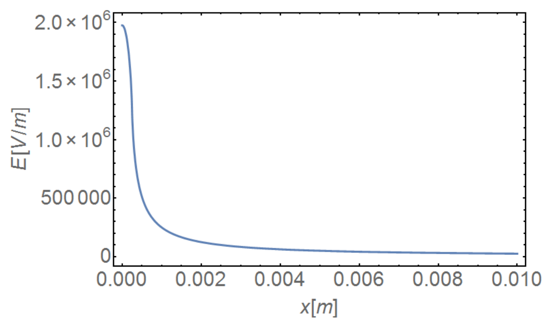

Fig. 6. Theoretical electric field on distance.

Many works [10 and references therein] pointed out that the energy of the protons obtained from laser-induced plasmas is a function of $I\lambda^2$ in the range of $10^{14} \div 10^{19}\ \frac{W}{cm^2}\,\mu m^2$. In this case, the relation for the maximum proton energy (in MeV) is:

$$E = 2 \cdot E_M = 3.5 \times 10^{-6}\ (I\lambda^2)^{1/3} \qquad (7)$$

with I is the laser intensity in Wcm^{-2} and λ is the laser wavelength in μm. Nevertheless, applying the above function to our case of $I \approx 10^9\ W/cm^2$, the resulting E_M is about $1.4\ keV$, not so different from those estimated above considering the accelerating field.

Conclusion

This work is devoted to the study of the phenomena involved in processes underlying ions acceleration in laser-matter interaction. The theory of double layer seems to be unable to explain the experimental results proposed. In effect, using the recorded signals of an high input impedance antenna, it appears that the more consistent theory seems to be the generation of an electric field induced by the acceleration of charged particles. If this is the case, the energy responsible for the acceleration doesn't came from an electric potential, but from the laser beam which acts as a ponderomotive force, impressing an high acceleration to electrons. Indeed, the *x*-dependence of the accelerating field lies between $1/x$ and $1/x^2$. This suggests an interplay between the field resulting from Larmor formula and that coming from Coulomb interaction (i.e. the double layer). The double layer alone would give a field with a different *x*-dependence, namely $1/x^3$. The electric field have been evaluated to be near 50 kV/m, which can generate protons of 1keV. Measurements by an electrostatic barrier justify the results.

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