Magnetic fields applied to laser-generated plasma to enhance the ion yield acceleration

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Abstract

A Nd:YAg laser operating at 10^{10} W/cm^2 intensity was employed to generated non-equilibrium plasma in vacuum irradiating polyethylene and aluminium targets. Plasma properties were monitored in high vacuum using Ion Collector (IC) and Ion Energy Analyzer (IEA). Plasmas were generated with and without magnetic fields directed along to the normal to the target surface and ranging between 0.1 and 0.15 Tesla. The magnetic fields produce ion focalization along the normal direction enhancing the axial ion current. The electron traps, produced along this axis by the magnetic fields, increase the ion acceleration, has demonstrated by IC measurements in time-of-flight configuration. With the used setup the ion current was increased of about 300%, while the ion energy of about 25%. Theoretical predictions, based on COMSOL simulation code, indicate that higher increments can be obtained using higher magnetic fields and laser intensities.

Introduction

Laser-generated plasma and ion acceleration from plasma expansion in vacuum represent relevant topics in many scientific fields, due to their large number of applications. In many cases ion beams with adequate characteristics, such as energy distribution, charge state and current, are required to produce useful studies concerning ion sources, ion acceleration, production of nuclear reactions, high temperature plasmas, and others [1].

In this work, it is used an axially symmetrical magnetic field system to obtain an increase of ion current and energy extracted from the laser-generated plasma. The use of an axially symmetrical magnetic field placed in front of the plasma plume, alters the emission of the charge particles from the plasma. The magnetic field introduces a distortion of the trajectories of electrons and ions emitted from the target, which, under certain conditions, can produce an ion beam focalization with low emittance and high current. Recent studies have shown that electron beams emitted from target, form traps in front of the magnets, which are responsible of dynamical charge cloud separation, with formation of high electrical fields responsible of high ion acceleration [2].

In our work a magnetic field system with axially symmetry, of the order of about 0.1 T, is used to drive the plasma charge particles generated by nanosecond laser intensity at 10^{10} W/cm^2. In these conditions, it was possible to observe an increment of the ion current and energy for protons, carbon and aluminum ions. The results obtained are discussed and presented.

Materials and methods

A Nd:YAg laser, with fundamental wavelength 1064 nm, maximum pulse duration 3 ns, and energy variable from 1 to 300 mJ, was employed to irradiate dielectric and metallic targets, in single shot mode. The laser beam is focused on the target, placed in vacuum chamber at a pressure of about 10^{-6} mbar, through an optical lens having a focal distance of 50 cm. The spot size on the target surface is about 0.5 mm^2. The laser beam incident angle on a target surface is 45°. The irradiated targets are constituted by polyethylene and pure aluminum. A photo and a scheme of the experimental setup are reported in Figure 1.

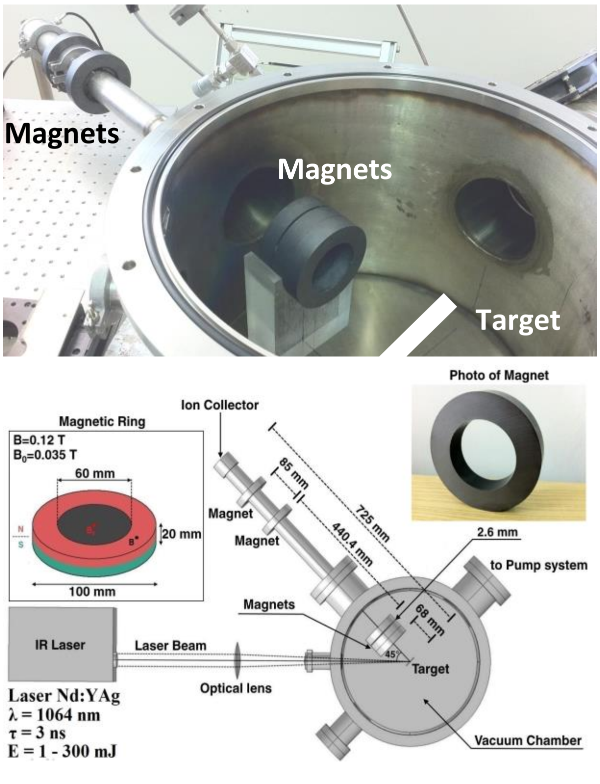

Figure 1: *Photo and Scheme of experimental setup.*

The magnet rings are permanent ferrite magnets. A single magnet has an outer diameter of 100 mm and an internal of 60 mm; its thickness is 20 mm. The produced magnetic field is axial (0.12 T on the surface of the magnet and 0.035 T at the center of it). The axis of the magnets is positioned along the normal to the target surface, in correspondence of the laser spot position.

At a distance of 68 mm from the target, it is inserted a system of three magnets, of which the first two are placed in contact, and the third is 2.6 mm far from the latter. Two other magnets are placed outside the vacuum chamber, at distances of 503 mm and 608 mm from the target. The tridimensional distributions of the magnetic field, generated along the axial symmetry, is reported in Figure 2.

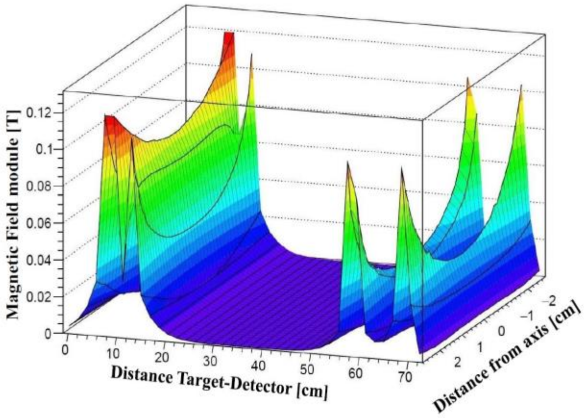

Figure 2: *Tridimensional distribution of magnetic field parallel to axis of the system.*

The detector used for the collection of the ions emitted from the plasma, is an ion collector (IC), placed at 725 mm distance from the target. The ion collector is polarized to -50 V with respect to the grid to reduce the secondary electron emission. This device is used in time of flight technique (TOF), which consists to evaluate the time that ions take to travel a known distance from the target to the detector, measured using a fast storage oscilloscope. The presented measurements were performed with the experimental setup just described applying or not the axial magnetic fields.

Results

In Figure 3 are shown the IC-TOF spectra obtained by irradiating targets of polyethylene and aluminum, in the system without and with the axial magnetic fields.

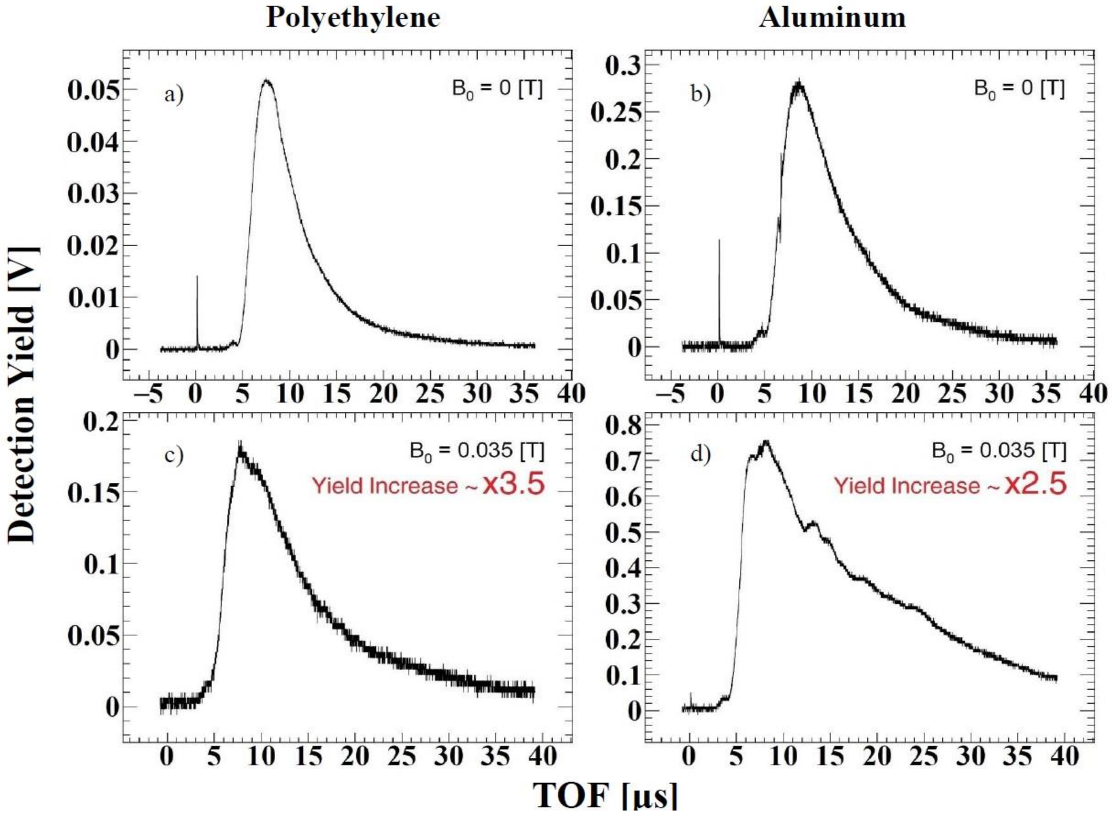

Figure 3: *Comparison of TOF ions spectra, obtained by IC measurement, for polyethylene and pure aluminum, without (a,b) and with (c,d) axial magnetic field system.*

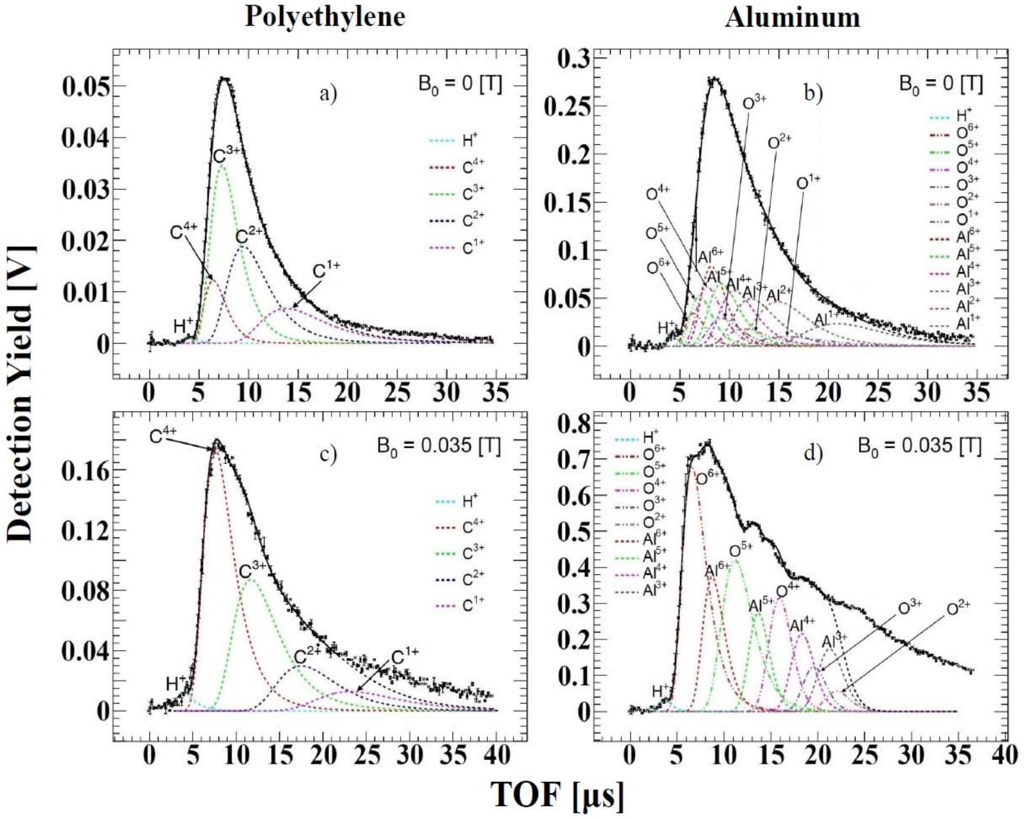

Figure 4: *Data fit, with CBS distribution, of TOF ions spectra, for polyethylene and pure aluminum respectively, without (a,b) and with (c,d) axial magnetic field system.*

The system of axial magnetic fields focuses the plasma ions enhancing the ion yield collected with the IC detector. Experimental data presented in Figure 3 show an increase of the detection yield using the magnets. The IC yield was evaluated about 3.5 times higher for polyethylene and about 2.5 times higher for pure aluminum, with respect to the case without magnets. Moreover, the presence of the magnetic field decreases the TOF of the detected ions demonstrating an increment of the mean ion energy acceleration. This energy increment for protons was evaluated of about a factor 25% higher with respect to the case without magnets.

From the literature it is clear that the curves shown in Figure 3, can be interpreted as convolution of velocities distributions like Coulomb-Boltzmann shifted (CBS) distributions of the individual ion components constituting the plasma. Each ion has a different distribution depending on its mass and charge state. The function used for the fit is the following [3]:

$$f(t) = A\sqrt{\left(\frac{m}{2\pi k_B T}\right)^3} \times \\ \times \exp\left[-\frac{m}{2k_B T}\left(\frac{L}{t} - \sqrt{\frac{\gamma k_B T}{m}} - \sqrt{\frac{2zeV_0}{m}}\right)^2\right] \quad (1)$$

where A is a normalization constant, m is the mass of the ion considered, L is the distance between the target and the detector (in our case 725 mm), γ represents the adiabatic expansion coefficient (which is 1.67 for the monoatomic species), ze is the charge which possesses the ion, V_0 is the equivalent potential in non-equilibrium plasma, k_B is the Boltzmann constant, and finally $k_B T$ is the equivalent plasma temperature in eV.

The analysis of the TOF ions spectra were necessary to determine the increase of the detection yield and energy for each ion species. A typical deconvolution analysis is reported in Figure 4.

Irradiating the polyethylene target and measuring the maximum kinetic energy of the protons and of the carbon ions it was possible to demonstrate that the first four charge states of carbon ions were produced by the laser-matter interaction.

By irradiating the pure aluminum target and measuring the proton and aluminum ion energy it was possible to demonstrate that the charge states from 1+ to 6+ of aluminum were produced. In addition, the first six charged states of oxygen, as contaminant, were also detected.

Discussion

The measurements of the ion current (yield) demonstrate that it increases in presence of the axial magnetic field application. The increase of the ion yield was evaluated not only experimentally but also theoretically through the COMSOL-Multiphysics code simulation program. The simulation of the charge particles produced by the laser-target interaction needs to include their mean energy and emission angular distributions vs. ion mass and charge state, according to literature [4, 5]. The simulation data have shown an excellent agreement with the experimental ones. In particular, the obtained experimental data and simulations show an increase in ion energy and ion yield when the axial magnetic field is applied.

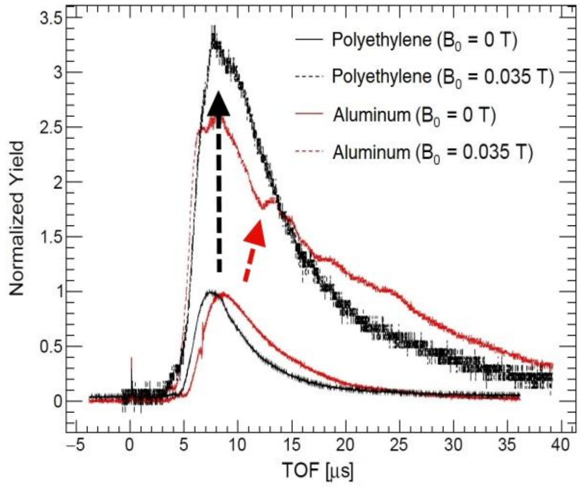

Figure 5: *Comparison between the TOF curves, for polyethylene and aluminum, normalized to the maximum yield values in the system without magnets.*

Figure 5 shows the overlaps between the TOF spectra for polyethylene and aluminum target irradiated by laser. This figure shows that the insertion of the axial magnets in the system produces a reduction of the TOF values, and thus a consequent increase of the ions energy. In addition, the TOF spectrum obtained by irradiating the aluminum target in the system with the magnets also precedes that obtained by irradiating polyethylene in the same conditions, demonstrating that the mean ion energy enhances with the electron density of the plasma due to the higher effect of charge separation.

To explain the increase of ionic energy observed, it is necessary to know the dynamics of electrons in the system of interest. With the simulation software COMSOL it is possible to simulate the motion of the electrons in the magnetic fields with axial symmetry, as reported in Figure 6.

Figure 6 shows the simulation of the electrons in the studied system. In presence of the magnets, the kinetic electrons produces two traps, as two negative clouds in front of the target surface, that are responsible for an increase of the plasma potential and of the ion acceleration. Without magnets, after 150 ns, the electrons emitted from the target are located at about 21 cm distance from the target, while with the magnets, this peak appears to be approximately to 5 cm distant from the target surface. Such distance reduction of the electron density changes the spatial charge distribution resulting an increment of the plasma potential, generating a high electric field responsible of higher ion acceleration.

The plasma potential increment can be extrapolated from the values obtained by the CBS fits and presented in Table 1. In this, we reports the plasma temperature k_BT and the

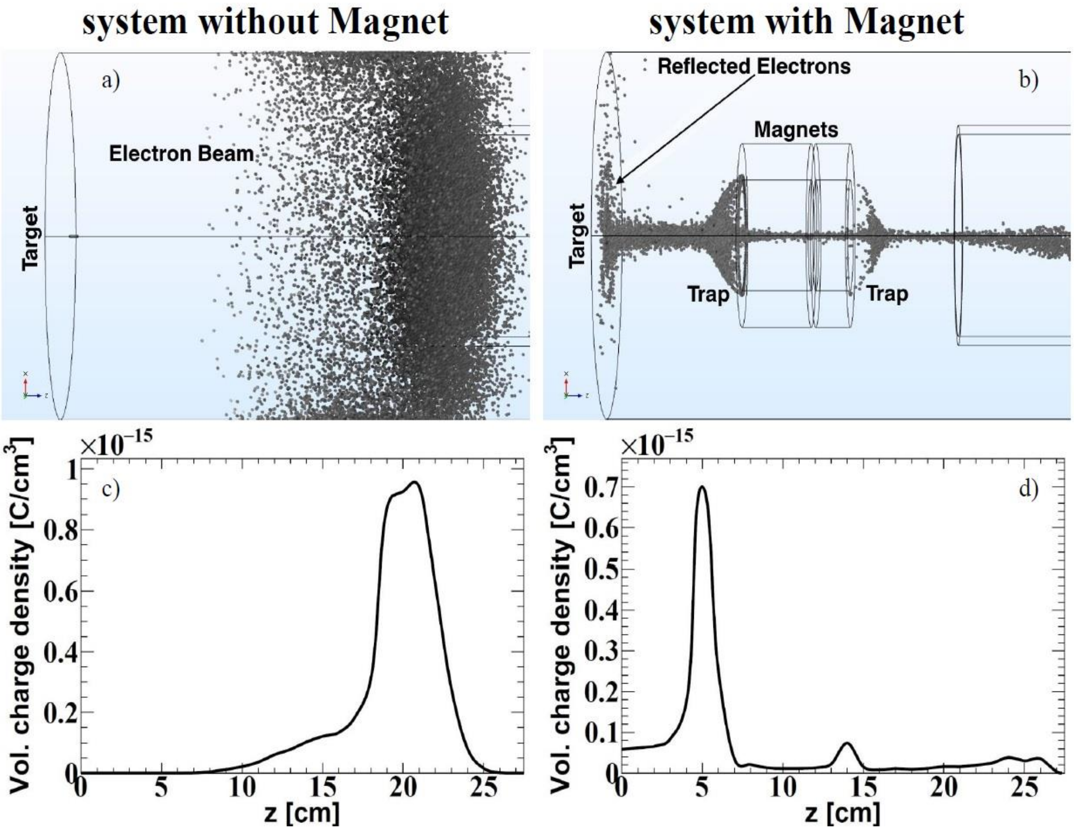

Figure 6: *Simulation, with COMSOL Multiphysics, of the dynamics for electrons, (30000 electrons with 10 eV energy, 150 ns after the emission from the target), in the system without and with the magnets (a,b). Volumetric charge density generated by the electrons, 150 ns after them emission from the target, versus distance from the target, in the system without and with magnetic fields (c,d).*

potential V_0 with and without the application of the magnetic fields.

The average value for energy for charge state estimated from the fits is 170 eV, for both targets. The increased energy, estimated in the case of protons, is approximately 11.6 eV in the case of polyethylene target; while it is approximately 43 eV in the case of aluminum target. The increase of proton energy is therefore most important for metallic targets due to their high electron density with respect to the insulator polymeric target.

Polyethylene

without magnet

	T [eV]	V_0 [V]
C	38	39.

with magnet

	T [eV]	V_0 [V]
C	38.00	50.9

Aluminum

without magnet

	T [eV]	V_0 [V]
O	36.7	64.3
Al	36.9	64.2

with magnet

	T [eV]	V_0 [V]
O	36.7	107.4
Al	36.9	106.3

Table 1: *Average values of temperature and potential of plasma, for polyethylene and aluminum targets, obtained from the fit of the TOF spectra, in the system with and without magnets.*

Conclusions

The results reported in this article show that the application of axial magnetic fields to the plasma, generated by a laser intensity of 10^{10} W/cm^2, increases the ion yield and the ion energy, in agreement with simulation data. The ion yield can be varied in accordance with the focal distance of a thin magnetic lens [6]. For the system of interested increases of ion yields approximately of 300% were obtained.

The perturbation of the emitted electron beams, due to the axial magnetic field, is responsible for the increase of plasma potential, and consequently of the increase of the ion energy. The ion energy enhances as result of the electron density of the irradiated target and of the electron traps generated in front of the target surface. Moreover, it depends on the proximity of the electron traps from the target itself. The simulations carried out with COMSOL Multiphysics have shown that the electrons remain trapped for times of the order of hundreds nanoseconds; the result is sufficient to accelerate ions at higher velocity. Experimental data confirm an increase in energy for the protons of the order of 25% or more.

Further analysis are in progress to modify the magnetic fields and their distance from the target, the nature of the target and the parameters of the laser-produced plasma.

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