Effect of neutron irradiation on the characteristics of laser produced plasma

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Abstract

Using a static mass-spectrometer we studied the effect of the target irradiation with neutrons on the parameters of the plasma particles generated from such irradiated targets under the action of laser radiation. We found that the defects in the crystal structure of targets, due to the irradiation, influence not only on the efficiency of the material evaporation process and emission of the plasma, but also on the efficiency of ionization and recombination processes, which takes place in the plasma bunch on the stage of formation and expansion.

1. Introduction

Intense pulsed heavy ion beams have been attracting a lot attention in past few years due to their possible applications in, e.g., materials processing including surface modification, thin film deposition, ablation of solid targets, non-equilibrium plasma production. High energy and charge state ion beams also present remarkable interest in fundamental and applied nuclear physics research. An example is the possibility to generate non-equilibrium plasma in a vacuum in order to obtain very high and very fast electric field transients, useful to accelerate ions [1, 2]. Plasma ions can also be used for heavy ion driven plasma research – the production and injection of ion streams into ion sources so that high currents and charge states can be extracted for post acceleration [3].

Laser-produced plasma is also known to be a source of ions the inertial confinement fusion [4-8], which has advantages over e.g. a common metal vapor vacuum arc method [8] as a source of ions. In inertial confinement fusion scenario the main requirements for the ion source are i) 10^{13}-10^{14} ions per pulse, ii) long-pulse over 1 μs, and 3) low charge state [8]. These requirements are meet by laser ion sources based on the pulsed laser ablation process [6]. Many theoretical [8,9] and experimental [9,10] works have been carried out in order to optimize the performance of the laser ion source and to determine important operating parameters such as the velocity, mass and charge-state distribution of the generated ion beam and plasma temperature. Previous works devoted to laser-matter interactions and generation of laser enhanced ion beams have shown that characteristics of plasma ions depend both on the parameters of the laser radiation (i.e. wavelength, intensity, duration and repetition frequency of the pulses, focal spot) and the properties of the target material (i.e. surface roughness, density and composition of the target). Very recently, Khalil and Gondal [9] studied generation of silver ions by the laser radiation for different wavelengths and pulse energies, as well as for different ambient gas pressure and applied electrical field. They showed that the velocity distribution function and current signals strongly depend on laser power, laser wavelength and gas pressure. Effect of repetition of laser impulses on the parameters of the generated plasma was recently investigated experimentally in Ref. [10]. It was found that the frequency of laser impulses has a significant effect on the parameters of plasma ions: with increasing the frequency of the laser the charge, energy and intensity of ions increase for a given parameters of the target. Gus'kov et al. [11] conducted numerical simulations for the radiation absorption, the energy transfer, and the plasma formation upon the interaction of a laser beam with a homogeneous medium consisting of light elements with a density not exceeding the critical plasma density. It was found that the spatial temperature distribution of the resultant plasma is determined by the anisotropy of energy transfer, which is in a good agreement with previous experimental findings [12]. Recent experiments [10] carried on porous targets with different densities, subjected to a laser radiation, also show that the charge, energy and intensity of plasma ions strongly depend on the target density. Experiments [13,14] on the effect of target composition of the formation of plasma ions show that the increase of the fraction of light element in two-element targets leads to the widening of the energy spectra of heavy ions by more than a factor of two. This effect is explained by the friction existing between light and heavy ions during their expansion away from the target.

In this work using time-of-flight measurements and the collector method we study the effect of target irradiation by neutron beams on the formation and expansion of plasma ions. Such neutron irradiation leads to the formation of surface defects, which in turn affects the plasma formation process [15]. Experiments on the effect of neutron irradiation is essential e.g. in the High Average Power Laser (HAPL) power plant design program, which aims in developing laser inertial fusion energy based on direct drive targets and a dry wall chamber [16]. In this scenario, the final optics system that focuses the laser onto the target includes grazing incidence metallic mirrors covered by a 50 micron thick aluminum coating. Although these mirrors are placed out of the direct line-of-sight of the target to protect from direct neutron damage [17], secondary neutrons still result in significant flux at the finale focusing mirrors. Together with the numerical calculations [18] experimental data for the estimate of the radiation damage are still essential.

2. Experimental setup

We study the effect of structural defects on the laser-generated plasma formation process during the interaction of Nd:YAG laser radiation with targets made of W and Al with Mn impurities. These defects were created by irradiating the targets in a vertical channel of the reactor with neutron beams. The intensity of the neutron beams were changed within the interval d=10^{15}-10^{21} neutron/cm^2 (n/cm^2) with the average energy of neutrons 1.5 MeV. The laser operated at 1,06 μm wavelength, 50 ns pulse duration, 5 J pulse energy and single shot mode. The laser beam was focused trough a convergent lens on a target placed inside a vacuum chamber at 10^{-6} Tor. The power density of the laser radiation on the surface of the target was in the range q=10^8-10^{12} W/cm^2. Plasma current was measured by the collector method and the plasma ions parameters by time-of-flight mass-spectrometer (the distance was L=362 cm). The surface area of the targets were 3.14 cm^2 and the thickness 1 mm. The target could be moved vertically with the vacuum feedthrough, so that each laser shot could hit a fresh surface to avoid the effect of crater formation. The surface morphology of the samples was investigated by electron microscopy.

3. Experimental results and discussions

Figure 1 shows the electron microscopy images of the surface of Al(Mn) sample without and with neutron irradiation of different doses. It is seen from this figure that sample irradiation leads to the increase of boundary of the grains and new pore will appear, the size and concentration of which is determined by the dose of the radiation (Fig. 1 (b)). However, with further increasing the dose of the radiation the annealing of some of the defects are observed (Fig. 1 (c)). Similar results have been obtained for the W target. The results of neutron-structural analysis show that the density of Al(Mn) target decreases by 8 % after irradiation with dose 10^{21} n/cm^2 compared to non-irradiated case. The resistance of the targets against the damages by the laser radiation (i.e. the size of the craters formed after the laser incident) also dependence on the dose of the radiation d – it decreases with increasing d. This resistance also depends on the target composition. To understand the latter effect we performed measurements on electric- and thermal conductivity of the samples and found that thermal conductivity of the sample decreases with increasing the dose of the radiation. However, this cannot be due to the reduction of the part

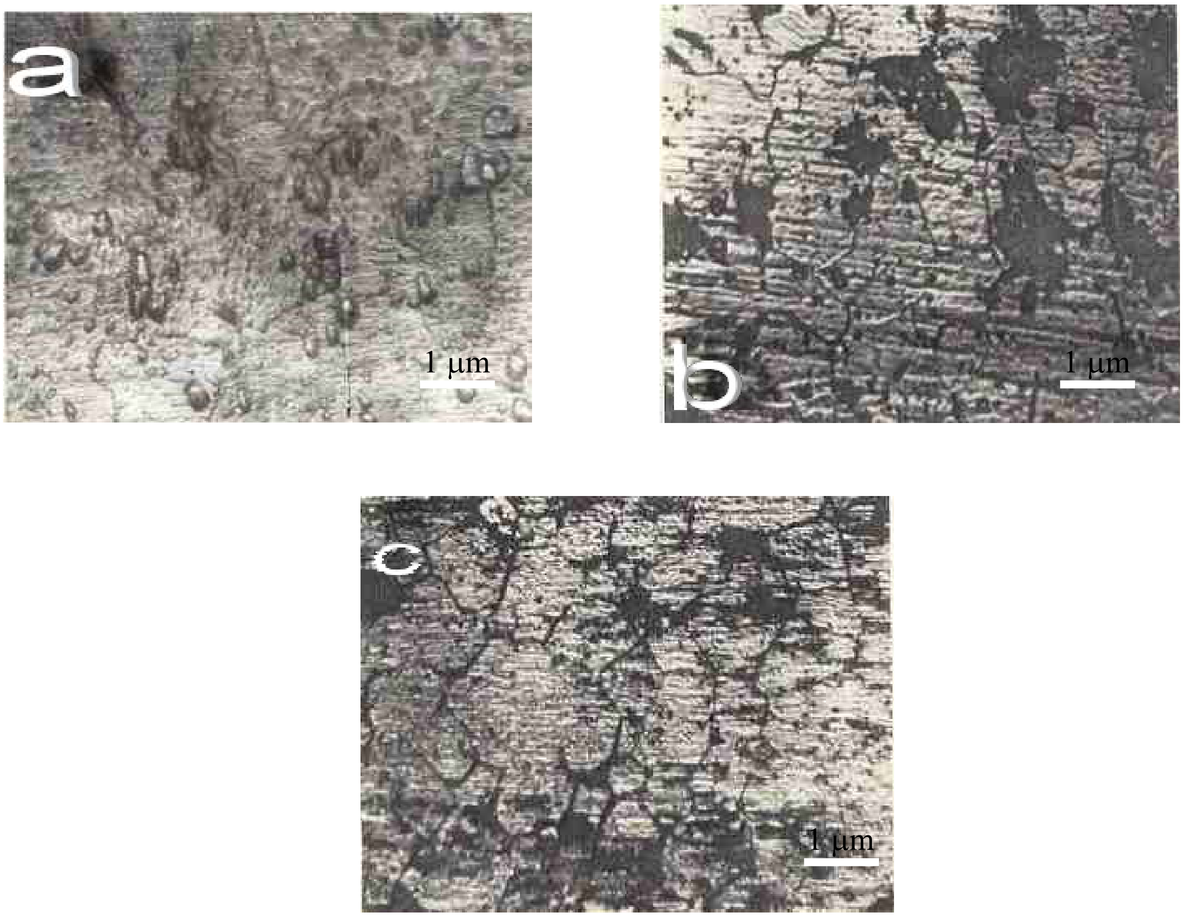

Fig. 1. Microstructure of Al(Mn) targets for different dose of neutron irradiation: (a) without irradiation, (b) $d=2\cdot10^{19}$ n/cm^2 and (c) $d=2\cdot10^{20}$ n/cm^2.

of the laser radiation absorbed by the target, as the measurements of electric conductivity show that the defects, caused by the neutron irradiation, lead to the degradation of conductivity of the sample. This indicates the enhancement of ability of irradiated targets to absorb the heating electromagnet radiation according to the expression $R=1-(2\omega/\pi\sigma)^{1/2}$ [15], where R – reflection coefficient of the target, ω - frequency of the laser radiation, and σ – conductivity.

Figure 2 shows the plasma currents as a function of time, generated at the interaction of laser radiation with power density $q=10^9$ W/cm^2 with the surface of Al(Mn) (a) and W (b) targets without (filled circles) and with (open circles) neutron irradiation of dose $d=10^{17}$ n/cm^2. As we see from this figure the emission of charged plasma particles increases with irradiating the sample with neutrons. The presence of neutron irradiation defects also affects the threshold of plasma formation. For example, the first plasma ions were detected at $q=9\ 10^7$ W/cm^2 for non-irradiated sample, while this value of the laser intensity is 10% smaller for the sample irradiated at $d=10^{19}$ n/cm^2. The charge composition of the plasma is also influenced by the irradiation: the maximal charge of ions in laser-produced plasma (the intensity of the laser radiation is $q=10^{11}$ W/cm^2) in non-irradiated Al(Mn) sample is $Z_{max}=8$, while this number equals to 9 and 10 for irradiated Al(Mn) samples with dose 10^{18} and 10^{19} n/cm^2, respectively. Qualitatively similar results have been obtained for the W sample, therefore, in the rest of the text we discuss the results obtained for the Al(Mn) targets.

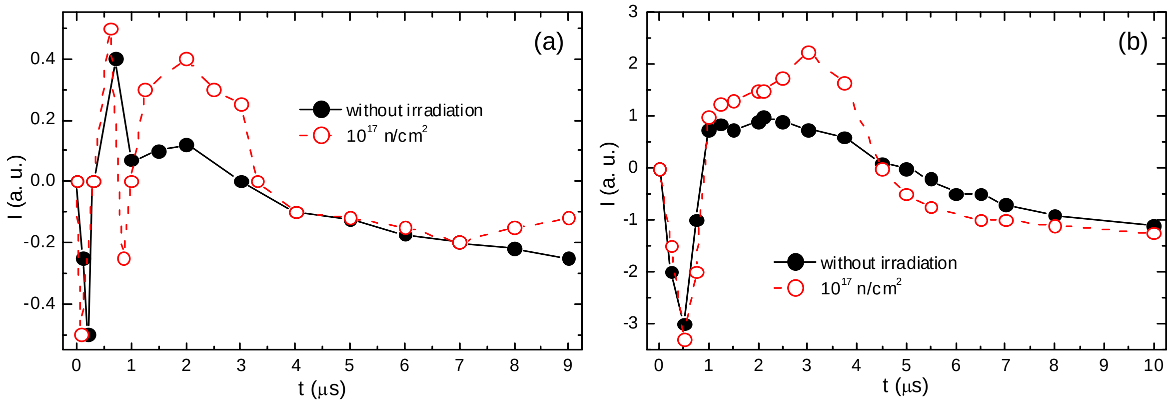

Fig. 2. Plasma currents generated during the interaction of laser radiation ($q=10^9$ W/cm^2) with Al(Mn) (a) and W (b) targets without (solid curve and solid circles) and with irradiation of dose $d=10^{17}$ n/cm^2 (dashed curve and open circles).

The energy distributions of Al^{2+} and Al^{3+} ions for different values of radiation dose d are shown in Fig. 3. From there we can see that the irradiation leads to some regularities in the plasma formation process. In the case of irradiated targets the energy spectra of ions expands both to low and high energy ranges (compare solid/black and dashed/red curves).. This shows not only that the plasma is heated to higher temperatures, but it also shows that the plasma ions have larger hydrodynamic acceleration at the initial stage of plasma expansion and the efficiency of recombination process becomes less pronounced. The increase of electron and ion currents in the plasma generated from irradiated targets may be due to the formation of radiation defects which changes the balance of energy of laser radiation spent for formation and heating of the plasma. This is most important factor to increase the characteristics of laser source of ions. However, starting from $d \sim 10^{19}$ n/cm^2 the maximal energy of the ions decreases again (compare dotted/green and dashed-dotted/blue curves). Figure 3 (c) shows the dependence of the intensity of Al^{3+} ions on the radiation dose. The intensity of ions also increases with increasing d, but starting from some critical dose of the irradiation d_c, it decreases again. Note that d_c depends on the charge composition of the ions.

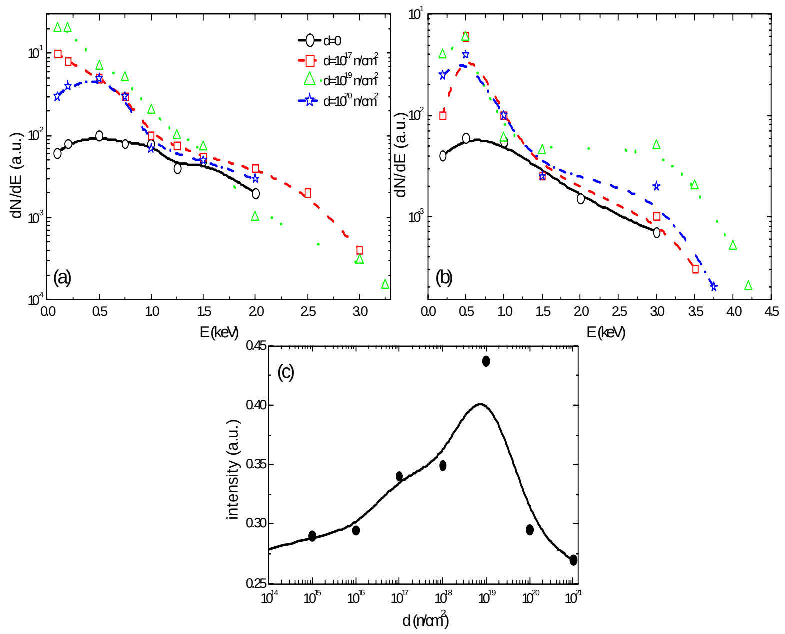

Fig. 3. Energy spectra of Al^{2+}(a) and Al^{3+} (b) ions generated from Al(Mn) target at $q=10^{11}$ W/cm^2 for different doses of the radiation d. (c) The intensity of Al^{3+} ions as a function of d.

We also performed measurements of spatial distribution of laser-plasma ions. Experiment results the irradiation of the targets with doses 10^{15}–10^{16} n/cm^2 does not have significant influence of the spatial distribution of the ions. Further increase of *d* leads to narrowing of the ions distribution and to the shift of the direction of the maximal ions expansion to smaller angles. For the case of irradiated targets with dose $d \geq 10^{19}$ n/cm^2 characteristic flow of Al ions is found. Figure 4 shows the spatial distribution of Al(Mn) plasma ions for different doses of the neutron irradiation. One of the reasons of narrowing of spatial distribution of ions beam is the decrease of the inertia of the plasma [15]. In our case this means that in the plasma formed with the laser radiation from the irradiated samples, the condition is reached which decreases recombination processes.

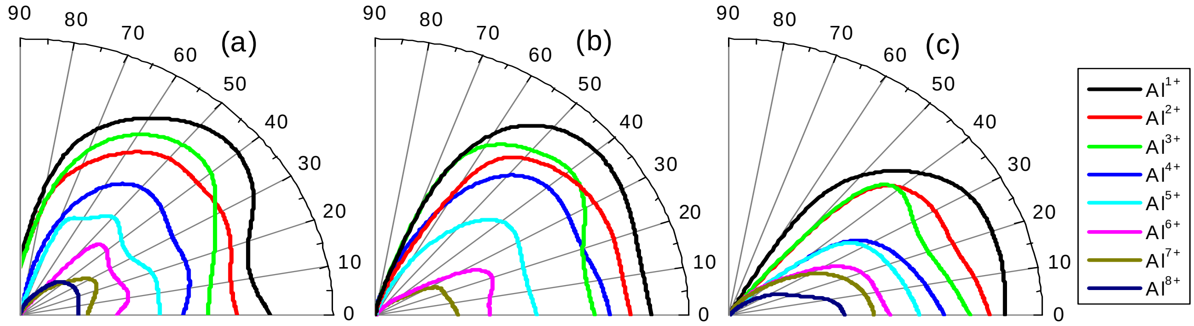

Fig. 4. Spatial distribution of plasma ions generated from Al(Mn) target with the laser radiation of intensity $q = 10^{11}$ W/cm^2 for the dose of the radiation: (a) d=0, (b) $d=10^{19}$ n/cm^2, and (c) 10^{21} n /cm^2.

Thus, on the base of analysis of experimental results on the dynamics of spatial distribution of ions, formation of energy spectra, as well as plasma currents we conclude that preliminary irradiation of Al targets, further interacted with the laser radiation, leads to the formation of the optimal condition for formation and expansion of plasma. This condition is able to increase efficiency of ionization process and possible decrease of the recombination process.

It is known that the reactor irradiation of the solids leads to the formation of stable structural defects due to breaking of bonds and shift of particles in the lattice points and between them [17]. As a results of shift of crystal particles from their regular position in the lattice strong potential and local Coulomb field is formed. The interaction of laser radiation with such irradiated targets is different from the interaction with non-irradiated samples because physical properties of irradiated samples are different from the reference sample. The experimental results show that irradiation leads not only to the deterioration of structure of the targets but also to the degradation of the heat and electric conductivity. At the same time the density of the target decreases and micro hardness increases.

Deterioration of electric conductivity properties of the samples means the increase of their ability to absorb the electromagnet radiation. The increase of the part of the laser radiation absorbed by the target, which has less thermal conductivity than the reference sample, leads to the increase of temperature of the target. The intensity of evaporation process in the sample is determined by the bound energy of atoms [19]. According to the theory of absolute velocity the possibility of elementary evaporation is [120]

$$\Omega = \frac{\kappa T}{h \; f / f^*} \exp\left\{ -\frac{\lambda_1}{\kappa T} \right\}$$

where k and h - Bolsman and Plank constant, f^* - statistic sum of activated complex in which the term of "reaction" coordinate is not taken into account, f – static sum connected with crystallic lattice of atoms, λ_1 – activation energy, which equals to the energy for evaporation of one atom at zero temperature, T - temperature of the layer where evaporation takes place. If we assume λ_1 and f constant, the probability of evaporation is larger due to high temperature. Taking into account the presence of the area with broken and partially weakened bounds in irradiated samples we can assume that these factors also increase the efficiency of the evaporation process.

4. Conclusions

We investigated the effect of radioactive irradiation of the targets on the parameters of plasma ions generated under the action of the laser radiation. For the same intensity of the laser radiation, the irradiation of the targets with neutrons leads to decrease of plasma formation threshold, as well as to increase of emission, charge and energy of ions and narrowing of the spatial distribution of the ions. The change of properties of irradiated targets caused by the formation of structural defects, influences on the efficiency of material evaporation and formation of plasma. The obtained results can be used to optimize the characteristics of plasma ions for sources of multi-charged ions.

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