Investigation of characteristics of Ho_2O_3 targets with different density by a laser mass-spectrometer

R.T.Khaydarov

Institute of Applied Physics, National University of Uzbekistan, 700174-Vuzgorodok, Tashkent

e-mail: rkhaydarov@nuuz.uzsci.net, rtkhaydarov@yahoo.com.ph

Abstract. Two-element plasma ions generated from porous (Ho_2O_3) target were studied depending on the target density (ρ) by mass-spectrometric method. Experimental results have shown that at low energy part of the spectra ($E \leq 50$ *eV*) maximal charge for oxygen ions is reached at low densities (ρ_1, ρ_2), while maximal charge of *Ho* ions is obtained at higher target densities ($\rho \geq \rho_3$). This effect is the results of non-equilibrium ionization processes in the plasma due to the changing of the volume, which absorbs laser radiation.

1. Introduction

According to the Inertial Confinement Fusion (ICF) scenario, [1-7] DT fuel is placed in a spherical capsule and compressed up to higher densities $\rho \sim (300–1000)$ g/cm^3 by the pulsed pressure from the external energy source – drivers. At the moment of largest compression a condition is reached necessary for higher density and temperature of the target. After that the fuel is ignited, *i.e.* $D+T$ fusion takes place with energy release as neutrons and α-particles. Neutrons leave the reaction area, α-particles decelerate and give their energy to the fuel, keeping the process of ignition. For this process it is essential that the "optical thickness" of the compressed fuel ρR (R is the radius of the compressed fuel) exceed the universal value $\rho R \geq 0.5$ g/cm^2, which is defined by the free pass of α-particle with energy 3.5 MeV, the speed of radiant energy dissipation from the DT plasma and the criterion of inertial confinement. In these conditions charged products of the reaction – α-particles give most of their energy to the dense plasma and the burning process takes place at temperatures 30 – 100 keV, corresponding to the maximal speed of *DT* reaction. Before the corresponding part of the fuel expands under the action of hydrodynamic pressure, during the time $\sim 10^{-10}$ s, it should consist ~30% of *DT* mass. Therefore, the requirement for the largest compression of the thermonuclear fuel is fulfilled by the larger coefficient of ignition and enhancement of thermonuclear energy G for the comparatively small amount of *DT* fuel.

It is known that special drivers – lasers, ions beams, Z-pinches – are used in ICF for the compression and ignition of microscopic targets with *DT* flues up to the thermonuclear temperatures. One of such drivers – Laser-plasma generator – consists of powerful frequency mode laser, the chamber of interaction with the target and a setup for the extraction of high-current ions beams. The system generates beams of large amount of highly charged atoms and nucleus of elements, including rare and radioactive isotopes to inject into the electro-physical equipments. This opens new perspectives in the development in science and technology: accelerators to investigate physics of high density of energy in the matter, for relativistic physics, equipments for radiational interaction with solid surfaces, as well as a drivers for ICF.

It is know that one of the main problems facing thermonuclear fusion is to find a source of ions having characteristics suitable for ICF. [6-11] Laser source of ions can provide the highest intensity of multiply charged ions for injection into practically any accelerator. For the practical use of these sources it is desirable to have high momentum without reduction in intensity and charge of ions. One of the ways to increase the momentum of ions is to use multi-element targets. It has been demonstrated that the energy spectra of ions obtained by laser irradiation of multi-element targets appreciably differ from the spectra of ions obtained from single element targets. [11-15] In Ref. [16] two-element PbMg targets were investigated where the concentration of light element Mg was fluently changed. It was shown that the energy spectra of both light and heavy ions were enlarged compared to the spectra of one-element plasma due to the energy exchange between light and heave ions. For example, ions from mono-element Pb and Mg targets have an energies in the range of 150-1200 eV and 250-2000 eV with maximum charge Z_{max}= 4 and 5 respectively. In the case of the two-element targets Z_{max} of both kinds of ions is at least one unit lower. The energy spectra of Pb ions extend to ≥ 4000 eV, whereas the spectra of Mg ions shrink to ≤ 1000 eV. For any concentration of Mg, two groups of ions of different spectral range are clearly seen and with increasing *n* the energy spectra of Mg ions remains virtually unaltered while the spectra of Pb ions extends to higher energies.

The characteristics of plasma ions can also be changed by using porous targets with different density ρ. In this case the formation of mass-charge and energy spectra of ions, as well as their intensity, is strongly influenced by the region of dense plasma inside the target, which effectively adsorbs the laser radiation. In this work we study mass-charge and energy spectra of multiply charged ions of plasma, generated from Ho_2O_3 targets of different density under the action of laser radiation.

2. Experimental setup

Experiments were carried out in a laser mass-spectrometer [16] with Neodymium glass laser (λ=1.06 μm, E=0.8-1 J, τ=15 ns, the average size of focal spot is 10^{-4} cm^2), which gives the power density of the laser radiation at the target surface up to q= 5 10^{10} W/cm^2. Laser beam was directed perpendicular to the surface of the target and each experimental result is the average over five impulses of the laser radiation. Ho_2O_3 targets with diameter 1.0 cm and thickness 0.5 cm are used in the experiment, which have density ρ_0=1.2 g/cm^3 (initial condition-powder), ρ_1=1.4 g/cm^3, ρ_2=2.8 g/cm^3, ρ_3=3.2 g/cm^3, ρ_4=3.5 g/cm^3, ρ_5=3.7 g/cm^3.

3. Experimental results and discussion

We obtained experimentally the mass-charge spectra of plasma ions depending on the target density ρ. As an example, we show in Figs. 1(a-c) typical mass-charge spectra of plasma ions for different target density ρ for the energy of single charged Ho^{+1} ions 50 eV. It is seen from this figure that at low values of ρ single charged Ho^{+1} ions and oxygen ions with charge O^{1+}, O^{2+}, O^{3+}, O^{4+} are detected. With increasing ρ *Ho* ions with higher charge appears and oxygen ions of higher charge disappear from the mass-charge spectra. The increase of ρ leads also to a nonlinear change of intensity of oxygen ions.

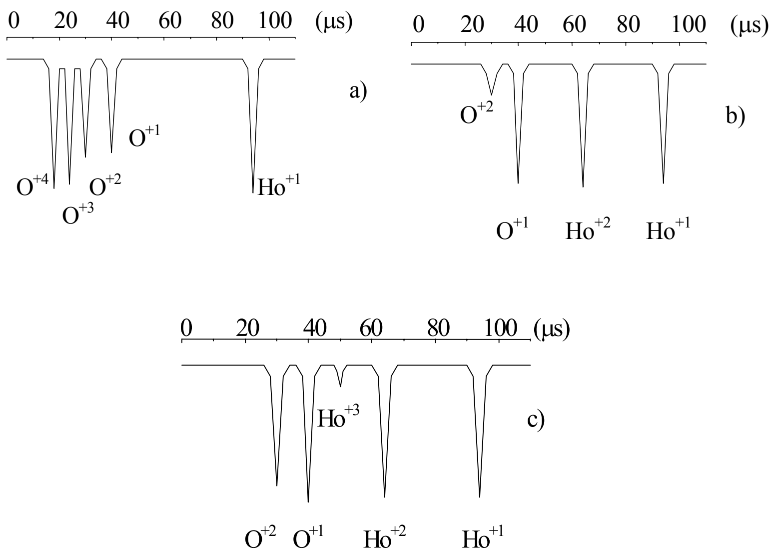

Figure 1. Typical mass-charge spectra of plasma ions obtained from Ho_2O_3 target at $q=5\ 10^{10}$ W/cm^2 for the target densities: a) $\rho=\rho_0$, b) ρ_1= 1.4 g/cm^3, and c) ρ_3=3.2 g/cm^3. Energy of Ho^{+1} ions equals to 50 eV.

Characteristic change of maximal charge Z_{max} of *Ho* and *O* ions is shown in Fig. 2 as a function of ρ for different values of energy of single charged *Ho* ions. It is seen from this figure that Z_{max} of *Ho* ions increases with increasing ρ. For example, the maximal charge of *Ho* ions increases from Z_{max}=1 to Z_{max}=4 with increasing ρ from ρ_1 to ρ_3, while the maximal charge of *O* ions decreases from Z_{max}=4 to Z_{max}=2. Further increase of ρ does not lead to the change of Z_{max}. These results show that at the interaction of laser radiation with porous Ho_2O_3 targets the ionization of oxygen ions is higher at low density of the target and at lower energies of ions and *Ho* ions are highly ionized at larger density of the target ($\rho \geq \rho_3$).

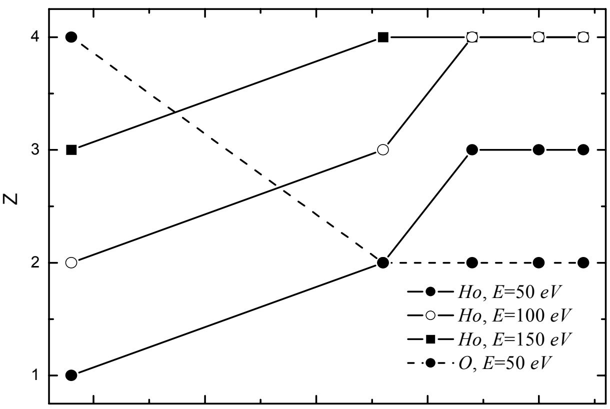

Figure 2. Maximal charge of Ho (solid curves) and oxygen (dashed curve) ions as a function of ρ for the energy of Ho^{+1} ions E=50 eV (solid circles), E=100 eV (open circles) and E=150 eV (squares).

From the obtained mass-charge spectra we constructed energy spectra of Ho_2O_3 plasma ions, which is shown, as an example, in Fig. 3 for $\rho=\rho_0$ (a), $\rho=\rho_2$ (b), $\rho=\rho_3$ (c) and $\rho=\rho_5$ (d). For any density of the target, two groups of ions with different spectral range and charge are clearly seen, but the structure and width of energy spectra and intensity and charge of different kind of ions strongly depend on ρ.

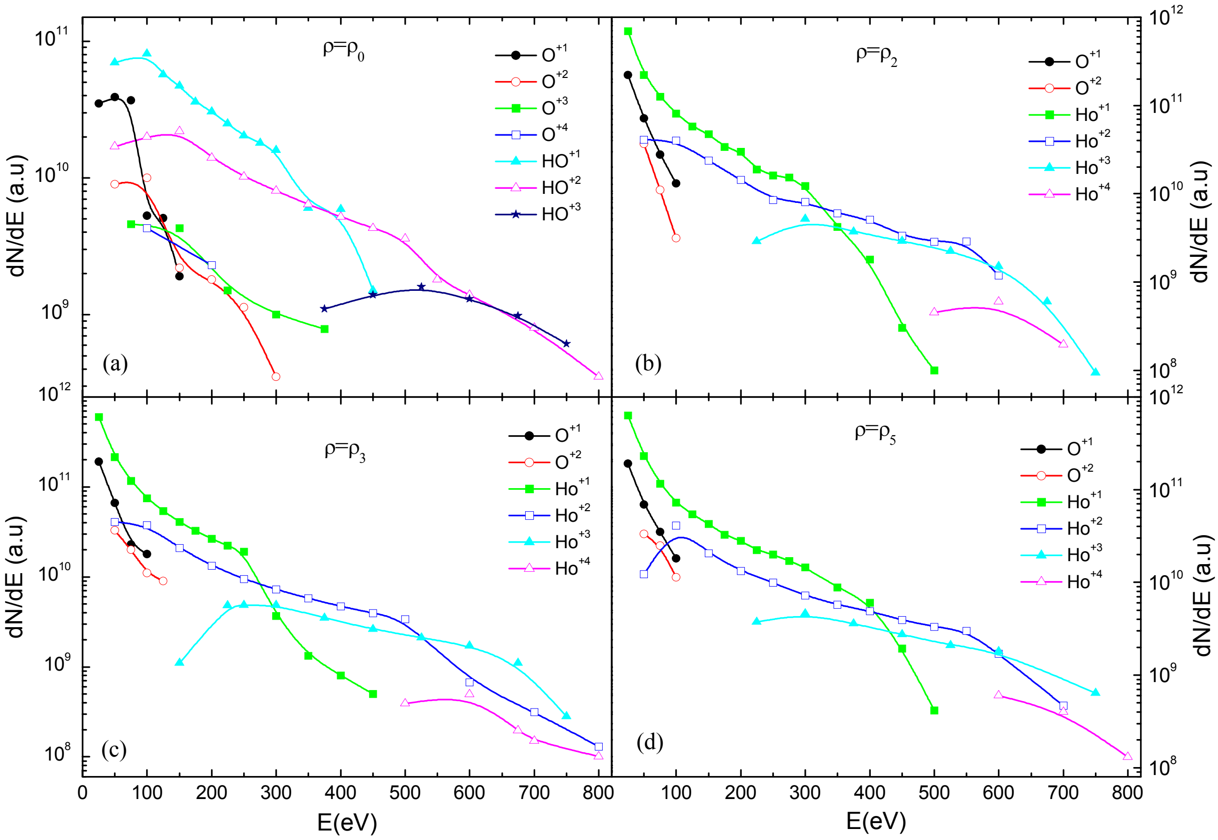

Figure 3. The energy spectra of ions from two-element Ho_2O_3 plasma for different values of target density: $\rho=\rho_0$ *(a),* $\rho=\rho_2$ *(b),* $\rho=\rho_3$ *(c) and* $\rho=\rho_5$ *(d).*

At low density of the target [Fig. 3(a)] oxygen ions with charge Z=1-4 have energies in the range of 25 – 370 *eV*. The maximum charge of *Ho* ions in this case equals to Z_{max}=3 and they have wider energy spectra (50 – 800 *eV*). With increasing target density *O* ions with larger charge (Z>2) disappear from the spectra and the energy range of oxygen ions considerably decreases [see Fig. 2(b)]. For example, the maximal energy of double charged O^{+2} ions decreases three times for larger $\rho=\rho_2$ compared to the reference sample ($\rho=\rho_0$). *Ho* ions with charge Z=4 are detected for $\rho=\rho_2$ and there is slight increase of energy diapason of *Ho* ions. With further increase of ρ [see Fig. 2 (c)] energy spectra of *O* ions remain unchanged and energy range of *Ho* ions increases. The maximal charge of both kinds of ions remains the same.

Fig. 4 shows the maximal energies of *Ho* ions as a function of ions charge for different ρ. It is seen from this figure that the maximal energy, as well as the energy range of ions does not depend on ρ linearly. This nonlinearity show the complex processes taking place at the interaction of laser radiation with such porous targets.

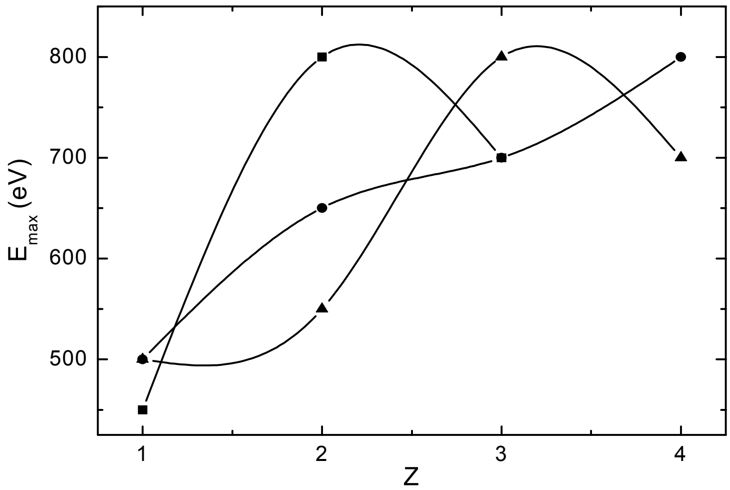

Figure 4. The maximal energy of Ho ions as a function of charge Z for $\rho=\rho_1$ *(squares),* $\rho=\rho_2$ *(circles), and* $\rho=\rho_3$ *(triangles).*

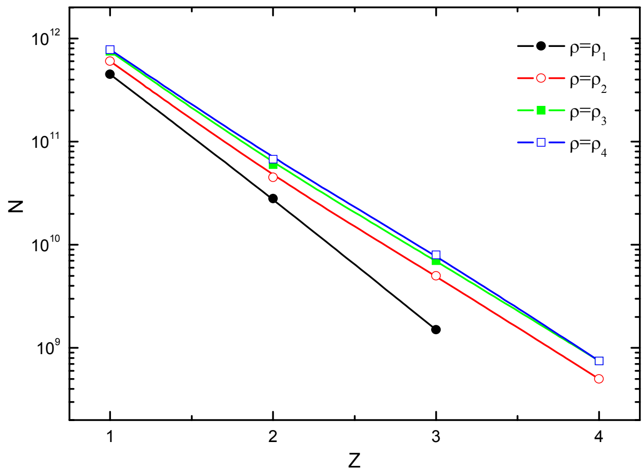

Figure 5. Total number of Ho ions N as a function of ions charge Z for $\rho=\rho_1$ *(solid circles),* $\rho=\rho_2$ *(open circles),* $\rho=\rho_3$ *(solid squares) and* $\rho=\rho_4$ *(open squares).*

Together with mass-charge and energy spectra of plasma ions, it is also of great importance the dependence of intensity of ions on the target density ρ. Figure 5 shows the total number of *Ho* ions of all charge for different ρ. It seen from this figure that more *Ho* ions are generated during the heat of the target with laser radiation with increasing the density of the target up to $\rho=\rho_3$. Further increase of ρ does not change the intensity of ions.

The experimental results given above show that the formation of mass-charge and energy spectra, intensity and charge multiplicity of *Ho* and *O* ions strongly depend on the density of the target. The structure of such porous materials consists of solid particles with different shape alternating with empty spaces. Therefore, the properties of such materials are determined with mass composition, sizes and density of those granules. When the laser radiation of higher intensity interacts with such system ionization processes dominates recombination processes in the plasma. These two processes considerably depend on the density ρ and a direct consequence of it is the different achievable charge Z_{max} for *Ho* and *O* ions. In the interval of density $\rho<\rho_3$, when there are more granules in the target, most of the laser radiation enter deep inside the sample and the radiation is absorbed "volumetrically" due to the "internal evaporation". In this case decrease of selective recombination losses takes place for multi-charged *O* ions, compared to *Ho* ions. Therefore, in this interval of the density ρ maximal charge of *O* ions is higher than the one of *Ho* ions. For larger values of $\rho\geq\rho_3$, when the granules are less in the target, the situation with maximal charge for different kinds of ions is changed. For larger target density ρ the laser radiation mostly interacts with the surface of the sample. In this case the ionization processes of *Ho* ions predominate and the recombination losses of multi-charge *Ho* ions decrease compared to the one of *O* ions. Therefore, the maximal charge of *Ho* ions is higher than the charge of *O* ions. We have to mention that the characteristics of laser-produced plasma, like maximal charge, energy and intensity of ions does not change with further increasing $\rho>\rho_3$. This indicates that starting from $\rho=\rho_3$ characteristics of our samples become close to the one of solid targets, therefore plasma characteristics does not depend on ρ in this range.

4. Conclusions

We have studied the influence of target nature on the formation of mass-charge and energy spectra of multiply-charged ions in laser produced plasma. For this purpose we used porous Ho_2O_3 targets with different densities ρ. Experimental results showed that the characteristics of plasma ions generated at the interaction of laser radiation with Ho_2O_3 targets strongly depend on the target density ρ. For small values of ρ light elements of the target (oxygen ions) have larger charge than *Ho* ions and they are detected in a large range of energy. By increasing ρ *O* ions with larger charge disappear in the spectra and the energy range of these ions become smaller. In this case *Ho* ions with higher charge is observed. This effect was explained by different nature of interaction of laser radiation with the target for different densities ρ. Experimental results presented in this paper permit us to conclude that the formation of charge and energy spectra of multiply charged ions in two-element Ho_2O_3 plasma is defined not only by the ionization and recombination processes, but also by the mutual interaction of ions of different species in the plasma. This interaction can be used to control the charge and intensity of plasma ions by changing the composition of the targets.

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