Au/Al Ion Energy Analysis of laser generating plasma at 10^{12} W/cm^2 intensity

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Abstract

Ion Energy Analyzer was employed to monitor non-equilibrium plasma produced by 10^{12} W/cm^2 intensity by 6 ns pulsed Nd:YAg laser. Gold films deposited on aluminium substrates were irradiated in high vacuum conditions. Aluminium and gold ion energy distributions and charge state distributions were investigated in different experimental conditions. The ion energy distributions follow a Coulomb-Boltzmann Shifted function from which it is possible to evaluate the plasma temperature, the charge state distributions and the average acceleration energy acquired per charge state.

At the used laser parameters, ion acceleration of the order of 1 keV per charge state and plasma temperature above 300 eV have been measured. Experiments performed at Brookhaven National Laboratory in New York, and at Messina University Lab, will be presented. Produced ions are prepared to be injected in RFQ linear accelerator for ion source applications, as it will be discussed.

Introduction

The production of a plasma with high equivalent temperature take place when a laser with high intensity interacts with a solid target in vacuum. The laser intensity is just one of the parameters that affect the plasma production, once that the laser setup is fixed the much important parameter become the composition of the target. Using laser intensity very high (around 10^{16-22} W/cm^2) it is possible to accelerate ions at MeV energies when it interacts with thin targets [1], but when the intensity is low (10^{10-14} W/cm^2) the produced plasma has ions at keV energies, high current, large energetic spread and good energy to be coupled to post acceleration systems. With the aim to increase the efficiency of Laser Ion Sources (LIS) we studied a particular target that consists of Al substrate with a thin film of gold deposited on its surface. The use of different thicknesses allows to investigate the relationship between the depth of the target material and plasma formation. A preliminary study was carried out in Brookhaven National Laboratory where a LIS system is in function to provide for ion beam that is extracted from the plasma and injected in an Electron Beam Ion Source (EBIS), or in a radiofrequency quadrupole accelerator (RFQ), system for subsequent steps of accelerations for nuclear and astrophysical applications[2]. In this kind of setup different chemical elements can be produced from LIS for many and different experiments.

Materials and methods

For the measurements was used a Nd:YAg laser with fundamental wavelength of 1064 nm, time per pulse of 6 ns and peak energy of 1094 mJ on target. The focal lens used had a focal length of 100 mm and produced a spot on the target with a diameter of about 100 μm. With these characteristics the laser intensity was 2.3×10^{12} W/cm^2. The used target were gold films deposited on Al substrate. The gold thicknesses were: 250 nm, 500 nm and 750 nm. In addition to these targets it was irradiated also a pure Al substrate.

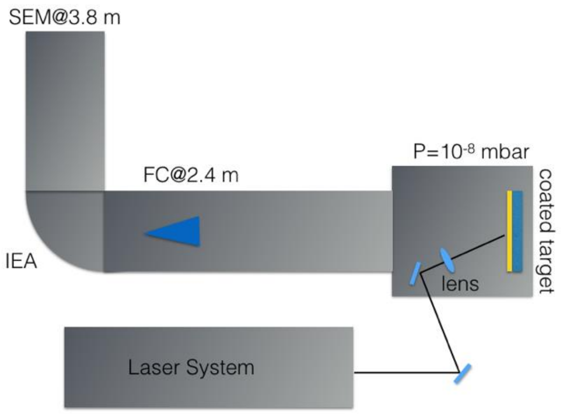

Figure 1: Used experimental Setup.

In Figure 1 it is possible to observe the experimental setup. The plasma diagnostics were based on a Faraday Cup (FC) operating in time-of-flight (TOF) configuration and an Ion Energy Analyser (IEA) mass spectrometer. This last is described like an electrostatic deflector with the time-of-flight method designed for the diagnostics of pulsed ion sources, as reported in Literature [4]. IEA uses a secondary electron multiplier (SEM) detectors, Hamamatsu R2362 model. The Faraday Cup was placed at 2.4 m from the target with a mechanical system for the extraction of FC during IEA measurement, while the SEM detector at 1.4 m from FC, for a total distance from the target of 3.8 m. Ion energy Analyzer (IEA), based on the electrostatic deflection of plasma emitted ions, gives the ion energy distributions and charge state distributions by varying the voltage of the deflection plates. The voltage was increases from ±1 V per plate up to a tension for which the faster ions was able to be detected, in this way it was possible to observe all the energy distributions inside the plasma. Targets were irradiated in high-vacuum conditions, at about 10^{-8} mbar, and were placed on a 2-axis linear stage and moved after every laser shot in order to irradiate always fresh surfaces and maintain the same experimental conditions.

Results

In Figure 2 is showed a time of flight (TOF) measurement of the radiation emitted from the laser generated plasma irradiating an Al pure target.

In this case it is possible to measure a TOF of 4.6 μs for faster Al ions that correspond to a energy of about 38 keV with an ion yield of 130 mV.

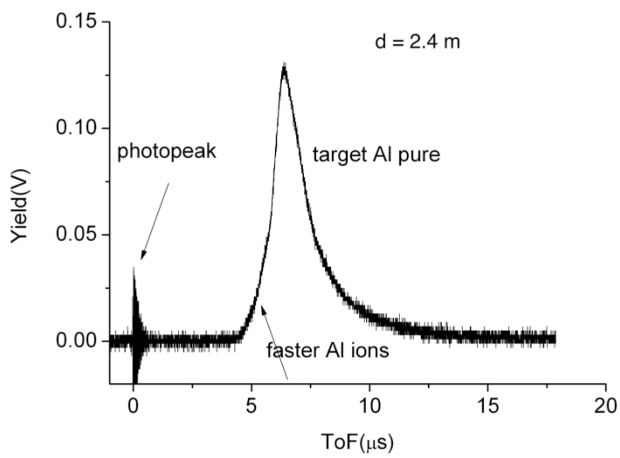

Figure 2: ToF measure of Al pure target

In Figure 3 and 4 is showed the TOF ions measurement relative to the 250 nm of Au deposited on Al and 750 nm of Au deposited on Al.

TOF are evaluated starting from the photopeak signal due to the FC detection of the photons emitted from the laser-matter interaction.

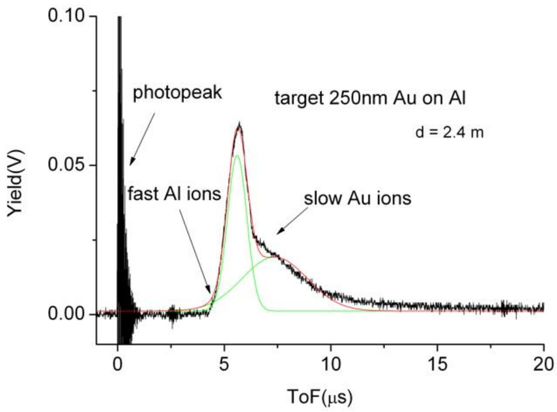

Figure 3: ToF Measure of 250 nm Au on Al

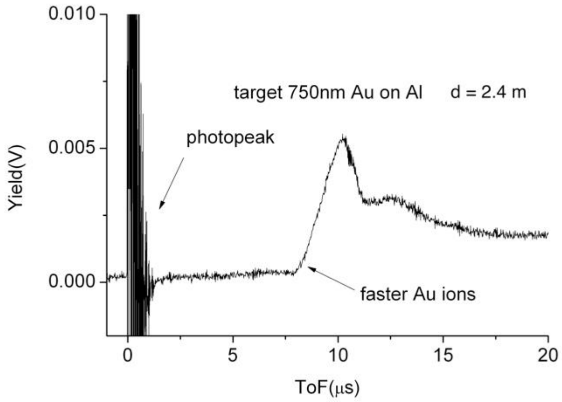

Figure 4: ToF Measure of 750 nm Au on Al

Observing the faster Au ion ToF values relative to the target obtained using 250 nm Au/Al and 750 nm Au/Al, we obtain the values of 4.3 μs and 8 μs, respectively. Such ToF correspond to a maximum kinetic energy of the Au ions corresponding to 43.9 keV and 92.5 keV, respectively. The Al yield decreases to 64 mV and 4.5 mV for 250 nm Au/Al and 750 nm, respectively. Figure 5 shows the IEA analysis relative to the ion energy distributions measured irradiating the pure Al target. It is possible to observe that 8 charge states of Al ions are detected. The analysis of the ion energy distributions indicate an average plasma temperature of about 600 eV and an energy per charge state of about 4.8 keV. Figure 6 shows the result of IEA analysis relative to the ion energy distributions measured irradiating the 750 nm Au/Al target. In this case it is possible to observe that 14 charge states of Au ions are detected. The analysis indicates an average plasma temperature of about 1.2 keV and an energy per charge state of 6.64 keV.

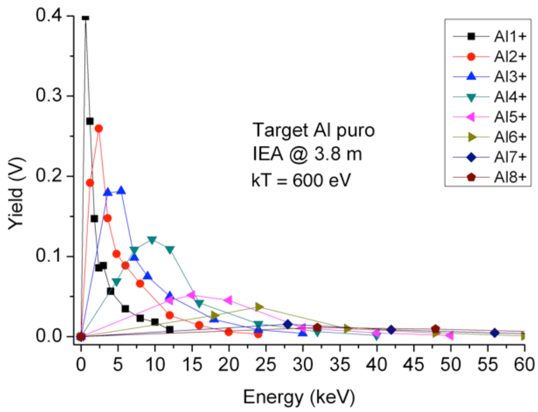

Figure 5: Ion distribution for Al pure target

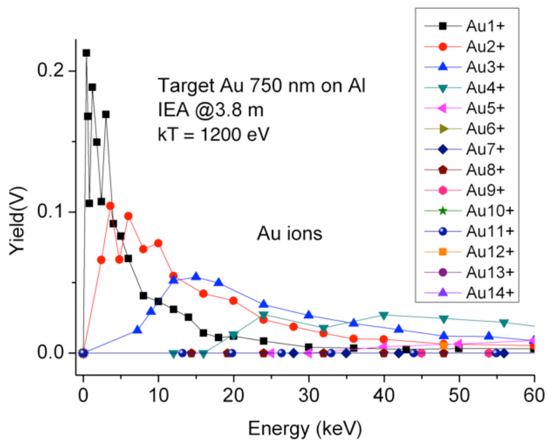

Figure 6: Ion distribution for 750 nm Au on Al

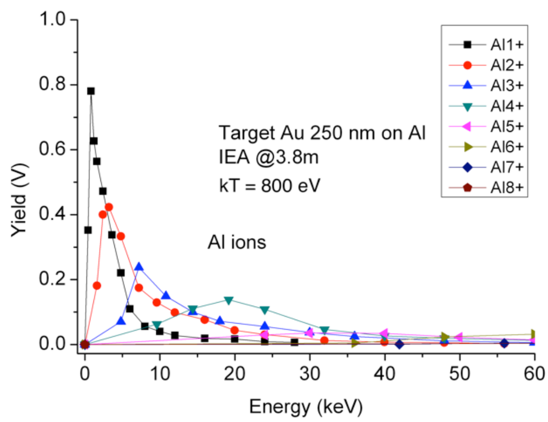

Figure 7: Ion distribution for 250 nm Au on Al substrate

The plasma obtained using the 250 nm Au/Al target indicates an intermediate energy per charge state (about 5.4 keV) and plasma temperature (about 800 eV) how is shown in Figure 7.

In Figure 8 is resumed the variation of Au and Al ion energy and Al ion yield as a function of the thickness of the gold on the aluminium

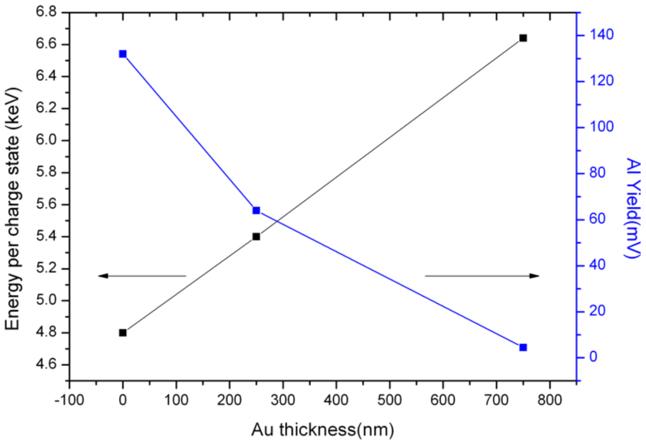

Figure 8: Energy per charge state and Au yields for irradiated targets

From these distributions it is possible to observe that they follow a Boltzmann trend from which it is possible to calculate, through a fit analysis, the average ion acceleration energy per charge states, the energy shift per charge state and the equivalent plasma temperature. This analysis can be performed using the Coulomb-Boltzmann Shifted distribution, as reported in literature [5]. Further information about these plasmas can be obtained observing the peak areas of each charge state. In Figure 9 is showed the histogram of the peak areas relative to the different ions of the Al pure target. In Figure 10 and Figure 11 are showed the areas of 250 nm Au on Al and 750 nm Au on Al, respectively. The average charge state for Al pure and 250 nm Au on Al targets is in both case the Al^{5+}, instead for 750 nm Au on Al the average charge state results be the Au^{6+} this means that the increment of electron density permit to enhance the mean charge state, i.e. to enhance the plasma temperature.

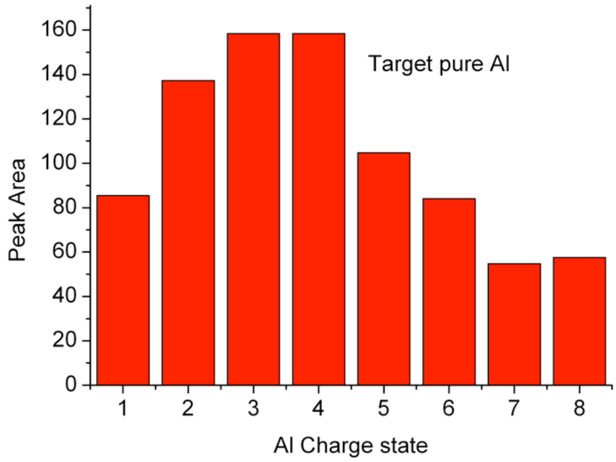

Figure 9: Histogram of peak Area obtained from ion distribution of Al pure target

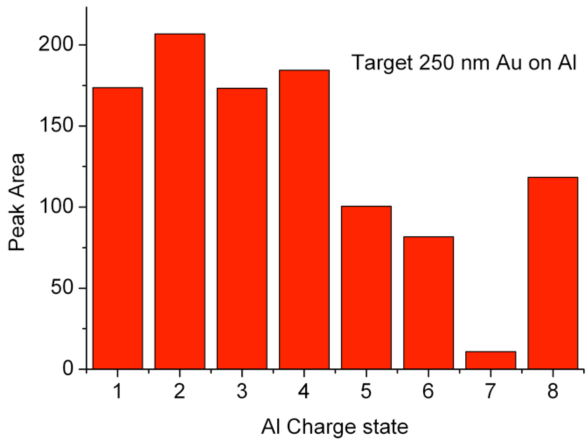

Figure 11: Histogram of peak area obtained from ion distribution of 750 nm Au on Al target

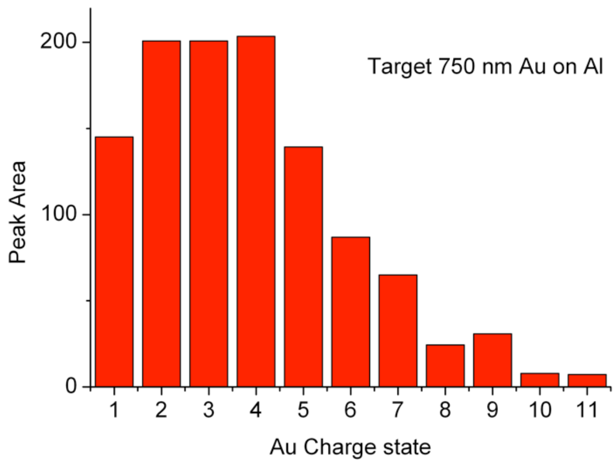

Figure 10: Histogram of peak area obtained from ion distribution of 250 nm Au on Al target

Additional information is obtained from the calculation of peak current and ion number. Considering the TOF spectra of Al pure target the yield is about 130 mV and using the impedance of the detector system of 50 Ω, from these the peak current is:

$$I = \frac{Y}{R} = \frac{0.13\,V}{50\,\Omega} = 0.0026\,A$$

Using the FWHM of peak (τ=1.5μs) the total charge that interact with the FC is:

$$Q = I \cdot \tau = 3.9\,nC$$

Remembering that the average charge state is 5^+ the number of ions is:

$$N = \frac{Q}{5e} = 4.8\ \cdot 10^9$$

The same calculation is performed for 250 nm Au on Al target, in this case the values of current, total charge and ions number are:

$$I = \frac{Y}{R} = \frac{0.064\,V}{50\,\Omega} = 0.0013A$$

$$Q = I \cdot \tau = 1.49\,nC$$

$$N = \frac{Q}{5e} = 1.86\ \cdot 10^9$$

Conclusions

This work shows how a plasma can increase its temperature increasing the electron density, in metals this can do adding in the plasma more electrons coming from a heavy metals. The increase of electron density creates greater charge density separation and so a bigger electric field driving the ion acceleration in non equilibrium plasmas. The Au on Al investigated targets highlighted that temperature increments can be reached thanks to the presence of Au with maximum thickness of about 750 nm deposited on Al surface. Greater thicknesses of Au does not permit to the laser to interact with the Al substrates.

Thus, in the case in which is useful to obtain Al ions from a laser ion source, the deposited film of Au may control the plasma temperature but it cannot be higher than 750 nm in thickness at which the laser ablation of Al is inhibited.

If the goal is to obtain high yield of Al ions is useful to have a coated film of 250 nm of gold on Al substrate because increase the production of Al and there are very low presence of Au in the plasma. In such conditions both RFQ systems and EBIS accelerators permit to receive high Al ion current from the plasma and to accelerate the ion beam at high kinetic energy, as requested.

References

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