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INFLUENCE OF AXIAL MAGNETIC FIELD TRAP ON LASER-GENERATED PLASMA

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Abstract - *In vacuum plasma generated by laser ablation of metallic targets (Cu and Ta) was investigated with and without the influence of 0.1 T axial magnetic field. The laser beam intensity, of the order of 10^{10} W/cm^2, was obtained by a Nd:Yag operating at 1064 nm wavelength, 9 ns pulse width and 500 mJ pulse energy. Time-of-flight measurements of ion emission were performed along the direction normal to the target surface by using an ion collector. Results demonstrated that the magnetic field creates an electron trap in front of the target. The electron charge density inside the trap modifies the electric potentials in the plasma inducing an higher ion acceleration. The presence of the electron cloud not only focuses the ion beam but also increases its energy, mean charge state and current.*

Introduction - Laser-generated plasma in vacuum are characterized by high temperature and density, high charge state and high ion energies along the expanding direction, i.e. orthogonally to the ablated target surface. Measurements with an ion energy analyser demonstrate that the distributions follow a "Coulomb-Boltzmann-shifted" function, as reported in previous experiments [1]. Increasing the charge state the ion kinetic energy increases, due to an equivalent acceleration voltage developed in the laser-generated plasma. A possible model suggests that this voltage is due to a momentary anisotropic charge distribution localized in front of the ablated target and due to the faster electron emission followed by the slower ion emission from the expanding plasma. Assuming that plasma is in local thermal equilibrium (LTE) conditions and that the equivalent voltage is applied over a distance of the order of the Debye length, it is possible to evaluate the high electric field generated in the plasma. The application of a high magnetic field to the plasma region alters the linear trajectories of the charged particles ejected from plasma in vacuum and modifies the resulting electric field. Ducruet et al. [2] and Wolowski et al. [3] demonstrated that the magnetic field confinement of the laser-generated plasma increases the recombination effects, decreases the mean energy of the ions and increases the current density of the ions along the normal direction.

Materials and Methods - A Nd:Yag laser, 1064 nm wavelength, 9 ns pulse width and 500 mJ pulse energy was employed to irradiate solid metallic targets (Cu and Ta) at 10^{-7} mbar vacuum pressure. The incidence angle of the laser beam was 56°, at which the laser spot size was 1.78 mm^2. The plasma was generated by the laser ablation with and without the influence of a permanent magnet. An axial magnet with a hallow cylinder (10 cm length, 23 cm external diameter and 15 cm internal diameter) was placed inside the vacuum chamber with the axis along the normal to the target surface. Inside the cylinder, the maximum intensity of the field was 0.1 T; externally the field decreases forming a minimum B module, |B|=0, at 3.5 cm distance from the cylinder bases and 3.0 cm from the target surface.

Fig. 1 shows a scheme of the magnet set-up reporting the geometry of the field with the magnetic iso-level curves at different values of B. More details on the used magnet are given in ref. [4]. An ion-collector (IC) and an ion energy analyzer (IEA) are placed at 63 cm and 153 cm from the target surface, respectively. A fast storage oscilloscope was employed to record the ion spectra and to calculate, from the time-of-flight (TOF) measurements, the mean velocities and kinetic energies of detected ions.

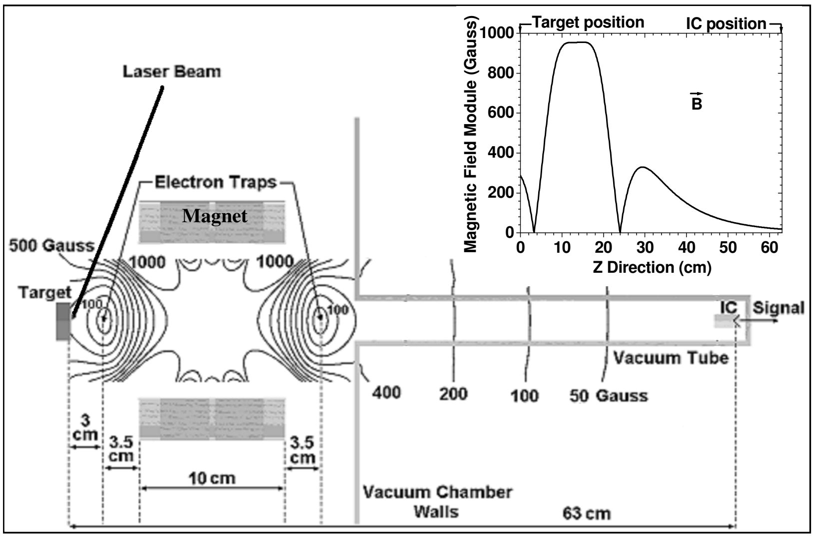

Fig. 1: Scheme of the experimental set-up and module of magnetic field (inset).

The ion spectra analysis was performed by using mathematical fits with Boltzmann-like functions for the different ion groups ejected from the plasma. The deconvolution process permitted to measure the mean ion energy as a function of the ion charge state and laser intensity, in order to calculate the ion yields, ion energy shifts and the plasma temperature. “Opera 3D” code [5] was employed to perform the computer simulation of particles trajectories into electro-magnetic fields. The ion and electron path simulations were of interest to understand the mechanisms of generation, development and kinetics of laser-generated plasma. Data analysis were compared to measurements of TOF performed with an ion-energy-analyzer (IEA) giving, from electrostatic deflection, energy and charge state of the ions ejected from Cu and Ta laser-generated plasmas, as presented in previous articles [1, 6].

Results and Discussion - Fig. 2 reports a comparison between some typical IC spectra detected along the normal direction to the target surface obtained ablating Cu at 294 mJ and Ta at 197 mJ, without (a, c) and with (b, d) the axial magnetic field application. Spectra show the laser photo-peak and the IC ion signals permitting to measure the average TOF times and the corresponding ion velocities and energies. IEA measurements demonstrated that, in the same experimental conditions, the detected charge states were 6+ for Cu and 5+ for Ta, as reported in literature [1, 6]. The TOF-IEA spectra are shown in the top of the Fig. 2a and 2c for Cu and Ta, respectively.

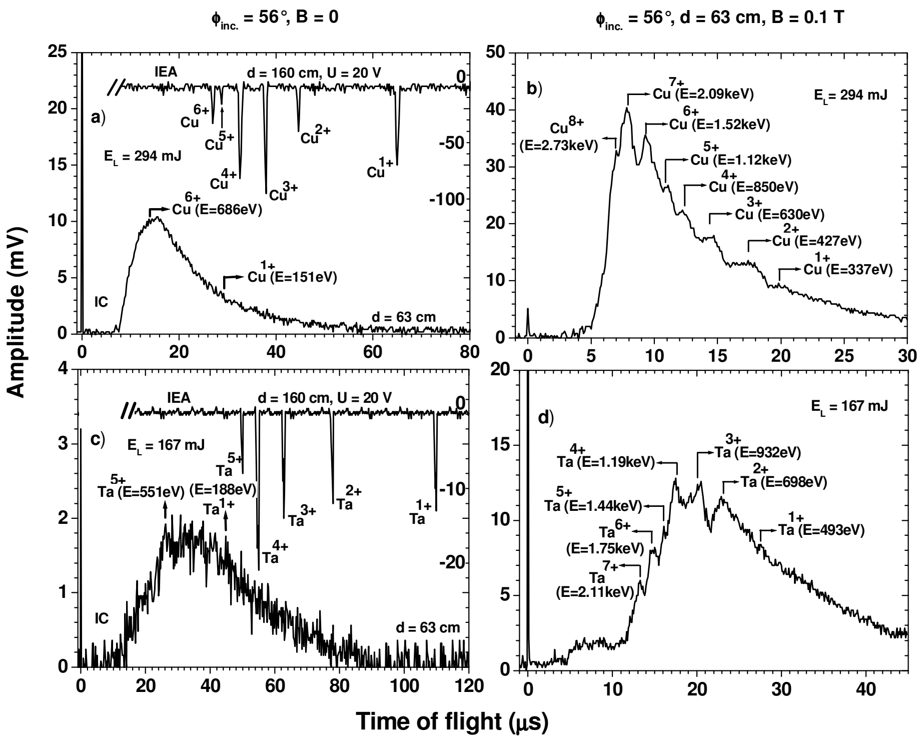

Fig. 2: TOF spectra comparison for Cu (a, b) and Ta (c, d) without and with magnetic field.

The comparisons of Fig. 2 demonstrate that significant differences occurs in the TOF spectra acquired without and with the axial magnetic field. By applying the magnetic field the energy of Cu^{1+} increases from 151 eV up to 337 eV; that of Cu^{6+} increases from 686 eV up to 1520 eV; that of Ta^{1+} increases from 188 eV up to 493 eV; that of Ta^{5+} increases from 551 eV up to 1440 eV. Results demonstrated that the integral ion yield increases in presence of the magnetic field with respect to the case without and that it is maximum at high laser energy. Moreover, the ion charge states increase from 6+ up to 8+ for Cu and from 5+ up to 7+ for Ta. At 63 cm IC-target distance the TOF spectra resolution is higher with respect to other distances. Thus, four main peculiarity can be observed: (i) the ion distributions become more energetic in presence of the magnetic field; (ii) the integral ion yield (ion charge) increases with the magnetic field application; (iii) the ion charge states increase with the use of magnetic field; (iv) the spectra are better TOF resolved with the use of the magnetic field. The first point is due to the increment of the equivalent voltage of ion acceleration in the non-equilibrium laser-generated plasma. Its generation is due to the electron trap at 3 cm distance from the target surface producing an electrostatic negative potential accelerating ions. The second point indicates that the magnetic field generates a significant ion focalization detectable, at 63 cm distance, as a maximum ion yield. This result is due to the magnetic and electric focalization of the ions towards the IC position caused by the high density of the electron cloud localized in the magnetic electron trap. The third point is due to the increment of the electron-ion interactions: not only ions cross and collide with more electrons along their path, specially at the electron trap place, but also during their target-trap flight, due to a large number of backscattered electrons from the trap. The increment of the electron-ion collisions increases the ionization processes producing higher ion yields and ion charge states.

The fourth point indicates that the TOF ion detection separates the ion charge states better with the use of the magnet. An optimum resolution distance of 63 cm was found for the two ablated elements irradiating at particular laser energies, 294 mJ for Cu and 167 mJ for Ta, while at other distances and energies the peak separation decreases.

Opera 3D simulation code permitted to explain obtained results on the base of the electron trajectory modifications due to the presence of the magnetic field. The simulations show that the electrons trajectories are strongly modified by the magnetic field while the ions trajectories modifications are negligible. Without the magnetic field the electron and ion streams are ejected from the plasma with linear trajectories starting from the laser spot size with maximum divergence angle of about ± 40° for Cu and ± 30° for Ta [7]. The simulations show that the electron trapping produces an increase of the electron density at 3 cm distance from the target surface which duration is of about 150 ns, as reported in ref. [8].

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