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# Expansion of tungsten ions emitted from laser-produced plasma in axial magnetic and electric fields

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**Abstract**

The experimental results of the investigations on the influence of external magnetic and electric fields on the characteristics of a tungsten ion stream emitted from a plasma produced by the Nd:glass laser (1 J, 1 ns) performed at IPPLM, Warsaw are presented. A negatively biased target up to −15 kV and a magnetic field up to 0.45 T were used in the experiment. A set of ion collectors and an electrostatic cylindrical ion energy analyzer located at small angles with respect to the laser beam axis and at large distances from the target were applied for ion measurements. The effect of an external magnetic field is essential to plasma expansion, but the effect of the retarding potential of the target is very weak in our experimental conditions. The aim of the studies was to prove the possibility of the optimization of ion beam parameters from laser-produced plasma for the particular application as a laser ion source coupled with the electron cyclotron resonance ion source for particle accelerators.

**Keywords:** Laser ion source; Laser-produced plasma in external magnetic and electric fields

## 1. INTRODUCTION

A laser-produced plasma can provide an ion source for different applications owing to the variability of plasma characteristics. The principal factors influencing the nature of the interaction between a laser radiation and a solid target in vacuum are the duration, wavelength, and power density of the laser pulse, laser light absorption processes, as well as physical and chemical properties of the target. Experiments have been carried out at IPPLM in Warsaw to show the beneficial effects of a magnetic axial field and a bias voltage on the extraction of the ions from the laser-produced plasma. These studies were motivated mainly by the laser ion source (LIS) applications as an ion source for a hybrid ion source consisting of the LIS as the first stage followed by an electron cyclotron resonance ion source (ECRIS) as the second stage, which should act as a charge-state multiplier. The ECLISSE experiment (ECR ion source coupled to a laser ion source for charge state enhancement) has been funded by INFN LNS in Catania and preliminary experiments (Gammino *et al.*, 2000) have been carried out at the IPPLM in Warsaw and at the INFN LNS in Catania.

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## 2. EXPERIMENTAL SETUP

The experiment was performed at the IPPLM in Warsaw, in collaboration with the above mentioned laboratories. A diagram of the experimental arrangement used is shown in Figure 1. The laser beam ($E_L \leq 1$ J, $\tau_L \sim 1$ ns, $\lambda_L = 1.06$ $\mu$m, laser beam diameter of about 20 mm, laser beam divergence of 0.5 mrad) was focused normally to the target surface by means of a lens (9) with the focal length of $f = 133.4$ cm (large focal length is expected for real ion injector) onto thick W disc targets of purity above 99.0%. Before the target was put inside the target chamber it was polished and cleaned.

The target (13) was fastened to the target holder (2) placed 0.8 cm off the laser beam axis to assure manifold laser shots on fresh target surface. The target holder construction makes it possible to bias the target $U_t$ to a high voltage ranging from +10 kV to −15 kV and to form a symmetric electric field in the space limited by the grounded shielding tube (3), the target (13), and the grounded diaphragm (5). This space is also filled by a nearly symmetric uniform longitudinal magnetic field with an induction of $B = 0.45$ T generated by Helmholtz coils (4).

The lens was placed outside the target chamber and could be moved for focusing within the range from −1.5 cm to +10 cm. The focus position, *FP* was changed over the range

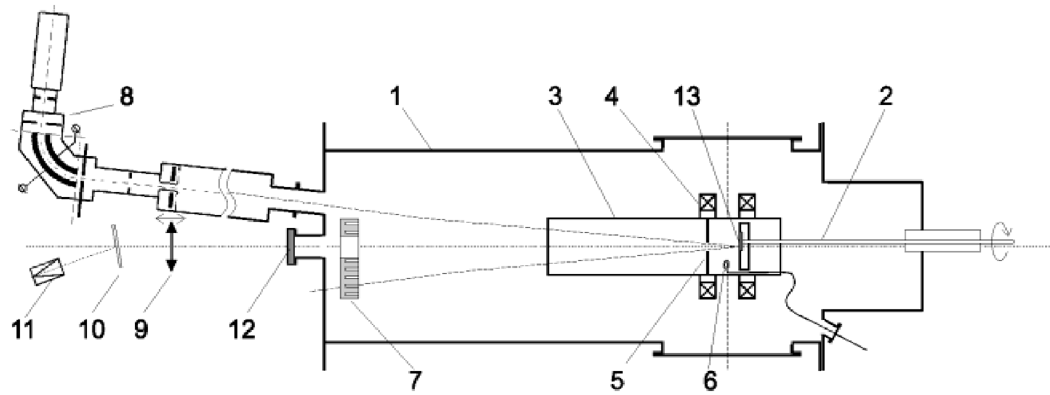


**Fig. 1.** Scheme of experimental setup. 1: target chamber, 2: target holder, 3: shielding tube, 4: Helmholtz coils, 5: grounded diaphragm, 6: magnetic probe, 7: set of ion collectors (SIC), 8: electrostatic ion energy analyzer (IEA), 9: focusing lens, 10: splitter, 11: laser energy meter, 12: glass window, 13: target.

from −1.5 cm to +10 cm ($FP = 0$ means that the target is located in the attest focus point, − and + mean that the attest focus point is in the front of the target surface and inside the target, respectively.

The ion diagnostics for measuring ion stream parameters, that is, a set of ion collectors, SIC (7), and an electrostatic cylindrical ion energy analyzer, IEA (8), were based on the time-of-flight method (Woryna *et al.*, 1996). A set of ion collectors consists of 17 Faraday cups biased negatively (−40 V) arranged along two perpendicular directions: 5 collectors placed in the north (N1–N5 collectors), south (S1–S5 collectors), and west (W1–W5 collectors) directions and 2 collectors in the east direction (E1–E2 collectors). W1–W5 collectors are located at distances about 78.1 cm from the target at angles of 2.1°, 3.2°, 4.3°, 5.4°, and 6.5° to the target normal. The effective aperture area of each collector is 0.114 cm$^2$ (solid angle of measurement of $1.867 \times 10^{-5}$ sr).

The IEA was located at 6° to the target normal and 181.8 cm from the target. A windowless electron multiplier was used as a detector at the output of the IEA. The pressure inside the target chamber and the IEA was lower than $10^{-5}$ Torr.

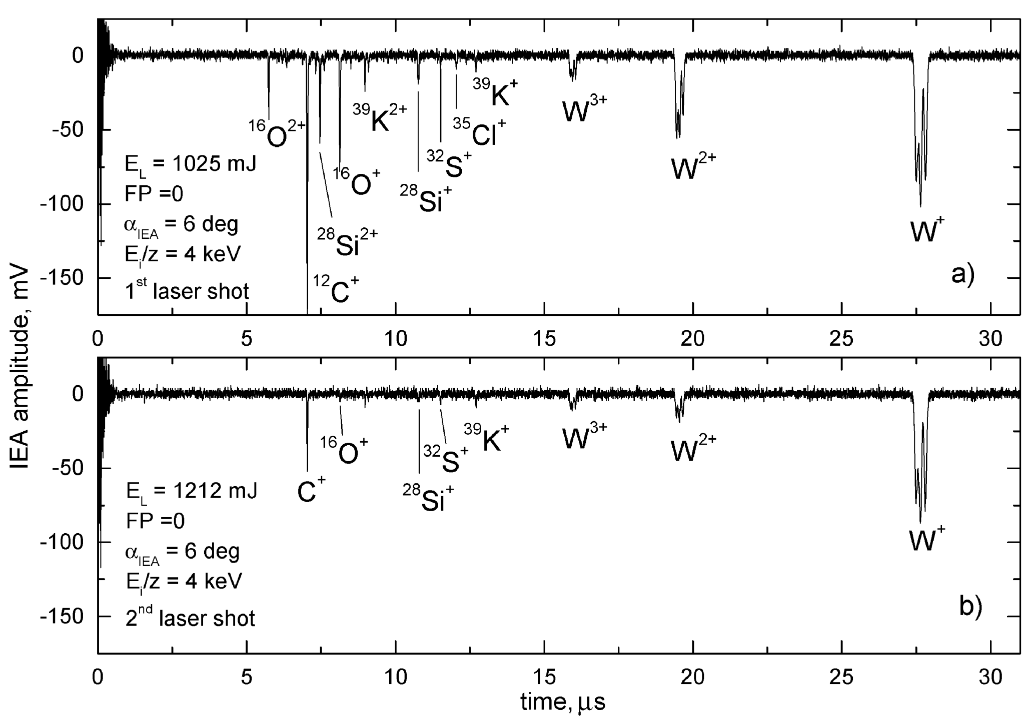


**Fig. 2.** Comparison of IEA spectra of W plasma for first laser shot (a) and second laser shot onto the same place (b).

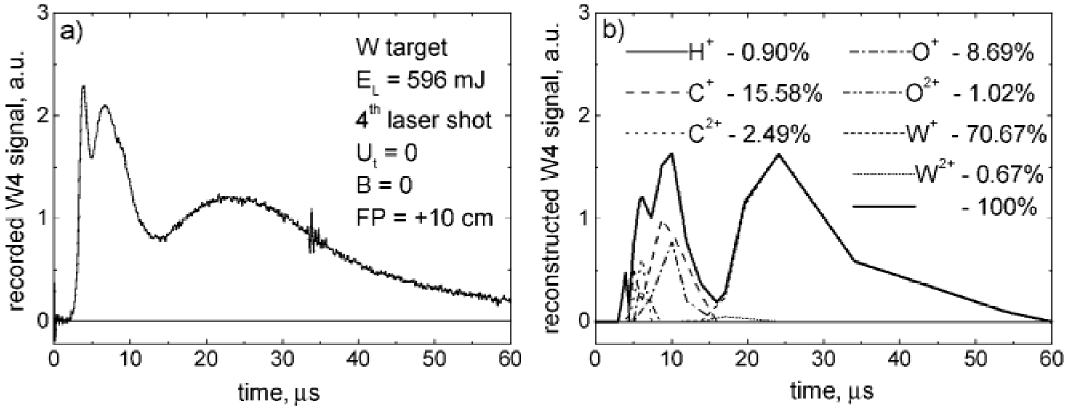


**Fig. 3.** Ion collector signals recorded with the use of W4 collector (a) and reconstructed on the basis of the IEA measurements (b).

## 3. EXPERIMENTAL RESULTS

### 3.1. Freely expanding plasma

Ion collector signals measured for the first laser shot show the existence of a large charge of contaminant ions and it should be treated as a laser cleaning shot. It was estimated that a number of successive laser shots onto the target under our experimental conditions does not essentially change the ion collector signal parameters with exception of the first laser shot onto a fresh target surface. A number of successive laser shots onto the target under our experimental conditions did not change total ion charge $Q_i$, and maximum ion current density $j_{max}$; however, the mean ion kinetic energy, $\langle E_i \rangle$, slowly increases with the increasing number of laser shots. Figure 2 shows the comparison of ion spectra measured with the use of the IEA for the first laser shot onto the fresh W target surface and for the second laser shot onto the same place on the target surface as the first laser shot.

On the basis of a series of IEA spectra measured at different analyzing potentials at nearly the same experimental conditions we reconstructed the W4 collector signal (Fig. 3). Since the gain of the WEM was not taken into account, the reconstructed W4 signal gives only qualitative information on the abundance of ion species. However, it gives information on the ranges of time of fight (or velocity, or energy) of ions in detail. It is seen that the valley on the collector signal, between the faster and slower groups of ions, practically separates the signal of contaminants and of the signal of tungsten ions, especially interesting for us. The faster ion group of the collector signal contains mostly ions of light contaminants (mainly $H^+$, $C^+$, $O^+$, $C^{2+}$, and $O^{2+}$). The slower ion group contains W ions only.

A series of laser shots was performed to investigate the effect of the influence of focus position ($FP$) on W plasma expansion. The $FP$ was changed over the range from $-1.5$ cm to $+10$ cm. The ion charge $Q_i$ [C/sr], the average ion kinetic energy $\langle E_i \rangle$ [keV], the maximum ion current density $j_{max}$ [mA/cm$^2$] and the maximum recorded charge state $z_{max}$ of W ions obtained for second laser shot onto the target were measured as a function of focus position. $Q_i$ and $j_{max}$ have minima, $z_{max}$ has maximum at specific value of $FP = +4$ cm while the $\langle E_i \rangle$ is nearly constant for $FP$ from 0 to 10 cm. As an example the dependence of $\langle E_i \rangle$ [keV] and $j_{max}$ [mA/cm$^2$] on the focus position are shown in Figure 4.

The dependence of the average ion kinetic energy, $\langle E_i \rangle$, and the maximum ion current density, $j_{max}$, on the laser energy $E_L$ registered with the use of W1 collector for the second laser shot is shown in Figure 5 for the slower ion group (W ions). The laser energy ranged from 0.25 to 1.2 J at a given focus position $FP = +10$ cm, and the bias voltage. The scaling of these parameters as a function of the laser energy differs significantly for various ion collectors.

On the basis of ion collector measurements the ion velocity distributions for W1–W4 collectors placed at different angles with respect to the target normal in the range from 2° to 6° were calculated. In the case of freely expanding plasma, the highest maximum velocity of ions is observed for W1 collector. For W2–W4 collectors, the maximum velocities have nearly the same values. The velocity distributions for W1 and W4 differ slightly in amplitude with a factor of about 2. Figure 6, curve a shows an example of the ion velocity distributions for freely expanding plasma calculated on the basis of W1 collector signal.

### 3.2. The influence of magnetic and electric fields on plasma expansion

The expansion of laser-produced plasma in external magnetic field was performed for $B = 0.45$ T and $FP = +10$ cm. Amplitudes of the slower ion group signals registered with the use of ion collectors are several time higher than for $B = 0$. The faster ion group signals (containing mainly contaminants) are similar in both cases.

The ion velocity distributions of W plasma expanding in the presence of magnetic and electric fields in comparison with the case of freely expanding plasma are shown in Figure 6. The velocity distribution of expanding W ions through

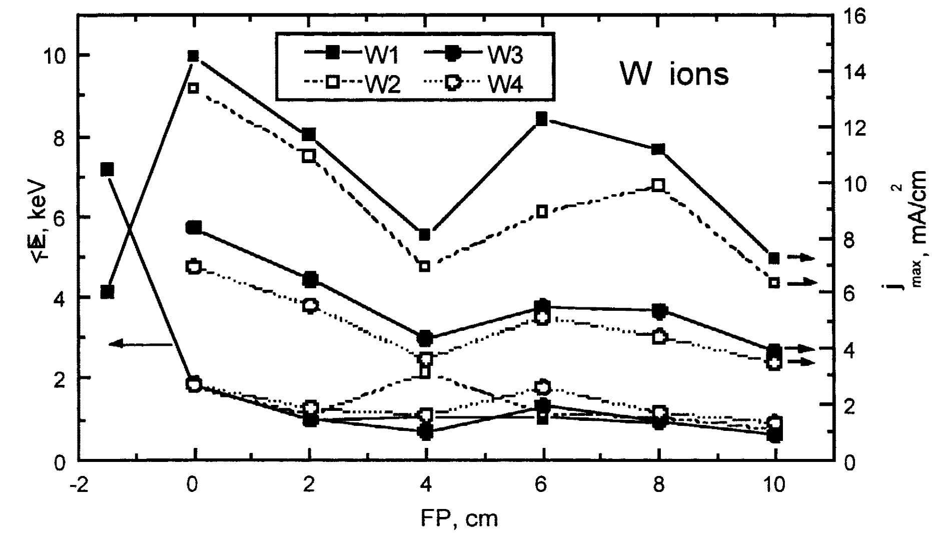


**Fig. 4.** Influence of focus position $FP$ on average ion kinetic energy $\langle E_i \rangle$ and maximum W ion current density $j_{max}$ recorded by W1–W4 collectors, $U_t = 0$, $B = 0$.

the external magnetic field, and determined from W1 collector signals, is shown in Figure 6 (curve c). These distributions differ from the ones obtained for $B = 0$ at $U_t = 0$ and $U_t = -5$ kV only in amplitude. The application of $U_t = -5$ kV results in the decreasing of maximum velocity of ions to about $2 \times 10^7$ cm/s from the original value of $2.8 \times 10^7$ cm/s for $U_t = 0$ (compare curves a and b). The amplitude of the ion velocity distributions of the slowest group containing W ions with velocity of $2.5 \times 10^6$ cm/s is about 5–20 times higher in comparison with the case of $B = 0$.

The potentials generated on the externally supplied target had a bipolar structure reaching values up to $V_t = 25$ kV registered up to 200 ns after the laser shot. Probably, owing to this bipolar potential, plasma cannot be effectively decelerated in an external electric field.

The influence of electric and magnetic fields on plasma parameters is also shown in Figure 7. The relative values of $e = \langle E_i \rangle (B = 0.45\,\text{T})/\langle E_i \rangle (B = 0)$ and $j = j_{max}(B = 0.45\,\text{T})/j_{max}(B = 0)$ are presented as a function of laser energy at $FP = +10$ cm for the case of $U_t = -5$ *kV*, $B = 0.45$ T. The

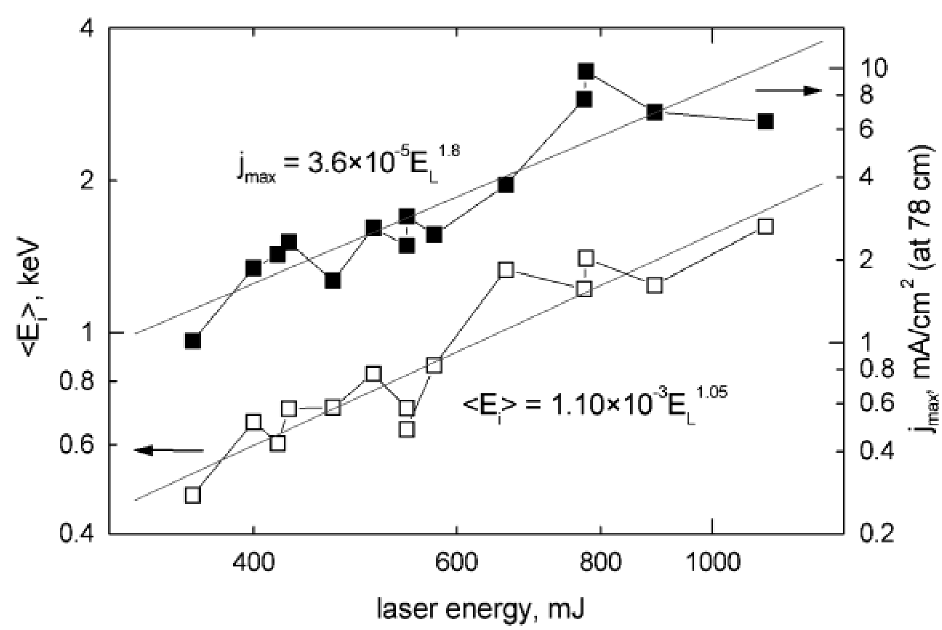


**Fig. 5.** The average ion kinetic energy $\langle E_i \rangle$ and the maximum W ion current density $j_{max}$ as a function of laser energy $E_L$ for W1 collector, $U_t = 0$, $B = 0$, and $FP = +10$ cm.

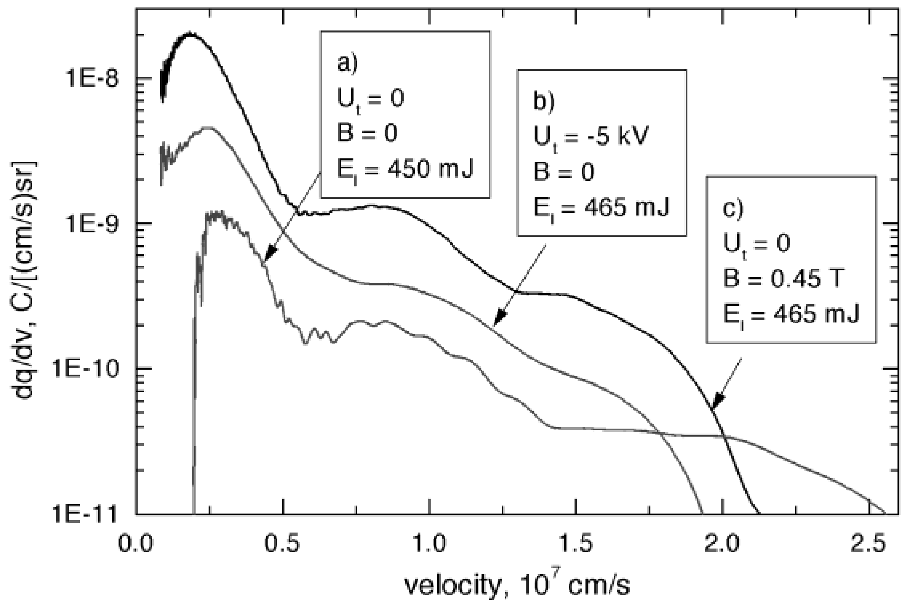


**Fig. 6.** Velocity distributions of laser-produced plasma expanding freely (a), in external electric field (b), and in external magnetic field (c), $FP = +10$ cm.

magnetic field causes the significant (2–3 times) increase of the $j_{max}$. It is evident that the relative value of the average ion energy decreases while the relative value of maximum ion current density slightly increases with the increasing laser energy. This dependence shows that the external electric field intensity applied in our experiment does not affect the scaling low.

## 4. CONCLUSION

One can conclude that under the experimental conditions the ion collector signal for the first laser shot shows the existence of a large amount of contaminant ions and the shot should be treated as a laser cleaning shot. The parameters of the ion collector signals remain similar during at least 10

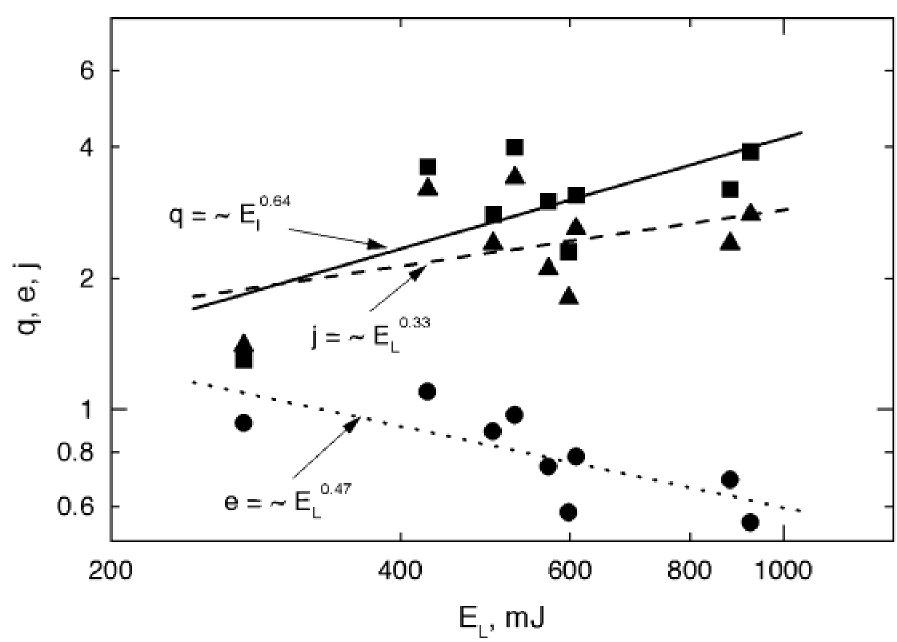


**Fig. 7.** The relative values of $e = \langle E_i \rangle\,(B = 0.45\text{ T})/\langle E_i \rangle(B = 0)$ and $j = j_{max}(B = 0.45\text{ T})/j_{max}(B = 0)$ as a function of laser energy at $FP = +10$ cm for the case of $U_t = -5$ kV, $B = 0.45$ T.

(successive) laser shots to the same place on the target excluding the first laser shot. Our attention was paid mainly to studying the slower ion group because the IEA measurements confirm that this group of ions contains W ions only ($\sim$90% of $W^+$ and $\sim$10% of $W^{2+}$). The faster ion group contains really light contaminant ions well separated from the W ions. We note that values of parameters important for coupling the LIS with the ECR were estimated for the freely expanding laser-produced plasma as follows: $\langle E_i \rangle \sim 0.5$–2 keV, $j_{max} > \sim$1–8 mA/cm$^2$ (at the distance of 78 cm from the target) in dependence on $E_L$ and *FP*.

The main parameters of the ion stream depend on the focus position. It was found that these parameters achieve the minima for $FP = +4$ cm. The discrepancy between the results presented here and those measured previously by us at the IP ASCR and at the IPPLM (Parys *et al.*, 1994; Láska *et al.*, 1996) is probably caused by different focusing lens systems used in these experiments (the expected focal length of our lens, $f = 133.4$ cm, was determined for a parallel laser beam) and is due to nonlinear effect of laser focus position on ion generation (Krása *et al.*, 1999).

In our experimental conditions, the external electric field has almost no influence on the plasma containing W ions (the slow ion group). The laser-produced-plasma expansion in the external electric field is also influenced by a plasma effect in the space in which the plasma is separated into electron and ion components. It means that a simple assumption on electrostatic deceleration of ions in a vacuum cannot be realized experimentally in our case. For future experiments, we are preparing another electric system for removing contaminant ions and selecting of ions with energy appropriate for efficient coupling the LIS and the ECRIS.

The external magnetic field evidently influences the parameters of laser-produced ions: Ion current density increases 2–3 times, and the average kinetic energy decreases up to 40% (for $E_L > 800$ mJ and at 2° to the target normal). This result is important for an efficient coupling of the laser ion source to the ECRIS in the frame of ECLISSE program.

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