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Laser ion sources for various applications

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This contribution presents the results of studies of ion emission from the high-Z plasma generated using short wavelength, short pulse lasers: Nd:glass laser at the IPPLM in Warsaw and iodine laser PERUN at the IP ASCR in Prague. These studies were motivated mainly by the laser-produced plasma applications as a heavy ion source for particle accelerators and for ion implantation. The properties of highly charged ion streams were investigated by ion diagnostic methods: ion collectors and a cylindrical electrostatic energy analyzer. The results proved the existence of highly charged ions with charges $z > 40$ (measured $z_{max} = 55$ for Ta) and with energies of several MeV in a far expansion zone. Ion current densities higher than 20 mA/cm^2 at about 1 m from the target were demonstrated. Construction of an effective laser heavy ion source seems thus to be not a principal, but rather a technological problem. ECLISE experiment (ECR ion source coupled to a laser ion source for charge state enhancement) has been founded by INFN LNS in Catania and preliminary experiments have been carried out at the IPPLM in Warsaw, in order to confirm the beneficial effects of the axial magnetic field of the ECR ion source on the extraction of ions from the LIS, and to evaluate the ion energy, which is the critical parameter for the coupling process. Direct implantation of ions from laser producd plasma has been investigated using PERUN laser system at the IP ASCR in Prague. Attention was devoted mainly to the properties of the ion streams from the laser-produced plasmas (Sn, Pb, Ag) as well as to the direct implantation of those ions into different materials.

1. Introduction

Studies of plasma produced with high-power laser are directed towards determination of physical processes in such plasmas as well as optimization of the indirect drive laser fusion, X-ray laser-plasma sources and sources of multicharged ions for heavy ion accelerators and accelerators for ion implantation.

Generation of the intense beams of the heavy multicharged ions is of great importance for the present and future particle accelerators. Up to now, the electron cyclotron resonance ion source (ECRIS) is usually used for heavy ion accelerators [1]. Generally, the quantity of ions from existing ECRIS does not fulfil the requirements for heavy ion colliders. Due to the growing demand for high current beams of multicharged ions, laser plasma as a potential source of multiply charged ions is intensely investigated. Laser ion source (LIS) can produce higher current densities of highly charged ions than the ECR ion source. LIS has the potential of producing intense beams of heavy ions (tens of $mAcm^{-2}$ at a distance of 100 cm) of a similar or higher charge state within a pulse of several microseconds [2]–[4]. It is important that in the case of LIS the ions are emitted from the plasma generated by the laser irradiation of the solid targets. At present, the commercial availability favours the CO_2 laser as a driver of the LIS for heavy ion accelerators [5] as an alternative to ECRIS. LIS based on the CO_2 laser is being built in CERN in cooperation with the Institute for Theoretical and Experimental Physics (ITEP) in Moscow and Troitsk Institute for Innovation nd Thermonuclear Investigations (TRINITI), Moscow Region [4]. From the comparison of experimental investigations made with the CO_2 lasers, Nd:glass lasers and iodine lasers [6] it results that laser emitting at the wavelength of about 1 μm represent an alternative approach for ion sources of the highly charged ions. At the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw and at the Institute of Physics ASCR in Prague joint studies were performed of the high-Z plasma produced by Nd:glass and iodine lasers for optimization of the multicharged ion emission from such a plasma [3], [7], [8].

At the South National Laboratory (LNS) in Catania, Italy, a hybrid ion source has been proposed, consisting of the LIS as the first stage, which gives intense currents of electrons and of multiply charged ions, followed by an ECRIS as the second stage, which should act as a charge state multiplier [9]. Considering that the laser beam, impinging onto a target, creates neutrals and positive ions, depending on the available laser power density it is necessary to investigate the possibility of obtaining multiply charged ion beams from a pulsed LIS to be coupled to the ECRIS plasma in the main stage, from which a pulsed or continuous beam of very high charge state ions will be obtained. The main tasks to be accomplished before coupling the two types of sources included:

– the study of the effect of axial magnetic field of ECRIS trap on the ion extraction from a LIS target (reported in [10]),

– the study of the minimization of energy spread of LIS beams so that coupling efficiency close to 100% could be reached (some calculations [11] suggest that it is possible when the ion energy does not exceed 100 eV).

For this purpose preliminary measurements are under way at IPPLM and INFN – LNS, which seem to demonstrate that energies below 500 eV or even lower are obtainable, on condition that the retarding potential is effective.

Extensive studies of implantation of ions into near surface layer of materials have demonstrated astonishing changes of such properties as surface tension, friction and durability. The cost of implanted ions is currently fairly high due to the limited ion current density of the usual ion sources, especially if ions from other than gaseous plasma sources must be used. The idea of using ions from a laser produced plasma for implantation of metals into solid without any post-acceleration to modify surface properties has appeared quite recently [12], [13]. The advent of the LIS, with many orders of magnitude higher current densities than with classical ion sources (ECR, electron beam ion source – EBIS, or vacuum arc – MEVVA), may change the scenario for a wide range of applications, making ion implantation as crucial a manufacturing technology in the future for other industries as it is today for microelectronics. Initial source characterization and implantation experiments have been performed by researchers from the AZ Regensburg and the IP ASCR using the PERUN high-power iodine laser and ion diagnostics developed by the IPPLM [15], [16].

The optimization of LIS for the particle accelerators or for the ion implantation motivated the need for deeper understanding of source physics. In this paper, results of measurements of the ion emission from plasma produced by means of the short pulse (1 ns), short wavelength (about 1 μm or less), high power density (up to 10^{15} Wcm^{-2}) lasers are presented. These experiments have been performed for proving the possibility of various applications of the laser produced plasma as an effective ion source.

2. Diagnostic apparatus

The time-of-light method [15] was mainly used in these studies to measure expanding plasma properties versus laser beam parameters and the focusing conditions. This method is correct in the case where the time of flight of the ions passing a distance from the target to the detector is larger than the laser pulse duration. Ion collectors (IC) and a cylindrical electrostatic ion energy analyzer (EIA) were used.

The ion velocity distribution, ion current density and angular distribution of ions expansion, as well as the total charge and the energy carried by the ions reaching collector were obtained from the ion collector signals. The form of the signal including the amplitude provides a good indication of the operating conditions (focus setting, laser stability). Two collectors of different construction were used: a flat circular collector and a ring collector which makes the measurements on the same axis as the IEA possible.

The IEA enables identification of the ion species produced, *i.e.*, their mass-to-charge state, ratio, energy and relative abundance. For the evaluation of IEA signals a computer program was developed [16]. In order to get the time, velocity or energy distribution of ions, a large number of ion spectra have to be measured at fixed laser parameters changing the deflection potential from one laser shot to another. The average charge state as a function of the ion energy and the percentage abundance are determined on the basis of the energy distribution. Calibration of windowless electron multipliers for Ta ions with charge states from $z = 12$ to $z = 49$ and energy to charge state ratios from 8 to 164 keV/z was performed using CRYEBIS at the Kansas State University [17].

3. Laser-produced plasma as a source of multiply charged heavy ions

3.1. Experimental setup

The investigations were performed at the IPPLM with the use of Nd:glass laser system of parameters: $\lambda_L = 1.06$ µm, $E_L \leqslant 10$ J, $t_L \sim 1$ ns [18], and at the IP ASCR with the use of the iodine laser system PERUN of parameters: $\lambda_L = 1.315$ µm, $E_L \approx 30$ J and $t_L = 350-700$ ps [19]. The Nd:glass laser in Warsaw gives a power density on the target $I_L \leqslant 10^{14}$ Wcm^{-2}. Besides the spherical focusing lens a combination of spherical lens with an ellipsoidal mirror with a central hole was used to allow access to the part of the plasma expanding directly against the laser beam.

The laser system PERUN has operated on the fundamental wavelength with the power density $I_L \leqslant 10^{15}$ Wcm^{-2} and on the 2nd and 3rd harmonics with about 50% conversion efficiency.

The chamber was fitted either with an aspherical lens optics or alternatively with a parabolic mirror having also a hole in the centre. The slabs of medium- and high-Z metals (Al, Fe, Co, Ni, Cu, Ag, Sn, Ta, W, Pt, Au, Pb and Bi) were used as the targets. A schematic diagram of the experimental setup used at the IP ASCR is shown in Fig. 1.

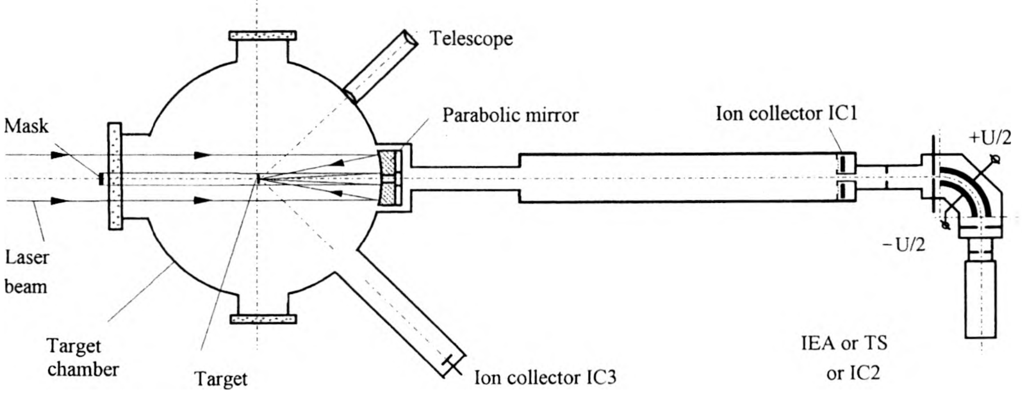

Fig. 1. Experimental setup at the IP ASCR in Prague with the mirror focusing system for studies of ion streams from the high Z-plasma.

3.2. Results

We varied the focal position versus the target surface, the target tilt angle, the laser energy and wavelength to achieve the maximum current of the highly charged ions [8], [19]. The ion yield depends strongly on the focus position with respect to the target surface. The maximum charge state of ions is less dependent on the focus setting than the IC current.

In the case of medium- and high-Z targets three ion groups can be observed: fast, thermal and slow. The ion collector signal if combined with the record of ion spectra from the IEA opens up the possibility of calculating the total number of highly charged ions with $z = 35-44$ in the fast group (*e.g.*, [20]–[23]). The main results obtained with the iodine laser used are summarised below. In Figure 2, an example of IC and IEA signals for Ta plasma registered in the experiment is shown. Figure 3 shows an example of the energy distribution of Ta ions measured by means of the IEA.

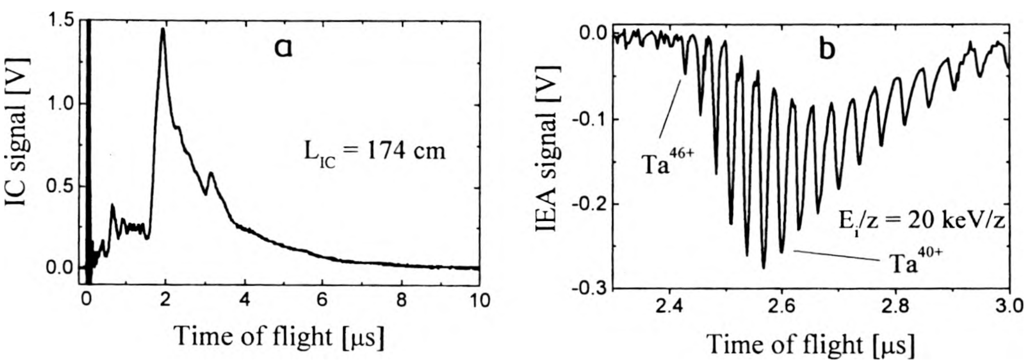

Fig. 2. Examples of the ion collector (a) and IEA (b) records for Ta plasma.

The peak current density 35.3 $mAcm^{-2}$ was calculated for 100 cm from the Ta target. With an ion pulse duration of about 1 μs the number of ions emitted in 1 sr is about 10^{13} per one laser shot. The experiments indicated the presence of Ta ions with charge states up to 55+. The electron temperature $T_{e,0} = 1.7$ keV and the average charge state of ions $\langle z_0 \rangle \sim 50$ in the focal spot were derived from these data. In the Table the main characteristics of different ions emitted from the laser-produced plasmas are presented [24].

T a b l e. Characteristics of the produced ions.

Element	$_{27}Co^{59}$	$_{47}Ag^{108}$	$_{50}Sn^{119}$	$_{73}Ta^{181}$	$_{79}Au^{197}$	$_{82}Pb^{207}$
z_{max}	25	36	38	55	51	51
$E_{i\,max}$ [MeV]	2.6	3.6	3.8	8.8	4.8	5
j_{max}^{*} [mA/cm²]	32.4	21.0	22.3	35.3	21.9	19.8

* Recalculated to the distance of 100 cm.

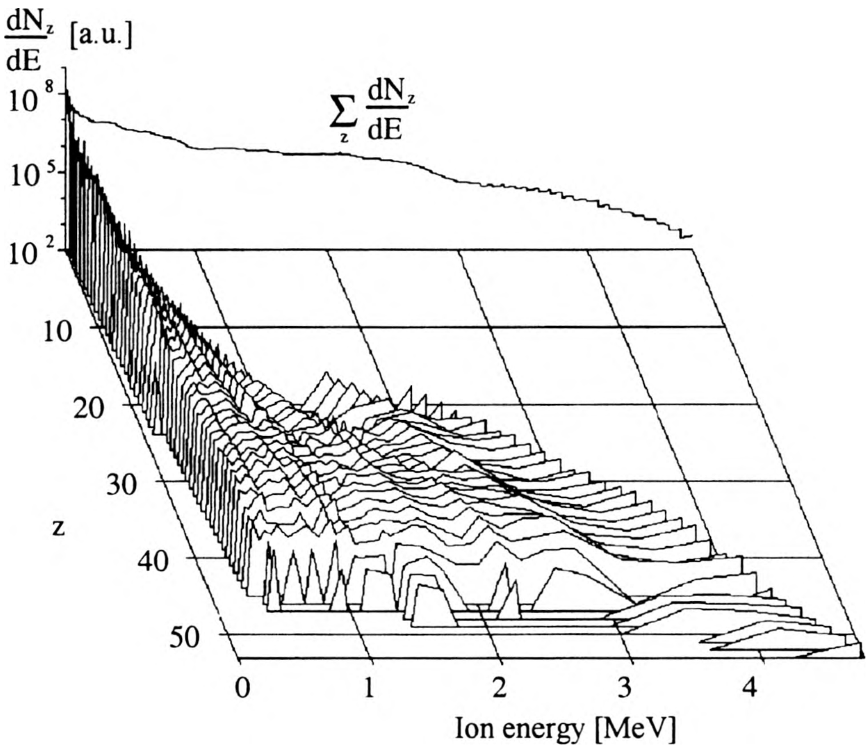

Fig. 3. Example of the charge-energy spectrum of Ta ions (iodine laser $1\omega_0$, 29 J, distance from the target 205 cm, 10° off the target normal).

Ions generated with the use of iodine laser were also registered by the Thomson parabola spectrometer [6], [8], [20], [21]. Although the Thomson spectrometer has low energetic dynamic range and low mass resolution [15] for energetic highly charged heavy ions, it can provide useful and quick information on ion species. The results of measurements performed with the use of Thomson spectrometer and ion collectors proved the existence of multiply charged ions with $z > 40$ and two or more groups of ions with different energies in far expansion zone [6], [20], [21], [25].

An explanation of the occurrence of the highly charged ions in the far expansion zone may be based on the presence of fast ion group in the ion collector signals and a charge distribution "freezing" during the plasma expansion. The existence of the fast group means that the plasma time evolution follows the mechanism of two-temperature expansion [26]. During the expansion phase, first the hot electrons leave the plasma pulling the ions behind. The thermal electrons follow guiding the thermal group. In some cases, in addition to the expansion process just described, emission from the target area irradiated by X-ray emission generated in the hot plasma, adds even a third maximum to the collector signal corresponding to the late arrival of slow ions [23], [27], [28]. To support this notion, a series of model calculations were performed assuming that the energy deposition process causes a two-temperature exponential profile of the electron density. The simulated collector signals and the ion charge distribution calculated on the basis of this simplified model are in a good agreement with the experimental results [27].

4. ECR coupled to LIS

4.1. Experimental setup

The first step in the investigation of coupling between LIS and ECRIS has consisted of some experiments [10] with the setup described in Fig. 4, which have been carried out at the IPPLM in cooperation with the LNS and IP ASCR, in order to confirm the beneficial effects of the axial magnetic field of the ECRIS on the extraction of the ions from the LIS for decreasing the beam divergence. The laser used was a Nd:glass laser ($\lambda_L = 10.6$ μm, $t_L = 1$ ns, beam diameter = 20 mm, divergence $\leqslant 0.5$ mrad); the energy was limited to 2 J maximum. The targets were disks of natural tungsten, molybdenum, tantalum and they were movable along the axis (± 25 mm). The focal length of the focusing lens was 133.4 cm. There was a possibility of applying a negative voltage to decelerate the laser produced ions but this part is still to be completed. Different configurations were investigated, by changing the focusing condition of the laser beam on the target, and the magnetic field between 0 and 0.42 T.

Five flat ion collectors (S1, S2, S3, S4, S5) viewing the target at 1.4°, 4.9°, 11.3°, 26.2°, and 68.7° angles (with respect to the laser beam axis) were placed at 738 mm, 703 mm, 512 mm, 193 mm and 370 mm, respectively. The IEA was placed at a distance of 1818 mm at an angle of 6°.

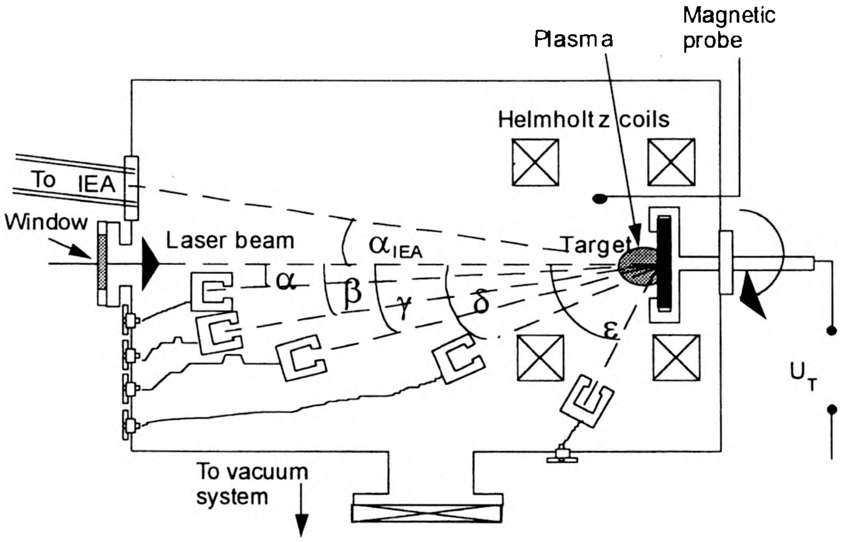

Fig. 4. Experimental setup (not in scale) for studies of the effect of magnetic field on the ion beam emitted from the laser plasma.

4.2. Results

In the case of W ions we observed that without the magnetic field, the peak current density (recalculated to the solid angle of each collector) on S1 is almost two orders of magnitude higher than the current measured on S4. Most of the current is within a cone of 0.2 sr, but a part of the ions are emitted into larger solid angles, up to 0.5 sr [10]. With respect to the solid angle of each collector, in the presence of the magnetic field the peak current density on S1 is a thousand times the peak current density on S4. The integrated charge per solid angle was $1.2 \cdot 10^{-2}$ Csr^{-1} on S1 and $3.8 \cdot 10^{-4}$ Csr^{-1} on S4, without the magnetic field; with the magnetic field these values changed to $4.3 \cdot 10^{-2}$ Csr^{-1} on S1 and $4.5 \cdot 10^{-7}$ Csr^{-1} on S4. In order to observe the different charge states and to evaluate the ion velocity distribution (which is the key parameter for the coupling to ECR plasma), we used the IEA [6], simultaneously with the monitoring collectors S1, S2 and S3.

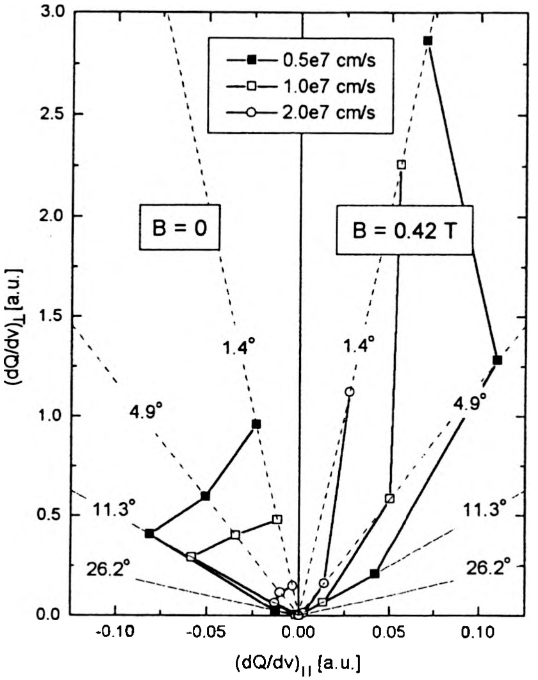

Fig. 5. Angular charge distributions of W ions for different ion velocities, without magnetic field (left) and with magnetic field (right).

In Figure 5, the charge of ions with a given velocity, derived from the ion collector signals [15], registered at different angles is shown. It can be observed that in the case of magnetic field applied the slow ions are detected at smaller angles. Also the amount of fastest ions at small angles is enhanced by the magnetic field.

The conclusion of the analysis with IEA was that the most of the current of W ions is on 1+ and 2+ charge states (50% and 35%), whereas only 15% of the beam is 3+ and 4+.

The results of the experiments, which are fully reported in [10] have shown that the number of ions with low energy (few tens of keV or less) is considerably greater than the number of fast ions. This result is really encouraging, because it is one order of magnitude below the velocity measured for highly charged ion production [29] and it is an acceptable value for an efficient coupling to the ECR plasma. Recent experiments carried out at INFN–LNS in Catania have shown a value of an average energy of the tantalium ions between 0.16 and 0.56 keV for different laser power densities below 10^{11} Wcm^{-2}.

5. LIS for ion implantation

5.1. Experimental setup

Photodissociation iodine laser PERUN was used for the generation of laser plasma of different elements. It operates with the wavelength $\lambda = 1.315$ μm, laser pulse energy $E_L \sim 40$ J, and laser pulse length $\tau_L \sim 300-700$ ps. After frequency conversion on the DKDP crystals the system operated also with the 2nd harmonic (0.657 μm) of the fundamental frequency. A short laser pulse and focus spot diameter of about 100 μm due to aspherical $f/2$ focusing optics allow us to achieve the laser power density up to $1 \cdot 10^{15}$ Wcm^{-2}. The distance of implanted samples from the irradiated target was usually less than 10 cm, resulting on ion current densities of about 10 Acm^{-2}. The angles of the ions impinging on the surfaces of the samples examined ranged from 0° to about 50°, relative to the normal to the target. The experimental setup is sketched in Fig. 6.

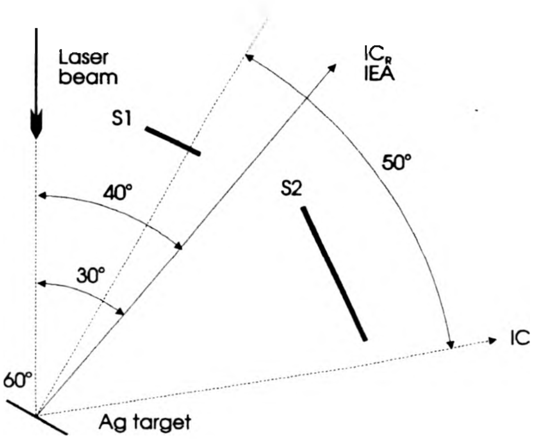

Fig. 6. Experimental arrangement for testing the implantation of ions from the laser plasma in different materials.

The ion collectors and ion energy analyzer were used for the determination of the properties of the plasma produced. The amount of implanted ions was measured at the Institute of Nuclear Physics, ASCR in Řež. by Rutherford backscattering spectrometry (RBS) using the GISA 3.99 computer program [30]. Electron micrographs of the surfaces of implanted samples were made at the Fachhochschule Regensburg and the samples were tested, *e.g.*, for a change in their coefficient of friction at the Research Laboratories of AMW in Munich. The absorption technique, which is based on the known dependence of the depth of implanted ions on their energy, was also used for checking the energy spectra of ions [31].

5.2. Experimental results

Several experiments on the implantation of different kinds of laser-produced ions (Sn, Ag, Au, Pb, Ta) into metals, Si, and organic materials, *e.g.*, kapton, have recently been performed at the IP ASCR in collaboration with the aforementioned laboratories. In this contribution, the properties of the ion streams from the laser-produced Ag plasma as well as the direct implantation of these Ag ions into Al samples are presented as an example [32], [34]. Ions with various charge states and energy distributions are generated by the interaction of intense laser radiation with solid targets. Several experiments were performed to compare ion production for the 1st and 2nd laser harmonics.

Typical IC and IEA records, showing three different Ag ion groups (**a**), and the IEA spectrum for Ag ions (**b**) are presented in Fig. 7. Due to the large step in ionization energy from Ag^{37+} to Ag^{38+} (2.43 keV – 5.21 keV), only charge states up to Ag^{37+} were recorded.

The Ag ions were implanted into samples under various experimental conditions, including the laser 1st or 2nd harmonic, pulse energy, pulse length, and focal position with regard to the Ag target surface. Implantation changed the colour of the organic material surface, with intensity corresponding to the spatial distribution of the ions emitted from the plasma. Similar spatial distribution of ions followed from the RBS analysis.

Curves 1 – 6 in Fig. 8 are depth profiles of the ions implanted at different angular positions and reflect the spatial distribution of the ions emitted from the plasma.

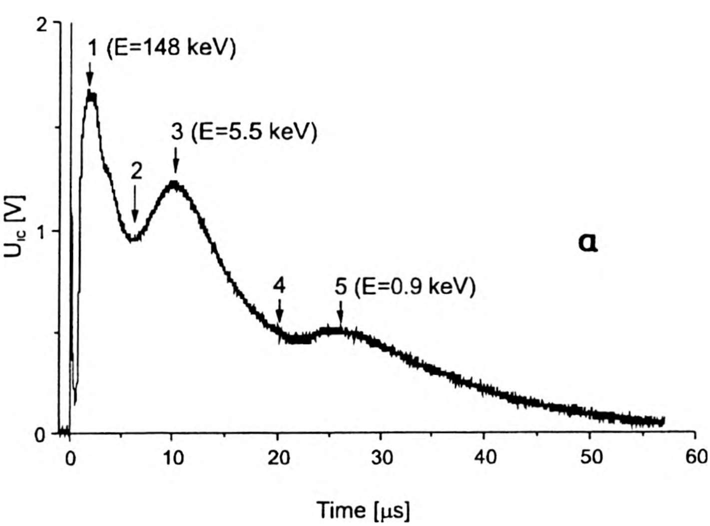

Fig. 7a

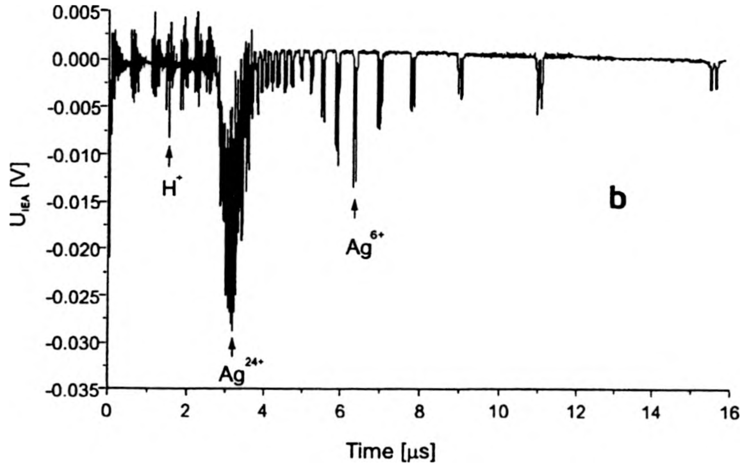

Fig. 7b

Fig. 7. Example of the IC (a) and IEA (b) records of Ag ions ($E_L = 14$ J, $2\omega_0$, $E_i/z = 10$ keV, $L_{IEA} = 210$ cm).

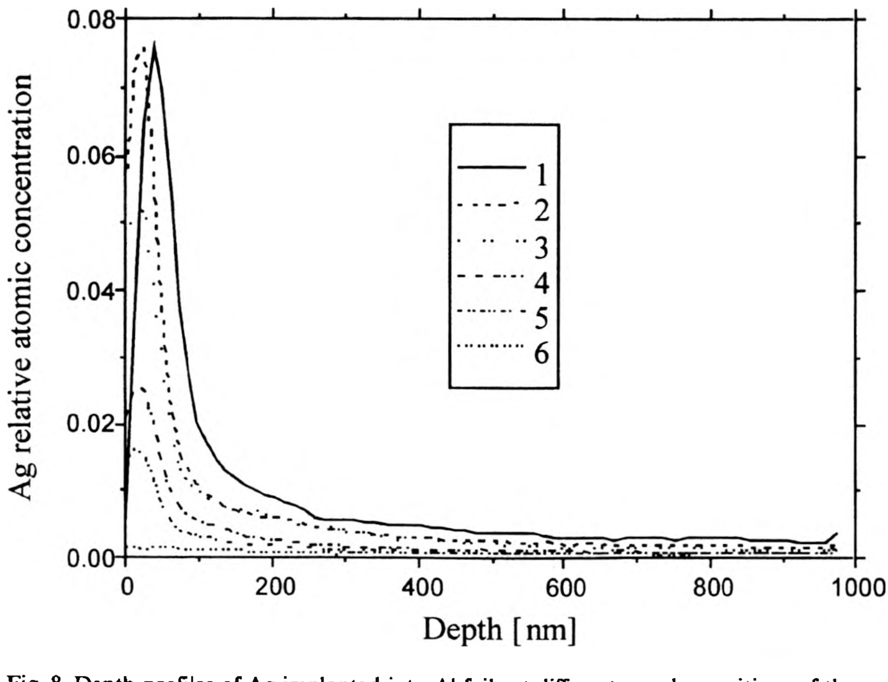

Fig. 8. Depth profiles of Ag implanted into Al foils at different angular positions of the samples: 1 — 15°, 2 — 21°, 3 — 26°, 4 — 31°, 5 — 36°, 6 — 40°.

At normal incidence, the maximum relative concentration of Ag atoms at a depth of about 40 nm below the Al sample surface was 7.6% (curve 1 in Fig. 8) and decreased to 5.2% at a depth of about 500 nm. The corresponding Ag atom density was $3.5 \cdot 10^{16}$ cm^{-2}. Detectable amounts of Ag ions were recorded at depths of up to 1000 nm.

6. Conclusions

The results proved the existence of highly charged ions with $z > 40$ in a far expansion zone. The higher the laser power density is applied, the higher the ion charge states are generated (measured $z_{max} = 55$ for Ta). The highest ion energy up to 8.8. MeV as well as maximum ion current density ~ 35 mAcm^{-2} (recalculated to the distance of 100 cm) were measured for Ta. The ion yield depends strongly on the focus position with respect to the target surface. The maximum charge state of ions as against the IC current is less dependent on the focus setting.

Thus, construction of laser ion source with ions of $z \sim 40$ and $E_i \sim 1$ MeV and with ion current density ~ 10 mAcm^{-2} at a distance of ~ 100 cm seems to be not a principal, but rather a technological problem. Practical reasons (high energy at 1 Hz repetition rate with 10^6 shots now achievable at lower price) dictated the use of the CO_2 laser as a first choice for a heavy ion source for heavy ion accelerators [33]. But the CO_2 laser has the long wavelength (10.6 μm) a badly controllable pulse length and a poor focusability. In a complementary region of high power densities and shorter wavelength lasers (Nd:glass and iodine lasers) the attainable charge states of the ions are generally much higher than when a CO_2 laser is used. It may well happen that the newly available high repetition rate, medium energy and small size systems in the near-infrared region will soon become drivers for the next generation of LIS [5], [22], [34].

We also demonstrated that the effect of the magnetic field is beneficial to the ion extraction from a LIS. Two other results are relevant: the amount of multiply charged ions which is made available for the coupling to the ECR plasma is quite large (of the order of hundreds mAcm^{-2}) and the energy is not so high to make the coupling inefficient. To have a complete view of this argument, the tests of the effects of retarding potential are of a paramount importance and more experiments will be carried out at IPPLM.

Apart from the importance of the laser ion source for particle accelerator physics [1], the laser-driven ion source should provide a lower cost and higher efficiency tool for implantation of metallic ions into solids [13]. The experiments performed proved once again the versatility and efficiency of LIS even for a direct ion implantation, with ion current densities of about 10 Acm^{-2} at a distance of 10 cm from the ion source. About 8% of Ag ions were implanted into both Al and organic samples. The spatial distribution of implanted Ag ions confirmed that the majority of ions are emitted normally to the target. Ion implantation produces surface layers that adhere to substrates much better than pure coating techniques, because the implanted layer becomes actually a part of the substrate, with no interface. This is an important feature in the case of deformable substrates or surfaces which are subjected to substantial forces.

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