Measurement of ion emission from plasmas obtained with a 600-fs KrF laser

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Abstract

Ion emission from plasmas obtained by the use of a 600-fs, 36-mJ KrF laser operating at 248 nm was measured and analysed for a variety of targets at different laser intensities. The intensity was set by changing the distance between the focusing lens and target. It was found that the ions emitted originate from impurities and ions from the bulk of the target can be produced only in the subsequent shots. Proton emission was identified from some targets, but the energy of the protons was low (less than 12 keV). A new SiC semiconductor detector proved to be applicable for the collection of the ions.

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1. Introduction

Small laser systems, e.g., table-top lasers, especially the ones which can operate in a repetitive mode, are attractive sources of ions and protons. There is an interest in using ions from such sources in medicine, technology (implantation), and technical physics (accelerators). Also, the study of ion emission characteristics in laser-produced plasmas plays an important role in understanding physical processes involved.

The aim of the present experiment was the evaluation of ion emission from plasmas produced by a femtosecond laser of relatively low output energy of about 36 mJ and the checking of the possibility of obtaining high-energy ions and protons. In the measurements, the femtosecond KrF laser operating at 248 nm, which is installed in the Department of Experimental Physics, University of Szeged, Hungary, was used. The ions were detected with the use of a ring ion collector and a new-type ion detector, which is based on a silicon carbide (SiC) semiconductor Schottky diode. The SiC detector has been fabricated at the Epitaxial Technology Centre (ETC), Catania, Italy (www.etc-epi.com).

2. Experimental set up

The output parameters of the KrF laser used were: wavelength 248 nm, pulse duration 600 fs and energy in front of the focusing lens about 36 mJ (with a spread of energy up to ± 7 mJ (20%)). The energy delivered to a target was about 31 mJ. The laser is able to operate in a repetitive mode but in the experiment it was operated in a single-shot mode. The targets used were: glassy-carbon, silicon, copper, stainless steel Fe:Ni,Cr, polypropylene $(C_3H_6)_n$, and plexiglass $(C_5O_2H_8)_n$. The laser beam was focused with a lens of 40-cm focal length, which was placed outside the experimental chamber. The intensity of the laser beam was regulated by varying the distance between the lens and the target. The target was illuminated by the laser beam obliquely, at the angle of 60° in relation to the target surface, while ion emission was measured along the line perpendicular to the surface of a target. At sharp focusing, the beam spot was an ellipse of about 10-μm and 14-μm axes and the beam intensity in the spot was about 4×10^{16} W/cm^2. The laser beam was s-polarized in order to avoid resonance absorption, and thus an uncontrolled acceleration of particles by the Langmuir-waves.

Two ion detectors of different types placed along the same line of view were used. One of them was a ring ion collector (RIC) of 22.5 mm in diameter and about 12-mm central hole (in front, there was a grid of 50 % transmission), and the second one was an SiC semiconductor detector placed immediately behind the hole. Such a geometrical configuration provided appropriate conditions for comparison, as the ion flux intensity was almost the same for both detectors. The SiC detector was blind to long-wave light (visible and infrared, of wavelength higher than 380 nm) emitted from plasma. Distances of the RIC and SiC detectors to the target were 60 cm and 74 cm, respectively. The internal structure of the SiC detector and the geometry of its front electrode, which consists of several sub-electrodes of areas 2 mm^2, 1 mm^2, and 0.25 mm^2, are shown in figure 1. In the experiment, the three sub-

electrodes (the largest ones) were connected together giving a common effective area 2+1+1 mm^2. The front electrode of the detector is made from Ni_2Si and it is 200 nm thick. The RIC detector was biased at -300 V, while the SiC detector at +300 V. The time-of-flight (TOF) spectra were measured by the TDS 2024 Tektronix oscilloscope.

3. Results of ion measurements and discussion

The TOF ion spectra for four targets (from six investigated) measured using collector at different focus positions (FP) in relation to the target' surface are shown in figure 2. The +FP means that focus is "inside" the target and –FP that it is in front of the target. The characteristic features of the spectra are as follows:

(1) The sets of TOF ion spectra for all individual targets look very similar. In particular, similar are the shapes and amplitudes of the corresponding peaks (for the same FP) and so is the character of movement of them in dependence on FP. It seems to be peculiar, as the materials of the targets are different (they have high and low atomic masses).

(2) The observed peaks are shifting towards the shorter times (which means the acceleration of ions) when the focus position becomes closer to the position of the front surface of the target. Precisely, the highest acceleration of ions is not exactly at zero focus position, but it is at about +1 mm. The focus position zero has been identified with the use of the Hartmann-plate method.

(3) The shapes of spectra are significantly different for positive (+) and negative (–) focus positions. It can be justified in the case of irradiation by a nanosecond laser pulse, as the volume where the expanding plasma is heated is different in positive and negative positions (see figure 3). There is no such difference in our case of a femtosecond pulse, as the expansion of plasma is then negligible (indicated as black area in figure 3). The difference in

the shapes of the corresponding positive and negative TOF ion spectra can be explained (a) by the existence of long lasting (nanosecond) pre-pulse or pedestal from the Amplified Spontaneous Emission (ASE) which produces plasma, and (b) by the lack of symmetry in the area and/or shape of the beam spot for positive and negative FP positions.

In the present experiments the energy of the laser system was increased using a further amplifier as compared with the previous experiments [1], the consequence of which was the originating of the pedestal from the ASE of the KrF amplifier to a level as high as 10^8 W/cm^2 and duration of about 15 ns. Our previous results using mass spectroscopy [1] showed that in the case of a prepulse level higher than 10^7 W/cm^2 photoabsorption and photoionization of the UV laser radiation may lead to the appearance of ions in front of the solid target, thus modifying laser-plasma interactions. The shifting FP to +1 mentioned in (2) also supports the explanation (a).

On the other hand, the suggested difference in the area of the beam spot may take place when there is astigmatism in the optical system and the laser spot is not axially symmetric (here, it is elliptical). Further investigations are needed to find a real explanation.

(4) In the first shot to the fresh surface of the target, three peaks can be observed for all types of targets (see figure 2). The first small peak “1” of the fastest ions which is observed in the metal targets and in plastic materials containing hydrogen can be easily identified as coming from the lightest ions, protons. There are two other peaks, which are dominating the spectrum. A two-peak structure was observed in other experiments and interpreted in different ways: in reference [2], the peak “2” - as coming from the main plume of plasma and the peak “3” - as a result of lateral heating of the target material; in references [3-4], peak “2” - from the surface impurities of the targets investigated and peak 3 - from the bulk material. Neither interpretation is satisfactory in our case, as it is revealed by the observation of the TOF ion spectra for the second and subsequent shots into the same place of

the target, see figure 4. For the target carbon, we conclude that the peak "2" comes from surface impurities since they are removed after several shots and peak "3" is just from carbon, which is the bulk material. For the target silicon, we conclude that both peaks "2" and "3" are from surface impurities and only peak "4" obtained in the second shot is from the bulk material, which is silicon. In the case of stainless steel, "2" and "3" are from surface impurities, but carbon is also contained in the bulk material. The peak "4" is from the bulk iron.

(5) Peaks of protons (of low intensity) were observed for metallic targets (Cu, stainless steel) and for plastic material (polypropylene) containing hydrogen. They can sometimes appear or rise in the second shot, too. It means that hydrogen is absorbed in the bulk of the materials. The energy of protons observed is quite low due to low value of $I\lambda^2$, where I is the laser intensity and λ its wavelength. At the best focusing condition the energy corresponding to the maximum of a peak was about 4 keV and the maximum energy was about 12 keV. We can notice that the use of an s-polarised laser beam and thus the lack of resonance ionization prevented the particle acceleration due to electron-plasma waves, thus ions were accelerated (besides the thermal effects) only by the ponderomotive force and the space charge caused by the shortage of the directly accelerated electrons.

We can thus conclude that all the ions observed in the first shot come from surface impurities and the ions from the bulk material can be obtained only in the second and subsequent shots. There is problem with identification of the peak "2". In literature [3], there is a suggestion that oxygen comes from the surface impurities, but in our case the peak "2" is placed at shorter times than the peak "3" from carbon, whereas atomic mass of oxygen is higher than that of carbon.

4. Evaluation of SiC detector

The SiC detector used in the experiment was not fully valuable for the measurement of the so low energy protons and ions identified in the experiment, as they cannot penetrate through the 200-nm Ni_2Si layer, as it was checked with the use of the SRIM code [5]. Nevertheless, the SiC semiconductor detector responded to ions and showed the same peaks as the ones measured with the RIC but with different proportion of intensities as it is shown in the case for the copper target, figure 5. The change of the proportions is explained by different mechanisms of operation of both the detectors. The SiC detector is more sensitive for ions of high energy than the ion collector which is typical for a semiconductor detector [6, 7]. We assume that the low energy ions could reach the active layer of the SiC detector with the part of the detector surface which is not covered by the Ni_2Si (which is between the sub-electrodes), see figure 1. This information is important for designing an SiC detector planned for measurement of low-energy ions and protons being in the range of tenths of keV. Such a detector should have a front electrode partly uncovered to ions (e,g., in the form of a grid or concentric rings). Another piece of information from the test measurements is the finding that it is not overloaded and can operate quite well when irradiated by a scattered 248-nm radiation from the KrF laser. The detector is not blind to the 248-nm radiation, but only to the long-wave radiation from plasma (visible and infrared).

5. Conclusions

From the analysis of the obtained results we conclude that the ion spectra measured from laser pulses interacting with a fresh target surface (from the first pulse) are fully determined by the impurity components of the surface. Only subsequent shots into the same place can deliver

ions from the bulk of material. Such a situation results from the very weak interaction of the femtosecond laser with the matter of a target (short time of interaction and low energy). It is likely that the emission of ions is influenced by a nanosecond pre-pulse and it can cause asymmetry in the shapes of TOF spectra for positive and negative focus positions. Proton emission is not present for all materials. It was observed only for metallic targets and for polypropylene, for which proton peaks were the highest. The emission can become more intense for second and subsequent shots into the same place. The SiC detector used was less suitable for the measurement of protons because only part of its surface, which was uncovered by the 200-nm thick front electrode, was sensitive to low-energy protons ($\leq$ 12 keV) observed in the experiment. Even at the limited active surface, the detector produces proton signals several times higher than the ones from the RIC.

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Figure captions

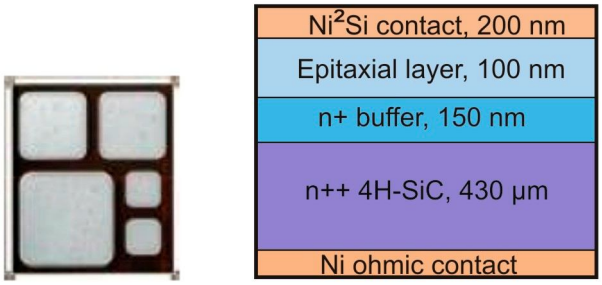
Figure 1. Top view and structure of the SiC detector.

Figure 2. TOF ion spectra for different targets obtained at different focus positions in relation to the front surface of the target. Positive (+) focus position + means that focus is "inside" a target.

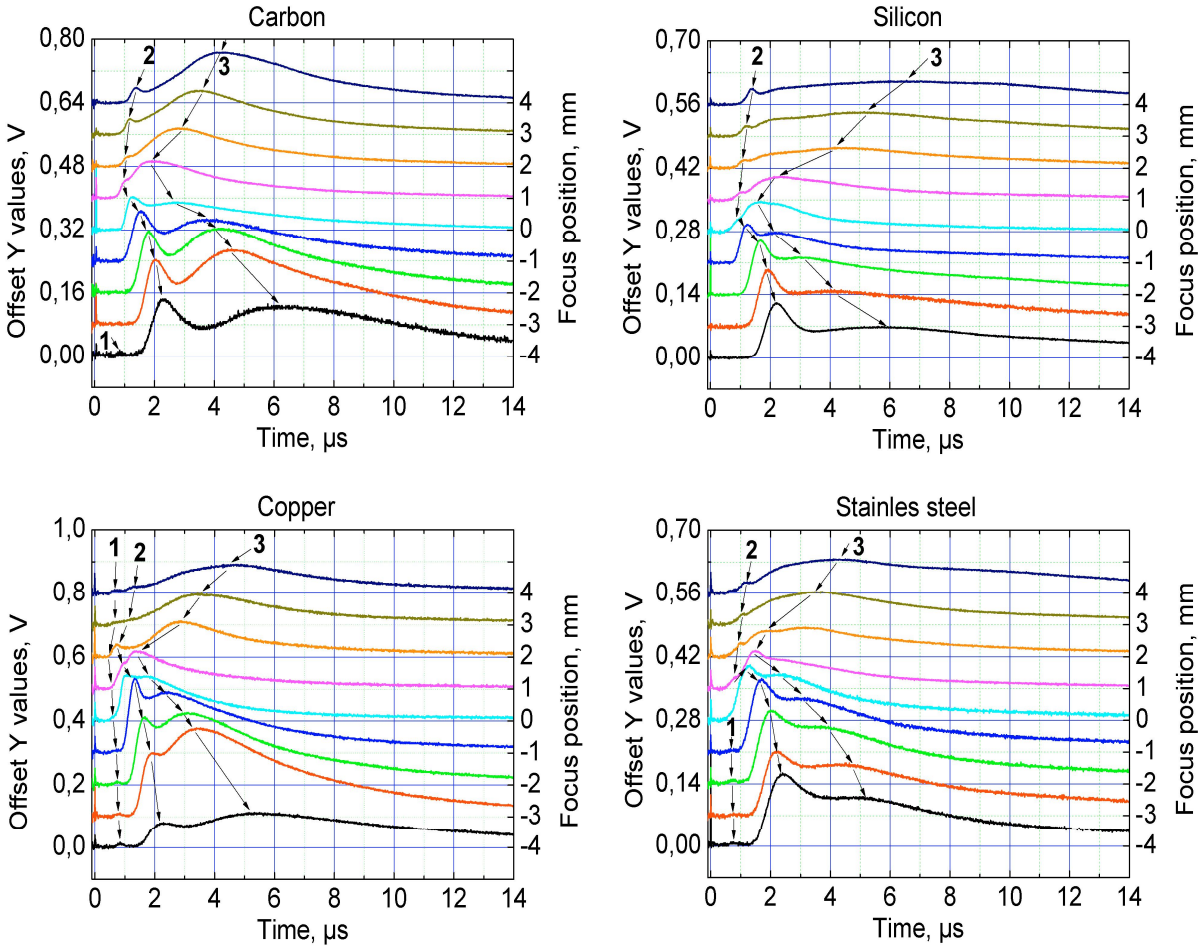
Figure 3. Difference in interaction of the laser beam - target in the cases for nanosecond and femtosecond plasmas.

Figure 4. Comparison of TOF spectra for the first shot and subsequent ones.

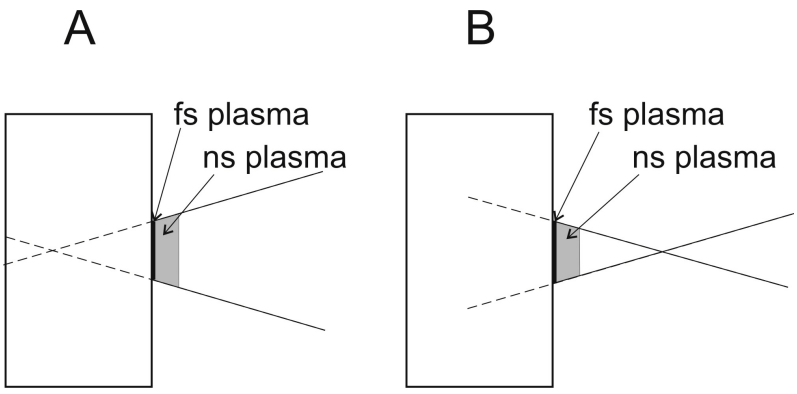
Figure 5. Comparison of TOF ion spectra measured with the ring ion collector (bottom curve) and the SiC semiconductor detector (upper curve).



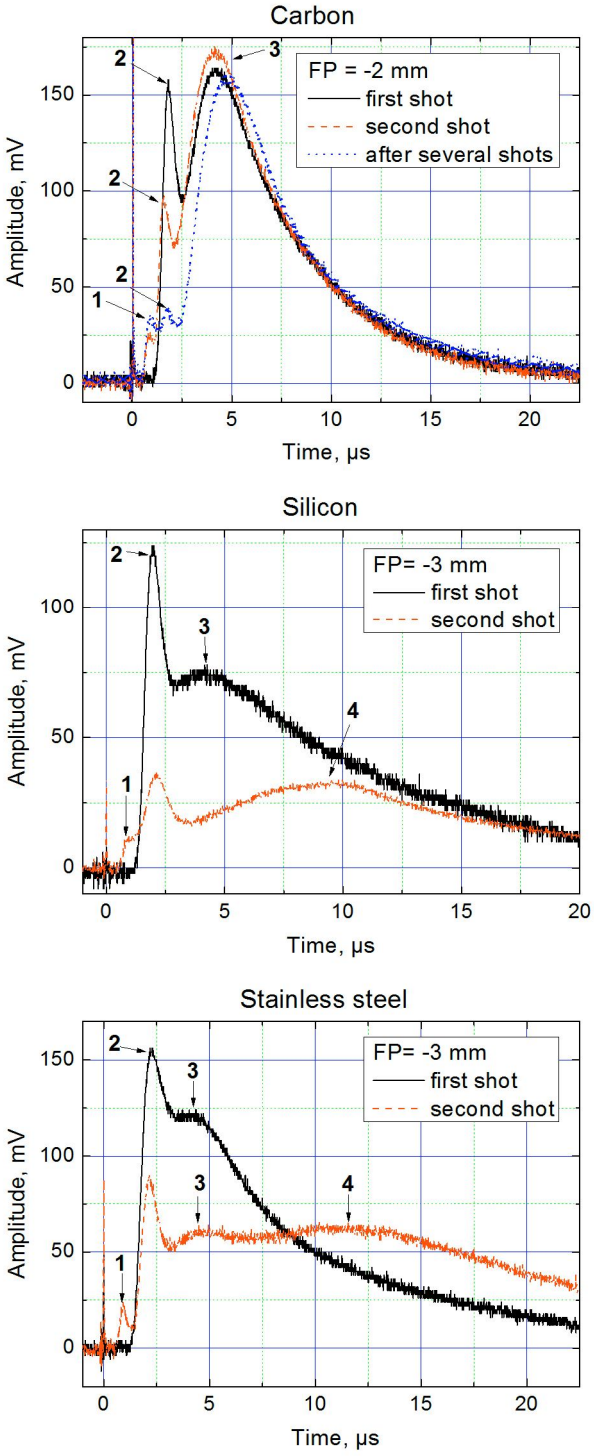
L. Ryc et al. **Figure 1.**



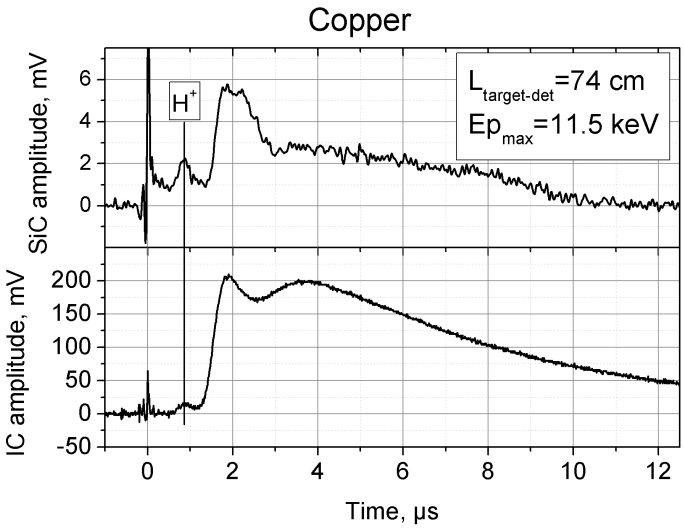
L. Ryc et al. **Figure 2.**



L. Ryc et al. **Figure 3.**



L. Ryc et al. **Figure 4.**



L. Ryc et al. **Figure 5.**