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Generation of MeV carbon and fluorine ions by subnanosecond laser pulses

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Abstract — Experiments were performed by using the pulses of the Laser System PALS (λ_0 = 1.315 μm, τ_L = ≈ 350 ps, $I_{max} \approx 6\times10^{15}$ W/cm^2) focused on thick polytetrafluoroethylene (teflon) and polyethylene (PE) targets. Qualitative changes in the generation of ion emission were observed when the distance between the laser beam focus and the irradiated target surface was varied. Fast ion groups expanding with the peak velocity up to ≈ 9×10^8 cm/s substituted slower thermal ion groups reached a peak velocity of ≈ 8×10^7 cm/s when the focus of laser pulses was moved about 200 μm below the target surface. As opposed to the thermal ion groups, the fast ion groups were composed mainly of a number of separated subgroups of C^{q+} (4≤q≤6) and F^{q+} (7≤q≤9) ions. The highest observed effective voltage accelerating carbon and fluorine ions along the target surface normal was ≈ 650 kV.

Time-of-flight spectra of the ions generated with a high intensity laser pulse focused onto a solid target give basic characteristics of the expanding plasma such as the ion velocity distributions, the total charge carried by ions, kind of ion groups (i.e. fast and thermal ones), reproducibility of the plasma generation, etc. Generally, the laser pulse intensity can be varied by changing the laser energy or spot size. The variation of the spot size results not only in a variation of the laser power density but also it affects the interaction of the laser beam with the pre-formed plasma expanding fully or partially into the laser beam channel. In the reported experiment the focus position (FP) setting was ascertained to be in front of the surface of slab metal targets of heavy elements. Its optimum depends on the applied laser energy [1]. At the optimum focus setting the highest charge states move with the highest velocity and the highest ion currents are produced. The convention used is that FP = 0 when the focus is at the target surface, while '−' and '+' signs mean that it is located in front and below of the target surface, respectively. Besides, characteristics of the generated ions show variations with a FP period of about 200 μm [2]. In contrast to the thermal ions, the TOF spectrum of which is usually smooth with several indistinct peaks, the current of fast ions shows a number of peaks, or even subgroups, the number of which depends on FP [1].

In a laser-produced plasma with several and/or many ion species, each with a different charge-to-mass ratio, the created ambipolar electric field tends to accelerate those species relative to each other, so that various ion groups are created. If the collisions between the ion species are sufficiently weak, the ion groups will indeed become separated in the velocity: e.g. PE plasma produced with the intensity $I\lambda^2 = 4.8 \times 10^{15}$ Wcm^{-2} μm^2 emits five peaks [3] composed of H^+, $C^{6+} - C^{4+}$, C^{3+}, C^{2+} and C^+ ions [4]. The number of subgroups of fast ions of light elements depends on the focused laser intensity. It should be also dependent on FP analogously to heavy ions [1,2], as demonstrated in this contribution.

The reported measurements were performed with the high-power iodine laser system at the PALS Research Centre ASCR in Prague ($\tau \approx 300$ ps; $\lambda = 1.315$ μm, the focal spot diameter ≈ 70 μm) [5]. In this experiment, the laser beam stroke the Teflon or PE target at an angle of 30° to the target normal. FP was varied in the range from –500 μm to 800 μm.

Time-resolved currents of ions were detected with the use of a ring ion collector (IC) placed in front of a cylindrical ion energy analyser (CEA). When FP was 600 μm and 700 μm below the surface of the Teflon and PE targets, respectively, slower thermal ion groups with velocity of about 1×10^8 cm/s were observed - see Fig. 1, TOF > 1.5 μs. If FP was shifted near to the surface, an irregular train of fast ion subgroups evolved. The number of these fast

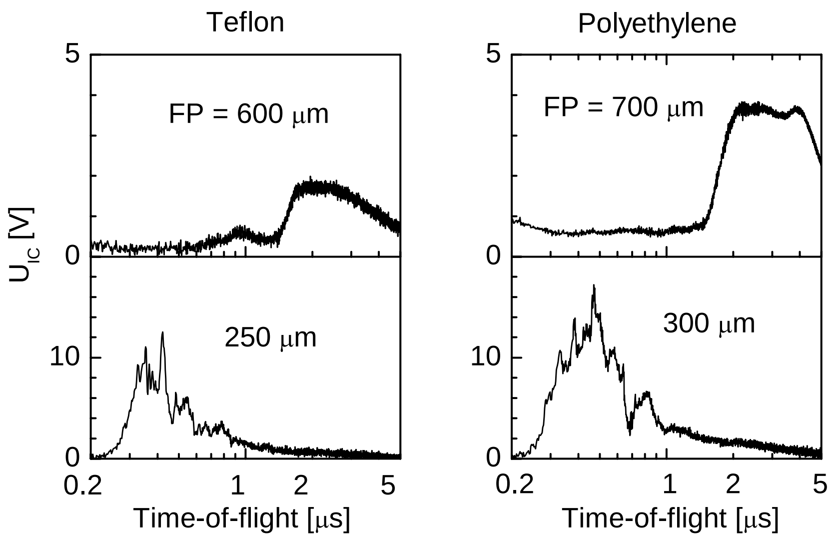

Fig. 1. *Time-resolved currents of ions created by laser irradiation of Teflon and PE targets at various focus positions (FP) below the target surface (L_{IC} = 1.8 m, $E_L \approx$ 150 J).*

subgroups increases when moving the PF up to ≈ 250 μm and 300 μm below the surface of the teflon and PE target, respectively. At this setting and for the applied laser energy equal to ≈ 150 J, the highest velocity of ions reached ≈ 9×10^8 cm/s. The corresponding kinetic energy of carbon and fluorine ions is about 5 MeV and 8 MeV, respectively.

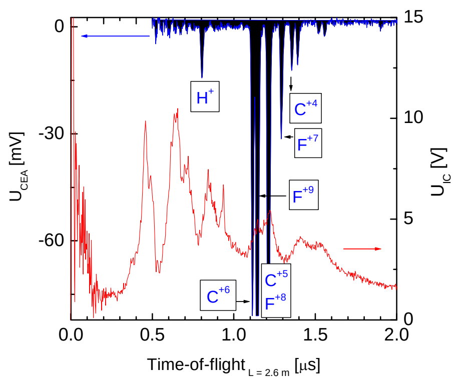

Fig. 2. *H^+, C^{+q} (4 ≤q≤6) and F^{+q} (6≤q≤9) ions dominate the fast ions emitted by Teflon plasma, as signals of IC (bottom curve) and of CEA (upper curve) show; FP = 300 μm. Only the ions with energy of q×120 keV passed through the CEA. The time scale of the IC signal was re-scaled for a CEA distance of 2.6 m from the target.*

The mass spectrum of the fast ions emitted by the teflon plasma, which was obtained with the use of CEA tuned for the ion energy of q×120 keV, is compared with the IC signal in Fig. 2. The diagrams show that the fast C^{q+} (1≤q≤3) and F^{q+} (1≤q≤4) ions are sporadically distributed and the C^{5+} and F^{8+} ions create a common TOF peak. Moreover, a comparison of the CEA spectrum and the IC signal shows that the separated peaks in the IC signal are composed mainly of C^{+q} (4 ≤ q≤ 6) and F^{+q} (6≤ q≤ 9) ions. Since these ion subgroups are separated, they must have been accelerated at different rates. Moreover, the ions contained in each subgroup should be also separated, since their acceleration rate in the ambipolar field is proportional to their charge-to-mass ratio, providing that the ion-ion collisions are sufficiently weak. In that case, the Teflon plasma can be analysed more easily than that of PE, since C^{6+} and F^{9+} ions behaved as a doublet whose constant value of the time-of-flight ratio $TOF_{F9+}/TOF_{C6+} = 1.0274$ due to a high time resolution makes it possible to distinguish them in the IC signal. The above ratio is independent of the accelerating electric field. Peaks of other doublets of ions (eg. C^{5+} and F^{8+}) can be also used, as shown in Fig. 3.

Having computed the TOF for various ion doublets under the assumption that they were accelerated by different voltages, and having compared them with peaks occurring in the TOF spectrum of the ion current, we obtained matching values of the effective accelerating voltage, as illustrated in Figs. 3 and 4. The numerals 1 to 10 were used for numbering the ion subgroups containing doublets of C^{6+} - F^{9+} and C^{5+} - F^{8+} ions, which were accelerated by the same voltage U and, thus, have energy E = qeU. The total number of the fast ion subgroups investigated was limited to 10, the label "1" belonging to

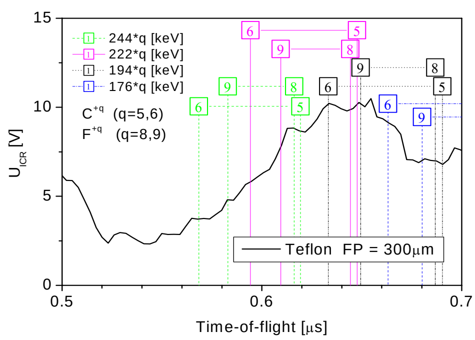

Fig. 3. *Analysis of the ion current emitted from Teflon plasma (see Fig.2, L_{IC}=2.6 m): the doublets of C^{+6}-F^{+9} and F^{+8}-C^{+5} ions expanded together starting from the instant of their generation and acceleration.*

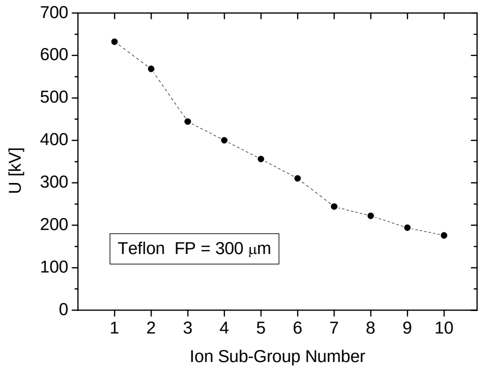

Fig. 4. *Effective voltage accelerating the C^{+6}, C^{+5}, F^{+9}, and F^{+8} ions, which build common subgroups. Numbering of the ion subgroups started from the fastest one passing the 2.6-m distance at 0.36 μs.*

the fastest ion subgroup. In contrast to the slower thermal ion groups (see Fig. 1, TOF > 1.5 μs), the TOF spectrum of fast ions reveals chaotic variations in the magnitude of current. Analogical conclusions can be done for the PE plasma. In this case, the peaks in TOF spectra are mainly composed of C^{q+} ($4 \leq q \leq 6$) and H^+ ions. The highest effective voltage accelerating these ions reaches ≈ 750 kV. The triplets of C^{q+} ($4 \leq q \leq 6$) ions are well distinguishable in the early TOF range only; later they merge into a noise-like broader peak. The repeated occurrence of doublets and triplets of ions in the TOF spectrum gives evidence on repeated plasma outbursts, which create the highest charge-states of the carbon and fluorine ions being gradually accelerated in a lower electric field.

In conclusion: the analysis based on retrieving doublets and triplets of ions in the time-resolved ion currents is a comparative method, which makes it possible to determine the effective voltage accelerating fast ion subgroups and the number of repeated plasma outbursts. The presented method is a useful tool for an analysis of the fast ions of light elements emitted by the laser-produced plasmas, if the single charge-states of ions create peaks separated in TOF spectrum. The highest effective voltage accelerating C^{q+} and F^{q+} ions reaches ≈ 750 kV.

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