*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.030 (2006)*

Time-of-flight spectroscopy of ion currents emitted by laser produced plasmas

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Abstract — Ion currents from a laser-produced plasma were analysed by a deconvolution of time-of-flight ion spectra. The deconvolution is based on the use of Kelly & Dreyfus function expressing the time-resolved ion current. The recovered currents of C^{q+} ($1 \leq q \leq 6$) ions, their peak velocities and abundances are presented. A current of multiply charged Au^{q+} ($1 \leq q \leq 9$) ions produced with a laser intensity $I_L = 3\times10^{10}$ W/cm^2 is deconvoluted to seven groups and the fastest one is compared with the reconstructed currents of single charge-states measured with a cylindrical electrostatic analyser (CEA). Eight groups of highly charged Au^{q+} ($q \leq 52$) ions ($I_L = 5\times10^{14}$ W/cm^2) were recovered from the current pulse. They are compared with the signal from the CEA and with their charge-state – energy spectrum.

The ion collectors (ICs) recording time-resolved ion currents belong to the standard TOF diagnostics, and, therefore, give basic characteristics of expanding laser-produced plasma such as the range of ion velocities, the total charge carried by ions, number of ion groups, the reproducibility of the plasma generation, etc. A novel method based on a deconvolution of TOF spectra with the use of an appropriate function makes it possible to enhance the number of principal parameters, which can be received by the ion current analyses. For a very low laser intensities just above the threshold of ablation, the Kelly&Dreyfus function expressing the ion current (or possibly flux of neutrals) can be applied for a current analysis [1]:

(1) $$I_{IC}(l,t) \propto t^{-5} \exp[-\beta_K^2 (l-ut)^2/t^2],$$

where β_K^2 is related to the Knudsen layer characteristics, namely $m/2kT_{KL}$ with T_{KL} the Knudsen layer temperature, and u is the centre-of-mass (drift) velocity. This model is based on assumptions that a hot gas plume of N_0 particles expands due to the symmetry along the normal to the irradiated surface with a centre-of-mass velocity u. Since the number density of particles remains high enough near the target, collisions among the emitted particles result in a "full-range" velocity distribution function in the centre-of-mass frame. This current function was also used for a deconvolution of TOF spectra to recover the currents of separate charge-states [2].

The goal of our contribution is to demonstrate usability, i.e. advantages and limitation, of deconvolution of TOF spectra recorded with an ion collector.

The ion collector captures ions passing a distance, l, with velocity v, which define the time-of-flight $t = l/v$. The total current, j_i, of ions having different charges, q, at the ion collector input grid is a sum $j_i(l,t) = \sum j_q(l,t)$, where $j_q(t)$ is the current of ions having the charge-state q. The current of ions collected by the ion collector depends also on the bias voltage U, which separate electrons and accelerates ions to the collector electrode. The total current of ions can be expressed in a form [3]:

(2) $$j_{IC,j}(l,t) \propto \sum_q eqt^{-4}\sqrt{(l/t)^2 + 2qU/m_i}\,\exp[-\beta_K^2(l/t - u_q)^2]$$

The deconvolution of a recorded current of C^{q+} ions using (2) is shown in Fig. 1. This analysis recovers not only the visible peaks, which produce a local maximum in the spectrum, but also the hidden peaks, which fail to produce a local maximum.

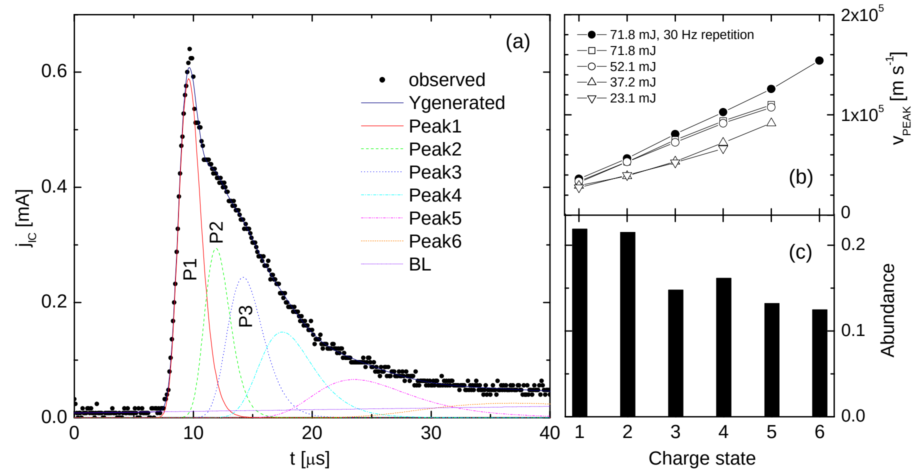

Fig. 1. (a) Deconvolution of the currents of C^{q+} ions ($1 \le q \le 6$) created with the Nd-YAG laser (71.8-mJ, repetition frequency of 30 Hz). The hidden Peak 1 corresponds to q = 6, Peak 2 to q = 5, etc. The line labelled "Ygenerated" shows the convolution of the recovered peaks. (b) The charge-state dependence of the ion peak velocity for different laser energy. The labels □,○,△,▽ represent data measured in a single shot mode of laser operation. (c) Abundance of C^{q+} ions produced with the repetition frequency of 30 Hz.

The fitted parameters of (2) characterise the properties of produced plasma, i.e. ions far from the irradiated target. Fig. 1b shows the laser-energy dependence of the peak velocities of groups of single charge-states. The corresponding temperature evaluated from the value of the fitted β parameter ranges from 5 to 25 eV. The abundance of single charge-states of the carbon ions, which is shown in Fig. 1c, is defined by

(3) $$q_{av} = \sum_q q \int n_q(t) \Big/ \sum_q \int n_q(t) \ ,$$

where $n_q(t)$ is determined by the ion current deconvolution.

If multiply charged ions of heavy elements are generated, the deconvolution of ion current to currents of single charged ions is restricted. The recorded ion current is composed of several ion groups, as Fig. 2 shows. The currents of single charge-states are weakly separated even far from the target, because the created electric field accelerates ions to velocities $\propto (q/m)^{1/2}$, and thus, differences in the peak velocities of multiply charged, for example, Au^{q+} ions are small (see Fig. 2b). The deconvolution is not able to recover currents of single charge-states. It recovers the hidden ion groups in this case. Moreover, different ion groups contain ions carrying the same charge-state, as it is evident in Fig. 2. By varying the distance of IC from the target it is possible to determine a critical zone, outside which the charge states of ions of the expanding plasma are frozen [4].

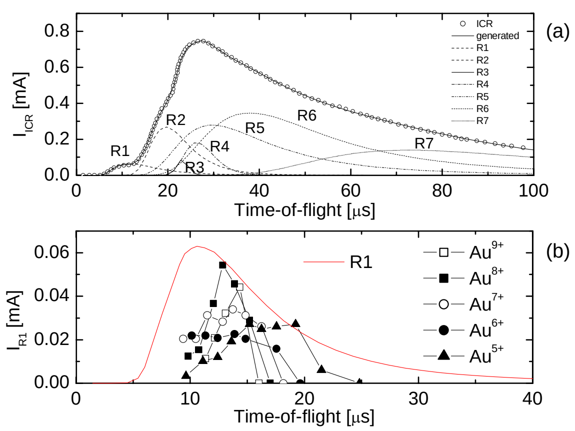

Fig. 2 Deconvolution of a current of Au^{q+} ions produced by a Nd:YAG (λ=1064 nm, $I_L = 3\times10^{10}$ W/cm^2) – (a). Comparison of the Au^{5+} to Au^{9+} ion currents reconstructed from the cylindrical electrostatic analyser spectra with the recovered peak R1 – (b).

The iodine laser PERUN delivering on a target an intensity of 5×10^{14} W/cm^2 ($2\omega_0$, $\tau_L\approx$400-ps) created plasma emitting Au^{q+} ions with q_{max}=52. The present analysis recovered eight ion current peaks (groups), see Fig. 3a. We plotted six of them completely, but the seventh one was broken off at 10 μs. Fig. 3b shows the signals of the CEA recorded for three ion energies per charge-state of 20 keV/q, 40 keV/q, and 70 keV/q. The signal corresponding to the ions with 20 keV/q is modulated in time according to the recovered peaks P3 to P5. The local current maximum attached to the charge-state of 28+ can be the ascribed to the convolution of the P4 and P5 peaks. The faster charge-states about 43+ contribute mainly to the current of the P3 peak. The currents of ions having energy per charge of 40 keV/q and 70 keV/q belong to P2 and P3 peaks and to P1 and P2 peaks, respectively. The peak P1 extra contains H+ ions. The peak energies of all the recovered ion groups are plotted in Fig. 3c, which shows ranges of the E_{ion}–q spectra recorded with the CEA. The routing separation of the ion groups into slow and fast ones should happen at the energy of about 250 keV. Láska et al. have already reported also seven ion sub-groups indicated in Ta^{q+} ion currents produced by laser intensities ranging from 6×10^{13} W/cm^2 to ≈ 1×10^{15} W/cm^2 [5]. These peaks were recovered as visible peaks with no numerical analysis of the TOF spectra. Production of a high energy and high charge-state of ions correspond to a nonlinear interaction of the created plasma with the incident laser beam, e.g. self-focusing effect. The experimentally determined intensity threshold for generation of highly charged, high-energy ions is ≈ 2×10^{14} W/cm^2.

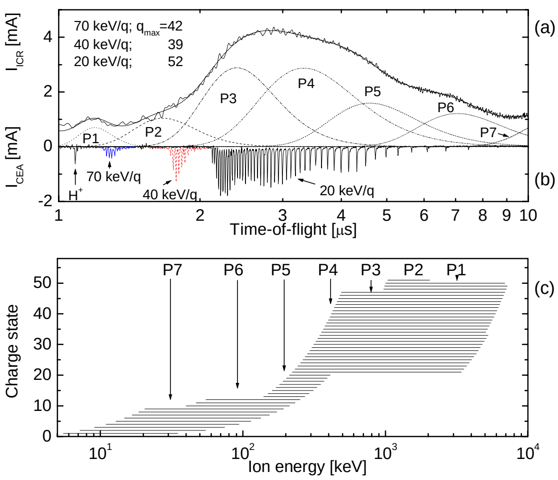

Fig. 3 Deconvolution of an ion collector signal to seven current peaks – (a). CEA spectra of Au^{q+} ions with E_{ion}/q = 20 keV/q, 40 keV/q, and 70 keV/q having q_{max} = 52, 39, and 42, respectively – (b). $q - E_{ion}$ spectrum of Au^{q+} ions emitted from a plasma produced with intensity of 5×10^{14} W/cm^2. The arrows show the positions of the recovered peaks – (c).

We can conclude that the deconvolution of ion currents emitted by a laser-produced plasma can recover currents of single charge-states of light elements and a number of ion groups (sub-groups) of heavy elements.

Acknowledgment

The Grant Agency of the ASCR (Grant IAA 1010405) supported this work.

References

[1] R. Kelly, R.W. Dreyfus: Surf. Sci. 198 (1988) 263.

[2] J. Krása et al.: Plasma Phys. Contr. Fusion 47 (2005) 1339.

[3] J. Krása et al.: Radiat. Eff. Defect. S. 161 (2006) 757.

[4] A. Lorusso: Appl. Phys. Lett. 86 (2005) 081501.

[5] L. Láska et al.: Plasma Phys. Contrl. Fusion 45 (2003) 585.