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X-ray spectroscopic study of charge exchange phenomena in plasma-wall interaction

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Abstract. Jets of energetic ions launched at laser-burnt-through foils represent an efficient tool for investigation of plasma interaction with solid surfaces (plasma-wall interaction, PWI) and for description of transient phenomena occurring close to the walls. Highly charged ions approaching the secondary target interpenetrate the near surface layer, collide with the counter-propagating matter and capture a large number of electrons. This results in a creation of atoms in highly excited Rydberg states or hollow ions with multiple inner vacancies; plasma jet and target ions may also undergo charge exchange (CE) processes. We report PWI experiments with Al/Si(PMMA) and Al/C targets irradiated at normal or oblique laser incidence. The distinct dip structures observed in red wings of Al Lyγ self-emission is interpreted in terms of CE between C^{6+} and Al^{12+} in the near-wall zone. The spectroscopic identification of CE phenomena is supported by results of analytical and numerical calculations.

1. INTRODUCTION

Plasma-wall interaction research directed at investigation of various mechanisms of the energy transfer in the near-wall region (e.g., ion deceleration and stopping, shock wave generation, formation of highly excited Rydberg states and hollow atoms, charge transfer and ion neutralization – for relevant Refs. see [1]) contributes to a detailed understanding of the material erosion and migration at surfaces of plasma facing components, thus providing application-important data necessary to a development of new-generation fusion reactors.

Well-defined jets of energetic laser-produced plasmas provide in combination with precise x-ray spectroscopy very sensitive and flexible tools for studying these effects. In the reported experiments, the charge exchange phenomena were investigated by analysing the spatially resolved, narrow-band x-ray spectra emitted from single-side laser-irradiated double-foil targets. We briefly describe the experimental configuration used, present new high-resolution spectroscopic data and interpret the structures observed in Al Lyγ line profiles in terms of CE between multicharged atoms. The identification of CE phenomena is supported by complementary diagnostics and by results of analytical and numerical calculations.

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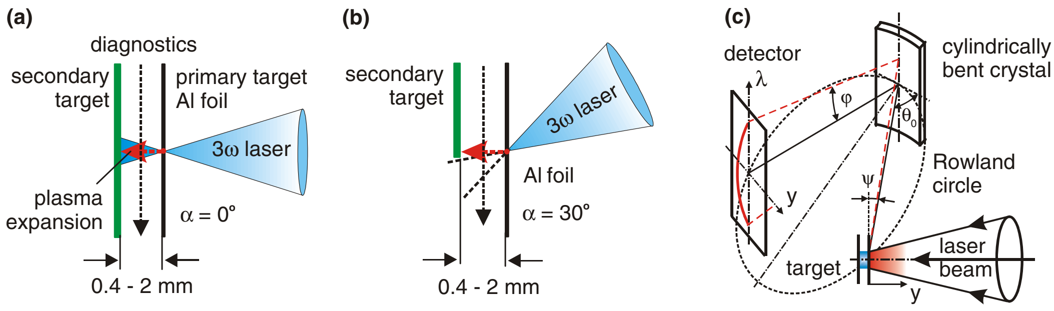

Figure 1. Plasma jet production at normal (a) or oblique laser incidence (b) and scheme of spectroscopic setup (c).

2. PALS EXPERIMENT

The experiments were carried out at the Prague iodine laser system PALS [2] delivering 50-150 J of frequency-tripled radiation (438 nm) in a pulse length of 0.25-0.3 ns. The laser beam was incident onto the jet-producing target (0.8-μm-thick Al foil) either perpendicularly to its surface (Fig. 1a) or inclined by 30° from the target normal (Fig. 1b). In both configurations, the plasma jets propagate primarily along the direction of the target normal. At normal incidence ($\alpha = 0^\circ$), the jet strikes the secondary target pre-ionized by the action of the transmitted laser light, i.e., the PWI effects are complemented by the interaction of two counter-propagating plasmas. In the oblique incidence case ($\alpha = 30^\circ$), the laser beam does not hit the secondary target and the expanding plasma interacts with the unperturbed surface, thus creating a better-characterized environment for PWI studies.

The standard diagnostic complex included optical spectroscopy, a pinhole camera coupled to a low–magnification x–ray streak camera, and a survey x–ray spectrometer with spherically bent mica crystal. The primary diagnostics was a high-resolution vertical geometry Johann spectrometer (VJS) using cylindrically bent crystal of quartz. As shown in Fig. 1c, the VJS disperses the radiation along a direction λ parallel to the crystal axis and provides two sets of mirror-symmetric spectra 1D spatially resolved along y-axis [3]. A simultaneous production of two sets of spectra facilitates computational reconstruction of spectroscopic data and increases their reliability.

The kinetics of the plasma formation was visualized by x-ray streak images. The record shown in Fig. 2a corresponds to the plasma outflow from the Al foil at normal laser irradiance (70 J, 0.3 ns, 5×10^{15} W/cm^2). The foil burns through before the laser pulse maximum and a considerable part of its energy creates the longer-duration counter-propagating plasma on the secondary target (massive Si coated by the 0.5-μm-thick layer of PMMA, $C_5H_8O_2$). Consequently, the interaction zone gradually moves from the Si towards the Al surface and the near-wall PWI effects may be partially blended by the colliding counter-streaming plasmas. In contrast, the plasma jet launched from the rear side of the Al foil at oblique laser incidence (57 J, 0.27 ns, 3×10^{14} W/cm^2) strikes the unperturbed C foil (Fig. 2b) and the interaction zone does not considerably detach from the secondary target surface.

3. THEORETICAL ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

VJS spectra corresponding to the above described experimental situations are presented in Fig. 3. The highly collisional plasma created at normal laser incidence (Fig. 3a) induces the full Al ions stopping in a distance of about 80 μm from the Si(PMMA) surface; the impact of Si ions from the longer-duration counter-streaming plasma on the Al foil is visualized via the Si Heβ emission. At oblique laser incidence (Fig. 3b), the trapping of Al ions close to the C surface is distinctly seen.

In both cases, the Al Ly γ emission from interaction zones displays a pronounced fine structure, i.e., depressions in the near red wing of the line profiles (marked by dashed lines in Fig. 4a and by arrows in

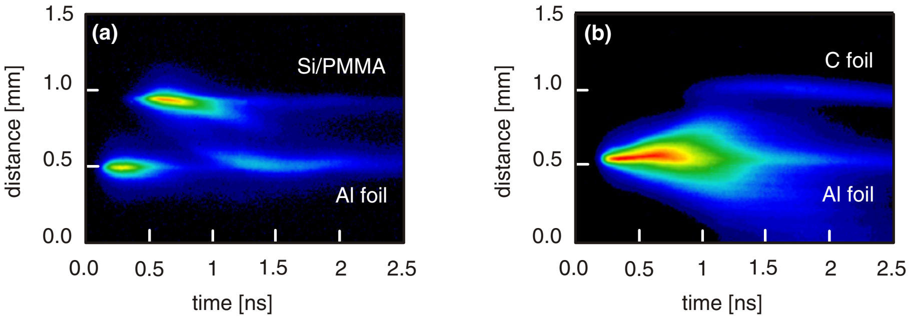

Figure 2. X-ray streak images of the plasma evolution at normal (a) and angle-irradiated (b) double-foil targets.

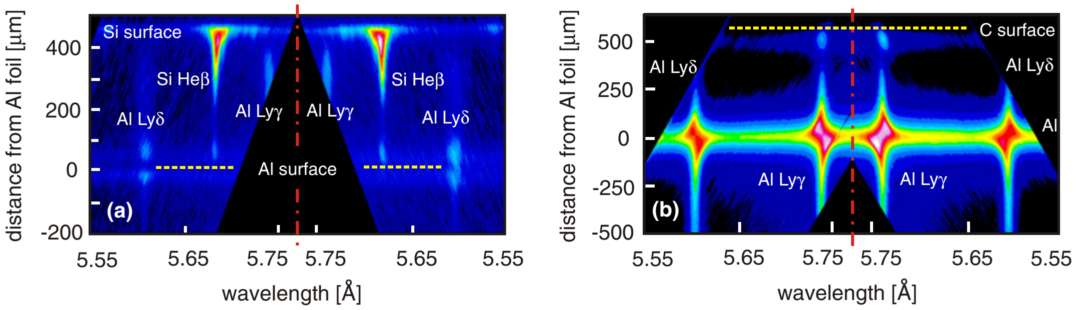

Figure 3. Spatially resolved spectra of Al Lyγ, δ self-emission from double-foil Al/Si(PMMA) and Al/C targets recorded by the VJS at normal (a) and oblique laser incidence (b). The laser irradiates Al foil from below.

Fig. 4b) which were extracted from the right-hand side spectra shown in Fig. 3. The separations of these dips from the line center do not show any noticeable dependence on the distance from the secondary target surface, and thus on the electron density n_e. This weak density dependence is a characteristic feature of the charge-exchange-caused dips (x-dips) – in distinction to the Langmuir-waves-caused dips whose positions scale as $n_e^{1/2}$. The found positions of the dips (3.1 ± 0.1 mÅ and 6.7 ± 0.2 mÅ from the density-shifted line centers) agree well with the theoretical positions of x-dips due to CE between C^{6+} and Al^{12+} ions [4]. Physically, the x-dips correspond to anti-crossings of terms of the one-electron quasi-molecule of nuclear charges Z_1 and Z_2: anti-crossings enhance CE. For the quasi-molecule of $Z_1 = 13$ and $Z_2 = 6$, the theory predicts three anti-crossings at different inter-nuclear distances (which are controlled by n_e and in general differ from the most probable one), thus usually only two of them are observed in the same line profile. The dip at 6.7 mÅ was already reported in experiments [5] which demonstrated for the first time x-dips in spectral lines of multicharged ions. Therefore the dips discussed here are clearly a manifestation of CE.

Theoretical predictions of environmental conditions necessary for observation of these x-dips [4] require the plasma temperature T at the level of several hundred eV and electron density within $\approx 2 \times 10^{20} - 1 \times 10^{22}\,\mathrm{cm}^{-3}$. The fulfilment of these conditions was checked by analysing the observed survey x–ray spectra and by hydrodynamic modelling of the experimental situations. The spectrum presented in Fig. 4c was recorded in the same laser shot as line profiles shown in Fig. 4b. The n_e distribution was derived from the FWHM widths of the Al Lyδ profiles, the T from the best fitting of the Al Lyα and β groups. The found values $n_e = 2.6 \times 10^{21} - 1 \times 10^{22}\,\mathrm{cm}^{-3}$ and $T = 550 \pm 50\,\mathrm{eV}$ are well compatible with the plasma parameters simulated using the two-dimensional (2D) Prague Arbitrary Lagrangian Eulerian hydrocode PALE [6]. The hydrodynamics was based on a quotidian equation of state (QEOS), classical Spitzer-Harm model for the heat conductivity, and a simple approximation of

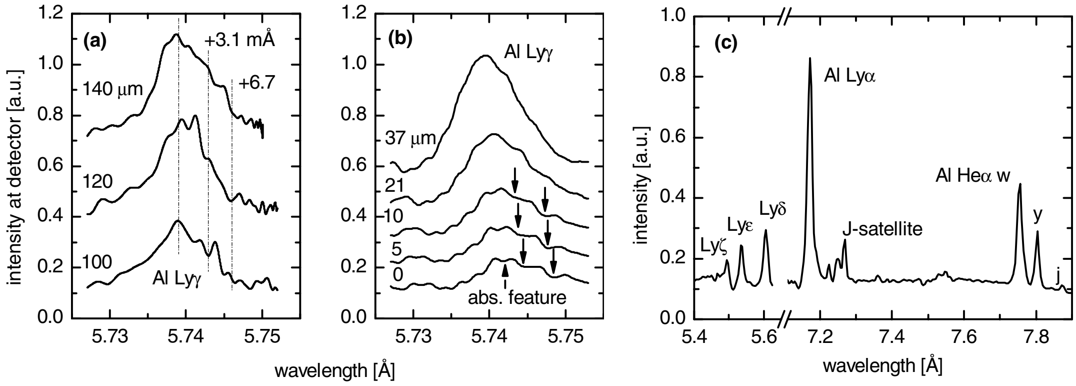

Figure 4. Detailed profiles of the Al Lyγ line observed at normal (a) and oblique laser incidence (b). The plasma parameters derived from the survey spectrum (c) fulfil criteria of charge exchange observation.

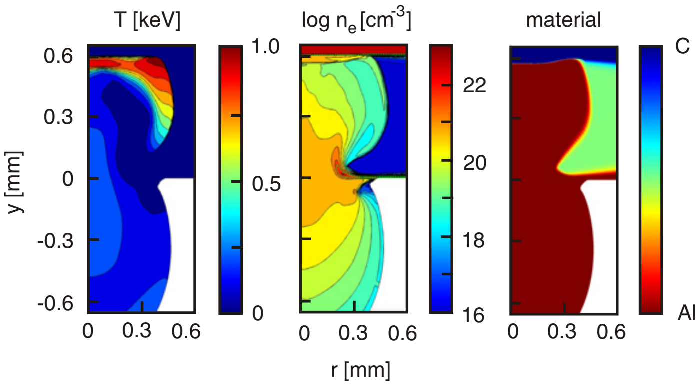

Figure 5. Two-dimensional PALE code simulation of the Al plasma interaction with the secondary C target.

the laser energy deposition at the critical density surface. The 2D distribution of the plasma parameters presented in Fig. 5 again corresponds to the oblique laser incidence onto the Al foil and to the time period of 0.7 ns after the laser pulse maximum, i.e., shortly after the Al plasma impact onto the C target. The results of simulations confirm that close to the C target surface, the plasma environmental conditions in interaction zones are favorable for the charge exchange observation.

To conclude, the spectroscopic experiments directed at investigation of the energetic plasma jets interaction with walls revealed reproducible modulation in red wings of the Al Lyγ self-emission from the near-wall zones. The found x-dips were attributed to the charge exchange between C^{6+} and Al^{12+} ions, their interpretation in terms of CE phenomena was supported by results of analytical and numerical calculations and by auxiliary diagnostics. As far as we know, this is the first x-ray identification of CE effects in the PWI research. Further analysis of the x-dips structure opens a space for retrieving novel fundamental data, e.g., on charge exchange rate coefficients [7].

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