X-ray visualization of charge exchange processes in plasma-wall interaction

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Bombardment of solid surfaces by fast ions has been of continuous interest for more than hundred years because of its numerous technical applications [1]. Nowadays, one of the most important fields of interest is connected with studies of the material erosion and migration at plasma-facing components, aiming at a design of the future reactor vessels for both magnetic and inertial confined fusion [2]. Further optimization of plasma-exposed materials requires a detailed understanding of transient processes accompanying interaction of solid surfaces with intense fluxes of high-temperature plasmas (hereafter, plasma-wall interaction, PWI).

Mechanisms of the energy transfer in the near-wall region include ion deceleration and stopping, shock wave generation, formation of highly excited Rydberg states or hollow atoms with multiple inner vacancies, charge transfer processes, and ion neutralization. In particular, the electron capture into high *n*-shells of impinging ions results in cascading processes including the emission of Auger electrons (intraatomic Auger deexcitation), optical and x-ray photons which carry information on charge exchange relaxation processes in the near-surface region. The purpose of this paper is to contribute to x-ray spectroscopic identification of charge-exchange processes (hereafter CE) in the near-wall zone of secondary targets exposed to intense fluxes of laser-produced plasma jets.

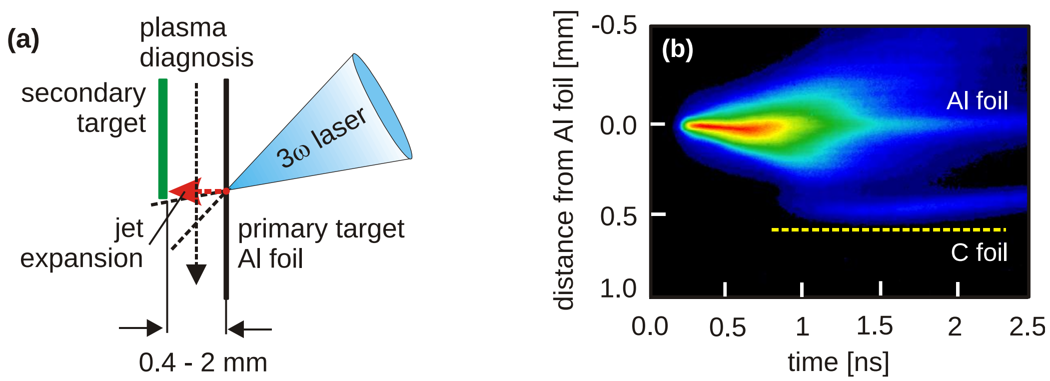

Figure 1. Scheme of the plasma jet production at oblique laser incidence on double-foil targets (a) and x-ray streak camera record of the plasma evolution at laser-irradiated Al/C target (b).

The experiment was performed on the iodine laser system of the PALS Research Centre [3]. The laser beam delivering 50-90 J of frequency-tripled radiation (438 nm) in a pulse length of 0.24-0.3 ns (full width at half maximum) was incident onto the primary, jet-producing target (0.8-μm-thick Al foil) at an angle inclined by α = 30º from the target normal. The reason for the oblique incidence laser-target geometry is explained in figure 1a. In this configuration, the laser beam does not hit the secondary target and the expanding plasma jet launched in a direction of normal to the Al foil surface interacts with the unperturbed target, thus creating a better-characterized environment for PWI studies. Optimum conditions for formation of high aspect-ratio jets were found when defocusing the beam to the focal spot radius of 150 μm [4]. The launching of the optimized plasma jet from the burnt-through Al foil and its interaction with the secondary C target is shown in figure 1b.

The standard diagnostic complex used in PALS PWI experiments consists of time-resolved x-ray imaging of the plasma expansion, optical spectroscopy, interferometry and several x-ray spectrometers. The primary diagnostics applied in the present study was a vertical dispersion Johann spectrometer (VJS) fitted with a cylindrically bent quartz crystal [5]. Hereafter we shall concentrate on evaluation of high-resolution spectra obtained by the VJS.

The spatially resolved x-ray spectrum presented in figure 2 was recorded at the oblique incidence of the laser beam (57 J, 0.27 ns, 2.5×10^{14} W/cm^2) striking the Al target from above. The Al foil and the 250-μm-thick pyrolytic graphite were interleaved by a distance of 590 μm. The plasma jets produced at both front and rear surfaces of the Al foil (spatial coordinate 0) are visualized via the emission of the Lyman series members γ and δ of the hydrogenic Al.

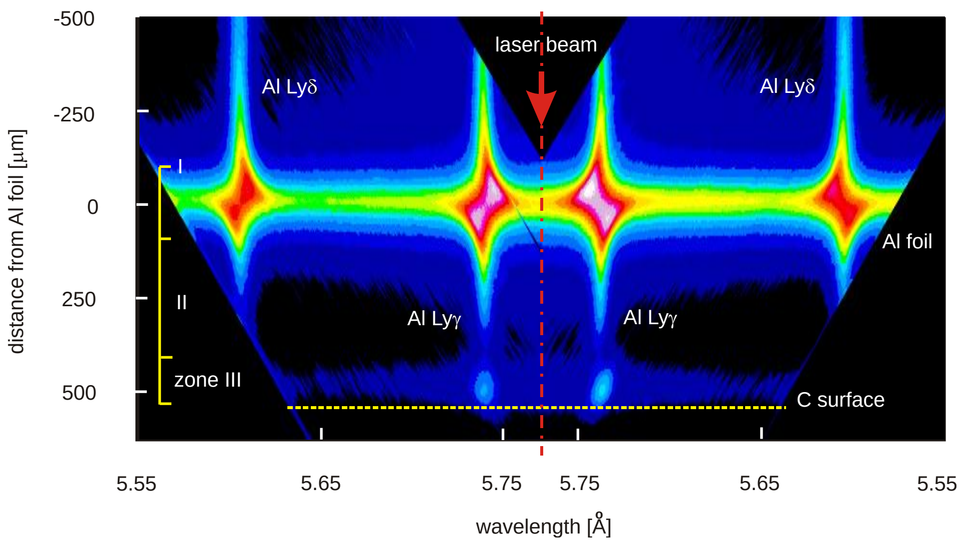

Figure 2. Spatially resolved x-ray spectrum of the hydrogenic Al self-emission recorded using the VJS.

Three zones marked in figure 2 characterize different stages of the jet expansion. In zone I extending within approximately ±100 μm from the Al target, the emitted lines display distinct Doppler shifts due to directional reversal of the plasma outflow at opposite sides of the burnt-through foil. Their detailed evaluation provided the effective lateral velocity component ~1.5×10^7 cm/s which agrees with the near-surface semi-spherical plasma expansion observed in interferometric measurements [4]. In zone II extending up to the distance of about 450 μm, the plasma propagates in a laminar flow and no large-scale plasma turbulences are visible. With the increasing distance from the primary target, the intensity of the Al Lyγ emission gradually decreases but then it again intensifies in zone III. Enhanced emission close to the C surface indicates deceleration, trapping and dissipation of Al ions at the secondary target.

Interpretation of spectra emitted from the near-wall zone requires knowledge of macroscopic plasma parameters. The analysis of the spectra recorded by the survey spectrometer provided the electron temperature $T_e \approx 450–550$ eV and electron density n_e within $0.5–5\times10^{21}$ cm^{-3}. The limited spatial resolution of the spectrometer (~20 μm) however hinders the more detailed characterization of the plasma; to remedy this, a series of simulations has been performed to evaluate the time-dependent distribution of the macroscopic plasma parameters.

Interpenetrating plasmas were modelled by a combination of the 2D hydrodynamic code PALE [6] with the 1.5 D multi-fluid code MULTIF [7]. The PALE simulations were used as input for the MULTIF description of the Al plasma impact on the cold C surface, production of the counter-streaming C plasma and subsequent collision and interpenetration of both plasmas. Figure 3 indicates a fast creation of a relatively thin (~20 μm) near-wall layer of highly ionized, strongly interpenetrating Al and C ions. The found environmental conditions are favourable for observation of charge exchange phenomena [8].

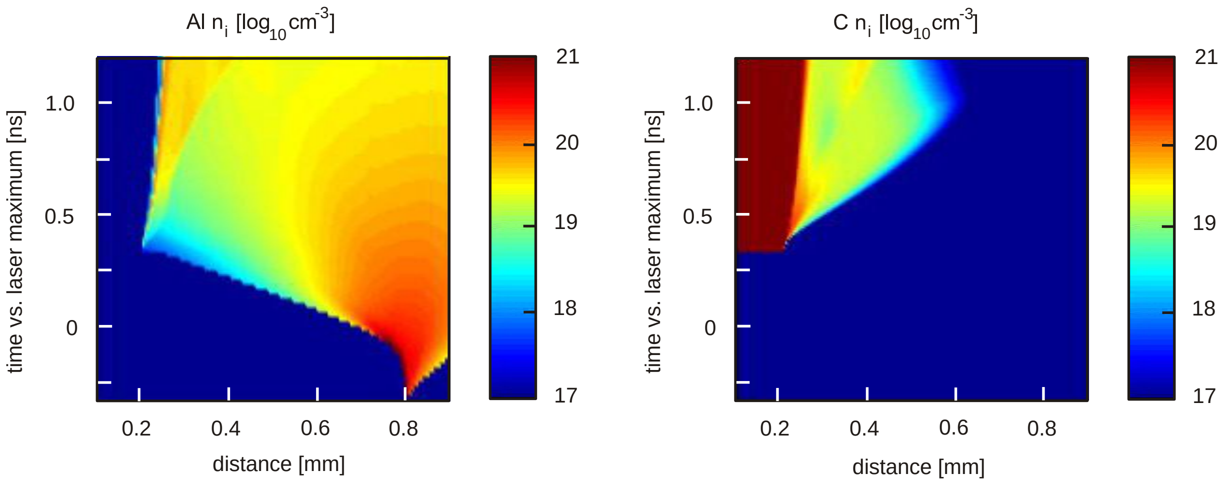

Figure 3. Time-space distribution of the plasma ion densities simulated by codes PALE and MULTIF.

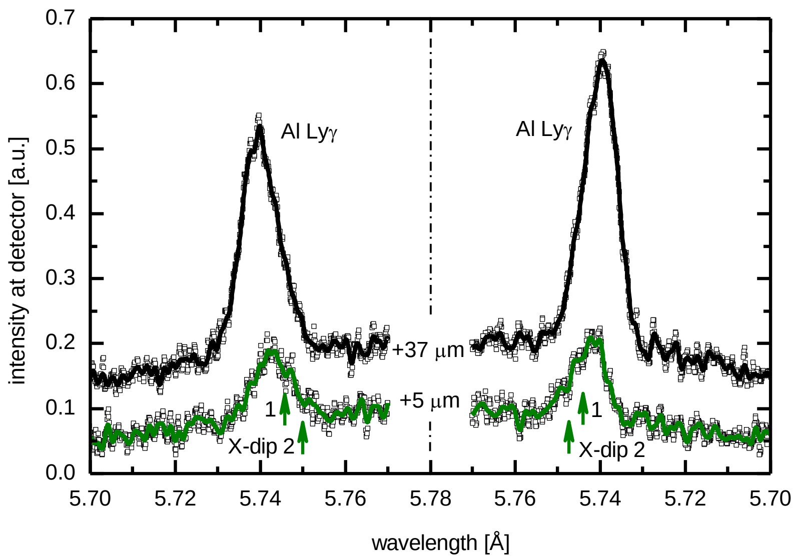

Figure 4. Reproducible X-dips structure in the mirror-symmetric Al Lyγ profiles (cf. figure 2) observed at marked distances from the C surface.

The detailed spectra of the Al Lyγ emission from the near-wall region are shown in figure 4. Their most exotic feature consists in the appearance of prominent depressions in the near red wing, whose separations from the line centres show a weak dependence on the distance from the target surface, and thus on n_e. This behaviour is characteristic for charge-exchange-caused dips (X-dips) [8,9]. Physically, X-dips correspond to anti-crossings of energy terms of the one-electron quasi-molecule of nuclear charges Z_1 and Z_2: anti-crossings enhance charge exchange. For the quasi-molecule $Al^{13+}eC^{6+}$, the analytic theory [8] predicts dip positions 3.1 mÅ and 6.7 mÅ; these values are in excellent agreement with the measured positions of both dips 3.1±0.2 mÅ and 6.6±0.2 mÅ, thus confirming conjecture about X-dips identification.

To conclude, the experiment performed at PALS is the first to yield with a high precision the X-dips positions in Al XIII Lyγ red wing. Their appearance in both mirror-symmetric parts of the spectra and their small density evolution, confirmed by the theoretical models, support the spectroscopic manifestations of charge-exchange phenomena in plasma-wall interaction.

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