Direct spectroscopic observation of ion deceleration accompanying laser plasma–wall interaction

O Renner¹, E Krouský¹, R Liska², M Šmíd³, O Larroche³, E Dalimier⁴,⁵ and F B Rosmej⁴,⁵

¹ Institute of Physics of the ASCR, Na Slovance 2, 182 21 Prague, Czech Republic
² Czech Technical University in Prague, FNSPE, 115 90 Prague, Czech Republic
³ CEA DIF, Bruyères le Châtel, 91297 Arpajon Cedex, France
⁴ Université Pierre et Marie Curie UPMC, LULI, UMR 7606, Paris, France
⁵ École Polytechnique, LULI, PAPD, Palaiseau, France

E-mail: renner@fzu.cz

Abstract. Interactions of plasma jets with solid surfaces are extensively studied in context with development of future fusion devices. In experiments carried out on the iodine laser system PALS, the energetic ions were produced at double–foil Al/Mg targets irradiated by one or two counter–propagating laser beams. The plasma jets from the rear surface of the laser–exploded Al foil streamed towards the Mg target representing the wall preheated by the action of the high–energy photons, particle and/or laser beams. Instead of being trapped by the cold secondary–target material, the forward–accelerated Al ions collided with the counter–propagating matter ejected from the wall. The environmental conditions in near–wall plasmas were analyzed with the high–resolution x–ray spectroscopy and temporally–resolved x–ray imaging. The deceleration of the incident Al ions in the near–wall region was directly observed and quantitatively characterized via Doppler shifts of the J–satellite from the Al Lyα spectral group. The interaction scenario was modelled using the 2D arbitrary Lagrangian Eulerian hydrocode PALE and the multifluid code MULTIF.

1. Introduction

The detailed knowledge of transient phenomena accompanying the interaction of plasma jets with surfaces of solid materials (hereafter plasma–wall interaction, PWI) is of paramount importance for numerous applications, starting from the construction of future fusion reactors and the design of sophisticated targets in indirect drive inertial confinement fusion schemes up to the astrophysics and laboratory experiments modeling various astrophysical situations (see e.g. [1] and references therein).

Due to the complexity of the problems studied, theoretical models of the PWI phenomena based on fluid hydrodynamic simulations, kinetic particle–in–cell approximations or their hybrids [2] provide only qualitative predictions of the shock formation induced by the ion impact and the subsequent plasma evolution. The acquisition of complex information on processes involved in near–wall plasma collisions depends mostly on the realization of well characterized experiments. In particular, laser–produced plasmas with a large span of selectable jet parameters (particle distribution, energy, degree of collimation) facilitate realization of diverse interaction regimes. Here we report precise x-ray spectroscopic measurements characterizing plasma interactions at laser–irradiated double–foil targets.
2. Experiment

The scheme of the experiment performed at the Prague iodine laser system PALS [3] is shown in figure 1. The double–foil targets consisting of two parallel foils of Al (thickness 0.8 µm) and Mg (thickness 2 µm) with a variable spacing were irradiated at normal incidence with one or two counter–propagating laser beams. These beams delivered 5–200 J of frequency–tripled radiation (0.44 µm) in a pulse length of 0.25–0.3 ns. Being focused to a diameter of 80 µm (main beam) or 50 µm (auxiliary beam), they yielded a maximum intensity of 1×10¹⁶ W/cm² on the target. The energetic plasma jets produced at the rear (non–irradiated) surface of the Al foil streamed towards the Mg target representing the wall preheated by the action of the high–energy photons, particle and/or laser beams. Thus instead of being trapped by the cold secondary–target material, the forward–accelerated Al ions collided with the counter–propagating matter ejected from the wall. In addition to the previously published results of the experiments with the single–side irradiated double–foil targets [4], here we concentrate on the evaluation of data obtained at foils separated by a distance of 600 µm and double–side irradiated by the laser energy of 115 J (Al foil) and 6 J (Mg foil).

The plasma interaction was monitored using a pinhole coupled to a low–magnification x–ray streak camera, optical spectroscopy and several x–ray spectrometers [5]. The time–resolved streak image presented in figure 2a demonstrates the temporally synchronized evolution of the plasma jets at both foils and, after approximately 1 ns, their strong interaction resulting in an enhanced x–ray emission from the plasma region close to the Mg foil. The primary diagnostic data was recorded using a vertical dispersion Johann spectrometer (VJS) fitted with the cylindrically bent crystal of quartz (100). The VJS provides simultaneously two sets of mirror–symmetric spectra [6]. The time–integrated spectrum shown in figure 2b is characterized by the high spectral (at the level of 8000) and 1D spatial resolution (8 µm) along the axis of the plasma jets expansion. By observing the plasma emission at an angle of ψ = 0.8º, i.e., in the direction almost parallel to the Al foil surface, the spectra integration over strong plasma gradients perpendicular to the foil surface was avoided.

Figure 1. Scheme of the plasma jet formation and spectra observation at laser–irradiated double–foil Al/Mg targets.

Figure 2. X–ray streak image of the plasma evolution at the two–side irradiated Al/Mg target (a) and the spatially resolved emission spectrum of the Al Lyα spectral group (b). The main laser beam irradiates the Al foil from above, the auxiliary beam strikes the Mg foil from below.
3. Results and discussion

The high–resolution spectra presented in figure 2b were used to derive the environmental conditions in the plasma interaction zone. The outer pair of the dominant spectral lines belongs to Lyα doublet of the hydrogenic Al, the inner pairs of lines are identified as dielectronic satellites 2l2l' → 1s2l' with the J–satellite closest to the axis of symmetry. The satellite–rich structure observed at the rear surface of the Al foil gradually reduces to the emission of the J–satellite only, the full satellite structure reappears near the Mg foil. This spectra behavior reflects the variable macroscopic parameters of the plasma jets. By comparing the experimental data with synthetic spectra produced by the collisional–radiative code MARIA [7], the effective plasma conditions corresponding to the Al Lyα group emission at the rear surface of the Al foil are characterized by the electron density \( n_e = (3–5) \times 10^{21} \text{ cm}^{-3} \), temperature \( T_e = 300 \text{ eV} \), and the photon path length \( L = 200 \mu\text{m} \). Close to the midplane, the plasma parameters are best fitted by \( n_e = 5 \times 10^{20} \text{ cm}^{-3} \), \( T_e > 700 \text{ eV} \), and \( L = 350 \mu\text{m} \), whereas in the interpenetration region close the Mg foil surface the plasma conditions are \( n_e \sim 3 \times 10^{21} \text{ cm}^{-3} \), \( T_e \sim 220 \text{ eV} \), and \( L \sim 500 \mu\text{m} \).

The validity of this interpretation of the observed spectral profiles was confirmed by theoretical modeling. An example of the results obtained by the Prague Arbitrary Lagrangian Eulerian hydrocode PALE [8] is shown in figure 3a. In this approach, after several steps of Lagrangian simulations the deformed moving mesh is reconstructed and the conservative quantities are remapped (Eulerian part) on to a smoother grid. Simulations indicate that already at time \( t = -150 \text{ ps} \) before the laser maximum, the upper Al foil burns through and the Al internal energy starts to decrease (mostly being transformed into the kinetic energy of expansion) despite a progressive laser absorption at the border of the hole in the Al foil. The lower Mg foil burns through slightly later at \( t = -80 \text{ ps} \); around this time, the compression of the counter–streaming plasmas attains its maximum and afterwards the plasmas between the foils start to expand in the radial direction \( r \). After \( t = 50 \text{ ps} \), the axial kinetic energy of Al ions starts to decrease, the Al plasma expansion in the direction of the laser axis is gradually slowed down by the counter–propagating Mg plasma.

The interpenetration of the Al and Mg ions was simulated with the multifluid code MULTIF [9]. MULTIF computes the hydrodynamics of an arbitrary number of the ion specii on a common Eulerian grid in the presence of a neutralizing electron background, and takes into account the interactions among all ion and electron fluids due to Coulomb collisions through slowing–down and heating terms. The geometry is 1.5–dimensional, with the main spatial resolution axis along the intertarget distance and a self-similar expansion model in the transverse directions. Each individual ion species is tracked by means of pseudo–Lagrangian markers, whose motion for the case of the Al ions interaction with the cold Mg foil is displayed in figure 3b. The trajectories of the fluid elements evidence regions where the Al and Mg plasmas interpenetrate and/or stagnate with respect to each other.

![Figure 3](image-url)
The region close to the Mg foil is of particular interest for studying the effects of the ion–wall interaction and plasma interpenetration phenomena. The presence of the Al emission near and below the Mg foil provides a clear evidence of the plasma interpenetration. Moreover, the distinct frequency shifts of spectral lines, which are clearly seen in figure 2b, provide an unique opportunity to measure precisely the ion deceleration via Doppler effect. The analysis of the frequency shifts measurements [1] indicates that the optically thin Al J–satellite is a suitable candidate for the visualization of the Al ion stopping. The previous experiments with single–side irradiated double–foil targets revealed almost monotonically decreasing red shifts of the J–satellite with the decreasing distance from the Mg foil [4]. This J–satellite behavior agrees with the expected stopping of the Al ions at the Mg foil.

The more complicated dependence of the ion deceleration close the wall was found in plasmas produced at the double–side irradiated Al/Mg targets. The velocity distribution of the Al ions follows from the above described simulations. Starting from the inner foil surface, the Al ions are accelerated until the zone of the intense plasma interaction; this results in the shift of the J–satellite to red. After passing a distance of about 250 μm from the Mg foil, the Al ion deceleration reveals in the decreasing Doppler shifts. The conversion of the observed shifts to ion velocities is shown in figure 4. Assuming the gradual deceleration and simple trapping of the Al ions at the Mg surface, the velocities should monotonically decrease to zero. In contrast, their detailed spatial distribution exhibits oscillations and even negative values which reflect the more complicated scenario of the ion deceleration including the ion back–scattering. The detailed interpretation of this phenomenon based on rigorous 2D description of the interpenetrating plasmas and post-processing of the hydrodynamic data is in progress.

Acknowledgments
This research was supported by the Czech Science Foundation Grant No. P205/10/0814 and the CNRS PICS project No. 4343. The experiments and their simulations were performed under the patronage of the Czech Ministry of Education, Youth, and Sports projects No. LC528 and 6840770022. The authors gratefully acknowledge the assistance of the PALS staff in performing the experiments.

References
[1] Renner O, Liska R and Rosmej F B 2009 Laser Part. Beams 26 in print
[2] Evans R G 2006 High Energy Density Physics 2 35–47
[3] Jungwirth K et al. 2001 Phys. Plasmas 8 2495–501
[4] Renner O et al. 2007 High Energy Density Physics 3 211–7
[5] Rosmej F B et al. 2006 Europhys. Lett. 76 815–21
[6] Renner O et al. 1997 Rev. Sci. Instrum. 68 2393–403
[7] Rosmej F B 2001 Europhys. Lett. 55 472–8
[8] Liska R., Limpouch J, Kucharik M and Renner O 2008 J. Phys.: Conf. Series 112, 022009
[9] Chenais-Popovics C et al. 1997 Phys. Plasmas 4 190–208