Applications of low-density foams for X-ray source studies
and laser beam smoothing

J Limpouch\textsuperscript{1}, O Renner\textsuperscript{2}, N G Borisenko\textsuperscript{3}, D Klír\textsuperscript{1}, V Kmetík\textsuperscript{4}, E Krousky\textsuperscript{2},
R Liska\textsuperscript{1}, K Mašek\textsuperscript{2}, W Nazarov\textsuperscript{5} and J Ullschmied\textsuperscript{4}

\textsuperscript{1}FNSPE, Czech Technical University in Prague, 115 19 Prague 1, Czech Republic
\textsuperscript{2}Institute of Physics, ASCR, Na Slovance 2, 182 21 Prague 8, Czech Republic
\textsuperscript{3}P. N. Lebedev Physics Institute, Russian Academy of Sciences, Moscow, Russia
\textsuperscript{4}Institute of Plasma Physics, Za Slovankou 3, 182 00 Prague 8, Czech Republic
\textsuperscript{5}School of Chemistry, University of St. Andrews, St. Andrews, Fife KY16 9ST, UK

limpouch@ishtar.fjfi.cvut.cz

Abstract. Layers of low density porous materials offer various applications in laser plasma interaction experiments. Two experimental studies of laser-foam interaction are presented. Firstly, time-integrated and time-resolved transmission of the laser beam through a layer of underdense plastic TAC (C\textsubscript{12}H\textsubscript{16}O\textsubscript{8}) foam was measured. The data are required for the design of dynamic smoothing of inhomogeneities inside a laser beam by its propagation through an underdense foam. Secondly, emission of K-shell lines from TMPTA (C\textsubscript{15}H\textsubscript{20}O\textsubscript{6}) foams of density 10 and 20 mg/cc doped by 10 or 20 weight % of chlorine was measured with a high spectral (>5000) and spatial (<10 \(\mu\)m) resolution. The demonstrated formation of a relatively thick homogenous plasma layer close to the foam surface may be used for atomic physics studies of multiply ionized dense plasmas.

1. Introduction

Detailed knowledge of laser interactions with low-density porous materials is important for foam employment in the target design that may significantly facilitate various applications of high power lasers. Foam layers may be used in direct drive inertial fusion targets to improve implosion symmetry [1]. Also ignition hohlraums may be filled with a low-density foam [2]. Alternatively, transparent underdense foam layer may serve as a dynamic phase plate in order to randomize and partly wash out inhomogeneity patterns inside a laser beam [3]. Foam layers may also be utilized for ion acceleration by relativistic femtosecond laser pulses [4]. When foam with high-Z additions is irradiated by a laser, a quasi-homogeneous layer of relatively dense and hot plasma may be generated that can be used for atomic physics and X-ray spectroscopy studies [5] and in astrophysics dedicated experiments [6].

In the first part of this paper, measurements of the laser light transmission through variable-thickness-layers of underdense foams (i.e. electron density \(n_e\) in the fully ionized homogenized foam is less than the laser critical density \(n_c\)) are presented. Aerogel 3D networks of cellulose triacetate (TAC – C\textsubscript{12}H\textsubscript{16}O\textsubscript{8}) with a typical pore size in the range of 0.5-3 \(\mu\)m [7] were used in this study that can both enlighten laser-foam interaction physics, and also investigate the inevitable loss of laser energy when foam is applied as a dynamic random phase plate for laser beam smoothing [3].

Secondly, preliminary results of our recent experiment studying X-ray emission in the vicinity of...
Cl He-α and Ly-α lines from chlorine-doped TMPTA (C15H20O6) aerogel foams [8] are presented. These foams with submicron pore size homogenize very quickly and a relatively thick, nearly homogeneous hot plasma layer is formed that may be used for atomic physics studies or, alternatively, as a well-characterized source of X-ray emission.

2. Laser transmission through underdense foams

Third harmonic (λ = 439 nm) of PALS iodine laser was incident normally on the foam surface placed 500 µm behind the best focus, and thus, the laser spot diameter on target was 300 µm and laser irradiances were in the range of I ≈ 10^{14} – 10^{15} W/cm². The TAC targets with densities 2.25, 4.5, and 9 mg/cm³ were deposited in 100, 200 and 400 µm thick washers. Optical streak camera and a calorimeter were used for measurement of the laser light transmission through the foam targets. Measurements with foams were related to the transmission of the laser pulse through the detection channel under the absence of any foam in the washer, i.e., laser was transmitted through a bare inner washer hole with the diameter of ~2.5 mm. The calorimetric measurements indicated that slightly less than a half (40-50%) of the nominal laser energy (measured in front of the target chamber) is transmitted through the hole. This reduction of the laser energy incident on the target has not been explained yet, and thus we show the nominal laser energies in this paper.

Temporal shapes of laser pulses transmitted through foams are presented in Fig.1. In all shots, the laser pulse leading edge penetrated through the transparent foam up to intensity of 3×10^{12} W/cm², which was 0.5 - 1% of the maximum. At this intensity level, overdense plasma was formed at the pore walls and the laser light was reflected, scattered and absorbed in the foam. For a 100 µm-thick foam layer with the density of 4.5 mg/cm³ (n_e ≈ 0.25 n_c), a partial laser transparency was restored at 250 ps after the laser pulse maximum. The penetration is restored earlier for lower density foams when foam area mass (density multiplied by thickness) is constant (frame b). The speed of the laser penetration grows slowly with the laser intensity. Penetration of the laser pulse leading edge may be a disadvantage for ablation pressure smoothing, as the imprint is formed at the laser pulse rising edge.

The maximum laser transmission was approximately 60% for the 100 µm-thick layer of the foam with density 2.25 mg/cm³. Relatively high energy losses are related to short (~ 320 ps FWHM) laser pulses, losses may be acceptable for typical laser pulses of a few ns duration.

3. X-ray emission spectra from chlorine-doped foams

The emitted X-ray spectra provide an important diagnostic tool to infer local plasma parameters, par-
Figure 2: Side-on slit images of foam emission recorded by X-ray streak camera (logarithm of signal, photons above 1 keV). Laser pulse (320 ps FWHM, $\lambda=439$ nm) is incident from the top on the foam surface (Depth=0), where the laser spot diameter spreads to 0.3 mm (laser is focused at 0.5 mm above surface); (a) foam 10 mg/cm$^3$, 20 weight % of Cl, $E_L=157$ J; (b) foam 20 mg/cm$^3$, 10 % Cl, $E_L=161$ J.

The principle diagnostics used in this experiment was a vertical-geometry Johann spectrometer (VJS). The VJS disperses the radiation in a direction parallel to the axis of the cylindrically bent crystal, i.e., as a function of the vertical divergence angle $\phi$. The instrument provides two identical sets of spectra symmetrically disposed about the central wavelength $\lambda_0$ [9]. The VJS was fitted with a crystal of quartz (100) bent to a radius of 77.2 mm and the spectral resolution in the vicinity of the chlorine He-$\alpha$ or Ly-$\alpha$ lines was above 5000. The VJS observed the spectrum emitted in a direction parallel to the target surface, with the spatial resolution of 8 $\mu$m normal to it. A hole widening with angle of 45° was cut through the foam washer to provide view below the foam surface. Alternatively, the hole in washer faced the X-ray streak camera and the spectra below the foam surface were blocked out by the washer; in this configuration, the position of the foam surface could be determined with an accuracy better than $\pm 16\mu$m.

The X-ray streak images shown in Fig.2 demonstrate a faster deepening of the heated layer for the foam of density 10 mg/cm$^3$ ($n_{eh}\approx 0.6 n_c$) than for the twice denser foam. The emitting zone does not reach the foam rear side at 480 $\mu$m in any case.

The X-ray spectra, recorded by the VJS in the neighborhood of chlorine He-$\alpha$ and Ly-$\alpha$ lines, are presented in Fig.3. The foam surface is marked by the full white line while the dashed lines denote the borders of the spatially uniform emission region. The lineouts corresponding to the emission from the depth of 32 $\mu$m below the surface (position of the upper dashed line in Fig.3) in the left-hand parts spectra are plotted in Fig.4 and decomposed to individual spectral lines. Based on the He-$\alpha$ spectrum fitting of the intercombination line (y), satellites jkl, ad, and qr, and using the FLY code, the plasma

Figure 3: The processed X-ray spectra of VJS spectrograph. The line spectra are emitted by chlorine dopant (20 weight %) in TMPTA foam of density 10 mg/cm$^3$. Laser pulse (320 ps FWHM, $\lambda=439$ nm) is incident from the top on foam surface (Depth=0), where laser spot $\varnothing=0.3$ mm (laser best focus 0.5 mm above surface). (a) spectrum in vicinity of chlorine He-$\alpha$ line, $E_L=212$ J; (b) spectrum in vicinity of Ly-$\alpha$ line, $E_L=209$ J.
Figure 4: Decomposition of the emission spectra (a) in the vicinity of He-α line (Fig. 3a) in depth of 32 µm below the foam surface (w is the resonance He-α line, y is the intercombination line, n, m, q, r, d, a, k, j are Li-like satellites from 1s2l2l' levels, n=3,4 sats denote Li-like satellites from 1s2l3l' and 1s2l4l' levels (b) in the vicinity of Ly-α line (Fig. 3b) including Ly-α doublet and He-like satellites.

parameters at the distance of 32 µm below the foam surface are \( n_e = 3\pm 1 \times 10^{21} \text{ cm}^{-3} \) and \( T_e = 750 \pm 50 \text{ eV} \). Using the ratio of the He-like satellite 2p2p' D to the Li-like satellite jkl and estimating the plasma diameter for an opacity correction at 250 µm, the deduced plasma temperature is a bit higher (950 eV). Obviously, in this way the parameters of the heated foam plasma can be deduced from the line emission spectra. The comparison of the experiment with numerical simulations of the laser-foam interaction, as well as a more detailed analysis of the experimental results, including the impact of the foam density and the chlorine content, is being prepared for a publication.

4. Conclusions
The integral and time-resolved transmission of the laser beam through a layer of underdense plastic TAC (C_{12}H_{16}O_8) foam was measured. The laser pulse leading edge penetrated through transparent foam up to the intensity \( 3 \times 10^{12} \text{ W/cm}^2 \), then the transparency was stopped and it was partially restored with a delay depending on the foam density and thickness. The energy losses may be acceptable for homogenization of laser beams of ns durations by their propagation through underdense foams.

Emission of K-shell lines from chlorine doped TMPTA foams was measured with a high spectral (>5000) and spatial (<10 µm) resolution and plasma parameters were deduced. Formation of a relatively thick homogenous plasma layer below the foam surface was observed.

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