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Observation of multiply ionized plasmas with dominant bound electron contribution to the index of refraction

J. Filevich[a,*], J.J. Rocca[a], M.C. Marconi[a], S.J. Moon[b], J. Nilsen[b], J.H. Scofield[b], J. Dunn[b], R.F. Smith[b], R. Keenan[b], J.R. Hunter[b], V.N. Shlyaptsev[c]

[a]NSF ERC for Extreme Ultraviolet Science and Technology and Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA

[b]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

[c]Department of Applied Science, University of California Davis-Livermore, Livermore, CA 94451, USA

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Abstract

We report anomalous fringe shifts observed in soft X-ray laser interferograms of laser-created Al plasmas. This clear experimental evidence shows that the contribution of bound electrons can dominate the index of refraction of laser-created plasmas at soft X-ray wavelengths, resulting in values greater than 1. The comparison of measured and simulated interferograms shows that this results from the dominant contribution of low-charge ions to the index of refraction. This usually neglected bound electron contribution can affect the propagation of soft X-ray radiation in plasmas and the interferometric diagnostics of plasmas for many elements.

Keywords: Interferometry; Soft X-ray laser; Index of refraction; Plasmas; Anomalous dispersion

1. Introduction

In multiply ionized laser-created plasmas the index of refraction is usually calculated assuming that the contribution of bound electrons is negligible compared with that of free electrons. For

*Corresponding author.
E-mail address: rage@engr.colostate.edu (J. Filevich).

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example, in all plasma interferometry experiments to date that used soft-X-ray laser probes, the spatial distribution of the electron density has been obtained assuming that the index of refraction is determined by the density of free electrons [1–7]. In partially ionized plasmas, two color interferometry is often used to separate the contribution to the index of refraction of neutral atoms and free electrons [8].

In this paper we present soft X-ray laser interferometry data obtained with a picosecond 14.7 nm (84.4 eV) laser probe that shows clear evidence that bound electrons can dominate the index of refraction in the late stages of the evolution of an Al plasma created by a high-power laser. The interferograms show that the fringes, late in the plasma evolution, in the periphery of the plasma and close to the target surface bend toward the target. In the experiment, the direction of these fringe shifts is indicative of an index of refraction greater than 1 (hereafter referred as negative fringe shifts). In contrast, at earlier times all the fringes are observed to bend away from the target (positive fringe shifts). The observation of similar negative fringe shifts was previously reported from an independently realized Al laser-created plasma soft X-ray laser interferometry experiment at 13.9 nm [9]. Analysis of our data, with the assistance of hydrodynamic simulations, indicates that late in the plasma evolution the contribution of bound electrons dominates the index of refraction, causing the observed negative fringe shifts in the periphery regions of the plasma. Herein we expand on results previously published in Ref. [10]. The significance of the result goes beyond the particular case of aluminum, as this effect can strongly affect the index of refraction of many ionized materials at soft X-ray laser wavelengths and needs to be carefully considered when analyzing experiments.

2. Experimental setup

The experiment was performed using a transient 14.7 nm Ni-like Pd soft X-ray laser [11] combined with an amplitude division diffraction grating interferometer (DGI) [4,7]. The soft X-ray laser was pumped by two beams from a chirped pulse amplification laser, the Compact Multipulse Terawatt (COMET) system at LLNL that operates at 1054 nm. An X-ray laser output of a few 10's of μJ was achieved by optically pumping a polished Pd target with a sequence of a 600-ps long pulse (2 J, $2 \times 10^{11}\,\mathrm{W\,cm^{-2}}$) and a 5-J energy short pulse of 6.7 ps or 13 ps (FWHM) duration at an incident intensity of 6×10^{13} and $3 \times 10^{13}\,\mathrm{W\,cm^{-2}}$, respectively. Traveling wave line focus excitation was achieved using a reflection echelon that consists of seven flat mirror segments placed before the focusing optics. Each mirror segment was offset by 0.12 cm to introduce the traveling wave toward the output of the laser with a delay of 7.7 ps per step. This results in a phase velocity of c along the line focus length and ensures that peak gain conditions are experienced by the propagating X-ray laser photons. The horizontal angular divergence of the soft X-ray laser was measured to be 2.8 mrad. The near field and far field beam characteristics were studied and the laser parameters were optimized to obtain beam properties suitable to perform interferometry. The temporal properties of the X-ray laser have been recently measured with a fast X-ray streak camera under the same laser pumping conditions as the interferometry experiments [12]. For saturated X-ray laser output the X-ray duration is typically in the range of 4.5–5.2 ps. With the longer 13 ps pumping pulse, the measured X-ray duration is slightly longer at 5.9 ps [12]. Therefore, the interferograms obtained with this setup have picosecond resolution.