Journal of Quantitative Spectroscopy & Radiative Transfer 99 (2006) 225–237

Journal of Quantitative Spectroscopy & Radiative Transfer

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Measurement of carbon ionization balance in high-temperature plasma mixtures by temporally resolved X-ray scattering

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Accepted 26 April 2005

Abstract

We have measured carbon ionization balance in a multi-component plasma in the high-temperature, up to fully ionized, regime by spectrally resolved X-ray scattering. In particular, the measurements have been performed in an underdense ($n_e \approx 10^{21}\,\mathrm{cm}^{-3}$) 0.35-μm laser-produced plasma, containing a mixture of C, H with Al and Ar impurities, by using time-resolved back-scattered spectra from a 9.0 keV Zn He-α X-ray probe detected with a high-efficiency graphite Bragg crystal coupled to a framing camera. Measured values for the plasma temperature and carbon ionization state as well as impurity concentrations were obtained by fitting the Doppler-broadened and Compton-shifted scattered spectra at various times after the plasma heating with a modified X-ray form factor that includes the full effects of cross-correlation between different species. These data test collisional-radiative and radiation hydrodynamics modeling from cold ($T_e \lesssim 5\,\mathrm{eV}$) to fully ionized carbon ($T_e \sim 280\,\mathrm{eV}$).
Published by Elsevier Ltd.

PACS: 52.70.La; 71.10.Ca; 61.10.Eq; 52.38.−r; 52.27.Gr; 61.20.Ne

Keywords: Laser-produced plasmas; X-ray scattering; Equation of state

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0022-4073/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.jqsrt.2005.05.017

1. Introduction

X-ray scattering from solid density plasmas has recently been demonstrated for the characterization of low-Z warm and dense states of matter [1,2], as created in high-energy-density experiments relevant for inertial confinement fusion (ICF) [3] and found in the interior of stars and planets. Highly ionized, multi-component and high-temperature coronal plasmas are also found in ICF research. For example, they are found in laser-irradiated cavities (hohlraums) used for capsule implosions. The microscopic state of such plasmas can significantly modify the energy deposition and propagation of laser beams inside the hohlraum through the growth of non-linear instability modes [4], and, at the same time, have important effects on X-ray drive and capsule symmetry [3,5]. In this paper, we show that the electron-velocity distribution and thus the electron temperature in fully ionized plasmas can be non-invasively measured by X-ray scattering. In addition, we extend energy resolved X-ray scattering measurements to the mid-Z and high-temperature domain by developing an improved description of the X-ray differential cross section that also includes cross correlation effects in multi-component environments. This is important for the future development of high-energy probes of hohlraum and ICF capsule compressed plasma conditions.

Although present X-ray scattering experiments only approximate the high accuracy of temperature measurements demonstrated with optical Thomson scattering [6], they offer a complementary diagnostics capability of high-temperature plasmas with the possibility of probing at densities well above solid, and with negligible refraction [3]. Moreover, since X-ray scattering accesses a spatial scale length which is much shorter than the typical Debye length of such plasmas, it can directly access the electron distribution function [7], and it may be developed into a possible diagnostic of a non-Maxwellian velocity distribution function in laser-heated high-temperature plasmas.

The paper is structured as follows. In Section 2 we will present the relevant modifications of the scattering cross section to multi-component plasmas. Section 3 will be devoted to the description of the X-ray scattering experiments on carbon plasma mixtures and their interpretations. Concluding remarks will be given in Section 4.

2. Theory

Following the discussion in Ref. [8], we describe the scattering from a uniform plasma containing n_e electrons per unit volume. Let us now assume we probe such a system with X-rays of frequency ω_0. Neglecting photo-absorption, during the scattering process the incident photon transfers a momentum $\hbar\mathbf{k}$ and an energy $\hbar\omega = \hbar\omega_0 - \hbar\omega_1$ to the electron, where ω_1 is the frequency of the scattered radiation, and in the non-relativistic limit ($\hbar\omega \ll \hbar\omega_0$) $k = |\mathbf{k}| \approx 4\pi/\lambda_0 \sin(\theta/2)$, with λ_0 the probe wavelength and θ the scattering angle. We denote with Z_f the average number of kinematically free electrons per ion (i.e., electrons which are not bound to any single atom). Following the approach of Chihara [9,10], the scattering cross section is described in terms of the dynamic structure factor of all the electrons in the plasma. The