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# X-ray probe development for collective scattering measurements in dense plasmas

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## Abstract

X-ray spectra and conversion efficiencies of the laser-produced chlorine Ly-$\alpha$ and K-$\alpha$ line radiation have been investigated to develop X-ray probes for the collective scattering regime. The Ly-$\alpha$ radiation was produced by either smoothed or un-smoothed laser beams with nanosecond-long laser pulses yielding high conversion efficiencies of up to 0.3% sufficient for X-ray scattering measurements. However, the time-integrated measurements show a significant dielectronic satellite emission on the red wing of the primary Ly-$\alpha$ line which must be avoided to resolve the plasmon feature in the scattering spectra. We find no red wing emission features for ultra-short pulse laser produced K-$\alpha$ radiation. The bandwidth of $\Delta E/E = 2 \times 10^{-3}$ is suited for collective scattering, but the conversion efficiency falls short of the high values achieved for the Ly-$\alpha$. These findings indicate that present laser-produced X-ray sources will restrict the choice of detectors and plasma conditions for collective X-ray scattering from dense plasmas.
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## 1. Introduction

X-ray Compton scattering from solid density plasmas has recently been successfully developed [1,2] for temperature and ionization balance measurements in high energy density experiments relevant for inertial confinement fusion (ICF) and laboratory astrophysics studies [3]. In these experiments, high energy X-rays (4.75 keV), in a nearly backscattering geometry, were used as probe radiation accessing a correlation-length ($L$) in the plasma that is significantly smaller than the typical screening length. In a classical plasma, this parameter corresponds to the usual Debye length, while in dense systems that approach the degenerate state a characteristic screening distance $\lambda_s$ [4] is used. X-ray photons of wavelength $\lambda_0$ that interact with the electrons of the dense plasma change on average the initial momentum by $\hbar\mathbf{k}$ due to the Compton effect, where $k = |\mathbf{k}| \approx 4\pi/\lambda_0 \sin(\theta_s/2)$, with $\theta_s$ the scattering angle. Thus the condition $L = 1/k \ll \lambda_s$ describes scattering from uncorrelated particles and is usually referred to as *non-collective* scattering. Under these conditions, the measured scattering spectra from the free electrons in the plasma directly represent the electron velocity distribution function [4,5], with a width that is directly proportional to $\sqrt{T_e}$ for a Maxwell–Boltzmann distribution, or $\sqrt{T_F}$ for a Fermi-degenerated plasma, where $T_e$ and $T_F$ are the electron temperature and the Fermi temperature of the electrons, respectively.

Thus, present X-ray scattering experiments [1,2,6] measure directly the electron temperature, $T_e$, while the electron density, $n_e$ can be inferred from the relative intensity of the Compton downshifted peak to the unshifted Rayleigh peak. The former is due to free or weakly bound electrons with ionization energy $E_I$ smaller than the Compton energy, $E_I < \hbar^2k^2/2m_e$, while the latter is due to tightly bound electrons with $E_I > \hbar^2k^2/2m_e$. In this way, non-collective measurements allow direct validation of dense matter ionization balance models.

On the other hand, $T_e$ and $n_e$ measurements are only the first step for a full optical characterization of warm and dense matter. In particular, the frequency response of high density plasmas under an external disturbance, i.e., the dispersion function, $\varepsilon(k, \omega)$, is of extreme interest as it determines reflectivity and transmission as well as thermal and electrical conductivities, thus being a critical parameter characterizing the state of dense matter and dense plasmas. For these reasons, X-ray scattering measurements at smaller $k$ values are of great interest for characterizing $\varepsilon(k, \omega)$. In this case *collective* scattering with $1/k \gtrsim \lambda_s$ provides frequency resonances, the so-called plasmon modes, [7,8] which are directly related to the electron plasma wave propagation and the optical properties of the plasma.

The aim of this investigation is to develop the capability to perform forward X-ray scattering experiments in the collective regime to observe plasmon resonances in warm and dense plasmas. The implementation of this diagnostics imposes strict requirements on the spectrometer resolution and efficiency, the X-ray probe bandwidth, as well as on the total X-ray probe fluence. For typical plasmas compressed above solid density, the plasmon peak is downshifted in energy with respect to the probe line by 20–60 eV. This small energy shift requires a small X-ray probe bandwidth of order $\Delta E/E = 2 \times 10^{-3}$ to resolve the shifted plasmon peak and the unshifted inelastic scattering feature. Previously used He-$\alpha$ X-ray line sources [1] are thus not applicable because the close proximity of the intercombination line (the triplet–singlet transition in highly ionized helium-like atoms) and dielectronic satellites result in an effective He-$\alpha$ source width of $\Delta E/E \approx 10^{-2}$. To overcome the problem of source bandwidth we have pursued the use of (1) high-energy laser