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Imaging scattered x-ray radiation for measurement of local electron density in high-energy-density experiments

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ABSTRACT

Imaging high-energy-density systems with scattered x-ray photons has several unique characteristics that differentiate it from the transmission radiography methods that have traditionally been used to diagnose these experiments. Because x-ray photons scatter primarily from the plasma electrons, the degree of scattering from any point in a target is roughly proportional to the electron density at that point. By constraining the directions of incident and scattered photons, the scattering event can be localized, resulting in a point-wise, internal map of the target electron density. Additionally, a scattering experiment is not restricted to the collinear source-target-detector geometry of transmission radiography. This flexibility allows for multiple detectors to image light from a single source, though potentially at different scattering angles or energy bands. Presented in this paper is the theoretical underpinning for scattered x-ray imaging, as well as a description of an upcoming proof-of-principle experiment to be conducted at the OMEGA Laser Facility.

1. Introduction

X-ray radiography has been used successfully as a diagnostic for high-energy-density (HED) experiments for several years [1–10]. Images of both radiative shocks and hydrodynamic instability experiments have yielded information relevant to astrophysical processes [11]. Recent examples of such experiments, conducted at the Omega laser at the University of Rochester (Rochester, NY), involve an x-ray source in the few keV range backlighting an experimental target package [12,13]. The Omega facility has also been used for an extensive range of Thomson scattering experiments, where scattered radiation is spectroscopically resolved and plasma features including electron temperature, electron density, and ionization state of shock compressed materials have been measured [14–16]. Such experiments have shown that, using moderate energy x-rays (4–10 keV), one can probe dense matter, up to 10^{24} g/cm^2, which will be necessary to diagnose the experiments that will be possible on the National Ignition Facility (NIF) [17]. These successes with scattered x-ray spectroscopy suggest that it may be possible also to employ two- dimensional imaging, which could have numerous advantages over the traditional transmission imaging.

The principle of using scattered light to image a structure was proposed several decades ago in the context of medical imaging of internal tissue [18]. These first experiments used exposure times of tens of hours to create the image, a fact which highlights the difficulty of the present nanosecond-scale diagnostics. Still, the numerous advantages to scattered x-ray imaging suggest it maybe a valuable tool in the challenging HED diagnostic environment. Because x-ray scattering occurs primarily as a result of photon interactions with plasma electrons, the degree of scattering is an approximate measure of electron density for a given volume in a target. If one can neglect multiple scattering, as is often justified, this localized interaction, with incident and scattered photon paths being defined and measured, respectively, allows one to make density measurements of internal structures. This is advantageous in many HED target geometries where relevant internal structure may be obscured by regions of higher attenuation when employing path-integrated transmission radiographic methods. Additionally, because scattering involves a change in direction of the incident radiation, multiple detectors can leverage a single x-ray source and can be located at a range of angles, granting greater flexibility in experimental design.

Scattered x-ray imaging presents numerous challenges beyond those of transmission radiography. The process of image formation is complicated by several physical processes that are not present in transmission radiography, where the only unknown parameter is the integrated absorption though a known distance of

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(inhomogeneous) material. For scattered x-ray imaging, an equivalent attenuation factor must be calculated along two unknown paths, where the vertex exists at the point of scattering. Moreover, because the total number of scattered photons is significantly reduced, relative to the number transmitted, the requirements of the x-ray source for these experiments are more stringent. However, with the laser power available on megajoule-class lasers such as the NIF, the prospects of scattered-light imaging may become feasible.

2. Scattering theory

To obtain a map of electron density, the probing photons must interact with individual particles such that the scattered flux is proportional to electron density. This is the incoherent scattering regime and is accessed when the scattering parameter is much less than unity [19]. Designated α, the scattering parameter is

$$\alpha = \frac{\lambda_\mathrm{i}}{4\pi\lambda_\mathrm{D}\sin(\theta/2)}, \tag{1}$$

where λ_i is incident wavelength, θ is the scattering angle, and λ_D is the Debye length of the system under investigation. The scattering parameter must be a small fraction of unity to ensure that scattered photons are not interacting with bulk plasma features [20]. For reasons discussed in the following sections, a higher energy x-ray source is often preferable, which serves to ensure this parameter is small. The applicable theory in the hard x-ray regime is the quantum-correct theory of Klein and Nishina, so for generality we will discuss the kinematics of the scattering process beginning with the Klein–Nishina formula for photon scattering differential cross-section. From Hussein ([21], Chapter 3) the Klein–Nishina formula is

$$\frac{d\sigma_\mathrm{e}(E,\Omega)}{d\Omega} = r_\mathrm{o}^2\left(\frac{1+\cos^2\theta}{2}\right)\left[\frac{1}{1+\alpha(1-\cos\theta)}\right]^2 \times \left(1+\frac{\alpha^2(1-\cos\theta)^2}{[1+\alpha(1-\cos\theta)](1+\cos^2\theta)}\right), \tag{2}$$

which represents the probability per electron of a photon scattering at angle θ into solid angle $d\Omega$, where $\alpha = E_\gamma/m_\mathrm{e}c^2$ and $r_\mathrm{o}^2 = 2.62\times10^{-13}$ cm is the classical electron radius.

In the limit of low photon energy ($\alpha\rightarrow0$) and integrated over all scattering angles θ, Eq. (2) reduces to the classical Thomson cross section: $\sigma_T = \frac{8\pi}{3}r_o^2 = 6.65\times10^{-25}$ cm^2. In the free-free scattering event described by Eq. (2) the electron can recoil, absorbing energy and leading to a downshift in photon energy given by the Compton formula

$$E' = \frac{E}{1+\frac{E}{m_\mathrm{e}c^2}(1-\cos\theta)}. \tag{3}$$

This energy shift is the basis for many of the Thomson scattering techniques which have been employed as HED experimental diagnostics. Future imaging x-ray experiments using multiple cameras may also be able to employ K-edge filters to take advantage of this energy shift to gain information about the ionization state of the target plasma. However, in the current experiment no spectral resolution will be available and Compton shifted radiation from free electrons will be indistinguishable from photons scattered off tightly bound atomic electrons. In such a bound–bound collision, both the differential scattering cross section and the energy of the scattered photon are modified by the electron binding energy. Because the momentum balance now involves the heavy atom, the energy of the scattered radiation is nearly equal to that of the incident radiation. To account for the binding energy in the scattering cross section, a multiplicative scaling factor is used

$$\frac{d\sigma_\mathrm{e}^\mathrm{B}(E,\Omega)}{d\Omega} = \frac{d\sigma_\mathrm{e}(E,\Omega)}{d\Omega}S(q,Z), \tag{4}$$

where the superscript 'B' indicates the modified differential cross section of the bound electrons. They are modified by the incoherent scattering factor $S(q,Z)$, where q is the momentum transfered from photon to electron and Z is the number of bound electrons. Values of $S(q, Z)$ have been extensively studied and tabulated for many elements from Z from 1 to 92 (Uranium) [22–26]. The limits of $S(q, Z)$ range from zero, representing complete photoabsorption (no scattering) to a maximum of Z [21] .

Evidently the detectable signal from any given region in the scattering volume is proportional to the total (bound and free) electron density. This is given by

$$n_\mathrm{e} = \frac{\rho Z}{Am_\mathrm{p}}, \tag{5}$$

where ρ is mass density, A is atomic mass and m_p is the proton mass. Taking $Z/A\approx\frac{1}{2}$ for elements other than hydrogen, this imaging system would probe changes in mass density. Initial experiments will attempt to distinguish a simple boundaries between materials, though future experiments might hope to leverage this technique to investigate detailed structure within a plasma system.

3. Defining the forward problem

Any imaging application involves the correlation of measured quantities with theoretical parameters. To do this one must establish the forward problem, which maps the range of theoretical parameters into the observable, measured data. The function for total signal reaching the detector, N_{det} can be written as

$$N_\mathrm{det} = \frac{E_\mathrm{L}}{h\nu}\eta_x \times n_e L\sigma_s\tau_{\mathrm{i}(d)} \times \left(\frac{\Omega_\mathrm{scat}}{4\pi}\right)\eta_i \times \left(\frac{\Omega_\mathrm{det}}{4\pi}\right)\eta_s + M. \tag{6}$$

The first term is a measure of photon number, with E_L being laser energy, $h\nu$ is the energy of photons created, and η_x is the conversion efficiency associated with this process. The scattering process is quantified by the second term where n_e is electron density, σ_s is the microscopic (per electron) scattering cross section, L is the traversed length and the time fraction $\tau_{i(d)}$ represents the time that the incident x-ray emitter is radiating or the detector gating time, whichever is shorter.[1] The experimental geometry is accounted for by the solid angles, where Ω_scat must be calculated relative to the x-ray source, while Ω_det represents the detector solid angle relative to the scattering volume. The terms for absorption of both incident and scattered light, η_i and η_s respectively, and are indicated in Fig. 1. They are given by the Beer–Lambert Law and are functions of photon energy and material traversed

$$\eta_i = e^{-\int_{x_a}^{x_p}\sigma_\mathrm{tot}(E_i,x)n_e(x)dx} \tag{7}$$

[1] If the source "on" time and the detector gating time do not coincide, the value of τ must reflect only the overlap time between the two. Also, this analysis does not include finite rise-time considerations for x-ray sources, as the high fluence needed for this application will in the short term necessitate longer pulse lengths for x-ray sources.