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X-Ray Generation from Metal Targets Coated with Wavelength-Scale Spheres

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Abstract: X-ray yield measurements from targets coated with wavelength-scale spheres are compared with measurements from polished targets. Evidence for a hotter resonant electron temperature due to field enhancements from Mie resonances in the spheres is investigated.

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1. Introduction

A major application of plasmas produced by high-intensity laser pulses is the generation of short bursts of x-rays. For efficient hard x-ray (>few keV) production the acceleration of hot electrons from resonant absorption processes should be optimized. Recent experiments have demonstrated enhancements in x-ray yield achieved by using structured surfaces such as gratings [1], velvets [2], and nanoparticles [3].

In this paper, we investigate hard x-ray (>100 keV) generation from copper targets coated with a partially covering layer of microspheres. When a spherical object is illuminated with light of a wavelength, λ , similar to the diameter, d , of the object, a complicated electric field pattern arises due to interference between the incident and scattered waves. The interaction of an intense laser with such a target can generate a spherical plasma with non-uniform heating across its surface [4, 5]. For example, Fig. 1 displays the electric field pattern of a $1\mu\text{m}$ spherical plasma irradiated with $0.8\mu\text{m}$ laser light. In particular, when the size parameter $m = \pi d/\lambda \approx 1$, the system can experience a Mie resonance in which the electric fields are greatly enhanced. By depositing wavelength-length scale spheres across the surface of a metal substrate, we aim to exploit the Mie resonance to increase the temperature of the resonantly heated electrons which are responsible for the generation of hard x-rays.

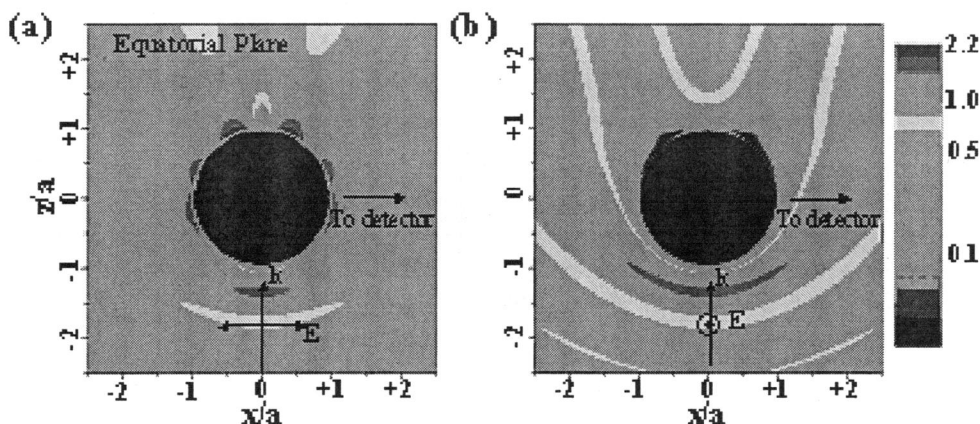


Fig. 1. Calculated electric field plot for an ionized, micron-diameter plasma sphere for laser polarization (a) parallel and (b) perpendicular to the page. The laser propagation direction is $+z$. Note the enhancement in the field visible in (a).

2. Target preparation

We prepared the targets using commercially available polystyrene spheres of diameter 0.26, 0.5, 1.0, 1.5 and $2.9\mu\text{m}$ with a size distribution of 3%, diluted with water to a concentration of $\approx 1:1000$, and applied to polished copper substrates. The solution was made more dilute for the smaller spheres to improve the consistency of the surface. We observed the target surfaces using a scanning electron microscope (SEM) to ascertain the uniformity of the coating and to check the depth of the sphere layers. SEM images of copper coated with a $2.9\mu\text{m}$ sphere solution, shown in Fig. 2, at magnification of (a) 100x and (b) 5000x demonstrate that the spheres form a monolayer over a large area.

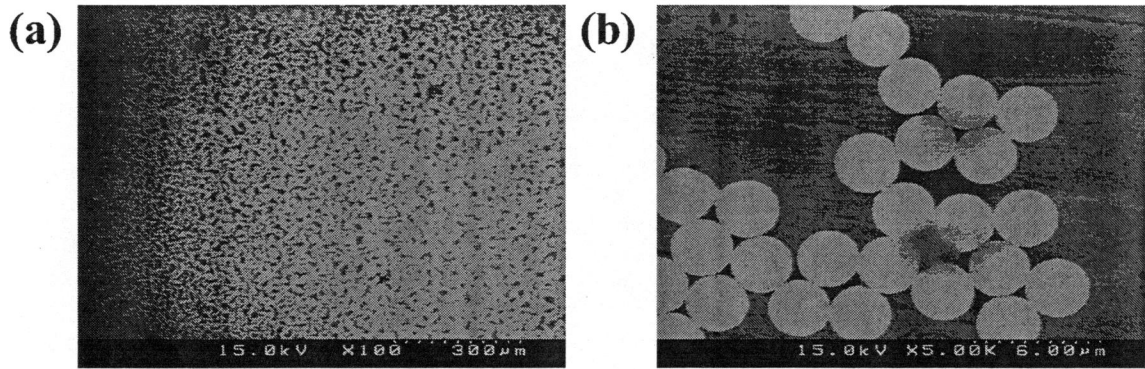


Fig. 2. Scanning electron microscope images of a copper substrate coated with $2.9\mu\text{m}$ spheres at (a) 100x and (b) 5000x magnification. Note the uniformity of coverage in (a) and the size consistency shown in (a).

3. Experiment

We performed the experiment using the THOR laser system at the University of Texas which provided 35 fs pulses at a wavelength of 800 nm. The pre-compression energy was set at ≈ 68 mJ yielding a focal intensity $\approx 1 \times 10^{18}$ Wcm $^{-2}$. This limit was required to avoid saturation of the x-ray detectors.

X-ray emission from the plasma was observed using six filtered NaI scintillation detectors arranged around the target chamber. The filters were composed of 125 mm Al (450 keV), 12 mm Cu (162 keV), 32 mm Cu (500 keV), 43 mm Cu (600 keV), 24 mm Pb (700 keV) and 44 mm Pb (900 keV), where the bracketed values are the $1/e^2$ cutoff energies of each filter after accounting for any extra material between the detector and the target.

Ion emission from the front surface of the target was measured using a charge collector (Faraday cup) at a distance of 0.20 m behind a mesh biased at -300V to reduce the emission of secondary electrons from the detector surface. A magnetic field of 1 kG was placed ≈ 1 cm in front of the collector to deflect electrons.

4. Results

We irradiated polished copper targets at laser incidence angles between 0° and 45° from the target normal to ascertain the optimum angle for hard x-ray production under our conditions. The maximum x-ray emission occurred for an incident angles $\approx 10^\circ$ - 20° suggesting that the dominant mechanism for hot electron generation was resonance absorption. The signal levels reduced towards 45° indicating that vacuum heating was inefficient. This was probably due to the formation of a preplasma caused by the interaction of a low level prepulse.

X-ray yields and ion spectra from polished copper targets were then directly compared to sphere coated copper targets at incidence angles of 0° , 10° , 24° and 45° . Initial results using $2.9 \mu\text{m}$ spheres are shown in Figs. 3 and 4. Fig. 3 shows the x-ray yield through the 32 mm Cu filter corresponding to an integrated signal of photon energies above ≈ 500 keV. The sphere-coated targets display a clear enhancement in yield at all four angles of incidence of the laser beam, even where resonance absorption is expected to be optimized in the polished copper target. This suggests that the presence of the spheres not only modifies the target surface allowing resonant processes at off-resonant angles but also increases the magnitude of the driving fields through an interference effect (Mie resonance) as predicted. We note that the size parameter for these spheres is relatively large, $m=11$, so the effect for smaller spheres should be even more significant.

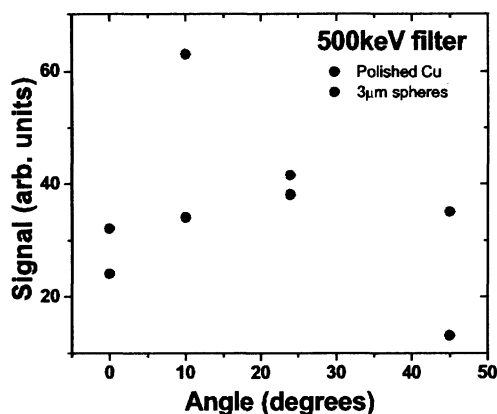


Fig. 3. Hard x-ray yields versus angle of incidence of the laser beam for polished copper targets and 2.9 μm sphere coated copper targets.

Time-of-flight (TOF) traces from polished copper and 2.9 μm sphere-coated copper, shown in Fig. 4, for an incident angle of 45° differed considerably. The earliest time we could resolve after the photon and hot electron burst was $\approx 1.12\mu\text{s}$. This TOF corresponds to protons of energy ≈ 200 eV, below which protons would be deflected by the 1 kG magnetic field. The maximum visible energy of ≈ 10 keV (assuming the ion mass of copper) is too low considering the much higher electron energies implied by the x-ray measurements. This suggests that we only see the colder ions from a distribution driven by two electron temperatures [6]. It is likely that the TOF trace from the sphere targets is predominantly carbon and oxygen whereas the signal from the metal may contain all three species (since contaminants will be present [7]). However, when we irradiated copper coated with a thin plastic film (13 μm), no ion signal was visible implying that the entire trace shown is due to copper ions. This would imply a significant shift in the thermal temperature of the plasma between the two cases and an energy spectrum calculated assuming that all the signal comes from copper ions is shown in the inset.

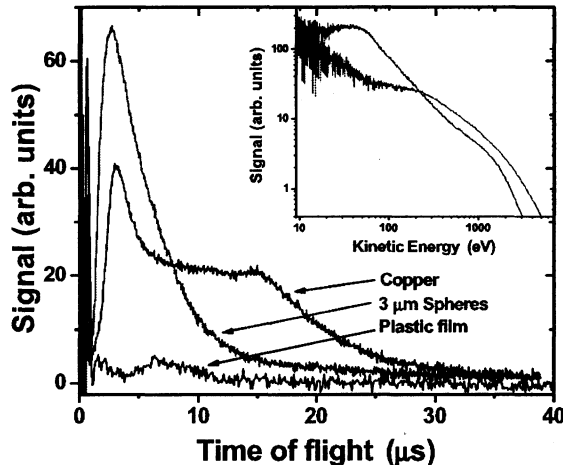


Fig. 4. Time-of-flight traces for polished copper targets and 2.9 μm sphere coated copper targets. (Inset) Kinetic energy spectra assuming Cu ions.

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