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Energetic electrons driven in the polarization direction of an intense laser beam incident normal to a solid target

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ABSTRACT

Experiments were performed at the LLNL Titan laser to measure the propagation direction of the energetic electrons that were generated during the interaction of the polarized laser beam with solid targets in the case of normal incidence. The energetic electrons propagated through vacuum to spectator metal wires in the polarization direction and in the perpendicular direction, and the K shell spectra from the different wire materials were recorded as functions of the distance from the laser focal spot. It was found that the fluence of the energetic electrons driven into the spectator wires in the polarization direction compared to the perpendicular direction was larger and increased with the distance from the focal spot. This indicates that energetic electrons are preferentially driven in the direction of the intense oscillating electric field of the incident laser beam in agreement with the multiphoton inverse Bremsstrahlung absorption process.

1. Introduction

Soon after the invention of the laser, it was realized that with sufficiently high laser intensity, atoms that are irradiated by the laser beam would be quickly ionized and the resulting free electrons would be accelerated to relativistic energies during a single cycle of the oscillating electric field of the laser beam [1]. From a classical physics point of view, the quiver energy of the oscillating electron is converted to directional energy during a collision with a nucleus [2]. From a quantum mechanical viewpoint, as illustrated schematically in Fig. 1, the electron absorbs multiple laser photons during the collision with a nucleus, the inverse of Bremsstrahlung emission, and the process was named multiphoton inverse Bremsstrahlung absorption (MIBA) [3]. The rate of energy increase is the product $\varepsilon_q \nu_{eff}$ where $\varepsilon_q = e^2E^2/2m\omega^2$ is the quiver energy, ν_{eff} is the effective collision frequency with the nucleus, E is the strength of the electric field having oscillation frequency ω, e is the electron charge, and m is the relativistic electron mass [4]. In the classical limit of small ħ, the reduced Planck constant, the quantum and classical expressions for the collision frequency agree except for a numerical factor of order unity [3].

A signature of the MIBA process is that the highest probability for multiphoton absorption occurs when the electron propagates perpendicular to the laser beam and in the polarization direction of the electric field after the collision with the nucleus [3]. In the case of oblique incidence, other laser–plasma interaction processes such as resonance absorption and other processes may act to accelerate electrons in the laser propagation direction and to expel electrons from the focused laser volume in all directions including the polarization direction [5], and electron jets in the *s* polarization direction of femtosecond laser pulses incident at 45° to the target surface were reported in Reference 6. In the case of normal incidence, no process other than MIBA selectively and efficiently accelerates energetic electrons in the polarization direction perpendicular to the laser beam and parallel to the target surface.

The selective acceleration of electrons in the polarization direction during the interaction of a normal-incidence laser beam with a solid target, as determined from the relative intensities of the K-shell spectra from irradiated and spectator wires of various materials, was first observed in a qualitative sense during experiments at the LULI laser facility [7]. A plane-polarized, femtosecond laser beam having 10^{20} W/cm^2 intensity and 27 MV/μm electric field strength was focused onto a metal wire (gadolinium or tungsten) that was embedded in the surface of an aluminum target, and MeV

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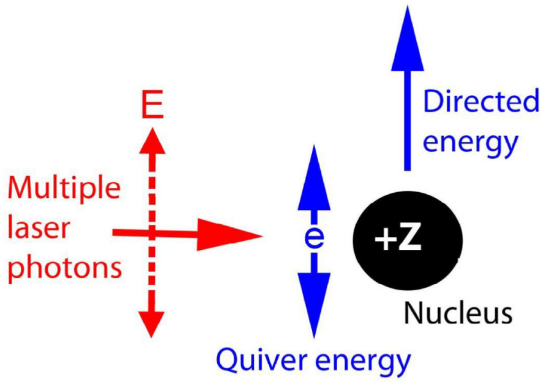

Fig. 1. Schematic of the multiphoton inverse Bremsstrahlung absorption (MIBA) process where an electron oscillating in the electric field E of an intense laser beam absorbs multiple photons during a collision with a nucleus having charge Z and propagates in the polarization direction with relativistic energy.

electrons were generated in the focal spot and propagated into the irradiated wire along the direction of the laser beam and also laterally to an embedded spectator wire of a different material (dysprosium or hafnium). The energetic electrons created 1s vacancies in both the irradiated and spectator wires, and the resulting time integrated K-shell spectra from the two different wire materials were recorded by a transmission crystal spectrometer. The ratio of the K-shell emissions from the irradiated and spectator wires is an indirect measure of the relative numbers of energetic electrons (normalized by emission rates and material properties) propagating in the forward direction of the laser beam and perpendicular to the laser beam. It was observed that more numerous energetic electrons were driven perpendicular to the laser beam than along the laser beam. In addition, it was observed that more numerous energetic electrons were driven in the polarization direction of the incident laser beam than in the perpendicular direction.

The present paper describes experiments utilizing laser-irradiated targets that are optimized for the quantitative study of the angular distribution of the energetic electrons propagating in the polarization direction and perpendicular to the polarization direction of the incident laser beam. The experiments were performed at the Titan laser facility at Lawrence Livermore National Laboratory. The Titan beam was incident normal to the face of the target shown in Fig. 2, and the electric field of the laser beam was plane-polarized in the vertical direction. The target was composed of a central irradiated wire that was positioned in a hole that was perpendicular to the face of a 3 mm aluminum cube. Arrayed about the central wire were four spectator wires that were pressed into grooves in the surface of the cube, two vertical wires of one material and two horizontal wires of a different material. The spectator wire diameters and groove widths were 0.5 mm, the groove depth was 0.5 mm, and the axes of the spectator wires were 0.25 mm below the plane of the cube surface. The central irradiated wire also had 0.5 mm diameter, and the tip of the central wire was 0.25 mm below the plane of the cube surface and on the axes of all four spectator wires. The tip of the irradiated wire and the ends of the spectator wires facing the irradiated wire were polished flat, and the separation gap between the ends of the spectator wires and the surface of the irradiated wire was varied on a sequence of laser shots. The laser beam was incident normal to the flat tip of the central wire (and to the face of the supporting target cube shown in Fig. 2), and the focal spot was positioned at the center of the wire as enabled by orthogonal viewing cameras. Thus energetic electrons that were generated in the focal spot propagated into the irradiated wire and laterally across the open gap to the four spectator wires.

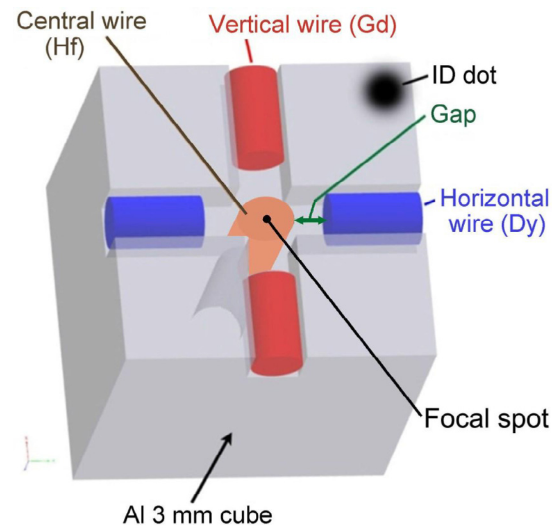

Fig. 2. The target showing the central irradiated wire, vertical wires in the direction of the polarization of the incident laser beam, and the horizontal wires in the perpendicular direction. The ID dot is an identification fiducial mark that was used to orient the target so that either the Gd wires or the Dy wires were vertical.

The central irradiated wire, the vertical wires, and the horizontal wires were of three different metals, for example Hf, Gd, and Dy as illustrated in Fig. 2. The energetic electrons accelerated from the focal spot propagated into the three wire materials and generated 1s vacancies and K-shell spectra that were recorded by a transmission crystal spectrometer. The ratios of the Kα spectral lines from the three materials indicated the relative numbers of energetic electrons propagating into the irradiated, vertical, and horizontal wires. In particular, the ratio of the Kα lines from the vertical and horizontal wires is a measure of the relative numbers of electrons propagating in the laser beam's polarization direction (vertical) and perpendicular to the polarization direction (horizontal).

The target is designed to mitigate laser shot-to-shot variations and other experimental uncertainties. For example, the emissions from the two vertical wires are summed as are the emissions from the two horizontal wires, and this mitigates small mis-positioning of the focal spot on the central wire: if the focal spot is off center toward a particular wire, then the emission from that wire would be stronger, the emission from the opposite wire of the same material would be weaker, and the sum of the emissions from the two wires would vary slowly with the off-center distance. In addition, the spectator wire materials are Gd and Dy, which have similar atomic numbers (64 and 66) and material properties, and the small differences in material properties such as energetic electron stopping power and Kα radiation generation tend to cancel out when taking the ratio of the emissions from the Gd and Dy wires. The normalizations used to relate the ratios of the x-ray emission signals from the irradiated and spectator wires to the ratios of the energetic electron fluences propagating in the irradiated and spectator wires are discussed below.

2. Experimental results

The experimental setup and the related study of the ranges of energetic electrons propagating from an irradiated wire through various materials to spectator wires are described in Reference 8. The Titan pulse typically had approximately 100 J energy, 1 ps duration, 10 µm focal spot diameter, and 10^{20} W/cm^2 focused intensity. Using orthogonal viewing cameras, the normal to the face of the target was oriented to be within 8° of the incident Titan laser beam.