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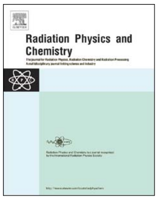

Photon dose estimation from ultraintense laser–solid interactions and shielding calculation with Monte Carlo simulation

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ABSTRACT

When a strong laser beam irradiates a solid target, a hot plasma is produced and high-energy electrons are usually generated (the so-called “hot electrons”). These energetic electrons subsequently generate hard X-rays in the solid target through the Bremsstrahlung process. To date, only limited studies have been conducted on this laser-induced radiological protection issue. In this study, extensive literature reviews on the physics and properties of hot electrons have been conducted. On the basis of these information, the photon dose generated by the interaction between hot electrons and a solid target was simulated with the Monte Carlo code FLUKA. With some reasonable assumptions, the calculated dose can be regarded as the upper boundary of the experimental results over the laser intensity ranging from 10^{19} to 10^{21} W/cm^2. Furthermore, an equation to estimate the photon dose generated from ultraintense laser–solid interactions based on the normalized laser intensity is derived. The shielding effects of common materials including concrete and lead were also studied for the laser-driven X-ray source. The dose transmission curves and tenth-value layers (TVLs) in concrete and lead were calculated through Monte Carlo simulations. These results could be used to perform a preliminary and fast radiation safety assessment for the X-rays generated from ultraintense laser–solid interactions.

1. Introduction

A hot plasma is produced when an ultraintense laser beam focuses on a solid target. Laser–plasma interactions subsequently accelerate the electrons in the plasma to relativistic energies through various physical processes such as J×B heating (Kruer and Estabrook, 1985; Pukhov and Meyer-ter-Vehn, 1998), resonance absorption (Forslund et al., 1977), vacuum heating (Brunel, 1987), and skin-layer heating (Bauer and Mulser, 2007). The generated hot electrons have a Maxwellian-type distribution characterized by an electron temperature T (Wilks and William, 1997; Beg et al., 1997; Haines et al., 2009). The interaction of these relativistic electrons with atoms of a solid target produces X-rays through the Bremsstrahlung process. In the last decade, many research groups (Guo et al., 2001; Magill et al., 2003; Chen et al., 2004; Courtois et al., 2011, 2013) have studied the generation of laser-driven Bremsstrahlung X-rays and some applications such as flash radiography and transmutation of long-lived nuclides.

At the same time, an ionizing radiation hazard produced from the interaction between the high-intensity laser and a solid target has been observed. Measurements show that this type of ionizing radiation can produce significant radiation dose. Borne et al. (2002) reported that photon dose varied between 0.7 and 73 mSv near the chamber at a laser intensity of ~10^{19} W/cm^2 for 150 laser shots with energies ranging from 1 to 20 J on solid targets such as Au, Al, and Teflon. Clarke et al. (2006) measured photon doses of up to 43 mSv at 1 m per shot at a laser intensity of ~4×10^{20} W/cm^2 with ~230 J energy on 1-mm-thick gold target at the Vulcan Petawatt (PW) laser. Henderson et al. (2014) measured photon doses of up to 70 mSv at 1 m outside the target chamber at a laser intensity of ~2×10^{21} W/cm^2 with ~510 J total energy on 2-mm gold targets at the Texas PW laser.

However, the radiation protection research on this type of ionizing radiation is very limited. The photon dose generated by ultraintense laser–solid interactions was studied by Hayashi et al. (2006). They proposed an equation to estimate the photon dose as a function of the electron temperature, and assumed that the relationship between the electron temperature and the laser intensity is given by Wilks' scaling (Wilks and William, 1997). Recently, Liang et al. (2015) have compared the equation results with a series of measurements at Stanford Linear Accelerator Center National Accelerator Laboratory's Matter in Extreme Conditions (MEC) facility and Lawrence Livermore National Laboratory (LLNL)'s Titan laser system. They found that by

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using Wilks' scaling to determine the electron temperature, the equation results would overestimate the photon dose at least an order of magnitude for laser intensities $>10^{19}$ W/cm^2.

For mitigating the X-ray hazards at high-intensity laser facilities to an acceptable level, Allott et al. (2000) used mass attenuation coefficients of lead (0.0497 cm^2/g)and concrete (0.0228 cm^2/g) for the photon energy of 10 MeV, and calculated the shielding requirements for the peak intensity of 10^{21} W/cm^2 at the PW laser. Qiu et al. (2014) calculated the dose transmission curves in several typical shielding materials for electron temperatures of 0.4 and 1 MeV. Although the laser-driven X-ray hazard imposes new constraints on radiation safety at high-intensity laser facilities, a comprehensive shielding calculation has not been still found for the laser intensity range of 10^{19}–10^{21} W/cm^2.

In this study, extensive literature on the physics and properties of hot electrons has been reviewed, including the laser-to-electron energy conversion efficiency, hot electron spectrum, and electron divergence. On the basis of these information, the photon dose generated from ultraintense laser–solid interactions was simulated with the Monte Carlo (MC) code FLUKA (Ferrari et al., 2005). The variations in photon dose with the electron temperature, target material and thickness, and hot electron divergence were studied. The shielding effects of common materials including concrete and lead were also studied for the laser-driven X-ray source. The dose transmission curves and tenth-value layers (TVLs) in concrete and lead were calculated through MC simulations for electron temperatures of 1–10 MeV, which covered the laser intensity range of 10^{19}–10^{21} W/cm^2.

2. Source term

As discussed above, Bremsstrahlung photons are generated by hot electrons, which are accelerated due to the laser–plasma interactions. To estimate the photon dose and carry out radiation protection studies, it is essential to understand the properties of hot electrons, and three key factors that describe the electron source term are discussed in the following sections:

1. Laser-to-electron energy conversion efficiency.
2. Hot electron spectrum.
3. Hot electron divergence.

2.1. Laser-to-electron energy conversion efficiency

Laser-to-electron energy conversion efficiency is used to characterize the hot electron yield, which represents the fraction of laser energy on the target converted to the total energy of hot electrons. Although the data are not always conclusive and consistent, many experiments show that 10–50% of laser energy is converted to hot electrons over the laser intensity range of 10^{18}–10^{20} W/cm^2 (Key et al., 1998; Hatchett et al., 2000; Yasuike et al., 2001). On the basis of some experimental results, Hayashi et al. (2006) used the conversion efficiencies of 30%, 40%, and 50% for laser intensities of 3×10^{19}, 10^{20}, and 3×10^{20} W/cm^2, respectively. Recent experimental results show an enhanced conversion efficiency at intensities above 10^{20} W/cm^2, reaching 80% for 45° incidence, and 60% for the near-normal incidence (Ping et al., 2008).

2.2. Hot electron spectrum

The energy spectrum of electrons generated from an ultraintense laser hitting a solid target can be described as the relativistic Maxwellian distribution (Phillips et al., 1999; Yabuuchi et al., 2007; Tanimoto et al., 2009): $f(E)=E^2\exp(-E/T)/(2T^3)$, where E is the electron energy and T is the electron temperature. Other distributions (Hatchett et al., 2000; Pennington et al., 2000; Ewald et al., 2003; Mordovanakis et al., 2010) are sometimes used to fit the experimental data, such as the Boltzmann distribution, $f(E)=\exp(-E/T)/T$ or the Maxwellian distribution, $f(E)=2(E/\pi)^{1/2}\exp(-E/T)/(T^{3/2})$. It can be seen that regardless of the distribution used, the exponentially decreasing feature is well known, and T is the key parameter to characterize the exponentially decreasing slope of the electron spectrum.

Previous studies have shown that T is mainly dependent on the normalized laser intensity ($I\lambda^2$), which is the product of the laser intensity (I) and the square of the laser wavelength (λ) (for common amplifying mediums, Nd: glass and Ti: sapphire laser, λ values are 1.054 and 0.8 μm, respectively). Various scaling laws to determine the relationship between T and $I\lambda^2$ have been derived in the past two decades, such as Wilks' scaling [Eq. (1)] (Wilks and William, 1997), Beg's scaling [Eq. (2)] (Beg et al., 1997), and Haines' scaling [Eq. (3)] (Haines et al., 2009). Wilks' scaling was derived on the basis of the ponderomotive force theory. Beg's scaling was obtained with fits to the measurement data at intensities between 10^{17} and 10^{19} W/cm^2. Haines's scaling has been recently derived applying the energy and momentum conservation laws:

$$T = 0.511 \times [(I\lambda^2/1.37 + 1)^{1/2} - 1], \tag{1}$$

$$T = 0.215 \times (I\lambda^2)^{1/3}, \tag{2}$$

$$T = 0.511 \times \{[(2I\lambda^2/1.37)^{1/2} + 1]^{1/2} - 1\}, \tag{3}$$

where T is the electron temperature in MeV, I is the laser intensity in units of 10^{18} W/cm^2 and λ is the laser wavelength in μm.

H. Chen et al. (2009) compared these scaling laws with recent experimental results at laser intensities above 10^{19} W/cm^2, as shown in Fig. 1. The experimental results show the electron temperature increases as $(I\lambda^2)^{0.34}$, which agrees well with Beg's scaling $(I\lambda^2)^{0.33}$. It can also be seen that Haines' scaling is in close agreement with the experimental scaling over the relevant intensity range. However, the electron temperature determined by Wilks' scaling is higher than the experimental data at laser intensities $\geq10^{19}$ W/cm^2 μm^2. As the laser intensity reaches up to 10^{21} W/cm^2 μm^2, Wilks' scaling is approximately five to six times higher than the experimental scaling. The numerical simulations indicate that Wilks' scaling overestimates the electron temperature because the plasma electron density profile steepens by photon pressure at intensities $>10^{20}$ W/cm^2 (Chrisman et al., 2008). Hence, in this study, Haines' scaling is adopted to determine the electron temperature T.

2.3. Hot electron divergence

Hot electrons usually have a large divergence. Increasing the electron divergence increases the isotropic dose and decreases the

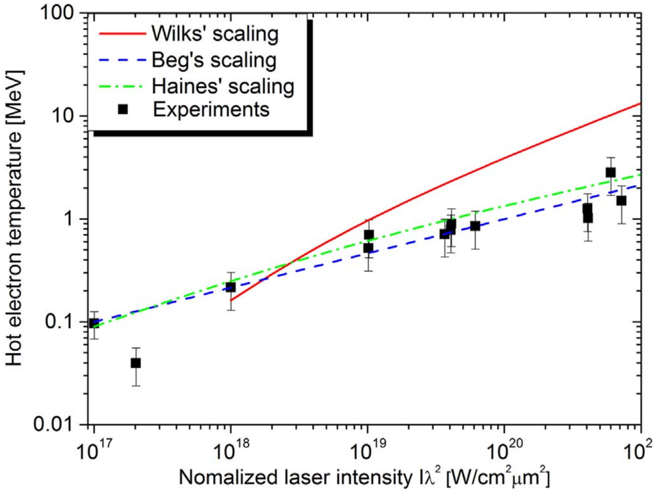

Fig. 1. Comparison of various temperature scaling laws and experimental data of T.