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PHOTON DOSE YIELD MODEL FOR HIGH-INTENSITY SHORT-PULSE LASER-SOLID EXPERIMENTS

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A photon dose yield model has been developed by the Radiation Protection group at SLAC National Accelerator Laboratory for high-intensity short-pulse laser-solid experiments between 10^{17} and 10^{22} W cm⁻². The model couples the particle-in-cell (PIC) plasma code EPOCH and the radiation transport code FLUKA to estimate the bremsstrahlung dose yield from laser-solid interactions. EPOCH characterizes the energy distribution, angular distribution, and laser-to-electron conversion efficiency of the hot electrons that are generated via laser-solid interactions, and FLUKA utilizes this hot electron source term to calculate bremsstrahlung photon dose yield. Comparison of the calculated bremsstrahlung dose yields to radiation measurement data are also made.

INTRODUCTION

Technological advances allow an increasing number of facilities around the world to install high-intensity multi-terawatt and petawatt lasers. At SLAC National Accelerator Laboratory's Matter in Extreme Condition (MEC) laser facility, experimenters focus a short-pulse laser to high intensities ($>10^{17}$ W cm⁻²) onto thin solid foils to study matter at high pressures and temperatures.¹ The interaction of a high-intensity laser with the foil in vacuum creates a plasma on the surface of the target, and subsequent interaction between the laser pulse and the plasma can accelerate plasma electrons to tens and even hundreds of MeV in energy.^{2,3}

These 'hot' electrons generate bremsstrahlung photons from interactions with the solid foil and target chamber wall. The mixed field of electrons and photons is a source of ionizing radiation and can create a radiation hazard to personnel working on or near such laser facilities, especially in the absence of sufficient shielding.^{4,5} The relation between high-intensity lasersolid interactions and the subsequently generated photon dose yields is crucial in developing radiological controls but is not well-quantified yet.

The particle-in-cell (PIC) plasma code EPOCH can simulate laser-plasma interactions and characterize key parameters of the hot electron source term: energy distribution, angular distribution, and laser-to-electron conversion efficiency. The Monte Carlo radiation transport and interaction code FLUKA can utilize EPOCH's electron results to calculate the ambient dose equivalent from bremsstrahlung photons. This paper describes a systematic study to develop a photon dose yield model as a function of laser intensity for high-intensity laser-solid experiments between 10^{17} and

 10^{22} W cm⁻² by coupling simulations in EPOCH and FLUKA. The photon dose yield model is also compared to measurement data from previous studies.⁶

EPOCH: HOT ELECTRON CHARACTERIZATION

The code EPOCH is a computational plasma physics simulation code and utilizes the particle-in-cell (PIC) algorithm to study high energy density physics and laser-plasma interactions. The code was developed at the University of Warwick as part of an open collaboration project to develop an advanced relativistic electromagnetic PIC code.⁸

The PIC method is suitable for simulating femtosecond, micron-scale laser-plasma interactions that are typical at SLAC's MEC and other short-pulse laser facilities worldwide. In the EPOCH simulation, physical particles are represented by a smaller number of 'macroparticles'. Interactions between macro-particles and electromagnetic fields (such as from the laser pulse) are tracked iteratively over time with two coupled solvers. The particle pusher moves charged particles under the influence of electromagnetic fields and calculates the currents due to particle motions. The field solver solves Maxwell's equations on a fixed spatial grid subject to the currents calculated from the particles motions.

EPOCH can characterize the hot electron source from laser-solid interactions (energy distribution, angular distribution, laser-to-electron conversion efficiency) as a function of laser intensity. The unique goal in this paper is to use this hot electron source term to calculate photon dose yields in FLUKA for radiation protection analysis.

2D EPOCH input

Simulations of laser-solid interactions were performed using EPOCH in two-dimensions (2D). The simulation

1

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T. LIANG ET AL.

box was 20 μ m long (in *x*) by 20 μ m wide (in *y*) on a 400 by 400 grid (grid size of 0.05 μ m). Outflow boundary conditions (fields and particles removed from simulation) were applied to the longitudinal 'left and right' boundaries in *x*. Periodic boundaries (fields and particles wrapped to opposite boundary) were applied to the lateral 'top and bottom' boundaries in *y*. The simulation was followed with a time step of 0.1 fs to a total time of 400 fs. At 400 fs, the laser beam has completely interacted with plasma, and the peak hot electron energies have already been achieved.

A *p*-polarized laser beam with wavelength (λ) of 0.8 μ m was emitted from the left boundary and propagated in *x*. The laser had a peak intensity (*I*) expressed in W cm⁻² with a Gaussian profile in space and time: $1/e^2$ radial spot size (ω_0) of 2 μ m and FWHM pulse length (τ) of 40 fs. This spot size, together with peak intensity *I*, sets the total laser pulse energy.

The laser pulse interacted with a plasma composed of electrons and mobile Cu ions. Implementing Al or Au ions in EPOCH did not affect results for the hot electron source term. Ions from solids are significantly more massive than the electrons and move very little during a fs time-scale.

The plasma had an exponential density ramp, which represents the behavior of pre-plasma expanding from the surface of the target, from $0.01n_c$ to $10n_c$ with a plasma scale length (L_s) that was optimized for maximum energy of the generated hot electrons.⁷ The plasma scale length L_s characterizes the density gradient of the plasma as the distance at which the electron density drops to 1/e. Following the density ramp, the plasma had a 4 μ m-thick flat density region of $10n_c$.

Hot electron energy distribution

Characterization of the hot electrons from PIC simulations involves fitting the slope of the high energy tail of the electron spectrum as seen in Figure 1. The hot electron population has a characteristic temperature T_h , which is commonly referred to as the hot electron temperature. There is also a low energy background population of 'cold' electrons. The hot electron population in Figure 1 is fitted with the Maxwellian distribution in Equation 1 as

$$f(E) \sim E^{1/2} \exp\left[\frac{-E}{T_h}\right]$$
 (1)

where E is the electron energy and T_h is the hot electron temperature. For the spectra in Figure 1, the Maxwellian fit gives a hot electron temperature of $T_h = 2.1$ MeV.

Figure 2 plots the hot electron temperature T_h as a function of laser intensity *I* from EPOCH simulations. The calculated T_h from EPOCH has a standard deviation of about 15% due to using different lower and upper energy bounds when fitting the hot electron spectra. A fit for the calculated hot electron temperatures is also given in Equation 2 as

$$T_h(I) = 1.05 \times 10^{-10} I^{0.514}$$
⁽²⁾

where T_h is in units of MeV and I is in W cm⁻². The EPOCH results agree well with scaling laws and PIC simulations from work by Wilks *et al.* (1992 & 1997)^{3,10} and Kluge *et al.* (2011).¹¹



Figure 1. Hot electron spectra at times 200, 300, and 400 fs calculated from an EPOCH simulation for 10^{20} W cm⁻². A Maxwellian fit yields a characteristic slope of $T_h = 2.1$ MeV.



Figure 2. The hot electron temperature scales with laser intensity and agrees well with literature.^{3,10,11}

The EPOCH simulations at each laser intensity were calculated for a plasma scale length that resulted in optimal hot electron heating and subsequent bremsstrahlung dose generation. Plasma electrons absorb energy from the laser via various mechanisms such as resonance absorption and ponderomotive heating, which are sensitive to laser intensity and plasma scale length. Resonance absorption occurs for

PHOTON DOSE YIELD MODEL FOR HIGH-INTENSITY SHORT-PULSE LASER-SOLID EXPERIMENTS

moderate laser intensities in the range of about 10^{14} – 10^{17} W cm⁻² and for a plasma scale length greater than the laser wavelength ($L_s > \lambda$). Ponderomotive heating dominates at higher laser intensities $I \ge 10^{18}$ W cm⁻² and for a plasma scale length comparable to the laser wavelength ($L_s \approx \lambda$).^{8,9}

Differences between the EPOCH results presented here and the formulas found in literature may be due because analytical models in literature often account for only one heating mechanism (such as ponderomotive heating). While these analytical models provide good estimates of T_h for $I \ge 10^{18}$ W cm⁻², they may underestimate T_h for lower laser intensities where mechanisms such as resonance absorption are more dominant.

PIC codes such as EPOCH do not differentiate between various electron heating mechanisms. Therefore, hot electron heating can be optimized by adjusting the plasma scale length parameter. This result can be seen in Figure 2 between 10^{17} and 10^{19} W cm⁻² where the EPOCH simulations gave T_h greater than values given in literature.

Hot electron angular distribution

During laser-plasma interactions, a population of hot electrons will stream out from the plasma in the upstream (backward) and another in the downstream (forward) direction. EPOCH simulations characterize the angular distributions of both these hot electron populations, which were fitted with the Gaussian function according to Equation 3.

$$f(\theta) \sim \exp\left[\frac{-\theta^2}{2\sigma^2}\right]$$
 (3)

Figure 3 plots the angular distributions of hot electrons streaming out of the plasma (integrated over the simulation time from 0 to 600 fs) in the forward and backward directions for 10^{20} W cm⁻², where σ was fitted to be 49° and 47° for the backward and forward directions, respectively. This agrees well with another PIC study by Sircombe *et al.* (2013) that found the hot electron angular distribution can be fitted with a Gaussian with σ of 40.3° at 6×10^{19} W cm⁻².¹²

The angular distributions of hot electrons streaming from the plasma within each 100 fs increment are also plotted to show that the distribution remains consistent over time. Therefore, it can also be assumed that the hot electrons not streaming out (remaining inside simulation) have similar Gaussian angular distributions.

The angular distributions of the hot electrons from 2D EPOCH simulations did not change significantly for different laser intensities from 10^{17} to 10^{22} W cm⁻², and σ was consistently within $45^{\circ}\pm 5^{\circ}$.

As seen in Figure 3, an additional component to the angular distribution is the ratio of hot electrons emitted in the forward and backward directions (or downstream



Forward hot electron angular distribution for $10^{20}~\text{W cm}^{-2}~(\lambda=0.8~\mu\text{m})$



Figure 3. The backward and forward hot electron angular distributions can be fitted with a Gaussian with standard deviation σ : (a) 49° and (b) 47°. A larger population of hot electrons are emitted in the laser's forward direction.

and upstream from the plasma). This was calculated by taking the ratio between the total energy of hot electrons traveling in the forward direction and those in the backward direction. The forward-to-backward ratio of hot electron yield is plotted in Figure 4 and scales as a function of laser intensity. The data fits well with the power function

$$f(I) = 2.8 \times 10^{-9} I^{0.46} \tag{4}$$

where I is the laser intensity in W cm⁻². At higher laser intensities, the hot electron emission and subsequent bremsstrahlung generated is increasingly forward-peaked.

The forward-to-backward ratio approaches 1:1 between 10^{18} and 10^{19} W cm⁻², but this does not suggest that the hot electron source is isotropic at these intensities. It only states that the total energy of hot electrons emitted in the forward and backward directions is the same.

T. LIANG ET AL.



Figure 4. The forward-to-backward ratio of hot electrons from 2D EPOCH simulations demonstrates that hot electron emission is forward-peaked with increasing laser intensity.

Laser-to-electron conversion efficiency

Only a fraction of the laser pulse energy from a highintensity laser beam is absorbed to create the hot electrons in the plasma. Work by Fuchs *et al.* (2006) determined the laser-to-electron conversion efficiency (η) as a function of laser intensity (W cm⁻²) to be as given in Equation 5 with a maximum of 50%.¹³

$$\eta = 1.2 \times 10^{-15} I^{0.74} \tag{5}$$

Experiments at different facilities have measured laser-to-electron conversion efficiencies between 10 and 50% at 10^{20} W cm⁻².¹⁴⁻¹⁶ For intensities greater than 10^{20} W cm⁻², Ping *et al.* (2008) measured conversion efficiencies upwards of 60–90% for different laser incidence angles.¹⁷

The wide range of reported conversion efficiencies in literature led Qiu *et al.* (2011) to develop a simple model of the laser-to-electron conversion efficiency for SLAC's Radiation Protection (RP) group to estimate the bremsstrahlung dose yields from lasersolid experiments. The model conservatively used an η of 30% for laser intensities below 10^{19} W cm⁻² and 50% above 10^{19} W cm⁻² for dose calculations.¹⁸ Calculations in EPOCH improve upon this simple

Calculations in EPOCH improve upon this simple model by taking the ratio between the total energy of all hot electrons and the total laser pulse energy. Figure 5 compares the η calculated using EPOCH with the scaling by Fuchs *et al.* (2006) and the radiation protection model proposed by Qiu *et al.* (2011).

FLUKA: PHOTON DOSE YIELD CALCULATION

The code FLUKA is a Monte Carlo multi-particle transport and interaction code that can perform radiation dose calculations and implement complex geometries. FLUKA can utilize the hot electron source term determined by EPOCH to calculate the bremsstrahlung



Figure 5. A comparison of the laser-to-electron conversion efficiency calculated from 2D EPOCH simulations and two other studies.

photon dose yield generated from such laser-solid interactions. In this paper, the photon dose yield at 1 meter (mSv J^{-1}) is calculated as a function of angle and is defined as the ambient dose equivalent of bremsstrahlung photons from hot electrons (mSv) normalized to the laser pulse energy on target (J).^{19,20}

FLUKA methodology

The geometry for FLUKA simulations consisted of a 2 cm by 2 cm Cu foil (common 'medium-Z' target for laser-solid experiments) with thickness equal to one continuous-slowing-down approximation (CSDA) range for an electron with energy of $1.5T_h$, which is the mean energy of the Maxwellian distribution from Equation 1.

A target sensitivity study for Cu and also plastic, Al, and Ta found that the bremsstrahlung dose yield generated from the target was optimal at 1×CSDA thickness and scaled with $\sqrt{Z_{\text{solid}}}/\sqrt{Z_{\text{Cu}}}$.⁷

The Cu foil was located inside vacuum at the center of a target chamber with an Al wall thickness of 2.54 cm Al and a radius of 1 meter. Hot electrons were emitted 10 μ m inside the Cu foil, and the ambient dose equivalent (mSv) of bremsstrahlung photons from hot electrons interacting with the target and Al chamber wall was calculated outside the target chamber.

As a reminder, the hot electron source as a function of laser intensity was determined by EPOCH: Maxwellian energy distribution starting at 0 MeV with temperature T_h (Figure 2), Gaussian angular distribution with $\sigma = 45^{\circ}$ (Figure 3), and forward-to-backward ratio (Figure 4). FLUKA calculations were normalized with the laser-to-electron conversion efficiency (Figure 5).

Photon dose yield model for laser-solid interactions

The previous radiation protection (RP) model at SLAC for estimating the bremsstrahlung photon dose yields



PHOTON DOSE YIELD MODEL FOR HIGH-INTENSITY SHORT-PULSE LASER-SOLID EXPERIMENTS

Figure 6. The revised model from EPOCH and FLUKA calculations agrees well with measurement data from SLAC MEC and Titan LLNL. Curves represent the photon dose yield with 2.54 cm Al shielding and in the 0° direction and at 1 meter. The measurements were taken outside the target chamber at varying angles and elevation (hence, the vertical spread). Differences between the model and measurements are due to target chamber attenuation, measurement angle, target Z, target thickness, detector sensitivity, and uncertainties in the laser beam characterization as described below.

from laser-solid interactions was based on work by Qiu *et al.* (2011) who expanded the model developed by Hayashi *et al.* (2006) to include laser intensities below 10^{19} W cm⁻². Both models used conservative assumptions for the hot electron source term to perform dose calculations.^{6,18,21}

Figure 6 plots the revised photon dose yield model (from EPOCH/FLUKA) for laser-solid interactions between 10^{17} to 10^{22} W cm⁻² at 1 meter in the 0°, 180° , and 90° directions. Shielding from 2.54 cm of Al is applied to the models to include attenuation from the target chamber.

Shown for comparison is the 0° 'adjusted' model at SLAC from previous work that applied reduction factors at high laser intensities and the measurement data from several laser-solid experiments at SLAC MEC and one at LLNL Titan. Details of the previous adjusted model and the measurements are covered in Reference 6.

For laser intensities $>10^{18}$ W cm⁻², the 0° revised model is lower than the previous 0° SLAC model because the systematic characterization of the hot electron source term with EPOCH corrected

several conservative assumptions used in the previous model. For example, the previous model used a 'harder' relativistic Maxwellian energy distribution (mean energy of $3 \times T_h$), a higher hot electron temperature T_h , and a mono-directional pencil beam of hot electrons.

The revised model in the 90° direction is consistently about a factor of 1/10 compared to the 0° direction. The 0° model is greater than the 180° model up to a factor of 10 at 10^{22} W cm⁻² higher laser intensities, but with lower intensities, the two models converge due to the ratio of forward-to-backward hot electrons (Figure 4).

The revised models in Figure 6 agree well with the measurement data, especially from about 10^{18} to 10^{20} W cm⁻². It is important to understand that the revised photon dose yield models are calculated from EPOCH and FLUKA simulations that used optimal parameters and may not exactly replicate measurements results. The model does not account for realistic effects of uneven target chamber attenuation, measurement angle, target Z, target thickness, detector sensitivity, and uncertainties in the laser beam characterization.

T. LIANG ET AL.

For example, the data at 10^{17} W cm⁻² in Figure 6 is greater than the model due to uncertainties in the laser energy on target. For the same measured dose, less energy on target results in a higher dose yield (mSv per J). In addition, the highest dose yields were measured outside the target chamber's 5 mm-thick glass viewports (less attenuation than from 2.54 cm Al).²²

At laser intensities above 10^{20} W cm⁻², some data points from the Titan experiment are greater than the revised model, while other points are just at the model or below. The data from the Titan laser facility were acquired parasitically to another experiment, meaning the laser and optics parameters were not controlled by the SLAC measurement team, and there was large uncertainty in the laser pulse energy on target in the range of about 50–400 J.²³

SUMMARY

The hot electron source term from laser-solid interactions has been characterized with the plasma physics code EPOCH. The hot electrons have a Maxwellian energy distribution with temperature T_h , a Gaussian angular distribution with $\sigma = 45^\circ$, and a laser-to-electron conversion efficiency that rises with laser intensity up to 60%. Radiation dose calculations that fully utilize the characterized hot electron source term have been performed with FLUKA to estimate the photon dose yield (mSv J⁻¹) from such laser-solid interactions.

For the first time, a photon dose yield model as a function of laser intensity has been developed by coupling a plasma code with a radiation transport code. The model provides a guideline for radiation hazard analysis for laser-solid interactions between 10^{17} and 10^{22} W cm⁻² and for developing controls (tenth-value layers in Ref. 7) at high-intensity laser facilities.

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REFERENCES

 Nagler, B. et al. The Matter in Extreme Conditions at the Linac Coherent Light Source. J. Synchrotron Radiat. 22, 520–525 (2015).

- Tajima, T. and Dawson, J. M. et al. Laser electron accelerator. Phys. Rev. Lett. 43, 267–270 (1979).
- Wilks, S. C. and Kruer, W. L. Absorption of Ultrashort, Ultra-Intense Laser Light by Solids and Overdense Plasmas. IEEE J. Quantum Electron. 33, 1954–1968 (1997).
- 4. Guo, T. et al. Generation of hard x rays by ultrafast terawatt lasers. Rev. Sci. Instr. **72**, 41–47 (2001).
- Chen, L. M. et al. Study of hard x-ray emission from intense femtosecond Ti:sapphire laser-solid target interactions. Phys. Plasmas 11, 4439–4445 (2004).
- Liang, T. et al. Radiation dose measurements for high-intensity laser interactions with solid targets at SLAC. Rad. Prot. Dosim., doi:10.1093/rpd/ ncv505, 1–10 (2016).
- Liang, T., Bauer, J., Liu, J. and Rokni, S. Development of a Photon Dose Yield Model for Laser-Solid Interaction by Coupling EPOCH and FLUKA. SLAC Radiation Physics Note RP–16–14, 1–28 (2016).
- Arber, T. D. et al. Contemporary particle-in-cell approach to laser-plasma modelling. Plasma Phys. Control. Fusion 57, 113001 (2015).
- McKenna, P., Neely, D., Bingham, R., Jaroszynski, D. A. Laser-Plasma Interactions and Applications. Springer International Publishing Switzerland, (2013).
- Wilks, S. C. et al. Absorption of Ultra-Intense Laser Pulses. Phys. Rev. Lett. 69, 1383–1386 (1992).
- Kluge, T. et al. Electron Temperature Scaling in Laser Interaction with Solids. Phys. Rev. Lett. 107, 205003 (2011).
- Sircombe, N. J, Hughes, S. J., and Ramsay, M. G. Integrated calculations of short-pulse laser interaction with matter. New J. of Phys. 15, 025025 (2013).
- Fuchs, J. et al. Laser-driven proton scaling laws and new paths towards energy increase. Nat. Phys. 2, 48–54 (2006).
- Key, M. H. et al. Hot electron production and heating by hot electrons in fast ignitor research. Phys. Plasmas 5, 1966–1972 (1998).
- Myatt, J. et al. High-intensity laser interactions with mass-limited solid targets and implications for fast-ignition experiments on OMEGA EP. Phys. Plasmas 14, 056301 (2007).
- Hatchett, S. P. et al. Electron, photon, and ion beams from relativistic interaction of Petawatt laser pulses with solid targets. Phys. Plasmas 7, 2076 (2000).

PHOTON DOSE YIELD MODEL FOR HIGH-INTENSITY SHORT-PULSE LASER-SOLID EXPERIMENTS

- 17. Ping, Y. et al. Absorption of Short Laser Pulses on Solid Targets in the Ultrarelativistic Regime. Phys. Rev. Lett. **100**, 085004 (2008).
- Qiu, R., Liu, J. C., Prinz, A. A., Rokni, S. H., Woods, M., and Xia, Z., Analysis and Mitigation of X-ray Hazard Generated from High Intensity Laser-Target Interactions. SLAC Publication, SLAC-PUB-14351 (2011).
- Böhlen, T. T., Cerutti, F., Chin, M. P. W., Fassò, A., Ferrari, A., Ortega, P. G., Mairani, A., Sala, P. R., Smirnov, G., and Vlachoudis, V. *The FLUKA Code: Developments and Challenges for High Energy and Medical Applications*. Nuclear Data Sheets **120**, 211–214 (2014).
- Ferrari, A., Sala, P. R., Fassò, A., and Ranft, J., FLUKA: a multi-particle transport code. CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
- Hayashi, Y. et al. Estimation of photon dose generated by a short pulse high power laser. Radiat. Prot. Dosim. 121, 99–107 (2006).
- Bauer, J. et al. Measurements of Ionizing Radiation Doses Induced by High Irradiance Laser on Targets in LCLS MEC Instrument. SLAC Publication SLAC PUB-15889, 1–39 (2013).
- Bauer, J., Liu, J. C., Prinz, A. A., Tran, H. and Xia, Z. *High Intensity Laser Induced Radiation Measurements at LLNL*. SLAC Radiation Physics Note RP–11–11, 1–16 (2011).