



## TECHNICAL BASIS FOR CLASSIFYING HIGH-INTENSITY LASERS AS RADIATION-GENERATING DEVICES

### 1.0 INTRODUCTION

With sufficient intensity, laser light can create plasmas on the surface of targets. The interaction of the laser field with free electrons in the plasma can create bremsstrahlung x-rays and other forms of ionizing radiation. With rising laser intensity, x-ray production rises in both intensity and photon energy. High-intensity lasers may create a non-negligible hazard of ionizing radiation.

For purposes of occupational radiation protection, a threshold of laser intensity may be chosen beyond which the laser system should be evaluated for ionizing radiation hazard and control. Below the threshold, a laser system may be considered harmless for production of ionizing radiation. Industry experience indicates that this threshold is on the order of  $10^{15}$  W·cm<sup>-2</sup>. Sandia has used this value as a screening threshold for classifying laser systems as radiation-generating devices (RGDs) since the initial publication of the Radiation Protection Procedures Manual (RPPM), but no documented technical basis exists for that choice.

### 1.1 Purpose & Scope

This document describes a technical basis for the choice of  $10^{15}$  W·cm<sup>-2</sup> as a screening threshold for exempting laser systems from the scope of RPPM Chapter 10, *Radiation-Generating Devices*. It also serves as a primer for the Radiation Protection (RP) Department on the physics of laser-induced ionizing radiation and offers guidance on the classification of high-intensity lasers as RGDs.

### 2.0 REFERENCES

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### 3.0 ATTACHMENTS

None.

### 4.0 TECHNICAL BASIS

#### 4.1 Physics of Laser-Driven Plasma Acceleration

Since at least the 1940s physicists have understood that intense low-frequency electromagnetic fields such as those existing in the corona of the sun are capable of accelerating charged particles to relativistic velocities. Fermi, McMillan and Teller, among others, developed this understanding to explain the origin of cosmic radiation <sup>(1, 2, 3)</sup>.

Particle accelerators developed in this era were capable of MeV energies over meter-scale distances. Modern successors can achieve GeV and even TeV energies, but only with kilometer-scale devices <sup>(4)</sup>. These conventional accelerators establish static or oscillating electromagnetic fields over evacuated beam paths of macroscopic dimensions, driven by various electrical power devices.

With the advent and development of lasers in the 1960s and 1970s, theorists began to recognize that intense lasers could be used to accelerate electrons <sup>(5)</sup> to MeV and even GeV energies over centimeter-scale distances <sup>(6)</sup>. By the turn of the century numerous researchers had demonstrated the viability of plasma acceleration in laser systems <sup>(7, 8)</sup>.

Laser acceleration is a species of plasma acceleration, wherein electromagnetic energy from a photon beam couples to the electrically conductive plasma, creating microscopic plasma oscillations called Langmuir waves. These space-charge oscillations in electron density can be relativistic and can create far greater electric fields—up to hundreds of  $\text{GV}\cdot\text{m}^{-1}$ —than is achievable with conventional accelerators, which are limited by the dielectric strength of available materials to gradients on the order of tens of  $\text{MV}\cdot\text{m}^{-1}$ . Under some plasma conditions, the free electrons in such gradients can be accelerated to MeV and GeV energies over mm- or cm-scale distances <sup>(7)</sup>.

The intense focus required for such acceleration energies demands very short laser pulses of picosecond duration or less. The inhomogeneous oscillating electromagnetic field produced by the passing pulse creates a non-linear force on the free electrons called ponderomotive force. Under some conditions the resulting acceleration is called laser (or plasma) “wake field” acceleration, by analogy to a surfer accelerated by an ocean wave <sup>(8)</sup>. Electrons can also absorb energy from the laser by inverse bremsstrahlung and by resonance absorption. The proportion between the modes by which the electrons absorb energy varies with the laser intensity and with the relationship between the laser wavelength and the plasma scale length <sup>(9, 10)</sup>.

The electrons can be artificially injected into the laser beam, but usually the accelerated electrons are drawn from the plasma that naturally forms in the focus of a high intensity beam on a target. Plasma formation on solid targets begins at intensities around  $10^{12} \text{ W}\cdot\text{cm}^{-2}$  <sup>(10)</sup>.

Since the photons in such a short laser pulse exhibit very high temporal and spatial coherence, the strength of the oscillating electromagnetic field and that of the ponderomotive force both scale with intensity. Intensity, sometimes called irradiance, is a measure of power per unit area and is usually expressed in units of  $\text{W}\cdot\text{cm}^{-2}$ . Laser systems used for electron acceleration typically achieve intensities between  $10^{17}$  and  $10^{22} \text{W}\cdot\text{cm}^{-2}$ , with proposed systems aiming for  $10^{23}$  to  $10^{24} \text{W}\cdot\text{cm}^{-2}$ .

Electrons in the plasma that have not undergone acceleration are known as “cold.” The average energy of “hot” (i.e. accelerated) electrons in the plasma, usually called the electron temperature or plasma temperature, scales with approximately the square root of the laser intensity. The temperature of the hot electrons is known to follow an approximately Maxwellian distribution, characterized by a high-energy tail whose population falls logarithmically with increasing energy above the average temperature <sup>(12)</sup>.

Particle-in-cell plasma simulations using the EPOCH code reported by Liang *et al* <sup>(9)</sup> give a fit for calculated hot electron temperature as

$$T_h(I) = 1.05 \times 10^{-10} I^{0.514} \tag{Eq. 1}$$

where  $T_h(I)$  is the hot electron temperature in MeV as a function of the intensity  $I$  in  $\text{W}\cdot\text{cm}^{-2}$ . They report good agreement between their simulations and theoretical scaling laws, as well as simulations by other authors.

From Eq. 1 we can construct a table correlating laser intensity and hot electron temperature.

Table 1, Hot Electron Temperature as a Function of Laser Intensity

<i>Laser Intensity I (W·cm<sup>-2</sup>)</i>	<i>Hot Electron Temperature T<sub>h</sub> (MeV)</i>
10 <sup>14</sup>	1.65E-03
10 <sup>15</sup>	5.39E-03
10 <sup>16</sup>	1.76E-02
10 <sup>17</sup>	5.74E-02
10 <sup>18</sup>	1.88E-01
10 <sup>19</sup>	6.13E-01
10 <sup>20</sup>	2.00E+00
10 <sup>21</sup>	6.53E+00
10 <sup>22</sup>	2.13E+01

## 4.2 Health Physics of High Intensity Laser Systems

The accelerated electrons in these systems naturally create bremsstrahlung as they interact with materials such as the target or the walls of the vacuum chamber, creating a radiation hazard outside the chamber. The health physics organizations at the experimental facilities have grappled with the challenge of characterizing the prompt bremsstrahlung, which exists for only the duration of the laser pulse <sup>(11)</sup>.

At the SLAC National Accelerator Laboratory, health physicists and other scientists have published several papers<sup>(9, 12, 13)</sup> regarding laser-produced bremsstrahlung at the Matter in Extreme Condition (MEC) laser facility. Liang *et al*<sup>(9)</sup> report a theoretically derived relationship between laser intensity (in the range of  $10^{17}$  and  $10^{22}$  W·cm<sup>-2</sup>) and dose rates outside the vacuum chamber. They report that the predicted values stand in reasonably good agreement with actual measurements at the facility.

Their reported values may serve as a starting-point estimate for uncharacterized systems, recognizing that many variables including chamber construction and geometry will affect the validity of comparison.

Perhaps more usefully, the values in Table 1 (derived from the same work) may be used to estimate the energy of the hot electrons, which relates to the bremsstrahlung spectrum by relationships known even to health physicists having no knowledge of laser systems. From the table we note that the hot electron temperature is only 6 keV at  $10^{15}$  W·cm<sup>-2</sup>. At this electron energy, the bremsstrahlung spectrum will be too soft to escape any vacuum chamber. This observation justifies treating laser systems below that intensity as non-RGDs.

At  $10^{16}$  W·cm<sup>-2</sup> the electron temperature rises to 18 keV. This value, if it were produced by an ordinary macroscopic accelerating potential across an evacuated gap, would correspond to an accelerating voltage of 18 kV, which is above the threshold of 15 kV for screening RGDs by Sandia policy<sup>(14)</sup>. Thus, the screening threshold for laser systems of  $10^{15}$  W·cm<sup>-2</sup> is consistent with the screening threshold for ordinary RGDs using an accelerating potential across an evacuated gap.

It should be noted that the literature also reports other ionizing radiation and nuclear reactions at higher intensities. Activation, neutron radiation, transmutation and even photo fission may occur under some conditions at intensities above  $10^{18}$  or  $10^{19}$  W·cm<sup>-2</sup><sup>(15)</sup>. Evaluation of these phenomena may be warranted at high intensities.

At Sandia, the highest laser intensity ever produced was about  $10^{21}$  W·cm<sup>-2</sup> in the 100 TW chamber. Although the Petawatt laser will be more powerful, its planned use is for longer pulses resulting in a lower intensity of  $10^{20}$  W·cm<sup>-2</sup><sup>(16)</sup>.

### **4.3 Conclusion**

Laser systems capable of creating intensities above  $10^{15}$  W·cm<sup>-2</sup> should be classified and controlled as RGDs.