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A Parameterization of X-Ray Production in Laser-Produced Plasmas

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A PARAMETERIZATION OF X-RAY PRODUCTION IN LASER-PRODUCED PLASMAS *

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ABSTRACT

A simple and algebraically tractable model is developed for the efficiency of x-ray production in a certain spectral region by laser driven plasmas. The model is used as an interpolation/extrapolation device for experimental and theoretical results from three different target concepts. These tests indicate that it is of use in its intended capacity. Certain relationships between independent parameters and scaling laws also result from this construction. Most notable among these is the prediction that the efficiency for producing line radiation in a certain narrow energy range scales like the inverse square of this energy.

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I. Introduction

Electromagnetic radiation from laser-driven plasmas has long been of interest. It is an important loss mechanism for laser-driven fusion experiments,¹ but it has the potential to be a radiation source with characteristics that would be useful in many diverse applications.² A number of experimental and theoretical studies of electromagnetic radiation production, especially in the x-ray region, has been prompted by these considerations. The experimental measurements are complicated by the difficulties of measuring absolute intensity under adverse conditions. The theoretical work usually consists of computer-based studies using models that necessarily include large quantities of numerical data to describe the relevant atomic properties. Hence, a complete characterization of the large parameter space for such studies will not soon be available.

The purpose of this work is to construct a model capable of correlating available information on x-ray production by laser-driven plasmas while retaining a simple and relatively transparent dependence on the relevant parameters. The property of central interest is the photon-production efficiency η for photons with energy near or exceeding some value ΔE_g . The emphasis is on simplicity. Obviously, there is no hope of incorporating all of the important physics into an algebraically tractable form. The approach used here to achieve this goal is to isolate the more relevant parameters and then derive the desired relationships by representing the many unattended complexities with empirical normalization constants. These constants will be determined by appeal to the available experimental and/or theoretical results.

This model is reasonably successful in correlating certain theoretical data for three quite different targets. In addition, an analysis of some experimental data from the study of laser interactions with solid targets is presented. Two empirical constants are required to predict η . The relationship between the values found for these constants provides some physical insight in two of the applications and they quantify the relative ordering of η for all three applications.

Such a model provides correlation/extrapolation information that should be useful in choosing parameters for future experiments or large-scale computations. However, because of the limited experience with this simple model, caution is obviously necessary in using it as an extrapolation or scaling device. Most notable of the scaling predictions is the increase of η with the square of the laser frequency and with the time the plasma absorbing the laser energy can be prevented from converting this energy to hydrodynamic motion, Δt_p . Also, η is observed to be proportional to ΔE_s^{-2} for the case of line radiation. This rapid decrease in line-radiation efficiency with increasing ΔE_s results in an estimate that bremsstrahlung and recombination radiation are each comparable to, or exceed, the intensity of line radiation for $\Delta E_s \geq 20$ keV, even under optimal condition for the line-radiation process. Some collaborative information for these predictions is cited.

The construction of the model is presented in Section II. A discussion of the model's physical content and any anticipated caveats are also presented in Section II. Applications to three different types of targets are presented in Section III and summary information is given in Section IV.

II. Theory

The production of radiation from a laser-driven plasma is modeled here by assuming a plasma with a fairly high conductivity has already been formed. This plasma will be a relatively efficient absorber of the laser energy unless the laser frequency exceeds the electron plasma frequency. This provides one of our basic relationships,

$$n_p = n_e \quad \text{with} \quad n_a = \frac{n_e}{Z-q} \quad (1)$$

The number per unit volume of electrons, n_e , is equated to the concentration of electrons, that is required to produce a plasma frequency equal to the laser frequency,³ n_p ,

$$n_p/\text{cm}^{-3} = 1.11 \times 10^{21} (\lambda/\mu\text{m})^{-2},$$

where λ is the laser wave length. The optimal concentration of target atoms, n_a , after imposing the condition for over-all charge neutrality upon the plasma is also given in Eqs. (1). Here Z is the nuclear charge and q is the number of electrons expected to be left on the target under the conditions created by the laser. The choice of q will be discussed later. Equation (1) and the following developments are based on the assumption that the target material consists of a single Z . Generalization to more complex targets is straightforward.

The mechanisms for the laser-light absorption will not be treated in this simplified approach. Instead, an artificial electron temperature T_e is defined by relating it to the incident laser energy J_1 through

$$(3/2) kT_e = \epsilon_d J_1 / (V n_e) \quad (2)$$

where V is the volume of the plasma heated by the laser and ϵ_d is an efficiency of deposition parameter to be determined. The value of T_e reflects an average of the electron temperature over V and the time the plasma can radiate, Δt_r . Typically, Δt_r would be equated to the lesser of the plasma disassembly time or the time required for significant cooling of the plasma. Hence, a judicious choice of T_e for a given J_1 and experimental situation is required to determine ϵ_d .

Equation (2) requires the electron degrees of freedom to be thermally equilibrated on a time scale short compared to Δt_r . This seems reasonable since the equilibrium time for electron degrees of freedom under conditions corresponding to a Nd-glass laser is short, less than 10^{-11} sec for $n_e \sim 10^{21} \text{ cm}^{-3}$ and $kT_e \leq 10 \text{ keV}$ compared to the time scales for other processes such as plasma expansion. Very roughly, this time scales like $(\lambda/\lambda_0)^2$ for other lasers, where λ_0 is the Nd-glass laser wave length and λ is the wave length for the laser in question. In addition, the time for a linear dimension of the plasma d_0 to double by free expansion is about

$$d_0 \sqrt{m_a/(3kT_e)} = 1.6 \times 10^{-8} (d_0/\text{cm}) \sqrt{(m_a/m_e)(\text{keV}/kT_e)} \text{ sec}$$

where m_a is the target atomic mass and m_e is the electron mass. Hence the electron thermalization time is expected to be short compared to the free-expansion time for typical conditions.

The classical absorption mechanism, i.e., inverse bremsstrahlung, would appear to well satisfy this view. Anomalous or collective absorption effects, which become increasingly important for increasing laser peak-power or decreasing laser pulse lengths Δt_l , tend to produce a non-thermal high-energy electron distribution strongly decoupled from the thermalized electrons.⁴ It is beyond the scope of this work to deal with this problem other than to point out that Eq. (2) may not be well suited to the anomalous absorption case.

The next step in this simplified model consists of constructing an equation describing the efficiency of radiation production in the range of energy defined by ΔE_g . Line radiation, radiative recombination, and bremsstrahlung can all contribute and results for each of these three forms of radiation are presented. Conditions that optimize line radiation⁵⁻⁸ are of central interest since it is anticipated that these conditions also optimize the total ΔE_g radiation from the plasma. Hence these conditions are discussed and the derivation of the line-radiation results are presented in some detail. The abbreviated treatments of recombination and bremsstrahlung follow.

The conditions that give rise to the large line radiation component correspond to a kT_e having the same order of magnitude as the excitation energy for a transition with a unit change in principle quantum number, $\Delta p = 1$ from a shell with principle quantum p_0 , where p_0 is the largest shell with significant occupation. See, for example, Refs. 5 and 9. Data in Table I of Ref. 9 for steady-state corona condition indicate, for example, that $kT_e \sim 0.33 \Delta E$ results in equal concentration of completely stripped and hydrogen-like oxygen atoms. Here ΔE is the energy of a $\Delta p = 1$, $p_0 = 1$ transition in hydrogen-like oxygen. This proportionality constant between kT and ΔE_g increases as the nuclear charge increases and also one expects that kT_e must be increased to maintain this condition in a plasma that is too dense to satisfy the corona conditions. The time for ionizing all electrons in shells with $p > p_0$ will tend to be relatively short compared to the plasma life-time discussed above³ while the life-time for stripping the p_0 shell can be significantly longer.^{3,10} The complexity of treating all of these considerations is considerable and will not be attempted. The gain in simplicity is balanced by the restriction of the theory's applicability to relatively narrow range of kT_e .

The rate of energy production per unit of plasma volume by line radiation from all transitions to p_0 with $\Delta p \geq 1$ is approximated by the single term $n_a C(p_0, T_e) \Delta E_s$, where $C(p_0, T_e)$ is an electron excitation rate from the p_0 shell with $\Delta p = 1$. The quantity ΔE_s is equated to the corresponding excitation energy. The photon energy production J_0 in the energy range near ΔE_s is then

$$J_0 = \epsilon_r(bb) \int_{t_0}^{t_p} dt n_a C(p_0, T_e) V \Delta E_s \quad (3)$$

The temporal details of the plasma evolution will be lumped into the mean-value estimate

$$J_0 \simeq \epsilon_r(bb) n_a C(p_0, T_e) V \Delta E_s \Delta t_p \quad (4)$$

Here $\epsilon_r(bb)$ is a constant to be chosen for different applications and must in some way represent the large quantity of information neglected in this simple approach. The plasma radiation life-time is signified by Δt_p . Of the many possible choices for the rate coefficient, a formula for the discrete excitation of positive ions

$$C(p_0, T_e) = 9.87 \times 10^{-11} f \alpha^{-1} e^{-\alpha} (\text{keV}/kT_e)^{1.5} (n_e/\text{cm}^{-3}) \text{sec}^{-1} \quad (5)$$

will be used. Equation (5) is an adaptation of one discussed elsewhere,¹¹ f is the optical oscillator strength, and

$$\alpha = \Delta E_s / kT_e \quad (6)$$

Equations (1), (2) (4) and (5) can be used to construct the efficiency for line radiation, which is equated to J_0/J_1 ,

$$\eta(bb) = 6.58 \times 10^{-11} \epsilon_r(bb) \epsilon_d \left(\frac{n_e/\text{cm}^{-3}}{Z-q} \right) (\Delta t_p/\text{sec}) (\Delta E_s/\text{keV})^{-1.5} f \alpha^{3/2} e^{-\alpha} \quad (7)$$

Equations (2) and (7) form the desired result and predict the efficiency for radiation production by lines in the ΔE_s range once ϵ_r and ϵ_d are assigned.

The efficiency for producing recombination or free-bound radiation with energy greater than or equal to ΔE_s is computed by adapting the hydrogenic formula, see p. 195 of Ref. 12, to this problem. The relationship

$$\Delta E_s = Z_{\text{eff}}^2 E_H / p_0^2 \quad (8)$$

is assumed, where Z_{eff} is an effective nuclear charge for the most populous ion and E_H is the hydrogen ionization energy. If one assumes that all ions of the plasma have this effective charge and that the lower limit on the radiation into all levels with $p \geq p_0$ is ΔE_s , the efficiency for recombination radiation with energy equal to or greater than ΔE_s ,

$$\eta(\text{fb}) = 7.43 \times 10^{-14} \epsilon_r(\text{fb}) \epsilon_d \alpha^{3/2} (\Delta E_s / \text{keV})^{1/2} \left(\frac{n_e / \text{cm}^{-3}}{Z - q} \right) (\Delta t_p / \text{sec}) \left\{ p_0 + 2 p_0^4 (2 p_0 + 1)^{-2} \right\}, \quad (9)$$

is easily established with the use of Eq. (2). Here $\epsilon_r(\text{fb})$ replaces $\epsilon_r(\text{bb})$ appearing in Eq. (7) and the $\left\{ . . . \right\}$ term is a good approximation for all p_0 to an infinite sum over p that appears in the hydrogenic formula for power from recombination radiation.¹²

The efficiency for producing radiation with energy greater than or equal to ΔE_s by bremsstrahlung is also easily computed if one assumes the hydrogenic formula for the bremsstrahlung emission coefficient, see page 193 of Ref. 12, and follows the procedures used in deriving Eq. (7). The result is

$$\eta(\text{ff}) = 2.02 \times 10^{-15} \epsilon_r(\text{ff}) \epsilon_d \sqrt{\alpha} e^{-\alpha} (\Delta E_s / \text{keV})^{-1/2} Z^2 (\Delta t_p / \text{sec}) \frac{n_e / \text{cm}^{-3}}{Z - q} \quad (10)$$

In this case an effective nuclear charge or an equivalent to Eq. (8) was not introduced. The partial screening of the nucleus by any bound electrons will reduce the effective value of Z^2 in the numerator, hence Eq. (10) tends to provide an upper bound to $\eta(ff)$.

Equations (7), (9), and (10), when used with Eq. (2), allow a prediction of the efficiency for ΔE_g radiation once ϵ_d and the ϵ_r parameters are determined. However, the connection of Eq. (2) with the usual laser parameters needs some amplification. Two distinct cases occur. In the case of a preformed plasma the relationship

$$n_e V = \text{constant} \quad (11)$$

is presumed. In one example treated here, this plasma is assumed to be completely irradiated by the laser so the plasma is cylindrical in shape. The laser pulse is idealized as a gaussian with uniform intensity over the spot size A . If the pulse width at one-half maximum power, W_0 , is Δt_l and the maximum power per unit area is ϕ_0 , then

$$J_1 = 0.601\sqrt{\pi} \Delta t_l W_0 = 0.601\sqrt{\pi} \Delta t_l A \phi_0 \quad (12)$$

results. A different relationship may be required for other applications. The second case is typical of laser interactions with large mass targets where the active volume of the plasma is not a constant. In these cases, the relationship

$$n_e V = \zeta J_1^{1-m} \quad (13)$$

replaces Eq. (11). Here ζ is not known and may depend very much on the details of the application. The quantity m also must be determined from data that are given. A number of theoretical and experimental studies of this

parameter are available. See, for example, Ref. 13 and the discussions and citations in Ref. 14. This has the effect of introducing another empirical constant into the theory and makes it impossible to independently determine a value for ϵ_d . Relationships like Eq. (12) are still applicable to this case but the laser and plasma parameters are no longer as clearly related as they were in the preformed-plasma application.

Some restrictions are implicit in this derivation. Also, after an assignment of the various parameters has been made for a particular set of conditions, the extrapolation of these predictions to a situation remote from those used in the normalization may lead to serious error. Items that make these statements necessary are: 1) The electron concentration must be near to but less than the plasma critical electron density. Equation (1) expresses only the optimal condition for the target concentration. 2) The time scales appear completely arbitrary, but restrictions such as $\Delta t_d \leq \Delta t_p$ seem obvious. Also, η can be made greater than unity by arbitrarily increasing Δt_p . Certain natural limitations on Δt_p will become evident in the applications. 3) No restrictions were placed on the choice of p_0 . However, one expects various factors to change with different p_0 . For example, $\Delta p = 0$ transitions are not important for large Z and $p_0 = 1$ (K-shell fluorescence or recombination for $\eta(bb)$ or $\eta(fb)$, respectively) but for $p_0 > 1$ they can be extremely important.¹⁵ Also, the specification of the effective number of radiating electrons, or, equivalently the oscillator strength appearing in Eq. (3) becomes more arbitrary for increasing p_0 . 4) Equation (7) reflects the number of electrons contributing to line radiation through the choice of f . Obviously, f should be a function of kT_e . Here f will be taken as a constant and the property that f must vanish as the occupancy of the p_0 shell goes to zero, with increasing kT_e replaced by the knowledge that Eq. (7) becomes an extreme upper bound for $kT_e \gg \Delta E_g$.

The extension to $kT_e \ll \Delta E_s$ is more secure, but $\eta(bb)$ will again tend to be an upper bound if weaker $\Delta p > 1$ excitation rates replace the $\Delta p = 1$ rate due to filling of the $p_0 + 1$ shell. Occupation arguments also make the choice of p_0 in Eq. (9) a function of kT_e . In this case, p_0 is related to ΔE_s through Eq. (8), or Eq. (14) and (15) below, and obviously recombination radiation to the p_0 shell is suppressed due to the increased occupancy of the p_0 level for decreasing kT_e . Again, these considerations will be ignored and the restricted usefulness of Eq. (9) accepted for $kT_e \ll \Delta E_s$. The ambiguity in occupation also effects the choice of q for Eqs. (7), (9) and (10). Equation (1) can strictly reflect charge neutrality only if one ionic charge is found in the plasma. Since this is unlikely for most situations, the choice for q must represent some effective number of bound electrons and, as is the case for f , it will not display the actual complex dependence on kT_e , n_e , etc. As indicated in the discussion following Eq. (10), the use of Z^2 will tend to make this formula an upper bound. This restriction is somewhat less critically related to the occupancy, so the predictions of $\eta(ff)$ should be more uniform over a larger range of kT_e .

5) The effect of collisional relaxation of excited states is only included in $\eta(bb)$ through the parameter $\epsilon_r(bb)$. Collisional relaxation rates are proportional to n_e and spontaneous radiation rates are proportional to ΔE_s^3 for the line-radiation case. Hence, extrapolating Eq. (7) as determined for one set of conditions to larger n_e or smaller ΔE_s will result in underestimating the collisional relaxation and overestimating $\eta(bb)$. Similar arguments apply to $\eta(fb)$. A more detailed analysis of this problem can be constructed from the information provided by Ref. 9.

6) The line and recombination radiation are characterized by a single value for ΔE_s . The actual range of transition energies implied by ΔE_s increases, on a relative basis, as p_0 increases. Hence, the application of Eqs. (7) and (9) become more questionable as one proceeds from considering K-shell to L-shell

to M-shell etc. radiation. Further, convenient relationships between ΔE_s , Z , and p_0 are desired. Since high accuracy is not required, the hydrogenic relationship

$$\Delta E_s = 27.21 \left[\frac{(Z-s)^2}{2p_0^2} - \frac{(Z-s')^2}{2(p_0+1)^2} \right] \text{ eV} \quad (14)$$

is useful, where s, s' are screening parameters appropriate to the p_0 , $p_0 + 1$ levels.¹⁶ Equation (14) will in fact only be used for the $p_0 = 1$ or K-shell case. A more accurate procedure is to rewrite Eq. (14) in the form

$$\Delta E_s = I(p_0, Z, q) \left\{ 1 - \left[\frac{p_0(Z-s')}{(p_0 + 1)(Z-s)} \right]^2 \right\} \quad (15)$$

where $I(p_0, Z, q)$ is an ionization energy for an ion described by the indicated parameters. Ionization-energy data for all atoms and ions are available in convenient form.¹⁷ Equations (14) and (15) are written for the line radiation case. The appropriate form for recombination radiation is obtained by dropping the second terms in Eqs. (14) and (15). Bremsstrahlung does not require a comparable relationship. For convenience, values based on Eq. (14) for K-shell line radiation and Eq. (15) for L- and M- shell line radiation are presented in Table I. Ground-state configurations for 2-, 7-, and 19-electron ions were assumed for K, L- and M-shell radiation in constructing Table I. Different choices for these various shells give a measure of the increasing problems in going to radiation from higher shell that were mentioned in the preceding discussion.

A number of interesting predictions are indicated by Eqs. (7), (9), and (10). First, the efficiency for all three is proportional to Δt_p and n_e . Experimental control of Δt_p may be difficult, but n_e is proportional to the

square of the laser frequency, see the discussion following Eq. (1), and can be varied over a rather wide range. There are considerable experimental data for laser-solid target interactions and evidence supporting this prediction is outlined in the following section.

The temperature dependence of the efficiency for the three types of radiation is not the same. The optimum efficiency for line radiation occurs at

$$\alpha = 1.5 \quad \text{or} \quad \Delta E_s = 1.5 \quad kT_e \quad (16)$$

and at

$$\alpha = 0.5 \quad \text{or} \quad \Delta E_s = 0.5 \quad kT_e \quad (17)$$

for bremsstrahlung. The formula for recombination radiation, Eq. (9), shows no optimum as a function of α or kT_e . This behavior is, none the less, qualitatively correct. For example, if a condition like $kT_e \sim \Delta E_s$ is achieved to satisfy the occupation requirements of Item 4), and subsequently kT_e is somehow rapidly lowered, the recombination efficiency predicted by Eq. (9) increases like $(kT_e)^{-1.5}$. This mechanism has been proposed as a method for building an x-ray laser.¹⁸

The relative efficiency of the various types of radiation is of some interest. The ratio of bremsstrahlung to line radiation turns out to be

$$R_{ff} = 3.07 \times 10^{-5} \quad Z^2 \quad (\Delta E_s / \text{keV}) (\alpha f)^{-1} \quad [\epsilon_r(ff) / \epsilon_r(bb)] \quad (18)$$

and the analogous ratio for recombination radiation is

$$R_{fb} = 1.13 \times 10^{-3} (\Delta E_s / \text{keV})^2 \quad f^{-1} \quad e^{\alpha} \quad [\epsilon_r(fb) / \epsilon_r(bb)] \left\{ p_0 + 2 p_0^4 (2p_0 + 1)^{-2} \right\}. \quad (19)$$

If one ignores the presence of the ϵ_r ratio, takes $f = 2$, $p_0 = 1$ (K-shell radiation) and assumes the optimum condition for line radiation, Eq. (16), it is easily demonstrated that $R_{ff} \geq 0.3$ for $\Delta E_s \geq 20$ keV, $Z \geq 45$ and that $R_{fb} \geq 1$ for $\Delta E_s \geq 18$ keV. (See Table I.) This relative weakening of $\eta(bb)$ for $\Delta E_s > 20$ keV is caused by its proportionality to

$$(Z-q)^{-1} (\Delta E_s)^{-1.5} \sim \Delta E_s^{-2},$$

which follows from Eqs. (7) and (14). This scaling is qualitatively like the results of more elaborate calculations^{8,10} and experiment,¹⁹ where high frequency radiation appears to be suppressed relative to expectations.

Finally, the optical oscillator strength f is qualitatively like the number of electrons in the p_0 shell. See Items 4) and 6) presented in the previous discussion. Hence, the choices of f appearing in Eq. (7) for K-shell, L-shell, etc. fluorescence should be proportional to $2p_0^2$ where $p_0 = 1, 2, \dots$ for K-, L-, ... shells. On the other hand, if one desires a common ΔE_s from these processes with differing p_0 , Table I indicates that $Z-q$ must also increase. If the number of electrons bound to the target, q , is defined as number of electrons in shells with $p < p_0$ and kT_e is assumed to be fixed, the over-all effect predicted by Eq. (7) is that the L-shell is about twice the K-shell and about equal to the M-shell fluorescence. The recombination radiation is predicted by Eq. (9) to have the ratios 1: 0.8: 0.15 for K-, L-, and M- shell processes if one assumes the same conditions. Bremsstrahlung is proportional to Z , so for these conditions it becomes more important as one goes from K- to L- to M- shell mechanisms. This bremsstrahlung estimate may emphasize large Z too much as was discussed in Item 4). The above arguments indicate that for radiation with $\Delta E_s < 20$ keV, the best efficiency can be achieved by optimizing the experimental parameters

for L- or M-shell line radiation. Mechanisms involving the L-shell are probably preferred because of points raised in Items 3) and 6). Experimental and theoretical data ^{14,20,21} that in part justify these predictions are discussed in Sec. III.

III. Applications

Theoretical data from three different plasma configurations will be studied within the framework just presented. A considerable quantity of experimental data are available for laser interactions with solid surfaces, so only a sample set of these data, chosen to best test the results presented in Sec. II, will be discussed. Again, the object of the applications is to test the interpolation or extrapolation accuracy of the theory once the normalization constants have been assigned.

Uniform Preformed Plasmas: The plasma is assumed to be preformed by exploding wires⁵ or any other means.¹⁰ The plasma is uniform in density with a cross section equal to the laser spot size A and with a sufficient length to absorb all of the laser energy. The plasma may be confined by external means; see Ref. 22 and the citations contained therein.

The detailed computation presented in Ref. 5 conforms almost exactly to the stated requirements. They treat aluminum targets preformed by exploding wires. Equation (14) indicates that $\Delta E_s = 1.69$ keV for $(p_0 = 1, \Delta p = 1)$ radiation. This corresponds fairly well to the energies expected from H- and He-like $\Delta p = 1$ transitions in aluminum.⁵ Other lines leading to K-shell radiation, $(p_0 = 1, \Delta p > 1)$, contribute as do lines leading to lower photon energies, $(p_0 > 1, \Delta p \geq 0)$. Under conditions⁵ optimal for total radiation production, the line radiation is also optimized and the ratio of brems/recombination/line radiation is 1/5/31. Equations (18) and (19) predict this proportionality to be 1/3/100

for $\Delta E_s = 1.69$ keV radiation. (The ϵ_r terms were ignored.) In keeping with the motivation to preserve simplicity, the rather clear dominance of line radiation suggests that the use of Eq. (7) alone to parameterize the X-radiation data of Ref. 5 is a good approximation. The total radiation efficiency η , is therefore equated to $\eta(bb)$ in the following developments.

Parameter values appropriate to the data presented in Ref. 5 are given in the Case 1 column of Table II. Most of the values listed are taken directly from Ref. 5. Exceptions include q and f . The optical oscillator strength will routinely be equated to the number of bound electrons in the active shell, $2p_0^2$, and any adjustments required to this upper bound are assumed to be incorporated into $\epsilon_r(bb)$. Choices for q are based on the number of electrons in shells below the radiatively active shell. That is $q = 0$ for the K-shell radiation, $q = 2$ for the L-shell radiation, etc. The other extreme choice would be to add to this q the active $2p_0^2$ electrons. This ambiguity in satisfying the charge neutrality requirements of Eq. (1) is another aspect of the difficulties discussed in Items 4) and 6) given in Sec. II. The importance of this choice is minimized by the empirical normalization but it will have some effect on the resulting extrapolation properties.

Predictions based on these parameters are shown in Fig. 1, where J_0 is plotted versus J_1 , as the solid curves. The straight line with unit slope represents the optimum efficiency, $\eta = 0.23$, that can be expected. That is, Eq. (16) is assumed to be satisfied and the subsequent adjustment in V or A required by Eqs. (2) and (12) is implied once J_1 has been assigned. The remaining two curves in Fig. 1 represent the variation of the efficiency with J_1 for the two fixed spot sizes treated in Ref. 5. See the values for the radius of the laser spot size given in Table II for Case 1. The effect of $\epsilon_r(bb)$ is to translate the solid curves in Fig. 1 vertically and the

effect of ϵ_d is to change the values of (J_0, J_1) for which the straight line becomes tangent to the curve. The shape of the curves is unchanged by the choices of ϵ_d or $\epsilon_r(bb)$. This flexibility is severely tested by the broad range of parameters considered in Ref. 5. Indeed, the suggestion and interpretation of the plot shown by Fig. 1 is about all that one might expect. The quantitative agreement is not particularly good, especially for conditions far removed from the optimal, but it is acceptable for such a simple model. See the closing discussion in Sec. II for reasons that suggest the failure of this model for conditions remote from those that give rise to maximal line radiation. Additional tests with data of the type provided by Ref. 5 would be useful and interesting.

The quantitative data provided in Ref. 10 are not presented in a form that is easily translated into the context of the present model, but their summary observation that η decreases strongly with increasing hardness of the radiation is consistent with the results given here. The present model can be applied to the type of plasma being studied in Ref. 22, but their choice of parameters is more appropriate to radiation from the valence shell than to the present interest in inner-shell phenomena.

As a final step in presenting data for a homogeneous preformed plasma, the extrapolation of this theory to other targets, or general Z , and to L- and M-shell radiation is presented. The parameters chosen for this exercise are given in Table II. Data are presented under the assumption that optimal conditions, as discussed above, have been achieved. The efficiency for K-shell line radiation is given in Fig. 2 as a function of both ΔE_s and Z . The relationship between ΔE_s and Z is given by Eq. (14). Also, see Table I. Analogous results for L- and M-shell radiation are shown respectively in Figs. 3 and 4. Equation (14) was replaced by Eq. (15) in the L- and M-shell calculations.

These figures graphically demonstrate the rapid decrease in efficiency with increasing ΔE_s and the limits placed on ΔE_s through the limits imposed by Z .

The curves presented in Figs. (2) - (4) are accurately represented by $\eta = C(\Delta E_s/\text{keV})^{-2}$. The observed values of C are 0.67 for K-shell radiation, 1.18 for L-shell radiation, and 1.28 for M-shell radiation. Hence if everything else were equal, the efficiency for producing ΔE_s radiation increases with increasing p_0 . Note should be taken of the uncertainty in such a large extrapolation from the conditions where tests against more reliable models were possible and the discussion presented in Sec. II.

Hot-Spot Model: Reference 8 presents theoretical data for radiation from a sphere of uniform, stationary plasma with a radius r equal to the radius of the laser spot size. This plasma is surrounded by a colder plasma to which the hot plasma loses energy by conduction. This is called the hot-spot model by its authors. Considerable detail is incorporated into this treatment and one of the major results presented is the K-shell fluorescence efficiency as a function of J_1 . Hence it is again appropriate to equate the efficiency for producing ΔE_s radiation to $\eta(\text{bb})$. Reference 8 considers carbon, fluorine, and aluminum targets.

The adaptation of the above theory to the hot-spot model is a straightforward task and the resulting parameters are listed under Case 5 in Table II. The only real ambiguity arises in trying to incorporate the conduction effects that are included in the hot-spot model. Not recognizing that the conduction effects will reduce kT_e can be expected to be increasingly in error as Z increases. This is simply due to the increase in electron conductivity with increasing temperature. A model incorporating conductivity losses into ϵ_d could be constructed, but this seems beyond the spirit of the present approach.

The first solution to the problem in choosing the two free parameters is to use the value found in the previous application for ϵ_d and to adjust $\epsilon_r(bb)$ to roughly reproduce the maximum magnitude of η for the carbon case. This is equivalent to ignoring the conduction losses. The resulting predictions are shown as the broken curves in Fig. 5. The solid curves reproduce the data given by Ref. 8. The agreement is reasonable for carbon and fluorine but the aluminum prediction is considerably in error. The argument given in the above paragraph implies an adjustment of ϵ_d should correct this situation and the value $\epsilon_d = 0.4$ works quite well; see the dot-dash curve in Fig. 5.

The present theory could be made to fit the Ref. 8 data quite accurately by treating ϵ_d and $\epsilon_r(bb)$ as arbitrary constants. Used as such, it provides a reasonably secure interpolation device. The rather reasonable agreement with intuitive choices for these parameters indicates that extrapolation of the hot-spot model to other targets would provide bounds on the expected efficiency, and with a reasonable model for the conductivity losses incorporated into ϵ_d , might provide at least semiquantitative extrapolation data.

Solid Surface Model: The interaction of a laser with a solid surface is quite complex and a complete theoretical treatment is not yet available.¹⁹ One reason for the qualified success of theory is the existence of a large body of experimental data. No attempt will be made to provide a comprehensive review of this physics. Again, quantitative predictions are not possible but certain interpolation/extrapolation features appear useful and some interpretive insight is provided for the examples that are considered.

It is not possible to determine ϵ_d when Eq. (13) is applicable since

$$kT_e = \epsilon_d J_1^m / \zeta = C_1 J_1^m \quad (20)$$

is the operative relationship between kT_e and J_1 . Obviously, only the ratio $C_1 = \epsilon_d/\zeta$ and m can be determined if one is given values of kT_e for a range of J_1 or, equivalently, ϕ_0 . The quantities C_1 and m may be quite dependent on parameters defining the characteristics of the laser. At the same time the experimental observation that kT_e is independent or very weakly dependent upon the target material for a given set of laser parameters supports the use of Eqs. (2), (11) - (13), and (20).^{14,21,23}

The impossibility of determining ϵ_d leads to rewriting Eq. (7) in the form

$$\eta(bb) = C_2 \alpha^{1.5} e^{\alpha(Z-q)^{-1}} (\Delta E_g/kcV)^{-1.5} \quad (21)$$

where

$$C_2 = 6.58 \times 10^{-11} f \epsilon_r(bb) \epsilon_d (n_e/cm^{-3}) (\Delta t_p/sec). \quad (22)$$

Equations (21) and (22) have the merit of lumping together the parameters with greatest uncertainty and consequently expedites the following discussion. The following discussion concentrates on the production of line radiation so the obvious analogues for Eqs. (9) and (10) will not be presented.

Note that values of C_2 can be deduced for the previous applications. These values are given in Table III.

The experimental data from Ref. 21 are reproduced in Fig. 6. They represent the measurement of radiation production from a series of solid materials with nuclear charge Z for a fixed set of laser parameters. The value $kT_e = 70$ eV applies to all of these data. The three different curves result from detectors sensitive to different ranges of ΔE_g ; see the figure caption. The three dashed curves are from Eq. (21), for K-, L-, and M- shell radiation reading from left to right. Normalization values, C_2 of Eq. (22), are given

in Table III. The vertical dotted curves represent the Z -dependence of the detectors efficiency for ΔE_s radiation from the three shells. That is, a target to the left of the vertical line produces ΔE_s radiation at an energy too low to be detected while a target to the right will produce detectable radiation at the relative intensity indicated by the dashed curves. The peaks formed by the intersection of the dotted and dashed curves is an obvious idealization of the shape of the peaks due to line radiation. The essential features of Eq. (21) are the Z -values at which the peaks occur, this dependence on Z as the detector energy response is changed, and the relative magnitudes of the peak heights. An increase in the peak widths as one goes from K- to L- to M- shell radiation is also predicted. Figure 6 indicates these properties are correlated best for the K-shell case and the agreement is generally acceptable.

A number of inferences due to this theory can be made. For example, if this experiment were repeated with a larger kT_e the solid curves would be expected to move closer together, and vice versa. That is, the dashed lines become less steep with increasing kT_e . The positions of the peaks with respect to Z will not change as kT_e changes since the locations of the dotted lines depend only on the energy range of the detectors. The ratio of peak height to the adjacent minimum value should decrease as the detector response is limited to larger energy ranges. This is due to the strong decrease in line radiation with increasing ΔE_s , relative to recombination and brems radiation, that was discussed in Sec. II.

Experiments similar to the one described in connection with Fig. 6 have reported the efficiency of radiation production for differing lasers and/or laser parameters.^{20,23,24} These data will be fit to Eq. (21) with the object of testing Eq. (22) for consistency in going from K- to L- to M-shell

radiation within a given experiment and for its ability to correlate the C_2 values found for different experiments. The results of fitting Eq. (21) to these data are summarized in Table III. The values deduced for C_2 from the earlier applications are also given. If one assumes that the only change in C_2 for going to K- to L- to M-shell radiation in a particular experiment is in the values for f , then the ratios of C_2 are predicted to be 1:4:9 for K- to L- to M-shell radiation. The experimental ratios are 1:3.5:6.3 for Ref. 24, 1:4.9:3.8 for Ref. 23, 1:3.4:1.4 for Ref. 21, and 1:0.3 for Ref. 20. The K- to L-shell experimental ratios are in acceptable agreement with the prediction but the M-shell experimental ratios are 1.4 to 6.4 times smaller than the prediction. The disparity in the M-shell ratios is not unlike that found in a more detailed corona-model calculation.²⁰ Considering the qualitative character of the theory, uncertainties in the experimental maxima locations, and the great range of experimental parameters, this is reasonably close to the ideal result of having one value for C_2 that scales according to Eq. (22) in going from K- to L- to M-shell processes for a given experiment.

Comparison of the C_2 values for K-shell radiation from the various experiments shows that the preformed plasma of Ref. 5 is clearly the most efficient radiator. This conforms to intuitive expectations. According to Eqs. (1) and (22), and the scaling with laser frequency discussed in Sec. II, the Ref. 23 and 24 values for C_2 should be similar. They also should be 10^2 times larger than the Ref. 20 values and 0.43 times smaller than the Ref. 21 values. The observed values are 10^3 for the first case and the Ref. 21 values are smaller than the Refs. 23 and 24 values. It should be noted that the Ref. 21 experiment was performed for $kT_e \ll \Delta E_g$, see Table III, and that the discussion presented in Sec. II anticipates difficulties with this theory for conditions remote from those stated by Eq. (16). This could explain the failure of the

Eq. (22) scaling between the Ref. 21 values and the Refs. 23 and 24 values. However, the available experimental evidence does not clearly support the scaling laws indicated by Eq. (22) and further tests would be useful.

An implication of Eqs. (13) and (20) should be noted. The restriction $0 \leq m \leq 1$ seems plausible with $m = 1$ corresponding to the most efficient result. See the above discussion. The infinite-mass targets^{13,14} seem to produce $m \leq 0.35$. This could, in principle, be improved by going to a finite-mass target thereby replacing Eq. (13) with Eq. (11). The available information on finite-sized targets²⁵ is not too promising but additional studies with this problem in mind would be interesting. Another indirect method that accomplishes the same end is to prepulse the target and create a finite quantity of plasma that then becomes decoupled from the remaining target mass. This preformed free plasma is then the target for the main laser pulse. This design has been studied with encouraging results.²⁴

The final application of Eqs. (20) - (22) will be to a theoretical computation of laser-solid interaction.²⁶ One purpose is to show how this parameterization can serve as an interpolation/extrapolation tool for large-scale computer calculations that treat the hydrodynamic and radiation complexities in some detail.²⁶

The computation is for $1.06 \mu\text{m}$ radiation on a flat Ni surface. The values $m = 0.3$ and $C_1 = 0.11$ were determined by a rough fit of Eq. (20) to the data shown in Fig. 7. The independent variable J_1 could obviously be replaced by another such as W_0 or ϕ_0 of Eq. (12). The relationship between these variables is of no interest for this application. The code value for the Ni L-shell fluorescence energy was 0.9 keV and the recombination edge occurred at about 1.1 keV; values rather different from those expected and from those predicted by Eq. (15). The value $\Delta E_s = 1.0 \text{ keV}$ was used in this application.

The value $C_2 = 2.73$ was found by normalizing Eq. (21) to the code predictions for $J_1 = 800$ joules. The two sets of data taken from the code are shown in Fig. 8 and are described in this figure's caption. The $\odot$ data that just span the L-shell fluorescence and recombination radiation are both more appropriate to and better described by Eq. (21).

This parameterization indicates that the efficiency for ΔE_g radiation has peaked at 0.04 for $J_1 = 500$ joules. Further numerical data may indicate revisions are necessary, but the available data are reasonably well represented. Extrapolation to other targets or situations can be made by utilizing the scaling indicated by Eq. (22). Limitations on this procedure are indicated by the applications given above. The m , C_1 coefficients of Eq. (20) must be considered unknown functions of the laser spot size, Δt_d , etc. but further numerical tests of the relationship provided here would be of much interest.

IV. Conclusions

The relatively crude but algebraically tractable model proposed here proved successful as an interpolation/extrapolation device in a number of contexts. The major value of the model is to give guidance in planning further experiments or large-scale numerical investigations. This model's predictions for improving the efficiency of and limitations on the production of radiation by laser driven plasmas, were discussed in detail. Some anticipated qualifications based upon the limited physical content of the model were also presented.

One of the most interesting predictions is the proportionability of the line-radiation efficiency to ΔE_g^{-2} . If this prediction is even qualitatively correct, it seems very unlikely for a laser-driven low-density plasma to be a competitive source to other schemes, such as traditional x-ray tubes or

bremsstrahlung converters, for $\Delta E_s > 20$ keV. Certain properties of the Z and ΔE_s dependence of the radiation efficiency observed in a number of experimental studies were successfully correlated. Evidence was reviewed for the proportionality of the radiation efficiency to number of electrons in the radiatively active shell and to the square of the laser frequency. Some support was noted, but additional tests would be useful.

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Table I.

Typical values for ΔE_s are shown to display the Z-dependence of line radiation from the K, L, and M shells. See Eqs. (14) and (15) plus the discussion following these equations.

ΔE_s / keV						
Z	K-shell	L-shell	Z	K-shell	L-shell	M-shell
6	0.352		40	16.2	2.56	
9	0.804		45	20.6	3.29	0.463
13	1.69		50	25.4	4.12	0.630
15	2.26		60	36.6	6.06	1.03
20	4.03	0.562	70	49.8	8.35	1.52
25	6.32	0.920	80	65.1	11.1	2.14
30	9.11	1.36	90	82.4	14.2	2.87
35	12.4	1.92				

Table II

Values for the parameters appearing in Eqs. (1) - (12) are listed for the various applications discussed in the text. Cases 1-4 are discussed in the Uniform Preformed Plasmas Section and Case 5 is discussed in the Hot-Spot Model Section.

	Case 1	Case 2	Case 3	Case 4	Case 5
p_0	1	1	2	3	1
Z	13	Z	Z	Z	6,9,13
q	0	0	2	10	0
ϵ_d	1.0	1.0	1.0	1.0	1.0 (0.4)
n_e	10^{21}cm^{-3}	10^{21}cm^{-3}	10^{21}cm^{-3}	10^{21}cm^{-3}	10^{21}cm^{-3}
r	0.03/0.05 cm	--	--	--	0.0023 cm*
d	$2.5\text{ cm}^\dagger$	$2.5\text{ cm}^\dagger$	$2.5\text{ cm}^\dagger$	$2.5\text{ cm}^\dagger$	--*
Δt_λ	10^{-9} sec	10^{-9} sec	10^{-9} sec	10^{-9} sec	$2.5 \times 10^{-11}\text{ sec}$
Δt_p	10^{-9} sec	10^{-9} sec	10^{-9} sec	10^{-9} sec	10^{-9} sec
f	2.0	2	8	18	2
$\epsilon_r(\text{bb})$	0.124	0.124	0.124	0.124	0.013

$\dagger A = \pi r^2$ and $V = \pi r^2 d$, where d is the plasma depth.

* $V = (4/3) \pi r^3$

Table III

The parameter C_2 , defined by Eq. (21) and determined by data from the indicated reference, is tabulated. The type of laser used to create the plasma is also indicated. The Ref. 5 value was deduced from the exploding-wire preformed plasma example and the Ref. 8 value pertains to the hot-spot model. The various quantities used to fit the experimental data from Refs. 20, 23, and 24 are also listed. The listed Z -values are near but not necessarily at the observed maxima. The peak due to M-shell radiation given by Ref. 20 was not treated because the observed maximum occurred for $Z \sim 47$ and the theoretical maximum is predicted for $Z \sim 60$. The experimentally determined temperatures are given in the last column.

Laser(Ref.)	C_2			$Z/(\Delta E_g/\text{keV})$			kT_e/keV
	K shell	L shell	M shell	K shell	L shell	M shell	
CO ₂ (20)	5.3-3	1.7-3	--	12/(1.44)	26/(1.00)	--	0.30
Ruby (21)	1.3-3	4.4-3	1.8-3	8/(0.633)	25/(0.920)	55/(0.823)	0.07
Nd-Glass(23)	3.0	14.7	11.5	12/(1.44)	26/(1.00)	52/(0.704)	0.365
Nd-Glass(24)	4.8	17	30	12/(1.44)	29/(1.26)	64/(1.22)	0.70
Nd-Glass(5)	16.3						
Nd-Glass(8)	1.71						

Figure Captions

- Figure 1. Predictions based on the parameters given by the Case 1 column in Table II are shown. The straight line corresponds to optimal efficiency, $\eta_1 = \eta(bb) = 0.23$. Curves 1 and 2 refer respectively to the $r = 0.05$ cm and $r = 0.03$ cm cases. The $\bigcirc$ data points are taken from Fig. 13 of Ref. 5 and these data should be compared to Curve 1. The $\square$ points were taken from the text of Ref. 5 and they should be compared to Curve 2.
- Figure 2. The efficiency for K-shell radiation, $\eta = \eta(bb)$, is shown for a uniform plasma consisting of a single material with atomic number Z . The nominal energy of the radiation is ΔE_s . This prediction corresponds to the maximum efficiency achievable for the choice of parameters listed as Case 2 in Table II.
- Figure 3. The efficiency for L-shell radiation, $\eta = \eta(bb)$, is shown for a uniform plasma consisting of a single material with atomic number Z . The nominal energy of the radiation is ΔE_s . This prediction corresponds to the maximum efficiency achievable for the choice of parameters listed as Case 3 in Table II.
- Figure 4. The efficiency for M-shell radiation, $\eta = \eta(bb)$, is shown for a uniform plasma consisting of a single material with atomic number Z . The nominal energy of the radiation is ΔE_s . This prediction corresponds to the maximum efficiency achievable for the choice of parameters listed as Case 4 in Table II.

- Figure 5. Data from the hot-spot model of Ref. 8 for the K-shell radiation efficiency from carbon, fluorine, and aluminum plasmas are shown as solid curves. The broken curves are the results from the present model with the parameters listed as Case 5 in Table II and $\eta = \eta(bb)$. The $-\cdot-$ is the same as broken curves but with ϵ_d replaced by the parenthetical entry given under Case 5 in Table II.
- Figure 6. The relative intensity, labeled ergs/sr, of radiation produced by ruby laser irradiation of targets with nuclear charge Z is plotted as $\odot$ for detector response to 0.6 keV or greater radiation, as Δ for 0.9 keV radiation, and as $\circ$ for 1.0 keV radiation. These experimental data are taken from Ref. 21 and the data points are connected by straight lines for visual purposes. The dotted and broken lines are theoretical curves discussed in the text.
- Figure 7. The effective kT_e is shown as a function of J_1 . These data are based on theoretical results from Ref. 26 for $1.06 \mu\text{m}$ radiation impinging on a solid Ni target. The solid line is a fit by Eq. (20) described in the text.
- Figure 8. The efficiency for producing radiation in a certain frequency range is shown as a function of J_1 . The $\odot$ data points are for $0.85 \leq h \leq 1.5$ keV and $\oplus$ are for $0.85 \leq h\nu < \infty$ keV radiation. These data are based on theoretical results from Ref. 26 for $1.06 \mu\text{m}$ radiation incident upon a solid Ni target. The solid curve is based on the present theory as discussed in Sec. III.

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