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TITLE PULSED LASER EFFECTS PHENOMENOLOGY

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Pulsed laser effects phenomenology

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ABSTRACT

A comprehensive overview of the phenomenology associated with the interaction of intense laser beams with matter is presented. The beam is assumed to be incident on a solid or liquid target located within a transport medium. The discussion is first categorized by the type of this medium; namely, vacuum, gas, liquid, solid or particulate. Then the dependence of the interaction is further classified by the laser flux, pulse length, wavelength and the target properties. The various classes of behavior are discussed along with the conditions for their occurrence. Classes discussed include: slow bulk heating, transparent vapor from the target surface, secondary energy transport to the ablation surface, laser absorption at the critical surface, shock induced blowoff, photoelectric cross section dependence on temperature and density, laser supported combustion and detonation, contained vaporization and Mie scattering.

1. INTRODUCTION

The various phenomena shown in the above diagram can all be induced by an intense laser beam. This paper gives an overview of these effects, explains the conditions under which they occur, and summarizes this in a figure in the final section, from which the above diagram is excerpted. Generally, only conditions are considered for which the laser is sufficiently intense to decompose, melt, or vaporize the target or transport medium. Laser target interaction appears complicated, largely because the parameter space is so large, both in terms of numbers of variables as well as the range of values of the variables. Many non-linear processes come and go throughout this parameter space. When the parameter space is systematically divided and the segments explored individually, much of the mystery disappears. In order to accomplish this it is crucial to keep track of all of the independent variables. For practical reasons, only judiciously selected combinations of these parameters are discussed, behavior in other regions can frequently be inferred from extensions of the phenomenology that is discussed. The discussion is limited to optical laser effects (where the laser photon wavelength range is about 0.25 μm to 10 μm and geometric optical lenses can be employed) except in Section 2.1.3.2 in which x-ray laser effects (where the wavelength is less than 0.25 μm) are discussed.

In general, the laser target interaction depends on the laser, transport medium and target characteristics. The important laser parameters are the wavelength, the flux on target (energy/time/area, sometimes called intensity), the temporal and

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spatial dependence of the flux and the angle of incidence. Sometimes it is convenient to refer to the dependence on fluence, which is the time integrated flux and to the dependence on energy which is the space integrated fluence. For simplicity, it is helpful to refer to the pulselength and beam diameter, usually with the assumption of constant, but sometimes specified, temporal and spatial flux dependencies. For given conditions, the discussion will begin with the start of the laser exposure and describe the evolution of the process with time. The exposure could be for a single laser pulse over a finite time or for a continuous wave lasting indefinitely. If the conditions at the start properly describe those set up from previous pulses, then the discussion is applicable to repetitive pulse exposures. There are many optical, thermal and hydrodynamic properties (which are generally temperature and density dependent) of the transport medium and target upon which the process is sometimes strongly dependent. However, in some regions, the process is essentially material independent; these regions are identified during discussion for the various conditions in Section 2.

The present understanding of laser target interaction has come from a combination of empirical data, analytical modeling and radiation-hydrodynamic calculations. Sometimes detailed microscopic behavior has to be measured in experiments to significantly advance understanding because macroscopic quantities frequently reveal little as a result of integrating factors and conservation laws. With the rapid advancement in laser technology, it is frequently important to be able to predict behavior under presently unobtainable conditions. Generally, the needed calculations can be done with existing, or improved, radiation-hydrodynamic codes which provide detailed information for comparison with data; however, generally these codes are necessarily large, complex, require large running time on large computers, need to be critically compared with available data to establish credibility, and provide only limited physical insight. Never the less, these codes play an essential role. Generally, the phenomenology within each limited region of parameter space can be analytically modeled given sufficient understanding of the process there. This usually gives the most physical insight and the best estimates of uncertainties in predictions; analytic work is also helpful in guiding what experiments and numerical calculations should be done next.

2. TRANSPORT MEDIUM

The nature of laser interaction with targets is strongly influenced by the medium in front of the target as to whether it is a vacuum, gas, liquid, solid or particulate dispersed within any one of these. Therefore, the interaction for each of these four categories will be discussed separately. The target is assumed to be a liquid or solid adjacent to the transport medium.

2.1. Vacuum transport medium

For targets in a vacuum, the laser flux determines characteristically different types of behavior. The value of the flux for different behaviors depends on wavelength and material properties as indicated below.

2.1.1. Low Flux

In this low flux regime, the target may be vaporized but the temperatures are low enough that the blowoff is not significantly ionized nor is the pressure high enough to cause shock wave effects. In this regime, the target has a certain reflectivity (or absorptivity which is one minus the reflectivity) that depends on the wavelength, material properties, surface condition and temperature; this determines what fraction of the laser flux is absorbed by the target. The absorbed energy is deposited over a depth determined by the skin depth (or absorption coefficient) for the laser photons. Thermal diffusion (which depends on thermal conductivity, specific heat and density and the temperature gradient) then transports this energy to greater depths. For some targets (e.g., metals) the diffusion depth greatly exceeds the skin depth at early times so that the process is controlled by thermal properties. For simplicity, it will be assumed that one or the other controls the process, however, in practice sometimes both will be important concurrently. Some heterogeneous targets (such as aerospace composites) may contain finite size material mixes with quite different diffusion to skin depth ratios, thus significantly complicating the analysis.

2.1.1.1. Semi-transparent target SLOW BULK HEATING. For semi-transparent (i.e., large skin depth compared to diffusion depth) targets, the temperature will rise in proportion to the energy deposition rate with an exponential decrease in temperature with depth determined by the absorption coefficient. Given sufficient exposure time and depending on thermal properties, the target will undergo one or more phase changes such as melt, vaporization, sublimation or chemical decomposition; this will start at the target surface because of the greater deposition rate there. Phase changes generally lead to dynamic, mechanical effects due to associated volume changes as discussed in following sections. Major complications arise for heterogeneous targets at this stage, which can result in ejecta of solid particles as discussed under Section 2.4. for a particulate transport medium.

2.1.1.2. Opaque target TRANSPARENT VAPOR. For opaque targets (i.e., small skin depth), the laser is absorbed in a small volume near the surface causing the number of photon interactions per target target atom (or molecule) to be relatively high. For long wavelength lasers, this just means a high heating rate. However, for short wavelength lasers this can result in significant photo-decomposition of the target.

2.1.1.2.1. Short wavelength. For short wavelength lasers (e.g., 0.25 μm or 5 eV photons), the photons may have sufficient energy to cause photodissociation of the target; that is, quantum absorption of a photon which breaks a molecular bond. If any of the reaction products are volatile and the rate is sufficiently high, then this process can be used to produce precisely controlled etching or cutting¹. At very high rates there will be associated thermal effects as discussed in the next section for long wavelengths.

2.1.1.2.2. Long wavelength. For long wavelength lasers (e.g., 10.6 μm or 0.1 eV photons), the photon energy is below the quantum absorption threshold so that photodissociation can not occur (however, collective photon effects occurring at very high fluxes are discussed in Section 2.1.3.1.1). In this case the situation is similar to that for semi-transparent targets except that the heating depth is controlled by thermal diffusion. This results in a fundamental difference because the temperature gradient driving the diffusion decreases with time. For example, the laser flux that the target will accommodate by diffusion without vaporizing is approximately inversely proportional to the square root of time. This character of diffusion establishes the threshold for ablation (either by vaporization or thermal decomposition of molecular compounds) both in terms of flux and fluence; this threshold does not depend on the wavelength except through the target reflectivity. Just above the ablation threshold, the ablated material is generally transparent to the laser beam allowing ablation to be sustained. Then the ablation rate is basically determined by the balance between absorbed flux and the product of the mass ablation rate times enthalpy change during ablation. The temperature, density and pressure in the ablated or blown off material can be calculated as a function of time and distance from the target from this model².

2.1.2. Medium Flux

The early stages of the process for medium flux is the same as for low flux. The essential distinction being made is that the laser intensity is now high enough to eventually cause plasma ignition, that is, to produce an ionized blowoff that strongly absorbs the laser beam by the inverse bremsstrahlung process (photon absorption by free electrons). The strong laser

absorption in the tenuous blowoff (with typical densities of 10^{-3} to 10^{-6} g/cm³) creates a hot plasma (a few eV to tens of eV temperature) that reradiates energy in all directions. The part of this reradiation that reaches the target is generally sufficiently intense to sustain the ablation process. However, it appears that under certain conditions the reradiation intensity may be too weak or may be blocked by the intervening plasma so that ablation is cut off, which will lead to oscillatory behavior because of the resultant drop in plasma density and thus laser absorption. Special tables of laser absorption coefficients and radiation opacities have been developed to improve the accuracy of calculations involving this secondary energy transport process³.

The plasma ignition process is complicated, and not fully understood, and in general involves conditions of non-local-thermodynamic equilibrium; however, simple modeling has shown to be effective under some conditions⁴. The inverse bremsstrahlung cross section increases rapidly with the number of free electrons per unit volume and with the photon wavelength. So, the blowoff becomes opaque for long wavelengths at lower free electron densities than for short wavelengths. However, for short wavelengths, part of the absorption can be by photoionization (assisted by thermal excitation), which produces free electrons, thus easing the ignition process. For long wavelengths, the ignition is by thermal ionization (given approximately by the Saha equation) and is cascading (thus the term "ignition"); some absorption produces some heating which in turn produces more free electrons per atom and stronger absorption, etc. The process also requires a sufficiently large number of atoms per unit volume in the blowoff, which is proportional to the mass ablation rate, and which, in turn, depends on the flux onto the ablation surface.

For laser fluxes well above those needed to cause plasma ignition, the ignition occurs very early in the laser pulse, in which case insignificant error results from assuming that plasma ignition existed at the start of the pulse. Also, once ignition has occurred, depending on conditions, the process may no longer be dependent on reflectivity at the laser wavelength by the target because the plasma may become very absorptive so that few laser photons reach the target thereafter. In fact, in certain parts of this regime the process tends to be material independent; the laser beam is almost completely absorbed in the plasma, the plasma reradiates a flux approximately as if it were a black body onto the target and this flux determines a nearly material independent ablation rate (as discussed in Section 2.1.1.2.2.) because the enthalpy change is associated with such a high temperature change (i.e., about 10 eV or greater). This is illustrated in Fig. 1 by the merger of the curves for different wavelengths and pulselengths (the model is time integrated so that, near the threshold where temperature in some cases varies with time, the results are not necessarily realistic).

Figure 1. Calculations of temperature versus flux from the Plasma Energy Balance Model⁵ for CO₂ (10.6 μ m) and KrF (0.25 μ m) lasers with 1 and 100 μ s pulse lengths and an Aluminum target using absorptivities of 0.5 or 0.1 as indicated.

For the ablation rates and the temperatures and densities that exist in the blowoff for this regime, the pressure imparted to the target by the blowoff can be quite large (bars to megabars). This will launch shock waves into the residual target which can cause damage to it, generally through reflection into tension at low shock impedance interfaces with resultant debonding or spallation. Also, the specific impulse or momentum per unit area (which is the integral of pressure over time) imparted to the target can be large enough to cause structural deformations by bending, cracking, etc. The response of targets to pressure and impulse can be calculated using hydrodynamic and finite element codes.

For laser applications designed to produce these deformations, the laser induced specific impulse is an important characterization of the process because of the strong influence of the momentum conservation law. Then, the impulse

coupling coefficient, defined as momentum per incident laser energy, (e.g., with units of dyne-seconds/Joule) is a good figure of merit for laser efficiency. In vacuum, this coupling coefficient, when considered as a function of flux or fluence while holding all other parameters fixed (such as pulselength, wavelength, and target) has a threshold per discussion in Section 2.1.1., reaches a maximum of about 1 to 10 d·s/J in the medium flux regime and tends to fall off in the high flux regime^{5,6}. At maximum coupling, about half of the absorbed laser energy goes into kinetic energy of the blowoff; this implies that at maximum, the energy per unit mass in the blowoff is approximately equal to one over the momentum coupling coefficient squared (i.e., about 10^5 to 10^7 J/g). The induced momentum is quite insensitive to the energy distribution within the blowoff mass, which allows simplification of calculations. Having a non-vacuum transport medium has a major influence on the coupling coefficient (by increasing the mass) as discussed in Sections 2.2 and 2.3. It is important to note that the photons impart negligible momentum to the target under the conditions being discussed and that the momentum of interest is equivalent to the sum by the product of blowoff mass increments times respective velocities.

2.1.2.1. Short pulselength. For short laser pulselengths, during which the blowoff does not have time to traverse distances comparable to the laser beam diameter, it can be assumed that the blowoff is ejected normal to the target. The blowoff velocity is proportional to the square root of the temperature (at 10 eV the velocity is about 2 cm/μs). In this regime, the modeling can be done in one dimension, which greatly simplifies calculations⁵. For the one dimensional regime, it is convenient to consider quantities per unit area (such as energy per unit area and momentum per unit area). Then, the maximum coupling, as stated above becomes 1 to 10 (d·s/cm²)/(J/cm²), which ties specific impulse to fluence. In this regime, for constant flux, about half of the momentum is applied during the laser pulse and half after; so, the peak pressure equals about half of the momentum divided by the pulselength. Combining this information with the coupling coefficient relates pressure to flux giving, at maximum, 1/2 to 5 (d/cm²)/(W/cm²). Also, for this situation, the energy per unit mass given above can be rewritten to relate mass ablation rate to flux; this gives 10^{-5} to 10^{-7} (g/cm²/s)/(W/cm²) or for a target density of 1 g/cm³, 10^{-7} to 10^{-9} μm/(W/cm²) at maximum coupling.

2.1.2.2. Long pulselength. For longer pulselengths, accurate calculations require detailed consideration of the two dimensional nature of the hydrodynamics of the blowoff and the radiation transport. This can be and is being done but the calculations are presently laborious^{7,8,9}. On the other hand, simple modeling of this situation gives approximately correct integral effects¹⁰. Recent experiments have been done in this regime with 1.05 μm wavelength photons and from 0.5 to 128 μs pulselengths¹¹.

For certain conditions in this regime, pseudo-steady state conditions tend to be set up early in the pulse and, afterward, the laser is absorbed at a location of about one laser beam diameter from the target with reradiation from this location sustaining ablation. Both the plasma and reradiation impinge upon the target outside the beam diameter and can cause significant pressure and ablation there. With metal targets, for example, there is generally a melt layer between the plasma and the remaining solid target which is extruded outward by pressure gradients within the plasma applied to the melted material thereby producing ejecta from the target.

2.1.3. High Flux.

The high flux regime is distinguished by short pulses (i.e., sub microsecond to sub picosecond) while the fluence may or may not be large. In addition to optical lasers this regime also contains x-ray lasers, which are discussed separately.

2.1.3.1. Optical laser At high flux, there are three classes of interest for optical lasers; namely, 1) very short pulselength (picoseconds or less) with relatively low fluence, 2) short pulselength with high fluence, and 3) semi-transparent targets at relatively low fluence.

2.1.3.1.1. Very high flux MULTI-PHOTON EFFECTS. This regime is distinguished by the presence of so many photons in so small a space over so short a time that the effects can not be adequately described by sequential photon-matter interactions. In the low flux end of this regime especially for long wavelengths, the collective effects of the photons provides an electric field of sufficient strength to break down surrounding matter causing ionization and subsequent effects from the released electrons. At the high flux end, interesting new physical phenomena have been postulated and measurements are beginning to be made with new bright source lasers that are being developed.

2.1.3.1.2. High fluence LASER ABSORBED AT CRITICAL DENSITY. This can occur in the Inertial Confinement Fusion regime where small fuel pellets are to be imploded by laser exposure with sufficient energy to cause fusion of hydrogen isotopes and produce a net energy release. The laser photons are resonantly absorbed in a small region of the target when the photons reaches the point where the laser frequency equals the plasma frequency. This is the point where the natural frequency of oscillation of the free electrons matches the electromagnetic field frequency of the photons and this happens at a certain number of free electrons per unit volume, called the critical density, which is inversely proportional to the photon wavelength squared. Energy absorption is in such a small mass that high energy (hot) electrons are produced and they are hotter for long wavelength because of the lower critical density. For long wavelengths, the hot electrons have sizable ranges compared to the pellet dimensions and can heat it throughout, which interferes with the imploding process, thus the interest in short wavelength lasers for fusion.

Laser absorption at the critical surface does not occur, except perhaps very early in the pulse, for medium fluxes because after a short time there is enough ionized blowoff in front of the target at densities below the critical density to absorb essentially all of the laser photons.

2.1.3.1.3. Semi-transparent targets HYDRODYNAMIC BLOWOFF For semi-transparent targets exposed to short pulselength lasers where the flux is not too high, it is possible to avoid either multi-photon or hot electron phenomena. In this case, the laser is absorbed exponentially over a sizable depth in a short time, which can lead to hydrodynamic blowoff.

In previous discussion, the blowoff has resulted from the expansion of decomposed or thermally vaporized target material. However, if a quantity of material is heated fast enough that thermal expansion can not take place during the heating, then high pressures will be created within the target. During subsequent expansion and pressure release, material can be ejected. In hydrodynamic terminology, the pressure release produces shock waves traveling at the material dependent velocity of a few m/sec, which cause front surface spall. This velocity sets the conditions for thickness and deposition time for this mechanism to occur. Since melted material has virtually no tensile strength, this generally means that under these conditions all melted material will be ejected, then the blowoff depth is equal to one over the absorption depth times the log of the deposited laser energy divided by the melt energy. The threshold of this hydrodynamic blowoff is where the deposited laser energy equals the melt energy, which is generally much lower than the vaporization energy. The momentum generated under these conditions can be calculated with simple modeling based upon the mass ejected and the energy deposited in it minus the enthalpy change to melt or vaporize it with an adjustment for redistribution of energy during hydrodynamic expansion. In this case, the maximum impulse coupling is approximately equal to one over the square root of the melt energy and the maximum in the coupling occurs at an absorbed fluence equal to two times the blowoff mass times the melt energy⁶. For a material with a melt energy of 1000 J/g, the maximum coupling would be 100 d-s/J.

2.1.3.2. X-ray laser As presently conceived, the x-ray laser necessarily has short pulselength^{1,2} which generally means relatively high flux. Fluences are considered that are from the threshold for blowoff up to many orders of magnitude higher. X-ray photon energies are assumed to be a fraction of a keV and up.

X-rays are absorbed by the photoelectric process and in contrast to inverse bremsstrahlung, the cross section for interaction is independent of temperature and density up to relatively high temperatures. For cases where the temperature is below this, the x-rays are absorbed exponentially with reasonably well known cross sections, especially for energies above a keV¹³. The cross section depends strongly on material atomic number. It also decreases rapidly with increasing photon energy, which causes the penetration depth to be relatively large at high energy. For example, the dose in carbon drops to

1/e in a distance of about 0.3 cm for a 10 keV photon; however, this distance is about 10^{-6} cm for 0.1 keV photons. For sub-keV photon energies, the maximum coupling coefficient is of the same order as for optical lasers incident on opaque targets, namely, 1-10 d-s/J. However, for higher photon energies, this value can be considerably higher because of the larger penetrations as discussed in Section 2.1.3.1.3 for hydrodynamic blowoff of melted material.

2.1.3.2.1. Low fluence The threshold for blowoff occurs at relatively low fluence and is caused by hydrodynamic ejection of melted material as described in Section 2.1.3.1.3. The analytical model referenced there applies for fluences up to those at which the cross section begins to be changed by target heating, which is discussed in the next section, even though, by this fluence most of the impulse results from vaporized, rather than melted material.

2.1.3.2.2. High fluence CROSS SECTION DEPENDS ON T AND p When the blowoff is heated sufficiently to thermally ionize the atoms, the photoelectric absorption cross section can change (either up or down), thus complicating the analysis. Also, at very high fluxes, the pressures and temperatures respectively can be of the order of a megabar and a hundred eV, in which case shock heating of the target and plasma reradiation need to be considered

2.2. Gas transport medium

For targets in a gas transport medium, the phenomenology is generally quite different from that for targets in a vacuum under conditions where the target would be decomposed, or thermally vaporized, dynamically. The reasons are: the gas provides a pre-existing medium that can fundamentally change the laser absorption process and the gas provides additional mass, M_{gas} (besides target blowoff, $M_{b.o.}$) for absorbing (or sharing) the deposited laser energy.

2.2.2. Long wavelength and/or high pressure gas. This regime was studied extensively in the 1970s^{14,15}. In this case, the laser flux is sufficiently small that, with no target, the laser would propagate through the gas without major attenuation. However, with a target, the laser quickly interacts with small surface imperfections producing multiple ionization points, which in turn initiate ionization of the gas. This ionization quickly spreads to cover the target. The ionized gas is opaque to the laser beam because of its inverse bremsstrahlung cross section; this terminates vaporization of the target, causing the mass of the blowoff to be near zero. The laser is absorbed in a front that propagates into the gas away from the target. The energy deposition in the gas produces a pressure wave that also propagates through the gas. The mass of gas into which the energy has flowed by the "end" of the process (i.e., when the pressures have dropped to practically ambient values) can be as much as 100 times larger than the corresponding blowoff mass that would be generated from a target in vacuum. This causes the momentum to be up to about 10 times larger, the blowoff temperatures to be much lower, the expansion velocity of the laser heated material to be considerably lower, and the pressures to be lower and last longer.

The details of this process differ considerably depending on whether the flux is low or high as discussed next¹⁵.

2.2.2.1. Low flux LASER SUPPORTED COMBUSTION. This case is similar to that of a chemical combustion front propagating through a gas following the ignition of burning at a disk with the exception that the energy deposited in the gas is from laser absorption instead of chemical reaction, thus the ascribed name, Laser Supported Combustion (LSC) wave. This occurs for relatively low fluxes where propagation velocity of the pressure wave in the gas

is faster than that of the "combustion" front (i.e., the combustion front moves subsonically).

2.2.2.2. High flux LASER SUPPORTED DETONATION. Similarly, this higher flux case is analogous to the detonation of high explosive where the laser energy deposition rate is sufficiently large that the laser deposition front propagates at the shock velocity so that the two fronts are coincident and the Chapman-Jouguet model used for high explosive modeling¹⁶ can be applied; thus the ascribed name, Laser Supported Detonation (LSD) wave.

2.2.1. Shorter wavelength and/or lower pressure gas IONIZED GAS NOT OPAQUE. For a given flux, at sufficiently short wavelengths and/or low pressure gases, the inverse bremsstrahlung cross section of the ionized gas described in Section 2.2.2. will not be large enough to strongly absorb the laser. Then, neither a LSC nor a LSD wave will occur. In this case, the phenomenology is more like that for targets in vacuum, with transparent vapor (Section 2.1.1.) or secondary energy transport (Section 2.1.2.) with the exception that the blowoff is slowed down and the densities kept higher through tamping and mixing of the blowoff with the gas. For experiments using a KrF (0.25 μm) laser under these conditions, the blowoff mass loss did not change between targets in vacuum and in air at one atmosphere of ambient pressure; however, the impulse coupling coefficient increased by about a factor of ten and the pressure pulse length was much longer¹⁷. For this case, the enhancement of momentum over vacuum is similar to that expected for LSC or LSD waves because the mass swept up during the process is similar, provided the observation time and target dimensions are sufficiently large to effectively integrate the total load produced.

2.3. Liquid or solid transport medium

For targets in a liquid or solid laser transport medium, under conditions for which target surface material is decomposed or thermally vaporized by the laser beam, the blowoff is contained in a definite volume by the transport medium. The phenomenology of this process is referred to as contained vaporization and the behavior differs greatly from that for similar laser exposures of targets in vacuum or gas.

The details of the laser absorption differ from that discussed in earlier sections because the blowoff is not as free to expand during the laser pulse. However, the integral effects are generally not strongly dependent on those details; many conclusions can be drawn simply from knowing the total energy that was absorbed at the interface. In the discussion below, it is assumed that this energy is known and that this energy is deposited in a time short compared to time for the subsequent hydrodynamic expansion, in which thermal and chemical processes play an important role. At high fluxes, shock wave effects will cause spallation, delamination, etc. as mentioned earlier; however, the discussion below will be limited to explanation of structural effects that happen on a longer time scale. Basically, under certain conditions, this longer process can lead to a large fraction of the absorbed energy going into work done, on the surrounding target and medium, by the expansion of the contained vapor. It is important to note that, in contrast to the situation for vacuum or gas transport mediums, conservation of momentum is not a valuable analytical tool because of the long times and the constraining forces surrounding the region of interest.

For opaque targets exposed to relatively high laser flux, the deposited energy density is well above the vaporization threshold. Assuming that the material is below the thermodynamic critical point, then the high pressures resultant from the energy deposition will cause expansion and the creation of a vapor cavity according to the equilibrium vapor pressure equation¹⁸. The pressure in the vapor cavity is approximately just equal to the energy per unit volume in the cavity. At this point, there are many concurrent processes such as thermal conduction away from the hot region, work continuing to be done by the high pressure vapor and further vaporization of the target as the volume of the vapor cavity grows. The interaction of the hot vapors with the relatively cold liquid or solid transport medium (which make up part of the vapor cavity wall) can be a very important additional process. Initially, both the energy in the cavity and the volume of the cavity are increasing so the pressure in the cavity depends on the specification of additional factors affecting the rate of change of these quantities. However, at some point no additional energy is entering the cavity and then the pressure will begin to fall. Finally, the cavity will stop growth when the pressure comes to equilibrium with the ambient pressure or with the restraining forces between the target and transport medium. The principal factor controlling this process (besides the restraining forces upon which work is being done) is the energy in the cavity. The choice of materials has a major influence

on this energy. Basically, this energy depends on whether the vapors are non-condensable or condensable as discussed below, with the distinction being whether the vapors respectively remain in the gaseous state or not at ambient temperature.

2.3.1. Non-condensable products. If the vapor products are non-condensable, either directly or through an exchange process, then the energy tends to stay in the vapor and a large fraction of the energy can go into work; for non-condensable vapors, the energy transport out of the cavity by conduction and radiation is relatively slow. If the initial vaporized target material is condensable, then this vapor tries to condense on the adjacent, cold, transport medium wall; thus providing rapid energy transport to this wall, which will generally cause it to vaporize. This exchange from primary vapor to secondary vapor is a very dynamic, thermo-chemical process that can happen very fast. If this secondary vapor contains non-condensable species, then much of the energy again will be trapped in the cavity keeping the pressure high and providing a large potential for work.

2.3.2. Condensable products. If the primary and secondary vapor species are all condensable, then the process can be quenched rapidly, thus producing only a very small amount of work. The quenching is accelerated by large surface area and large thermal conductivity, which allows the cavity surface temperature to rapidly drop to where the vapor pressure is below the value that causes displacement against restraining forces. Experiments have been done in which the work done by this process was reduced by a factor of one hundred by changing the transport medium so that only condensable products would be produced¹⁹.

2.4. Particulate transport medium

If the transport medium (or the target) contains particulate (in either vacuum, gas, liquid or solid), then the individual particles will act as scattering centers and they may or may not also absorb photons from the laser beam depending on their optical properties (as discussed in Section 2.1.1). For spherical particles at low flux (i.e., for constant optical properties and particle size), the effect on the laser beam is explained well by Mie scattering theory²⁰; at high flux, the types of effects discussed in earlier sections may influence the response, thus complicating the analysis. For arbitrary particle shapes the theory is much more complicated and the analysis is usually approximated from Mie theory. The Mie theory provides the basis for calculating the photon intensity in all directions; the behavior differs significantly depending on whether the particle circumference is small or large compared to the photon wavelength.

2.4.1. Particle circumference smaller than wavelength. When the particle is small compared to the photon wavelength, the Mie theory reduces to Rayleigh scattering²⁰. In this regime, for fixed particle size, the total scattering is inversely proportional to the fourth power of the wavelength, or for fixed wavelength, the total scattering is proportional to the fourth power of the particle size. Thus, the scattering of photons decreases very rapidly as the particles get smaller. However, those that are scattered tend to be scattered at large angles.

2.4.2. Particle circumference larger than wavelength. For opaque particles with a circumference about equal to or larger than the photon wavelength, the Mie theory gives equal values for both the scattering and absorption cross sections with each being equal to the geometric cross section of the particle; the total beam attenuation is calculated from the sum of these two, which is called the extinction cross section. In this case, for fixed wavelength, the total scattering is proportional to the second power of the particle size. Combining both small and large particle cross section behavior with the fact that the mass of the particle is proportional to the third power of the particle size shows that maximum beam attenuation per unit mass of particulate is obtained with particle sizes about equal to the wavelength. The scattering for large particles is peaked in the forward direction. For large targets compared to the beam diameter that are close to the scattering centers, these forward scattered photons will still reach the target.

From the point of view of the effect of the laser beam on the particle, when the particle is large compared to the wavelength, the particle can be thought of as a target in a vacuum, air, liquid or solid transport medium as discussed above. For semi-transparent (spherical) particles, the particles will focus the beam per geometric optics considerations, causing

higher laser intensities within the particle or in the transport medium immediately beyond the particle causing break down and ionization in these regions²¹.

3. SUMMARY

This paper has presented a "roadmap" for what conditions cause the various kinds of phenomena that occur when intense lasers interact with matter. Although, many different types of effects occur and the details can be complicated, the general behavior, when examined in specific regions where all relevant parameters are defined, follows patterns understandable in simple terms. Figure 2 presents the combined roadmap for reference purposes.

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Figure 2. Roadmap for laser-matter interaction phenomenology.