Preprint
UCRL-JC-141561

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This article was submitted to
18th American Institute of Physics International Committee for Future Accelerators Advance Beam Dynamics Workshop on Future Light Sources
Arcidosso, Italy
September 10-15, 2000

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

November 28, 2000

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R. W. Lee[a], H. A. Baldis[b], R. C. Cauble[a], and O. L. Landen[a], J. S. Wark[c], A. Ng[d], S. J. Rose[e], C Lewis[f], D. Riley[f], J.-C. Gauthier[g], and P. Audebert[g]

[a]L-399 Lawrence Livermore National Laboratory, Livermore, CA
[b]Institute for Laser Science and Applications / University of California, Davis
[c]Department of Physics, Clarendon Laboratory, Oxford University, Oxford, UK
[d]Department of Physics & Astronomy, University of British Columbia, Canada
[e]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, UK
[f]Physics Department, Queen's University Belfast, Belfast, Northern Ireland
[g]LULI UMR 7605 Ecole Polytechnique-CNRS/CEA-Université Paris VI France

Abstract: The construction of a short pulse tunable x-ray laser source will be a watershed for plasma-based and warm dense matter research. The areas we will discuss below can be separated broadly into warm dense matter (WDM) research, laser probing of near solid density plasmas, and laser-plasma spectroscopy of ions in plasmas.

The area of WDM refers to that part of the density-temperature phase space where the standard theories of condensed matter physics and/or plasma statistical physics are invalid. Warm dense matter, therefore, defines a region between solids and plasmas, a regime that is found in planetary interiors, cool dense stars, and in every plasma device where one starts from a solid, *e.g.*, laser-solid matter produced plasma as well as all inertial fusion schemes.

The study of dense plasmas has been severely hampered by the fact that laser-based methods have been unavailable. The single most useful diagnostic of local plasma conditions, *e.g.*, the temperature (T_e), the density (n_e), and the ionization (Z), has been Thomson scattering. However, due to the fact that visible light will not propagate at electron densities, $n_{e,} \geq 10^{22}$ cm^{-3} implies dense plasmas can not be probed. The 4th generation sources, LCLS and Tesla will remove these restrictions.

Laser-based plasma spectroscopic techniques have been used with great success to determine the line shapes of atomic transitions in plasmas, study the population kinetics of atomic systems embedded in plasmas, and look at redistribution of radiation. However. the possibilities end for plasmas with $n_e \geq 10^{22}$ since light propagation through the medium is severely altered by the plasma. The entire field of high Z plasma kinetics from laser produced plasma will then be available to study with the tunable source.

I. BACKGROUND

Since the late 1960's plasma-based research has moved toward higher density regimes. The advent of laser-produced plasmas and laser-based plasma diagnostics have fueled interest in the formation of plasmas at densities nearing solid density.

There are two separate areas where the 4^{th} generation sources, LCLS and Tesla, can play a critical role in moving this field substantially forward. The first is in the area of warm dense matter research, while the second is in the area of plasma spectroscopic techniques.

We note that whether we are interested in creating warm dense matter, performing Thomson scattering, or probing a plasma the LCLS/Tesla capability provides a major advance on any capability that exists with 3^{rd} generation sources. The key to the advance is the tunable, narrow band x-ray source with very short pulse duration. Since the individual bunch photon intensity is the essential quantity for all the plasma-based research, the comparison of the LCLS/Tesla to current synchrotron sources is best summarized by comparing peak spectral brightness. Indeed, one finds a 10 order of magnitude enhancement that will make the LCLS/Tesla a most promising source for plasma based research. The utility of the high repetition rate of other sources, *e.g.*, APS or ESRF, are not useful here since we require a single photon pulse to either heat, scatter, or probe matter that is transient. Indeed, to create solid matter that is at a temperature greater than 1 eV temperature while not expanding requires the LCLS/Tesla.

Further, to measure the Thomson signal in a dense plasma or the warm dense matter regime requires a Thomson probe, here the 4^{th} generation, with temporal duration that is short compared to the evolution of the system but long enough to probe the plasma collective modes. The LCLS with the nominal 200 fs pulse duration will be able to probe the electron feature, arising from the collective behavior of the electrons, for an electron density of 10^{22} cm^{-3} one finds that 1 fs is sufficient for collective response. However, the ion collective behavior will take on the order 100 fs leading to possibility that the collective ion acoustic modes will not be sampled appropriately. The evolution of the system will proceed on the order of a picosecond. This indicates that any probe of the system must have a pulse duration on the ps time scale.

Finally, the spectroscopic probing of high energy density plasmas requires a short pulse high energy source. For the source to be useful as a spectroscopic probe requires a spectrally tunable source for which the number of photons per mode must be on the order of unity. Photons per mode measure of the probe's ability to dominate a radiative transition that is required to provide observable signal and due to the high peak brightness the 4^{th} generation sources will provide this capability.

A. Warm Dense Matter

With a short duration pulse containing a substantial number of high energy photons one can generate solid matter at temperatures of ≤ 10 eV, *i.e.*, warm dense matter. The interest in the warm dense matter regime arises because in dense plasmas the atoms and/or ions will start to behave in a manner that is intrinsically coupled to the plasma. That is, the plasma starts to exhibit long- and short-range order due to the correlating effects of the atoms/ions. This intriguing regime where the plasma can no longer be considered a thermal bath and the atoms are no longer well described by their isolated atom behavior provides a tremendous challenge to researchers. In the limit of dense cool plasmas one obviously arrives at the threshold of condensed matter. Here the problem has changed from a perturbative approach to ground-state methods where complete renormalization of the atom/ion and it environment is essential.

From the prospective of plasma studies the defining quantity is the coupling parameter Γ, *i.e.*, the ratio of the inter-atomic potential energy to the thermal energy given by the equation:

$$\Gamma = \frac{Z^2 e^2}{r_0 kT} \text{ with } r_0 = \left(\frac{3Z}{4\pi n_e}\right)^{1/3}$$

where Z is the ion charge and r_o is the interparticle spacing given in terms of the electron density n_e.

The regions of interest span the density-temperature phase space going from modestly coupled ($\Gamma \leq 1$) to strongly coupled ($\Gamma > 1$), while bridging the transition regimes between solid to liquid to plasma.

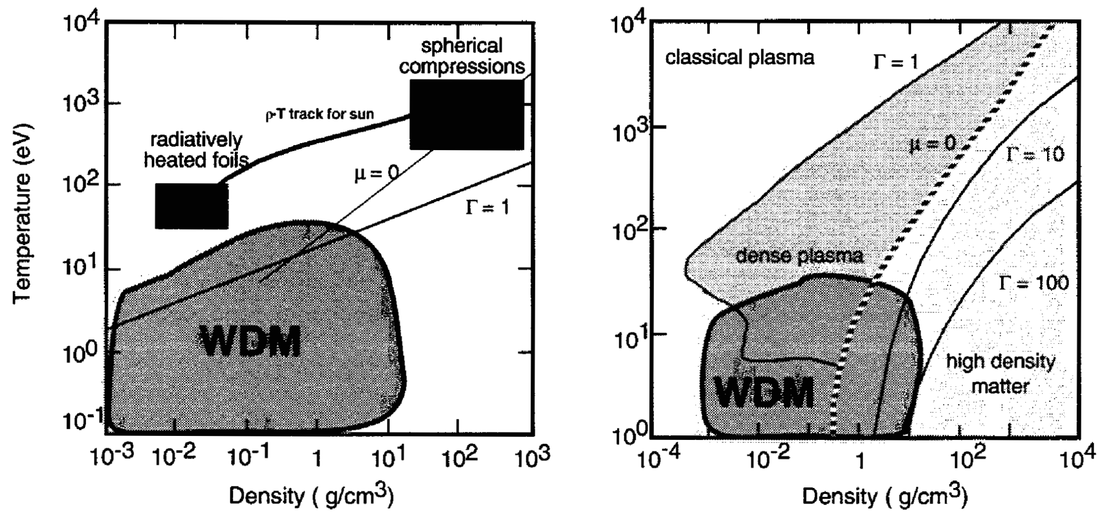

Figure 1. The temperature-density phase diagram for hydrogen on the left and aluminum on the right. The relevant regimes are noted, as are the various values of the coupling Γ. The regions greatest uncertainty are roughly noted by the black outlined areas. Also indicated is the region where degeneracy will become important: it is the region to the right of the line where the chemical potential $\mu = 0$.

In figure 1 above we show the region of the temperature-density plane where warm dense matter studies are important. Here we show the temperature (T) in eV versus the density (ρ) in g/cm^3 both for hydrogen, a low Z element, and aluminum, a moderate Z element. The region where the theoretical uncertainties are largest are those where the standard theoretical approaches fail and experiments are exceedingly difficult. The difficulty arises theoretically from the fact that this is a regime where there are no obvious expansion parameters, as the usual perturbation expansions in small parameters used in plasma phase theories are no longer valid. Further, there becomes an increased importance on density-dependent effects, *e.g.*, pressure ionization, as the surroundings starts to impinge on the internal structure of the ion or atom. Experimentally the study of warm dense matter is difficult, as the isolation of samples in this regime is complicated. Indeed, although the plasma evolution of *every* ρ-T path that starts from the solid phase goes through this regime and plays an important role in its evolution, trying to isolate warm dense matter remains a major challenge.

It has been exceedingly difficult to perform experiments in the warm dense matter regime, which is, simply, why we know so little about it. As a first step, one must create a well-characterized warm dense matter state; the second is to gain information on the state through experiments. The first step has been the problem: warm dense matter is not a limiting case of matter, *e.g.*, high- or low-temperature. When created in a laboratory environment, it does not tend to remain in a specified thermodynamic state for very long, making characterization difficult. The only other imaginable method to produce the kind of warm dense matter of interest here might be to use sub-30-fs laser pulses on sub-100-Å-thick foils and perform thermodynamic measurements on a few-fs timescale over extremely small spatial dimensions. To be able to do this on comparatively macroscopic samples with 4th generation sources will be a boon.

B. Plasma Spectroscopic Studies

There is great interest in the higher temperature dense plasma regime. Here the problem arises from the production of high temperature plasmas at electron densities in excess of 10^{22} cm^{-3}. In any experiment where a high intensity, *e.g.*, $I \geq 10^{12}$ W/cm^2, laser irradiates a solid target there will be a region of the solid that is hot and near solid densities. Lasers with wavelengths > 0.25 µm do not directly heat the solid as they can not propagate beyond the critical electron density ~ 10^{21} cm^{-3} x $(1\mu m/\lambda_{laser})^2$ [8]; however, heat flow from the surface efficiently generates the hot dense medium.[8] The spectroscopic information derived from these plasmas provides, on the one hand, diagnostic information about the plasma itself, while on the other hand we can investigate, using spectroscopy, our understanding of the mechanism at play in the creation of the plasma and the interaction of the atoms/ions with the plasma in which it is embedded. Here the LCLS/Tesla will provide two related and intriguing possibilities. First, there is the possibility to perform Thomson scattering on plasmas at solid density.[9,10] Second, we can explore laser pump-probe techniques for high density plasmas that have been used in low densities plasmas to measure line shapes, observe radiation redistribution, and determine the kinetics processes.[11,12]

1. Thomson Scattering

Thomson scattering provides an *in situ* measurement of the temperature, density, charge state, and collective behavior of the plasma. Indeed, the Thomson scattering diagnostic is directly related to the dynamic structure factor, $S(k,\omega)$, of the plasma and thus provides insight into the theoretical predictions from different theories. It is fair to say that in recent years each effort at diagnosing a higher density plasma, *i.e.*, higher than 10^{20} cm^{-3}, using Thomson scattering has led to new and important discoveries.[13] These experiments have, of course, been few since the constraints on the experiments are substantial. Here we believe that the 4th generation sources will provide a major advance in diagnosing dense plasmas. This is clearly a complement to the concept of creating warm dense matter, as Thomson scattering can provide a diagnostic of the warm dense matter conditions. However, the preconditions for the interpretation of the scattering data is that there is a valid theoretical model for the $S(k,\omega)$ in the high density regime, and this in itself will be a challenge. The tunable nature of the x-ray source, the high energy, bandwidth, the short pulse duration and, importantly, the very high peak photon flux make this source the only one that can address the Thomson scattering of transient plasmas.

2. Laser Pump Probe Techniques

The mechanisms involved in the formation of a plasma and the details of the kinetics processes can be illuminated by using a laser as a pump to selectively populate levels and thus redistribute radiation. In a particularly intriguing possibility one will be able to study the formation of laboratory x-ray lasers that currently depend on kinetics processes.[14] Thus, one could disentangle the plasma production from the inversion-forming processes that lead to the x-ray lasing. It is clear that numerous aspects of plasma spectroscopy have been severely constrained by a lack of data. The 4th generation sources will provide a substantial improvement in the development of our understanding of intrinsic line shape formation, level shifts, radiation transfer, and detailed kinetics processes.

In both of these areas the LCLS/Tesla will provide information that would not be obtainable with any other source. The combination of the short pulse length, the tunable wavelength, the repetition rate, and the energy per pulse will make the data derived from these plasma-based experiments a major advance in our knowledge in this area.

II. SCIENTIFIC PROJECTS

A. Creating and Probing the Warm Dense Matter Regime

The first scientific project comes in the area of warm dense matter research. This regime is accessed in all laboratory experiments where one creates a plasma from solid or near solid density targets; however, it is difficult to study this part of the plasma creation process in isolation. Rapid temporal variations, steep spatial gradients, and uncertain energy sources lead to indecipherable complexity. Indeed, although there has been much interest in this regime, witnessed by the literature on strongly coupled plasmas, there has been little progress.[15] The interest generated in laboratory experiments is mirrored in the astrophysical literature where the warm dense matter regime is found, for example, in the structural formation of large planets and brown dwarfs.[16,17,18,19,20]

The fact that the LCLS will allow the creation and probing of the warm dense matter regime in the laboratory, as discussed briefly below, will provide a set of data that will spark the field. The idea is simple but the impact will be vast, as the data obtained in the generation of the warm dense matter along an isochore, *i.e.*, a track of constant density, with subsequent probing along the release isentrope, *i.e.*, a track of constant entropy, will be unique and critically important for progress in the field. The importance of this data derives from the fact that to date the only possible method of generating warm dense matter is by shocking the material. The shock method provides information along the principal Hugoniot, that is, the locus of points in the pressure-density space that are accessed by a single shock – one point for each shock. Although this has been quite useful, it is a very limited set of data providing little information on the general behavior in the warm dense matter regime. Indeed, the amount of data that is currently available is so proscribed that one finds insufficient constraints on theoretical development. This can be illustrated by the curves in figure 2 where several predictions for an isochore of aluminum is presented in the temperature and density phase space. Note that the four theories shown in the figure *all* predict theoretical Hugoniots that fit the experimentally determined Hugoniots, but all differ rather dramatically along the isochore. As aluminum is the most studied material, figure 2 can be interpreted as the minimum degree of uncertainty in this field of research and makes obvious the need for experimental data in this regime.[21]

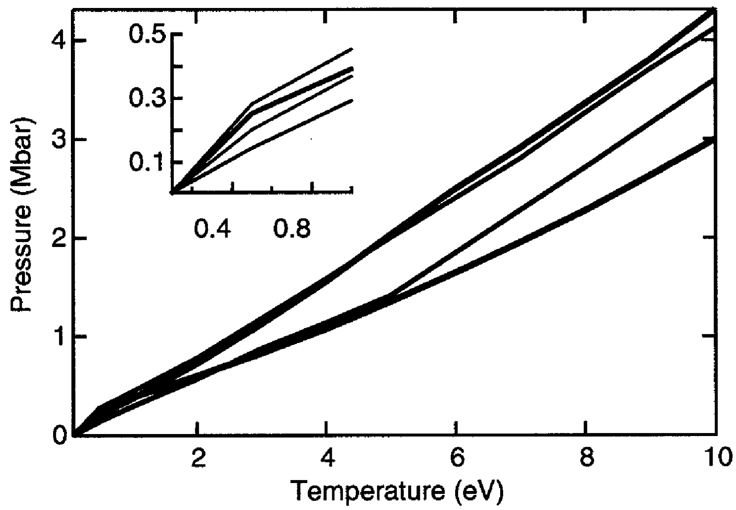

Figure 2. The isochore for aluminum in the warm dense matter regime for four theoretical models that all provide predictions that agree with the experimental point along a the principal Hugoniot. The inset shows the low pressure low density region expanded. Data derived from the LCLS will assist in motivating theoretical developments for this important regime.

B. Plasma Spectroscopic Studies

The 4th generation sources will be employed in plasma-based experiments to address the foundation of plasma creation in transition to hot dense matter providing a truly unique method to probe the spectroscopy of the hot dense matter. The probing of dense plasmas, whether these be warm or hot, will move to a new level of sophistication with the use of x-ray Thomson scattering. While, the active probing of the a hot dense plasma will be advanced by extending the methods of laser fluorescence spectroscopy that are employed in low density plasmas with visible lasers to high density using these x-ray laser sources.[22]

1. *Thomson Scattering*

One can extend the power of spectrally resolved Thomson scattering to the x-ray regime for direct measurements of the ionization state, density, temperature and the microscopic behavior of strongly coupled plasmas and warm dense solids. [10] This would be the first direct measurement of microscopic parameters of solid density matter, which could be used to properly interpret measurements of material properties such as thermal and electrical conductivity, equation of state (EOS) and opacity found in astrophysical environments as well as in virtually all plasma production devices.

Thomson scattering is characterized by the scattering parameter α, proportional to the ratio of the laser probe scale-length, λ_L, to the Debye length, λ_D, and the scattering angle Θ:

$$\alpha = \lambda_L/2\pi\lambda_D \sin(\Theta/2) = 1/k_L\lambda_D \sin(\Theta/2) \qquad (1)$$

For $\alpha < 1$, spectrally-resolved incoherent Thomson scattering provides information on the velocity v, hence temperature, and the directed flow of free electrons from the Doppler shifts experienced by scattered probe photons. For $\alpha > 1$, the collective scattering regime, the scattering is sensitive to temporal correlations between electron motion separated by more than a Debye length, hence the scattering is dominated by ion-acoustic and electron plasma wave resonances, the latter set by the Bohm-Gross dispersion relation.[8] The frequency shift of the resonance is dependent on density through the plasma frequency while the width of the resonances yields information on the wave damping rates. In the intermediate regime, *i.e.*, near $\alpha = 1$, the form of the high frequency electron plasma component depends strongly on both the electron temperature and density, providing a robust internal measurement of these basic plasma parameters, confirmed by spectroscopy.

In figure 3 we show the T-n_e regimes accessible by Thomson scattering with $\alpha = 2$ for various wavelength probes λ_L. Such Thomson scattering accesses regimes in which the Debye length is of order the probe wavelength. By switching from a visible laser probe at 5000 Å to an x-ray probe at, *e.g.*, 1.5 Å, we can effectively probe plasmas with Debye lengths of the order of the interparticle spacing or shorter (1 Å). Stated differently, for a given plasma temperature, we should be able to access a density that is 6-7 orders of magnitude higher than previously attempted. In particular, figure 3 shows that the solid density regime at $\sim 3\times10^{23}$ cm^{-3} crosses the strongly coupled plasma regime precisely where it is accessible by 1.5-12 Å Thomson scattering.

A schematic of the expected generic scattered spectrum features is shown in figure 4. Coherent scattering from tightly bound electrons (Z_{tb} per atom) will provide an unshifted peak at the probe wavelength whose intensity is proportional to Z_{tb}^2. Incoherent Compton scattering from weakly bound electrons (Z_{wb} per atom) should provide a second peak downshifted in energy by the order of $h\nu/mc^2$, with an intensity proportional to Z_{wb}. Thomson scattering from free electrons (Z_f per atom) should provide a dispersed spectrum centered on the Compton peak, with a spectrally integrated intensity varying as Z_f. The form of the spectrum will in general depend on the free electron density, n_e, free electron and/or Fermi temperature T_{Fermi} and electron-ion collisionality ν_{ei}. Hence, by spectrally resolving the scattered x-rays we would gain access, for the first time, to an unparalleled source of information on warm dense matter.

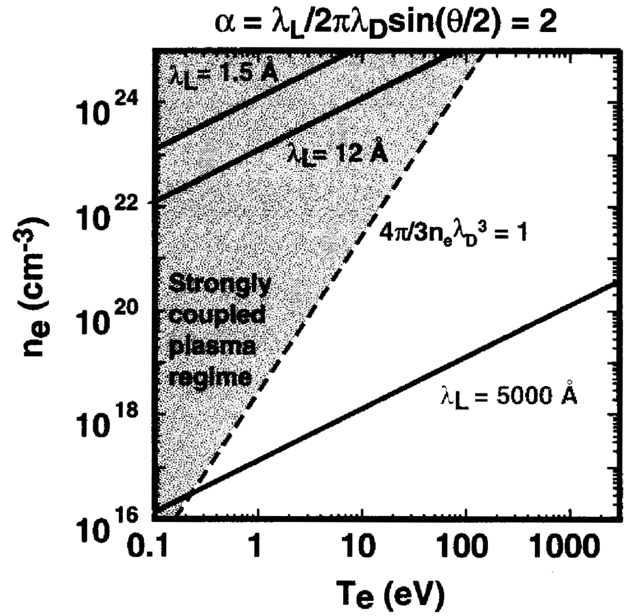

Figure 3. The temperature and electron density phase space indicating the non-ideal plasma regime by the shaded area. In the non-ideal region there is less than one particle per Debye sphere, thus leading to a breakdown in the Debye screening concept. The black dashed line indicates one particle per Debye sphere. Further, we indicate by solid lines the temperature and density at which the scattering parameter α is 2. One can easily observe that for the LCLS, whether at 1.5 Å or 12 Å, the dense regime is accessible, while for the nominal visible laser at 5000 Å one does not access the regime.

For example, we should be able to infer Z_f, Z_{tb}, and Z_{wb} from the relative importance of coherent, incoherent and free electron scattering contributions. This would allow us to discriminate between different ionization balance models used to define the EOS of these plasmas. [25] We should be able to infer the free electron temperature and density (and hence ionization state since the ion density is effectively hydrodynamically frozen) from the shape of the Thomson scattered spectrum for $\alpha \approx 1$, hence shedding further light on the equilibrium states of warm dense matter. We should be able to infer the plasma collisionality from the shape of the free electron spectral peak for $\alpha > 1$, hence allowing us to test the validity of various strongly-coupled statistical physics models.

We note that there is an ongoing effort to use laboratory produced soft x-ray lasers as Thomson scattering probes. Although there has been much progress recently reported it is important to review these efforts to understand fully the capabilities that will become available only when a 4th generation device is commissioned. There is now a laser-driven soft x-ray laser systems capable of producing megawatts of stimulated emission in the range of 100Å - 200Å from Ni-like collisional excitation schemes [26, 27].

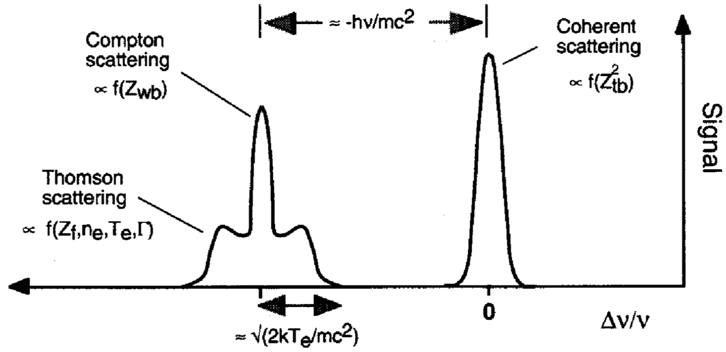

Figure 4. Schematic of spectrally-resolved x-ray scattering spectrum expected, with information provided by each feature noted. The definition of weakly bound and tightly bound electrons depend on their binding energy relative to the Compton energy shift. Those with binding energies (ionization potentials) less than the Compton shift are categorized weakly bound.

In a recent paper [28] calculations and theoretical analysis discussed the first application of a x-ray laser for probing hot, high-density plasmas ($n_e \geq 10^{23}$ cm^{-3}) using a Ni-like transient collisional excitation x-ray laser as a probe. Theoretical predictions were used to diagnose the electron temperature in short pulse (500 fs) laser produced plasmas. Necessary conditions were found for the probe intensity, spectral resolution of the spectrometer and sensitivity of the scattered x-ray detection system for the measurement of electron temperature.

In the analysis an x-ray probe is scattered from the high-density plasma produced by a subpicosecond laser pulse. The range of plasma parameters was $T_e \sim 50$ eV and $n_e \geq 10^{23}$ cm^{-3}, and the wavelength of the Thomson probe ($\lambda = 147$ Å) lead to values of $\alpha > 1$ for all scattering angles θ, thus remaining in the collective regime. The x-ray laser [26] produces a beam which is characterized by the coherence lengths on the order of 220 µm in the longitudinal direction and approximately 10 µm in the transverse direction. Both values are much longer than the correlation lengths of ion acoustic fluctuations produced in the plasma.

Using the expression for the dynamical form factor, $S(k,\omega)$, spatially averaged profiles of the Thomson scattering cross-sections have been calculated at different times. Early time scattering is characterized by the wide separation of ion-acoustic maxima due to larger temperature, but smaller scattering levels. At these early times, before the foil explosion, the effective scattering volume is smaller, reducing the overall scattered power. It was found that with an assumed instrumental resolution of $\Delta\lambda/\lambda \leq 10^{-4}$ the two ion-acoustic peaks may be differentiated and thus the T_e determined. Estimates of instrumental sensitivity show that approximately 70 photons are detected within an instrumental resolution channel when the solid angle collection and reflectivity of a large cylindrical optic, entrance slit transmission, multilayer grating reflectivity and typical back-thinned CCD quantum efficiency are included. Moreover, it was calculated that intensities near $I_p = 10^{12}$ W/cm^2 are required to probe these simulated plasmas, close to the current operating regime of the Ni-like transient x-ray laser system, *i.e.*, 2×10^{11} W/cm^2).

This effort is a step towards the future realization of a 4th generation Thomson scattering experiments. Although Thomson scattering using soft x-ray lasers can provide unique information from high-density plasmas, its application right now is severely limited to the microscopic plasmas created with high-power short pulse lasers. Further, the relatively large attenuation and refraction that occur in dense plasmas, as well as the inherently low shot rate will make these measurements difficult. Nevertheless, these experiments will prove invaluable to the application of x-ray Thomson scattering for the future sources.

We note in closing that there is the intriguing possibility of using part of the LCLS beam, for example the spontaneous background, to warm a sample and then use the LCLS to probe it with Thomson scattering. This is in distinction to the idea that we create the plasma using a standard long pulse laser system. The experiments using them LCLS as the heater and probe are much more demanding as the number of free electrons may decrease by at least an order of magnitude. Note that the number of free electrons is a matter of great controversy in this regime as the definition of "free" is open to debate. [29] Further, the need to delay the heater from the probe by x-ray optics creates addition losses of $\sim 10^{-4}$ yielding the total number of detected photons per shot on the order of ~ 1. While this is still detectable, and with the high repetition rate of the LCLS one can easily obtain spectrally dispersed data, the first experiments in both the warm dense matter regime and the plasma Thomson scattering at higher temperatures should be the independently pursued.

2. Laser Pump Probe Techniques

Since the creation of high density laser produced plasmas there have been virtually no quantitative *in situ* measurements of the kinetic rates or the populations. This is a major impediment to progress, as population kinetics of highly stripped ions is a complex problem. The complexity derives from the large number of states that must be considered in a model and the detail to which one must incorporate these states. The situation is made more difficult yet due to the fact that these plasmas tend to have rapid time evolution and large spatial gradients. [8]

Indeed, much of the effort to improve the situation has been focused on target design and advanced diagnostic development; however, the difficulties in determining the level populations or the kinetic rates remains. Therefore the interest, which comes from all areas involved with dense plasma studies and its underlying theoretical problems, *e.g.*, laboratory x-ray laser generation, laser plasma production, astrophysics, and inertial fusion, has never been met with substantial improvements in experiments.

The import of the 4th generation sources for high energy density plasma experiments is that one can use these x-ray sources to pump individual transitions in a plasma creating enhanced population in the excited states that can be easily monitored. The idea has been used in lower density plasmas with visible lasers and can, with the LCLS, be employed to advance the study of high density plasmas. [30]

Variations on the idea of pumping individual transition in high energy density plasma include the selective pumping of the wings of a line transition to observe redistribution within the line profile and pumping of selected transitions to attempt to understand the inversion mechanisms for the production of laboratory x-ray lasers. In all of these applications the tests of the theoretical developments in the areas of atomic processes, kinetics model creation, line shape formation, and x-ray gain studies would be the first of their kind as there are currently no available probes.

There are several constraints on the x-ray source for it to be useful as a laser probe of the high energy density regime. First, the probe must be tunable and this is easily satisfied. Second, the line width of the pump must be such that it can pump entire line profiles and also be capable – for studies of redistribution within line profiles – of pumping parts of the line profile. Again, these conditions will be readily met. Finally, we need to have a pump that can move enough population from one state to another so that the population changes can be monitored. This last requirement can be verified by looking at the radiative pumping rate, R_{LU}, due to the source compared to the spontaneous emission rate, A_{UL}, of the transition being pumped. This is proportional to the number of photons per mode and is given by [31]

$$\frac{R_{LU}}{A_{UL}} = 6.67x10^{-22}\frac{g_U}{g_L}\lambda_{\AA}^5 I_o^{laser}(\tfrac{W}{cm^2})\frac{[,]}{\delta_\lambda\Delta_\lambda} \qquad (2)$$

where the g's are the statistical weights of the upper and lower states, λ_L and I_o are the source wavelength and intensity. The δ_λ and Δ_λ are the bandwidths of the x-ray source and the line shape of the transition being pumped, while [,] represent the minimum of the two. Two important insights emerge when evaluating equation 2. First, if we conservatively assume $I_o \sim 10^{14}$ and $[,]/\delta_\lambda\Delta_\lambda \sim 0.001$ we find that the ratio is approximately 1 for λ_L of 10 Å. This number is at least 10^3 larger than can be obtained by using a plasma source to pump a transition. Second, the ratio does not increase with decreasing source wavelength, indicating that large numbers of photons per mode will not be available as we move toward shorter wavelengths. This is due to the fact that the spontaneous rate has a strong inverse dependence on wavelength. Of course, matching, or at least controlling the source bandwidth can have salutary effects as indicated by equation 2.

The possibilities provided by plasma spectroscopic probing are illustrated with the simulation of an aluminum layer tamped on both sides with a thin layer of CH plastic irradiated by x-rays. [32] An undiluted radiation field emitted from the rear side of a 1000 Å Au target impinges on the Al foil, heating it uniformly. The Au foil is irradiated by a single 1 ns, temporally square-shaped pulse of 0.52 μm light at an intensity of $1.6x10^{14}$ W/cm^2.[33]

The emission spectrum will be the observable and it is shown in figure 5 at two times in the evolution of the plasma, one near the initiation of the x-ray pulse and the other at 18 ps later. The most notable feature is that there is a substantial increase in the hydrogenic transitions. For example, the Lyman α line at ~ 1724 eV which is unobservable in the He-like background emission without the LCLS pump, rises well above the background with the x-ray pump. Further the structure of the He-like resonance series starting at ~1598 eV and ending at the bound-free continuum near 2086 eV is substantially changed by the pumping. Indeed the Li-like satellite transitions seen on the low energy side of the He-like $1s^2$-1s2l transitions are substantially enhanced. The major effect of the pump, although it is tuned to a particular transition, is to cause photoionization due to the pump strength. The ionization of the Li-like stage and the pumping of population from the He-like ground state up to the H-like ion stage cause a slow recombination decay back towards the He-like ground state.

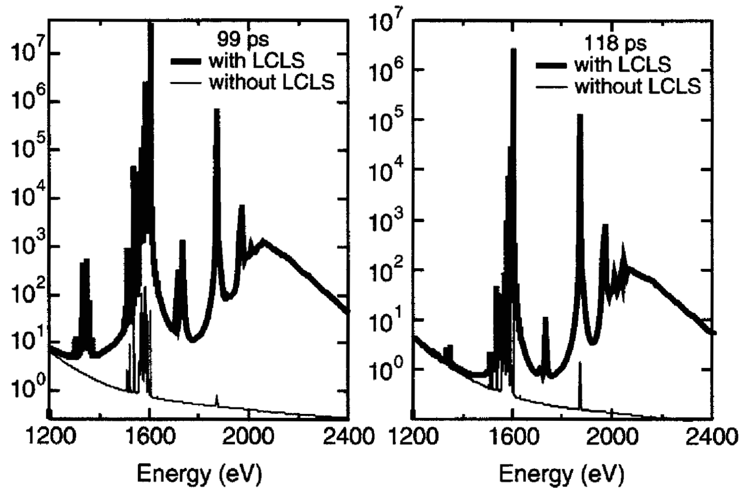

Figure 11. The logarithm of the emissivity versus spectral energy for two times in the evolution of an exploding aluminum foil. The emission from the plasma with no LCLS pump is the thin line while the thick line spectra indicate the emission when the LCLS pumps the He-like n =1 to n = 3 transition. The He-like emission, from, *e.g.*, n =2, 3 and 4 at 1598 eV, 1868 eV, and 1963 eV, respectively, increases substantially while the H-like n=2 emission at 1724 eV arises with the pump.

It is clear from the emission spectra shown in figure 5 that one could use a fraction of the LCLS pump to generate observable signals. The detailed information that can be obtained from these measurements would provide unique constraints on the complex processes necessary to construct a complete kinetics model for the highly charged ions. Indeed, we chose to use as an example the K-shell spectra as it is easily interpretable; however, the generation of L-shell and M-shell models are also of importance and raise the level of complexity substantially. Thus, one can understand the need for experiments that can provide basic information on the processes necessary to build kinetics models.

III. SUMMARY

The next generation of light sources will be a convergence of two experimental capabilities. One the one hand, we will have a light source with its the repetition rate and ability to serve a large user community, and on the other we will have a laser with its high peak brightness, coherence, and extremely short pule duration. The confluence of these two capabilities opens the door for an extremely novel set of experiment in the plasma and warm dense matter regimes. The discussion above has briefly touched on some of the preliminary aspects of these experiments. We point out that much more investigation is required.

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This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.