Radiative Properties of Hot Dense Matter

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THE RESULTS OF SIMULATIONS AND EXPERIMENTS DESIGNED TO STUDY RADIATIVE TRANSFER IN DENSE PLASMAS

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ABSTRACT

In this paper, we develop a scheme and discuss the tools necessary for the systematic study of radiative transfer in hot dense plasmas. We propose that an optimal plasma environment can be created by heating a layered target by x-rays. The design and analysis of experiments on such a plasma are possible with computer simulations now available. A synthetic spectra from a radiative transfer code, ALTAIR, which is capable of treating the complex line transfer occuring in the plasma, is given to illustrate the power of such computer simulations. We also present preliminary measurements of the angular distribution of x-ray radiation from the rearside of a thin foil target that could be used as a source of x-rays to create a plasma.

1. Introduction

The study of radiative transfer in laser-produced laboratory plasmas has remained a formidable problem both experimentally and theoretically. The subject has traditionally been treated as a subordinate to the goals of programs such as inertial confinement fusion and x-ray lasers, however here, we are concerned with plasma conditions that are optimal to study the phenomenon of radiative transfer itself. In this paper, we present a detailed simulation and discuss the experiments which are essential to attain a more sophisticated understanding of radiative transfer in a hot dense environment.

To study radiative transfer requires that the plasma exist in a restricted temperature and density regime. On one hand, the plasma should be dense since the opacity of the plasma is exponentially dependent on the density. But on the other hand, if it is too dense the plasma is not in a radiatively dominated regime because the collisional decay rate will dominate the radiative decay rate. In the ideal case, the spectroscopic analysis of such a plasma is greatly simplified if the plasma has both a constant temperature and a constant density which do not vary in time during the measurements. The plasma must satisfy a compromise of these demands and exist in a geometry which allows the maximum access for the diagnostics.

2. Target Design

To create such a plasma, we propose the use of a solid target that is irradiated by an intense x-ray source. The target will be called a "sandwich" and its design enables systematic variations of parameters that will affect the radiative transfer. The sandwich discussed here is a three-layered target in which a tracer foil is placed between two layers of a lower Z material that act as tampers. The typical sandwich is a tracer foil of aluminum, placed between two layers of plastic. It is heated by x-rays provided by a separate high-Z laser-irradiated foil. The inner foil of the sandwich, the tracer, becomes the plasma of interest which is modeled.

The advantage of using an x-ray source for plasma formation is two-fold. First, the x-ray drive is separate and can be standardized so that it does not critically depend on the uniformity of the laser irradiance. More importantly, unlike the absorption of optical laser light which occurs primarily at the critical density surface, the absorption of x-rays increases in the target as a smooth function of the optical depth. Thus, the x-ray heating of a sandwich described above can create a plasma without sharp temperature and density gradients.

A hydrodynamics code was used to model the expansion of the cold sandwich due to an x-ray source. The radiation drive spectrum was assumed to be a typical Au x-ray spectrum which peaks in the N and O bands. The input x-ray spectra were from a plasma created by a 0.53 µm laser, at an intensity of 10^{15} W/cm^2, having a flat-topped pulse with a duration of 1 ns. The time-resolved spectra are based on the measurements by D. Kania of the x-ray spectrum with a set of filtered diodes.[1]

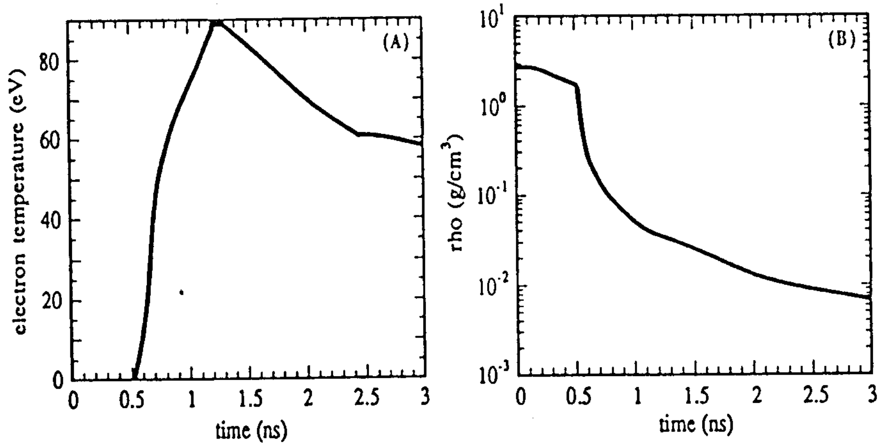

Fig. 1 The temperature profile (A) and the electron density profile (B) of a sandwich target, 1000 Å of Al coated on either side by 1 µm CH. The difference in the profiles taken at the the center of the tracer and at its interface with the CH tamper are negligible.

In Fig. 1, we show the calculated temperature and density profiles of the standard target, 1000 Å Al coated on each side by 1 µm CH. The peak in the temperature occurs at the peak in the x-ray driving source. After rapidly rising during the laser pulse, the temperature is essentially constant. The mass density, on the other hand, rapidly falls after the initial shock and then falls more slowly after the end of the laser pulse. Since the photon mean free paths are less than one, the x-rays penetrate and heat the entire sandwich. Therefore, a typical characteristic of the plasmas created from an optically thin sample is its homogeneity in temperature and density throughout the tracer layer.

Changing the parameters of such a sample directly influences the plasma characteristics. An illustration of how different tamper thicknesses affect the density is given in Fig. 2. In the 3 µm case, we see the appearance of a density plateau. This plateau is due to the confinement of the aluminum expansion by the plastic. Since the whole sample is heated at the same time, the aluminum tracer layer can only decrease in density when the tamper has sufficiently ablated away. As the plastic tamper is increased in thickness, the density plateau lasts longer in time.

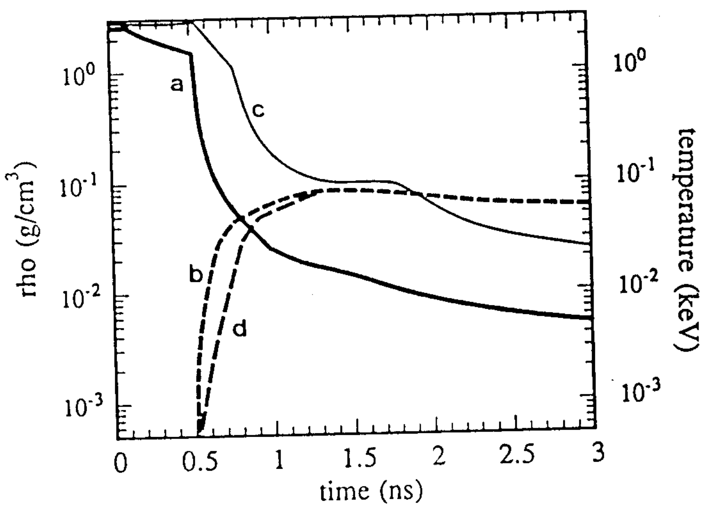

Fig. 2 The temperature (dotted lines) and density (solid lines) profiles for two different thicknesses of tampers: 1.) undertamped sample, 0.5 µm thick CH tamper (a,b), 2.) overtamped sample, 3 µm thick CH tamper (c,d).

The choice of the tracer material can be used to control the ionization balance. Since the total energy contained in the x-ray source emission is the maximum energy available to heat the sandwich, the maximum isoelectronic sequence attainable can be estimated by considering the equivalent black body temperature of the x-ray source. For instance, at typical laser energies and conversion efficiencies, gold x-ray emission will create an aluminum plasma having a maximum electron temperature of approximately 100 eV. Due to the nature of the non-LTE spectra accessible, in order to access a large variety of different ionization stages, the Z of the tracer layer must be changed.

Finally, the thickness of the tracer layer is also important. To study the details of radiative transfer, the individual line profiles of the spectra must be analyzed. With this type of target, the formation of the line spectra can be studied by changing the thickness of the tracer layer. As the thickness is increased, the plasma size and thus the optical depth of the plasma is increased.

3. Simulations of the Radiative Transfer in the Sandwich Target

With the present state of high speed computers and complex algorithms it is now feasible to perform the analysis of experimental studies and indeed design radiative transfer experiments. The purpose of this example is not to be a definitive study, but to demonstrate the capability and power of these codes. Two general types of codes are available: those that treat the radiative transfer in a bulk manner with a treatment of the opacity in frequency groups, and those that are capable of actually treating the radiative transfer of particular lines. An example of the first type of code is XRAD which is available at the Ecole Polytechnique and incorporates non-LTE opacity coefficients.[2] It can be used to map the general evolution of the plasma parameters such as the gradient of the electron temperature due to x-ray heating. A more detailed radiative transfer code available at Lawrence Livermore Laboratory is called ALTAIR, which treats line transfer by an equivalent two-level atom scheme.[3] The resolution of the lines means that it can treat the problem of photon escape in the wings of the line profile.

A simulation of the sandwich target was performed by ALTAIR. This code demands the input of an atomic model. For this simulation, an aluminum model, generated by the YODA/ADAM suite of codes, having the carbon-like through fully stripped ions was employed. The most detailed representations exist in the He-like and Li–like ionization stages in order to properly represent the recombination of the plasma due to dielectronic recombination. A more thorough description of the model is given elsewhere.[4]

The code can be run in one of two modes. The most rigorous test of the code would be to input the experimental x-ray heating spectra as a function of angle and wavelength. However, experimental data of this detail is not available. The second mode is to run the code as a hydrodynamics code postprocessor. This method of employing the code is valid if we assume that the detailed radiative transfer does not significantly affect the hydrodynamic evolution of the plasma. For our purposes, the second representation is sufficient since the radiative heating of a cold target is treated well enough in the hydrodynamics code to determine the temperature and density profiles.

The calculations show that since the temperature of the heated sandwich is less than 1 keV, the strongest emission is due to the L-shell transitions of Al (sub-keV x-rays). Figure 3 shows the detailed L-shell emission at two different times in order to demonstrate the evolution of the spectra. This figure shows that the qualitative structure of the spectrum changes and that a spectral resolution on the order of 500, and temporal resolution of the order 250 ps are needed to resolve these changes.

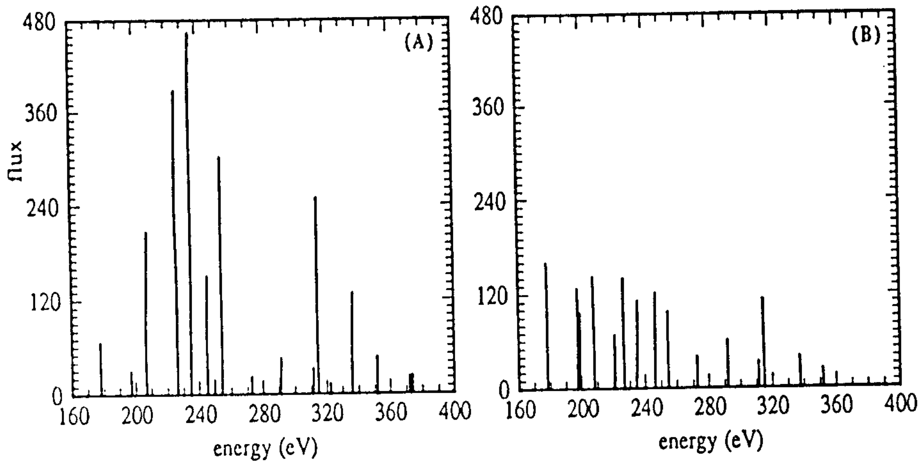

Fig. 3 The L-shell spectra predicted by a radiative transfer simulation: A) the spectrum at 1.5 ns, B) the spectrum at 3.0 ns. The 1 ns x-ray heating pulse is centered at 0.5 ns.

With a code of this type, a direct comparison with experiments discussed above can be made - the thickness of the tracer layer can be changed and ALTAIR can be used to study the line formation of the spectra as a function of its optical depth. More detailed simulations of different types of plasmas can reveal other significant parameters that are experimentally accessible and theoretically meaningful.

4. Angular Distribution Measurements

Significant uncertainties still exist that hinder comparisons between calculations and experiments. For instance, a variable that is necessary for the simulations, but experimentally unmeasured, is the spatial distribution of the radiative heating source. Such unknowns need to be determined before conclusive comparisons can be performed. The experiment described below is a first step to bridge this gap.

Recent experiments at the Rutherford Appleton Laboratory were performed to measure the angular distribution of x-ray radiation from the rearside of a thin foil target. Six beams were used in a cluster formation with random phase plates to improve the uniformity of the focal spot. The laser wavelength was 0.53 µm and the pulse duration was 600 ps at full-width-half-maximum. The energy on target ranged from 200 to 400 J. The typical target was a 2000Å Bi coating on a 1 µm substrate of parylene-E.

The primary diagnostics in this analysis were x-ray diodes which were filtered with 1 µm Fe and 60 µm Be. The response of the diodes allowed us to probe two broad-band channels: the sub-keV x-rays (0.2 to 0.75 keV) and the keV x-rays (> 0.75 keV). In order to maximize the angular coverage, the target was placed in three positions, 0° (perpendicular to the laser axis), +10°, and -10°. Thus, the data were taken at eight angles with respect to the normal of the target surface: 5°, 15°, 25°, 35°,45°, 50°, 60°, and 70°. Other supporting diagnostics included a flat-field XUV Harada grating streak camera which gave spectral information from 20 to 60 Å, and a flat-field response diode.

The diodes were made of a machined aluminum photocathode and a copper grid anode and give time-integrated signals due to the limited response of the diodes. A deconvolution of the signals was performed using a computer program wh'ch uses the x-ray data tables of McMaster.[5] A synthetic spectrum is modified until the resulting detector response is within 20 % of the experimental signal. The full details of the method of deconvolution are given in a paper by Alaterre et al.[6]

A synthetic spectrum was used to initiate the deconvolution routine since the channel responses are not constant and not enough diodes were available to resolve the spectrum. The general features of this spectrum were modeled after experimental spectra of the rearside emission of gold foils taken by D. Babonneau, et al.[7] The two main features are a black body spectrum to represent the N and O bands, and a gaussian peak, which sits on top of an exponentially decreasing continuum, to represent the M band emission.

The results in figure 4 indicate that the angular distributions for both regimes are approximately isotropic for angles greater than 25°. The conversion efficiencies are of the expected order .[1] Shots on other types of high Z targets (Sm, Sn) during the experiment are consistent with these results. The relative error of these measurements due to the filter transmission, the uniformity and integrity of the target coating, and the quality of the diode photocathodes is of the order of 35%.

One expects angular isotropy for the high energy x-rays since the plasma is optically thin to the radiation. However, for the soft-x-rays, one might assume the plasma would follow a Lambertian cosine law, since the plasma is optically thick to this radiation. A possible explanation for the isotropy is the deformation of the target during the laser pulse. If we assume that the foil moves with a velocity of 5×10^6 cm/sec the movement of the front surface could be as much as 50 µm, 10 % of the laser focal spot. In a spherical expansion, this implies a deformation of a planar focal spot to a sphere having a radius of 650 µm.

In addition, the results are also affected by the difference in angular dependence of the path length of photons through the plastic. Since the absorption of the x-rays depends exponentially on the path length, this difference for the soft x-rays traversing the plastic is pronounced. For the extreme case, the absorption is 30% greater at 5° than at 90°. However, the details of the deformation are dependent on laser irradiation conditions and therefore difficult to account for in the calculations.

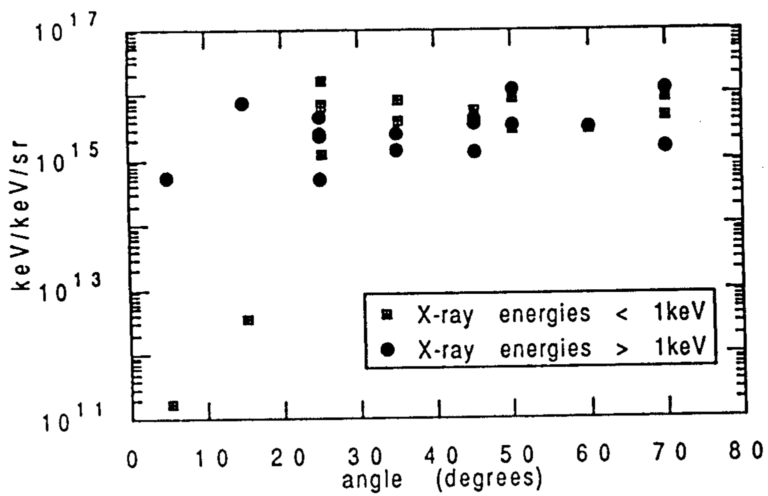

Fig. 4 The angular distributions of x-rays in keV/keV/sr versus angle measured with respect to the target plane (laser axis is at 90°). The distribution for x-rays < 0.75 keV is not corrected for the attenuation of the plastic substrate.

Although, the spectral bands are wide in this measurement, they are sufficient to indicate the nature of the problem. A complete measurement must be done with well-measured filters and more spectral bands before a conclusive characterization can be done. In future measurements, the spectral bands in the energy range of less than 500 eV must be well-resolved since the bulk of the heating will be due to photons in this energy range. For targets with thicker substrates, the change in the opacity of the heated material may also play a role.

5. Conclusions

First, the target and method to produce a plasma that is suitable for the study of radiative transfer is discussed. Using an x-ray drive spectrum will create a plasma of sufficient temperature to perform radiative transfer experiments. The primary advantage is that resulting plasma is not subject to turbulent hydrodynamical forces that create non-uniform plasma temperature and density gradients. Thus it is possible to isolate the study the physics of radiative transfer from the study of the physics of the laser absorption or turbulence. A sandwich target heated by x-rays is modeled, showing that the plasma conditions can be controlled by the fabrication of the target. Thus we can envision experiments, using a standardized x-ray heating source, in which the opacity of the plasma is systematically varied.

Second, the codes are now in place to be able to perform radiative transfer calculations in rigorous detail. Thus, plasma parameters identical to those in the experiments can be systematically varied in order to analyze experiments and devise new experiments that test our understanding of the radiative transfer.

Third, to benchmark the simulations and to develop a standardized, well characterized x-ray source, detailed information about the spectral and angular distribution of the heating x-ray source must be experimentally known. Preliminary experiments show that the effect of the substrate and expansion of a thin foil target can affect the distribution so that assumptions concerning its isotropy may not be justified.

We are now at a stage where the detailed study of radiative transfer can be experimentally and numerically performed. The simulations should be used in tandem with experiments to advance our level of understanding of radiative transfer in dense plasmas.

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ANALYSIS OF TIME- AND SPACE-RESOLVED NA-, NE-, AND F-LIKE EMISSION FROM A LASER-PRODUCED BROMINE PLASMA

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ABSTRACT

Advances in the efficiency and accuracy of computational atomic physics and collisional-radiative modeling promise to place the analysis and diagnostic application of L-shell emission on a par with the simpler K-shell regime. Coincident improvements in spectroscopic plasma measurements yield optically thin emission spectra from small, homogeneous regions of plasma, localized both in space and time. Together, these developments can severely test models for high-density, high-temperature plasma formation and evolution, and non-LTE atomic kinetics. In this paper we present highly resolved measurements of n=3 to n=2 X-ray line emission from a laser-produced bromine micro-dot plasma. The emission is both space- and time-resolved, allowing us to apply simple, steady-state, 0-dimensional spectroscopic models to the analysis. These relativistic, multi-configurational, distorted wave collisional-radiative models were created using the HULLAC atomic physics package. Using these models, we have analyzed the F-like, Ne-like and Na-like (satellite) spectra with respect to temperature, density, and charge-state distribution. This procedure leads to a full characterization of the plasma conditions.

1. Introduction

Culminating a multi-year effort to obtain highly resolved emission spectra from small, static, uniform volumes of plasma, a series of experiments was recently completed at the CHROMA laser facility at KMS Fusion. In these experiments, microdot targets were used to obtain narrow tubes of ablating plasma that were viewed radially by framing, microchannel plate intensified, crystal spectrometers, with slits for spatial resolution in the axial direction.[1] With a PET crystal in the spectrometer, the experiment provided spectral resolution of $\lambda/\delta\lambda \sim 2500$, in a cylindrical volume of plasma ~50 μm in diameter and 25 μm high, with a time resolution of 200 ps.