**Atomic Processes of Hot Ultra-Dense Plasmas
Technical Progress Report for FY01
National Laser User Facility Grant**

**C.F. Hooper, Jr., D.A. Haynes, Jr.,
J. Delettrez, P. Jaanimagi, S.P. Regan,
I.E. Golovkin, R.R. Peterson, N.D. Delamater**

August 2001

UWFDM-1156

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Atomic Processes of Hot Ultra-Dense Plasmas
Technical Progress Report for FY01
National Laser User Facility Grant

Principal Investigator:
C. F. Hooper, Jr.
DEPARTMENT OF PHYSICS, UNIVERSITY OF FLORIDA
GAINESVILLE, FLORIDA

Co-Principal Investigator:
D. A. Haynes, Jr.
FUSION TECHNOLOGY INSTITUTE, UNIVERSITY OF WISCONSIN
MADISON, WISCONSIN

In collaboration with:
J. Delettrez, P. Jaanimagi, S. P. Regan
LABORATORY FOR LASER ENERGETICS, UNIVERSITY OF ROCHESTER
ROCHESTER, NEW YORK

I.E. Golovkin, R. R. Peterson
FUSION TECHNOLOGY INSTITUTE, UNIVERSITY OF WISCONSIN
MADISON, WISCONSIN

N. D. Delamater
LOS ALAMOS NATIONAL LABORATORY, LOS ALAMOS, NEW MEXICO
(Currently on sabbatical at University of Florida)

Abstract

The experimental and theoretical activities of our FY01 NLUF work have been largely successful, and we are on track for completing our proposed two year investigation of the atomic physics of hot, ultra-dense plasmas by the end of FY02. The experimental activities were two half days of shots (2/21/01 and 8/2/01). All of the time-resolved x-ray spectroscopic data from the February shots has been reduced and analyzed. Four shots using the 1 ns square pulse shape SG1014 were complete successes, reproducibly achieving peak observed electron densities at or above $2x10^{24}$/cc. The results from the February experiments clearly demonstrate large plasma-induced line shifts. To achieve observable higher densities, the August shots concentrated on the use of the shaped pulse, RM1107, reduced total fill pressures, and reduced Ar partial pressure. In order to probe the ultrahigh densities that occur near stagnation, clear spectroscopic signals of the Ar K-shell lines must be observed. In the February shots Ar lines were not observed through the stagnation, due to the low core electron temperatures caused by the enhanced radiative cooling of the Ar. Higher densities were most likely achieved in these shots; however, the diagnostic lines were not present. With the lower Ar dopant levels of the August shots the Ar lines were observed throughout the implosion. We believe the ultrahigh density portions of these shots were observed. Though the August spectral data are still being digitized, the raw data appear promising. The theoretical activities include the development of a fully nonlinear semiclassical electron broadening theory for the Ar Ly-β through –δ lines, and the automation of the data fitting procedure using a highly optimized least-squares minimization.

Introduction

Atomic processes of radiators immersed in hot, dense plasmas are perturbed by the plasma environment. This perturbation is interesting in and of itself, as a challenging application of the statistical mechanics of dense plasmas. The perturbation also leads to observable and diagnostically useful variations in the spectrum emitted by the radiators. Through the years, with the support of NLUF, we have pursued both of these aspects of dense plasma physics, taking advantage of their synergy to make advances in both the theory and diagnostic application of dense plasma spectroscopy.

Our focus for this current work is on using the OMEGA laser to produce hot, ultra-dense plasmas. The eleven shots we have performed so far to accomplish this goal are summarized in Table 1. By hot, we mean plasmas in which the free electron distribution is non-degenerate ($kT\_e>1.5$ keV for the densities we hope to achieve). By ultra-dense, we mean plasmas with electron densities sufficient to call into question the usual approximations of Stark broadening theory ($n_e \sim 5 \times 10^{24}$/cc). These usual approximations include the separate calculation of members of a Rydberg series ($1snl \rightarrow 1s^2$ in He-like Ar, $nl \rightarrow 1s$ in H-like Ar), and the use of a second-order electron line broadening theory. Taking advantage of the recent significant advances in beam smoothing, energy balance, and experience with direct drive implosions, we have designed a two year campaign of four half days of shots to study the physics of hot, ultra-dense plasmas. Having just (8/2/01) completed our second half day of shots, we believe that we are on track to accomplish our goals by the end of FY02.

After this Introduction, preshot simulations of the implosions and a summary of results from February will be detailed to motivate our August 2001 experimental plan. Then the experimental data, its reduction and analysis, will be discussed. We will introduce advances in the theory of dense plasma spectroscopy and in our ability to infer emissivity averaged core densities and temperatures. We will briefly discuss how the use of our spectroscopic model of Ar-doped cores has become an essential component in Dr. S. P. Regan's method of determining the amount of plastic mixed into the core during the deceleration phase of microballoon implosions. Then, after listing the students involved in and the presentations and papers that have arisen as a result of this work, we conclude with a brief outline of our plans for FY02.

Preshot simulations and our experimental plan

The HYADES 1-D hydrodynamics code was used for preshot simulations of the NLUF argon spectroscopy implosions. The HYADES[i] code is a one-dimensional, three-temperature, three-geometry, Lagrangian hydrodynamics and energy transport code. The electron and ion components are treated separately in a fluid approximation and are loosely coupled to each other, each in thermodynamic equilibrium and described by Maxwell-Boltzmann statistics. The code simulations used multigroup radiation transport in
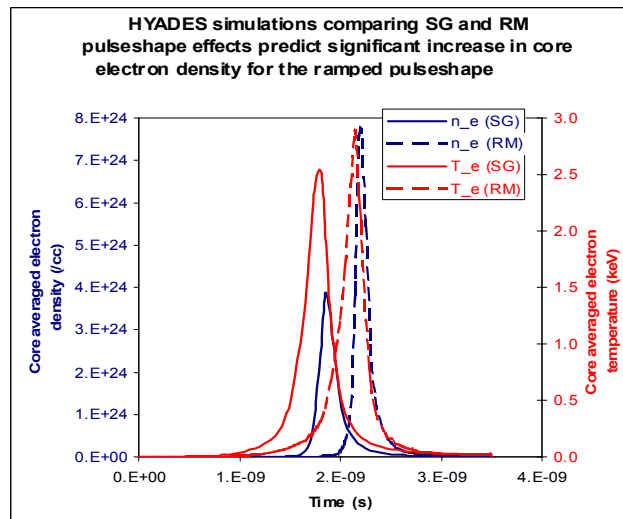

Figure 1. HYADES simulations of core averaged electron densities and temperatures for 940 micron inner diameter CH microballoons filled with 15 atmospheres of DD. SG refers to the 1 ns square pulse SG1014, and RM to the 1 ns ramp to 1 ns flat-top RM1107.

Table 1: Shot summary: 22531-22535 were shot in February, 2001, 24140-24145 in August, 2001.

Shot Number	Fill Gas	Shell Thickness (microns)	Pulse Shape	UV Energy on Target	Comments
22531	1% Ar in 15 atm DD	20.1	RM1102a	17.9 kJ	Pulse shaping hardware failure
22532	1% Ar in 15 atm DD	19.9	SG1014	23.0 kJ	Excellent Ar K-shell data
22533	2% Ar in 15 atm DD	19.9	SG1014	22.6 kJ	Darkroom technician error (wedge placed over data); short-duration 'shocked' K-shell lines
22534	1% Ar in 15 atm DD	20.0	SG1014	22.6 kJ	Excellent Ar K-shell data
22535	2% Ar in 15 atm DD	20.1	SG1014	21.0 kJ	Excellent Ar K-shell data, though the spectrum does not show the 'shocked' structure typical to 2% Ar shots
24140	0.3% Ar in 10 atm DD	18.5	SG1014	23.3 kJ	Excellent Ar K-shell data, our highest YOC for square pulse shots
24141	0.3% Ar in 15 atm DD	18.5	SG1014	23.2 kJ	Excellent Ar K-shell data
24142	0.3% Ar in 15 atm DD	18.5	RM1107	19.1 kJ	Excellent Ar K-shell data
24143	0.3% Ar in 15 atm DD	18.5	RM1107	19.0 kJ	Excellent Ar K-shell data
24144	0.3% Ar in 10 atm DD	18.6	RM1107	19.0 kJ	Excellent Ar K-shell data, our highest YOC for shaped pulse shots
24145	0.25% Ar in 7 atm DD	19.8	RM1107	19.2 kJ	Excellent Ar K-shell data

the diffusion approximation and LTE average atom ionization. The thermodynamic and equation of state quantities are derived from realistic (SESAME or other theoretical models) tables. HYADES also includes thermonuclear burn of hydrogen isotopes and transports the fusion products using a particle tracking prescription.

For four of our NLUF shots in February, 2001, CH capsules with 20 μm shell thickness, diameter of about 940 μm and gas fill of 15 atm DD and 1% or 2% atomic argon were imploded using a 1 ns square pulse shape (SG1014). These shots yielded observable imploded core electron densities of above $2x10^{24}$/cc and neutron yields of about 10^{11} using a 1 ns square laser pulse with 23 kJ energy. Though the achieved densities may have been higher, the Ar K-shell line emission may have been quenched due to radiative cooling from the relatively high concentration of Ar, or a mismatch between the times of peak density and temperature. It was desired to observe higher electron densities for our dense plasma studies, since the most interesting line shift and line merging effects are important for electron densities near $5x10^{24}$/cc. For the August, 2001 series of shots, we made some target design changes in an attempt to achieve higher imploded core densities. The most important change was to use a ramped laser pulse (1 ns rise to 1 ns flat) which (in 1-D simulations) more effectively drives the target to a higher degree of compression, as illustrated in Figure 1. (Our February attempt to use this pulse shape failed because of a hardware problem with the pulse shaping system that has since been repaired.) The shell diameter and thickness were kept approximately the same as in the February shots, but we also chose to use some targets with only 7 atm to 10 atm DD fill. The lower deuterium gas fill in the shell allows a potentially higher convergence to be achieved (CR~25), barring deleterious 3-D effects due to beam imbalance, pointing and timing errors, single beam non-uniformity or target imperfections. The simulations using the ramped pulse indicated that imploded core electron densities of $5x10^{24}$/cc to $8x10^{24}$/cc could be achieved with targets of 15 atm DD fill and 10 atm DD fill. We also chose to decrease the total argon fill for the recent shots, using only 0.3% atomic argon instead of the 1% we used in the February shots. The reduced argon fill has the advantage of affecting the implosion hydrodynamics less

since the radiative cooling will be reduced and the spectra in the region of the bound-free helium-like argon edge will be cleaner and easier to analyze than would be the case for a lower core electron temperature. An important spectral region of our analysis is in the area of the Lyman-β and higher Lyman series lines, so the higher core temperatures achieved with a reduced argon amount is beneficial so long as the total argon line emission signal is observable, and will also serve to keep the temperatures in the 'hot', non-degenerate plasma regime.

Though the spectral data from the recent August shots are still being digitized, it is possible to say that many of our objectives have been met since the quality of the SSC data is excellent and broadened Ar lines from hydrogen-like and helium-like argon are evident in the raw data. The initial results of neutron diagnostics for total yield and implosion bang-time are in good agreement with the HYADES simulations for the 1 ns shots we did with 10 atm and 15 atm DD fill. The YOC (observed yield/clean 1-D yield) was about 25%-30% for the 1 ns shots and the measured bang times of 1.85 ns are in close agreement with the HYADES times of 1.95 ns. The ramped pulse shots produced high quality spectral data, but it is not yet clear how high the achieved imploded core densities actually were. The neutron yield was low, with YOC of about 5% for the 10 atm shot. The measured bang time of 2.39 ns agreed well with the calculated bang time of 2.4 ns. While it remains to be seen what the achieved imploded core electron densities actually were, it is fair to say that our results with these implosions are in line with other similar direct drive implosions at high convergence, in that reduced neutron yields are generally seen at CR > 20 or so. It is possible that we may want to increase the CH shell thickness to 24 microns and continue to use the ramped pulse in our attempts to achieve somewhat higher core electron densities in our future shots. The thicker shell may smooth out the effects of converging shocks produced with the ramped pulse implosion and mitigate the effects of beam power imbalance and allow a more effective implosion. An example of a high density ($n_e \sim 4 \times 10^{24}$/cc) spectrum from such a shot (taken as part of LLE's ISE campaign) is shown in the next section.

Data reduction and analysis

Taking advantage of a similarly instrumented LLE/ISE campaign, our shots have occurred in the afternoons after mornings in which our primary diagnostics were fielded. Thus, the timing, pointing, and setup of our instruments was already established. The LLE campaign was shooting lower Ar concentrations, and the only change we made was to increase the filtering in the primary streak camera to avoid saturating the streak tube. As a result, we have excellent time-resolved spectral data and framing camera images from each of our shots. By sacrificing some total beam energy, we achieved excellent energy balance ($\Delta E/E \sim 3\%$ (RMS)). The framing camera images and the static pinhole images all show nearly circular core images, showing no significant excursions from spherical implosion.

Our primary diagnostic was a streaked x-ray crystal spectrometer, SSCA operating with a flat RbAP (rubidium acid phthalate) crystal and a Au photocathode. The instrument provided an ~ 1.9 ns window with a resolution of 25 ps. The sweep speed of the camera (averaging 48 ps/mm) was measured by LLE scientists on the days of our shots using a temporally modulated ultraviolet fiducial laser pulse. The spectra were recorded on Kodak T-max 3200 film, and digitized using LLE's PDS (Perkin-Elmer Photometric Data System) microdensitometer. Corrections for film sensitivity were conducted using step wedge data on the film from each shot. Known filter and photocathode response were taken into account. Streak camera distortions (curvature of isotemporal lines and streak angle) and crystal/photocathode irregularities were corrected using a wavelength fiducial (a 1 mm strip of lead tape over the photocathode slit) and the images of targets in which the fuel contained no Ar (Figure 2). Timing with respect to the laser is accomplished through a technique developed at LLE: a streak camera covering the Ar K-shell, operated at a slower streak speed captured both the coronal emission of the CH plasma and the peak of core x-ray emission. Lineouts averaging over 25 picoseconds were then extracted from the images, and the resulting time-dependent spectra exhibited time-varying Ar K-shell data, including the He-β, -γ, −δ and Ly-α, -β, -γ resonance lines, associated satellites and the He-like and H-like photoionization edges (Figure 3). Spectral dispersion was determined using early time (low density, low shift) lineouts. The variations in resonance line intensities and widths result from time-varying core temperatures and densities.

Our analysis proceeds by performing a least squares (χ^2) fit to the spectral data using our model. The model contains Stark broadened lineshapes, NLTE population distributions, and corrections for the transfer of the thick alpha lines and the opacity of the diagnostic lines. The free parameters in our model are the emissivity-

SSCA_22506 Wedged

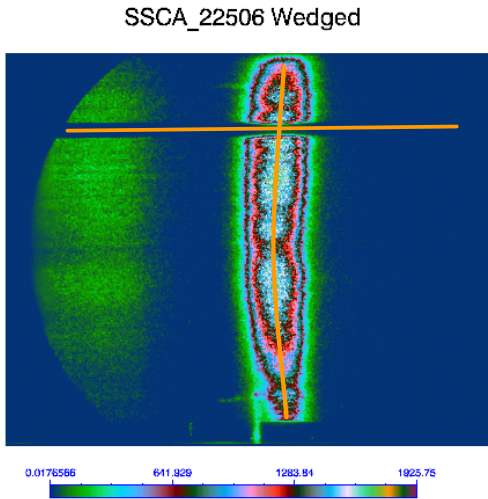SSCA_22506
Wedged, Corrected for angle and curvature

Figure 2a. SSCA data from a no Ar shot, showing the curvature of the isotemporal lines and the streak angle.

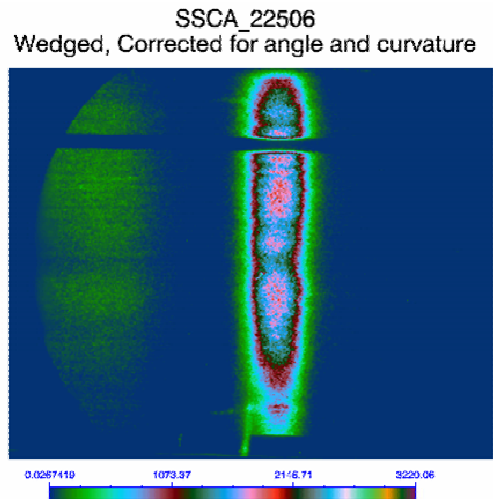Figure 2b. SSCA image from Figure 2a corrected for curvature of the isotemporal lines and for streak angle.

SSCA 22532 (1% Ar)
Wedge, Rotation, and Curvature Corrected
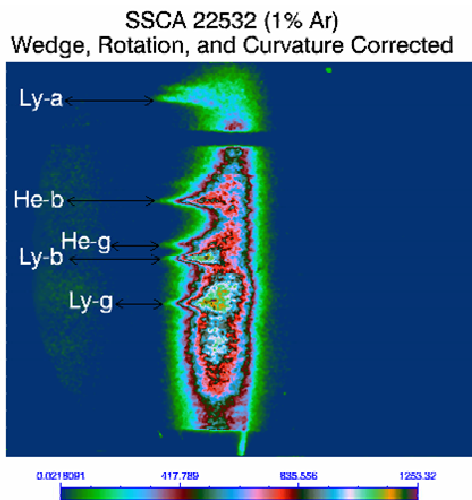
Ly-a
He-b
He-g
Ly-b
Ly-g

Figure 3. SSCA data from an Ar-doped shot. The locations of the Ar K-shell resonance lines are indicated. Time goes from left to right, and photon energy from top to bottom. Notice that the lines broaden and shift as the implosion proceeds towards stagnation. The gap in the spectrum between the Ly-a and He-b lines is the wavelength fiducial.
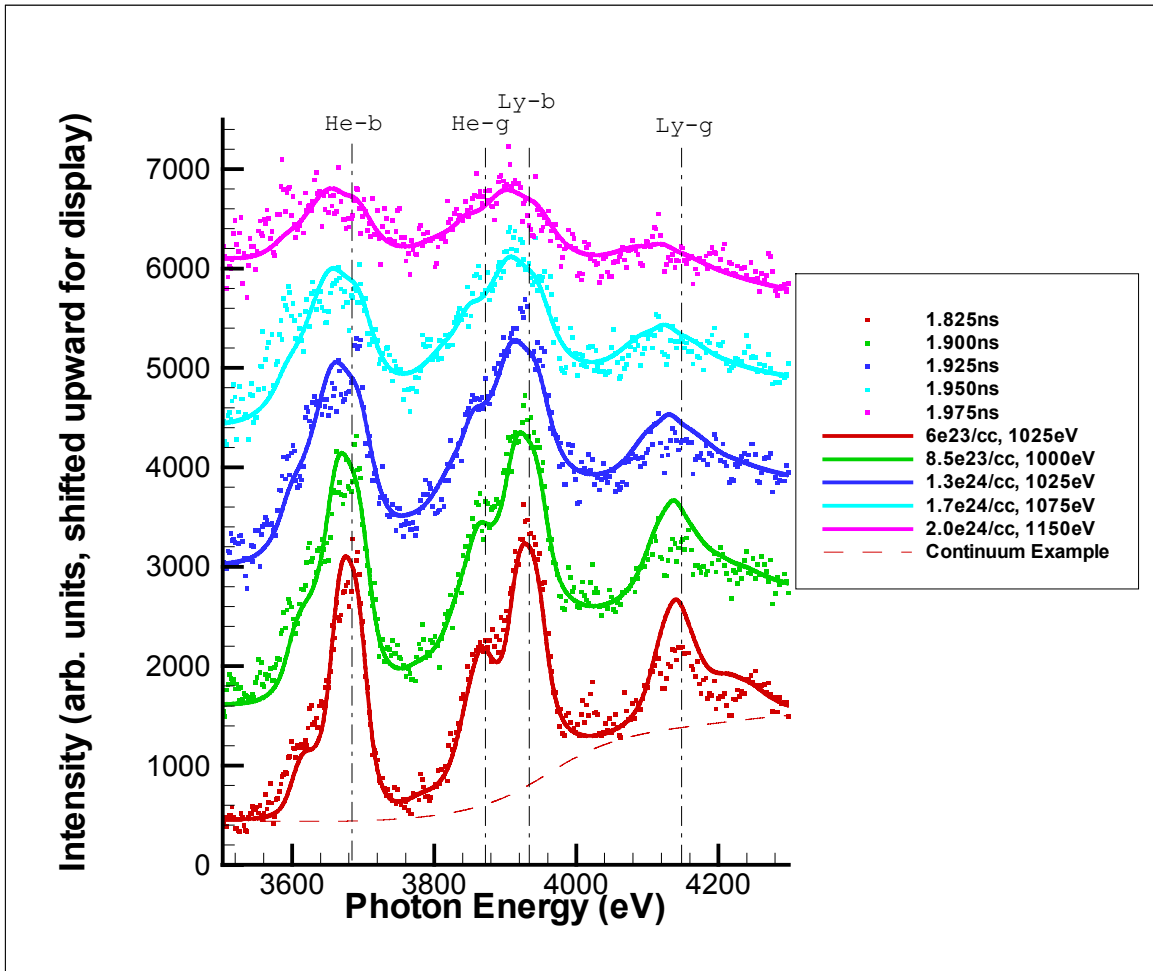
Figure 4. Time resolved spectral data and fits from shot 22534. Note the increasing shift of the gamma lines as the density increases, and the pronounced He-like edge. The experimental data is labeled with start of the 25 ps interval over which the spectrum was averaged (with respect to the start of the laser pulse). An example of the shape of the continuum (free-free, free-bound) typical to the data from the 1% Ar capsule is displayed. Vertical lines indicate the isolated-atom locations of the prominent transitions.

averaged core electron temperatures and densities. This fitting process leads to an inference of time-dependent core conditions, something useful in its own right. However, it also confirmed that these shots provided plasma conditions approaching those need for our investigations. We regularly reached densities above 2×10^{24}/cc. An example of the spectral fits is shown given in Figure 4. Though the spectral data from August have yet to be digitized, we are optimistic that we observed even higher electron densities. At 2×10^{24}/cc, the ultra-dense deviations from the linear theory of Stark broadening are subtle, but we see indications in the data that the nonlinear theory fits yield somewhat lower χ^2 than those from the linear theory, especially in the region of the Ly-γ line, as is shown below in Figure 5. However, we are confident that changes that we made in August and propose for next year will result in densities where the differences are not subtle. Electron densities of 4×10^{24}/cc have been inferred in similar capsules (see Figure 6).

The lineshapes in our model are calculated using MERL, a constantly improving Multi-Electron Radiator Lineshape code developed at the University of Florida over a number of years.[ii] Recent improvements include the accounting for ion dynamics effects important in the formation of lines from plasmas where the spectroscopic dopant is immersed in a plasma of relatively light, fast moving hydrogen isotopes, the inclusion of plasma induced line shifts, and the simultaneous calculation of emission spectra from several members of a Rydberg series. It is interesting to note that these improvements to the code have been directly related to our experimental campaign. We set out to calculate and observe ion dynamics effects in the mid-1990s.[iii] During the analysis of the resulting experimental data, we found that the higher lying members of a Rydberg series
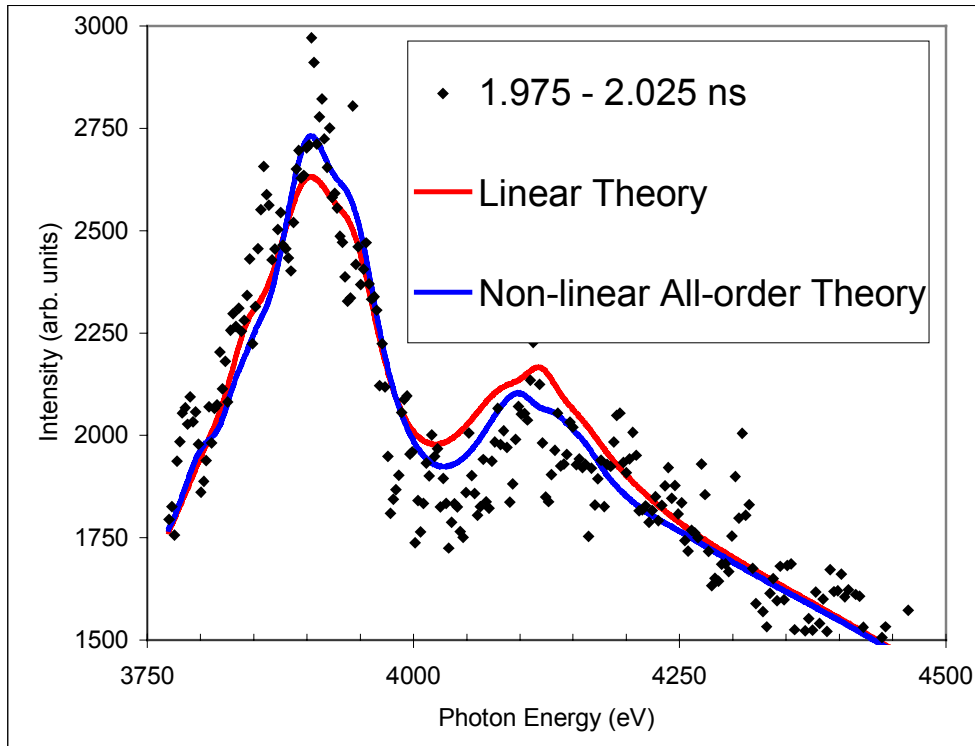
Figure 5. Fits to a lineout from 22534 from a linear, 2nd order theory of electron broadening and from the nonlinear, all-order semiclassical theory, for an electron density of 2.1×10^{24}/cc, and a temperature of 1150 eV. The χ^2 of the fit from the nonlinear theory is lower than that from the linear theory, though the difference in appearance is subtle. At densities near 5×10^{24}/cc, the difference will not be as subtle, as seen in Figure 7.

consistently shifted to the red of their isolated atom positions, and that this shift was approximately linear in electron density. We then set out to calculate this shift, and to perform experiments to critically test the resulting theory.[iv] These experiments led to densities sufficiently high that the old practice of separately calculating the Stark broadened lineshapes and adding them up with the proper relative intensities became suspect.[v] Our current experimental and theoretical work attempts to calculate and observe lines from these plasmas to test our new, non linear theory of Stark broadening at ultrahigh densities.[vi] The NLTE population kinetics of the Ar energy levels is performed using CRETIN[vii] and a detailed 1380 level model with sufficient detail to track K-shell resonance lines and their prominent satellites. The effect of the transfer of the optically thick He- and Ly-α lines on the ionization balance is approximated using a smaller atomic model and solving the transfer equation using Mancini's escape factors.[viii] The opacity broadening of the relatively thin beta and gamma lines used in our analysis is considerably less than the Stark broadening, and is accounted for using the slab opacity formalism.[ix]

Figure 4 presents results from analysis of shot 22534 (1% atomic fraction Ar in 15 atm DD), which had some interesting features presenting a challenge in the fitting of the data. The biggest concerned the fitting of the background and He ionization edge, which was very noticeable in the data. In the theoretical fit of the edge, we placed the location of the edge at a position predicted by the frequently used continuum lowering model developed by Stewart and Pyatt.[x] The height of the edge is approximated by assuming an LTE ratio between the populations of the uppermost observed He-like line and the H-like ground state. Though this fitting procedure produces adequate fits, it is found the apparent edge in the data is shifted slightly further to the red than predicted by Stewart and Pyatt, particularly at the highest densities observed. However, because this edge lies underneath the Ly-β line for these densities, determining its exact location will require a more sophisticated analysis. (Such a method is discussed below.) Figure 4 also demonstrates plasma induced line shifts. An independent verification of the shift using the Ly-γ line is important because there are no other intense spectral features nearby to complicate the analysis. To aid in the analysis of this spectral region, we halve the amount of Al filtering used for our August shots to reduce the scatter in the spectral data. We also hope to observe effects on this line due to line merging when the core electron density in the plasma increases
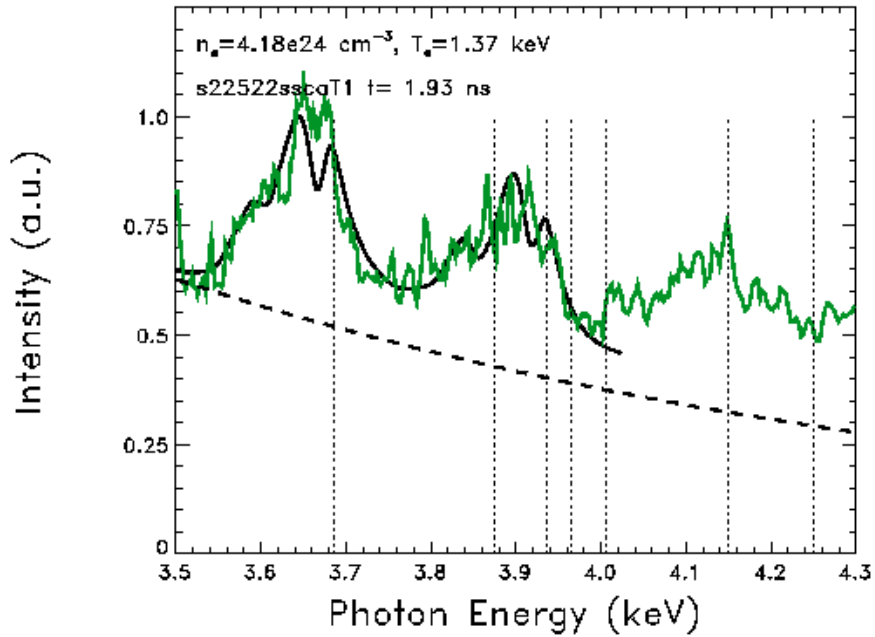
Figure 6. A lineout from shot 22522. 15 atm DD, doped with 0.18% Ar, and a 24 micron thick shell. A fit to spectral region of the He-β, -γ, and Ly-β indicates an electron density of over 4×10^{24}/cc. The dashed vertical lines indicate the isolated atom positions of the K-shell resonance lines. The fit to the spectral range above 4 keV is in progress. This result informs our belief that direct-drive implosions on OMEGA can produce the densities in which we are interested.

up toward 5×10^{24}/cc. The analysis of the February shots guided our experimental design for August, showing that we could reduce both the Ar concentration and the filtering, and showing the need for a change in pulse shape or target design. Figure 6 shows results from a fit of a lineout near stagnation of shot 22522, also taken on 2/21/01 with a 24 micron thick shell, 15 atm of DD doped with 0.18% Ar. The inferred electron density is above 4×10^{24}/cc, and indicates that directly driven implosions on OMEGA can produce our required densities.

Our spectral fitting routine has been enhanced to improve the determination of experimental conditions, most importantly density and temperature, of gas-filled microballoons imploded by lasers. To determine these parameters, an electron temperature- and density-dependent theoretical spectral profile is produced, which is then compared with the experimental data. The original method to fit these lines was to continue generating different theoretical profiles, until values of density and temperature were found that, to the eye, seemed to come closest to the data. Then the fitting parameters were manually varied about that point until chi-squared, the sum of the squares of the differences between fit and data, was minimized. There were several drawbacks to this method. It was labor intensive, requiring the user to provide iterative guesses for the parameters, and uncertainties for each inferred parameter were not automatically produced.

The automated spectral fitting program adapted here is based on NLFIT, an algorithm created by Dr. Robert Coldwell at the University of Florida.[xi] It is based on a quickly-converging nonlinear least squares optimization routine, requiring fewer than 10 spectral evaluations for each of our lineouts. For NLFIT, the user supplies a fitting function with a number of different parameters. These parameters include physical values such as temperature, density, and brightness, as well as coefficients for a background function. The user also supplies a weight for each data point; if there is reason to believe a certain data point or set of data points is unreliable, the corresponding weights can be adjusted to take that into account. NLFIT can also attempt to infer the correct weights for the points from the scatter in the data. NLFIT then runs through a minimization routine, and the result is an inferred value for each fitted parameter as well the uncertainty in the inference.

For data sets with simple background shapes, NLFIT has already shown to be a useful, practical fitting tool. The fits are done much faster; the time to fit an entire set of experimental spectra which would have before been measured in hours can now be completed in less than ½ hour. The work being done currently is aimed

at improving the representation of the background to fit more complicated data, especially with regard to continuum edges, which appear as a step in the data. Parameterizing the step by its position and width will allow us to infer the location of the continuum edge. By using cubic spline functions to model this edge and other background structures, the fitted parameters of density and temperature will be more accurate. Also, the location of these continuum shifts can give information about the state of the plasma, and compared to existing theoretical predictions of continuum lowering.

By automating the fitting process, the fits are done faster than before, and a measure of the error range for the density and temperature inferences is easily produced. For the current spectral data, the model gives very precise fits, with the resulting errors bars significantly smaller than the conservative 10% accuracy we estimate for the theories and calculations underlying the spectral model.

We note in passing that the spectral model developed over the years of our participation in NLUF has proved useful in recent programmatic work our collaborators are performing at LLE. Dr. S. P. Regan combines the density and temperature inferences obtained from analysis of the Ar K-shell spectrum with x-ray images of the core and particle based ρr measurements to obtain an inference of the amount of CH shell that has mixed in with the core by the time of peak neutron emission. One of the *sine qua non* of this analytical technique is an accurate model of Ar K-shell emission over a wide range of temperatures and densities. Dr. Regan uses our recently developed ArTAB to generate a lookup table of Ar K-shell spectra as a function of plasma conditions and composition. The work using Ar K-shell spectroscopy to characterize plasma conditions was published in LLE Review.[xii] A Physics of Plasma article comparing these inferences to emissivity averaged values from LILAC simulations is in preparation, as is a Physical Review Letter on the inference of mix amounts. Particularly important is that Dr. Regan's analysis proceeds using merely 0.18% Ar in 15 atm DD, thus reducing the perturbation of the spectroscopic dopant on the hydrodynamics of the implosion, and making Ar K-shell spectroscopy a more attractive programmatic diagnostic.

Improvements in the theory of ultrahigh density Stark-broadened line profiles

The importance of an all-order model (Reference vi) is that it gives a consistently correct treatment of electron broadening from line center out to the far wings of a line profile, whereas a second-order model will begin to break down in the far wings of a sufficiently broad line profile or spectral feature. As we shall see later, the inclusion of higher-order terms is important when we allow mixing between the upper states of the members of a Rydberg series. In Figure 7, results of calculations using both 2nd order and an all order theory are presented, showing that ultrahigh densities will be needed to experimentally discriminate between the two theories.

When calculating theoretical profiles of a Rydberg series of spectra, a higher-lying member of the Rydberg series will undergo a shift to lower energy which is larger than the shift of the next lower adjacent member of the series. This shift results from penetrating collisions by plasma electrons, the net effect of which is to reduce the effective charge of the nucleus, lowering the transition energies. As the electron density of the plasma increases, the shift of the higher lying member becomes increasingly larger than the shift of the adjacent lower lying member, thereby causing a merging of adjacent members of the Rydberg series.

Mixing between the upper states of adjacent members of the Rydberg series controls how these members merge together. If we allowed no mixing between the upper states of the members of the series, we would have higher lying members of the series shifting past lower lying members of the series, which is physically unrealistic. Therefore, the mixing between the upper states of the adjacent members of the series is crucial in the calculation of spectral lines which are beginning to merge together. Recently, we have done some calculations which possibly show experimentally noticeable differences between the two models at higher core electron densities (around 5.0×10^{24}/cc). It appears that the higher order terms play a significant role in how the upper states of different members of the Rydberg series interact with each other.

From Figure 7, we see that as the electron density increases, the merged Lyman -γ and -δ spectral feature tends to shift by a smaller amount in the all-order electron broadening model as compared to the second-order model. At a core electron density of 5×10^{24}/cc, the shift is approximately 75 eV smaller. With instrumental broadening effects on the order of 15 eV at most, a difference of this size should be noticeable in the data.
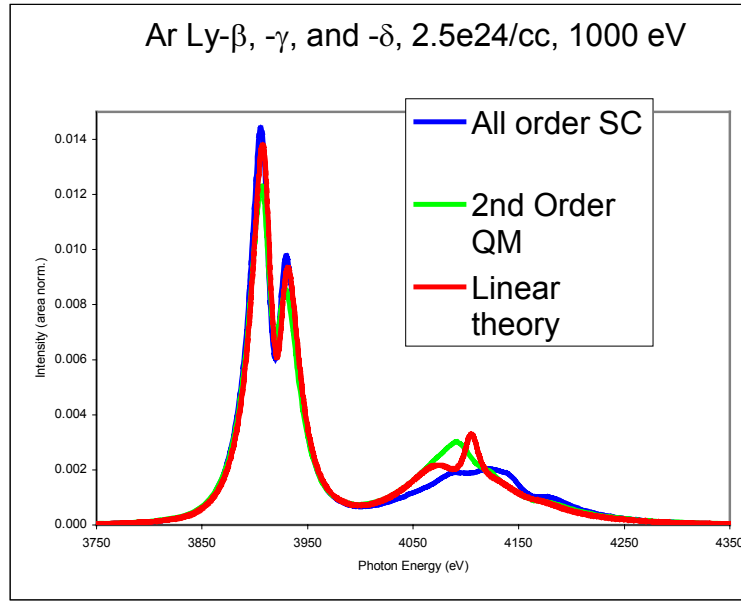
Figure 7a. Three calculations of the Ar Ly-β, -γ, and -δ lines, differing in the approximation used for the electron broadening. The conditions are 1% Ar in DD, $n_e=2.5\times10^{24}$/cc, $kT_e=1$ keV.
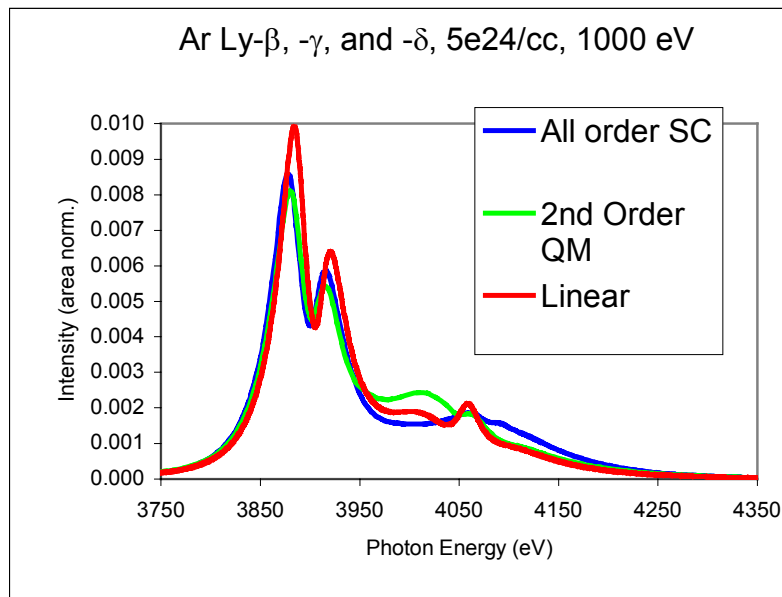

Figure 7b. Three calculations of the Ar Ly-β, -γ, and -δ lines, differing in the approximation used for the electron broadening. The conditions are 1% Ar in DD, $n_e=5\times10^{24}$/cc, $kT_e=1$ keV.

FY01 graduate student and post-doctoral fellow education and participation

University of Florida graduate students Mark Gunderson and Jeffrey Wrighton are intimately involved with the analysis of these experiments. They attended the August shot day, receiving a valuable educational experience, both in Dr. Jaanimagi's lab where they were given a detailed look into streak cameras, and throughout the laser facility. Our senior student, Mr. Gunderson, is set to graduate with his Ph.D. at the end of the upcoming Spring semester. His dissertation title is *All-order, Full-Coulomb Electron Broadening Calculations for High-Z Radiators in Hot, Dense Plasmas with a Focus on Spectral Line Merging*. Mr. Gunderson's all-order, semiclassical calculation of electron perturbations gives us the unique ability of correctly calculating Stark broadened line profiles from merged Rydberg series members in dense plasmas, necessary for the analysis of the spectral range including the Ar Ly-β, -γ, and –δ lines at the densities we expect to achieve. Mr. Wrighton is improving the automation of the analysis process and the evaluation of uncertainty in inferred quantities discussed above. Dr. Igor Golovkin joined the Fusion Technology Institute at UW as a post-doctoral fellow in January. He was also present for the August shot day, receiving an introduction into the experimental realities associated with the collection of the spectra and monochromatic images he analyzed for his University of Nevada, Reno dissertation on the analysis of gradients in dense plasmas. Dr. Golovkin has calculated emissivity profiles for Ar-doped directly-driven microballoon implosions to assess the impact of emissivity averaging on the inference of plasma conditions in our experiments. This NLUF award provided salary support for Mr. Gunderson and Mr. Wrighton and travel funds for the students and Dr. Golovkin to participate in the August shot day.

Related presentations and publications

- C. F. Hooper, Jr., et al. "Plasma Induced Line Shifts and Line Merging in Hot, Dense Plasmas" to be presented at IFSA2001.
- D. A. Haynes, Jr., et al. "ArFIT: A Detailed Model of Ar K-shell Line Emission from High Energy Density Plasmas" to be presented at IFSA2001.
- M. A. Gunderson, et al. "Spectral Line Merging Using an All-order Full-Coulomb Electron Broadening Model" to be presented at APS/DPP2001.
- S. P. Regan, et al. "Characterization of Direct-Drive-Implosion Core Conditions on OMEGA with Time-Resolved Ar *K*-Shell Spectroscopy" LLE Review **86** 47 (2001), and presentations at Anomalous Absorption 2001, IFSA2001, and APS/DPP 2001.

Planned FY02 experimental activities

Because our detailed plans for the experiments to be performed in FY02 depend on the results from our pending analysis of the data from the August 2001 experiments, we give a brief outline of our planned activities. We anticipate 2 half days of shots at OMEGA, one in late January, and one in August. We will again use direct-drive implosions to attempt to achieve densities of ~5×10^{24}/cc. Depending on the results from our analysis of the shaped pulse August shots, we will concentrate either on increasing the shell thickness or decreasing the fill pressure. We are currently performing simulations of these variations using both HYADES and BUCKY. We are very satisfied with the diagnostic suite, and the only changes would be the use of the new TIM-based PJX streak camera that should be available as early as January. As we currently use only 5 of the available 6 TIMS (and, at most, 3 with film) the addition of another instrument should not delay our shot cycle.

[i] J. T. Larsen, *HYADES Manual and Users' Guide* (Cascade Applied Sciences, Boulder, Co. (1999)).
[ii] L. A. Woltz and C. F. Hooper, Jr., Phys. Rev. A **38** 4766 (1988).
[iii] D. A. Haynes, Jr. *et al.*, Phys. Rev. E **53** 1042 (1996).
[iv] G. C. Junkel, *et al.*, Phys. Rev. E **62** 5584 (2000).
[v] D. A. Haynes, Jr., *et al.* in *Proceedings of 2001 Atomic Processes in Plasmas* (AIP 2001).
[vi] M. A. Gunderson, *et al.* J. Quant. Spectrosc. and Radiat. Transfer, in press (2001).
[vii] H. A. Scott and R. W. Mayle, Appl. Phys. B **58** 35 (1994).
[viii] R. C. Mancini, *et al.*, J. Phys. B **20** 2975 (1987).
[ix] N. Delamater, *et al.*, Phys. Rev. A **31** 2460 (1985).
[x] J. C. Stewart and K. D. Pyatt, Astrophys. J. **160** 245 (1966).
[xi] R. L. Coldwell and G. J. Bamford, *The Theory and Operation of Spectral Analysis Using ROBFIT* (AIP, New York, NY 1991).
[xii] S. P. Regan, *et al.*, in Laboratory for Laser Energetics LLE Review **86** 47 (2001).