Reconstruction and Analysis of Temperature Spatial Profiles from Inertial Confinement Fusion Implosion Cores

R. C. Mancini, L.A. Welser, T. Nagayama
Department of Physics, University of Nevada, Reno, M.S. 220, Reno, NV 89557

R. Tommasini, J. A. Koch, N. Izumi
Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550-9234

J. A. Delettrez, S. P. Regan, V. A. Smalyuk
Laboratory for Laser Energetics, University of Rochester, NY 14623

I. E. Golovkin
Prism Computational Sciences, Madison, WI 53711

Abstract

We discuss several methods for the extraction of temperature spatial profiles in inertial confinement fusion implosion cores based on the analysis of the x-ray emission from spectroscopic tracers added to the deuterium fuel. The ideas rely on (1) detailed spectral models that take into account collisional-radiative atomic kinetics, Stark broadened line shapes, and radiation transport calculations, (2) the availability of narrow-band, gated pinhole and slit x-ray images, and space-resolved line spectra of the core, and (3) several data analysis and reconstruction methods that include a multi-objective search and optimization technique based on a novel application of Pareto genetic algorithms to plasma spectroscopy. The spectroscopic analysis yields the spatial profiles of temperature in the core at the collapse of the implosion. Results are illustrated with data recorded in implosion experiments driven by the OMEGA laser.

I. Introduction

Identifying the spatial structure of implosion core temperature and density conditions is of current interest in Inertial Confinement Fusion (ICF) experiments, and it is also critical for the design of ignition experiments [1-5]. We report here on the extraction of temperature gradients from direct-drive ICF experiments performed at the Laboratory for Laser Energetics' OMEGA laser facility. The temperature gradients are determined spectroscopically via an emissivity ratio technique, in which the ratio of Lyβ/Heβ line transition emissivities from an argon dopant added to the fuel is sensitive to the temperature.

II. Experimental Details

The direct-drive experiments discussed here consisted of imploding spherical plastic microballoon targets irradiated with the OMEGA laser system. The microballoons had an initial diameter of 434.2 μm, a plastic wall thickness of 26.6 μm, and an outer Al layer of 0.1 μm. They were filled with 20 atm of deuterium gas and a tracer amount (i.e. 0.072 atm) of argon, which was used as a spectroscopic diagnostic.

In order to extract information on the spatial structure of the implosion cores, good quality spatial images of the argon emission are necessary. To this end, the Direct-Drive Multi-Monochromatic X-ray Imager (DDMMI) was used to record argon line transition emission images in the range of interest [6]. The DDMMI consists of a pinhole array placed as close as possible to the core in order to maximize the signal and as well as the magnification, and a multi-layer mirror Bragg reflector to provide spectral dispersion. The data were recorded by time-gated framing cameras. The data presented here represent one line-of-sight. Additional lines-of-sight from quasi-orthogonal directions will be studied in the future.

III. Data Processing

Data recorded by the DDMMI must be objectively processed to provide narrow-band images of the core. A graphical user interface has been developed in IDL to accomplish this multi-step procedure [7,8]. Figure 1 shows the DDMMI data after it has been corrected for the photon-energy dependent corrections relating to Be filter transmission, reflectivity of the multi-layer mirror, and the spectral response of the multi-channel plates. The horizontal and vertical axes are spatial, and the horizontal axis also represents the energy dispersion in the data. Small sub-images associated with individual pinholes can be seen, and the tilt of the columns results in each sub-image recording a slightly shifted energy range. Therefore, in order to compile a spatial image which represents a Lyβ or a Heβ, it is necessary to integrate several of these sub-images. In this case, six sub-images have been carefully aligned and added to compile Lyβ, Heβ, and continuum composite images. The continuum images are scaled to the level under the respective lines, and can then be subtracted from the Lyβ and Heβ images.

These resulting narrow-band images are shown in Figure 2. Previous work [7,8] has concentrated on analyzing angle-averaged radial lineouts of images from indirect drive experiments. This is only appropriate in situations of relatively good spherical symmetry, and effectively results in one "average" radial spatial distribution over the whole core. The images in Figure 2, however, display noticeable asymmetries, which are more accurately dealt with in the following way. Each column (perpendicular to the horizontal hohlraum axis) is actually a core slice which represents the integral of the emissivity along a chord in each spatial zone. A column is individually symmetrized about its local axis of symmetry. Across the image, this local symmetry axis is termed the 'gummy-worm axis'. Following the symmetrization of the columnar intensity profiles, an Abel inversion performs a geometric transformation linking intensity profiles on the image plane to an emissivity distribution inside the implosion core [9]. The emissivity profiles (which are, by extension, also symmetrized about the gummy-worm axis) are directly used in the calculation of the temperature.

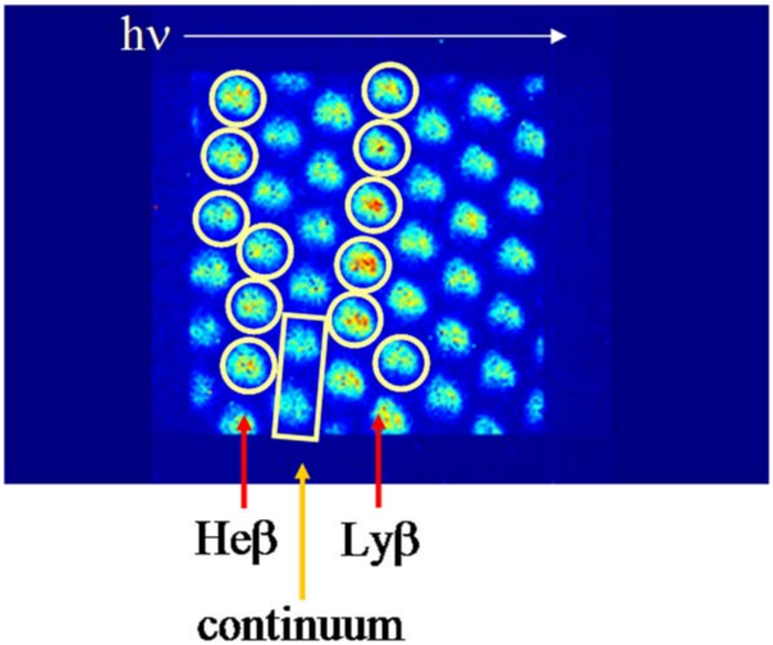

Figure 1: A DDMMI image from a direct-drive ICF experiment has sub-images containing portions of Lyβ, Heβ, and continuum emission.

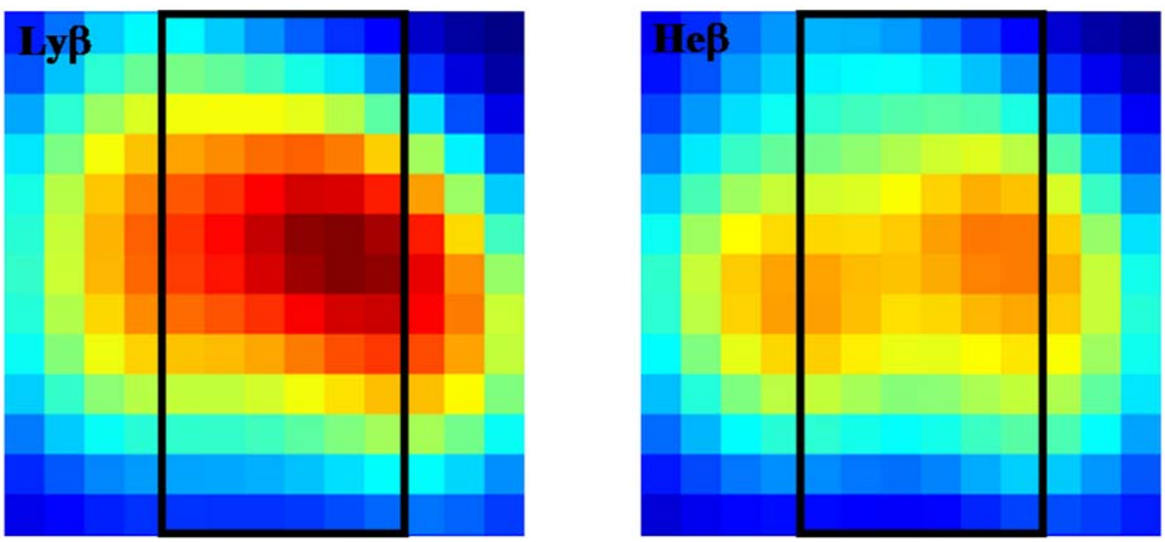

Figure 2: Spatial images of Lyβ and Heβ line emission from a direct-drive experiment, with the central column noted. The core size is approximately 60 μm, which is comparable to that predicted by 1-D hydro simulations.

IV. Spectroscopic Determination of Temperature Spatial Structure

The emissivity ratio of Lyβ/Heβ is strongly dependent on temperature but only weakly dependent on electron density [5,10]. Therefore, it can be used as an efficient temperature diagnostic. The analysis consists of identifying two distinct quantities: the experimental emissivity ratio and the corresponding theoretical emissivity ratio as calculated by a physics model [11]. Using emissivity profiles from corresponding columns of the Lyβ and Heβ images shown in Figure 2, an experimental emissivity ratio spatial profile can be defined for each column. This experimental data is then contour-mapped onto a surface depicting the theoretical Lyβ/Heβ emissivity ratio as a function of temperature and density. This procedure provides a direct relation between experiment and theory, and can be seen in Figure 3. The emissivity ratio surface demonstrates that the Lyβ/Heβ ratio is weakly dependent on density, but is clearly sensitive to temperature. The experimental emissivity ratio is described in six spatial zones, and therefore six contours are shown on the surface. The temperature gradient is calculated by averaging the temperature values across the contours in a reasonable density range. The resulting temperature gradient from the central column of Figure 2 is presented in Figure 4. The uncertainty bars represent the weak density sensitivity of the model. The temperature peaks in the central region of the core and decreases to the outer edge. This trend is consistent, and the gradients themselves are similar, throughout the columns. The spatial structure extracted via this method is compared to results of 1-D hydro simulations, also shown in Figure 4, which are generally steeper but still predict values in the range of 700-1200 eV over the time frame captured by the experimental data.

V. Conclusion

This work constitutes the first application of our spectroscopic gradient determination methods to a direct-drive case. Specifically, we have used the Lyβ/Heβ line transition emissivity ratio's sensitivity to temperature in order to extract the temperature spatial structure. We plan to analyze data from multiple lines-of-sight in order to eventually reconstruct quasi-3D maps of the core temperature and density.

VI. Acknowledgements

This work is supported by DOE-NLUF Grant DE-FG52-2005NA26012, and LLNL Contract W-7405-Eng-48.

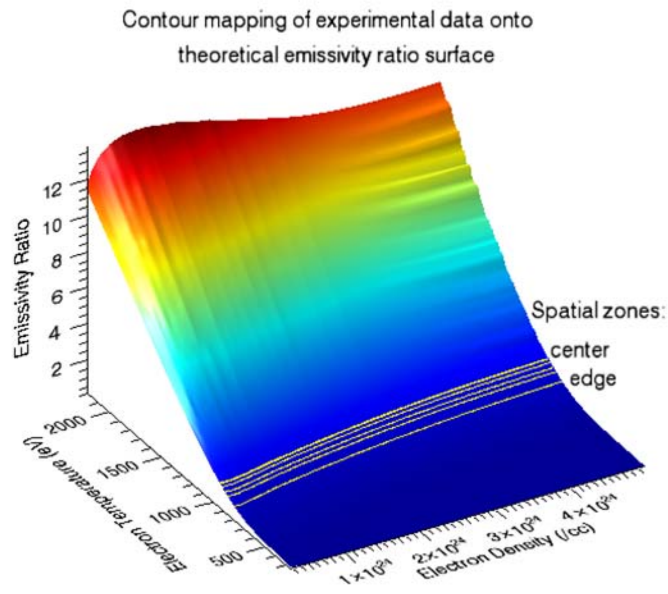

Figure 3: Contour mapping of experimental Lyβ/Heβ emissivity ratio values onto the theoretical emissivity ratio surface.

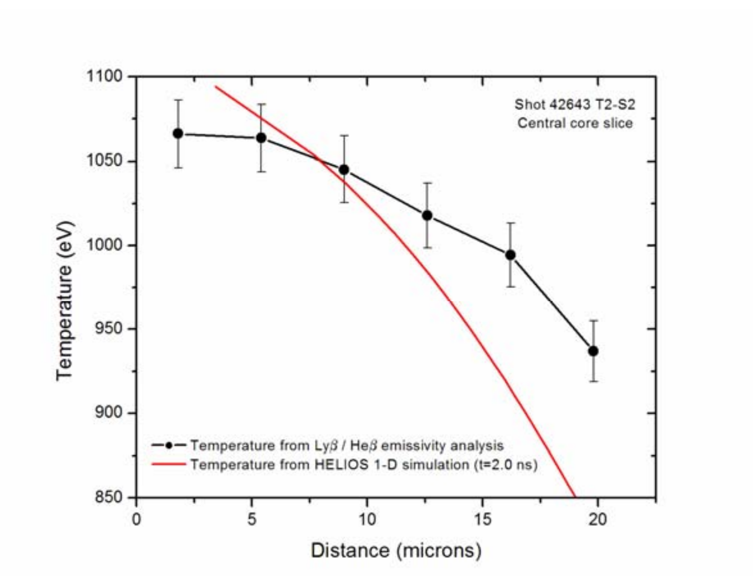

Figure 4: The temperature gradient resulting from the Lyβ/Heβ emissivity ratio analysis, for the central column or core slice of the images.

VII. References

1. I.E. Golovkin, R.C. Mancini, S. Louis, Y. Ochi, K. Fujita, H. Nishimura, H. Shiraga, N. Miyanaga, H. Azechi, R. Butzbach, I. Uschmann, E. Forster, J. Delettrez, J.A. Koch, R.W. Lee, and L. Klein. *Physical Review Letters*, **88**, 045002-1, 2002.
2. S.P. Regan, J.A. Delettrez, R. Epstein, P.A. Jaanimagi, B. Yaakobi, V.A. Smalyuk, F.J. Marshall, D.D. Meyerhofer, W. Seka, D.A. Haynes, I.E. Golovkin, and C.F. Hooper. *Physics of Plasmas*, **9**, 1357, 2002.
3. A.A. Hauer, N.D. Delamater, and Z.M. Koenig. *Laser and Particle Beams*, **9**, 3, 1991.
4. B.A. Hammel, C.J. Keane, D.R. Kania, J.D. Kilkenny, R.W. Lee, R. Pasha, R.E. Turner, and N.D. Delamater. *Review of Scientific Instruments*, **63**, 5017, 1992.
5. C.J. Keane, B.A. Hammel, D.R. Kania, J.D. Kilkenny, R.W. Lee, A.L. Osterheld, L.J. Suter, R.C. Mancini, C.F. Hooper, and N.D. Delamater. *Physics of Fluids B*, **5**, 3328, 1993.
6. J.A. Koch, T.W. Barbee, N. Izumi, R. Tommasini, R.C. Mancini, L.A. Welser, and F.J. Marshall. *Review of Scientific Instruments*, **76**, 073708, 2005.
7. L.A. Welser, R.C. Mancini, J.A. Koch, H.E. Dalhed, R.W. Lee, I.E. Golovkin, F.J. Marshall, J.A. Delettrez, and L. Klein. *Review of Scientific Instruments*, **74**, 1951, 2003.
8. L.A. Welser, R.C. Mancini, J.A. Koch, N. Izumi, H.E. Dalhed, H. Scott, T.W. Barbee, R.W. Lee, I.E. Golovkin, F.J. Marshall, J.A. Delettrez, and L. Klein. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **81**, 487, 2003.
9. K. Bockasten. *Journal of the Optical Society of America*, **51**, 943, 1951.
10. L.A. Welser, R.C. Mancini, J.A. Koch, N. Izumi, S.J. Louis, I.E. Golovkin, T.W. Barbee, S.W. Haan, J.A. Delettrez, F.J. Marshall, S.P. Regan, V.A. Smalyuk, D.A. Haynes, and R.W. Lee. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **99**, 649-657, 2006.
11. I.E. Golovkin and R.C. Mancini. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **65**, 273, 2000.