Four-objective analysis including an optically thick line to extract electron temperature and density profiles in ICF implosion cores

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Abstract. We discuss a search and reconstruction method for the simultaneous and self-consistent analysis of a set of image intensity spatial profiles from several narrow-band x-ray pinhole images from argon-doped inertial confinement fusion implosion cores, and the space-integrated line spectrum. The atomic and radiation physics model is embedded into an inversion algorithm, which consists of a Pareto genetic algorithm followed by a Levenberg-Marquardt non-linear least-squares minimization step, in order to extract the core spatial structure. To find out the best combination of experimental objectives for the analysis, two different combinations of objectives, including optically thick argon Lyα line, were tested and their results were compared with the results from a previous 3-objective analysis. © 2007 American Institute of Physics.

1. Introduction

Inertial Confinement Fusion (ICF) is one of the important techniques being studied to achieve self-sustained nuclear fusion reactions for future energy production. A plastic spherical shell containing fuel gas (deuterium or tritium) ablates due to the direct- or indirect-drive energy deposition on its surface, and creates a shock wave propagating towards the center of the capsule, which compresses the shell. This compression drives abrupt increase in temperature and pressure of the fuel gas in the core, and allows ions to overcome the Coulomb potential and achieve nuclear fusion reactions. The temperature and density distributions in the core are very important parameters for achieving self-sustained fusion reactions and efficient fuel burning. Therefore, the extraction of the spatial distributions of temperature and density in an implosion core is an important problem of direct- and indirect-drive ICF to study the dynamics of the implosion, and to benchmark hydrodynamic codes.

One approach to attack this problem is based on a search and reconstruction (SR) in parameter space of the temperature and density spatial profiles that yield the best, simultaneous and self-consistent, fits to several pieces of spectroscopic data. Each piece of data to be fitted (i.e., approximated) represents an objective, and thus this search and reconstruction method is an example of multi-objective data analysis. In previous work, the use of genetic algorithms in single-objective spectroscopic data analysis, and two- and three-objective spectroscopic determination of implosion...
core spatial structure have been demonstrated using Pareto genetic algorithms (PGA) to drive the search in parameter space [1-3]. Also, we have shown that an inversion method consisting of the PGA and a “fine-tuner” added flexibility in the selection and combination of objectives, and permitted use of intensity image data without geometry inversion [4]. The PGA combines the robustness and versatility of a single-objective genetic algorithm with the Pareto domination technique of multi-objective optimization, and the fine-tuning method is based on a Levenberg-Marquardt non-linear least-squares-minimization that refines the results of the PGA to provide the very best fits to the objectives. Here, we extend previous work by adding an optically thick image as a fourth objective, and tested more combinations of objectives to find out possible best combinations of objectives for the analysis. It has previously been difficult to use optically thick image data in the analysis [1-3].

The case of application is that of an argon-doped, deuterium-filled implosion core where a tracer amount of argon was added to the deuterium gas fill for diagnostic purposes. At the collapse of the implosion, bright argon line emission is recorded with a Multi-Monochromatic x-ray Imager (MMI) equipped with a pinhole array that records a large number of implosion core images, where each one represents a slightly different photon energy range [5]. Processing of these image data yields narrow-band x-ray pinhole images of the core characteristic of a photon energy range of the order of the broadening of the diagnostic spectral line feature [6].

2. Physics model and inversion method

The atomic and radiation physics model employed to compute the intensity distribution of the pinhole core image considers the self-consistent solution of a set of collisional-radiative atomic kinetics rate equations and the radiation transport equation. Atomic processes include electron collisional excitation and deexcitation, electron collisional ionization and recombination, spontaneous radiative decay and photoexcitation, stimulated emission, photoionization and radiative recombination, and autoionization and electron capture. The electron distribution function is assumed to be in equilibrium (i.e., Maxwellian) and detailed spectral line shapes account for Stark, Doppler, and natural broadening [7]. Once the argon atomic level populations have been determined, they are used to calculate the photon energy dependent emissivity and opacity distributions which are also dependent on the plasma electron density and temperature. The image intensity distribution is then computed via a numerical integration of the formal solution of the radiation transport equation along a discrete set of chords in the core; namely, the intensity at any point on the image is given by:

\[ I_\nu(y) = \int \varepsilon_\nu e^{-\tau_\nu(x)} dx \]  

where \( y \) is the chord coordinate, \( x \) is an integration coordinate along the chord, \( \varepsilon_\nu \) is the photon energy dependent emissivity, and \( \tau_\nu \) is the optical depth of a point of coordinate \( x \) along the chord. While the work in references 2 and 3 assumed a slab geometry of physical thickness given by an average chord length, here we consider an axially symmetric core slice (or disk) and integrate equation (1) along a set of chords of different lengths in the disk. Hence, opacity effects are carefully taken into account both in the atomic level population calculation and in the transport of the radiation through the plasma source. This physics model, which computes emergent intensity profiles and the space-integrated spectrum from given temperature and density profiles, was embedded into an inversion method to extract the temperature and density profiles from the experimental objectives.

The inversion method consists of two algorithms: the Pareto genetic algorithm, which is a robust search and optimization algorithm for multi-objective problems [1-3], and the Levenberg Marquardt non-linear least-squares-minimization method [8]. For a given set of input data, first, the PGA code is run to search in parameter space for a good approximation to the temperature and density spatial profiles that yield very good fits to the data. We emphasize that the PGA code starts the search with a random distribution of initial profiles and it is thus unbiased.
Then, the best profiles found by the PGA are used to initialize a nonlinear least-squares-minimization procedure, based on the Levenberg-Marquardt method [8], to further improve the quality of the fits. This two-step-procedure exploits the complementary characteristics of these algorithms. On the one hand, the PGA starts from an unbiased initialization and efficiently produces a good approximation to the optimal solution. A series of PGA runs where the only change is a different initial random seed is thus useful to check the uniqueness of the solution of the data fitting problem. On the other hand, the PGA result is also a very good initial seed for the nonlinear least-squares-minimization procedure which quickly converges to the optimal solution provided that it is well initialized. However, the PGA is not an efficient algorithm to perform this final convergence to the best solution. Hence, the combination of both algorithms represents an excellent strategy for objectively fitting data with a minimum number of assumptions.

3. Results

The analysis method was applied to data recorded in a series of indirect-drive shots performed at the OMEGA laser facility of the Laboratory for Laser Energetics at the University of Rochester. In these experiments plastic shells of 512 µm in diameter, wall thickness of 35 µm, and filled with 50 atm of deuterium and 0.1 atm of argon were driven by the radiation field created in a 2.5 mm long gold Hohlraum illuminated by 30 UV OMEGA beams each having an energy on target of 500 J [3]. The implosion was viewed through diagnostic holes drilled in the Hohlraum walls. The MMI instrument recorded x-ray gated narrow-band images in the photon energy range from 3200 eV to 4200 eV, which includes the argon Lyα (1s\(^2\)S – 2p\(^2\)P), Heβ (1s\(^2\)S – 1s3p\(^1\)P), and Lyβ (1s\(^2\)S – 3p\(^2\)P) lines and their associated Li- and He-like satellite transitions, respectively. This portion of the argon line spectrum was selected for analysis because it is sensitive to electron density and temperature through the density and temperature dependence of the level population kinetics and the density dependence of the Stark-broadened line shapes [7].

The data for the analysis discussed here were taken from the central core slice recorded in indirect-drive OMEGA shot 36980. The spatial grid uses a mesh of six zones for the radial r coordinate in the core slice (i.e., object space) and the y coordinate on the image plane. This is consistent with the spatial resolution expected for the MMI instrument which is about 7–10 µm [5]; no additional instrument effect is currently included.

In reference 4, we showed that the PGA-driven search and reconstruction (SR) method works successfully with intensity profiles on the image plane; previously, we had only tested it with Abel-inverted emissivity profiles obtained under the assumption of negligible optical depth [2, 3]. Furthermore, working with image intensity profiles on the image plane instead of emissivity profiles in the object space renders the method suitable to work with optically thin as well as optically thick lines. Here, we show results obtained with four objectives based on including the additional constraint of the optically thick Lyα image intensity profile.

The 3-objective analysis of the same set of data from OMEGA shot 36980 using the Heβ and Lyβ intensity profiles and the line spectrum (labeled “3 Obj. Int.” in Figures 1 and 2) are compared in Figures 1 and 2 with a 4-objective analysis based on the Lyα, Heβ, and Lyβ intensity profiles and the
Figure 1(a) and 1(b) compare the electron temperature and density profiles, respectively. The comparison of temperature and density profiles between “3 Obj. Int.” and “4 Obj. Int.” is good and it shows small discrepancies only close to the center of the core slice which is the region where we usually find the largest differences. These results indicate that 3- and 4-objective analysis runs produce consistent results. We note that the fits displayed in Figure 2 are all of comparable quality as well.

Following up on the discussion of Ref. 3 and the results displayed in Figs. 1 and 2, one could argue that 3-objectives is then the minimum number of objectives required to determine a unique solution for the spatial structure. However, the PGA-driven search and reconstruction allows us to run an over-constrained analysis of the data; we are currently investigating whether or not this fact can be used to improve (i.e. reduce) the uncertainties in the results. The results from either “3 Obj. Int.” and “4 Obj. Lyβ/Heβ” are qualitatively similar but show quantitative differences of less than 15%. This is good since it points out the robustness of the SR analysis with respect to different types of objectives. These small quantitative differences can be interpreted in terms of differences in objective’s scaling constants used in the different runs.

Further work is in progress to extend this method to analysis of sets of simultaneous multi-core-slice analysis to construct quasi-3D electron temperature and density distributions by taking advantage of data from several core slices obtained from the same intensity image.

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