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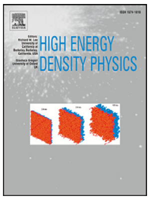

X-ray Doppler Velocimetry: An imaging diagnostic of 3D fluid flow in turbulent plasma

J.A. Koch[a,*], J.E. Field[b], J.D. Kilkenny[c], E. Harding[d], G.A. Rochau[d], A.M. Covington[e], E.C. Dutra[a], R.R. Freeman[a], G.N. Hall[b], M.J. Haugh[a], J.A. King[a]

[a] Nevada National Security Site, Livermore Operations, Livermore, CA, USA
[b] Lawrence Livermore National Laboratory, Livermore, CA, USA
[c] General Atomics, San Diego, CA, USA
[d] Sandia National Laboratory, Albuquerque, NM, USA
[e] University of Nevada, Reno, NV, USA

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ABSTRACT

We describe a novel technique for measuring bulk fluid motion in materials that is particularly applicable to very hot, x-ray emitting plasmas in the high energy density physics (HEDP) regime. This X-ray Doppler Velocimetry technique relies on monochromatic imaging in multiple closely-spaced wavelength bands near the center of an x-ray emission line in a plasma, and utilizes bent crystals to provide the monochromatic images. Shorter wavelength bands are preferentially sensitive to plasma moving toward the viewer, while longer wavelength bands are preferentially sensitive to plasma moving away from the viewer. Combining multiple images in different wavelength bands allows for reconstruction of the fluid velocity field integrated along the line of sight. Extensions are also possible for absorption geometries, and for three dimensions. We describe the technique, and we present the results of simulations performed to benchmark the viability of the technique for implosion plasma diagnosis.

1. Introduction

After several years of focused effort, the National Ignition Campaign [1] at the National Ignition Facility (NIF) [2] ended in 2012 without achieving the goal of ignition and thermonuclear burn in the laboratory. The reasons for this failure are not currently understood, and a variety of possible explanations have been proposed, but it is likely that at least part of the explanation is bulk fluid motion in the compressed hot spot [3]. Turbulent motion, on spatial scales much larger than the mean ion scattering distance, serves as an energy sink, trapping residual implosion kinetic energy that could otherwise transfer to thermal heating and neutron production. Currently, no diagnostics can measure the residual kinetic energy contained in bulk fluid motion in the hot spot, and this gap between needs and capabilities motivated the present work.

Astronomers have long utilized multispectral imaging at radio frequencies to measure bulk motion of gas clouds, for example in distant galaxies [4]. Doppler frequency shifts of the very narrow 21 cm hyperfine transition in neutral hydrogen provide information on motion of the emitting atoms. Combining spectroscopy and imaging (multispectral imaging) allows maps of gas cloud motion to be generated that show bulk motion such as rotation [5]. This is information that cannot be obtained from single-wavelength or broadband imaging alone.

An analogous instrument that can measure Doppler wavelength shifts of x-rays emitted by plasmas, locally in an imaging system, would allow bulk motion in the plasma to be diagnosed. We propose to accomplish this using near normal–incidence spherical, toroidal, or ellipsoidal bent crystals that are already widely used for quasi-monochromatic x-ray imaging applications [6–11]. These systems can provide very large collection solid angles when the angle of incidence is close to normal and the crystal quality is high, and can be very efficient when used with narrowband emission line sources [12]. Use of multiple crystals, each tuned to a slightly different wavelength band, can in principle allow a map of fluid velocity (averaged along the line of sight) to be generated, and this is the essential concept behind X-ray Doppler Velocimetry (XDV) [13].

In this paper, we discuss the details of a particular implementation of XDV, intended to diagnose residual kinetic energy in NIF implosion plasmas. We utilize 3D simulations of a particular implosion, with some assumptions and approximations and coupled to a 3D instrument ray trace simulation, to produce simulated XDV image data that be examined and compared with simulated broadband pinhole images of the same plasma from the same line of sight. We also explore variations in viewing line of sight at a single time,

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[*] Corresponding author.
E-mail address: kochja@nv.doe.gov (J.A. Koch).

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and in time along a single line of sight. We conclude that available evidence indicates that the XDV diagnostic will work as intended for this application, even with a time-integrated detector. We also describe plans for fielding a XDV prototype system on other facilities in proof-of-principle experimental demonstrations.

2. Conceptual design

The conceptual geometry of XDV is shown in Fig. 1. Five identical bent imaging crystals, with the same interplanar spacing d, are arranged to view a plasma along a near-common line of sight, and each is configured with a slightly different Bragg angle θ_B. The Bragg equation $\lambda = 2d\sin\theta_B$ implies that the center bandpass of each crystal falls at a slightly different wavelength λ. If we configure the range of wavelengths to run from the red wing to the blue wing of the unshifted center of an x-ray emission line from the plasma, then five different quasi-monochromatic images will be generated. Each image will emphasize velocities corresponding to the Doppler shifts of the centers of the pass bands of the five crystals. This is shown schematically in Fig. 2.

The number of crystals is arbitrarily chosen here to be five. A lower bound is two crystals, the minimum necessary to show differences between images in different wavelength bands, while an upper bound will be limited by the complexity of the instrument and ultimately by view differences between lines of sight, necessary due to the non-zero dimensions of the crystals and mounting fixtures. However we note that, in principle, many different crystals from many lines of sight could be utilized to create a fully 3D map of fluid motion in the plasma.

A similar instrument was fielded for multispectral imaging at the Gekko laser facility [8,14]. In those experiments, an array of monochromatic imaging crystals was used to produce multi-spectral images of an implosion plasma, in widely separated bands corresponding to different emission lines and continuum. The purpose of that diagnostic was to provide maps of electron temperature and density gradients. The key feature of XDV is that the emission bands are both very narrow, and closely spaced within the spectral width of a single line, in order to produce maps of Doppler shifts and therefore fluid velocity.

3. Simulations of a NIF implosion experiment

In order to evaluate the diagnostic potential of XDV as applied to an implosion experiment at the NIF, we used a 3D Hydra [15] post-shot simulation of a particular NIF implosion, NIF shot N130927. We then post-processed the simulation results in two stages to generate a series of simulated XDV images.

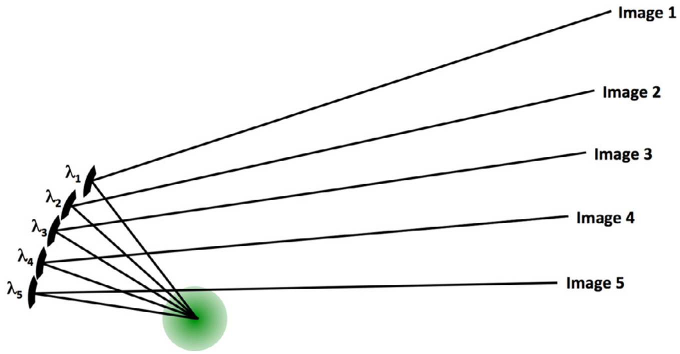

Fig. 1. Conceptual sketch of XDV. Here, five identical imaging crystals project five separate images of the source onto a detector that could be time-integrated or gated at a common time. The crystals are sensitive to different x-ray energies in closely spaced bands near the center wavelength of an emission line from the source. Combining the images, for example, by color-coding, would generate a multispectral image mapping line-of-sight velocity into. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

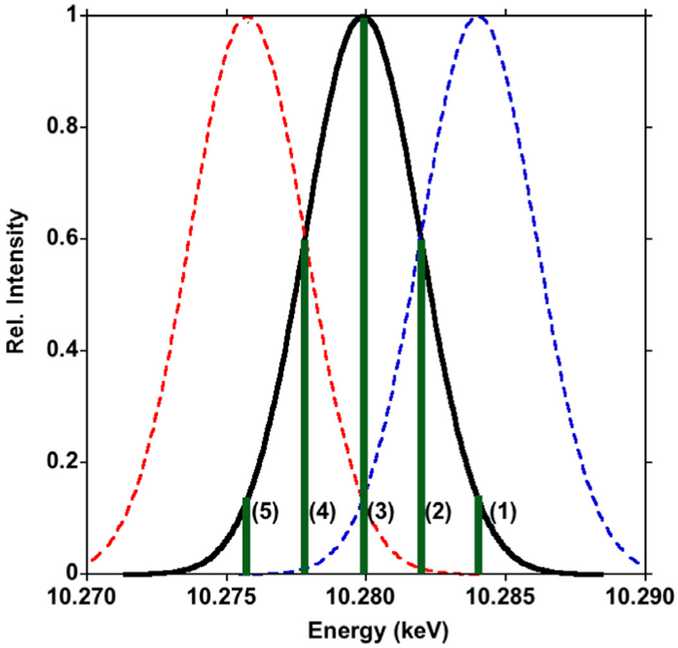

Fig. 2. Sketch of the center wavelength distribution of the crystals shown in Fig. 1. An unshifted line would appear brightest in the middle crystal (3). If the source was moving toward the crystal, the line would shift to the right and the source would appear brightest in the blue-tuned crystal (1). If the source was moving away from the crystal, the source would appear brightest in the red-tuned crystal (5). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

First, for a variety of lines of sight, at a variety of times during the implosion, we generated 2D moment maps integrated through the depth of the plasma under the assumption that the plasma was uniformly doped with germanium that emitted an optically thin He-α line at an x-ray energy of $E = 10.28$ keV. The moments were integrated line of sight intensity $\langle I \rangle$ using a Bremsstrahlung approximation $N^2\exp(-E/T)$, intensity-weighted fluid velocity $\langle IV \rangle$, and intensity-weighted square of fluid velocity $\langle IV^2 \rangle$ at each 1×1 μm pixel in a 2D plane perpendicular to the line of sight. Using the defining equations for the Doppler shift and the standard deviation, we then calculated normalized intensity ($\propto \langle I \rangle$), spectral line center wavelength ($\propto \langle IV \rangle / \langle I \rangle$), and spectral line width due to fluid flow ($\propto \sqrt{\langle IV^2 \rangle / \langle I \rangle - \langle IV \rangle^2 / \langle I \rangle^2}$) at each pixel. Convolving the bulk fluid motional broadening with an assumed microscopic thermal broadening consistent with a uniform 4 keV ion temperature yielded our source objects, for each line of sight and at each time. We note that peak depth-averaged fluid velocities exceed 200 km/s in these post-processed moment maps, which is nearly the peak implosion velocity. This indicates that, in 3D, some portions of the plasma retain their peak implosion velocities even at the time of peak compression, whereas in a 1D approximation, the plasma would be stagnant with no residual kinetic energy.

Next, we used the intensity, center wavelength, and line width maps as sources for a 3D instrument ray trace using a custom Monte Carlo code that is a modification of earlier codes used for similar purposes [12,16]. The ray trace simulation maps an arbitrary source to an image plane in full 3-D, using source and geometry information as well as crystal properties (d spacing, bandwidth, surface figure). We assume quartz (0,7,1), bent to a 390 mm spherical radius of curvature with a 2.8 mm circular aperture diameter, and we choose five center wavelengths spanning an energy range of 10.276–10.284 keV. This range corresponds to ± 120 km/s motional