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# Tomographic reconstruction of high energy density plasmas with picosecond temporal resolution

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## Abstract

Three-dimensional reconstruction of the electron density in a plasma can be obtained by passing multiple beams at different field angles simultaneously through a plasma and performing a tomographic reconstruction of the measured field-dependent phase profiles. In this letter, a relatively simple experimental setup is proposed and simulations are carried out to verify the technique. The plasma distribution is modeled as a discreet number of phase screens and a Zernike polynomial representation of the phase screens is used to reconstruct the plasma profile. Using a subpicosecond laser, the complete three-dimensional electron density of the plasma can be obtained with a time resolution limited only by the transit time of the probe through the plasma.

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Tomographic reconstruction of plasmas has primarily focused at measuring the self-emission generated by these plasmas at multiple field angles and this has been almost exclusively performed in lower density plasmas, more typical of magnetically confined plasmas.[1,2] This article deals with tomographic reconstruction of the three-dimensional electron density profile in high-density plasmas, such as occur in Z-pinches and laser-produced plasmas, using active probing. Electron density measurements in high-density plasmas using active probes have been obtained using a variety of techniques including interferometry[3], moiré deflectometry[4] and grid image refractometry[5]. Other techniques such as Shack-Hartmann sensing[6] and curvature sensing[7] have also been proposed. These techniques measure the two-dimensional line-integral density through the plasma. In some instances, three-dimensional profiles have been calculated from these line-integral measurements by assuming that the plasmas are symmetrical in one-dimension. This assumption allows Abel inversion of the line-integral measurement to reconstruct an idealized three-dimensional electron density profile of the plasma. In reality plasmas suffer from hydrodynamic or magneto-hydrodynamic instabilities and are produced from non-ideal surface or illumination irregularities that invalidate the symmetry assumption. By extracting the true three-dimensional distribution of the plasmas, detailed studies of instabilities, stagnation physics and the effects of initial conditions can be undertaken. This paper presents a technique and a relatively simple experimental setup that allows the three-dimensional electron density of a high-energy density plasma to be determined without a-priori assumptions regarding the symmetry of the plasma.

The approach taken to determine the three-dimensional distribution of the electron density in the plasma is to make multiple measurements of the plasma at different field angles and then to use tomographic techniques to reconstruct the three-dimesnional profile of the plasma from the line-integral measurements at the different field angles. The specific approach taken to tomographically reconstruct the wave-front of the rays passing through the plasma was to utilize a Zernike polynomial expansion at each of the axial planes representing the plasma.[8] The electron density profile is then determined from the reconstructed phases. In particular, a circular pupil was assumed and Zernike polynomials were chosen to represent the plasma phase profile since they represent an orthonormal basis set over the unit circle. This allows the tomography problem to be written as a system of algebraic equations for the unknown Zernike coefficients. By collecting line-integrated phase information from the different field angles, the appropriate coefficients for the Zernike polynomial series can be solved for and hence the phase/electron density at each layer determined. The resultant system of algebraic equations can be expressed in matrix form, B=HA where B is an array of optical path differences for each ray traversing the plasma, H is the array of Zernike polynomial values for the intersection of each ray at each of the phase screens.[8] To retrieve the Zernike coefficients, A, for the phase/electron density, it is necessary to solve the algebraic system by inverting the H array. For the results presented below, the A array was solved by inverting the matrix H via singular value decomposition.

For the simulations described below, the plasma was modeled as a cylinder with a Gaussian profile such as might be expected from a z-pinch plasma or a line focus laser-produced plasma. A Kolmogorov turbulence spectrum[9] was superimposed on top of the profile to remove symmetry and the resultant profile was then broken up into three equally spaced planes. The probe beams were incident on the plasma at nine different field angles and the simulated probe beams were passed through these screens to measure the line-integrated phase along each of nine separate field angles. The line-integrated phases along each of the nine separate field angles was reconstructed and the piston component removed. The phases determined from the different field angles were then used to tomographically reconstruct the three-dimensional phase profile for the plasma. In the simulation, the phase profiles were fit using the first 30 Zernike polynomials.

A relatively simple experimental setup for performing the measurements required for tomographic reconstruction is shown in Figure 1. Using a short pulse laser, tomographic reconstruction with picosecond resolution can be obtained. In Figure 1, two crossed gratings are used to generate nine probe beams at different field angles through the plasma. Utilizing the m=0 and ±1 orders of the gratings, nine separate angles can be recorded simultaneously. A second "low pitch" lenslet array is used to collimate the separate probe beams and image the plasma plane onto the charge-coupled device, CCD, camera. In Fig. 1a a cyclical interferometer[10] is used to measure the phase perturbation introduced in the probe beams passing through the plasma and in Fig. 1b a much more compact design based on a Shack-Hartmann wave-front sensor[6] is used to measure the phase perturbations. Both of these wave-front sensors can be used relatively easily with limited coherence length short pulse lasers.

The simulations performed a ray trace of the probe beam through the simulated phase screens representing the plasma. The three screens representing the plasma were each separated by 500 microns and contained a density profile, $n_e$, that was Gaussian along the horizontal axis, x, and also along the direction of the nine probe beams, z,

$$n_e = 1.5\exp\left[-\left(\frac{z}{750\ \mu m}\right)^2\right]\exp\left[-\left(\frac{x}{1.34\ mm}\right)^2\right](15 + \text{Kol. Tur.}), \quad (1$$

where the Kol. Tur. represents the Kolmogorov turbulence spectrum[9] that was added to the phase screens to eliminate symmetry.

The simulations results for the tomographic reconstruction of the plasma are shown in Figure 2. The original phase screens representing the plasma are shown as the three images in the top row. The reconstructed phase using the tomographic reconstruction of the measurements at each of the field angles is shown as the middle row and very closely represent the original phase screens. The difference between the original phase and the reconstructed phase is displayed in the bottom row. This difference is primarily a tilt error between the two sets of phases. The variance between the reconstructed and the applied phase is given in Figure 3. The largest variance between the reconstructed and the applied phase is in the second screen where the variance is 0.12 $rad^2$.

The low variance between the original phases and tomographically reconstructed phases demonstrates that this technique can quantitatively determine the three-dimensional phase profile of a high-density plasma. Given the compact design presented in this article, these measurements can be made with a relatively simple optical setup and can provide for three-dimensional reconstruction of high-density plasmas using existing lasers. When a short-pulse laser is used for these measurements, a three-dimensional electron density profile of the plasma can be obtained with picosecond temporal resolution.

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# FIGURE CAPTIONS

Figure 1 Experimental setups for the three-dimensional tomographic reconstruction of the electron density in high density plasmas. Figure 1a represents a setup using a cyclical interferometer and Figure 1b represents an alternative system utilizing a Shack-Hartmann wave-front sensor. In both cases two crossed transmission gratings are used to generate nine beams at different field angles to probe the plasma and enable a tomographic reconstruction of the three-dimensional electron density profile. A “low pitch” lenslet array is used in both cases to collimate the separate beams and reimage the plane of the plasma onto the wave-front detector.

Figure 2 Tomographic reconstruction results comparing the reconstructed phase profiles with the phase profiles placed on the phase screens representing the plasma. The three images on the top row represent the applied phase while the three in the middle row represent the reconstructed phase at each of the three planes in the plasma. The three bottom row images show the difference in phase between the applied and reconstructed phases at each of the planes representing the plasma.

Figure 3 Variance in the phase between the applied and reconstructed phases at each of the three screens representing the plasma.

# FIGURES

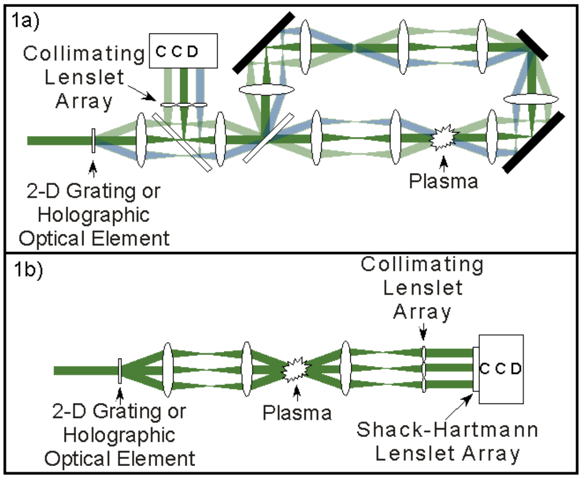
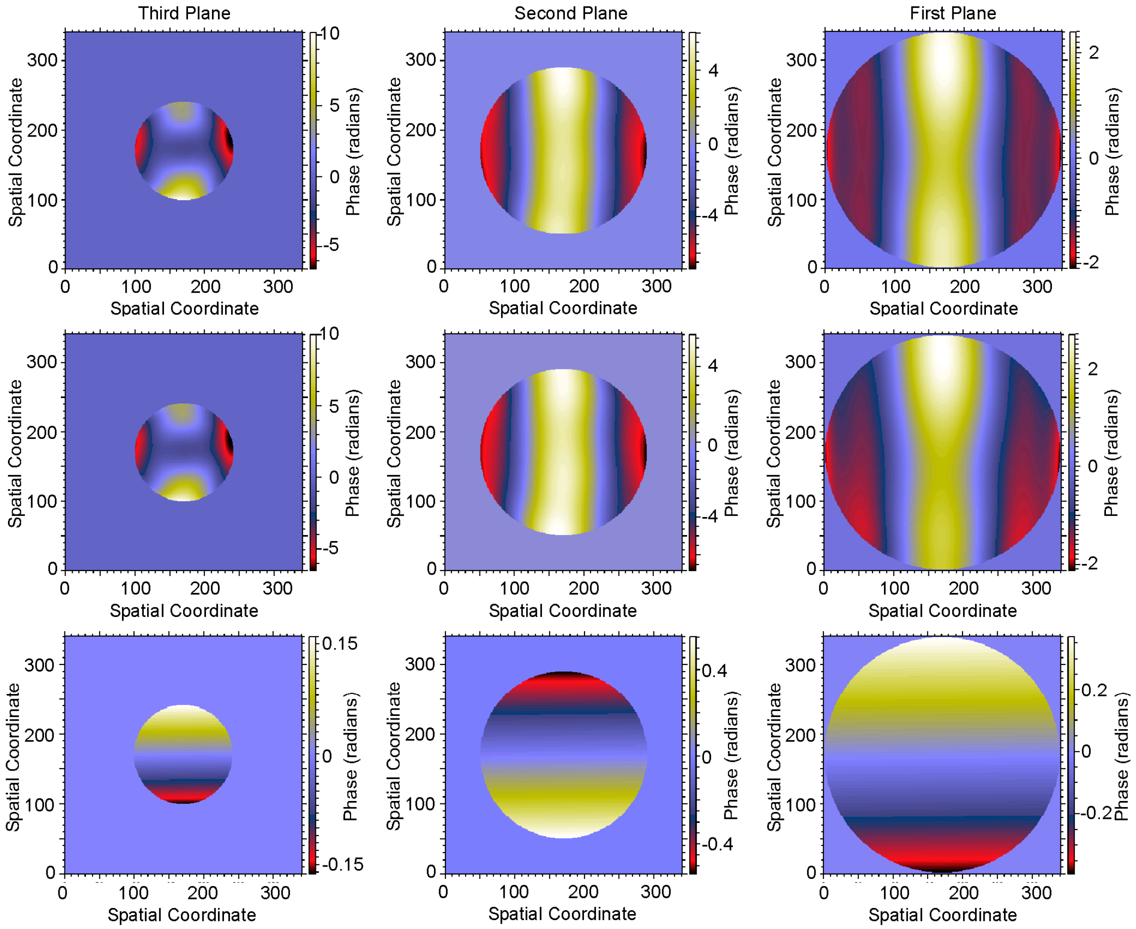


Figure 1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First Plane
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Figure 2

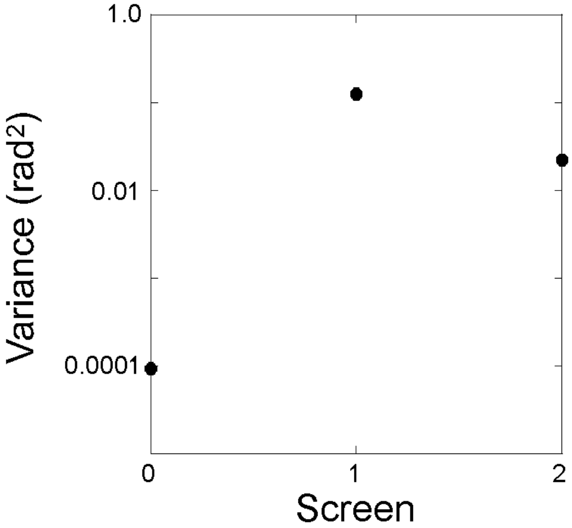

Figure 3