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Improved optical tomography device

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We report the development of an improved optical tomography diagnostic which measures the velocity-space distribution of a laboratory plasma in two dimensions. The new device is capable of imaging plasma distributions over a wider range of magnetic fields and plasma column diameters than the previous design, while minimizing the risk of misdiagnosis due to perturbations caused by inserting the device in the plasma. Computer-aided control of the diagnostic allows a greater number of single-dimensional scans to be collected in a shorter amount of time, resulting in increased resolution of the reconstructed image while freeing up more time for the user to perform the experiment. Recent data using the new device are presented to show improvement of resolution gained by doubling the number of total scans. Finally, we present a method to identify velocity-space nonuniformities without the need to reconstruct a complete image.

I. INTRODUCTION

When considering the velocity-space diagnosis of a laboratory plasma, one sometimes is content to specify all of the useful information in terms of velocity distribution functions parallel with and perpendicular to the confining magnetic field. These two distributions are used to obtain the plasma drift speed and temperature (v_d , $T_\perp$, and $T_\parallel$) and may be sufficient to describe the behavior of the plasma. Under certain environments, however, this information is inadequate. For example, ion heating in a nonuniform field can produce an ion conic,^{1,2} which has a preference in velocity pitch-angle, and is not characterized exclusively by the above parameters. Under such environments, a more comprehensive diagnostic approach is required.

The optical tomography diagnostic^{3,4} was developed at Irvine as a way to obtain the full ion velocity distribution of a laboratory plasma. This is achieved by measuring the distribution in a single dimension by laser-induced fluorescence (LIF)⁵ methods and then repeating the measurement over a range of angles. The collection of one-dimensional LIF scans is then processed numerically by filtered back-projection, a tomographic method well known in the medical sciences community,^{6,7} but relatively unknown in plasma physics. The result of the processing is a complete two-dimensional reconstruction of the velocity distribution. The original device, developed by McWilliams and Koslover, demonstrated the feasibility of tomographic measurements in a laboratory plasma. The current device extends the abilities of the original design by taking a full set of scans at least an order of magnitude faster in time (total time 2.5 min), under a wider range of magnetic fields ($B > 0.5$ kG) and plasma column diameters ($d \approx 10$ cm). Table I summarizes the differences between the first- and second-generation devices. A description of the new tomography device is given in Sec. II. Section III shows high- and medium-resolution velocity distributions obtained with the new device, and Sec. IV illustrates how to find anomalies in a distribution with only a single scan.

II. EXPERIMENTAL ARRANGEMENT AND TOMOGRAPHY DIAGNOSTIC

A. Setup

The experiments involving the tomography diagnostic were performed in a quiescent plasma device.⁸ A schematic of the arrangement is given in Fig. 1. The plasma generator was a standard Q -machine tungsten hot plate providing a 5-cm diameter barium plasma column at the source. Density at the plasma source was on the order of $0.5\text{--}5.0 \times 10^9 \text{ cm}^{-3}$. Plasma temperature at the source was $T_i = 22$ eV, $T_e = 0.2$ eV. The magnetic field ranged from 1.6 to 4.2 kG, and, depending on the experiment performed, was either uniform or divergent. When plasma heating was desired, an antenna placed 30 cm downstream of the source provided radio frequency power applied directly to the plasma. Ion plasma density was inferred from Langmuir probe measurements. Ion velocity distributions were obtained by LIF measurements.

B. LIF and reconstructive tomography

LIF is used in the laboratory to measure one-dimensional velocity distribution functions. A narrow-band ($\delta\omega < 1$ MHz) laser introduced into the plasma may excite atomic transitions of the constituent ions. For an ion moving with velocity $\mathbf{v}_i$ and electronic transition frequency ω_0 , excitation and fluorescence will occur when

$$\omega_l - \mathbf{k}_l \cdot \mathbf{v}_i = \omega_0, \quad (1)$$

where ω_l and $\mathbf{k}_l$ are the frequency and wave number of the laser, respectively. The fluorescent photon flux is proportional to the number of ions at that velocity (within the bandwidth of the laser). By sweeping out the appropriate range of laser frequencies, one obtains the one-dimensional velocity distribution for ions with a velocity component in the direction of the laser propagation.

One may think of this distribution as the line integral of the full velocity distribution, i.e., $f(v_x, v_z)$ is integrated over the velocity component(s) orthogonal to $\mathbf{k}_l$ to obtain $f(v_\theta)$, where θ represents the angle between the laser direction and the x axis, defined as the direction normal to the magnetic

TABLE I. Summary of changes made to the original optical tomography device, and resulting improvements in performance.

Changes in tomographic device	Original device	New device
Automated rotation	No	Yes
Laser input polarization	No	Yes
Distance from hook to optical detection site	2.5 cm	5.0 cm
Laser line	5854 Å	4934 Å
Resulting improvements		
Zeeman lines	10	4
(with polarizer)	6	2
Scan collection time	30 min	2.5 min
Minimum magnetic field	4 kG	0.5 kG
Maximum plasma column diameter for unperturbed measurement [$f(v_{\perp})$]	5.0 cm	10.0 cm

field. [Note here we have integrated the function over v_y , since the symmetry of the distribution due to the ion gyromotion makes examining $f(v_y)$ superfluous.] Expressing this result mathematically yields $f(v_{\theta})$ as a velocity-space “projection” of the distribution $f(v_x, v_z)$

$$f(v_{\theta}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(v_x, v_z) \delta(v_x \cos \theta + v_z \sin \theta - v_{\theta}) dv_x dv_z. \quad (2)$$

From a collection of line integrals, one may invoke the reverse process, known as filtered back-projection (not derived here), to obtain the complete distribution $f(v_x, v_z)$,

$$f(v_x, v_z) = \int_0^{\pi} \int_{-\infty}^{\infty} h(v_{\theta}) \delta(v_x \cos \theta + v_z \sin \theta - v_{\theta}) dv_{\theta} d\theta, \quad (3)$$

FIG. 1. Sample experimental configuration in which the tomography device was used. The plasma spreads radially outward due to the magnetic-field gradient from source to optical detection site.

FIG. 2. Schematic of tomography apparatus inserted into the plasma device. The hook has freedom of rotation at any angle relative to the external magnetic field.

where $h(v_{\theta})$ is a one-dimensional velocity distribution convolved with a filter function designed to compensate for “smearing” of the higher velocity-space harmonics, a natural effect of conventional back-projection.

Of course it is not practical to measure the velocity distribution at an infinity of unique angles relative to the external $\mathbf{B}$ field. Instead, we collect a finite set of one-dimensional distributions by scanning the laser at an angle $n(\delta\theta)$, where n runs between 0 and $N-1$, and N is the total number of scans collected. $\delta\theta$ is chosen such that $N(\delta\theta) = \pi$, or 180° of rotation. This collection of one-dimensional scans is then processed by quadrature either on a PC or a workstation.

Note that it is usually necessary to translate the one-dimensional images numerically prior to filtered back-projection. This is easy to accomplish, since the origin of a velocity-space distribution is almost always shown to be the maximum of $f(v_x)$, the distribution measured perpendicular to the external $\mathbf{B}$ field. Experimentally, this is verified by examining $f(v_x)$ with the laser pointing perpendicular to the field, and then measuring it again with the laser pointing directly opposite that of the first measurement. If the maximum of $f(v_x)$ is at $v_x=0$, then the peak of the distribution will not appear translated between measurements.

C. Optical tomography device

The tomography hook is shown in Fig. 2. It consists of a $\frac{3}{8}$ -in. diameter stainless-steel rod bent into the shape of a shepherd's hook, with a fiber optic passing through it. The fiber is terminated just short of a 2-cm focal length lens cemented on the end of the hook. The fiber optic is positioned so that the laser diagnostic beam passing through the lens will focus in the center of the plasma, thereby minimizing the light collection spot size. The top of the lens sits approximately 5 cm away from the center of the plasma column. The top of the lens is covered with a circular cut of dichroic sheet polarizer aligned so that the electric-field vector of the output light is always perpendicular to the external magnetic field, regardless of the rotation angle of the hook. The back end of the hook passes through an O-ring assembly

FIG. 3. Simplified sketch of servo/worm-gear assembly and block diagram of motor controller.

mounted to the machine, which gives the hook vacuum-safe freedom of radial motion and rotation so that the diagnostic beam may be positioned at any angle relative to the external magnetic field.

Figure 3 shows a simplified sketch of the worm-gear assembly used to rotate the hook, and a block diagram of the computer-driven motor control. The gear is mounted to the hook, and the worm is attached directly to a DC servo motor. The servo is powered by an amplifier and its position is monitored by an optical encoder. The servo/encoder assembly is driven by a digital motion controller (Galil DMC-100) installed as a unit on a CAMAC device, thereby allowing the user to rotate the hook remotely by computer. Use of this assembly results in a drastic reduction in the time needed to collect a set of one-dimensional scans.

Singly ionized barium has many atomic transitions in the visible spectrum, and a judicious choice of transition is pivotal to the success of tomography in lower magnetic fields. Consider the Grotrian diagram for singly ionized barium in Fig. 4. Each transition is split into several nondegenerate components from anomalous Zeeman splitting due to the external magnetic field. This has the effect of multiple overlapping velocity distributions, as shown in Fig. 5. The 5854-Å line, chosen for the first-generation diagnostic, has ten Zeeman components, which are separable only by a combination of large (5 kG) magnetic-field and numerical line removal methods (such methods usually produce only marginal results if the number of extra components exceeds one). By choosing the 4934-Å line (Fig. 6) and aligning the tomography hook polarizer properly, the number of Zeeman lines is reduced to two. The remaining lines usually are sufficiently separate not to require numerical removal of the spurious distribution.

III. RESULTS

A typical tomographic reconstruction of a heated laboratory plasma is shown in Fig. 7(a). The plasma shown here was a low-density ($<10^9 \text{ cm}^{-3}$), uniform-field ($B=2.6 \text{ kG}$)

FIG. 4. Partial Grotrian diagram of Ba^+ with Zeeman splitting of appropriate transitions.

plasma heated by externally driven low-frequency ($\omega/k \approx v_{ti}$) lower hybrid waves.⁹ Here, v_z represents the velocity parallel to the external magnetic field, and v_y represents one component of velocity perpendicular to the field. Each line on the graph represents a contour of constant f , decreasing outward in 10% intervals, so that the last contour is 10% of f_{max} . The elliptical shape of the contours stretching in v_y indicates a fourfold increase in temperature perpendicular to the field. This distribution was taken from a sequence of 32 one-dimensional scans.

A. Resolution considerations

Usually a scan collection sequence involves a trade-off between total collection time and quality of the final two-dimensional distribution. To show the effects of resolution on the number of scans, the above 32-scan sequence is compared to Fig. 7(b), a 16-scan sequence, generated by processing every other scan in Figure 7(a). The second of the two graphs reveals "ripples" in the contours, which peak roughly at angles where the distribution is measured. The ripples are a result of small irregularities in each of the one-dimensional distributions; these irregularities are most likely to occur in low-density or rf heated plasmas, where the laser-induced fluorescent photon flux is low. As the number of scans is increased, the irregularities in the one-dimensional distributions are averaged (smoothed) out of the final image, and the

FIG. 5. Effect of Zeeman splitting on a typical velocity distribution for the 5854-Å line. (a) Computer-generated Maxwellian distribution. Temperature is 0.5 eV. (b) Relative intensities and separations of each component in a 1.5-kG magnetic field. Solid lines: Laser electric-field polarization parallel with B field (π components); dashed lines: Electric-field polarization perpendicular with B field (σ components). (c) Superposition of each component to show actual distortion of distribution. (d) Superposition of only the σ components, the result of placing an input polarizer in front of the laser. Note that there are two sets of three unresolved components, which shows an input polarizer here is not useful.

rippling effect is reduced. To achieve nominal resolution in most plasma circumstances, 32 scans, collected in about 5 min, is sufficient. Alternately, one may collect 16 scans in half the time, and simply accept contour ripples as an artifact of the reconstruction process.

B. Additional gains

Here, we briefly discuss some important gains made from using the improved design, and why the new one is better. Among the important features of the new tomography device is the improved collection time from 30 min (hand turned, single person) to about 2.5 min (computer controlled). The improved speed has the dual advantage of more time for the physicist to do physics, and the ability to complete a collection for a single 2D reconstruction in much less time than it takes for the plasma parameters to change (typi-

FIG. 6. Effect of Zeeman splitting on a 0.5-eV distribution in a 1.5-kG magnetic field, for fluorescence of the 4934-Å line. (a), (b), and (c) are the unperturbed computer-generated distribution, separations/intensities, and superposition of each component, respectively. (d) is the resulting line split for σ polarized incident light, showing that an input polarizer on the tomography hook almost completely resolves the actual distribution without the need for numerical separation.

cally 20–30 min). Computer controlled motion has an additional advantage over hand rotation of being able to position the hook to within one half of a degree of the desired angle. Finally, it should be pointed out that the choice of the 4934-Å line with an input polarizer results in a sufficiently wide Zeeman line separation that the original scan need not be subject to computer algorithms to remove the spurious components (necessary at all magnetic fields for the original device).

IV. FAST IDENTIFICATION OF ANOMALOUS VELOCITY DISTRIBUTIONS

The usefulness of the tomography device lies in the fact that it can reconstruct details about the full velocity distribution, and is especially important when considering non-Maxwellian distributions, such as ion conics, since the structure of these “anomalous distributions” cannot be obtained from simple measurements perpendicular to and parallel with the confining magnetic field. While a collection of one-

FIG. 7. Typical velocity distribution for a heated laboratory plasma, showing the effects of resolution on number of one-dimensional measurements. (a) is the distribution reconstructed from 32 individual 1D scans. (b) is the same distribution, reconstructed from every other 1D scan in (a).

dimensional scans is gathered in less than 3 min, it may still be desirable to have some idea of the velocity distribution structure before gathering a full set of data. For example, the user might like to know if a laboratory conic exists in the plasma without having to make a complete set of measurements, thereby saving more time on the search.

One way to identify an ion conic with a single scan is to make use of the fact that the conic exhibits a higher flux at a preferred velocity pitch-angle. By projecting a conic at the angle of maximum pitch, one may visualize that the projection will reveal a greater thermal spread on one side of the distribution maximum than the other, as shown in Fig. 8(a). Experimentally, all that is necessary is to align the tomography hook off-axis [say, 45° relative to $f(v_\perp)$]. One may then may search for and identify a conic more quickly by varying important experimental parameters such as magnetic-field ra-

FIG. 8. (a) Sample measurement of velocity distribution used to identify non-Maxwellian 2D distributions. Solid line: Distribution measured at an angle 135° (-45°) with respect to $f(v_y)$; dotted line: closest Maxwellian approximation of distribution, considering only the left-half side of $f_{\max}$. Increase in photon flux to the right of $f_{\max}$ is the signature of an ion conic. (b) is the complete reconstructed distribution. The stretching of the contours at approximately $\pm 50^\circ$ of v_z is indicative of a high ion flux at that angle, and is the primary characteristic of an ion conic.

tios and ion heating at the source instead of waiting for the entire tomographic reconstruction to occur.

The reconstructed distribution corresponding to Fig. 8(a) is shown in Fig. 8(b). This distribution was obtained by heating the plasma near the source by low-frequency electrostatic waves generated by parametric decay of high-frequency ($\omega/k \gg v_{ti}$) lower hybrid waves,¹⁰ and having the plasma flow adiabatically in a spatially decreasing magnetic field; the scans were collected downstream of the source, where the field was smallest. The conic is identified by observing the contours bent into a triangular shape and stretched along a preferred velocity pitch. By rotating the contours about the axial (z) direction (as would be the case for a three-dimensional reconstruction), the corresponding surfaces would take on the shape of a cone.

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