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Velocity Space Diffusion in Q-Machine Plasmas

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Abstract—We report measurements of test particle diffusion in velocity space. Test particles are created and examined using the method of optical tagging, an extension of laser-induced fluorescence. In quiet plasma conditions ($\delta n/n \leq 0.01\%$) results show diffusion to be linear with density in agreement with classical theory. Measurements taken in the presence of drift waves ($\delta n/n \approx 6\%$) show resonant particle interactions. Applications to magnetospheric phenomena will be discussed.

I. INTRODUCTION

FUNDAMENTAL understanding of situations involving particle-particle or wave-particle interactions can be achieved by measurements of particle phase space transport. Laser-induced fluorescence [1] (LIF) provides an excellent method, that of optical tagging [2], to study the transport of test ions in both velocity and configuration space. This method has a long history of use in ion transport measurements. Spatial diffusion resulting from ion-ion collisions [3] and from broadband electrostatic ion cyclotron waves [4] was measured by McWilliams *et al.* Skiff *et al.* [5] performed similar measurements when the transport was due to stochastic wave-particle interactions. Measurements have been made by Fasoli *et al.* [6] that probed the effects of neutral particle density on cross field diffusion. The measurements described here are unique in that they follow a particle's trajectory in velocity space.

This article is a writeup of a poster presented at the Workshop of Plasma Experiments in the Laboratory and in Space held July 1–5, 1991, in Alpbach, Austria. Most of these data are preliminary and further details will be published. Section II briefly describes the use of optical tagging in this experiment. Section III discusses the interpretation of the experimental data and provides the results predicted by classical test particle theory. Current experimental results are presented in Section IV. Lastly, in Section V, possible applications of the technique to problems in space physics will be discussed.

II. EXPERIMENTAL SETUP

The experiments described herein were performed on a single ended Q-machine (see Fig. 1) [7], [8]. The plasma had a diameter of 5 cm and an axial length of 1.3 m. The confining axial magnetic field was 5.0 kG. A background pressure of less than 3×10^{-6} torr was maintained at all times. With this pressure, the cross section for ion-neutral collisions is thought to be 10^3 less than that for ion-ion collisions. The ions are

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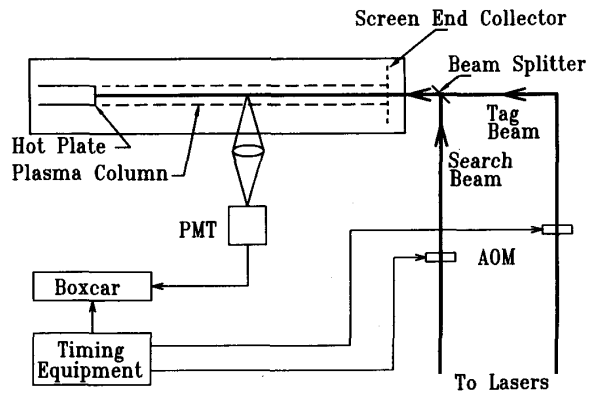


Fig. 1. A schematic of the experimental setup used for the velocity space tagging experiments.

accelerated through a sheath at the hot plate to a axial drift speed of about 7×10^4 cm/s.

Plasma density was measured using a Langmuir probe and was also inferred from the angle of propagation of the lower hybrid wave. Ion temperature in the perpendicular and parallel directions as well as the ion drift velocity was measured with LIF. The details of LIF and optical tagging (OT) have been detailed elsewhere [1], [9]. In brief, this technique takes advantage of the fact that the laser line width is much more narrow than the Doppler-broadened absorption line of the plasma. The absorption of a photon by an ion results in the ion moving to an excited state. This state is very short-lived (on the time scale of the experiment) and decays down to a lower energy state by emitting a photon. This photon is collected by a lens system external to the Q machine. The frequency of the laser can be swept over a broad range. The light intensity from the plasma can then be measured as a function of the laser frequency. Doppler shift relates the frequency to the velocity and thus $f(v)$ can be measured. Additionally, the laser can be held constant in frequency and therefore excite only one velocity component of the ion distribution.

In the tagging experiment it is necessary to pulse the laser light. This is accomplished by using acoustic optical modulators (AOM). The experiment also requires two separate lasers. The first laser is tuned to excite Ba ions from the ground state to a specific excited state. From there they can decay back to the ground state or to a metastable state (lifetime long compared with time scale of the experiment). If the particle decays to this metastable state, the particles are considered tagged (they can now be distinguished from the background particles). The second laser, tuned to excite particles in the same metastable state, is used to detect the tagged particles.

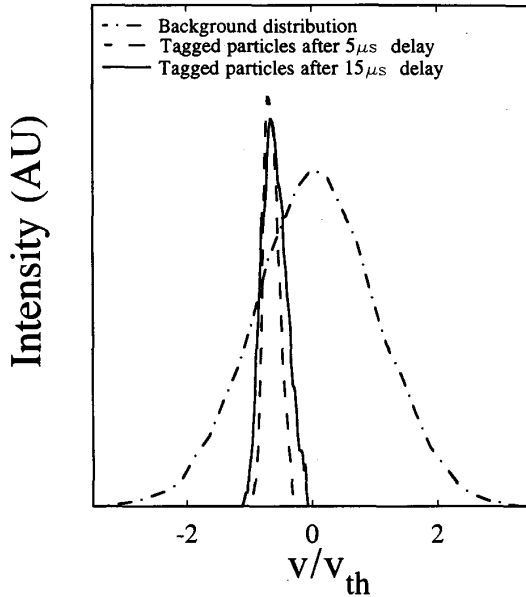


Fig. 2. An example of raw data. Note the change between the tagged distributions.

Background subtraction of the particles naturally occurring in the state leaves a signal from the tagged particles only. The tagging laser is held at a constant frequency and the search laser is scanned in frequency. Thus, a particle velocity class is tagged, and the subsequent velocity distribution of the tagged particles is measured. The number of particles tagged in this experiment was approximately 1 to 3% of the total density. All tagging measurements were made in the axial direction only.

III. THEORY

This section presents the method used to interpret the experimental data. Additionally, the theory for collision-induced transport of test particles is provided.

Fig. 2 shows both a scan of the background particles and a scan of the tagged population at two times. The data are interpreted in the following way.

Measurements were made in the direction parallel to the magnetic field, so a one-dimensional model is used. The initial distribution of tagged particles can be represented approximately by a drifting Maxwellian:

$$n(v, t = 0) = \frac{n_T}{\sqrt{2\pi\sigma_T^2}} \exp\left(-\frac{(v - v_T)^2}{2\sigma_T^2}\right),$$

where n is the density, σ represents the width of the velocity distribution, and the subscript T refers to the tagged particle.

The time evolution the velocity distribution is given by the one-dimensional velocity space continuity equation:

$$\frac{\partial n(v)}{\partial t} + \frac{\partial \Gamma}{\partial v} = 0.$$

Taking the flux, Γ , to be the sum of a convection term and a diffusion term gives

$$\Gamma = n \frac{\langle v \rangle}{\tau_c} + \frac{\langle v^2 \rangle}{\tau_D} \frac{\partial n(v)}{\partial v}.$$

By defining the following,

$$C_v \equiv \frac{\langle v \rangle}{\tau_c}$$

and

$$D_v \equiv \frac{\langle v^2 \rangle}{\tau_D},$$

we can write

$$\frac{\partial n(v, t)}{\partial t} + \frac{\partial}{\partial v} \left(C_v n(v, t) + D_v \frac{\partial n(v, t)}{\partial v} \right).$$

For times short enough to consider the transport to be independent of the velocity, the solution of this equation is

$$n(v, t) = \frac{n_T}{\sqrt{2\pi}} \frac{1}{\sigma_T^2 + 2Dt} \exp\left(-\frac{(v_T - v - C_v t)^2}{2(\sigma_T^2 + 2Dt)}\right). \quad (1)$$

Thus, the change in the first and second moments of the measured tagged particle distribution gives, respectively, the convection and diffusion rates.

Rostoker [10] calculated the theory for the diffusion and convection of test ions in a quiet plasma. By quiet plasma we mean that the fluctuation level is so small that the velocity space transport is due only to particle collisions. The results for our conditions follow:

$$C_{v_z} = \left\langle \frac{\delta v}{\delta t} \right\rangle = \frac{2\pi e^4 n \ln \Lambda}{m_i^2} \frac{1}{v_{th}^2} \frac{\partial \operatorname{erf}(x)}{\partial x}, \quad (2)$$

$$D_{v_z v_z} = \left\langle \frac{\delta v_i \delta v_j}{\delta t} \right\rangle = \frac{-8\pi e^4 \ln \Lambda}{m^2 v_{th}} \frac{1}{4\sqrt{2}x} \frac{\partial \operatorname{erf}(x)}{\partial x}, \quad (3)$$

where $\Lambda = 3/2(k^3 T^3 / \pi n)^{1/2} 1/e^3$, $v_{th} = \sqrt{kT/m_i}$ and $x = y/\sqrt{2}v_{th}$. Here k is the Boltzman constant, T is the temperature, n is the plasma density, m_i is the ion mass, and z represents the coordinate axis aligned with the magnetic field.

IV. RESULTS

Measurements of ion temperature consistently showed $T_{i\perp} \simeq 0.18$ eV, and $T_{i\parallel} \simeq 0.14$ eV. The range of densities used was 5×10^8 to 7×10^9 /cm³. Independent measurements of these quantities are required to calculate (2) and (3).

Diffusion measurements were performed in two situations. In the first, the density profile of the plasma had a flat region 2 cm in diameter. Probe measurements in this area show that the fluctuation level ($\delta n/n$) was below 1×10^{-3} % RMS. Results from measurements taken in this area will be referred to as quiet plasma results. Additionally, a second set of measurements was made in the presence of a radial density gradient and accompanying drift waves. The drift waves

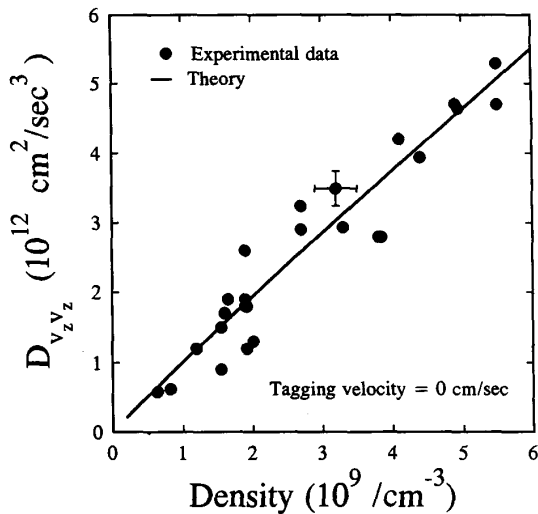


Fig. 3. Density dependence of the diffusion coefficient for a quiet plasma.

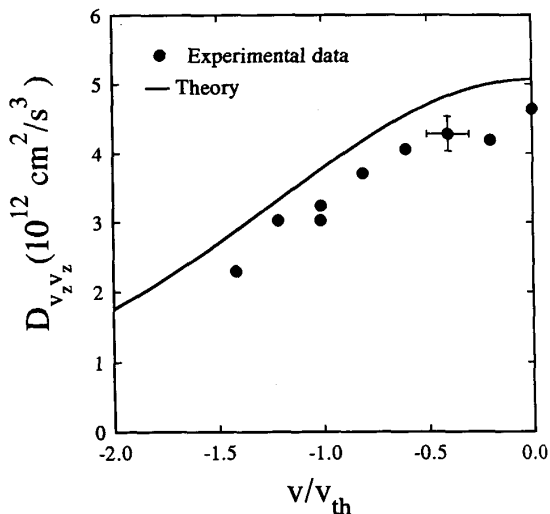


Fig. 4. Diffusion coefficient as a function of the particles initial velocity in a quiet plasma.

present were measured to have a $\delta n/n$ of about 6% and a frequency of 1.5 kHz.

Fig. 3 shows the density dependence of the diffusion coefficient in a quiet plasma. The velocity of the tagged particles was 0.0 cm/s in the plasma frame. The theory line was calculated using (3). The magnitude of diffusion appears correct and the dependence is linear, as expected. There are no normalizing coefficients used to adjust the data to the theory.

Fig. 4 shows the velocity dependence of the diffusion coefficient in theory and from experimental measurements. The roughly 10% difference between the theory line and experimental points is most likely due to errors in measurement of the density.

Fig. 5 shows the convection measurements for the quiet plasma case. The theory line is provided by (2). The error

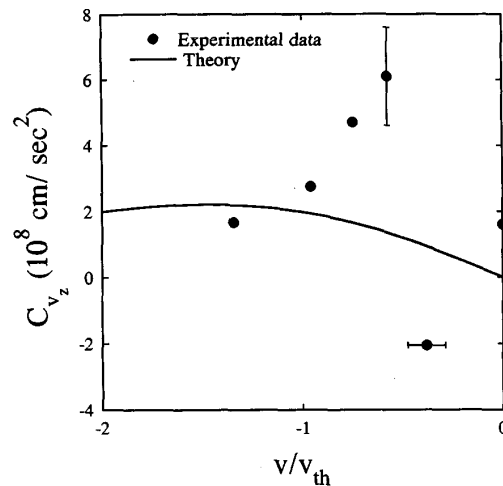


Fig. 5. Velocity dependence of the convection term in a quiet plasma.

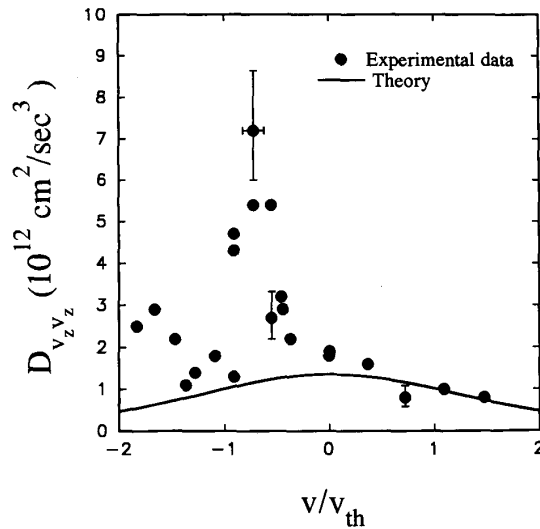


Fig. 6. Diffusion coefficient in the presence of drift waves. Note the peak in diffusion at about -0.7 of the thermal velocity.

bars are noticeably larger and the data more scattered. This is most likely due to the laser drifting over the time of the measurement (roughly 5 min per point). Since measurements of the convection coefficient depend on the relative position of the two tagged particle distributions, it is very sensitive to laser drift. In contrast, the diffusion coefficient depends on the measured widths of the tagged particle distributions, not on the relative position of the two. Therefore, the nature of the experimental measuring technique implies that the diffusion measurement will have better repeatability than the convection coefficient.

Fig. 6 shows the diffusion measurements taken in the presence of drift waves. The theory line is that predicted by (3). Note the roughly eightfold increase in diffusion at a velocity -0.7 that of the thermal velocity. At positive velocities the predictions of the collisional theory are restored.

V. DISCUSSION

Our results show that in a quiet plasma there is good agreement with collisional theory concerning the magnitude and the density dependence of the diffusion coefficient. The velocity dependence of the diffusion coefficient also appears to be correct. The magnitude of measured convection coefficient is within a factor of 2 or 3 of what is expected by theory. However, the velocity dependence of the convection coefficient cannot be seen in the data. It is also seen that it takes only a low-amplitude, low-frequency drift wave to upset the classical picture and make such predictions incomplete.

The subject of performing measurements of this nature in the magnetosphere was discussed by one of the authors and participants at the workshop. The conclusion was that improvements in technology may soon make possible limited LIF measurements of naturally occurring particles or of seed particles.

However, in the short term measurements such as the one described here will be performed only in the laboratory. These may still be able to make significant contributions to the understanding of phenomena that occur in the magnetosphere.

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REFERENCES

- [1] D. N. Hill, S. Fornaca, and M. G. Wickham, "Single frequency scanning laser as a plasma diagnostic," *Rev. Sci. Instrum.*, vol. 54, p. 309, 1983.
- [2] R. Stern, D. Hill, and N. Rynn, "Direct ion-transport measurement by optical tagging," *Phys. Lett.*, vol. 93A, no. 3, p. 127, 1983.
- [3] R. McWilliams and M. Okubo, "The transport of test ions in a quiet plasma," *Phys. Fluids*, vol. 30, p. 2849, 1987.
- [4] R. McWilliams, D. Hill, N. Wolf, and N. Rynn, "Cross field ion transport and heating due to parametric decay of lower hybrid waves," *Phys. Rev. Lett.*, vol. 50, no. 11, p. 836, 1983.
- [5] F. Skiff *et al.*, "Conservation laws and transport in Hamiltonian chaos," *Phys. Rev. Lett.*, vol. 61, no. 18, p. 2034, 1988.
- [6] A. Fasoli, F. Skiff, T. Godd, P. Paris, and M. Tran, "Test-ion diffusion in a magnetized plasma," this issue.
- [7] N. Rynn and N. D'Angelo, "Device for generating a low temperature highly ionized cesium plasma," *Rev. Sci. Instrum.*, vol. 31, p. 1326, 1961.
- [8] N. Rynn, "Improved quiescent plasma sources," *Rev. Sci. Instrum.*, vol. 35, p. 40, 1964.
- [9] R. A. Stern, D. N. Hill, and N. Rynn, "Azimuthal coherent ion-ring-beam generation in unstable magnetized plasmas," *Phys. Rev. Lett.*, vol. 47, p. 792, 1981.
- [10] N. Rostoker, "Fluctuations of a plasma," *Nucl. Fusion*, vol. 1, p. 101, 1961.

Jeffrey Bowles, photograph and biography not available at the time of publication.

Roger McWilliams, photograph and biography not available at the time of publication.

Nathan Rynn (S'42-A'46-M'50-SM'52-F'80-LF'89), for a photograph and biography, please see the Guest Editorial in this issue.