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EXPERIMENTAL INVESTIGATION OF THE NONLINEAR EVOLUTION
OF AN IMPURITY-DRIVEN DRIFT WAVE

BY

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APRIL 1982

MASTER

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

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EXPERIMENTAL INVESTIGATION OF THE NONLINEAR EVOLUTION
OF AN IMPURITY-DRIVEN DRIFT WAVE

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ABSTRACT

An impurity-driven drift wave is observed to be destabilized by the reversed density gradient of a singly-ionized heavy-impurity-ion population in a Q-machine plasma. The evolution of the instability is investigated as it progresses from the initial linear exponential growth phase, into a nonlinear saturated state, whereupon strong radially outward anomalous diffusion is observed. The relationship between the anomalous diffusion coefficient and the wave amplitude is in agreement with estimates obtained from the nonlinear drift-wave turbulence theory of Dupree.

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I. Introduction

It is well known that low-frequency ($\omega \ll \omega_{ci}$, ω_{ci} is the ion gyrofrequency) drift waves, driven unstable by the free energy of the plasma density gradient, can lead to enhanced diffusion of plasma across the confining magnetic field. The existence of an impurity-driven drift-wave (IDDW) was first predicted theoretically by Coppi et al.¹ from the collisionless Vlasov equation. The main requirements for the instability are the presence of a small concentration of heavy impurity ions with a density gradient opposite to that of the main ions and wave propagation with phase velocity $v_I < \omega/k_z < v_i \ll v_e$, where v_j is the thermal velocity of species j , and $j = I, i$, and e denote impurity ions, main ions, and electrons. Instability growth results either from the parallel Landau resonance¹ between the wave and the main ions ($v_I \ll \omega/k_z \ll v_i$) or from collisional dissipation of the impurity ions^{2,3} ($v_I < \omega/k_z < v_i \ll v_e$, with $v_I \ll \omega$).

Notably, in the present work, a collisional IDDW is found in the usual drift-wave velocity range, $v_I < v_i \ll \omega/k_z \ll v_e$. This range may, in fact, be more suitable than the other ($v_I < \omega/k_z < v_i \ll v_e$) to model present-day tokamaks; e.g., in PLT,⁴ typically $\omega/k_z \sim \omega_{qR} \sim 1.6 \times 10^8$ cm/s $\gg v_i \sim 1 \times 10^7$ cm/s, for $\omega/2\pi \sim 50$ kHz, $q_{edge} \approx 4$, $R \approx 130$ cm, and $T_i \sim 100$ eV near the plasma edge.

The most significant results of this work are (1) the first experimental observation of an IDDW, and the identification of the IDDW instability by means of a careful comparison of experimental results with theoretical predictions, (2) the observation of strong, radially outward, anomalous diffusion in the presence of the IDDW fluctuations, and (3) experimental results in agreement with both Dupree's estimate for the minimum drift-wave fluctuation level required for the onset of anomalous diffusion, and also the

theoretically predicted transition to strong turbulence at large fluctuation amplitudes.

II. Linear Theory

For a local slab model (with magnetic field in the z direction and pressure gradient in the x direction), the collisional form of the IDW is governed by a dispersion relation of the form

$$\varepsilon = 1 + \chi_e + \chi_i + \chi_I = 0, \quad (1)$$

where χ_s is the polarizability of species s :

$$\chi_e = \frac{k_{De}^2}{k^2} \left[1 + i \bar{v}_e \left(\frac{\tilde{\omega} - \omega_e^*}{k_z^2 v_e^2} \right) \right], \quad (2a)$$

$$\begin{aligned} \chi_j = \frac{k_{Dj}^2}{k^2} \left[1 - \left(1 - \frac{\omega_j^*}{\tilde{\omega}} \right) \Gamma_{0j} \right] \\ + i \frac{\bar{v}_j}{\tilde{\omega}} \left(1 - \frac{\omega_j^*}{\tilde{\omega}} \right) \right], \end{aligned} \quad (2b)$$

$$\text{where } \Gamma_{0j} \equiv \tau_0 (b_j) \exp(-b_j)$$

$$b_j \equiv \frac{1}{2} k_{\perp}^2 \rho_j^2, \quad j = i, e, \quad (2c)$$

and the effective collision frequencies, $\bar{v}_j$, are expressed by⁵

$$\bar{v}_j = v_j \begin{cases} 0.7 (1 + 0.2517b_j) b_j^2 + 2.8b_j \bar{r}_{j,j}^{-2} + 1.6\bar{r}_{j,j}^{-4}, \\ \text{for } b_j < 1, |\bar{r}_{j,j}| \gg 1 \\ \frac{3(\pi+1)}{8\pi^{1/2}} b_j^{1/2}, \text{ for } b_j > 1, |\bar{r}_{j,j}| \gg 1 \end{cases} \quad (2d)$$

for $j = i, I$. Here ρ_j is the gyroradius and ω_j^* is the diamagnetic drift frequency of species j ; $v_i = (1+f) v_{ii}$, $v_I = (1+f \mu^{1/2}) v_{ii}/\mu$, $\mu = m_I/m_i$, $f = n_I/n_i$, $v_{ii} = 4\pi^{1/2} e^4 n_i (\ln \Lambda)/(3m_i^{1/2} T_i^{3/2})$, $\bar{v}_e = 4.18 \times 10^{-6} n_e (\ln \Lambda)/T_e^{3/2}$, and

$$\bar{r}_{j,j} = \frac{\hat{\omega} + i v_j}{|k_z| v_j}.$$

Substituting Eqs. (2a-d) into Eq. (1), one obtains the frequency of the wave in the plasma frame $\hat{\omega} \equiv \omega - \omega_{ExB}$ and the growth rate γ :

$$\hat{\omega} = -(\omega_i^* r_{0i} + f \omega_I^* r_{0I})/D, \quad (3)$$

$$\gamma = \gamma_e + \gamma_i + \gamma_I, \quad (4)$$

$$\gamma_e = \frac{\hat{\omega}}{D} \frac{T_i}{T_e} (1+f) + \frac{(\omega_e^* - \hat{\omega}) \bar{v}_e}{k_z^2 v_e^2}, \quad (4a)$$

$$\gamma_i = -\frac{\bar{v}_i}{D} \left(1 - \frac{\omega_i^*}{\tilde{\omega}} \right), \quad (4b)$$

$$\gamma_I = -f \frac{\bar{v}_I}{D} \left(1 - \frac{\omega_I^*}{\tilde{\omega}} \right), \quad (4c)$$

$$D = \frac{T_i}{T_e} (1 + f) + (1 - r_{0i}) + f (1 - r_{0I}).$$

The impurity-ion collisions contribute to destabilization of the drift wave. This process can be understood as a transfer of momentum [$\propto n_I m_I (\bar{v}_I^* - \tilde{\omega}/k_\theta)$] to the wave from the impurity ions as they drift. Conversely, the transfer of momentum from the wave to the main ions damps the wave at a rate $\propto n_I m_I (\bar{v}_I^* - \tilde{\omega}/k_\theta)$. The mode should be localized near the maximum of $n_I \omega_I^*/n_i$, in the region where the impurity density is increasing radially outward.

III. Apparatus

The experiment was performed on the Princeton Q-1 machine⁶ operated as a double-plasma device (Fig. 1). A potassium (main-ion, $m_K = 39$ a.m.u.) plasma is produced at one ionizer plate and a cesium (impurity-ion, $m_{Cs} = 133$ a.m.u.) plasma is produced at the other. Radial temperature gradients are negligible ($\partial \ln T_j / \partial \ln n \ll 1$, $j = K, Cs, e$), and a straight, uniform magnetic field ($B = 1.6$ kG) confines the plasma radially.

To create a region in the plasma where the impurity-ion density $n_{Cs}(r)$ increases radially outward, the Cs ions are injected into the target K plasma through an annular mesh (inner radius = $r_1 = 8$ mm, outer radius = $r_2 = 12$ mm). To do so, a solid baffle with an annular, mesh-covered orifice is

mounted perpendicular to the magnetic field in front of the Cs end plate, 92 cm ($= L$) away from the K plate. The mesh (80 lines/cm, $\lambda_{\text{mesh}} < \lambda_{\text{De}}$) is biased negatively ($V_{\text{mesh}} \sim -18$ V) to prevent electron flow in either direction.

With the K end-plate grounded and the Cs plate biased negatively ($V_{\text{Cs}} \sim -3\text{V} \ll -T_{\text{Cs}}/e$), the Cs ions are repelled by the potential barrier at the mesh and cannot enter the K target-plasma (see Fig. 1b). The K ions are lost at the mesh/baffle after a single axial transit with a lifetime (approximately 2 msec) too short to allow for appreciable collisional radial diffusion. So the K plasma density profile is relatively flat (Fig. 2), as in a single-ended Q-machine.

If the Cs ionizer-plate voltage is raised to make the potential of the driver plasma section equal to that of the target plasma (i.e., $V_{\text{Cs}} = 0$, see Fig. 1b), then the Cs ions may freely enter the K plasma (with negligible beam energy) through the annular mesh, so that a Cs-density profile, peaked near $r = 10$ mm, is superimposed on the existing K profile (Fig. 2). The Cs density is increasing radially outward for $r < 10$ mm. The density of the injected Cs can be controlled by varying either the Cs end-plate voltage (V_{Cs}) or the production of plasma at the Cs ionizer-plate.

IV. Linear Experimental Results

As the density of impurity (Cs) ions injected through the annular mesh is increased, the drift wave is observed to be destabilized when n_{I}/n_1 exceeds a threshold value $\{(\frac{n_{\text{I}}}{n_1}) > 0.05\}$. The radial localization and dependence on impurity fraction is illustrated in Fig. 2, which shows that the cesium (impurity) is concentrated along the plasma column in the annular cylindrical region. The uppermost trace is the total ion-saturation current to the probe

with full cesium injection (i.e., $V_{Cs} = 0$ volts). The lower trace is the cesium density, corrected for the dependence of the probe sensitivity on ion mass.

The fluctuating component of the total ion-saturation current, I (or $\tilde{I}$), normalized to the total DC ion-saturation current, I (or n), is shown in Fig. 3. This ratio, indicating the strength of the IDDW, is maximum at the inner edge of the annular region where the product $f\omega_I^*$ is a maximum, as is predicted by theory. When a smaller annular mesh ($r_1 = 5$ mm; $r_2 = 7$ mm) is used, the instability is localized near $r = 4$ mm, again at the inner edge of the annular region. The oscillation is very coherent, with a spectral width $\Delta\omega/\omega \lesssim 0.5\%$. A coherent $m = 4$ mode is dominant in the range 1.9 kG $< B < 4.8$ kG.

In Fig. 4 the $\tilde{\omega}$ vs. m results are presented. The multi-mode spectrum occurring above 4 kG allows measurements of $\tilde{\omega}$ and γ vs. m with all other plasma parameters held constant. The spectrum is divided into the low- m harmonics ($m = 1, 2, 3$) which are localized at $r = 6$ mm, and the high- m modes ($m = 3$ to 10) which are localized at $r = 8$ mm. The frequency increase vs. m is nearly linear at small m , then reaches a maximum, and finally decreases at high m due to the gyroradius correction at high m ($b_j \sim 1$ at $m = 6$ for cesium, and at $m = 11$ for potassium). The experimental results are in good agreement with theory.

In Fig. 5 the real frequency is plotted vs. impurity fraction. Theory predicts that the frequency decreases with increasing f simply because the addition of the impurity ions with reversed density gradient reduces the total electron density gradient ($= \omega_e^*$). Experimental data support the theory.

Due to the finite gyroradius effects on ion collisions, linear theory predicts the most unstable mode in the $r = 7$ to 8 mm region to be the $m = 4$.

As shown in Fig. 6, the maximum instability amplitude is indeed found to occur at $m = 4$, and the magnitude of the measured linear growth rate of the $m = 4$ and 5 modes agrees with theory within a factor of 2.

To gain some insight into the physical mechanism which drives this IDW, consider the magnetic field dependence of the instability amplitude (Fig. 7). At very low magnetic fields ($B < 2$ kG), the IDW is observed to be stable regardless of the level of cesium injection. As the magnetic field is increased, with strong cesium injection ($f = 0.8$), the $m = 4$ mode has a very sharp observed onset at $B = 1.9$ kG. The mode amplitude forms a plateau for $2.4 < B < 4.8$ kG and declines sharply as the frequency spectrum becomes noisier at $B > 5.0$ kG. The mode remains unstable up to the highest available magnetic field ($B = 6.3$ kG).

These main features agree well with the theoretical results of Eq. (4), as shown in Fig. 7(a). The theory indicates a sharp onset at low magnetic field ($B = 2.9$ kG), a plateau out to $B = 4.8$ kG, beyond which γ decreases sharply to lower level, although remaining unstable at higher B . The stabilization at low (and high) B occurs for the same physical reason which causes stabilization at high (and low) m : that is the balance between the main-ion and impurity-ion viscosity. The electron destabilization is negligible for all B .⁷

To understand the features of Fig. 7, consider the ratio of ion growth rates (where $\gamma_i < 0$):

$$g \equiv -\frac{\gamma_I}{\gamma_i} = -\frac{f \bar{v}_I (\tilde{\omega} - \omega_I^*)}{\bar{v}_i (\tilde{\omega} - \omega_i^*)}, \quad (5)$$

where the ion viscosities scale like

$$\bar{\nu}_j \propto B^{-4}, \text{ for } b_j < 1, \quad (6a)$$

and

$$\bar{\nu}_j \propto B^{-1}, \text{ for } b_j > 1, j = i, I. \quad (6b)$$

The wave is unstable for $g > 1$.

In the high field limit ($B \gg 5$ kG), where $b_i < b_I \ll 1$ and $\tilde{\omega} \approx \omega_e^*$, $g (= 2.20)$ is independent of B , and, since both of the ion viscosities scale like B^{-4} , $\gamma (= \gamma_I + \gamma_i)$ also scales like B^{-4} at high B , as in Fig. 7. For intermediate magnetic fields, in the range $2.3 < B < 4.6$ kG, γ_I goes roughly like B^{-1} (since $b_I > 1$), while γ_i continues to scale like B^{-4} (since $b_i < 1$), so that g decreases with decreasing B to a point where $g \approx 1$ (marginally stable) at $B = 2.9$ kG. The strong scaling of the main-ion damping ($\gamma_i \propto B^{-4}$) relative to impurity-ion destabilization ($\gamma_I \propto B^{-1}$) provides a very sharp onset (where $g = 1$) at low B , as observed in the experiment. The maximum growth rate occurs at $B = 4.6$ kG, where $b_I = 1$.

V. Nonlinear Experimental Results

It has been demonstrated that the linear properties of this IDDW are well described by a linear kinetic theory. The wave is unstable in the presence of a sufficiently strong, reversed density gradient of the impurity ions. As the fluctuations grow exponentially to large amplitude, however, the free energy of the wave, which drives the instability, is partially converted into the fluctuation energy of the wave.

Thus a mode which feeds on the free energy of the impurity-ion density gradient is capable of destroying that density gradient if the wave grows to

sufficiently large amplitude. The implication of this to magnetically confined plasmas such as the tokamak is that a strong localization of impurities at the plasma edge can drive drift-wave turbulence resulting in a redistribution of the impurities. In fact, in many tokamak experiments the impurities are not observed to diffuse inward or accumulate on axis, as expected from neoclassical (collisional) considerations.⁸⁻¹¹ Apparently there exists a strong anomalous diffusion and recycling of impurities at the tokamak edge.¹⁰ Such anomalous diffusion in low- β , magnetically confined plasmas is usually attributed to low-frequency drift-wave instabilities.

By pulsing the impurity-ion injection, the development of the instability has been observed as it progresses from the linear exponential growth phase into a nonlinearly saturated state, where strong radially outward anomalous diffusion is driven by a wave-particle interaction. The corresponding anomalous diffusion coefficient, D_A , can be calculated from the observed response of the plasma density.

Shown in Fig. 8 is the time-dependent total ion-saturation current ($I = I_K + I_{CS} + \tilde{I}$) at four different radial positions during an experiment in which the Cs injection is repetitively gated on and off. Each trace is the superposition of oscilloscope sweeps from many gate cycles, demonstrating the reproducibility of the phenomenon. The rising edge of the gate bias (lower trace), which is applied to the Cs end-plate, triggers the oscilloscope, defining $t = 0$, at which time $I = I_K$.

As the Cs density reaches its maximum level (via axial drift and axial diffusion⁷), the IDW fluctuation grows and saturates within approximately 3 msec. Coincident with the saturation of the IDW, the average total density (corresponding to the vertical center of the envelope of the trace) falls substantially ($\Delta n/n \sim 20\%$) and quickly ($\Delta t \sim 2$ msec).

The density loss is most pronounced where $\tilde{n}/n$ is a maximum; however, anomalous diffusion is observed to affect even the center of the plasma column ($r = 0$) where $\tilde{n} = 0$. This is likely due to an effective axial averaging of the characteristics of the wave-induced anomalous diffusion. Since the time required for axial plasma transport ($\tau_{||} \sim 3$ msec) is of the same order as the time for anomalous radial pump-out ($\tau_A \sim a \lambda_n / D_A \gtrsim 3$ msec, where $\lambda_n = n(dn/dr)^{-1}$), plasma loss from any axial location appears as a density reduction along the entire plasma column.

The anomalous diffusion coefficient has been determined by comparing the density before and after the onset of the instability⁷ at $r = 4$ mm for various values of B and f and is plotted vs. $\tilde{n}/n$ in Fig. 9. Note that D_A is as much as 500 times greater than the classical collisional diffusion coefficient, $D_C \sim 2$ cm²/sec, and up to 1.7 times the Bohm diffusion coefficient, $D_B \sim 650$ cm²/sec. Drift-wave-induced anomalous diffusion near to^{12,13} or exceeding¹⁴ D_B has been previously observed in Q-machines.

Also plotted in Fig. 9 is the result for the anomalous diffusion coefficient, D_D , from the drift-wave turbulence theory of Dupree^{15,16} for a single-mode oscillation:

$$D_A = D_D = \begin{cases} \frac{\tilde{n}}{n} \left(\frac{c T_e}{\sqrt{2}} \right) \left(1 - \frac{1}{R^2} \right)^{1/2}, & \text{for } R > 1 \\ 0 & \text{for } R < 1 \end{cases} \quad (7a)$$

$$\text{where } R = \frac{\tilde{n}}{n} \frac{\lambda_n k_{\perp}}{2} \quad (7b)$$

is the effective Reynolds number,^{15,16} essentially the ratio of linear to nonlinear coherence time ($R \gg 1$ implies strong turbulence). $\tilde{n}/n = e\tilde{\phi}/T_e$ has been assumed here.

Equation 7 has two distinctive features. First, there is a critical wave-fluctuation level, $(\tilde{n}/n)_c = 2/\lambda_n k_\perp$, below which the wave amplitude is too weak to trap the ions so that $D_D = 0$. The observed $(\tilde{n}/n)_c \sim 5\%$ in Fig. 9 is in good agreement with theory: $(\tilde{n}/n)_c = 5.8\%$, taking $\lambda_n = 3.5$ cm and $k_\perp = 7.0$ cm⁻¹, as measured. Second, $D_D \propto \tilde{n}/n$, asymptotically, for $(\tilde{n}/n) \gg (\tilde{n}/n)_c$, i.e., $R \gg 1$, also in agreement with the data in Fig. 9.

Drift-wave-induced anomalous diffusion has been measured in several previous experiments^{12-14,17,18} and compared with various theories. In the present experiment, the data presented in Fig. 9 clearly demonstrate quantitative agreement with both of the characteristic features of Dupree's nonlinear theory of drift-wave turbulence, i.e., strong-turbulence scaling of the anomalous diffusion coefficient, and the onset of anomalous diffusion at a critical wave-fluctuation level. Of course, any other nonlinear theory with these two properties could be equally well supported by these experimental results, while nonlinear theories without them, such as quasi-linear and weak turbulence theories, can be ruled out in this situation.

VI. Summary

The first experimental identification of an impurity-driven drift-wave instability has been presented. The linear characteristics of the wave are well described by a linear dispersion relation, derived from a local slab-model kinetic theory including collisions. The destabilizing mechanism is associated with the viscosity of the impurity ions; the free energy to drive the instability is provided by their reversed density gradient.

The anomalous diffusion coefficient, D_A , has been calculated unambiguously from the observed response of the plasma density. The excellent agreement between the observed D_A and the result of Dupree's nonlinear drift-wave turbulence theory, D_D , gives strong support to the hypothesis that transverse ion-trapping by drift-waves provides the mechanism for both enhanced diffusion and amplitude saturation.

The implications for impurity transport in a tokamak are that drift-wave fluctuations at the plasma edge can drive strong anomalous diffusion of impurity ions, which may explain the non-neoclassical recycling of impurities at the edge. In fact, the drift-wave fluctuations causing the anomalous transport may be destabilized by the impurity ions.

In this regard, it may be feasible to improve the plasma recycling (and resultant cooling) at the edge by injecting low-Z impurities which excite or enhance drift-wave fluctuations locally at the edge of the plasma.

Acknowledgments

The authors wish to thank V. Arunasalam, T.K. Chu, H.W. Hendel, P.K. Kaw, R. McWilliams, R.W. Motley, M. Ono, D.E. Voss and R.B. White for useful discussions and assistance, and L. Gereg, T. Holoman and R. Labau for technical support. This work was supported by the U.S. Department of Energy, contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

Fig. 1 (a) Schematic of Q-1 device, (b) axial dependence of plasma potential.

Fig. 2 Radial profiles of potassium and cesium densities and instability amplitude. Upper two traces: ion-saturation current with (upper trace) and without (middle trace) cesium injection. Lower trace: cesium density profile ($n_{Cs} = \sqrt{\mu} n_K I_{Cs}/I_K$). Mesh size and location, and Larmor radii of K and Cs are also shown.

Fig. 3 Normalized instability amplitude, $\tilde{n}/n$, vs. radius for various cesium end-plate voltages.

Fig. 4 Frequency vs. azimuthal mode number: theory and experiment. Solid curve: theory for $r = 8$ mm. Dots: data from high- m modes localized at $r = 8$ mm. Circles: low- m modes localized at $r = 6$ mm. $B = 4.8$ kG, $f = 0.8$, $\langle \omega_{I/m}^* \rangle = -2400 \text{ sec}^{-1}$, $\langle \omega_{I/m}^* \rangle = +2500 \text{ sec}^{-1}$ for theory and experiment. $\langle \rangle$ denotes an axial average along the plasma column.

Fig. 5 Experimental (solid circles) and theoretical (solid curve) frequency vs. impurity fraction for $m = 4$, $B = 3.8$ kG.

Fig. 6 Dependence on azimuthal mode number of: theoretical net growth rate, γ (solid line); and data for both the normalized instability amplitude, $\tilde{n}/n$ (solid circles for high- m), and the measured linear growth rate, γ (x data points). The scale for theoretical γ is normalized to match $\tilde{n}/n$ at $m = 4$.

Fig. 7 Dependence on magnetic field of (a) normalized instability-fluctuation amplitude data, $\tilde{n}/n$ (solid circles), and theoretical γ (solid curve). The measured parameters (and assumptions) used in the calculations are: $m = 4$, $f = 0.8$; $r = 8$ mm; $\tau = 1.2$; $\langle \omega_{\perp}^*/m \rangle = -3000$ sec^{-1} and $\langle \omega_{\perp}^*/m \rangle = +2500$ sec^{-1} at $B = 4.8$ kG; $\langle \omega_{\perp}^* \rangle \propto 1/B$, i.e., $\nabla n_j = \text{const.}$, $j = i, I$; $n_K = 5 \times 10^9$ cm^{-3} . (b) Finite Larmor radius parameters, $b_j = k_{\perp}^2 \rho_j^2$, $j = i, I$, vs. B .

Fig. 8 Four upper traces: total ion-saturation current ($I = I_K + I_{Cs} + \tilde{I}$) vs. time (5 msec/div.) at four radial locations (labelled in mm.) as Cs injection is gated on (triggering oscilloscope) and off. The DC baseline for each trace is labelled $I_r = 0$ ($r = 0, 4, 8, 12$); I_K indicates the K ion-saturation current prior to Cs injection. Lower trace: square-wave gate bias applied to Cs end-plate. $B = 2.5$ kG, n_K ($r = 0$) = 6.6×10^9 cm^{-3} , $m = 4$ (only mode present), $z = 1$ cm.

Fig. 9 Anomalous diffusion coefficient, D_A , vs. normalized wave-amplitude, $\tilde{n}/n$. Data points represent $r = 4$ (± 1) mm, $1.7 < B < 3.8$ kG (most are $B \approx 2.5$ kG), $n \sim 10^{10}$ cm^{-3} , $0.5 < f < 0.9$, $z = 1, 30$, and 60 cm; $m = 4$ (only mode present), $\tau_{\parallel} = 2.67$ msec, $\lambda_n = 3.5$ cm. Curve labelled D_D : anomalous diffusion coefficient from Dupree's theory; straight line: large $\tilde{n}/n$ asymptote of curve. $D_B = c T_e/16$ eB is Bohm diffusion coefficient.

(a)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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Fig. 8

Fig. 9