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MASTER

DIFFUSION AND FLUCTUATION MEASUREMENTS IN THE TRAPPED ELECTRON AND TRAPPED ION REGIMES

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ABSTRACT

Experiments have been performed in the Wisconsin Levitated Octupole with a weak toroidal magnetic field added to the octupole field. When the ions were collisionless or collisional, the diffusion scaling observed in the absolute minimum-B regions indicated convective diffusion driven by mirror-trapped electrons. When the ions were collisionless, both a dissipative trapped ion mode and a collisionless trapped ion mode were observed in the average minimum-B region. These modes were distinguished by their propagation direction in the plasma frame and were not present without the weak toroidal field or when the ions were made collisional. When these modes were present, the plasma transport was increased by an order of magnitude.

Experiments have been performed in the General Atomic dc Octopole in the regimes in which dissipative trapped electron and trapped ion modes are expected to occur. Dissipative trapped electron modes have been observed and studied in detail. The trapped ion regime has been attained by means of rf ion heating at the lower hybrid frequency, and fluctuations that appear to be collisionless ion drift waves driven by ion Landau resonances have been observed in the private flux regions. These ion modes may provide a confinement limit on tokamaks that are operated in parameter ranges for which the dissipative trapped particle modes are unimportant.

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I. Introduction

The addition of a weak toroidal field to the toroidal octupole field with the internal rings levitated caused a change in the cross-field transport in a collisionless plasma from convective diffusion¹, which was seen in both the absolute and average minimum-B regions, to transport which was different in the two regions. The 1-dimensional density profile, $n(\psi)$, where ψ is the poloidal flux function, is shown in Fig. 1a at two times after the gun-produced plasma was injected into the containment zone. The regional dependence of $D_{\perp}$, the diffusion coefficient, caused a ψ -dependent particle lifetime τ_p . In the average minimum-B region outside ψ_s , τ_p was a factor of 4 shorter than τ_p inside ψ_s . Shown in Fig. 1b is the density fluctuation level, $\delta n/n$, as a function of ψ for fluctuations with $1 \text{ kHz} < f < 1 \text{ MHz}$. The decreased τ_p appeared where $\delta n/n$ was large.

Inside ψ_s where $\delta n/n$ was small, the likely transport mechanism is convective diffusion driven by mirror-trapped collisionless electrons which are not neutralized by circulating particles or shear². Outside ψ_s , trapped ion instabilities were responsible for the transport. A dissipative trapped ion mode^{3,4} was observed just outside ψ_s between ψ_s and $\psi = 6.1$ and a collisionless mode^{3,5} was observed outside $\psi = 6.1$.

The plasma parameters were as follows: (1) Initial peak density of $1 \times 10^9 \text{ cm}^{-3}$. (2) Initial T_i of 30 eV with a decay time of 10 msec. (3) Initial T_e of 5 eV with a decay time of 30 msec. (4) The ion mean free path, λ_i , was 100 m in the region where the dissipative trapped ion mode was seen and was 10^2 - 10^4 m over the region where the collisionless mode was seen. The modes were not observed when λ_i was less than 10^2 m.

The machine parameters were as follows: (1) Average poloidal field was 2 kG at the internal ring surface ($\psi = 2.5$) and 1.3 kG at the minimum $d\ell/B_p$ flux surface ($\psi_c = 7.8$). (2) The toroidal field was 0.38 kG at the minor axis. (3) The mirror throat connection length outside ψ_s was 1-3 m. (4) Shown in Fig. 1c is the value of the safety factor, q , as a function of ψ .

Fig. 1a - Observed density profile for 11 msec and 19 msec after injection of the plasma.

Fig. 1b - Density fluctuation level, $\delta n/n$, as a function of position ψ .

Fig. 1c - Value of the safety factor, q , as a function of position ψ .

II. Absolute Minimum-B Region

Inside ψ_s , the magnitude and scaling of $D_{\perp}$ was measured directly. The particle flux measured by striped particle collectors⁶ mounted on the internal ring surface and the observed density gradient near the ring yield a value of the local D . Shown in Fig. 2 is the observed scaling of $D_{\perp}$ with B_{AVE} for three values of the density indicating that $D \propto n^{-1}$ and independent of B . (In the figure, B_{AVE} is the typical value of

Fig. 2 - Observed values of $D_{\perp}$ versus B for three values of the density in a collisionless ion and electron plasma.

Fig. 3 - Observed values of $D_{\perp}$ versus B for two values of the density in the collisional ion, collisionless electron plasma.

B in the absolute minimum- B region and is equal to half the value of B at the ring surface.) This n^{-1} scaling was also verified by fitting the observed profile shape to the shape predicted by a 1-dimensional diffusion model¹.

A survey was made of the density and floating potential fluctuation amplitudes in the range $1 \text{ kHz} < f < 1 \text{ MHz}$ with representative values given in Fig. 1b. In the private flux region around the internal ring, the amplitudes of the fluctuations could account for at most 2% of the observed transport. In the bottom of the poloidal field mirrors, however, aperiodic density and potential fluctuations were observed with $f \leq 1 \text{ kHz}$ and $\delta n/n$ 5%. We suspect that these fluctuations were caused by vortices generated by excess charge trapped in the local mirrors of the poloidal magnetic field.

The existence of these vortices has been investigated theoretically and in simulations by Kamimura and Dawson² and the observed scaling agrees with that proposed by the theory. In an attempt to discover if the trapped charges were electrons or ions, the ions were cooled to near room temperature by injection of neutral hydrogen to a pressure of about 5×10^{-6} Torr. The electrons were cooled to about 1.5 eV creating a collisional ion and collisionless electron plasma, $\omega_{pe}/\omega_{ci} \sim 100$. Shown in Fig. 3 is the observed scaling of $D_{\perp}$ with B for two values of the density in the collisional ion plasma. The scaling of $D_{\perp}$ was unchanged, indicating that the electrons trapped in the mirrors were responsible for the observed diffusion. If the magnitude of the observed $D_{\perp}$ is to be reconciled with the magnitude predicted by Ref. 2, an enhanced energy level in the vortex spectrum must be postulated with an effective temperature, T^* , of $\sim 500 \text{ eV}$ in the hot ion plasma and $\sim 150 \text{ eV}$ in the cold ion plasma. The mechanism responsible for these enhanced energy levels is not known, but oscillations at ω_{ci} were observed due to current flowing along magnetic field lines. The current was generated by imperfect crowbar-ring of the magnetic field with $|E| \sim 0.1 \text{ v/m}$. These fluctuations may couple to the vortex modes generating an enhanced energy level.

III. Average Minimum- B Region

Outside ψ_S , two collisionless trapped ion modes were observed. A dissipative mode was observed in a narrow region of ψ -space between $\psi = 5.7$ and $\psi = 6.1$ and a collisionless mode was observed in the region outside $\psi = 6.1$. These modes were identified by their propagation direction in the plasma frame; the fluctuations associated with the dissipative mode propagated in

the electron diamagnetic drift direction and those associated with the collisionless mode propagated in the ion diamagnetic drift direction.

An $\vec{E} \times \vec{B}$ drift due to a steady radial electric field Doppler shifted the velocities and both modes were observed to propagate in the ion diamagnetic drift direction in the laboratory frame. The Doppler shift was accounted for using an $\vec{E} \times \vec{B}$ drift magnitude based on radial floating potential profile data since it was observed that $\vec{V}_{Te} = 0$. The transition between the modes was, in any case, very distinct in the observed data, $V_{\zeta,lab}$, the laboratory frame toroidal phase velocity. In Fig. 4 we show $V_{\zeta,lab}$ as a function of position ψ .

In Table I the important parameters describing the two observed modes are listed.

The calculated growth $\gamma = \omega_r^2/v_{ef}$ is greater than v_{ef} so the commonly taken ordering for the dissipative mode is violated for our observed case. However, we point out that in an octupole there exists a significant regime, for which there is presently very little theoretical work, between the usual dissipative regime ($\gamma < v_{ef}$) and the collisionless ion, low frequency interchange mode described by Rosenbluth.⁵ The interchange mode is driven by the small fraction of trapped particles ($\sqrt{\epsilon_b} \sim 0.1$) with a net average magnetic drift in the bad curvature direction. Thus, to be collisionless, we must have $\gamma > v_{g0}/\epsilon_b$. Therefore, the ordering $v_{g0}/\epsilon < \gamma < v_{g0}/\epsilon_b$, constitutes a large regime in an octupole with a weak toroidal field. Furthermore, the toroidal magnetic drift due to the poloidal field gradients is of the order of the diamagnetic drifts, which also requires different ordering than commonly taken when the trapped ion modes are theoretically analyzed.

Fig. 4 - The observed phase velocity of the fluctuations in the lab frame, $V_{\zeta,lab}$, are plotted as a function of position ψ .

Experiments at General Atomic

I. Dissipative Trapped Electron Mode

The trapped electron modes have been studied in the General Atomic dc Octopole primarily in helium plasma, at densities between 10^7 and 10^9 cm $^{-3}$. The electron temperature is held constant at 1 eV by nonresonant wave heating, and $T_i \sim 0.05$ eV. The poloidal field averaged on the stability limit flux surface is 115 G, and the toroidal field was varied between 0 and 250 G. From the beginning of the discharge, large fluctuations are observed in the common flux region outside the separatrix. Figure 5 shows the density and density fluctuation distribution near an octopole hoop. The safety factor q is also plotted in Fig. 5. The plasma density is peaked at the separatrix flux surface ψ_s , where $q(\psi)$ diverges. The fluctuation amplitude is maximum near the surface for which $\partial q(\psi)/\partial \psi = 0$, which is the layer of zero average shear, although locally the shear length can be as short as 25 cm for B_t such that $q(\psi_s) = 1$, where ψ_s is the minimum length line. The fluctuation is large, typically $\delta n/n \sim 0.4$.

The fluctuations are highly coherent and monochromatic, so the poloidal and toroidal wavelengths can be determined from probe phase shifts, and from these data the parallel and perpendicular wavenumbers can be found. Typically, $\lambda_{\perp} \approx 30$ cm and $\lambda_{\parallel} \approx 20$ -50 m. The real part of the frequency is 3 kHz, which corresponds well with the electron diamagnetic drift frequency when account is taken of wave slowing due to finite ion mass effects. Scalings of the wave phase velocity with T_e and B verify the drift nature of the fluctuation.

The various electron drift waves may be distinguished by the dependence of the saturated amplitude on plasma parameters. The saturated amplitude is plotted in Fig. 6 as a function of density, which is proportional to v_{eff}/ω for fixed T_e , where v_{eff} is the effective electron collision frequency. The density for which $v_{eff}/\omega = 1$ is indicated by the arrow. The peaking at high density, $n > 10^9$ cm $^{-3}$, for which there are few trapped electrons, is caused by the collisional drift wave. The low density fluctuations can be attributed to the dissipative trapped electron mode driven by finite ion mass,⁷ since the theoretical linear growth rate for this instability is peaked at $v_{eff}/\omega \approx 1$, which is also shown in Fig. 6. The data points show a maximum at a somewhat lower collision frequency, $v_{eff}/\omega \approx 0.5$.

Details concerning this fluctuation, such as radial mode structure, mode frequency, and perpendicular and parallel wavenumbers have been explained by a nonlocal analysis of the dissipative trapped electron mode.

II. Modes with Trapped Ions

Experiments are performed on laser-generated lithium-ion plasma. Lithium is chosen because its vapor pressure at room temperature is very low (10^{-13} torr) so that recycling of plasma particles at the limiters is greatly reduced from that of a gas. In addition the ion mass is small so ion gyroradius limitations are minimized. Typically, the lithium neutral density is less than 10% of the electron density, which reduces ion charge exchange energy losses to negligible values. Ion energy confinement appears to be consistent in magnitude with that expected from neoclassical collisional transport, so that little power absorption is required to increase T_i to 3-5 eV. Wave heating at the ion cyclotron frequency, lower hybrid frequency, and electron cyclotron frequency has been used to heat ions and electrons; under most conditions, these heating techniques produce plasma with $T_i \approx T_e$, in the range 0.5 to 5 eV. The densities used lie between 10^{10} cm $^{-3}$ and 10^8 cm $^{-3}$, so the electron and ion mean-free paths, λ_e and λ_i ,

lie between 0.1 and 2000 m, while the mirror length is 0.5-3 m. The averaged poloidal field is 350-500 G, and the toroidal field was varied between 0 and 1000 G.

In the private flux volume inside the separatrix, fluctuation levels up to $\delta n/n \sim 0.2$ are observed near and on the ring side of the density gradient maximum. This location is an absolute minimum-B for all toroidal fields used in this study, and it is characterized by moderately strong shear; quantitatively, the average curvature radius is about 30 cm, the minimum shear length is 25 cm, and the density gradient scale length is about 1 cm near the hoop. The absolute minimum-B configuration suppresses MHD modes or modes driven by local bad curvature, while the shear is effective in stabilizing modes with long parallel wavelengths. In Fig. 7 the fluctuation amplitudes are plotted as a function of v_i^* and v_e^* , where $v_{i,e}^* = v_{i,e} L_M / \sqrt{k T_{i,e} / m_{i,e}}$, and L_M is the mirror length. The amplitude is nearly constant at 15-20% for data with $v_e^* < 1$. For high collisionality, the wave amplitude drops to less than 5%. The frequency for these fluctuations is always in the range of 1-5 kHz, while the electron bounce frequency is 200-400 kHz and the ion bounce frequency is 1-5 kHz. Depending on toroidal field, the trapping fraction $\sqrt{\epsilon}$ lies between 0.1 and 0.5, and q lies between 0 and 0.3.

For $v_i^* \lesssim 1$, the wave phase velocity lies in the ion diamagnetic drift direction, after the Doppler shift correction is made. This mode always has frequency close to the ion bounce frequency, so it may be the collisionless ion mode discussed by Coppi, Rosenbluth, and Rutherford⁸ driven by trapped ions. The dispersion relation for this mode,

$$\left(1 + \frac{T_i}{T_e}\right) - \frac{\omega_{*i}}{\omega} \left[b_T + \left(\frac{\omega}{\omega_{bi}}\right)^2 \right] = 0 \quad ,$$

where $b_T = \frac{1}{2} k_\perp^2 \rho_B^2$ and ρ_B is the poloidal gyroorbit size, indicates that $\omega < \omega_{*i}$, with which the data agree. This mode may be more virulent than the trapped particle modes for collisionality between that required for the temperature-gradient driven dissipative trapped electron mode and the dissipative trapped ion mode.

The characteristics of these modes are summarized in Table II.

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TABLE I.

	<u>Dissipative</u>	<u>Collisionless</u>
Toroidal field, minor axis	0.38 kG	0.38 kG
Average poloidal field	0.80 kG	0.8-1.4 kG
Safety factor (q)	0.25	0.17-0.25
Connection length (L_c)	~3 m	~1-3 m
Trapped fraction	0.85	0.65-0.85
Effective elec. detrapping freq (ν_{ef})	$4 \times 10^3 \text{ sec}^{-1}$	$< 4 \times 10^3 \text{ sec}^{-1}$
Ion mean free path	10^2 m	10^2-10^4 m
Angular frequency plasma frame	$(+) 6 \times 10^4 \text{ sec}^{-1}$	$(-) 6 \times 10^4 \text{ to}$ $(-) 1 \times 10^5 \text{ sec}^{-1}$
Perpendicular wavelength	5-10 cm	15-35 cm
Parallel wavelength	5-10 m	--
ω_e^*	$\sim (+) 1 \times 10^5 \text{ sec}^{-1}$	$(+) 5 \times 10^4 \text{ to}$ $2 \times 10^5 \text{ cm}^2/\text{sec}^{-1}$
Diffusion coefficient (D_i)	$6 \times 10^3 \text{ cm}^2/\text{sec}$	$10^4-10^5 \text{ cm}^2/\text{sec}$
Calculated growth	$\gamma = \omega_e^2 / \nu_{ef}$ $\sim 1 \times 10^6 \text{ sec}$	--

(+) = propagates in electron diamagnetic drift direction.

TABLE II.

	<u>Trapped Electron</u>	<u>Ions Trapped</u>
Location	Outside Ψ_s	Inside Ψ_s
Trapped fraction	0.7	0.1-0.4
Safety factor	0-2	0.1-0.3
Mirror length(m)	1-10	0.5-2
Density(cm^{-3})	10^8 - 10^9	10^8 - 10^9
Electron temperature(eV)	0.5-2.0	1-4
Ion temperature(eV)	0.05	1-4
Electron mean-free path(m)	>5	>5
Ion mean-free path(m)	<0.25	>5
Frequency(kHz)	1-3	1-5
Perpendicular wavelength(cm)	30-40	10-30
Phase velocity(cm/sec)	3×10^4 - 10^5	5×10^4 - 10^5
Direction parallel to diamagnetic drift of	electrons	ions
Diamagnetic drift frequency(kHz)	10	30-15
Amplitude($\delta n/n$)	.3-.4	.2

Figures

- 1a. Observed density profile for 11 msec and 19 msec after injection of the plasma.
- 1b. Density fluctuation level, $\delta n/n$, as a function of position, ψ .
- 1c. Value of the safety factor, q , as a function of ψ .
2. Observed values of D_A versus B for three values of the density in the collisionless ion and electron plasma.
3. Observed value of D_A versus B for two values of the density in the collisional ion, collisionless electron plasma.
4. The observed phase velocity of the fluctuations in the lab frame, $V_{c,lab}$, are plotted as a function of position ψ .
5. Plasma density, density fluctuation, and safety factor q as a function of distance from a hoop surface.
- 6a. Plasma fluctuation level as a function of density. The arrow on the abscissa indicates where $v_{eff}/\omega = 1$.
- 6b. Theoretical growth rate for the dissipative trapped electron mode driven by ion inertia, as a function of v_{eff}/ω .
7. Fluctuation amplitude on the hoop side of the separatrix, as a function of v_i^* and v_e^* .