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BY

K. ANDO, S. EJIMA, S. DAVIS,
R. HAWRYLUK, H. HSUAN, D. MEADE,
M. OKABAYASHI, N. SAUTHOFF,
J. SCHMIDT AND J. SINNIS

PLASMA PHYSICS
LABORATORY

MASTER

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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TRANSPORT AND DIVERTOR STUDIES IN THE FM-1 SPHERATOR^{*}

K. Ando,[†] S. Ejima,[†] S. Davis, R. Hawryluk, H. Hsuan,
D. Meade, M. Okabayashi, N. Sauthoff, J. Schmidt, and J. Sinnis

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540, USA

Fundamental problems of toroidal fusion devices have been investigated in the FM-1 Spherator. These subjects include the transport due to drift wave turbulence in the trapped electron regime, poloidal divertor and impurities, and lower hybrid heating.

1. INTRODUCTION

The FM-1 Spherator is an internal ring device with a levitated superconducting ring¹ with a current capability of 350 kAt. The current for the toroidal field, which provides the magnetic shear and average minimum-B, can be varied up to 750 kAt.² In the present series of experiments, the ratio of the toroidal field to the poloidal field B_T/B_P is in the range of $0 < B_T/B_P \leq 2$ with the ring current of 100-275 kAt.[†] Plasmas are produced by electron cyclotron resonance heating at 5.6 GHz or 10.6 GHz. The typical plasma parameters are given in Table I. Parametric studies of the plasma confinement time were reported in Ref. 2. A typical magnetic field configuration is shown in Fig. 1.

Recent experiments on the FM-1 Spherator have investigated several areas of interest in toroidal confinement and heating including (1) the effect of trapped electrons on the thermal conductivity, (2) shear stabilization of drift wave turbulence, (3) nonlinear saturation of drift waves, (4) poloidal divertor behavior and impurity transport, and (5) rf heating.

Trapped electron drift instabilities were found to produce a sizable electron thermal conductivity. The parametric dependence of this conductivity was studied using pulsed heating at the upper hybrid resonance.

Correlation techniques were used to study the mode structure and effects of magnetic shear on the drift wave turbulence. Modes with radial group velocities smaller than expected theoretically were found to exist. This may explain the insufficiency of shear stabilization of this turbulence.

The level of the nonlinear saturation of the turbulence was in agreement with that expected from wave-particle scattering.

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Studies of the poloidal divertor on FM-1 have shown that no unexpected processes limit the plasma flow into the divertor. The plasma flow velocity was measured utilizing ion sound wave propagation and found to be about one-third of the ion sound speed. These results along with the measured thickness of the plasma scrape-off in the divertor are in agreement with the ion sound flow model.

Barium test ions were used to study the diffusion of high mass, high-Z impurities. The barium transport was best described by superimposing anomalous and classical inward diffusion coefficients.

Electrostatic coupling was used to excite plasma waves above the lower hybrid frequency. Using this coupling technique efficient electron heating was observed. Although decay waves were excited at harmonics of the ion cyclotron frequency little or no ion heating was observed.

2. ANOMALOUS TRANSPORT AND DRIFT WAVE TURBULENCE

Recent studies of drift wave turbulence on FM-1 have focused on several aspects. The energy transport (thermal conductivity) in the trapped electron regime has been examined and compared with the theoretical prediction based on the trapped electron mode. The radial and toroidal structure of drift modes was studied to examine the mechanisms of shear stabilization. Experiments related to the nonlinear saturation of the turbulence were carried out.

2.1. The electron thermal conductivity in the trapped electron regime

The electron thermal conductivity in the trapped electron regime has been studied using pulsed microwave heating. A short pulse of microwave power was used to raise the electron temperature in an area near the location of the upper hybrid resonance. The thermal transport can be determined by measuring the spreading of an initially localized heat source. The details of the experimental techniques are given in Ref. 3. In this configuration the main stabilization is due to the magnetic shear since curvature is unfavorable. In the present experiment the magnetic surfaces are nearly coincident with the constant B surfaces and are similar to those of $B_E = 0.6 - 0.8$ case in Ref. 4. However, a variation of magnetic field magnitude of 40% still exists within magnetic surfaces.

Figures 2(a) and (b) show the dependence of the thermal conductivity $K_{\perp}$ and the particle diffusion coefficient $D_{\perp}$ on T_e and shear length L_s , where the particle diffusion coefficient is determined with a steady-state discharge plasma. The parametric dependence of $K_{\perp}$ is similar to that of $D_{\perp}$. The empirical formula obtained from these experiments is

$$K_{\perp} \approx 1/800 (T_e/16B) L_s/a \quad (1)$$

$$\approx 1/800 (T_e/16B_p) (B_T \gg B_p, L_s/a \sim B^2/B_p B_T) \quad (2)$$

where the B dependence is added based on the experiment reported in Ref. 2. Equation (1) gives a result similar to poloidal Bohm diffusion (as discussed by GA)⁵ for the case of $B_T \gg B_p$. The ratio of $K_{\perp}$ to $D_{\perp}$ was estimated with quasilinear theory used to include corrections for different plasma conditions between pulsed and steady-state discharge plasmas (the details will be published), giving

$$K_{\perp} \sim (3 - 5) D_{\perp} \quad (3)$$

In order to investigate the possible mechanisms for the anomalous transport, the fluctuations associated with the heat conduction were

investigated. The results are listed in Table II. In this plasma parameter range three types of drift wave instability may exist: (1) collisionless drift instability, (2) trapped ion instability, and (3) trapped electron instability. To determine the wave energy source for the observed fluctuations, the dependence on the electron temperature gradient ($\eta \equiv d \ln T_e / d \ln n_e$) was also studied. The comparison between $\eta_e > 0$ and $\eta_e < 0$ are shown in Fig. 3. In the case of $\eta_e < 0$ the electron thermal conduction was much smaller than that for $\eta_e > 0$ and the fluctuation level was reduced for the case $\eta_e < 0$. The observed η_e dependence does not agree with the collisionless drift instability. The trapped ion mode may be ruled out based on the observed shear dependence. Therefore, the results indicate that the anomalous electron thermal conductivity is due to the trapped electron instability. The magnitude of anomalous transport due to trapped electron mode is investigated solving the dispersion relation numerically. The coefficient estimated by maximizing $(\gamma/k_{\perp}^2)$ is $(1/20 \sim 1/100) D_B$ depending upon plasma parameters, which is also consistent with the observed value.

2.2 Shear stabilization

As was discussed in Section 2.1, the magnetic shear is important in determining anomalous transport. In order to clarify the mechanism of shear stabilization, detailed measurements of wave energy propagation in the radial and toroidal directions have been conducted using correlation techniques. According to the available theoretical prediction the radial^{7,8} wave energy transport should appear as a radial motion of wave packets. For drift waves, the real part of dispersion relation $\omega = \omega_{*e} (1 - k_{\perp}^2 \rho_{*e}^2 T_e / T_i + k_{\parallel}^2 c^2 / \omega^2)$ gives $(k_r / \omega) (\partial \omega / \partial k_r) = - 2 k_{\perp}^2 \rho_{*e}^2 T_e / T_i$ which is a backward wave in the radial direction.

Figure 4(a) is a plot of the cross correlation $C(x_1, x_2, \tau) = \int_{-\infty}^{\infty} dt f(x_1, t) f(x_2, t - \tau)$ of the ion saturation current fluctuations on two probes, one held stationary near the fluctuation maximum and the other swept radially; the two probes are adjacent at the maximum of the correlation for $\tau = 0$. In this helium discharge, the observed phase velocity of 6×10^4 cm/sec agrees with the theory. On the other hand, the envelope maximum is seen to have moved at less than 10% of the phase velocity, indicating that the group velocity is less than 6×10^3 cm/sec. For a heavier ion mass (argon) the result is shown in Fig. 4(b). Theoretically $k_r / \omega (\partial \omega / \partial k_r) = - 0.1$ for a helium plasma and -1.0 for argon. However, for argon the observed value of the group velocity is much smaller than the expected value. The radial mode structure in the helium plasma shows a radial decay length shorter than a wavelength, which appears to contradict the typical eigenmode solutions.^{9,10}

Toroidal mode structure is shown in Fig. 5. The dependence of toroidal wave number k_{ϕ} on toroidal magnetic field strength is consistent with $k_{\phi} B = 0$ at the center of the mode with poloidal quantization. Measurements of the same mode at different radii give identical toroidal mode numbers, demonstrating a change of $k_{\parallel} = k_{\phi} (x/L_s)$, thus eliminating the possibility of flutes.

2.3 Nonlinear saturation

The nonlinear saturation of drift wave turbulence plays a very important role in determining the anomalous transport coefficients. Although a significant theoretical effort^{11,12} has been expended on this subject very few experiments have been carried out to test the theoretical results, particularly in toroidal confinement devices. In the FM-1 Spherator the magnitude of fluctuation level is $0.1 \sim 0.02$ depending upon conditions. Two types of nonlinear mechanisms may lead to drift wave amplitude saturation.

These are: (1) mode-mode coupling¹¹ and (2) wave-particle scattering.¹² The observed magnitude is too small to be explained by mode-mode coupling. The possibility of wave-particle scattering was studied by measuring the perpendicular wavelength λ_ϕ , fluctuation amplitude, and local density gradient over the plasma volume. It was observed that k_ϕ is constant ($k_\phi \approx 2\pi/1.0$ cm) on the outside density gradient. The fluctuation level scales as $1/a$ as shown in Fig. 6. Assuming $k_r \sim k_\phi$, the magnitude of fluctuation level, $\delta n/n$, is given by

$$\delta n/n \approx 1/(k_r a) \quad (4)$$

which is the result given by wave-particle scattering.

3. POLOIDAL DIVERTOR

3.1. Function of the divertor

The initial objective of the FM-1 divertor experiments was to study plasma-divertor flow models to be used for designing the poloidal divertors in future devices. Experiments were carried out to determine the plasma flow velocity and density profiles inside the divertor chamber, the space potential and electron temperature profiles, the plasma capture efficiency of the divertor, and the neutral pressure rise in the divertor chamber due to the plasma flow.

Good agreement was obtained between the predictions of the ion sound velocity flow model and the measured density profiles and flow velocities. This flow model treats the plasma transport parallel and perpendicular to the magnetic field separately. The plasma is assumed to diffuse across the magnetic field with a diffusion coefficient which is comparable to the diffusion coefficient just inside the containment region. The parallel flow is determined with a combined fluid-kinetic theory,¹³ which predicts a plasma flow velocity in the divertor chamber which is close to the ion sound speed. The plasma flow measurements described below are in good agreement with this prediction. The parallel and perpendicular transport equations can be combined to give a plasma scrape-off thickness in qualitative agreement with the plasma profiles observed in the divertor.

The measured space potential in the divertor showed a large potential step ($\delta\phi \sim 5$ kT/e) across the magnetic field separatrix. The private flux surfaces of the divertor coil were charged positive relative to the surfaces common to the divertor coil and levitated ring. The potential step occurred over a distance comparable to the ion gyroradius. The potential step probably results from the fact that the plasma flows into the divertor along field lines outside the separatrix and only the ions have the ability to penetrate the flux surfaces inside the separatrix for a distance greater than an electron gyroradius. This potential step will result in large plasma velocities perpendicular to the magnetic field in the vicinity of the separatrix.

The electron temperature profile in the divertor is similar to the density profile. If a normal plasma sheath is assumed to exist at the neutralizer plate this result is consistent with an electron thermal conductivity which is a few times larger than the particle transport.

The plasma capture efficiency of the divertor was optimized by varying the divertor coil current relative to other coil currents. An efficiency of 80% has been obtained.

Neutral baffling was used to limit the neutral back-flow from the divertor chamber. Measurements of the divertor and main chamber pressure along with plasma density are shown in Fig. 7. These experiments were carried out with argon to maximize the divertor pressure increase. During the plasma discharge the containment volume pressure is reduced due to plasma capture of the neutrals along with the reduction of the neutral density due to transport into the divertor. The plasma transport into the divertor results in a sizable increase in divertor pressure, which is consistent with that predicted using the measured divertor capture efficiency and computed neutral conductance out of the divertor chamber.

3.2. Measurement of the plasma flow into the divertor

An ion acoustic wave was excited at the divertor throat between the poloidal divertor and the main plasma confinement volume. The difference between the wave propagation velocities parallel and antiparallel to the streaming plasma provides a measure of the plasma flow velocity into the divertor chamber.

Figure 8 shows the wave propagation parallel to the plasma flow for an argon plasma at a pressure of 1.8×10^{-5} torr. The plasma flow velocity was obtained by assuming that the downstream (parallel) wave propagates with a speed of $v_{\text{wave}} + v_{\text{flow}}$ and the upstream (antiparallel) wave propagates with a speed of $v_{\text{wave}} - v_{\text{flow}}$. For these experiments the electron temperature at the divertor throat was approximately 2.0 eV independent of the ion mass. Figure 9 shows that the plasma flow velocity is proportional to the square root of the ion mass and the absolute value is about 1/3 of the ion acoustic speed for $T_e = 2.0$ eV. It was determined that the plasma flow speed varied as the square root of the electron temperature. Therefore $v_{\text{flow}} = \alpha \sqrt{T_e / M_i}$, $\alpha = 0.3$. The factor $\alpha = 0.3$ is about one-half the value predicted in Ref. 13.

The effect of plasma confinement on the flow velocity was studied. The main body plasma confinement time can be reduced by a factor of 7-10 by reducing the toroidal field strength. It was found that the plasma flow velocity was relatively insensitive to the toroidal field, which indicates that main plasma confinement time is not an important parameter in determining the flow velocity.

4. IMPURITY TRANSPORT

$Z = 2$ barium test ions were injected into a $Z = 1$ plasma with various plasma ion masses to study the transport of high mass, high- Z impurities. An extensive theoretical effort has gone into determining the classical impurity transport coefficient.¹⁴ The objectives of the FM-1 experiments were to determine to what extent the theories could be verified and whether the anomalous effects modify the transport coefficients.

Barium was chosen as a test ion because it is easily ionized to the $Z = 2$ state. Other important properties of barium are that it is not a natural impurity and it can be easily introduced into the discharge and spectroscopically detected.

Since the classical barium diffusion is expected to depend on the plasma density and plasma ion mass the barium confinement was determined as a function of these two parameters. The result of these measurements is shown in Fig. 10. The low density confinement time of the barium was comparable for all the background plasma ions used, although the low density confinement time in deuterium exceeded that in other gases by a small factor. These barium confinement times were about the same as the confinement time of the background plasma (i.e., within a factor of 2). The

confinement time of barium increased as the background plasma density was increased.

The barium confinement time was also measured as a function of plasma density for a toroidal magnetic field which was a factor of 2 greater than the one used for the measurements described above. For this condition the low density barium confinement was slightly improved over the lower field case, however, the improvement of the confinement with plasma density was much less pronounced.

Since the classical transport of the barium is proportional to plasma density the zero density extrapolation of the barium confinement time should be a measure of the nonclassical (anomalous) effects causing barium transport.

An increase in barium confinement time with increasing plasma density should result from the superposition of the anomalous outward diffusion and the theoretically predicted classical inward diffusion¹⁵ as plasma density is increased. The plasma density at which this increase in confinement should occur is in the parameter regime where the measurements were made. The rate of improvement of the barium confinement time with increasing plasma density should scale as the square root of the plasma ion mass. This expectation is consistent with the observed mass dependence of the barium confinement.

The background plasma confinement time is observed to decrease at high plasma density. This occurs because ionization is produced at the upper hybrid layer which moves toward the plasma boundary at high density. This may explain the fact that the barium confinement time decreases at high plasma density for argon and xenon plasmas.

5. LOWER HYBRID RESONANCE HEATING

Lower hybrid resonance heating experiments have been conducted using two plates driven out of phase on the exterior of the plasma along the poloidal field with power up to 4 kW. Parametric dependences of the heating efficiency and the localization of the heating region were studied. Oscillations near the ion cyclotron harmonics and sidebands separated from the incident frequency by the ion cyclotron harmonics were observed. The electron heating efficiency is 20 ~ 40% with only a weak density dependence. At low plasma density $\omega \gg \omega_{LH}$ the electron temperature was increased over the entire plasma volume, whereas at high density $\omega \sim \omega_{LH}$ heating took place at the boundary. The ion temperature was measured by Doppler broadening of the 4686 Å line. No significant ion heating was observed, in contrast with the work of T. K. Chu, et al.,¹⁶ who observed strong ion heating coincident with the appearance of oscillations near the ion cyclotron frequency.

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† Permanent address: The Institute of Physical and Chemical Research Tokyo, Japan.

‡ Present address: General Atomic Company, P. O. Box 81608, San Diego, California 92138.

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Table I

T_e	$0.5 \sim 20 \text{ eV}$
T_i	$\sim 3 \text{ eV}$
n_e	$0.2 \sim 5 \times 10^{11} \text{ cm}^{-3}$
B_e	$2 \sim 4 \text{ KG}$
B_T/B_P	$0.1 \sim 2$
connection length	$\sim 100 \text{ cm}$
shear length	$\sim 100 \text{ cm}$
τ_{Bohm} at $T_e = 1 \text{ eV}$	10 msec
τ_{obs} at $T_e = 1 \text{ eV}, n_e = 1 \times 10^{11} \text{ cm}^{-3}$	0.7 sec

Table II

T_e	$2 \sim 20 \text{ eV}$
n_e	$2 \sim 5 \times 10^{10} \text{ cm}^{-3}$
gas	Helium
ω_{be}	$\sim 6 \times 10^6$
ν_{ei}	$0.1 \sim 1 \times 10^5$
ω_{be}/ν_{ei}	~ 10
ω_{bi}/ν_{ii}	~ 1
measured λ_1	$\sim 1.5 \text{ cm}$
measured $\omega/2\pi$	$20 \sim 40 \text{ KHz}$
drift direction	electron diamagnetic drift
$\omega_{*e}/2\pi$ for measured λ_1	$\sim 40 \text{ KHz}$

743577

Fig. 1. Typical magnetic field configuration with poloidal divertor.

743498, 743502

Fig. 2. Comparison of the dependence of the electron thermal conductivity $K_{\perp}$ and particle diffusion coefficient $D_{\perp}$ on electron temperature T_e and magnetic shear length L_s . In the trapped electron regime ($T_e > 2$ eV) $K_{\perp}$ is proportional to $D_{\perp}$. The classical value of $K_{\perp}$ is smaller than the observed value by a factor of $10^2 - 10^3$. The T_e dependence was done with $TF=0.7$. (TF is the toroidal field current I_{TF} normalized by the ring current I_{PF} .)

743731, 743730

Fig. 3. Comparison of thermal conduction for $\eta_e > 0$ and $\eta_e < 0$. Ion saturation current before heating reflect the density profile because the electron temperature profile is flat. The case $\eta_e < 0$, which is produced by a short pulse of S-band power, shows almost no spreading after 1 msec. On the other hand, large thermal conduction is observed in the case of $\eta_e > 0$, produced by a short pulse of x-band power.

743733, 743734

Fig. 4. Cross correlation of ion saturation current fluctuations on probes displaced radially in (a) helium and (B) argon plasmas.

743735

Fig. 5. Cross correlation of ion saturation current fluctuations on probes displaced toroidally in a helium plasma.

743736

Fig. 6. Density and turbulence profiles along with the spatial variation of the inverse density scale length.

743254

Fig. 7. Plasma density, confinement and divertor chamber pressures before, during and after an ECRH discharge.

(5 μ sec / div)

743419

Fig. 8. The time of flight measurement of ion acoustic waves excited at the divertor throat. The upper trace is the received signal and the lower trace the excitation signal.

743496

Fig. 9. The dependence of the plasma flow speed into the divertor versus ion mass. The observed velocity is proportional to the square root of the ion mass.

743574

Fig. 10. The observed barium decay times (solid curves) are shown as a function of background plasma peak density for various gases in the FM-1 high shear magnetic field configuration. Also shown is the barium confinement in argon with low shear. The dashed curves are the numerically determined confinement times for a comparable slab geometry.

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