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**PLASMA DIFFUSION DUE TO MAGNETIC
FIELD FLUCTUATIONS**

BY

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**PLASMA PHYSICS
LABORATORY**

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Plasma Diffusion Due to Magnetic Field Fluctuations

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Plasma diffusion due to magnetic field fluctuations has been studied in two dimensions for a plasma near thermal equilibrium and when the fluctuations are supra-thermal. It is found that near thermal equilibrium electron diffusion varies as B^{-2} when the collisionless skin depth is greater than the thermal electron gyro-radius and is generally smaller than the diffusion due to collisions or electrostatic fluctuations for a low- β plasma. When the suprathermal magnetic fluctuation exists because of macroscopic plasma currents, electron diffusion is enhanced due to the coalescence of current filaments and magnetic islands. Magnetic field energy is found to condense to the longest wavelength available in the system and stays there longer than the electron diffusion time scale.

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Fig

I. Introduction

Anomalous plasma diffusion due to electric and magnetic fluctuations in a confining magnetic field has been one of the critical issues for the successful achievement for controlled thermonuclear fusion. From the earliest days to the present, confinement of plasmas has been the major subject along with plasma heating in order to achieve the thermonuclear reaction. It was Bohm who pointed out that the enhanced electric and magnetic field fluctuations could give rise to anomalous diffusion which could be orders of magnitude greater than the classical diffusion in high temperature collisionless plasmas.¹ While the high temperature plasmas confined in a strong magnetic field are likely subject to instabilities of various origin, it was hoped that the plasma diffusion could follow the classical diffusion when the instabilities are suppressed and the fluctuations are those of thermal noise level.

It was recently pointed out that the problem of anomalous plasma diffusion goes much deeper than it was believed in the earlier days.² As fusion plasma achieves higher and higher temperature, it was shown that even the thermal fluctuations can dominate over the classical diffusion for the transport of particles and energy across the magnetic field. While the enhanced diffusion due to thermal fluctuations may be greater than the classical diffusion, it is often too small to explain the experimental results unless the fluctuation level is above the thermal noise. There are mechanisms for plasma instabilities to feed the energy into thermal fluctuations so that the diffusion is greatly enhanced.

Excitation of large amplitude convective cells due to drift instabilities is one of such examples.³ However, these studies on anomalous diffusion have been restricted primarily on electrostatic fluctuations appropriate only for low density and low temperature plasmas.

Recently, it was pointed out that thermal magnetic field fluctuations could give rise to enhanced diffusion comparable to classical diffusion.⁴ It was shown, however, that diffusion is generally smaller than the diffusion due to electrostatic fluctuations near thermal equilibrium.⁵ In practice, there are many situations where a plasma is carrying currents which then enhance magnetic fluctuations. Under such cases, it is possible that the diffusion caused by magnetic field fluctuation may dominate over the diffusion due to electrostatic fluctuations. This is particularly true for the electrons since they can diffuse much faster along the field lines than the ions owing to their large thermal speed.

In this paper, we consider a two dimensional problem in which a plasma is immersed in a strong external uniform magnetic field, B_0 , aligned along the z direction. We consider first the case where the fluctuations are thermal. It is found that when the electron-ion collisions are taken into account appropriately, the electron diffusion arising from magnetic fluctuations varies as B^{-2} when the collisionless skin depth is larger than the electron gyroradius. This diffusion is generally smaller than the classical diffusion and it is also smaller than the diffusion due to the electrostatic fluctuation in a low- β plasma.

When there are macroscopic currents present, diffusion is enhanced by magnetic fluctuations which can dominate the diffusion caused by electrostatic fluctuations. Under such conditions it was found that the current filaments and the magnetic field fluctuations tend to coalesce into larger filaments and islands owing to the nonlinear interactions among the current filaments. The resultant rapid electron motion along the field lines further enhance the coalescence and thermal electron diffusion. It was found that the magnetic field energy condenses at the longest wavelength mode available and stay there for the time scale longer than that determined from the electron diffusion. This is because the coalescence of islands takes place exclusively among the current filaments in the same direction, and the current neutralization cannot take place on the same time scale even if the electrons are apparently spread out more or less smoothly over the entire region.

In the following, theoretical considerations on plasma diffusion due to various origins are given in Sec. II. Simulation results and the comparison with theory are given in Sec. III for a thermal plasma. Enhanced magnetic fluctuations due to macroscopic current filaments and electron diffusion are studied in Sec. IV. Discussion and concluding remarks are given in Sec. V.

II. Thermal Fluctuations and Electron Diffusion

Let us consider a two dimensional plasma in a strong external magnetic field aligned in the z direction. Variations are allowed only in the x - y plane. It is well known that under such conditions, there exist both d.c. electrostatic and d.c. magnetic fluctuations. The electrostatic fluctuations are generated by the charges across the magnetic field which are dissipated very slowly by the plasma diffusion. The decay rate for the electrostatic fluctuations for a mode with its wavelength $k_{\perp}$ is given by²

$$\omega = -i \frac{k_{\perp}^2 D_c}{1 + \Omega_i^2 / \omega_{pi}^2} \quad (1)$$

where D_c is the ion diffusion caused by ion-ion collisions or the anomalous diffusion from fluctuating electrostatic fields which is given by²

$$D_c = \frac{c}{B_0} \left(\frac{T}{1 + \omega_{pi}^2 / \Omega_i^2} \right)^{1/2} \left(\ln \frac{L}{2\pi\rho_i} \right)^{1/2} \quad (2)$$

where L and ρ_i are the plasma size and the thermal ion gyro-radius. ω_{pi} and Ω_i are ion plasma and gyrofrequencies, respectively.

Magnetic field fluctuations are generated by the electron currents along the external magnetic field which are dissipated either by the electron-ion collisions or by the viscosity through the self-diffusion of the electrons. The decay rate is given by⁴

$$\omega = -i \frac{\nu_{ei} + k_{\perp}^2 D_e}{1 + \omega_{pe}^2 / c^2 k_{\perp}^2} \quad (3)$$

Classically, $D_e \sim \rho_e^2 v_{ee}$ and $v_{ee} \sim v_{ei}$ so that the collisional damping is always dominant over the viscosity damping for long wavelength modes ($k_1 \rho_e \leq 1$) which are important for determining electron diffusion. This is one of the major differences between the convective cell diffusion and the diffusion due to magnetic fluctuations. The convective cells are maintained by the ion inertia while the current fluctuations are due to electrons which are subject to the collisional damping. When this is the case, electron self-diffusion may be given by

$$D_{MC} \equiv \frac{1}{2} \sum_k \langle v_{1k}^2 \rangle \tau_k = \frac{v_e^2}{2} \sum_k \frac{\langle B_k^2 \rangle}{B_0^2} \tau_k.$$

Using the expression for the mode energy and the correlation time⁴

$$L^2 \frac{\langle B_k^2 \rangle}{8\pi} = \frac{T_e}{2} \frac{1}{1 + c^2 k^2 / \omega_{pe}^2}$$

and

$$\tau_k = \frac{1 + \omega_{pe}^2 / c^2 k^2}{v_{ei}},$$

we find

$$D_{MC} = \frac{T_e^2}{B_0^2} \frac{\omega_{pe}^2}{m_e c^2} \frac{1}{v_{ei}} \ln \frac{L}{\rho_e} \quad (4)$$

which varies as B_0^{-2} and is independent of plasma density.

When the fluctuations are near thermal level, the diffusion calculated here is rather modest and does not usually exceed the classical diffusion particularly in three dimensions where Eq.(4) must be divided by the system length. Let us note that the collisional damping $[(c^2 / \omega_{pe}^2) v_{ei} k_1^2]$ is generally much greater than the diffusing orbit decorrelation rate given by $k_1^2 D$ for

most of the laboratory plasmas, unless the induced diffusion is far above the classical diffusion. This is because the skin depth (c/ω_{pe}) is usually greater than the electron gyroradius. Of course, when the magnetic fluctuations exceed thermal level by orders of magnitude, then $k_{\perp}^2 D$ decorrelation may dominate over the other. The diffusion will thus take the Bohm-type scaling given by⁴

$$D_M = \frac{T}{B_0} \left[\frac{2}{m_e} \ln \left(\frac{L \omega_{pe}}{2\pi c} \right) \right]^{1/2} \quad (5)$$

When there are both electrostatic and magnetostatic fluctuations present, particle diffusions do not always add up even when the displacements of particles due to electric and magnetic fields are independent. For example, if we assume the decorrelation caused by diffusing orbit $k_{\perp}^2 D$ gives the dominant time step. Then the diffusion resulting from electric and magnetic fluctuations will be

$$D = \sum_k \left\langle \left(\frac{cE_k}{B_0} + v_e \frac{B_k}{B_0} \right)^2 \right\rangle \frac{1}{k_{\perp}^2 D}$$

or

$$D = (D_C^2 + D_M^2)^{1/2} \quad (6)$$

which is always smaller than the sum of two diffusions. This is because the decorrelation rate is enhanced when two diffusion processes are present simultaneously.

When the plasma β becomes large, magnetic fluctuations can couple to electrostatic fluctuations and affect their life time

by shorting the charges associated with the convective cells.⁵ This will take place when the decorrelation arising from electron motion along the perturbed magnetic field ($k_{\parallel} v_e$) becomes comparable to perpendicular phase mixing rate $k_{\perp}^2 D_C$.⁶ Equating $k_{\parallel} v_e$ with $k_{\perp}^2 D_C$, the critical β_C will be estimated to be

$$\beta_C \approx \frac{T}{\langle B_{\perp}^2 \rangle} k_{\perp}^2 \left(\frac{m_e}{m_i} \right) \quad (7)$$

where $\langle B_{\perp}^2 \rangle$ is the fluctuating magnetic field perpendicular to B_0 and $\omega_{pi}^2 \gg \Omega_i^2$ is assumed. Near thermal equilibrium, $\langle B_{\perp}^2 \rangle / T \sim 4\pi \omega_{pe}^2 / c^2$ so that the critical β would be

$$\beta_C \approx \frac{c^2 k_{\perp}^2}{4\pi \omega_{pe}^2} \frac{m_e}{m_i}.$$

Beyond the critical β , the diffusion caused by electrostatic convective cells decreases in a similar manner for a sheared field⁶ and the diffusion due to magnetic field fluctuations dominates. Under such conditions, Eq. (6) will no longer hold and the diffusion will be essentially given by either D_{MC} or D_M .

So far, we considered only the low-frequency fluctuations, ($\omega \approx 0$). In addition to such fluctuations, short-wavelength lower hybrid fluctuations could give rise to electron diffusion which is given by²

$$D_L = \frac{c}{B_0} \left(\frac{T}{1 + \omega_{pe}^2 / \Omega_e^2} \right)^{1/2} \left(\ln \frac{\omega^2 + k_{\max}^4 D_L}{\omega^2} \right)^{1/2} \quad (8)$$

where $\omega \approx \omega_{pi}$ is the lower hybrid frequency.

When the magnetic fluctuations are above thermal, it is difficult to derive a formula for particle diffusion because the spectrum of suprathermal magnetic fluctuations is determined by the nonlinear interactions among the current filaments. It is shown later that the nonlinear interactions (mode-coupling) among current filaments causes the coalescence of small magnetic islands to larger ones. When coalescence begins, electron motion along such field lines further enhance the generation of larger and larger magnetic islands. This will be discussed later in Sec. IV.

III. Results of Simulations Near Thermal Equilibrium

Let us now look at the results of particle simulations using a two-and-a-half dimensional magnetostatic model. Both ions and electrons are pushed using the full Lorentz force. In addition, pitch angle collisions are built in the code through the Monte Carlo technique which gives accurate small angle electron collisions with heavy ions.⁷ Compressional component of the self-consistent magnetic field is neglected assuming it is much smaller than the external field. Typically, 64×64 spatial grid, 4096 ions and electrons, $m_i/m_e = 25 \sim 400$, $T_e/T_i = 1 \sim 4$, $v_e/c = 1/5$, $\lambda_e/\Delta = 1$, and $\omega_{pe}\Delta t = 0.2$ are used where Δ is the spatial mesh; λ_e is the electron Debye length and Δt is the time step of integration. Magnetic fields are changed so that $\omega_{pe}/\Omega_e = 0.5, 1$, and 1.5 have been studied which correspond to $\beta = 0.025, 0.1$, and 0.2 respectively. Plasma is uniform and the self-diffusion of ions and electrons are measured.

In order to make the origin of diffusion clear, simulations with only magnetostatic fluctuations, with only electrostatic fluctuations are carried out in addition to the simulations with all the fields.

Figure 1 shows typical results for the electron diffusion $\langle(\Delta x)^2\rangle$ and $\langle(\Delta y)^2\rangle$ with time for $\omega_{pe}/\Omega_e = 1 (\beta = 10\%)$. When there are no macroscopic fluctuations present, classical diffusion due to electron-ion collisions is accurately reproduced. When the magnetostatic fluctuations are turned on, electron diffusion is enhanced immediately. Ion diffusion under such

situation remains negligibly small so that it is not shown. When the electrostatic field is turned on while the magnetostatic fluctuations are suppressed, ion diffusion is greatly enhanced and it becomes comparable to electron diffusion. This is obviously caused by thermally excited convective cells. Finally, when all the fields are on, electron diffusion is further enhanced.

However, it is less than the sum of two diffusions due to magnetic fluctuations and electric fluctuations alone. This is because the diffusion due to electric and magnetic fluctuations do not simply add up as discussed. Ion diffusion is almost the same as the diffusion with only electrostatic fields.

Figure 2 shows the ion diffusion coefficient (a) and electron diffusion coefficient (b) for three different magnetic field strength. Ion diffusion is little affected by the magnetic fluctuations and is almost independent of magnitude of external magnetic field. Indeed the ion diffusion agrees well with convective diffusion given by Eq. (2) as shown in Fig. 2.

Electron diffusion is somewhat more complicated. The results are shown in several steps: when there exist only magnetostatic fluctuations; when there exist only electrostatic fluctuations and both. Collisions are added in the simulations for these results. When there are only magnetic fluctuations present in the simulations in addition to electron collisions, electron diffusion goes B^{-2} and agrees well with Eq. (4) as shown in Fig. 2(b).

When there are only electrostatic fluctuations present, electron diffusion is almost independent of B_0 and is close to the ion diffusion. This diffusion is again due to electrostatic

convective cells. Owing to the finite gyroradius effects or due to the presence of lower hybrid oscillations, electron diffusion is greater than the ion diffusion in the absence of magnetic fluctuations. When both the electric and magnetic fields are present, electron diffusion is enhanced and almost independent of magnetic field indicating the diffusion is primarily due to electrostatic fluctuations. Electron diffusion is again larger than the ion diffusion owing to magnetic fluctuations and electrostatic lower hybrid waves. As seen in Fig. 2(b), diffusion due to various origins does not add up as discussed in Sec. II. This is particularly true for high β where the diffusion due to electric and magnetic fields are comparable. It is clear from these measurements, for a plasma near thermal equilibrium, enhanced diffusion, due to electrostatic fluctuations, is in general greater than the diffusion due to magnetic fluctuations for a low β plasma. One should keep in mind that for this example, electron diffusion due to magnetic field is unrealistically small because of the use of a small mass ratio in the simulations. Nonetheless, β is large here and D_M or D_{MC} is small in comparison with D_C as discussed in Sec. II.

As β increases, diffusion caused by magnetic fluctuations becomes important and eventually dominates the diffusion due to electrostatic fluctuations by shorting out the charges associated with these fluctuations.

One can get an idea for electron diffusion by following a set of test particles in time as shown in Fig. 3. A set of electrons initially in a small box are followed in time when there are only magnetic fluctuations as shown in Fig. 3(a) and all the

fields are present as shown in Fig. 3(b). Very little spreading is observed when only magnetic fields are present while the spreading is faster with the electrostatic fields. It should be noted that the electrons do not spread out isotropically in space which is one of the characteristics of plasma diffusion due to macroscopic plasma flow associated with collective electric and magnetic fluctuations.

It is interesting and important to measure the decorrelation time of the electrostatic as well as magnetostatic fields since various assumptions are made for estimating the diffusion coefficient. It has been shown,⁵ in the absence of electron collisions, that the magnetic field fluctuations hardly decayed when electrostatic fields were suppressed. Furthermore, both the electric and magnetic field correlations decayed at a rate given by $k_{\perp}^2 D$ owing to the strong coupling between electric and magnetic fluctuations through particle diffusion. Here, we study the effects of collisions on the magnetic fluctuations.

Figure 4 shows the measurements of the auto-correlation function for magnetic field fluctuations, $B_x(3,1)$ for Fig. 4(a), and $B_x(4,1)$ for Fig. 4(b), when the electrostatic fluctuations are suppressed. For both cases, initial monotonic decay is followed by the incoherent oscillations due to apparently nonlinear mode coupling effects. The initial decay time is estimated to be about $70 \omega_{pe}^{-1}$ and $40 \omega_{pe}^{-1}$ for Fig. 4(a) and Fig. 4(b) which are within a factor of 2 from Eq. (3). All the other modes showed the similar behavior and in particular the rapid decay of the correlations has never been observed for the collisionless simulations.⁵ Frequency spectrum, not shown here, indicates the presence of zero frequency magnetic field fluctuations as predicted.

IV. Suprathermal Magnetic Fluctuations

We have seen the diffusion of electrons due to magnetic field fluctuations to be rather modest and is generally smaller than the diffusion caused by electrostatic fluctuations when the fluctuations are at the thermal level. There are situations, however, where the magnetic field fluctuations are considerably higher than the thermal noise level even when the electrostatic fluctuations are not enhanced. This is because the laboratory plasmas are often unstable with respect to magnetic field fluctuations which could enhance the particle diffusion. Current carrying plasmas can also enhance magnetic field fluctuations.

In this section, enhanced magnetic fluctuations and their nonlinear interactions are considered along with the enhanced plasma diffusion. We consider macroscopic current filaments initially aligned along the external magnetic field in the z direction. Current filaments are arranged so that they form a checker-board pattern as shown in Fig. 5. In this example, 16 filaments of electron currents are considered and the average drift speed for each filament is taken to be the same as the ion sound speed. The total electron current is taken to vanish. $m_i/m_e = 100$, $T_e/T_i = 4$, $\omega_{pe}/\Omega_e = 1$, $c/v_e = 5$, and 64×64 grid and particles are used. Initially, the size of each current filament is several ion gyroradii. Note $\beta = 10\%$ here. Collisions are neglected altogether since it is expected that nonlinear interactions among the macroscopic filaments dominate the collisional process.

Figure 6 shows the time development of the vector potential contours which represent field lines in the $x-y$ plane. Initially, well-organized 16 magnetic islands start coalescing at an early time into larger islands and eventually develop into two large magnetic islands associated with the positive and negative current filaments by the end of the run ($t = 4000 \omega_{pe}^{-1}$). Note the time scale is long enough for a shear Alfvén wave to move across the system by the end of the run. This pattern persists for a very long time. Because the current filaments in the same direction attract each other, nonlinear interactions among the filaments tend to generate the coalescence of filaments. Hence, larger magnetic islands result. Furthermore, electron free streaming, along the reconnected field lines enhance the coalescence of the current filaments and the associated magnetic islands. Dissipation of the net current is very small under such condition. The currents in the opposite direction do not coalesce and they indeed repel each other. Magnetic islands coalescence has been studied based on ideal magnetohydrodynamic equations which do not include dissipation or kinetic effects such as free streaming of electrons.^{8,9}

Figure 7 shows the instantaneous spectrum of magnetic field energy ($B_x^2 + B_y^2$) for each Fourier mode. Initially, $(m,n) = (2,2)$ mode ($k_x = 2\pi m/L_x$, $k_y = 2\pi n/L_y$) is excited by the initial current filaments as described. Random thermal motion of the electrons also generates magnetic fluctuations near thermal level for all the modes in the system. Because of the nonlinear interactions among the current filaments and the electron streaming, the shift of the magnetic energy into larger fluctuations is clearly seen.

Note, it is not only the magnetic islands but also current filaments coalesce into larger perturbations. This is clearly seen in Fig. 7 at $t = 2000$ where most of the magnetic field energy is going to the smaller $k_{\perp}$ modes. By the end of the run, most of the magnetic energy is condensed at the largest wavelength. The expected thermal level of the magnetic field fluctuations for the corresponding thermal plasma is given by

$$\frac{B_k^2}{8\pi} = \frac{T_e}{2} \frac{1}{1 + (k^2 c^2 / \omega_{pe}^2) \exp(k^2 a^2)} \quad (7)$$

and is indicated in Fig. 7. Here a is the half-width of gaussian-shaped simulation particles. Note the energy in the large k 's is close to the thermal level while the enhanced level of fluctuations for small k 's persists for a long time, longer than the particle diffusion time.

Figure 8 shows the measurements of the test particle diffusion for the ions and electrons. Up until $t = 2000 \omega_{pe}^{-1}$, $\langle (\Delta x^e)^2 \rangle$, and $\langle (\Delta y^e)^2 \rangle$ are about equal. However, $\langle (\Delta y^e)^2 \rangle$ increases much faster after $t = 2000 \omega_{pe}^{-1}$, due to the coalescence of magnetic energy into $B_y(1,0)$ mode. $D_x^e \approx 0.15$ is closely to thermal diffusion as shown in Fig. 2(b) while $D_y^e \approx 0.75$ is much larger than that. The ion-diffusion coefficient $D_i \approx 0.095$ is close to the thermal diffusion caused by electrostatic fluctuations owing to their small thermal speed. Using the measured diffusion in Eq. (3), the characteristic time for the damping is at most $3000 \omega_{pe}^{-1}$ and $300 \omega_{pe}^{-1}$ for (1,0) and (2,0) magnetic fluctuations in the system. Apparently, the observed large scale magnetic fluctuations persist

much longer than the time estimated from particle diffusion. In fact, the magnetic energy in the longest wavelength mode is still increasing. This appears as a paradox, however, it can be explained in a following manner. As already mentioned, coalescence and reconnection of islands and current filaments take place almost exclusively among the current filaments in the same direction. Since the enhanced electron diffusion is along the perturbed magnetic field, diffusion does not immediately lead to the current neutralization no matter how complicated the field lines are. Of course, diffusion due to collisions and, perhaps, electrostatic fluctuations eventually cause the neutralization of the current. However, this takes a long time. In this sense, the diffusion due to magnetic islands is different from the classical diffusion or convective cell diffusion which dissipate the current as the particles diffuse. Figure 9 shows a set of test particle orbits originating from one of the current filaments. As the time goes on, electrons spread out from the initial box and appear to cover the entire space more or less evenly.

Finally, Fig. 10 indicates the kinetic energy of electrons and ions, electrostatic, and magnetic field energies in time. Magnetic field energy increases as the result of coalescence. Electrons lose their kinetic energy in order to compensate the increase of magnetic energy. Slight increase of ion energy may be collisional coupling with electrons. It was found that the electrostatic energy stays at the thermal level throughout the entire run.

Similar results are obtained for the coalescence of the current filaments and magnetic islands for a much smaller β , provided, a large mass ratio of ions to electrons is used. Figure 11 shows such results where $m_i/m_e = 400$ and $\beta = 1\%$ are used. Starting from the same initial configuration shown in Fig. 5, coalescence of magnetic islands into the largest island can be clearly seen and the magnetic field energy stays there for an extended time.

V. Discussions and Conclusions

Particle diffusion due to magnetic field fluctuations in two dimensions has been studied in some detail. When the fluctuations are of thermal level, the diffusion varies as B^{-2} in general and is smaller than that caused by electrostatic fluctuations for a low β plasma. When the macroscopic currents are present, magnetic field fluctuations can cause diffusion which exceeds the diffusion due to electrostatic fluctuations. Coalescence of magnetic islands and current filaments results due to the nonlinear interaction (mode coupling) of the current filaments and the resultant streaming of electrons along the field lines. The latter is due to the kinetic nature of a plasma. Large scale magnetic islands persist longer than the time scale of particle diffusion.

It should be emphasized that the results presented here are only two-dimensional while the real experiments are three dimensional. It is true that the three-dimensional variations of magnetic field lines are much more complicated and can be quite different. However, two-dimensional situation can also take place in three dimensions. Our results show that the magnetic fluctuations tend to develop into a coherent structure which would then compete with the stochastic wandering of each individual field line which can take place in three dimensions.¹⁰ Which process is more important? This is not known and the detailed work is underway using a three-dimensional simulation model.

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Figure Captions

Fig. 1. Test electron diffusion due to collisions only (open circles), collisions and magnetic fluctuations (solid squares), electrostatic fluctuations (triangles), and both electric and magnetic fluctuations (solid circles). Test ion diffusion (crosses) due to electric and magnetic fluctuations.

Fig. 2. Ion-diffusion coefficients (a) and electron diffusion coefficients (b) with collisions (solid squares), collisions and magnetic fluctuations (open circles), electrostatic fluctuations (open squares) and electric and magnetic fluctuations (solid circles).

Fig. 3. Sketch of test particle diffusion for the case of magnetic field fluctuations only (top row) and electric and magnetic fluctuations (bottom row).

Fig. 4. Autocorrelation function for the magnetic fluctuations of $B_x(3,1)$ and $B_x(4,1)$ modes.

Fig. 5. Initial arrangement of the 16 current filaments aligned along the z direction.

Fig. 6. Coalescence of magnetic energy into the longest wavelength mode available in the system.

Fig. 7. Instantaneous magnetic field energy spectrum for 3 different time steps.

Fig. 8. Test particle diffusion for the ions and electrons.

Fig. 9. Spreading a set of electrons initially in one of the 16 current filaments.

Fig. 10. Time development of kinetic energies of ions and electrons, magnetic and electrostatic fluctuation energies.

Fig. 11. Coalescence of magnetic islands in a low β plasma ($\beta = 1\%$).

Fig. 1. 782311

Fig. 2. 782318

Fig. 3. 782310

Fig. 4. 782316

Fig. 5. 792307

Fig. 6. 782322

Fig. 7. 782312

Fig. 8. 782313

Fig. 9. 782309

Fig. 10. 782315

Fig. 11. 782314

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