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NEUTRAL BEAM INJECTION AND PLASMA
CONVECTION IN A MAGNETIC FIELD

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Injection of a neutral beam into a plasma in a magnetic field has been studied by means of numerical plasma simulations. It is found that, in the absence of a rotational transform, the convection electric field arising from the polarization charges at the edges of the beam is dissipated by turbulent plasma convection, leading to anomalous plasma diffusion across the magnetic field. The convection electric field increases with the beam density and beam energy. In the presence of a rotational transform, polarization charges can be neutralized by the electron motion along the magnetic field. Even in the presence of a rotational transform, a steady-state convection electric field and, hence, anomalous plasma diffusion can develop when a neutral beam is constantly injected into a plasma. Theoretical investigations on the convection electric field are described for a plasma in the presence of a rotational transform.

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I. INTRODUCTION

Interaction of a neutral gas with a plasma in a magnetic field has been of considerable interest in astrophysics, space physics, and plasma physics. Alfvén suggested, for example, a possibility of an enhanced ionization of a neutral gas streaming across a plasma in a magnetic field.¹ Such a critical ionization process may be important in satellite interaction with space plasmas and neutral gas in space.²

In laboratory experiments, neutral beam injection into a confined plasma has proven to be an efficient means to heat the plasma to thermonuclear temperatures.³⁻⁵ As the neutral particles are ionized via charge exchange and collisions with the ambient particles, they are trapped by the ambient magnetic field. The subsequent thermalization of the beam particles heats the plasma substantially. There are indications, however, that a powerful neutral injection leads to deterioration of plasma confinement.^{6,7}

We have shown earlier,⁸ by means of two-dimensional plasma simulations, that a neutral injection into a plasma in a magnetic field generates a large-scale plasma convection via $cE \times B/B^2$ drift, leading to anomalous diffusion associated with turbulent plasma convection. It was found that the injection of a neutral beam into a plasma can lead to the excitation of both the high frequency electrostatic instability near the ion cyclotron harmonics as well as the low frequency plasma convective motion. The high frequency instability is essentially a loss-cone instability arising from the velocity space anisotropy so that its dominant nonlinear effect is the velocity space diffusion toward an isotropic distribution. The low frequency convective motion is generated by the electric field associated with the injection of a neutral beam and is identified as the cause for anomalous plasma diffusion.⁸ Application to a toroidal geometry is also considered.⁹

In this report, we shall study the plasma convection and the convection electric field in the presence of a neutral injection with and without a rotational transform of the magnetic field. In the presence of a rotational transform, it is essential to have a steady-state neutral injection in order to maintain a convection electric field. Otherwise, the motion of the electrons along the magnetic field quickly neutralizes polarization charges, thereby eliminating plasma convection. In Sec. II, results of simulations without a rotational transform ($k_z = 0$) are studied. In particular, the convection electric field is studied in detail, including its dependence on beam density, energy, and the magnetic field strength.

In Sec. III, a rotational transform is introduced along with the steady-state injection of a neutral beam. It is shown that a steady-state convection electric field persists whose intensity is determined by the balance between the neutral injection and dissipation of the charges by the motion of electrons along the magnetic field or by turbulent convection. Applications of the results to a magnetically confined plasma are discussed in Sec. IV.

II. CONVECTION ELECTRIC FIELD

We shall first study the convection electric field generated by the neutral beam injection across the magnetic field in the absence of a rotational transform. The simulation model used is the same as that developed earlier⁸ in which a neutral beam with a finite width δ is injected into a uniform ambient plasma across a magnetic field. The neutral particles are assumed ionized via various atomic processes. The self-consistent motion of the beam and ambient plasmas after ionization is followed via numerical simulations. Let us first study an example of the numerical simulation where the neutral density is equal to the ambient density and the injection energy

is 25 times the plasma thermal energy.⁸ Figure 1 shows the instantaneous plots of the beam ion location in the (x,y) plane at four different steps. The parameters of the simulation are the following: a 64×64 grid, 4 particles per grid for the ambient ions and electrons uniformly distributed in the (x,y) plane, 4 particles per grid for the beam ions and electrons initially located at $(3/8)L_y \leq y \leq (5/8)L_y$ and uniformly distributed in x, $\omega_{ce}/\omega_{pe} = 2$ for the ambient electrons where ω_{ce} is the electron gyrofrequency, $\omega_{ce} = |e|B/m_e c$ and ω_{pe} is the ambient electron plasma frequency, $\omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2}$, mass ratio $m_i/m_e = 2$, ambient ion gyroradius $r_i/\Delta = 0.707$, beam ion gyroradius $r_{bi}/\Delta = 3.5$ where Δ is the grid size. The Debye length of the ambient electrons and ions, $\lambda_{De}, \lambda_{Di}$, is taken equal to the grid size. The magnetic field is in the z direction, $\vec{B} = (0,0,B)$.

As is clearly seen in Fig. 1, convective plasma motion is generated by the electric field. Such a convection is unstable at the boundaries of the neutral beam against the Kelvin-Helmholtz instability, leading to the formation of vortices and turbulent diffusion. The magnitude of the diffusion coefficient and its scaling law have been studied in detail earlier.⁸ Note the ion location in Fig. 1(b) is shifted downward from the initial location of the neutral beam by the amount of roughly the beam ion gyroradius. The electrons shift in the opposite direction, thereby generating charges at the boundary of the beam.

Figure 2 shows the electrostatic potential contours averaged over the five electron plasma periods at three different steps. Two pairs of positive and negative potential contours develop into large amplitude as the Kelvin-Helmholtz instability grows. Note there is clear correspondence between the flow patterns in Fig. 1 and the potential contours in Fig. 2. The amplitude of the potential contours is large, $-0.35 \leq e\phi/T \leq 0.35$, which is one of the

characteristics of the convective cells.¹⁰ T is the temperature of the ambient plasma.

The time-averaged electric field associated with the polarization charges is plotted in Fig. 3 at four different time steps. The electric field $\bar{E}$ is a dimensionless electric field used in the simulations and is given by

$$\bar{E}_y = \frac{e}{m_e} \frac{E_y}{\omega_{pe}^2 \Delta} . \quad (1)$$

The location of the initial neutral beam deposition is shown by the shaded area. Note $\bar{E}_y$ is averaged over x in Fig. 3. At earlier times, the shape of the electric field is a square with the sharp gradients at the edges of the neutral beam. At later times, the shape is broadened in accordance with the anomalous plasma diffusion due to turbulent plasma convection. Note the periodic boundary condition is used for both the field and particles so that the average electric field is taken to be zero in the simulation. This is because

$$\int_0^{L_y} \bar{E}_y dy = \phi(0) - \phi(L_y) = 0 . \quad (2)$$

The magnitude of the electric field may be estimated in the following manner. The polarization charges appear at the boundary of the neutral beam as a result of trapping and the subsequent gyromotion of the ionized neutral beam particles. Assuming the width of the charge layer is w , the jump of the electric field ΔE_y across the boundary may be given by

$$\Delta E_y = 2\pi en_b w , \quad (3)$$

where we assumed the charge density in the boundary layer falls off more or less linearly with the distance. w must be approximately given by the beam ion gyrodiameter before anomalous diffusion dissipates a sharp density gradient. This is supported by the profile of $\bar{E}_y$ given by Fig. 3 and by the number of other simulations. Then, we have

$$w \approx 2r_{bi} = \frac{2V_0}{\omega_{ci}} . \quad (4)$$

Using Eq. (4) in Eq. (3), we find $\Delta \bar{E}_y = (n_b/n_0) r_{bi}/\Delta = 3.5$ which is somewhat larger than the simulation result of $\Delta \bar{E}_y = 2.4$ shown in Fig. 3.

When the magnetic field is increased, the width of the boundary layer decreases as B^{-1} so that the convection electric field given by Eq. (3) decreases. When the magnetic field is reduced so that the ion gyroradius becomes much larger than the Debye length, the width of the boundary layer cannot increase with the gyroradius since the motion of a particle in the boundary layer is affected by both the electric and magnetic fields.

Figure 4 shows the summary of the seven simulations in which the magnetic field strength is varied while keeping all the other parameters the same as before. The points in Fig. 7 correspond to the initial amplitude of the electric field measured in the simulations. At high magnetic fields where $\omega_{ci}/\omega_{pi} = 1.4, 2.8, \text{ and } 5.6$, the simulations show that the electric field indeed decreases as B^{-1} in agreement with Eq. (4). For weaker fields, $\omega_{pi} \geq \omega_{ci}$, the electric field increases with the magnetic field, which is in sharp contrast to the high field region where E_y decreases with the magnetic field as B^{-1} .

The determination of the width of the boundary layer in this region, $\omega_{pi} \geq \omega_{ci}$, is complicated since the motion of the ions are affected by both the

magnetic field and the electric field. Instead, the magnitude of the convection electric field can be found from the Ohm's law in a conducting fluid. In the limit of a large electrical conductivity, there should not be any effective electric field in a moving plasma across the magnetic field so that

$$\underline{E} + \frac{1}{c} \underline{V} \times \underline{B} = 0 \quad (5)$$

is satisfied. Equation (5) must be good approximation in a collisionless plasma without a magnetic field. When the magnetic field is sufficiently small in the simulations so that the motions of electrons and ions are dominated by the electric field, we expect Eq. (5) holds since the magnetic field may be neglected. This takes place in the limit of $\omega_{pi} \gg \omega_{ci}$, so that we find $E_y = V_x B/c$ or $\bar{E}_y = (\omega_{ce}/\omega_{pe}) V_x / \omega_{pe} \Delta$ which is proportional to B as expected. Note V_x is the flow velocity of the ambient and the beam plasmas so that V_x is, in general, smaller than the injection speed V_0 of the neutral beam. One can determine V_x and hence the convection electric field assuming the injection energy is converted to the plasma flow energy and the electric field energy [see Eq. (5) of Ref. 8]. For $\omega_{pi}^2 / \omega_{ci}^2 \gg 1$, we find

$$E_y = \frac{V_0 B}{c} \left(\frac{n_b}{n_o + n_b} \right)^{1/2} \quad (6)$$

so that $V_x = (n_b / (n_o + n_b))^{1/2} V_0$. Equation (6) agrees well with the results of simulations.

Next, the dependence of the electric field on the beam density was studied by changing the beam density while fixing the ambient plasma density at $n_o = 4/\Delta^2$ and the magnetic field at $\omega_{ci}/\omega_{pi} = 1.4$. According to Eq. (3),

the jump of the electric field should increase linearly with n_b when the width w is independent of the density.

Figure 5 shows the results of the simulations varying the beam density from $n_b/n_o = 1/4$ to $n_b/n_o = 16$. At a low density beam, the electric field indeed increases linearly with n_b as predicted from Eq. (3) with the width w given by the beam ion gyroradius. At a higher beam density, however, the electric field increases much slower with the beam density as seen in Fig. 5, corresponding to the points at $n_b/n_o = 4$ and 16. This can be explained in the following manner. As the beam density increases over the ambient density, the plasma frequency exceeds the ion gyrofrequency. For example, at $n_b/n_o = 4$, $\omega_{pb}/\omega_{ce} = 1$ and at $n_b/n_o = 16$, $\omega_{pb}/\omega_{ce} = 2$, which suggests that increasing the beam density corresponds to decreasing the magnetic field as in Fig. 4. Here $\omega_{pb} = (4\pi e^2 n_b / m_e)^{1/2}$ is the beam electron plasma frequency. At high beam density, the convection electric field may be determined by Eq. (6) which gives $\bar{E}_y = 7$ for $n_b/n_o \gg 1$ in reasonable agreement with the simulation.

When the beam injection energy is increased, the electric field is found to increase according to Eq. (3) with $w = 2r_{bi}$. Figure 6 shows the results of the simulations with three different injection energies while keeping $n_b = n_o$ and $\omega_{ci}/\omega_{pi} = 1.4$. Since $w = 2r_{bi} = 2V_o/\omega_{ci}$, we should expect $\Delta E_y \sim T_b^{1/2}$ where $T_b = 1/2 m_i V_o^2$ is the injection energy. Data shown in Fig. 6 clearly support this.

Let us now study what happens when the mass ratio is increased toward a more realistic value. Figure 7 shows results of the simulation at $\omega_{pet} = 500$ with $m_i/m_e = 100$ and $\omega_{ci}/\omega_{pi} = 0.2$. The beam ion energy $T_b = 1/2 m_i V_o^2$ is kept the same at $25 T_e$ so that $V_o/v_e = 5 (m_e/m_i)^{1/2} = 0.5$, giving the beam ion gyroradius $r_{bi}/\Delta = 25$. Note the calculation was performed on a 64×128 grid so that the initial beam width $\delta/\Delta = 32$. Both the electron and the ion

distributions in the (x,y) plane in Fig. 7(a), (b) clearly indicate that the flow patterns develop into vortices. The corresponding electrostatic potential contours are shown in Fig. 7(c) and the averaged electric field $\bar{E}_y$ is in Fig. 7(d). It is clear that the beam particles maintain the original profile more or less despite the fact that the beam ion gyroradius is now much larger. Note the width of the boundary layer of the electric field in Fig. 7(d) is $(30 \sim 40)\Delta$, much broader than the earlier results with the smaller mass ratio. This width is much larger than the hybrid gyroradius, $(r_{be}r_{bi})^{1/2} \sim 3.5\Delta$ and is close to the beam ion gyroradius. The beam particles diffuse out as the shear velocity develops to form vortices and, hence, turbulent plasma diffusion.

Figure 8 shows the corresponding instantaneous electron and ion density profiles at $\omega_{pe}t = 500$. It is clear that the initial profiles are more or less maintained despite the fact that the beam ion gyrodiameter is comparable to the width of the beam. Note the measurement was performed at $\omega_{pe}t = 500$ which corresponds to $\omega_{ci}t = 10$. The results of the simulation suggest that the initial square beam profile relaxes toward an equilibrium profile during a few ion gyroperiods before large-scale convections wipe out the density profile via anomalous diffusion. Beam ions are confined not only by the magnetic field but also by the electrostatic potential provided by the electrons in this regime when $\omega_{pi} \gg \omega_{ci}$.

Figure 9 summarizes the dependence of the jump of the electric field in the boundary layer on the mass ratios using $\omega_{ce}/\omega_{pe} = 2$ and $n_o = n_b$. The electric field decreases slowly with the mass ratio saturating at a larger mass ratio. Note that as the mass ratio is increased, ω_{pi}/ω_{ci} increases to 5 for $m_i/m_e = 100$. Therefore for $m_i/m = 16$ and 100, the convection electric field approaches the value given by Eq. (6). The results of the simulations

lie between the values given by Eqs. (3) and (6). These results with larger mass ratios suggest that similar physics must hold at the realistic mass of the ions.

III. NEUTRAL INJECTION IN THE PRESENCE OF A ROTATIONAL TRANSFORM

We shall now consider the effects of a rotational transform on the convection electric field and hence anomalous plasma diffusion. The simulation model used in this calculation is sketched in Fig. 10. The model is similar to the previous two-dimensional model without a rotational transform,⁸ but this time the magnetic field has both B_y and B_z components as shown in Fig. 10. The neutral particles are injected across the magnetic field into the ambient plasma. The injected particles are randomly located along the beam path in a region defined by

$$0 \leq x \leq L_x$$
$$(3/8) L_y \leq y \leq (5/8) L_y . \quad (7)$$

These neutral particles are constantly injected into the ambient plasma at the injection velocity $\underline{V}_0 = V_0 \hat{x}$ and are assumed ionized as soon as they enter the region defined by Eq. (7). The injection rate is varied by changing the interval of the injections in the simulations. Note the length L_x corresponds to the ionization mean-free path for the neutral particles. Because of the presence of a rotational transform, polarization charges at the boundaries of the beam can be neutralized by the plasma flow along the magnetic field in addition to the mixing caused by the turbulent diffusion.

The charge density ρ_b at the boundary may be calculated from the balance

between the source created by the neutral injection and dissipation by plasma flow along magnetic field,

$$\frac{\partial \rho_b}{\partial t} = S - \frac{\rho_b}{\tau}, \quad (8)$$

where

$$S = \frac{en_b v_o}{L_x} \quad (9)$$

is the source due to injection and

$$\tau = \frac{\delta}{\alpha v_e} \frac{B_z}{B_y} \quad (10)$$

is the decay time of the charges determined by the electron thermal motion along the magnetic field. α is a numerical factor of the order of 1 which represents the effects of suprathermal electrons as well as electron acceleration by the polarization electric field. Note the decay time defined by Eq. (10) is valid only in a straight magnetic field. In the presence of curvature and gradient drifts of the beam ions such as in the toroidal magnetic field, electron motion along the magnetic field cannot neutralize the ion charges completely as the ions move out from the magnetic surface.

In steady state, we find

$$\rho_b = \tau S = \frac{en_b}{\alpha} \frac{B_z}{B_y} \frac{v_o}{v_e} \frac{\delta}{L_x} \quad (11)$$

for the charges in the boundary layer. ρ_b is proportional to $(B_z/B_y)\delta$ since it is the length of the field line between the two polarization charges. ρ_b

is proportional to $n_b V_0 / L_x$ since it is proportional to the density buildup due to beam injection.

In the following, results of the simulations with a rotational transform will be given in the presence of a constant injection of the beam.

Figures 11, 12, and 13 represent results of a simulation with a 64×64 grid, 256×256 ambient electrons and ions, $\omega_{ci}/\omega_{pi} = 1.4$, $m_i/m_e = 2$, $\lambda_{De}/\Delta = \lambda_{Di}/\Delta = 1$, $T_b/T = 25$, and $B_y/B_z = 0.01$. Beam particles are randomly injected into the area given by Eq. (7). For each injection, a group of 16×4 pairs of particles representing beam ions and electrons are injected over the 64×16 grid points at a time and the frequency of the injection is varied in order to change the beam power. In this example shown in Figs. 11, 12, and 13, the injection was repeated at every 5 simulation time steps with the time step of the simulation $\Delta t = 0.25 \omega_{pe}^{-1}$. This allows the injected beam density to increase by $16 \times 4 / (64 \times 16)$ at every $1.25 \omega_{pe}^{-1}$ time step, so that

$$S/e = \frac{1}{1.25} \times \frac{1}{16} \omega_{pe} / \Delta^2 = 0.05 \omega_{pe} / \Delta^2 .$$

The decay time of the charges by the motion of electrons along the magnetic field is given for $\delta = 16\Delta$, $v_e = \omega_{pe}\Delta$, and $B_z/B_y = 100$ to be

$$\tau = 16 \times 100 / \alpha \omega_{pe}^{-1} = 800 \omega_{pe}^{-1} \text{ for } \alpha = 2 ,$$

so that

$$\rho_b/e = S\tau/e = 40/\Delta^2 ,$$

which is much larger than the ambient density of $16/\Delta^2$. It is clear that in

this case, the injection is very strong and the dissipation is weak so that the rotational transform does not play a significant role. In such a case, it is clear that the polarization charges build up until they are dissipated by turbulent diffusion similar to the cases without a rotational transform.

Figures 11 and 12 confirm this conclusion, indicating the development of vortices and large-scale potential contours similar to the two-dimensional results given by Figs. 1 and 2 where no rotational transform was present. It is clear that large-scale vortices can persist even in the presence of a rotational transform since the electrons cannot completely neutralize the polarization charges at once. The residual charges can eventually cause macroscopic plasma convection when the associated convection electric field is above the thermal fluctuation.

Figure 13 shows the measured average electric field $\bar{E}_y$ with time. The electric field builds up at early times, $\omega_{pe}t = 25$ and 100 reaching $\Delta\bar{E}_y = 0.7$. This electric field is smaller than the two-dimensional results without a rotational transform as shown in Fig. 3 in which the beam density $\rho_b/e = 4/\Delta^2$ was used. As the charges build up, large-scale plasma convection rotates the neutral beam particles so that the spatial structure of $\bar{E}_y$ becomes more complicated.

The displacements of a set of test particles, $\langle (DX)^2 \rangle$ and $\langle (DY)^2 \rangle$, are shown for the ambient ions in Fig. 14. The diffusion coefficient may be estimated from the slope of the curve.⁸ For a short time, both $\langle (DX)^2 \rangle$ and $\langle (DY)^2 \rangle$ increase much faster than t indicating the coherent convections generated by the neutral injection. At later times, $\omega_{pe}t \geq 600$, turbulent mixing of the particle motion due to the convection electric field has established a diffusive state, so that $\langle (DX)^2 \rangle$ and $\langle (DY)^2 \rangle \sim t$, giving the measured diffusion coefficients $D_x = D_y = 1/\Delta^2\omega_{pe}$, roughly the same magnitude

as in the earlier simulations without a rotational transform.⁸ Note $\langle (DX)^2 \rangle$ decreases slightly for $\omega_{pe}t = 300 \sim 600$, corresponding to the rotation of particles riding on the vortex motion of the fluid elements. Such vortices interact nonlinearly when the turbulence develops fully giving rise to the irreversible diffusion process for particles.

In order to study the effects of the rotational transform, one can increase B_y/B_z in Eq. (11) so that the electrons can neutralize the ions at the boundary more rapidly. Figure 15 shows results of the simulation in which $B_y/B_z = 0.05$ is taken, while all the other parameters are kept the same. Since the electrons can neutralize ion charges much faster, the charge density at the boundary is reduced to

$$\rho_b/e = St/\alpha \approx 8/\Delta^2 \text{ for } \alpha = 2 ,$$

which is smaller than the ambient plasma density of $16/\Delta^2$. Coherent structure of the electrostatic potential contours is clearly visible in Fig. 15(a) but the amplitude of the potential is much smaller. Note also the size of the vortices remain as there is no coalescence to form large-scale vortices. One can compare this result with the low density beam injection in Fig. 5 where the $n_b/n_0 = 0.25$ case shows generation of a small convection electric field.

Test particle displacement, $\langle (DX)^2 \rangle$, shown in Fig. 15(b) indicates a much smaller displacement in this case compared to the result in Fig. 14 with a much smaller rotational transform. One can clearly identify that at later times, $\omega_{pe}t \geq 500$, the rate of increase of $\langle (DX)^2 \rangle$ decreases reaching a diffusion process after the initial laminar convection is dissipated.

With the further increase of the rotational transform to $B_y/B_z = 0.1$, much smaller diffusion is found as shown in Fig. 16. In this case, the charge

dissipation is so effective that only a small amount of net charges remain at the boundary giving

$$n_b/e = 4/\Delta^2$$

This amount of charge is much smaller than the ambient density. The diffusion coefficient after the initial convections is found to be, from Fig. 16,

$$D_x = \frac{\langle (DX)^2 \rangle}{2t} = 2 \times 10^{-3} \Delta^2 \omega_{pe}^2$$

which is three orders of magnitude smaller than the previous case with $B_y/B_z = 0.01$. In this case the time it takes for an electron to move across the neutral beam width δ and to neutralize an ion is given by, from Eq. (10),

$$\tau = \frac{\delta}{\alpha v_e} \frac{B_z}{B_y} \approx 80 \omega_{pe}^{-1}$$

for $\delta = 16\Delta$, $v_e = 1 \Delta \omega_{pe}$, $\alpha = 2$ and $B_y/B_z = 0.1$. This time should give us an estimate of the time scale for the dissipation of the charges. However, the behavior of $\langle (DX)^2 \rangle$ in Fig. 16 suggests that the convection persists much longer, $\omega_{pe}t = (300 \sim 400)$. Clearly, the estimate given by Eq. (10) gives the time scale much shorter than the simulation result. As the electrons stream toward the ions, electrons are accelerated and tend to overshoot ions because of their inertia. Beyond the dissipation time of $t \approx 400 \omega_{pe}^{-1}$, the slope of $\langle (DX)^2 \rangle$ with respect to time changes to a constant, which is a characteristic behavior of a diffusion process.

One can also reduce the effects of a convection electric field by reducing the injection rate of the neutral beam. According to Eq. (11), the

steady-state charge is directly proportional to S so that for a given value of a rotational transform, one can reduce the electric field and hence the anomalous diffusion by reducing S . Figure 17 shows results of a simulation using the same parameters as in the case shown in Figs. 11, 12, and 13 except for the injection rate which is reduced by a factor of 2, so that

$$S/e = 0.025 \omega_{pe}/\Delta^2$$

and

$$\rho_b/e = 20/\Delta^2.$$

This value is comparable to the ambient density of $n_0 = 16/\Delta^2$. One can expect development of large-scale plasma convections and, hence, anomalous diffusion as seen in Fig. 17 at $\omega_{pe}t = 500$. The familiar vortex pattern is clearly visible in the ambient ion (x,y) plot. The displacement of the ambient electrons with time, $\langle (DX)^2 \rangle$, shows a behavior similar to that in Fig. 14, but the magnitude of the displacement is reduced due to the weaker neutral injection. Note $\langle (DX)^2 \rangle$ shows an oscillating behavior near $\omega_{pe}t = 500$, suggesting the rotation of particles associated with the vortex motion of the plasma.

Figure 18 shows the results of the simulation where the neutral injection rate is decreased by another factor of two so that $S/e = 0.012 \omega_{pe}/\Delta^2$ while keeping all the other simulation parameters the same. We observe the development of coherent potential structures in Fig. 18(a) and the convection electric field in Fig. 18(b) generated by the neutral injection. Note the amplitude of the electric field is much smaller. In fact, the steady-state

charge density at the boundary is given by

$$\rho_b/e = 10/\Delta^2 ,$$

which is about 60% of the ambient density.

We should emphasize here that the charges built up by neutral injection need not be the same order of magnitude to the ambient density in order to cause anomalous plasma diffusion. The only requirement appears that the convection electric field must exceed the thermal fluctuation level of the electric field which is artificially high in plasma simulations compared to the noise level in a real plasma due to the use of a small number of simulation particles.

The last example is the case where $m_i/m_e = 100$, $B_y/B_z = 0.01$, and $S/e = 0.05 \omega_{pe}/\Delta^2$ to test if a similar plasma convection takes place for a plasma with a larger mass ratio. Since the steady-state charge in Eq. (11) is independent of the mass ratio, we expect that the convection electric field develops to the same extent as in the previous cases, except that the time scale for plasma convection is much slower. This is because the ions are now moving much slower due to their large mass, and the development of the polarization charges due to ion gyration becomes much slower.

Figures 19(a)-(d) show results of such a simulation using $m_i/m_e = 100$ at $\omega_{pet} = 1250$. While the development of macroscopic structures in the potential is slow, one can clearly see such formation both in the potential contours as well as in the electron positions in the (x,y) plane shown in (a) and (b). The corresponding averaged electric field E_y indicates the characteristic square profile inherent to neutral injection as shown in Fig. 19(c). The amplitude of this convection electric field is maintained for a long time

suggesting the charges generated by neutral injection are balanced with dissipation caused by plasma convection and by plasma flow along the magnetic field. The resultant diffusion of test ions in x , $\langle (DX)^2 \rangle$, is shown in Fig. 19(d). The diffusion grows much faster at a later phase of the simulation as the macroscopic convection develops, suggesting that a similar anomalous plasma diffusion can take place in a large mass ratio, real plasma.

IV. DISCUSSIONS

We have shown that the injection of energetic neutral particles into a confined plasma can lead to the development of a convection electric field caused by the polarization charges. In the absence of a rotational transform, such charges build up until anomalous diffusion dissipates them via turbulent mixing. In the presence of a rotational transform, polarization charges can be dissipated by the motion of electrons along the magnetic field. The resultant steady-state charges can be estimated by balancing the source of the charges via neutral injection with the dissipation as shown in Eq. (11). Whether or not such charges and, hence, the resultant electric field are important need careful consideration. Obviously, if such charges or the electric field are much smaller than the thermal fluctuations, they are not important. If they are above the thermal level, they are likely to create substantial anomaly in the turbulent plasma convection and plasma diffusion in a magnetic field.

Let us consider, as an example, a neutral beam injection experiment in a tokamak such as TFTR.⁷ Powerful neutral beam particles are injected across the toroidal magnetic field in order to heat the plasma into the thermonuclear temperature. The power of an injector is about 3 MW and the beam energy is about 90 keV, giving the injection velocity $V_0 = 3 \times 10^6$ m/sec. Beam density

at the injector can be estimated from the current and the size of the injector with its height $h = 0.3$ m and the width 0.3 m, giving the beam density $n_b = 10^{15}/\text{m}^3$. The beam density in the plasma must decrease because the beam particles spread along the toroidal magnetic field. Assuming there are four injectors along the torus with the major radius $R_0 = 2.5$ m, the beam density becomes $n_b = 8 \times 10^{13}/\text{m}^3$.

The charge density due to neutral injection can be estimated from Eq. (11) so that

$$\rho_b = en_b \frac{B_z}{B_y} \frac{V_o}{v_e} \frac{\delta}{L_x} .$$

For TFTR, $B_z/B_y \approx 5$, $V_o/v_e \approx 0.1$ for a 5-keV electron temperature. L_x is the mean-free path of the beam ionization and is of the order of the minor radius, $L_x \approx 1$ m, so that we find

$$\rho_b \approx 2 \times 10^{-6} \text{ Q/m}^3 .$$

The vertical electric field due to neutral injection would be

$$E_v = \frac{\rho_b}{\epsilon_0} w \approx 2.7 \times 10^5 w \text{ V/m} ,$$

where w is the width of the boundary layer. If we assume w is given by the beam ion gyroradius, then $w \approx 0.5$ cm. In this case, the vertical electric field is found to be $E_v \approx 1.4 \times 10^3$ V/m. If one uses Eq. (6) to estimate the convection electric field with the ambient plasma density $n_0 \approx 4 \times 10^{13} \text{ cm}^{-3}$, we find $E_v = 7.5 \times 10^3$ V/m. Note that the electric field is large in magnitude compared with, say, the Pfirsch-Schlüter electric field which is -

15 mV/m in TFTR.⁹ While the neutral-beam-heated TFTR plasma is not in the Pfirsch-Schlüter regime, the low temperature edge plasma may be in the collisional regime. Anomalous particle diffusion near the edge may be greatly enhanced by the presence of a convection electric field caused by neutral injections.

Note the estimate of the electric field based on Eq. (11) must be modified in a number of ways in order to apply it to a toroidal geometry. First, as the electrons move along the magnetic field to neutralize ions, beam ions move across the magnetic field due to yB drift so that they do not stay on the same magnetic surface. The distance of this vertical drift is a fraction of one cm for the TFTR parameters during the electron transit time. This effect should enhance the electric field. On the other hand, as the electrons move along field lines, they spread over the magnetic surface. Since the number of the injectors along the torus is finite, the convection electric field introduces toroidal asymmetry which may be very important for plasma transport. Preliminary results of numerical simulations in a toroidal geometry indicate a development of asymmetric electrostatic potential and, hence, plasma convection associated with neutral injection.¹¹ Details of the results of the simulations in a toroidal geometry will be reported elsewhere.

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FIGURE CAPTIONS

Fig. 1 Results of a two-dimensional simulation without a rotational transform. Beam ion locations in the (x,y) plane are shown at (a) $\omega_{pe}t = 0$, (b) $\omega_{pe}t = 50$, (c) $\omega_{pe}t = 100$ and (d) $\omega_{pe}t = 150$. Note the ion locations develop vortex structure in time.

Fig. 2 Electrostatic potential contours are shown at (a) $\omega_{pe}t = 50$, (b) $\omega_{pe}t = 100$, and (c) $\omega_{pe}t = 150$. Note the laminar structure develops into large-scale vortices in time. The amplitudes of the contours are (a) $-0.25 \leq e\phi/T \leq 0.25$, (b) $-0.35 \leq e\phi/T \leq 0.35$, (c) $-0.31 \leq e\phi/T \leq 0.34$.

Fig. 3 Measured convection electric field at four different time steps. The initial location of the neutral beam is indicated by a hatched area. Note the profile of the electric field spreads as the plasma convection and hence anomalous diffusion develop.

Fig. 4 Results of seven simulations varying the magnetic field strength. Note for strong magnetic field, $\omega_{ci}/\omega_{pi} \geq 1$, $\Delta\bar{E}_y \sim B^{-1}$ in agreement with Eqs. (3) and (4). $\Delta\bar{E}_y \sim B$ for $\omega_{ci}/\omega_{pi} < 1$ in agreement with Eq. (6).

Fig. 5 Results of four simulations varying the beam density. At low beam density, $\Delta\bar{E}_y \sim n_b$ but for higher beam density, $n_b/n_o \geq 1$, $\Delta\bar{E}_y$ increases much slower.

Fig. 6 Results of the simulations varying beam injection energy. Note the convection electric field ΔE_y is roughly proportional to $T_b^{1/2}$.

Fig. 7 Results of the simulations using $m_i/m_e = 100$. Locations of the electrons (a), ions (b), the electrostatic potential contours (c), and (d) the convection electric field $\bar{E}_y$ at $\omega_{pe}t = 500$.

Fig. 8 Electron and ion densities at $\omega_{pe}t = 500$ for the same run as in Fig. 7. Note the sharp density gradient is well maintained.

Fig. 9 Results of the simulations varying the mass ratio. Note the electric field $\bar{E}_y$ decreases slowly as the mass ratio is increased.

Fig. 10 Sketch of the simulation model in the presence of a rotational transform and a steady-state neutral injection. Neutral particles are assumed ionized upon entering the plasma. Note L_x corresponds to the ionization mean-free path.

Fig. 11 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta^2$. Locations of a set of ions are shown at (a) $\omega_{pe}t = 100$, (b) $\omega_{pe}t = 200$, (c) $\omega_{pe}t = 300$, and (d) $\omega_{pe}t = 400$. Note the development of vortices similar to the case without a rotational transform.

Fig. 12 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta^2$. Electrostatic potential contours are shown at four different time steps given in Fig. 11. The amplitude of the

potential is (a) $-0.065 \leq e\phi/T \leq 0.064$ at $\omega_{pe}t = 100$, (b) $-0.068 \leq e\phi/T \leq 0.12$ at $\omega_{pe}t = 200$, (c) $-0.071 \leq e\phi/T \leq 0.066$ at $\omega_{pe}t = 300$, and (d) $-0.081 \leq e\phi/T \leq 0.08$ at $\omega_{pe}t = 400$.

Fig. 13 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta^2$. Electrostatic electric field due to neutral injection is shown at four different times.

Fig. 14 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta^2$. Displacements, $\langle (Dx)^2 \rangle$ and $\langle (Dy)^2 \rangle$, for a set of ambient ions are shown to measure the anomalous diffusion coefficient due to neutral injection.

Fig. 15 Results of the simulation using $B_y/B_z = 0.05$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta$. The amplitude of the electrostatic potential contour shown in (a) is much smaller, $-0.7 \times 10^{-2} \leq e\phi/T \leq 0.69 \times 10^{-2}$ and the corresponding ion displacement $\langle (Dx)^2 \rangle$ is shown in (b).

Fig. 16 Results of the simulation using $B_y/B_z = 0.1$, $n_b/n_o = 1/256$, and $S/e = 0.05 \omega_{pe}/\Delta^2$. Note the displacement of the ions became much smaller leading to a smaller diffusion coefficient.

Fig. 17 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_o = 1/256$, and $S/e = 0.025 \omega_{pe}/\Delta^2$. Locations of the set of ions shown in (a) clearly indicate the development of turbulent convections. Displacement of the ions shown in (b) indicates an anomalous diffusion.

Fig. 18 Results of the simulation using $B_y/B_z = 0.01$, $n_n/n_0 = 1/256$, and $S/e = 0.0125 \omega_{pe}/\Delta^2$. Electrostatic potential contours in (a) where amplitudes vary $-0.033 \leq e\phi/T \leq 0.022$ and the convection electric field E_y in (b).

Fig. 19 Results of the simulation using $B_y/B_z = 0.01$, $n_b/n_0 = 1/236$, $S/e = 0.05 \omega_{pe}/\Delta^2$ and $m_i/m_e = 100$ at $\omega_{pe}t = 1250$. Shown are (a) the electrostatic potential contours whose amplitudes vary $-0.14 \leq e\phi/T \leq 0.092$, (b) locations of a set of electrons, (c) convection electric field due to neutral injection, and (d) the displacement of ions across the magnetic field.

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Fig. 1

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Fig. 2

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Fig. 3

Fig. 3

Fig. 5

Fig. 6

Fig. 7

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Fig. 9

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Fig. 10

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Fig. 11

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Fig. 12

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Fig. 13

Fig. 14

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Fig. 15

Fig. 16

#88T0008

Fig. 17

#88T0020

Fig. 18

Fig. 19

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