CONFINEMENT ASYMMETRY AND TRAPPED PARTICLE EFFECTS ON RADIAL TRANSPORT IN CHARGED PLASMAS

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Weak axial variations in $B(z)$ or $\phi(z)$ in "axisymmetric" plasma traps cause a fraction of the particles to be trapped axially, with a velocity-space separatrix between trapped and passing populations. The trapped and passing particles experience different dynamics in response to a variety of θ-asymmetries in the $\mathbf{E}\times\mathbf{B}$ rotating plasma, so a discontinuity in the velocity-space distribution $f(\mathbf{v})$ tends to form at the separatrix. Collisional scatterings thus cause large fluxes as they smooth the distribution in a boundary layer near the separatrix. In essence, this separatrix dissipation damps the AC or DC longitudinal currents induced by plasma waves or confinement field asymmetries. This trapped-particle-mediated damping and "neoclassical" particle transport often dominates in cylindrical pure electron plasmas, and may be important in other nominally symmetric open systems.

I. INTRODUCTION

The main goal of our current experiments is to elucidate the influence of confinement field imperfections on dissipation and transport processes in magnetically confined plasmas. In general, this is an overwhelming task, and to make progress we have intentionally chosen the simplest possible case: pure electron plasmas confined in the "axisymmetric" cylindrical Penning-Malmberg trap. In these plasmas the transport and dissipation processes are not complicated by the mutual interaction between different sign charges.

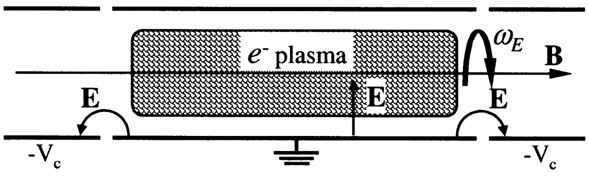

Figure 1: Penning-Malmberg trap with cylindrical electrodes.

We find that the dominant mode damping and particle transport is often due to weak axial variations in the confinement fields $B(z)$ or $\varphi(z)$ which axially trap a small fraction of the electrons. Moreover, the measured mode damping rates are found to be directly proportional to the measured particle transport rates, since they are both caused by the same collisional dissipation at the trapped particle separatrix. This has provided interpretation for many prior experiments which observed "anomalous" damping or transport. The most surprising aspect of these results is that even small trapped particle populations (1%) can dominate the bulk plasma transport. Thus, even weak magnetic mirrors ($\delta B/B \sim 10^{-3}$) or small confinement potential variations ($\delta v/v \sim 10^{-2}$) are observed to provide the dominant transport in these nominally symmetric open systems.

A schematic diagram for the electron trap is shown in Fig. 1. There is a nearly uniform magnetic field, $B\hat{z}$, with weak axial variations $\delta B/B \sim 0.001$. The conducting cylindrical wall is divided axially into several sections, with the two end sections held at a negative potential. The electron plasma resides in the central section, with axial confinement provided by the negative end voltages, and radial confinement provided by the magnetic field. The gyro-radius and the Debye shielding length are small compared to the plasma radius, so the cross-field motion may be described by $\mathbf{E}\times\mathbf{B}$ drift dynamics. To receive wave fluctuations and to manipulate by plasma by applied potentials, several sections of the central trap are also divided into isolated θ-sectors. The detailed description of apparatus and experimental techniques can be found elsewhere [1, 2].

Referring again to Fig. 1, one can see that axial confinement is guaranteed simply by turning the voltage on the end electrodes sufficiently high. It is the radial confinement (provided by the axisymmetric magnetic field) that one must worry about. However, there is a very powerful constraint on radial transport based on conservation of the total canonical angular momentum P_θ. Like-particle interactions, however complex and nonlinear, can not cause the single sign of charge plasma to expand radially, because the total canonical angular momentum must be conserved due to cylindrical symmetry [3]. The total canonical angular momentum P_θ is the sum of a mechanical and a vector-potential contribution, as

$$P_\theta = \sum_j \left[m_e v_{\theta j} r_j + \frac{eB_z}{2c}\left(R_w^2 - r_j^2\right) \right] \approx \frac{eB}{2c}\left[R_w^2 - \langle r^2 \rangle\right];$$

here r_j is the distance of particle j from the axis, $v_{\theta j}$ is its velocity in the θ-direction, m_e is its mass (let's consider electrons), and the summation is over all particles. For kiloGauss fields and elecronVolt energies, the mechanical contribution (first term) is several orders less than the electromagnetic part, and can be safely neglected. If there are no θ-dependent external couplings applying torques, then P_θ = constant and $\langle r^2 \rangle$ = constant; the mean square radius of the plasma is conserved, i.e. there is no bulk expansion.

θ-asymmetries in the confinement fields, however, enable radial expansion. We define the expansion rate as the rate of $\dot{P}_\theta / P_\theta$, i.e.,

$$\nu_P \equiv \frac{1}{\langle r_j^2 \rangle} \frac{\partial \langle r_j^2 \rangle}{\partial t}.$$

In practice, confinement times of hours are routinely obtained [4, 5], allowing some unique research opportunities. Note that this simple result is not realized for (quasi) neutral plasmas. The constraint $\sum_j r_j^2$ = constant is replaced by $\sum_j e_j r_j^2$ = constant; so an electron and ion can move radially together and still preserve P_θ. This is exactly what happens in electron-ion collisional processes, both classical and neoclassical transport, as well as in many instabilities.

II. OUTLINE OF ASYMMETRY-INDUCED DISSIPATIVE PROCESSES

However, small θ-*asymmetries* (field errors) always exist in the electric or magnetic confinement fields, and they apply torques which change the angular momentum of the plasma, causing the mean square radius of the plasma to expand slowly.

Figure 2 shows a conceptual outline of the plasma response to these asymmetries in terms of DC and AC *asymmetry-induced currents.* These currents are an integral part of rotating charged plasma equilibrium in the presence of conducting walls of a finite radius. Due to Coulomb interaction with asymmetric (m_θ, $k_z \neq 0$) image charges at the wall some plasma particles tend to accumulate in particular (θ, z)-domains. As these particles $\mathbf{E} \times \mathbf{B}$ rotate around the axis (at frequency ω_E), they flow gradually along magnetic field lines into the next attractive domain, and so on. Thus, in the case of static asymmetries the closed loops of DC asymmetry-induced currents sustain the rotating plasma equilibrium. Addition of a "diocotron" mode displacement (see Fig. 2) modulates these currents at the mode frequency ω_D, and these AC currents are readily detected. In this case they were first called "sloshing currents" [6].

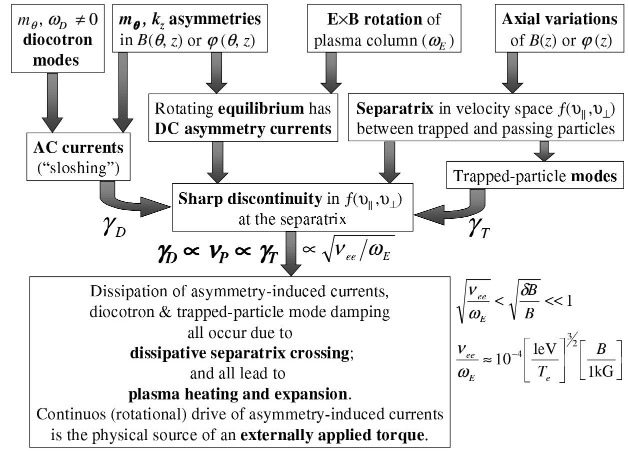

Figure 2: Conceptual outline of plasma response to confinement asymmetries.

However, these currents alone can not impose any self-consistence torque on a single-species plasma. There is a need in strong dissipation mechanism ("drag force") breaking the second adiabatic invariant and allowing 2D potential (electrostatic) energy to flow to 3D thermal energy of plasma particles.

One of the most important features that distinguish real traps from their theoretical idealization is the presence at some finite level of either magnetic field ripples

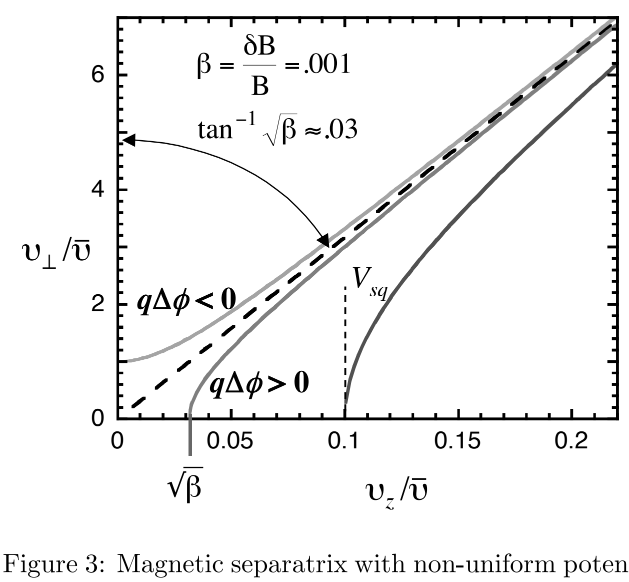

Figure 3: Magnetic separatrix with non-uniform potentials along field lines.

$\delta B(z)$ or space potential variations $\varphi(z)$ along the magnetic field lines. This *axial inhomogeneity* marks some area in the velocity space (see Fig. 3) as locally trapped particles, while the rest of it are the passing particles. These locally trapped particles do not participate in the asymmetry-induced DC flows or mode-induced sloshing current dynamics.

It is noteworthy that even if the fraction of locally trapped particles may looks negligibly small, the drag they impose on passing particles is not. In essence, the electron plasma is not a "single-species" plasma anymore, and there is a drag between the trapped and passing "species." This drag is determined by the diffusive exchange across the separatrix cone in velocity space. Surprisingly, this drag is roughly *constant* at small $\delta B/B$ when the width of the diffusive layer in velocity space, $\bar{v}(\nu_{ee}/\omega_E)^{1/2}$, is less than the typical width of the trapped particle area, $\bar{v}(\delta B/B)^{1/2}$. Thus, in nearly collisionless plasmas with $\nu_{ee}/\omega_E \equiv \varepsilon(B,T) \ll 1$, it is readily place the equivalent limit on the saturation level of magnetic ripple influence, $\delta B/B \geq \varepsilon$.

III. SOME EXPERIMENTAL RESULTS

Electric trapping by axial variations of $\varphi(z)$ at the wall creates trapped and passing populations, with the trapped particles predominanting at larger radii. This trapping enables the novel "trapped particle diocotron modes" [1], which have served as a unique and well controlled diagnostic tool. These trapped particle modes are readily exited from the wall sectors, and the exited modes then ring down exponentially with the damping rate γ_T unambiguously obtained. What is important here is that these modes posses exactly the same separatrix dissipation mechanism as the DC asymmetry-induced currents, causing γ_T to be directly proportional to the bulk transport rate ν_P.

These modes consist of trapped particles on either side of an electrostatic barrier which execute $\mathbf{E}\times\mathbf{B}$ drift oscillations that are 180° out of phase, while passing particles move along field lines (like sloshing currents) to Debye shield the potential perturbations developed by trapped particles. The main damping of these modes is due to separatrix diffusion, and an analytical treatment is being developed [7]. Since particles on either side of the separatrix are involved in completely different types of motion, there is a discontinuity in the perturbed particle distribution function. As a result, electron-electron collisions produce a large flux of particles across the separatrix. The continual trapping and detrapping of particles results in radial transport of particles and mode damping, as it readily observed in computer simulations [8]. These dissipative separatrix crossing can also be induced by resonant RF fields [9], allowing the process to be investigated in detail.

The damping rate γ_T has a strong and complicated dependence on the (non-equilibrium) plasma parameters characterizing the separatrix [7]. The bulk plasma transport arises from the very same dissipation mechanism of asymmetry-induced currents (see Fig. 2), so it has the same dependence on plasma parameters. Thus, the ratio ν_P/γ_T shows stunningly simple and robust scalings for all other plasma and trap parameters [2, 10]. Indeed, experiments over a wide range of parameters have confirmed that the tilt-asymmetry-induced transport is directly proportional to the trapped particle mode damping rate γ_T, when there is a significant fraction of electrically trapped particles to measure the dynamics of this mode. This transport differs markedly from the traditional perspective of single particle resonant transport theory [11]. We emphasize that the effect is dominant in low-collisionality plasmas even though very few particles are trapped, because this separatrix dissipation scales with collisionality like $(\nu_{ee}/\omega_E)^{1/2}$, rather than $(\nu_{ee}/\omega_E)^1$.

Similarly, the nominally stable electron plasma diocotron modes ($k_z = 0$, $m_\theta = 1, 2, ...$) exhibit strong exponential damping when the confinement fields have weak θ-asymmetries and z-variations. It is known that the confinement asymmetries cause these ordinary diocotron modes to excite "sloshing currents" [6], which may be treated as a variation of the general class of asymmetry-induced currents. Hence, they are subject to the same damping due to collisional dissipation at the velocity space separatrix between axially trapped and passing particles (see Fig. 2). Indeed, we find that the damping rate γ_D of the diocotron mode with frequency ω_D exhibits robust scaling (see Fig. 4) of $\gamma_D/\omega_D \approx (\nu_P/\omega_x)\ \alpha^2$, where the term with magnetic field tilt angle α represents the fraction of the diocotron wave energy carried by the sloshing particles. The dimensional factor ω_x has magnitude $\omega_x \approx 2\pi\, sec^{-1}$, and is independent of the plasma and trap parameters; but it is not yet understood theoretically. This scaling is observed for a wide range of plasma parameters, for various asymmetry types and strengths, and for both collisional and stimulated separatrix crossing. Taking into account that $\nu_P \propto \alpha^2/B^{-3}$ [2, 10] we obtain $\gamma_D \propto \alpha^4 B^{-3}$. This scaling has been verified in our experiments independently on the γ_D/ν_P scaling, and its strong dependence on the magnetic field and its asymmetry explains the anomalous diocotron mode decay observed in prior experiments at low magnetic fields.

IV. CONCLUSIONS

Recent experiments and theory on pure electron plasmas have shown how containment field asymmetries cause bulk plasma transport due to a collisional coupling between asymmetry-driven axial currents and lo-

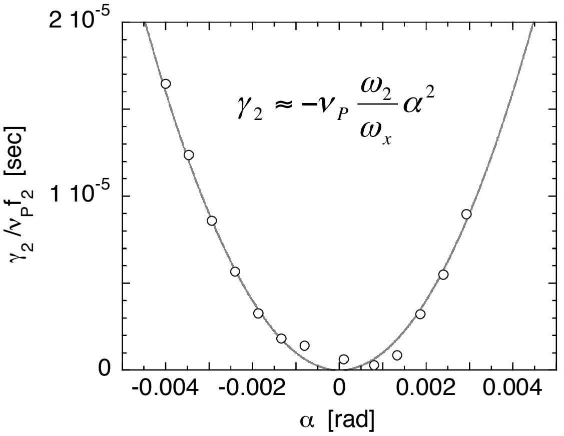

Figure 4: Measured damping rate γ_D of the $m_\theta = 2$ diocotron mode normalized by the measured transport rate ν_P versus applied magnetic tile asymmetry α.

cally trapped particles. The axial currents are sloshing particles driven by the equilibrium plasma rotation (or by mode induced plasma dynamics) in response to confinement field asymmetries. The trapped particles arise due to exceedingly small azimuthally symmetric ripples in the magnetic or electric confinement fields; surprisingly, even weak mirrors create a separatrix in velocity space with a substantial diffusive flow of plasma particles across its surface. This separatrix crossing breaks the longitudinal adiabatic invariant, allowing 2D potential (electrostatic) energy to flow to 3D kinetics, and thus enabling external asymmetries to generate strong transport. The effect is dominant in low-collisionality plasmas even though very few particles are trapped, because this separatrix dissipation scales with collisionality like $(\nu_{ee}/\omega_E)^{1/2}$, rather than as $(\nu_{ee}/\omega_E)^1$. This loss mechanism appears to be dominant in a variety of pure electron plasma containment regimes; and it may also be relevant to quasi-neutral plasma transport since comparable and even higher level of charge imbalance (resulting in plasma potential of order 10^1–10^3 V) is commonplace in mirror traps.

This collisional scattering across the separatrix is the main dissipation mechanism of these asymmetry-induced currents; for both equilibrium currents and mode-driven currents. Experiments over a wide range of parameters clearly show that the asymmetry-induced transport and the observed mode damping rates are directly proportional to the dissipation rate of the asymmetry-induced currents. The scalings of transport and mode damping with all plasma parameters (magnetic field, plasma density and temperature, fraction of trapped particles, asymmetry strength) have been measured, with unrivaled correspondence to this simple model.

ACKNOWLEDGMENTS

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