Mitigation of Drift Instabilities by a Small Radial Flux of Charged Particles through the Landau-Resonant Layer

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Abstract. Experiments and theory on electron columns have characterized a novel *algebraic* damping of diocotron-like modes, caused by a small flux of halo particles through the resonant layer [1]. The damping rate is proportional to the flux. We have also investigated the diocotron instability which occurs when a small fraction of ions is transiting the electron plasma [2]. Dissimilar bounce-averaged **E**×**B** drift dynamics of the ions and electrons polarizes the diocotron mode density perturbations, developing instability analogous to the classical flute instability. The *exponential* growth rate is proportional to the fractional neutralization and to the phase separation between electrons and ions in the wave perturbation. Here, we have shown that the flux-driven *algebraic* damping eliminates the ion-induced *exponential* instability of diocotron-like modes. Physically, the electric field from the resonant particles in the low-density halo acts back on the dense plasma core, causing **E**×**B** drift motion of the core back down toward the trap axis, resulting in a damping of the mode.

FLUX-DRIVEN ALGEBRAIC DAMPING OF DIOCOTRON MODES

Nonneutral plasmas confined in Penning-Malmberg (PM) traps have been, and continue to be, the subject of comprehensive studies, driven in a large part by a broad range of applications. Diocotron modes in a PM trap are the **E**×**B** drift orbits of the plasma arising due to the electric field from the image charge induced at the surface of the confining walls (electrodes). They can be described as surface modes propagating azimuthally around the core of nonneutral plasma columns, or as the orbit of a column displaced off-axis by a distance D. The plasma column consists of a high-density core ($n_c \sim 10^7 cm^{-3}$) surrounded a relatively low-density halo ($n_h \sim 0.01 n_c$) of outward drifting particles. At the critical radius in the halo, the azimuthal **E**×**B** drift rotation velocity of the halo matches the phase velocity of the mode potential, and their resonant interaction gives rise to (first exponential in time) Landau damping [3]. For many years, it was thought that there can be no wave-particle resonance for the first azimuthal ($m_\theta = 1$) diocotron mode, since its resonant radius is at the wall ($r_{res} = R_w$) and the unperturbed density is zero at the wall.

However, recent experiments have observed a novel algebraic damping of the $m_\theta = 1$ diocotron mode when a weak transport process sweeps a low density halo of particles out from a dense central core to the wall [1, 4]. This new flux-driven damping mechanism is also observed for diocotron waves with higher azimuthal wave numbers $m_\theta = 2, 3, \ldots$ The algebraic damping begins at a time t_* when the halo reaches the resonant radius of the mode $r_{res}(m_\theta)$, where $\omega_m = m_\theta \omega_{E\times B}(r_{res})$. Here $\omega_m \equiv 2\pi f_m$ is the mode frequency, $\omega_{E\times B}(r)$ is the **E**×**B** drift rotation frequency, and $D_m(t)$ is the mode amplitude. Then the damping proceeds as

$$D_m(t_* + \Delta t) = D_m(t_*) - \gamma \Delta t, \quad (1)$$

where the *algebraic* damping rate $\gamma(m_\theta)$ is proportional to the flux of halo particles

$$F \equiv -(1/N) dN/dt \quad (2)$$

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through the resonant layer $2\pi r_{res}$, i.e.,

$$\gamma(m_\theta) = \beta(m_\theta)F, \text{ where } \beta(m_\theta) \sim 1. \tag{3}$$

This gives

$$dD_m/dt = -\gamma, \tag{4}$$

which is quite different from an exponential decrease.

Figure 1 shows the cross section of an electron plasma column that has been displaced off the trap axis through the excitation of a $m_\theta = 1$ (displacement) diocotron mode. The displacement has magnitude D in the direction of $\bar{\theta} = 0$. The gray lines are equipotential contours as seen in the mode frame. In this frame the **E**×**B** drift flow is along the equipotential curves. The black-to-yellow shaded region represents the relatively high density plasma core. In this region the equipotential curves are essentially displaced circles, until the resonant region near the wall.

Near the left edge are the "cat's eye" orbits, which show the equipotential contours for particles that are trapped in the wave trough. In order to make the "cat's eye" orbits easier to spot in Fig. 1, the ratio of the displacement to the wall radius (i.e., $d \equiv D/R_w$) was taken to represent the largest of experimental values, i.e., $d = 0.1$. The green dotted-dashed equipotential contour in Fig.1 is a critical path just inside the (presumptive) blue dashed scrape–off layer (SOL) at $\bar{\theta} = 0$. The SOL is at least as thick as a cyclotron radius, but not modelled in any detail. When transport moves a particle through this critical contour, the particle hits the SOL and is absorbed by the wall before returning to $\bar{\theta} = 0$. The red solid curve in Fig. 1 shows the trajectory of such a particle.

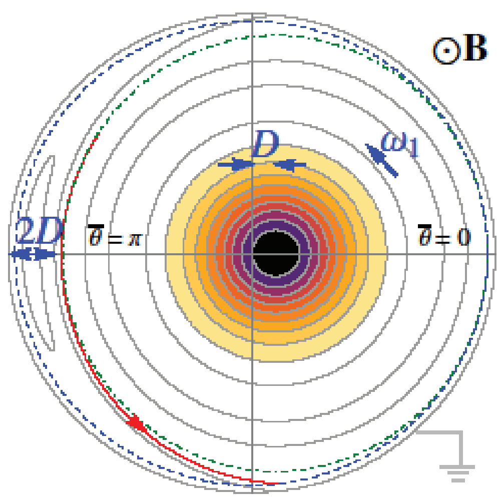

FIGURE 1. Instantaneous cross section of an electron plasma column in the diocotron displacement $\vec{D}$. The black-to-orange filled region is the dense plasma core. The gray lines are the equipotential contours in the mode frame. The green dotted-dashed curve is resonance contour. The red solid curve is a resonant particle trajectory. The blue dashed curve is the scrape-off layer.

As particles are swept across the resonant layer, there is an up-down asymmetry in the distribution of resonant particles and corresponding image-charges. This asymmetry creates a component of electric field which is transverse to the displacement $\vec{D}$ and causes the **E**×**B** drift motion of the dense plasma core back toward the trap axis, that is, a damping of the mode. A much more detailed description of the experiment and theoretical considerations can be found in Refs. [1, 4–6], correspondingly. Physically, the electric field from the resonant particles in the halo acts back causing **E**×**B** drift motion of the plasma core, and this motion produces a slow rate of change of the diocotron wave amplitude $d(t)$ [5].

In our experiments we have quantitatively measured this novel algebraic damping of the first two azimuthal diocotron modes [1, 4]. In principle, this flux-driven damping would also apply for $m_\theta = 3$ and higher modes, but their resonant radii are much closer to the plasma core radius R_c by $r_{res}(m) = R_c/\sqrt{1-(1/m)(1-R_c^{2m}/R_w^{2m})}$, and such modes typically already suffer large ordinary Landau damping.

ION-INDUCED INSTABILITY OF DIOCOTRON MODES

Instabilities of diocotron modes are commonly observed when small ion fractions are introduced to pure electron plasmas. For many years, it was thought that these instabilities are driven by the different drift rotation frequencies caused by inertial effects (mass difference). However, in past experiments [2, 7] we have shown that an ion contamination of pure electron plasmas leads to the ion-induced diocotron (IID) instability, determined by the differences in z-bounce-averaged $\omega_{E\times B}(r)$ for electrons and ions with different z-bounce regions (as in "nested" or double-well traps configuration). Quite often, an ion fraction is continuously produced in warm(ish) electron plasma experiments, and special arrangements need to be made to prevent those ions from being trapped.

Broadly speaking, the dissimilar bounce-averaged **E**×**B** drift dynamics of the ions and electrons polarizes the diocotron mode density perturbations, developing instability analogous to the classical curvature-driven flute instability. The resulting exponential growth shows $dD/dt = \Gamma D$, with growth rate Γ proportional to the fractional neutralization (N_i/N_e) and to the phase separation $\in_\varphi$ between electrons and ions in the wave perturbation, i.e.,

$$\Gamma_m = \left(\frac{N_i}{N_e}\right) \in_\varphi f_m, \tag{5}$$

where $\in_\varphi \leq 1$ (see [2]).

Figure 2 shows the measured growth rate of the $m_\theta = 1$ IID instability as a linear function of the background pressure. Here the primary ions are coming along magnetic field lines as a result of ionization of a residual gas by the 30 eV electron beam continuously emitted by the electron injection filament. Thus the acquired fractional neutralization is proportional to the background pressure P. As one can easily estimate, a typical ion fraction formed at these ultra-high vacuum conditions is indeed very small, namely $N_i/N_e \sim \Gamma/f_1 \sim 10^{-5}$ (here, at magnetic field $B = 12\ kG$ we have $f_1(B) \approx 2.2\ kHz$). The evident "offset" at the zero pressure asymptote is due to ionization of neutrals absorbed by the entrance (injection) grid.

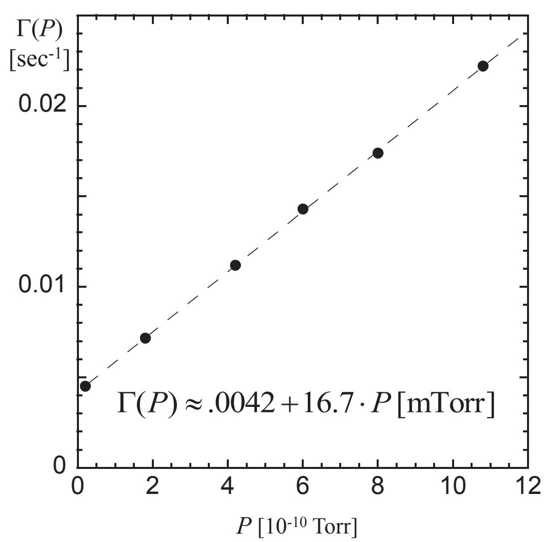

FIGURE 2. Exponential growth rates Γ of the ion-induced diocotron (IID) instability as a function of the background pressure P.

FLUX-DRIVEN MITIGATION OF THE ION-INDUCED DIOCOTRON INSTABILITY

In Fig. 3(a) the solid blue line shows an example of the IID instability growing exponentially from the noise level amplitude of $d \sim 10^{-4}$ over 3 decades in 300 *sec* confinement time. Here, the exponential growth rate is $\Gamma/f_1 \approx 9.7 \cdot 10^{-6}$, which is close to its maximum value in Fig. 2. For amplitudes $d > 0.1$ the mode behavior becomes highly nonlinear. In this particular evolution the electron temperature is kept above $T \geq 0.5\ eV$ by continuously applying a non-resonant wiggle heating.

When the wiggle heating is turned off, cyclotron cooling of electrons (with time constant $\tau_c(12\ kG) \approx 3\ sec$) drives plasma temperature down to its room (wall) values $T \approx 0.03\ eV$. For ill-understood reasons, a low density halo then starts to leak out of the core, rather than the whole core expanding slightly. In about 30 *sec* after the cooling, the front of the halo reaches the wall radius (equal to the Landau-resonance radius for the $m_\theta = 1$ diocotron mode), and the flux-driven algebraic damping starts to contribute to the mode amplitude evolution, as $d(\Delta t) = d_* \exp(\Gamma\Delta t) - \gamma\Delta t$. If one has $> \Gamma(P) \cdot d_*$, then the instability is suppressed (mitigated) down to the noise level. Figure 3(a) shows several IID instability evolutions with different halo flux "turn-on" times followed by the fast *algebraic* damping of the mode.

However, if the instability growth rate Γ and/or the acquired amplitude $d(t)$ are already big enough, so that the *algebraic* damping rate $< \Gamma(\mathrm{P}) \cdot d_*$, then the flux of charged particles through the Landau-resonant layer leads only to a moderation of the instability growth rate Γ, as shown for comparison in Fig. 3(b). By its very nature the *algebraic* damping of exponential instabilities is most effective at low wave amplitudes $d(t)$, so this new mitigation mechanism can be highly effective at preventing the exponential ion-induced instability, even for seemingly small particle fluxes through the resonant layer. Any *algebraic* damping wins over exponential instabilities from the noise.

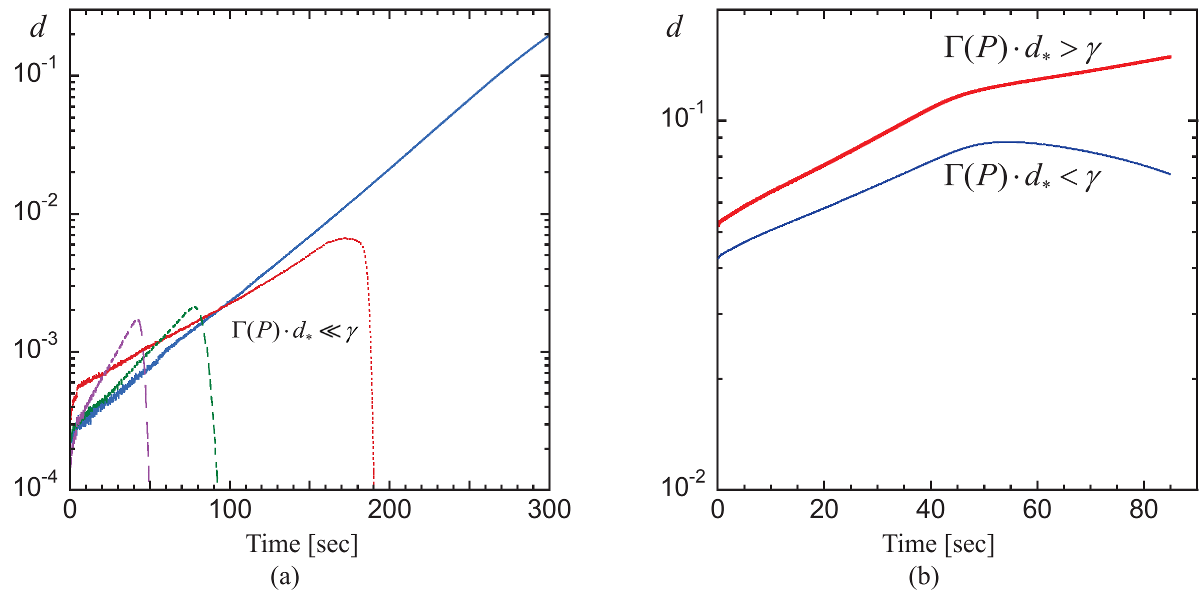

FIGURE 3. Flux-driven mitigation of the IID instability:

(a) The solid (blue) line shows exponential growth of the $m_\theta = 1$ diocotron mode from the noise level for over 3 decades in amplitude when no halo particles flux formed. The dotted (red), short-dashed (green), and long-dashed (purple) lines show the IID instability evolutions with different growth rates $\Gamma(P)$ and 160 sec, 60 sec, and 20 sec halo initiation times, respectively.

(b) Examples of the $m_\theta = 1$ IID instability evolutions near the mitigation threshold $\Gamma(P) \cdot d_* \approx \gamma$. Flux-driven damping for $t \geq 45\ sec$ lessens the instability, or causes only a moderate damping.

CONCLUSIONS

In summary, the linear-in-time *algebraic* damping of both $m_\theta = 1$ and $m_\theta = 2$ diocotron modes has been demonstrated in our experiments. This damping begins when an outward flux of **E**×**B** drifting halo particles reaches the Landau-resonant radius $r_{res}(m_\theta)$, and the damping rate γ is directly proportional to the flux value. This flux-driven damping effectively eliminates the ion-induced instability of diocotron modes, and one may suggest that a similar flux-driven damping might be used to mitigate the classical flute instabilities in cylindrical (*quasi*-)neutral plasmas confined in non-uniform magnetic fields [8–10].

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REFERENCES

[1] A.A. Kabantsev, C.Y. Chim, T.M. O'Neil, and C.F. Driscoll, Phys. Rev. Letters **112**, 115003-5 (2014).
[2] A.A. Kabantsev and C.F. Driscoll, Trans. Fusion Sc. and Tech. **51**, 96-99 (2007).
[3] D.A. Schecter, D.H.E. Dubin, A.C. Cass, C.F. Driscoll, I.M. Lansky, and T.M. O'Neil, Phys. Fluids **12**, 2397-2412 (2000).
[4] A.A. Kabantsev, T.M. O'Neil, and C.F. Driscoll, “Algebraic Damping of Diocotron Waves by a Flux of Particles through the Wave Resonant Layer,” in *Non-Neutral Plasma Physics VIII*, AIP Conference Proceedings **1521**, edited by X. Sarasola *et al*. (American Institute of Physics, Melville, NY, 2013), pp. 35-42.
[5] C.Y. Chim and T.M. O'Neil, Physics of Plasmas **23**, 050801-5 (2016).
[6] C.Y. Chim and T.M. O'Neil, Physics of Plasmas **23**, 072113-18 (2016).
[7] A.A. Kabantsev and C.F. Driscoll, “Diocotron Instabilities in an Electron Column Induced by a Small Fraction of Transient Positive Ions,” in *Non-Neutral Plasma Physics V*, AIP Conference Proceedings **692**, edited by M. Shauer *et al*. (American Institute of Physics, Melville, NY, 2003), pp. 61-68.
[8] I. Be’ery, O. Seemann, G. Goldstein, A. Fisher, and A. Ron, Plasma Phys. Control. Fusion **56**, 025006 (2014).
[9] F. Brochard, G. Bonhomme, E. Gravier, S. Oldenburger, and M. Philipp, Phys. Plasmas **13**, 052509-9 (2006).
[10] W. Horton, Reviews of Modern Physics **71**, 735-778 (1999).