Observations of an Ion-Driven Instability in Non-Neutral Plasmas Confined on Magnetic Surfaces

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The first detailed experimental study of an instability driven by the presence of a finite ion fraction in an electron-rich non-neutral plasma confined on magnetic surfaces is presented. The instability has a poloidal mode number $m = 1$, implying that the parallel force balance of the electron fluid is broken and that the instability involves rotation of the entire plasma, equivalent to ion-resonant instabilities in Penning traps and toroidal field traps. The mode appears when the ion density exceeds approximately 10% of the electron density. The measured frequency decreases with increasing magnetic field strength, and increases with increasing radial electric field, showing that the instability is linked to the $E \times B$ flow of the electron plasma. The frequency does not, however, scale exactly with E/B, and it depends on the ion species that is introduced, implying that the instability consists of interacting perturbations of ions and electrons.

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Introduction.—Non-neutral plasmas confined on magnetic surfaces have only recently begun to be studied [1,2]. Theory predicts that pure electron plasmas confined on magnetic surfaces are stable to low frequency ($\omega \ll \omega_p$) oscillations. This is predicted because parallel force balance pertains to a whole magnetic surface, causing the plasma to be in a minimum energy state [3,4]. Any macroscopic motion of the plasma out of the magnetic surface will violate electron force balance along the magnetic field [5,6], except if the rotational transform of the magnetic surface is a low order rational and the perturbation has a corresponding mode structure. This is in contrast to non-neutral plasmas confined on Penning or pure-toroidal field traps [7–9], which are in a maximum energy state [10], and where parallel streaming cannot stabilize an azimuthal mode. Although they are in a maximum energy state, Penning and pure-toroidal equilibria are stable in the absence of dissipation [11,12] and have excellent confinement properties due to angular momentum conservation [13]. Despite the stabilizing effect of magnetic surfaces, instabilities have now been observed in non-neutral plasmas confined in two stellarators, the Compact Helical System [14], and the Columbia Non-neutral Torus (CNT). In CNT, stable plasmas can be created at low neutral pressures [15], but the plasma is unstable when ion content is sufficiently high. This Letter presents and discusses detailed measurements of this instability in CNT, including the dependence on magnetic field strength, ion species, plasma potential, ion fraction, and the poloidal mode number.

The CNT experiment.—CNT is a low-aspect-ratio stellarator [16], made from four circular, planar coils, dedicated to the study of non-neutral plasmas. The rotational transform of the magnetic surfaces ranges from $0.12 < \iota < 0.23$. Steady state plasmas are created by injecting electrons from an internal, negatively biased filament held on the magnetic axis. For these plasmas, the central plasma potential, ϕ_{plasma}, is essentially equal to the negative bias voltage of the emitter. Electrostatic perturbations inside the plasma are detected by measuring the ac currents on floating emissive probes that are connected to a high voltage capacitor, the emitter, or a set of external capacitive probes. Unless specifically stated, a single ceramic rod holds the emitter and the emissive probes in the thin cross section of the plasma. The density, temperature, and potential profiles of stable pure electron plasmas have been measured using particle flux probes [15,17]. CNT pure electron plasmas are characterized by $\lambda_D/\langle a\rangle \approx 0.1$, with $\langle a\rangle = 15$ cm being the average poloidal radius of the plasma. For a $\phi_{\text{plasma}} = -200$ V plasma, $n_e \approx 7.5 \times 10^{11}\ \text{m}^{-3}$ and $T_e = 4$ eV in the bulk of the plasma and rises to ≈ 20 eV near the edge [15].

Steady state ion fraction.—In a toroidal electron plasma without an ion loss mechanism, ions will accumulate until the plasma either disperses or is neutralized. However, in CNT a ceramic rod inside the plasma acts as a sink for ions. The experiments reported here involve plasmas in a steady state; electron losses are balanced by emission from the axial emitter, while ionization is balanced by ions becoming neutralized when they strike the ceramic rod. The ion density in CNT has been measured directly with an ion saturation probe and is in good agreement with a simple model of the above-mentioned ion density balance [18]. The ion trajectories are being modeled numerically, and results from this effort will be reported in a future publication.

Basic observations.—Figure 1 shows the measured fluctuations for three different neutral pressures, corresponding to robustly stable, marginally unstable, and robustly unstable plasmas, respectively. When the mode is robustly unstable, the oscillations settle into a steady state with an approximately constant frequency and amplitude.

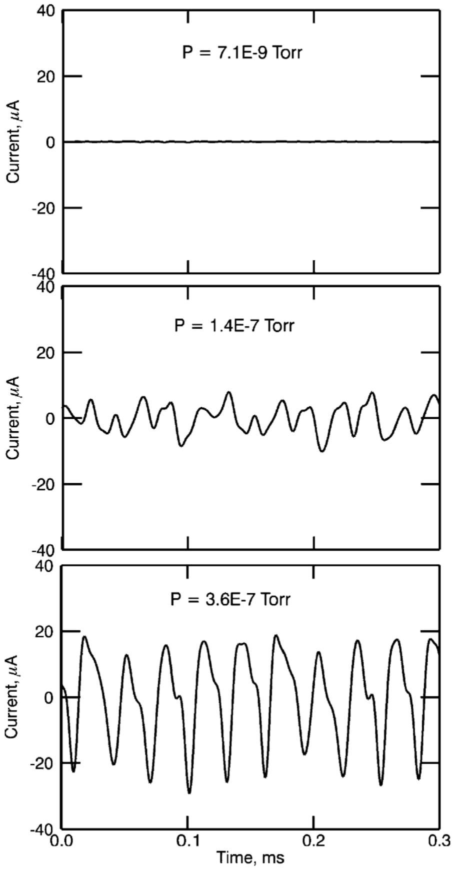

FIG. 1. The fluctuation level in the core plasma is shown for three levels of ion content, corresponding to stable, marginally unstable, and robustly unstable conditions. Results shown are from a −200 Volt, 0.02 Tesla plasma, with N_2 gas.

Spatial structure.—The spatial structure of this mode has been studied using four capacitive (image charge) probes placed poloidally around the $\phi = 90°$ toroidal cross section of the plasma. Figure 2 shows the measured phase difference between the image charge measurements, with probe 1 as the reference. Also shown are the predictions for $m = 1$ and $m = 2$ poloidal modes, showing that the mode clearly has $m = 1$. The phase predictions for $m = 1$ and $m = 2$ are calculated assuming a circular cross sectional shape of the mode, a reasonable approximation at $\phi = 90°$ where these measurements are made. The mode is moving in the direction of the $E \times B$ rotation of the electron plasma, as expected.

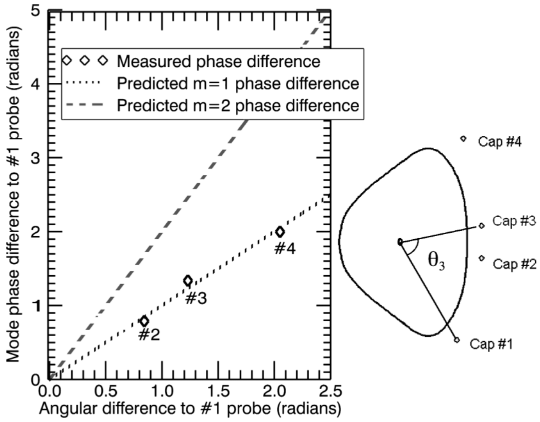

FIG. 2. (Left) The measured phase of the instability on probes 2–4 relative to the phase on probe 1, plotted as a function of the θ difference between these probes and probe 1. The vertex of the angle θ is the magnetic axis. Results shown are from a $\phi_{\text{plasma}} = -300$ V, $B = 0.1$ T plasma, with $p_n = 2.2 \times 10^{-7}$ Torr of N_2 ($n_i/n_e \approx 0.2$). (Right) The location of the external capacitors, along with the $\phi = 90°$ cross section of the last closed magnetic flux surface and the magnetic axis.

Dependence on neutral pressure.—Figure 3 shows the root mean square (rms) of the signal on an emissive probe as well as the average emission current from the emitter, both plotted vs the background neutral pressure. Since these plasmas are in steady state, the average emission current equals the average electron loss rate and is inversely proportional to the electron confinement time. For $p_n < 1.4 \times 10^{-7}$ Torr, where p_n is the neutral pressure, the plasma is stable and the electron loss rate displays an offset linear relationship with neutral pressure. The scaling of confinement in this stable regime is described in Ref. [19]. For $p_n > 1.4 \times 10^{-7}$ Torr, where the ion fraction is estimated to be $n_i/n_e > 0.1$ [18], the plasma is unstable, and the scaling of emission current with neutral pressure is faster than linear. Thus, the ion-driven instability degrades confinement, although not dramatically.

The threshold for instability is $n_i/n_e \approx 0.1$ for ${N_2}^+$ ions at magnetic field strengths of 0.02 T and 0.10 T, and for ${H_2}^+$ ions at $B = 0.02$ T.

The presence of additional ceramic rods inside the plasma has a stabilizing effect. At $B = 0.02$ T and $\phi_{\text{plasma}} = -200$ V, the neutral pressure threshold for instability changed from 1.2×10^{-7} Torr to 2.8×10^{-7} Torr when a second rod was at a symmetric location in the plasma. Because insulating rods absorb ions [18] and lower the ion fraction at a given neutral pressure, this

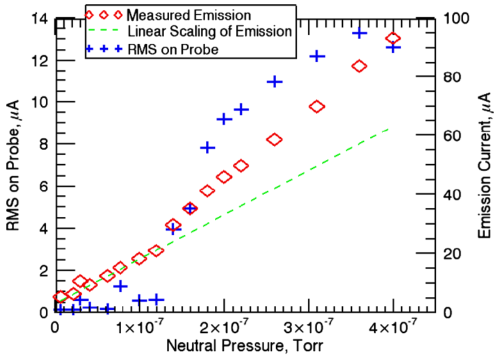

FIG. 3 (color online). Measurements of average emission current and the rms of the signal on the emissive probe as a function of neutral pressure of N_2 at $B = 0.02$ T, $\phi_{\text{plasma}} = -200$ V.

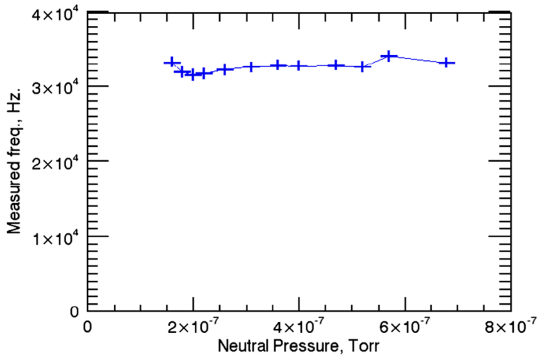

FIG. 4 (color online). Frequency of instability vs neutral pressure of N_2, at $B = 0.02$ T, and $\phi_{\text{plasma}} = -200$ V.

proves that it is the presence of a finite ion fraction, not the neutrals, that is destabilizing the plasma.

Figure 4 shows the dependence of the mode frequency on neutral pressure. The negligible dependence on neutral pressure shows that the frequency does not depend on the ion fraction, n_i/n_e. Because these experiments have a set emitter bias, increasing the ion fraction does not alter the overall voltage drop across the plasma; neither the $E \times B$ flow velocities nor the frequencies of ion motion change.

Dependence on magnetic field, ϕ_{plasma}, and ion species.—The frequency of the oscillation clearly depends on the ionic species, being larger for the lighter species (H_2) than for the heavier species (N_2), as shown in Fig. 5. The frequency decreases with B. For H_2, the frequency scales approximately as $1/B$, except at the very lowest magnetic field strengths, $B \leq 0.02$ T, where the observed frequency is lower than what is expected from a $1/B$ scaling. For N_2, a similar trend is seen, but the deviation from $1/B$ scaling occurs for $B \leq 0.04$ T, i.e., the $1/B$ scaling does not fit the observed frequencies as well. This is consistent with the fact that $H_2{}^+$ ions move closer to the $E \times B$ frequency than $N_2{}^+$ ions (see discussion).

Figure 6 shows the steady state amplitude of the oscillation vs B-field strength for H_2, N_2, and Kr. With H_2, the amplitude decreases rapidly as B is increased; the oscillations are very small for $B > 0.06$ T, indicating near stabilization of the oscillation. For the other species, there is a weak tendency toward lower amplitudes at the highest B fields, but the oscillation amplitude is still large even at $B = 0.1$ T. $H_2{}^+$ ions at 0.1 Tesla have $r_L \ll \langle a \rangle$, and move close to the $E \times B$ velocity.

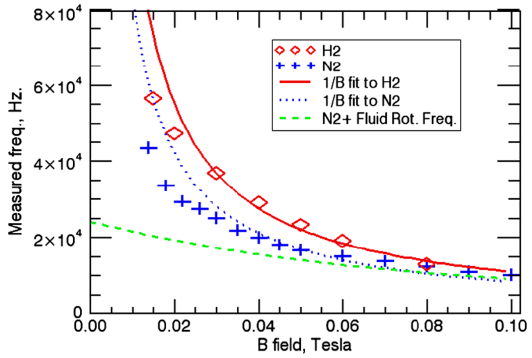

FIG. 5 (color online). The frequency of the instability vs magnetic field strength, for H_2 and N_2 at $\phi_{\text{plasma}} = -200$ V.

The frequency of the instability increases linearly with ϕ_{plasma}, as expected for a rotating mode that scales with the $E \times B/B^2$ rotation.

Discussion.—The $m = 1$ poloidal mode structure is the same as that of ion-driven instabilities in Penning and pure-toroidal traps [8,9,20]. This is a poloidal rotational motion of the entire plasma column. The $m = 1$ mode does not correspond to a rational surface in CNT, implying that the parallel force balance of the electron fluid is broken. A global instability that does not resonate with a rational surface has never before been observed in a stellarator.

The $E \times B$ rotation frequencies, calculated from the numerically reconstructed equilibria of CNT [21] range from $\omega_{E\times B} = 1.0 - 2.5 \times 10^4$ Hz across the magnetic surfaces, at $\phi_{\text{plasma}} = -200$ V, $B = 0.08$ T. A low density oscillation with azimuthal mode number l in a cylindrical pure electron plasma has the frequency $\omega_l = \omega_{E\times B}[l - 1 + (R_p/R_c)^{2l}]$ [22]; for high l this is $\omega_l \approx l\omega_{E\times B}$. The lowest frequency oscillation that resonates with a rational magnetic surface will be at $\iota = 1/7$, with a frequency of at least 7.0×10^4 Hz at 0.08 T. This is much higher than the measured frequencies of the instability at $B = 0.08$ T, and provides further evidence that the mode is not resonant with a rational magnetic surface. The measured mode frequency is equal to or less than the $E \times B$ rotation frequency, consistent with an $m = 1$ mode structure, as measured with the capacitive probes.

The frequency scaling with B provides insight into the fundamental physics of this instability. In a cylindrical approximation the ion fluid rotation frequency in a non-neutral ion-electron plasma is given by [22]

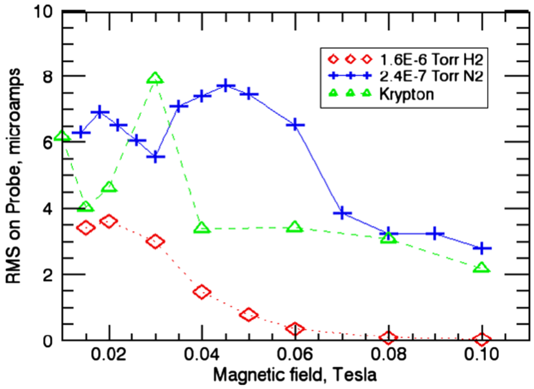

FIG. 6 (color online). The rms of the signal on an emissive probe in the plasma vs B, for H_2, N_2, and Kr gas at $\phi_{\text{plasma}} = 200$ V.

$$\omega_i = \frac{-\omega_{\mathrm{ci}}}{2}\left\{1 - \sqrt{1 + \frac{4\omega_{E\times B}}{\omega_{\mathrm{ci}}}}\right\}.$$

At high B and low M_i, this frequency approaches the $E \times B$ rotation frequency, and at low B or high M_i it approaches a finite frequency, $\omega_i = \sqrt{n_e e^2(1 - n_i/n_e)/(2\epsilon_0 M_i)}$. A plot of the ion fluid rotation frequency for $N_2{}^+$ and typical electron densities in CNT is shown in Fig. 5. The electrons, being much less massive, have a fluid velocity very close to the $E \times B$ velocity even at the lowest B fields used here, which scales as $1/B$. As seen in Fig. 5, the ion fluid ω_i, electron fluid (following a $1/B$ scaling), and the measured mode frequency are all quite similar at large B. At low B, however, the ion rotation frequency is much lower than the electron rotation frequency, and the observed mode frequency is in between the two. This frequency dependence, along with the dependence on ion mass and the lack of dependence on n_i/n_e, resembles the theoretically predicted frequency dependence of the ion resonance instability in a cylindrical plasma, with ions that are permanently trapped [23,24]. Like the theory described in [23,24], the mode discussed here consists of interacting perturbations of electrons and ions.

There are important differences between the ion-driven instability discussed here and the ones observed in Penning and pure-toroidal traps. In Penning or Penning double well traps, the ion-resonant mode has a finite growth rate at essentially any neutral pressure, and the mode grows steadily until the plasma disperses [20,25]. In CNT and in full toroidal traps non-neutral plasmas are stable for low ion fractions $n_i/n_e < 0.1$ [8,15]. In a full toroidal trap, however, the mode rapidly grows until the entire plasma disperses [8,24], while in CNT its amplitude saturates at a level low enough that the confinement of the plasma is not strongly affected; see Fig. 3. The observed saturation of the instability at a low level in CNT is similar to what is observed in high pressure quasineutral plasmas that are driven to MHD instability in a stellarator [26].

In CNT, the time for an untrapped electron at the high density part of an $m = 1$, $n = 0$ perturbation to stream along the magnetic field at the thermal velocity to the low density part of the perturbation is ≈ 5 μs, faster than the period of an oscillation or the calculated $E \times B$ frequency. Thus the measured density perturbations should have adequate time to damp out via parallel streaming, and it is unlikely that parallel plasma oscillations can couple to the instability. On the other hand, numerical simulations have shown that the fraction of electrons on trapped orbits is $\epsilon \approx 0.65$ in CNT. It is possible that the violation of electron parallel force balance reported in this Letter comes about because of the large fraction of these trapped electrons.

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