Antenna excitation of drift wave in a toroidal plasma

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In a magnetized toroidal plasma, an antenna tunable in vertical wave number is used to excite density perturbations. Coherent detection is performed by means of Langmuir probes to directly determine both the wave vector and the plasma response induced by the antenna. Comparison between the theoretical density response predicted by the generalized Hasegawa-Wakatani model, and the experimentally determined density response enables us the identification of one peak of the plasma response as a drift wave. © 2007 American Institute of Physics. [DOI: 10.1063/1.2784464]

I. INTRODUCTION

In magnetically confined plasmas, drift wave turbulence is generally believed to be responsible for anomalous cross-field energy and particle transport, reducing the energy confinement. Improvements in such confinement, below the level determined purely by collisional transport, may be achieved through an active control of drift wave and further understanding of its dynamics.

Basic experimental investigations aimed at controlling drift waves are performed in both high and low temperature plasmas. These investigations started with modes suppression in plasmas using Langmuir probes,1,2 and developed into a more sophisticated approach based on the launching of drift waves using array antennas.3–8 Using the latter approach, Schröder5 and co-workers have investigated the reduction of the drift wave turbulence by driving preselected modes at the expense of the broadband density fluctuations spectrum. The experiments were performed in a linearly magnetized device using a large array antenna, which coupled nonlinearly to drift waves and strongly modified the plasma dynamics. Both experiment and simulations have shown that the spatio-temporal driver signal has a strong influence on the dynamics of the pre-existing drift wave. Such influence tend to overshadow the underlying drift wave dynamics.

In this work, we report drift wave linear excitation in a toroidal plasma using an electrostatic antenna. Understanding the underlying physics in the linear properties of drift mode excitation is a necessary step into the investigation of nonlinear phenomena (e.g., modulational instability, three-wave coupling). Such understanding could open the way for potential drift wave control scenarios. A necessary condition for the investigation in a linear regime of an antenna excitation is its minimal perturbation to both the background profile and the plasma dynamics. To the best of our knowledge, this regime has not been considered by any previous work.

Electrostatic antenna excitation in the plasma described below is performed in the region of maximum density gradient in the low B-field side (LFS) where both interchange and drift modes coexist. A key feature of this antenna is its tunability in both frequency and vertical wave number \( k_z \). This feature enables excitation in the plasma frame by compensating for the \( \mathbf{E} \times \mathbf{B} \) drift and by selecting the range of vertical wave number proposed to the plasma dynamics. Using an extensive coverage of Langmuir probes in the plasma cross section, direct measurements of both the wave vector \( \mathbf{k} \) and the density response induced by the antenna excitation are obtained. Given these measured quantities, one can compare the predicted theoretical plasma response with the observed density response in the plasma frame. A model of the driven system based on a generalized Hasegawa-Wakatani9 is used to identify the linearly excited modes.

The remainder of this paper is organized as follows: Sec. II briefly describes the experimental setup, introduces the tunable antenna as the exciter and the arrays of Langmuir probes as the detectors. Section III presents the density fluctuation spectra with and without an antenna drive demonstrating the nonperturbative nature of the excitation. In addition, an analysis of the spectral features of the density fluctuations is shown. Section IV describes the coherent detection technique and the experimental results. In Sec. V, we solve the linearized Hasegawa-Wakatani equations in the limits strictly given by the experimental measurements. The comparison of the experimental results with the model and a discussion are given in Sec. VI, followed by a summary in Sec. VII.

II. EXPERIMENTAL APPARATUS

The experiments are performed on a magnetized plasma contained in the toroidal device TORPEX.10 The major radius is \( R=1 \) m; the minor radius is \( r=20 \) cm. Typically argon, hydrogen, and helium plasma are produced using microwaves at 2.45 GHz injected from the LFS.11 In the present experiment, hydrogen plasmas are produced under a neutral background pressure of \( 6 \times 10^{-5} \) mbar with a microwave power of 400 W during 1200 ms, a vertical magnetic field of \( B_z=1.2 \) mT, and a toroidal magnetic field of \( B_\phi=76 \) mT on axis.12 The electron and ion temperatures are...
4 eV and ≤0.1 eV, respectively, for electron density of the order of 10¹⁶ m⁻³.

Arrays of Langmuir probes (e.g., HEXTIP, Ref. 13) covering the torus cross section are used to characterize the plasma in terms of 2D profiles of temperature, density, and potential (plasma and floating). The root-mean-square (rms) level of fluctuations and time-averaged density profiles are shown in Fig. 1(a). Figures 1(b) and 1(c) represent the 2D profiles of the plasma potential and \( \mathbf{E} \times \mathbf{B} \) velocity, respectively.

Low frequency oscillations are generated using an antenna [Fig. 1(d)] that consists of four identical rectangular metallic electrodes \( (d_1 \times d_2, d_1 = 30 \text{ mm along } B_\phi, d_2 = 8 \text{ mm along } B_z, \text{ and thickness } 0.9 \text{ mm}) \) distributed along the vertical direction. The vertical separation between adjacent electrodes is \( D = 20 \text{ mm.} \) Each electrode is driven independently with a sinusoidal potential up to 25 V peak-peak whose frequency is smaller than \( \omega_{ci} = eB/m_i. \) The relative phase shift between adjacent electrodes \( (\Delta \varphi_{12} = \Delta \varphi_{13} = \Delta \varphi_{14}) \) can be varied from \(-\pi\) to \( \pi, \) which results in the tunability of the vertical wave number \( k_z = \Delta \varphi/D \{ -\pi/D, \pi/D \}. \)

The relatively small sized antenna is mounted on a movable system that allows for radial positioning. The electrode dimensions render the antenna interaction with the perpendicular magnetic field negligible; the density profile and related fluctuations remain unchanged with and without antenna inserted in the plasma. Hence, this antenna does not act as a limiter.

The detection of the plasma response is carried out using three sets of Langmuir probe arrays biased in the ion saturation regime. The first two sets of probes are toroidally separated by about 60° and 150° with respect to the antenna plates. The third array (HEXTIP) is located about 20° from the antenna. These three sets of probes are used to simultaneously sample the toroidal, radial, and vertical directions.

III. INTRINSIC FLUCTUATIONS

Using a spectral analysis, we compare the intrinsic density fluctuations to density fluctuations when the antenna is driven. Furthermore, we characterize the naturally occurring modes. Figure 2 shows the density fluctuations power spectra with and without drive applied to the antenna obtained with Langmuir probes positioned at \( r_o = 66 \text{ mm and } z = 0; \) this position corresponds to the cross-sectional location of the antenna. Two frequency peaks (4 kHz and 12 kHz) are observed, with the dominant spectral feature being 12 kHz. In simple magnetized toroidal plasmas, both drift and interchange modes coexist in the LFS as shown in Ref. 14. These two modes can be distinguished through their distinct parallel wave number. The lower frequency peak has already been characterized as drift mode in Refs. 16 and 17, where a finite parallel wave number of 0.5 rad/m is reported. As for the dominant peak, its frequency corresponds to the induced \( \mathbf{E} \times \mathbf{B} \) frequency in the LFS \( \left[ V_{\mathbf{E} \times \mathbf{B}} \left( B^2 + B_z^2 \right) / R B_z \right] \sim 12 \text{ kHz} \). This suggests that its frequency in the plasma frame is zero, which is reminiscent of an interchange mode. Further characterization of this mode is obtained by explicitly measuring its parallel wave number.

Figure 3(a) shows measurements of the parallel wave number of the dominant mode. These measurements are performed using the phase shifts between two toroidally separated Langmuir probes (see details in Appendix A of Ref. 18). Here, the measured wave number component along the vector joining the two Langmuir probes is given by

\[
\hat{k}_p = \Delta \varphi/D \{ -\pi/D, \pi/D \}.
\]

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** (Color online) Experimental 2D profiles and experimental setup. (a) Typical time-averaged density profile \( (T_e = 5 \text{ eV}) \) measured (when the antenna is immersed in the plasma) using the HEXTIP array of probes covering the whole cross section. In addition, the antenna plates position is indicated in dashed lines. The gray contour lines represent contours at 25% (outermost), 50%, and 75% of the maximum root-mean-square density fluctuation. (b) The plasma potential profile. (c) The measured \( V_{d-E} \) profile. In (b) and (c) the antenna plates are illustrated with dashed lines. (d) Experimental setup. A driving signal \( \cos(a t + \phi) \) is applied simultaneously on A, B, C, and D. HFS is the high field side.

![Figure 2](https://example.com/figure2.png)

**FIG. 2.** (Color online) Density fluctuations frequency power spectra (in a linear scale) with and without drive applied to the antenna. These frequency spectra are recorded at \( r_o = 6.6 \text{ cm and } z = 0 \) and are normalized to the rms fluctuations.
$k^m_\parallel (z)=k_i+e$, where $\Delta \phi$ is the toroidal angular separation between the probes, and $e=k_i(z/B_0-B_0/\Delta z/R \Delta \phi)$ is the correction due to the helical topology of the magnetic field lines. For $z=z_0$ corresponding to the magnetic field line pitch, $k^m_\parallel (z_0)$ is effectively $k_i$. Figure 3(b) enables the determination of the magnetic field line pitch $z_0$ by maximizing the cross-coherence between two toroidally separated probes. This corresponding maximum is illustrated with the vertical dotted lines in both Figs. 3(a) and 3(b). In Fig. 3(a), the parallel wavenumber giving the maximum coherence is zero within experimental uncertainty, which suggests that the dominant peak is a flute mode and more specifically an interchange mode whose real frequency in the plasma frame is also zero. Hence, the interchange Doppler-shifted frequency in the laboratory frame is given by the induced $\mathbf{E} \times \mathbf{B}$ frequency.

In both cases (with and without antenna drive) in Fig. 2, the spectra are identical, demonstrating that the antenna-drive perturbation to the background plasma dynamics is minimal. In addition, measurements have shown that two modes with distinct parallel dynamics (drift and interchange) coexist in the LFS. The identical spectra and therefore the nonperturbative nature of the antenna drive makes the detection of antenna-driven density fluctuations difficult using conventional spectral power analysis. This calls for the use of coherent detection, described in Sec. IV.

**IV. METHOD AND EXPERIMENTAL RESULTS**

**A. Synchronous detection: Description**

In our experiment the characteristic scale length for spatial fluctuations is typically of the order of the ions sound Larmor radius $r_\parallel = (\omega_0^2/\Omega_i)^{1/2}$. Since $r_\parallel/\mathcal{L}_n \ll 1$ [where $\mathcal{L}_n=\left(1/\mathcal{n} \partial/n\right)^{-1}/r_\parallel$ is the radial density gradient scale length], and assuming that the characteristic amplitude of potential fluctuations is $(T_e/\mathcal{n})r_\parallel/\mathcal{L}_n$, waves have small amplitudes compared to the equilibrium potential. Waves with amplitudes that are small compared to the background amplitude fluctuations are routinely detected using the coherent detection technique.19–21

A coherently detected signal is obtained by multiplying the signal under study with the in-phase (real) and quadrature (imaginary, shifted $\pi/2$) components of a reference signal of frequency $f_0$. The magnitude $\mathcal{R}$ and phase $\Psi$ of this detected signal are then determined from these two components. The detected signal is typically referred to as the response function of the system under examination. Applied to density measurements from Langmuir probes, the magnitude of the response function becomes the density response and is referred to as $n$ in Sec. V. In this experiment, the density response is obtained as a function of the imposed $k_i=\Delta \varphi/D$ on the antenna. The sign convention for the remainder of this work is that a negative $\Delta \varphi$ corresponds to an upward vertical propagation (i.e., $\mathbf{E} \times \mathbf{B}$ direction when $\mathbf{B} > 0$). The amplitude density response, resolved in $k_z$, is obtained with a signal-to-noise ratio of 10 dB. The noise corresponds to the background fluctuations at the frequency of the applied signal when no drive is applied to the antenna. Figure 4 shows an example of the density response to the antenna induced perturbation measured using HEXTIP. Both in-phase and quadrature components are represented over the whole poloidal cross-section. A characterization of the observed wave-like antenna excitation is sought in terms of the plasma dispersion.

**B. Experimental results**

The coherently detected signals $\mathcal{R}$ and $\Psi$ are measured as functions of $\Delta \varphi$, $\omega_0$ (the drive frequency), and the position $(r,z)$. Through a frequency scan, we maximize the response function magnitude $\mathcal{R}$. The frequency in the laboratory frame at this maximum is $\omega_0/(2\pi)=12$ kHz that also corresponds to the induced $\mathbf{E} \times \mathbf{B}$ frequency on the LFS set by the magnetic field line pitch and the $\mathbf{E} \times \mathbf{B}$ velocity. Adjusting the antenna drive frequency to the induced $\mathbf{E} \times \mathbf{B}$ frequency enables the antenna excitation to be performed in the plasma reference frame.

The maximum density response is obtained when the excitation of the antenna is performed at a radial position $(r_0=66 \text{ mm})$ corresponding to the maximum density gradient.
This suggests that the source of the excitation is localized at the maximum density gradient. Further characterization of the density response function is provided using the coherently detected phase shift from which a wave vector is determined. Both density response and wave vector measurements are the necessary ingredients for a complete characterization, in terms of the plasma dynamics, of the antenna induced excitation.

1. Wave vs disturbances

As a first test of the nature of the antenna-induced excitation in Fig. 4, we perform measurements of the density response resolved in $k_z$ as a function of the toroidal magnetic field $B_\phi$ direction (sign reversal). In toroidal plasmas a sign reversal of the toroidal field results in a change of direction of the vertical plasma dynamics. In particular, reversing the sign of $B_\phi$ leads to the reversal of the $E \times B$ velocity, and of all the diamagnetic drifts. This reversal enables a vertical wave number selection as the only wave number compatible with the plasma dynamics yields a maximum density response.

Figure 5 shows the density response as a function of the imposed vertical wave number for both signs of the toroidal magnetic field. The shaded areas are centered around peaks of narrower width of the density response obtained with the same magnitude of the imposed wave number $|k_z|=|k_0|$. More specifically, the peak of the density response corresponding to $k_0 \sim -50$ rad/m when $B_\phi > 0$ is the peak of density response for $k_0 \sim +50$ rad/m when $B_\phi$ is reversed. This systematic correspondence between both signs of the toroidal field and vertical wave number suggests that either the antenna couples to an electrostatic wave in the vertical direction with nonzero intrinsic frequency, or to an antenna-induced nonpropagating disturbance vertically convected away by the $E \times B$ flow. In the latter situation, a passively convected disturbance would produce a maximum density response centered around $|k_z|$. This illustrates the systematic correspondence between field reversal and sign reversal of the imposed vertical wave number. The vertical axis is the magnitude of the density response function measured at $r_0=66$ mm and $z=0$. 

![FIG. 4. (Color online) Example of density response measured using HEXTIP (array of Langmuir probes illustrated with crosses). The real part of the plasma response function is shown in the left panel and its imaginary part in the right panel. In both plots, the antenna plates location is represented by thickened dashed lines. The signals are normalized with respect to the maximum signal detected during the vertical wave number scan. The imposed wave number $k_z$ on the antenna is 31 rad/m.](image1)

![FIG. 5. Density response function as a function of the toroidal magnetic field sign. The top (bottom) panel shows the response function for the case of $B_{\text{tor}}>0$ ($B_{\text{tor}}<0$). The shaded areas track the peaks of the density response centered around $|k_z|$. This illustrates the systematic correspondence between field reversal and sign reversal of the imposed vertical wave number. The vertical axis is the magnitude of the density response function measured at $r_0=66$ mm and $z=0$.](image2)
density response corresponding to the zero frequency \( \omega_0 - V_E B_z / B_z = 0 \) in the plasma frame, and would not be affected by any imposed vertical wave number. Since this density response did not result as described in the Sec. V, the latter characterization is ruled out. The sign reversal approach is similar to the Ref. 3 co-rotating and counter rotating approach, except that in our experiment this test confirms the toroidal field sign dependence in the coupling mechanism. The suggestion that the antenna couples to an electrostatic wave leads to a second test which requires further analysis of the response function in terms of the dispersion relation supported by the plasma dynamics.

2. Antenna excitation induced wave vector

The response function phase \( \Psi \) is obtained using a linear array of closely spaced (18 mm) Langmuir probes that sample the vertical direction. Figure 6 shows an example of the phase shift measured at different vertically separated positions, as well as the associated magnitude of the density response. From these measured phase shifts, we determine the vertical wave number which we refer to as \( k_z \). This wave number is selected by a combination of the plasma dynamics and the antenna \( k \)-spectrum. We extend this technique to determine the other components of the excitation induced wave vector [radial wave number \( k_r \) and the parallel wave number \( k_p \)] using another set of Langmuir probes that samples the radial and the toroidal directions (see Sec. II for description). Figure 7 shows measurements of the radial and vertical wave numbers as a function of the imposed frequency in the plasma frame from which we determine \( k_z \). In this figure one clearly sees that \( k_r \) is much smaller than \( k_z \).

The parallel wave number is obtained between two field-aligned Langmuir probes (described in Sec. III) whose relative toroidal separation is 90°. This field-alignment is verified by determining the maximum coherence in the density response measured between these two probes. Figure 8

FIG. 6. Example of phase measurements. Synchronously detected density response (magnitude and phase) is obtained using a linear array of Langmuir probes. This array samples a vertical strip in the \( E \times B \) direction for the case with \( \bar{\omega}/(2\pi) = (\omega_0 - k_z V_{E \times B})/(2\pi) \sim 28 \text{ kHz} \) \( \bar{\omega}/(2\pi) \) is the drive frequency and \( V_{E \times B} \) at the antenna position is \( \sim 1.1 \text{ km/s} \), see Fig. 1(c). The slope of the bottom plot is the vertical wave number.

FIG. 7. Perpendicular wave number measurements. The top panel shows the measured radial wave number and the bottom panel the measured vertical wave number as a function of the Doppler-shifted frequency \( \bar{\omega}/(2\pi) \). The velocity \( E \times B \) is determined from Fig. 1(c).

FIG. 8. Coherently detected parallel wave number. This wave number is determined by using two toroidally field-aligned Langmuir probes.
shows coherently detected measurements of parallel wave number as a function of the imposed frequency in the plasma frame. This variation over the tuning range of the finite parallel wave number suggests that a coupling between the perpendicular and parallel dynamics, as the antenna tunability is performed over the cross section. The error bars are statistical estimates of the deviations from the average parallel wavenumber. This average is obtained from N ensembles of 30 ms long signals, from which a statistical deviation from the mean can be computed. Information on the wave-vector k, coupled with the measured density response, provides the necessary ingredients to identify the nature of the antenna-induced excitation.

V. PLASMA AND ANTENNA MODEL

The plasma density response to an electrostatic perturbation induced by the antenna is described using a generalized Hasegawa-Wakatani fluid model, with \( T_i = 0 \) and \( T_e \) constant (\( T_i / T_e < 1 \) in our experiment). We assume an equilibrium density (provided by the 2D experimental measurements) with dependence on the radial direction and no dependence in the vertical direction \( z \). We also include the constant field line curvature present in the experimental setup, and a density gradient obtained from the time-averaged density profile [see Fig. 1(a)] such that \( 1/k_i \sim \rho_i \leq L_n < R \) (\( R \) is the major radius). Considering that the fluctuations induced by the antenna are small in amplitude compared to the background fluctuations, we use the linearized equations for the model written in the plasma frame as

\[
\begin{align*}
\alpha \frac{n}{n_0} + \frac{e}{T_e} \beta \phi &= S_n, \\
\gamma \frac{n}{n_0} + \frac{e}{T_e} \zeta \phi &= S_{\phi},
\end{align*}
\]

\[
\begin{align*}
\alpha = \left( i \omega - 2i\omega_d + \frac{c_i^2 k_i^2}{v_i} \right), \quad \beta = \left( 2i\omega_d + i\omega_s - \frac{c_i^2 k_i^2}{v_i} \right), \\
\gamma = -2i\omega_d + c_i^2 k_i^2 / v_i, \quad \zeta = \left[ i\omega_p^2 \left( \frac{\partial^2}{\partial z^2} - k_i^2 \right) - \frac{c_i^2 k_i^2}{v_i^2} \right],
\end{align*}
\]

where \( v_i = n e^2 / m_i \) (\( \eta \) is the parallel resistivity). The density and the potential perturbations due to the antenna are \( n \) and \( \phi \), \( \omega_d = k_i \rho_i v_{\phi,i} / R \) and \( \omega_s = k_i \rho_i v_{\phi,s} / L_n \) are the curvature and the drift frequencies, \( S_n \) and \( S_{\phi} \) are the density and vorticity sources driven by the antenna. The term \( S_{\phi} \) corresponds to charge density fluctuations driven by the antenna. It is assumed that all the quantities are proportional to \( \exp[i(\omega t + k_i \rho_i + k_i z + k_d r)] \) (\( \mu \) denotes the toroidal direction). In comparison to the model in Ref. 3, we neglect nonlinearities and we take into account the magnetic field line curvature. The plasma density response can be written as

\[
\begin{align*}
\frac{S_n}{S_{\phi}} &= \frac{2i\omega_d + i\omega_s - \frac{c_i^2 k_i^2}{v_i}}{2i\omega_d + i\omega_s - \frac{c_i^2 k_i^2}{v_i}}, \\
\frac{S_{\phi}}{D(k, \omega)} &= \left( 2i\omega_d + i\omega_s - \frac{c_i^2 k_i^2}{v_i} \right) S_{\phi} / D(k, \omega),
\end{align*}
\]

where \( D(k, \omega) \) is the dispersion function,

\[
D(k, \omega) = k_i^2 \rho_i^2 \omega^2 - \left[ 2i\omega_d \rho_i^2 + i(1 + k_i^2 \rho_i^2) \frac{c_i^2}{v_i^2} \right] \omega
\]

\[
- 2i\omega_d (2\omega_d + \omega_s) - \frac{c_i^2}{v_i^2} (2\omega_d + \omega_s),
\]

whose roots provide the eigenfrequencies of the system. Given the experimental value (see Fig. 8) of \( k_i \), the resonance \( c_i^2 k_i^2 / v_i \gg \omega > \omega_j \) is valid, in which case Eq. (4) yields a drift wave dispersion relation \( D_w = 1 + k_i^2 \rho_i^2 \omega + (2\omega_d + \omega_s) \). The plasma density response then becomes

\[
n = \frac{i(S_n - S_{\phi})}{(1 + k_i^2 \rho_i^2 \omega + (2\omega_d + \omega_s))},
\]

where the term \( (S_n - S_{\phi}) \) represents an effective driving term. A resonance in the plasma density response at \( \omega = -(2\omega_d + \omega_s) / (1 + k_i^2 \rho_i^2) \) corresponds to the real frequency of the drift wave with an associated damping rate \( \gamma / \omega_r \sim 0.002 \).

VI. COMPARISON AND DISCUSSION

In Fig. 9 the experimental plasma density response (thick solid line) is compared with two estimates of the response given by Eq. (5). The dotted line represents the response \( n \) evaluated as

\[
n = \frac{1}{D_w(\omega, < k_z^m >)} ,
\]

where \( < k_z^m > = 60 \text{ rad/m} \) is the mean value of the measured vertical wave numbers [(\( k_z \)] is assumed small). The dashed-dotted line represents a more accurate estimation, given by

\[
n = \frac{A(k^m) \rho_i}{D_w(\omega, k)} ,
\]

where \( k = (k_x, k_z, k_d) \) is the measured wave vector, and the antenna \( k^- \)-spectrum is the following\( ^{23} \)

\[
A(k) = \frac{\sin \left( \frac{k_d z}{2} \right) \cos \left( \frac{3(k - k_d) D}{2} \right) + \cos \left( \frac{k - k_d) D}{2} \right) \left( k, D^2 \right) / 2 )}{(k_d / 2) / 2}
\]

where \( k_d = D \phi / D \) is the imposed wave number. One clearly identifies a mode corresponding to a drift wave with frequency \( \phi / (2 \pi) \sim 7.8 \text{ kHz} \) in the plasma frame. This frequency converted in the laboratory frame corresponds to
∼4 kHz and is in agreement in Fig. 2. Does this mode amplitude vary linearly with the excitation voltage applied to the antenna?

Figure 10 shows variations of the amplitude of the density response as a function of the potential applied to the antenna tuned to various peaks (see Table I). As shown in Fig. 10(a), the amplitude of density response induced by the antenna tuned at \( \bar{\omega}/(2\pi) \sim 7.8 \text{ kHz} \) varies linearly with the applied potential up to 25 V. This dependence corroborates that the response function at 7.8 kHz is linearly driven by the antenna. The other peaks (not described by the model), on the other hand, are already saturated [see Figs. 10(b)–10(d)] for the same range of excitation voltages. Thus, a characterization of these peaks in terms of the linear dispersion function presented above is not adequate. This suggests that nonlinear and/or saturated additional modes, not described by the current model, may be at play: this is a subject of further investigations.

VII. SUMMARY AND CONCLUSION

In this work, we have presented a novel tool for the generation of electrostatic wave in the drift frequency range. Using a tunable antenna with minimal perturbation to both background profile and plasma dynamics, we have demonstrated that electrostatic excitations can be linearly excited, and observed as a function of the drive frequency and the imposed vertical wave number. The drive frequency is adjusted to the induced \( \mathbf{E} \times \mathbf{B} \) frequency and yields a maximum density response. This convenient drive frequency enables the antenna excitation in the plasma frame making comparison with theoretical predictions suitable.

Direct measurements of the plasma response and of the wave vector \( \mathbf{k} \) necessary for the identification of the antenna excited mode are obtained using a coherent detection technique. In a plasma where large background fluctuations are present, the coherent detection is a necessary technique to...
TABLE I. Summary of the peaks of the measured density response 
\[ \bar{\omega}(\omega_0 - k_{E\times B}) \].

<table>
<thead>
<tr>
<th>( \bar{\omega}/(2\pi) ) (kHz)</th>
<th>( \delta\bar{\omega}/(2\pi) ) (kHz)</th>
</tr>
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<tbody>
<tr>
<td>5.6</td>
<td>1.8</td>
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<tr>
<td>7.8</td>
<td>1.3</td>
</tr>
<tr>
<td>21.2</td>
<td>3.8</td>
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<tr>
<td>36</td>
<td>1.5</td>
</tr>
</tbody>
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overcome fluctuations induced noise. Using this technique, the measured response containing multiple peaks, summarized in Table I, is obtained. The comparison of the measured response with the theoretical predictions of the Hasegawa-Wakatani model on the basis of the launched antenna \( k \)-spectrum and experimentally measured wave vector was performed.

The predicted density response shows agreement for one peak the experimentally measured density response corresponding to a resonant peak that matches a drift wave mode. The other peaks, on the other hand, remain unexplained with the current linear model. In addition, we find that the amplitude of resonant peak varies linearly with the excitation potential applied to the antenna. A linear excitation of drift waves is thus shown in a toroidal plasma using a tunable antenna positioned in the region of maximum density gradient. Finally, in this paper, we have ignored potential wave-wave nonlinear coupling. Such detailed analysis is a large undertaking and will be the subject of future investigations.

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15The distinction between drift and interchange modes cannot be clearly established using phase shift measurements between density and potential. Indeed, in Refs. 16 and 24, it has been shown this phase shift can vary over a wide range. Thus, relying on phase shift measurements between identity and potential can be misleading in characterizing the wave nature.