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Remote launching of plasma modes in the drift frequency range

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Abstract. Two different methods for the creation of low-frequency waves in the drift plasma frequency range ($f_{\mathrm{d}} \approx$ 20–50 kHz) have been investigated in the TAU-1 device. The first method is based on the beat process between two initially excited oblique Langmuir waves, when the frequency of the beat wave is near the draft plasma frequency. The second method is based on the modulation of the initial excited oblique Langmuir wave by a low-frequency signal ($f \approx f_{\mathrm{d}}$). The shape of the frequency spectra is significantly modified by the presence of the externally excited waves.

1. Introduction

Understanding the origin of plasma turbulence in magnetically confined plasmas remains one of the key issues confronting plasma physics research. Although many different mechanisms to explain plasma turbulence have been investigated in the last decade, the dominant free-energy source driving fluctuations has not been fully identified yet (Connor 1995, Hidalgo 1995).

The development of methods to modify and control plasma turbulence appears to be a promising area of research in plasma physics (Sen 1994, Buddemeier and Ströhljein 1995). Both intrusive (Weynants and Van Oost 1993) and non-intrusive (La Haye *et al* 1993) techniques have been proposed to control turbulence in fusion plasmas. Particularly active has been the development of biasing schemes to control the generation of electric fields (Weynants and Van Oost 1993 and references therein). Recently, a wave-launcher system consisting of material probes has been successfully used to excite modes in the plasma frequency range relevant in anomalous transport in the TEXT-U plasma boundary region (Uckan *et al* 1995). In addition, feedback experiments have been used to improve our understanding of the basic physics of plasma instabilities and to provide a means for controlling them (Sen 1994, Uckan *et al* 1995).

The purpose of the present work is to study the possibility of launching, in a remote way, plasma modes in the drift frequency range where most of the anomalous transport takes place, and to investigate the interaction between broadband turbulence and the externally excited plasma drift modes.

The paper has been organized as follows. In section 2, we give a description of the experiment. The experimental methods to excite plasma waves in the drift plasma wave interval are discussed in section 3. The influence of the externally excited waves on the

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plasma drift modes is discussed in section 4. Nonlinear mechanism studies between the excited modes and the underlying broadband turbulence are presented in section 5. Finally, conclusions are given in section 6.

2. Description of the experiment

The present experiments were carried out in the TAU-1 linear device (Asadullin *et al* 1978). The plasma column (radius $r = 2$ cm and length $L = 100$ cm, $r \ll L$) was produced in continuous or pulsed regimes by means of an electron beam (acceleration voltage, $U_b = 50$–150 V, and current, $I_b = 50$–150 mA) in argon plasmas and magnetic field $H = 0.4$–0.6 T. Plasma density on the plasma axis was varied from $n_e(0) \approx 3 \times 10^9$ cm^{-3} up to $n_e(0) \approx 4 \times 10^{10}$ cm^{-3} with electron and ion temperatures in the range $T_e(0) = 5$–7 eV and $T_i(0) \approx 0.1 \times T_e(0)$, respectively.

Two radio-frequency generators connected to half-cylindrical plates were used to excite two oblique Langmuir waves ($U_{01} = U_{02} \approx 0.1$–20 V; $f_{01}, f_{02} = 20$– 28 MHz) which were utilized as the pump waves (Batanov *et al* 1993). The relation between the characteristic plasma frequencies and the frequencies of the pump waves (ω_{01}, ω_{02}) was the following:

$$\omega_d < \omega_s < \omega_{Li} = \omega_{LH} < \omega_{01}, \omega_{02} \ll \omega_{Le}, \omega_{ge}$$

where ω_{ge} is the electron gyrofrequency; ω_d, ω_s, ω_{LH} are the drift, ion-sound and lower-hybrid frequencies; ω_{Li}, ω_{Le} are ion and electron Langmuir frequencies ($\omega_d \approx 0.5$–1×10^5 s^{-1}, $\omega_{Le} \approx 5 \times 10^9$ s^{-1}). Pump waves with frequencies close to 24 MHz were excited in stationary and pulsated regimes. The frequency difference between the two generators could be varied in a continuous way from 10 kHz up to 3 MHz. In addition, one of the pump waves can be varied in amplitude by means of a modulating signal of frequency in the range 10–80 kHz and modulation depth ranging from 10% up to 60%.

Plasma parameters were determined by means of Langmuir probe measurements. Langmuir probe measurements of plasma fluctuations were previously compared with optical measurements of plasma fluctuations under the same experimental conditions (Dergachev *et al* 1980). No evidence of probe-induced plasma perturbations on fluctuation spectra measurements was observed.

Plasma fluctuations have been characterized by fluctuations in the ion saturation current. Standard linear spectral analysis (power spectrum) has been applied to quantify the amplitude of the individual Fourier components and bispectral analysis techniques have been used to detect the presence of phase coherence among different spectral components (Young and Powers 1979, Hidalgo *et al* 1993, Milligen *et al* 1995 and references therein). The two-point correlation method was used for measuring the wavenumber components in radial (k_r), poloidal (k_θ) and longitudinal ($k_\parallel$) directions.

Two different regimes of plasma fluctuations have been observed in the TAU-1 device: a discrete spectrum with a few frequency harmonics and a continuous spectrum with a lot of harmonics (close to turbulence). The regime of operation, either the discrete or the turbulent, was completely defined by plasma parameters such as magnetic field, gas pressure and beam current. These two different fluctuation regimes are shown in figure 1(a, b). Figure 1(c) shows the measured wavenumber–frequency dispersion relation of fluctuations in the initial plasma and of the externally excited waves (see section 3). Fluctuations are dominated by frequencies in the range $f = \omega/2\pi \approx 10$–200 kHz with perpendicular wavenumbers $k_\perp \approx 0.5$–2.5 cm^{-1} ($k_\perp^2 = k_r^2 + k_\theta^2$). The longitudinal wavevector component of fluctuations was $k_\parallel \approx 2\pi/L \approx 0.06$ cm^{-1}, L being the length of the plasma chamber ($L = 100$ cm).

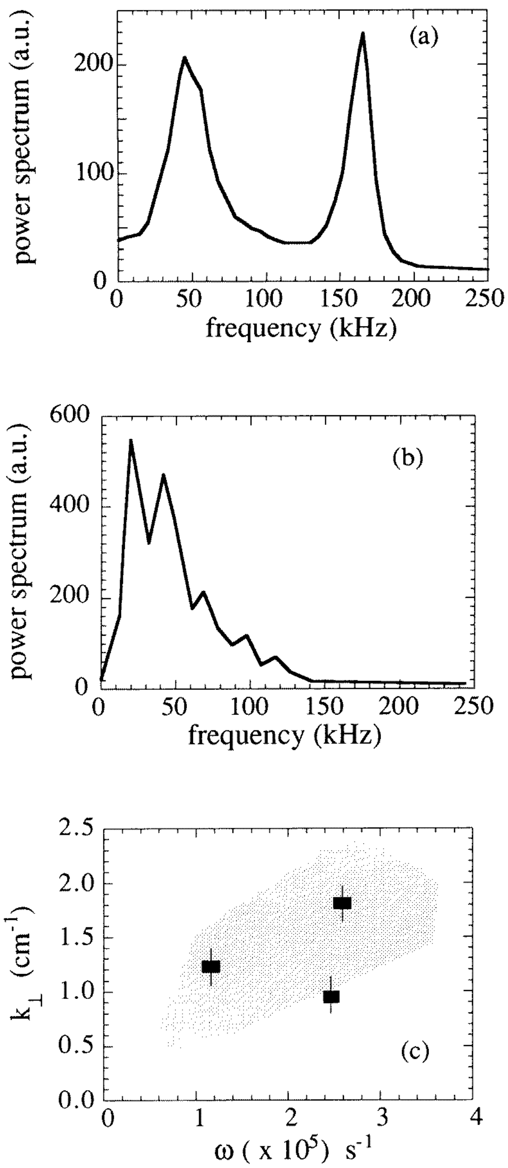

Figure 1. Regimes of operation of the TAU- 1 device: (*a*) discrete fluctuation spectrum ($H = 0.5$ T, $p = 3 \times 10^{-4}$ torr, $n_e = 10^{10}$ cm^{-3}); (*b*) turbulent spectrum ($H = 0.7$ T, $p = 3 \times 10^{-4}$ torr, $n_e = 7 \times 10^9$ cm^{-3}); and (*c*) wavenumber–frequency dispersion relation for fluctuations in initial plasma conditions (grey area) and for externally excited waves (black points).

3. Launching of plasma waves in the drift frequency range

Two different experimental methods have been used for the production of low-frequency waves in the drift plasma frequency range (10–100 kHz). The first method is based on the beat process between two initially excited oblique Langmuir waves, when the frequency of the beat wave is near the drift plasma frequency. The second method is based on the amplitude modulation of the initial excited oblique Langmuir wave by a low-frequency signal (10–40 kHz).

The beat process between two oblique Langmuir waves has been experimentally investigated in detail in previous works (Batanov *et al* 1991, 1993). Figure 2(*a*) shows the excitation of the beat wave in drift frequency range (60 kHz) by two oblique Langmuir waves.

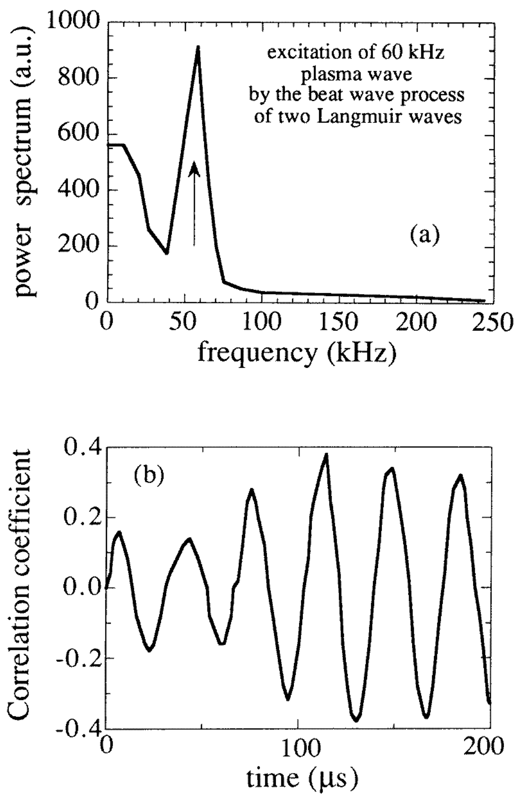

Figure 2. (*a*) 60 kHz externally excited plasma waves by the beat process between two oblique Langmuir waves ($E_{01} = 2$ V cm^{-1}, $E_{02} = 2$ V cm^{-1}). Measurements were carried out in plasmas with the following parameters: $H = 0.65$ T, $p = 3 \times 10^{-4}$ torr, $n_e = 7 \times 10^9$ cm^{-3}; (*b*) cross-correlation coefficient between plasma fluctuations and the generator signal at the modulation frequency (30 kHz) as a function of the delay time.

Low-frequency waves have also been excited in the plasma column by means of amplitude modulation of one of the oblique Langmuir waves in the drift frequency range. Three parameters of the incident modulated wave were independently modified: the modulation depth (10–50%), the intensity of the wave (3–8 V cm^{-1}) and the frequency of modulation (10–40 kHz). This wave will be referred to as the modulated low-frequency wave. Excitation of low-frequency modes in the plasma were observed when the modulation depth was larger than 10% for $E = 8$ V cm^{-1} and larger than 30% for $E = 3$ V cm^{-1}. Figure 2(*b*) shows the cross-correlation function between the plasma fluctuations in the Langmuir probe ion saturation current and the generator signal at the frequency of modulation (30 kHz). The cross-correlation function increases on a timescale of about five periods of the modulating signal. Similar results were found for the beat excited waves.

The intensity of the modulated low-frequency wave depends on the intensity of the single oblique wave and modulation depth, while the intensity of the beat low-frequency wave depends on the intensity of both oblique Langmuir waves involved.

The nature of these externally excited waves (either beat or modulated waves) is very similar. Measurements of frequency–wavenumber vector components of externally excited low-frequency waves show that their ω–k dispersion relationship overlaps with the dispersion relationship of initial drift waves (see figure 1(*c*)). Parallel wavenumbers are close to those of the initial drift modes ($k_\parallel \approx 0.06$ cm^{-1}). The radial profile of the intensity of the excited low-frequency waves shows a maximum in the plasma centre for low values of plasma density ($n_e < 10^{10}$ cm^{-3}), whereas at higher densities ($n_e \geqslant 10^{10}$ cm^{-3}) the maximum is at about the half radius. Therefore, the excited low-frequency wave were of a drift wave nature in the latter case. The radial intensity distribution for the low plasma density waves allowed us to interpret this artificial wave as a forced drift mode.

4. Influence of externally excited waves on plasma drift modes

The influence of low-frequency beat waves (20 kHz, $E_{01} = 2.5$ V cm^{-1}, $E_{02} = 2.5$ V cm^{-1}) on the turbulent spectrum is presented in figure 3(*a*). In this case, the amplitude of the externally excited wave is close to the level of the initial background fluctuations. The initial drift frequency spectrum changed: the maximum spectral amplitude is shifted to the lower frequencies.

The externally excited waves launched into the plasma by means of a 40 kHz modulated wave ($E_{HF} = 5$ V cm^{-1} and 40% modulation depth) are clearly observed in the Fourier power spectrum (figure 3(*b*)). No evidence of modification of the frequency spectra is seen when the intensity of the incident wave was decreased to 3 V cm^{-1} keeping the modulation depth constant (30%). It should be noted that the initial turbulent spectra were the same in these two experiments (see figure 3(*a*) and (*b*)); however, the plasma response on modulated and beat low frequency was different.

There are different mechanisms through which pump waves and modulated or beat low-frequency waves can modify plasma drift turbulence:

(i) Direct influence of high frequency ($\approx$ 25 MHz) waves on drift wave dispersion. However, previous experiments (Asadullin *et al* 1979) have shown that under the present conditions ($E < 8$ V cm^{-1}) the influence of the high frequency waves on the drift frequency modes is negligible (the observed shift in the drift frequency spectra was in the range of a few per cent).

(ii) Excitation of non-linear instabilities (such as the decay instability or the Langmuir sound-scattering instability) in the high-frequency wave field. In fact, previous experiments (Batanov *et al* 1983) have shown the arising of Langmuir sound-scattering in the presence of oblique Langmuir waves which might change drift frequency spectra and plasma parameters. Modification of the electron temperature has been observed when the pump wave fields are larger than 5–6 V cm^{-1} whereas modification in the plasma density profile only occurred for pump fields stronger than 10 V cm^{-1}.

(iii) The direct influence of the beat or modulated low-frequency wave on plasma drift. Thus, when the pump waves field is relatively low (E_0 or $E_{01} + E_{02} < 8$ V cm^{-1}), the direct influence of the beat or the modulated low-frequency wave on plasma drift modes should be dominant.

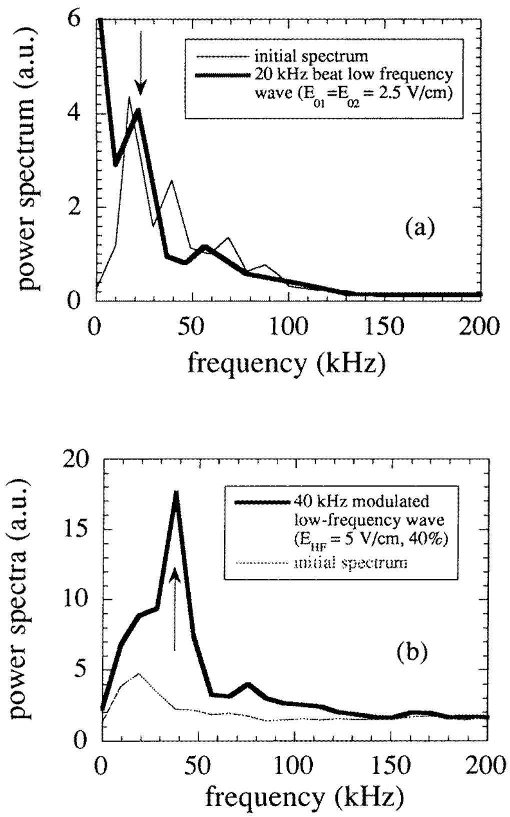

Figure 3. (*a*) Frequency spectra of plasma fluctuations with and without externally excited waves (20 kHz beat low-frequency with $E_{01} = E_{02} = 2.5$ V cm^{-1}). (*b*) Frequency spectra of plasma fluctuations with and without externally excited waves (40 kHz modulated low-frequency wave, $E_{\mathrm{HF}} = 5$ V cm^{-1}, 40% modulation depth). Measurements were carried out in plasmas with the following parameters: $H = 0.65$ T, $p = 3 \times 10^{-4}$ torr, $n_e = 7 \times 10^9$ cm^{-3}.

5. Non-linear analysis

Fourier analysis provides information on the amplitude of the different Fourier modes contributing to the broadband fluctuation spectra but does not give any information about the phase coupling among different spectral components. Non-linear mechanisms (i.e. wave–wave coupling) might play key roles in redistributing the energy supply to the fluctuating plasma parameters through different plasma instabilities. In order to study the possible non-linear link between externally excited modes and plasma broadband fluctuations we have investigated the non-linear characteristics of drift plasma turbulence with and without the presence of the externally excited modes by using bispectral analysis.

The *bicoherency* is defined as

$$b^2(f_1, f_2) = B(f_1, f_2)^2/(\langle|X_{f_1}X_{f_2}|^2\rangle P(f))$$

where $B(f_1, f_2)$ is the *bispectrum* defined as $B(f_1, f_2) = \langle X_{f_1}X_{f_2}X_f^*\rangle$, $P(f)$ the auto-power spectrum $P(f) = \langle X_f X_f^*\rangle$, X_f is the Fourier transform of the time trace $x(t)$ and $\langle\,\rangle$ means ensemble averaging over many statistically similar realizations. The bicoherency measures the fraction of the fluctuation power at frequency f which is phase correlated with the spectral components at frequency f_1 and f_2 obeying the summation rule $f = f_1 \pm f_2$. The bicoherency thus quantifies the degree of coupling between three Fourier modes. The bicoherency is bounded between 0 and 1: when $b^2(f_1, f_2)$ is equal to one then the fluctuations at frequency f are completely coupled with the frequency components at frequency f_1 and f_2 and completely uncoupled for a value of zero. The frequency-resolved bicoherence is defined by $b^2(f) = \sum_{f=f_1+f_2} b^2(f_1, f_2)$.

The level of phase coherence revealed by bicoherence analysis depends on the plasma conditions. Figure 4 shows the frequency resolved bicoherence measured in plasmas with a low level of plasma turbulence ($\tilde{I}_s/I_s < 0.1$). The corresponding frequency spectra are shown in figure 3. The level of bicoherence is close to the noise level in the initial plasma. Bicoherence analysis reveals that the externally excited wave is nonlinearly coupled to the plasma fluctuations, the enhancement in $b^2(f)$ being maximum at frequencies near the harmonics of the launched mode. The influence of externally excited waves on the characteristics of broadband fluctuations has been also investigated in plasma with a high level of turbulence. Under such plasma conditions the level of bicoherence, which is significant initially, is not modified by the presence of the externally excited waves.

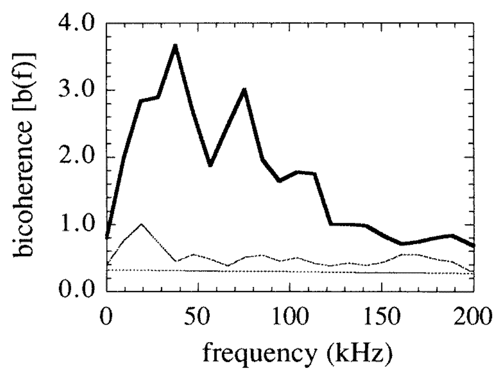

Figure 4. Frequency resolved bicoherence with and without externally excited plasma waves. The corresponding frequency spectra are shown in figure 3(*b*). The horizontal straight line indicates the noise level.

Although we cannot completely exclude the possibility that some fraction of the phase coherence revealed by bicoherence in some plasma conditions could be explained on the basis of nonlinearities in the launched waves (in the present experiment the harmonic level in the HF generator was in the region of 10^{-4}), the present results seem to indicate that there is a non-negligible coupling with plasma broadband turbulence. In addition, the effect of nonlinearities introduced by the presence of the density and temperature fluctuations in the I_s-probe interpretation should be considered. Further investigations are in progress to quantify these effects.

6. Conclusions

Two different methods for the creation of low-frequency waves in the drift plasma frequency range ($f_d \approx$ 20–50 kHz) have been successfully investigated in the TAU-1 device. The first method is based on the beat process between two initially excited oblique Langmuir waves, when the frequency of the beat wave is near the drift plasma frequency. The second method is based on the modulation of the initial excited oblique Langmuir wave by a low-frequency signal ($f \approx f_d$). The shape of the frequency spectra is significantly modified by the presence of the externally excited waves. Future work will further investigate nonlinear interaction mechanisms between externally launched waves and plasma fluctuations and will explore the possibility of control and modification of plasma turbulence through feedback techniques.

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