PHYSICS OF PLASMAS VOLUME 10, NUMBER 10 OCTOBER 2003

Effect of parallel velocity shear on the electrostatic ion-cyclotron instability in filamentary current channels

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(Received 31 March 2003; accepted 1 July 2003)

The effect of magnetic field-aligned ion flow with a transverse flow velocity gradient (parallel velocity shear) on the excitation of the electrostatic ion cyclotron (EIC) instability in narrow current channels (width<ion gyroradius) is studied experimentally in a double-ended Q machine. The presence of parallel velocity shear may lead to the excitation of the EIC instability even in current filaments too small to otherwise support the instability. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1604394]

I. INTRODUCTION

It has been known for over 40 years that a magnetic field-aligned current may lead to the excitation of the electrostatic ion cyclotron (EIC) instability.[1] This instability was first observed in a Q machine when the electron current to a 6.4 mm diam collector located on the axis of a 3 cm diam plasma column was sufficiently large to raise the electron drift velocity to ~10 times the ion thermal speed, a relatively modest threshold.[2] The instability leads to very large fluctuations (>50%) in the current at a frequency slightly above the ion-cyclotron frequency. The oscillations are not restricted to the current channel but also propagate as density and potential fluctuations at a large angle to the magnetic field. The wave vector of these EIC waves has components both perpendicular and parallel to the magnetic field, with $k_{\perp} \gg k_{\parallel}$, and $k_{\perp}\ \rho_i \sim 1$, where ρ_i is the ion gyroradius. The parallel phase velocity is in the direction of the electron drift which provides the wave-particle resonance necessary to excite the instability.

Many of the characteristics of this instability that have been investigated experimentally were in agreement with the (local) theory of Drummond and Rosenbluth, appropriate to a uniform, magnetized plasma, in which the electrons drift along $\mathbf{B}$ field lines with the same drift velocity $\mathbf{v}_D$, at all points in the plasma.[3] Their treatment, however, could not account for certain aspects of the instability related to inhomogeneities present in laboratory plasmas. For example, the effect that the finite width of the current channel has on the excitation of the instability was not considered until the nonlocal theory of Bakshi *et al.*,[4] was presented. They found that if the width of the current channel was reduced to just a few ion Larmor radii, the EIC instability was quenched. This phenomenon, known as filamental quenching, was studied experimentally by Cartier *et al.*[5] The effects of a transverse gradient in the plasma flow velocity parallel to the magnetic field on the excitation of EIC waves has also been analyzed by Ganguli *et al.*[6] They showed that ion flow gradients (parallel velocity shear) can give rise to a new class of ion cyclotron waves via inverse cyclotron damping, with a resulting multiple cyclotron harmonic spectrum. The effect of parallel velocity shear on EIC wave excitation was studied experimentally by Agrimson *et al.*[7] who pointed out that the typical configuration used to study EIC wave production in the laboratory necessarily included the presence of parallel ion flow with transverse shear. These experiments[7] provided clear evidence that parallel velocity shear does play a role in the excitation of EIC waves. Further observations of inverse ion-cyclotron damping induced by parallel velocity shear have been published.[8]

In the present work, experimental evidence is presented which shows that the filamental quenching of the EIC instability may be rendered ineffective if, in addition to field-aligned current, parallel velocity shear is present in the ion flow. Observations show that the EIC instability can be excited in narrow current channels (widths $\lesssim \rho_i$) if a sufficient amount of parallel velocity shear is also present. In Sec. II the experimental setup is described. The experimental results and discussion are presented in Sec. III.

II. EXPERIMENTAL SETUP

The experiments were performed in a double-ended Q machine, shown schematically in Fig. 1. The plasma sources consist of two 6 cm diam tantalum plates (HP1 and HP2) separated by 2 m longitudinally. Each hot plate is heated from behind by electron bombardment to a temperature of ≈2200 K. Two cesium atomic beam ovens (not shown) provide neutral Cs atoms that are directed on the hot plates where they undergo surface ionization. Together with the thermionically emitted electrons, the Cs^+ ions are confined radially by a uniform magnetic field up to 0.5 T. The plasma density and electron temperature (measured with a Langmuir disk probe) are typically: $n_i = n_e \approx 10^{10}\ \mathrm{cm}^{-3}$, and $T_e \approx T_i \approx 0.2$ eV.

Ions produced on either hot plate are accelerated along the magnetic field by the ~2–3 V potential drop that is present in the sheaths at the hot plates. In double-ended operation, the net bulk ion flow can be controlled by adjusting the temperatures on the hot plates. For example, by appropriate adjustment of the heating power to each plate the sources can be balanced so that no net flow results. To produce a configuration with parallel velocity shear (flow with a transverse velocity gradient), the "ring and disk" configuration was used, as shown in Fig. 1. At one plasma cross section a metal ring (R) of 8 cm outer diameter and 2.3 cm

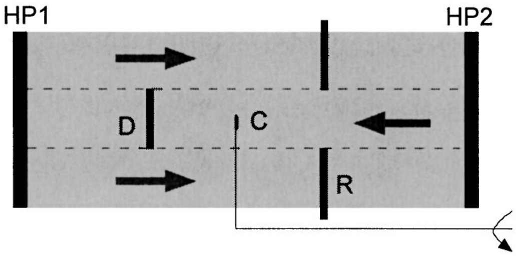

FIG. 1. Schematic of the experimental setup. Cesium plasma is produced by contact ionization of Cs atoms from atomic beam ovens (not shown) on the two hot plates (HP1, HP2). The ring+disk configuration (R,D) is used to produce magnetic field-aligned ion flow with a fluid velocity gradient in the direction perpendicular to **B**. A small disk collector (C) is used to drive electron current along the magnetic field lines.

inner diameter was located and at another plasma cross section a metal disk (D) of 2.2 cm diam. When both the ring and disk are biased a few volts negative to collect essentially the full ion current, a counter streaming exists in the plasma between the inner core and outer cylindrical shell. This ring+disk configuration is the same as that used by D'Angelo and von Goeler[9] to excite the low frequency parallel velocity shear instability. The observation of this low frequency instability ($f \sim$ few kHz) with maximum amplitude in the annular region near the edge of the disk is taken as an indication of the presence of parallel velocity shear. Note that the ring and disk are always biased at the same potential so that no radial electric fields are introduced into the plasma. A typical profile of the floating potential of a Langmuir probe that was scanned across the plasma column is shown in Fig. 2. The top trace is the dc component of the potential showing that it is relatively uniform across the column. The lower trace is the fluctuating (ac) component showing the presence of the low frequency parallel velocity shear instability. In a previous experiment which used the identical ring+disk configuration, the presence of transverse shear in the parallel ion flow was verified by measurements of the ion flux using a double-sided Langmuir probe (see Fig. 4 of Ref. 10).

A magnetic field-aligned electron current was produced by biasing a small collector (C) to a potential above the floating potential. This generally produces an electron drift

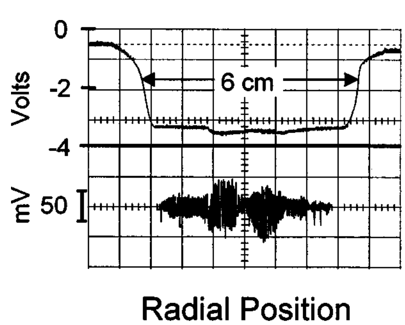

FIG. 2. Upper trace: radial profile of the floating potential of a Langmuir probe. Lower trace: radial profile of low frequency oscillations driven by transverse shear in the parallel ion flow. The positions of peak amplitude correspond to the regions of largest shear.

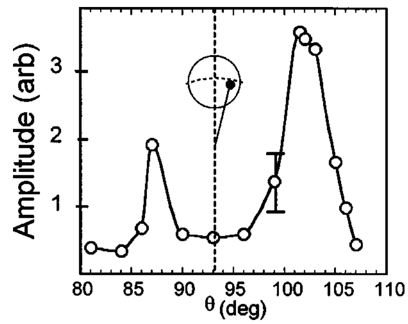

FIG. 3. Amplitude of the EIC instability ($f=39$ kHz) as a function of the radial position (θ) of the collector in the plasma column. The center of the column corresponds to roughly $\theta=93°$ (dashed line) and the edges of the disk at $\theta=87°$ and $\theta=102°$. Here $B=2800$ G, $\rho_i=2$ mm, $r_c=1.5$ mm, $V_c=-0.4$ V, and $V_{rd}=-5$ V. The baseline corresponds to the background noise level.

along **B**, relative to the ions, of 10–15 times the ion thermal speed. The collector was movable in both the radial and axial directions.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experiment was conducted to see if, in the presence of parallel velocity shear, the EIC instability could be excited even in narrow current channels where the width was on the order of or less than the ion gyroradius. The ring and disk were biased to -5 V, sufficient to collect the ion current and produce the shear layer. The collector was biased to -0.4 V, which was sufficient to drive a magnetic field-aligned electron current since the floating potential is typically -2 to -3 V. The magnetic field was set to 2800 G, giving an ion gyroradius, $\rho_i=2$ mm and ion gyrofrequency $f_{ci}=32.5$ kHz. A collector with a radius of $r_c=1.5$ mm ($<\rho_i$) and biased to drive electron current, was located at various radial positions and the amplitude of any EIC oscillations was recorded. The radial positioning of the collector is accomplished by rotating the support shaft across the plasma cross section. A plot of the EIC oscillation amplitude, excited at a frequency $f=39$ kHz versus the rotation angle θ is shown in Fig. 3. The center of the plasma column corresponds to $\theta \approx 93°$ and the radial locations of the region of parallel velocity shear correspond to $\theta \approx 87°$ and $\theta \approx 102°$. The EIC wave amplitude is maximum in the shear layer, whereas in the center of the plasma, where there is no shear, the wave amplitude is very small. The asymmetry in the amplitude maxima at 87° and 102° are likely due to nonuniformities in the shear on either side of the plasma column. These nonuniformities are also reflected in the low frequency mode which also shows a larger amplitude at $\theta \approx 102°$. Note that the low frequency and EIC modes are simultaneously present. Evidently, the presence of parallel velocity shear in the current channel is sufficient to overcome the filamental quenching.

To provide further evidence for the role of parallel velocity shear in exciting the EIC instability the collector was fixed at a radial position of 102° and the bias voltage on the ring and disk, V_{rd}, was varied. If the ring and disk are biased sufficiently negative, then the full ion current is collected from either hot plate, and under this condition, the counter-

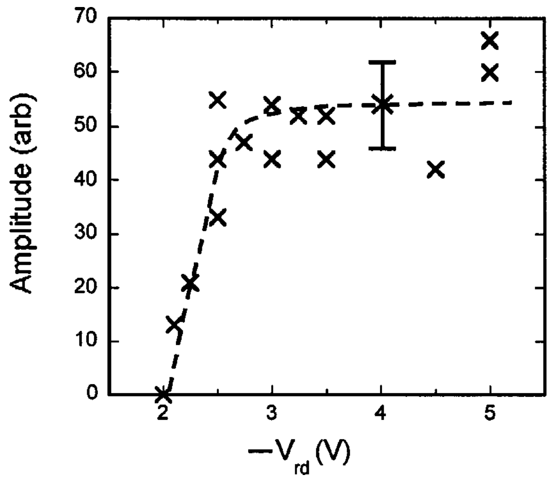

FIG. 4. Amplitude of EIC instability for the collector at $\theta = 102°$ versus the negative ring + disk bias voltage. Same conditions as in Fig. 3.

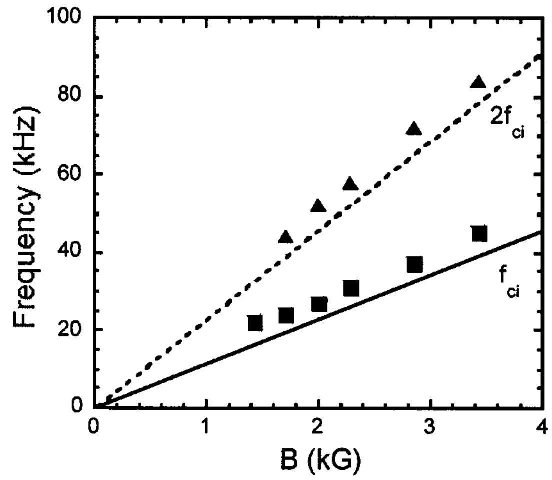

FIG. 5. Dependence of the frequency of the fundamental and first harmonic EIC mode on magnetic field strength for a collector located in the region of transverse shear (102°). Solid line: f_{ci}; dashed line: 2 f_{ci}.

streaming (i.e., shear) is present. However, if the voltage is increased to around -2 V the ions begin being reflected from the ring and disk and there is no flow or shear. The variation of the amplitude of the EIC mode as V_{rd} is increased and is shown in Fig. 4. There is a slight ($\sim 10\%$) increase in the mode frequency which occurs near the onset of the mode. The EIC instability is only excited when the parallel velocity shear is present. For $-V_{rd} > 3$ V the wave amplitude remains roughly constant since the magnitude of the shear is not expected to change due to the fact that the flow velocity does not change with increasing $-V_{rd}$ for $-V_{rd} > 3$ V. This is also evidenced by the observation that the amplitude of the low frequency instability also remains constant. We believe this to be the simplest and most reasonable explanation for the amplitude remaining constant.

The type of measurements shown in Fig. 3 were repeated at a somewhat larger value of the magnetic field and using a smaller collector. With $B = 3360$ G the ion gyroradius is reduced to $\rho_i = 1.5$ mm and a collector of radius $r_c = 0.8$ mm was used. In this case with $r_c \sim \rho_i/2$, the filamental quenching should be even more effective. The result was very similar to that shown in Fig. 3, i.e., the EIC instability was only excited in the region where the shear was present.

The theory of the effect of parallel velocity shear on EIC waves (Ref. 6) requires that the waves have both parallel and perpendicular (in this case azimuthal) wave vectors. Measurements of k_z and k_θ were not deemed feasible here due to the very small size of the current channels in which the waves were excited. Propagation measurements of multiharmonic EIC waves destabilized in the presence of parallel velocity shear were presented in Ref. 8, the first to document the perpendicular propagation characteristics of this type of wave.

To verify that the observed instability was indeed the typical EIC mode,[1,2] the collector was positioned in the region of transverse shear (102°) and wave spectra were obtained for various magnetic field strengths. The results, summarized in Fig. 5, show that the frequencies of the fundamental and first harmonic are somewhat above the corresponding gyrofrequencies and exhibit the typical linear variation with B which is a characteristic of EIC modes.

The following observations should also be noted in connection with other possible EIC wave excitation mechanisms, e.g., radial electric fields or density gradients, that could affect the interpretation of the results presented here. Although density gradients and small radial electric fields were present in the experiment, they were the same whether the shear was on or off. Thus, neither density gradients nor radial electric fields appear to have played a critical role in the excitation of the EIC waves.

In summary, experimental measurements have been presented on the effect of parallel velocity shear on the excitation of the EIC instability in narrow current channels. The results indicate that the presence of parallel velocity shear may lead to the excitation of the instability, even in narrow current filaments that could otherwise not sustain the instability. These laboratory observations may provide guidance in understanding the occurrence of ion cyclotron waves in regions containing filamentary current structures (arcs) and localized ion beams.[11]

ACKNOWLEDGMENTS

The authors thank G. Ganguli for fruitful discussions on the effects of parallel velocity shear.

This work was supported by the NSF.

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