Laboratory Studies of the Effect of Parallel Velocity Shear on Electrostatic Ion Waves in a Magnetized Plasma

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Abstract

Parallel velocity shear (PVS) is a plasma configuration with ion flow parallel to the magnetic field but with a velocity gradient transverse (to B). PVS is commonly observed along the Earth's auroral field lines and, in association with magnetic field-aligned currents, may excite ion acoustic and ion cyclotron waves. This presentation reviews Iowa experiments investigating the effect of PVS on excitation of (1) ion acoustic waves by subcritical currents in a plasma having equal ion and electron temperatures, and (2) electrostatic ion cyclotron waves in plasmas with and without field-aligned current.

1. Introduction

The configuration of parallel velocity shear is shown schematically in Fig. 1. The plasma is formed in a uniform magnetic field and the ions flow along the magnetic field with a flow speed, $v_{iz}(x)$ that varies from one field line to the next. The shear in the ion flow is characterized by the flow gradient, $V_d' = dv_{iz}/dx$. In addition, the plasma may carry an electrical current if there is a field-aligned drift of the electrons, v_{ed} relative to the ions.

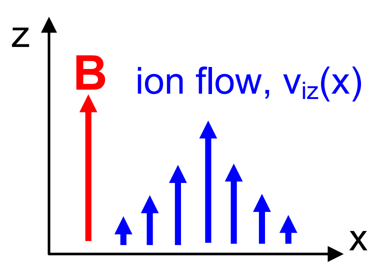

FIG. 1. Schematic of the parallel velocity shear configuration

Magnetic field-aligned currents have traditionally been invoked to explain satellite observations of electrostatic ion waves, in particular, waves near the proton gyrofrequency in the Earth's auroral region [1]. In some instances however, the waves are observed at times when the electron drift is below the critical value required for their excitation. Observations of enhanced radar backscatter from the topside ionosphere has also been interpreted as indications of the presence of ion acoustic modes due to current-driven instabilities at times when $T_e \approx T_i$, where such processes are expected to be only marginally unstable [2]. Ion acoustic fluctuations have also been observed on the FREJA S/C in the auroral topside ionosphere [3].

A considerable advance in the theoretical interpretation of topside ionospheric processes has been made by taking into account the inhomogeneous nature of the Earth's auroral zone. A significant feature of this region, as observed by measurements with the FAST S/C, is the presence of localized high speed ion flows along the magnetic field lines with strong shear in the perpendicular direction [1]. As shown by Gavrishchaka et al. [4], such inhomogeneous flows can lower the threshold for the excitation of current-driven ion acoustic waves even in plasmas in which $T_e/T_i \sim 1$, where otherwise ion acoustic waves are severely Landau damped. Ganguli et al. [5], using Vlasov theory and PIC simulations, have analyzed the effect of inhomogeneous parallel ion flow on the excitation of electrostatic ion cyclotron (EIC) waves in an attempt to understand in-situ observations of these waves in the presence of levels of field-aligned currents that were generally subcritical. They discovered that ion flow gradients could give rise to a new class of ion cyclotron waves driven by 'inverse cyclotron damping" even in the absence of field-aligned current. Furthermore, the ion flow gradient mechanism can drive multiple cyclotron harmonics, giving rise naturally (linear superposition) to "spiky" waveforms, as observed on the FAST S/C [1]. It has also been pointed out that perpendicular shear in the magnetic field aligned plasma flow could drive waves with frequencies ~ ion cyclotron frequency within the context of fluid theory. Using an extension of the early work of D'Angelo [6] on shear-driven Kelvin Helmholtz waves, Merlino [7], using a purely fluid treatment that also included a density gradient, showed that parallel velocity shear could excite EIC waves in a plasma with no current.

This paper will provide brief summaries of some of the experimental work, performed at the University of Iowa, on the effect of parallel velocity shear on the excitation of both ion acoustic and ion cyclotron waves. The experiments were performed in a Q machine, which will be described in the next section.

2. The Q Machine

The experiments were performed in the basic device called a Q machine which produces a thermally ionized plasma that is relatively free from low frequency instabilities, hence "quiescent" [8]. A schematic of a Q machine is shown in Fig. 2.

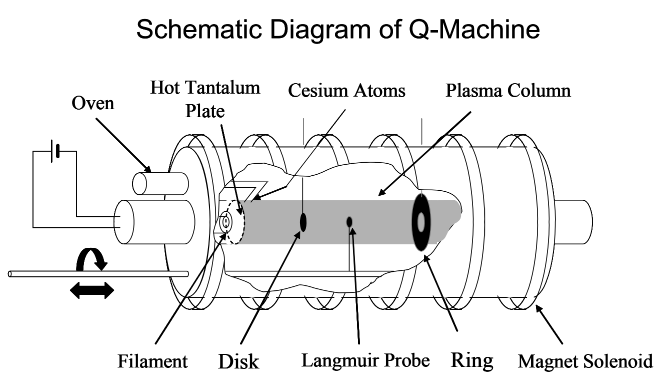

FIG. 2. Cutaway view of the Q machine showing the hot plate ionizer, atomic beam oven, solenoid coils and Langmuir probe.

The Q machine utilizes as the plasma source a hot plate (~2200 K), either of tungsten or tantalum (typically 3 -8 cm in diameter) which is heated by electron bombardment of thermionically produced electrons from a filament located directly behind it. Singly charged ions are formed when alkali metal atoms (Cs or K), produced in an atomic beam oven, come into contact with the hot plate. Electrons are also thermionically emitted by the hot plate, and together with the ions constitute the plasma which is confined radially by a solenoidal magnetic field, typically up to 0.5 T. Both electrons and ions are in thermal equilibrium with the hot plate, and thus have temperatures $T_e \approx T_i \approx T_{HP} \approx 0.2$ eV. Both the electrons and ions are well-magnetized (electron and ion gyroradii << plasma radius) with densities in the range $10^8 - 10^{12}$ cm^{-3}, and the plasma is nearly fully-ionized. The Q machine can be operated either in single-ended mode (one hot plate ionizer) or in double-ended mode (2 hot plate ionizers at opposite ends of the device). In the double-ended mode of operation, the plasma can be configured, using the "ring + disk", to produce the necessary conditions for studying instabilities driven by parallel velocity shear [9].

3. Excitation of Ion-Acoustic-Like Waves by Subcritical Currents in a Plasma Having Equal Electron and Ion Temperatures

In a plasma with $T_e/T_i \sim 1$, an electron drift speed on the order of the electron thermal speed is required to excite ion acoustic oscillations. However, the critical electron drift is significantly reduced in the presence of inhomogeneous ion flow parallel to the magnetic field [4]. This theoretical prediction was tested in an experiment reported by Agrimson et al. [10]. A single-ended Q machine was configured to produce a plasma having magnetic field aligned electron current and parallel velocity shear. The shear is characterized by the parameter V_d'. Under conditions in which $V_d' \simeq 0$, the electron drift speed associated with the magnetic field aligned current was insufficient to excite the ion acoustic instability. However, when additional free energy was available due to the presence of parallel velocity shear, i.e., $V_d' \neq 0$, an instability was excited with propagation characteristics that were consistent with theoretical predictions in [4].

4. Effect of Parallel Velocity Shear on the Excitation of Electrostatic Ion Cyclotron Waves

Three experiments were performed on EIC wave excitation to investigate the effects of parallel velocity shear: (1) in a plasma in which both magnetic field-aligned current and parallel velocity shear was present [11], and (2) in a plasma with only parallel velocity shear and no current [12]. This experiment was designed to specifically test the critical prediction of the theory [5] that EIC waves can be excited, in the presence of perpendicular shear flow by inverse cyclotron damping. (3) The final experiment focused more directly on the multiharmonic EIC wave spectra and "spiky" waveforms that are associated with parallel velocity shear in a current-free plasma [13].

4.1 Effect of Parallel Velocity Shear on EIC Wave Excitation in a Plasma with Magnetic Field-Aligned Current

In this experiment [11] the amplitude of the EIC waves was measured as the amount of parallel velocity shear was varied for constant electron current along the magnetic field. The EIC wave amplitude was found to decrease in conjunction with the disappearance of the ion flow shear. In another experiment, the spatial variation of the EIC wave amplitude was measured. In this case we found that the wave amplitude was a maximum in the region of strongest ion flow shear. These experiments provided strong evidence that parallel velocity shear played an important role in the excitation of EIC waves, as predicted by the theoretical analyses.

4.2 Amplification of EIC Waves in a Plasma with Parallel Velocity Shear and No Magnetic Field-Aligned Current

This experiment [12] was designed to test the prediction that in a current-free plasma, the presence of ion flow shear could promote the growth of EIC waves via inverse cyclotron damping. The approach was to launch an ion-cyclotron wave from an electrostatic antenna into a current-free plasma and follow its evolution as it propagated into a region of parallel velocity shear. First, we looked at the case in which there was no parallel velocity shear and observed that the EIC wave (a pure sine wave of frequency slightly above the ion gyrofrequency) continuously decreased in amplitude as it propagated across the plasma column. In the presence of parallel velocity shear, however we observed a significant amplification of the EIC wave amplitude in the region of strong parallel velocity shear. In a complementary experiment we investigated the effect of applying a broadband (white noise) signal to the antenna which covered a frequency span of several cyclotron harmonics. A spectral analysis of the signal from an electric probe located in the region of strong parallel velocity shear showed a simultaneous amplification of the fundamental EIC mode and four harmonics. The observed wave amplification of the EIC modes is consistent with the prediction of inverse cyclotron excitation. Furthermore, the observed amplification of the broadband wave packet at multiple cyclotron harmonics is an important confirmation of the prediction that the level of parallel velocity shear necessary to excite the fundamental EIC mode is also sufficient to excite a multiharmonic EIC spectrum.

4.3 Generation of "Spiky" Potential Structures Associated with Shear-Driven EIC Waves.

A ubiquitous feature of electric field structures observed on satellites in the auroral region is their spiky, repetitive nature. Both unipolar and bipolar potential structures have been observed with repetition frequencies just above the local hydrogen cyclotron frequency [1]. As noted in the discussion of Sec. 4.2, parallel velocity shear can simultaneously excite multiple harmonic EIC waves. Waveforms of the potential fluctuations observed on electric probes in the experiments described above also show repetitive spiky structures on timescales of the ion cyclotron period. As pointed out by Ganguli et al. [5], such spiky waveforms may simply be the result of a linear superposition of spontaneously generated, phase-locked multimode EIC waves. This was demonstrated [13] by constructing a model time series using a linear superposition of waves of the form $\Sigma A_n \sin(n\omega_o t+\varphi_n)$, where the A_n were the measured amplitudes of the EIC fundamental and harmonic modes, and ω_o was the fundamental mode frequency. When the modes were taken to be in phase (φ_n =0 for all modes), the model time series was a faithful reconstruction of the actual measured time series.

5. Conclusions

A summary of results of a series of experiments conducted at the University of Iowa investigating the effect of parallel velocity shear on ion acoustic and ion cyclotron waves has been presented. It has been demonstrated that parallel velocity shear can be an important, if not decisive, excitation mechanism of these plasma modes. Ion acoustic wave generation by subcritical currents (for a plasma with $Te = T_i$) was observed when parallel velocity shear was present. It is important to note that in a Q machine plasma without shear, ion acoustic waves are damped over a spatial distance of less than one wavelength. Electrostatic ion cyclotron wave growth has been observed in a current-free plasma when free energy due to parallel velocity shear was available. Parallel velocity shear is capable of generating a multimode EIC spectrum with high order harmonics having amplitudes comparable to the fundamental. This cannot be explained by a current-driven mechanism [5].

6. Acknowledgments

This work was supported by the U. S. National Science Foundation and Department of Energy.

7. References

1. V. Gavrishchaka, et. al., Phys. Rev. Lett. **85**, Nov. 2000, pp. 4285-4288.
2. J. C. Foster, C. del Pozo, K. Groves and J.-P. St. Maurice, Geophys. Res. Lett. **15**, Feb. 1988, pp. 160-163.
3. J.-E. Wahlund, et al., Geophys. Res. Lett. **21**, Aug. 1994, pp. 1835-1838.
4. V. V. Gavrishchaka, S. B. Ganguli and G. I. Ganguli, Phys. Rev. Lett. **80**, Jan. 1998, pp. 728-731.
5. G. Ganguli, S. Slinker, V. Gavrishchaka, and W. Scales, Phys. Plasmas **9**, May 2002, pp. 2321-2329.
6. N. D'Angelo, Phys. Fluids **8**, Sept. 1965, pp. 1448-1750.
7. R. L. Merlino, Phys. Plasmas **9**, May 2002, pp. 1824-1825.
8. R. W. Motley, *Q Machines*, Academic, San Diego, CA, 1975.
9. N. D'Angelo and S. v. Goeler, Phys. Fluids **9**, Feb. 1966, pp. 309-313.
10. E. Agrimson, N. D'Angelo and R. L. Melrino, Phys. Rev. Lett. **86**, June 2001, pp. 5282-5285.
11. E. P. Agrimson, N. D'Angelo and R. L. Merlino, Phys. Lett. A **293**, Feb. 2002. pp. 260-265.
12. Su-Hyun Kim, E. Agrimson, M. J. Miller, N. D'Angelo, R. L. Merlino, and G. I. Ganguli, Phys. Plasmas **11**, Sept. 2004, pp. 4501-4505.
13. Su-Hyun Kim, R. L. Merlino, and G. I. Ganguli, Phys. Plasmas **13**, Jan. 2006, p. 012901.