Electrostatic ion-cyclotron waves in a plasma with negative ions

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Electrostatic ion-cyclotron (EIC) waves have been investigated in plasmas containing K^+ positive ions, electrons, and SF_6^- negative ions. Two EIC wave modes are generally present, the K^+ and SF_6^- modes. Their frequencies increase with increasing ϵ, the percentage of negative ions, while the critical electron drift velocities for excitation of either mode decrease with increasing ϵ. The observations are discussed on the basis of available theories.

I. INTRODUCTION

Electrostatic ion-cyclotron (EIC) waves have been investigated for over two decades, and various aspects of this phenomenon continue to be of interest (see, e.g., Ref. 1).

Our group has recently studied EIC waves in plasmas with two positive ion species,[2,3] with particular emphasis on aspects of relevance to the physics of the Earth's ionosphere. D'Angelo and Merlino[4] have also analyzed EIC wave modes in a plasma consisting of positive ions, negative ions, and electrons, an investigation prompted by a similar one performed on ion-acoustic waves in a plasma containing negative ions.[5]

Laboratory plasmas containing appreciable fractions of negative ions have been produced for a number of years. For instance, von Goeler *et al.*[6] directed a beam of CsCl onto the hot tungsten plate of a Q machine, creating a plasma consisting of Cs^+, Cl^-, and electrons. Wong *et al.*[7] obtained a plasma with SF_6^- negative ions by introducing the electronegative SF_6 gas into an argon discharge. More recently, a very detailed investigation of various types of negative-ion plasma sources has been reported by Sheehan and Rynn.[8] One of the methods they have investigated consists of introducing SF_6 gas into a standard Q-machine plasma. Note that SF_6 possesses a large electron capture cross section for the low-energy (~ 0.2 eV) electrons of a Q machine and, therefore, it is even more effective in producing the negative ions than, for example, in the argon discharge plasmas of Wong *et al.*[7]

EIC waves in a plasma containing negative iodine ions were observed by Sheehan.[9]

In the present paper we report on an experimental investigation of EIC waves in a plasma composed of K^+ positive ions, SF_6^- negative ions, and electrons. The experiments were performed in the Iowa Q machine and the negative ions were produced by leaking variable amounts of SF_6 gas into the device. The paper is organized as follows. In Sec. II we present a description of the experimental setup, with special emphasis on the methods used to determine the relative concentration of the negative ions. Section III contains the experimental results. It is shown, in particular, that as the percentage of negative ions is increased, the EIC wave frequencies of both the positive ion and of the negative ion modes increase, while the electron drifts required for wave excitation decrease. Section IV contains a discussion of the experimental results and a comparison with available theories.

II. EXPERIMENTAL SETUP

The experiments were performed in the Iowa single-ended Q machine. A tantalum plate of 6 cm diameter is heated by electron bombardment to a temperature of ~ 2300 °K. Potassium neutral atoms from an atomic beam oven are surface ionized on the plate and a plasma column is formed, ~ 1 m long, which is confined radially by a magnetic field of up to ~ 5 kG. Typical plasma parameters are an electron density $n \approx 10^9$–10^{10} cm^{-3}, electron and ion temperatures $T_e \approx T_{K^+} \approx 0.2$ eV, and a base pressure in the vacuum vessel of $\sim 1 \times 10^{-6}$ Torr. SF_6 gas in variable amounts can be introduced into the vessel by means of a leak valve.

The diagnostics consist of Langmuir probes and an ion mass spectrometer,[10] which has already been successfully used in other wave experiments.[3] The EIC waves are excited, as is usual in this type of experiment, by drawing an electron current along the axis of the plasma column to an exciter disk of 11 mm diameter. The spectral properties of the EIC waves are analyzed with an HP 3585A spectrum analyzer.

The experiments are typically conducted by leaking increasing amounts of SF_6 into a K^+, e^- plasma. Generally, the SF_6 partial pressure is varied in the range 0 Torr to $\sim 1 \times 10^{-5}$ Torr. At each SF_6 pressure, the percentage concentration of negative ions,

$$\epsilon = n_{SF_6^-}/n_{K^+},$$

was determined by essentially the same method used previously by, for example, Wong *et al.*[7] As SF_6 gas is introduced into the device and more and more electrons attach to SF_6 molecules, the ratio of the negative saturation current (resulting from electrons and negative ions) to the positive saturation current (resulting from positive ions) collected by a Langmuir probe, steadily decreases. Under the assumption that the negative saturation current is almost entirely due to the electrons (since their mobility is much larger than that of the negative ions), it is easily seen that, for constant positive ion density,

$$\epsilon = 1 - I_{-,s}/I^0_{-,s},$$

where $I_{-,s}$ is the negative saturation current at some given SF_6 partial pressure and $I^0_{-,s}$ is the value of $I_{-,s}$ when the SF_6 pressure is zero. The assumption that negative ions provide only a negligible contribution to the negative saturation current is valid at least up to values of ϵ as large as $\sim 98\%$.

An additional, more direct observation of the presence of negative ions was provided by the mass spectrometer de-

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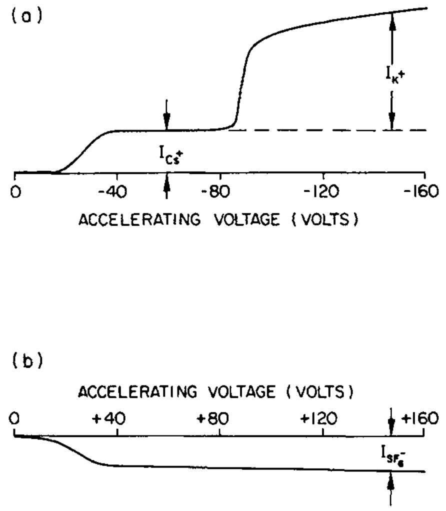

FIG. 1. Examples of data from the ion mass spectrometer for a plasma with two positive ion species (Cs^+ and K^+) and the SF_6^- negative ion species: (a) the Cs^+ and K^+ currents; (b) the SF_6^- current.

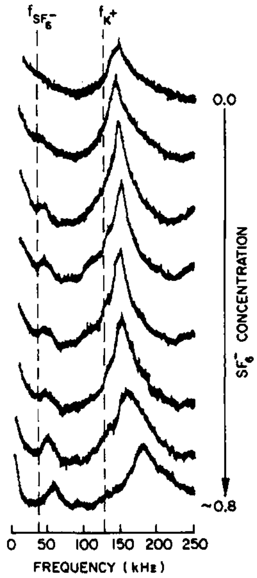

FIG. 3. Evolution of the EIC wave spectrum with ϵ, the percentage of SF_6^- ions. The SF_6^- concentration increases from top to bottom. The dashed lines indicate the cyclotron frequencies of SF_6^- and K^+ at a magnetic field of 3500 G.

scribed by Suszcynsky *et al.*[10] The spectrometer features an acceleration region that can accelerate either positive or negative thermal ions through a series of three tantalum electrodes at a 30° angle to the magnetic field of the Q machine, and a collection region in which ions are selectively collected, depending on the size of their gyroradii, by a cylindrical collector. Relative ion concentrations can be estimated from measurements of the collector current as a function of the accelerating voltage. As an example of data from this spectrometer for a plasma in which two positive ion species (K^+ and Cs^+ ions) are present together with SF_6^- negative ions and electrons, Figs. 1(a) and 1(b) show the collector current as a function of accelerating voltage, at a magnetic field of 3000 G.

III. EXPERIMENTAL RESULTS

We begin this section by showing curves of ϵ vs z, the axial distance from the hot plate, for several values of the SF_6 partial pressure (Fig. 2). Evidently, in most of the cases shown in Fig. 2, there is little variation of ϵ with z, in the range 35 cm$\leqslant z \leqslant$70 cm. The exciter disk is located at $z = 75$ cm.

The evolution of the EIC wave spectrum with ϵ is shown in Fig. 3. Two modes are generally seen, a low-frequency mode associated with the SF_6^- ion and a high-frequency K^+ ion mode. The variation of the K^+ and SF_6^- mode frequencies with magnetic field strength is shown in Fig. 4, for two different values of ϵ, namely $\epsilon \simeq 0.45$ and $\epsilon \simeq 0.85$. The dashed lines indicate the K^+ and SF_6^- cyclotron frequencies, while the solid lines are the results of fluid theory calculations on EIC waves, performed by extending the analysis of D'Angelo and Merlino,[4] valid for cold ions, to the case of finite ion temperatures, $T_{K^+} = T_{SF_6^-} = T_e$. In Fig. 5 the frequencies of the SF_6^- and K^+ modes are shown as a function of ϵ, for a fixed value of the magnetic field ($B = 3500$ G). The solid lines are the results of the fluid theory calculations.

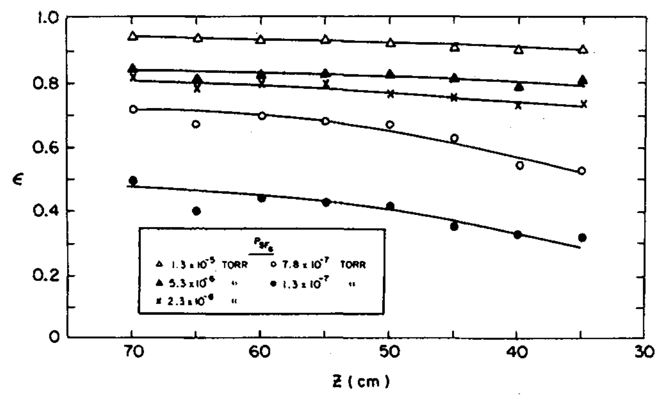

FIG. 2. The percentage of negative ions ϵ as a function of axial distance, z (cm), for several values of the SF_6 partial pressure. The tantalum hot plate is at $z = 0$ cm; the EIC wave exciter disk is at $z = 75$ cm.

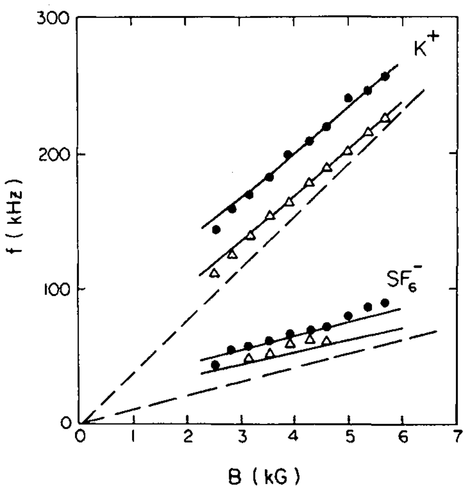

FIG. 4. Measured frequencies of the K^+ and SF_6^- modes versus magnetic field strength, for $\epsilon \simeq 0.45$ (△) and $\epsilon \simeq 0.85$ (●). The dashed lines indicate the ion-cyclotron frequencies for K^+ and SF_6^-, while the solid lines are obtained from fluid calculations on EIC waves.

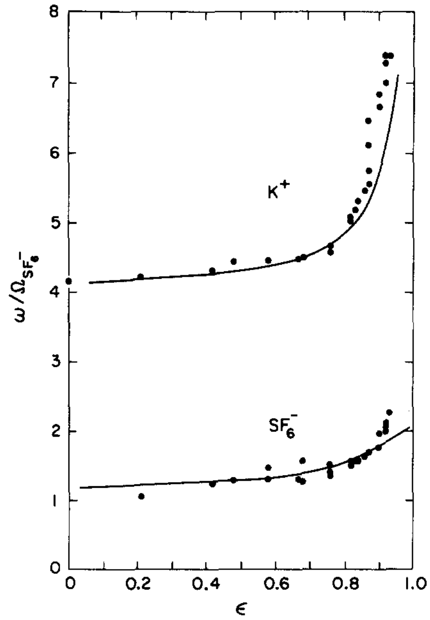

FIG. 5. The measured frequencies of the SF_6^- and K^+ modes as a function of ϵ, the percentage of negative ions. The frequencies are given in terms of the SF_6^- cyclotron frequency ($B = 3500$ G). The solid lines are the results of calculations from fluid theory.

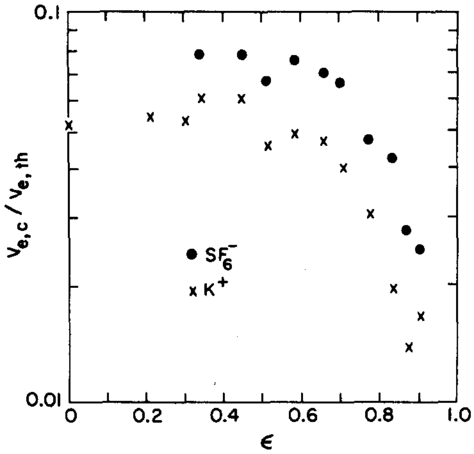

FIG. 6. The critical drift velocities (in terms of the electron thermal speed) for the EIC modes of SF_6^- and K^+, as functions of ϵ. Here $B = 2800$ G.

They are expected to be valid for values of $K_\perp \rho_i \lesssim 1$ ($K_\perp$ is the perpendicular component of the propagation vector and ρ_i is the ion gyroradius). As an example, for K^+ ions at $B = 3500$ G, $K_\perp \rho_i \simeq 0.3$.

Next, the behavior of $v_{e,c}$ vs ϵ was investigated, where $v_{e,c}$ is the critical velocity of the electrons along the magnetic field, for excitation of either the SF_6^- mode or the K^+ mode. The drift velocity v_e of the electrons along the magnetic field was obtained from the measured current to the exciter disk, $I = enAv_e$, where A is the disk area. The plasma density n was independently determined by means of a Langmuir probe. As already noted in Sec. II, the negative ion contribution to the disk curent I is generally negligible. The measured critical drifts, given in terms of the electron thermal speed, $v_{e,\text{th}}$, are presented as a function of ϵ in Fig. 6. Evidently, both modes are more easily excited as the relative concentration of negative ions becomes larger than ~ 0.7.

IV. DISCUSSION AND CONCLUSIONS

In a plasma consisting of K^+, SF_6^-, and electrons, two distinct EIC modes may be excited at the same time by drawing an electron current along the magnetic field, to a positively biased exciter disk. The main results of this investigation are the following.

(a) The frequencies of both the K^+ and the SF_6^- mode increase with increasing ϵ, the percentage of negative ions. The rate of increase is most pronounced for $\epsilon \gtrsim 0.7$.

(b) The electron drift velocities, along the magnetic field, needed to excite either mode decrease with increasing ϵ. The rate of decrease of the critical drifts becomes particularly significant for $\epsilon \gtrsim 0.7$.

Point (a) is easily accounted for by calculations, based on a three-fluid model, similar to those performed by D'Angelo and Merlino.[4] The results under (b), on the other hand, cannot be directly compared with any theory at present, since, to our knowledge, no calculations of EIC wave critical drifts have been performed for plasmas consisting of positive ions, negative ions, and electrons. One may suspect that the observed decrease of $v_{e,c}$ with increasing ϵ is probably related to the corresponding increase of the wave frequencies (Fig. 5). A frequency (and phase velocity) increase should, in turn, result in a decrease of both Landau and cyclotron damping. A similar effect has been predicted by D'Angelo[11] for the critical drift for *ion-acoustic* waves in a plasma with negative ions (see, in particular, Fig. 1 and Fig. 2 of Ref. 11). Detailed calculations of critical drifts for EIC modes in plasmas with negative ions are needed for proper comparison with our present experimental results and those of future, similar experiments.

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