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An Experimental Study of Ion Cyclotron Wave Instability Under Magnetic Field Aligned Flow Shear

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ABSTRACT

Since the electron distribution function does not flatten as electrons flow through the plasma volume, Q-machine experiments on ion cyclotron waves cannot be considered quasilinearly stabilized. A study on the experimental enhancement of electrostatic ion cyclotron (EIC) waves in a magnetized plasma by shear of parallel ion flow is presented in this work. In order to create transverse velocity gradients in inhomogeneous ion flows, a number of experiments were conducted using a double-ended Q-machine under controlled plasma conditions. It is observed that ion cyclotron waves cannot be stabilized quasilinearly in these systems because the electron distribution function does not relax fast enough as the electrons travel through the plasma. One way in which ion flow gradients influence wave formation is through the geographical link between regions of high shear and wave intensity.

Key Words: *Electrostatic, Plasma, Shear, Velocity, Ion cyclotron.*

I. INTRODUCTION

Molecular clouds, exoplanetary atmospheres, comet tails, and planetary ionospheres are just a few examples of the many astrophysical and space settings where partial ionization plasmas are prevalent. A great deal of neutral particles coexist with charged neutral atomic species (electrons and ions) in these systems, which is different from fully ionized plasmas. The presence of neutrals introduces additional collisional mechanisms that significantly influence the behavior of plasma. In particular, complex physical processes not seen in fully ionized media emerge as a result of interactions between ions and neutral and electrons and neutral. The stabilization, damping, and propagation characteristics of the plasma waves are all affected by these interactions.

The interaction between neutral and charged particles in weakly ionized plasmas can significantly alter the dynamics of the plasma waves' basic mode. Some waves, such as magnetoacoustic waves, ion acoustic waves (IAWs), and Alfvened waves, have their dispersion properties changed by collisional processes. The solar atmosphere and lower ionospheric regions experience more dampening or, in rare cases, more instability due to the ion-neutral interaction. In addition, the evolution and stability of the waves are controlled by the energy injected or dissipated in the plasma system by means of inelastic collisions, which encompass ionization, excitation, and charge exchange processes. Thus, it is well-known that ion neutral collisions play a significant role in regulating the behavior of partly ionized astrophysical plasmas.

Because of their strong interaction with ion gyrating in a magnetic field, ion cyclotron waves (ICWs) are the most important mode of plasma waves. These waves, which exhibit an extremely significant difference at frequencies close to the ion cyclotron frequency (0ci), are frequently detected in a wide range of environments, such as the solar wind, the Earth's magnetosphere, the inner heliosphere, and plasma equipment used in laboratories. To mention only a few important phenomena directly related to ICWs, there is ion acceleration, heating, and pitch-angle scattering. To comprehend the energy transfer and particle behavior of space plasmas, one must be familiar with the mechanisms involved.

Because of the electrostatic component of the ion cyclotron mode, the electrostatic ion cyclotron wave (EIC) is the most important subclass of ICWs. Because of their exceptional efficiency in transferring energy to ions, especially heavy ion species, EIC waves have garnered a lot of interest in the scientific literature. Ion species in Earth's ionosphere, like as NO + and O +, are believed to be energized and transversely heated by EIC waves. Because of this, they are highly useful for describing ion heating processes in the atmosphere and ion outflows. Accordingly, in order to resolve the basic issues in astrophysical plasma physics, one must have an in-depth understanding of the dynamics of EIC waves.

Neutral particles frequently collide with partially ionized plasmas in other locations, such as the solar chromosphere and the E-region of the ionosphere. Because of their critical role in wave propagation and instability generation, collision impacts must be considered in such a scenario. Theoretical efforts have been made in the past to incorporate ion-neutral collisions into EIC wave analysis; however, some of these models either failed to be completely self-consistent or were rendered ineffective by experimental data.

New information has highlighted the necessity to reconsider this matter. It has been shown, for instance, that EIC waves may be transmitted to lower frequencies than the traditional ion cyclotron frequency, provided that ion to neutral collisions is properly considered. This finding goes against the conventional wisdom about cyclotron waves. In addition, plasma laboratory investigations that attempt to mimic ionosphere conditions have shown that the fundamental frequency of EIC waves may arise in places around a fraction of 4ci from the theoretical claims. Curiously, these measurements also show that the wave frequency increases with increasing ion neutral collisionality, a characteristic that was not well accounted for in the earlier theoretical models.

Given these discrepancies between theory and experiment, it is evident that a more comprehensive and coherent approach is needed to analyze EIC waves in partly ionized plasmas. To accurately depict the wave behavior, it is necessary to account for the interplay of ion-neutral collisions, plasma inhomogeneity, and flow processes.

II. REVIEW OF LITERATURE

Mundhra, Raksha & Deka, P. (2023). The existence of lower hybrid drift wave (LHDW) turbulence is used to study the instability of ion cyclotron waves (ICWs). Various low-frequency drift wave turbulence fields are supported by plasma inhomogeneity in the Earth's magnetopause region, which is caused by density gradients in different parts of the medium. Lower hybrid drift waves (LHDWs) are one type of drift phenomenon that meets the resonance criteria $\omega - k \bullet v = 0$. A nonlinear wave-particle interaction model has been investigated, in which the resonant wave that accelerates the particle at the magnetopause might, via a modified field, impart its energy to ion cyclotron waves. The resonant requirement $\Omega - K \bullet v \neq 0$ and the nonlinear scattering criterion $\Omega - \ddot{\upsilon} - (K - k) \bullet v \neq 0$ are never satisfied by unstable ion cyclotron waves that are generated by nonlinear energy transfer, even if the two waves have different frequencies. The resonant and non-resonant waves' frequencies are denoted by ω and Ω, respectively, while the corresponding wave numbers are denoted by k and K. In the presence of lower hybrid drift waves (LHDWs) turbulence, we have established a nonlinear dispersion relation for ion cyclotron waves (ICWs). Using data from satellite observations, the rate of development of ion cyclotron waves in the magnetopause area has been calculated.

Telloni, Daniele et al., (2019) A description and investigation of the nature of the polarization state of solar wind parallel variations at proton scales are provided in this letter using magnetic helicity. Investigating the role of the proton cyclotron instability in the production of ion cyclotron waves (ICWs) in solar wind turbulence is our current scientific endeavor. It is found that the wave polarization is significantly affected by the proton temperature anisotropy and the power level of magnetic fluctuations at fluid scales. Here we see how resonant dissipation of high-frequency Alfvén waves can increase the temperature anisotropy of protons by heating them in a direction perpendicular to the magnetic field. Solar wind turbulence has a robust link between fluid and kinetic scales, as demonstrated by the results. When the solar wind's velocity distribution becomes unstable as a result of proton cyclotron instability, ICWs are produced locally.

Volwerk, M. et al., (2013) During Rosetta's approach to 67P/Churyumov-Gerasimenko, a theoretical model is given for the creation of ion cyclotron waves. The passage of the observational threshold is calculated for different comet activity levels; this threshold is obtained from the wave power in the undisturbed solar wind close to the comet's position during the approach phase at the correct frequency. The frequency and shape of water-group ion cyclotron waves may be estimated using the Giotto flyby at 27P/Grigg-Skjellerup. At 67P/Churyumov-Gerasimenko, with a notional outgassing rate of Q = 350×1023 molecules per second, water-group ion cyclotron waves should be seen at 600,000 km from the nucleus. The comet's true outgassing rate may be inferred from the first spot where cyclotron waves were detected during the Rosetta approach phase.

Pilipenko, Viacheslav et al., (2012) Here are the outcomes of ion-cyclotron (IC) wave observations conducted by the ST-5 satellites in the upper ionosphere (at altitudes ranging from several hundred to thousands of kilometers). For this study, over the course of three months in 2006, three nearly identical microsatellites were tracked at distances ranging from a few hundred to several thousand kilometers. The distinctive scale from the first tens to hundred kilometers is evident in the restricted localization of all ion-cyclotron wave packets discovered by two or three probes, as they were all observed at crossing one and the same latitude. Regardless, none of the three satellites detected IC waves with identical amplitudes. Simultaneously, while ST-5 was flying close to the ground-based induction magnetometer, an extended ground emission in the same frequency band was associated with an IC wave burst in the topside ionosphere. The fact that an IC instability arises under a pulse regime with a typical duration of up to about 10 minutes suggests that this is the case. The polarization structure of recorded transverse waves is characterized by a shift in the rotation direction when a satellite passes the wave structure. From the perspective of the current theories of IC wave production and waveguide propagation, the observed effects are examined.

Tyagi, Ram et al., (2011) Investigations into the electrostatic ion cyclotron (EIC) instability, parallel flow velocity shear, and characteristics solution method in plasma with massive positive ions and electrons, in the presence of a uniform direct-current (DC) electric field perpendicular to the ambient magnetic field, as well as kinetic theory. The computational method has computed the growth rate and the true frequency. Shear scale length, homogeneous d, and many other characteristics all have an impact factors affecting growth rate, including electric field, magnetic field, electron ion temperature ratio, angle between wave number k ⊥ and k |, and the impact of homogeneous. The experimental data have been used to explore the effects of the electric and magnetic fields on actual frequencies. We also examine potential industrial and laboratory plasma applications.

Jian, Lan et al., (2009) By analyzing the solar wind at 1 AU with the help of high-resolution STEREO magnetic field data, we have detected robust narrow-band ion cyclotron waves (ICWs). In the solar wind model, the waves travel at a speed lower than the local proton gyrofrequency and in a direction almost parallel to the magnetic field. The waves lack a planetary source as the twin STEREO probes were very far from any planet, including Earth. It is common for ICWs to manifest when the radial component of the interplanetary magnetic field exceeds the normal Parker spiral. There is no local generation of waves by ion pickup because the wave frequency in the spacecraft frame is greater than the local proton gyrofrequency. The data points to the super-Alfvénic solar wind as the mechanism responsible for wave production and its outward propagation. While the waves are inherently left-handed in the solar wind frame, they seem to be right-handed and left-handed in the spacecraft frame, corresponding to outward and inward propagation, respectively. The left-handed and right-handed waves' respective amplitudes provide credence to the closer-to-Sun genesis theory.

Alba, Swanny et al., (2000) One way to analyze the propagation of electrostatic waves over a magnetic field is to use the frequency range of an ion cyclotron in a toroidal device. B. The electrostatic ion cyclotron waves are excited by injecting an electromagnetic signal through an antenna system located in the middle of the plasma. First time the reversal mode has been seen in plasmas of deuterium and hydrogen. By comparing the experimental results to the theoretical dispersion relation, one may indirectly ascertain the ion temperature, which typically falls within the range of 0.05 to 0.3 eV.

III. EXPERIMENTAL SETUP

Figure 1 is a schematic of a double-ended Q machine, which was used for the tests. Two tantalum plates, HP1 and HP2, with a diameter of 6 cm and a longitudinal separation of 2 m, are the plasma sources. The temperature of each hot plate is raised to around 2200 K by using electron bombardment to heat it from behind. Neutral cesium atoms are guided onto the heated plates and ionized on their surfaces using two cesium atomic beam furnaces. A homogeneous magnetic field, usually between 0.2 and 0.4 T, radially confines the Cs+ ions and the electrons released thermionically. Ne = 1010 cm^{-3} and Ti = 0.2 eV are the usual values for the plasma density and electron temperature, as measured using a Langmuir disk probe. There are about fifteen ion gyrodiameters enclosed inside the plasma column with a magnetic field of 0.3 T, as a 0.2 eV Cs+ ion has a gyroradius of 1.8 mm.

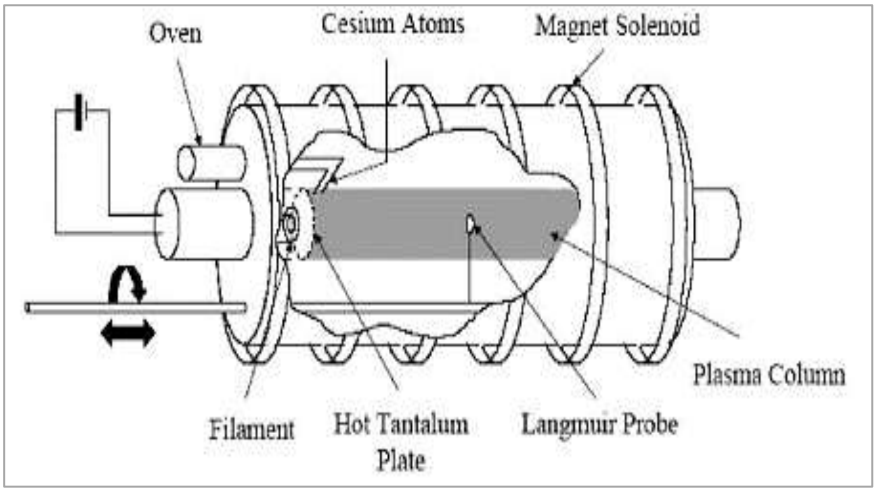

Figure 1: Double-Ended Q Machine

The ~2 - 3 V potential drop in the sheaths at the heated plates accelerates the ions generated on either plate along the magnetic field. By manipulating the temperatures of the hot plates, the net bulk ion flow may be regulated in a double-ended process. One way to do this is to evenly distribute the heating power to each plate; this will ensure that there is no net flow. As seen in Figure 2, the "ring and disk" arrangement was employed to create a setup characterized by parallel velocity shear, which is flow characterized by a transverse velocity gradient. There was a 2.2 cm diameter metal disk D and an 8 cm outer diameter and 2.3 cm inner diameter metal ring R at two separate plasma cross sections. To gather nearly all of the ion current, bias the ring and disk a few volts negative. This creates a counter flow in the plasma between the core and the outside cylindrical shell.

The shear region's usual width was several ion gyroradii, according to earlier studies of the radial profile of the ion fluxes performed using a double-sided Langmuir probe. To prevent the introduction of radial electric fields into the plasma, the ring and disk are continuously biased at the same potential. In the velocity shear area, Langmuir probe measurements of the radial plasma potential profiles demonstrate the absence of radial electric fields. D'Angelo and von Goeler16 also utilized this ring+disk combination to stimulate the low frequency parallel velocity shear instability. A straightforward sign of the presence of parallel velocity shear is the observation of this low frequency instability (f ~ 1-2 kHz) with maximal amplitude in the annular area near the edge of the disk. If the ring+disk bias is increased to more than -1 V, the low frequency mode will not be visible.

As the EIC waves traveled across the areas of transverse velocity shear, we evaluated their amplitude at different radial points after launching them into the plasma using an antenna. The rectangular stainless-steel strip of 5 cm in length and 1 cm broad was used as antenna A in Fig. 2. It was introduced through a radial port and positioned so that its length ran parallel to the magnetic field, with the normal to the antenna plane being perpendicular to B. The antenna's radial location might be changed. Broadband (white noise) or a variable-frequency RF sine wave signal of several volts was sent to the antenna. An 0.8 mm disk-shaped Langmuir probe with floating potential oscillations was used to detect the waves. The probe may be positioned at any angle relative to the two heated plates or spun in an arc over the plasma column to collect samples from various radial locations.

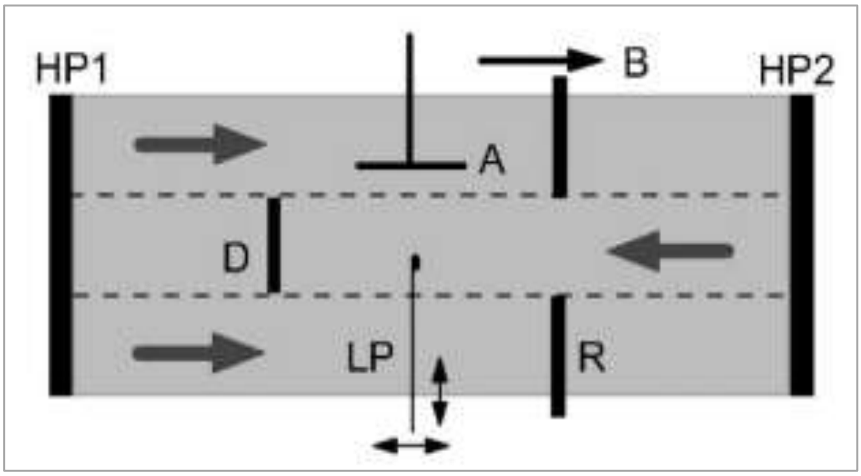

Figure 2: Inhomogeneous Ion Flow Setup

An annular zone (dashed lines) with a transverse gradient in the ion flow is created by using the ring R and disk D. Antenna A is used to transmit EIC waves, which are picked up by the Langmuir probe LP.

IV. RESULTS AND DISCUSSION

Analysis of Single Mode Wave Enhancement

The cesium ion gyrofrequency in the initial set of tests was 32 kHz, with the magnetic field set at 3000 G. To initiate the basic electrostatic ion-cyclotron mode, an input signal with a frequency of 34 kHz was used, and the antenna was positioned radially about 2 mm outside of the velocity shear area. As the EIC wave traveled through the magnetic field, spectra of the oscillations of the floating potential of a Langmuir probe were collected at different radial points in the plasma cross section that coincided with the antenna center. Figures 3 and 4 display the outcomes of these measurements. Figure 3 shows the amplitude of the EIC fundamental mode as a function of radial distance from the plasma center (r = 0). In the absence of ion flow shear, the amplitude for the scenario where the ring and disk are biased at VRD = −0.8 V is shown by the dotted line.

The EIC amplitude here drops as the probe moves away from the 1.5 cm antenna in the absence of shear. Nevertheless, the amplitude measurements (solid squares) revealed noticeable improvements (amplification) at the radial places where the shear was present when the ring and disk were bi-assed at VRD = -4V to generate parallel flow with transverse shear. The amplitude difference between the shear- and non-shear-cases (solid line) is plotted in Figure 4 to further highlight this point. The amplitude of the low-frequency (1-2 kHz) waves created by the velocity shear, which were initially detected by D'Angelo and von Goeler, is also plotted (dashed line) in Figure 4. Where there is considerable velocity shear is also where the low frequency waves are at their most amplitude. Therefore, the existence of parallel ion flow shear is definitely associated with the amplification of the EIC waves.

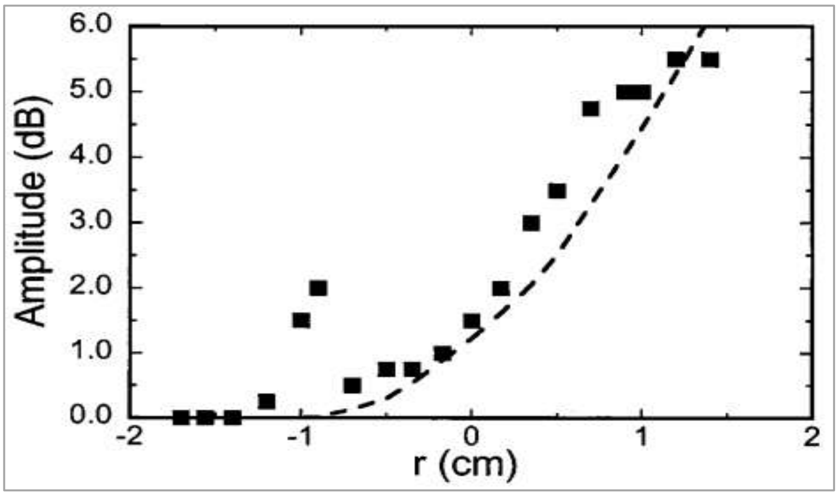

Figure 3: Radial Variation of Fundamental EIC Mode Amplitude

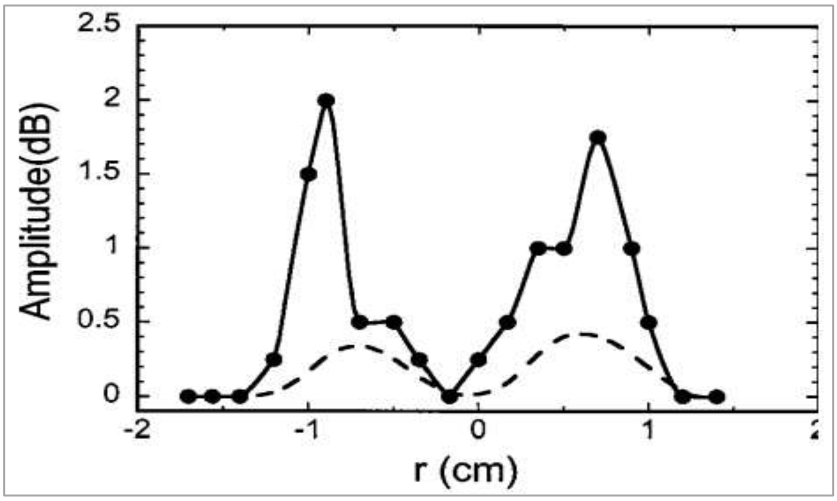

Figure 4: EIC Amplitude Difference with and Without Ion Flow Shear

Repeating the experiment with an input frequency matching the first cyclotron harmonic f =2fci yielded almost the same findings (i.e., wave amplifaction at the velocity shear area), as shown in Figures 3 and 4. Input frequencies up to 200 kHz were also studied for amplification at higher harmonics. The tracking generator of a spectrum analyzer was used to apply a signal of continually increasing frequency to the antenna, while the probe was fixed in the velocity shear area, in order to take this measurement. The amplitude of the signal on the probe was recorded at each frequency as the applied signal's frequency was gradually raised; the resultant spectrum is displayed in Fig. 5. Within a small range of frequencies close to the ion gyrofrequency and its harmonics, the plasma reacts. The plasma noise in the background is layered with the spectral peaks. For higher harmonics, the peaks are wider. Similar harmonic spectra have been seen on board the FAST satellite.

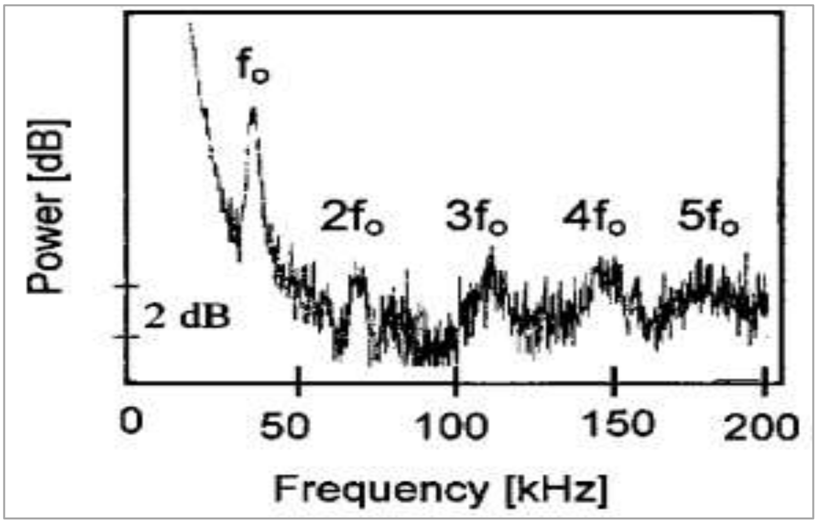

Figure 5: Multiple Harmonic Ion-Cyclotron Wave Spectrum

Simultaneous Amplification of Multiple Cyclotron Harmonics

Analyzed in Fig. 5 is the effect of sweeping the input frequency up to 200 kHz on the amplification of distinct cyclotron harmonics. A broadband input signal was also tested to see how it would affect the antenna. Hundreds of kilohertz's worth of cyclotron harmonics are all inputted at once in this scenario. An emitter-base junction transistor with reversed bias was employed as the source of noise. An rf amplifier was used to boost the output to an adequate level. The resulting white noise signal was quite flat throughout a wide frequency range, from a few kilohertz up to around 1 MHz. In the shear area, the probe's spectra of floating potential oscillations were produced by applying this signal to the antenna. In Figure 6, we can see the background plasma noise spectra in the absence of flow shear and antenna signal. But when the ring+disk was biased to generate shear and the broadband signal was fed into the antenna, the resultant spectrum in Fig. 7 shows that the basic EIC mode and four harmonics are amplified at the same time.

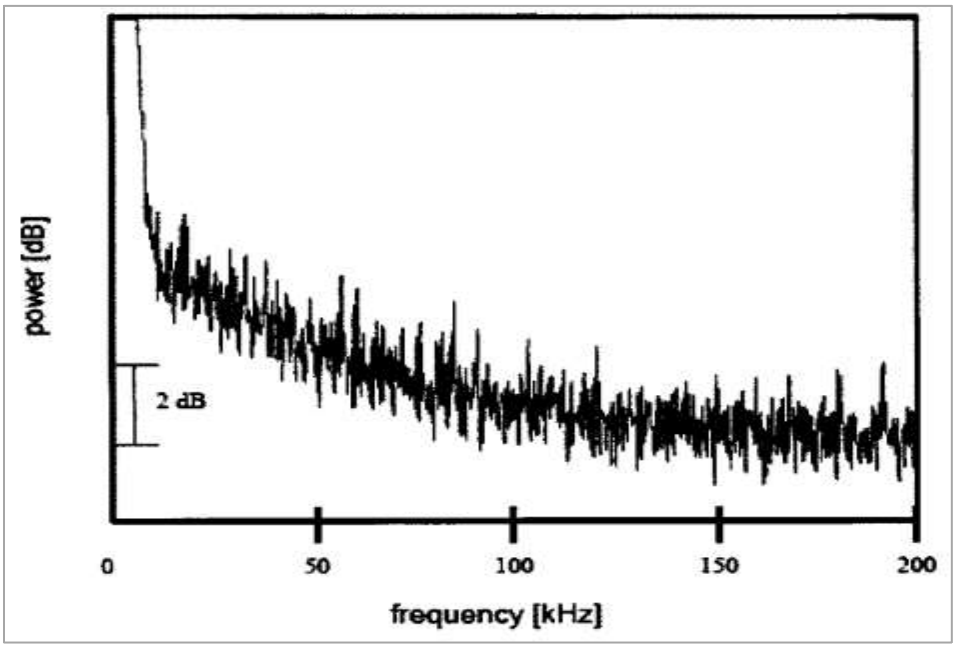

Figure 6: Broadband Excitation of Ion Cyclotron Harmonics
Background Plasma Noise Spectrum Without Ion Flow Shear and in The Absence of Antenna Excitation

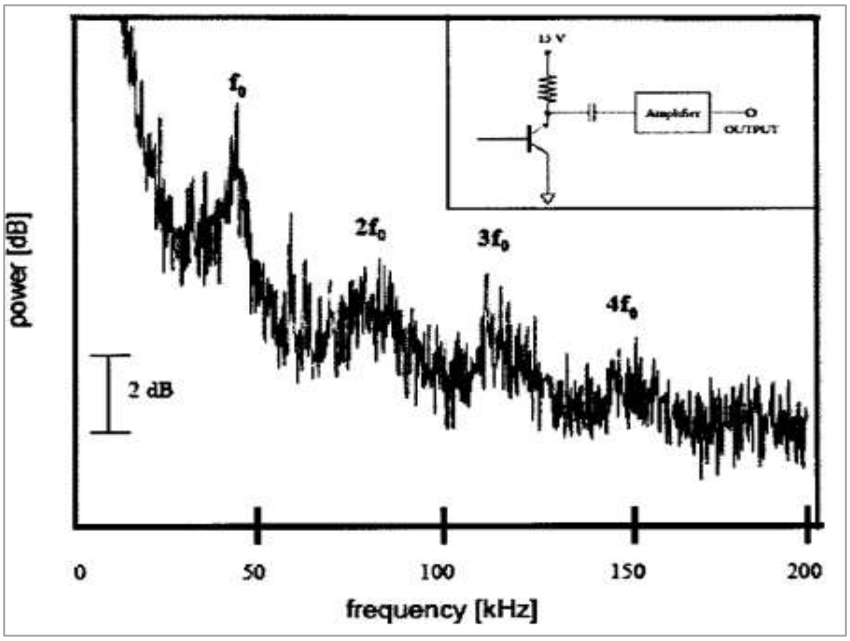

Figure 7: Multiple Harmonic Spectrum of Ion Cyclotron Waves Observed in The Presence of Ion Flow Shear Under Broadband Antenna Excitation

V. CONCLUSION

Electrostatic ion cyclotron waves in magnetized plasma are strongly influenced by parallel ion flow shear, as confirmed by the present investigation. This is readily apparent in experimental results where velocity shear is shown to significantly amplify wave amplitudes, particularly in the most intense shear regions. Consistently seen in both the fundamental ion cyclotron frequency and higher harmonics, this augmentation demonstrates the robustness of the shear-driven mechanism. The discovery also establishes that the quasilinear contribution to wave propagation from electrons' inability to stable in the plasma volume is substantial. Another evidence that flow gradients can be utilized as a significant source of plasma instability is the close proximity of maximum shear and high wave activity.

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