PARAMETRIC EXCITATION OF
NON-RESONANT ION CYCLOTRON
QUASI-MODE

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Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ * ; Microfiche \$3.00

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

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PPPL-1395

December 1977

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PARAMETRIC EXCITATION OF NON-RESONANT
ION CYCLOTRON QUASI-MODE*

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ABSTRACT

Parametric excitation of non-resonant ion cyclotron quasi-mode in a low density (i.e., $\omega_{pi} \approx \omega_{ci}$) plasma is observed when the pump frequency is $\omega_o \gtrsim 2\omega_{ci}$. The ion heating associated with the decay is also observed. Such processes may take place near the plasma surface during ICRF heating experiments in tokamaks.

In this letter we wish to report experimental observation of parametric excitation of a non-resonant ion cyclotron quasi-mode when a radio frequency field near the ion cyclotron frequency is applied in a magnetized plasma. The observed frequency for the quasi-mode is very close to the ion cyclotron frequency, and thus, this type of decay may cause an anomalous heating of ions and production of energetic tails. Such processes may take place near the plasma surface during ICRF heating of tokamak plasmas, and may lead to anomalous loading of the induction coil as well as production of high energy ions (which lead to impurity flux from the chamber walls).¹ For this reason, it is important to understand the mechanism of this decay and to establish under what condition it may be important. In our experiments we observed particularly strong excitation of this mode in the low density regime, namely $2\omega_{ci} \approx \omega_{pi} \approx \omega_o$ (where ω_{pi} is the ion plasma frequency, and ω_o is the pump frequency).

The present instability is induced mainly by electron $E \times B$ drift, although ion drift can be significant for $\omega_o \lesssim 3\Omega_i$. Assuming the lower sideband to be resonant and ignoring the upper sideband, one obtains a dispersion relation for the threshold:²

$$U^2 = 4 \frac{\omega_o^2 \epsilon \epsilon^-}{k^2 \chi_e \chi_i}, \quad (1a)$$

where $U = c(\vec{E} \times \vec{B}_o) \cdot \vec{k} / B_o^2 k$ is the electron $E \times B$ drift velocity, $\epsilon = 1 + \chi_e + \chi_i$ and ϵ^- are the plasma dielectric constant for the low frequency and the lower sideband mode, respectively. It is not difficult to include the upper sideband and also ion drift velocity

in Eq. (1a); however, their contributions are not essential for the understanding of the physics of the instability. Here, we are particularly interested in the regime $\omega_o \approx \omega_{pi} \approx \alpha \omega_{ci}$, where $\alpha \approx 2-4$. We note that in previous studies typically $\alpha \approx 20-30$ was considered.³ One can write Eq. (1a) in terms of real and imaginary parts of ϵ , ϵ^- , χ_e , and χ_i :

$$U^2 = 4 \frac{\omega_o^2}{k^2} \cdot \frac{\text{Im} \epsilon \text{Im} \epsilon^- + \text{Re} \epsilon \text{Re} \epsilon^- + i[\text{Re} \epsilon^- \text{Im} \epsilon - \text{Re} \epsilon \text{Im} \epsilon^-]}{\text{Im} \chi_e \text{Im} \chi_i - \text{Re} \chi_e \text{Re} \chi_i + i[-\text{Re} \chi_i \text{Im} \chi_e - \text{Re} \chi_e \text{Im} \chi_i]} \quad (1b)$$

We note that although the lower sideband is near resonance, in the present case it is necessary to keep $\text{Re} \epsilon^-$ in Eq. (1b), since usually $\text{Re} \epsilon^- = 0(\text{Im} \epsilon^-)$. By ignoring $\text{Im} \chi_e$ terms, Eq. (1b) can be reduced to a simpler expression:

$$\left(\frac{U}{Cs}\right)^2 = 4 \left(\frac{\omega_o}{kCs}\right)^2 \left(\frac{|\epsilon|}{\text{Re} \chi_e}\right)^2 \cdot \frac{\text{Im} \epsilon^-}{\text{Im} \chi_i} \quad (2)$$

where Cs is the ion acoustic speed and k is the decay wave number. Eq. (2) typically yields a threshold comparable to that of the ion quasi-mode² when $\omega \approx \Omega_i$. It is apparent from Eq. (2) that the threshold is high unless either $\text{Im} \chi_i$ is large or the low frequency mode is resonant (i.e. $\epsilon \approx 0$). An analysis shows that although a resonant decay usually has a lower threshold, the condition it imposes on the plasma parameters through the selection rule makes its occurrence rather limited. On the other hand, the condition is much less stringent for the ion cyclotron quasi-mode decay and one might expect it to be more relevant for the RF heating experiment.

The experiments were performed in the Princeton University L-4 device.⁴ The range of experimental parameters were as follows: the magnetic field, $B_0 \leq 4.2$ kG; the plasma density, $n_0 = 3 \times 10^8 \sim 10^9 \text{ cm}^{-3}$; the temperature, $T_e = 3\text{-}5$ eV and $T_i < 0.1$ eV; and the neutral gas filling pressure in the experiment region, $P \approx 5 \times 10^{-5}$ torr. Since an accurate determination of the magnetic field strength was crucial in this experiment, we have carefully calibrated the magnetic field monitor with the NMR technique. Thus the field strength or the ion cyclotron frequency could be determined with an accuracy of better than 0.5%. The magnetic field variations in radial and axial directions were less than 0.5%. In addition to the experimental set up described in an earlier article,⁴ we have added a perpendicular ion energy analyzer. The same RF induction coil was used to impress a radially uniform electric field in the plasma.

As the pump power was increased above a certain threshold level, we observed a sudden onset of parametric decay. A typical decay frequency spectrum obtained in a helium plasma is shown in the insert of Fig. 1. The frequency matching condition was found to be satisfied within experimental uncertainty, and the low frequency decay peak falls very closely on the helium ion cyclotron frequency. (We note that similar decay spectra were also observed in a neon plasma.) The subsequent data presented in this paper were obtained in a helium plasma. In Fig. 1, we have plotted the observed decay frequencies versus the magnetic field strength, with the pump frequency fixed at 4 MHz. As shown by the figure, the decay exists for a wide range of magnetic fields ($\omega_0/\Omega_{\text{He}} = 2.0 - 6.0$, where $\Omega_{\text{He}} = 2\pi f_{\text{ci}}(\text{He})$ is the helium ion cyclotron frequency), and the low frequency mode follows the

helium ion cyclotron frequency rather closely. We have also varied the pump frequency and observed the same variation of the low frequency mode with respect to the magnetic field.

To determine the exact nature of the decay waves, we have measured both their parallel and perpendicular wavelengths with interferometric techniques. The measured perpendicular wavelengths for the low frequency and the lower sideband were almost the same and, depending upon the plasma parameters, varied in the range of 0.4 cm to 2 cm. The parallel wavelength of the low frequency mode was 15 ~ 16 cm, and that of the lower sideband was $\lambda_{\parallel 2} \gtrsim 150$ cm. By observing the relation of measured wavelengths to the plasma density, we have concluded that the lower sideband was a cold lower hybrid wave.⁵ The low frequency mode only existed inside the RF induction coil structure and was heavily damped outside. The measured dispersion relation of the low frequency mode is shown in Fig. 2(a) by the circles, and the theoretical dispersion relationship of the electrostatic ion cyclotron wave is shown by a solid curve.⁶ The measured dispersion relation shows a clear deviation of the observed mode from the electrostatic ion cyclotron wave (except when $\omega/\Omega_{\text{He}} \approx 1.1$). Since the observed parallel wavelength is between 15 to 16 cm, the parallel phase velocity, $\omega/k_{\parallel}$, is usually much less than the electron thermal speed; and thus electron Landau damping does not play an essential role in this decay. Since for this decay $k_{\parallel}/k_{\perp} \ll 1$, decay into the "obliquely propagating second ion cyclotron wave" with $k_{\parallel} \sim k_{\perp}$, proposed by Chu et al. for a similar decay spectra, must be excluded.⁷

Additional data concerning this decay had been obtained by studying the variation of the ion cyclotron quasi-mode frequency and also the threshold with the plasma density. The experimentally measured values are plotted (circles) in Fig. 2(b). The decay spectra near $f_{ci}(\text{He})$ are shown in the inserts a, b, and c of Fig. 2(b). In order to understand this threshold and the frequency variation, we have numerically calculated the threshold using Eq. (1b), as a function of the plasma density. The electron-neutral collisions, ion-neutral collisions, and electron Landau damping were included in the imaginary part of the lower sideband dielectric constant. The ion-neutral collisions and electron Landau damping were used for the lower frequency mode. The solid curves shown in Fig. 2(b) represents the theoretically calculated threshold values. For each plasma density, the theory shows a threshold minimum for a certain frequency. As the density decreases, the frequency corresponding to threshold minimum moves from the below ion cyclotron frequency to the above, and this is consistent with the experimentally observed variation.

We have also calculated the threshold including the convective loss of the lower hybrid wave in the axial direction due to the finite size pump.³ The dashed curves in Fig. 2(b) show the numerical result including convective loss with no reflection from the end of the machine. The relative position of the threshold minimum remain unchanged, however the convective loss predicts threshold electric field approximately twice higher than those observed in the experiment. We believe since the axial wavelength of the sideband is comparable to the machine length, reflections from the end of the device may occur which would reduce

the convective losses. In particular, assuming the reflection coefficient $R \approx 0.5$, we can obtain perfect agreement between theory and experiment.

Since the ion cyclotron quasi-mode is excited near the ion cyclotron frequency, one would expect heating of ions associated with this instability. In order to measure a small increment in T_i , we propagated small amplitude electrostatic ion cyclotron test waves during the RF heating (outside the RF coils but along the same magnetic field lines as the decay region). It was previously shown that one could estimate the ion temperature from the measured dispersion relation of the electrostatic ion cyclotron waves.^{4,8} In Fig. 3, we show the experimentally measured values of ω and k (circles and crosses), and the theoretically calculated dispersion relation for various ion temperatures are shown by the solid and the dashed curves. We note that, near $\omega \approx 2\Omega_{He}$, a considerable change in the dispersion relation takes place when the ion cyclotron quasi-mode is parametrically excited. From the theoretical dispersion relation plots in Fig. 3, one can conclude that due to parametric excitation the main body of ions are heated from near room temperature (or $T_i \approx 0.025$ eV) to approximately $T_i \approx .2$ eV.

In order to detect energetic ions, we have used a perpendicular ion energy analyzer. The physical size of the analyzer is approximately 3 mm in diameter, and the separation between the electron respelling grid and ion collector plate is 0.3 mm. With this analyzer, one can look for the ions with an ion gyro radius larger than 0.3 mm (which corresponds to 0.5 eV for our experimental parameters). Therefore with this energy analyzer we should be

able to look for the hot energy tail $E_i \gtrsim 0.5$ eV. In Fig. 4, we plotted the collector ion current versus the bias voltage on a semi-log paper. We see that there is a considerable amount of hot ion tail produced as a result of the excitation of the ion cyclotron quasi-mode. We also show that when the plasma parameters are changed so no decay occurs, little change in E_i due to the presence of pump electric field was observed.

In conclusion, we have observed parametric excitation of the ion cyclotron quasi-mode in a low density plasma. The decay was observed for a wide range of magnetic fields, pump frequencies, and plasma densities. The experimental measured variation of the ion cyclotron quasi-mode frequency was shown to agree well with the theory. The measured threshold was in reasonable agreement with the theory. Associated with this decay, strong ion heating (tail as well as the main body) was observed.

We have also estimated the threshold of similar decay into the ion cyclotron quasi-mode near the edge in a typical tokamak plasma ($T_e \approx T_i \approx 20$ eV; neutral density, $n_0 \approx 10^{13}$; $B_0 \approx 20 \sim 30$ kG in a deuterium plasma), and found a relatively low threshold of $U/Cs \approx 0.1$, which for the above parameters the RF electric field $E_{ox} \approx 60$ V/cm. Since this electric field is usually exceeded near the exciter coil during the ICRF heating of tokamak plasma, we expect similar instability and ion tail production to occur.

We thank M. Yamada and K.-L. Wong for their helpful discussions, and J. Johnson, J. Taylor, and W. L. Hsu for their technical assistance.

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*This work was supported by the United States Energy Research and Development Administration, Contract EY-76-C-02-3073.

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Fig. 1. The observed decay frequency versus magnetic field strength. $f_0 = 4$ MHz. The insert shows a typical decay spectrum in a helium plasma. $B_0 = 3.15$ kG.

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Fig. 2(a). Measured dispersion relation of the ion cyclotron quasi-mode (circles) and the theoretical dispersion relationship of the electrostatic ion cyclotron wave (solid curve). $f_0 = 4$ MHz. $B_0 = 3.15$ kG.

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Fig. 2(b). Threshold and the decay frequency ($\omega \approx \Omega_{He}$) for various plasma density n_{He} (as labeled). Dashed and solid curves show the typical theoretical threshold with and without convective loss, and dots represent the experimentally measured values. Inserts show the decay spectra of the ion cyclotron quasi-mode for various plasma density. A marker (small peak) is placed at $\omega = \Omega_{He}$. Scale: 50 kHz/Div. $B_0 = 3.15$ kG.

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Fig. 3. The electrostatic ion cyclotron wave dispersion relation. The crosses are the measured dispersion in the absence of parametric decay and the circles are the measured value during decay. Solid and dotted curves are the theoretical dispersion relation for various ion temperatures.

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Fig. 4. The perpendicular ion energy analyzer ion collector current versus the bias voltage. The parameters are pump RF electric field.