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REMOTE PLASMA CONTROL, HEATING AND MEASUREMENTS OF ELECTRON DISTRIBUTION AND TRAPPED PARTICLES BY NON-LINEAR ELECTROMAGNETIC INTERACTIONS*

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Abstract

REMOTE PLASMA CONTROL, HEATING AND MEASUREMENTS OF ELECTRON DISTRIBUTION AND TRAPPED PARTICLES BY NON-LINEAR ELECTROMAGNETIC INTERACTIONS.

Non-linear electromagnetic interactions with plasmas are generalized to include excitations at both cut-offs and resonances for extraordinary and ordinary modes of propagation. Experimental confirmations are presented. The collisionless and efficient nature of a "double-resonance" scheme in which high-frequency electron resonant modes couple to low-frequency resonant ion modes is exploited for plasma control and heating of plasma ions when a direct coupling to ion modes is not feasible. A new method of measuring electron velocity distribution functions at various radii of a fusion plasma is presented in which the cross-sections of laser scattering are dramatically increased. Finally, the electromagnetic excitation and detection of magnetically trapped particles via the echo technique are examined.

We wish to present a generalized view on the remote interaction [1] of, and study of fusion plasmas by, electromagnetic radiation at the electron characteristic frequencies—cut-offs and resonances. The central idea is that electromagnetic fields incident on the plasma are enhanced at these frequencies and the electron orbits are significantly perturbed to produce, through nonlinear mixing, new plasma modes. If these new modes are also resonant, such an interaction scheme is called the "Double Resonance Method". The "double resonance" interaction can be summarized as follows and in Table I.

1. Parametric Excitation [2] (Unmodulated Carrier).

Here one large amplitude, high frequency wave drives a low frequency "signal" wave and an "idler" wave, whose frequency matches the difference of the driver and signal frequencies. A low frequency wave present initially (as part of the fluctuation spectrum) is amplified. This interaction occurs only if the pump wave power exceeds an absolute threshold which depends not only on the damping and other energy loss mechanisms but, more importantly, on the initial amplitude of the fluctuations. Another type of excitation with an unmodulated carrier occurs when the RF can induce zeroth-order changes in plasma parameters (e.g., density gradient) which then trigger instabilities (e.g., drift waves).

2. Mode-Coupling Excitation (Modulated Carrier).

Here two large amplitude, high frequency waves drive a low frequency wave at their difference frequency. This will amplify fluctuations present initially and also produce low frequency waves even if they are not favored

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TABLE I. CLASSIFICATION OF TYPES OF INTERACTION AND EXPERIMENTAL VERIFICATION.

Characteristic Frequencies Types of Interaction		Cut-off			Resonances	
Parametric Coupling	Modes	Experimental Verification	Application	Modes	Experimental Verification	Appli-
	X		(ii)	X	this paper	(i)
	0	ref. 3,4 & this paper	(iii)	0*		
Mode Coupling	X	ref. 1	(i), (ii)	X	ref. 1	(i), (iii)
	0	this paper	(i), (ii)	0*		

* Although the cold plasma theory predicts only a cut-off for the 0-mode, inclusion of the plasma pressure shows that electrostatic plasma waves (resonance) and ion waves can be excited. Rigorously speaking, the cut-off of the EM wave and the resonance of the electrostatic modes can occur simultaneously.

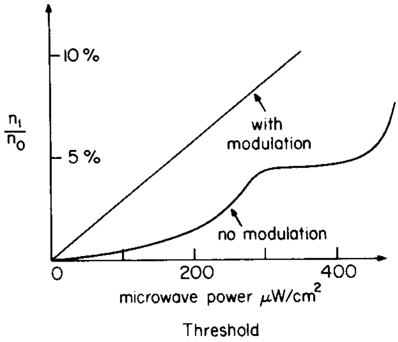

FIG. 1. Comparison between threshold behaviour of parametric and mode-coupling excitations. The amplitude of the excited electrostatic ion cyclotron mode is plotted versus the power of the high-frequency extraordinary mode. Parametric excitation is effective only after a certain threshold is reached.

in the natural spectrum. As shown in our experimental results (Fig. 1) there is no real "threshold" for mode-coupling excitation, although the loss mechanisms will partially determine the final saturated amplitude of the low frequency wave and, therefore, the input power required to produce detectable effects. Finally, the nonlinear couplings will peak where the RF electric field is large; for the X-mode $(\underline{E} \perp \underline{B}_o)$ this will occur near the right hand cut-off and upper hybrid resonance; and for the 0-mode $(\underline{E} \parallel \underline{B}_o)$ at the plasma cut-off.

As experimental results on the excitation at upper hybrid resonances have already appeared in literature [1], we shall present new experimental data involving the characteristic frequency at cut-off for the parametric and mode coupling cases. Although the fields are not as strongly enhanced as at resonance, the cut-off has the distinct advantage that it is always accessible.

Recent Experimental Results on Interactions at Cut-off.

1. Mode Coupling at the Cut-off Frequency of X Mode

A microwave beam in the extraordinary mode at frequency ω_μ modulated at the electrostatic ion cyclotron frequency ω_i is irradiated on a Q-device (f_{pe} = electron plasma frequency = 1.2 GHz, f_{ce} = electron cyclotron frequency = 3.7 GHz, $T_e = T_i$ = 0.2 eV). As the magnetic field is decreased (Fig. 2) there reaches a point where only an interaction at cut-off is possible; i.e., $\omega_\mu = \omega_R > \omega_{h\ max}$ where $\omega_R \approx (\omega_{ce}^2 + 2\omega_{pe}^2)^{1/2}$ and $\omega_{h\ max} = (\omega_c^{\ 2} + \omega_p^{\ 2})^{1/2}$.

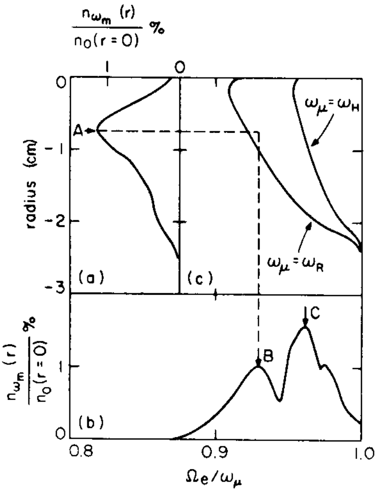

FIG. 2. Experimental verification of excitation at cut-off of extraordinary mode.
a) Radial amplitude profile of excited electrostatic ion cyclotron waves at a B field (Ω_e/ω_μ = 0.923) denoted by the arrow B.
b) Amplitude of excited electrostatic ion cyclotron waves versus variation in B field Ω_e/ω_μ measured with probe at radius A. Arrow B indicates the cut-off excitation, while arrow C the upper hybrid excitation.
c) Loci of $\omega_\mu = \omega_h$ and $\omega_\mu = \omega_R$ versus Ω_e/ω_μ. The radial density variation is included. The interaction at cut-off is confirmed when $\omega_\mu = \omega_R > \omega_{h\ max}$. Coincident enhancements of excited ion oscillations are observed at a radial location and B field that correspond to the locus $\omega_\mu = \omega_R$.

The amplitude of the excited ion oscillations $n_i/n_o(\omega_{ci})$ is monitored as function of radius and magnetic field. Coincident enhancements of $n_i/n_o(\omega_{ci})$ are observed at peaks A, B at the radius where $\omega_\mu = \omega_R$, indicating the occurrence of the cut-off interaction. The power required is approximately 3.0 mW/cm.

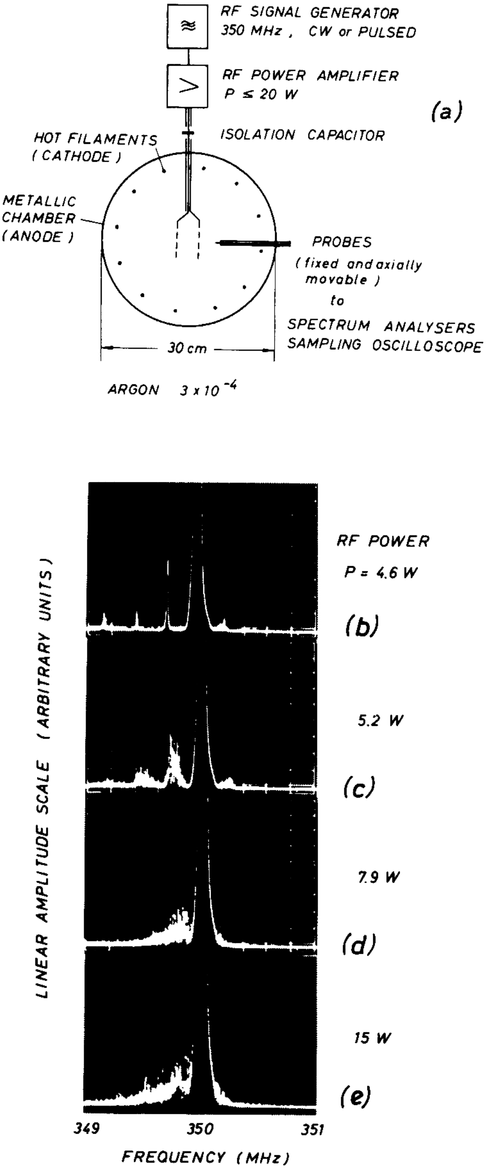

FIG. 3. Parametric excitation near $\omega_\mu = \omega_{pe}$.

a) Experimental arrangement in the UCLA DP device. Typical parameters of the plasma generated by a dc discharge in argon at 3×10^{-4} Torr are: $T_e \cong 2$ eV, $T_i \cong 0.2$ eV, $n_0 \cong 10^9$ cm^{-3}, $\delta n/n_i \approx 10^{-3}$. The pump rf electric field with frequency $f_0 = 350$ MHz is provided by a parallel-plate capacitor (4 cm × 4 cm wire grids, 3 cm spacing) immersed into the center of the plasma. The electrodes are coupled capacitively to the rf generator in order to avoid dc currents flowing into the plasma.

b), c), d), e) Spectra of the pump and the electrostatic plasma waves versus input pump power; the signals were detected by a shielded probe inside the plasma.

2. Mode Coupling at the Cut-off Frequency of O-mode.

Similar interactions between the high frequency electromagnetic waves in the ordinary mode and the electrostatic ion cyclotron modes are observed. The O-mode excitation is confirmed by noting that $\omega_u \tilde{=} \omega_p(r_o)$, where r_o = the radius of interaction, and that the interaction is insensitive to changes in the B field. The threshold power for the excitation of electrostatic ion cyclotron modes ($n_o \simeq 10^{11}$ cm^{-3}, $T_e = T_i = 0.2$ eV) is 3.0 mW/cm .

3. Parametric Coupling Between an Electromagnetic Pump ω_o, an Electron Plasma Wave ω_e, and an Ion Acoustic Wave ω_i; $\omega_o = \omega_e + \omega_i$.

The experiment [3] is performed in a uniform, quiescent, collisionless magnetic-field-free plasma as produced by the UCLA double-plasma devices. The pump electromagnetic field with frequency f_o = 350 MHz is provided by a parallel-plate capacitor immersed in the center of the plasma. The rf spectrum of a signal picked up by a shielded probe inside the plasma is shown in Fig. 3b-d. The incident rf signal is tuned to the electron plasma frequency as determined from Langmuir probe measurements. As the rf pump power is raised beyond a sharp threshold ($P_t \simeq 4.5$ watts) a nearly monochromatic sideband appears at $\omega_e = \omega_o - \omega_i$ below the pump frequency ω_o. With increasing pump power the sideband grows, smaller sidebands appear at $\omega_o + \omega_i$, $\omega_o - 2\omega_i$ (Fig. 3b), the lines broaden (Fig. 3c,d) and finally approach a continuous noise spectrum (Fig. 3e).

The asymmetric line shape is a result of the downward decay of the pump into electron and ion modes. The threshold field of E_{th} = 7V/cm and the measured wave number of the electron and ion modes k = 5.3 cm^{-1} are in good agreement with the theoretical predictions E_{th} = 5.1 V/cm and k = 6.3 cm^{-1}. The concept of parametric coupling was also demonstrated recently in an ionospheric experiment [4].

Applications to Fusion Plasmas

1. Plasma Control.

Control of low-frequency instabilities in toroidal devices can be achieved by feedback stabilization if localized signals can be injected into the interior of a thermonuclear plasma. A complete remote detection and feedback stabilization using microwaves have been demonstrated. Since it operates directly on the internal electric field in a plasma, the double resonance method is intrinsically more efficient than the method of neutral beams [5]. If the density is between 10^{15} and 10^{16} cm^{-3}, the wavelength of the incident beam with $\omega = \omega_h$ lies in the range 300-750 μm. This is the range covered by recently developed far-infrared lasers, such as HCN, which can provide much higher power than submillimeter microwave generators. There is, however, a problem of accessibility. The thickness d of the evanescent layer between the $\omega = \omega_r$ and $\omega = \omega_h$ radii is easily found to be

$$d = \omega_c \Lambda(\omega_o - \omega_c)/\omega_p^2$$

where Λ is the density scale length. In the experiments described above, $k_o d$ is approximately $3(\Lambda/\lambda_o) \simeq 0.5$, where $k_o = \omega_o/c$, and the Budden tunneling factor $\exp-(1/2)\pi\, k_o d) \simeq 0.5$ is not significant. In a reactor, however, $k_o d$ will be larger than 10^3, and no tunneling to the resonance layer can be expected. There are three ways around this problem.

a) The interaction at the cut-off can be used. For an O-mode, Ginzburg [6] has shown that the electric field near the cut-off reaches an amplitude 1.9 $(k_o\Lambda)^{1/6}$ times the incident amplitude. Thus the cut-off interaction would be expected to be relatively stronger in a fusion plasma than in the present experiments.

b) For $\omega_p < \omega_c$, the evanescent layer can be avoided by making use of the magnetic field inhomogeneity [7] in a torus. The laser beam must then be injected, by means of a mirror, from the strong field side of a torus near the major axis.

c) The radiation at $\omega = \omega_h$ can be generated at the resonant layer by a second nonlinear process in which two CO_2 lasers operating on different lines produce a difference frequency equal to ω_h. One of the lasers is then modulated at the feedback frequency. The efficiency has been calculated by Etievant et al. [8] and depends critically on the width of the resonance. It is probable, however, that a weakly nonlinear theory such as this will not describe the results adequately. Even if the down-conversion is efficient, the efficiency will still be limited by the Manley-Rowe relation to the ratio of wavelengths ($\sim$ 3%). This should not be a hardship, since currently available dc power from CO_2 lasers is more than 10^7 times that available from HCN lasers.

2. Ion Heating at the Electrostatic Ion Cyclotron Frequencies and Lower Hybrid Frequency.

We wish to point out an rf heating method which is external to the plasma and does not suffer from the coupling problems of most ion cyclotron heating schemes [9].

Rf power is coupled with high efficiency into the plasma at electron resonances such as the electron cyclotron and the upper hybrid resonance or with lower efficiency at the electron plasma frequency. Due to gradients and/or parametric effects electron normal modes couple to ion normal modes such as drift waves, ion cyclotron and acoustic waves [1]. For low damping ion waves easily become unstable and build up to significant amplitudes. For single-frequency heating a minimum threshold field is required to excite ion oscillations. However, with two heating frequencies separated in frequency by an ion resonance such as the lower hybrid resonance, forced ion oscillations are obtained for any heating power.

The driven electrostatic ion oscillations lead to an ion temperature increase when the phase between field and particle velocity is randomized. In a collisionless plasma this is accomplished by modulating the frequency difference stochastically with correlation time approximately equal to the ion oscillation period. With the results of Fig. 1 and an ion heating model developed in [10] we estimate a required X-mode heating power $P_{\mathrm{absorbed}} \simeq 4$ W/cm^2 to raise the ion temperature from 0.2 eV to 1 eV on a Q-machine plasma at B = 800 G.

3. Measurement of the Electron Velocity Distribution.

In fusion plasmas it is of interest to measure the electron distribution at various radii. Since laser scattering by electron plasma waves has a much larger cross section (NL^3, the number of electrons participating in the collective motion) than scattering by incoherent electrons, we propose a method which involves the parametric excitation of electron plasma waves by an electromagnetic wave in the ordinary mode, matched to the plasma wave frequency at the desired radius.

As suggested by our experimental findings [scattering wavelength $\lambda \ll$ density gradient length, $n_o/(dn_o/dx)$] the parametric excitation of electron plasma waves can be enhanced by the high energy tail in the electron distribution. The overall enhancement can be estimated as

$$\frac{S_{par}(\omega_e,k_e)}{S_{eq}(\omega_e,k_e)} \propto \frac{f_o(v=\omega_e/k_e)}{\frac{\partial f_o}{\partial v}(v=\omega_e/k_e)} \; \frac{1}{[1 - E^2/E^2_{thres}]}$$

where $S_{par}(\omega_e)$ is the power spectrum of plasma fluctuations under parametric excitation which are enhanced by the high energy tail, and $S_{eq}(\omega_e)$ is the power spectrum for a Maxwellian plasma without parametric excitation and high energy tail. The factor $f_o(v)/f_o'(v)$ represents the Cerenkov emission of plasma waves by non-thermal electrons. Our experimental results have shown that an enhancement by several orders of magnitude can be expected. An excitation source of 1 watt at ω_e should be sufficient. The detection of the plasma waves (ω_e, k_e) is accomplished by the scattering of another pulsed laser beam of much higher frequency and power. The angle of the scattering determines $\underline{k}_e$, and the upper and lower sidebands of the high frequency beam can yield amplitude of plasma waves propagating along or opposite to the direction of current flow on Tokamaks or spherators. By measuring a range of k_e's through variation of the detection angle θ, the amplitudes of plasma waves at different phase velocities ω_e/k_e and $f_o(v=\omega_e/k_e)$ can be estimated.

4. Measurement of Trapped Particle Behavior.

Recently the excitation and detection of magnetically trapped particle echoes have been proposed [11] to study the lifetime, orbits, and diffusion rate of such particles. The spatially selective nature of the electromagnetic excitation at either the cyclotron frequency or the upper hybrid frequency which resonantly changes V is particularly suited to this task. The bounce frequency

$$\omega_b^{-1} = \frac{1}{2\pi} \oint ds \left[\frac{2}{m} (W - \mu B - q\Phi) \right]^{-1/2}$$

and hence the phase of the magnetically trapped particle, is altered if $\mu = 1/2\ MV^2/B$ is changed by two successive electromagnetic impulses separated by τ. Depending on their phase $\theta = \omega_b \tau$ with respect to these pulses some trapped particles acquire higher or lower energy and their bounce frequencies are correspondingly increased or reduced. These accelerations and decelerations of various groups of trapped particles in phase space permit a regrouping of the trapped particles at time τ after the second impulse; echoes can be observed as collective radiation from the trapped particles.

By following the procedure of ref. 11 we derive an expression for the number of trapped particles that regroup to form echoes as:

$$|n^{(2)}/N_o|_{echo} = (\delta W/\bar{W})^2\ (\bar{\omega}_b T_o)^2$$

where $\underline{T}_o$ = the duration of the excitation electromagnetic pulse
$\bar{\omega}_b$ = the average bounce frequenccy,
$\delta\bar{W} = \delta(1/2\ mV^2)$ = change in perpendicular energy as a result of resonant acceleration by the pulse of electromagnetic waves at ω_b of duration T_o,
$\bar{W}$ = average energy of trapped particle.

An estimate of the magnitude and duration of the applied perturbation pulses can be made, based on our experience with electrostatic trapped particles [3] that an echo $n^{(2)}/N_o \gtrsim 10^{-2}$ can be detected. The precise time of occurrence of echoes makes it possible to devise detection schemes with the above sensitivity. We found that $q\phi/W \simeq 0.1$ and $\omega_b T_o \simeq 0.5$ can be sufficient to generate observable echoes. Under present parameters of fusion devices, $\bar{W} = 500$ eV and $(\bar{\omega}_b)_{el} \simeq 10^9$ rad/sec, electromagnetic pulses of 10 W and duration 10 nsec can be employed to generate trapped particle echoes.

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