INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

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RESEARCH REPORT

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<abstract>

Suprathermal electrons which carry a seed current are generated by non-resonant parametric decay instability during initial phase of lower hybrid current startup in the JIPP T-IIU tokamak. From the numerical analysis, it is found that parametrically excited lower hybrid waves at lower side band can bridge the spectral gap between the thermal velocity and the low velocity end in the pump power spectrum.

Startup and steady-state operation of plasma current by rf in a tokamak have attracted considerable attention from reactor consideration because the tokamak design would become practical by removing an ohmic-heating coil system. Recently, WT-2[1], JIPP T-IIU[2] and PLT[3] groups have succeeded in plasma current startup by lower hybrid(LH) wave up to 5, 20, 100 kA, respectively. As is discussed in the papers on LH current startup[1,3] and sustainment[4], the mechanisms of creating an initial seed current without an ohmic field and filling up the velocity gap between the bulk electron thermal velocity and the low velocity end in power spectrum of the pump wave have become interesting problems. In WT-2[1] suprathermal electrons as carrier of the seed current are provided by electron cyclotron heating (ECH), while in PLT[3] energetic electrons higher than 20 keV may be produced by initial boost of small flux of vertical field. We showed that the plasma current could be started up by LH power even in the absence of preionization by ECH[2]. In this letter we report that suprathermal electrons resulted from the non-resonant parametric decay instability generate the seed current in early phase of discharge and that LH waves parametrically excited at the lower side band (LSB) with respect to the pump frequency can bridge the spectral gap.

The experiment was carried out in the Japanese Institute of Plasma Physics (JIPP) T-IIU tokamak[2] with minor radius a= 0.25 m and major radius 0.93 m. By injecting 35.5 GHz microwave power with ordinary mode[5] at electron cyclotron resonance (ECR), an initial hydrogen plasma with the central electron temperature T_{e0} $\sim$ 20 eV and density n_{e0} $\sim 4\times 10^{12}$ cm^{-3} is produced in the magnetic field B_t of 12.7 kG. Pulse height analysis of soft X-rays shows that ECR plasma has no suprathermal electron, and presents a striking contrast to the enhanced soft X-ray emissions from ECR plasma in WT-2[1]. The rf power of 800 MHz is launched into the ECR plasma *via* a pair of C-shaped waveguides[6]. The phase angle between the waveguides is set equal to 180 degrees in order to minimize the reflection power. Temporal evolution of plasma parameters for typical discharge is plotted in Figs. 1(a)~(h). When rf pulse is switched on at 7 ms after ECH pulse, a strong signal of LSB by parametric instability P_{lsb} appears during about 20 ms (referred to as phase I) and then decreases to the low level (referred to as phase II). At the same time, a large number of fast neutral (FN) particles $N_{fn\perp}$ with 1.8 keV which are measured perpendicularly are counted. The count of soft X-rays N_{sx} at the energy of 5 keV increases during phase I. The frequencies of parametrically excited LSB's [the insert in Fig. 1(g)] correspond nearly to the ion cyclotron harmonics ($\omega_{ci}/2\pi$= 19 MHz) at the rf probe. The amplitude of LSB received is not so large as that in LH ion heating experiment, because the growth rate at lower density plasma of $n_e=(0.5\text{-}1)\times 10^{11}$ cm^{-3} where the rf probe is immersed is considerably small. As shown in Figs. 1(g) and (h), ion tail formation correlates well with the occurrence of parametric decay instability. The measured energy spectra of FN particles at t= 75 ms (phase I) and at 145 ms (phase II) show that ion tail with apparent temperature $T_{i\perp h}\sim 1$ keV is clearly formed in both phases. Because no FN particles with such high energy are counted by the parallel FN analyzer, it is concluded that ions are accelerated across the toroidal field by decay waves and are not thermalized because of weak poloidal field and low density. As for the electrons, T_{e0} obtained from the intensity ratio of oxygen lines increases from 20 to 100 eV during phase I [in Fig. 1(f)] . It is noted that a small number of suprathermal electrons lower than 5 keV are counted by pulse height analyzer (PHA) before t~80 ms (phase I), though energetic electrons higher than 5 keV are hardly observed. Therefore, it is likely that the plasma current I_p of ~ 3 kA is carried by these suprathermal electrons. After $t \sim 85$ ms (phase II), energetic electron tail with 30 keV is observed by the PHA. The result indicates that larger plasma current in phase II is carried primarily by the energetic electron tail. The generation of suprathermal electrons and heating of bulk electrons in phase I are qualitatively similar to the earlier experiments in the linear machine of Porkolab et al.[7] and Wong et al.[8]. They observed strong electron heating and tail formation due to electron Landau damping of LSB wave generated by parametric instability of electron plasma waves. Theoretical power spectrum $P(N_{0\parallel})$ and integrated power spectrum are plotted in Fig. 2(a), where $N_{0\parallel}$ ($=ck_{0\parallel}/\omega_0$) is the parallel refractive index of the pump wave. Most of rf power is in the $N_{0\parallel}$-range from 5 to 1.3 which is determined by accessibility condition and interacts directly with fast electrons of which resonant energy E_{res} is 10-100 keV. It is obvious that suprathermal electrons as the seed current in phase I are not generated by the pump wave but by the parametric instability. At the end of phase I, the parametric instability becomes weak because rf pump wave may be weakened through direct interactions with fast electrons. In phase II, there is no clear mechanism for supplying the suprathermal electrons except very weak parametric instability indicated in Figs. 1(g) and (h). Non-linear wave interactions[9] due to occurrence of energetic electron tail may play a role of providing suprathermal electrons as the seed current. The function of parametric instability in initial phase of LH current startup is a contrast to that in LH current drive for an ohmic plasma[10], where the excitation of the parametric instability is described to be ineffective for the driving.

As shown in Fig. 1(b), the loop voltage V_{loop} increases negatively when the energetic electron tail is created. The dc field generates return current of bulk electrons to conserve the poloidal flux. It becomes evident that bulk electrons are mainly heated by return current in phase II and partially in phase I[11] .

The generation of suprathermal electrons by parametric instability is examined numerically by the method similar to that of Takase et al.[12] and Porkolab[13] . By taking the measured values of T_{e0} and $\bar{n}_e$ into consideration, the profiles of T_e and n_e are assumed as follows: $T_e(r)= T_{e0}(1-r^2/a^2)^2$ at $r< (4/5)a$ and $n_e(r)= n_{e0}(1-r^2/a^2)$ at $r< (7/8)a$. The peripheral profiles are obtained by exterpolating T_e and n_e measured by a floating double probe at the shadow of the limiter and by connecting smoothly the above-mentioned profiles [Fig. 3(a)] . We solve the parametric dispersion relation with the assumption of $T_i = T_e/3$ ignoring the pump of finite extent with the model of plane stratified plasma, $\varepsilon + (\mu^2/4)\chi_e\chi_i/\varepsilon^- = 0$. Here, ε and ε^- are the dielectric functions at the low frequency $(\omega, \vec{k})$ and at the LSB $(\omega^- = \omega - \omega_0, \vec{k}^- = \vec{k} - \vec{k}_0)$, $\chi_e (\chi_i)$ the electron (ion) susceptibility at the low frequency, and μ the coupling constant. Perpendicular and parallel pump fields($E_{0\perp}(r)$ and $E_{0\parallel}(r)$), derived by WKB method are estimated by using the conservation law of power flow taking into account of accessible rate of power $\xi(r)$. Here, $N_{0\parallel} = 1.5$ corresponding to the main part of spectrum determined by accessibility is used. The growth rate γ/ω_0 maximized with respect to $k_\perp$ and real part ω_R/ω_0 at various radial positions are calculated as functions of $ck_\parallel/\omega_0$. By transforming the results into $|\gamma/\omega_R^-|$ and $|\omega_R^-/\omega_0|$ *vs.* refractive index $N_\parallel^-$ $(=ck_\parallel^-/\omega_R^-)$ of LSB with $k_\parallel^- = k_\parallel - k_{0\parallel}$ and $\omega_R^- = \omega_R - \omega_0$, the result at four radial positions at t= 64 ms (curves (1)~(4)) is shown in Fig. 2(b). It is confirmed that ε is entirely away from the resonance $(\varepsilon(\omega, \vec{k}) \neq 0)$ and that low frequency wave which is the quasimode (QM) is characterized by $\omega_R = O(k_\parallel v_{te})$. The excited LSB at each radial position is the LH wave which satisfies the dispersion relation $\varepsilon^-(\omega^-, \vec{k}^-) \sim 0$ and

$|N_\parallel|$ which gives the maximum growth rate is nearly equal to $c/(3.5v_{te})$ for each curve (also see Fig. 3(e)). Excited LSB heats the bulk electrons by electron Landau damping and generates the suprathermal electrons. Because the growth rate $\gamma/\omega_{\bar{R}}$ of LSB monotonically decreases with decreasing $N_\parallel$, the energy gap between near the electron thermal velocity and the low velocity end of grill power spectrum is almost filled up by LSB. It is noted that the broad spectrum of $N_\parallel$ was observed by laser scattering method in the Alcator-C LH ion heating experiment[14]. Radial distributions of various plasma parameters at t= 64 ms, which give the maximum growth rate with respect to $k_\parallel$ and $k_\perp$ are plotted in Figs. 3(b) $\sim$ (f). As a result of WKB approximation, pump $E_{0\parallel}$ decreases while $E_{0\perp}$ increases up to 3 kV/cm as the wave propagates inwards [Fig. 3(c)] . The maximum growth rate of LSB and QM takes place at $r\sim$ $(3/4)a$ [Fig. 3(d)] . The origin of coupling is $\vec{E}_{0\perp} \times \vec{B}_t$ rather than $\vec{E}_{0\parallel}$ except near the waveguides, because $\omega_0/\omega_{LH} < (\omega_0/\omega_{ci})^{1/2}$ (=6.4). It can be concluded that ion tail formation originates in ion cyclotron damping of QM rather than that of LSB, because $|\omega_{\bar{R}}/k_\perp^- v_{ti}|$ = 15 $\sim$ 60, $k_\perp v_{ti}/\omega_{ci}$ = 0.5 $\sim$ 2.5 [Figs. 3(e) and (f)] and $(\omega - n\omega_{ci})/k_\parallel v_{ti} < 1$. No QM contributes to create the suprathermal electrons, because $\omega_R/k_\parallel v_{te} <$ about 0.3 .

In conclusion, the toroidal plasma current is started up by the suprathermal electrons which are produced by parametrically excited LH wave at LSB. The power spectrum of excited LSB can fill up the spectral gap at the early phase of the discharge. The suprathermal electrons as carrier of the seed current are accelerated by both LSB and pump wave, until larger plasma current flows.

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Figure Captions

Fig. 1. Time evolution of (a) ECH and rf power P_{ECH} and P_{LH}, plasma current I_p, (b) loop voltage, (c) line-averaged plasma density, (d) microwave emission near the second electron cyclotron harmonic I_{ece}, (e) counts of soft X-rays at the energy of 5 keV, (f) central electron temperature measured by a floating double probe (·), intensity ratio of oxygen line (+) and Thomson scattering (∘), (g) lower side band power at f= 700 MHz received by the rf probe, and frequency spectrum, and (h) counts of fast neutral particles measured perpendicularly at the energy of 1.8 keV.

Fig. 2. (a) Power spectrum and integrated power spectrum of pump waves at the phase difference of 180 degrees between the waveguides. (b) Growth rate and frequency maximized with $k_\perp$ as a function of parallel refractive index of lower side band wave. Curves (1), (2), (3) and (4) are calculated by the plasma parameters in r=0, 12.5, 18.8 and 27.0 cm at t= 64 ms. For references, resonant energy of electron E_{res} coresponding to $N_{0\parallel}$ and $N_{\bar{\parallel}}$ is shown in both figures.

Fig. 3. Radial variations of (a) temperature, density and ω_0/ω_{LH}, (b) coupling constant μ and accessible rate of pump wave ξ, (c) parallel and perpendicular pump electric fields, (d) normalized growth rate γ/ω_0 of low frequency wave maximized with $k_\parallel$ and $k_\perp$, and normalized frequency ω_R/ω_0, (e) $|\omega_{\bar{R}}/k_{\bar{\parallel}} v_{te}|$ and $|\omega_{\bar{R}}/k_{\bar{\perp}} v_{ti}|$ at the maximum growth rate, (f) $\omega_R/k_\parallel v_{te}$ and $k_\perp v_{ti}/\omega_{ci}$ at the maximum growth rate. The results of (a)~ (f) are calculated from parameters at t= 64 ms.

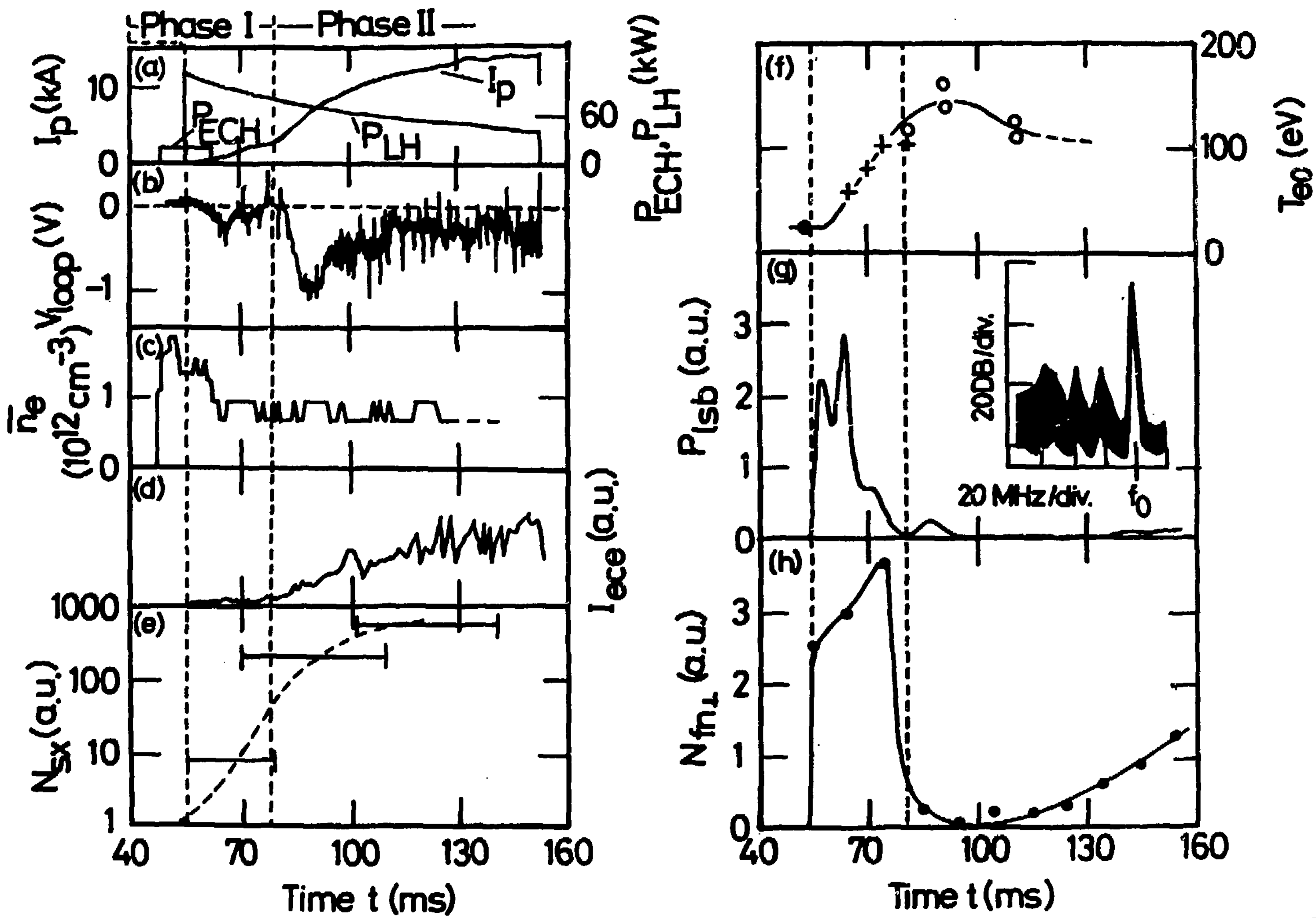
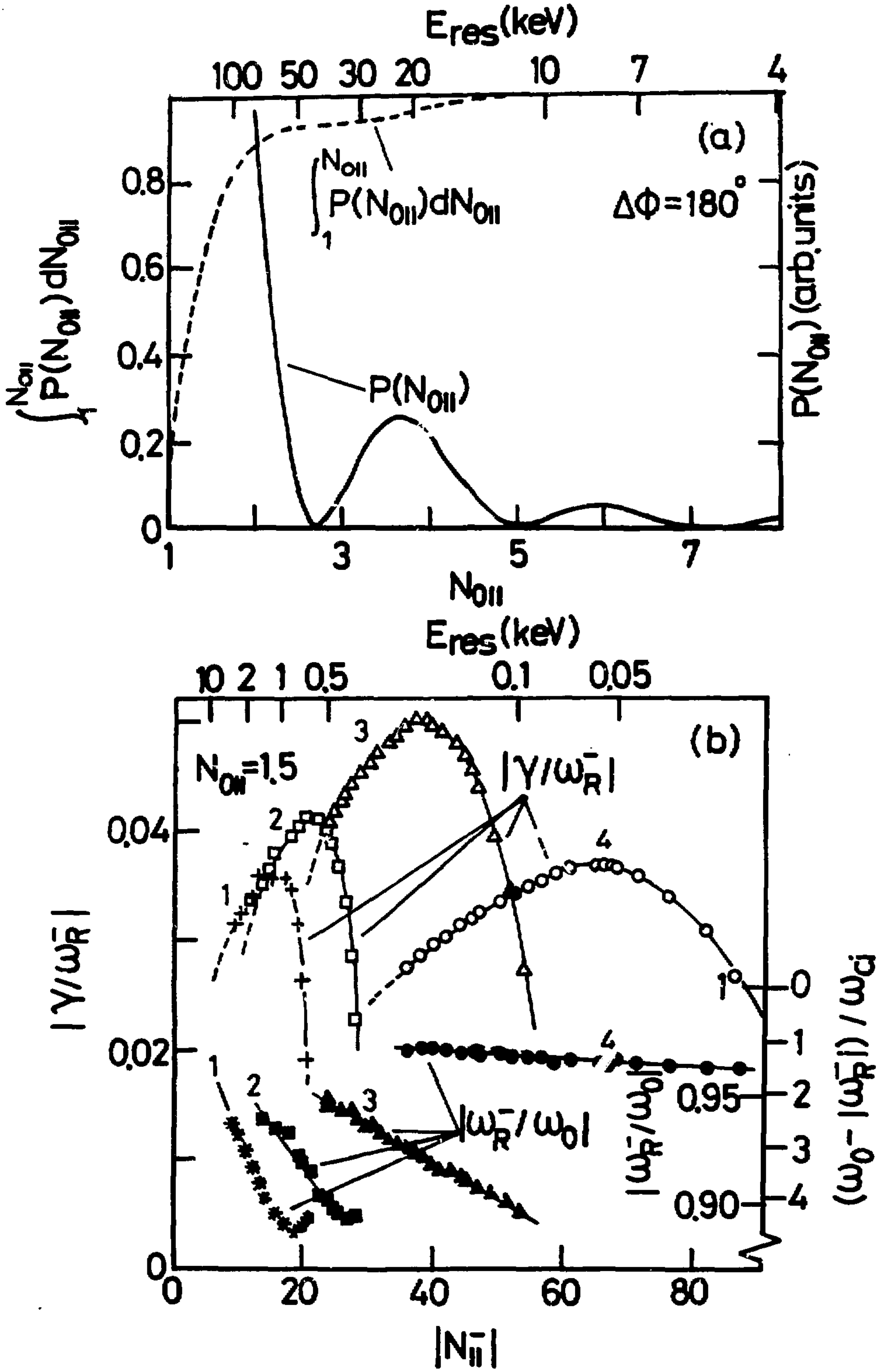

Phase I
Phase II
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Ip
PECH
PLH
Ip (kA)
PECH, PLH (kW)
Vloop (V)
ne (10^12 cm^-3)
Iece (a.u.)
Nsx (a.u.)
Te0 (eV)
Plsb (a.u.)
Nfn⊥ (a.u.)
20DB/div.
20 MHz/div.
f0
Time t (ms)
Time t (ms)

Fig.1.



Eres(keV)
100 50 30 20 10 7 4
(a)
ΔΦ=180°
P(N011)
N011
0.8
0.6
0.4
0.2
0
1 3 5 7
P(N011) (arb.units)
Eres(keV)
10 2 1 0.5 0.1 0.05
(b)
N011=1.5
|γ/ωR⁻|
|ωR⁻/ω0|
0.04
0.02
0
0 20 40 60 80
|N∥⁻|
0.95
0.90
(ω0 − |ωR⁻|) / ωci

Fig. 2.

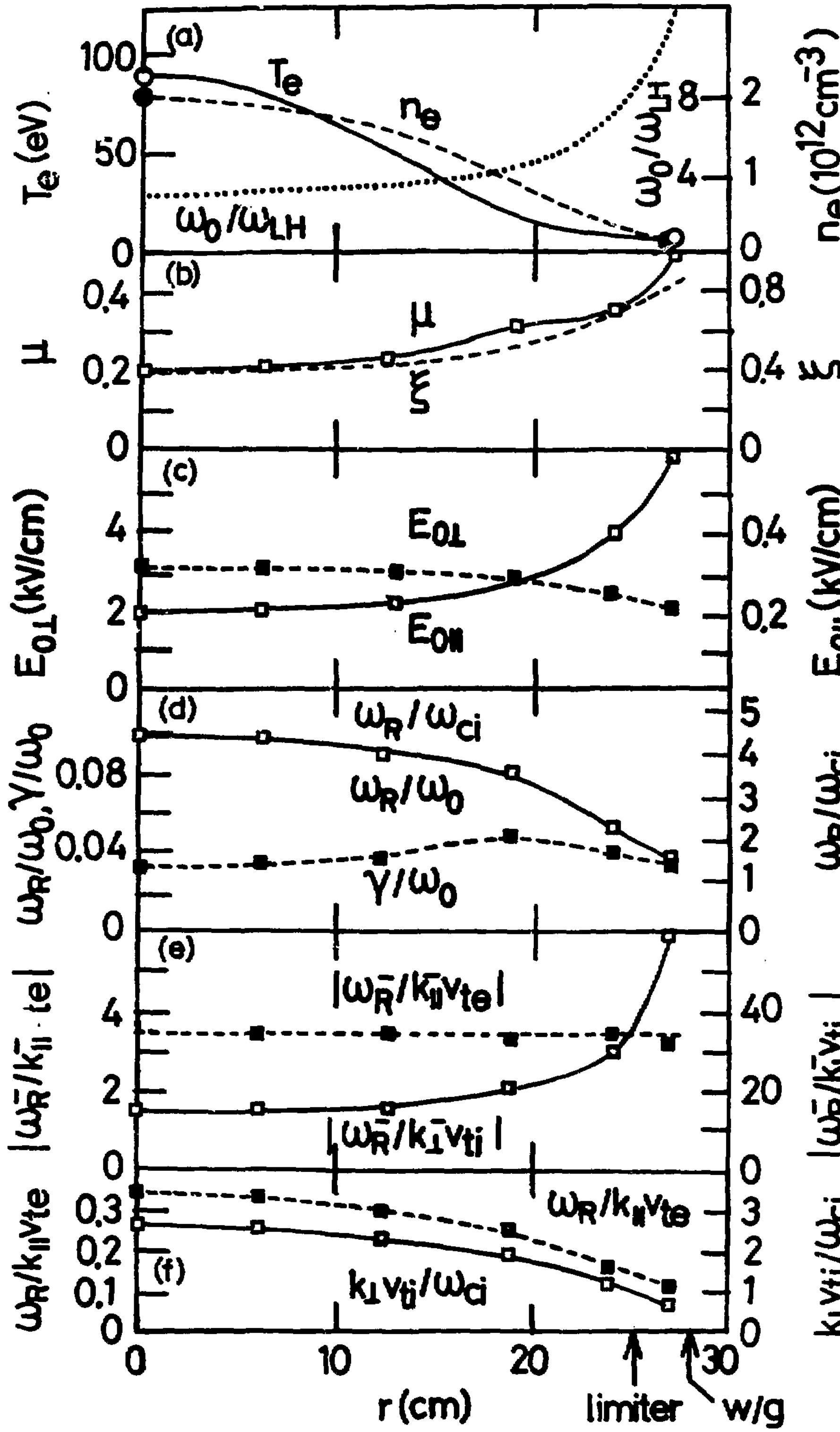

(a)
(b)
(c)
(d)
(e)
(f)
Te (eV)
ne (10^12 cm^-3)
ω0/ωLH
Te
ne
μ
ξ
E0⊥ (kV/cm)
E0∥ (kV/cm)
E0⊥
E0∥
ωR/ω0, γ/ω0
ωR/ωci
ωR/ω0
γ/ω0
|ωR/kII vte|
|ωR/k⊥ vti|
ωR/kII vte
k⊥vti/ωci
r (cm)
limiter
w/g

Fig. 3.