OBSERVATION OF PARAMETRIC INSTABILITIES
IN LOWER HYBRID
RADIO FREQUENCY HEATING OF TOKAMAKS

BY

M. PORKOLAB, S. BERNABEI, W. M. HOOKE
R. W. MOTLEY AND T. NAGASHIMA

PLASMA PHYSICS
LABORATORY

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Energy Research and Development Administration Contract E(11-1)-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

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

Observation of Parametric Instabilities in Lower Hybrid
Radio Frequency Heating of Tokamaks

M. Porkolab, S. Bernabei, W. M. Hooke, R. W. Motley
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

T. Nagashima
Japan Atomic Energy Research Institute
Tokai Ibaraki-ken, Japan

December 1976

PPPL-1311

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

cf
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Observation of Parametric Instabilities in Lower Hybrid

Radio Frequency Heating of Tokamaks

M. Porkolab, S. Bernabei, W. M. Hooke, R. W. Motley
Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540

and T. Nagashima
Japan Atomic Energy Research Institute
Tokai Ibaraki-ken, Japan

ABSTRACT

Experimental data is presented which shows that during lower hybrid radio frequency heating of the Princeton ATC Tokamak, parametric instabilities are excited, and the ion heating correlates with the presence of the parametric spectra. A theoretical interpretation of the parametric instabilities is presented.

Radio frequency heating near the lower hybrid frequency may offer an attractive means to heat high temperature plasmas toward thermonuclear conditions.¹ We wish to present experimental results which show that during lower hybrid heating (LHH) of present day tokamaks parametric instabilities play a fundamental role. In particular, our results show that the ion heating observed in the recent ATC Tokamak LHH experiments is associated with the presence of parametric instabilities. Furthermore, the shape of the decay spectrum, when compared with theoretical calculations, allows us to estimate the position of the decay region, and this in turn gives us information about the radial location of the heating.

The experiments were performed on the Princeton ATC Tokamak.² An electrostatic probe was inserted in the plasma diagonally across the torus

from the port where microwave power, up to 120 kW at 800 MHz, was injected through a single waveguide or a split waveguide. The two sections of the split waveguide were driven in phase opposition, (i.e., 180° out of phase). The cross-sectional area of both waveguide systems was 10 x 20 cm. The details of the heating results were reported recently,³ The movable probe was a coaxial shielded T-shaped electrostatic rf probe, with a frequency response good up to 1 GHz (flat within 3 dB). The probe was located radially in the shadow of the limiter, but near the end of the experiments it was pushed several centimeters inside the plasma column. This resulted in an increase of the decay spectrum by as much as 10 dB, indicating that the waves originate from points deeper in the plasma than the normal probe position. During these experiments the plasma parameters were as follows: $B = 15-20$ kG, minor radius $a = 17$ cm, average density (measured by a microwave interferometer) $\bar{n}_0 \approx 5 \times 10^{12} - 3 \times 10^{13}$ in H^+ or D^+ plasma. The electron temperatures were typically $T_e \approx 0.8 - 1.2$ keV at the center, decreasing rapidly to $T_e \approx 500$ eV in $r \approx 4-5$ cm, and at $r \approx (2/3)a$ $T_e \approx 200 - 300$ eV. The ion temperature is $T_i \approx 250$ at the center, and is assumed to be decreasing more slowly radially outward. Thus, while near $r \approx 0$ $T_e \approx 3 T_i$, near $r \approx (2/3)a$ $T_e \approx T_i$. The electron density profiles decreased much more slowly than the electron temperature profiles,³ typically $n_a(r) \approx n_{\max}/2$ at $r \approx (2/3)a$.

As the injected microwave power was increased above a critical threshold value, parametric decay spectra of the form shown in Fig. 1 were observed on the rf probe. In the present case the threshold power was about $P_{in} \approx 10$ kW (net transmitted power). We see that sidebands as well as the low frequency spectra are observed so that the usual frequency selection rules are approximately satisfied. Note that the upper sideband is negligibly small as compared with the lower sideband, indicating

weak linear damping of these modes. We note that the spread of the decay spectra is typically $\Delta f \approx 250$ MHz, so that $\Delta f/f_0 \approx 0.30$. Although the spectrum is relatively broad, beats of the ion cyclotron frequency and its harmonics are often visible on top of the broad background spectrum. The cyclotron harmonics are particularly pronounced at lower powers, at some particular densities, and using a single waveguide. An example of such a spectrum is also shown in Fig. 1(e,f). One often observes a peak in the spectrum near $\Delta f/f_0 \approx 0.20$, and a relatively large gap in the sideband (as opposed to the low frequency spectrum), separated from the 800 MHz pump frequency by about 50 - 100 MHz, (i.e., several ion cyclotron harmonics). This gap may be due to trapping part of the decay spectrum inside the plasma (so it does not propagate out to the probe). Finally, a narrow peak around $f \approx 14$ MHz (independent of ion mass) is also often observed.

As the density was varied, we found that for lower densities the threshold increased in a systematic way. For densities such that $1.9 \lesssim \omega_0/\omega_{LH}(\text{max})$ no decay was observed in either D^+ or H^+ plasma for the maximum transmitted power of $P = 120$ kW. In Fig. 2 we show the magnitude of the maxima of the sideband decay waves as a function of input power for three different densities in Deuterium. The curves A, B, C, correspond to mean densities of $\bar{n}_0 = (1.8, 1.4 \text{ and } 1.17) \times 10^{13} \text{ cm}^{-3}$, respectively. Using $n_{\text{max}} \approx 1.5 \bar{n}_0$, we obtain $\omega_0/\omega_{LH}(\text{max}) \approx 1.4, 1.7, \text{ and } 1.8$, respectively. For densities $\bar{n}_0 \lesssim 9 \times 10^{12} \text{ cm}^{-3}$ (or $\omega_0/\omega_{LH}(\text{max}) \gtrsim 1.9$) no parametric decay was observed in D^+ plasma for $P \lesssim 120$ kW. In H^+ plasma no decay was observed for $\bar{n}_0 < 6 \times 10^{12} \text{ cm}^{-3}$ or $\omega_0/\omega_{LH}(\text{max}) \gtrsim 1.40$. Of course, if decay occurred radially outward from the center, locally higher values of $[\omega_0/\omega_{LH}(r)]$ may be

allowed. However, the fact that there is a rather sharp low density limit beyond which no parametric decay was observed, shows that decay cannot occur much above $(\omega_o/\omega_{LH}) \approx 2$. This experimental observation suggests that parametric decay (at least for the main part of the spectrum) must occur within the bulk of the plasma, i.e., mostly near densities $n > 6 \times 10^{12}$, (but not necessarily at the center). Thus, we must be observing rf signals on our probe which propagate out of the interior. We also remark that the very low frequency part of the spectrum (i.e., $\omega < \omega_{ci}$) had sometimes a lower density threshold than the higher frequency components; thus, this part of the spectrum may be produced further outside radially, possibly due to the portion of pump power coupled to the fast mode.³ However, at the low densities this part of the spectrum was typically 20 - 30 dB down from the pump wave amplitude, and had no observable heating associated with it.

In Fig. 2(b), we show in H^+ the power dependence of various measures of the decay wave intensity, and the change in the main body of the ion energy distribution function as measured by a charge exchange neutral analyzer. Similar results were obtained in D^+ gas. In these experiments we found that there was a direct correspondence between the production of fast charge exchange neutrals (both for the low energy "bulk" component and the high energy tail) and parametric decay: both had the same input power threshold, and the same density threshold. In particular, as the density was lowered below the critical values presented in Fig. 2, neither parametric decay nor ion heating was observed. This correlation between parametric decay and ion heating was observed for both the single, and the split waveguide couplers.

Several important questions arise in connection with the present results: (a) What is the exact process by which the parametric instabilities are excited; (b) Where is the location of the parametric decay and thus the associated ion heating; (c) What is the mechanism by which the ions are heated. We have carried out an extensive theoretical investigation to answer some of these questions, especially those related to the linear theory of parametric instabilities, the effects of inhomogeneities, and some work concerning the ion heating. The details of this theoretical work will be presented elsewhere.⁴ Here we wish to summarize some of these results inasmuch as they help to interpret the present experimental results. Our theoretical investigation (both analytical and numerical) indicate that in order to explain the frequency spread of $(\Delta f/f) \approx 0.3$, one must have $\omega_o/\omega_{LH} \text{ (local)} \lesssim 2$. In this regime it is possible to excite both cold lower hybrid waves and hot ion plasma waves and/or ion Bernstein waves as sidebands. The low frequency modes in the regime $\omega_o/\omega_{LH} \text{ (local)} \lesssim 2$ correspond to ion-cyclotron (quasi) modes and/or electron-Landau damped quasi-modes, depending upon T_e , T_i , $k_\parallel \lambda_D$, and U/C_s (where λ_D is the electron Debye length, $U = c E_o/B$ is the $\underline{E} \times \underline{B}$ drift velocity, and C_s is the speed of sound).^{4,5} In Fig. 3, we show examples from our numerical results,⁴ which demonstrate a frequency spread of $\Delta f/f_o \lesssim 0.3$, as observed experimentally. We note more pronounced ion cyclotron harmonics as T_e/T_i approaches unity. We also note that the maximum frequency separation corresponds to the turning point of the sideband waves ω_2 (i.e., the transition point from backward to forward waves). In general, the numerically obtained decay spectra shows good qualitative agreement (even though one might expect nonlinear effects to distort spectra).

An important theoretical question is the effect of non-uniformities of the pump wave upon the instability thresholds. If we assume that the pump wave is confined by resonance cones to a finite width as defined by the waveguides, finite length stabilization eliminates most instabilities for $(\omega_o/\omega_{LH}) > 2$.^{4,5} On the contrary, for $\omega_o/\omega_{LH} < 2$ decay into the hot ion plasma waves (the short wavelength forward wave branch in Fig. 3) can occur due to the low convective losses of these waves. In addition, decay into the backward wave branch may also occur if the sidebands form standing modes in the toroidal direction near the rational magnetic surfaces, (these modes have recently been discussed by Coppi, et al.⁶). Again, the condition for the existence of these modes is that $\omega_o/\omega_{LH} \lesssim 2$. In this case convection due to shear determines the threshold. Our estimates indicate that the threshold due to shear is $U/C_s \lesssim 0.5$. The foregoing considerations for the ATC parameters predict threshold power in the range of $P_{in} \approx 10-100$ kW for $(\omega_o/\omega_{LH}) < 2$, roughly in agreement with experimental observations.

Our analysis also indicates that whereas for $(T_e/T_i) \approx 1$, $\text{Im } \chi_i(\omega) \approx \text{Im } \chi_e(\omega)$, for $(T_e/T_i) = 3$, $\text{Im } \chi_e(\omega) \gg \text{Im } \chi_i(\omega)$ (where $\chi_j(\omega)$ is the susceptibility of species j). Since according to quasi-linear theory, heating of a particular species of particles is proportional to $\text{Im } \chi_j$, we believe that the main body of ions are heated by the low frequency ion cyclotron quasi-modes (i.e., where $T_e \approx T_i$). On the other hand, we expect that the sideband heats mainly the parallel component of the electrons, and the perpendicular tail of the ions. For $T_e \gtrsim 3T_i$, even the low frequency quasi-modes should heat the bulk electron temperature. Combined with the experimentally measured density and temperature profiles, these results suggest that in ATC parametric decay and ion heating

should occur in the region $0.5 \lesssim (r/a) \lesssim 0.8$ where $2 \gtrsim T_e/T_i \gtrsim 1$, and $n(r) \approx n_0(\text{max})/(2)$. Of course, strong turbulence effects may modify some of these conclusions; for example, the sideband may also interact with the main body ion temperature if the wave amplitudes are sufficiently large.⁴ A more detailed account of this work will be reported elsewhere.

One of us (M.P.) wishes to thank the Alexander von Humboldt Foundation for an honorary fellowship at the Max Planck Institute, Garching, Germany, where part of the theoretical work was carried out. We thank Dr. R. A. Ellis, Jr., for helping with the construction of the rf probe. We also thank the operating crew of ATC.

Work supported by the U.S. Energy Research and Development Administration under Contract No. E(11-1)-3073.

REFERENCES

- ¹T. H. Stix, Phys. Rev. Lett. 15, 878 (1965); V. E., Golant, Zh. Tekh. Fiz. 41, 2492 (1971) [Sov. Phys. Tech. Phys. 16, 1980 (1973)].
- ²K. Bol, et. al., Phys. Rev. Lett. 29, 1495 (1972).
- ³S. Bernabei, et. al., presented at the Third Symposium on Plasma Heating in Toroidal Devices (Int. Sch. of Plasma Physics, Varenna, Italy, 1976), (to be published).
- ⁴M. Porkolab, ibid; also, to be published.
- ⁵M. Porkolab, Phys. Fluids 17, 1432 (1974); also, in Proceedings of the Symposium on Plasma Heating in Toroidal Devices, (Editrice Compositori, Bologna, Italy, 1974), pp. 28-49.
- ⁶B. Coppi, et. al., Nuclear Fusion 16, 309 (1976).

766183

Fig. 1 (a-d). Parametric decay spectrum due to a split waveguide; D_2 gas; $n = 1.8 \times 10^{13} \text{ cm}^{-3}$. (a) $P_{in} = 63 \text{ kW}$, (b) $P_{in} = 41 \text{ kW}$, (c) $P_{in} = 19 \text{ kW}$, (d) $P_{in} = 1.5 \text{ kW}$, $f_{ci} \approx 13 \text{ MHz}$. (e-f) Parametric decay spectrum due to a single waveguide; H_2 gas; $n = 1.2 \times 10^{13} \text{ cm}^{-3}$, $P_{in} = 35 \text{ kW}$, (e) low frequency spectrum, (f) pump and sideband; $f_{ci} \approx 25 \text{ MHz}$.

766184

Fig. 2(a). Sideband amplitude versus P_{in} for a split waveguide coupler; D_2 gas. (A) $n = 1.8 \times 10^{13} \text{ cm}^{-3}$, (B) $n = 1.4 \times 10^{13} \text{ cm}^{-3}$, (C) $n = 1.1 \times 10^{13} \text{ cm}^{-3}$. For $n < 9 \times 10^{12} \text{ cm}^{-3}$, $P < 100 \text{ kW}$, no decay is observed. (b) T_{il} and decay wave amplitude versus P_{in} . H_2 gas; $n = 1.5 \times 10^{13} \text{ cm}^{-3}$.

766185

Fig. 3. Frequency (ω) and growth rate (γ_0) as a function of $k\lambda_{De}$ in H^+ plasma. (a) $\omega_0/\omega_{LH} = 1.57$, $T_e/T_i = 3$, $U/C_s = 1$, $k_{\perp}\lambda_{De} = 2 \times 10^{-3}$, $k_{\parallel}\lambda_{De} = 6 \times 10^{-3}$, $\omega_{pe}^2/\omega_{ce}^2 = 0.25$; (b) $\omega_0/\omega_{LH} = 1.91$, $T_e/T_i = 1$, $U/C_s = 1$, $k_{\perp}\lambda_{De} = 6 \times 10^{-3}$, $k_{\parallel}\lambda_{De} = 1 \times 10^{-2}$, $\omega_{pe}^2/\omega_{ce}^2 = 0.152$. For both (a) and (b) $\omega_{ci}/\omega_0 = 0.033$.