(FWHM) of the shape resonance to be 23 ± 6 meV, consistent with the theoretical predictions which range from 15 to 28 meV.[1,3] The energy interval between the peaks is estimated to be 53 meV, compared to 46 meV in, for example, Broad and Reinhardt's[1] prediction. With normalization at low energy the data match the continuum at high energy.

Previous observations of the shape resonance in electron scattering from hydrogen have been reported,[7,8] but attempts to see it in the emission from an arc-discharge plasma,[9] and in a stellar spectrum,[10] have failed. The Feshbach resonance has, to our knowledge, so far gone unreported. We regard the observations reported here as persuasive evidence for the existence of these resonances in photoabsorption, but leave to future work the task of refining our preliminary measurement of cross sections and widths. The apparatus is also being modified to study the Stark-effect quenching of these structures.

We thank Dr. P. A. Lovoi for his contributions, Dr. W. A. Fitzsimmons for his advice, J. Hontas and J. Sanchez for their skilled workmanship, and Professor C. Leavitt for his support. We are indebted to the personnel of the LAMPF accelerator, especially J. van Dyke and Dr. R. Werbeck, for their large contribution to the success of this experiment.

*Work performed mostly under the auspices of the U. S. Energy Research and Development Administration.

[1]J. T. Broad and W. P. Reinhardt, Phys. Rev. A 14, 2159 (1976).

[2]J. Macek, Proc. Phys. Soc., London 92, 365 (1967).

[3]C. D. Lin, Phys. Rev. Lett. 35, 1150 (1975).

[4]See S. J. Risley, in *Atomic Physics IV. Proceedings of the Fourth International Conference on Atomic Physics, 1974*, edited by G. Zu Putlitz, E. W. Weber, and A. Winnacker (Plenum, New York, 1975), for a more complete list of references to earlier work.

[5]W. P. Reinhardt, private communication.

[6]We are using "chopped beam" from the LAMPF accelerator.

[7]J. W. McGowan, J. F. Williams, and F. K. Carley, Phys. Rev. 180, 132 (1969).

[8]J. F. Williams and B. A. Willis, J. Phys. B 7, L61 (1974).

[9]W. R. Ott, J. Slater, J. Cooper, and G. Gieres, Phys. Rev. A 12, 2009 (1975).

[10]T. P. Snow, Astrophys. J. 198, 361 (1975).

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

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

and

T. Nagashima
Japan Atomic Energy Research Institute, Tokai Ibaraki-ken, Japan
(Received 29 November 1976)

Experimental data are presented which show that during lower-hybrid, radio-frequency heating of the Princeton University adiabatic toroidal compressor 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 adiabatic toroidal compressor (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 University 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 wave guide or a split wave guide.

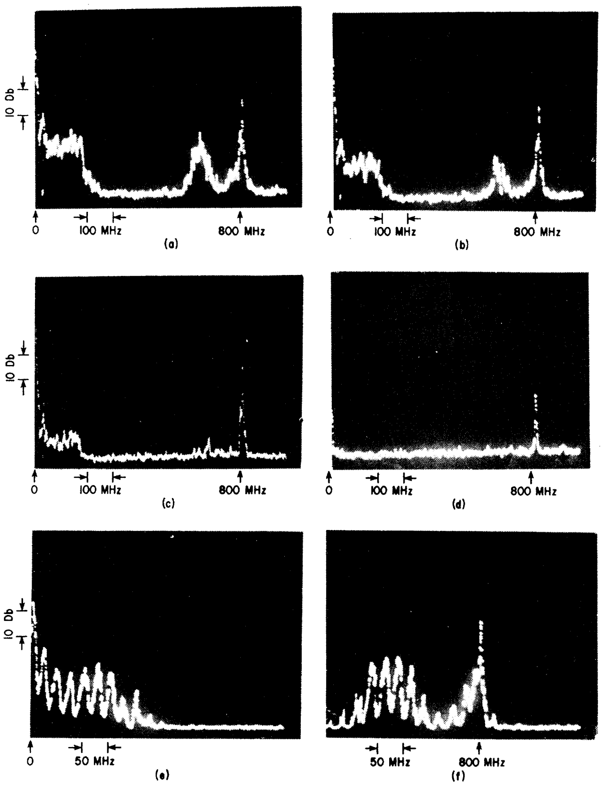

FIG. 1. (a)–(d) Parametric-decay spectrum due to a split wave guide; D_2 gas; $\bar{n}=1.8\times10^{13}$ cm^{-3}. (a) $P_{in}=63$ kW, (b) $P_{in}=41$ kW, (c) $P_{in}=19$ kW, and (d) $P_{in}=1.5$ kW; $f_{ci}\simeq 13$ MHz. (e), (f) Parametric-decay spectrum due to a single wave guide; H_2 gas; $\bar{n}=1.2\times10^{13}$ cm^{-3}, $P_{in}=35$ kW. (e) Low-frequency spectrum, and (f) pump and sideband; $f_{ci}\simeq 25$ MHz.

The two sections of the split wave guide were driven in phase opposition (i.e., 180° out of phase). The cross-sectional area of both wave-guide systems was 10 cm × 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, and average density (measured by a microwave interferometer) $\bar{n}_0\simeq5\times10^{12}-3\times10^{13}$ in H^+ or D^+ plasma. The electron temperatures were typically $T_e\simeq0.8-1.2$ keV at the center, decreasing rapidly to $T_e\simeq500$ eV for $r\simeq4-5$ cm, and at $r\simeq\frac{2}{3}a$, $T_e\simeq200-300$ eV. The ion temperature is $T_i\simeq250$ at the center, and is assumed to be decreasing more slowly radially outward. Thus, near $r\simeq0$, $T_e\simeq3T_i$, while near $r\simeq\frac{2}{3}a$, $T_e\simeq T_i$. The electron-density profiles decreased much more slowly than the electron-temperature profiles[3]; typically $n_a(r)\simeq\frac{1}{2}n_{max}$ at $r\simeq\frac{2}{3}a$.

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 $P_{in}\simeq10$ 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 $\Delta f\simeq250$ MHz, so that $\Delta f/f_0\simeq0.30$. 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 with use of a single wave guide. An example of such a spectrum is also shown in Figs. 1(e) and 1(f). One often observes a peak in the spectrum near $\Delta f/f_0\simeq0.20$, 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 $f\simeq14$ 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 $1.9\lesssim\omega_0/\omega_{LH}^{max}$ 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, and C, correspond to mean densities of $\bar{n}_0=(1.8,\ 1.4,\ \text{and}\ 1.17)\times10^{13}$ cm^{-3}, respectively. Using $n_{max}\simeq1.5\bar{n}_0$, we obtain $\omega_0/\omega_{LH}^{max}\simeq1.4$, 1.7, and 1.8, respectively. For densities $\bar{n}_0\lesssim9\times10^{12}$ cm^{-3} [or $\omega_0/\omega_{LH}^{max}\gtrsim1.9$] no parametric decay was observed in D^+ plasma for

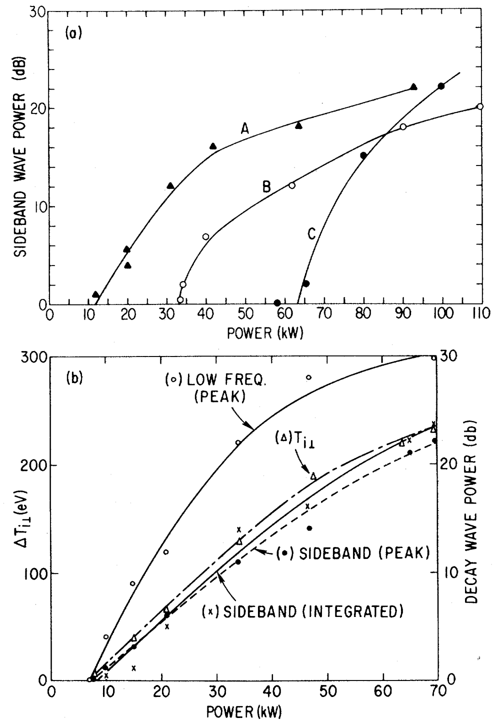

FIG. 2. (a) Sideband amplitude vs P_{in} for a split-wave-guide coupler; D_2 gas. Curve A, $\bar{n} = 1.3\times10^{13}$ cm^{-3}; curve B, $\bar{n} = 1.4\times10^{13}$ cm^{-3}; and curve C, $\bar{n} = 1.1\times10^{13}$ cm^{-3}. For $\bar{n} < 9\times10^{12}$ cm^{-3} and $P \leq 100$ kW, no decay is observed. (b) $\Delta T_{i\perp}$ and decay-wave amplitude vs P_{in}. H_2 gas; $\bar{n}$ 1.5×10^{13} cm^{-3}.

$P \lesssim 120$ kW. In H^+ plasma no decay was observed for $\bar{n}_0 < 6\times10^{12}$ cm^{-3} or $\omega_0/\omega_{LH}^{max} \gtrsim 1.40$. 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 $\omega_0/\omega_{LH} \simeq 2$. 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 $n > 6\times10^{12}$ (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-wave-guide 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 and 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 investigations (both analytical and numerical) indicate that in order to explain the frequency spread of $\Delta f/f \simeq 0.3$, one must have $\omega_0/\omega_{LH}^{local} \lesssim 2$. 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 $\omega_0/\omega_{LH}^{local} \lesssim 2$ correspond to ion-cyclotron (quasi-) modes and/or electron-Landau damped quasimodes, depending upon T_e, T_i, $k_\parallel\lambda_D$, and U/C_s (where λ_D is the electron Debye length, $U = cE_0/B$ is the magnitude of the $\vec{E}\times\vec{B}$ 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 $\Delta f/f_0 \lesssim 0.3$, 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

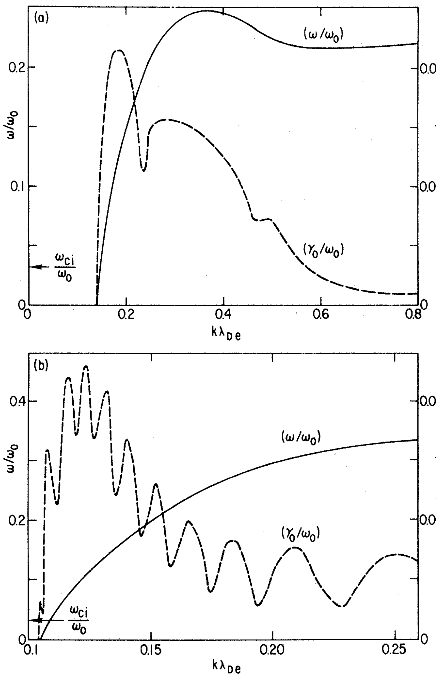

FIG. 3. Frequency (ω) and growth rate (γ_0) as a function of $k\lambda_{D_e}$ in H^+ plasma. (a) $\omega_0/\omega_{LH}=1.57$, $T_e/T_i=3$, $U/C_s=1$, $k_{0\parallel}\lambda_{De}=2\times10^{-3}$, $k_\parallel\lambda_{De}=6\times10^{-3}$, $\omega_{pe}^2/\omega_{ce}^2=0.25$; (b) $\omega_0/\omega_{LH}=1.91$, $T_e/T_i=1$, $U/C_s=1$, $k_{0\parallel}\lambda_{De}=6\times10^{-3}$, $k_\parallel\lambda_{De}=1\times10^{-2}$, $\omega_{pe}^2/\omega_{ce}^2=0.152$. For both (a) and (b), $\omega_{ci}/\omega_0=0.033$.

point of the sideband waves ω_2 (i.e., the transition point from backward to forward waves). In general, the numerically obtained decay spectra show good qualitative agreement (even though one might expect nonlinear effects to distort the spectra).

An important theoretical question is the effect of nonuniformities 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 wave guides, finite-length stabilization elimates most instabilities for $\omega_0/\omega_{LH}>2$.[4,5] On the contrary, for $\omega_0/\omega_{LH}<2$ 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 $\omega_0/\omega_{LH}\lesssim2$. In this case, convection due to shear determines the threshold. Our estimates indicate that the threshold due to shear is $U/C_s\lesssim0.5$. The foregoing considerations for the ATC parameters predict threshold power in the range of $P_{in}\simeq10$–100 kW for $\omega_0/\omega_{LH}<2$, roughly in agreement with experimental observations.

Our analysis also indicates that whereas for $T_e/T_i=1$, $\mathrm{Im}\chi_i(\omega)\simeq\mathrm{Im}\chi_e(\omega)$, we have for $T_e/T_i=3$, $I_m\chi_e(\omega)\gg\mathrm{Im}\chi_i(\omega)$ [where $\chi_j(\omega)$ is the susceptibility of species j]. Since according to quasilinear theory, heating of a particular species of particles is proportional to $\mathrm{Im}\chi_j$, we believe that the main body of ions are heated by the low-frequency ion-cyclotron quasimodes (i.e., where $T_e\simeq T_i$). 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 $T_e\gtrsim3T_i$, even the low-frequency quasimodes 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 $0.5\lesssim r/a\lesssim0.8$, where $2\gtrsim T_e/T_i\gtrsim1$, and $n(r)\simeq\frac{1}{2}n_0^{\max}$. Of course, strong turbulence effects may 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-Institut, 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.

[1]T. H. Stix, Phys. Rev. Lett. 15, 878 (1965); V. E., Golant, Zh. Tekh. Fiz. 41, 2492 (1971) [Sov. Phys. Tech. Phys. 16, 1980 (1973)].

[2]K. Bol *et al.*, Phys. Rev. Lett. 29, 1495 (1972).

[3]S. Bernabei *et al.*, in Proceedings of the Third Symposium on Plasma Heating in Toroidal Devices, International School of Plasma Physics, Varenna Italy, 1976 (to be published).

[4]M. Porkolab, in Proceedings of the Third Symposium on Plasma Heating in Toroidal Devices, International School of Plasma Physics, Varenna, Italy, 1976 (to be published).

[5]M. Porkolab, Phys. Fluids 17, 1432 (1974), and also in *Proceedings of the Symposium on Plasma Heating in Toroidal Devices* (Editrice Compositori, Bologna, 1974), pp. 28–49.

[6]B. Coppi *et al.*, Nucl. Fusion 16, 309 (1976).

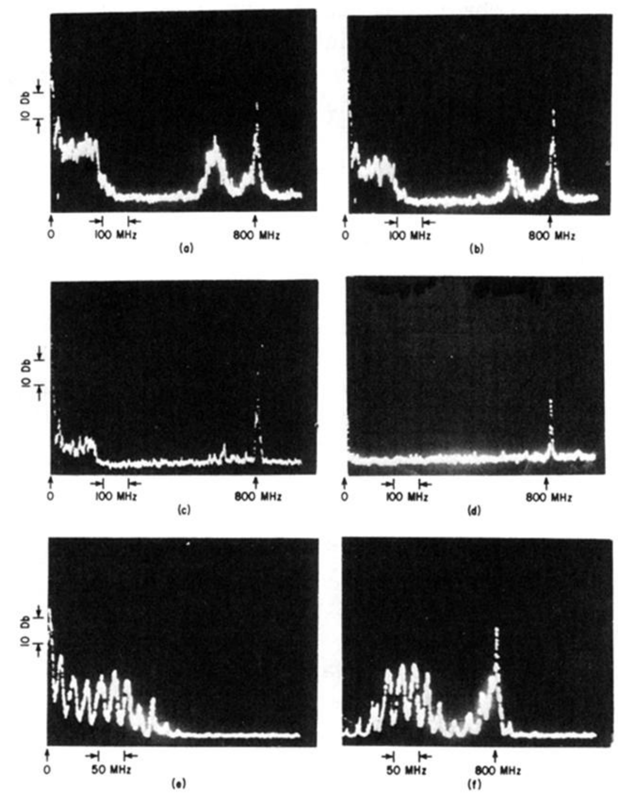

FIG. 1. (a)–(d) Parametric-decay spectrum due to a split wave guide; D_2 gas; $\bar{n} = 1.8 \times 10^{13}$ cm^{-3}. (a) $P_{\rm in} = 63$ kW, (b) $P_{\rm in} = 41$ kW, (c) $P_{\rm in} = 19$ kW, and (d) $P_{\rm in} = 1.5$ kW; $f_{ci} \simeq 13$ MHz. (e),(f) Parametric-decay spectrum due to a single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