Observation of a parametric decay instability of a lower hybrid wave in the central plasma in the FT-2 tokamak

V. N. Budnikov, L. A. Esipov, M. A. Irzak, K. M. Novik, A. Yu. Stepanov, and V. O. Aleksandrov
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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The parametric decay of a lower hybrid wave with a large frequency shift, localized in narrow spatial regions where the density is lower than the lower hybrid density by a factor of two or three, has been observed for the first time. This decay into very slow waves can explain the central heating of the bulk of the ions and also the production of peripheral ions as the plasma density is raised.

Many studies of lower hybrid heating of plasmas in tokamaks have detected the excitation of parametric instabilities in the peripheral regions of the plasma. These instabilities are believed to be responsible for the peripheral absorption of the wave and for the production of fast peripheral ions, which quickly escape from the plasma. In some cases the process completely suppresses the penetration of waves into the central plasma region and also the heating of the bulk plasma, which is linked with a slowing of the wave near the lower hybrid resonance, i.e., at a plasma density approaching the lower hybrid density n_{LH} (Ref. 1).

In an effort to determine the relationship between the production of fast ions and the onset of parametric instabilities, a study has been made of the fluxes of charge-exchange neutrals in the FT-2 tokamak. These fluxes reflect the appearance and behavior of the ions which are produced. In addition, a probing of short waves excited in the plasma during the launching of rf power has been carried out. The method of intensified scattering of microwaves was used to study these waves.[2]

High-frequency waves in the lower hybrid range at the frequency $f_0 = 920$ MHz were excited in the plasma of the FT-2 tokamak ($R = 55$ cm, $a = 8$ cm, $B = 20$ kG, and $I_p = 20$ kA) by a two-waveguide grill from the outer side of the torus. It was found that the fast ions begin to appear at densities $n_{e0} = n^* \approx (0.3\text{–}0.5) n_{LH}$, which are so low that the conditions for a linear conversion do not hold in the plasma volume. The fast ions which are produced at $n_{e0} \approx n^*$ are localized in the central plasma. The value of n^* depends on the power; for example, at $P_{\rm rf} = 50$ kW it is $n^* = 1.5 \times 10^{13}$ cm^{-3}, while at $P_{\rm rf} = 100$ kW it is $n^* = 1.2 \times 10^{13}$ cm^{-3}. The lower hybrid density for these experimental conditions ($B = 20$ kG, $Z_{\rm eff} = 2$), on the other hand, is $n_{LH} = 4 \times 10^{13}$ cm^{-3}.

In the intensified-scattering method, an extraordinary wave at the frequency $f_{\rm b}$ is used to probe the waves in the plasma. For this frequency there exists an accessible upper-hybrid-resonance surface in the plasma volume. If the waves of interest are excited at the pump frequency f_0 or at a shifted frequency $f = f_0 + \delta f$ in the plasma, the backscattered signal at the frequency $f_s = f_{\rm b} \pm (f_0 + \delta f)$ is formed in a narrow region near the point of the upper hybrid resonance and carries information about the waves in this region. In the experiments, a probing wave with a power of 1 W at the frequency $f_{\rm b} = 59$ GHz was launched into the plasma by a horn from the inner side of the torus, in a cross section 90° away from the grill along the major circumference. The position of the upper-hybrid-resonance point for the given probing frequency was calculated from the local values of the magnetic field $B(r)$ and the density $n(r)$. The magnetic field and the density vary in the course of the rf pulse, so there is an automatic scanning along the major radius. The time evolution of the signal representing the intensified scattering at the frequency 660 MHz, with a bandwidth of 200 MHz, is shown by the oscilloscope trace in Fig. 1. A spike in the signal reflects the passage of the upper-hybrid-resonance point through the region in which the short waves are localized.

Figure 2 shows the spectrum of the intensified-scattering signal recorded at $B = 18.5$ kG, $n_{e0} = 2.5 \times 10^{13}$ cm^{-3}, $I_p = 18$ kA, and $P_{\rm rf} = 80$ kW. The point of the upper hybrid resonance for the probing wave was at $R = 60.2$ cm ($r = 5.2$ cm). A typical feature of the spectrum of the intensified-scattering signal is that the frequencies which are detected are discrete: In addition to the "line" at the pump frequency, there is a line at a shifted frequency in the region 590–680 MHz. The widths of these lines are 2–4 MHz. In certain cases, we saw two or three lines at shifted frequencies during observation of the spectrum in a 25-MHz band (the distance between the lines

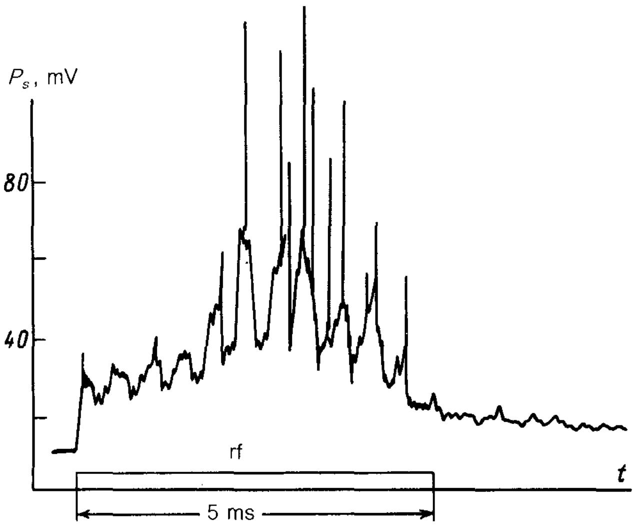

FIG. 1. Oscilloscope trace of the intensified-scattering signal.

was 5–20 MHz). The spatial distributions of the signals representing the scattering at the frequency f_0 and at the shifted frequencies are quite different: The signal at f_0 is detected at all observation points along the radius, while the signals at the shifted frequencies are characterized by a sharp spatial localization, in a narrow interval along the radius, less than a centimeter wide (Fig. 3). This result is evidence of a sharp localization of the short waves at a shifted frequency. The local density at the point at which the signal reaches a maximum, n_e, approximately coincides with the threshold density n^*, at which ions with an energy of 1–2 keV begin to appear. As the plasma

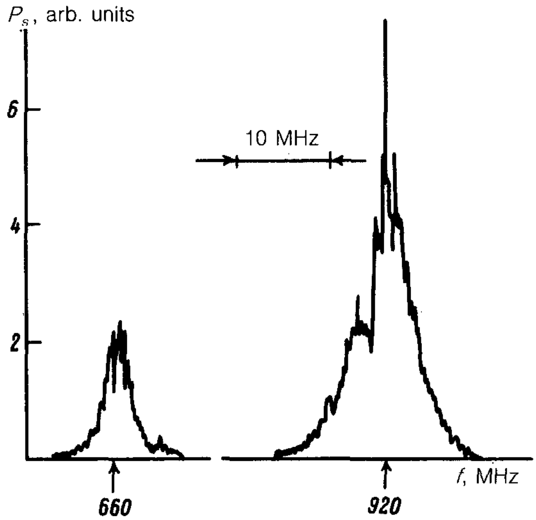

FIG. 2. Spectrum of the intensified-scattering signal.

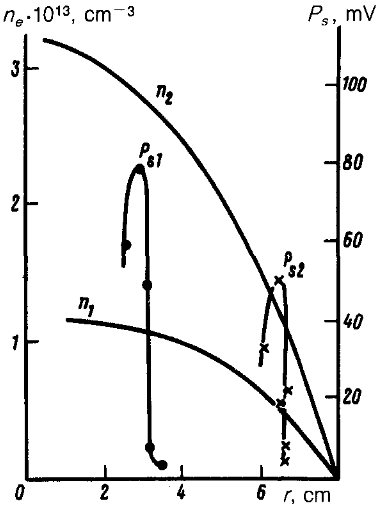

FIG. 3. Spatial distribution of the intensified-scattering signal ($B = 18.5$ kG, $I_p = 18$ kA, $P_{rf} = 100$ kW). 1—$n_{e0} = 1.2\times10^{13}$ cm^{-3}; 2—$n_{e0} = 3.3\times10^{13}$ cm^{-3}.

density is raised, the region in which the intensified-scattering signal is localized shifts toward the periphery, but the local density corresponding to the maximum remains essentially constant. As the heating power is raised, the maximum shifts toward the periphery and assumes a position where the local density is lower. These events correlate with the decrease in the threshold density as the power is raised.

The structure of the observed spectrum is characteristic of a parametric decay instability. It has the unusual characteristic of being discrete: The previously observed parametric spectra with a large frequency shift are continuous from f_0 to $0.7f_0$. The formation of these spectra has been linked with an induced scattering (a decay involving quasimodes).[1] The sharp localization of the decay region, its shift opposite the wave into a region of lower density as the power is raised, and the "line nature" of the spectrum apparently indicate that the instability occurs under conditions near the threshold. The narrow lines in the spectrum may also be evidence of a coherence of the processes which are occurring. This coherence might in turn be linked with the formation of a feedback loop, i.e., with the development of an absolute parametric instability. Such a process was described in Ref. 3.

One of the daughter waves, that with the higher frequency, $f_1 \approx 0.7f_0$, can naturally be regarded as a lower hybrid wave, while the other, $f_2 \approx 0.3f_0$, should apparently be an ion Bernstein mode. (This wave was not detected experimentally because of an absence of measuring equipment.) Since we have $f_1 \approx 0.7f_0$, the decay region $n^* \approx (0.3\text{–}0.5)n_{LH}$ represents for the f_1 wave a region which is near the point of its linear conversion, where this wave can interact efficiently with ions and be damped.

In summary, our experiments suggest that the lower hybrid heating of ions in a tokamak occurs by the following scheme: The energy transport into the tokamak occurs at the source frequency f_0 up to a density $n^* \approx (0.3\text{–}0.5)n_{LH}$, where a decay results in the excitation of two very slow waves, at frequencies $0.7f_0$ and $0.3f_0$, which interact efficiently with ions. According to this scheme, rf energy is easily transported to the central part of the tokamak, since the wave f_0 easily reaches the region with $n^* \lesssim 0.5 n_{LH}$, but it cannot penetrate into the dense central plasma, with the density n_{LH}, as has been shown by ray-path calculations incorporating the actual geometry of the tokamak plasma. The central heating of the bulk of the ions, with $n_{e0} \approx n^*$, and the production of peripheral ions at an elevated density $n_{e0} \sim n_{LH} > n^*$ can be explained in a consistent way with the help of the decay process which we have observed here: This decay is "tied" to the local density n^* and moves toward the periphery as the central density increases.

[1] V. E. Golant and V. I. Fedorov, Radio-Frequency Methods for Heating Plasmas in Toroidal Fusion Devices, Energoatomizdat, Moscow, 1986, p. 116.

[2] V. O. Aleksandrov *et al.*, in: Questions of Atomic Science and Engineering. Series on Thermonuclear Fusion, 1986, No. 1, p. 30.

[3] V. I. Arkhipenko, V. N. Budnikov, E. Z. Gusakov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 17 (1987) [JETP Lett. **46**, 20 (1987)].

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