Electron-cyclotron-resonance production and heating of a current-free plasma by an extraordinary wave in the L-2 stellarator

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The first experimental results on the production and heating of a current-free plasma by an extraordinary wave in the electron-cyclotron-resonance regime in the L-2 stellarator are reported.

Electron cyclotron heating of plasmas is now used widely as an auxiliary heating method in tokamaks[1] and to produce and heat current-free plasmas in stellarators.[2,3]

In the experiments in the L-2 stellarator, whose parameters are given in Ref. 4, a current-free plasma was produced under electron-cyclotron-resonance conditions at the fundamental electron gyrofrequency ω_{He} ($\omega_{\mathrm{He}} = \omega_0$, where ω_0 is the frequency of the microwave field). In contrast with the similar experiments in Refs. 2 and 3, where waveguide modes were used with waves of both polarizations ($\overline{E}_0 \perp \overline{B}$ and $\overline{E}_0 \| \overline{B}$), in the present experiments we used a wave with the extraordinary polarization ($\overline{E}_0 \perp \overline{B}$).

A gyrotron with a wavelength $\lambda_0 \cong 1$ cm was used. After the waveguide mode of the gyrotron was converted into a plane-polarized microwave beam, the power was injected into the chamber as a Gaussian beam with the extraordinary polarization by means of a quasioptical mirror system. The power in the beam at the entrance to the chamber, with a divergence of $\approx 6°$ and a diameter of 50 mm in the focal plane, was $P_0 = 80$–100 kW. The length of the microwave pulse was $\cong 10$ ms. The microwave power was injected into the vacuum chamber through an upper branch pipe; for the particular configuration of the modulus of the magnetic field in the L-2, this injection arrangement corresponded to the injection of an extraordinary wave from the side of the strong field. The results reported below were obtained at a magnetic field corresponding to satisfaction of the resonant condition $\omega_0 = \omega_{\mathrm{He}}$ in the central part of the plasma column.

Figure 1 shows the time evolution of $\bar{n}_e$ (the electron density averaged over a ray), $W = (3/2)\,\overline{n_e(T_e + T_i)V}$ (the plasma energy, determined from the plasma diamagnetism; V is the volume of the plasma column); and T_e (the central electron temperature, measured by laser scattering). A regime with a highly efficient absorption of micro-

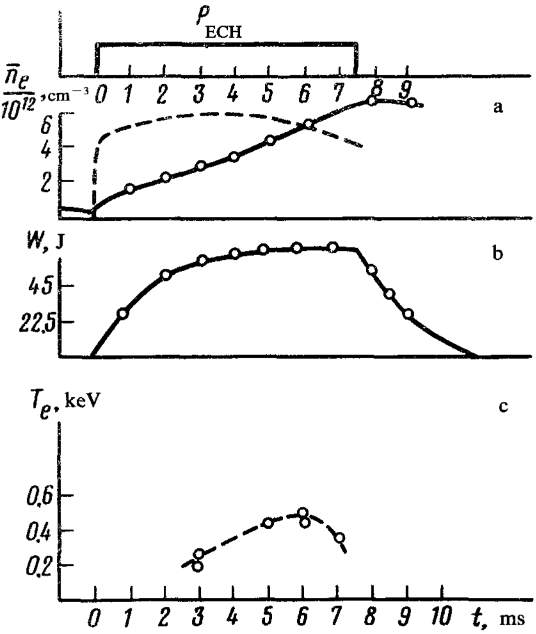

FIG. 1. Time evolution of the plasma properties.

wave power and plasma heating (Figs. 1b and 1c) is achieved through a preliminary ionization of the gas [$\bar{n}_{e0} \cong (0.5\text{–}1) \times 10^{12}$ cm^3] and through a slow increase in the plasma density throughout the microwave pulse (solid curve in Fig. 1a). In this regime the electron temperture peaks during the second half of the microwave pulse and then falls off slowly.

A regime with a low absorption efficiency, which is characterized by a rapid increase in the density (in 200–300 μs; the dashed curve in Fig. 1a), occurs when the preliminary ionization is omitted or produces too low an electron density ($\bar{n}_{e0} < 0.5 \times 10^{12}$ cm^{-3}). In this case the electron temperature does not exceed 100 eV at any point during the microwave pulse.

It appears that the difference in heating efficiency resulting from different density rise rates (the solid and dashed curves in Fig. 1a) is due to a density and temperature dependence of the optical thickness of the plasma for the extraordinary wave. The optical thickness is $\Gamma \sim (n_{\text{cr}}/T_e$, where $n_{\text{cr}} = \omega_0^2 m_e / 4\pi e^2$ is the critical plasma density. At $n_{\text{cr}}/n \ll 1$ the optical thickness leads to a high absorption, even at $T_e \cong 10\text{–}20$ eV; as the density n_e rises slowly, and n_{cr}/n decreases, this high absorption level is maintained by the increasing electron temperture. When n_e increases rapidly (in 200–300 μs), on the other hand, the optical thickness becomes small ($n_{\text{cr}}/n \cong 1$, $T_e \cong 10\text{–}20$ eV). The microwave power absorbed under these conditions is low, and the electron temperture remains frozen at < 100 eV.

Figure 2 shows the spatial profiles $T_e(r)$, $T_i(r)$, and $n_e(r)$. The density profile is approximately parabolic, while the $T_i(r)$ profile found from the energy spectrum of the

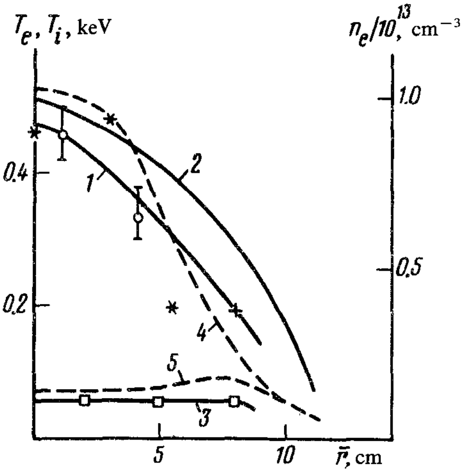

FIG. 2. Radial profiles of the plasma properties. 1–3: Experimental. 1—$T_e(r)$; 2—$n_e(r)$; 3—$T_i(r)$. 4, 5: Calculated. 4—$T_e(r)$; 5—$T_i(r)$. *—Result of a measurement of the soft x-ray emission by a foil method; O—laser-scattering measurement; + —spectroscopic measurements.

charge-exchange neutrals turns out to be flat, and the temperature does not exceed 60 eV at $r \leqslant 0.8a$. The electron-temperature profile implies that the microwave energy is absorbed primarily in the central zone ($r/a \leqslant 0.5$).

Numerical calculations of the energy balance have been carried out on the basis of the neoclassical theory[5] under the assumption that an absorbed microwave power of 45 kW is distributed uniformly over the interval $0 \leqslant r/a \leqslant 0.5$. The results are shown in Fig. 2. We see that the absolute values of the electron and ion temperatures and their radial profiles are in approximate agreement with the experimental results.

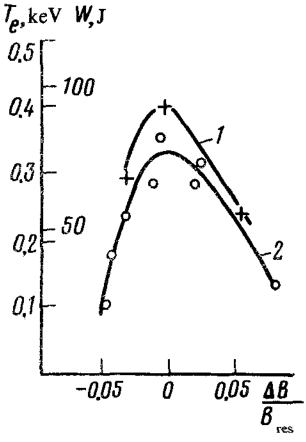

FIG. 3. 1—Electron temperature at the center of the plasma column; 2—plasma energy, versus the deviation from resonance $\Delta B/B_{\text{res}}$.

Our measurements of the dependence of the plasma properties on the deviation from the resonant value of the field show (Fig. 3) that the plasma energy and the central electron temperature $T_e(0)$ depend strongly on the resonance conditions. At a deviation from resonance $\Delta B/B_{\rm res} = \pm(3\text{–}5)\%$, the central temperature $T_e(0)$ and the energy decrease by a factor of several units.

Estimates based on the rate of increase of the plasma energy upon the application of the microwave power pulse and the decrease in the plasma energy at the end of this pulse show that the absorbed microwave power is $P_{\rm abs} \cong 45\text{–}30$ kW, and the energy lifetime is $\tau_E \cong 2\text{–}3$ ms. This value of τ_E also agrees well with the results of the numerical calculations.

These first experiments on the production and heating of a current-free plasma by an extraordinary wave at the first harmonic of the electron gyrofrequency in the L-2 stellarator demonstrate that the microwave power is absorbed highly efficiently ($\cong 35\text{–}45\%$), so that it is possible to produce a plasma with $T_e(0) \cong 500$ eV and $T_i(0) \cong 60$ eV at $\bar{n}_e \cong 4\text{–}6 \times 10^{12}$ cm^{-3}. The total plasma energy is 80–90 J, and the energy lifetime is $\tau_E \cong 2\text{–}3$ ms.

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