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We report results of electron cyclotron heating (ECH) experiments in which 80-kW of microwave power from a 35-GHz gyrotron is injected into tokamak with large single pass absorption. For 10-ms microwave pulses, incident from the high field side of the torus, the central electron temperature increases from 850 eV to 1250 eV, in agreement with empirical transport code calculations. For the first time in a tokamak, we demonstrate that electron temperature scales linearly with ECH power.

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HEATING AT THE ELECTRON CYCLOTRON FREQUENCY
IN THE ISX-B TOKAMAK

Plasma heating by microwaves at the electron cyclotron resonance frequency has been demonstrated to be an effective technique in a variety of confinement devices.[1-3] The recent development of the gyrotron[4] as a high power, short wavelength microwave source has made it possible to perform electron cyclotron heating experiments in tokamaks.[5] Numerous advantages are evident in this method of heating tokamak plasma. As depicted in Fig. 1, the microwave energy can be deposited in a thin resonant layer which exists at the major radius (R) where the electron cyclotron frequency (f_c) is equal to the microwave source frequency (f_g). The microwave absorption coefficient increases with electron temperature[6] T_e, making this an attractive scheme for supplemental heating. The wave damping mechanism is linear and heats the bulk of the electrons, rather than producing a high energy tail. Antenna structures are small compared with those required for heating at the ion cyclotron or lower hybrid frequencies, since ECH wavelengths are less than 1 cm for most tokamaks.

There exist several theories[7-11] of ECH in tokamaks which predict that the extraordinary wave is more heavily damped than the ordinary wave at oblique incidence from the high field side. For the parameters of the ISX-B tokamak (major radius R_0 = 93 cm, minor radius a = 27 cm, T_e = 1 keV), theory[7] predicts 100% single pass absorption of the extraordinary wave, while

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the ordinary wave can undergo about 50% single pass absorption, depending upon the angle of incidence and the electron density.

Previous experiments by Alikaev et al.[5] used short (750 μs) microwave pulses at power levels of less than 60 kW to perform bulk heating in the TM-3 tokamak (R_0 = 40 cm, a = 8 cm). The energy confinement time, τ_E, in this device was about 300 μs with a plasma current of 60 kA. Because of the small plasma volume and low electron temperature (400 eV) in TM-3, significant single pass absorption could not occur.[7] Since the unpolarized microwaves were launched from the low field side of the tokamak, the extraordinary wave component encountered a cutoff and could not propagate directly to the cyclotron resonance.

Here we present the results of ECH experiments in which the larger size of the tokamak and higher electron temperature ($\sim$1 keV) assure high single pass microwave absorption. The energy confinement time (τ_E = 10-15 ms) and ohmic heating power (100-150 kW) in ISX-B are roughly comparable to the NRL gyrotron[12] pulse length (10-20 ms) and output power (100-140 kW). Thus, these experiments provide a significant scaling of the previous ECH research.

The NRL gyrotron oscillator operated at a frequency (f_g = 35.08 GHz) which corresponds to a resonant field of 12.5 kG with cutoff densities of 1.5×10^{13} cm^{-3} for the ordinary wave and 3×10^{13} cm^{-3} for the extraordinary wave. Microwave output was in the TE_{01} circular mode, which was transmitted to the tokamak with overmoded copper waveguide (6 cm i.d.). Transmission losses between the gyrotron and the tokamak were about 1 dB. As shown in Fig. 1, the microwave power was launched into the plasma from the midplane of the high field side of the tokamak, eliminating the cutoff of the extraordinary wave that occurs on the low field side. The incident angle was set at 45^{0} from a major radius at the plasma edge. Ray tracing calculations[7] in toroidal geometry predict that this angle of incidence results in almost 100% single pass absorption of the extraordinary wave and less than 50% single pass absorption of the ordinary wave. Since the radiated power was an equal mixture of ordinary and extraordinary waves one expects a single pass heating efficiency of less than 75%. Of the radiation which is not absorbed in a single pass only a small fraction is reflected directly back to the center of the plasma because of both the extraordinary wave cutoff and the divergence of the microwave beam ($\pm 17^{0}$).

Several electron temperature diagnostics were located about 180^{0} around the torus from the antenna. A laser Thomson scattering system had the capability of 4 pulses per tokamak shot with pulse separations as small as 1 ms, enabling the time evolution of T_e to be measured during the heating pulse. Detection of the black-body emission at the second cyclotron harmonic provided a continuous measurement of the electron temperature. This diagnostic utilized a standard superheterodyne receiver, with a local oscillator frequency of 70.5 GHz, and I.F. amplifier with 60 MHz bandwidth. Detuning the local oscillator from the second harmonic of the gyrotron frequency eliminated the enhanced second harmonic generation that was observed at exactly 2 f_g. A similar superheterodyne receiver with a local oscillator frequency of 58 GHz measured the electron temperature at a major radius R = 112 cm, as illustrated by the region in Fig. 1 where f_c = 29 GHz.

A comparison is given in Figs. 2(a) and 2(b) of the electron temperature and density profiles before and after electron cyclotron resonance heating. These results were obtained with ~80 kW of microwave power applied for 10 ms, with the resonant magnetic field located at the center of the plasma.

Peak electron density was slightly above the cutoff density for the ordinary wave but below the extraordinary wave cutoff density. The central electron temperature increased from 850 eV to 1250 eV, becoming more peaked at the center, as expected. This temperature increase is verified by the increase in the second harmonic cyclotron emission. Assuming 100% microwave absorption with a gaussian energy deposition profile centered at the resonant surface, a transport code predicts this temperature increase for an empirical electron heat conduction coefficient that is independent of T_e. For a microwave input power of 80 kW the heating efficiency is estimated to be about 60% from a power balance equation that includes: (i) the change in plasma electron energy (from 766 J to 850 J) divided by the ECH pulse length (10 ms), (ii) the decrease in ohmic heating power (30 kW), and (iii) the change in electron energy divided by the electron energy confinement time (9.1 ms). During the microwave pulse, the central electron density is seen to decrease by about 15%. This large density decrease was usually observed during the microwave pulse in these experiments. No hard x-rays were generated by the ECH, and the soft x-ray spectrum did not exhibit a high energy tail, confirming that the bulk of the electrons were heated.

The temporal evolution of the electron density, loop voltage, and central electron temperature are shown in Fig. 3(a) for 80 kW microwave injection with 16 ms ECH pulse duration. Electron temperature at the center of the plasma [Fig. 3(b)] increased from 850 eV to approximately 1300 eV with fairly close agreement between the Thomson scattering and second cyclotron harmonic detection (SHD) diagnostics. An empirical transport code yields a temperature rise and decay that closely resembles the SHD diagnostic.

Loop voltage decreased during the ECH pulse from approximately 1.1 V to 0.66 V, which, from the Spitzer resistivity, indicates an electron temperature increase of about 40%. Both the horizontal and vertical line-average densities decreased by approximately 15% during the heating pulse. A density decrease has also been observed in neutral beam heated plasmas in ISX-B. The experimental density decrease is anomalously large with ECH, since empirical transport code calculations predict only a 2% decrease in line-average density. This explains why the experimental SHD electron temperatures are slightly higher than the theoretical values in Fig. 3(b).

In order to determine whether the electron cyclotron heating is linear, the gyrotron power was varied. These results, shown in Fig. 4, indicate a linear dependence of T_e on microwave power with a heating rate of ~6 eV per kilowatt. The agreement between the Thomson scattering data and the second cyclotron harmonic detection data is evidence that nonthermal electrons are not produced by ECH. This is the first time that a linear heating rate has been demonstrated for heating at the electron cyclotron frequency in a tokamak.

No ion heating was observed in these ECH experiments. One does not expect ion heating since the low plasma density provides weak coupling between electrons and ions; the microwave pulse lengths (10-16 ms) and energy confinement time (10 ms) are much shorter than the electron-ion equilibration time (~50 ms). However, as tokamaks are scaled toward reactor parameters and gyrotrons with higher frequencies and longer pulses are developed, significant ion heating could occur. Results of the present experiments indicate that ECH may prove to be an important supplementary technique for heating CTR plasmas toward ignition temperature.

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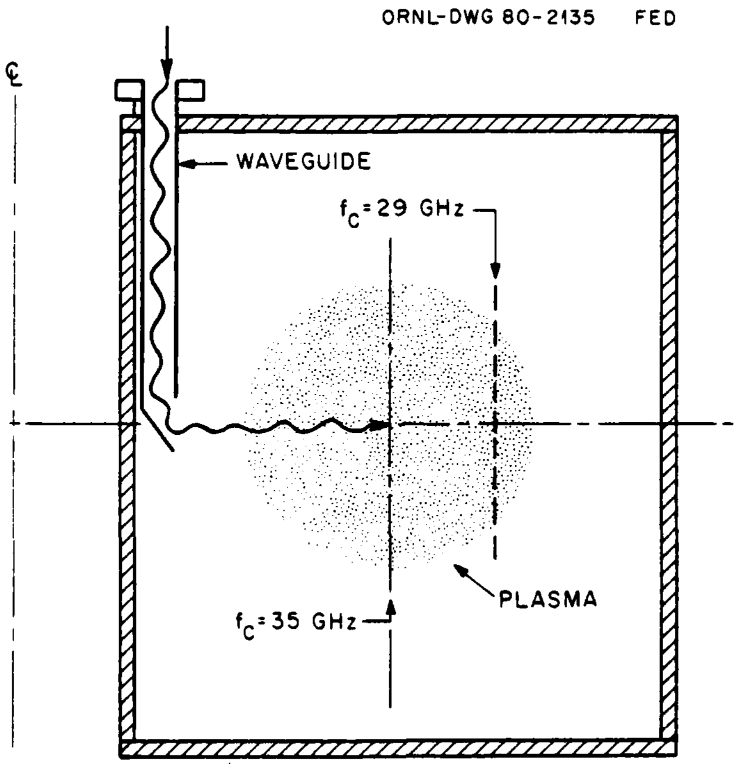

Fig. 1 — Experimental configuration. The electron cyclotron frequency (f_c) is shown for a toroidal magnetic field (B_T) of 12.5 kG on axis. The ECH resonant surface (f_c = 35 GHz) is located at the center of the plasma.

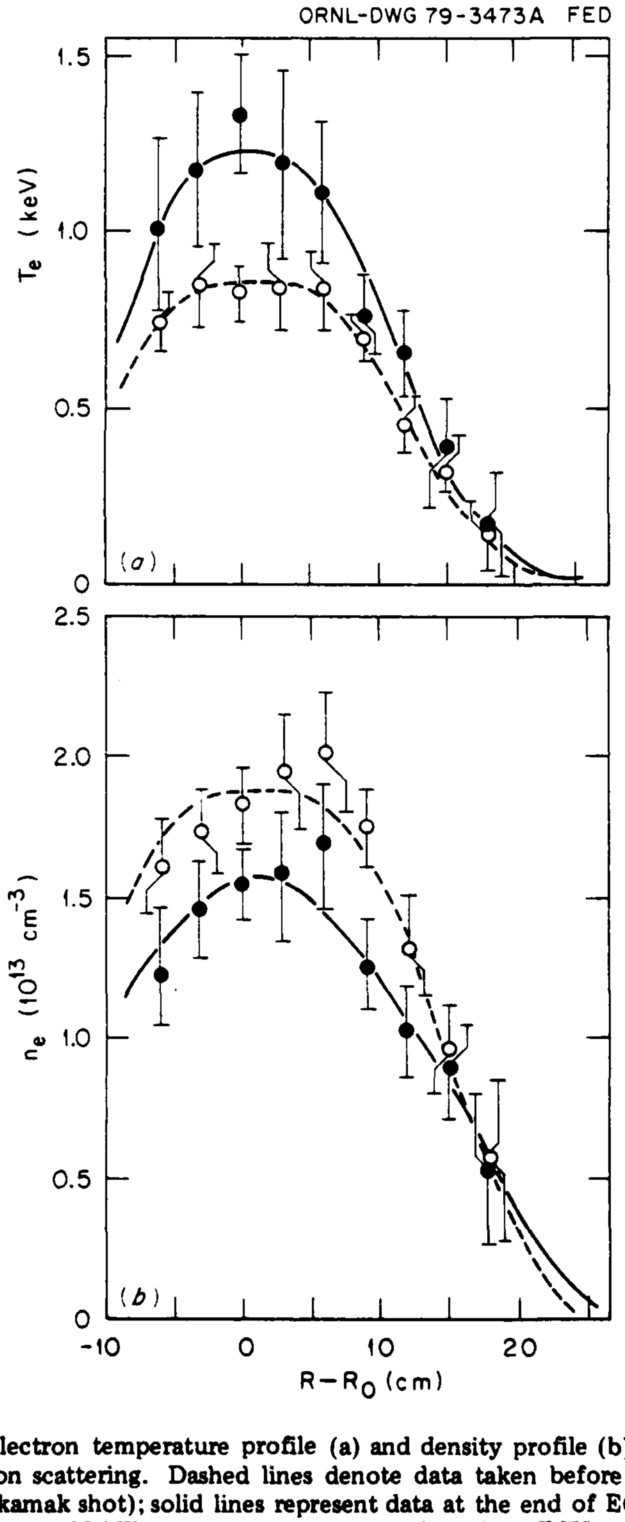

Fig. 2 — Electron temperature profile (a) and density profile (b) measured by Thomson scattering. Dashed lines denote data taken before ECH (118 ms into tokamak shot); solid lines represent data at the end of ECH (at 130 ms). Data is for 80-kW microwave injection with a 10-ms ECH pulse starting at 120 ms. B_T was 12.5 kG, line-average electron density ($\bar{n}_e$) was ~10^{13} cm^{-3}, and plasma current (Ip) was 83 kA.

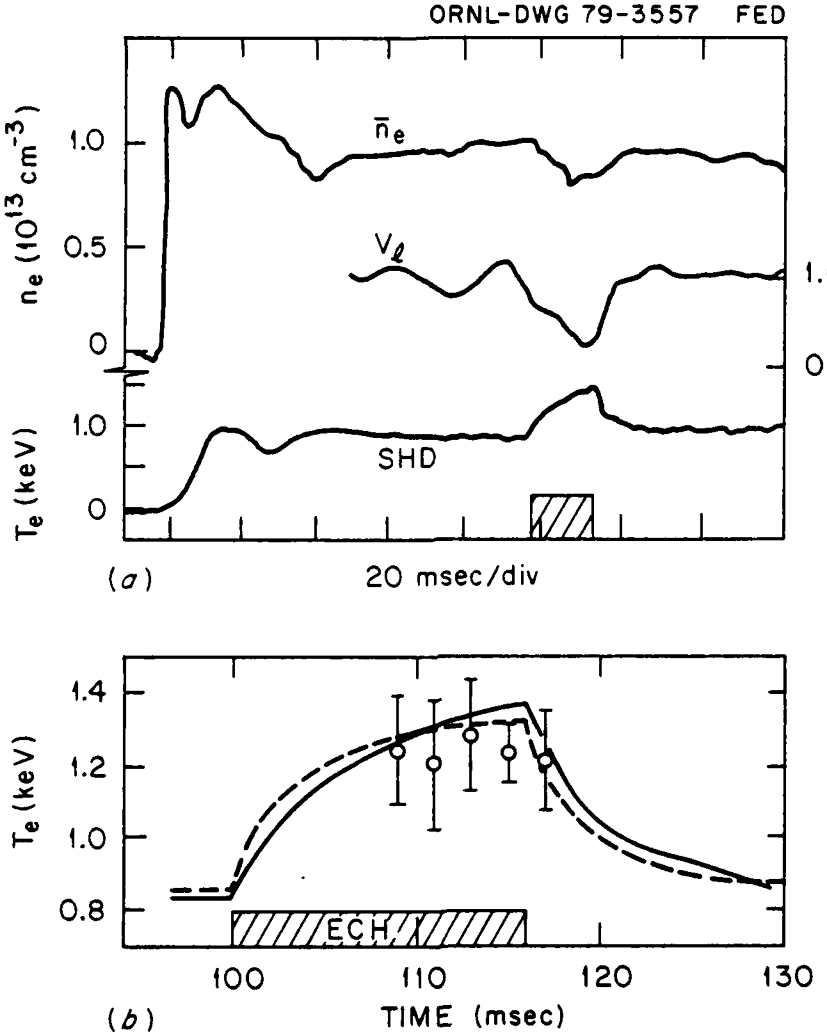

Fig. 3 — (a) Central electron temperature (from second harmonic cyclotron emission), loop voltage (V_ℓ), and line-average electron density vs time for 80-kW microwave pulse of 16-ms duration. (b) Electron temperature measurements from second cyclotron harmonic detection are indicated by a solid line, Thomson scattering measurements by circles, and electron temperature calculated from empirical transport code is shown by dashed line. Plasma parameters were: $B_T \cong 12.5$ kG, $\bar{n}_e \cong 10^{13}$ cm^{-3}, and Ip = 115 kA.

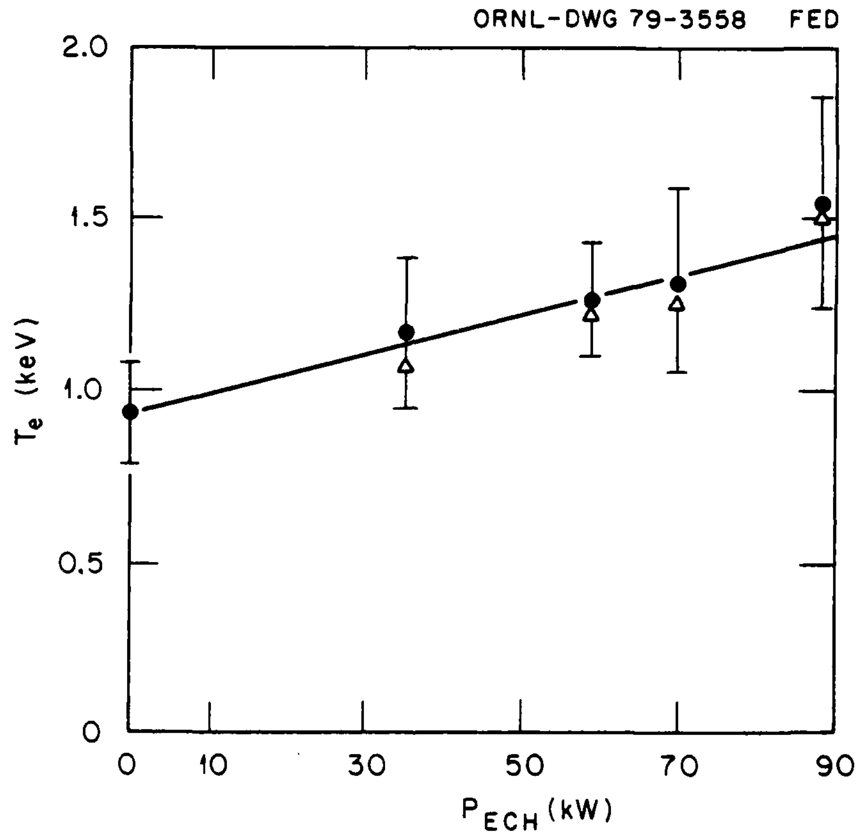

Fig. 4 — Central electron temperature vs microwave power with 15 ms ECH pulse length. Electron temperature measured by Thomson scattering (Φ) and second harmonic cyclotron emission (Δ). Plasma parameters were: $B_T \cong 12.5$ kG, $n_e \cong 10^{13}$ cm^{-3}, and I_P = 85 kA.

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