High-Power Electron Landau-Heating Experiments in the Lower Hybrid Frequency Range in a Tokamak Plasma

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The effectiveness of plasma heating by electron Landau interaction in the lower hybrid range of frequencies in tokamak plasmas is demonstrated. Upon injection of 850 kW of rf power at a density of $\bar{n}_e \simeq 1.4\times10^{14}$ cm^{-3}, an electron temperature increase of 1.0 keV and an ion temperature increase of 0.8 keV was achieved. These results are compared with transport and ray-tracing code predictions.

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In this Letter experimental results are presented which demonstrate for the first time that substantial electron Landau heating in the lower hybrid frequency range[1] can be achieved in magnetically confined high-temperature ($T_e \sim T_i \gtrsim 1$ keV) and high-density ($\bar{n}_e \gtrsim 1\times10^{14}$ cm^{-3}) plasmas. In the present experiments $f/f_{\rm LH}(0) \gtrsim 2$ [where $f_{\rm LH}(0)$ is the lower hybrid frequency at the plasma center] so that direct ion Landau heating by the waves can be excluded.[1] Bulk ion heating is achieved by collisional equilibration between electrons and ions. In previous electron Landau-heating experiments only 100–200 kW of rf power was injected, mostly at lower densities, and the associated electron heating was modest.[2-4] The present experiments indicate the potential attractiveness of lower hybrid rf heating of fusion-grade plasmas.

The experiments were carried out in the Alcator C tokamak (major radius $R=64$ cm, minor radius $a=16.5$ cm), at magnetic fields in the range $B_T \sim 7$–11 T. Three types of limiter materials were used: molybdenum, graphite, and silicon-carbide–coated graphite. The lower hybrid waves were launched by two 4×4 waveguide arrays located 180° relative to each other around the torus.[5] Each array was fed by four 250-kW, 4.6-GHz Varian klystrons, and adjacent columns of waveguides were phased 180° relative to each other. The power spectrum of the launched waves extended from $N_{\parallel}=ck_{\parallel}/\omega \simeq \pm2$ to $N_{\parallel}=\pm4$, and had maxima at $N_{\parallel}\simeq\pm3.1$.[6]

Figure 1 shows the time evolution of plasma parameters during a typical high-rf-power shot in deuterium plasma with silicon-carbide–coated graphite limiters. The ion temperature measurements were carried out by neutron yield analysis (corrected for impurity influx) and by a mass-resolving charge-exchange fast-neutral analyzer looking perpendicular to the magnetic field. The fast-neutral energy spectrum was measured every

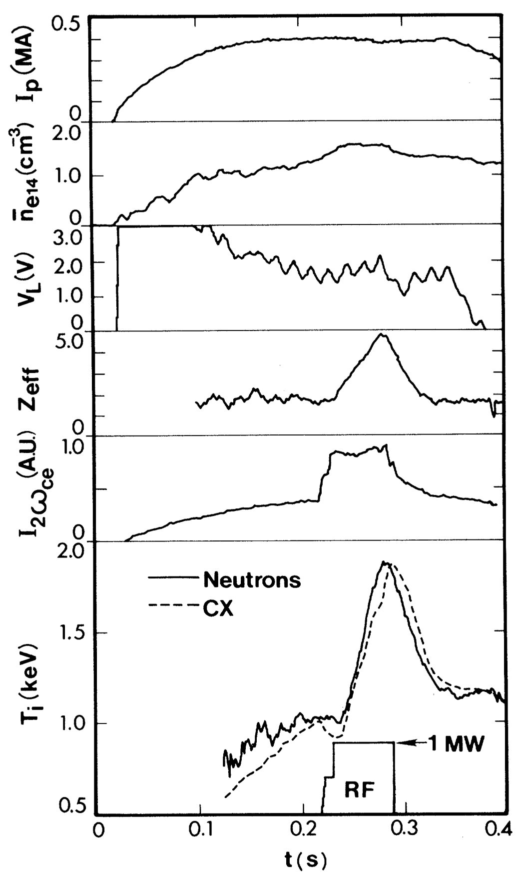

FIG. 1. Time history of a typical rf shot. $B=9$ T, D^+ ions, and $\bar{n}_{e14}$ is in units of 10^{14} cm^{-3}.

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millisecond and averaged for 5 ms. The energy spectrum of fast neutrals was found to be Maxwellian during the rf pulse, and no evidence of ion tail formation was observed under the present experimental conditions.[7] In the present case approximately 1.0 MW of net rf power was injected into a deuterium plasma at a line-average density of $\bar{n}_e \simeq 1.3\times10^{14}$ cm^{-3} at $B_T = 9$ T and $I_p = 400$ kA. The central ion temperature rises from $T_{i0}(0) \simeq 1.0$ keV before the rf injection to $T_i(0) \simeq 1.85$ keV during injection. After termination of the rf pulse the ion temperature decreases with a decay time of 15–20 ms, which is comparable with the estimated ion energy confinement time characteristic of Ohmic discharges at these densities. During the rf pulse the density rises at most by 20%. In addition, large increases in the $2\omega_{ce}$ and soft–x-ray detector signals are observed, implying electron heating and/or production of a highly non-Maxwellian electron distribution function. Furthermore, at power levels $P > 0.5$ MW a strong influx of impurities, consisting mainly of limiter materials, is observed. For example, in the case of Fig. 1 the effective ion charge, $Z_{\rm eff}$ rises from an initial value of 1.6 to approximately 4–5. In the present case the impurity influx consists mainly of carbon and silicon atoms.[8] Because of the significant rise in $Z_{\rm eff}$ during rf injection, the loop voltage does not decrease[9] as might be expected during electron heating.

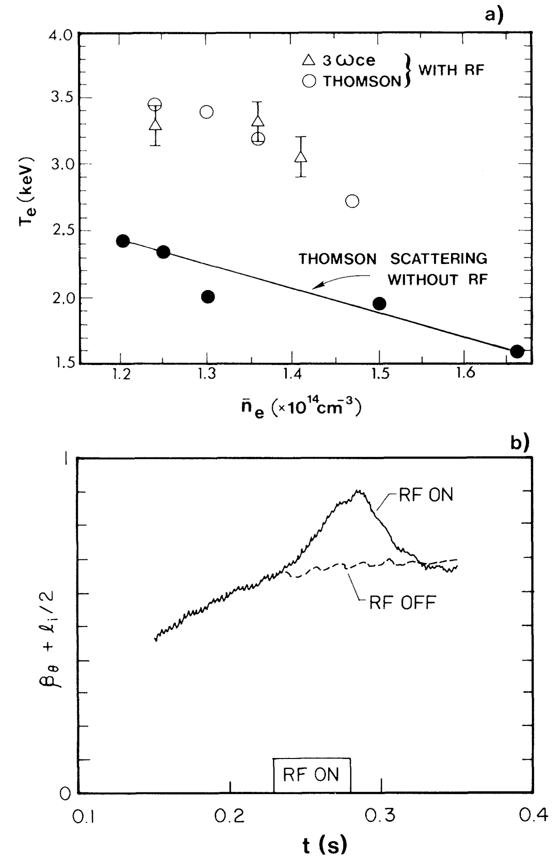

FIG. 2. (a) T_e vs $\bar{n}_e$ measured by Thomson scattering, and by $3\omega_{ce}$ x-mode transmission/absorption techniques with use of a far-infrared laser (Ref. 10). (b) $\beta_\theta + l_i/2$ vs time. Same conditions as in (a). The base line may be uncertain by a value up to 0.2.

In Fig. 2(a) measurements of $T_e(0)$, the central electron temperature, using Thomson scattering and $3\omega_{ce}$ x-mode transmission/absorption techniques,[10] are shown. At higher densities (and in particular at $\bar{n}_e \simeq 1.4\times10^{14}$ cm^{-3}) upon injection of 0.8 to 1.0 MW of rf power, the central electron temperature increases from a pre-rf value of $T_{e0}(0) \simeq 2.0$ keV to $T_e(0) \simeq 3.0$ keV. Soft–x-ray pulse-height analysis confirms these results.

In Fig. 2(b) magnetic-loop measurements of $\beta_\theta + l_i/2$ are shown. Here β_θ, the poloidal beta, corresponds to roughly 0.22 in the Ohmic-heated case. During rf injection the total signal increases by 0.20. An analysis of these results indicates that for unchanging radial temperature profiles β_θ would increase by 0.12 as a result of the temperature rise (including the effects associated with the increased carbon impurity level). The difference between the measured and the calculated values indicates either broadened temperature profiles or increases in $l_i/2$ on time scales faster than the current diffusion time (an unlikely event).

Figure 3 shows results of x-ray measurements with a mercuric-iodide (HgI_2) detector which indicate the existence of a large electron tail at densities $\bar{n}_e \leq 1.8\times10^{14}$ cm^{-3} in hydrogen, and $\bar{n}_e \leq 2.4\times10^{14}$ cm^{-3} in deuterium plasma during rf injection.[11] The fraction of electrons in the electron tail, n_T, was estimated to be $n_T/n_e \simeq 10^{-3}$ at $P_{\rm rf} \sim 1$ MW and at $\bar{n}_e \sim 1.4\times10^{14}$ cm^{-3}. The mean energy of the x-ray tail was typically 10–20 keV at the above density (depending on ion species and power). As the density was increased above these critical values, the electron tails disappeared and instead, ion tails originating from the plasma edge appeared.[7] At the same time bulk plasma heating was no longer observed. Thus, for our plasma parameters and rf frequency of 4.6 GHz the "density limit" for interaction with electrons is near $\bar{n}_e \simeq (2.1\pm0.3)\times10^{14}$ cm^{-3} (depending upon ion species). Since in both hydrogen and deuterium plasmas bulk heating was observed only when $\omega \gtrsim 2\omega_{\rm LH}(0)$, it can be concluded that heating is due to electron Landau interaction. This is further corroborated by the existence of the large electron tail.

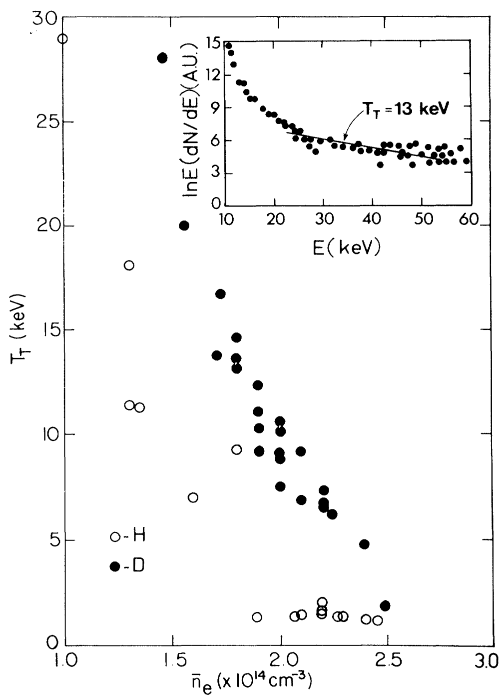

FIG. 3. Effective mean soft-x-ray tail energy, T_T, vs density. $B = 8$ T, $P_{\rm rf} = 400 \pm 50$ kW. The inset shows the energy spectrum at $\bar{n}_e = 1.3 \times 10^{14}$ cm^{-3} in hydrogen plasma.

A summary of heating results with different limiter materials is given in Table I. At low power levels ($P_{\rm rf} \lesssim 0.5$ MW) the heating rates are comparable (within experimental error). With either graphite or molybdenum limiters the heating quality factor, $\eta = \delta \sum_j T_j \bar{n}_j / P_{\rm rf}$ (where j is the species index) is of the order of 10×10^{13} eV cm^{-3}/kW. At higher power levels ($P_{\rm rf} > 0.5$ MW) and at low densities ($\bar{n}_e \lesssim 1.3 \times 10^{14}$ cm^{-3}), strong radiation losses due to significant molybdenum impurity influxes limit the heating efficiency when molybdenum limiters are used.[8] At higher powers the best heating rates ($\eta \sim 22$) were obtained with silicon-carbide–coated graphite limiters (where the reduced ion density due to an increase of $Z_{\rm eff}$ to 5 was included by assuming carbon impurity ions).

In order to interpret these experimental results, extensive computer code modeling, comprising a one-dimensional transport code, a toroidal lower hybrid wave ray-tracing code, and a Fokker-Planck code (including the Ohmic dc electric field), was performed.[12] Carbon impurity injection simultaneously with rf power injection was included. The electron and ion thermal diffusivities were fixed at the Ohmic values even during rf injection (which is not inconsistent with the Z mode of tokamak operation[9]). Depending on edge conditions, for the specific case of 850-kW injected rf power, 100–300 kW may have been absorbed by collisions near the periphery of the plasma column ($r/a \gtrsim 0.8$), and approximately 550–750 kW was absorbed by quasilinear mechanisms at $r/a \lesssim 0.5$. Only modest increases ($\Delta P_{\rm Oh} \lesssim 50$ kW) in the Ohmic power depostion were observed. In the code simulations the central electron temperature rose from an initial value of 2.0 keV to 3.0–3.2 keV during rf and carbon injection, and the central ion temperture rose from 1.0 keV to 1.9–2.0 keV. With use of $Z_{\rm eff} = 5$, flat density profiles $[n(a)/n(0) = 0.3]$, and low edge temperatures $[T_e(a) = 30$ eV$]$, up to 300 kW of power was lost due to collisional absorption at $r/a \gtrsim 0.8$. In this case $\beta_\theta + l_i/2$ increased only by a value of ~ 0.1. Higher edge temperatures $[T_e(a) = 50$ eV$]$ or more peaked density profiles $[n_e(a)/n_e(0) = 0.15]$ and a $Z_{\rm eff} = 4.0$ resulted in significantly reduced collisional power losses ($P_{\rm coll} \simeq 100$ kW) in the edge region. The resulting temperature profiles were broader, and, in agreement with the experimental results, β_θ rose by about ~ 0.20 while l_i remained nearly constant. The central temperature rises remained the same as in the previous case. Because of the broadened temperature profiles during rf injection, the effective global energy confinement time, τ_E, decreased to ~ 13 msec from the initial Ohmic value of ~ 16 msec. Finally, the Fokker-Planck code predicted $n_T/n_e \simeq (0.5–1) \times 10^{-3}$, in good agreement with experimental observations.

TABLE I. Heating rates, $\eta = \delta \sum_j T_{j0} \bar{n}_j / P_{\rm rf}$ (in units of 10^{13} eV cm^{-3}/kW).

$P_{\rm rf}$ (MW)	Limiter	$\bar{n}_e$ (10^{14} cm^{-3})	ΔT_e (eV)	ΔT_i (eV)	η
0.5	C	0.8	500	50	9
	Mo	1.5	270	100	11
0.9	C	1.7	400	200	10
	SiC	1.4	1000	800	22

In analyzing these results, it was recognized that a substantial increase in $Z_{\rm eff}$ (up to values of 5) by carbon impurities ($Z_I = 6$) would significantly reduce the number of ions in the plasma. This would raise the ion temperature since there are fewer ions to heat, and therefore the electron temperature, under the assumption that the thermal diffusivities remained unchanged during rf injection. To clarify the consequences of low-Z impurity injection, a code simulation was performed by injecting only carbon impurities without rf power, so as to raise $Z_{\rm eff}$ to 5. Simultaneously, the Ohmic current was reduced so as to maintain the same Ohmic power as in the rf-plus-carbon-injection case. The thermal diffusivities were again held constant. Electron and ion temperature rises of the order of 40% of those obtained in the presence of rf power were obtained.

In summary, the effectiveness of electron Landau heating in the lower hybrid range of frequencies at reactor-relevant densities has been demonstrated up to 1-MW rf power level. At power flux levels $P_{\rm rf}/S > 0.15$ MW/m^2 (where S is the plasma surface area) significant impurity influx, consisting mainly of limiter material, has been observed. Initial theoretical modeling of these results indicates that in Alcator C (60–85)% of the rf power may have been deposited in the inner half of the plasma column.

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