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IN THE PLT TOKAMAK

By

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Electron Heating Using Lower Hybrid Waves
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Abstract

Lower hybrid waves with a narrow high velocity wave spectrum have been used to achieve high central electron temperatures in a tokamak plasma. Waves with a frequency of 2.45 GHz launched by a 16-waveguide grill at a power level less than 600 kW were used to increase the central electron temperature of the PLT plasma from 2.2 keV to 5 keV. The magnitude of the temperature increase depends strongly on the phase difference between the waveguides and on the direction of the launched wave. A reduction in the central electron thermal diffusivity is associated with the peaked electron temperature profiles of lower hybrid current-driven plasmas.

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Lower hybrid waves have been applied to high temperature tokamak plasmas demonstrating effects of current drive,¹ current start-up,²⁻⁴ suppression of sawtooth oscillations,⁵⁻⁷ and both electron and ion heating.⁸⁻¹² The experimental results presented here show that high central electron temperature can be achieved with a modest power level under conditions that are also the most suitable for good current drive. The higher velocity waves with narrower wave spectrum provide more efficient current drive,¹² and produce a larger increase in the central electron temperature, which decouples from the current profile.¹³

The experiment was carried out in the PLT tokamak with a major radius $R = 132$ cm, a minor radius $a = 39$ cm, and a magnetic field $B_T = 3.1$ T. The lower hybrid waves were launched using a 16-element grill with a narrow power spectrum ($\Delta n_{||} = 0.45$ FWHM, where $n_{||} = ck_{||}/\omega$). By adjusting the relative phasing between adjacent waveguide elements, the peak value of $n_{||}$ was tuned between $n_{||0} = 1.4 - 3.6$, and the wave could be launched in the direction of the electron drift velocity (favoring current drive) or in the opposite direction (opposing the current). Ray tracing calculations indicate that an upshift in $n_{||}$ of $\approx 10\%$ occurs on the first pass of the wave as it penetrates to the plasma center. The target plasmas had a line average density $\bar{n}_e = 10^{13}$ cm⁻³, and the plasma current was held constant (by adjusting the current in the ohmic primary) during the application of 500 - 600 kW of lower hybrid power. The effective ionic charge of the plasma, Z_{eff} , was 3.4 (from Spitzer resistivity).

Electron temperature profiles for several phase differences, as measured by a multipoint Thomson scattering system,¹⁴ are compared in Fig. 1 to a profile before the application of rf power. As the phase difference, $\Delta\Phi$, was varied from 180° to -90° (waves in the

direction of the electron drift), the profile became more peaked, reaching a central electron temperature, $T_e(0)$, of nearly 5 keV. (In other experiments with similar conditions, central electron temperatures as high as 6 keV were obtained.) Although there was a large change in the central temperature, the outer portion ($r/a > 0.5$) of the profiles in all of these cases was similar.

Figure 2 shows several plasma parameters during a shot with the waveguide grill phased for current drive ($\Delta\Phi = -90^\circ$, $n_{||0} = 1.8$) with a launched power $P_{rf} = 585$ kW. The loop voltage drops nearly to zero during the rf pulse. There was no increase in the line-averaged electron density during the lower hybrid pulse, and the signal from the visible bremsstrahlung ($I_{brem} \propto n_e^2 Z_{eff} T_e^{-1/2}$) indicated no significant change in the effective charge (Z_{eff}) of the plasma. (Since I_{brem} was a line-integrated signal, the $T_e^{-1/2}$ dependence accounts for at most a 12% change in Z_{eff} for constant I_{brem} .) The increase in the plasma equilibrium measurement of $\beta_\theta + 1/2$ during the rf pulse was due primarily to an increase in β_θ ,¹⁵ due to a high energy superthermal tail created by the lower hybrid waves.

The superthermal current generated by the waves was estimated, using a method similar to that of Ref. 16, with the assumption that the Z_{eff} of the plasma did not change during the application of rf power. The voltage on axis, V_{axis} , was calculated from the external circuits (ohmic primary and vertical field) taking into account the change in $LI^2/2$. The resistivity, R_Ω , of the thermal plasma was calculated from the Thomson scattering profile during the rf pulse using the value of Z_{eff} prior to the application of rf power. In this way, the thermal current, $I_{th} = V_{axis}/R_\Omega$, was calculated, the total plasma current, I_p , was measured, and the superthermal current was the difference ($I_{st} = I_p - I_{th}$). In the ohmic case, $I_{th} = I_p$. In the -90° (current drive) case of Fig. 2, V_{axis} was slightly negative; therefore, the superthermal current slightly exceeds the

plasma current ($I_{st} > I_p$), with $I_{th} < 0$.

The central electron temperature increase during the rf pulse over that of the ohmic value can be seen in Fig. 3 as a function of waveguide phasing ($\Delta T_e(0) = T_e(0)_{rf} - T_e(0)_{ohmic}$). (Here $T_e(0)$ is the average of the electron temperature over ± 3.5 cm around the plasma center.) The solid data points have peak values of $n_{||0}$ ranging between $n_{||0} = 1.4$ ($\Delta\Phi = -67.5^\circ$) and $n_{||0} = 3.6$ ($\Delta\Phi = 180^\circ$). A symmetric spectrum was produced by phasing the adjacent waveguides $00\pi\pi\dots00\pi\pi$ such that the launched power was evenly divided between a positive lobe ($n_{||0} = +1.8$, similar to $\Delta\Phi = -90^\circ$) and a negative lobe ($n_{||0} = -1.8$, similar to $\Delta\Phi = +90^\circ$); the representation $\Delta\Phi = \pm 90^\circ$ will be used for this spectrum (open points in Fig. 3). The rf input power for these data varied between 500 kW and 600 kW, while the ohmic power input, $P_{oh} = V_{axis} I_p$, varied with $\Delta\Phi$ since the programming of the ohmic primary was such that I_p was held constant, but generally P_{oh} was decreasing with decreasing $n_{||}$. Total power input ($P_{tot} = P_{oh} + P_{rf}$) was shown in Fig. 3. A strong increase of the electron temperature with $\Delta\Phi$ can be seen for faster waves (lower $n_{||}$). The symmetrically launched wave ($\Delta\Phi = \pm 90^\circ$) results in a much lower electron temperature increase than one launched entirely in the current drive direction ($\Delta\Phi = -90^\circ$). In another experiment, with a wave launched in the reverse (anti-current) direction ($\Delta\Phi = +90^\circ$) with similar power and plasma density, the temperature increase was also much lower (represented by a cross in Fig. 3) than that seen with waves launched in the current drive direction. Also shown in Fig. 3 are the superthermal current and bulk electron energy confinement time, τ_{Ee} , versus $\Delta\Phi$. (τ_{Ee} is the total electron energy of the thermal electrons divided by the total input power; the energy content of the superthermal tail is not taken into account.) The faster waves (lower $n_{||}$) show an improved electron confinement over the ohmic value of 16.9 ms.

The overall trend of increasing central temperature with lower n_H correlates with the amount of superthermal tail current being driven. There is a local maximum in the central electron heating at $\Delta\Phi = -90^\circ$. The faster wave spectra ($\Delta\Phi = -75^\circ$ and -67.5°) have an increasing fraction of power inaccessible to the plasma center at this plasma density; the accessibility of the wave diminishes as the n_H value decreases. Approximately 5% of the $\Delta\Phi = -75^\circ$ spectrum and about 20% of the $\Delta\Phi = -67.5^\circ$ spectrum were not accessible inside $r=a/2$. Also, faster wave spectra drive tail electrons to higher energy with slowing down times approaching the tail confinement time resulting in decreased coupling to the bulk electrons. Together, these two effects may be responsible for the reduced central temperature for $\Delta\Phi > -90^\circ$.

Sawteeth were present in these discharges before the lower hybrid power was applied. Sawteeth were suppressed in those discharges with $-135^\circ \leq \Delta\Phi \leq -67.5^\circ$. There was a large variation in the central temperatures ($\Delta T_e(0) \approx 2$ keV) over the range of plasmas in which the sawteeth were suppressed. At this density and rf power level, sawteeth were present in the reverse current case ($\Delta\Phi = +90^\circ$) and the symmetric cases ($\Delta\Phi = \pm 90^\circ, 180^\circ$). With only half the rf power of the $\Delta\Phi = \pm 90^\circ$ case, lower hybrid waves with $\Delta\Phi = -90^\circ$ ($P_{rf} = 285$ kW) did suppress sawteeth. This asymmetry in the ability of the lower hybrid waves to suppress sawteeth has been observed previously.¹¹

In the ohmic case, the current carriers are thermal electrons, and the electron temperature profile is indicative of the current profile. In the case when all the current is being carried by high energy superthermal electrons (with the fractional number of superthermal to thermal electrons $< 1\%$), the temperature profile is no longer coupled to the current profile. The superthermal current profile is believed to be broader than the thermal current profile

of the no-rf case, judging from hard X-ray profiles and the fact that the sawtooth oscillations disappeared. (Direct measurements of the broadening of the current profile during lower hybrid current drive have been made on ASDEX.¹³)

If the lower hybrid waves were heating electrons by directly coupling to the bulk, one would expect to see the best heating with the slower waves (higher $n_{||}$), provided that the slower waves penetrate into the plasma. Presumably, the lower hybrid wave deposits its power by damping on the superthermal tail electrons, and the suprathermals heat the bulk plasma by collisions with thermal electrons. The power deposition profile to the bulk electrons by the lower hybrid, therefore, is given approximately by the hard X-ray profile, which was measured by an array of detectors along seven vertical chords ($h\nu > 100$ keV). Figure 4a, which compares the $T_e^{3/2}$ profile for the ohmic case with the Abel-inverted hard X-ray profile of the current-driven plasma ($\Delta\phi = -90^\circ$) divided by $n_e(r)$, shows that the hard x-ray profile is slightly broader.

As $\Delta\phi$ decreases from 180° to -90° , the total plasma current was the same, but the fraction of the current being carried by the thermal electrons was decreasing. The total power input to the plasma was also decreasing, since the rf power was roughly constant and the external power input was decreasing in order to keep the current constant. Figure 1, therefore, shows the transition of the electron temperature profile from the no-rf case (thermal current carriers), to the case when all the current was superthermal. This gradual transition suggests that a new equilibrium was established in which a larger T_e gradient could be tolerated in the central ($r/a = 0.2$) portion of the plasma. This increased gradient in T_e implies (with the broader deposition profile of Fig. 4a) a large decrease in the electron thermal diffusivity χ_e in the plasma center

with rf current drive over the ohmic case with only thermal current carriers.

A one-dimensional analysis was performed in order to examine the change in χ_e during lower hybrid current drive. Experimentally obtained electron temperature and density profiles were used, and the Abel-inverted hard X-ray profile divided by $n_e(r)$ was used for the deposition profile of the rf power to the bulk electrons. It was assumed that all the rf power was eventually deposited in the bulk electrons; the energy of the superthermal tail was not included. In this low density discharge, energy losses by electrons to ions are negligible as are radiation losses from the central region of the plasma. In the ohmic case, sawteeth were present, so a simple model of the losses due to sawtooth transport was used. The energy change inside the $q=1$ surface during the rise of the sawtooth was estimated from the sawtooth amplitude ($\Delta T_{\text{saw}}(0) = 0.2$ keV in the ohmic plasma). Dividing this energy by the sawtooth period ($\tau_{\text{saw}} = 5.3$ ms) gave the average power needed to change the internal plasma kinetic energy which was equivalent to the average power expelled from the interior by sawteeth. The equation for the radial thermal diffusivity is

$$n_e \frac{\partial T_e}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \chi_e n_e \frac{\partial T_e}{\partial r} \right] - \frac{2}{3} \left[Q_{\text{in}} - Q_{\text{saw}} - Q_{\text{rad}} - Q_{\text{ei}} - Q_{\text{tail}} \right],$$

where Q_{in} is the power supplied to the bulk electrons, Q_{saw} is the power transported by sawteeth ($Q_{\text{saw}}=0$ except at the sawtooth crash when $2/3 Q_{\text{saw}}(r) = n_e(r) \Delta T_{\text{saw}}(r) / t_{\text{crash}}$, where the duration of the crash $t_{\text{crash}} \ll \tau_{\text{saw}}$), Q_{rad} is radiated power, Q_{ei} is power lost to ions, and Q_{tail} is power stored in the tail as well as direct losses from the tail. Here it is assumed that Q_{rad} , Q_{ei} , Q_{tail} are negligible. The thermal diffusion is then given by

$$\chi_e(r) = \frac{\int_0^r \left(n_e \frac{\partial T_e}{\partial t} - \frac{2}{3} Q_{in} - \frac{2}{3} Q_{saw} \right) r' dr'}{n_e \frac{\partial T_e}{\partial t}}$$

where $n_e \partial T_e / \partial t + 2/3 Q_{saw} = n_e \Delta T_{saw} / \tau_{saw}$, averaging over one sawtooth cycle for the ohmic plasma and zero in the nonsawtoothed current-driven plasma. $Q_{in}(r)$ is proportional to $T_e^{3/2}(r)$ for the ohmic plasma and is proportional to the hard X-ray profile divided by $n_e(r)$ in the current-driven plasma.

Figure 4b compares the calculated χ_e profiles for the ohmic (dashed line) and $\Delta\Phi = -90^\circ$ lower hybrid (solid line) cases shown in Fig. 1. The central value of χ_e in the lower hybrid case has decreased substantially from the ohmic case.

In conclusion, high central electron temperatures were achieved using a narrow $n_{||}$ spectrum of lower hybrid waves with low $n_{||}$ launched in the direction of the electron drift velocity. Waves launched to drive current produced much better electron heating than identical spectra launched symmetrically or in the anti-current direction at a given $n_{||}$, suggesting that the presence of a large superthermal current was necessary for electron heating. The elimination of sawteeth alone does not explain the large temperature rise since a large variation in central temperatures was observed even while no sawteeth existed. Bulk electron energy confinement improves over the ohmic level for faster waves launched to drive current with the rf power used in this experiment ($P_{rf} < 600$ kW). A large decrease in the central value of χ_e from the ohmic value occurs in a lower hybrid plasma with a large superthermal current, resulting in a highly peaked electron temperature profile.

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Figure Captions

Fig. 1 Electron temperature profiles measured at 600 ms by Thomson scattering comparing plasmas with no rf (open symbols) with the application of 500 - 600 kW of lower hybrid power at several waveguide phases. The phase differences -90° , -105° , -120° , 180° correspond to $n_{\parallel 0}$'s of 1.8, 2.1, 2.4, and 3.6, respectively.

Fig. 2 Time history of some plasma parameters for waveguide phasing of $\Delta\Phi = -90^\circ$.

Fig. 3 Plot of $T_e(0)$, total input power, superthermal current, and τ_{Ee} versus waveguide phase difference. Solid symbols are for waves launched in the direction of the electron drift velocity. Cross indicates waves launched in the reverse direction. Open symbol is for symmetrically launched waves.

Fig. 4 (a) $T_e^{3/2}$ profile for ohmic discharge compared to Abel-inverted hard X-ray profile during the lower hybrid pulse. (b) Plot of $\chi_e(r)$ during lower hybrid (solid line) and before lower hybrid (dashed line) pulse.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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