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ABSTRACT

Substantial electron heating by energetic neutral beam injection has been observed in Oak Ridge Tokamak (ORMAK) plasmas. Impurity radiation is enhanced by injection but only to the degree expected for ohmically heated discharges with the same total power input to electrons, and the heat conduction loss is not degraded from that with ohmic heating alone. The scaling of average electron temperature with total power input to electrons is approximately the same with and without injection.

*Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

Injection of energetic neutral beams is the principal method proposed for heating tokamak plasmas to fusion temperatures. While large increases in ion temperature with injection have been observed in ORMAK,[1] TFR,[2] and other tokamaks,[3] little, if any, electron heating has been reported. For substantial electron temperature increases with injection, the injection power delivered to electrons ($P_{inj,e}$) must significantly exceed the sum of: (1) a reduction of ohmic heating power (due to the temperature increase and a possible injection-induced current[4]); and (2) an increase in electron power losses during injection (in particular, impurity radiation loss). In previous experiments,[1,2] this requirement was not well satisfied, and the expected temperature increases have been within experimental uncertainties.

Here we report for the first time a substantial rise in the electron temperature with injection. In comparison with our earlier work, the heating was enhanced by higher available coinjection power (beam current parallel to discharge current) and by operation at lower impurity levels (lower effective ionic charge, Z_{eff}).

In this Letter, we document observations of electron heating by injection and then present results that show an equivalence of ohmic heating and injection powers in determining the scalings of electron temperature and power loss.

We first discuss in some detail the evolution of a plasma in which the injection heating is maximized by operation with injection power greater than the ohmic heating power. Figure 1 illustrates the behaviors of several parameters for this discharge. The discharge is sustained for 130 msec at a flat-top current of 70 kA with a toroidal field of

15 kG, giving a safety factor, $q(a_\ell)$, of 7 at the limiter radius of 23 cm. At 20 msec after breakdown additional hydrogen gas is admitted to maintain the line-average electron density, $\bar{n}_e$, at $\approx 1.7 \times 10^{13}$ cm^{-3}. Injection of 340 kW H^o power starts at 40 msec and lasts for 35 msec. Calculations[4] indicate that the injected power transferred to electrons, $P_{inj,e}$, is about half of the total injected power. The loop voltage (and thus ohmic heating power, P_{OH}) decreases considerably during injection, mainly due to a rising electron temperature. Therefore at 75 msec, $P_{inj,e}$ ($\approx$160 kW) significantly exceeds P_{OH}($\approx$100 kW).

Figure 2 shows the time history of the peak electron temperature $(T_e)_{max}$; the density-averaged electron temperature, $\langle T_e \rangle$; the electron thermal energy, W_e — all derived from Thomson scattering; and of the peak ion temperature, $(T_i)_{max}$ — derived from charge-exchange measurements. Similar temporal behavior of $(T_e)_{max}$ is also indicated by a less certain measurement from soft x-ray energy spectra [using a Si(Li) detector] averaged over 10-msec intervals. In the absence of injection, electron temperatures similar to those at 35 msec are observed for most of the discharge duration. Although both measures of the electron temperature, $(T_e)_{max}$ and $\langle T_e \rangle$, increase rather slowly during the beam pulse, growth of electron energy content saturates after about 15 msec. This time is consistent with that expected from the fast ion slowing down time[4] ($\approx$10 msec) and the electron energy confinement time ($\approx$5 msec). However, the decay of W_e after cessation of injection is much slower than expected, and $(T_e)_{max}$ remains higher than its initial value. In contrast to the electron behavior, $(T_i)_{max}$ decays from 700 eV (at 75 msec) to the original value of 200 eV with the expected time constant ($\approx$15 msec) after injection.

This suggests that the T_e behavior after injection is controlled by changes in the power loss mechanisms rather than by the decay of the power transferred from residual fast ions. In this connection, we first note that internal disruptions[5] are not a significant factor in this experiment or in the others reported below.

We next consider the effect of impurities and the radiative power loss. The average value of the effective ionic charge, $\overline{Z}_{eff}$, inferred from the usual resistance measurement[1] increases from 2.5 (before and after the injection pulse) to 3.5 during injection. The estimate during injection neglects a possible injection-induced current.[4] Inclusion of this current implies a central value, $Z_{eff}(0)$ as high as 5 (at 75 msec) without appreciable change in $\overline{Z}_{eff}$.

The behavior of Z_{eff} inferred from the resistance measurement is consistent with the values inferred from vacuum ultraviolet spectroscopic measurements. The latter measurements show that radiation from ORMAK is dominated by lines of oxygen (the main contributor to Z_{eff}) and by narrow-band continua in the 20-100 Å range.[6] Figure 3(a) illustrates the evolutions of the resonance line of O^{6+} (21.6 Å) and the nearby continuum (20.1 Å). The O^{6+} line radiation begins to appear about 10 msec after breakdown, but is quenched by the gas puff. As soon as injection begins, the line intensity of O^{6+} increases strongly due to the rise of T_e, but the fact that it does not "burn through" indicates that oxygen is being transported into the interior of the plasma. This model is corroborated by the rapid decrease of the intensity after injection stops; it seems that this behavior cannot be caused solely by the decrease of T_e after injection, but must be the result of a reduced inward transport of oxygen.

More importantly, the continuum radiation, which is responsible for most of the radiated power, exhibits the same behavior. This highly structured continuum[6] is believed to arise from aggregates of closely spaced lines of tungsten.[7] The intensities at various wavelengths between 20 and 50 Å increase by factors of 2-3 during injection. The signals fall off rapidly when injection stops, and it is estimated that the incoming flux of tungsten decreases by 30-50%.[2]

As expected, there is a close correlation of the continuum radiation with signals from a pyroelectric radiometer [Fig. 3(b)] which measures the total radiated power (P_{rad}) falling on the wall (with some small contribution from charge-exchange neutrals).[6] The latter signal increases by a factor of 1.5-2 during injection, but the ratio of P_{rad} to total input power is nearly constant (≈50%) throughout the discharge duration.

Another important energy loss mechanism for the electrons is heat conduction. In order to estimate this loss contribution, we calculate an energy confinement time

$$\tau_{Ee} = W_e/(P_{OH} + P_{inj,e} - \dot{W}_e - P_{rad} - P_{ei}).$$

Here P_{ei}, the electron-ion heat transfer, is normally small. The quantity τ_{Ee} is an energy confinement time primarily related to electron heat conduction loss, but also reflecting smaller losses due to ionization and convection. Using the radiometer values for P_{rad}, we find that the calculated values of τ_{Ee} for the equilibria before, during, and after injection are roughly constant (ranging between 6 and 9 msec with rather large uncertainties). The behavior of τ_{Ee} indicates that the heat conduction loss during injection is not degraded relative to that with ohmic heating alone.

Thus far we have discussed studies of the discharge at low current, low density, and the highest injection power. Varying the injection power with other discharge conditions fixed produced $\langle T_e \rangle$ values that increased monotonically with injection power. The electron heating also occurs in high current discharges. For example, at the highest power with I = 175 kA, we obtain $T_e(0) = 0.85 \rightarrow 1.3$ keV and $\langle T_e \rangle = 0.55 \rightarrow 0.7$ keV ($B_T = 26$ kG, $\bar{n}_e = 2.2 \times 10^{13}$ cm^{-3}, $P_{OH} = 480$ kW, and $P_{inj,e} = 120$ kW).

Correlation of the results described above with those of several other experiments indicate a general equivalence of injection and ohmic heating powers.

When the beam heating is simulated by a 40-msec ohmic heating pulse ($I = 70 \rightarrow 110 \rightarrow 70$ kA), we observe an electron temperature behavior similar to that with injection. T_e is left higher after the pulse, again primarily due to the reduction of P_{rad}. As in the injection case, the ratio of P_{rad} to the total power input is approximately constant. The value, ≈50% as in the injection cases, is like that observed in normal ohmically heated discharges over a wide range of conditions. The enhanced radiative loss observed in the injection experiment therefore is believed to be due to increased power input, and not specifically related to injection.

Losses through heat conduction also demonstrate the general equivalence of discharges with and without injection. For ohmically heated discharges τ_{Ee} increases with density, and the same trend is noted with injection. The specific experiment here was injection at the highest power into a 70 kA discharge, but this time at higher density ($\overline{n}_e = 3.3 \times 10^{13}$ cm^{-3}). τ_{Ee} was higher (≈15 msec), and as a result the observed increase of $\langle T_e \rangle$ was only slightly less than that at the lower density.

Finally, Fig. 4 shows $\langle T_e \rangle$ as a function of total power input into electrons ($P_{OH} + P_{inj,e}$), for a variety of discharges at different currents, densities, and toroidal fields. The scaling of $\langle T_e \rangle$ with total input power appears to be the same for plasmas with ohmic heating alone as for those with injection. Again we note the apparent absence of losses specific to injection.

In summary, we have observed electron heating by neutral beam injection and have observed that $\langle T_e \rangle$ increases with total power ($P_{OH} + P_{inj,e}$). To first order, there are no power losses specific to injection. This study, combined with the significant ion heating previously demonstrated, increases our confidence in the use of neutral beam injection for supplementing ohmic heating in tokamak plasmas.

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FIGURE CAPTIONS

Fig. 1. Time history of discharge parameters; plasma current (I), loop voltage (V), line-average electron density ($\bar{n}_e$), central electron density [$n_e(0)$], and timings of gas puffing and neutral beam injection. The parameters shown here are those averaged over 42 reproducible shots with 340-kV injection power.

Fig. 2. Evolution of the peak [$(T_e)_{max}$] and density-averaged ($\langle T_e \rangle$) electron temperatures, peak ion temperature [$(T_i)_{max}$] and electron thermal energy (W_e) with 340-kW injection power.

Fig. 3. Time dependences of (a) the spectral intensities at 21.6 Å (the O^{6+} resonance line and continuum) and 20.1 Å (the continuum) as measured by a grazing incidence spectrometer, and (b) the total power falling on the wall meausred by a pyroelectric radiometer, for the 340-kW injection case.

Fig. 4. Scaling of $\langle T_e \rangle$ with the total electron power input with and without injection. The data (shown by crosses) for ohmic heating along are the results of scaling experiments in which the operational parameters (B_T, I, and $\bar{n}_e$) were deliberately changed to study scalings of plasma parameters, producing large scatters of $\langle T_e \rangle$.

ORNL-DWG 77-6489R

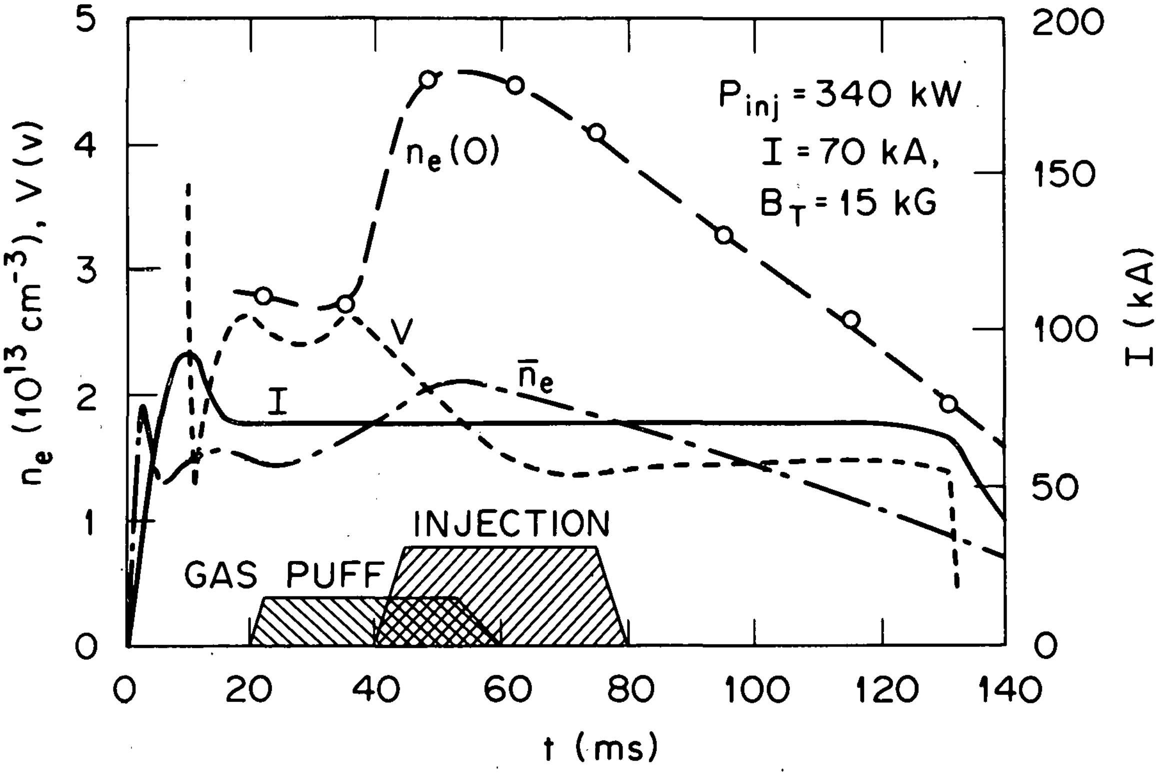


Figure 1

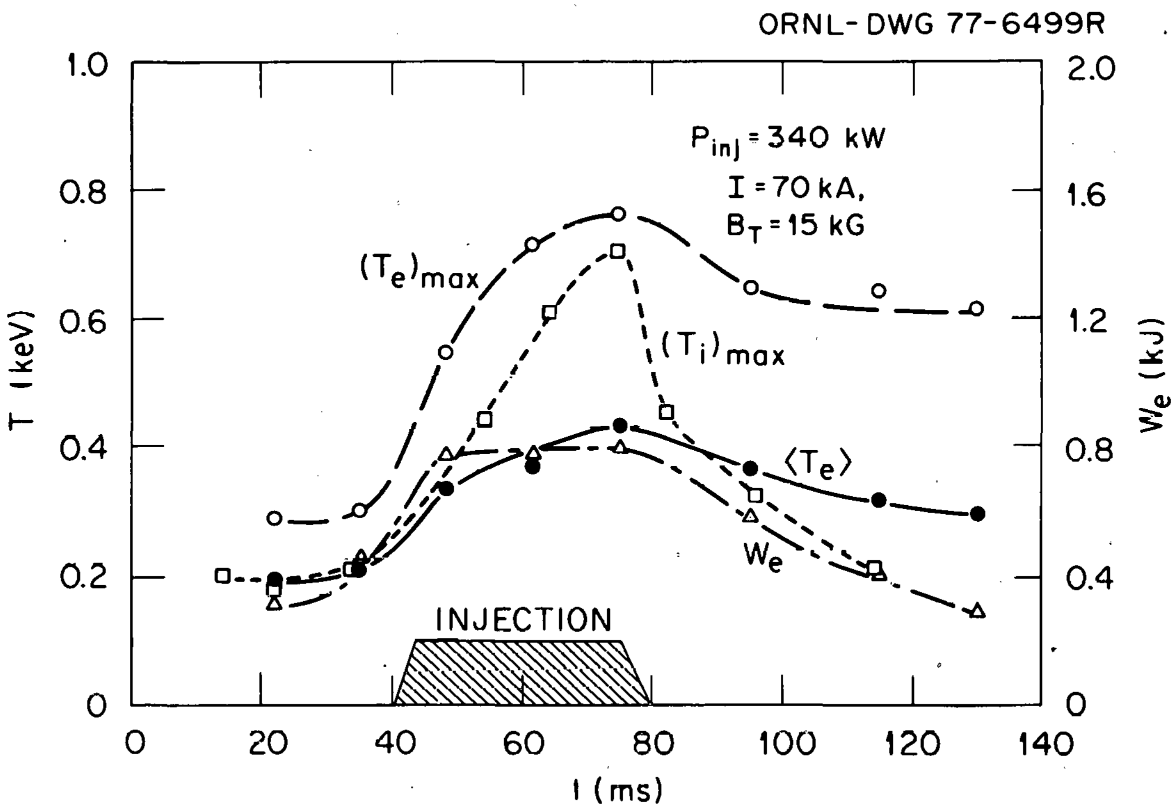

ORNL-DWG 77-6499R
P_{inj} = 340 kW
I = 70 kA,
B_T = 15 kG
$(T_e)_{max}$
$(T_i)_{max}$
$\langle T_e \rangle$
W_e
INJECTION
T (keV)
W_e (kJ)
t (ms)
1.0
0.8
0.6
0.4
0.2
0
2.0
1.6
1.2
0.8
0.4
0
0
20
40
60
80
100
120
140

Figure 2

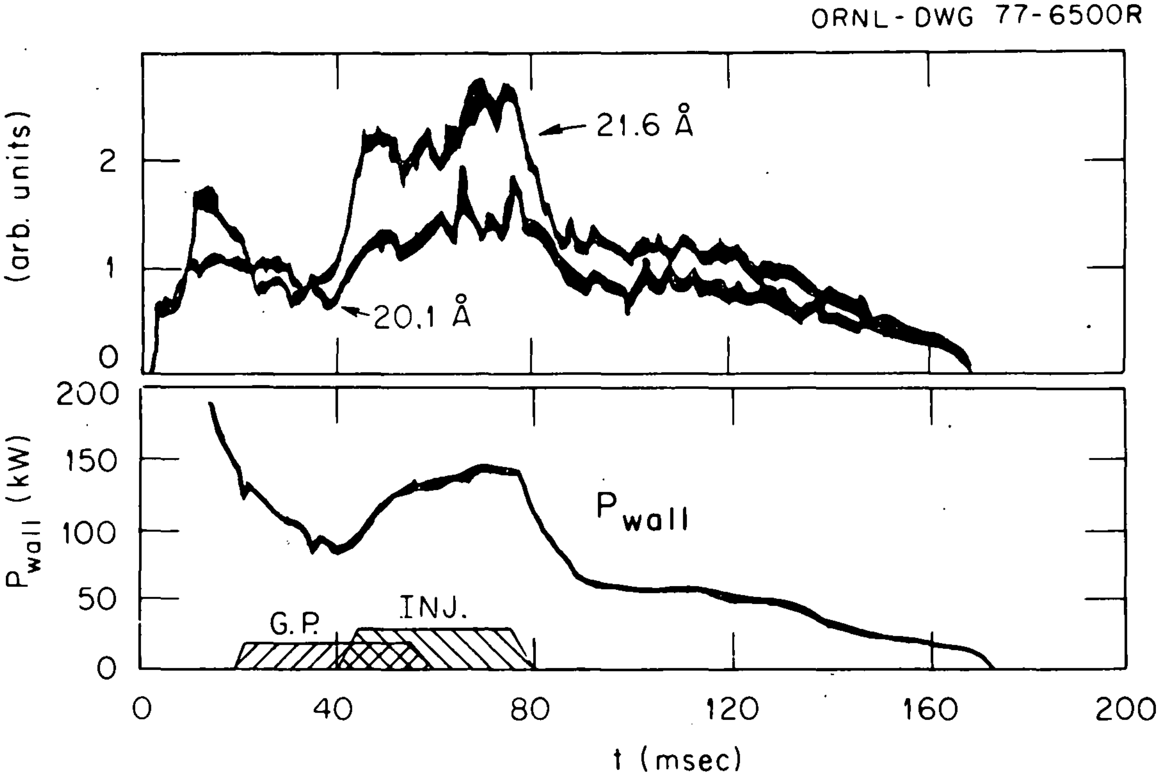
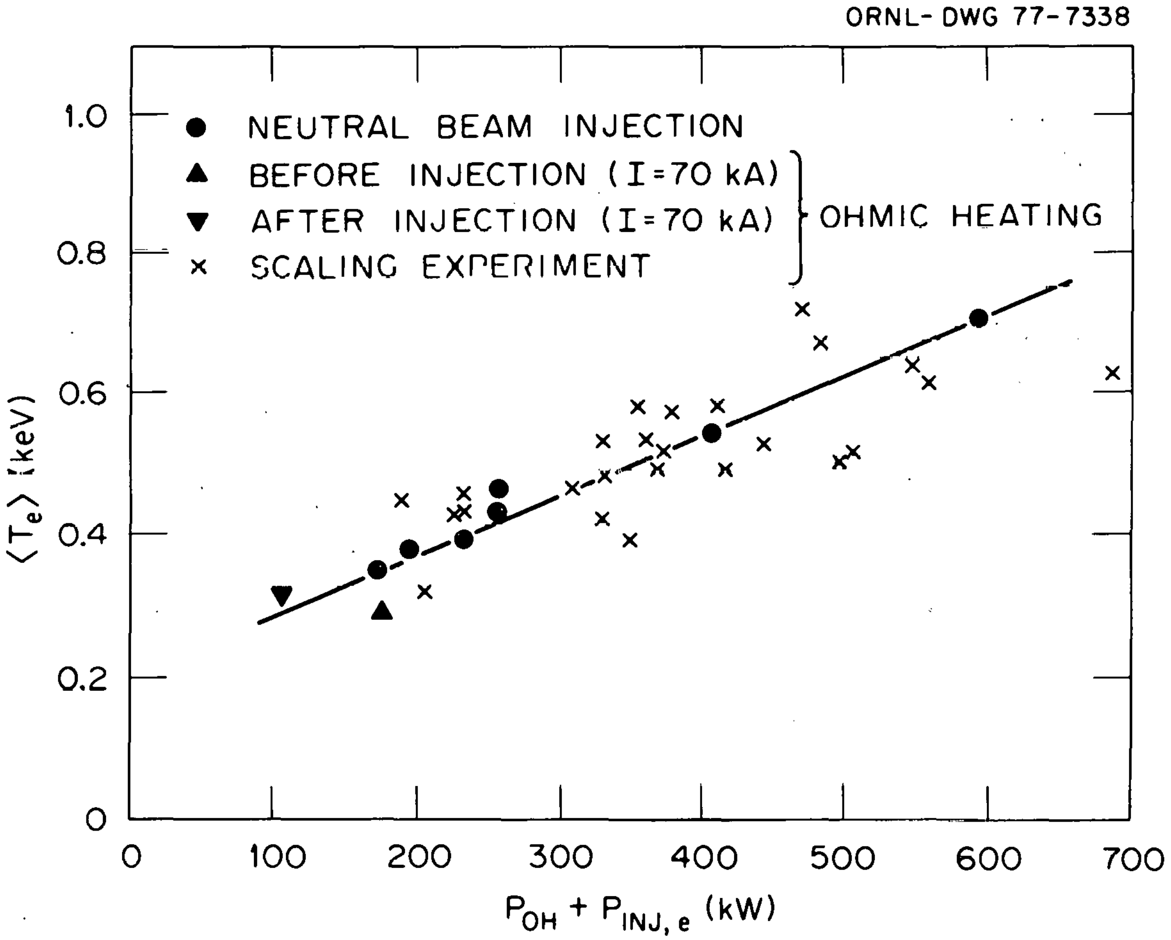

ORNL-DWG 77-6500R
(arb. units)
0
1
2
21.6 Å
20.1 Å
P_{wall} (kW)
0
50
100
150
200
P_{wall}
G.P.
INJ.
0
40
80
120
160
200
t (msec)

Figure 3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● NEUTRAL BEAM INJECTION
▲ BEFORE INJECTION (I=70 kA)
▼ AFTER INJECTION (I=70 kA)
× SCALING EXPERIMENT
OHMIC HEATING
1.0
0.8
0.6
0.4
0.2
0
⟨T_e⟩ (keV)
0
100
200
300
400
500
600
700
P_OH + P_INJ, e (kW)

Figure 4

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