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[9]B. H. Ripin, Appl. Phys. Lett. 30, 134 (1977).

[10]The possiblity that the plasma blowoff may not be strictly one dimensional for grazing incidence is suggested by interferograms at normal incidence such as Fig. 3(c).

Electron Heating by Neutral-Beam Injection in the Oak Ridge Tokamak

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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 electron heat conduction loss is comparable with that in Ohmically heated plasmas. The scaling of average electron temperature with total power input to electrons is approximately the same with or without injection.

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 ($P_{\text{inj},e}$) 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.[5] In comparison with our earlier work,[1] the heating was enhanced by higher available co-injection 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 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 $\approx 1.7\times10^{13}$ cm^{-3}. Injection to 340 kW

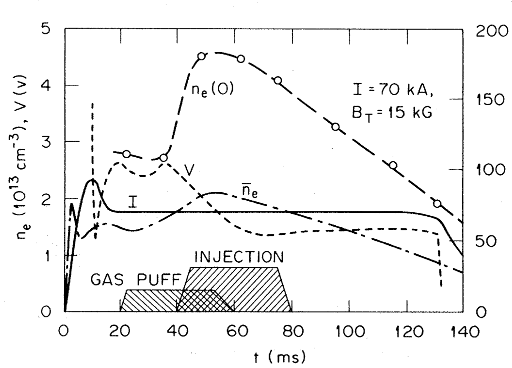

FIG. 1. Time histories of discharge parameters; plasma current (I), loop voltage (V), line-average electron density ($\bar{n}_e$), central electron density [$n_e(0)$], and timings of gas puffing and neutral-beam injection. The parameters shown here are those averaged over 42 reproducible discharges with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

H^0 power starts at 40 msec and lasts for 35 msec. Calculations[4] indicate that $P_{inj,e}$ is about half of the total injected power. The loop voltage (and thus Ohmic-heating power, P_{OH}) decreases considerably (by 45%) during injection, mainly due to a rising electron temperature. Therefore at 75 msec, $P_{inj,e}$ (≈ 160 kW) significantly exceeds P_{OH} (≈ 100 kW, or ≈ 80 kW if a 20% correction is included for the calculated beam-induced current[4]).

The radial distributions of the electron temperature and density before, during, and after the injection period were measured[6] from Thomson scattering. Injection increases T_e significantly at all radii and produces a change in the $T_e(r)$ profile. An initially broad profile becomes more peaked during injection and remains peaked after injection stops. Figure 2 illustrates the time histories of the peak electron temperature, $(T_e)_{max}$, and the density-averaged electron temperature, $\langle T_e \rangle$, derived from these measurements, together with the corresponding temperatures without injection. Similar temporal behaviors of $(T_e)_{max}$ are also indicated by a less certain measurement from soft-x-ray energy spectra [using a Si(Li) detector] averaged over 10-msec intervals. With injection $\langle T_e \rangle$ increases by a factor of 2, and $(T_e)_{max}$ rises by an even larger factor. The slow rise in the temperatures during injection is primarily due to a concurrent density increase since the electron energy content, W_e, saturates after ≈ 15 msec [Fig. 3(a)], a period consistent with the 10-msec fast-ion slowing down time[4] and the 5-msec electron-energy replacement time.

After injection stops, however, $(T_e)_{max}$ and $\langle T_e \rangle$ remain higher than their initial values. This

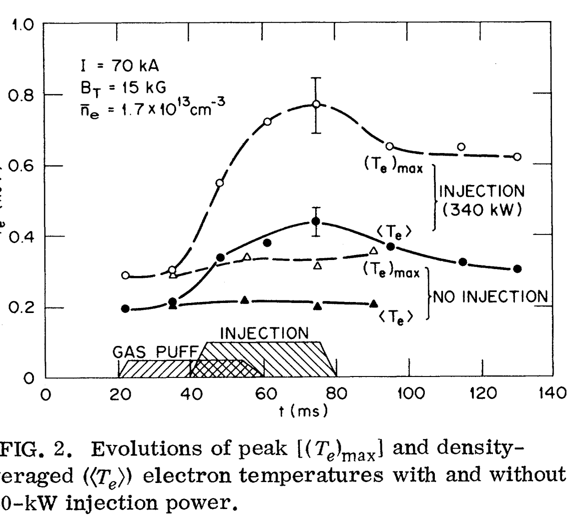

FIG. 2. Evolutions of peak [$(T_e)_{max}$] and density-averaged ($\langle T_e \rangle$) electron temperatures with and without 340-kW injection power.

"hysteresis" phenomenon complicates evaluation of the injection effects, but even if the value of $\langle T_e \rangle$ at 115 msec is taken as the base temperature, we would infer a 40% increase of $\langle T_e \rangle$ due to injection. In contrast to the electron behavior, the peak ion temperature, $(T_i)_{max}$, decays in the expected time, indicating that the power transferred from residual fast ions decays as expected. Since the Ohmic-heating power is lower after injection (110 kW at 115 msec versus 180 kW at 22 msec), the power loss is lower after injection than before injection. In this connection we first note that internal disruptions[7] are not a significant factor in this experiment or in the other experiments reported below.

We next consider the effect of impurities and the radiative power loss. The usual resistance measurement[1] indicates that $\bar{Z}_{eff}$ increases from 2.5 (before and after injection) to 3.5 during injection. Vacuum-ultraviolet spectroscopic 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 which are primarily due to aggregates of unresolved tungsten lines.[8] Figure 3(b) 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

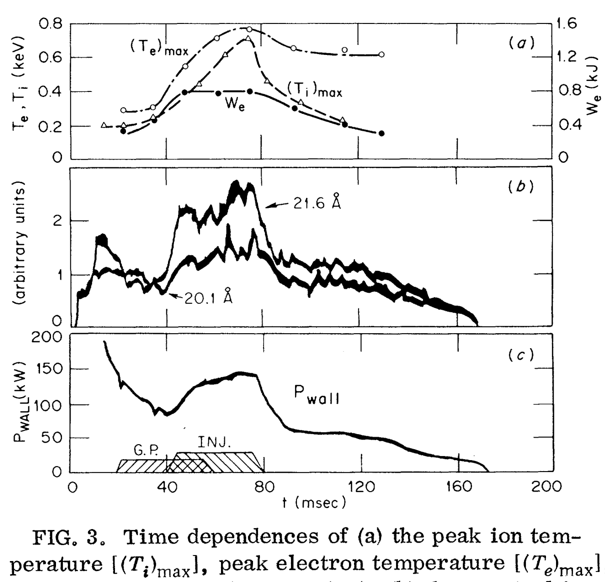

FIG. 3. Time dependences of (a) the peak ion temperature [$(T_i)_{max}$], peak electron temperature [$(T_e)_{max}$], and electron thermal energy (W_e); (b) the spectral intensities at 21.6 Å (the O^{6+} resonance line and continuum) and 20.1 Å (the continuum) as measured by a grazing-incidence spectrometer; and (c) the total power falling on the wall measured by a pyroelectric radiometer, for the 340-kW injection case.

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. Also the tungsten radiation, which is responsible for the largest fraction of the radiation power after the initial phase, exhibits similar behavior. The intensities at various wavelengths between 20 and 50 Å increase by factors of 2–3 during injection, but fall off rapidly when injection stops. It is estimated that the tungesten influx decreases by 30–50% after beam turnoff.

As expected, there is a close correlation of the tungsten radiation with signals from a pyroelectric radiometer [Fig. 3(c)] which measures the total radiated power ($P_{\rm rad}$) falling on the wall (with some small contribution from charge-exchange neutrals). The value of $P_{\rm rad}$ increases by a factor of 1.5–2 during injection and is reduced after injection to $\approx 65\%$ of that before injection. The ratio of $P_{\rm rad}$ to total input power is nearly constant ($\approx 55\%$) throughout the discharge duration.

The combination of the above observations demonstrates the direct transfer of beam energy to electrons and the subsequent heating. Both the electron temperature and energy content increase during injection while the Ohmic-heating power input decreases. The radiation power with injection far exceeds the Ohmic-heating power input, implying that a large fraction of the power which heats electrons must come directly from injection.

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

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

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. From the radiometer values for $P_{\rm rad}$, we find that the values of τ_{Ee} increase from ≈ 5 msec (at 22 msec) to ≈ 8 msec (at 75 and 115 msec) with rather large uncertainties. These results indicate that the electron–heat-conduction loss during injection is comparable with that during Ohmic heating alone, and that the loss after injection is lower than that before injection.

The base case discussed above was at low current, low density, and the highest injection power ($P_{{\rm inj},e} = 160$ kW). Varying the injection power with other discharge conditions fixed produced $\langle T_e \rangle$ values that decreased with decreasing $P_{{\rm inj},e}$ but $\langle T_e \rangle$ during injection at the lowest power (60 kW) was still higher than that after injection (at 115 msec) in the base case.

Substantial increases in electron temperature also occur with injection in high-current discharges. Here the higher starting temperature makes the radiative processes less susceptible to the temperature change, and the injection-induced change in the T_e profiles is less than that in the previous cases. With $I = 175$ kA and $P_{{\rm inj},e} = 120$ kW, we obtain $T_e(0) = 0.85 \rightarrow 1.3$ keV and $\langle T_e \rangle = 0.56 \rightarrow 0.71$ keV ($B_T = 26$ kG, $\bar{n}_e = 2.2 \times 10^{13}$ cm^{-3}, and $P_{\rm OH} = 480$ 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. As in the injection case, the ratio of $P_{\rm rad}$ to the total power input is approximately constant. The value, $\approx 50\%$ as in the injection cases, is like that observed in normal Ohmically heated discharges over a wide range of conditions.[9] 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 ($\bar{n}_e = 3.3 \times 10^{13}$ 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 to electrons ($P_{\rm OH} + P_{{\rm inj},e}$) for a variety of discharges at different currents, densities, and toroidal fields. The scaling of $\langle T_e \rangle$ with total

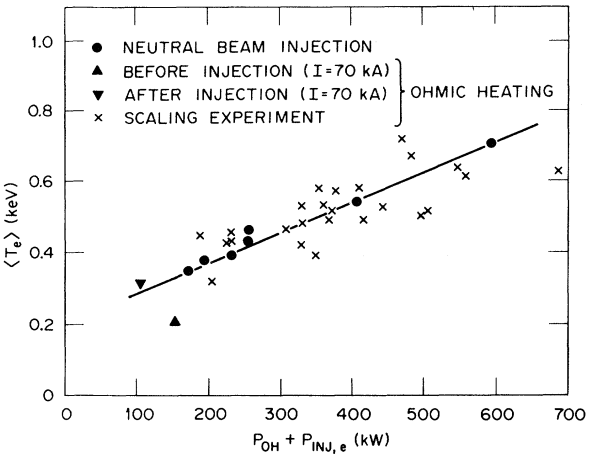

FIG. 4. Scaling of $\langle T_e \rangle$ with the total electron power input with and without injection. The data (shown by crosses) for Ohmic heating alone are the results of the scaling experiments (Ref. 9) in which the operational parameters (B_T, I, and $\bar{n}_e$) were deliberately changed to study scalings of plasma parameters, producing large scatters of $\langle T_e \rangle$.

input power appears to be the same for plasmas 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.

The work presented here is the result of the efforts of the entire ORMAK group in cooperation with the Plasma Heating and Fueling Section of the Fusion Energy Division. The authors gratefully acknowledge, in particular, the efforts of J. D. Callen, H. C. Howe, G. L. Jahns, H. E. Ketterer, J. T. Mihalczo, A. P. Navarro, R. V. Neidigh, G. H. Neilson, V. K. Paré, D. L. Shaefer, J. B. Wilgen, and W. R. Wing. Finally, the encouragement and support of J. F. Clarke and G. G. Kelley are gratefully acknowledged. This research was sponsored by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation.

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