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RELATION OF NEUTRAL BEAM INJECTION TO IMPURITY BEHAVIOR AND EXTENSION OF PLASMA PARAMETERS IN ORMAK*

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Abstract: Neutral beam injection extends the plasma parameter range (n_e , β_T , q , T_i) in ORMAK over that obtainable with ohmic heating alone. Impurity radiation also increases due to the added power, especially with counterinjection. Impurity trapping of injected beam neutrals is observed, but the large toroidal rotation velocities expected for unidirectional injection do not occur.

Introduction: In addition to heating future tokamak plasmas, massive neutral beam injection power may also permit attainment of higher plasma densities and higher toroidal beta β_T . Possible problems could be (1) large beam-induced toroidal rotation velocities or (2) increased impurity influx that leads to additional radiation losses and prevents beam penetration of the plasma.

Extension of Plasma Density Limit:

As shown in Fig. 1, the density limits for ohmically heated plasmas in ORMAK (gas puffing limit ≈ 1.6 times steady filling limit) and in other tokamaks are proportional to B_T/R_0 [1], which is a measure of the central current density since $q(0) \approx 1$. This suggests that the maximum density is proportional to ohmic heating power. On this basis, we might expect the combination of neutral beam injection (as an auxiliary power input) and gas

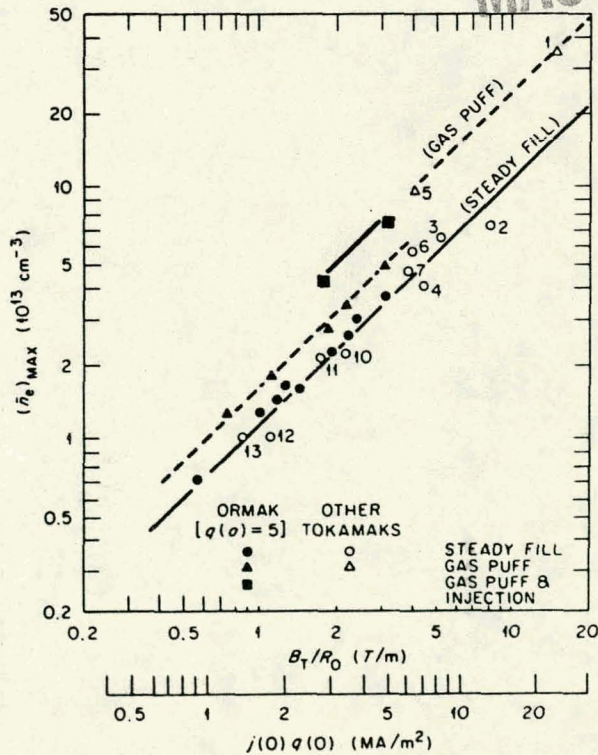


Figure 1

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puffing (to provide an adequate particle source) to increase the attainable density. In fact, this does occur, as shown in Fig. 1.

Extension of β_T and q with Injection: For the highest density reached in ORMAK ($\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$) with gas puffing and 240 kW injection [$q(a) = 5$ at $B_T = 25 \text{ kG}$], we obtain $\tau_E = 15 \text{ ms}$, $\beta_T(0) = 1.2\%$, and $\bar{\beta}_T = 0.4\%$. Similar values for β_T can be obtained at lower $q(a)$ with injection. Injection of 340 kW permits grossly stable and reproducible discharges with broad $T_e(r)$ profiles and normal internal MHD activity at $q(a)$ down to 2.6 ($B_T = 10.4 \text{ kG}$), which is not possible without injection. For this case $\bar{n}_e = 1.8 \times 10^{13} \text{ cm}^{-3}$, $\beta_T(0) = 1.4\%$, and $\bar{\beta}_T = 0.4\%$. Calculations and equilibrium measurements indicate that the stored fast-ion energy approximately equals the bulk plasma energy. Thus we estimate the total (beam + plasma) β_T values to be $\approx 3\%$ peak and $\approx 1\%$ average.

Effect of Injection on Impurities: Impurity radiation is increased by coinjection, but only to the degree expected for ohmically heated discharges with the same total power input to electrons [2]. The radiation loss is $\approx 50\%$ of the total electron power input both with and without injection. Figure 2

illustrates the increased radiation due to added coinjection power for the base electron heating case described in our companion paper [2]. The signals are representative of the behavior of O^{6+} (21.6 Å), a segment of continuum thought to be due to closely spaced lines of tungsten (20.1 Å), and the total radiated power (P_{wall}).

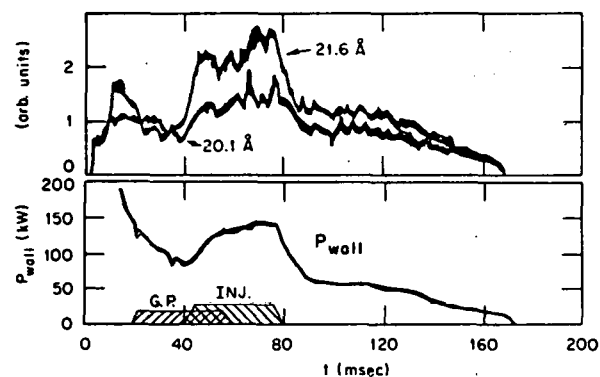


Figure 2

Counterinjection produces a larger increase in impurity radiation than does the same amount of coinjection power. This aspect is indicated in Fig. 3 for a line of Fe XVI (360.8 Å). Figure 4 shows the $T_e(r)$ profiles obtained for this case. The depression of the central electron temperature with counterinjection is thought to be related to tungsten impurity radiation cooling.

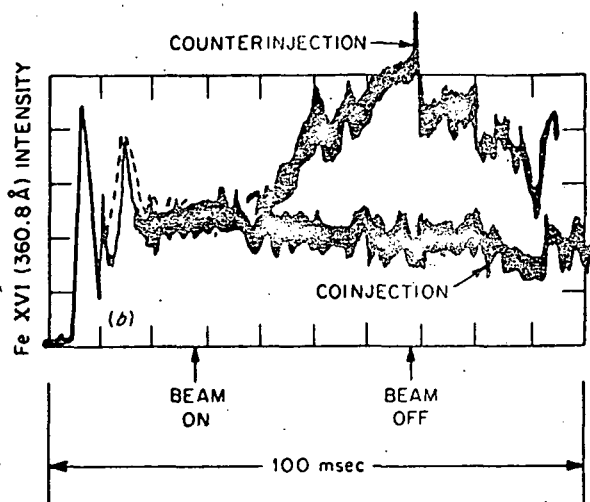


Figure 3

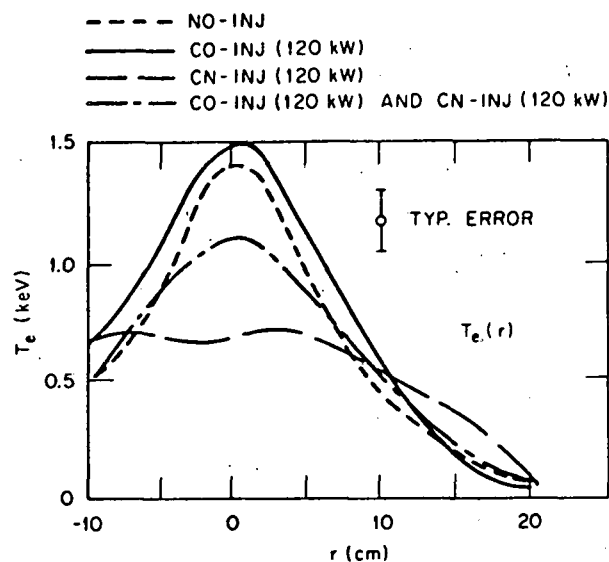


Figure 4

Absence of Beam-Induced Toroidal Rotation: Despite the deleterious effects associated with counterinjection, there has been a supposed need for counter-injected beams to balance the toroidal momentum input expected from co-injected neutral beams. The ion toroidal flow velocity calculated from a toroidal momentum balance equation has been compared with that estimated from the Doppler shift of the H_α line profile and from comparison of the parallel and perpendicular charge-exchange energy distributions ($\Delta V_{\parallel} \sim 2 \times 10^6$ cm/s). Agreement occurs only if the toroidal momentum damping time in the plasma interior is ~ 100 μ s, much faster than any calculated interaction time (e.g. charge-exchange time ~ 50 ms).

Effect of Impurities on Injection: The role of neutral beam trapping by charge transfer to impurities can be significant, as shown by the measurements at ORNL by Phaneuf and co-workers of the cross sections for charge exchange between H⁰ and various light (C, O) and heavy (Fe) ionized impurities present in tokamaks, and by calculations and beam trapping measurements on TFR by Moriette. Direct spectroscopic evidence for the charge transfer reaction $H^0 + O^{8+} \rightarrow H^+ + (O^{7+})^*$ is observed during ORMAK injection experiments. The intensity of the Balmer- α line of O VIII (102 Å) increases a factor of 4 within 4 ms after beam turn on, whereas the intensities of the Lyman- α , - β ,

and γ lines of O VIII and the Balmer- β line of O VIII increase less than 20% in this interval, indicating a direct interaction between the neutral beam and the plasma.

When impurity charge exchange is included in calculations of the beam power deposition, the peak of the power deposition curve for the highest density case shifts from $r = 0$ to $r = 15.5$ cm (limiter radius $a = 23$ cm) and the injection power density exceeds the ohmic power density for $r > 14$ cm. This additional power input in the plasma may permit attainment of the higher plasma density before disruption occurs by heating the plasma edge and thus forestalling shrinkage of the current channel.

Summary: Addition of neutral beam injection power permits attainment of higher density and β_T and of stable operation at lower q than without injection. The impurity radiation also increases, but only in proportion to the added power.

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References:

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- [2] M. Murakami, J. F. Lyon et al., this conference.