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INJECTION-DOMINATED TOKAMAK EXPERIMENTS AT ORNL[*]

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Abstract

Experiments on the Oak Ridge Tokamak (ORMAK) have demonstrated ion and electron heating and improvements in $\overline{\beta}_T$, $\overline{n}_e$, and $q(a_\ell)$ with neutral beam injection. They have also emphasized the need for low impurity levels in injected plasmas and the advantages of co- as opposed to counterinjection. These results, together with the favorable confinement and impurity results obtained in the Impurity Study Experiment (ISX-A) are encouraging in terms of injection-dominated, high beta experiments planned for ISX-B. This device will use 3.0 MW of injection power to study beta limits, confinement, heating, and impurity control in noncircular cross-section plasmas.

I. Introduction

Neutral beam injection has been established in experiments on ORMAK[1,2] and a number of other tokamaks[3] as an effective method of supplemental heating. Its role is now being extended in devices with injected power several times greater than ohmic power. In particular, the ISX-B tokamak at ORNL will be operated in this beam-dominated mode to study confinement scaling, impurity control, and high beta stability limits in plasmas with different cross sections (circular, elliptical, and D-shaped). In this paper we discuss this application of injection heating in terms of the conclusions drawn from ORMAK injection experiments, the encouraging results from ISX-A at low toroidal fields, and the problems which will be addressed on ISX-B.

II. Conclusions of ORMAK Injection Studies

A. Coupling of beam power to plasma[4]

The trapping of beam neutrals, showing down and pitch angle scattering of fast ions, and power transfer to plasma electrons and ions is well understood in terms of purely classical processes. For example, fast ion distributions observed in ORMAK agree with those calculated theoretically. An important implication of this classical picture is the need to minimize Z_{eff} in injected plasmas, especially with counterinjection, because a high Z_{eff} reduces beam penetration and enhances fast ion pitch angle scattering and subsequent loss.

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B. Ion heating[1]

Figure 1 shows the power balance in ORMAK for a 360-kW H^0 beam injected into a hydrogen plasma. Power to the ions is derived mainly from the beams, resulting in a three-fold increase in ion temperature over that obtained with ohmic heating alone. Because the ion temperature exceeds that of the electrons, the usual power transfer between the two components is reversed. The scaling of ion temperature with injection power in ORMAK is roughly linear and consistent with the classical transfer of injected power to the ions and loss through neoclassical heat conduction.

C. Electron heating[2]

The injection contribution to electron heating was verified by reducing ohmic heating power at maximum injection power, allowing injection to dominate the electron power input, and well as that of the ions, as Fig. 2 shows. Significant heating of both species was observed. Important prerequisites for this experiment were a reduction in Z_{eff} from the normally high ORMAK values to about 2.5 to 3.5 and the avoidance of counterinjection. Even so, radiation, primarily from heavy ions (tungsten from the limiter), accounted for 60% of the power losses. A significant observation is that no injection-specific losses were introduced, which implies a general equivalence of ohmic power (P_{OH}) and injected power to electrons ($P_{inj,e}$). This was further confirmed in scaling studies showing electron temperature to increase as a function of ($P_{OH} + P_{inj,e}$).

D. High beta experiments

The achievement of high beta values in ISX-B will require high densities and low toroidal fields, or equivalently low safety factor $q(a_\ell)$, with injection heating. Good confinement and stability must of course be maintained as well. In ORMAK, both higher densities and lower $q(a_\ell)$ values were obtained with injection than with ohmic heating alone (see Fig. 3).[9] Using 340 kW of injection at $q(a_\ell)$ of 2.6, average toroidal beta $\overline{\beta}_T$ of 1% was obtained, with a peak value $\beta_T(0)$ estimated to be 3%. These values reflect approximately equal contributions from energy stored in the plasma and that in the fast ions (i.e., $\Gamma \approx 1$).

E. Co- and counterinjection studies

Counterinjection was found to be undesirable relative to coinjection because it leads to reduced heating efficiency and increased impurity influx. The consequences are indicated by the electron temperature profiles in Fig. 4, where radiation losses due to increased heavy impurity levels resulting from counterinjection caused significant cooling of the electrons in ORMAK plasmas. Although the effects of counterinjection are improved by increasing the plasma current, this requires higher toroidal fields for a given $q(a_\ell)$. Furthermore, undirectional (co) injection may contribute significantly to the plasma current under some conditions. Hence it is advantageous to avoid counterinjection if possible.

It is postulated that the toroidal momentum input from unidirectional injection may lead to excessively high toroidal ion drift velocities. However, no such drifts were observed in ORMAK, even with 340-kW unbalanced coinjection power. Momentum balance arguments invoking classical damping mechanisms predict large drift velocities, well beyond the uncertainties in the measurements, which were based on H_α line profiles[5] and charge-exchange spectra. This result implies the existence of nonclassical momentum transfer processes. On the other hand, there is experimental evidence for induced rotation on PLT;[6] hence the need for balanced co- and counterinjection is uncertain.

III. ISX Injection Studies

A. ISX-A[7]

Injection studies on ISX-B are designed both to extend the favorable results of ORMAK and to solve some of the problems which were identified. In particular the need for reducing Z_{eff} and heavy impurity levels was repeatedly demonstrated. Both of these goals were accomplished in the ohmically-heated ISX-A, through the use of all-metal vacuum vessel construction and stainless steel limiters. Average Z_{eff} values of 1.5 typical and 1.0 minimum were obtained, and wall power losses were reduced to 25-40% of ohmic power, compared to 50-80% in ORMAK. One result of this improvement is illustrated in Fig. 3; ISX-A operated stably at low $q(a_\ell)$ and at high density for its toroidal field, comparable with other clean tokamaks. Confinement times of 30 msec, obtained in deuterium plasmas at $\bar{n}_e \approx 3 \times 10^{13}$ cm^{-3}, were also favorable relative to empirical scaling predictions. Other parameters for this device are summarized in Table I.

B. ISX-B

The main features of the ISX-B tokamak are massive injection power density (P_{inj} = 1.8 MW, later 3 MW; a = 27 cm, and R_0 = 92 cm), control of plasma cross section (circular, elliptical, and D-shaped up to 1.9:1 elongation), and relatively low toroidal field (1.8 T max.). Other parameters are given in Table II. The primary goal of this experiment, which will begin late in 1978, will be to investigate beta limits. Based on empirical scaling laws, the available power is sufficient to test stability limits for $\bar{\beta}_T \gtrsim 10\%$ (for circular plasmas $\bar{\beta}_T$ is limited theoretically to $\approx$2%). Typical plasma parameters expected are $q(a_\ell) \sim 3$, $\tau_E \sim 50$ msec, $\bar{n}_e \sim 10^{14}$ cm^{-3}, and $T_e \approx T_i \sim 2$ keV. In this context, the low Z_{eff}, low $q(a_\ell)$, high densities, and high confinement times obtained on ISX-A are especially encouraging as they constitute very favorable plasma conditions for injection.

Because of the high injection power densities available, injection heating studies begun on ORMAK can be extended. The impurity questions must also be readdressed in the presence of these intense power levels, and provision for a bundle divertor has been made should such means become necessary for impurity control. Another important question is whether the favorable confinement times observed in ISX-A are sustained in ISX-B, in which $P_{inj} \gg P_{OH}$.

The unresolved question of toroidal drifts will be investigated early, since initially only coinjection will be used. A related issue is that of beam-induced plasma currents, which could be used to supplement ohmic heating transformer-driven currents. In ISX-B, predicted beam-driven currents are comparable to I_p, hence a significant test is possible.

A test of ripple-assisted injection trapping,[8] a scheme for reducing the beam energy requirements in TFTR and other large machines will be carried out. The effects of the imposed ripple field on plasma confinement and transport and on fast ion losses will also be examined.

IV. Conclusion

Experiments on ORMAK demonstrated the feasibility, in terms of effects on confinement and stability, of tokamak operation dominated by injection power. The effectiveness of injection is maximized by good energy confinement, low impurity levels, and the avoidance of counterinjection. ISX-B will combine these findings with the favorable base conditions obtained in ISX-A to test stability limits, confinement scaling, injection heating, and impurity control in high beta plasmas of different cross sections.

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Figure Captions

Fig. 1. Ion power balance is dominated by 360-kW injection (2/3 co- 1/3 counterinjection). T_i exceeds T_e and power flows from ions to electrons. Lack of electron heating results from increased losses due to counterinjection.

Fig. 2. At reduced P_{OH}, injection dominates both electron and ion power balance; heating of both species is observed.

Fig. 3. Operating regimes of tokamaks in normalized ($\bar{n}_e$, I_p) space, after DITE.[9] Injection allows operation at higher densities, lower q. ISX parameters are typical of those obtained with gas puffing in clean devices.

Fig. 4. Counter-injection leads to poor energy confinement, indicated by cooling of electrons.

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Table I. ISX-A parameters

$a_\ell = 26$ cm, $R_0 = 92$ cm

	Self-consistent	Max (min)	
B_T	1.28	1.48	T
I_p	120	175	kA
$q(a_\ell)$	4.0	2.5 (min)	
$\bar{n}_e$	3.3×10^{13}	7.0×10^{13}	cm^{-3}
V_{loop}	1.1	0.9 (min)	V
$T_e(0)$	0.64	1.5	keV
$\langle T_e \rangle$	0.38	0.50	keV
$T_i(0)$	0.52	0.57	keV
$\langle \beta_p \rangle$	0.55	0.76	%
$\langle \beta_T \rangle$	0.28	0.52	%
$\beta_T(0)$	1.6	2.2	%
τ_E	30	30	msec
Z_{eff}	1.6	1.0 (min)	

Table II. ISX-B parameters

R_0	92	cm
a	27	cm
b/a	1.9 (max)	
B_T	1.8 (max)	T
I_p	200 (max)	kA
Δ(core flux)	0.9 (max)	V-sec
Limiter	Stainless steel	
Injectors	2	Coinjectors
E_{inj}	40	keV
P_{inj}	1.8 (1978)	MW
	3.0 (1980)	MW
OH pulse	200 (min)	msec
Inj. pulse	200 (min)	msec

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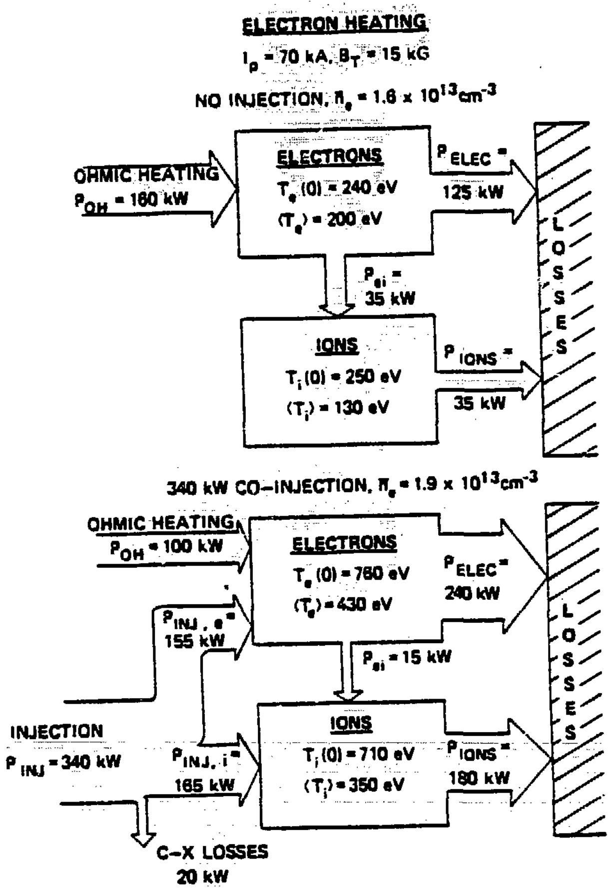

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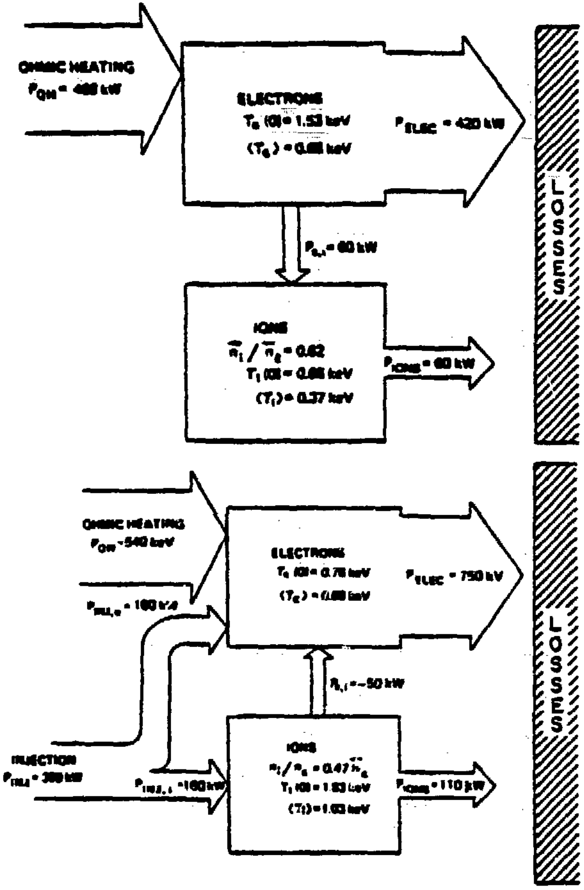
$I_p = 175$ kA, $B_T = 25$ kG, $\bar{n}_e = 2.8 \times 10^{13} \text{cm}^{-3}$



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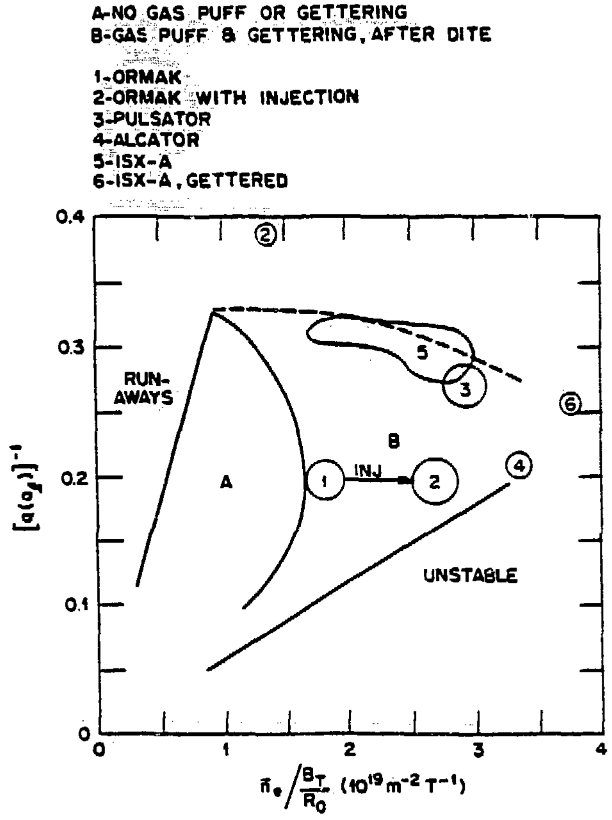

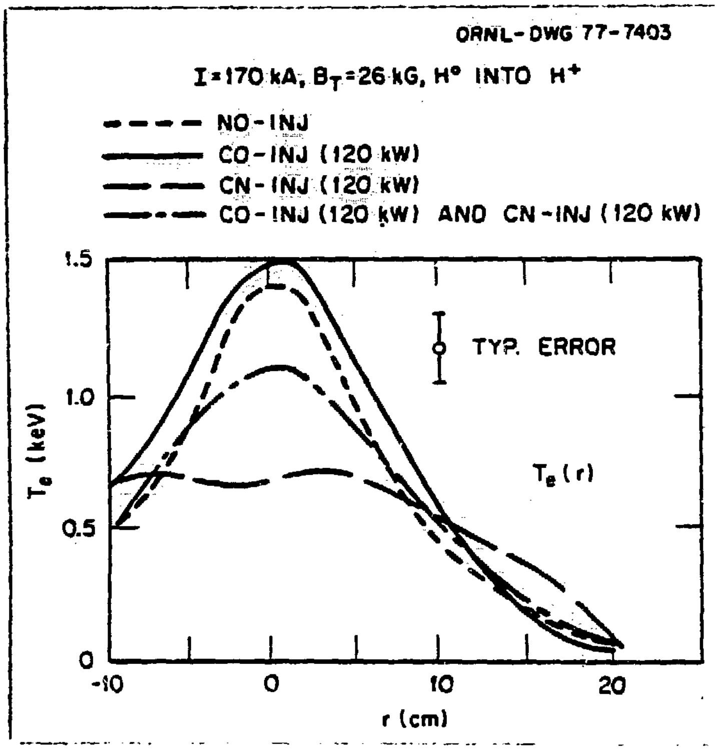
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I=170 kA, B_T=26 kG, H° INTO H⁺
NO-INJ
CO-INJ (120 kW)
CN-INJ (120 kW)
CO-INJ (120 kW) AND CN-INJ (120 kW)
TYP. ERROR
T_e (r)
T_e (keV)
1.5
1.0
0.5
0
-10
0
10
20
r (cm)