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NEUTRAL BEAM INJECTION EXPERIMENTS AT ORNL: FUELING ASPECTS*

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Summary

The Oak Ridge National Laboratory (ORNL) neutral beam injection program, beginning with the Oak Ridge Tokamak (ORMAK) and continuing with the Impurity Study Experiment (ISX), is reviewed. The emphasis of these experiments has been on plasma heating, but some insights into the fueling issue have been provided as well. However, there is no conclusive evidence as yet for any significant impact of injection on the plasma particle balance.

I. Introduction

Experiments on ORMAK and other devices have established neutral beam injection as a viable scheme for plasma heating in tokamaks.[1,2] From perturbation levels of 45 kW in 1972, injection power into ORMAK was increased to 360 kW in 1976, providing the first demonstration of injection-dominated ($P_{inj} > P_{OH}$) tokamak operation. The program will continue in 1978 with the installation of 1.8 MW injection on ISX. This device is expected to produce high-$\overline{\beta}$ plasmas by means of very intense neutral injection ($P_{inj} >> P_{OH}$).

In Section II of this paper we review the major results of injection experiments on ORMAK, which were concerned primarily with ion and electron heating and with the effects of injection on other plasma properties (density, confinement, Z_{eff}, etc.). Specific results which bear upon the fueling issue are also discussed. In Section III, we briefly summarize the experimental plans for ISX-B, which include a test of ripple injection. In Section IV, we discuss the applicability of injection to plasma fueling.

II. The ORMAK Injection Program

The ORMAK device had provision for four tangential injectors, two parallel and two antiparallel to the plasma current, as shown in Fig. 1. These were initially 25-kV, 4- to 6-A sources developed at Oak Ridge. Through optimization and upgrading, we ultimately obtained as much as 360 kW of delivered power from two injectors operating near 30 keV.[3]

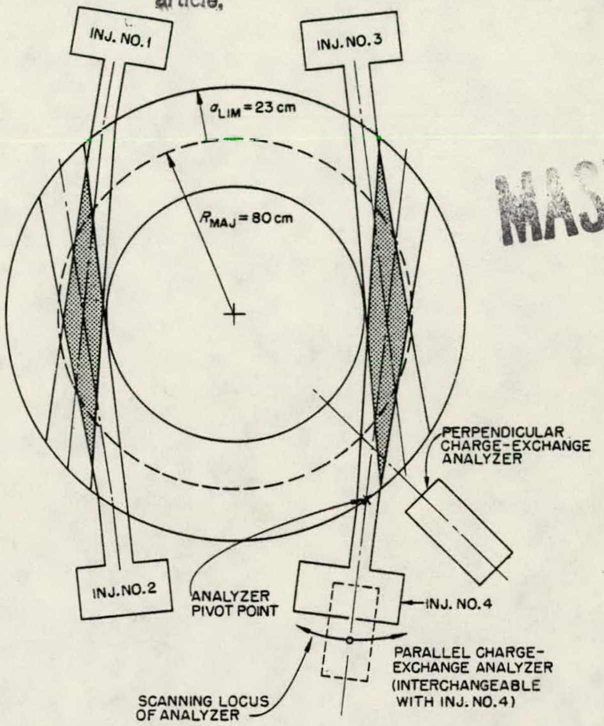

Fig. 1. ORMAK injector layout. ORMAK had provision for two co- and two counterinjectors.

Ion temperature was found to increase roughly linearly with injected power, as Fig. 2 shows.[2] Within the uncertainties in the measurement, the scaling is consistent with our theoretical understanding of beam trapping and slowing down and of ion heat conduction.

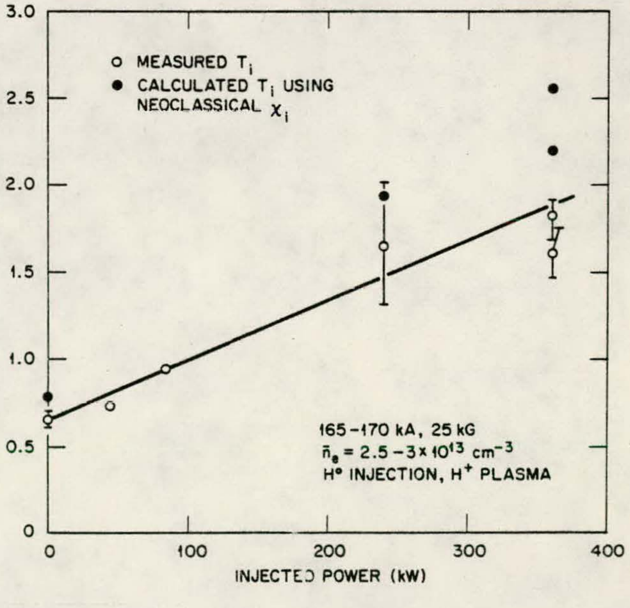

Fig. 2. Ion temperature scaling was roughly linear with power in ORMAK, consistent with neoclassical calculations. Error bars and scatter indicate uncertainties in determining ion temperature from charge-exchange neutrals in the presence of injection.

In all of these scaling studies, ohmic heating was the primary source of plasma energy. At the high power end of Fig. 2, the injection contribution to the power balance becomes significant, to the extent that the temperature of the ions exceeds that of the electrons. As Fig. 3 shows, the power flow between electrons and ions is reversed under such conditions. Finally, we enter another important regime by reducing I_p so that $P_{inj} > P_{OH}$. Here, we find that (after

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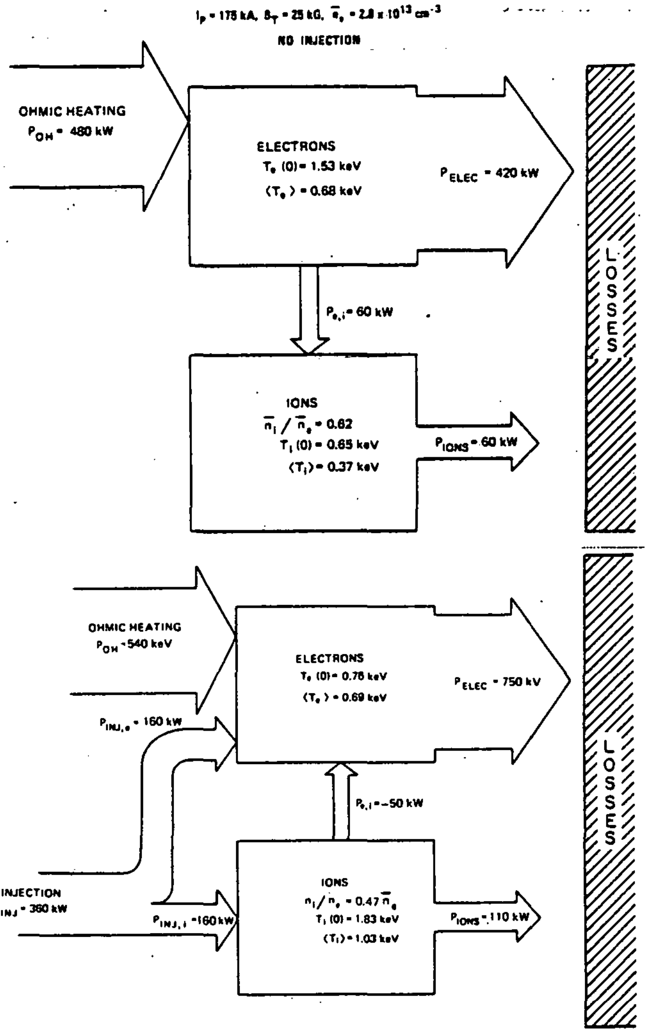

Fig. 3. Injection drastically alters the power balance in the plasma from that obtained with ohmic heating alone. The figure shows 360 kW (2/3 co-, 1/3 counterinjection), $T_i < T_e$, and power flows from ions to electrons; electron energy losses are also greater.

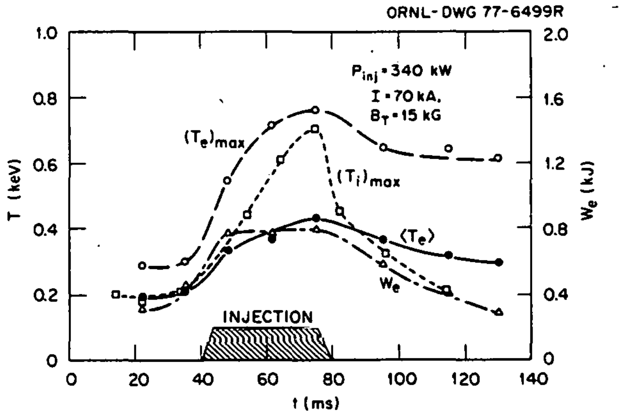

Fig. 4. Electron heating by injection is observed when $P_{inj} > P_{OH}$ and impurities are reduced (from Ref. 4).

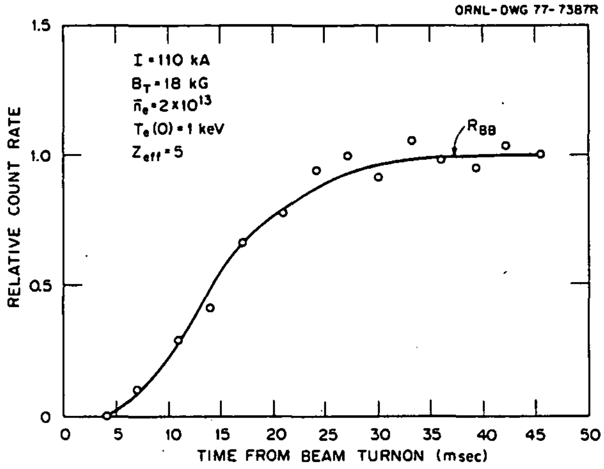

Fig. 5. Neutron production rates measured and calculated from a deuterium beam slowing down in a hydrogen plasma. Beam deuterons react with already trapped slowing-down deuterons (from Ref. 6).

impurity levels are sufficiently reduced) it is possible to obtain beam heating of electrons as well as of ions; the time dependences of ion and electron temperatures for this experiment are shown in Fig. 4.[4]

The results of these experiments on ORMAK imply that injection can be a dominant power source, greatly exceeding ohmic contributions, in future tokamak experiments. It is then appropriate to ask whether it might be an important particle source as well. In the 360-kW ORMAK case, the total injected beam current from the three energy constituents was about 19 A. This corresponds to a volume-averaged gross particle deposition rate, n_b, of 1.2 × 10^{14} cm^{-3} s^{-1}; for $\bar{n}_e$ ~ 2 × 10^{13}, the replacement time $\bar{n}_e/\bar{n}_b$ is 170 ms. Since the beam pulse lengths were only about 50 ms, and since other sources such as cold gas from the drift tubes and enhanced impurity stripping were attendant with injection, it was not possible to determine any net contribution of beam particles to the bulk population.

A number of experiments were done in which we observed the slowing-down fast ion population. Figure 5 shows the neutron production rate from injected deuterium atoms interacting with already trapped deuterons in hydrogen plasma.[5] The observed temporal behavior is consistent with calculations which assume that the primary beam reacts only with other fast deuterons that have scattered in angle but have not lost much energy. However, it is inconsistent with any buildup of "stopped" beam particles joining the bulk plasma. In Fig. 6, relative perpendicular charge-exchange spectra in the fast ion band are plotted comparing co- and counterinjection cases in low current discharges. Coinjected fast ions are better confined and are more likely to survive the slowing-down and scattering process to a 90° angle, as this figure indicates. Both of these observations are consistent with particle orbit and Fokker-Planck calculations, supporting the conclusion that beam trapping and slowing-down phenomena are well understood at this time.

To complete the picture for an understanding of beam refueling requires knowledge of particle confinement mechanisms and how they are affected by injection. Local background replacement rates computed from neutral densities [$n_0(0)$ ~ 10^8 cm^{-3}] in ORMAK are quite low, suggesting long effective particle lifetimes. The rapid uniform density increase observed with gas puffing suggests the presence of a strong inward plasma transport mechanism, and we note that density

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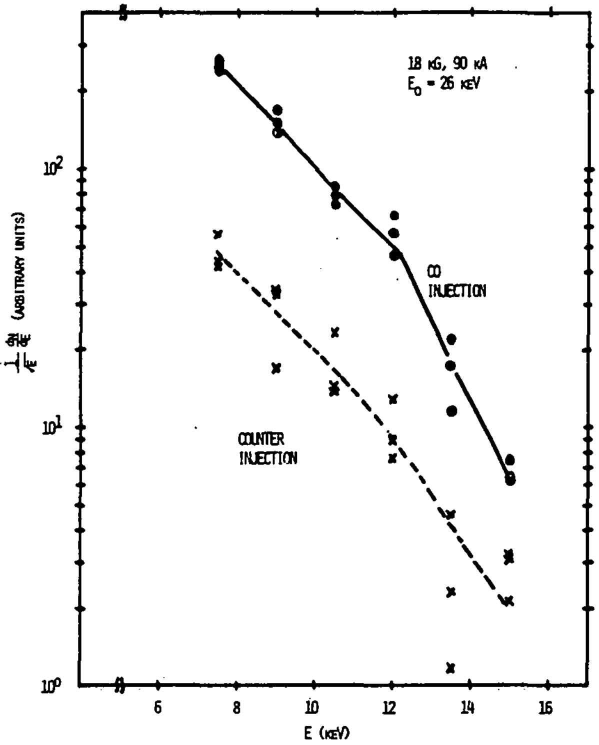

PERPENDICULAR FAST ION DISTRIBUTION

Fig. 6. In low current discharges, coinjected ions are better confined than counterinjected ions. This is predictable from particle trajectory calculations.

limits with gas puffing are apparently raised by injection, as Fig. 7 indicates. However, beyond such evidence there is as yet no coherent understanding of particle confinement and transport.

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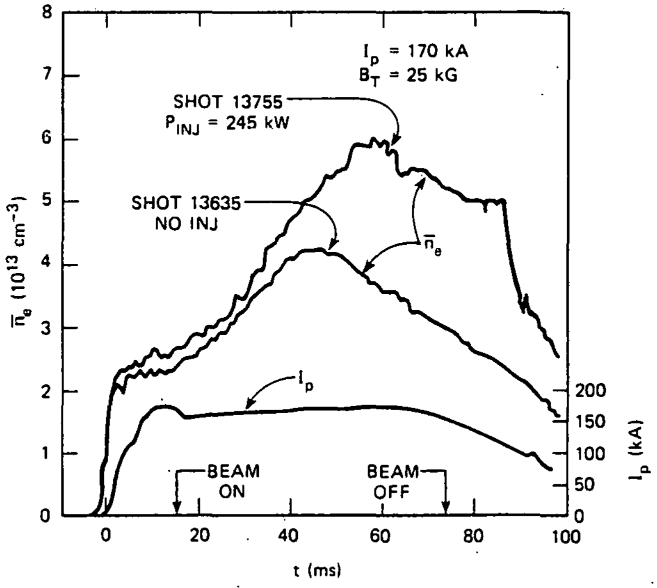

Fig. 7. Injection apparently raises the disruptive limit on density obtainable with gas puffing.

III. The ISX Injection Program

In 1978, the ISX device will be upgraded by the installation of a new heavy-duty liner, a more sophisticated poloidal field system, and two neutral beam injectors. The injectors are 40-kV, 60-A sources of the type developed for the Princeton Large Torus (PLT) and will deliver up to 1.8 MW of total coinjected power to the plasma (a planned source upgrade will increase this to 3 MW). Table I summarizes the parameters of this device, designated ISX-B.

Table I. ISX-B parameters

Device	
Major radius, R_o	92 cm
Minor radius, a	27 cm
Elongation, ε (b/a)	1.5
Volume	2.3×10^6 cm^3
Maximum toroidal field, (B_T/R_o)	1.8 T
Maximum plasma current, I_p	200 kA
Iron core	0.9 V-s
Injectors	
Number	2
Type	Coinjection
Beam energy, E_{inj}	40 keV
Beam power, P_{inj}	1.8 MW[a]
Beam species	40:20:13.3 keV
Beam power	85:12:3 = 100%
Beam current	38:11:4 = 53 A
N_b	23:0.7:0.3 = 3.4×10^{20} s^{-1}

[a] To be upgraded to 3 MW at a later date

The injection program on ISX-B is in some ways an extension of work begun on ORMAK. With P_{inj}/P_{OH} of up to 10, ISX-B will operate as a device which is clearly injection-driven. We plan, as a major aspect of the program, to test the limits of such a device; average values of exceeding 5% have been predicted. Impurity and surface work has already started on ISX-A and will continue in the upgraded machine as well.

An experimental test of ripple injection is also being prepared in collaboration with Princeton Plasma Physics Laboratory (PPPL). This scheme would reduce the energy requirements for beam penetration[6] and is thus important to the feasibility of beam fueling.

A layout of this experiment is shown in Fig. 8. An ORMAK 10-cm source located between TF coils beneath the device will produce up to 5 A of neutrals injected vertically at energies variable between 15 and 40 keV. At high densities ($\bar{n}_e$ 10^{14} cm^{3}) and low beam energies (E_{inj} 20 keV), beam trapping occurs near the edge of the plasma. A vertically asymmetric ripple produced by a pair of coils adjacent to the injector should enhance the upward transport of the trapped fast ions toward the plasma center. The effect will be measured in terms of increased central fast ion population, as inferred from charge-exchange neutrals when the ripple is turned on.

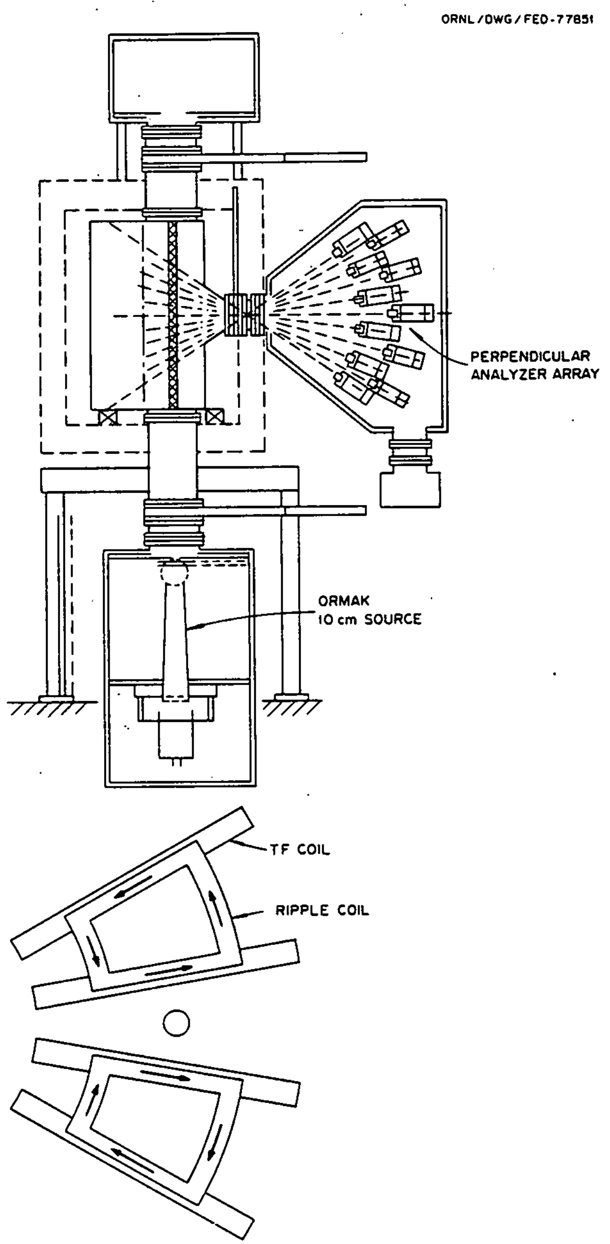

Fig. 8. Schematic layout of ripple injection experiment.

As one means of studying the particle deposition and confinement, ISX-B will employ mass-resolved neutral diagnostics. Ions introduced by puffing, injection, or pellets may then be identified by using a hydrogen isotope (H or D) different from that of the bulk plasma, and analyzing the resulting charge-exchange neutrals by both mass and energy. This feature will be especially valuable in the ripple injection experiment where the test beam deposition will be overwhelmed by that of the primary injectors.

IV. Conclusion

The ORNL injection program has been directed toward the goal of injection-driven tokamak operation. Emphasis has been on ion and electron heating with attention to the effects of injection on confinement, impurities, and bulk drifts. The results to date indicate that injection can serve as the primary power source to a tokamak plasma; this assumption will be further tested on ISX-B.

While injection can be a dominant power source, it does not necessarily represent a significant particle source in these experiments. The reason is that since injection energies are high for penetration requirements, beam currents $I_{inj} = P_{inj}/E_{inj}$ are correspondingly small. For example, we estimate the volume-averaged particle deposition, n_b, for ISX-B with 1.8 MW of injection to be $1.4 \cdot 10^{14}$ cm^{-3} sec^{-1}. For this to sustain a density $\bar{n}_e$ of only $5 \cdot 10^{13}$ requires effective bulk particle lifetimes of 350 ms; there will very likely be observable local effects due to the peaked beam deposition profile, however. Injection would appear to offer the advantage of fueling the center of the discharge; however, results to date suggest that cold gas puffing does this just as well. For these reasons, the desirability of injection as a particle source would seem to depend on some or all of the following developments in the future:

1. Particle lifetimes turn out to be long enough that little replacement is needed.
2. It becomes necessary as a means of fueling the plasma center directly.
3. Energy requirements for penetration become reduced (e.g., by ripple injection), thereby permitting larger beam currents for a given power.

This report is a summary of work done on ORMAK and ISX. As such, it represents contributions from the entire staff of the Tokamak Experimental Program.

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