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Abstract. The plasma conditions attained in the ohmically heated ORMAK experiment provide a satisfactory base for neutral injection heating. Plasma flows and radial electric fields of the same magnitude as those expected to result from neutral injection have been observed in ORMAK. They appear to have no deleterious effect on the plasma.

Introduction. As of the writing of this paper the ORMAK experiment is being modified to accept two 125 kW neutral beam injector modules[1]. Experimental results are expected by August and will be included in the oral presentation. In this paper we will concentrate on those properties of the existing ORMAK plasma which might be expected to influence the outcome of the neutral injection experiment.

ORMAK Plasma Conditions. The overall energy balance in ORMAK has been shown to depend heavily on n_0 , the density of neutral atoms in the plasma[2]. When charge exchange dominates the ion energy loss process, the bulk ion temperature can be found by equating the electron-ion heat transfer rate to the charge exchange losses:

$$3\left(\frac{m}{M}\right)n_e v_{ei}(T_e - T_i) = n_0 \sigma_{cx} v_i n_i \times (T_i - T_0) \quad (1)$$

This equation can be solved for T_i using the fact[3] that the function $f_A = (T_e/T_i - 1)/(T_e/T_i)^{3/2}$ is approximately constant ($f_A = .38$) over the range of experimental temperatures. Calculations of neutral transport in the plasma and observations of the Doppler width of H_α light from the plasma core indicate that the neutral temperature T_0 is between 1/3 to 1/2 of T_i . Therefore, we will replace $T_i - T_0$ in Equation (1) by αT_i . If $\alpha = 1$, all of the ion energy is lost per

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charge exchange collision. The bulk ion temperature is then $T_i = 2.76 \sqrt{n_e/n_0}$ eV. Experimental ion temperatures are shown in Fig. 1 as a function of $\sqrt{n_e/n_0}$. The electron density was obtained from a microwave interferometer and the neutral density from an absolutely calibrated neutral particle spectrometer. Figure 1 indicates the dominance of charge exchange losses even though the data shown were obtained for plasma currents between 60 and 160 kA. Computer simulation of the plasma including transport losses which depend on plasma current gives very good agreement with the experimental data[2].

FIG. 1

The detailed mechanism determining the level of neutrals in the plasma is unclear. However, we have observed experimentally that the central neutral density is inversely proportional to n_e^2 . Figure 2 shows this dependence using the same data as in Fig. 1. The implication of this data is that charge exchange losses decrease rapidly as the plasma density increases.

Expected Plasma Conditions with Injection.

We have used the ORNL simulation code to obtain a prediction of the ion temperature to be expected with injection heating in the presence of neutrals. The code uses the

transport coefficients found to fit the ohmically heated plasma parameters[2].

The calculation is pessimistic in that the beam particles are assumed lost at each charge exchange with no account taken of the significant probability of retrapping. Ion temperatures in excess of 1 keV are obtained with $n_0 = 8 \times 10^8 \text{ cm}^{-3}$.

This calculation does not include any anomalous processes produced by the injected beam. At the level of injection expected in ORMAK, significant perturbations in the plasma current distribution, momentum, radial electric field and net charge can be expected[4]. The first of these can be minimized by injection of the two beams. The latter three are related by the equation for equilibrium flow in a collisionless toroidal plasma[5].

$$u_{\parallel} = -\frac{T_i}{B_p} \left\{ \frac{n'}{n} - .17 \frac{T_i'}{T_i} - \frac{E_r}{T_i} \right\} \quad (2)$$

Since Equation 2 should apply in the ORMAK plasma, we expect the neutral injection process to modify the toroidal flow either by direct momentum input or by changing E_r . However, we have observed both poloidal and toroidal flows in ohmically heated ORMAK which have the same magnitude as the flows which could be produced by neutral injection[4].

Observations of Plasma Flow in ORMAK. Figure 3 shows the poloidal rotation inferred from Doppler shift measurements of the H_{α} radiation of neutrals inside the plasma. It is only observed at the beginning and end of a discharge when the ion temperature is low and when pulses of runaway electrons appear at the limiter. A linear relationship is obtained between the poloidal velocity and the number of runaway electrons striking the limiter.

FIG. 3

This leads us to assign this poloidal rotation to an E_r/B_{Toroidal} flow in a positive radial electric field. No deleterious effect on the plasma was noted during this rotation although the electric field inferred for the highest velocities measured is 2000 V/cm which is comparable to the fields expected with injection.

The toroidal flow which is observed during the hot ion phase of the discharge is shown in Fig. 3 as a function of the Doppler temperature of the neutrals. The linear relationship shown is predicted by Equation 2 if E_r/T_i is small with respect to (n'/n) . It may be that the observed toroidal flow is the equilibrium neoclassical flow. However, inserting values for n'/n obtained from the ORNL simulation code in Equation 2 gives values of $u_{||}$ a factor of 2 lower than those observed experimentally. In any case the observed toroidal flows are comparable with those which might be produced by neutral injection and again no deleterious effects are seen.

REFERENCES

- [1] L. D. Stewart, et al., Third Int. Symp. on Toroidal Plasma Confinement, Garching, Germany (1973).
- [2] G. G. Kelley, et al., IBID.
- [3] L. A. Artsimovich, Nuclear Fusion, 12, 215 (1972).
- [4] J. D. Callen, J. F. Clarke, and J. A. Rome, Third Int. Symp. on Toroidal Plasma Confinement, Garching, Germany (1973).
- [5] M. N. Rosenbluth, et al., Fourth Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin (1971).