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ABSTRACT

The beam driven current produced by neutral injection into the DITE tokamak has been measured. The variation of this current with electron density and gas current has also been investigated. Good agreement is found between experiment and a model in which the Fokker-Planck equation describes the fast ion distribution and a magnetic field diffusion equation gives the time dependence of the electromagnetic fields.

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The possibility of using fast ions produced by tangential neutral injection to generate a current in a toroidal reactor was first proposed by Ohkawa[1]. This beam driven current has been observed in the otherwise currentless low temperature plasma in the Culham Levitron[2]. Here we report the first measurements of this current in a tokamak.

The experiments were performed on the DITE tokamak[3] which has major and minor radii R = 1.17 m and a = 0.26 m, toroidal field $B_T \leqslant$ 2.7 T and plasma current $I_p \leqslant$ 250 kA. The neutral hydrogen injection system[4] provides power $P_I \leqslant$ 1.2 MW to the plasma at energies up to 24 keV, with the beam in a tangential direction.

In DITE the beam driven current changes the plasma loop voltage because the ohmic heating transformer circuit maintains the total current constant. When the beam is in the same direction (co-injection) as the transformer induced current, some of the latter is replaced by the beam driven current and the required loop voltage is reduced. For counter-injection the opposite occurs. However, the plasma loop voltage (V_ℓ) can also be affected by changes in electron temperature profile $T_e(r)$ and the plasma effective ionic charge (Z_{eff}). These quantities were therefore measured and their effect on V_ℓ calculated. The reduction in Z_{eff} caused by the injection of particles with atomic number $Z_b = 1$ is negligible, as is that caused by charge exchange of the beam with the impurity species[5].

The magnitude of the beam driven current depends upon the circulating fast ion current. This exceeds the equivalent injected current by the stacking factor $S = v_f \tau_s/2\pi R$ where v_f is the fast ion velocity and the slowing down time τ_s varies as $T_e^{3/2}/n_e$, where n_e is the electron density. Thus S is greatest for low n_e and high T_e. However, at low n_e the plasma neutral density is larger and so an appreciable fraction of the fast ions can be lost by charge exchange. Because the charge exchange cross-section

is lower for He, most of the experiments used helium target plasmas. The fraction of the total current driven by the beam was increased by decreasing the total current to 80 kA.

Experiments were conducted over a range of electron densities and gas currents for both D and He plasmas (Table 1). The time dependence of the plasma loop voltage (Fig. 1) showed a substantial drop during injection. The profiles of T_e (Fig. 2) from Thomson scattering and n_e from 2 mm microwave interferometry, were measured before, during and after injection. The profiles taken before and after injection are used to calculate Z_{eff}. During injection Z_{eff} cannot be measured by this method because of the effect of the beam driven current. A linear variation of Z_{eff} with time during injection is assumed. This is supported by the time dependence of the soft X-ray continuum intensity[6].

The measurements of V_ℓ are compared with a theoretical model similar to that used by Singer et al[7]. However, the experimental profiles of n_e and T_e are used as input to the model instead of theoretical profiles. The fast ion current is obtained from the Fokker-Planck drift kinetic equation which includes fast ion collisions with the thermal ions and electrons, and acceleration of the fast ions by the electric field. The equation is solved numerically as a function of time on each magnetic surface. The radial profile of the beam driven current density (j_{bd}) is then obtained from the fast ion current density (j_{fast}) using the expression given in ref. (8), which for this case reduces to

$$j_{bd}(r) = j_{fast}(r)[1 - Z_b/Z_{eff}]. \qquad \ldots (1)$$

The second term on the rhs of equation (1) is the back electron current produced by momentum transfer from the fast ions. In DITE

it approaches 50% of j_{fast}. Changes in the back electron current caused by plasma rotation, trapped electrons and the neoclassical current contribute less than 10% to the beam driven current and are neglected.

The electric field (E) is obtained as a function of time and radius from Ohm's law and Maxwell's equations,

$$\sigma E = j - j_{bd} \qquad \ldots (2)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_o \frac{\partial j}{\partial t} \qquad \ldots (3)$$

in which σ is the Spitzer[9] conductivity and j is the total current density. Equations (2) and (3) are solved numerically subject to the constraint that the total current is constant.

Fig. 1 shows good agreement between experimental and theoretical loop voltages for both a low and a high density discharge. Also in Fig. 1 are theoretical curves with the beam driven current omitted. For the low density case (Fig. 1a), the reduction in loop voltage is entirely attributable to the beam driven current, which replaces 33 kA of the original 80 kA of transformer driven current. In the high density case (Fig. 1b) the change in loop voltage is largely caused by changes in the T_e profile.

The change in loop voltage (ΔV_ℓ) produced by the beam driven current is compared with theory (excluding charge exchange losses) in Fig. 3 for a range of densities, currents and Z_{eff} (Table 1). The experimental ΔV_ℓ is the difference between curves like (iii) and (i) of Fig. 1, while the theoretical ΔV_ℓ is the difference between curves like (iii) and (ii). The expected reversal of sign between co- and counter-injection is observed. The errors on the points are derived by following the errors on the measurements of T_e through the theoretical calculations of the

loop voltages. The agreement between theory and experiment demonstrates the existence of the beam driven current and its variation with plasma parameters.

An independent check on the calculated fast ion distribution is provided by the simultaneous measurement of both the vertical field (B_V) required to maintain plasma equilibrium and the plasma diamagnetism (β_{loop}). For non-isotropic velocity distributions, B_V is given by Shafranov's formula[10]

$$B_V = \frac{\mu_o I_p}{4\pi R} \{\ln \frac{8R}{a} - \frac{3}{2} + \frac{\ell_i}{2} + \frac{3}{4}\beta_\perp + \frac{3}{2}\beta_{||}\} \qquad \ldots (4)$$

and

$$\beta_{loop} = \frac{3}{2}\beta_\perp \qquad \ldots (5)$$

where ℓ_i is the inductance per unit length and

$$\beta_{||,\perp} = 4\Sigma m_i \, v^2_{i||,\perp}/3\mu_o R I_p^2 \qquad \ldots (6)$$

with the sum over all plasma particles of mass m_i and velocity v_i. The inductance is obtained from the measured profiles, $T_e(r)$, assuming j is proportional to $T_e^{3/2}$. The background plasma pressure is assumed isotropic so that its contribution to $\beta_{||,\perp}$ can be obtained from the measured profiles $T_e(r)$ and $n_e(r)$. Solution of equations (4) and (5) then allows $\beta_{||,\perp}$ for the fast ions to be obtained. The dominant term is $\beta_{||}$ which is essentially the centrifugal pressure of the confined fast ions. In Fig. 4 this is compared with values calculated from the Fokker-Planck code. The good agreement constitutes an experimental check on the calculated total fast ion current and consequently on the neglect of charge exchange.

In summary, these experiments have demonstrated the presence of the beam driven current in a tokamak for both co- and counter-injection. The measurements are in good agreement with a kinetic theory in which the dominant terms are the fast ion current and the back electron current

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TABLE 1

Summary of experimental results before (first line) and during (second line) injection for each discharge

Discharge Working gas	I_p (kA)	B_T (T)	V_ℓ (V)	$n_e(0)$ (10^{19} m^{-3})	$T_e(0)$ (keV)	Z_{eff}	P_I (MW)
(A), He	80 80	2.2	1.8 1.1	2.2 4.0	0.58 0.67	3.0 4.0	0.9
(B), D_2	90 95	2.2	2.1 0.4	3.0 5.0	0.63 0.90	1.9 2.8	1.0
(C), He	92 94	2.2	1.9 1.1	1.6 3.1	0.65 0.67	3.7 3.7	0.95
(D), He	94 94	2.2	2.0 1.2	6.2 7.8	0.63 0.69	1.7 2.1	0.95
(E), He	167 167	2.7	1.5 1.2	2.5 5.0	1.4 1.1	3.0 5.0	0.97
(F), He	-156 -156	2.7	-1.4 -2.2	2.8 4.1	0.91 0.74	1.9 3.0	1.0

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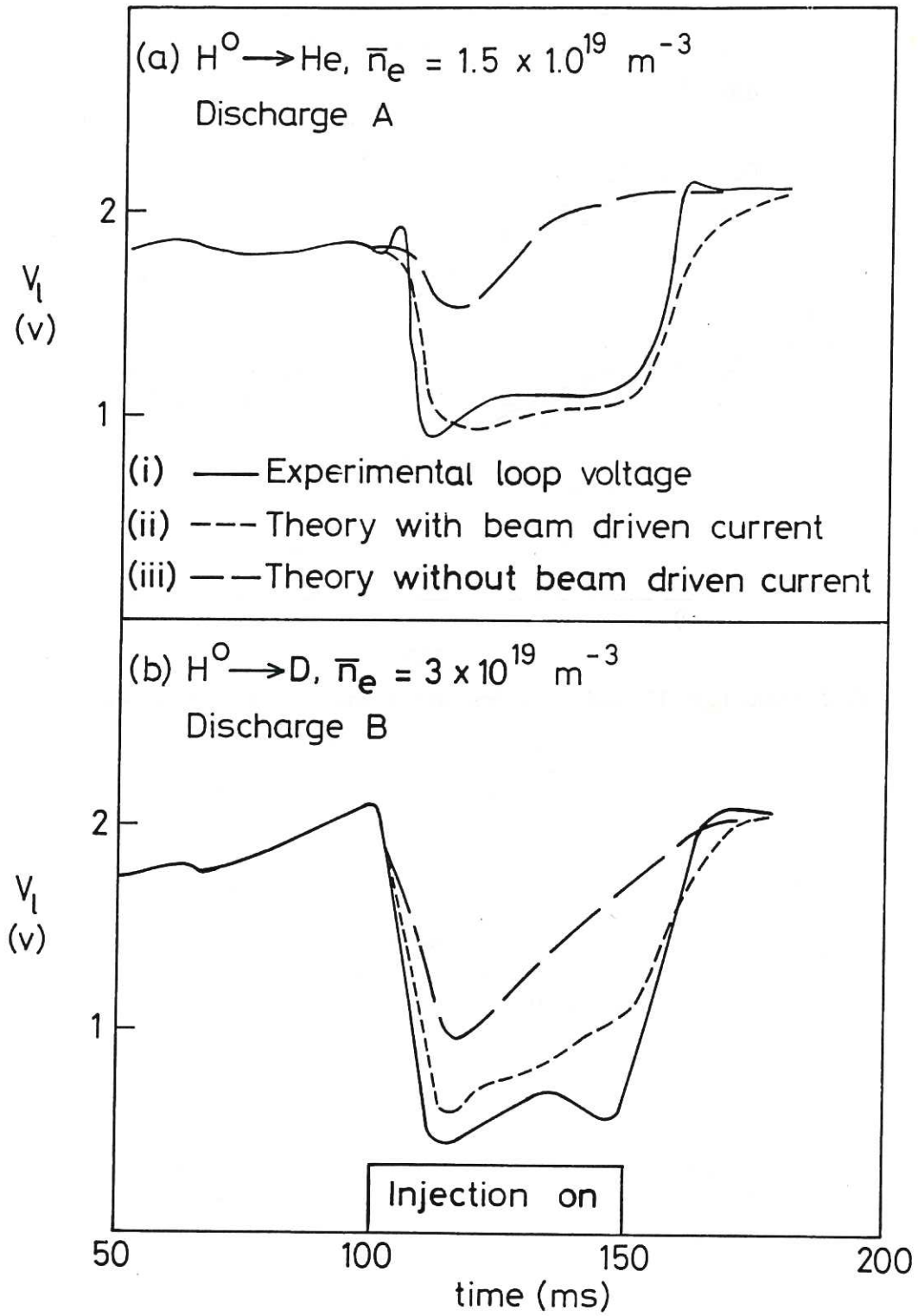

Fig.1 Experimental and calculated plasma loop voltages.

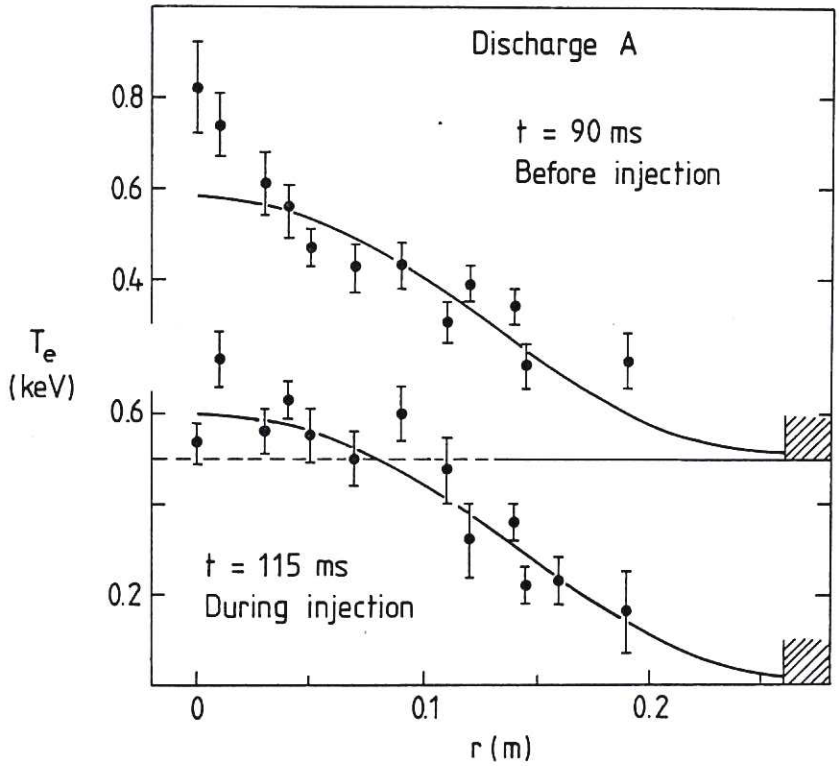

Fig.2 Profiles $T_e(r)$. The solid lines are best fits of an analytic function to the data.

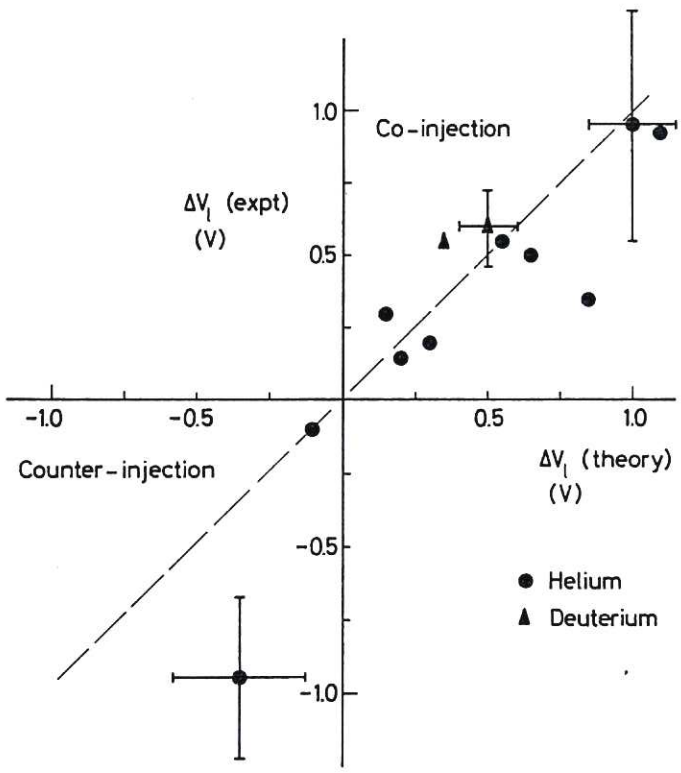

Fig.3 Experimental and theoretical loop voltages (ΔV_ℓ) caused by the beam current. Each point corresponds to the measurement of a T_e profile.

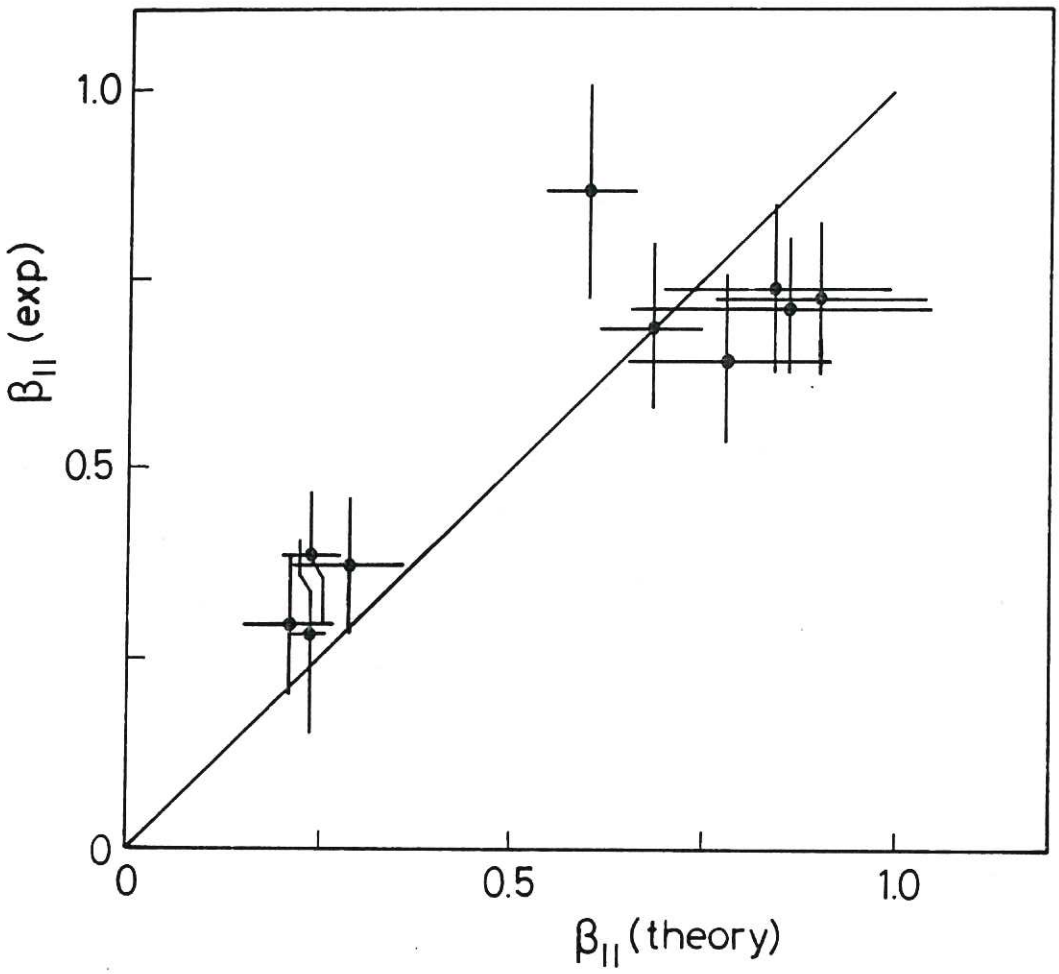

Fig.4 Experimental and theoretical values of $\beta_{||}$.