STUDIES OF TOKAMAK TRANSPORT BASED ON PELLET INJECTION

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INTRODUCTION

The injection of frozen deuterium pellets into Tokamaks has been proposed as a re-fueling method, and for profile modification. A third use for injected pellets, which forms the subject of this paper, is to facilitate understanding of particle and energy transport. We report on the injection of cylindrical (0.9x0.9 mm) pellets into ASDEX (R = 165 cm, a = 40 cm) discharges of either the Ohmic or low-power ("L mode")[1] neutral beam type. Pellets were injected at approximately 600 m/sec using a pneumatic injector developed by Büchl, et al.,[2] which is capable of firing two pellets either simultaneously or with a time delay. The principal measurements involved penetration depth, and evolution of electron density and temperature profiles.

PENETRATION DEPTH

At line averaged densities ($\overline{n}_e = (1/2a)\int n_e d\ell$) greater than about $3.5 \times 10^{13}\mathrm{cm}^{-3}$ for Ohmic discharges ($T_e \approx 600$ eV), the ablation rate was approximately that given by Milora-Foster model,[3] which resulted in a penetration depth of approximately 30 cm. For lower densities, the ablation depth was typically 15 cm or less at $n_e = 2\mathrm{x}10^{13}\mathrm{cm}^{-3}$. This enhanced ablation rate is believed to be due to the presence of a small high energy electron component, and can be roughly correlated with the runaway population of the discharge. For neutral beam discharges at the higher densities, penetration was small ($\leqslant 10$ cm) due to the higher temperatures ($T_e \gtrsim 1100$ eV) of these discharges and ablation by fast ions.

PARTICLE TRANSPORT

Several experiments over the past years[4] have produced results consistent with suggestions made independently by Engelhardt, et al.[5] and Coppi and Sharky[6] that particle flux in Tokamaks can be represented by an expression of the form

$$\Gamma_r = -D\left[\frac{\partial n}{\partial r} + \alpha(r)\,\frac{2r}{a^2}\,n\right] \qquad (1)$$

where $\alpha = 1$ in Engelhardt's model and $(1 - r^2/a^2)^{-1}$ in Coppi's model. D is taken to be constant, and is on the order of $0.5\mathrm{x}10^4\ \mathrm{cm}^2/\mathrm{sec}$, much larger than neoclassical. Data was used from a 2-channel HCN interferometer to attempt to determine the applicability of Eq. (1) to the perturbation in Γ caused by pellet injection. The interferometer measured line densities on two horizontal chords, one through the midplane and one displaced 20 cm. The pelled-induced perturbation satisfies the continuity equation

$$\frac{\partial \hat{n}}{\partial t} + \mathrm{div}\,\vec{\hat{\Gamma}} = \sigma \qquad (2)$$

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provided the "steady state" sources are not strongly altered by the pellet particles, which are assumed to be fully ionized during the ablation process. The procedure adopted was to solve equation (1) for various D, and the two values of α , using the measured penetration depth and pellet size, and an initial particle deposition profile similar to that given by the Milora-Foster theory. From the calculated values of $\hat{n}$ (r,t), the two interferometer channel time histories were calculated, with D and varied to give the best fit. An example of this is shown in Fig. 1, where $\alpha = 1$. It is clear that $D = 4000\ cm^2\ sec^{-1}$ gives the closest fit. In general, the Coppi model gave a poorer fit. The agreement was not quite as good at lower densities, for shallower penetration, but indicated that D increases with decreasing density, as expected. A limited amount of data was obtained for L mode neutral beam discharges, and indicated a dramatic reduction in particle confinement.

For shots with relatively deep pellet penetration, the calculations referred to above generally indicate a rapid adjustment to a nearly parabolic profile, in 10 ms or so, followed by an overall relaxation to the original "plateau" profile during the next 50-100 ms. This latter portion of the decay can be used to infer a global particle decay time, τ_p. It can be shown, using a simple zero-dimensional model coupling the global neutral (divertor chamber) and electron populations that the relaxation of the pellet-induced density perturbation is a function primarily of τ_p, and is relatively insensitive to the recycling coefficient. (This is in direct contrast to gas switch-off experiments where the decay time depends primarily on $\tau_p/(1-r)$). In this way we determine values of τ_p of >150 ms for the pellet-injected population, as opposed to typically 60 ms for τ_p determined in steady state profiles maintained by a feedback-controlled gas value. This reflects the fact that particles closer to the magnetic axis are better confined, and is consistent with the form of Γ as given by equation (1).

ENERGY TRANSPORT

A four channel ECE system[7] was used to measure the electron temperature profiles as a function of time. Figure 2 shows $T_e(t)$ at four radii following pellet injection into a relatively high density Ohmic discharge. The pellet penetrates to about $r = 10$ cm in 0.5 ms, so that the simultaneous temperature depression on the outer three channels is to be expected. It is somewhat surprising that the temperature also decreases simultaneously at the innermost location, but transport within the $q = 1$ surface is known to be very rapid. The observed initial temperature depression is nearly adiabatic. That is, the observed ΔT_e is consistent with a redistribution of the original thermal energy among the original and new (pellet-supplied) particles.

It was an unexpected feature of these experiments that an initial temperature drop was always measured simultaneously at all radii, regardless of pellet penetration depth, although the subsequent T_e (t) was sensitive to penetration depth. A striking example is shown in Fig. 3 for a double pellet injection into a neutral beam heated discharge, when the penetration was less than 10 cm beyond the separatrix. Measurements errors arising from refraction or cut-off have been calculated and ruled out, so that the traces are believed to be accurate temperature records. Calculations by Lengyel[9] suggest that multiple charge exchange processes may be responsbile for the observed behaviour, while the other explanations are still being investigated.

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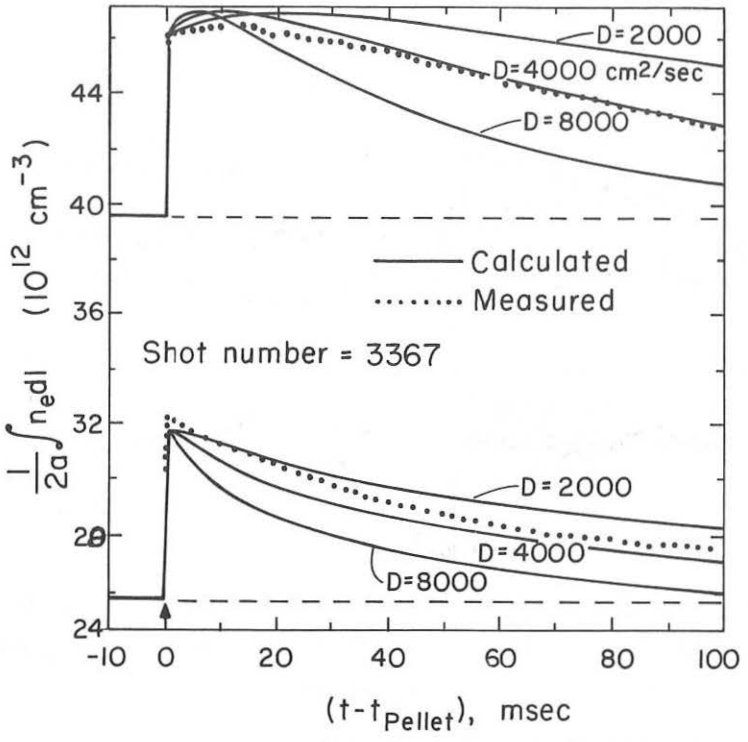

Fig. 1. Comparison of Calculated and Measured $\overline{n}_e$ Traces Using Englehardt Flux Model. Upper curves are for mid-plane chord, lower curves for chord displaced by 20 cm. Ohmic discharge.

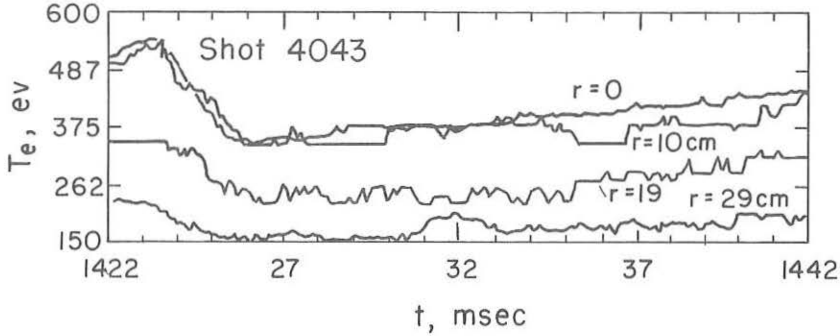

Fig. 2. Temperature Histories at 4 Radii, Following Pellet Injection into Ohmic Discharge at 1423 msec. Pellet penetration to r ≈ 10 cm.

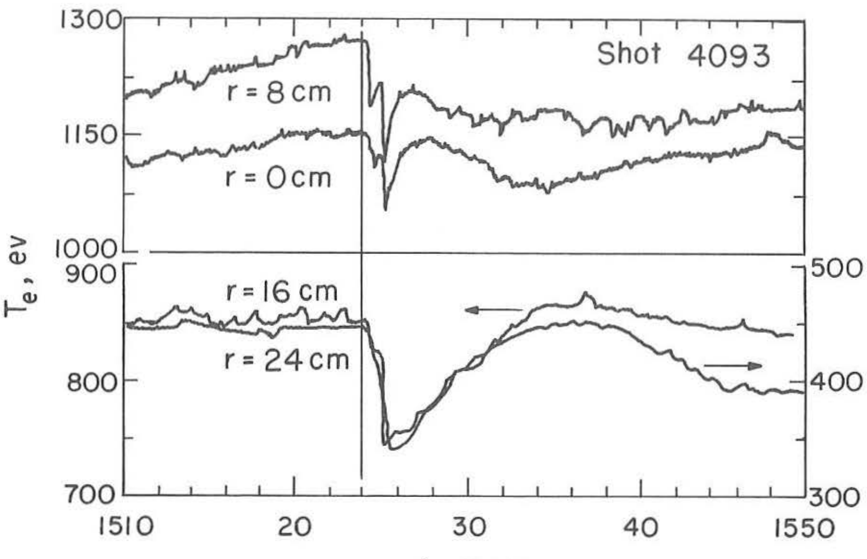

Fig. 3. Temperature Histories at 4 Radii, Following Pellet Injection into N.B. (L Mode) Discharge at 1524 msec. Note simultaneous T_e depression on all channels, despite pellet penetration only to r ≈ 30 cm.