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ABSTRACT

A density clamp is observed in DITE tokamak with neutral beam injection heating. Measurements in the scrape-off plasma are described which show an increase in the particle flux to the limiters during injection. This is sufficient to account for the density clamp without requiring a change in the recycling coefficient.

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Cold gas feed from the plasma boundary is the usual method of raising the density in present-day tokamaks. On ISX-B it was noticed that the rate of rise of density was strongly reduced during heating experiments with neutral beam injection [1,2], an effect described as a density 'clamp'. Similar results have been obtained on other tokamaks with neutral injection [3,4,5] and other heating methods [3,6,7,8]. There has been some debate whether this effect is principally due to a decrease in the recycling of particles from the vacuum vessel and limiters [2,4,8] or an increase in the particle flux from the discharge [1,5] equivalent to a decrease in particle confinement time, τ_p.

Measurements in DITE indicate that an increase in the particle flux to the limiters is the main cause of the density clamp; an increase which is consistent with changes in the scrape-off plasma due to increased conduction and convection losses from the confinement region. No appreciable change in the recycling coefficient is required to explain our results.

The density clamp in DITE occurs in a wide range of conditions with both deuterium and helium plasmas and with co- and counter-injection. It is sensitive to the major radius of the discharge, R, increasing in severity as R is reduced so that the discharge contacts the limiters on the inside edge, and weakening or almost disappearing when R is increased by ~ 80mm. This effect has not been explored in detail but seems to indicate that the clamp is sensitive to boundary conditions.

Measurements of the scrape-off plasma were made in the following parameter range: major radius = 1.17m, toroidal field = 2T, plasma current, I_p = 110-150kA and line averaged electron density, $\bar{n}_e$ = 2-3.5 x $10^{19}m^{-3}$. The two limiters were of titanium with circular apertures of radius = 0.26m. The working gas was deuterium and the vacuum vessel was gettered with titanium [9]. The density was maintained or increased by cold gas feed, in the absence of which it decayed with a time constant of 20-30ms. For these conditions the recycling coefficient, β is expected to lie in the range 0.5-0.8 [10].

As in ref [4] the global particle balance is written,

$$\frac{dN}{dt} = S - (1 - \beta) \int \Gamma \, ds, \qquad \ldots (1)$$

where N is total number of electrons in the discharge, S is the electron source term resulting from the cold gas feed and beam injected neutrals and $\int \Gamma \, ds = N/\tau_p$ is the integral of the charged particle flux over the discharge boundary. S and β can be taken to include the effect of recycling charge exchange neutrals. The observed decrease in dN/dt on injection, in spite of the increased particle source term from the neutral beam, can be explained by an increase by a factor of approximately two in either $(1 - \beta)$ or $\int \Gamma \, ds$.

In our case the discharge boundary is formed by the electrostatic sheath between the plasma in the scrape-off region and the limiters. The energy which is conducted and convected from the confinement region flows to the limiters along field lines of effective length, ℓ_c. Since the measurements show that $\ell_c \lesssim \lambda_e$, the electron mean free path, this flow is convective and there is a definite relationship between the particle and energy fluxes parallel to the field. The ratio between the heat flux, Q and the particle flux Γ is determined by the sheath at the limiter and defines the heat transport coefficient, γ given by

$$Q = \gamma \, e \, T_e \, \Gamma, \qquad \ldots (2)$$

where T_e is the electron temperature. For deuterium plasma γ lies in the range 10-15 [11] and is only weakly dependent on T_e, thus an increase in Q necessarily entails an increase in T_e or Γ or both. Further, the particle flux in the sheath is given by

$$\Gamma = 0.4 \, n_e \, c_s, \qquad \ldots (3)$$

where c_s is the local sound speed.

Measurements of n_e and T_e in the scrape-off plasma using a double

Langmuir probe [12] are shown in Fig. 1 for three discharges. In two cases ~ 800kW of neutral beam heating was applied from 72ms. The heat flux estimated from the Langmuir probe measurement, using equation (2) and (3), increased during injection by a factor of two to four. This is approximately consistent with the increased conduction and convection losses estimated from the difference between total power input and total radiation losses, not including possible changes in the scrape-off layer thickness. The corresponding increase in Γ from equation (3) is a factor of two, just what is required to explain the density clamp.

The Langmuir probe measurements are supported by direct measurements of deuteron flux using a rotating carbon collection probe [13,14] as shown in Fig. 2. Again, the particle flux increases by a factor of two during injection at r = 0.255m and at r = 0.27m showing that the thickness of the scrape-off layer is relatively constant.

An alternative explanation for the density clamp due to a change in β would require a fall from the expected value of 0.5 in the ohmically heated phase to about 0.25. A fall of this magnitude requires the mean particle energy incident on the limiters to increase from 50eV to about 1keV [10]. This is clearly unreasonable and we conclude, in agreement with ref [1] that possible changes in the recycling coefficient are too small to explain the clamp phenomenon.

Our measurements do not identify the mechanisms responsible for the increased particle flow into the scrape-off plasma from the confinement region. We note, however, that the particle transport in the confined plasma must be affected by changes in the scrape-off plasma. If the particle loss rate were unchanged, equations (2) and (3) show that T_e would have to increase further and n_e decrease in the scrape-off plasma. These changes would automatically increase the density gradient in the boundary region, requiring a decrease in the diffusion coefficient. The observed increase in Γ and slight reduction or levelling of n_e are thus seen as the discharge response to the new boundary conditions imposed by increased power flow to the limiters.

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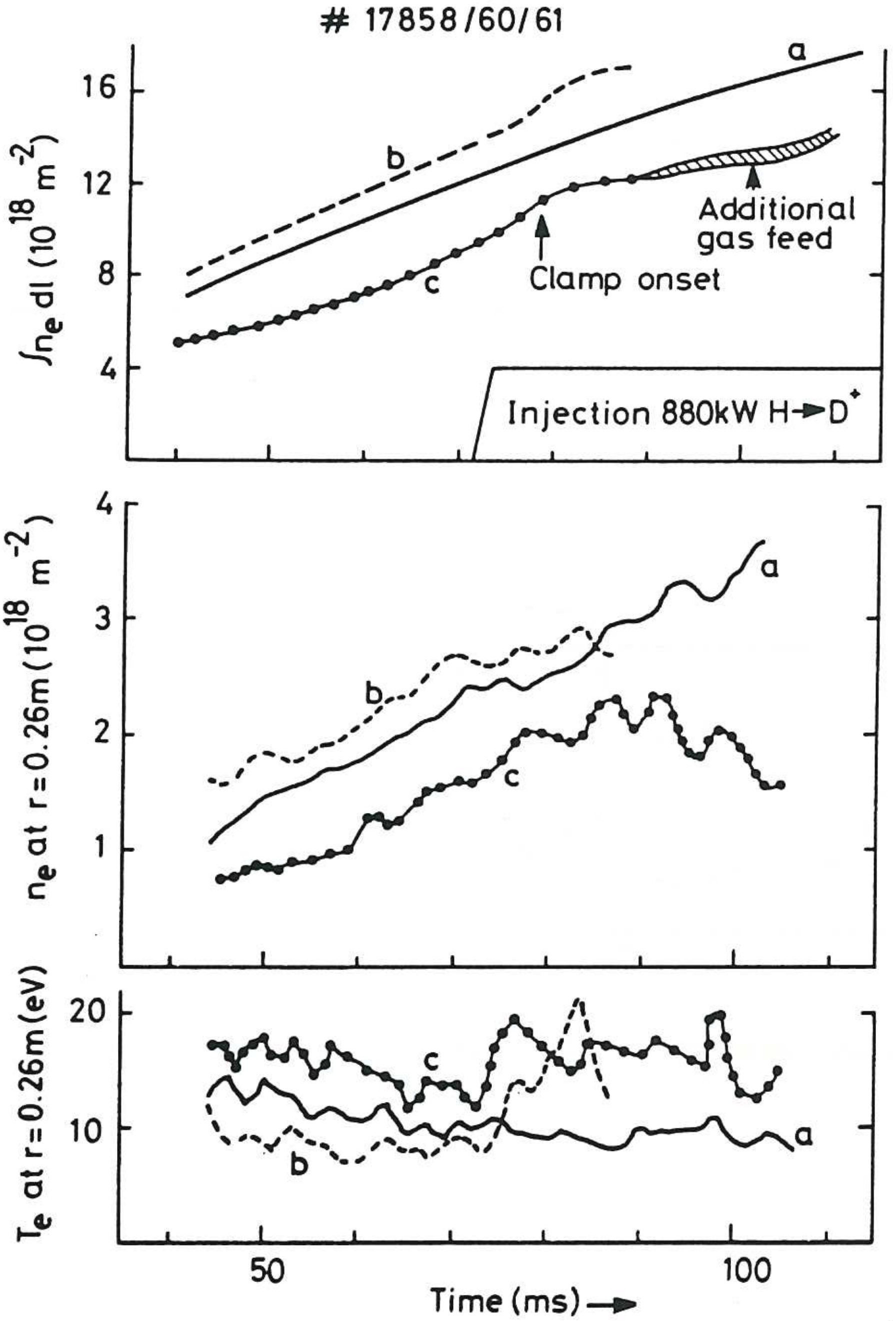

Fig.1 Traces of 2mm microwave interferometer (top) and density (centre) and temperature (bottom) from a double Langmuir probe in the scrape-off plasma; (a) no injection (b) and (c) 880kW injection, showing a density clamp at 80ms.

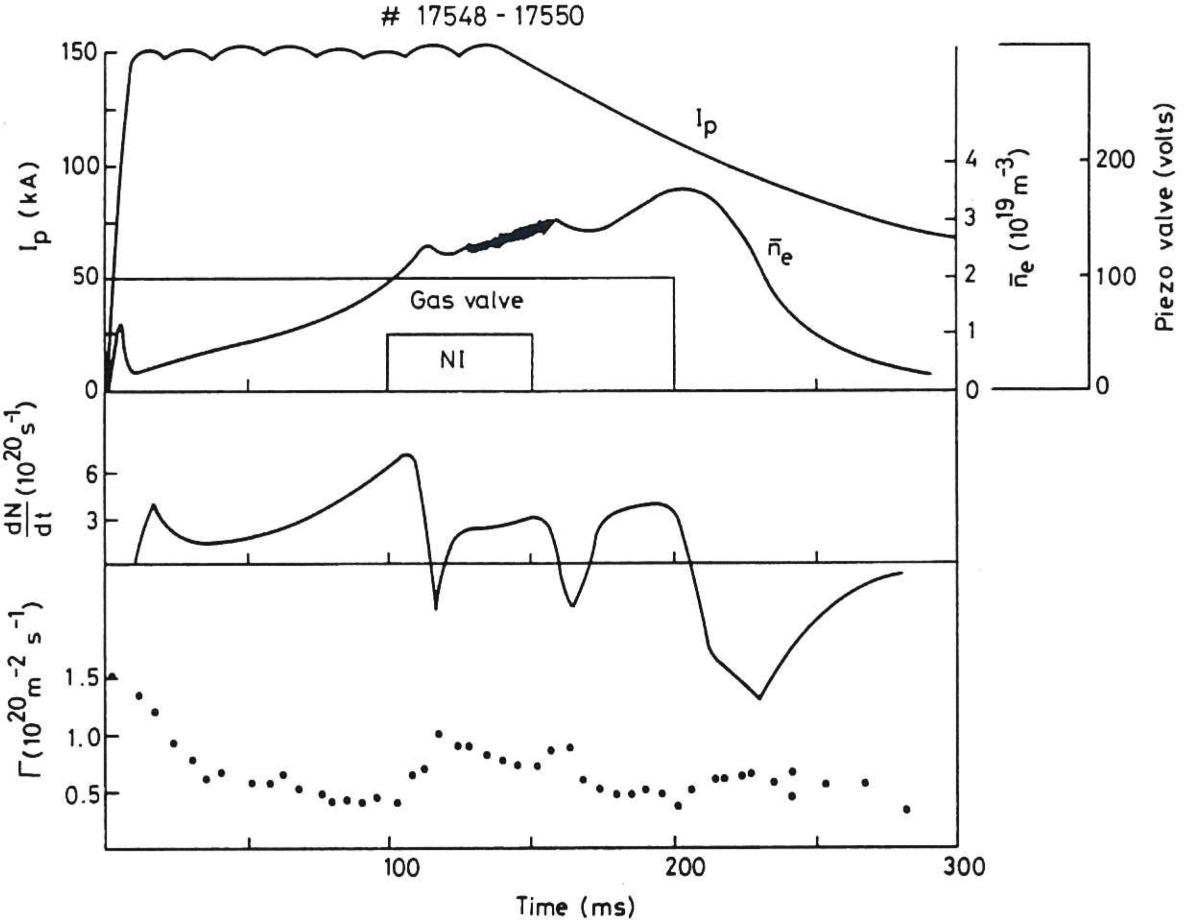

Fig.2 Discharge with density clamp showing, from top: plasma current, mean density from microwave interferometer, rate of change of total particle content and particle flux in the scrape-off plasma from a carbon desorption probe.