Quasi Stationary D_2 Pellet Injection into ASDEX Divertor Discharges

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Introduction

We report on deuterium divertor discharges in ASDEX where the particle inventory is sustained entirely, after an initial gas fuelling phase, by the injection of a series of up to 80 frozen D_2 pellets, 1 mm in diameter and 1.2 mm long ($N_D \leq 4.5 \times 10^{19}$), at intervals ranging from 20 to 50 ms, and speeds to 720 m/s, by means of a centrifuge /1/. Investigations performed on Ohmic, NI, and ICRH heated discharges have shown that the most important parameter characterizing the discharges is the ratio of the pellet penetration depth, Δ , to the fall-off length for neutral particles in a gas fuelled case (typically 5 - 8 cm in ASDEX).

For shallow penetration, only minor differences, relative to gas fuelled shots, are observed. In contrast, with deep penetration (e.g. $\Delta \gtrsim a/2$) the density profile is more peaked, and the temperature profile flattened, when compared with gas fuelled discharges at the same line integrated density, $\bar{n}_e$. The discussion here concentrates on these characteristic "deep fuelling discharges". Because of the limited pellet size and velocities presently available, these deep fuelling discharges are Ohmically heated with $T_e \leq 1$ keV. In the following paragraphs we discuss energy and particle confinement, aspects of recycling, and density limits.

Energy balance

Figures 1 and 2 show the time dependence of several plasma parameters for a representative deep penetration (20 cm), ohmically heated, pellet fuelled discharge (# 14669, $q = 3.4$, $B = 2.2$ T). In this case the density was first increased to $\bar{n}_e = 1 \times 10^{19}$ m^{-3} at 500 ms by a gas valve, which was then turned off. Pellets were injected at 35 ms intervals, beginning at 522 ms, causing the cycle-time-averaged density $(\bar{n}_e)_c$ to increase to 3×10^{19} m^{-3}. When a pellet enters, the temperature drops rapidly throughout the plasma /2/; the density peaks continuously within a given pellet cycle, and is more peaked for later cycles in the series. The neutron fluence drops and recovers, as T_i recovers.

We have analyzed individual pellet cycles, using both a transport code /3/ based on measured time-dependent T_e, n_e, and P_{rad} profiles, and global magnetic measurements, and cycle-averaged agreement is obtained. The results of such analyses for the 12th pellet cycle of shot 14669 are given in fig. 3. It can be seen that β_p increases throughout the cycle, and drops discontinuously at the time of injection of pellet # 13, indicating a non-adiabatic injection, with a loss of about 2 kJ plasma energy. Such a loss at

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each injection event constitutes a time-averaged loss of up to 100 kW which lowers the value of $(\tau_E)_{cycl} = (1/\Delta t)\int \tau_E dt$, from the 55 ms measured within the cycle, to about 45 ms averaged over the cycle + injection, in approximate agreement with the long-time-averaged (several cycle) global magnetics value. This should be compared with τ_E = 74 ms obtained in a gas fuelled comparison shot (# 14671) with the same time-averaged $\bar{n}_e(t)$ (see fig. 1).

The local transport analysis shows that within error bars, χ_e and χ_i are unchanged between the gas fuelled and pellet fuelled discharges: χ_e corresponds to the normal scaling observed in ASDEX /4/, while χ_i is one times neoclassical.

The analysis further reveals that three mechanisms are responsible for the reduction in total energy confinement seen in these deep fuelled, peaked discharges: (1) There is an enhanced convection of energy from the inner to outer plasma regions due to the cycle-averaged net outward particle flux Γ_p, which must equal the pellet fuelling rate. For the cycle discussed here, the convective power is about 150 kW at $r = a/2$. (2) There is increased radiation, consistent with the peaking of the density profile (P_{rad} increases from 106 kW (# 14671) to 150 kW (# 14669). (3) The non-globally-adiabatic pellet injection constitutes a time-averaged loss rate of about 100 kW for the quasi-steady phase of # 14669.

Particle Balance

For the deep penetration case described above, the equivalent particle supply rate is about 60 % of that required for the gas fuelled comparison shot (# 14671). The divertor plasma and neutral densities remain consistently below that of the comparison shot, reaching values of about 80 % and 50 % near the end of the 1.2 second injection phase.

The flux of particles leaving the plasma seems to fall rapidly after a first very short burst, resulting from the non-adiabatic injection, and starts to recover about 20 ms after injection. This suggests that an enhanced inward convection may be present early in the cycle. The effective particle confinement time, $\tau_{eff} = N/\dot{N}$, is about 130 ms at the beginning of the cycle and 100 ms at the end, during the quasi-stationary phase of shot # 14669. The time averaged true particle confinement times, estimated from the recycling flux and particle supply rate, are about 120 ms and 45 ms for the pellet and gas fuelled shots, respectively.

Plasma boundary and divertor

The plasma boundary density shows a sharp peak ($\Delta t \lesssim$ 5 ms) immediately after injection, near the separatrix, which then is followed by a pronounced decrease of the density fall-off length, which recovers later in the cycle. The plasma density in the divertor likewise shows a sharp spike followed by a pronounced decay, and finally recovery (fig. 2): These observations are in qualitative agreement with the ASDEX edge-layer theory described in ref. /5/.

Density limit

A density limit in Ohmic pellet shots can be attained by increasing the $\bar{n}_e$ at the time injection begins, and/or by increasing the pellet injection frequency. The results from a limited number of such discharges are: (1) Peak densities 20 - 40 % higher than in gas fuelled discharges at the same q(a) are obtained before discharges is accompanied by very strong central peaking of density and radiation ($n_{eo} \leq .8 \times 10^{20}$ at $q = 3.4$, $I_p = 310$ kA; $P_{rad}(o) \simeq .35\ \mathrm{W/cm^3}$), and collapse of the central temperature. In contrast to the situation in gas fuelled density limit discharges /6,7/, strong and asymmetric radiation from the boundary is not observed and strong disruptions do not occur. Sometimes the discharge recovers to its predisturbance state. The observations are in line with the interpretation of the usual density limit as a boundary density limit. With pellet refuelling it is possible to decouple the central density from its boundary limit. The density limit in pellet fuelled NI discharges could only be reached by supplemental gas puffing. As expected, no characteristic differences from gas fuelled shots were found.

Conclusions

Deep penetration pellet fuelled ohmic discharges in ASDEX reach higher density limits and require a lower particle supply rate than gas fuelled discharges. The peaked profiles, along with slightly non-adiabatic injection events, however, lead to a degradation of energy confinement, caused by enhanced convection and radiation.

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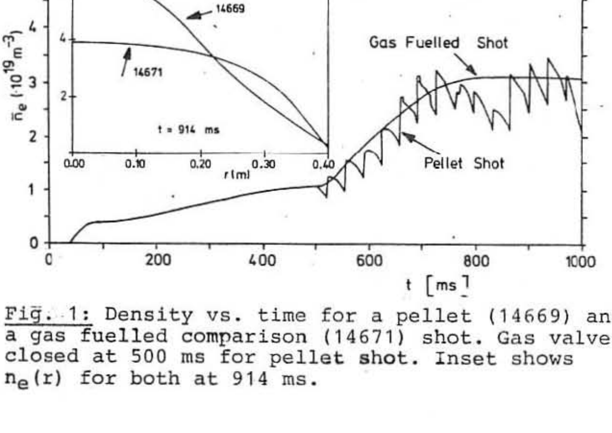

Fig. 1: Density vs. time for a pellet (14669) and a gas fuelled comparison (14671) shot. Gas valve closed at 500 ms for pellet shot. Inset shows $n_e(r)$ for both at 914 ms.

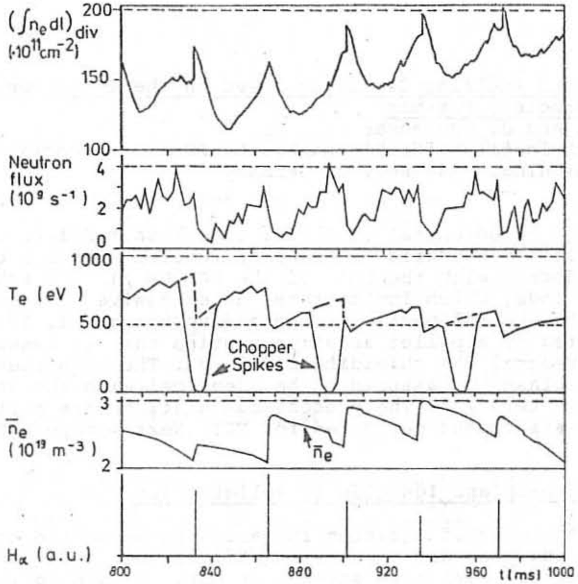

Fig. 2: Representative diagnostic traces, shot 14669. H_α light spikes indicate pellet injection times.

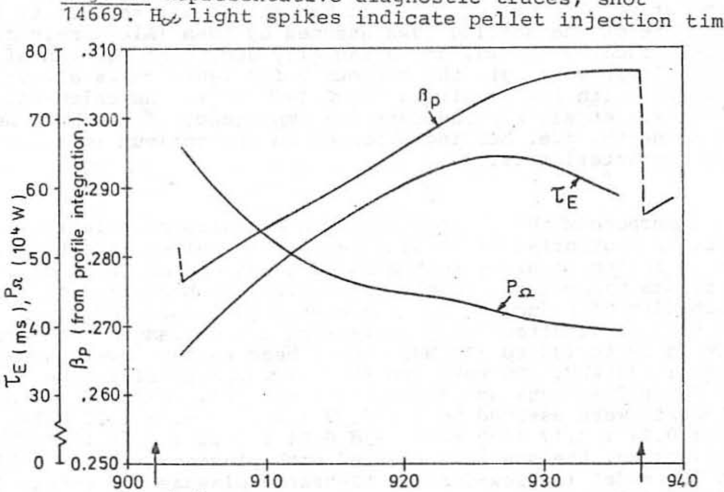

Fig. 3: Time dependence of β_p, τ_E, P_Ω within 12th pellet cycle, shot 14669. Note: τ_E is 48 ms when non-adiabatic injection is included. For gas comparison shot: β_p = .300, P_Ω = 300 kW, τ_E = 74 ms.