# PELLETS IN LARGE TOKAMAKS TFTR AND JET*

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Abstract

In TFTR and JET experiments, pellet fueling has been extended to larger, higher temperature devices. We will review selected current results in the light of earlier experiments. Penetration depths are generally in agreement with modelling when ablation by thermal electrons dominates, but local deposition may differ from predictions based solely on the prepellet Te profile. Deposition at the plasma edge can be enhanced. Deposition near the plasma center may also be altered, particularly in JET. Fueling efficiency is high, but at present strongly peaked density profiles are obtained only with pellet penetration approaching or beyond the plasma center. Density achieved with pellets in ohmic plasmas is greater than that attainable with deuterium gas puffing in both these large devices as in previous experiments. Locked modes limit this density in JET but not yet in TFTR. Strong electron temperature perturbations can be tolerated in these large devices as on smaller machines allowing modification of the current profile leading to a change in the time evolution of the central q value and suppression of existing sawtooth relaxations or delay of their onset. In ohmic discharges plasma reheating is moderate, typically 1.5 keV. Axial voltage is maintained. Loss of central density can be extremely slow. Decay rates of 1.5 to 2 sec are observed. With heating, Te > 5 keV is rapidly achieved. Axial voltages may strongly decrease. Under these conditions central particle loss rates can be enhanced. Decay rates in JET at 5 - 8 keV are approximately 0.75 s. Energy confinement is observed to improve in TFTR ohmic discharges as was seen in earlier experiments. With beam heating in TFTR, central energy confinement was not degraded during the reheat following the pellet perturbation. However, central power deposition was low in these cases due to diminished beam penetration. In recent JET experiments, application of central RF heating following a pellet fueling sequence has shown strong central electron and ion heating.

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**1.0 Introduction:** In the past 10 or more years, pellet fuelling experiments have been conducted over a wide range of machine geometry, pellet size and plasma parameters. With experiments on TFTR, JET and now JT60[1], pellet fuelling has been extended to larger, high current, high temperature devices. Figure 1 illustrates the range of machine geometry over which tokamak experiments have been conducted since the first results from Ormak[2] and ISX-A[3]. The range of minor radius and plasma volume is roughly one and three orders of magnitude respectively. The increase in plasma volume particularly has permitted use of pellets up to 4mm in diameter ($4 \times 10^{21}$ $D^o$), with a capabilty for injection of 6mm pellets in place at

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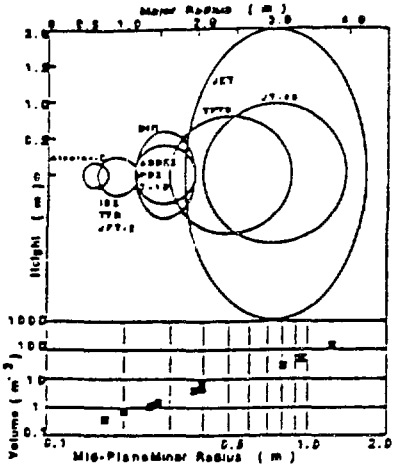


Figure 1: Device cross-sections, volume and minor radius of tokamaks employing pellet fuelling in past and current experiments.

JET. In the large tokamaks, use of these size pellets has extended pellet ablation studies to electron temperatures approaching 4keV, has produced peaked density profiles at high density, and has improved plasma performance. In this paper we will discuss pellet experiments in TFTR and JET, contrasting results in these larger machines with those obtained earlier in smaller tokamaks. Pellet penetration and mass deposition, average and core density, particle and energy confinement, and finally high power operation will be discussed.

**2.0 Penetration and Mass Deposition:** The neutral gas shielding model for hydrogenic pellet ablation is generally correct in predicting pellet penetration in ohmic plasmas at moderate electron temperatures (<1keV) [4]. The large tokamak experiments provide a test of this model at higher electron temperatures (< 4keV). At these temperatures, the ablation model in its most recent form [5] remains in general agreement with measurements of pellet penetration when ablation by thermal electrons dominates [6,7], but local deposition may differ from predictions based solely on the pre-pellet electron temperature profile. In large machine geometry the time scale is long for the decay of the density profile established by a pellet during the ablation process ($t_{decay} >> t_{ablation}$). Details of that profile are therefore readily seen using local density measurements following pellet injection obtained with multi-point Thomson scattering systems. Fuelling efficiency is high (70%) in ohmic plasmas, but may degrade during auxiliary heating[7]. Compared to calculations, deposition of mass near the plasma edge appears to be enhanced. Deposition near the plasma center may also be altered, particularly in JET.

**2.1 Non-Central Deposition:** Figures 2.1 and 2.2 illustrates a JET pellet fuelling event leading to hollow density profiles. Pellet penetration to 3.18m is determined from the duration and spatial extent of the light present during ablation. Penetration to 3.26m is predicted by the ablation model. Formation of an inverted density profile is predicted by the ablation model and is observed. However, the measured density peak occurs at a larger minor radius than predicted, the two locations differing by some 0.5m. The discrepancy between measured and calculated profiles indicates that ablation and deposition can be more rapid at large minor radii than predicted. The agreement as to overall penetration depth implies that this higher ablation rate is in some way compensated deeper within the plasma. Such deposition would be consistent with enhanced energy flux to the pellet in the plasma outer region and diminished flux within the plasma interior. The profile of electron temperature shown gives some indication of this possibility. The post-pellet temperature profile still reflects in general terms the measured local pellet mass perturbation but the central value appears to reflect some additional radial energy flow. Alternatively, a temperature dependence for the ablation process which is stronger at low tempertures, $T_e$<1 to 1.5keV, and weaker above this temperature may be indicated.

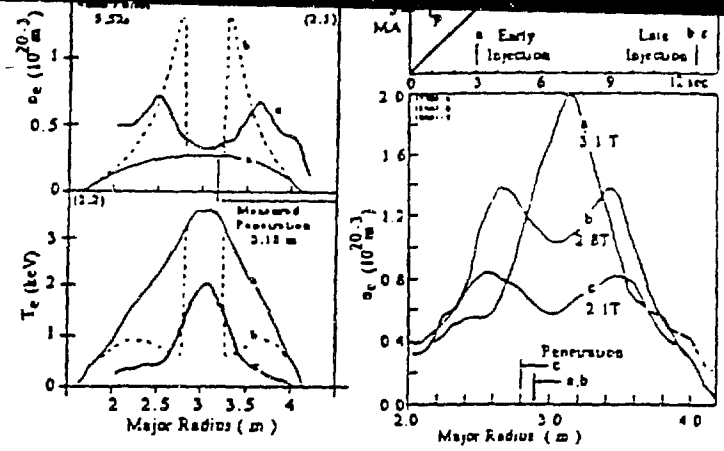


Figure 2: Pellet Deposition in JET. Figure 2.1:Non-Central Deposition-Density Profiles: a)before pellet injection, b) following pellet injection, calculated from the local ablation rate dN/dt distributed over a flux surface and added to local target density, c) approximately 20ms after pellet injection, measured with the LIDAR Thompson Scattering system. Figure 2.2: Non -Central Deposition -Temperature Profiles: a)before injection, b)calculated following injection assuming adiabatic deposition, c)measured approximately 20ms after injection. Figure 2.3: Central Deposition -Density Profiles: a)early injection limiter plasma, b)Late injection, x-point plasma, $B_T$=2.8 and 2.1T. Profiles are measured approximately 20ms after injection (LIDAR). Target density profiles are similar to figure 2.1.

As the figure indicates, rapid inward flow of significant pellet mass during or immediately following pellet ablation ($t \sim t_{ablation}$) has not yet been observed in TFTR or JET, even for large pellet perturbations. If such rapid flow, observed in earlier experiments on Alcator[8] is associated with the pellet perturbation itself, then the time scale for, and potential speed of, mass flow during or shortly after the ablation process is likely to be similar in large and small devices. The magnitude of the pellet perturbation relative to the plasma target density is the same or possibly larger in the large devices; the resulting perturbed electron temperature and sound speed are therefore similar. The distance to the plasma core, however, has increased by an order of magnitude from 0.03m to some 0.3 to 0.5m, while mass deposition is possibly enhanced at large radius. If present, rapid mass flow to the plasma core under these conditions should be less in the larger devices. If the inward mass flow is associated with a strong convective flow on a longer time scale[9], such flows have not yet been produced in pellet fuelling experiments on TFTR and JET.

**2.2 Central Penetration:** In past experiments, penetration to or beyond the plasma magnetic axis led to deposition strongly peaked on axis in the region of small volume and highest pre-pellet temperature. In large tokamaks this effect is also observed. Strong peaking of the density profile is seen under these conditions in both TFTR (figure 3) and in JET (figure 2.3). However, in JET such strong peaking is not always observed. When pellets are injected late in the current flattop, the deposition peak can shift off axis, although measured penetration depth remains apparently beyond the magnetic axis. Figure 2.3 illustrates this result, comparing post-pellet density profiles for three injection events. The early injection event took place prior to sawtooth onset and the presence of a q=1 surface in the plasma[10]. The late injection events took place long after sawtooth oscillations were present. The location of the density maximum is near the usual q=1 radius and appears to shift outward with lower TF. This apparent change in deposition between early and late injection may be associated with a vertical deflection of the pellet trajectory not present early in the discharge. This possibility can not be eliminated until the trajectory itself is photographed, but a significant deflection would be required. An alternative explanation may be associated with enhanced ablation at, or just outside, q=1 due to a collapse of energy content within the q=1 surface triggered by the pellet [11]. Such an enhancement in ablation rate near the q=1 surface might also be associated with the formation of the helical structures "snakes" observed on JET following some pellet events[12].

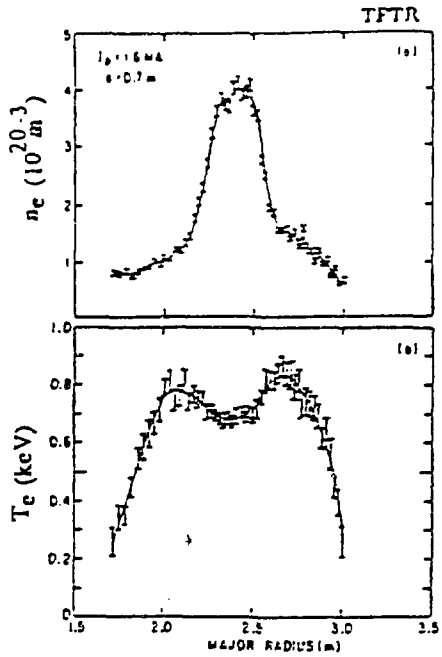


Figure 3: Electron density (a) and temperature (b) profiles following the last pellet of a 3 pellet sequence (TFTR).

Production of highly peaked density profiles has been most easily achieved in TFTR and JET by pellet penetration to the plasma core early in the discharge using either a single pellet event (single pellets or multiple pellets closely spaced in time) or a multiple pellet sequence with pellets timed so as to produce and maintain low central electron temperatures and central penetration during the pellet sequence.

**3.0 Average and Central Density:** Pellet fuelling as a mechanism to achieve high density operation has been well established by past experiments. In TFTR and JET density achieved with pellets in ohmic plasmas is also greater than that attainable with deuterium gas puffing. Both multiple pellet (5 pellets - TFTR, 32 pellets - JET) and single pellet fuelling experiments have been conducted. In both machines $n_e R q_{cyl}/B_T=20$ has been achieved in ohmic discharges, extending by roughly a factor of 2 the value attained by gas puffing. In JET this limit corresponds to that attained with gas fuelling in auxiliary heated discharges and is associated with the formation of locked modes[13]. As in smaller devices, large perturbations in central density and electron temperature can be obtained without disruption by direct pellet fuelling of the plasma core, utilizing a single large pellet or simultaneous injection of multiple pellets forming a single pellet event. However, these experiments often approach the density limit. As in earlier experiments on other tokamaks, disruptions can occur with increased frequency when experimental conditions are not ideal. A central density of 4 x $10^{20}$ m$^{-3}$ has been achieved in TFTR (figure 3) and 2 x $10^{20}$ m$^{-3}$ on JET (figure 2.3). Peaking factors, $n_e(0)/\langle n_e\rangle_{vol}$, from 2.5 to 4 are attained. Even in these large tokamaks at high current (1.5 to 3MA) central electron temperatures can fall below 1keV immediately following the pellet event (figure 3). Under these conditions, the MHD behavior of the discharge can be modified. In particular, as in earlier experiments, sawtooth oscillations can be supressed [14], or when pellet fuelling is employed prior to the onset of sawtooth oscillations, that onset time can be signifigantly delayed [10], allowing heating experiments to be conducted during a sawtooth free period.

**4.0 Particle Confinement:** Relaxation of the density profile in large devices following a pellet perturbation occurs on time scales longer than those observed in previous experiments. Decay times of 100ms in Alcator C[8] are extended to 1 to 2 seconds on TFTR and JET. The general evolution of the profile shape appears to be similar however. Figure 4 shows the evolution of the density profile and the diffusion coefficient inferred from the

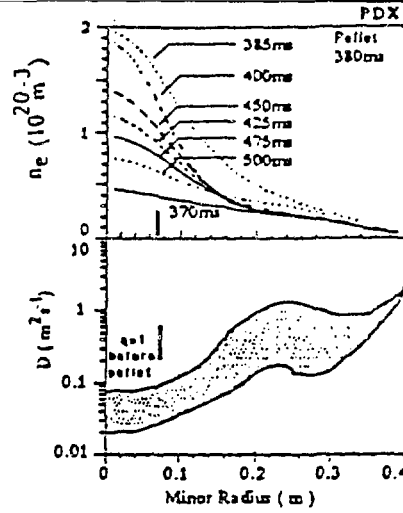


Figure 4: PDX x-point plasma. 4a) Density profile evolution during 115ms following pellet injection. 4b) Range of particle diffusivity during period of density evolution inferred from measured $dn_e/dt$, computed source term and neoclassical (Ware) pinch.

measured particle fluxes in PDX [15]. Modeling of the profile evolution on TFTR and JET yields coefficients of similar or lesser magnitude. Figure 5 illustrates the profile evolution for a TFTR discharge[14]. The diffusion coefficient obtained during the density decay, assuming diffusive flow alone, or including the neoclassical (Ware) pinch, shows a strong radial dependence with values of approximately $0.05m^2s^{-1}$ obtained within the plasma core. In JET this radial dependence has been modeled using an abrupt transition from a low value within the core to a larger edge value, suggesting a separation of the plasma into a weakly anomalous core region and more strongly anomalous outer region. Figure 6 shows the transport coefficient inferred from two JET cases, one ohmic, the other with strong core RF heating[16]. In TFTR this radial variation has been modeled using an $(r/a)^2$ radial dependence[17].

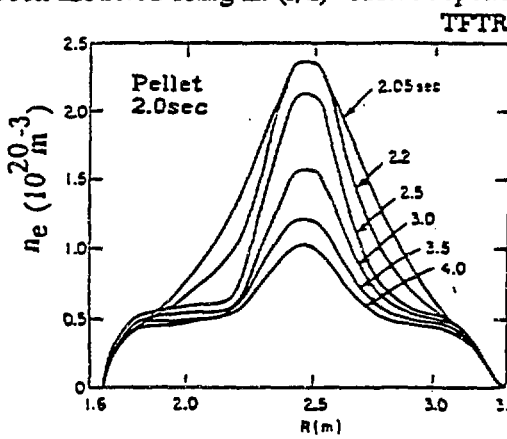


Figure 5: TFTR limiter plasma. Evolution of the density profile during 2s period following pellet fuelling. Persistance of a dense core and formation of broad density pedestal is similar to smaller devices.

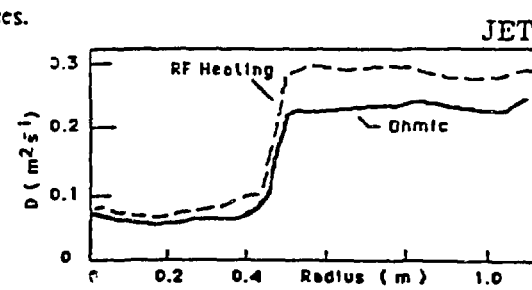


Figure 6: Radial variation of diffusion coefficient used to model evolution of density profile following pellet injection on JET during ohmic and RF heated discharges. Neoclassical (Ware) pinch is incorporated in particle flux calculations.

High density operation obtained with pellet fuelling reduces $Z_{eff}$ immediately following pellet injection on TFTR and JET, as in past experiments. Values for Zeff<1.5 have been obtained[18]. Low anomalous diffusive loss within the plasma core, the presence of strong density and temperature gradients at low collisionality, and the absence of sawteeth, all serve to accentuate neoclassical impurity transport effects seen in past experiments [19]. In TFTR and JET impurity transport is consistent with a neoclassical model incorporating a particle diffusivity similar to that used to model electron transport [17,20]. In JET, increased core impurity concentration can occur in both ohmic and auxiliary heated discharges, appearing on a 1 second time scale. In these large, high temperature devices with low Z limiters, such impurity accumulation leads to dilution rather than radiation collapse.

**5.0 Energy Confinement:** One of the primary reasons for applying pellet fuelling on large tokamaks has been in an effort to produce peaked density profiles and improved energy confinement, as was obtained in earlier experiments[8,21]. Improved confinement has been obtained following pellet injection for periods greater than 1 second in some cases. In TFTR ohmic discharges an enhancement from 1.5 to 1.8 times the saturated ohmic level was found, as illustrated in figure 7[14]. In auxiliary heated discharges, TFTR results (figure 8) using beam heating showed reduced core thermal diffusivity, although in these discharges heating power profiles were peaked outside the plasma core due to poor beam penetration at high density [22]. In more recent JET experiments (figure 9), transport coefficients of similar magnitude within the plasma core have been obtained even in the presence of strong central RF heating (0.8MW/m$^3$), high temperatures ($T_i$=$T_e$=10keV) and low collisionality $\upsilon^*_i$ and $\upsilon^*_e$< 0.1 [10,23,24,25,26]. These values of $\chi_i$ and $\chi_e$ are roughly 1/2 to 1/3 those obtained later in

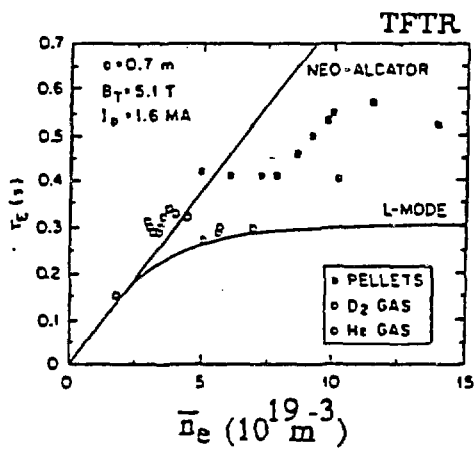


**Figure7:** Variation of global confinement with line density in ohmic TFTR discharges. Saturated ohmic level obtained with gas puffing is roughly L-mode level[25].

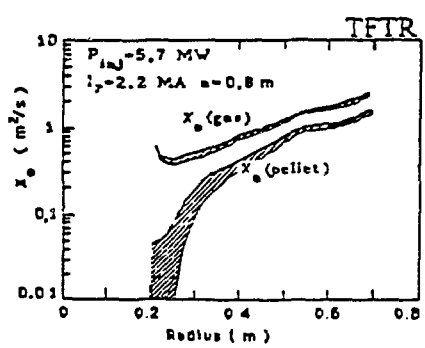


**Figure 8:** Thermal diffusivity during beam heating in pellet fuelled and gas fuelled TFTR discharges. The radial variation in $\chi_e$ was obtained assuming an ion thermal diffusivity in the range from 1 to 3 times the neoclassical value (0.1 to 0.3 m$^2$s$^{-1}$ in the region 0.2 to 0.4m). The range of $\chi_e$ values shown in each case indicates the variation obtained for a multiplier of 1 and 3.

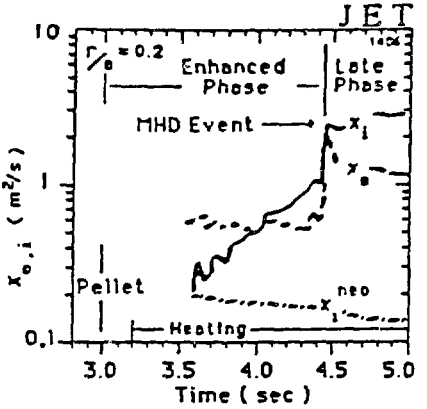


Figure 9: Thermal diffusivity during on axis RF heating in pellet fuelled JET discharges. Variation with time of values at r/a=0.2 is plotted. Core value of $\chi_i$ is determined from measured $T_i(0)$. Radial variation similar to $\chi_e$ is assumed. In this calculation total ion heating is assumed to be 50% of the RF input power at all times.

the discharge in the presence of broad density but similar heating profiles. When both the heating and density profiles were strongly peaked within the plasma core, global confinement 1.6x the L-mode[26] value (3MA and 10MW) was obtained. In large, high temperature devices fast ions can contribute significantly to the plasma energy content, and may have slowing down times greater than the thermal plasma confinement time, perhaps distorting the comparison with L-mode scaling. In the high density pellet case however, the thermal plasma energy content is the dominant global term.

**6.0 High Power Operation:** At high power, peaked profiles produced by beam fuelling lead to enhanced performance, which is often terminated by a strong carbon influx[27]. Pellet fuelling during the heating pulse has recently been used in such discharges, not to peak the density profile, but to introduce deuterium and delay the onset of high carbon influx[28]. Neutron rates in this case have been enhanced by a further 20%.

**7.0 Summary:** In TFTR and JET experiments, pellet fuelling has been extended to larger, higher temperature devices. Penetration depths are in general agreement with calculations when ablation by thermal electrons dominates, but local deposition may differ from predictions. Deposition at the plasma edge can be enhanced. Deposition near the plasma center may also be altered. Fueling efficiency is high, but at present strongly peaked density profiles are obtained only with pellet penetration approaching or beyond the plasma center. As in earlier experiments in smaller devices: density achieved with pellets in ohmic plasmas is greater than that attainable with deuterium gas puffing, significant electron temperature perturbations can be tolerated, supression of existing sawtooth relaxations or delay of their onset is obtained, decay of the density perturbation is slow with density decay times of 1.5 to 2s observed, energy confinement is observed to improve and with core heating $T_e(0)>5$keV is rapidly achieved. In addition pellet fuelling during low density high power beam heating has been used to delay onset of high carbon influx, and further enhance plasma performance.

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