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ITER Pellet Fueling

W. A. Houlberg

1. ITER Fueling Issues

The most fundamental requirement of a fueling system for ITER is to provide an efficient means of injecting tritium fuel. In pellet fueling experiments, plasma particle confinement times are improved over those obtained with neutral gas injection, particularly for divertor geometries where direct particle recycle to the plasma is low. Penetration beyond the poor confinement plasma edge region gives a minimum requirement for fuel injection. This is easily met by existing pellet sizes and velocities under all ITER plasma conditions. The minimum penetration requirement may also provide enough control of plasma edge conditions to promote the transition from L-Mode to H-Mode confinement. However, this needs experimental verification and a better understanding of the physics underlying H-Mode and L-Mode confinement. Multiple-pellet injection experiments in progress on Asdex, JET, and Tore-Supra should provide information of direct relevance to ITER. Deeper penetration could provide additional particle and energy confinement benefits.

Improved energy confinement with pellet injection has been demonstrated on many experiments. The degree of improvement varies from experiment to experiment, in part due to variations in operating conditions, but up to a factor of two improvement over gas fueling is commonly found. The reasons for this improvement are not understood, but speculation is that the peaking of the density profile with pellet injection may reduce transport from η_i modes or some other related instabilities. The degree to which the density profile can be controlled with pellet injection depends on both the pellet penetration depth and internal plasma transport characteristics (diffusive and pinch terms).

In fusion plasmas, where the thermal balance is sustained by production and confinement of energetic alphas, significant benefits should be gained from centrally peaked density profiles. For a given plasma particle content (average density) and energy content (average beta) more fusion power is produced as the density profile becomes more centrally peaked because of the n^2 dependence of the fusion rate. As a demonstration of this effect, record neutron production rates were recently produced in JET with ICRH heating of highly peaked density profiles created by pellet injection. Peaked density profiles should thus reduce the energy confinement time required for ignition in ITER. A more centrally peaked fast alpha profile may lead to improved fast alpha confinement characteristics and improved thermal energy confinement through

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the more centrally peaked heating profile. On the other hand, the more peaked fast alpha and thermal pressure profiles could drive instabilities that are deleterious to the plasma. These are issues that the Compact Ignition Tokamak (CIT) project intends to address. As theoretical issues they are very difficult to resolve *a priori*.

Density profiles exhibit a much broader range of shapes than temperature profiles but the development of models for density profile evolution has been secondary to the development of models for temperature profile evolution. The dramatic broadening of density profiles in H-Mode plasmas serves to highlight some of the dramatic transitions that can occur between ohmic and auxiliary heated plasmas. The growing database on density profile evolution in pellet-injected plasmas is helping to push the development of particle transport models and improvements should be seen in the next few years. Quantifying the relationships between density profiles, improved energy confinement, and pellet injection parameters therefore remains a difficult issue.

This uncertainly in particle transport leads to uncertainties in how hard the technology of pellet injectors, or other fueling schemes, should be pushed to improve penetration. The key to understanding the link between pellet penetration and the density profile lies primarily in an examination of particle transport, and secondarily in fuel penetration. Most pellet injection data in ohmic plasmas shows a very rapid peaking of the density profile after partial pellet penetration, followed by a generally much slower decay of the plasma particle content. The data suggests the existence of a strong pinch term in the particle flux. H-Mode plasmas exhibit broader density profiles and at times even inverted (at least transiently) after the L-Mode to H-Mode transition. To what extent will particle transport processes augment or defeat expected gains from increased penetration associated with increased pellet velocity?

2. ITER Pellet Sizes, Ablation, and Penetration

Table 1
ITER-like Parameters

R_o (m)	5.50
a_o (m)	1.83
κ	2.0
B_{To} (T)	5.45
I_o (MA)	20
Calculated Parameters	
$< n_{Gr} >$ (m^{-3})	1.6×10^{20}
V_p (m^3)	690
N_{Gr}	1.1×10^{23}

A characteristic set of ITER-like machine parameters are shown in Table 1. The total particle content of the plasma at the nominal Greenwald density limit gives an indication of the relative density perturbation for each of the pellet sizes chosen. The sizes represent 10%, 20%, and 30% perturbations at a nominal average plasma density

of $10^{20}\,m^{-3}$. At the time of pellet injection the density should be about half a pellet perturbation below the time-averaged operating density.

For reference in the following discussion, the JET pellet injector is a repeating pneumatic type with three barrels, each separately programmable for maximum fueling flexibility. It has a repetition rate of up to 5 Hz for the smallest pellets, 2 Hz for the medium pellets, and 1 Hz for the largest pellets. Velocities range from about 1.2 km/s at the highest repetition rate to about 1.4 km/s at lower repetition rates.

Table 2 shows a selection of pellet sizes and their absolute and fractional particle content (in terms of the plasma content at the nominal Greenwald density limit for the ITER-like parameters of Table 1). The required repetition rate, f_p, can be determined from the effective particle confinement time, τ_p^{eff}, and fractional mass content of each pellet, $g_p = N_p/N_{plasma}$, as $f_p = (g_p \tau_p^{eff})^{-1}$. The repetition rates of the JET injector should come close to meeting ITER requirements, depending on τ_p^{eff} and the number of injectors used. Rates of the order of several Hz could be a major challenge for advanced, high velocity injectors.

Table 2
Pellet Sizes and
Fraction of Greenwald Limit

Spherical Radius r_p (mm)	N_p 10^{22}	%
3.0	0.7	6.4
3.8	1.4	12.7
4.3	2.0	18.2

The model [1] used for pellet ablation is an upgraded version of the Milora-Foster neutral gas shielding model [2] and has been tested extensively against JET single pellet injection data.[3,4] Figures 1 and 2 show the results of these studies.

Figure 1 covers the single pellet data from the Garching injector[3] and includes pellet velocities of 0.75 – 1.2 km/s, ohmic heating, ICRH heating up to 6 MW, and NBI heating up to 8 MW, for pellet sizes of nominal spherical radii 1.95 mm (3.6 mm diameter and length cylinders) and 2.34 mm (4.6 mm cylinders). Deviation from the agreement line is within the error bars from uncertainties in velocity (measured by time-of-flight between two diodes for each pellet), electron temperature profile (from ECE data), density profile (from a fit to data from 7 FIR chords), and pellet mass (approximated as 85% of the ideal mass for the smaller pellets and 70% for the larger pellets). The agreement is obtained with a neutral cloud thickness of 1 mm (effective ionization radius of $r_c = r_p + 1$ mm decreasing as the pellet ablates). These ablation calculations ignore the effects of fast ions and yet agreement with the experimental results for the highest NBI powers (8 MW) and ICRH powers (6 MW) indicates that in neither case are fast ions important. With fast ions included in the model for the 8 MW NBI case a difference of only 2 cm was found in the penetration depth. The fast ion tails generated during ICRH heating are apparently weak enough in the outer

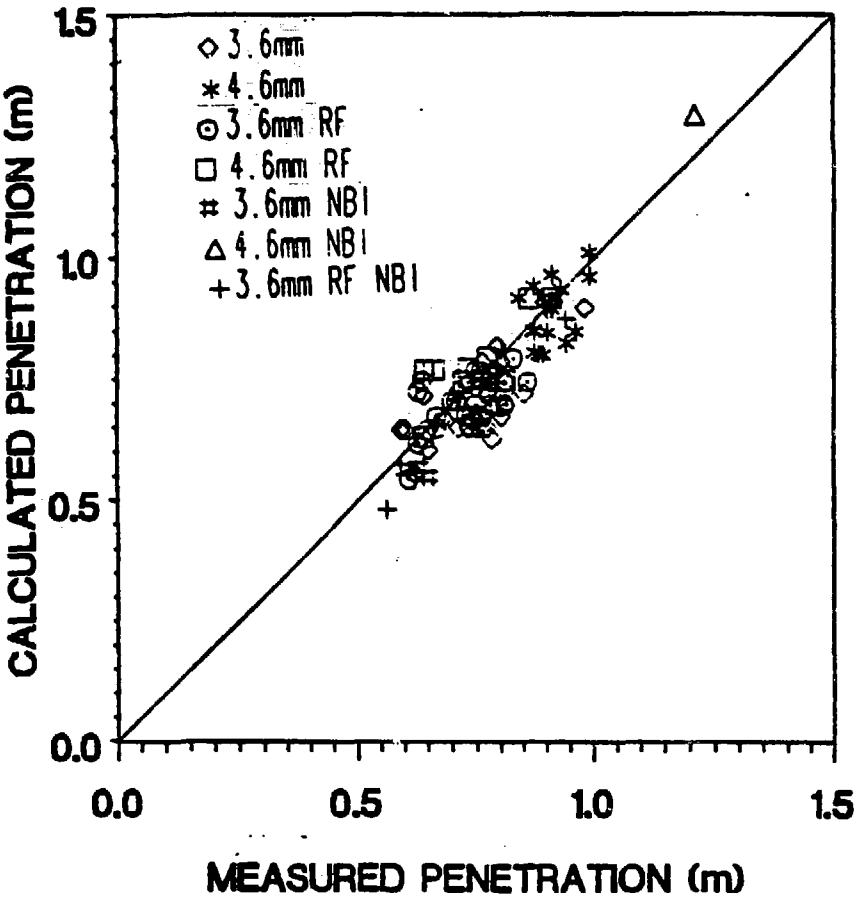

Figure 1: Calculated and measured pellet penetration for a wide range of JET plasma conditions for the single-shot Garching injector. Agreement with measured penetration depths is obtained with the effective ionization radius being 1 mm larger than the pellet radius, $r_c = r_p + 1\,\mathrm{mm}$.

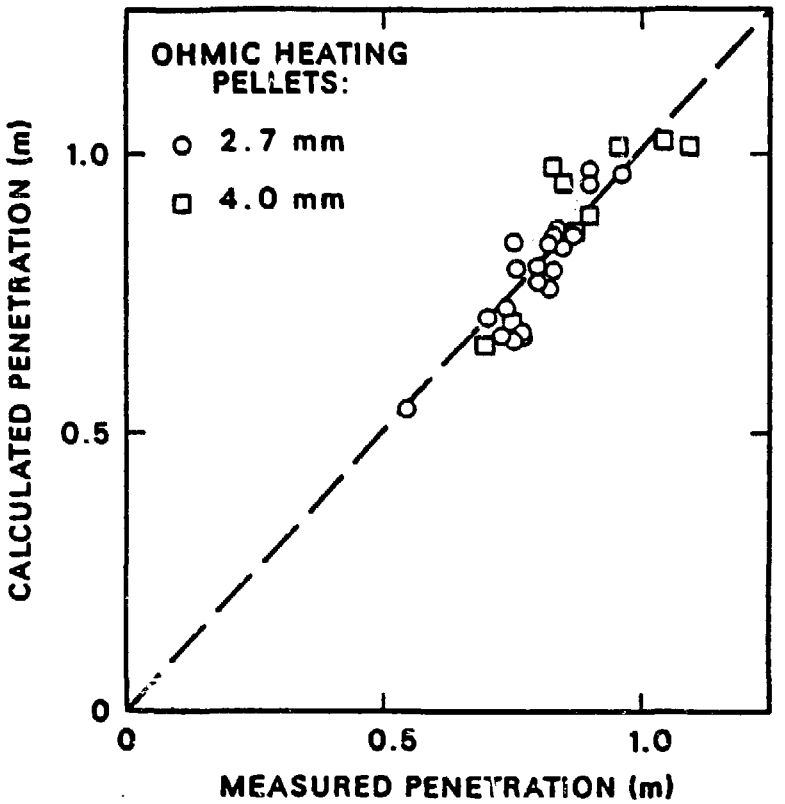

Figure 2: Calculated and measured pellet penetration for ohmic JET plasmas for the multi-pellet ORNL injector. Agreement with measured penetration depths is obtained with the effective ionization radius being 1 mm larger than the pellet radius.

portion of the plasma (where the pellets penetrate) that their influence on ablation is not significant.

Similar agreement is shown for the nominal 2.7 mm and 4.0 mm pellets (equal diameter and length cylinders) from the ORNL injector[4] for velocities of 1.0 – 1.4 km/s. The mass of individual pellets was determined from scaling the calibrated signal from the microwave cavities. The deeper penetration by the small pellets was obtained by injecting during the current ramp phase. Many other 2.7 mm pellets passed beyond the magnetic axis ($\geq$ 1 m), in agreement with the model, but an accurate measure of the penetration depth could not be obtained from the vertical soft x-ray data because the signal perturbation was too small.

The data from pellets injected into beam-heated TFTR plasmas provides a reference point for evaluating the effects of fast alphas.[1] A classical, local slowing-down distribution of fast alphas should not contribute to pellet ablation in ITER, or any other fusion plasma.[1] When $T_e \geq 4.7$ keV, the neutral shield that is required to stop the plasma electrons is thick enough to stop 3.5 MeV alphas. For $T_e \leq 4.7$ keV the fast alpha population is so low that it would not enhance ablation even if the energy flux is not attenuated by the shield.

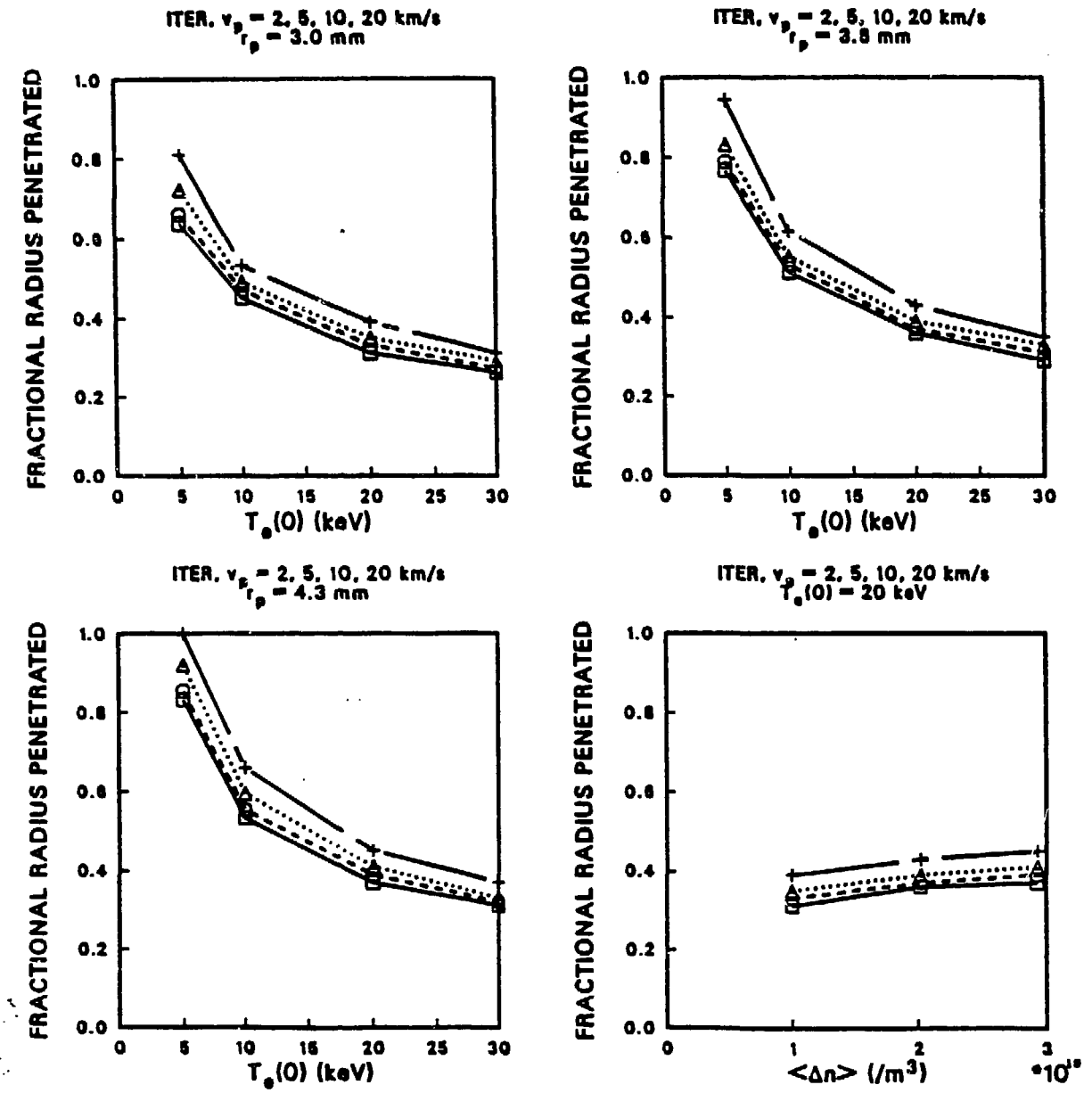

Figure 3: Fractional radius penetrated in ITER decreases rapidly with increasing plasma electron temperature. Penetration improvement with velocity and mass is relatively weak with the neutral and plasma shielding model.

Stand-alone pellet penetration studies have been carried out for ITER with the JET-benchmarked ablation model using the pellet sizes of Table 2 and velocities up to 20 km/s. Figure 3 shows the fractional radius penetrated (distance penetrated divided by minor radius) as a function of the central electron temperature for a neutral cloud thickness normal to the field of 1 mm as indicated by the JET data. The electron temperature profile was assumed parabolic-squared and the density profile square-root parabolic (with $n(0) = 1.2 \times 10^{20}\,\mathrm{m}^{-3}$, corresponding to $\langle n \rangle = 1.0 \times 10^{20}\,\mathrm{m}^{-3}$) in all cases. It can be seen that penetration improves weakly with increasing velocity beyond 2.0 km/s.

Fractional volume penetrated is perhaps a more relevant measure of fueling effectiveness. Figure 4 shows the volume penetration for the same set of pellets and conditions considered in Figure 3. Penetration by any of the pellets during the start-up phase, $T_e(0) \leq 10\,\mathrm{keV}$, is excellent and should lead to more peaked density profiles, a boost in fusion rates, and reduced auxiliary power requirements. At least 50% of the plasma volume is actively fueled by the pellets for central temperatures up to 30 keV. These results are insensitive to the plasma density but fairly sensitive to the electron temperature and its profile (as are other variations of the neutral shielding model). With a parabolic temperature profile the electron temperature is higher in the outer region of the plasma and penetration is reduced. Volume penetration would be expected to decrease to roughly 40% from the nominal 60% obtained with the largest pellets when $T_e(0) = 30\,\mathrm{keV}$. The more linear temperature profiles observed in experiments are generally closer to parabolic-squared than parabolic.

There are additional shielding effects that may become important in higher temperature plasmas (e.g., magnetic shielding) that could improve the scaling of penetration with pellet velocity. In the present model the effective thickness of the neutral shield normal to the magnetic field (the transition from spherical flow to flow along the magnetic field) has been taken as a constant value of 1 mm independent of pellet size, ablation rate, or plasma conditions. This is likely not the actual case and needs further study. Lengyel has been examining this issue.[5] Figures 5 and 6 show the variation in fractional radius and volume penetrated respectively when the neutral shield thickness is decreased to 0.5 mm (improved penetration) or increased to 2.0 mm (decreased penetration). Decreasing the ionization radius causes the flow of ionized ablatant along the magnetic field to be restricted to a smaller tube and therefore more effective in shielding the incoming hot electrons. The ionization radius could be even larger than considered here. In that case, high beta effects in the ionized cloud could reduce the effective ionization radius (the radius of the flux tube intercepted far from the pellet).

Modifications to the neutral shielding model are not likely to change the conclusion that penetration to or near the magnetic axis will require extremely high velocities. So understanding the natural tendency of tokamak plasmas to fill in a hollow density profile after partial pellet penetration becomes critical.

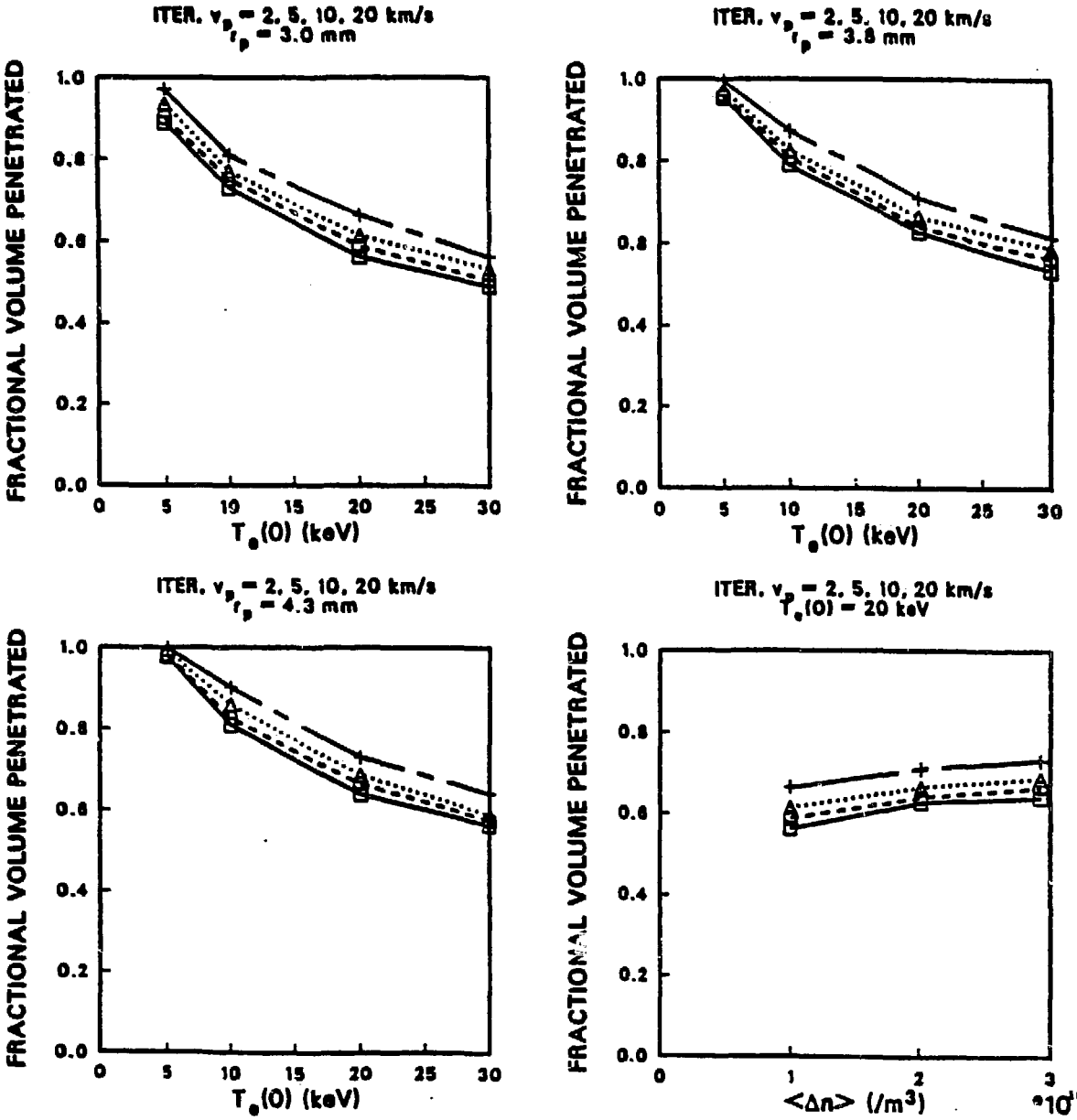

Figure 4: Fractional volume penetrated in ITER is good with a parabolic-squared electron temperature profile.

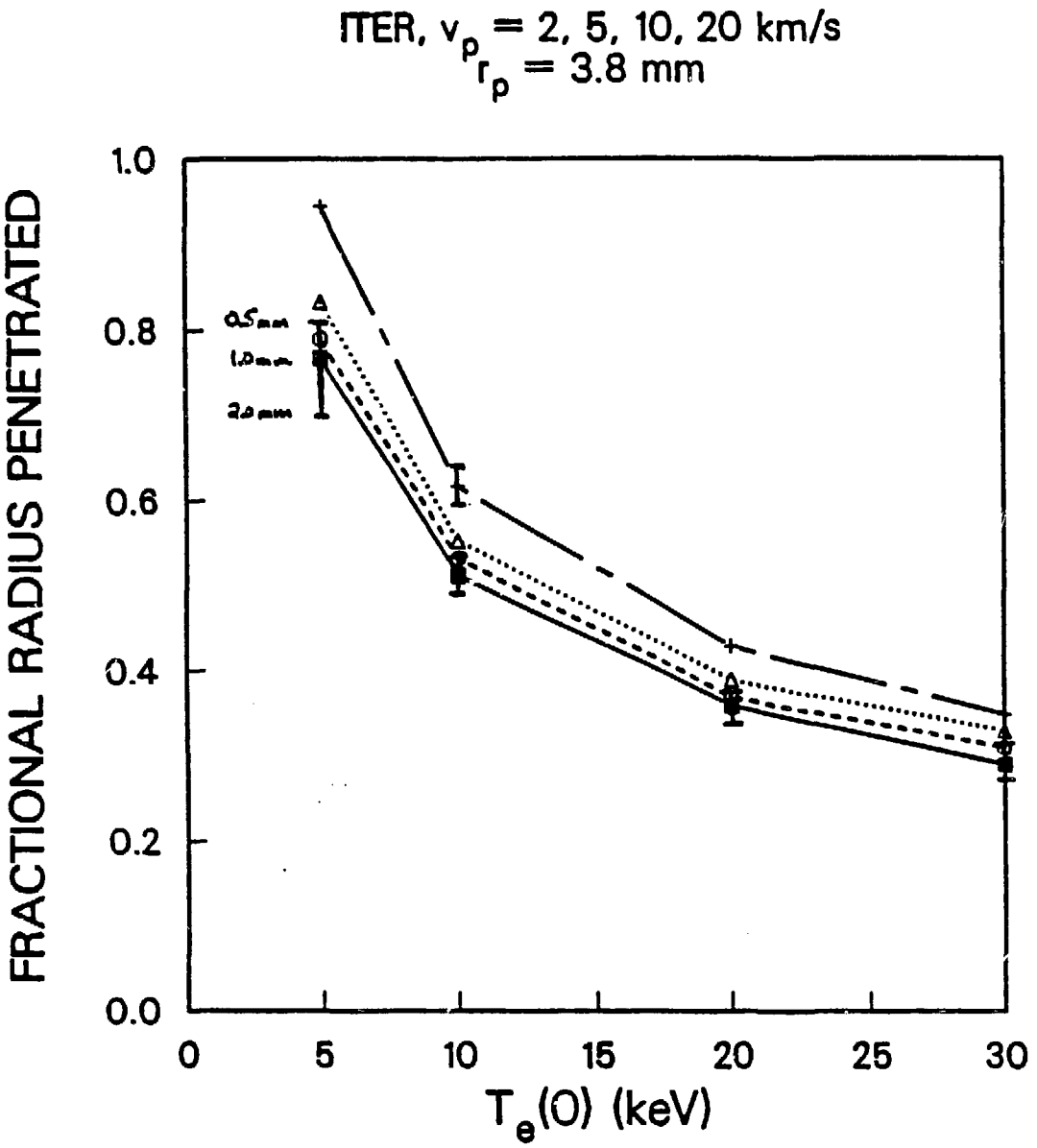

Figure 5: Fractional radius penetrated in ITER showing the sensitivity to the effective ionization radius.

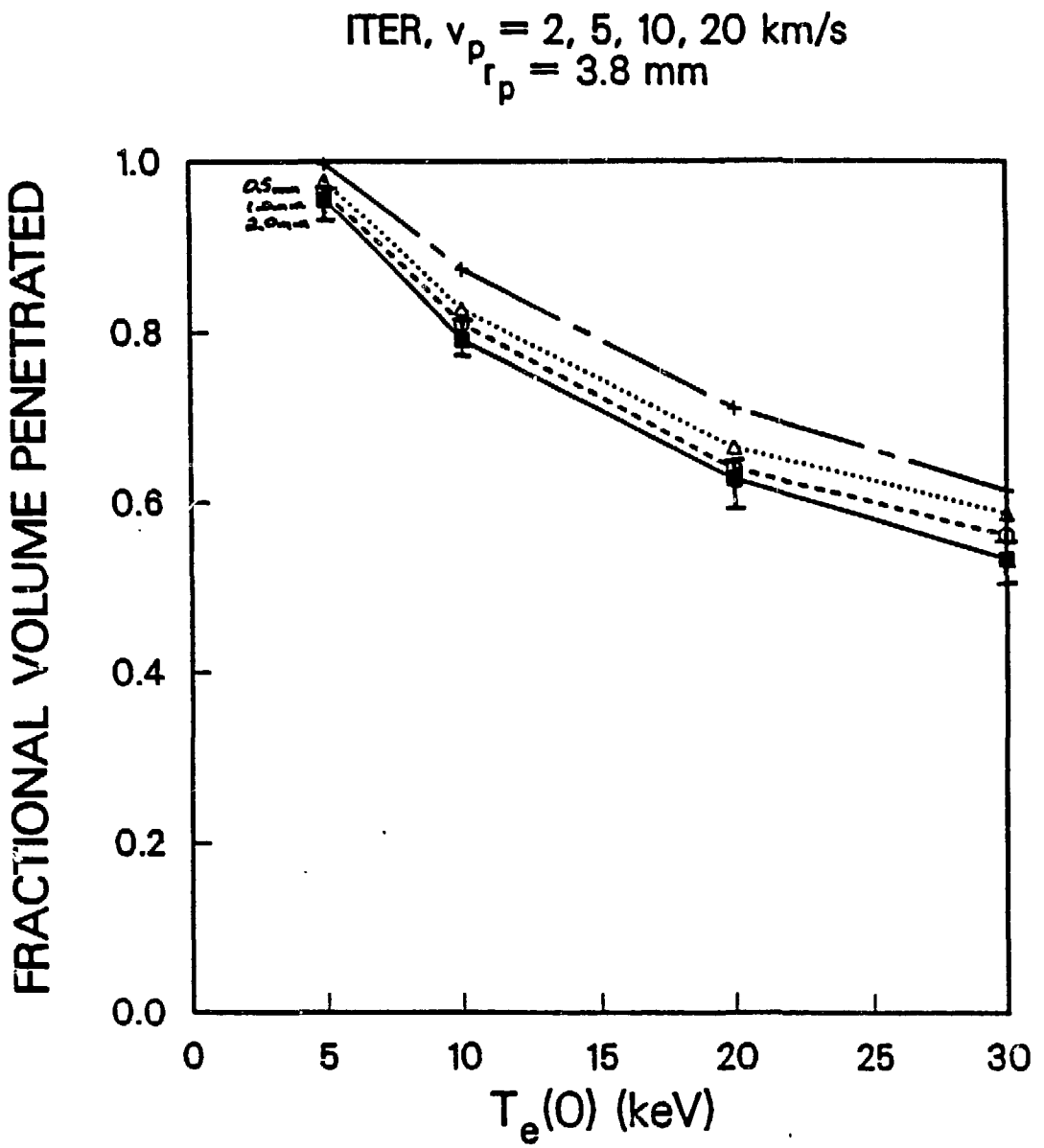

Figure 6: Fractional volume penetrated in ITER showing the sensitivity to the effective ionization radius.

3. ITER Pellet Injector Requirements

The technological means of increasing penetration are pellet size and velocity. Increasing pellet size is straightforward in present injectors. The largest pellets produced by the JET pellet injector (nominal 6.0 mm diameter and length cylinders for a net effective spherical radius of 3.0 mm) are smaller than the smallest pellets considered here for ITER. Increased pellet size is generally easy except that at some point the decay heating in tritium pellets could make it difficult to maintain frozen pellets. Tritium pellet experiments are presently being conducted on the Tritium Systems Test Assembly (TSTA) with an ORNL injector to address this issue. Increasing pellet velocity is another matter. New technology is required for velocities much above the presently achieved $\approx 1.4\,\mathrm{km/s}$ for repetitive injection of deuterium pellets with the JET injector. Although penetration improves only weakly with increasing velocity in the present ablation model, there is enough uncertainty in extrapolating to higher plasma temperatures and enough promise of improved performance to warrant development of higher velocity options.

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