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Summary Abstract:Pellet Fueling Experiments in Alcator C

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SUMMARY ABSTRACT: PELLET FUELING EXPERIMENTS IN ALCATOR C

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ABSTRACT

A series of pellet fueling experiments was carried out on Alcator C with a four-shot injector capable of firing hydrogen and deuterium pellets at speeds near 1 km/sec. [1,2] Injection of high-speed pellets provides a means for directly fueling the core of the tokamak discharge. In these experiments, the line averaged density was raised to $1 \times 10^{15}/\text{cm}^3$ with a peaked density profile. Peak to average ratios for the pellet fueled plasmas were approximately 2 compared to ratios of 1.2 - 1.4 for those fueled by gas puffing. Energy confinement for pellet fueled discharges was better than for those fueled by gas puffing at densities above 2×10^{14}, where the latter shows a pronounced saturation. [3] Energy transport in the pellet fueled plasmas could be modelled by $\chi_e \propto 1/n_e$ and $\chi_i = 1 \times$ neoclassical. With the improved confinement and higher densities, record values of $n\tau = .6 - .8 \times 10^{14}$ sec/cm^3 and peak plasma pressure = 8.1 atm were achieved. An unexpected feature of the pellet experiments was the extremely rapid readjustment of temperature and density profiles in the first few hundred microseconds after injection. Observation of the profiles indicates that transport mechanisms approximately 100 times faster than normal are operating during this period. This profile readjustment only involves the inner regions of the discharge and does not lead to any net loss of particles or energy.

PELLET INJECTOR SYSTEM

The injector used in these studies was capable of producing up to four pellets of either hydrogen or deuterium with top velocities approaching 1000 m/sec and whose firing times could be independently programmed. Each hydrogen pellet contained 6×10^{19} atoms which corresponds to $\langle n_e \rangle = 2 \times 10^{14}$ cm^{-3} in Alcator C; $a = 16.5$ cm, $R = 64$ cm. Due to its higher number density, deuterium pellets contain about 15% more particles. The pellets are accelerated by a puff of high pressure gas; in these experiments helium at 20 atm was used. By changing the propellant gas, pellet velocities could be varied over a wide range. In order to avoid contaminating the plasma or complicating analysis of the experiment it was necessary to keep the propellant gas from entering the torus. This was accomplished by a combination of differential pumping and baffling.

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GENERAL OBSERVATIONS

The target plasmas for pellet experiments had Bt = 80 - 120 kG, Ip = 400 - 800 kA, $T_e(0)$ = 1400 - 2000 eV, $T_i(0)$ = 1000 - 1400 eV, and $\bar{n}_e = 2 - 6 \times 10^{14}$ cm^{-3}. In these plasmas, hydrogen pellets last 100 - 150 μsec and with their nominal velocities penetrate 8 - 12 cm or to within 4 - 8 cm of the magnetic axis. The pellets do not reach the q = 1 surface which is between 2 and 3.5 cm. Pellet ablation was monitored by measuring Balmer alpha light emitted from the cloud of gas evaporating from the pellet surface. H_α intensity should be roughly proportional to the rate of evaporation and ionization. [4] The ablation rates measured were in agreement with the neutral shielding model. [5]

A set of traces from a typical pellet injection discharge is shown in figure 1. In this shot a single deuterium pellet was injected into an established deuterium discharge at 390 msec. Line averaged density increases immediately by 3×10^{14} cm^{-3} then decays slowly back to its original value. Electron and ion temperature drop as the discharge is diluted by cold particles from the evaporating pellet. The temperature recovers more quickly than the density resulting in a net gain in total plasma energy. This is also indicated by the rise in β_p. The surface voltage jumps up by .5 to 1.0 volts and the plasma current drops slightly. The soft x-ray signal and the neutron rate drop initially, then increase as the temperature recovers, reaching many times their original values. Peak neutron rates in the range $1 - 2 \times 10^{13}$/sec have been measured.

ENERGY CONFINEMENT

The plasma energy content is evaluated by integrating the density and temperature profiles. Because the temperature rise is faster than the density fall, the energy content begins to rise immediately after injection and peaks as the temperature recovers it original value. This observation is confirmed by the magnetic measurements. A set of B_θ loops gives $\Lambda = \beta_p + \ell_i/2$, which shows a similar increase. Measurements of plasma diamagnetism confirm that this change is predominantly in β_p, which when converted to a change in plasma energy agrees quantitatively with the profile data. Values of β_p as high as .5 have been observed at Ip = 780 kA, which corresponds to a plasma energy of 80 kJ.

It is clear that the increased plasma energy at fixed power implies that energy confinement has improved in these shots. Of course the discharges have higher density after injection and confinement has some residual density dependence even in the saturated regime. The crucial comparison is between pellet and gas fueled discharges at fixed density. That comparison is shown in figure 2, where the confinement times are calculated including the transient effects. The values are shown for times 30 - 50 msec after injection when the temperatures have recovered. The pellet fueled shots do not show the confinement rollover at 2×10^{14} and are as much as 70% higher than the gas fueled shots at the highest density. Figure 2 also compares the experimental data with results of a ONETWO [6] simulation where transport is modelled with $\chi_e \propto 1/n_e$ and $\chi_i = 1 \times$ neoclassical. The confinement parameter $n(o)\tau_E$ is plotted for these shots in figure 3. With improved confinement and peaked density profiles the difference between gas puffing and pellet fueling becomes even clearer with several of the pellet shots exceeding the Lawson $n\tau$ criterion for thermalized breakeven. [7]

FAST PROFILE READJUSTMENT

The particles which are released from a pellet are rapidly ionized and should subsequently be tied to the magnetic flux surfaces. Figure 4a shows the density profiles that are predicted by adding particles from an ablating pellet to the background plasma. Since the pellets do not reach the magnetic axis in this experiment strongly inverted profiles are obtained. By conserving energy on each surface we obtain the perturbed temperature profiles shown in figure 4b. We would expect both of these profiles to relax on a 10 - 20 msec timescale by normal (non-classical) crossfield transport. The experimental result is quite different, as can be seen by figures 5a and 5b which show Thomson scattering data taken in the first millisecond after injection. The density profile is initially hollow, as predicted, but in less than 500 μsec it fills in and peaks. The temperature profile reacts even more quickly, the temperature falling to its new equilibrium shape in less than 250 μsec. It is important to realize that the pellet evaporates completely about 6 cm from the axis. This result is confirmed by ECE measurements (fig. 6) which show the evolution of the temperature profile immediately following injection. The central temperature begins to drop within 50 - 100 μsec of the time the pellet touches the outer edge of the discharge and the profile adjusts nearly continuously to a gaussian shape. Despite the very rapid transport implied by these observations, there is no measurable energy or particle loss from the plasma. This profile adjustment is sometimes accompanied by strong $m = 1$, $n = 1$ oscillations, which can be seen on the soft x-ray traces in figure 7. Although the perturbations are clear in the x-ray measurements, they cannot be seen on the electron temperature and may be the result of poloidally asymmetric clumps of density rotating in the plasma. The relationship between the oscillations and the profile readjustment are not clear at this time.

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REFERENCES

1. M. Greenwald, et al., Phys. Rev. Lett., 53, 352 (1984).
2. M. Greenwald, et al., Proceedings of the 4th International Symposium on Heating in Toroidal Plasmas, Rome, Italy, (1984).
3. S. Fairfax, et al., Proceedings of the 8th International Conference on Plasma Physics and Controlled Nuclear Fusion Research - Brussels, Vol. 1, pg. 439 (1980).
4. C. A. Foster, et.al., Nucl. Fus. 17, 1067 (1977)
5. P. B. Parks, R. J. Turnbull, C. A. Foster, Nuclear Fusion, 17, 539 (1977).
6. W. W. Pfeiffer, et al., General Atomic Report, GA A16178 (1980).
7. J. D. Lawson, Proc. Phy. Soc. B, 70, 6 (1957).

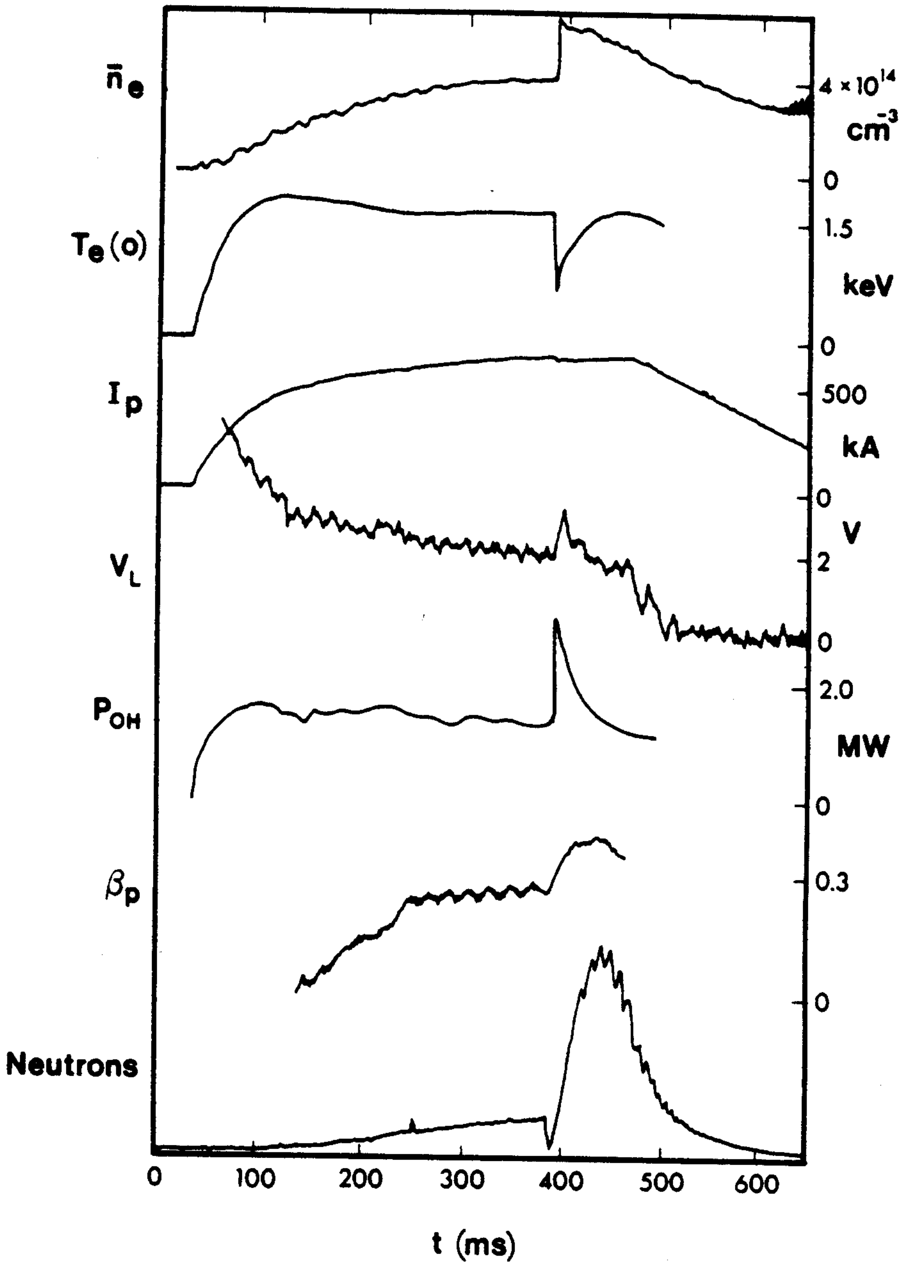

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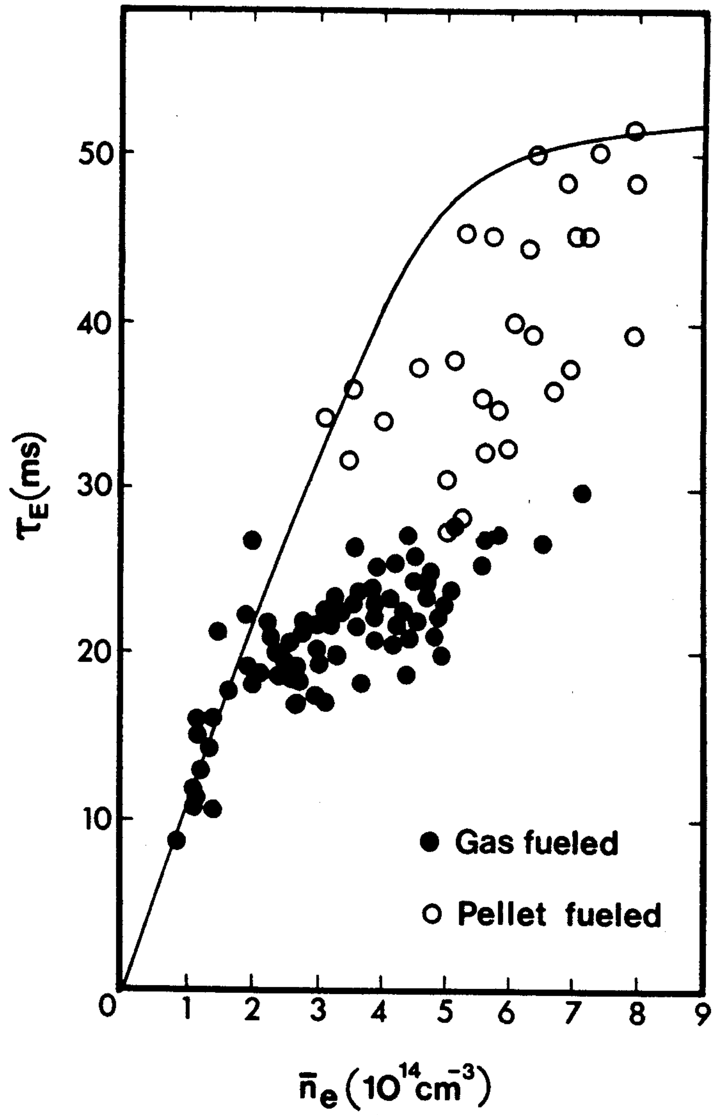
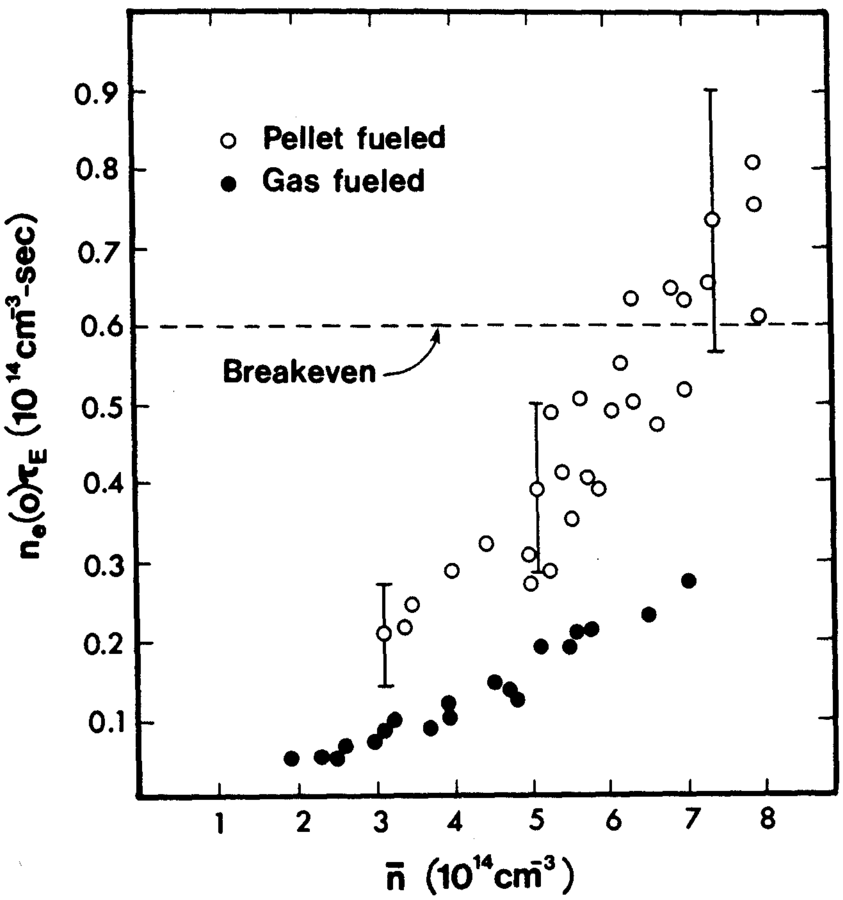
FIGURE 1



τ_E(ms)
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
$\bar{n}_e$ (10^{14}cm^{-3})
● Gas fueled
○ Pellet fueled

85-26

Confinement Parameter



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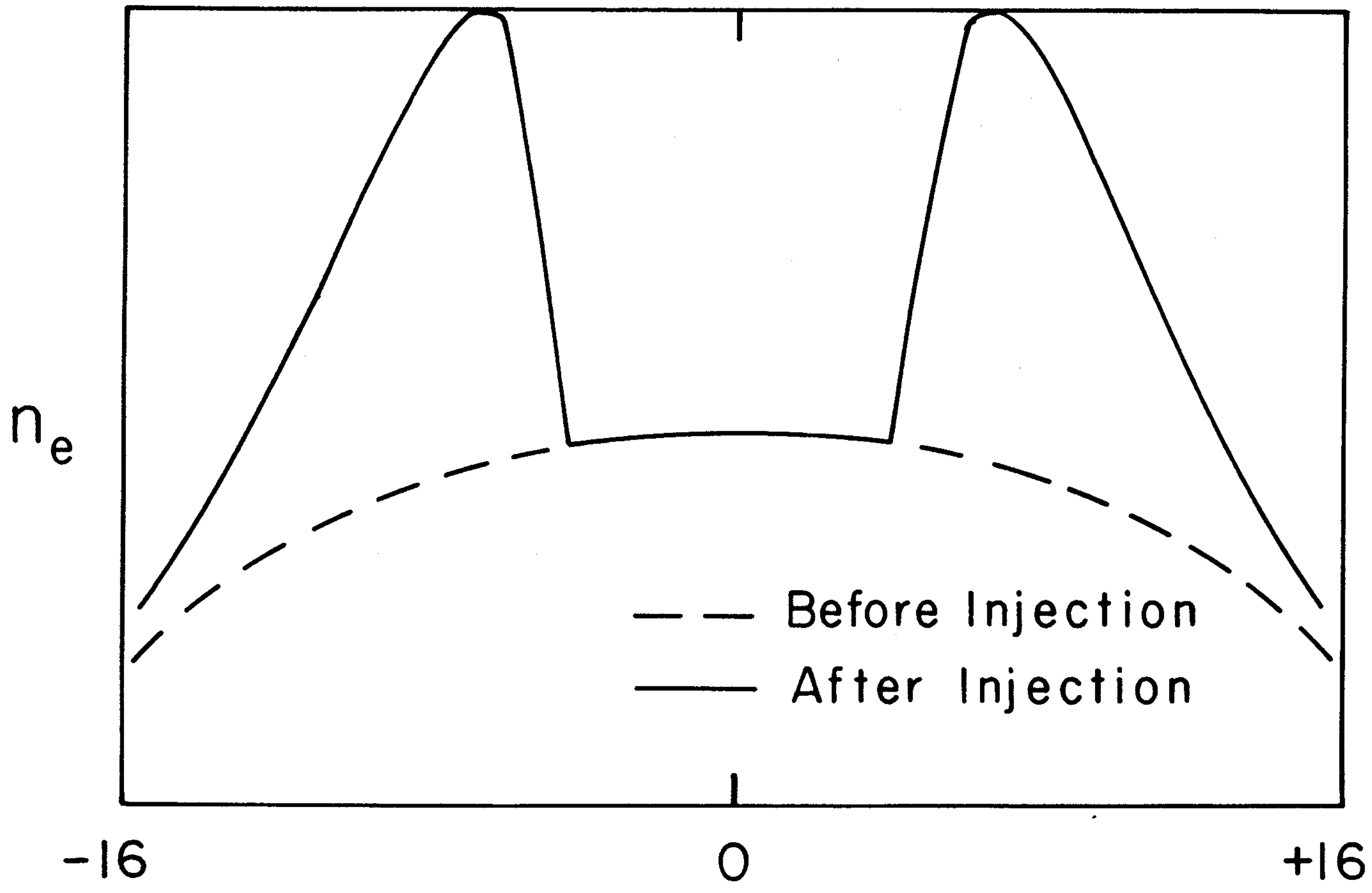
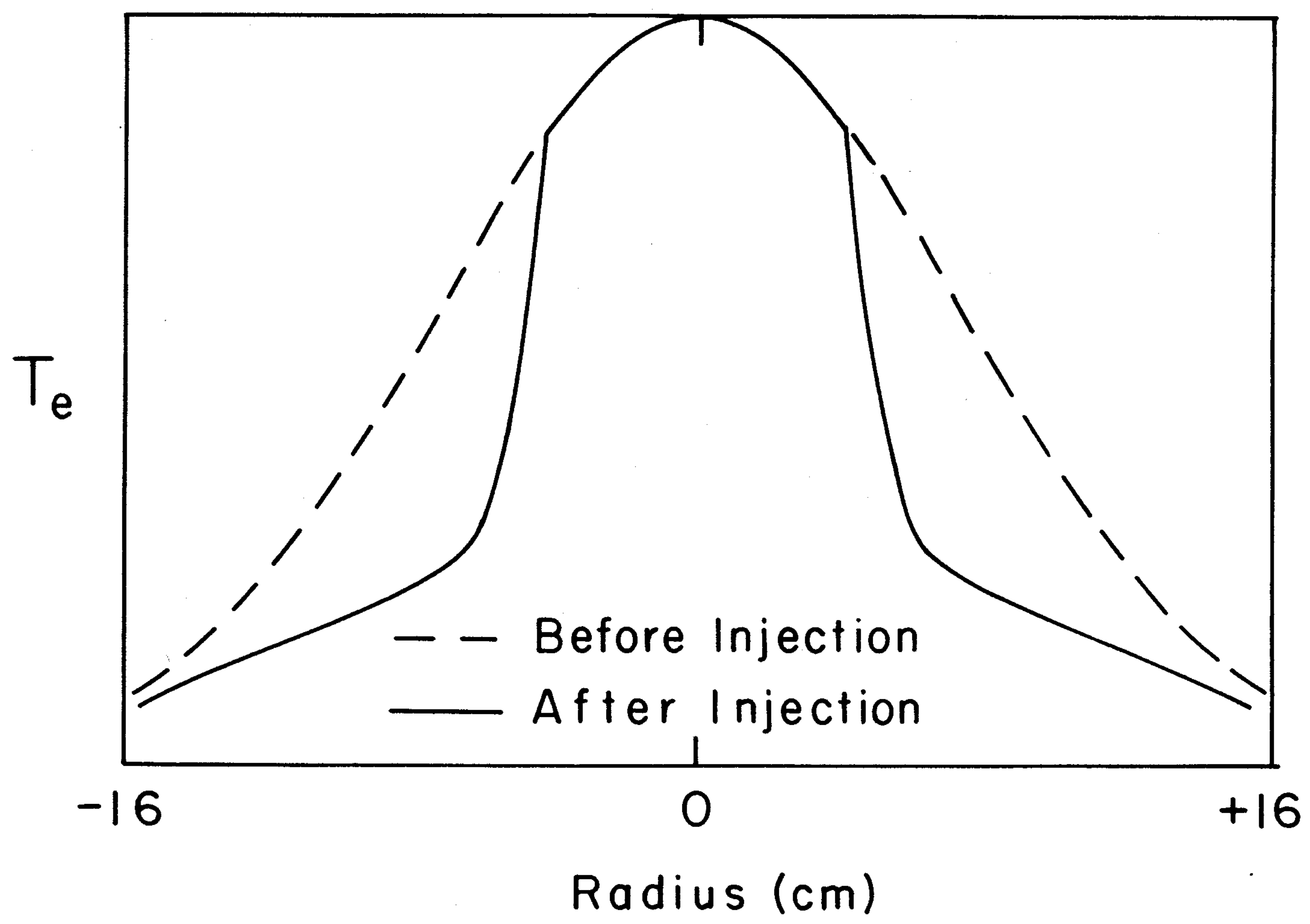
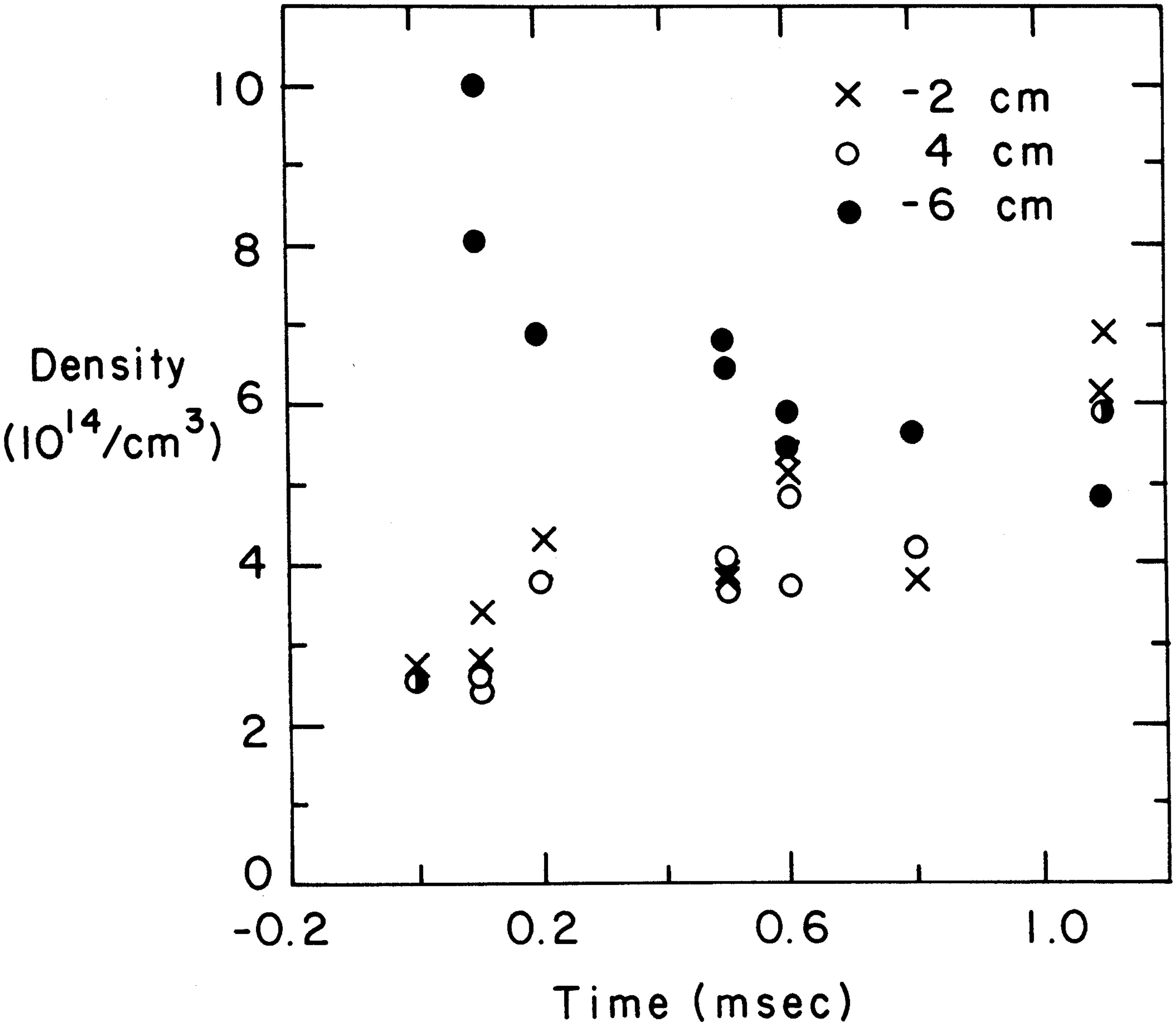
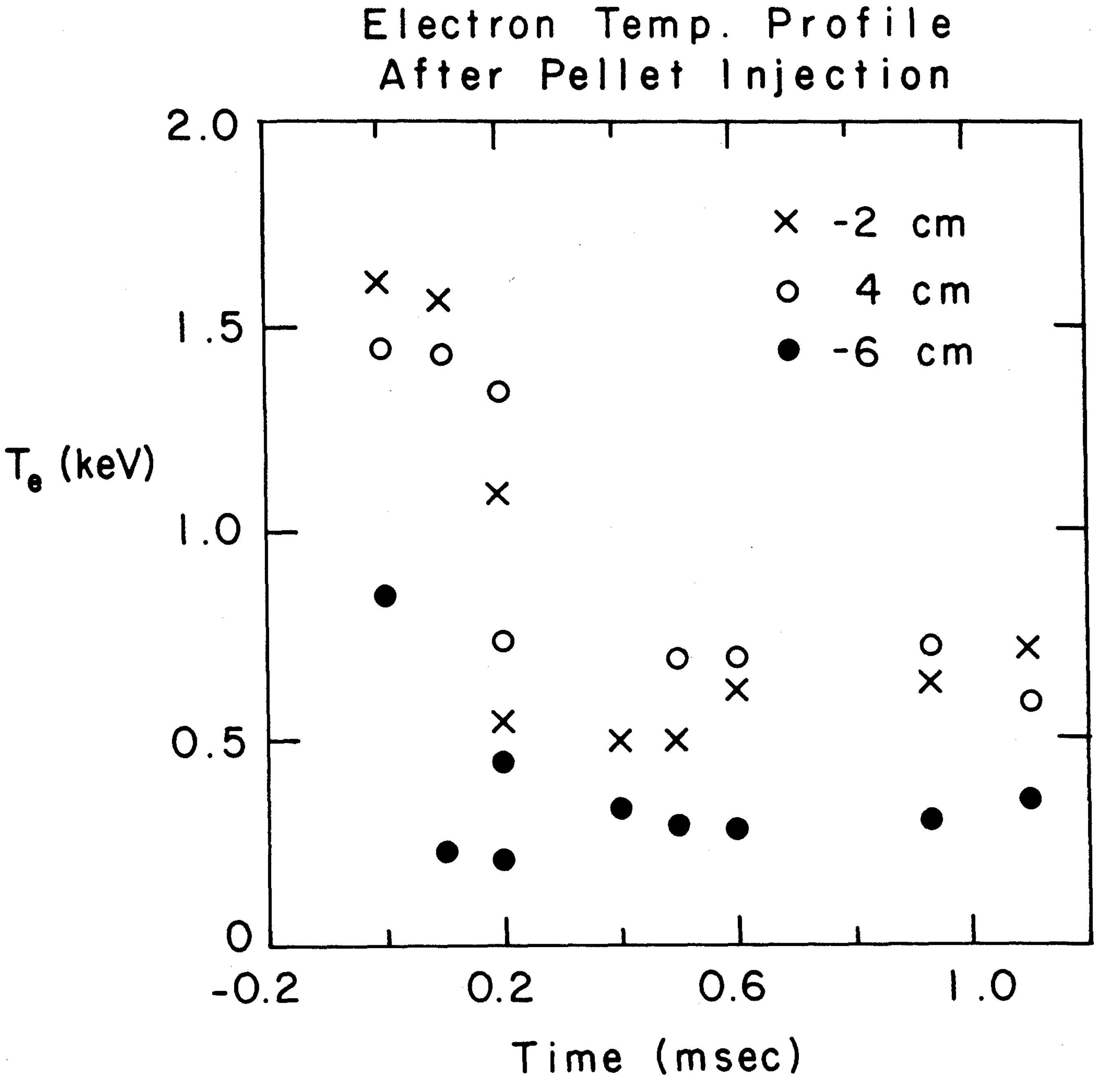
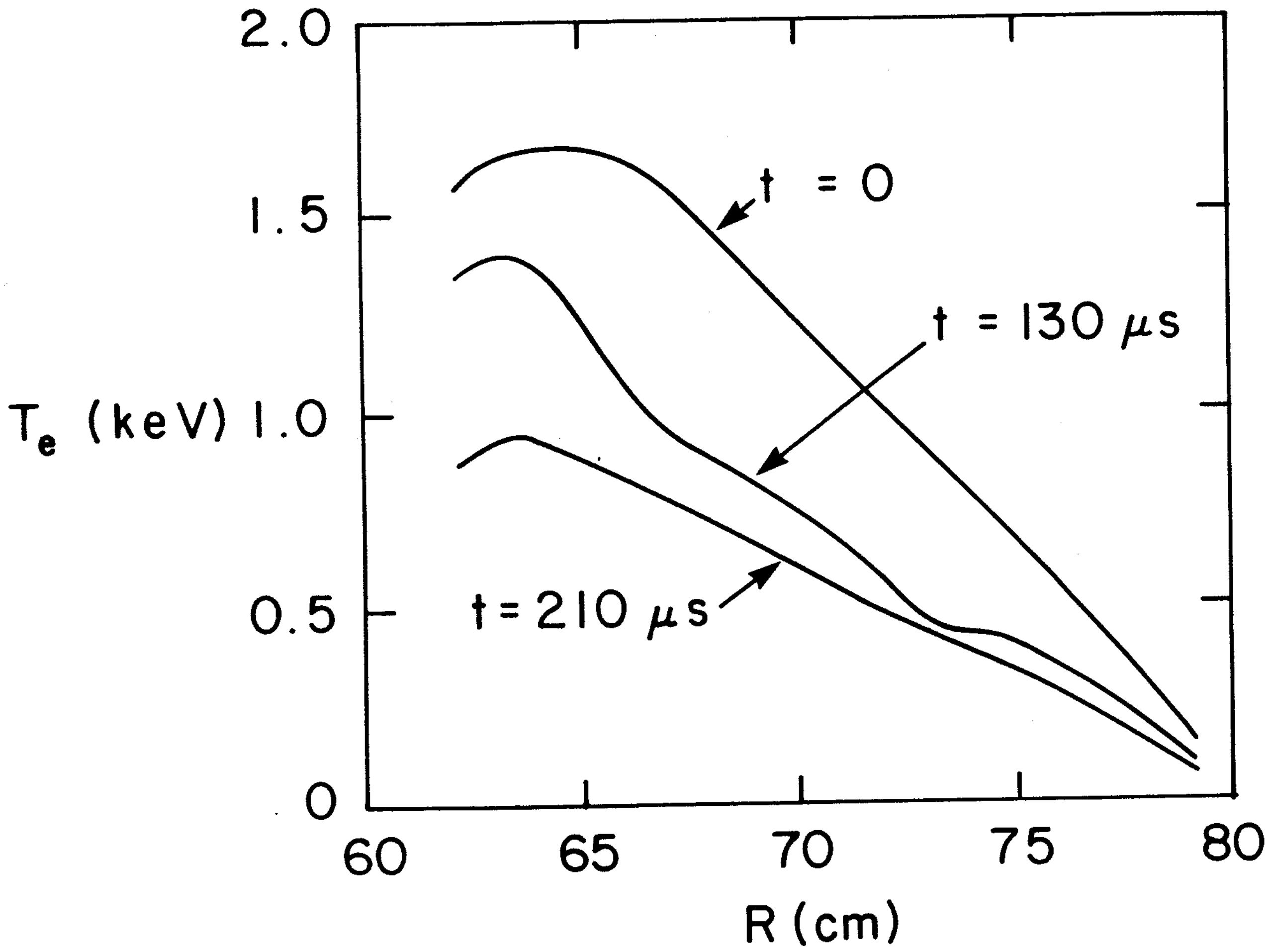

n_e
Before Injection
After Injection
-16
0
+16

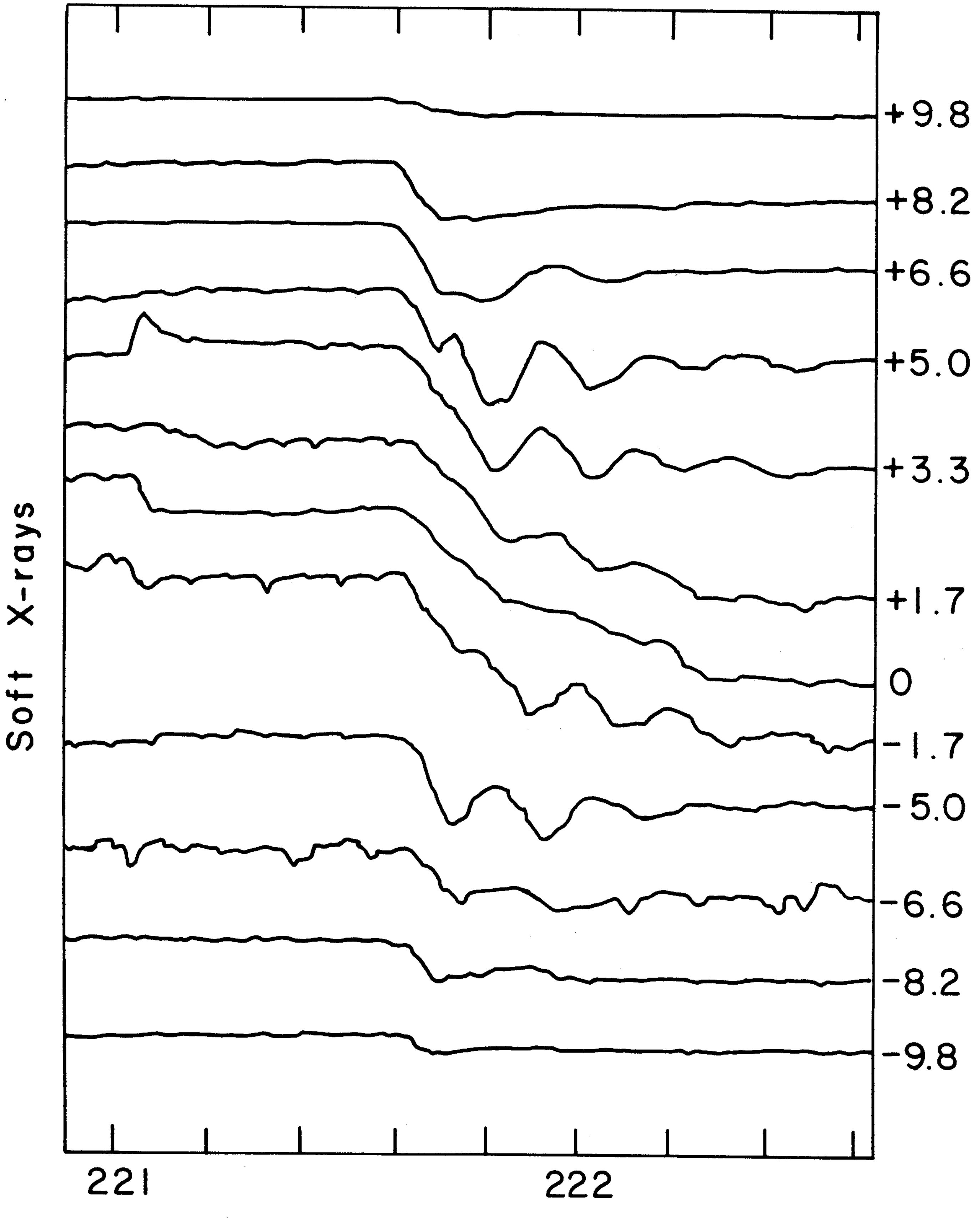

T_e
Before Injection
After Injection
-16
0
+16
Radius (cm)

Electron Density Profile After Pellet Injection




Electron Temp. Profile
After Pellet Injection
× -2 cm
○ 4 cm
● -6 cm
T_e (keV)
2.0
1.5
1.0
0.5
0
-0.2
0.2
0.6
1.0
Time (msec)


2.0
1.5
T_e (keV) 1.0
0.5
0
60
65
70
75
80
R (cm)
t = 0
t = 130 μs
t = 210 μs


Soft X-rays
+9.8
+8.2
+6.6
+5.0
+3.3
+1.7
0
-1.7
-5.0
-6.6
-8.2
-9.8
221
222
Time (msec)