

PFC/JA-85-36

$m = 1, n = 1$ OSCILLATIONS FOLLOWING THE INJECTION OF
A FUEL PELLETT ON THE ALCATOR C TOKAMAK

J. Parker*, M. Greenwald, R. Petrasso, R. Granetz,
C. Gomez

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

*Advanced Technology Engineering
Varian Associates
Beverly, MA 01915

October 1985

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

By acceptance of this article, the publisher and/or recipient acknowledges the U.S. Government's right to retain a non-exclusive, royalty-free license in and to any copyright covering this paper.

Submitted for publication to: Phys. Rev. Lett.

**$m = 1, n = 1$ Oscillations Following the Injection of a
Fuel Pellet on the Alcator C Tokamak**

J. Parker*, M. Greenwald, R. Petrasso, R. Granetz, C. Gomez
Plasma Fusion Center, Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

Immediately following the injection of a fuel pellet, strong $m = 1, n = 1$ oscillations of the soft X-ray signals are sometimes observed. Measurements of the electron temperature during this period indicate that the X-ray fluctuations cannot be accounted for by temperature variations. This implies that the densities must vary. Experimental data and computer modeling support the conclusion that a coherent fluctuation of the electron/proton density and of a light impurity can account for the measured results.

The injection of high speed frozen hydrogen pellets has been proposed as an alternative fueling method for fusion devices.¹ Experiments that we have conducted on the Alcator C tokamak show an improvement of the global energy confinement as a result of the pellet fueling², allowing record values of the $n\tau_E$ product to be achieved. Immediately following the pellet injection event, strong $m = 1$, $n = 1$ oscillations of the soft X-ray signals are sometimes observed.³ Careful measurements of the electron temperature from electron cyclotron emission during this period indicate that the X-ray fluctuations cannot be accounted for by temperature variations. This implies that the densities must vary. Experimental data and computer modeling support this conclusion, indicating that the fluctuation of the electron/proton density accompanied by the fluctuation of a light impurity can account for the data. In the collisional approximation, the dispersion relation for very low frequency waves is derived from fluid theory³ and a regime of propagation is found that is consistent with the data. This letter summarizes the results of these studies.

The pneumatic injector used on Alcator C was designed at the Oak Ridge National Laboratory and was built at MIT⁴. It is capable of firing four independently timed hydrogen pellets with velocities between 8 and 9×10^4 cm/sec. During the injection, as the pellet is evaporated, the plasma temperature drops abruptly and the electron density rises sharply. The pellets survive for 100 to 150 μ sec in the Alcator C plasmas and, assuming that the trajectory and velocity remain constant during the injection, penetrate from 9 to 12 cm (16.5 cm minor radius and 64 cm major radius). The pellets do not reach the $q = 1$ surface but do deposit their fuel deep inside the plasma. Each pellet contains 6×10^{19} particles and corresponds to $\langle n_e \rangle = 2 \times 10^{14}$ cm⁻³ in Alcator C. These experiments were conducted with $B_T = 80$ to 120 kG, $I_p = 400$ to 800 kA, $T_e(0) \sim 1000$ to 1600 eV, and line averaged target plasma densities of $\bar{n}_e(0) = 2$ to 6×10^{14} cm⁻³.

The onset of strong oscillations within 100 μ sec following the pellet injection can accompany the pellet event and were observed using various sets of soft X-ray imaging arrays. The oscillations persist for ~ 1 millisecond, and are characterized by a frequency of ~ 5 kHz and a fluctuation level of $\Delta\tilde{A}/A \sim 25\%$, where $\Delta\tilde{A}/A$

is the normalized peak-to-peak chordal X-ray signal variation. The imaging arrays viewed the plasma both horizontally and vertically with a low energy cutoff of either 1 keV or 3 keV. The superimposition of the +5 cm and -5 cm horizontal chords seen in Fig. 1 clearly shows the $m = 1$ character of the mode. The data indicates a broad $m = 1$ component peaked at approximately 5 cm (Fig. 2) and shows no significant contribution from higher m modes. With the addition of the vertical viewing array, it was determined that the oscillations result from a plasma rotation, and a bulk poloidal rotation velocity of 1.4×10^5 cm/sec was calculated. Although the pressure profile during this period is not known, for a peaked pressure profile, the mode rotates in the electron diamagnetic drift direction. The toroidal mode structure was investigated with three multi-channel soft X-ray arrays placed toroidally around the tokamak. The data indicates an $n = 1$ mode with k_{\parallel} parallel to B_{ϕ} .

The $m = 1, n = 1$ behavior observed at first suggested that the pellet might be interacting with the $m = 1$ island structure of the sawtooth⁵ commonly seen in tokamak discharges however, our experimental data indicates that this is not the case⁶. The sawtooth instability is observed during normal Alcator C operations and has been studied in great detail here as well as elsewhere^{7,8,9}. The spatial structure of the sawtooth $m = 1$ precursor oscillations is observed to be strongest at the $q = 1$ surface. For the discharge shown in Fig. 2, the $q = 1$ surface has a location of approximately 3.5 cm. On this shot, the pellet penetrates to approximately 6 cm from the magnetic axis and does not reach the $q = 1$ surface. As indicated in Fig. 2, the $m = 1$ oscillations peak at $r \sim 5$ cm, well outside the $q = 1$ surface. This has been characteristic of all the shots analyzed, with the oscillation peak varying from 5 to 7 cm. In addition, a comparison of the location of the normalized peak of the pellet $m = 1$ oscillations to the value of the safety factor at the limiter, q_L , indicates that the $m = 1$ oscillation peak is independent of q_L and, further, these oscillations have even been observed to occur in non-sawtooth discharges ($q > 1$ everywhere).

The intensity of the soft X-ray emission is a function of T_e , n_e , n_{proton} , and n_x ,

the impurity densities. In general, the $m = 1$ precursor oscillations of the sawtooth disruption, as measured with the soft X-ray diagnostic, are largely attributed to perturbation of the electron temperature. This is confirmed by independent electron temperature measurements.^{8,11} If a similar process accounts for the pellet-induced $m = 1$ oscillations, a rough estimate of the necessary temperature fluctuation can be made. Fig. 3 shows one characteristic example where, 300 μsec after the pellet event when the temperature profile is again Gaussian, a peak-to-peak X-ray fluctuation of $\sim 32\%$ is measured. If this perturbation is entirely accounted for on the basis of a temperature variation, the lower bound for the peak-to-peak $\Delta T_e/T_e$ is $\sim 9\%$ ³. During this period, careful measurements of the temperature profile using the ECE diagnostic were made. The experiment was done from the side of the tokamak using two detectors viewing the plasma along the same chord. For a fixed toroidal magnetic field, one ECE channel was tuned to the plasma center and held constant as a reference. The frequency of the second view was tuned from shot to shot, producing a radial scan of the plasma electron temperature. Within our experimental error, 300 μsec after the pellet event, no T_e variation during the oscillations is measured (Fig. 3). The ECE measurement is sensitive to 15 eV or $\sim 2\%$. Thus, within the constraints of the assumptions made, the pellet-induced oscillations cannot be accounted for on the basis of a temperature fluctuation. This implies that the perturbations are due to density variations.

Having drawn this conclusion, an effort was made to investigate the density dependence during the pellet-induced oscillations. Two diagnostics on Alcator C that are sensitive to the densities on the 10 μsec time scale were used for this study. The first is a spatially resolving visible light detector system¹². The measured visible continuum signal is a function of n_e , n_{proton} , n_z , and T_e and, as can be seen in Fig. 4, is strongly correlated with the soft X-ray fluctuations. The second instrument, a FIR laser interferometer¹³, measures the line integral of the electron density and, as is apparent in Fig. 4, does not correlate with the soft X-ray fluctuations. The disparity between the visible continuum and FIR interferometer may be due to the fact that the FIR interferometer is sensitive to only n_e variations whereas the

visible continuum signal is a function of n_e , n_{proton} , and n_z . From X-ray and UV spectroscopic data, the pellet is measured not to add impurities to the plasma and the plasma Z_{eff} is observed to drop. As a result, it seems unlikely that the perturbation of "clean" plasma produced by the pellet event leads to a fluctuation of n_z alone. Thus, both the electron and ion densities must be fluctuating. Simple computer simulations support this conclusion, finding that coherent electron and impurity density fluctuations are consistent with the measured data. The computer calculations are strongly dependent on the magnitude of the impurity fluctuation and weakly dependent on the magnitude of the electron density variation.

For the post-pellet plasma conditions, $(\frac{\omega}{k})_{wave} < v_{ti} \ll v_{te}$ and $\omega_{wave} \ll \omega_{ci} \ll \omega_{ce}$, where v_{ti} and v_{te} are the ion and electron thermal velocities and ω_{ci} and ω_{ce} are the ion and electron cyclotron frequencies respectively. The measured data has characteristics of a sound wave and propagates both parallel and perpendicular to the magnetic field. In addition, the wave frequency is the same order as the ion-ion collision frequency and the mean free path between collisions is approximately equal to the mode wavelength. Thus, the pellet-induced perturbation propagates in a regime that is neither collisional nor collisionless. In the collisional limit, a possible theoretical explanation has come from extending work which contains contributions from both ion acoustic and drift waves.¹⁴ In this limit the dispersion relation derived from fluid theory³ yields a range of ion acoustic solutions retarded by the perpendicular drift velocity; we speculate that these solutions may correspond to the measured results.

In conclusion, immediately following the injection of a fuel pellet, strong $m = 1$, $n = 1$ oscillations of the soft X-ray signals are sometimes observed to occur. The normalized amplitude of the mode consistently peaks outside of the location of the $q = 1$ surface and it is determined from the data that the pellet is not interacting with the sawtooth structure. After careful electron temperature and soft X-ray measurements, it is concluded that the pellet-induced oscillations cannot be accounted for on the basis of a temperature fluctuation. This implies that the density must vary. Experimental data and computer simulations support this conclusion,

indicating that the coherent fluctuations of both the electron and impurity densities can account for the measured signals. It is speculated that the injection of a pellet drastically perturbs the equilibrium conditions producing an extremely steep outward temperature gradient and inward density gradient and that these gradients drive the ion drift instability. After the pellet has ablated, as the initial gradients relax, the external driving force vanishes. The plasma then evolves in time with the ion mode produced by the initial perturbation, rotating in both the $+\hat{\phi}$ and $+\hat{\theta}$ directions. It is believed that it is this density fluctuation when accompanied by an impurity that has been observed.

There are many aspects of this question that remain uncertain, particularly on the theoretical front, and that warrant further study. Additional details concerning this work and the analysis described herein can be found elsewhere³.

Acknowledgements:

The authors wish to acknowledge the assistance of the Alcator C group and the helpful discussions with Drs. R. Gandy and R. Parker.

This work is supported by U. S. Department of Energy contract number DE-AC02-78ET51013.

Figure Captions:

1. Superimposition of the +5 cm and -5 cm horizontally viewing soft X-ray chords showing the pellet-induced oscillations. The time of the pellet injection is indicated by the arrow.
2. Fluctuation amplitude of the pellet-induced oscillations versus chord impact parameter. The location of the $q = 1$ surface, determined from Abel inversion of the X-ray data, is indicated by the arrow.
3. Composite drawing of the +7.2 cm soft X-ray and the +8 cm ECE chords showing a discharge which exhibits strong X-ray oscillations with $< 2\% T_e$ variation. For this discharge, the peak of the X-ray oscillations occur at ~ 7 cm.
4. Composite drawing of the soft X-ray, visible continuum and FIR interferometer signals during the pellet-induced oscillations.

References:

- * Present address: Advanced Technology Engineering, Varian Associates, Beverly, MA 01915
1. U.S. DOE, *Proceedings of the Fusion Fueling Workshop*, CONF-771129(1978).
 2. M. Greenwald, et al., *Phys. Rev. Lett.*, Vol. 53,352(1984).
 3. J. Parker, *Plasma Fusion Center Report*, PFC/RR-85-8 (1985).
 4. J. Parker, et al., *Bull. Am. Phys. Soc.*, Vol. 27,1037(1982).
 5. S. von Goeler, W. Stodiek, N. Sauthoff, *Phys. Rev. Lett.*, Vol. 33,1201(1974).
 6. Specifically, work done by the TFR team¹⁰ indicates that the magnetic reconnection during the sawtooth instability is not complete and that a residual $m = 1$ island survives after the $m = 0$ crash. Our original speculation was that the pellet was interacting with this established $m = 1$ structure to produce the $m = 1$ X-ray signals observed.
 7. R. Petrasso, M. Gerassimenko, F.H. Seguin, R. Krogstad, E. Marmor, *Nucl. Fusion*, Vol. 21,881(1981).
 8. D. Launois, *Seventh European Conference on Controlled Fusion and Plasma Physics*, Lausanne, Vol. 2,1(1975).
 9. G.L. Jahns, M. Soler, B.V. Waddel, J.D. Callen, H.R. Hicks, *Nucl. Fusion*, Vol. 18,609(1978).
 10. M.A. Dubois, A.L. Pecquet, C. Reverdin, *Nucl. Fusion*, Vol. 23,147(1983).
 11. R. Gandy, Personal communiqué.
 12. Foord, M.E., Marmor, E.S., Terry, J.L., *Rev. Sci. Instrum.*, Vol. 53,(1982)1407.
 13. S.M. Wolfe, *Bull. Am. Phys. Soc.*, Vol. 24,(1979)996.
 14. N.A. Krall, A.W. Trivelpiece, Principles of Plasma Physics, (McGraw-Hill, New York,1973).

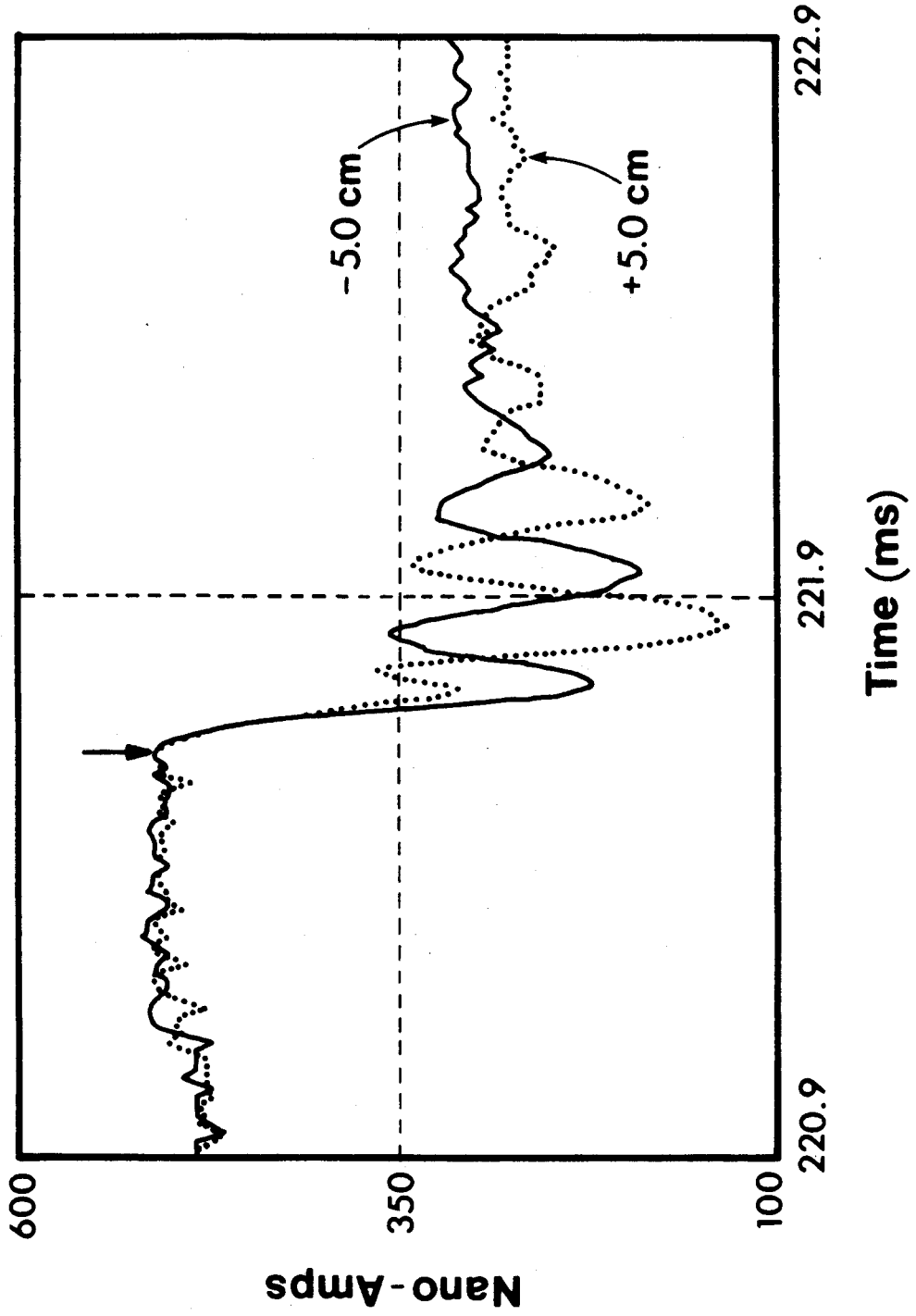


FIGURE 1

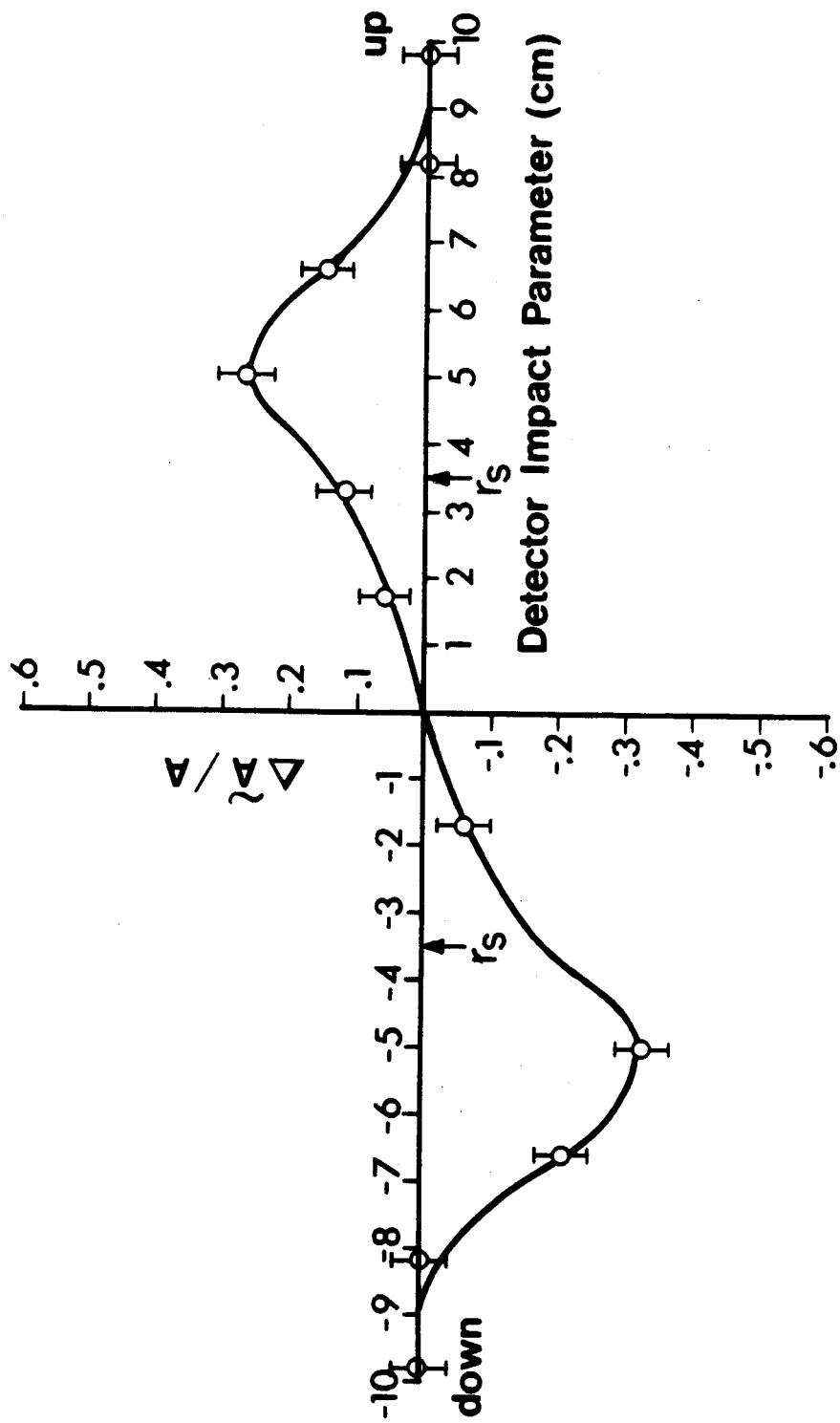


FIGURE 2

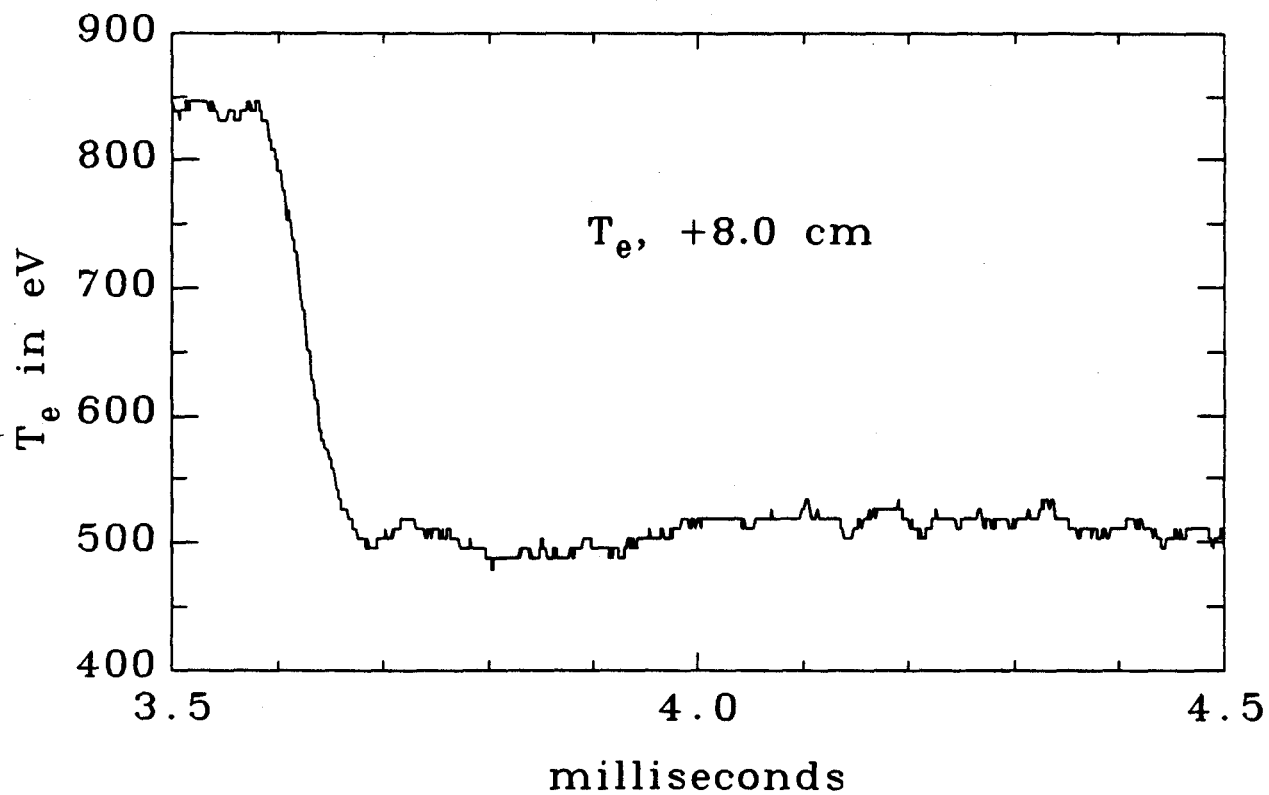
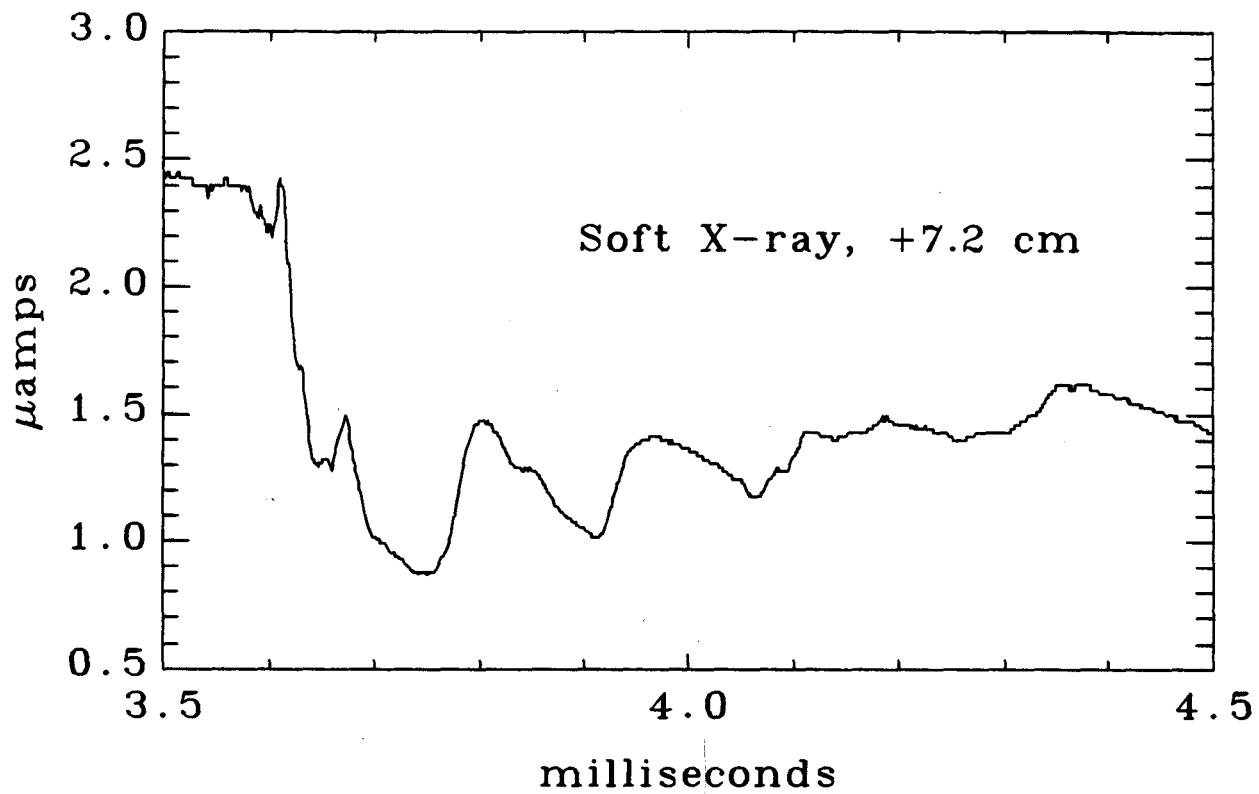


FIGURE 3

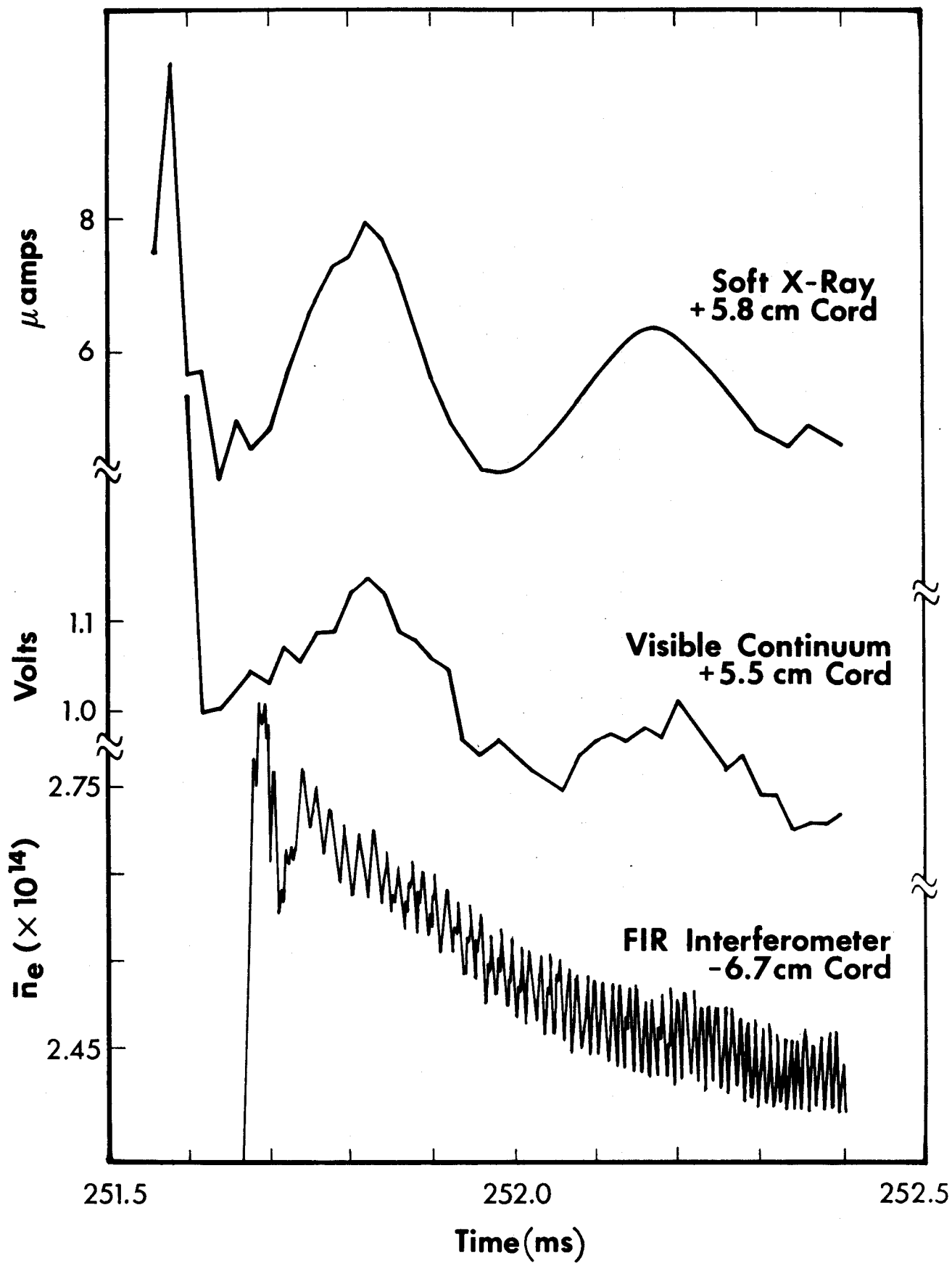


FIGURE 4