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# IMPURITY GENERATION DURING INTENSE LOWER HYBRID HEATING EXPERIMENTS ON THE ALCATOR C TOKAMAK

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# ABSTRACT

Experiments are underway on the Alcator C Tokamak with over 1 MW of RF power injected into the plasma at a frequency of 4.6 GHz to study both heating and current drive effects. During these studies, impurity generation from limiter structures has been observed. The RF induced impurity influx is a strongly nonlinear function of net injected power. For $P_{rf} <$ 500 kW, only small effects are seen. As $P_{rf}$ approaches 1 MW, however, sharp increases in impurity influxes and $Z_{eff}$ are observed. Three different limiter materials have been used during these studies: molybdenum, graphite, and silicon-carbide coated graphite. In each case, the materials of the limiter structure are seen to dominate the increased impurity influx. In a typical case, with $P_{rf} = 1.0$ MW, $\bar{n}_e = 1.3 \times 10^{14}$ cm$^{-3}$, and the SiC coated limiters, $Z_{eff}$ is seen to increase from 1.5 before the RF pulse to about 4 during the heating. At the same time, central $T_e$ increases from 2000 eV to 3000 eV and central $T_i$ from 1200 eV to 1800 eV. Similar effects are seen in both $H_2$ and $D_2$ working gas discharges. The contribution to impurity generation of nonthermal electrons, which are produced by the RF, is under investigation. Changes in edge plasma temperature and density, as well as the possibility that the particle transport is affected by the RF, are also being examined. Results of the experiments with the three different limiter materials are compared, and contributions of impurity radiation to the overall power balance are estimated.

## I. Introduction

Impurities play a role in the development of nearly all tokamak discharges. However, through the application of various techniques, including discharge cleaning (both glow and pulsed), baking and gettering, and through judicious choices of limiter design and materials [1], it has been generally possible to run these devices over wide parameter ranges with only minor perturbations of plasma resistivity and power balance caused by impurities. This is especially true in the case of ohmically heated discharges. As auxiliary input powers, particularly from various forms of RF, reach levels of 1 MW or greater, certain presently operating devices begin to see strong impurity effects once again. In the case of ICRF heating, the TFR experience is one such example [2]. In this case, as RF power levels exceed 1 MW, nickel influxes are large, resulting in most of the input power being radiated away. The walls, limiters and antenna faraday shields were all made from Inconel, and which of these structures was the main source of the Ni was not resolved. On the TCA device [3], Alfven wave heating, at power levels of only 90 kW, has yielded disastrous results with respect to metal contamination of the plasma. In this case, the limiter, antenna and wall materials were stainless steel. Recent results from ICRF heating of the PLT device have been more favorable [4]. At the 1 MW level, metal densities are seen to double, but do not dominate the discharge characteristics, with less than 15% of the central input power being radiated away. Because of PLT's larger size compared to the other devices, the surface power loadings are, of course, lower in this case.

Experiments are presently underway on the Alcator C tokamak to study current drive and heating using lower hybrid RF at $\nu = 4.6$ GHz [5]. To date, up to 1 MW of power has been coupled into the plasma, and it is the purpose of this paper to describe the changes in impurity influxes and concentrations which result, particularly in the plasma heating regimes which have been studied. Experiments using limiters composed of molybdenum, silicon-carbide coated graphite, and bare graphite have been performed, and the results are described below.

## II. Experimental Results

The results are grouped according to the particular limiter design in use. For $P_{rf}$ up to 1 MW, there have been three types of limiter used: (1) molybdenum; (2) SiC coated graphite; (3) a combination which is primarily Mo with graphite sections in the outer midplane. In all cases, it is the material of the limiter which is seen to dominate the RF induced impurity influx. The limiters themselves are structurally similar. Each is composed of complete poloidal rings of small blocks attached to a stainless steel spine. Each ring consists of a large number of blocks, and there are a total of four rings. Two rings are paired at each of two ports, the ports being separated toroidally by 180 degrees. The total surface area of the limiters is about 1200 $cm^2$.

### II.(a) Molybdenum Limiters

The time histories of various plasma parameters during a typical LHRF heating discharge with Mo limiters are shown in figure 1. In this case the total forward RF power coupled into the vacuum chamber ($P_{rf}$) was 950 kW. The central chord brightness at $\lambda$ = 75 Å is indicative of Mo behavior in the plasma. This wavelength is in the center of a pseudo-continuum [6] which includes lines from many ionization states, up to MoXXX, and this emission is predominantly from the regions of the plasma where $500 \text{ eV} < T_e < 1500 \text{ eV}$ [7]. This is thus a good indicator of the time history of the Mo density, provided that the electron density and temperature are not changing significantly. It is clear from figure 1 that there is a large increase in the Mo level in the plasma during the RF pulse. The decay after the turn off of the RF is consistent with impurity transport times measured in other experiments [8]. The fifth trace in figure 1 shows the brightness at $\lambda = 5360$ Å, which is due mainly to free-free bremsstrahlung. Since the emissivity is proportional to $n_e^2 Z_{eff}/\sqrt{T_e}$, it can be used to infer a "line-averaged" $Z_{eff}$ [9], which is shown as the last trace in the figure. It can be seen that before the RF power is injected, $Z_{eff} = 1.5$. The enhancement over 1 is due mostly to carbon in the plasma, which is the dominant low Z impurity.

During the RF pulse, with the Mo limiters, the C levels do not change significantly, and we infer that the change in $Z_{eff}$ is due almost entirely to the increased molybdenum. It is thus possible to calculate the absolute Mo density in the plasma. Although bolometric measurements of total radiated power were not available during these experiments, using the cooling rate formalism of Post et. al. [10], the resulting radiated power loss from the plasma due to the molybdenum can be estimated. Assuming that $n_{Mo}(r)/n_e(r) = \text{constant}$, the result is that about 1 MW is radiated away. It must be pointed out that there are large uncertainties in this calculation. In particular, the cooling rates, according to the authors of reference 10, are only accurate to about a factor of 2. A direct comparison between the brightness at 75 Å and bolometric measurements has been made, in non-RF discharges [11]. In these cases, the cooling rate model, combined with the $Z_{eff}$ measurement, predicted central radiated power densities which were 25% higher than was actually observed. Using these observations as a "calibration" for the technique would imply that ~ 850 MW is radiated during the RF case examined here. The resultant heating is modest, with $T_e$ increasing by about 400 eV and $T_i$ by about 200 eV.

## II.(b) Silicon-Carbide Coated Graphite Limiters

In order to reduce the levels of high Z (Mo) impurities in the LHRF heated plasmas, the Mo limiters were replaced with limiters utilizing coated graphite blocks. The coatings are chemical vapor deposited silicon carbide, with a coating thickness of about 100 micron. The blocks were baked in vacuum to a temperature of 900° C after coating and before being installed in the tokamak. Mo levels with these limiters decreased by about a factor of 20 to 30 when compared to similar ohmic discharges with the Mo limiters. During the LHRF heating, only small increases in the Mo level are seen (<30%). However, both Si and C levels are seen to increase substantially. Figure 2 shows the time development of several plasma parameters with $P_{rf}$ = 850 kW and the SiC limiters. Along with the increases of Si and C influx, as evidenced by line radiation from ionization states near the edge of the plasma, strong increases of $Z_{eff}$ are also seen. Figure 2 shows the $Z_{eff}$ time history for this discharge, and there is clearly a much larger perturbation to this parameter than was the case with the Mo limiters. Although $Z_{eff}$ increases substantially, the electron temperature also goes up, and the net ohmic input power is not greatly increased (<15%). $T_e$ in this case, as inferred from both soft x-rays and Thomson scattering, increases from 2000 eV before the RF, to about 3000 eV during the heating pulse. The time history of the ion temperature is also shown in figure 2, with $T_i$ almost doubling during the heating. It thus appears that the central radiation problem has been been largely alleviated, allowing for the good heating. However, plasma purity has been seriously compromised. The increase of $Z_{eff}$ is a very non-linear function of $P_{rf}$. Figure 3 shows the results of a power scan with fixed $n_e$, $I_p$, and $B_t$. Below about 500 kW, little or no effect is seen. As the power level approaches 1 MW, the change in $Z_{eff}$ is seen to increase sharply.

In order to investigate the effects of the increasing low Z impurity content on the confinement properties, experiments are being carried out to inject $N_2$ into discharges similar to those being heated. Preliminary results indicate that some of the ion heating might be explained by the rise in $Z_{eff}$ alone.

### II.(c) Electron Tail

One of the main effects which the LHRF has on the plasma is to produce a population of non-thermal electrons, with energies in the range of 20 keV to over 300 keV. Figure 4 shows typical x-ray spectra, with and without the RF (Mo limiter, $P_{rf}$ = 500 kW). At $P_{rf}$ = 900 kW, estimates indicate that the fractional population of these non thermal electrons is on the order of $10^{-3}$. Since they have energies of 10 or more times the thermal, if these electrons are relatively poorly confined, they could account for a significant energy loss from the plasma. Furthermore, they might be expected to scrape-off in a small poloidal portion of the limiters, due to the small outward shift of their drift surfaces relative to the flux surfaces. Post-mortem examination of the SiC coated limiters indicates that there is indeed much damage in a poloidally localized region of the limiters near the outside mid-plane. The total area affected is about 5 $cm^2$. If, in fact, 100 kW, or more, is carried out of the plasma by the non-thermal electrons, the resulting power loading ($\gtrsim$ 20 $kW/cm^2$) would be sufficient to give rise to rapid surface melting (for Mo or SiC) or sublimation (graphite). This then might be the major cause of the impurity generation.

Supporting evidence that the impurity generation is caused by the non-thermal electrons comes from a comparison of similar discharges, one with good heating, and the other for unknown reasons, with little generation of non-thermals, and at the same time almost no heating, impurity generation, or rise in $Z_{eff}$. Two such shots are compared in figures 5 and 6. Figure 5 shows a typical case with large increases in $Z_{eff}$ as well as Si and C levels in the plasma. In this case, $\Delta T_i$ = 800 eV. Figure 6 shows a discharge from the same day, where the pre-RF plasma conditions are apparently quite similar to those of figure 5. However, the RF appears not to have coupled as well to the electrons in this second case, with the result that there is a smaller generation of Si and C, and the $\Delta Z_{eff}$ is also much smaller. At the same time $\Delta T_i$ was only 200 eV for this shot.

## II.(d) Hybrid Limiter

To test further the idea that the impurities might be coming mostly from the heating of the outside midplane of the limiters, a so-called "hybrid" limiter was installed into the tokamak. This limiter consists of Mo, with the exception of 4 blocks at the outside midplane each ring, which are uncoated graphite. Initial results from this limiter show that at levels approaching 1 MW, the effects on both Mo and C are small. Figure 7 shows time histories for a typical case. Neutron rates indicate $\Delta T_i$ =

250 eV for this discharge during the RF. Although some of the improvement in the impurity situation with this limiter might be related to the presence of the graphite blocks on the outside midplane, the "hybrid" limiter is different in another important way from the previous limiters. The damage to the SiC blocks was mostly in the radially leading 2 to 3 mm. It was therefore decided to flatten the blocks on the "hybrid" limiter. The density scrapeoff length, as measured previously with Langmuir probes, was found to be about 3 mm [12]. It is therefore probable that in the "hybrid" limiter, the loading is spread out over roughly 2 to 3 times the area. It is likely that this is the main reason for the improvement with this limiter.

## III. Discussion

While non-thermal electron heating of the limiter surface is the prime candidate to explain the observed impurity effects during the LHRF experiments on Alcator C, other processes cannot be ruled out. Probe measurements, one cm beyond the limiter, indicate that the electron temperature increases from about 5 eV before the RF, to about 7.5 eV during. These temperatures are too low to result in significant sputtering of limiter material due to acceleration of ions across the expected sheath ($\sim 4 \times T_e$). Another possibility is that either the RF directly, or the non-thermal electrons, affect the potential drop across the sheath at the limiters, again leading to ion sputtering. A definitive resolution of these questions awaits further experimentation.

## IV. Conclusions

Lower Hybrid heating experiments on the Alcator C tokamak indicate that as $P_{rf}$ approaches 1 MW, impurity effects begin to play a large role in the evolution of the discharges. The mechanism of limiter surface heating due to RF produced non-thermal electrons is identified as the prime candidate which could explain the impurity influx. With Mo limiters, the radiated power from the plasma rises dramatically, approaching a significant fraction of the total input power. With silicon carbide coated graphite limiters, efficient electron and ion heating are achieved, but at the expense of plasma purity as reflected by an increasing $Z_{eff}$. Experiments are continuing, both to delineate more precisely the responsible mechanisms, and, if possible, to reduce these impurity effects as the RF power is further increased.

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# FIGURE CAPTIONS

Fig. 1 Time histories of various plasma parameters for a typical heating discharge with molybdenum limiters. In this case, the peak parameters are $I_p$ = 400 kA, $\bar{n}_e = 1.6 \times 10^{14}$ cm$^{-3}$, $P_{RF}$ = 950 kW, $B_T$ = 9.3 T.

Fig. 2 Typical heating discharge with silicon carbide coated graphite limiters: $I_p$ = 400 kA, $\bar{n}_e = 1.7 \times 10^{14}$ cm$^{-3}$, $P_{RF}$ = 850 kW, $B_T$ = 9.3 T.

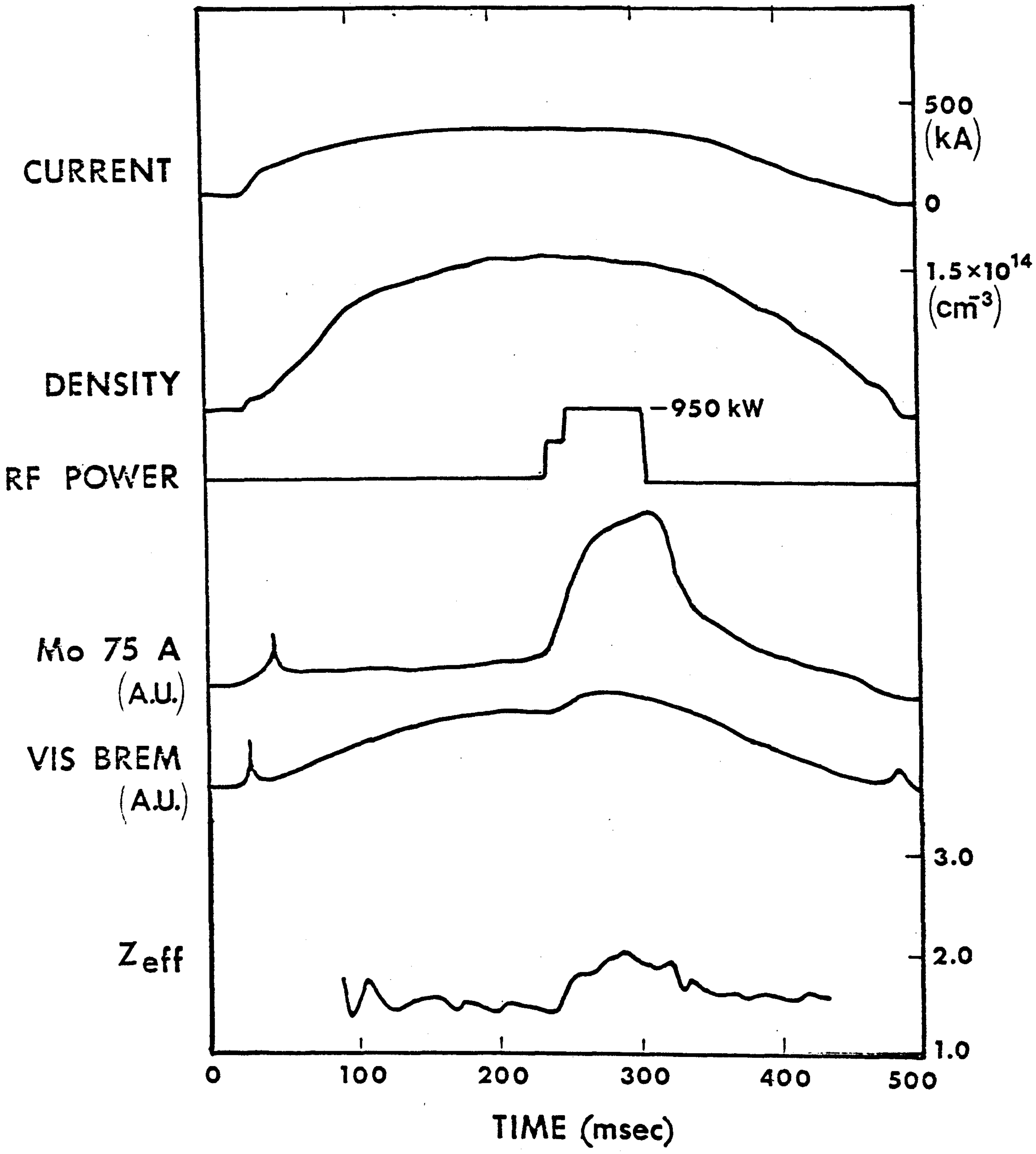
Fig. 3 Power scan for $\Delta Z_{eff}$ vs. $P_{RF}$ with SiC limiters.

Fig. 4 X-ray spectrum, with and without the RF.

Fig. 5 Typical good heating shot with SiC limiters. $P_{RF}$ = 850 kW.

Fig. 6 A shot with similar plasma conditions to those of figure 5, but exhibiting small impurity effects and little heating.

Fig. 7 Typical shot with "hybrid" limiter.



CURRENT
500
(kA)
0
DENSITY
1.5×10^14
(cm^-3)
RF POWER
950 kW
Mo 75 A
(A.U.)
VIS BREM
(A.U.)
Zeff
3.0
2.0
1.0
0
100
200
300
400
500
TIME (msec)

FIGURE 1

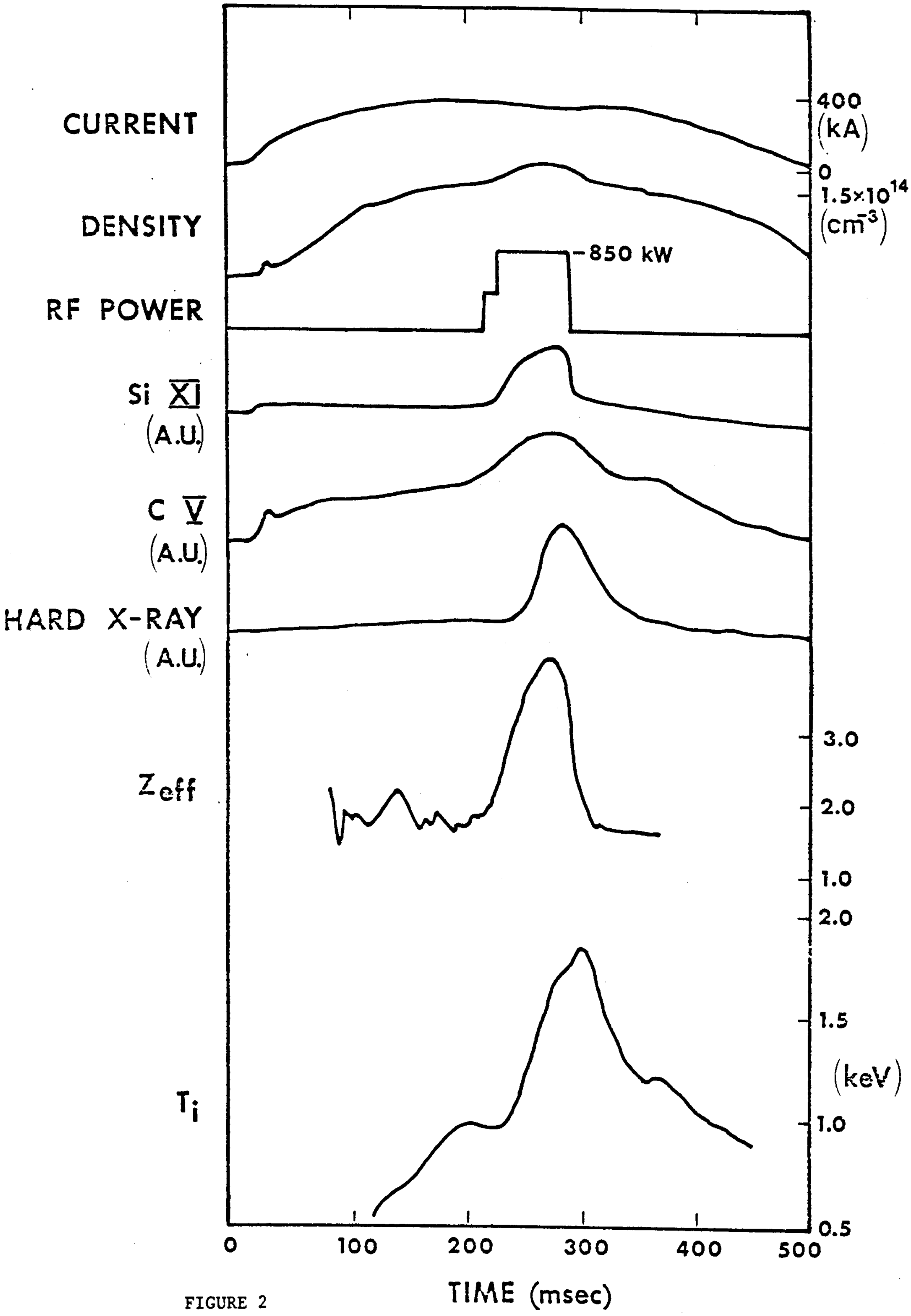

CURRENT
400 (kA)
0
DENSITY
1.5×10^14 (cm^-3)
RF POWER
850 kW
Si XI (A.U.)
C V (A.U.)
HARD X-RAY (A.U.)
Zeff
3.0
2.0
1.0
Ti
2.0
1.5
(keV)
1.0
0.5
0
100
200
300
400
500
TIME (msec)

FIGURE 2

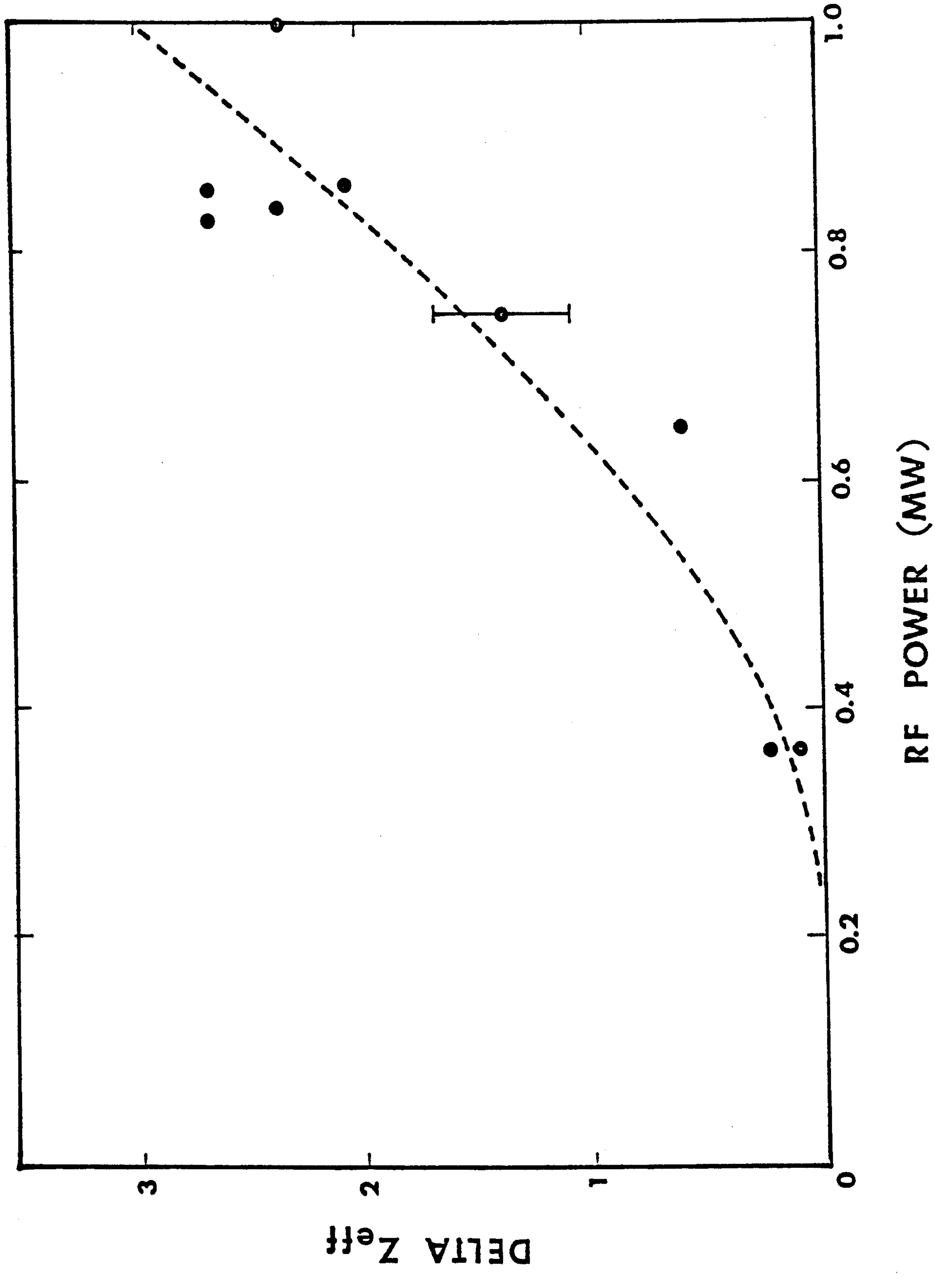


FIGURE 3

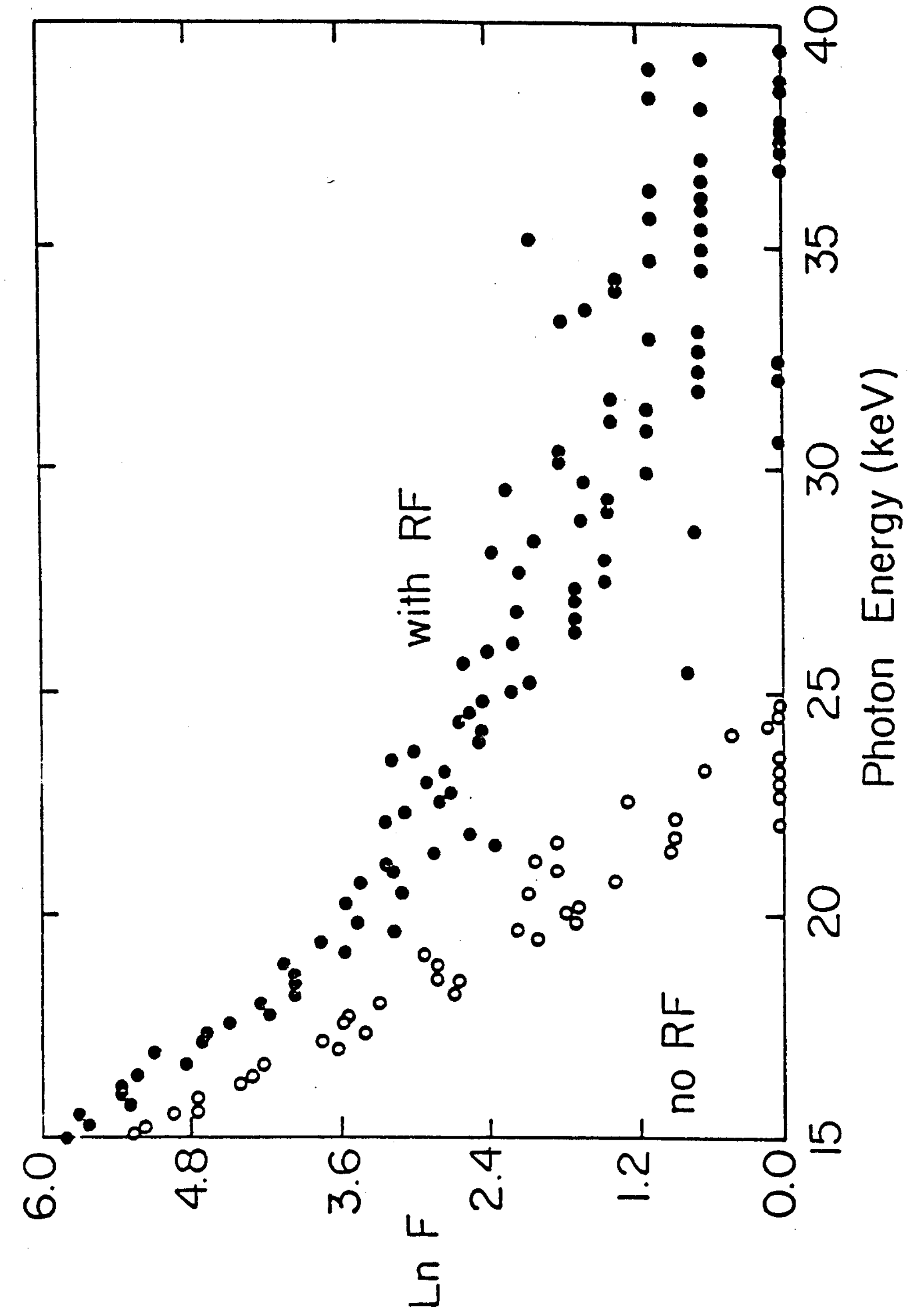


FIGURE 4

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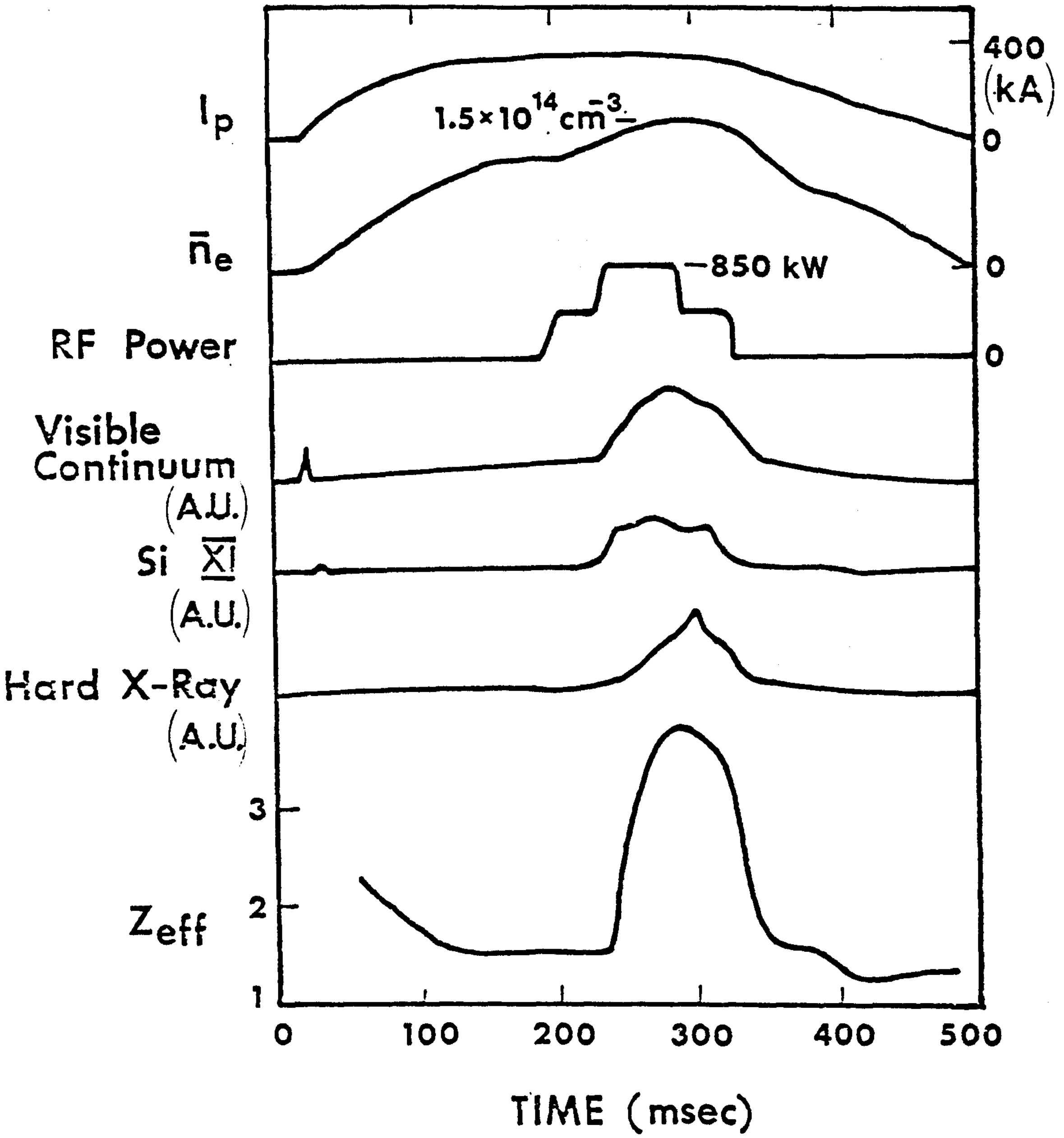

$I_p$
400 (kA)
0
$1.5\times10^{14}$ cm$^{-3}$
$\bar{n}_e$
0
850 kW
RF Power
0
Visible Continuum (A.U.)
Si XI (A.U.)
Hard X-Ray (A.U.)
$Z_{eff}$
1
2
3
0
100
200
300
400
500
TIME (msec)

FIGURE 5

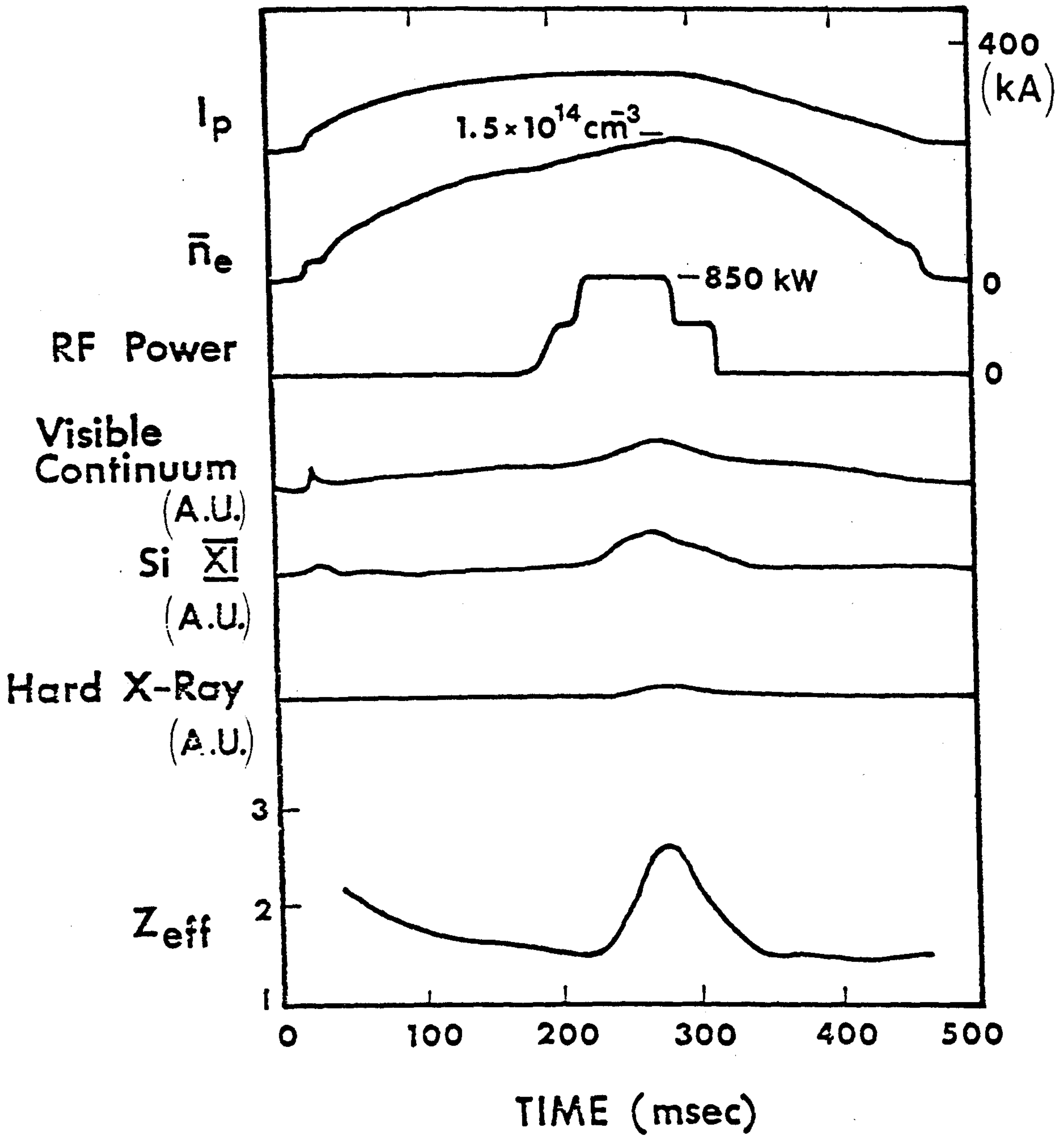
$I_p$
400 (kA)
$1.5\times10^{14}$ cm$^{-3}$
$\bar{n}_e$
850 kW
0
RF Power
0
Visible Continuum (A.U.)
Si XI (A.U.)
Hard X-Ray (A.U.)
$Z_{eff}$
3
2
1
0
100
200
300
400
500
TIME (msec)

FIGURE 6

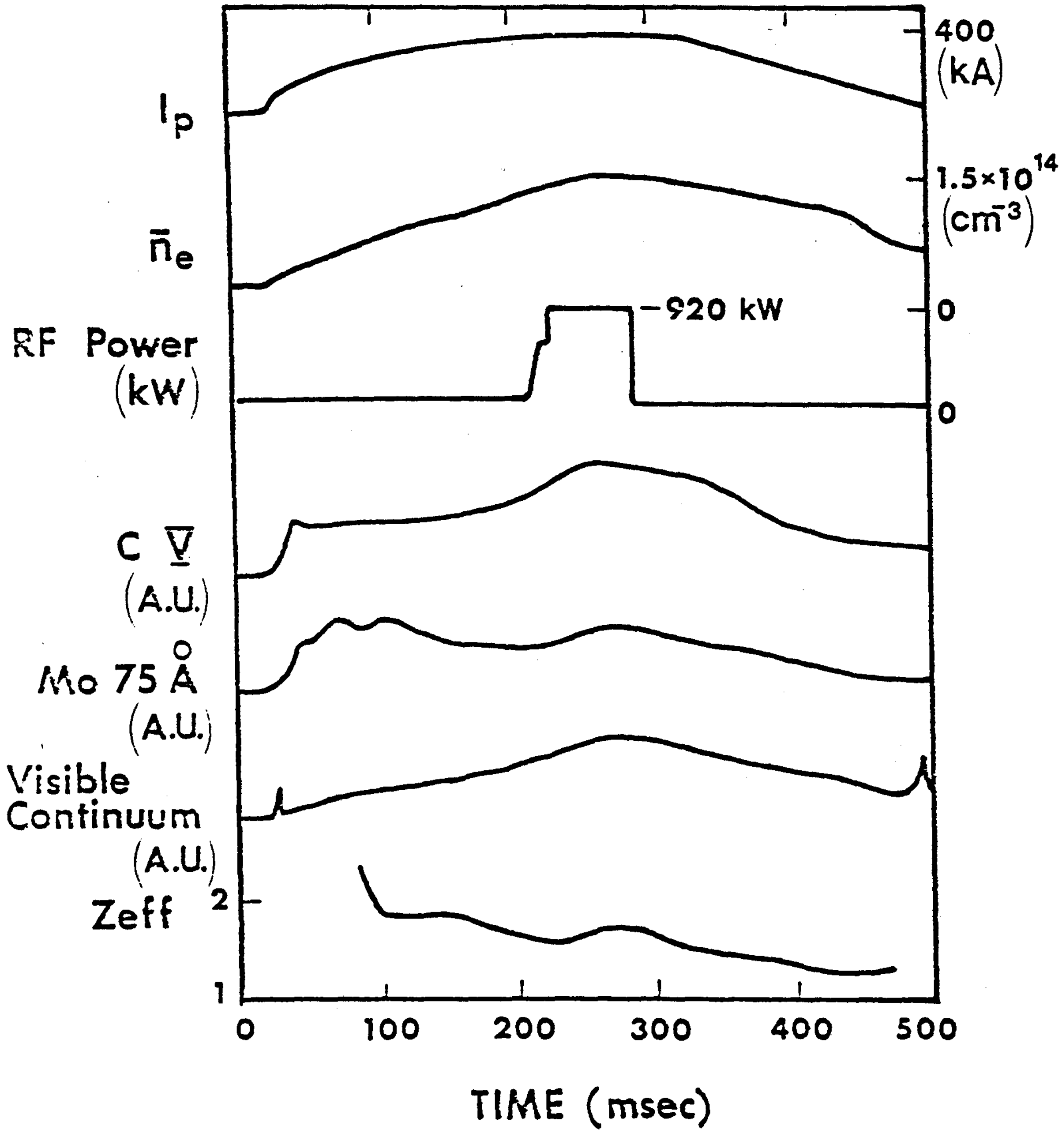
$I_p$
400 (kA)
$\bar{n}_e$
$1.5\times10^{14}$ ($cm^{-3}$)
RF Power (kW)
920 kW
0
0
C V (A.U.)
Mo 75 Å (A.U.)
Visible Continuum (A.U.)
Zeff
2
1
0
100
200
300
400
500
TIME (msec)

FIGURE 7