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EXPERIMENTAL VALIDATION OF TRANSIENT PLASMA EFFECTS USED IN HIGH ALTITUDE ELECTROMAGNETIC PULSE CALCULATIONS

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A theory, developed by the Air Force Weapons Laboratory (AFWL), has predicted that an electromagnetic pulse (EMP) propagating through the high altitude EMP source region will be severely attenuated by conduction currents in this region. It is the purpose of the work discussed in this report to test this theory experimentally. The plasma facilities at the University of Arizona in the Department of Electrical Engineering were modified under a previous contract, and this report describes the results of experiments that were performed with

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ABSTRACT (Cont'd)

this modified system. The important result that has been obtained is the observation of electron heating by the pulse. The theory predicts that the EMP should be capable of heating electrons up to approximately 100 eV. Electrons have been observed with temperatures in this range, as well as in the vicinity of 50 eV. The attempts to quantitatively correlate this data with the AFWL theory have had little success so far.

PREFACE

The theoretical work underlying the experimental effort described in this report has been developed by Capt. William A. Seidler at the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. The experimental program herein described has proceeded under the direction of Dr. Robert N. Carlile, Professor of Electrical Engineering, Department of Electrical Engineering, The University of Arizona, Tucson, Arizona. Three graduate students have been involved with the development of this program: Robert B. Piejak, Ph.D. candidate, Gary L. Jackson, Ph.D. candidate, and Gary L. Hagedon, M.S. candidate.

TABLE OF CONTENTS

I. Introduction

The work discussed in this report concerns the propagation of an electromagnetic pulse (EMP) through the high altitude EMP source region. The objective of this work has been to obtain experimental data on the nonlinear absorption of an EMP by conduction currents within the high altitude EMP source region that could be compared with theoretical predictions. This work directly supports the Minuteman, AWACS, B-1, and C^3 programs.

A theory, developed at the Air Force Weapons Laboratory (AFWL) (ref. 1), predicts that an EMP will be severely attenuated by conduction currents in the high altitude EMP source region. In order to test the validity of this theory, the plasma facilities in the Department of Electrical Engineering at The University of Arizona have been appropriately modified under a previous contract, F29601-74-C-0110, so that propagation of an EMP through an ionospheric plasma could be simulated.

The details of this modification are given in reference 2. In brief, a TEM parallel plate waveguide is immersed in a uniform nitrogen plasma. By means of conical transitions and other types of transitions, the TEM waveguide is impedance matched to a pulse generator at its output. In the TEM waveguide, a simulated EMP with a risetime of 100 picoseconds and a peak amplitude of about 6×10^2 volt/cm has currently been achieved. The fall time of the EMP is variable. The repetition rate for this EMP is about 100 pulses per second. Diagnostic systems allow ambient electron number density and electron temperature to be measured and velocity distribution function of electrons (and hence peak electron temperature) to be measured under pulsed conditions.

In Section II a brief description of the system is given with emphasis on modifications not discussed in reference 2. In Section III, the experimental results obtained are presented. In Section IV are given recommendations for future work.

II. Brief Description of Experimental System

The plasma system and the diagnostic systems have been described in detail in reference 2. This report discusses only those parts of the system which have been modified during the present effort.

A. Electron Beam-Produced Plasma

In the measurements made in this study, we have used exclusively the electron beam-produced plasma. We found that the plasma could be made more uniform and the number density of electrons more repeatable and easier to control if we used a set of three grids in front of the cathode. The first grid allows control of cathode current and was particularly critical. This grid was made from a sheet of 1/16 inch thick molybdenum. Holes, 1/16 inch in diameter were drilled through this plate at regular intervals so that the ratio hole area to opaque area is unity. This grid was placed about 3/16 inch from the cathode surface. Considerable care was exercised to make the planar surfaces of these two structures parallel to one another.

We have found that this type of grid allows stable operation of the plasma. The cross-section of the plasma is quite uniform. We theorize that this grid allows the cathode surface to be at a more uniform temperature with corresponding uniform emitting characteristics.

The second grid, which was a coarse tungsten wire mesh, was on occasion operated positive with respect to the first grid. The grid allows us to bombard the cathode surface with nitrogen ions. In the event that the cathode surface becomes contaminated, ion bombardment allows the contamination to be reduced. If contamination does occur, the two methods we have available for cleaning up the surface is to increase the cathode surface temperature to the "activation" value (about 1250°C) by increasing current through the cathode filament, and ion bombardment. By means of these various techniques, the contamination problem was minimized.

The third grid which is also a coarse tungsten wire mesh has as its function to control the energy of the cathode emitted electrons at the point where they effectively enter the plasma region.

With this cathode system, a controllable, reproducible uniform plasma was obtained. The first and third grids were usually maintained near zero volts with respect to the stainless steel envelope. The second grid was also maintained near zero volts except when we wished to ion bombard the cathode. Under these conditions, the electron number density of the plasma column versus cathode voltage V_c (negative with respect to the envelope) is quite repeatable. In Figure 1, we have plotted number density n_e (cm^{-3}) versus V_c (volts) for a nitrogen gas plasma. Data were taken at pressures of 6 and 10 microns. We see that for a given V_c the number density n_e is not sensitive to pressure in this pressure range. The value of n_e can be changed from 10^7 to 10^9 cm^{-3} over a cathode voltage range of 20 to 90 volts. We believe that lower number densities could be achieved by extrapolating the curve in Figure 1.

B. EMP Generator, TEM Waveguide, Electrostatic Analyzer Probe, and Langmuir Probes

The EMP Generator, TEM Waveguide, Electrostatic Analyzer Probe, and Langmuir Probes are basically the same as those described in reference

2. In regard to measurement of electron number density n_e, results from the longitudinal Langmuir probe are shown in Figure 2. In this figure, n_e is plotted as a function of longitudinal position, z. We see that the relatively large error in the measurements ($\pm$ 20%) makes it difficult to determine the uniformity of the plasma in the longitudinal direction. Improvement of our Langmuir probe measuring techniques, plus use of the electromagnetic cavity which was not in operation, should reduce this error.

In this effort, the electrostatic analyzer probe was so arranged that it could measure energy distribution function of electrons in the logitudinal direction (z) either under steady state conditions or pulsed conditions. By steady state conditions, we mean in the absence of a pulse. By pulsed conditions, we mean that the distribution function could be measured at time T after the pulse had propagated down the waveguide. In theory, T, can be anything from a few nanoseconds to tens of microseconds.

III. Results

In this section we shall state the results that we have obtained under the technical phase of the study.

AFWL has supplied this project with theoretical data showing the peak amplitude of the EMP, E_o (volt/cm), versus pressure of N_2 in microns required to obtain a peak heating of electrons $T_{e_{max}}$ of 100 eV. The parameters for these data are an ambient electron temperature T_{eo} of 1.5 eV, approximately that which is found in our laboratory plasma (we have more recently determined that T_{eo} is more correctly 3-5 eV), n_e equal to 7×10^6 cm^{-3}, and a rise time for the EMP of 182 picoseconds.

We have scaled this information to other values of n_e but the same T_{eo} of 1.5 eV according to the scaling laws described in reference 2.

We were thus able to obtain a theoretical curve of E_o versus n_e to give a Te_{max} of 100 eV at a constant pressure of N_2. A typical curve for a pressure of 10 microns is shown in Figure 3. Also shown in that figure is the pulse generator power supply setting required to give the desired E_o.

In the measurements reported here, the magnetic field was kept low enough (about 60 gauss) such that the results were insensitive to it, i.e., increasing the magnetic field by a factor of 1.5 did not produce any measurable change in the results.

The earliest evidence that energetic electrons were being produced by the EMP is shown in Figure 4. This figure shows the distribution function obtained at various times T after the EMP propagated through the plasma. A steady state (ambient) distribution function is shown for a reference. The main peak is due to electrons emitted by the cathode, and occurs at about 15 eV. Although these electrons entered the plasma at an energy of about 45 eV, inelastic collisions have reduced their energy to 15 eV, at a location 90 cm further down the system where the electrostatic analyzer probe is located. Notice that 1.25 microseconds after the pulse, there is the beginning of secondary peak at 35 eV. At 50 microseconds after the pulse, this secondary peak has disappeared. This partial secondary peak <u>could</u> be due to electrons generated by the EMP. One would expect that at 50 microseconds, a much longer time, the generated electrons would have diffused out of the finite system so that the secondary peak would not be present.

The most conclusive data that we have obtained which demonstrate electron heating due to the EMP are shown in Figure 5. Reference is made in that figure to the photographs labeled (a) and (b). These photos show the current collected by the collector of the electrostatic analyzer probe (EAP) verus time. The horizontal time scale is 20 naoseconds per cm. In photo (a), the control grid of the EAP was set at 250 volts, i.e., only electrons with energies greater than 250 volts could reach the collector. Presumably, this high a control grid voltage would stop all electrons, and zero current should be collected. The humped curve that one sees in photo (a) is due to EMP coupling, i.e., the probe at the present time acts like an antenna and receives a small part of the EMP. Since the hump is about 60 nanoseconds wide, there is a long time constant associated with the antenna response (the pulse is of the order of 1 nanosecond long). In the absence of a plasma, one sees the response in photo (a), which confirms that the hump is due to coupling to the EMP and is not related to electron current collected in the EAP.

In photo (b), the voltage on the control grid was reduced to zero. Now all electrons entering the probe can arrive at the collector. One now sees a decaying response with a time constant of about 160 nanoseconds. This indicates an increase in the electron density due to the EMP.

If we increase the control grid voltage, we find that the time constant of the decaying response decreases, and the response approaches photo (a) between 80 and 120 volts. This would indicate that the electrons constituting the increased number density have maximum energies in the range 80 to 120 eV. The decreased decay time is neatly accounted for because when slow electrons are eliminated by increasing the control grid voltage, the remaining faster electrons will diffuse out of the finite plasma column at a faster rate than when the slower electrons are present.

In addition, we ran a distribution function measurement at varying values of peak pulse electric field E_o and tabulated the peak electron temperature. The results are shown in Table 1. This peak temperature was, in fact, a secondary peak like that in Figure 4 at 1.25 μs, but much more distinct than that shown in Figure 4. The main peak occurs at about 15 eV and is due to the fast electrons emitted by the cathode. These results are at variance with the AFWL theory, which predicts a much more sensitive dependence of peak electron temperature to peak EMP.

Unfortunately, we have not been able to repeat these results; the reason for this is not clear to us. However, we are confident that Figure 5 (b) does indicate that the EMP generates energetic electrons as the AWFL theory predicts.

IV. Suggestions for Further Work

The fast electrons emitted by the cathode are causing the large peak in the distribution function in Figure 4 to mask the smaller secondary peak which we feel is due to electron heating of the EMP.

There appears to be a rather simple solution to this problem. We need to merely pulse the cathode off during the time that the pulse propagates down the system. For example, suppose that we pulse the cathode off for 20 microseconds. A 50 eV cathode-emitted electron will disappear in about 1/4 microseconds. Thus, after perhaps 1 microsecond, one could expect that all cathode-emitted electrons will have drained out of the plasma. The slow electrons, on the other hand, will be trapped in the system: between the mirror magnetic field at one end and the electric fields at the cathode structure at the other. The magnetic field will keep these electrons from diffusing transverse to the system. The diffusion time for the slow electrons is of the order of milliseconds.

Table 1. PEAK EMP AMPLITUDE VERSUS PEAK ELECTRON ENERGY
Pressure, 6 microns, N_2; n_{eo}, 1.5×10^8 cm^{-3}; T_{eo}, 5 eV;
EMP rise time, 200 picoseconds; EMP fall time, 1.5 nanoseconds.

E_o (volt/cm)	$T_{e_{max}}$, peak electron energy (eV)
333	57
250	56
167	55
100	54

During approximately 1 microsecond after the cathode electrons have drained out, any electron density gradients due to these cathode electrons will have disappeared.

Now we propagate the EMP which traverses the system in about 3 nanoseconds. We may now observe heating of electrons without the masking effect of the cathode-emitted electrons.

It is our intention to make this modification to the system.

V. SUMMARY

Pulsed electric fields with peak amplitudes predicted to produce 100 ev electrons within the nitrogen plasma of the experiment were propagated through the TEM waveguide of the experiment. Electrons were found to increase in number density and energy similar to that predicted by the theory developed at the Air Force Weapons Laboratory.

REFERENCES

1. Seidler, W. A., "Pulsed Power Heating of the D-Region," Proceedings of the 1975 Symposium of the Effect of the Ionosphere on Space Systems and Communications, Paper 3-7, Naval Research Laboratory, January 20, 1975.

2. Carlile, R., "An Experimental Study of the Nonlinear Propagation of an Electromagnetic Pulse Through the Ionosphere," AFWL-TR-75-115, Air Force Weapons Laboratory, December 1975.

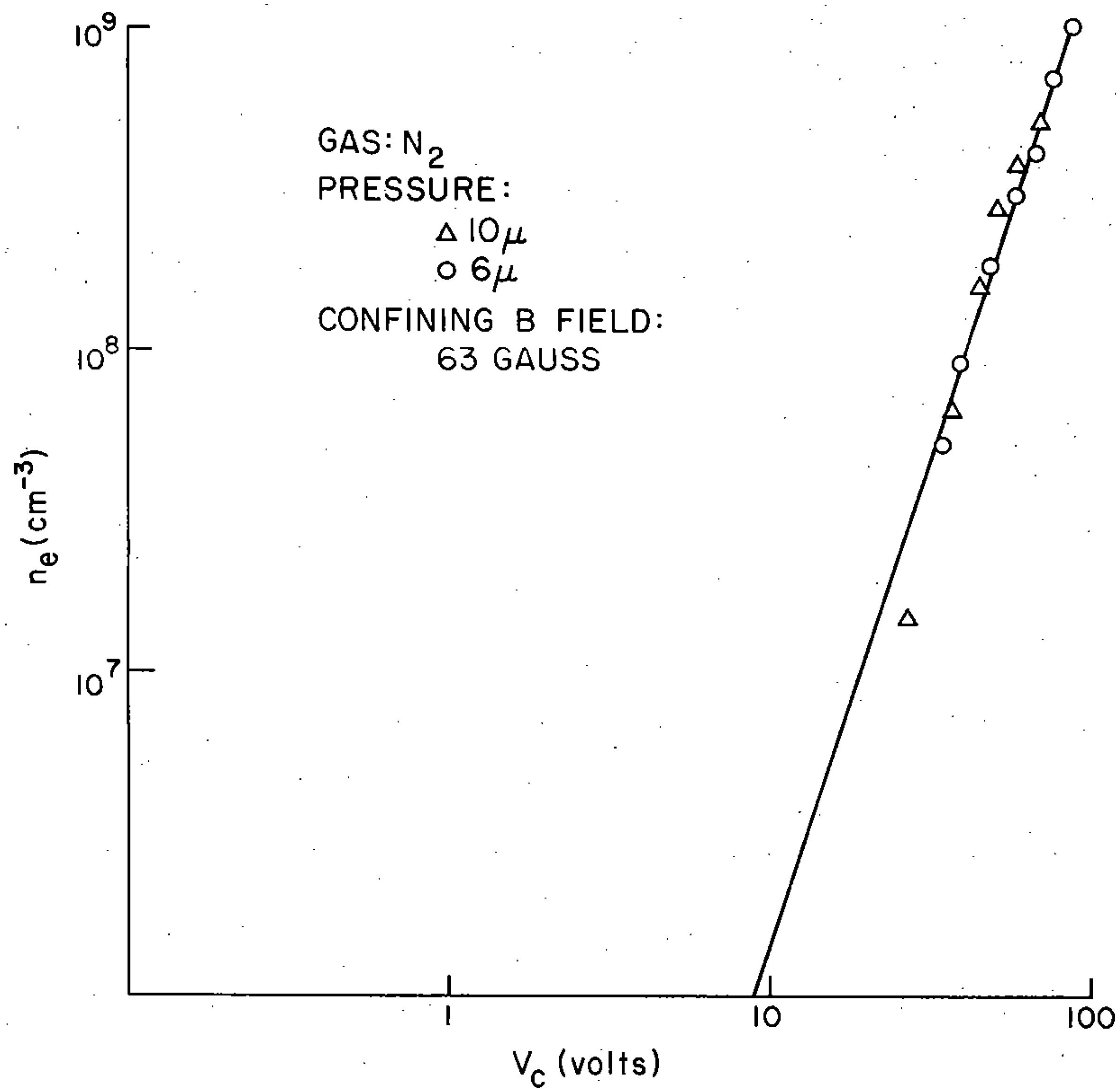


Figure 1. Electron beam-produced plasma. Ambient electron number density n_{eo} vs. cathode voltage V_c (negative). Grids 1, 2, and 3 are at zero volts. All voltages measured with respect to stainless steel envolope. Gas: nitrogen; pressure: 10 microns; confining magnetic field: 63 gauss.

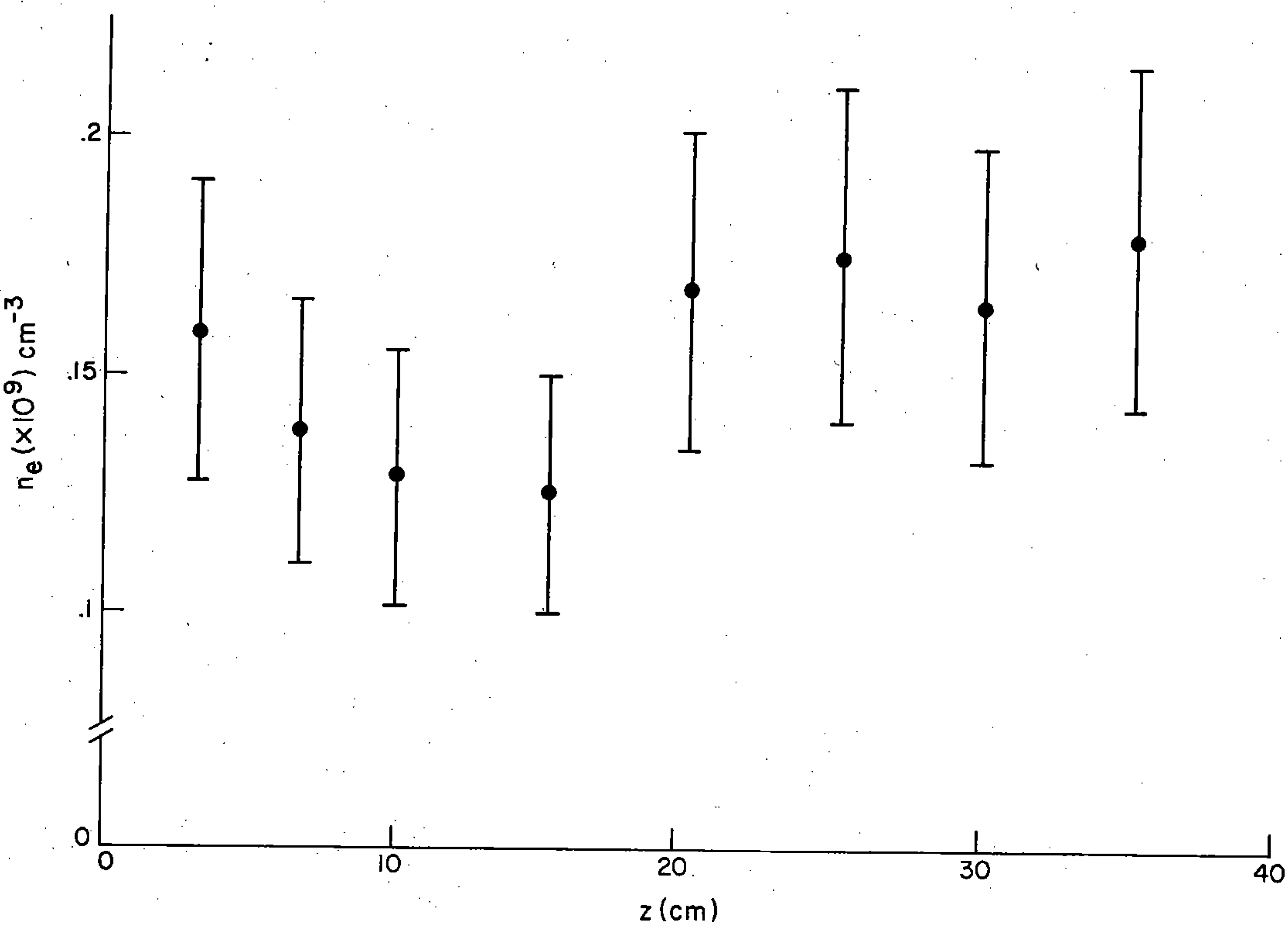


Figure 2. Ambient electron number density n_{eo} versus distance z. z = 0 corresponds to the input to the TEM waveguide, i.e., at the junction of the conical taper and the waveguide at the end of the system where the EMP cnters, and thus, at the far end of the plasma column. Confining megnetic field, 63 gauss.

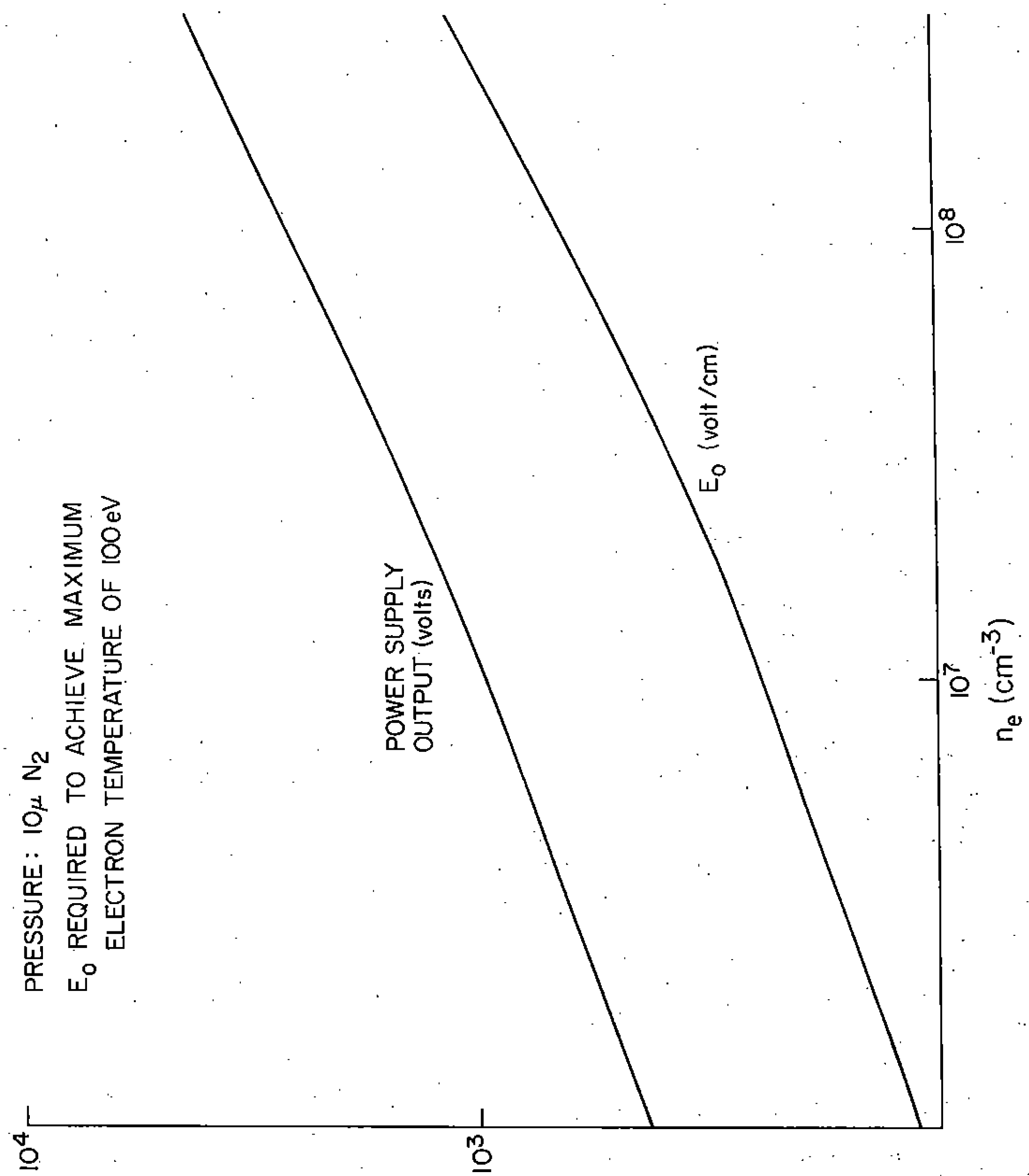


Figure 3. Peak pulse electric field E_o vs. ambient electron number density n_{eo} required at a nitrogen pressure of 10 microns to heat electrons to a maximum temperature of 100 eV. Also shown is pulse generator power supply setting required to obtain E_o. E_o curve obtained from scaling theoretical data supplied by Seidler[1].

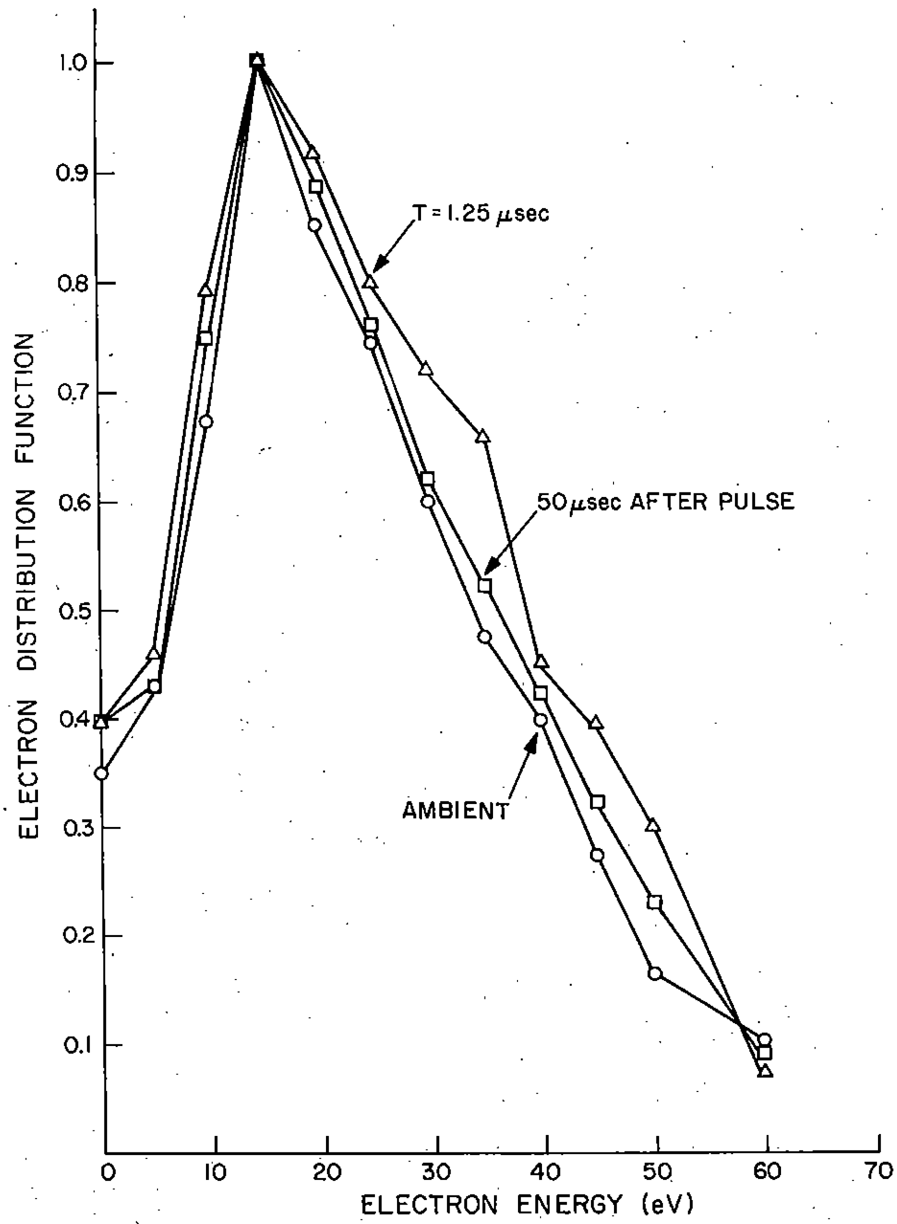
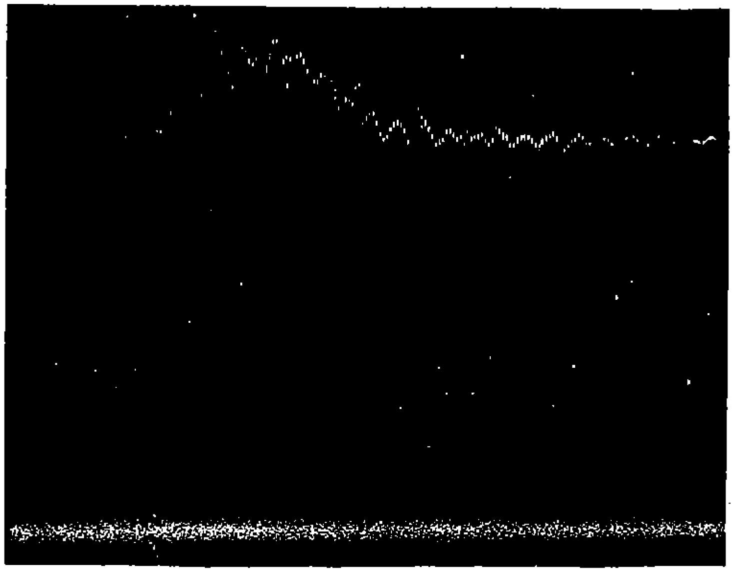
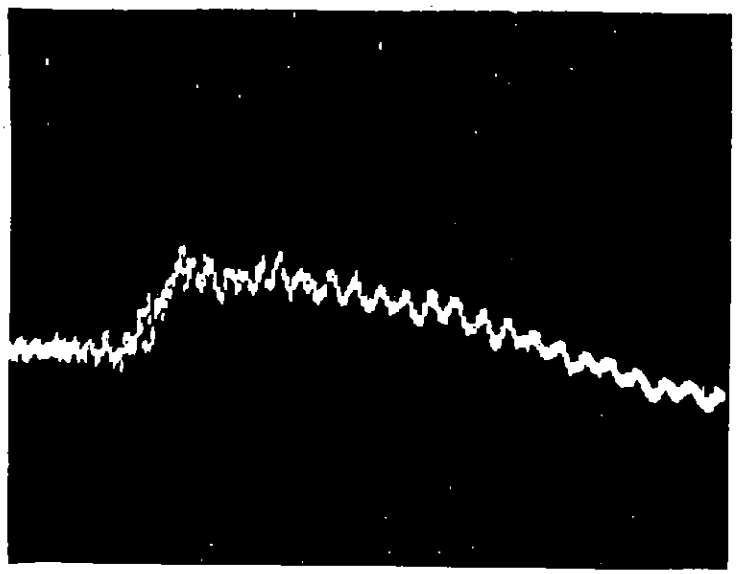


Figure 4. Electron distribution function vs electron energy for steady state (ambient), and for T = 1.25 microsecond and 50 microsecond; E_o, 333 volt/cm; pressure, 4 microns; n_{eo}, 1.8 x 10^8 cm^{-3}; rise time of EMP, 180 picoseconds; EMP fall time, 1.5 nanoseconds; T_{eo}, 5 eV.



(a)



(b)

Figure 5. Current arriving at collector of electrostatic analyzer probe (EAP) versus time. Horizontal time scale: 20 nanoseconds per cm. (a) Control grid of EAP is 250 volts (no current collected); (b) Control grid set to zero volts (all electrons entering EAP collected): Pressure, 6 microns of N_2; n_{eo}, ambient electron number density, 1.5×10^8 cm^{-3}; T_{eo}, ambient electron temperature, 5 eV; peak EMP electric field, 333 volt/cm; EMP rise time, 180 picoseconds, EMP fall time, 1.5 nanoseconds.