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LAWRENCE RADIATION LABORATORY
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ABSTRACT

A current-free magnetized plasma with independently variable density and electron temperature has been produced and studied. The plasma, which may be either steady state or pulsed, is generated at one end of a 1.5-meter-long vacuum system by a 10 GHz microwave discharge at electron gyroresonance in a dc magnetic field. In the main body of the plasma the magnetic field can be varied from 1 to 10 kG and plasma densities $5 \times 10^{8} \lesssim n_e \lesssim 5 \times 10^{11}$ cm^{-3} and temperatures $2 \lesssim T_e \lesssim 20$ eV, $T_i \lesssim 1$ eV can be achieved. All the noble gases as well as hydrogen have been used at pressures ranging from 2×10^{-5} to 2×10^{-3} torr. Electron plasma waves and ion acoustic waves have both been used for diagnostic purposes. Unless special precautions are taken, the plasma has density fluctuation of 5 to 10%. A feedback control system which uses a rapidly responding adjustment of discharge power has been used to significantly reduce these fluctuations. This control will also keep the plasma density steady even in the presence of fluctuations in line voltage or gas feed.

I. INTRODUCTION

Many quantitative experiments in fundamental plasma physics require the existence of well-controlled well-behaved plasmas. In recent years much progress has been made in the art of producing such plasmas in the laboratory. The parameters and conditions are, of course, dictated by the particular phenomena under study. The most common requirements are (a) steady state or at least good reproducibility, (b) relative quiescence, i.e., relatively low level of fluctuations, and (c) reasonable distributions in velocity and conficturation space. Sometimes it is also important that the degree of ionization be high, or at least that the mean free path be long.

The best known examples of sugh high-quality plasma sources are the surface-ionized alkali and alkaline earth vapor systems, which, when combined with strong magnetic fields, are commonly known as "Q-machines" (RYNN, 1964). Surface-ionized plasmas suffer from a number of inherent limitations. The most serious of these are the low level and the narrow range in temperature (a few thousand degrees) caused by the necessary contact with the hot end plates. This causes the plasma to be collision-dominated at rather low densities. Furthermore, because of the large mass of most metal atoms, the ions' radii of gyration are often neither large nor small compared with other critical dimensions. In spite of these shortcomings, Q-machine plasmas have been extremely successful as tools for a variety of studies. Up-to-date discussions, including descriptions of such devices, can be found elsewhere (D'ANGELO, 1969; PARDO and ROBERTSON, 1966) and therefore are not presented here.

When other ion species are to be used, such as the noble gases or hydrogen, or even the very popular mercury vapor, ionization by electron impact is obviously the most suitable mechanism of plasma production.* This does not mean that the experiments necessarily have to be performed inside active discharges, i.e., in the presence of substantial electric fields and currents. For instance, if only very small degrees of ionization and low electron temperatures are required, discharge afterglows can be adequate, although ionization by low-density electron beams may well be preferable (DUNN and SELF, 1964).† These techniques fail, however, when the degree of ionization needs to be substantial to minimize collisions with neutral atoms or when the electron temperature has to be several electron volts in order to produce thermal effects or to avoid Coulomb collisions. In order to produce these latter conditions, electrons must be continually heated somewhere within the plasma by means of electric power input. Fortunately, because of the very large thermal conductivity of the electrons and their poor energy coupling to the ions, this heating region can be sharply localized in a small portion of the plasma while the bulk remains virtually current-free and easily accessible for the intended experiments. We shall use, for short, the term "extruded discharges" (KUNKEL, 1966).

Several types of extruded discharges have been described in the literature. Most of these, and certainly the earliest versions, use electrodes with dc power inputs such as "Duoplasmatrons" (BOESCHOTEN and SCHWIRZKE, 1962; MALMBERG et al., 1964), "reflex arcs" (HALL and GARDNER, 1962), hollow-cathode arcs (LEVIN and OLESON, 1968; LEONARD, 1969), or straight hot-cathode arc discharges (TAKAYAMA et al., 1967).

Impressive ion densities, up to 10^{14} cm^{-3}, have been reported (LEONARD, 1969), but the plasmas so produced are not necessarily low in fluctuation level (HALL and GARDNER, 1962) and the electron velocity distribution may contain substantial high-energy components. In all of these the plasma streams out through an orifice in one of the electrodes. More recently, electrodeless high-frequency discharges at or near electron cyclotron resonance (ECR) are being developed for similar purposes, but very little of this work has yet been published (LISITANO et al., 1968; MICHAEL et al., 1969; MIX et al., 1969; GENTLE AND MALEIN, 1968; BROWN et al., 1970a). Since there appears to be considerable interest in this type of plasma generation, we report here on our version, which we have called COMPLEX ("Cold Microwave Plasma Experiment").

II. THE COMPLEX DEVICE

As in all ECR experiments our plasma source is based on the fact that at gyroresonance electrons gain energy and can cause ionization efficiently, even at very low gas pressures. In addition, it should be noted that the energy gain in gyroresonant heating is primarily transverse to the magnetic field, so that insertion of a magnetic mirror between the discharge region and the main plasma chamber will discriminate somewhat against the flux of hot electrons from the source region. Since low-energy electrons scatter more rapidly into the loss cone, it is hoped that an overabundance of high-energy electrons in the effusing plasma can be avoided. This feature distinguishes our arrangement from most of the other ECR plasma generators. Furthermore, we have introduced a feedback control that serves to reduce drastically all low-frequency fluctuations in the plasma output, regardless of whether they are caused by instabilities in the discharge or by fluctuations in the power supply.

The principal components of the COMPLEX experiment are shown schematically in Fig. 1. A current-free, steady-state or quasi-steady-state plasma is produced by the application of cw or pulsed microwave power at the electron cyclotron frequency appropriate to the confining magnetic field in region I, the discharge chamber. The cylindrical copper vacuum vessel is situated with a dc axial magnetic field, variable up to 10 kG and constant in time to ≈ 0.1% (the thick copper vessel provides a significant filtering action). The axial magnetic field shape can be varied easily over a wide range, and is usually arranged to be uniform to within ≈ 5% in region II, the test region, over a length of ≈ 80 cm. The "microwave discharge chamber", into which the high-power microwaves are fed as described below, is separated from the main test region my a metal partition with a 5-cm-diam orifice; this orifice can carry a honeycomb structure of 0.125-in. mesh, 2 in. long, designed to block the microwaves but pass plasma. Normal operation is with a steady flow of hydrogen gas at a pressure of from $\approx 5 \times 10^{-6}$ to $\approx 5 \times 10^{-4}$ torr. The vessel is pumped with a 6-in. oil-diffusion pump, liquid-nitrogen trapped, and has a base pressure of 1×10^{-7} torr.

Microwave power of up to 1 kW cw at 10.4 GHz is coupled to the discharge chamber by one of three possible methods: (a) filling the chamber with rf from a flush-mounted side port, thus operating it as a multimode cavity, (b) beaming in rf through an axially located microwave horn, and (c) employing a "Lisitano Coil" (LISITANO et al., 1968) (2 in. i.d. and 6 in. long). In all cases the discharge is located within a magnetic field having electron-cyclotron resonance zones (3.7 kG for our frequency). The different methods have their separate regimes of optimum operation, and by employing the most appropriate method, the range of parameters achievable can be extended. However, our "standard" setup includes the Lisitano Coil.

Representative sets of plasma densities found in region II as a function of microwave power (dissipated in the Lisitano Coil discharge), of gas pressure (read by a gauge downstream), and of magnetic field in region II are shown in Figs. 2, 3, and 4 respectively. As might be expected, at fixed gas density the plasma production efficiency is seen to decrease with increasing degree of ionization, and it increases generally with the gas pressure until a certain optimum is reached. Beyond this optimal gas density the yield falls rapidly with increasing pressure, presumably because the electron energy loss is dominated by energy transfer to the gas molecules instead of a direct loss to the walls. The dependence of the electron density on the magnetic field is not so easily understood, even qualitatively, except that at least a part of the reduction at low fields must obviously be caused by the expansion of the flux tube that guides the plasma from region I to region II.

At any rate, from these figures it is clear that by means of an adjustment of the power the downstream plasma density can be kept fixed while the gas pressure or the magnetic field in the test region is varied over a wide range.

In actual operation, a digital voltmeter connected to a Langmuir probe circuit provides a continuous monitor of ion density, and the pressure, power, and magnetic field can be adjusted as required rapidly and easily. Our experimental interest is in the downstream plasma in the region of uniform magnetic field, which usually forms a column of ≈ 5 cm diameter and ≈ 1 m length. The observations reported were all made in this region.

III. PLASMA PROPERTIES

The diagnostic methods we have used to investigate the plasma properties include Langmuir probes, microwave interferometry, an electrostatic energy analyzer, spectroscopic measurements, and some measurements on the propagation of electron plasma waves as well as ion acoustic waves. We have measured, as a function of external parameters, charged particle densities and spatial variations, electron temperature and energy distribution, and have been able to put limits on ion temperature, percentage ionization, and axial plasma flow speed. In addition, we have investigated the effect of all parameters on the fluctuations in ion density.

A. Charged Particle Densities

A high-sensitivity 8.6-mm microwave interferometer was constructed and has been used to measure electron density at a fixed axial location; the interferometer possesses some novel features and has been described elsewhere (BROWN et al., 1970b). Radially and axially movable Langmuir probes have allowed a spatially resolved measurement of ion density. In general, the agreement between the two methods is good; the apparent density measured by a probe depends on the magnetic field, and a complete report of an experimental analysis of this effect is in preparation. For the present purposes, however, we can state the following conclusions:

1. The range of density achievable is $5 \times 10^8 \lesssim n_e \lesssim 5 \times 10^{11}$ cm^{-3}.

2. There is, in general, an axial falloff in density, typically by a factor of 2 in a distance of 1 m.

3. The radial density distribution is fairly smooth, with a generally broad maximum near the center, and can to some extent be tailored by fine adjustment of external parameters. Some observed radial profiles of ion saturation current are shown in Fig. 5.

4. The radial density distribution preserves its shape with axial distance. A series of experiments we are currently carrying out is involved with the propagation characteristics of high-frequency (several hundred MHz) electron plasma waves. One can look upon these measurements (e.g., of wavelength) as an electron density diagnostic, and the results so obtained are consistent with the above conclusions.

B. Electron Temperature

The electron temperature is most conveniently determined from a Langmuir-probe characteristic. This method appears to work fairly well for our plasma in spite of the strong magnetic field. No theory exists for our collected ion current when the ion gyroradius is not very large compared with the probe diameter (SANMARTIN, 1970). Extrapolation of the ion-saturation current is not reliable in such cases, and this unreliability, in turn, leaves an uncertainty in the electron component of the characteristic. Nevertheless, reasonable electron-retardation profiles are usually found in COMPLEX, as shown in Fig. 6, so that electron "temperatures" can be assigned. In order to confirm this conclusion we have also used a three-grid electrostatic energy analyzer, axially located at the "end" of the plasma column and having an acceptance aperture of 4 cm, to observe in more detail the distribution function (see Fig. 7). We can summarize our findings:

1. The electron temperature can be varied over a limited interval by a suitable choice of rf power and gas density, as shown in Fig. 8. The achievable range is $2 \lesssim T_e \lesssim 20$ eV.
2. The axial temperature distribution has a falloff somewhat less rapid than that of density, typically ≈ 10 to 30% in 1 m.
3. The radial distribution of temperature is usually flatter than the density distribution.
4. On the central axis, the energy distribution is fairly Maxwellian, but the departure from Maxwellian becomes more pronounced at larger radii.
5. There is under no condition a "bump" in the tail of the distribution, at least within the limits of our measurements for energies $\lesssim 30\ kT_e$, though the tail is more highly populated than Maxwellian in spite of the mirror between regions I and II.

C. Ion Temperature

Using phase-sensitive detection techniques, we have attempted to measure the ion temperature from the Doppler broadening of selected spectral lines, in both hydrogen and helium plasmas. As was expected, the ion temperature was found to be much less than the electron temperature, and we can only say that $T_i \lesssim 1$ eV, the instrumental limit of resolution. Measurements made on similar plasma sources elsewhere (MIX et al., 1969; PORKOLAB, 1969) are quite consistent with this result. The best estimate of ion temperature, under typical conditions, is provided by our interpretation of probe response in a magnetic field; these measurements give $T_i \approx 0.5$ eV (BROWN et al., 1970a).

D. Percentage Ionization

This parameter can be estimated approximately from the measured neutral gas pressure and electron density. If no special attempt is made to maximize ionization, typical operating conditions can result in very low percentage ionization, < 1%. Our Lisitano coil is arranged with the gas feed through the coil structure itself, so that all the input gas passes through the ionizing region. Using the Lisitano coil, we find that the percentage ionization, under optimum coupling conditions of power to plasma, is limited almost entirely by the pumping speed of the vacuum system alone. At a microwave power of several hundred watts the maximum percentage ionization in our device is ≈ 50%.

E. Axial Plasma Flow

In one-sided extruded discharges, just as in single-ended Q-machines, the plasma leaves the source region with a nonzero net flow speed. For some experiments, particularly for those involving slow wave propagation, and for the proper interpretation of Langmuir-probe ion saturation current data, this plasma flow must be taken into consideration. Therefore the magnitude of the flow speed is a parameter of interest and must be determined by a separate measurement. Unfortunately, attempts at Doppler-shift measurements on spectral lines failed because of inadequate resolving power of our spectroscopic equipment and because of a dearth of suitable (i.e., ionic) emission lines. We therefore determined the plasma flow velocity by measuring the difference in upstream and downstream propagation speed of acoustic waves.

The most common method of launching and detecting of ion waves that propagate along a plasma column such as ours makes use of metallic wire grids immersed in the plasma. Our measurements were done by mounting a fixed grid near the upstream end of region II and installing a movable second grid both as detector for downstream propagation and exciter for upstream propagation. Operation in this case was limited to rather low plasma densities because the upstream grid was easily damaged by overheating. As a test signal a single negative pulse of $\approx 5\ \mu$sec duration was used. As noted by others in similar studies, such a pulse generates several distinct signals that are detectable by biased probes, and care must be taken to identify the one that propagates with the ion-acoustic speed. If we denote the downstream propagation speed of the proper signal by v^+ and the upstream propagation speed by v^-, we interpret the quantity $v_0 \equiv \frac{1}{2}(v^+ - v^-)$ as the plasma flow velocity and $\bar{v} \equiv \frac{1}{2}(v^+ + v^-)$ as the "true" signal speed, i.e., the signal propagation speed in the frame of the streaming plasma. A comparison of $\bar{v}$ with $c_s \equiv \sqrt{k(\gamma_i T_i + \gamma_e T_e)/m_i}$ will then serve as a check whether the correct signal was selected as the plasma sound wave. A set of results for the noble gases is summarized in Fig. 9, where c_s was computed from the measured value of T_e and T_i was assumed to be much smaller than T_e. It is seen that the flow speed is always smaller than the sound speed, and tends to be in the neighborhood of $0.5\ c_s$. This is not unreasonable for an extruded discharge. The uncertainties in v_0 are rather large because v_0 is obtained by subtraction.

Unfortunately, the method could not be applied to our hydrogen plasma because the determination of v^- was very poor in this case. It seems likely that a special effort in sound-wave launching and detection would yield more precise values for the plasma flow velocity.

The two-grid method described so far has two shortcomings: (a) As mentioned above, the danger of overheating the upstream grid places an upper limit on the plasma density, and (b) the presence of the upstream grid is likely to alter the downstream plasma. In particular, the flow speed itself may well be affected, so that the information obtained may not be applicable to an extruded discharge with a different grid or to one without any grid. For instance, it is interesting to note that within the limits of accuracy of the measurements the flow velocities shown in Fig. 9b are independent of axial position, and so are the plasma densities! This quite different from the usual density decrease with axial distance observed in the absence of a grid. It is therefore desirable to determine the plasma flow without the use of an upstream grid.

It turns out that in the COMPLEX device a compression wave that travels with the plasma-acoustic speed can be launched by simply applying a brief pulse of incremental power to the discharge via the klystron amplifier. Again, such a pulse generates several distinct signals that propagate along the plasma column. But the acoustic wave is easily recognized, and a portion of it can be reflected at a metallic end plate. Both signals are detectable by a movable Langmuir probe, as shown in Fig. 10, and the density increment is discernible even in the microwave interferometer reading. Although no great accuracy can be claimed for this method (the pulse length must be quite long to allow a response in the discharge), the data confirm the previous findings, i.e., v_0 is comparable to but always somewhat less than c_s. Moreover, there is an indication that in the absence of the grid the flow accelerates with distance from the source, which suggests that the commonly observed density decrease with distance from the source is largely due to axial expansion rather than to anomalous diffusion radially across the magnetic field. This latter conclusion is consistent with the observation that the radial density profile is independent of axial position. Unfortunately, it was again not possible to use this technique in hydrogen, because the pulses could not be made sharp enough to allow measurement of the rather large acoustic speeds.

A separate report on studies of ion-wave propagation is in preparation.

F. Density Fluctuations

We have investigated thoroughly the effect of all parameters on the percentage fluctuation in ion saturation current to a Langmuir probe. If no special measures are taken the rms fluctuation level is always 5 to 10%, with only little variation with magnetic field strength, gas pressure, and type (H_2. He, N_2, A, Kr), as well as with microwave power and coupling method. We have tried to "line tie" the plasma to a conducting plate at one end of the column, and have found that the presence of the plate alone has no effect on the plasma, but the fluctuation level can be reduced to $\lesssim 2\%$ by drawing a small current to the plate ($\approx$ 10 to 100 mA/cm^2);a similar reduction can be effected by replacing the plate by an electron-emitting ($\gtrsim$ 1 A/cm^2) surface, in which case the improved noise level is localized to the flux tube tied to the emitter. The cooling problems associated with the use of a large heated plate are great, and we have not pursued this method further. Some reduction in fluctuation level has been effected by the inclusion of a feedback loop in the system, which is now described.

IV. FEEDBACK CONTROL

The mechanisms responsible for density fluctuations in steady-state plasma sources are not fully understood. The discharge plasma iteself may be suffering from one or several of the known plasma instabilities driven by the electric current or other distortions of the velocity distribution, or by a density-gradient effect, or by some complicated process involving the ionization rate. There also may be unsteady interactions at the boundaries, such as unstable sheaths, giving rise to high-frequency oscillations, or irregular gas exchange with the surfaces which would lead to slow fluctuations or gradual drifts. All too often it is therefore found difficult or impossible to utilize electric discharges for the production of highly ionized plasma in a truly steady state and free from substantial fluctuations.

Rather than attempt to produce stable conditions in the discharge, we decided to reduce the variations in the plasma output by an automatic and prompt adjustment of the discharge power. This is possible because in our case we have available a control over the microwave power flow into the plasma source. A feedback system which makes use of this control can provide both long-term constancy and a drastic reduction in fluctuation level, at least at the lower frequencies. Since this control affects the plasma as a whole, a signal is needed which represents the average or the total condition of the plasma. The system used (Fig. 1) has as its sensor a photomultiplier arranged to view the total light emitted by the plasma at the mouth of the Lisitano coil. This provides a fast response signal spatially integrated over the resonance region. The signal is compared with a present reference level and the error signal so obtained is amplified, phase shifted, and fed back to a PIN diode modulator in the microwave generator. As with all feedback systems the gain and phase shifts must be designed to give negative feedback at all frequencies at which the gain exceeds unity. The system employs both dc and ac loops and covers a frequency range from 0 to $\approx$ 50 kHz. The low-frequency gain is several hundred and the high-frequency ($\gtrsim$ kHz) gain is less than ten. Only copper-stabilized operational amplifiers are used in the dc loop, so that the system has negligible dc drift.

This method does reduce the fluctuations in our plasma, and that improvement has been observed in several ways (Fig. 1). The effect of the feedback upon the upstream plasma can be seen in the signal from the upstream photomultiplier. Since this is the signal that is used by the feedback system, one expects the greatest improvement here. The downstream plasma was observed with a separate photomultiplier, and with a Langmuir probe biased to monitor ion saturation current.

Feedback affects all three of these signals. This effect can be considered as consisting of two more or less separate regimes--long-term stabilization and the suppression of low-frequency ($\approx$ kHz) fluctuations. Without feedback the average signal (averaged over $\approx$ 1 sec) from the upstream photomultiplier is unsteady, and may vary by up to

10% within a few minutes. With feedback this fluctuation disappears and the signal holds constant for an hour or more to within ≈ 0.1%. Without feeback, 10% fluctuations are also typical of the average (≈ 1 sec) current drawn by the probe in the downstream plasma. With feedback such fluctuations can be reduced to about 1%. Similar improvement is seen by the downstream phototube.

Spectra of the noise seen by the upstream photomultiplier with and without feedback (with conditions otherwise identical) were recorded (Fig. 11a) by using a wave analyzer (Hewlett-Packard type 302 with motorized dial). These spectra show the whole range of frequencies over which there is any significant negative feedback. The noise in the upstream plasma--at least as measured by this signal--is almost completely eliminated below 5 kHz ($\gtrsim$ two orders of magnitude reduction), and is much reduced everywhere below 50 kHz. Since this upper frequency limit is due to the electronics of the system, the upper limit of the method of control may be higher still. Our interest is not primarily in the plasma in this region, apart from its bearing on the downstream plasma. A number of experiments, however, are very directly concerned with hot-electron mirror-contained microwave-produced plasma (DANDL et al., 1964; TANAKA et al., 1966) and the application of a feedback system of the type described here may, in some instances be desirable.

In Fig. 11b is shown a similar spectrum analysis of the signal from the probe in the downstream plasma. The higher-frequency noise, which does not originate in the source, is not affected by feedback. There is considerable improvement at lower frequencies, though as is shown in more detail in Fig. 11c. There is here a white noise spectrum which is reduced by feedback. Also present when there is no feedback are two peaks at about 20 and 140 Hz. These appear to be instabilities in the resonance region. Their exact nature has not been investigated except to note that they are strongly dependent on neutral gas pressure and, as can be seen, they are eliminated by feedback. The feedback was found to be most effective when the downstream magnetic field was fixed at the resonance value (3.7 kG). This was the arrangement when the data of Fig. 11c were taken. Less reduction in the white noise was seen under other conditions, but such features as the two peaks are always completely eliminated by feedback. If there is transmitter noise or 60-Hz noise (not seen in Fig. 11c) in the plasma, this also is completely eliminated by feedback.

The probe ion saturation current is a measure of ion density. The light emitted from the plasma, however, is due to only the more energetic electrons because the average electron energy (≈ 10 eV) is less than that needed to excite a neutral atom. Nevertheless,* spectra of low-frequency noise in the signal from the downstream photomultiplier are quite similar to those from the probe, and comparable improvement due to feedback is seen. The indication is that if one can stabilize a plasma source one can thereby reduce the fluctuations in various different aspects of the resulting plasma.

It should be pointed out that fluctuations in our plasma source can be reduced by carefully "tuning" the gas pressure, magnetic field strength, and microwave power. Regimes can be found where the behavior is good and where the addition of the feedback control effects little additional improvement in the downstream plasma. (The upstream plasma is always improved). The "quasi-quiescent" regimes are, however, only a small part of the entire range of achievable parameter space. The significance of our system is that it can considerably increase the extent of the "quasi-quiescent" regimes.

Although these experiments were performed on a microwave-produced plasma, the type of feedback used should be applicable to any plasma preparation process in which there exists a sufficiently rapid control over the power input to the plasma. The method has its obvious limitations, but this system may well complement other feedback stabilization schemes which are directed toward specific plasma instability modes. The method might be improved by more sophisticated optical sensing (e.g., wavelength and spatial localization) and optical sensing, when possible, should provide a convenient nonperturbing sensor for the feedback stabilization of instability modes in fusion type plasmas and in laboratory plasmas such as that in COMPLEX. We note finally that the long term density stability which results from feedback control is a feature which would be attractive in any laboratory plasma.

FOOTNOTES

Page 1

[*] Work done under the auspices of the U. S. Atomic Energy Commission.

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[*] Photoionization provides also a possible mechanism for some gases, but steady-state operation seems difficult to achieve for the required powerful sources of a far-ultraviolet radiation.

[†] The extended negative glow of the so-called brush-cathode discharge (PERSSON, 1965) may be included here although it constitutes a part of an active discharge. Perhaps the most interesting such source, however, is the UCLA Plasma Device; cf. R. J. Taylor, H. Ikezi, and K. R. MacKenzie, in Proceedings of the 2nd International Conference on the Physics of Quiescent Plasmas, Paris, 1969, Vol. 3, p. 57.

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[*] Furthermore, any modulation of input source power is seen by the probe after a delay of about 30 μsec, whereas the same signal is seen by the downstream photomultiplier without any such delay. Finally, an attempt was made to operate the control system with the downstream photomultiplier as sensor. This was successful to the extent that the control did function and fluctuations in the sensor signal were reduced, but no effect was seen on the probe, further indicating the different nature of the two signals.

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FIGURE LEGENDS

Fig. 1. The COMPLEX Device, including schematic for the feedback control and a typical plot of magnetic field strength on the axis.

Fig. 2. Electron density on axis in region II vs Lisitano-coil discharge power for two different gas pressures. The gas is hydrogen. Densities below 3.5×10^9 cm^{-3} can readily be achieved, either by attenuation of the plasma flow through a grid, or by removal of the Lisitano coil and use of ordinary cavity excitation.

Fig. 3. Electron densities on axis in region II vs gas pressure (hydrogen) at various discharge power levels.

Fig. 4. Electron density vs magnetic field on axis in region II at two pressures (hydrogen). The power is 100 W. The dip at 3.8 kG is not fully understood, but it is probably related to the gyroresonance at that field.

Fig. 5. Two different radial profiles of the ion saturation current, i_{sat}.

Fig. 6. Two curves of adjusted Langmuir-probe current, ln $(i - i_{sat})$, vs probe potential V_p.

Fig. 7. Example of an electron-energy analyzer current.

Fig. 8. Electron temperature vs discharge power at constant electron density, $n_e = 4 \times 10^{10}$ cm^{-3}, in hydrogen. To accomplish this the gas pressure had to be varied from 2×10^{-5} to 2×10^{-4} torr.

Fig. 9 (a) Comparison of mean signal speed with the calculated acoustic speed $c_s \equiv \sqrt{kT_e/m_i}$ for the noble gases He, Ne, Ar, and Kr. Note that $\gamma = 1$ here because the large electron thermal conductivity keeps the compressions isothermal rather than adiabatic. (b) Comparison of inferred plasma flow speed v_0 with c_s for the same conditions.

Fig. 10. Probe signals vs time at different locations on the axis, when a discharge power purst is used to launch a density wave which is partially reflected at a metal end plate. A microwave interferometer signal at a location near the end plate is also shown.

Fig. 11. (a) Spectra of signal received by upstream photomultiplier (0 to 50 kHz), with and without feedback. (b) Spectra of signal received by the Langmuir probe (0 to 25 kHz), with and without feedback. (c) Same as (b) except 0 to 1 kHz.

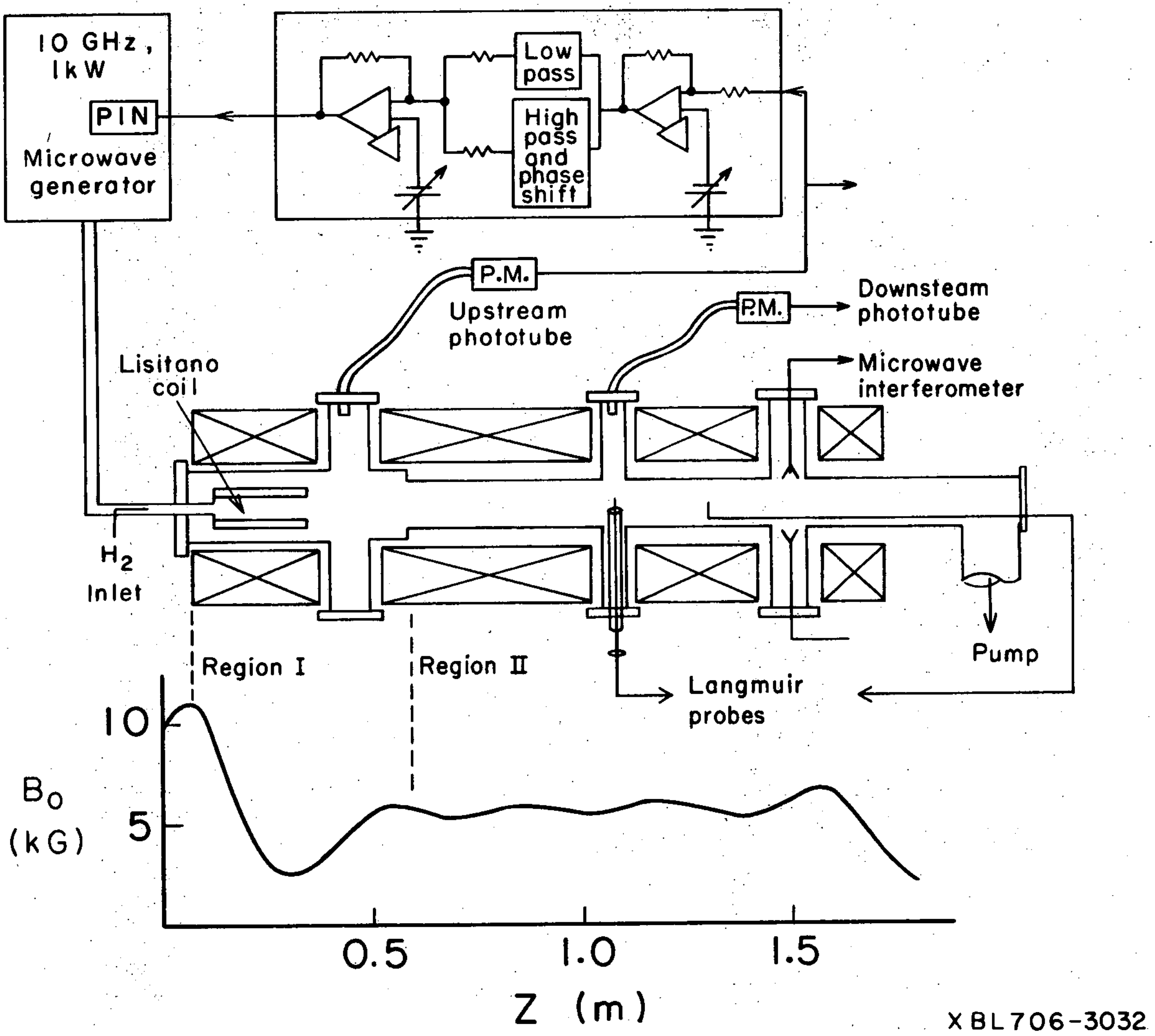
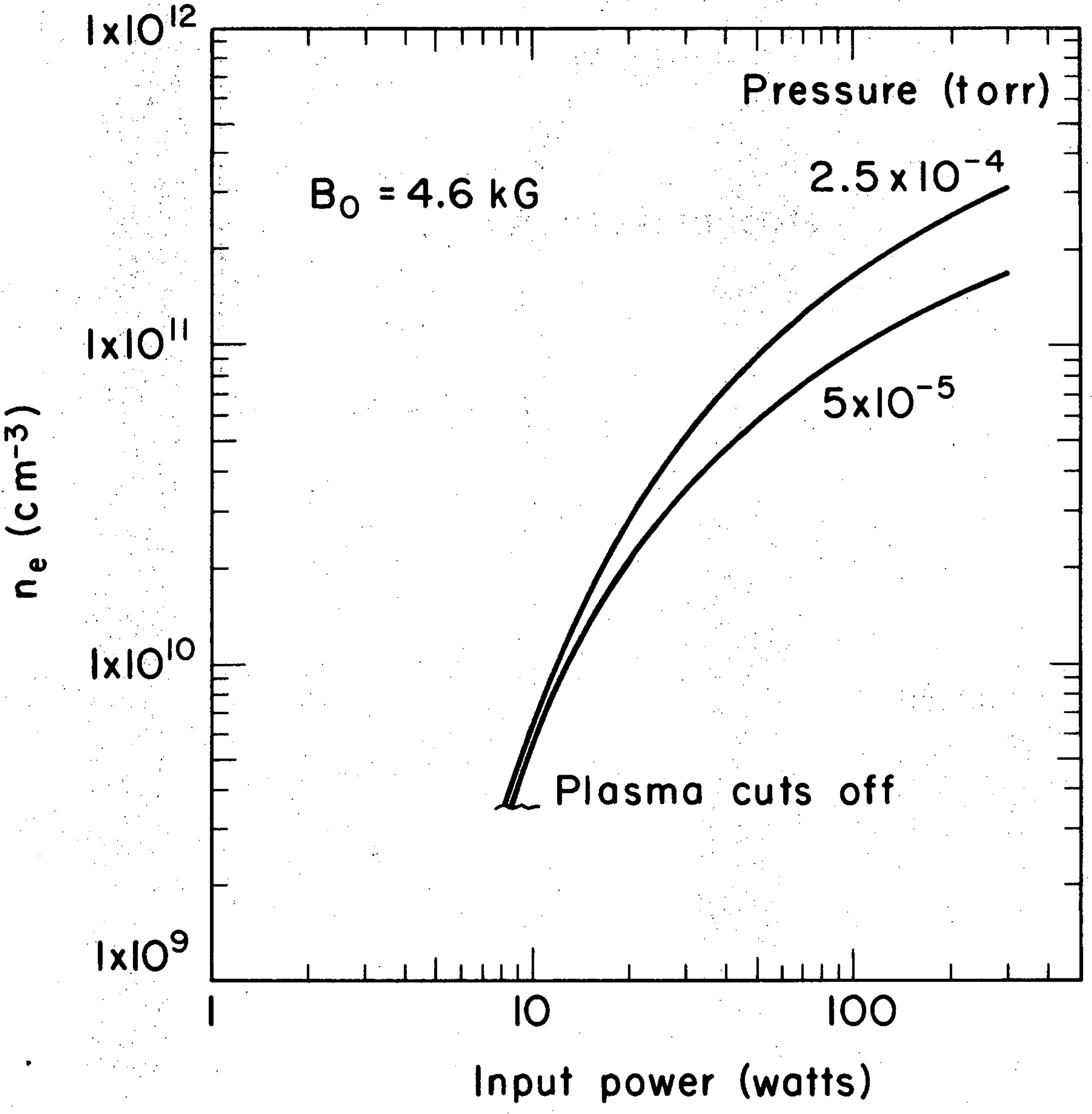
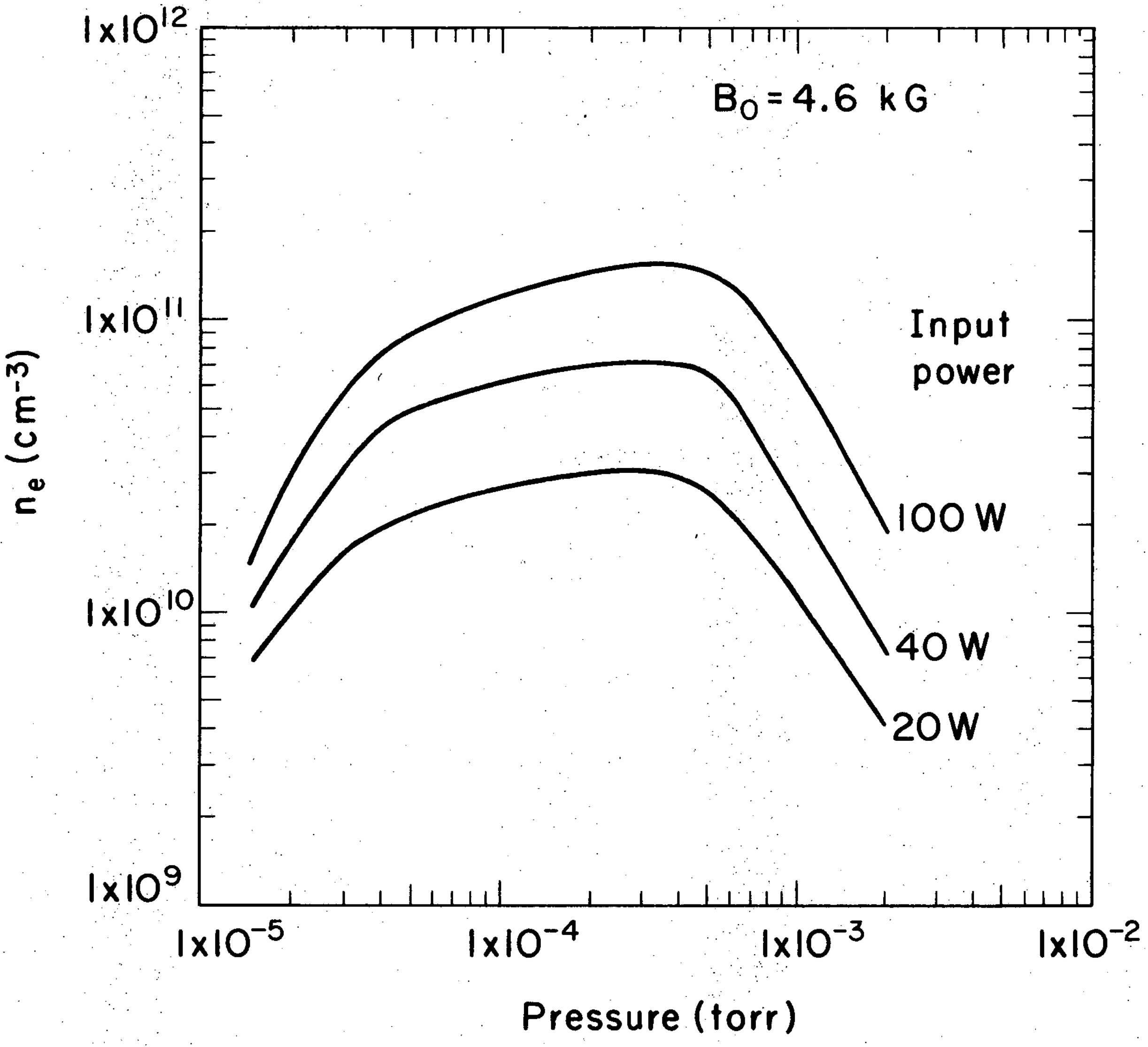

10 GHz, 1kW
PIN
Microwave generator
Low pass
High pass and phase shift
P.M.
Upstream phototube
P.M.
Downsteam phototube
Microwave interferometer
Lisitano coil
H_2 Inlet
Pump
Region I
Region II
Langmuir probes
B_0 (kG)
10
5
0.5
1.0
1.5
Z (m)
XBL706-3032

Fig. 1



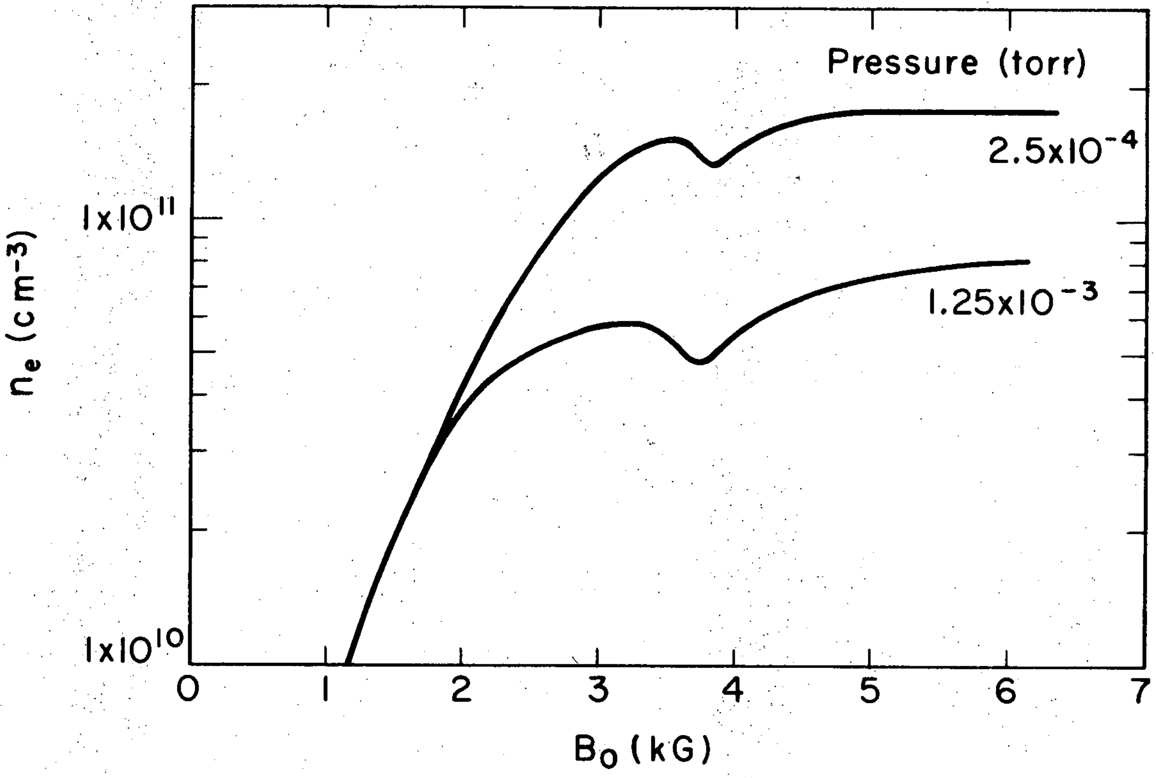
XBL705-2809

Fig. 2



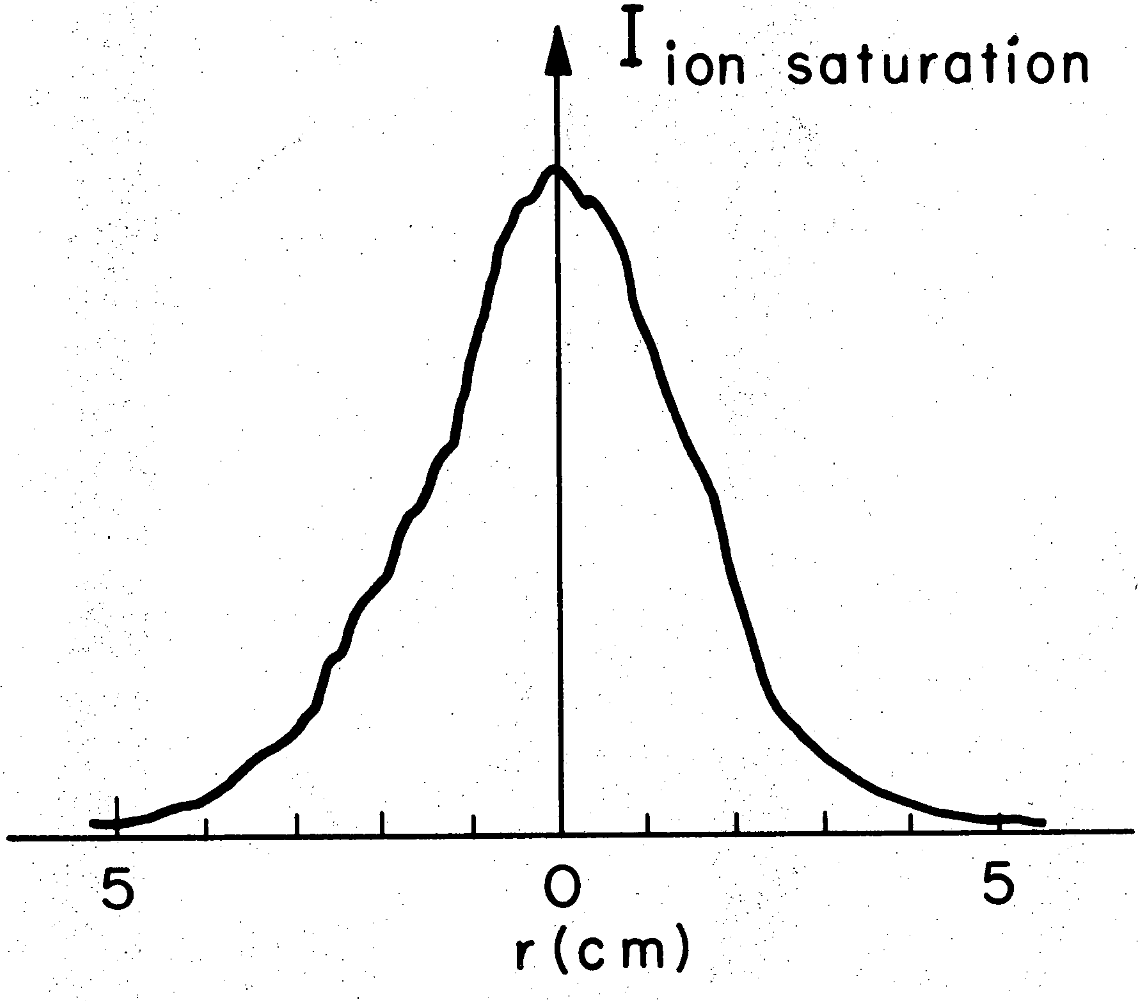
XBL705-2810

Fig. 3



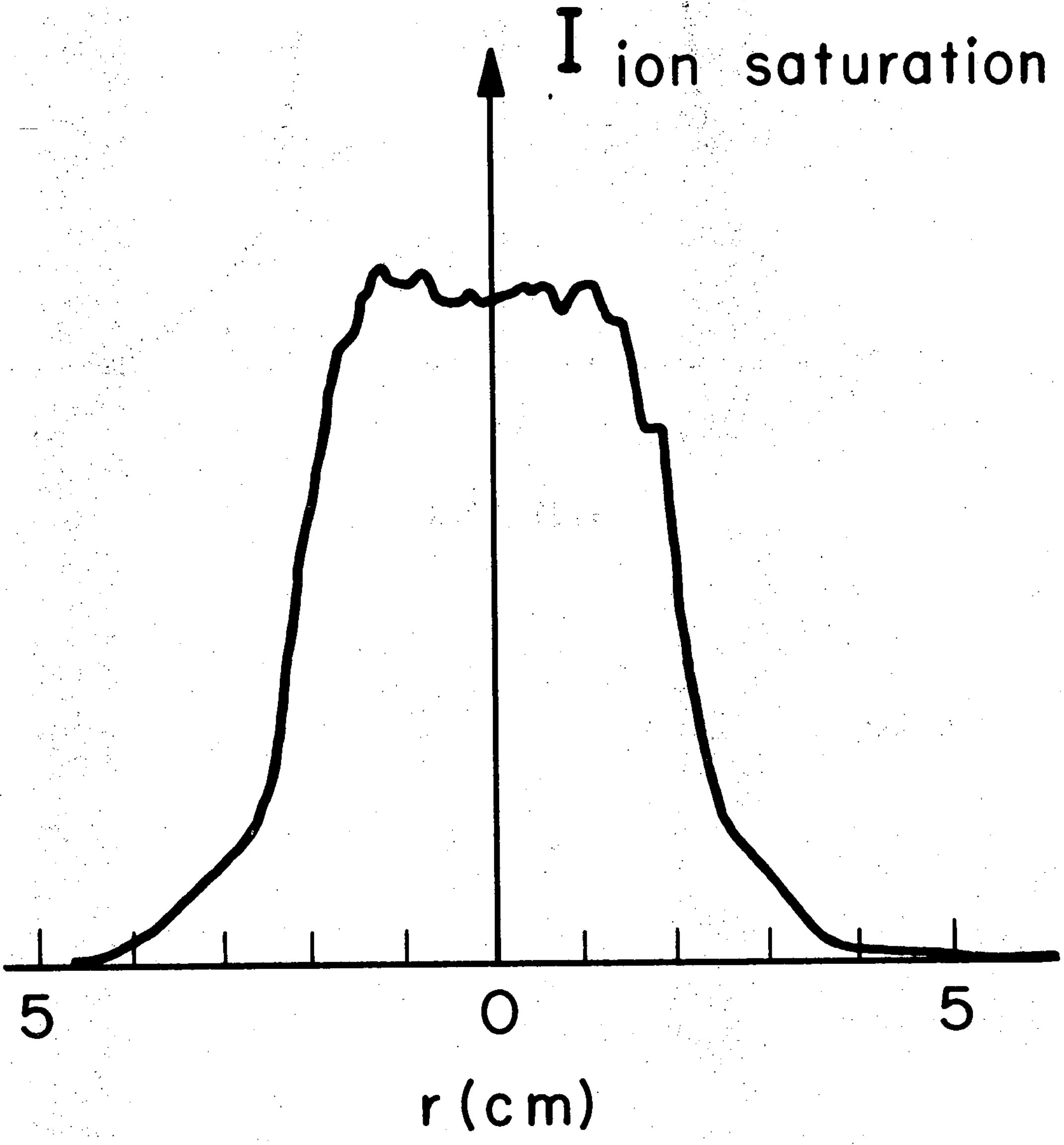
XBL705-2811

Fig. 4



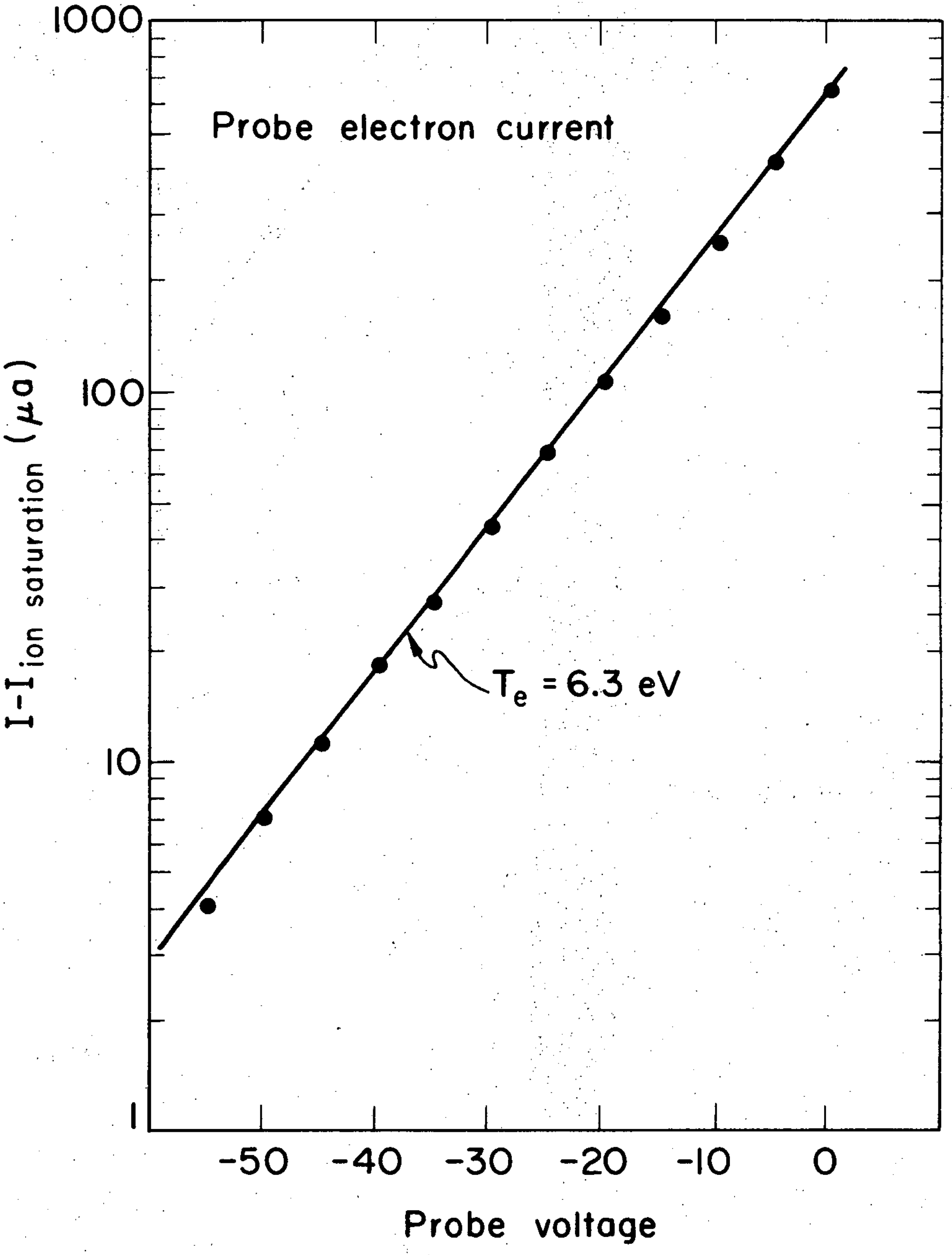
XBL705-2812

Fig. 5a



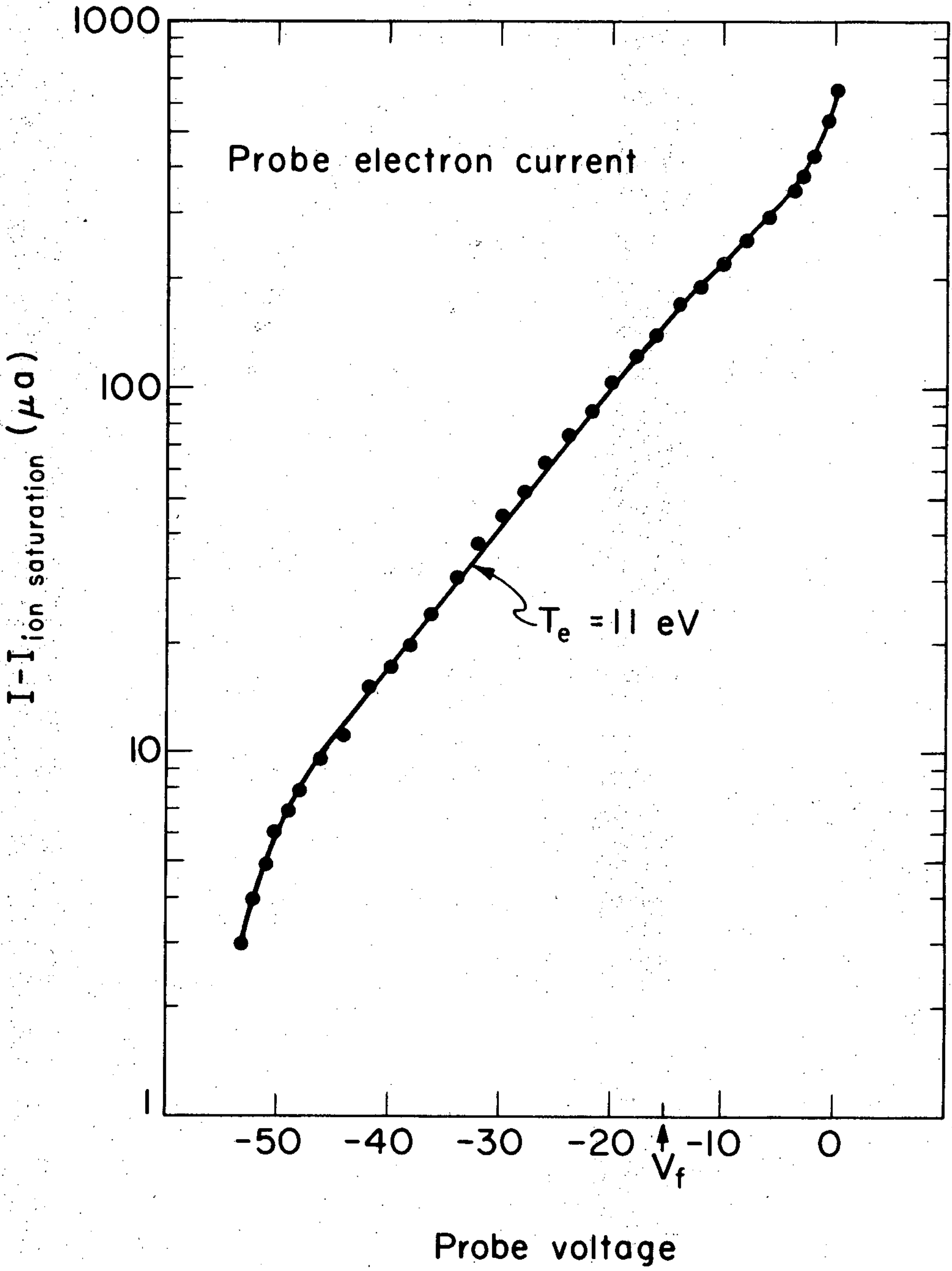
XBL705-2813

Fig. 5b



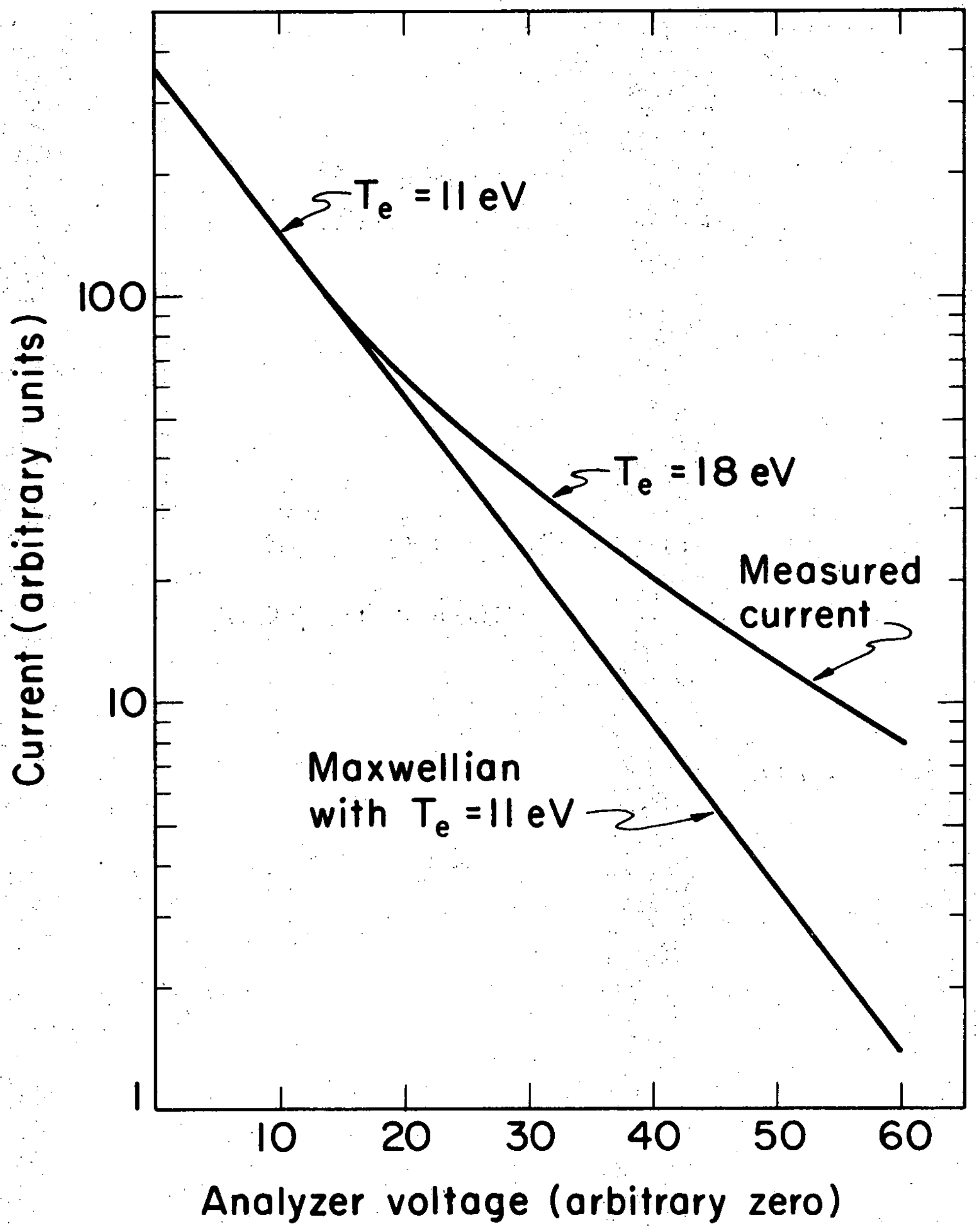
XBL705-2814

Fig. 6a



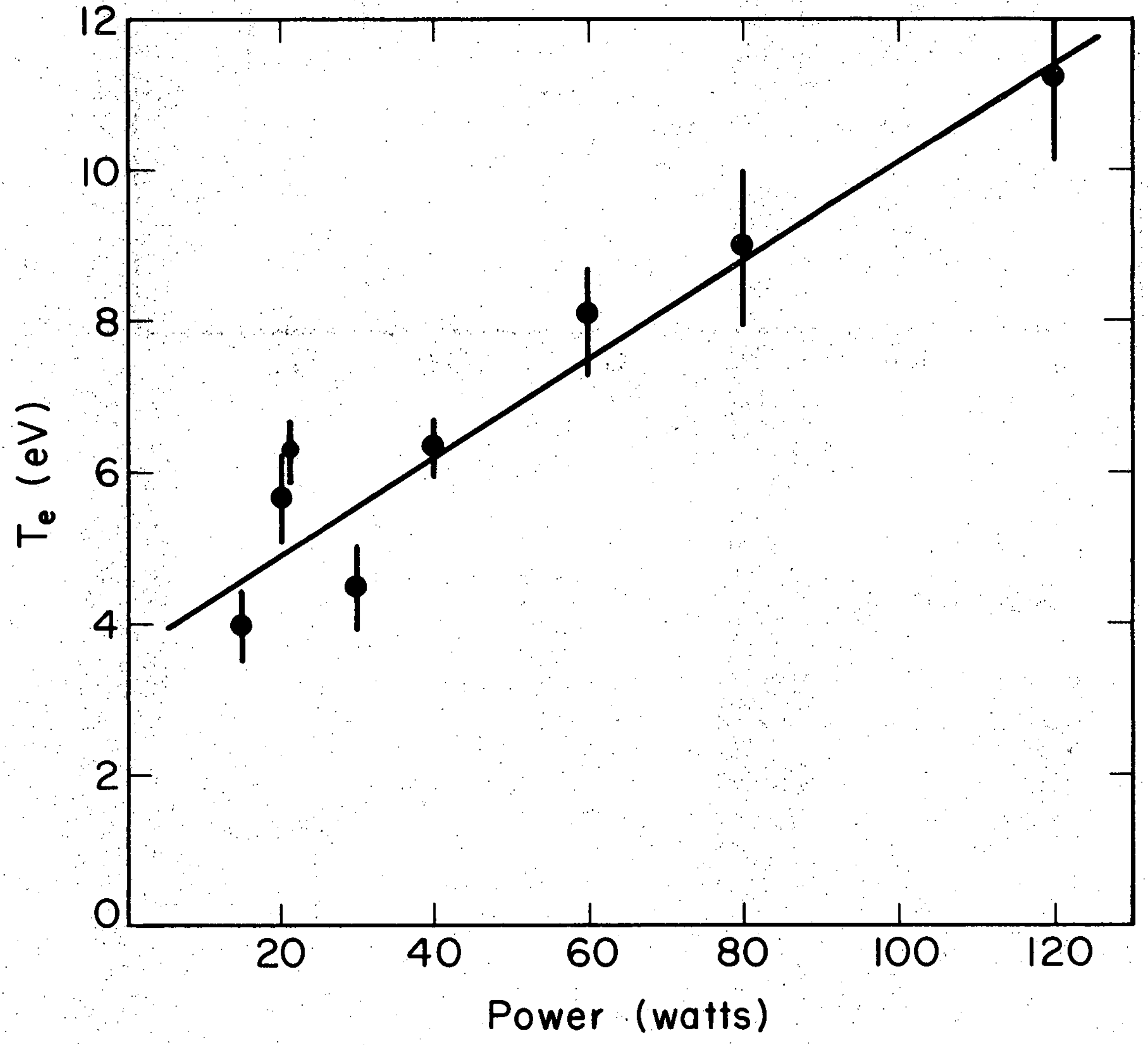
XBL705-2815

Fig. 6b



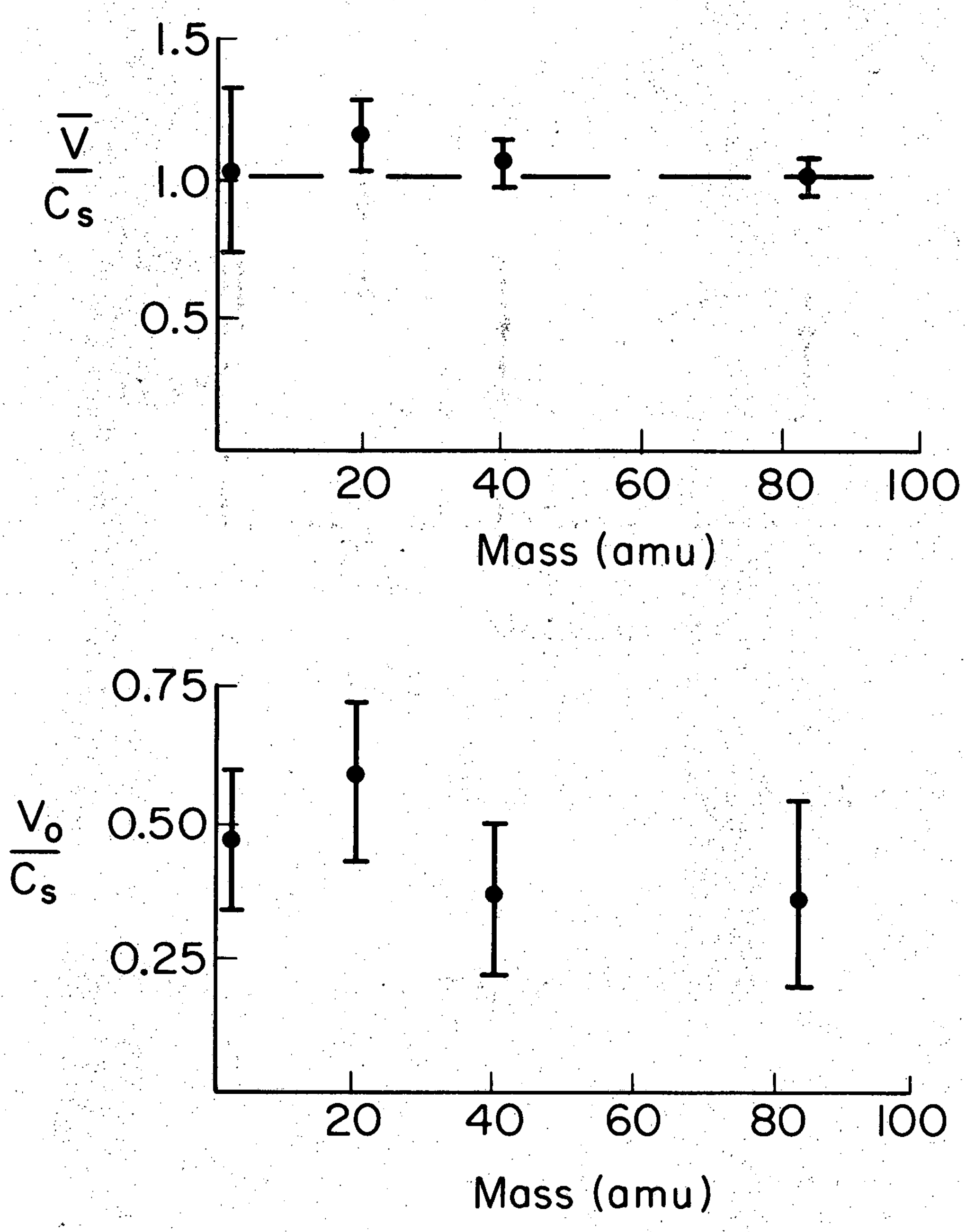
XBL705-2816

Fig. 7



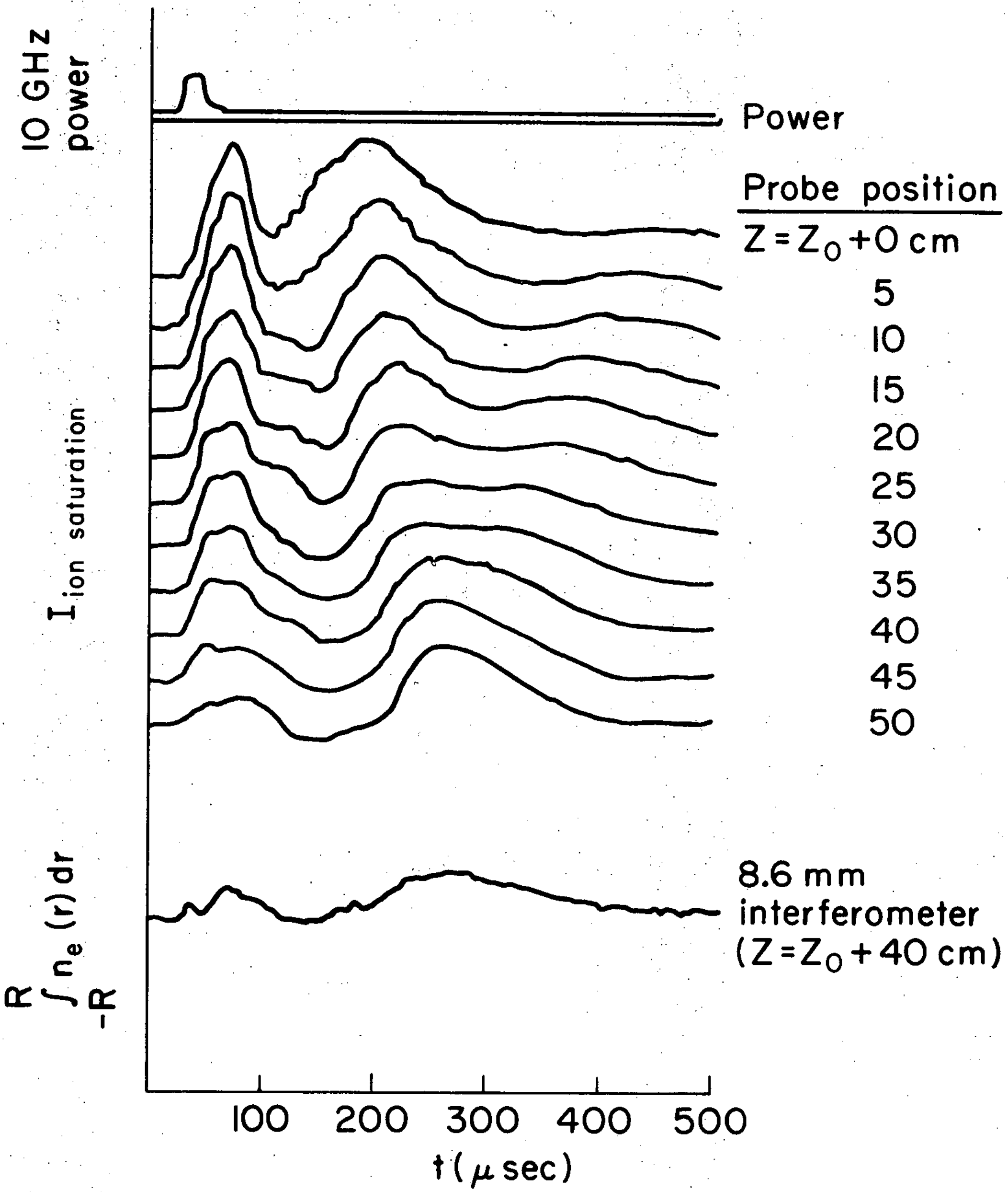
XBL705-2817

Fig. 8



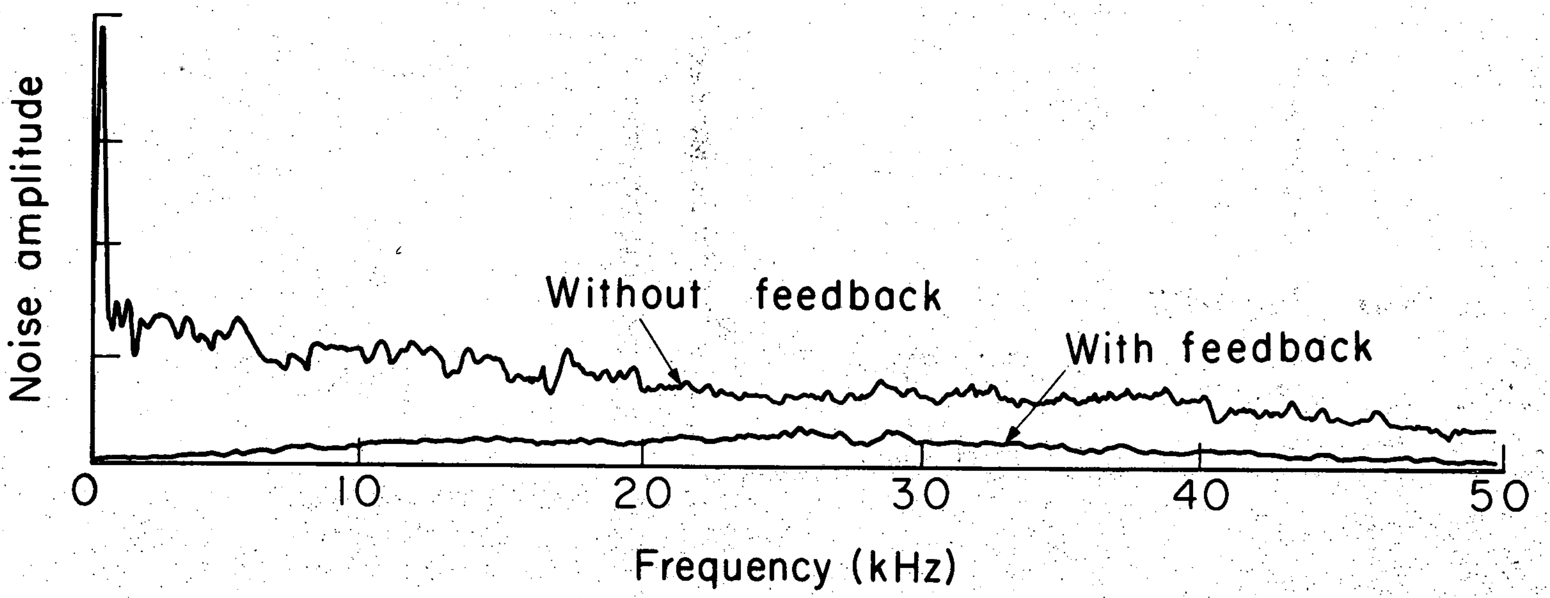
XBL706-3036

Figs. 9a, 9b



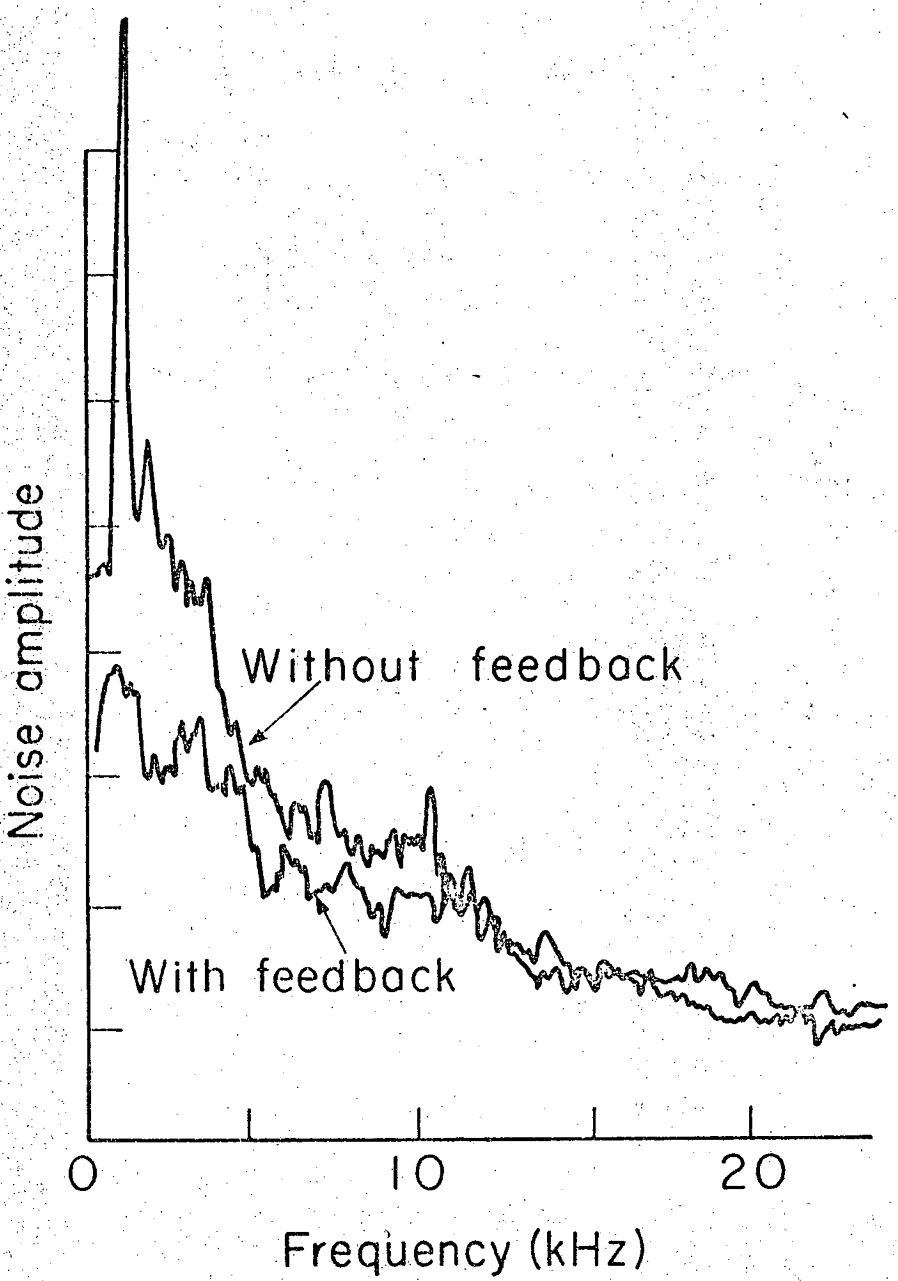
XBL705-2807

Fig. 10



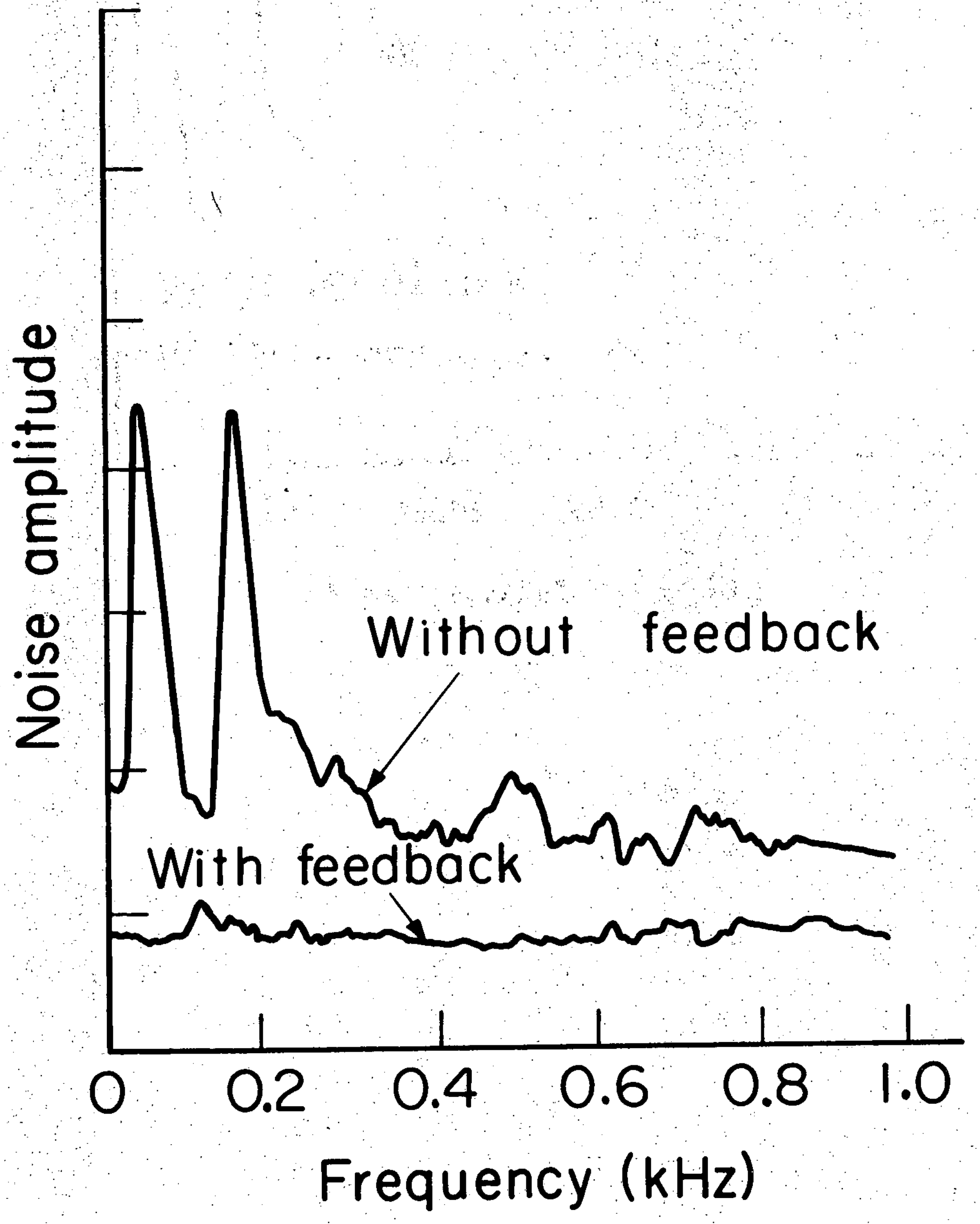
XBL706-3035

Fig. 11a



XBL706-3034

Fig. 11b



XBL706-3033

Fig. 11c

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