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A Review of the Beam Plasma Discharge*

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This review of strong beam-plasma experiments comes almost 20 years after the first modern experiments that defined what we now call the Beam Plasma Discharge (BPD). The basic high frequency interaction that drives the BPD was first proposed by Langmuir many years earlier to explain the paradoxically short scattering distance for the primary electrons in a low-pressure, hot cathode gas discharge. This was followed by a series of experiments over the next 20 years, that essentially confirmed this conjecture. Here, however, we shall restrict ourselves to researches subsequent to about 1958. An excellent survey of fluctuations in gas discharges is in [1].

Since that time there has been much experimental and theoretical work devoted to elucidating the details of the processes at work in the BPD. Today, there is nearly general agreement on how the discharge is formed, and a fair amount is known about the secondary, nonlinear processes that are driven by the basic high frequency, 2-stream interaction. However, we are still short of the kind of detailed engineering knowledge required to *design* a system that will have the most efficient energy transfer from an electron beam to a plasma of specified characteristics: $n(\bar{r})$ in a field $\overline{B}(\bar{r})$. This has become a "practical" problem since Beam Plasma Interaction (BPI) may be a useful way to heat the electrons of a highly ionized, hot ion plasma, confined in a min–B (Baseball) magnetic field. In this case the plasma parameters, $n(\bar{r})$, are fixed by external means. How does one select the optimum design of electron gun? What power level? What perveance? What pulse length? The answers to such questions are not available today, and intuition or rule–of–thumb must be resorted to.

Rather than survey the field historically, we will try to discuss what is known about the effects of the major independent variables in these experiments. These may be organized as follows.

ELECTRON GUN
- Perveance
- Power level
- Magnitude of $|v_\perp / v_\parallel|$ in initial electron beam
- Beam shape: solid or hollow
- Modulation

MAGNETIC FIELD
- Field shape
- Mirror
- Anti–mirror
- Min–B configuration
- Field strength $(\omega_{ce}/\omega_p \gtreqless 1?)$

NEUTRAL GAS PRESSURE (for BPD)

PLASMA SHAPE, $n(\bar{r})$ (for BPI)

This set of independent parameters leads to experiments in which one tries to determine

$$n_e(\bar{r}, t), n_i(\bar{r}, t), f(\bar{v}_e, t), f(\bar{v}_i, t)$$

that result from the BPD process. In order to follow the process, we observe the fluctuation spectrum $P(\omega, \bar{r}, t)$, and $f(\bar{v}, t)$ of the spent beam, as well as other macroscopic variables.

Because of the difficulties involved, one usually settles for grosser, ensemble measurements such as

$T_{e,i}$ of the bulk

Te_h of the hot electrons

Diamagnetism $(nev_\perp)$, etc.

The theory of the BPD began, of course, with simple linear models. These were followed by quasi-linear models, and a few particle simulation studies. In assessing these, it will be necessary to understand the basic assumptions in the models, and how these compare with experimental facts.

The rapid development of the field has resulted in many nearly simultaneous publications that, although independent, nearly duplicate each other both in approach and results. Thus the specific references will be to papers best known to the author, even though others may have done the same work, maybe earlier. For this, we can only apologize!

An important early review of the Beam Plasma Interaction (theory and experiment) is contained in [2]. A recent review of BPD experiments along somewhat different lines than this report is in [3].

BASIC IDEAS AND PHENOMENA

The linear theory predicts that slow, electrostatic waves can propagate along a magnetized plasma column, and that an electron beam flowing along the axis of the plasma may excite unstable (growing) waves, at a number of specific frequencies and bands. These instabilities correspond to synchronous interaction with forward or backward waves, and to reactive medium amplification [4], [5], [6].

The linear partial differential equation of the system is generally solved for the sinusoidal steady state, resulting in a dispersion equation $F(\underline{\omega}, \underline{\bar{k}}) = 0$ where either ω or k (or both) may be complex. The solutions may be for plane waves, in which case $\underline{\bar{k}} = \underline{\bar{k}}_\perp + \underline{\bar{k}}_\parallel$. For finite radius, cylndrical systems, one adopts the waveguide technique and finds the transverse behavior for a given mode $\underline{\bar{E}}(r, \theta)e^{(\omega t - k_\parallel z)}$, and then we have $F(\underline{\omega}, \underline{k}_\parallel) = 0$. One may then assume real $k_\parallel$ and find the corresponding complex $\underline{\omega}$, or vice versa. The former case corresponds to fields growing in time (absolute instabilities), the latter to fields growing in space (convective instabilities). As we shall see, the experimental evidence is now firm that the instability is convective in a uniform (anti-mirror) B field. Despite this, much of the quasi-linear theory and computer modeling proceeds from the assumption that the linear instability is characterized by complex ω and real k.

In experiments, one observes a major rf emission close to the upper hybrid frequency. If $\omega_p > \omega$, this is at $\sim \omega_{pe}$. There is also a wide band of lower frequency emission extending from ω_{ce} down to very low values. Some details of this band have been studied, but they are very complex and not thoroughly understood.

In most experiments on the BPD, the minimum neutral gas pressure required to ignite the discharge is high enough so that the steady state condition reached within a few μ sec is $\omega_p > \omega_{c\epsilon}$, often by factors of 5–10. There are few experiments on beam plasma interaction when, in the steady state, $\omega_p/\omega_{ce} < 1$.

If the magnetic field is an anti–mirror, a beam plasma discharge is formed with $Te \approx V_i$ (the neutral gas ionization energy). If the field is mirror shaped, a small population (few percent) of the electrons is heated to very large energies—as high as 200-400 kev, although beam injection energies are only a few kev.

In a well developed BPD, the induced low frequency fluctuations of the plasma are very strong, and significant ion heating and acceleration is observed.

Velocity analyses of the emerging beam indicate that the initial very narrow distribution becomes widely smeared, and estimates of power transfer to the plasma are as high as 20-30%of the initial beam power.

One set of experiments showed the importance of magnetic field strength. Diamagnetism ($neV_\perp$) increased by almost 3 magnitudes in going from ~3 to ~30 kG.

No detailed experiments have been reported with more complex field shapes such as Ioffe bars (superposed mirror and multipole fields) or baseball configurations, although preliminary experiments have been made.

Electron beams have been launched in various ways: solid pencil beams launched from Pierce type guns with perveance of about 10^{-6}; hollow beams from magnetron guns with perveance $5 - 15 \times 10^{-6}$; off-axis guns launching spiral beams; and hollow beams flowing through a cusped magnetic field and forming an ensemble of spiral beams. Power levels have ranged from a few watts to ~0.5 Mw. These beams may all be classed as space charge limited (SCL) beams, and may be operated continuously or in long pulses, .1—1 msec. Another class of beams has become important in recent years: the "intense" or "relativistic" beams operating in the range 0.1—1 Mev with currents of 10's to 100's of kAmps. Pulse lengths are usually $\lesssim 1\mu$ sec. These intense beams interact with plasmas in some ways like the SCL beams, generating intense microwave radiation in the self-generated plasma. However, they will be only briefly discussed here, mainly because of the author's lack of direct experience in the field.

Most experiments with the BPD using SCL beams are in the pressure range $10^{-5} - 10^{-3}$Torr; however, there have been experiments up to about 50 Torr with intense beams.

In uniform fields (anti–mirrors), the measured instability is clearly convective: complex $\underline{k}$ and real ω. There are a few measurements of the spatial variation of the field in mirrors, but the results are unclear and further studies are required.

In the following sections we shall examine these matters in greater detail.

POWER SPECTRUM

In the evolution of the BPD, after the beam is first turned on we start with $\omega_p \ll \omega_{ce}$ and induced oscillations begin at about ω_{ce}, when the plasma density created by beam impact on the neutrals reaches some critical density. It is generally believed that this is an interaction between the backward wave of the upper hybrid branch, and is an absolute instability. The oscillations are strong enough to completely disrupt the beam and prevent it, momentarily, from reaching the collector [7]. The oscillatory energy induced in the plasm electrons is sufficient to ionize the surrounding gas; and with $dn/dt \; \alpha \; n$, the growth of plasma density becomes exponential. The density continues to grow so that finally $\omega_p > \omega_{ce}$, at which time the oscillations appear at the frequency ω_p. The instantaneous frequency varies rapidly and is well correlated with fluctuations in ω_p[8]. When $\omega_p \rightarrow n\omega_{ce}$ there is a strong damping indicative of electron cyclotron damping [8].

The nonlinear evolution of the oscillations is complex. In experiments with low power beams (1000 v, 1 mA) interacting with a pre-formed plasma, the parametric down-conversion from the primary ω_{UH} oscillations can be followed accurately, and one observes the excitation of ion acoustic waves [9]. With higher power beams (kw's) the low frequency spectrum becomes very broad ("turbulent"). Strong ion-acoustic oscilations are observed, and ions are accelerated to energies in excess of 100 ev. [10], [11], [12], [13], [14], [15], [16].

The linear dispersion equations of beam plasma interaction predict growing waves at very low frequencies [17],[6]. However, it is not clear from the experiments if the direct excitation of these waves ever competes with the electronic oscillations at ω_{UH}. The observed low frequency oscillations are generally attributed to nonlinear processes driven by the high frequency oscillations.

In a uniform B field, with beam powers of several kw, there is a nearly continous (time averaged) spectrum extending from ω_{ce} down to less than 100 MHz with no obvious structure.

Finally, there is a flute-like instability in the range 10—100 kHz. This is beam-driven and is not observed in the after-glow plasma.

The convective nature of the ω_p instability is best demonstrated by some unpublished measurements made in our laboratory [1]. The discharge was excited by a magnetron injection gun (~3 kv, 2.5A) in a long uniform field. (Similar clear evidence of the convective nature of the instability is given in [14] for a low power BPD (1 kv, 30 mA)). Measurements were made through narrow YIG filters in order to concentrate on a desired instantaneous frequency. Fig. 1 shows $|E|^2(z)$ growing exponentially and then saturating. Interference measurements between a fixed and movable probe yielded phase velocity, or $k_{||}$. From a series of such measurements, the curves of Fig. 2 were constructed showing $Im(k_{||})$ and $Re(k_{||})$ vs. f. The pronounced dips in $Im(k_{||})$ at $n\omega_{ce}$ correspond to the earlier observations in [8]. The phase velocity is nearly equal to the beam velocity. The behavior of both the $Re(k)$ and $Im(k)$ resembles the reactive medium instability [6] with maximum gain at ω_p.

The transverse behavior of the fields is unexpected. In Fig. 3 we show $|E|^2(\theta)$, measured at constant radius around the beam and at an axial position well before saturation. Also shown is the angular cross-correlation between oscillations detected by a fixed and by a rotatable probe. Superimposed, is the beam current measured just outside the gun. The current dips correspond to the location of thin wire suports holding a shield in front of the cathode. The correspondence between the limits of correlation and the current dips is striking. Similar, but qualitative, results are reported in [15]. One is lead to picture a system consisting of several separate, parallel, beamlets, each driving its own instability. The system does *not* behave as a simple plasma waveguide with a well-defined transverse mode structure. The separate beams could have been produced by the Kyhl-Webster instability that afflicts annular or strip beams in magnetic fields [18]. This is a "dc" or configuration instability driven by the space charge field of the beam. It amplifies initial deviations from perfect cylindrical symmetry, and the current dips caused by the wire supports probably caused this beam to break up accordingly. Unfortunately, no measurements were made at the time to confirm these speculations; although we have seen the break-up of a hollow beam in a different plasma experiment.

The spatial behavior of the high frequency oscillations in the *mirror field* BPD has not been as carefully studied. Early measurements [8] are difficult to interpret as either convective or absolute instabilities. If the instability turns out to be absolute, one may conjecture that the convective instability of the uniform field case is transformed to an absolute instability by the positive feedback arising from the trapped high speed electrons. (In high gain klystrons, the collector must be carefully designed to prevent high speed, reflected electrons from re-entering the interaction region and causing regeneration or positive feedback.)

The analysis of the mirror system is complicated by the axial nonuniformity of n and $|B|$. It is generally agreed that the detected frequency corresponds (roughly) to ω_p at midplane, but not much more can be said quantitatively.

The correlation between the instantaneous high frequency oscillations and density was first shown in [8]. Fig. 8 shows the instantaneous frequency plotted against the electron density determined from Langmuir probe

[1] These experiments were made by J. Mangano in the MIT Research Laboratory of Elecronics, Private Communication.

curves in the above experiment. The probe signals (V,I) were passed through gates activated by the output of a narrow band YIG filter tuned to a specified frequency in the range of ω_p. (In this way, a complete probe curve was plotted for each frequency and it was possible to compute the instantaneous value of n that corresponded to the instantaneous value of the frequency.) The wide fluctuations in n are striking. Fig. 5 shows the time averaged "ω_p spectrum" taken with somewhat lower beam power than in Fig. 4. The wide, and rapid changes in ω_p, apparently driven by changes in density n, are difficult to explain. The time constant for ionization given the low neutral densities within the plasma and an electron temperature $Te \approx 20$ ev is 10's of μ-seconds, while the fluctuations are much more rapid. Thus, it is probable that strong, low frequency oscillations are modulating the density in the path of the beam.

The time-averaged low frequency spectrum of the above experiment shows no particular structure except a very sharp upper cut-off at ω_{ce}, Fig. 6. Since we know that ω_p is fluctuating wildly, we can assume the same is true of this spectrum. A desirable experiment would be to gate the spectrum analyzer with the appearance of a particular value of ω_p, as was done for the probe curves described above. In this way, one might hope to observe some structure that could be interpreted.

The time correlation of the density jumps has been studied in [10],[11] and related to the detailed shape of the energy spectrum of the emerging beam. Ion acoustic waves [12] are shown to be excited by the very rapid ionization that occurs in the BPD. These waves in turn are shown to accelerate ions, and also to modify the original concentration of the plasma so that the high frequency oscillations are momentarily quenched. The relaxation time is shown to be related to the ion acoustic oscillations.

ELECTRON BEAM PARAMETERS

The evidence is strong that higher beam perveance results in a more intense plasma discharge, although few such comparisons have been made with constant beam power. In one experiment [19], in a mirror field, the cathode of a magnetron gun was temperature limited to emit a current of only $\frac{1}{2}$ Amp (instead of its usual 10 Amps). At 10 kv, this produced a weak BPD, and no X-ray emission was observed. With the voltage ***lowered*** to 7 kv, X-ray emission began. The effective perveance was higher at the lower voltage. Under space charge limited conditions, X-ray intensity increased continuously with increasing voltage. In some experiments using a triode magnetron gun [20], the microperveance was variable over the range $4 < K < 28$ by controlling the voltage on the anode adjacent to the cathode. Beam power was kept constant (at 6.3 kw) by controlling the final acceleration voltage. The power absorbed by the plasma was maximum at about 10μ pervs, falling off to about half at 28. It is not known if the optimum at 10μ pervs is a true optimum of this single variable, or if the control anode caused other changes in the beam, such as the ratio of $v_\perp/v_\parallel$, which we shall see is important, too.

In mirror magnetic fields, the intensity of the discharge, as measured by the hot electron temperature, is a strong function of beam power [21]. In a 600G , 3.6 mirror ratio field, using a magnetron gun of 15×10^{-6} perveance, T_h varied between 1 and 35 keV with $T_h \; a \; V^3$ (or $T_h \sim P^{6/5}$ if perveance is assumed constant).

The importance of the perpendicular beam velocity was first pointed out in [8]. A spiraling pencil beam produced a discharge at a critical gas pressure about 1/10th that required for an axial beam. Later experiments [22],[23] with hollow beams fired through a cusp confirmed these observations. Given the gyratory trajectories, one might expect induced oscillations at ω_{ce}; instead, oscillations were observed at about f_p, 8 GHz, with $f_{ce} \approx 2.8$ GHz. In this respect, the behavior is superficially like that of the BPD with $v_\perp/v_\parallel = 0$.

In experiments with a relativistic beam (120 kv, 8-10 kA), a magnetic lens was used to control $v_\perp/v_\parallel$, producing values as high as 0.5. It was shown that the radiated rf power increased monotonically with the value of $v_\perp/v_\parallel$. Peak powers of 60 Mw at 12 GHz were generated.

In similar, but very low power experiments, (200 v, 1 mA, 13 Gauss) with a hollow beam penetrating a cusp [24], it was shown that the oscillations were at about ω_p; but ω_p limited itself to steady state values of about $n\omega_{ce}$ (always, somewhat greater).

More powerful experiments were reported with SCL electron guns mounted at an angle to the magnetic field [33], the plasma heating was greatly enhanced over the case with parallel injection for which $v_\perp/v_\parallel \approx 0$.

Since $v_\perp$ seems to play such an important role in determining the intensity of a BPD, we need finer grain data. Does the effect grow continuously as $v_\perp/v_\parallel$ varies over the range from 0 to some maximum? Or is there a threshold, below which the electrostatic interaction driven by $v_\parallel$ dominates; and above which $v_\perp$ dominates?

The beam launched by a magnetron injection gun can exhibit a wide range of $v_\perp/v_\parallel$, depending on the electrode shapes and on the parameter $\frac{\sqrt{V}}{B}$ at the gun. We are making computer simulations of magnetron guns by techniques similar to those used for studying gyrotron guns [2]. Our problem differs from the gyrotron in that we operate space charge limited rather than temperature limited, and the angle between the cathode surface and $\overline{B}$ is small. The gun we have analyzed is typical of those used in past BPD experiments, with perveance $\approx 10 - 15 \times 10^{-6}$, depending upon the value of $\frac{\sqrt{V}}{B}$. When this parameter was small ($V = 1$ kv) the emerging beam was very laminar and $v_\perp/v_\parallel \lesssim .04$. Increasing V to about 3 kv caused $v_\perp/v_\parallel \approx .14$. Although this value seems modest, recall that firing the beam into a mirror from outside may cause it to reach a B field 3–5 times that at the gun. This would multiply $v_\perp/v_\parallel$ by about 2 and bring it into the range of the experiments reported above.

The conventional BPD can be modified so as to take on some of the attributes of the PIG discharge. This was done in a reflex, or double cathode geometry [26], and later with a single beam [15] configuration. As in the ordinary BPD, the interaction was accompanied by strong high frequency radiation, and by very intense X-ray production. In addition, the injected and trapped primary electrons depressed the potential on the axis to produce a strong, radial "dc" field. It was believed that this was responsible for the observed ion heating of some hundreds of e.v.

BEAM MODULATION

In addition to the d.c. properties of the electron beam entering the plasma, the time variation is of interest. One can modulate the beam in various ways, and there have been studies of the effects of such modulations covering the frequency range from the upper-hybrid (GHz) down to the ion cyclotron frequency (MHz). With one exception, the modulation has been "axial": grid controlled curent modulation or velocity modulation. The exception was an experiment using "transverse modulation".

Modulation of a beam at GHz rates, corresponding to ω_p, is subject to the usual vacuum tube difficulties of transit time and coupling at centimeter or millimeter wavelengths. Grid modulation of powerful beams becomes essentially impossible, and velocity modulation by cavity fields, or distributed modulation by traveling wave structures (helices) must be used. In the BPD, oscillations at 10–30 GHz (ω_p) are easily excited by beams of 5–10 kev energy, whose radii greatly exceed the usual criterion $\omega b/v_o \lesssim 2$ for coupling to the fringing fields of cavities or helices. Because pre-modulation of such large diameter beams at these frequencies is so difficult, it may have no "practical" applications. Nevertheless, it has been possible to make experiments that are of

[2]The work is by A. Ezzeddine , Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Mass.

scientific interest. It was shown in [14] that a strongly modulated beam at ω_p has a faster growth rate of the convective instability; but the saturated level of oscillation in the plasma hardly differs from the case of the unmodulated beam.

The effect of pre-modulation of the beam on the nature of the BPD was extensively studied in [27]. It was shown that the width of the BPD spectrum could be narrowed dramatically, and the conditions for quenching the discharge by strong modulation were established.

Low frequency beam modulation as a way of enhancing ion heating has been studied, using density modulation at $n\omega_{ci}$ [28],[29], and *transverse* modulation [30]. Although ion heating was observed with density modulation at ω_{ci} [29] it was reported that for $n \gtrsim 5 \times 10^9/c.c.$ the heating disappeared. On the other hand, *transverse* (details unspecified) modulation of a 2.5 kev, 2 Amp beam produced effective heating within the BPD ($n \lesssim 10^{12}$,$|B| = 0.1 - 3$ kG), and ion temperature increased from 8–14 ev, unmodulated, to about 5 or 6 times higher with modulation [30].

Density modulation in the vicinity of ω_{pi} [31] was shown to excite well-defined resonances on the plasma column, and ion heating occured at these resonances. Ti reached 35 ev in a very low power experiment (beam power $\approx$ 1–3 watts). In the experiments of [28] the modulation frequency range was from below f_{ci} (840 kHz) to well over f_{pi} (~7 MHz). There was a tiny peak at f_{ci}, and a larger one at f_{pi}, and then the density of hot ions increased to very much higher levels at 60 MHz. No explanation was given for the increased yield at the higher frequencies. The experimental evidence of enhanced ion heating by modulated beams is strong. However, it is not clear if the heating is due to a direct interaction between the modulated beam and the ions; or if the modulation of the beam plasma discharge excites low frequency oscillations that couple to the ions.

MAGNETIC FIELD

The most dramatic effect of magnetic field shape is the production of hot electrons in mirror fields but not in anti-mirror fields [54], [3]. The hot electrons are characterized by a large ratio of $v_\perp/v_\parallel$. This is indicated by their very long life time in the afterglow plasma; in [19] it was reported that X-rays were detected as long as 2 seconds after the beam was shut off. It is generally assumed that these electrons are heated by an electron cyclotron interaction. Since there is little or no power detected at ω_{ce} (when $\omega_p > \omega_{ce}$), the resonance heating must occur by a Doppler shift that transforms the ω_p oscillations to ω_{ce} (or $n\omega_{ce}$) in the frame of the hot electrons. The very high energies observed, $>$ 100 kev, must be the result of multiple passes through a heating zone. This is possible for electrons trapped in a mirror, and primary beam electrons that are trapped by the BP oscillations may be the ones that are so heated. In an anti-mirror, there is no axial trapping, and therefore the process cannot even start. Large mirror ratios, 3–5, seem to be more efficient in generating hot electrons, than smaller ratios.

The effect of field strength has been studied by several authors. In [19] it was shown that the diamagnetic effect ($W_\perp$) increased monotonically with field strength, over a limited range (375–1125 G). In a later set of experiments [32], [33] the field was varied from 3–30 kG. $W_\perp$ increased by almost a factor of 10^3. At the highest fields reached, $\omega_{ce} \approx \omega_p/2$. (The beam power was 300 kw, and the density was $n = 7 \times 10^{13}$). Whereas, typical perpendicular energy levels are $nV_\perp \lesssim 10^{15}$ in the kGauss range, they reached levels of nearly 10^{17} in the high field experiments. Electron temperatures of 1–2 kev were reported. These two papers do not comment on the presence of "hot" electrons or the ratio n_H/n. In low field experiments in mirrors, the bulk of the perpendicular energy appears to be due to the small number of very hot electrons [19]. The authors of [33] state that maximum heating is reached at $\omega_p = 2\omega_{ce}$. However, the experimental curve shown in the reference is steep and shows no evidence that it would saturate at even higher field levels. If electron beams are to be employed for some aspects of plasma heating in CTR devices with their usual strong magnetic fields, it appears that the efficiency of beam plasma interaction (BPI) for heating may be much greater than has been observed in experiments at lower field strengths.

There have been a few experiments on plasma heating in combined mirror- and multi-pole (Ioffe bar) fields [34] and in Baseball fields [35] but these have been preliminary and no detailed results are yet available. In a hexapole field, at small radii $B_\perp$ is small, so that the cross section of a small diameter electron beam is nearly unaffected as it traverses the system. In a true min-B field produced by a quadrupole and a mirror, $B_\perp$ increases rapidly for $r > 0$. Thus, if the gun is located outside the mirror in a region of relatively weak B field, the beam will diverge along the "fan" as it goes through the mirror region. Whether this will reduce the effectiveness of the BPI has still to be determined.

A number of experiments have been made with $B = 0$. In [36] a 26 kv 8 Amp beam was used. The plasma produced was relatively thin, $\sim 8 \times 10^{10} cm^{-3}$. Although the emerging beam showed an energy spread of almost 15 kev, it had lost only 1–2%of its original energy. Other experiments have been made to simulate conditions in space, and they have been made in very large chambers. In [37] it was observed that the maximum frequency emitted was at $\omega_p/\sqrt{2}$, the surface mode of oscillation of the column. Photographs are shown of the light along the beam trajectory. The growth in intensity, and lateral spreading of the light can be interpreted as showing exponential growth, saturation,and decay.

NEUTRAL GAS PRESSURE

For parallel beams ($v_\perp \approx 0$) the critical pressure for the onset of the BPD in H_2 is $p \gtrsim 5 \times 10^{-4}$ Torr. The behavior over a range of pressures is reported in [38]. A modest beam 2-5 kev, 10–50 mA was used in a uniform field. They observed a rapid rise of plasma density from 10^9 to 3×10^{12} between 10^{-3} and 2×10^{-3} Torr, followed by an almost constant density up to 10^{-2} Torr. In mirror field experiments, we have observed that the X-ray intensity (flux and energy) reaches a peak at pressures slightly above the critical pressure, and then decreases at higher pressures.

It is clear that the blanket of neutral gas surrounding the plasma is an energy sink. Ions are cooled by charge exchange, and the energy needed to ionize and excite the neutral gas tends to clamp the bulk T_e at about 20 ev. An experiment is needed in which a "fully" ionized plasma is excited by a beam. The plasma trapped in a static mirror by injection of an intense plasma beam [39],[34] may be the basis for such an experiment. The experiment in [34] was a step in this direction. It is possible to produce a mirror trapped plasma of $n \gtrsim 10^{13}$, $Ti \approx 200 - 300$ ev, $Te \approx 20$ ev, and neutral pressure $p_o \lesssim 1 - 2 \times 10^{-6}$ Torr. A Ti-washer gun, located in a guide field outside the mirror peak, pulsed for $\sim \frac{1}{2}$ msec at 2-4 kA, is the source. Preliminary BPI experiments were made, but few quantitative data of the type indicated here were taken.

Although the detailed behavior of the BPD is very complex, a surprisingly accurate model based only on a gross energy balance equation and a particle balance equation has been developed [40]. The calculated densities and electron temperatures, as functions of neutral pressure agree rather well with the experiment.

THEORY

The theory of nonlinear behavior of the beam plasma interaction (a beam flowing through an externally produced, fully ionized, plasma) has been studied by many authors. The approaches have been: analytical (quasi-linear), and numerical simulation. With few exceptions, the studies have focused on a presumed temporal growth. The quasi-linear studies have proceeded from an assumed excitation by a real k spectrum and have followed the evolution of the interaction from the resulting complex ω spectrum. An example is [41]. Among the conclusions is the observation that the growth is limited by trapping of the beam electrons, and that the plasma continues to behave linearly.

Computer simulations have been carried out with the assumption of periodic boundary conditions [42],[43]. This model also leads to temporal growth. An alternative numerical model assumes a long (semi-infinite) plasma with a modulated beam injected at $z = 0$. This was studied for a beam-plasma amplifier [44] and for strong beam plasma interaction [45]. In these studies *convective* growth was observed. The equations studied are the same, the approaches differ in the choice of boundary, or initial, conditions. In one case, the assumption is of an inital noise-like variation of n along z that can be Fourier analyzed into a k spectrum. In the other case, a noise-like time variation is assumed at the plane $z = 0$. This is Fourier analyzed into an ω spectrum that modulates the incoming beam. *A priori*, it is not clear how one decides which model better represents the physical situation, so one must use the *a posteriori* method of comparing with experiments.

Fig. 7 [45] is a plot of the computed interaction between a finite diameter (disc) beam flowing in an infinite cross-section uniform plasma, magnetic effects were ignored. Fig. 8 shows the same situation for the case of a linearly growing plasma density (as would occur in one side of a mirror-confined plasma). The beam is initially velocity modulated by a wide noise spectrum spanning the range of $\omega_p(z)$. The growth is clearly convective, but the non-uniform plasma interaction is slower, with E field strengths (acceleration) less by an order of magnitude than for the uniform density case. With the disc-beam-non-uniform model, maximum a.c. field strengths of about $\sim 6 \times 10^3$ v/cm were found (beam $v_o = 5 \times 10^9$ cm/sec and $f_p = 10^{10} sec^{-1}$).

The experiments and these computations both show convective growth. However, the experimental observation of strong cyclotron damping in axially uniform plasmas, and the observation that mirror fields result in more intense BPD's (rather than weaker as predicted by the computer models) points to the importance of gyratory interaction as a contributing mechanism.

INTENSE BEAMS

Intense, "relativistic" beams are characterized by currents far in excess of the usual space charge limits. The linear theory of a beam in a neutralizing plasma predicts a maximum perveance of $\sim$ 200×10^{-6}, at which point a non-oscillating instability sets in [46]. By contrast, the so-called relativistic beams with $V \approx$ $300 - 500$ kv may have currents in excess of 10^5 Amps. Since a sizable fraction of the accelerating energy appears as transverse motion, the axial drift energy is less than the accelerating energy and the effective perveance far exceeds the above limit.

Less detail is available about the beam-plasma discharges initiated by such beams, than for SCL beams. The fact that pulses are short, typically $\lesssim 100$ nsec, and the interval between pulses is long, makes it much harder to collect fine grain data. Nevertheless, strong ω_p oscillations are detected, and it is generally believed that the interaction is the same as for the lower current beams.

An interesting experiment is reported in [47], [48] with a 100 kv, 10 kA beam, in a mirror (5 kG) magnetic field. The transverse velocity $v_{\perp}/v_{\parallel} = 0.4$ was high. They show that a group of high energy ions, approaching 20%, is formed by interactions with ω_{ci} oscillations, parametrically excited by the main electron interactions. With $v_{\perp}/v_{\parallel}$ small, there was only a few percent of such hot ions.

As this report was being completed, a publication appeared [55] describing the heating of a highly ionized plasma by a relativistic beam (1 Mv, 140 kA, 50 nsec). The plasma, produced by a plasma gun, had a peak density $\sim 10^{14} cm^{-3}$. The electron beam was fired into the decaying plasma so that the instantaneous density could be chosen at will. The magnetic field was ~4 kG with a mirror ratio of 1.2.

Another class of intense beams exists, that is even less well understood. These are streams from plasma guns. They were first studied in [49],[50],[51],[52],[53]. We have studied the plasma stream from a Ti washer gun in a uniform field $B \approx 2 - 4$ kG. It carries a *net electron* current of 100–400 Amps when the applied voltage and current are 100-200 v, and ~2000 Amps. The average plasma density is $\gtrsim 10^{13} cm^{-3}$ in the stream. The ions are observed to have very high values of perpendicular energy: exceeding hundreds of volts. The electron energy extends out to 600–700 eV. Most of the energy is perpendicular. Clearly, some very strong collective effects are at work here. We have examined the rf spectrum, and find very low power emanations in the microwave region. There is an indication of a "peak" around ω_{pi} but the data are still inconclusive, and one cannot say if this is another member of the two-stream instability family, or if the formation and disruption of a virtual cathode [52], with the consequent production of strong radial and axial space charge fields is the driving force.

SUMMARY

In this brief review we have concentrated on a few aspects of the complex set of phenomena characterizing the beam plasma discharge.

The evolution of the upper hybrid oscillations in the uniform B field is now reasonably well understood. In the mirror system our knowledge is much less complete. The wide spectrum (turbulent) of the low frequency oscillations is complex in nature and is poorly understood. Nevertheless, it is clear that significant ion heating results from parametrically induced oscillations. These, in turn, may be so large as to disrupt the high frequency oscillations, leading to a quenched behavior.

At high B fields ($\gtrsim 10 - 20$ kG) the energy transfer to the plasma is greatly enhanced, and may be of importance in CTR mirror experiments.

The efficiency of the BPI is greatly enhanced if the incident beam has an appreciable value of $v_{\perp}/v_{\parallel}$ ($\sim 0.3 - 0.4$), thus emphasizing the importance of careful gun design, integrated with the magnetic field profile in the particular experiment.

Pre-modulation of the beam enhances ion heating, particularly transverse modulation at ω_{ci}.

The experimental evidence that the basic instability is convective is a challenge to the theorists to reconcile the quasi-linear theory and its predictions with the experiments. The experiments indicate that a theory of the BPD must take into account the strong electron-cyclotron damping in order to properly describe the process.

The potential use of BPI for plasma heating in thermo-nuclear experiments raises a number of questions that have not been hitherto addressed. How does the transverse field of a min-B mirror affect the interaction? How does a strong BPI affect the plasma loss rate out of the trap? Is it more effective to deliver an "impulse" of energy, such as characterizes a relativistic beam, in a time $\lesssim 50 - 100$ nsec, or is the lower-power-longer-

duration of an SCL beam more effective? For moderate length plasmas (~1 meter) is there a beam injection energy so high that the growth length exceeds the plasma length?

Clearly, new experiments and theoretical efforts are needed.

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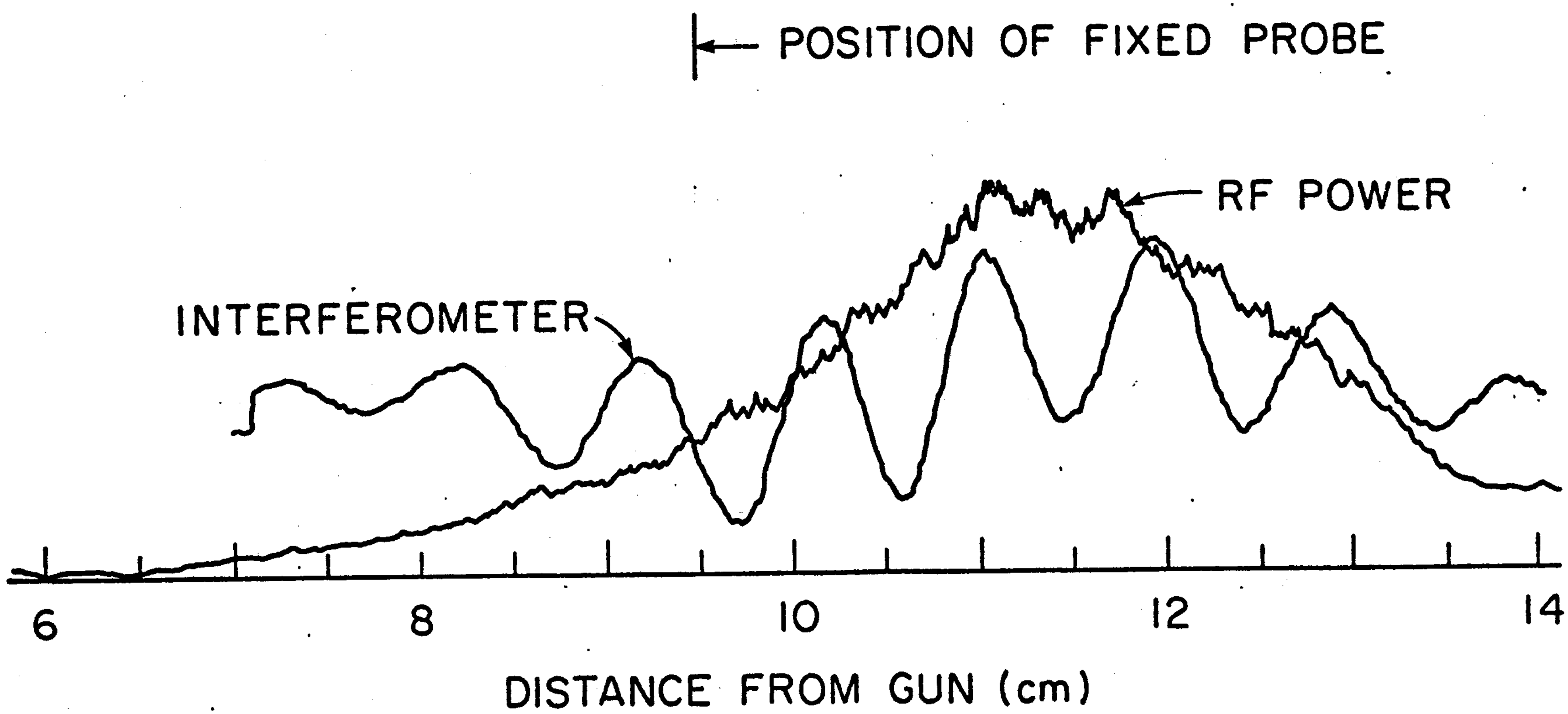
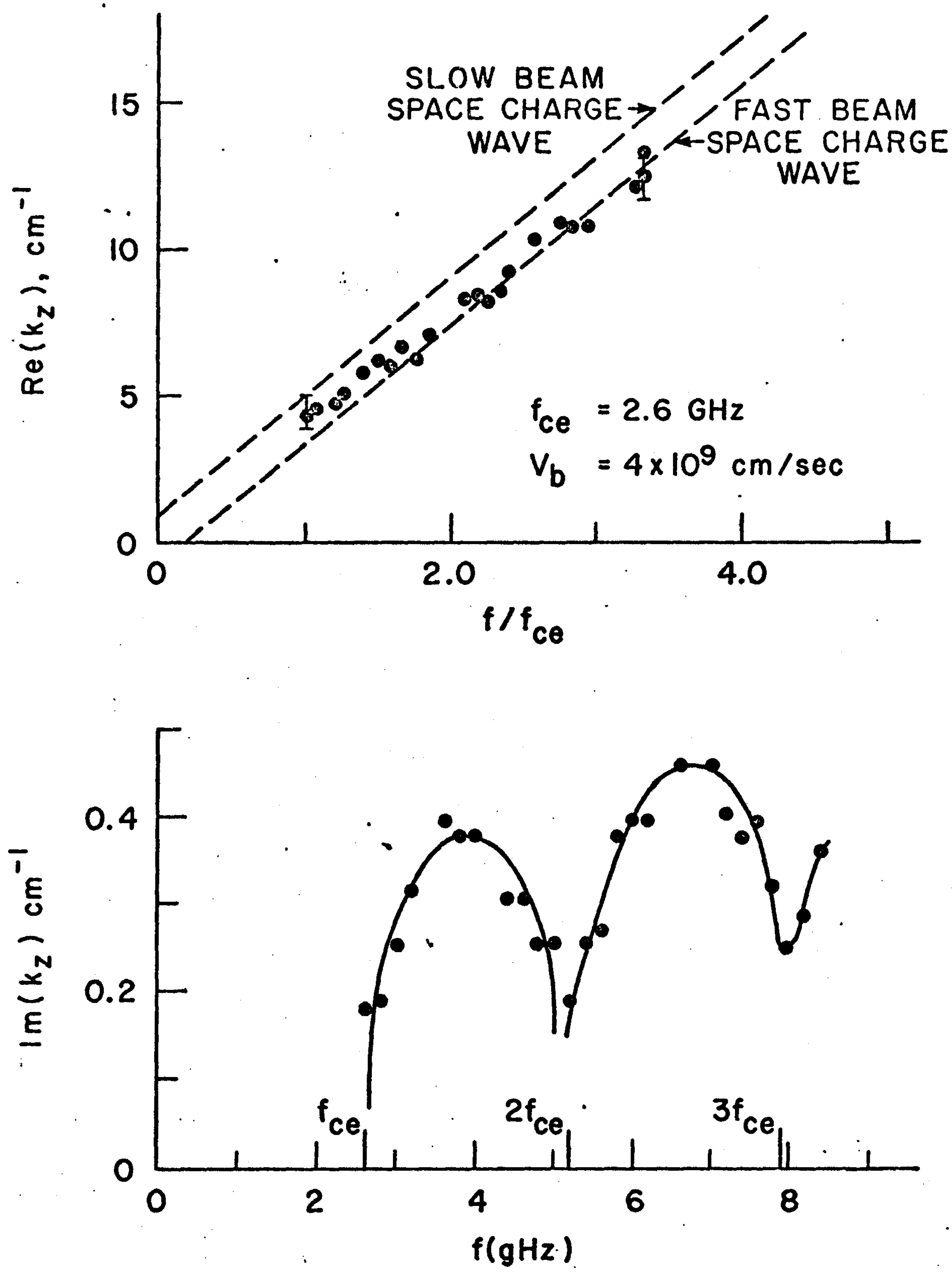

POSITION OF FIXED PROBE
RF POWER
INTERFEROMETER
6
8
10
12
14
DISTANCE FROM GUN (cm)

FIGURE 1



REAL AND IMAGINARY PARTS
OF k_z VERSUS FREQUENCY

FIGURE 2

MANGANO
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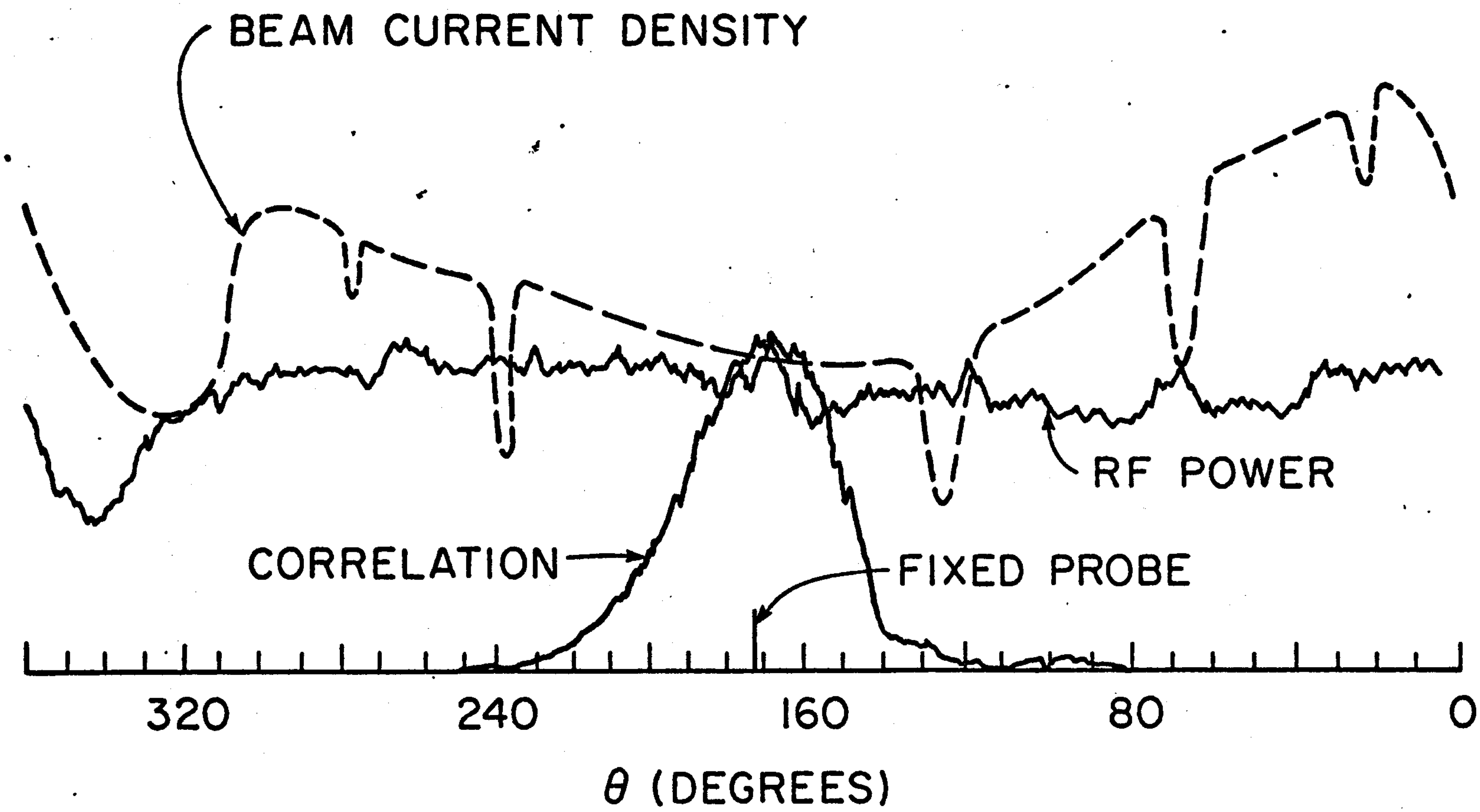
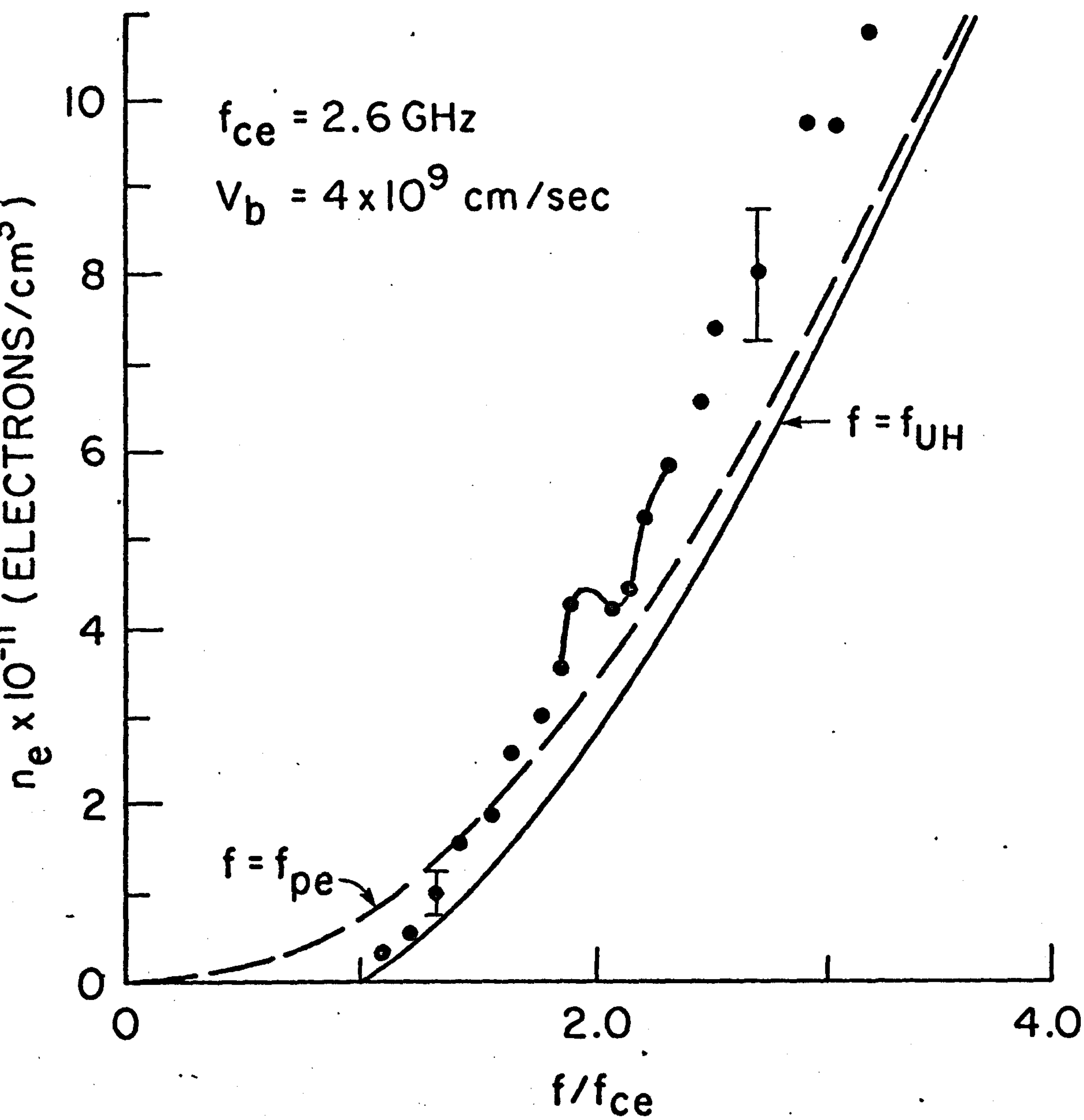


ANGULAR VARIATIONS IN HOLLOW BEAM

FIGURE 3



INSTANTANEOUS FREQUENCY VS. INSTANTANEOUS DENSITY

FIGURE 4

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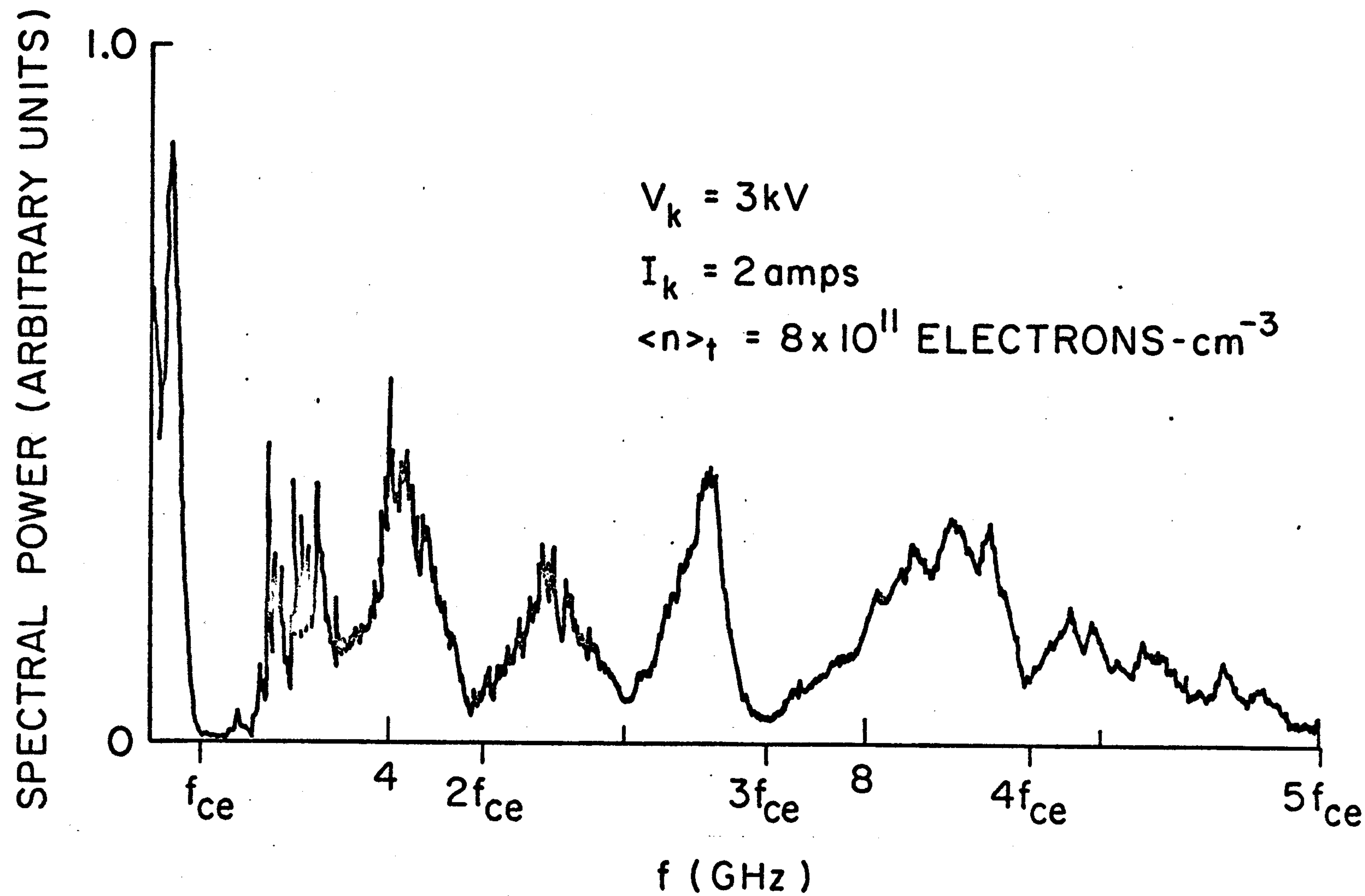

TIME AVERAGED SPECTRUM OF BPD

FIGURE 5

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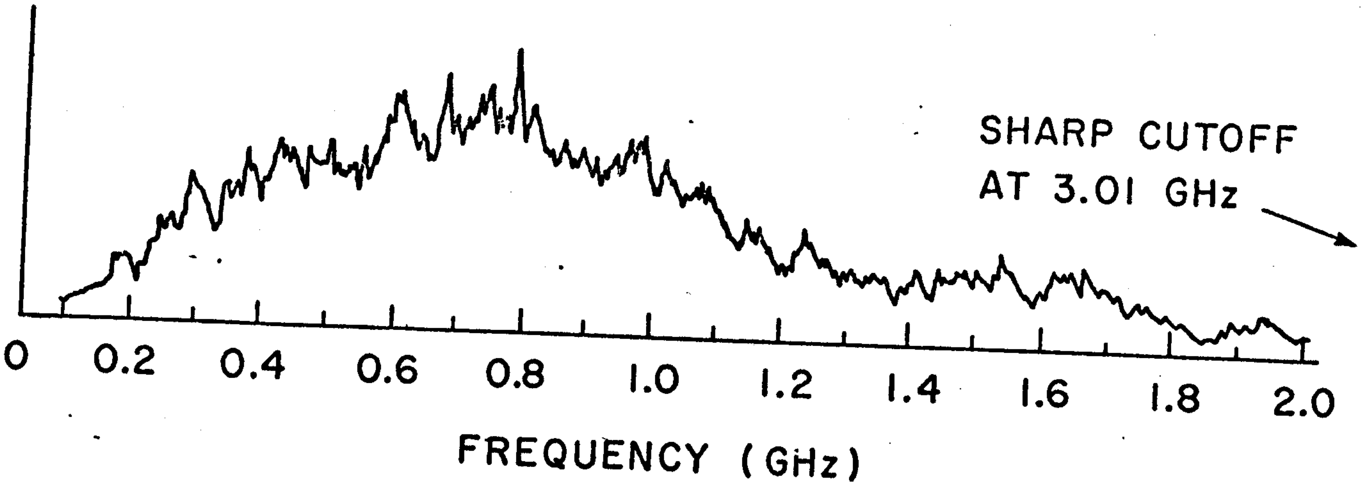

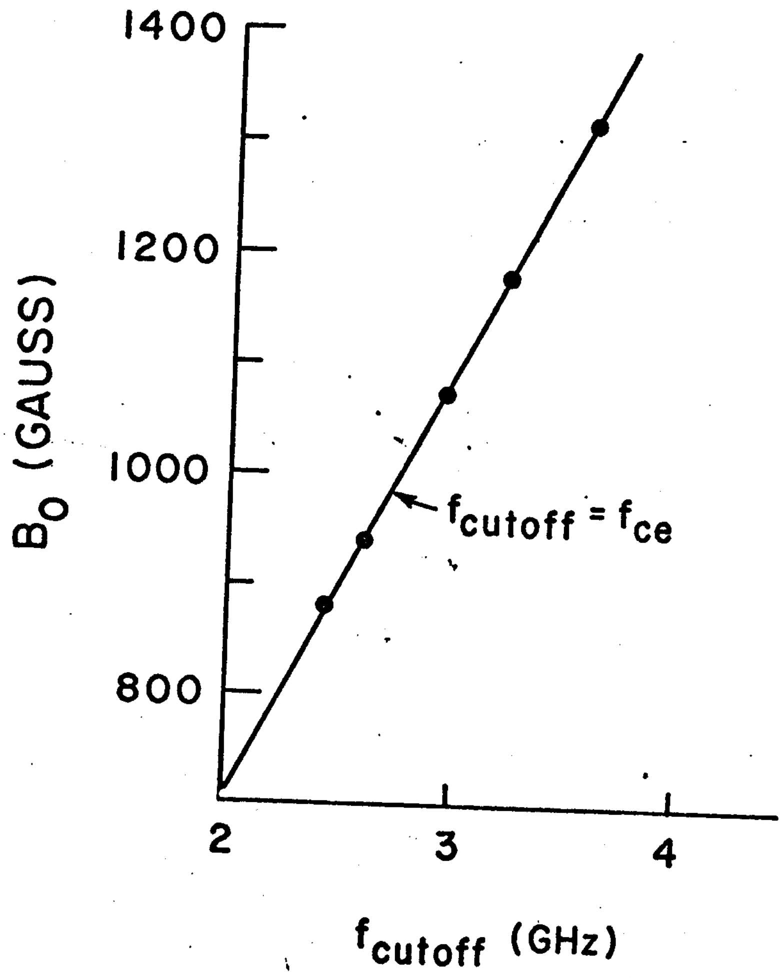

TIME AVERAGED LOW-FREQUENCY SPECTRUM

FIGURE 6

MANGANO
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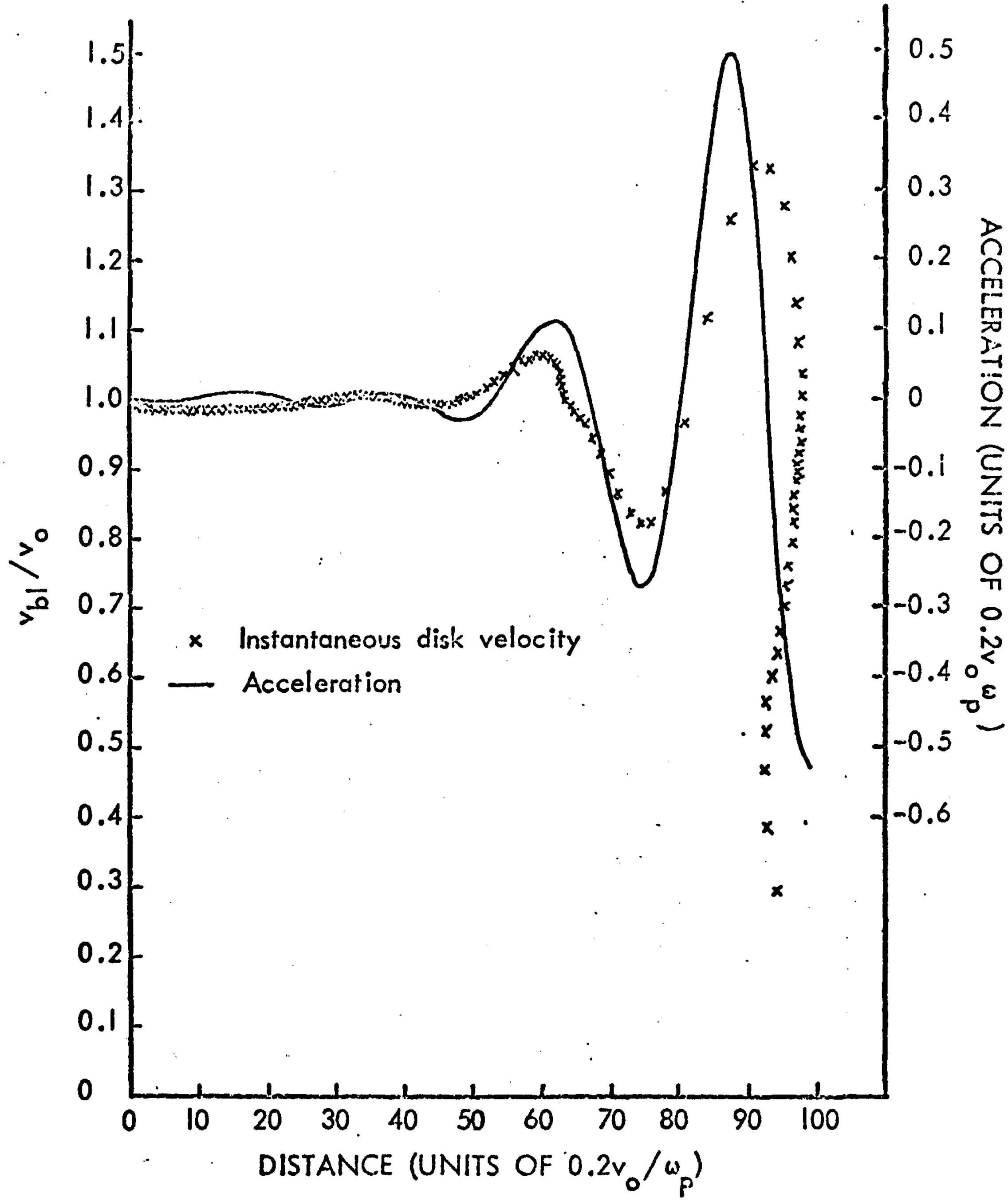

Disk beam in uniform plasma. Wideband excitation. $t = 300/\omega_p$. $\omega_{pb}^2/\omega_p^2 = 0.002$. $r_o = 0.075$ in. Note the much larger fields and beam velocity spread than in the nonuniform plasma case (Fig.6.4), even though the interaction length here is only 1/6 as long. The fields are still increasing in time.

FIGURE 7

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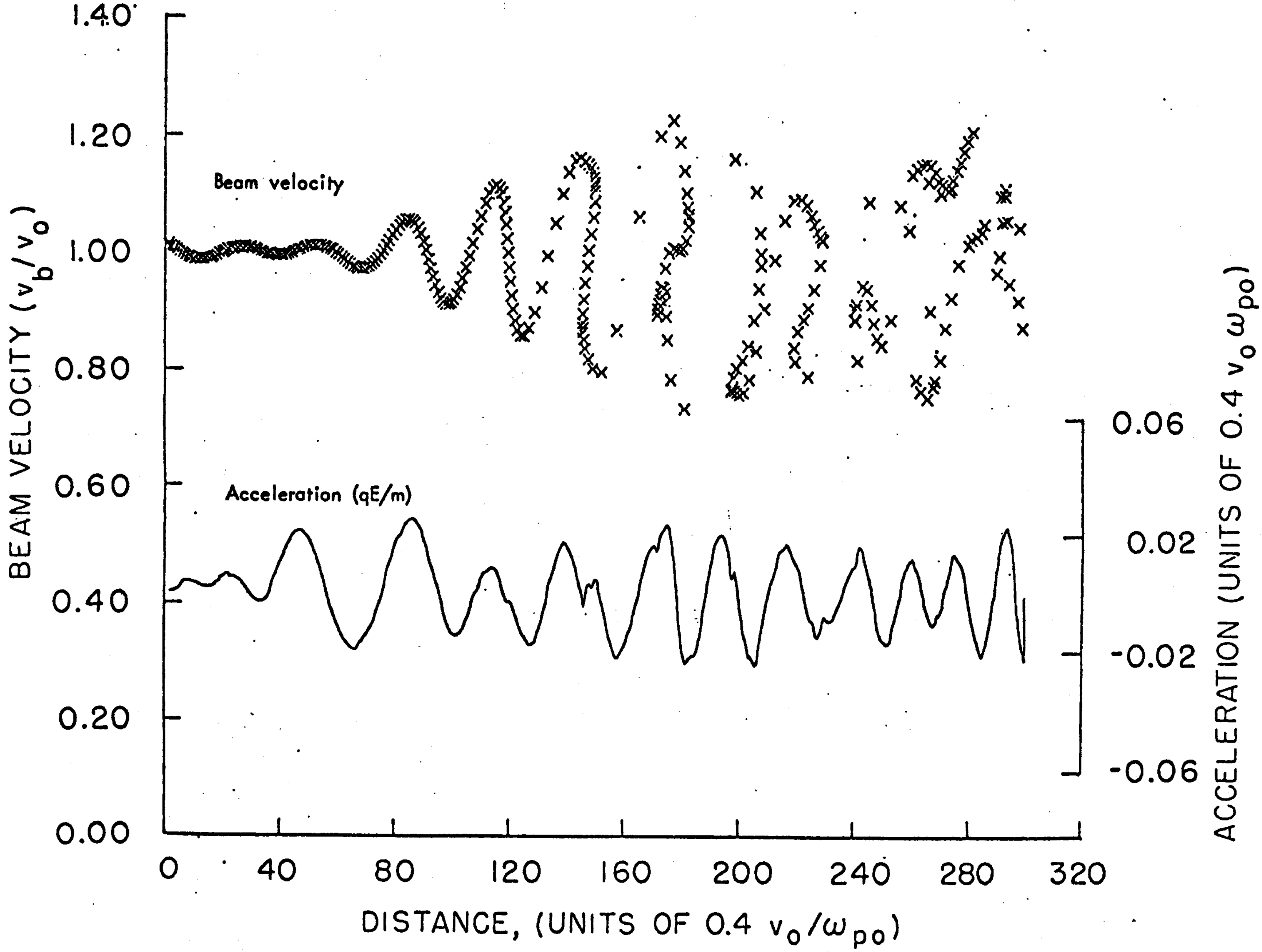

SNAPSHOT OF DISK BEAM IN NONUNIFORM PLASMA $t = 260/\omega_{po}$

FIGURE 8

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