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Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Ninth Annual Meeting of the Plasma Physics Division of the American Physical Society
Austin, Texas, November 8-11, 1967

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ABSTRACT

In a continuation of previous work, correlation measurements have been made in an annular Hall-current plasma accelerator having an axial electric field, a radial magnetic field and a slightly-ionized, low-current and low-pressure argon discharge. The fluctuations are measured using electrostatic probes. Measurements of the r.m.s. amplitudes, amplitude spectra, and the space-time correlations of the fluctuations have been made with a correlation analyzer having a response up to 500 khz. Results are presented and discussed for two typical discharges having different ratios of coherent low-frequency fluctuations (due to azimuthal rotation) to "non-coherent" fluctuations. Frequency filtering of the probe signals was used to study the coherent fluctuations separately from the "non-coherent" fluctuations. Comparison of the results for floating, ion-collecting and electron-collecting conditions of the probe permits some inferences to be drawn regarding the nature of the fluctuations.

INTRODUCTION

Plasmas frequently exhibit fluctuations, which may be classed as plasma instabilities or plasma turbulence. These fluctuations may have an important role in determining the behavior of the

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bulk plasma. For example, it is possible that the anomalous diffusion arises as a consequence of the plasma fluctuations (e.g. ref. 1).

Many specific modes of plasma instability have been predicted theoretically and observed experimentally. Some theoretical work has been done on the more general problem of plasma turbulence (e.g. ref. 2). However, detailed experimental measurements of the characteristics of fluctuations within a plasma have been undertaken less frequently. The present work was initiated in an attempt to adapt techniques long used in studies of fluid-dynamic turbulence to the plasma case. This involves measurements of the mean-square, the frequency spectrum, and particularly the space-time correlations of the fluctuating quantities for a plasma of interest. Although plasma fluctuations range over a wide band of frequencies, the present research was directed toward the lower end of the spectrum to minimize the difficulties with the diagnostics. The particular type of plasma chosen for investigation is a slightly ionized low-pressure and low-current argon plasma subjected to crossed electric and magnetic fields. Preliminary results were previously reported (ref. 3). This paper presents subsequent results of this research.

APPARATUS AND PROCEDURE

The plasma used in the present investigation was generated by the low-density Hall-current plasma accelerator (ref. 3) shown in Figure 1. The accelerator length was 7.62 cm. Two configurations of this accelerator were used and were identical except as noted below:

Accelerator	Inner diameter, d_i, cm	Outer diameter, d_o, cm
A	3.81	7.62
B	5.08	10.16

A cylindrical coordinate system (r, θ, z) is used in this presentation with the $z = 0$ plane at the end-plane of the magnet and the anode at $z = -7.62$ cm. The magnetic field is radial and the electric field is axial. The cathode is a radial arrangement of tantalum wires operated usually in the emission-limited regime. The direct current power supplies for the cathode, anode, and magnet had extremely low ripple to minimize any externally-induced noise and/or oscillations.

All of the data given are for a plasma in which the average electron temperature was about 10 ev and the average electron number density about 5.0×10^{10} cm^{-3}. The data were obtained for two conditions of operation as follows:

Condition	Accelerator	Magnetic field	Current, amp
I	A	Weak	0.40
II	B	Strong	0.60

The fluctuations were measured with 0.025 mm diameter tungsten Langmuir probes at various conditions of probe bias voltage. The probes were inserted between the cathode wires. The fluctuating signals were obtained across 1000 Ω resistors. For correlation measurements the output signals of two probes were fed into differential amplifiers. For all of the measurements reported herein the probes were radially one-fifth of the annular plasma thickness from the inner wall. The two probes used in the correlation measurements are identified by the subscripts, 1 or 2, on the position coordinates of the probes.

The frequency spectrum up through 600 khz was measured and recorded using a heterodyne-type spectrum analyzer. For the correlation work the fluctuations from the two probes were fed into a Honeywell 9410 Correlator. This instrument was found to have a response flat up to 300 khz and at 500 khz was only 3 db down. The outputs of the correlator, namely, the auto correlation or cross correlation as a function of the time-delay, were fed into an X-Y recorder.

RESULTS AND DISCUSSION

The earlier results (ref. 3) showed a large degree of correlation between points anywhere in the plasma volume of the accelerator. In other words the scale of the fluctuations was at least of the order of the size of the device. The data resembled that obtained in fluctuating fields which exhibit a loss of coherence as the two probes are more widely separated. No definite evidence of the convective effect of the fluctuations was then observed.

Figure 2 shows the amplitude spectra for the two conditions. The Langmuir probes are at ion saturation and the axial and azimuthal positions are $z = 0$ and $\theta = \pi$. Both curves have resonances near the lower frequency end of the spectrum. Except for the resonances the spectra are quite similar to those observed in turbulent airflows. The resonances observed in the figure are indications of coherent fluctuations which is the result of a helical disturbance rotating about the axis. This is a phenomenon not unique to this particular plasma. The rotation has been found to occur in Q-discharges and many other plasmas of contemporary interest (ref. 1).

The two conditions labeled I and II in Figure 2 possess two different magnitudes of that portion of the fluctuations due to the helical motion in relation to the mean-square of the fluctuations. For condition I the fluctuations duc to the rotation are quite evident but not dominant. For condition II these fluctuations dominate the spectrum. The resonance for condition II is so strong that a first harmonic peak appears in the spectrum. Condition II differs from condition I mainly by an increase in magnetic field strength and an increase in cross-sectional area of the accelerator.

The cross-correlation coefficients, R, for Conditions I and II are given in Figure 3 as a function of τ, the time displacement, in microseconds. For both curves the two Langmuir probes are positioned at z = 0 and $\theta_1 = \pi$, $\theta_2 = 0$. The probes are at ion saturation for both conditions. When compared to the spectral curves of the previous figure, the main features of those cross-correlation curves in Figure 3 can be easily understood. For Condition I the most highly correlated region is near $\tau = 0$ with R peaking sharply to a value greater than 0.50. Going away from $\tau = 0$ the curves have the appearance of damped sinusoids. However, the degree of correlation exhibited by curve I near $\tau = 0$ is greater than twice that for the sinusoidal portion. In other words, while the cross-correlation resultfor Condition I indicate that there is a resonance inthe fluctuation; it further shows that the resonance is definitely not dominant. When the cross-correlation results of Condition II are examined, it is readily apparent that these fluctuations are dominated by the resonant part of thespectrum. The narrow peak is still evident at $\tau = 0$, but, the magnitude of the correlation of the narrow peak is less than in the sinusoidal portion of the curve. For both Conditions I and II the narrow peak(turbulent-like portion of the fluctuations) exhibits no measurable convection. (Convection would result in a displacement of the peak from $\tau = 0$).

In order to indicate the helical character of the disturbance results are presented of some measurements taken with the two probes set at various axial displacements at an azimuthal displacement, $\Delta\theta = \pi$. Although not presented herein, results of measurements for various other azimuthal displacements of the probes also are consistent with the helical picture of the disturbance. In Figure 4 the correlation coefficient, R is shown as a function of the time displacement, τ , for Condition II. Both probes are at ion saturation and have an azimuthal displacement of $-\pi$ radians. The four curves in the figure are for axial displacement Δz of 0, -1.90, -3.81, and -5.72 cm. The "sinusoidally" varying portions of the curves show the expected shift in τ of the peaks from one curve to the next. Convection velocities can be computed from this data. These local convection velocities increase from 6×10^5 cm/sec near the anode to 30×10^5 cm/sec near the cathode. The average for the entire set of data is 9×10^5 cm/sec. These results are considered to be correct with regard to the order of magnitude and the trend with position from the anode. Further refinement of technique and analysis should improve the quantitative accuracy. For all of the curves on Figure 4, narrow peaks occur at or very near $\tau = 0$, i.e. values of τ less than .06 μsecs. This implies that the fluctuations so represented have no convection velocity less than 10^8 cm/sec.

The coherent and non-coherent portions of the fluctuations can be studied separately by filtering the original signal. The results of one such procedure are given in figure 5 which compares the R versus τ curves for no frequency filtering, 50 khz high-pass frequency band and 50 khz low-pass frequency band. The data are for Condition II with the probes at ion saturation with $z_1 = z_2 = 0$ and $\theta_2 - \theta_1 = -\pi$. The value of 50 khz for the band rejection was chosen to assure sufficient rejection of the resonance peak during the high-pass band analysis. Comparison of the three curves verifies the picture which has been given of the nature of the fluctuations. Rejecting the higher frequency fluctuations yields an almost sinusoidal curve which shows loss of coherence as τ increases. On the other hand removal of the resonance peak leaves a cross-correlation curve which peaks sharply at $\tau = 0$ and is essentially zero at other values of τ.

The results discussed to this point have been obtained with Langmuir probes operating in the ion saturation condition. If other values of probe bias are used, different results may be obtained as shown in figure 6. Here are plotted the amplitude spectra for three probe bias conditions - ion saturation, floating, and electron-collecting. The electron-collecting condition is not electron-saturation which would draw such large currents as to damage the probes, but an intermediate condition. In figure 6a the data have been normalized to zero db at 100 khz for convenience in comparing the curves. In figure 6b the relative amplitudes are retained. As one makes the probe bias voltage more positive the level of fluctuations increases and the increase is quite rapid indeed once the bias voltage increases past the floating point. This is illustrated by the difference in levels of the curves in figure 6b. As the probe bias voltage is increased from ion collection to a typical electron collection condition the magnitude of the fluctuations at the lower end of the frequency spectrum increases by more than 10 db (relative to the 100 khz equalization). At the upper end of the frequency spectrum the slopes are all nearly the same. This limiting slope for the floating and ion saturation condition is about -2.1. That for the electron collection condition is about -1.9. Near the mid-range of frequencies as the bias voltage is increased from ion collection, the peak decreases in magnitude and almost disappears at floating. The peak begins to reappear as the bias is further increased to the typical electron collection condition.

The effect of the probe bias suggests that the helical, rotating disturbance may be a fluctuation in plasma density. Such a fluctuation would be expected to provide a signal at both ion saturation and electron collection conditions. A density fluctuation of itself would provide no signal at floating conditions. The floating probe most probably records plasma potential fluctuations, although effects of temperature variations could also be present.

This interpretation is consistent with the results shown in figure 7. This shows the cross-correlations and auto-correlations for probes floating and at ion saturation. These results are for Condition II with $z = 0$ and $\Delta\theta = -\pi$. The auto-correlation results are consistent with the spectra of figure 6, again showing the loss of the coherent part of the fluctuations at floating conditions. The cross-correlation curve for the floating condition has the same general character as that of figure 5 for ion saturation with the fluctuations below 50 khz being rejected. If the floating probes are indeed sensing fluctuations in the plasma potential, the similarity noticed may imply that the turbulent-like portion of the fluctuations at ion saturation also result from plasma potential fluctuations.

CONCLUDING REMARKS

This study of a particular fluctuating plasma with Langmuir probes has shown that the fluctuations can be separated into two types. One is a convective, strongly coherent fluctuation which rotates in a helical fashion about the axis, and appears to be primarily a fluctuation in plasma density. The second type is a non-convective, turbulent-like fluctuation, relatively unaffected by probe bias, which appears to result from fluctuations in plasma potential.

The existence of these two types of fluctuations, and the sensitivity of the results to the bias of the probe may help to explain differences in results found by various investigation.

The separation of the two types of fluctuations by frequency filtering permits their independent examination.

Although data thus far have been obtained only with Langmuir probes, the techniques used should be equally applicable to other sensors. Obvious extensions of this approach would include the use, for example, of emissive probes and magnetic probes.

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2. C. M. Tchen, Bull. Am. Phys. Soc. 12, 754 (1967).
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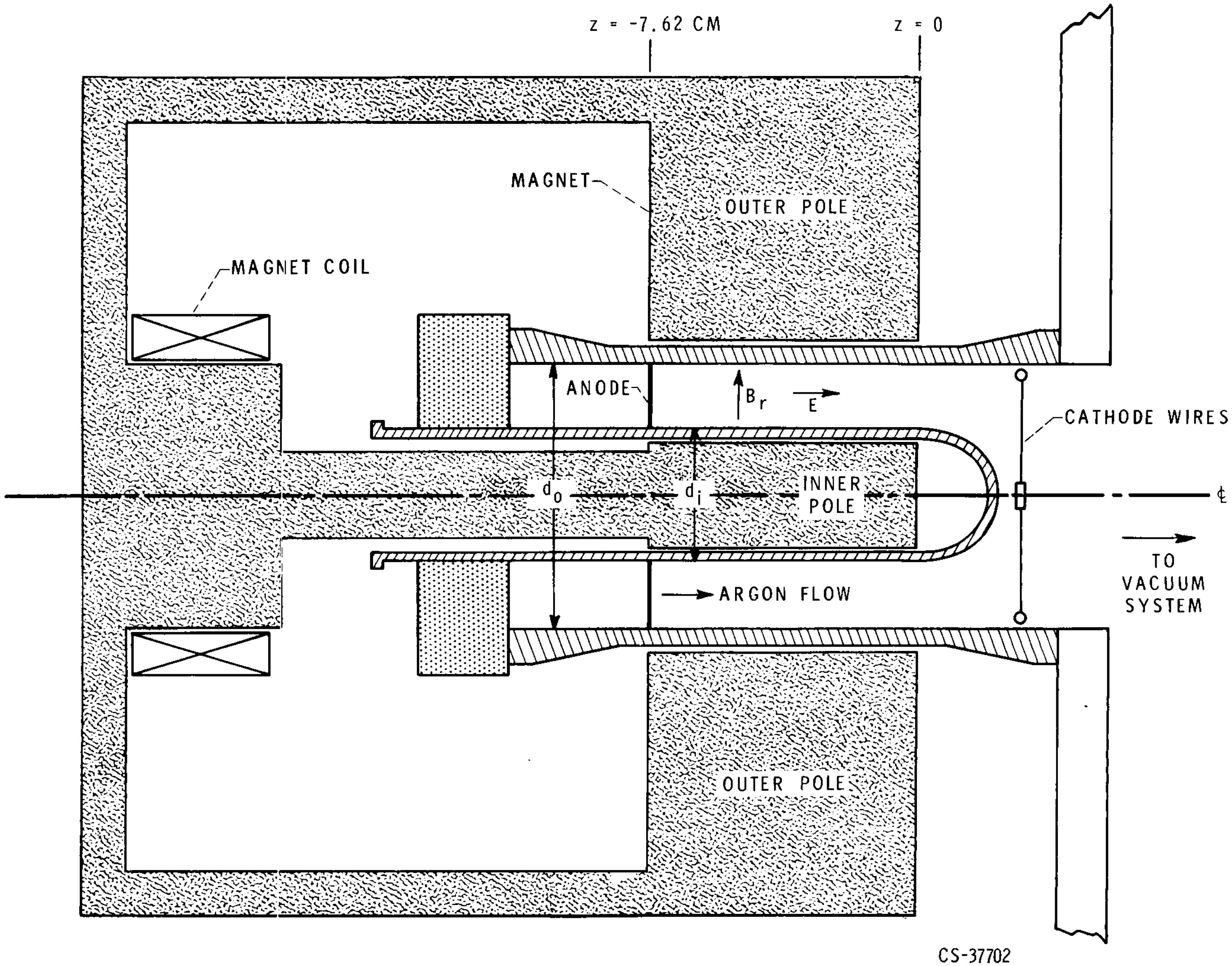

Figure 1. - Sketch of Hall current accelerator.

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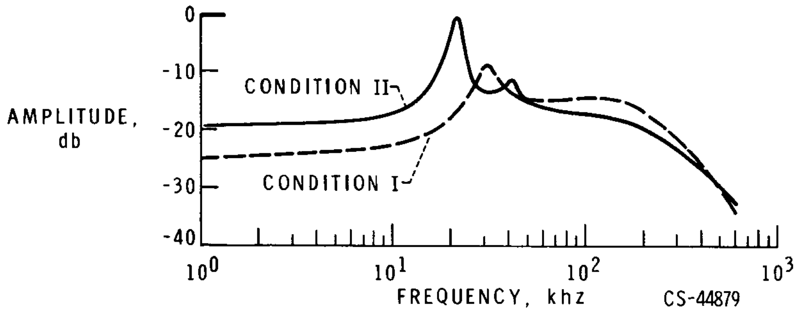

Figure 2. - Comparison of the amplitude spectra for Conditions I and II; probe at ion saturation, $z_1 = 0$, $\theta = -\pi$.

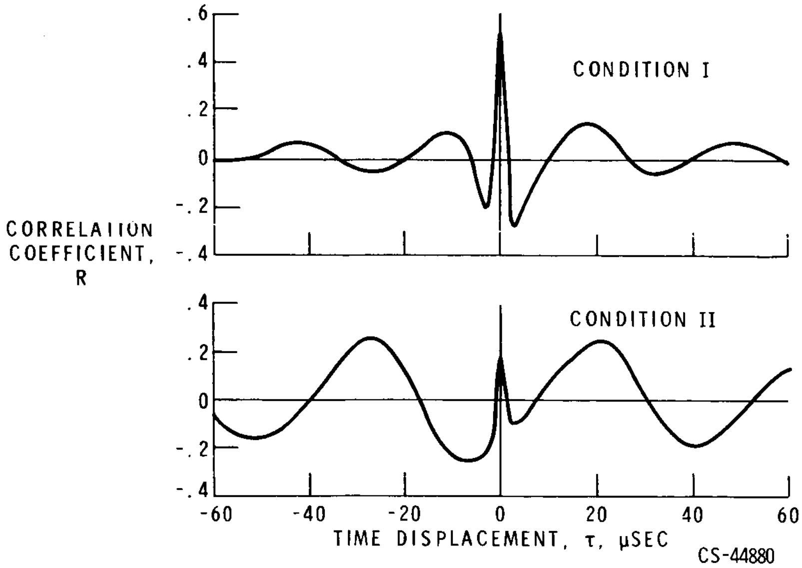

Figure 3. - Comparison of cross-correlations for Conditions I and II; probes at ion saturation, $z_1 = z_2 = 0$ and $\theta_2 - \theta_1 = -\pi$.

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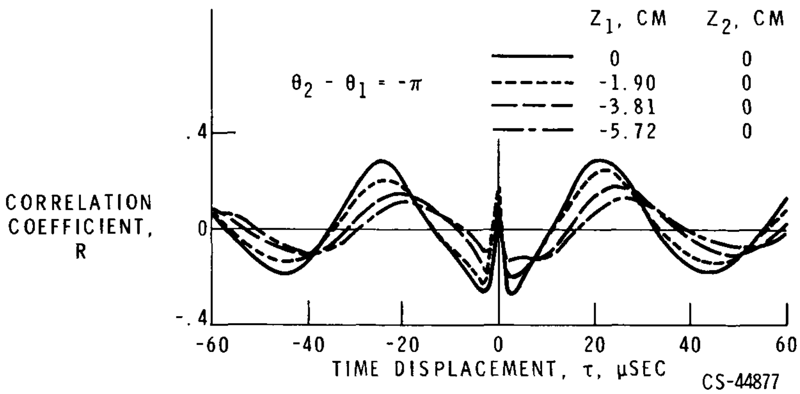


Figure 4. - Comparison of cross-correlations for various axial displacements of the probes at ion saturation; Condition II.

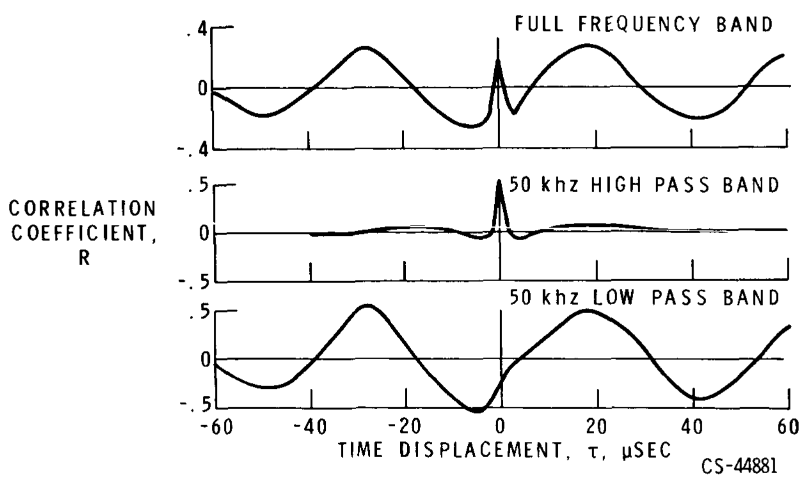
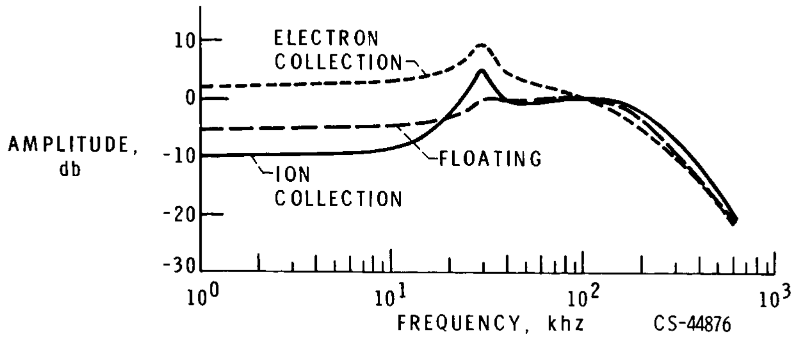


Figure 5. - Comparison of cross-correlations for full frequency band fluctuations with cross-correlations of fluctuations subjected to 50 khz high-pass and low-pass frequency filtering; probes at ion saturation, $z_1 = z_2 = 0$, and $\theta_2 - \theta_1 = -\pi$, Condition II.



(a) Amplitude levels arbitrarily set at 0 db for frequency of 100 khz.

Figure 6. - Comparison of amplitude spectra for probe at ion saturation, floating, and collecting electrons; $z_1 = 0$, $\theta_1 = \pi$, Condition I.

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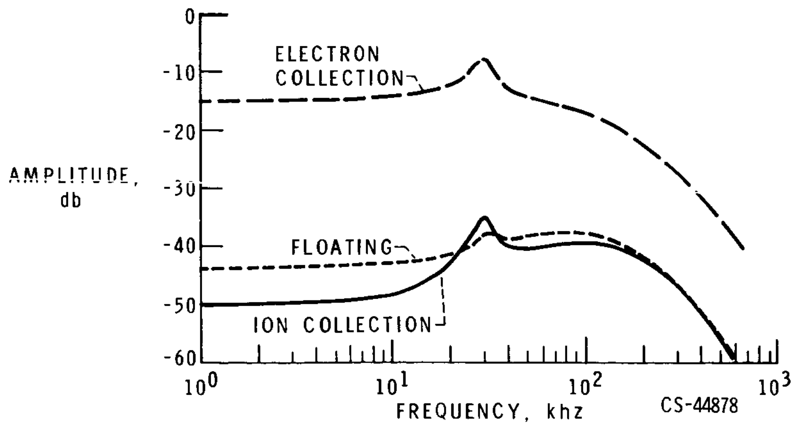

(b) Relative amplitude levels between curves not arbitrary.

Figure 6. - Concluded.

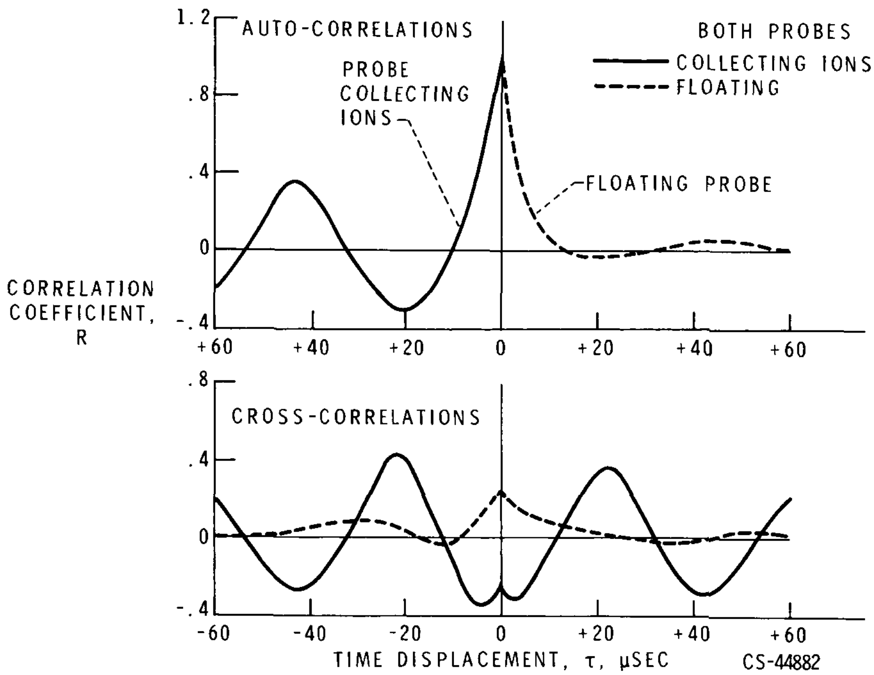

Figure 7. - Comparison of correlations for probes at ion saturation with those for probes floating; $z_1 = z_2 = 0$, $\theta_2 - \theta_1 = -\pi$, Condition II.