Measurement of DC Electric Fields in a Plasma

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PLASMA PHYSICS
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AEC RESEARCH AND DEVELOPMENT REPORT

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Measurement of DC Electric Fields in a Plasma

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ABSTRACT

Accurate measurements of dc electric fields in a low-density plasma can be made with a probe by giving the plasma a small displacement at 10 Hz and using a lock-in amplifier to detect the 10 Hz component of the probe floating potential.

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I. INTRODUCTION

Two recent developments in the study of plasma confinement by magnetic fields have underlined the importance of dc electric fields. The first is the observation that anomalous plasma losses in at least two types of devices[1,2] are caused in part by $\underset{\sim}{E} \times \underset{\sim}{B}$ drifts in steady electric fields. The second is the realization that drift waves are greatly affected by radial electric fields E_r in regard to both frequency and excitation threshold.[3] Since not only E_r but also its derivatives E_r' and E_r'' can be shown theoretically to have an effect on drift waves, it is clear that the usual method of measuring the plasma potential profile $\phi(r)$ and taking its derivatives will not be sufficiently accurate for this application.

In this paper we describe a method which gives $E_r(r)$ directly. The method is basically to use a vibrating floating probe, which would give an oscillatory signal proportional to the gradient of ϕ in the direction of vibration. Because of the danger of generating electrostatic charges in the cable connected to such a probe, we have chosen instead to vibrate the plasma relative to the probe. This method was tested in a contact-ionized potassium plasma in a Q machine.[4] In this type of plasma, measurements of ϕ are complicated by slow drifts in probe floating potential V_f due to changes in the work function of the alkali-metal coated probe surface. If the vibration period is short compared to the time scale of these drifts, our measurement of $\underset{\sim}{\nabla}\phi$ is clearly unaffected by these drifts.

II. THEORY

We consider a plasma confined by a uniform magnetic field $\mathbf{B} = B\hat{\mathbf{z}}$ in which the lines of force are charged to different potentials, given by the function $\phi(r,\theta)$. For definiteness, we consider the measurement of $E_r = -\partial\phi/\partial r$ with a probe located at $\theta = \theta_o$ and movable along the radius r. Extension of the method to the measurement of any component of $\mathbf{E}$ in the plane perpendicular to $\mathbf{B}$ and to nonuniform fields $\mathbf{B}$ is straightforward. Suppressing the argument θ and expanding $\phi(r,\theta)$ in a Taylor series about r_o, we have

$$\phi(r) = \phi(r_o) + \phi'(r - r_o) + \frac{1}{2}\phi''(r - r_o)^2 + \frac{1}{6}\phi'''(r - r_o)^3 + \dots \quad . \tag{1}$$

The probe is assumed to be vibrating about $r = r_o$, so that its position is given by

$$r(t) = r_o + R_1 \sin \omega t \quad . \tag{2}$$

The floating potential of the probe is given by[5]

$$e(V_f - \phi) = -C\,kT_e \quad , \tag{3}$$

where C is a positive constant. Combining Eqs. (1) - (3), we find

$$\begin{aligned} V_f(t) = {} & -C\,kT_e/e + \phi(r_o) + \left(R_1\phi' + \frac{1}{8}R_1^3\phi'''\right)\sin \omega t \\ & - \frac{1}{4}R_1^2\phi''\cos 2\,\omega t - \frac{1}{24}R_1^3\phi'''\sin 3\,\omega t + \dots \quad . \end{aligned} \tag{4}$$

Therefore, if kT_e is constant over the scale of R_1, and R_1 is small compared with the scale Λ over which ϕ varies, the amplitude of $V_f(t)$ at the frequency ω gives the radial electric field at $r = r_o$. If kT_e is constant over the whole plasma, the profile of $E_r(r)$ can be obtained by moving the probe radially, thus changing r_o.

In Eq. (4) the coefficients of the terms in $\cos\omega t$, $\sin 2\omega t$, etc. vanish to order $(R_1/\Lambda)^3$. This would not be true if Eq. (2) contained higher harmonics. For instance, if we add a term $R_2 \sin(2\omega t + \delta)$ to Eq. (2), we would find corrections to Eq. (4), the leading terms of which are

$$\tfrac{1}{2} R_1 R_2 \phi'' (\cos\delta \cos\omega t - \sin\delta \sin\omega t) + R_1 R_2 \phi' (\sin\delta \cos 2\omega t + \cos\delta \sin 2\omega t) + \ldots .$$

It is therefore important that the harmonic content of $r(t)$ be kept reasonably small.

Equation (4) also reveals that, in principle, the derivatives of E_r can be obtained from the amplitude of $V_f(t)$ at harmonics of ω. However, the signal decreases by a factor R_1/Λ with each successive harmonic. In spite of considerable effort, we were unable to detect even the first harmonic because of low-frequency flicker noise in the plasma.

III. APPARATUS

A schematic of the Q machine is shown in Fig. 1. The 5 cm diam, 326 cm long plasma column is produced by contact ionization of potassium atoms directed at the tungsten end plates at 2500 K. The main confining field B_z is 2 kG, uniform to 1%. The plasma is displaced relative to the probe (shown at the midplane) by the addition of two sets of coils, in the positions shown, which produce an ac field $B_\perp$ of the order of 50 gauss peak to peak. These coils displace the lines of force uniformly by about 1 mm, leaving the magnetic field uniform near the midplane and undisturbed near the ends of the machine. The auxiliary coils consist of 20 turns of ordinary hook-up wire wound on 30 × 30 cm square forms. Two sets of coils at right angles provide either horizontal or vertical displacement of the plasma.

Figure 2 is a block diagram of the electronics. The auxiliary coils are driven to about 30 A peak to peak at about 18 Hz by a transformerless transistor amplifier with an output impedance of about 1 Ω. The probe floating potential is taken with a unity-gain, high-impedance isolation amplifier with 3 dB points at 2 Hz and 150 kHz. The 18 Hz component of V_f which is phase locked to a reference signal from the audio oscillator is detected by a lock-in amplifier. The output of the latter, proportional to E_r, is plotted against probe radial position r_o on an X-Y recorder.

IV. MEASUREMENTS

Figure 3 shows a scan of $E_r(r)$, as compared with a scan of $\phi(r)$. The sensitivity of the method is demonstrated by the narrow downward spike at the left of the E_r trace; the corresponding discontinuity on the ϕ trace is barely discernible. The reproducibility of the method is demonstrated in Fig. 4, which shows two successive scans of $E_r(r)$. It is seen that the results are reproducible to within the width of the ink line. The integrating time constant of the lock-in amplifier was set at 1 sec, and the probe was moved slowly by a motor drive, requiring several minutes for a radial scan.

In Fig. 1 we have shown that the potential V_b of the vacuum chamber and of the aperture limiters can be varied by a power supply. Using this method, we have been able to measure small changes in E_r when V_b is changed. These measurements will be published elsewhere.

V. EXPERIMENTAL CHECKS

1) Plasma displacement. The theoretical displacement of the plasma was computed using the measured dimensions of the auxiliary coils. It was found that the displacement was uniform to a high degree over the entire cross section of the plasma. The actual displacement was measured by applying dc to the coils and observing the shift in $\phi(r)$. The measured shift agreed with the calculations.

2) Stray fields. The computations also showed that when the displacement is supposed to be in the x direction, the spurious displacement in the y direction due to possible errors in coil shape and position was entirely negligible. As a check, we measured $E_y(x)$ by energizing the perpendicular set of coils. The profile of E_y bore no resemblance to that of E_x, and the magnitude of E_y was less than $|E_x|$, but E_y was not zero because there was a finite component E_θ in the plasma.

3) Linearity. Figure 5 shows the magnitude of the lock-in amplifier signal as a function of the magnitude of the plasma displacement for six probe positions. It is seen that in every case the signal varies linearly with displacement, as expected. However, the points taken with the probe extending across the axis to the far side of the plasma do not extrapolate to

zero at $B_\perp = 0$. The cause of this effect is unknown; perhaps there is some pickup at 18 Hz in spite of the careful shielding of the probes. Because of this effect, there is an uncertainty of order $\lesssim 10\%$ in the absolute value of E_r.

4) Frequency dependence. Figure 6 shows the magnitude of the E signal versus driving frequency, for various magnitudes of $B_\perp$ and for two probe positions. In choosing a frequency, one must be sure that the plasma is displaced adiabatically. A measure of the relaxation time of the plasma is given by the time required for an acoustic wave to travel the length of the machine. In our case, this time is ~ 3 msec; hence we worked at frequencies << 300 Hz. In spite of these precautions, we find on Fig. 6 that the signal increases as f decreases, for reasons we do not understand. The lock-in amplifier is retuned in frequency and phase at each frequency. As long as f is kept fixed, this method gives the relative values of E_r correctly; to get the absolute value of E_r correctly, one has to extrapolate to $f = 0$.

5) Absolute value of E_r. If such an extrapolation is used to obtain $|E_r|$, the resulting magnitude agrees with that obtained from the slope of the trace of $\phi(r)$ to within 10%. The gain of the circuitry was calibrated by injecting a known signal at the probe.

6) Effect of $B_\perp$ on the plasma. The application of the $B_\perp$ field did not excite any observable oscillations in the plasma. To check this, we measured the $|E|$ signal with a probe located near the end of the machine, where the lines of force are undisturbed. The signal was zero.

7) Finite probe size. The probes used were cylinders 0.05 mm in diam and 2 mm long. Increasing the diameter a factor of 5 did not change $|E_r|$.

8) Harmonic distortion. The distortion in the amplifier driving the auxiliary coils was measured; it was less than 0.15%.

9) Lock-in amplifier adjustment. The RC time constant of the lock-in amplifier and the scanning speed of the probe drive were varied to be sure that they introduced no error in $E_r(r)$. The lock-in amplifier had sufficiently low Q that detuning of the amplifier did not introduce any error.

10) Asymmetric distributions. Measurements of E_θ by this method were consistent with the asymmetry of the isopotential surfaces as found from maps of $\phi(r, \theta)$ over an entire cross section.

VI. ACKNOWLEDGMENTS

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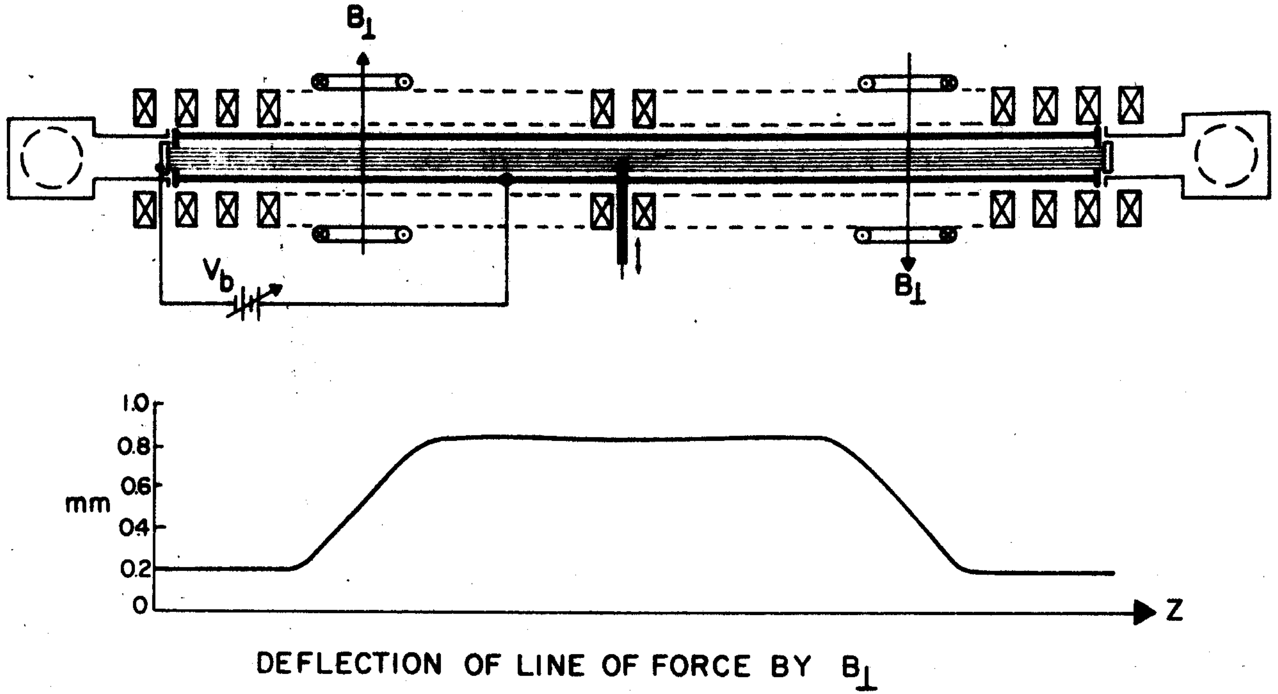

Fig. 1. Schematic of apparatus. The computed deflection of a line of force by the auxiliary coils is shown.

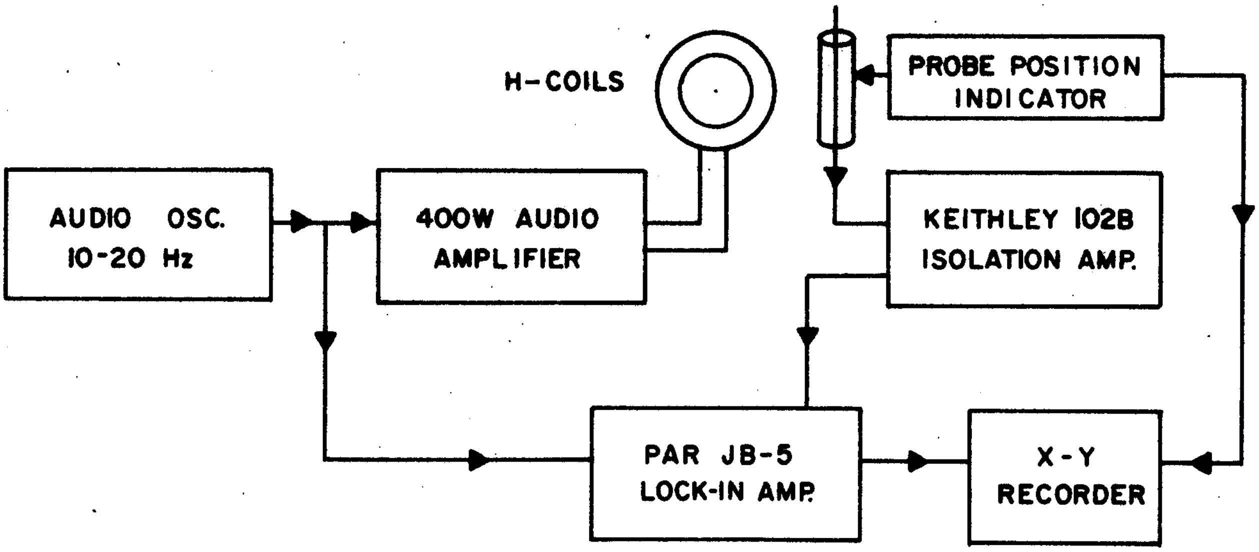

Fig. 2. Block diagram of circuitry.

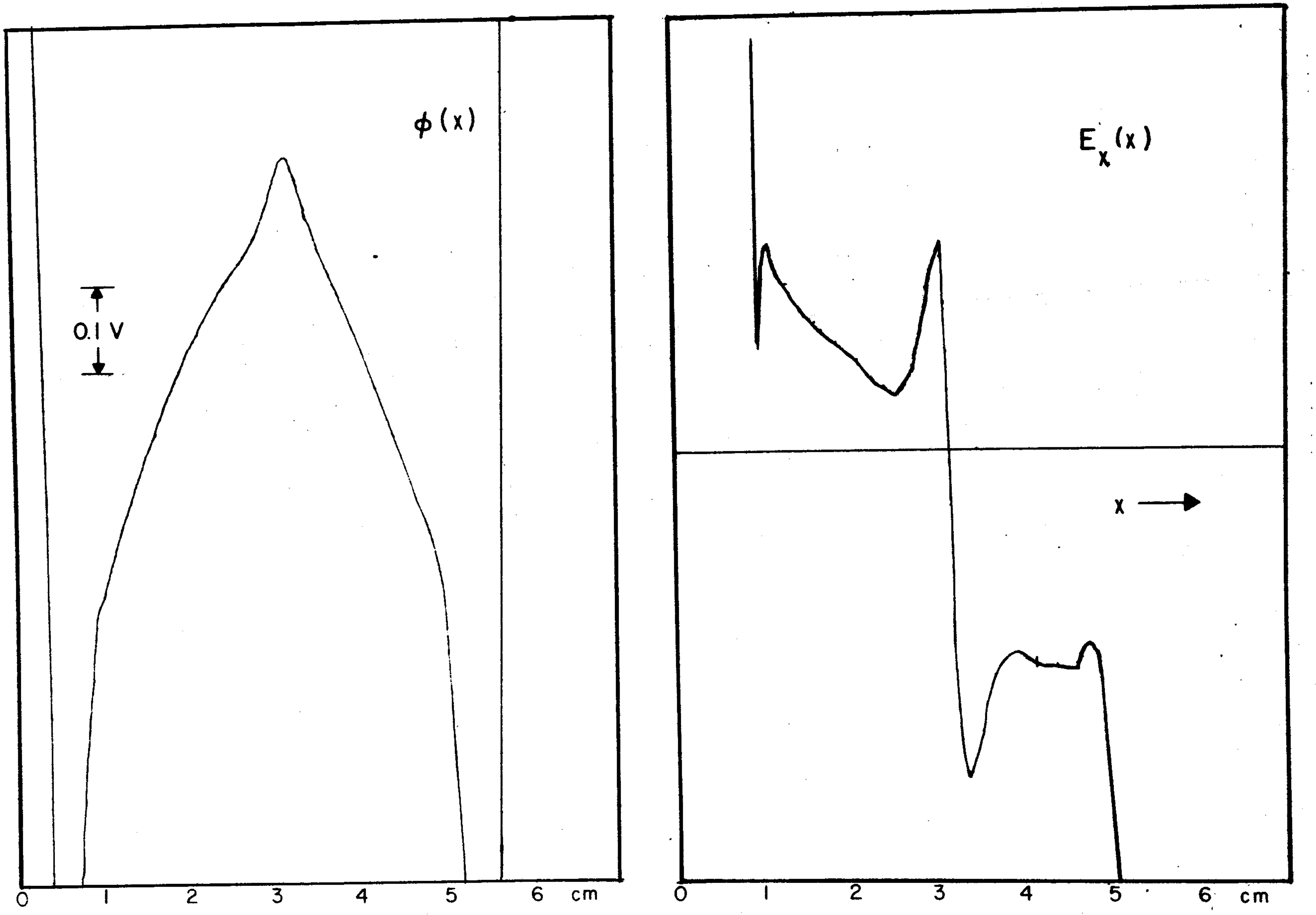

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Fig. 3. X-Y recorder tracings of $\phi(x)$ and $E_x(x)$. The abscissa is the probe position in the x (radial) direction, the center of the plasma being at x = 3.2 cm. The horizontal line indicated $E_x(x)$ was actually taken point by point in this case.

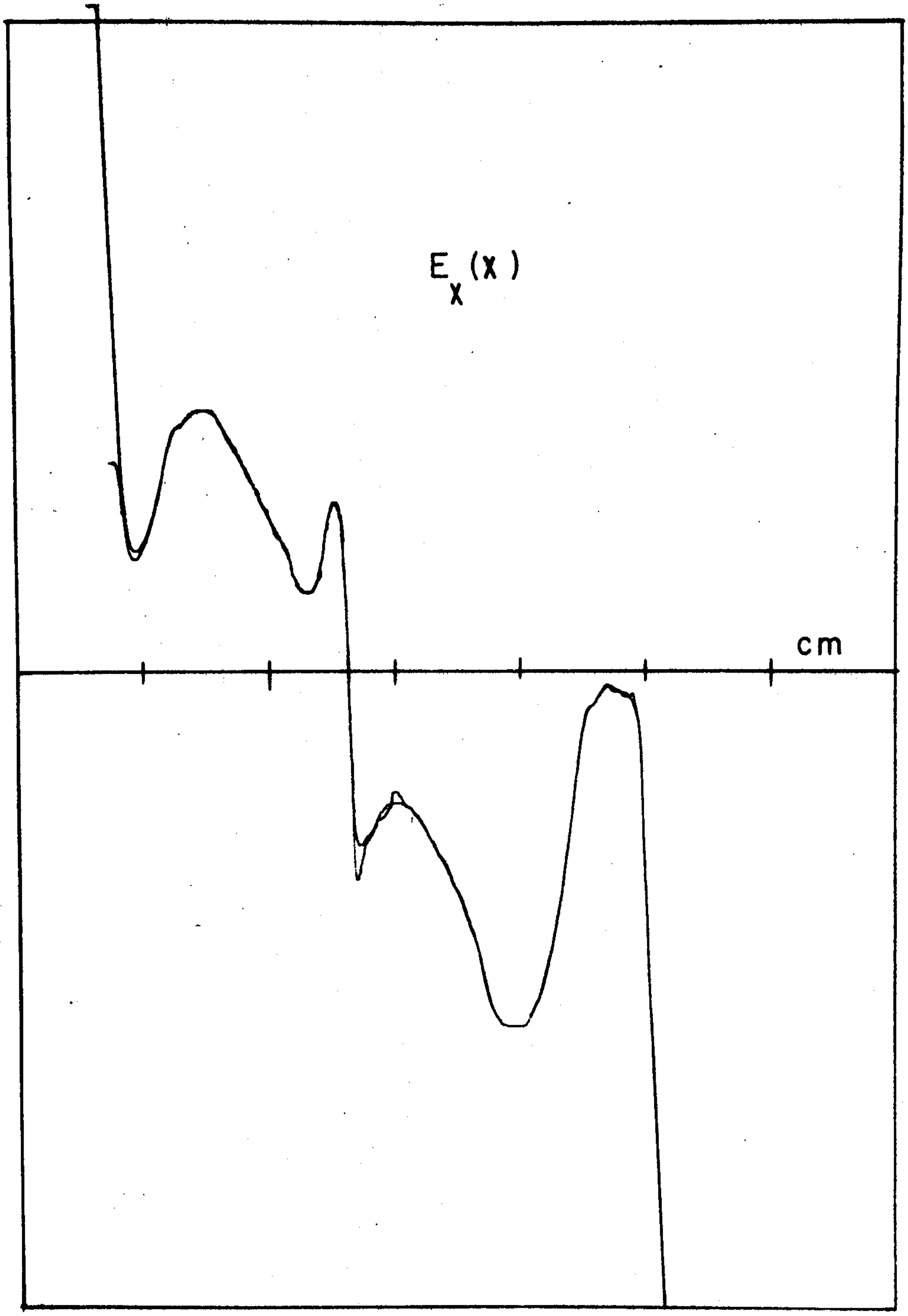

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Fig. 4. Overlay of two successive X-Y recorder traces of $E_x(x)$, showing reproducibility.

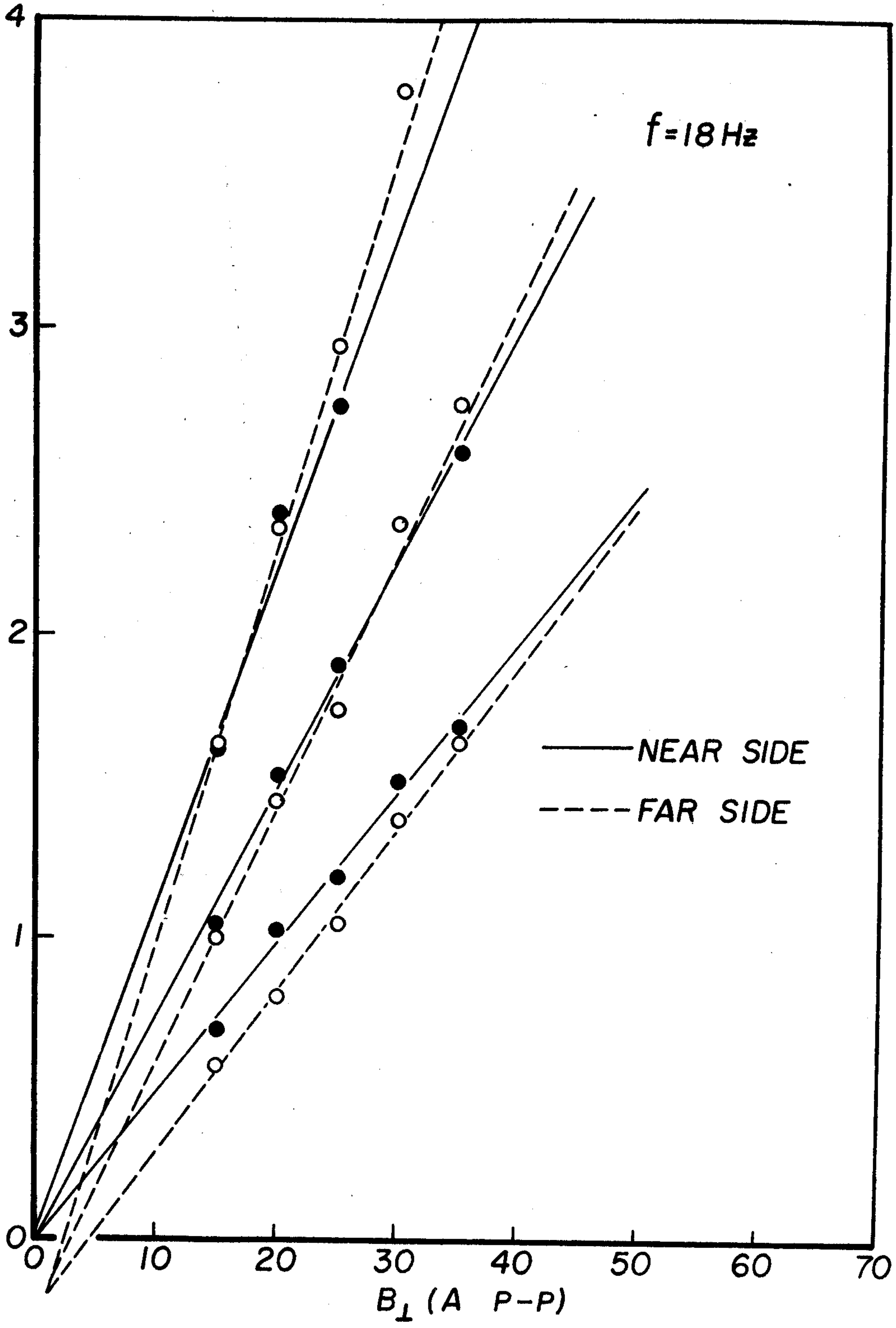

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Fig. 5. Magnitude |E| of the electric field signal versus current in the auxiliary coils producing $B_\perp$. Each set of points connected by a line was taken at a different probe position. The open points were taken with the probe extending through the plasma to the far side.

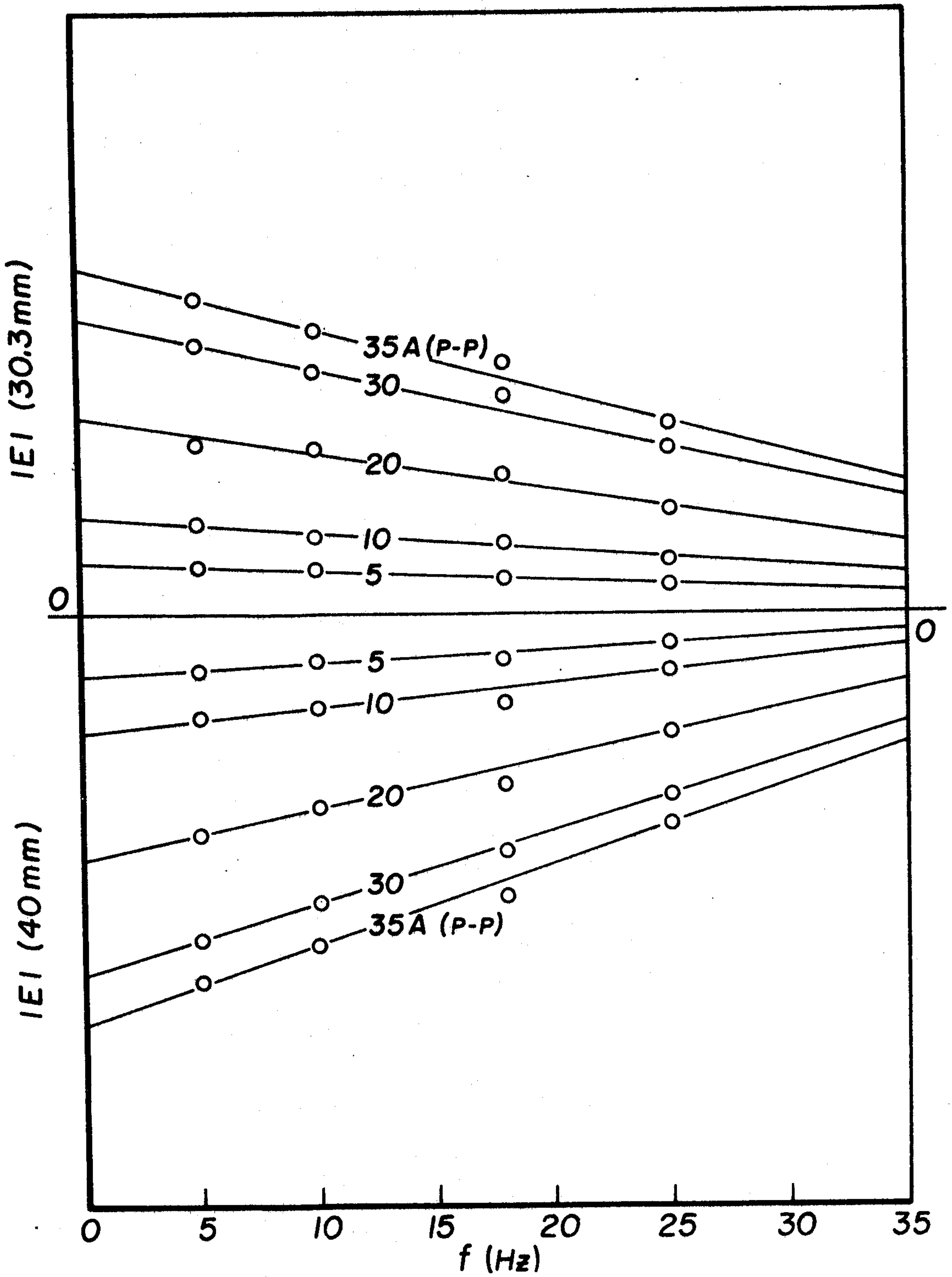

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Fig. 6. Magnitude | E | of signal versus operating frequency f for two probe positions (30.3 mm, near side and 40 mm, far side) and for various currents in the auxiliary coils (given in amperes, peak to peak).