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ABSTRACT

The radial distributions of floating potential in the positive column of a glow discharge in a longitudinal magnetic field have been measured with electric probes designed to minimize the perturbation of the plasma. Ecker has showed that the shape of these distributions can provide a sensitive indication of the presence of enhanced electron-ion interactions. We see no evidence for enhanced interactions; at magnetic field strengths below the threshold of the previously observed helical instability the results are compatible with the classical ambipolar theory of the positive column.

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I. INTRODUCTION

The electric potential distribution within a plasma is related to the relative loss rates of the positively and negatively charged components. A number of investigators experimentally have observed charged-particle losses considerably in excess of the predictions for a quasi-stationary plasma contained by a magnetic field; these losses lead to speculation about an "enhanced" diffusion, also called "drain" diffusion.[1] Recent examples for fully and weakly ionized gases, respectively, are found in the Stellarator work of Ellis et al.[2] and the glow-discharge positive column studies of Hoh and Lehnert.[3] Many other examples of diffusion experiments can be found in the review papers by Lehnert[4] and Boeschoten.[5]

Although the diffusion processes in fully and weakly ionized gases are basically quite different, some enhanced interaction process might be common to both of them. In the case of the positive column, the increase in particle losses observed by Lehnert and Hoh at a critical magnetic field were shown by Allen et al.[6] to be associated with the onset of a macroscopic helical instability. The theory has been given by Kadomtsev and Nedospasov.[7]

The question remained as to whether a small amount of enhanced diffusion due to other effects might also occur in the positive column. It has been shown by Ecker[8] that the radial potential distribution in a cylindrical

positive column can be affected strongly by the presence of enhanced diffusion. In the present investigation the potential distribution in a helium positive column has been measured as a function of magnetic field with several probe geometries. It will be demonstrated that radially inserted probes can perturb the potential seriously, but when this perturbation was removed no indication of enhanced diffusion was found below the critical magnetic field at which the spiral instability develops.

II. THEORY

A. The Classical Theory

The stable positive column is a quasi-neutral, weakly ionized plasma. Its properties can be predicted by considering the particle and energy balance in a given geometry. The particle balance is described by

$$\nabla^2 n(\vec{r}) + \frac{\nu_i}{D_a} n(\vec{r}) = 0. \tag{1}$$

Here, n is the particle density, ν_i is the number of ion pairs produced per second per electron, and $D_a(B)$ is given by

$$D_a(B) = \frac{D_+\mu_- + D_-\mu_+}{\mu_+ + \mu_-} \cdot \frac{1}{1 + \mu_+ \mu_- B^2}; \tag{2}$$

$D_\pm$, $\mu_\pm$ are the diffusion coefficients and mobilities at B = 0, and volume recombination and electron attachment have been neglected. In a long cylindrical geometry, provided ν_i is independent of n, the solution of equation (1) is

$$n(r) = n(0)\, J_0\left(\sqrt{\frac{\nu_i}{D_a}}\right) r. \tag{3}$$

From the boundary conditions, expressions relating the ionization rate and, hence, the electron temperature T_- to the parameters of a discharge can be obtained.

The longitudinal electric field is determined by the power input required to maintain the electron distribution at a temperature T_-. If $X(T_-)$ denotes the fractional energy loss by an electron in a collision including elastic, inelastic, and wall losses, and if quadratic ionization processes--i.e., ionization from excited atomic states--are excluded, the electric field is found to be

$$E_z = \left(\frac{64}{\pi}\right)^{1/4} \left(X(T_-)\right)^{1/2} \frac{kT_-}{\Lambda_- e} \text{ volts/cm,} \tag{4}$$

where Λ_- is the transport mean free path of an electron.[9] The effect of an increase of the longitudinal magnetic field is to decrease the electron temperature by decreasing particle losses, which in turn is reflected in a diminished longitudinal electric field. This has been confirmed experimentally at magnetic fields up to 600 gauss by the experiment of Bickerton and von Engel[10] and by the experiments of Lehnert and Hoh at magnetic fields into the kilogauss range.[3] A departure from the monotonic decrease of E_z with increasing B, such as was found by Lehnert and Hoh at high magnetic fields, may consequently be taken as an indication of a change in the particle loss.

Another parameter which is susceptible experimental investigation is the radial potential distribution. Assuming ambipolar diffusion and neglecting ion-electron interactions, the radial potential distribution in a cylindrical column is found to be

$$\frac{eU(r)}{kT_-} = \frac{1+\mu_+\mu_- B^2 \left(\frac{\mu_+}{\mu_-} - \frac{T_+}{T_-}\right)}{1+\mu_+\mu_- B^2} \ln\left[J_0\left(\frac{2.4\,r}{R}\right)\right], \qquad (5)$$

that exhibits a monotonic increase or decrease with radius depending on the relations between μ_+, μ_-, T_+, T_-. Eickerton and von Engle also observed the predicted reduction of the radial electric field with increasing magnetic field in their experiment; however, their results displayed large asymmetries across the diameter of the tube, which they suggested might be caused by unequal interactions between the wall sheath and the sheath at the tip of their radial probe.[10]

B. Theory of Simon

In ambipolar diffusion of singly ionized particles, the radial particle currents Γ_{r-}, Γ_{r+} are equal. In order to account for the large radial losses observed in low-pressure short arcs, Simon has considered the case in which the radial electron current Γ_{r-} equals zero. According to Simon, such a condition can be realized physically if the electrons are free to flow along any magnetic-field line to conducting surfaces at the ends of the plasma column.[11] He has suggested that in contact with a plasma even normally insulating materials might act as equipotential surfaces. (Neidigh has obtained some experimental evidence that tends to corroborate this supposition.[12]) Ecker has shown that in this case the radial potential distribution is given by

$$\frac{eU(r)}{kT_-} = \ln\left[J_0\left(\frac{2.4r}{R}\right)\right], \qquad (6)$$

a result that is the same as that obtained for ambipolar diffusion in the case of

no magnetic field.[8] It is interesting to note that the radial potential distribution is independent of the magnetic field strength in the case of Simon diffusion.

C. The Theory of Ecker

Ecker has obtained the general expression for the radial potential distribution that allows for arbitrary values for $\epsilon = \frac{\Gamma_{r-}}{\Gamma_{r+}}$, and that includes an arbitrary electron-ion interaction term η, that might be associated with micro-instabilities.[8]

Defining $\sigma_{r\pm} = e\eta\, \mu_{\pm}\, n(r)$, and assuming that

$$\mu_- \gg \mu_+$$

and $U = 0$ at $r = 0$,

then

$$\frac{eU}{kT} = \left(1 + \frac{T_+}{T_-}\right)(1 - \epsilon)\sigma_{0+}\left(\frac{n}{n(0)} - 1\right) - \frac{1 + \mu_+\mu_- B^2\left(\frac{\mu_+}{\mu_-} - \epsilon\frac{T_+}{T_-}\right)}{1 + (\mu_+^2 + \epsilon\mu_+\mu_-)B^2}\ln\frac{n(0)}{n}$$

$$+ \left(1 + \frac{T_+}{T_-}\right)\left\{(1 - 2\epsilon)\mu_+^2 B^2 + \epsilon\mu_+\mu_- B^2 + \mu_+^4 B^4(1 - 2\epsilon + 2\epsilon^2)\right.$$

$$\left. + \mu_+^3\mu_- B^4(\epsilon - 1)^2\epsilon + \mu_+^5\mu_-^{-1}B^4(\epsilon - 1)\right] \Big/ \left[1 + \mu_+^2 B^2 + \mu_+\mu_-\epsilon B^2\right]\Bigg\} \tag{7}$$

$$\ln\left\{\frac{1 + \dfrac{\sigma_{0-} + \sigma_{0+}}{1 + \mu_+^2 B^2 + \mu_+\mu_- B^2\epsilon}\,\dfrac{n}{n(0)}}{1 + \dfrac{\sigma_{0-} + \sigma_{0+}}{1 + \mu_+^2 B^2 + \mu_+\mu_- B^2\epsilon}}\right\}.$$

Using the Bessel function density distribution obtained for the positive column and assuming no enhanced interactions, the previous solution for ambipolar diffusion is recovered by setting $\epsilon = 1$, and the Simon diffusion case is recovered by setting $\epsilon = 0$. Intermediate values of ϵ are, of course, permissible.

The criterion (developed by Simon[11]) that is sufficient for transverse diffusion to be ambipolar in a plasma column of radius R, where the column is immersed in a magnetic field of length L and terminated at both ends by conducting surfaces, is

$$\frac{L}{R} > \left\{\frac{\ell}{R}\right\}^{1/2} \omega_- \tau_- , \tag{8}$$

where $1/\ell = (1/n)(dn/dr)$, n is the elctron density, ω_- is the cyclotron frequency, and τ_- is the electron-neutral collision time. This criterion is satisfied in many of the present operating conditions, and we have seen no indications of other than ambipolar transverse diffusion even in rather short tubes. In the "long tube" experiment considered in this paper, we will use $\epsilon = 1$; for this case the radial potential variation in a positive column is given by

$$\frac{eU(r)}{kT_-} = \frac{1 + \mu_+\mu_- B^2 \left(\frac{\mu_+}{\mu_-} - \frac{T_+}{T_-}\right)}{1 + \mu_+\mu_- B^2} \ln\left[J_0\left(\frac{2.4r}{R}\right)\right]$$

$$+ \frac{\mu_+\mu_- B^2\left(1 + \frac{T_+}{T_-}\right)}{1 + \mu_+\mu_- B^2} \ln \frac{1 + \frac{\sigma_{0+} + \sigma_{0-}}{1 + \mu_+\mu_- B^2} J_0\left(\frac{2.4r}{R}\right)}{1 + \frac{\sigma_{0+} + \sigma_{0-}}{1 + \mu_+\mu_- B^2}} . \tag{9}$$

If the second term on the right of the equation is appreciable, i.e., $\eta \neq 0$, the shape of the U(r)-versus-r curve is noticeably modified, and a minimum is developed as shown in Fig. 1. In plotting Fig. 1, values q and T_-/T_+ that are representative of the positive column in a longitudinal magnetic field have been chosen; the value of $\sigma_{0+} + \sigma_{0-} = 5$

implies the presence of a greatly enhanced interaction. In this example the axial electric field would be increased above the classical value by a large amount if the increased interaction were uniformly distributed across the tube. However, Ecker has argued[8] that enhanced interactions could exist throughout a large fraction of the plasma without appreciably affecting E_z, but potential curves of the general shape shown in Fig. 1 would still be obtained. It appears possible, therefore, that a semi-quantitative determination of the radial potential distribution can be used as a measure of the presence or absence of any enhanced interaction and also to indicate the magnitude of η

III. THE EXPERIMENT

The basic physical arrangement is shown in Fig. 2; this is known as the long-tube geometry. Discharges in pyrex tubes 300 cm long and 2.75 cm in radius were studied; currents from 50 to 500 mA dc were drawn from a hot tungsten cathode and an electronically regulated constant-current power supply. A number of electric probes made from glass-coated 0.5 mm tungsten rod, ground flat at one end and protruding slightly into the tube from the tube wall, were spaced along the tube as shown in Fig. 2. Midway between the electrodes, Langmuir probes of various shapes and types could be introduced into the tube and moved along a diameter by means of a micrometer screw. The region of the tube in the vicinity of the radially movable probes was provided with several wall probes. The perturbing effect of the radial probe on the plasma could thus be monitored to some extent by monitoring the axial electric field. An oil diffusion pump with a refrigerated baffle and a liquid nitrogen trap gave a system of base pressure of the order of 10^{-7} mm of mercury; there was no provision for baking

the tube. During an experimental run gases were continuously bled through the system, sometimes through a charcoal trap kept at liquid nitrogen temperatures.

The floating-potential difference between two probes, one fixed at the wall, the other movable along a tube diameter containing the wall probe, is shown in Fig. 3. In this case the movable probe was made of 1.5-mm-diameter tungsten coated with glass to a diameter of 3 mm and ground flat at the collecting end. These curves would appear to satisfy Ecker's criterion for the presence of enhanced diffusion (see Fig. 1). Curves similar in shape to Fig. 3 were obtained for other gas pressures and probe diameters decreasing to a 0.25-mm-diameter anodized aluminum wire as well as for spherical and cylindrical collecting areas. The minima were often less pronounced, but asymmetrical curves were always obtained. Measurements of the axial electric field as a function of the position of the radial probe indicated that the existing potential distribution was significantly perturbed by the radial probe. In view of this and in the absence of symmetry about the center of the tube (see also Fig. 6 of ref. 10), it is clear that this technique is unsatisfactory for determining radial potential distributions.

Assuming that only the radial part of the probe appreciably perturbed the plasma potential distribution, we separated the collecting area from the radial portion of the probe as shown in Fig. 4. At the same time an attempt to calculate the probe perturbation in such an asymmetric geometry was made for the B = 0 case by Masterson et al.[13, 14] They found quantitative agreement with the experimental results, but their analysis has not been extended

to the $B > 0$ regime. These probes were made of 0.25-mm-diameter anodized wire. The anodizing process provides a dielectric coating of excellent quality 0.025 mm thick. The portions of the probes that were parallel to the axis of the discharge tube varied in length from 3 to 10 cm.

If the tip of the probe was not adjacent to a wall probe (Fig. 4), it was found that suitable reference potentials could be obtained either at the anode or by means of a voltage divider connected to two wall probes spanning the position of the radial probe. Typical results are shown in Fig. 5 through Fig. 7. The lines are not theoretical curves but are drawn in to show the trends of the experimental distributions, and data for the various magnetic fields have been normalized to the maximum in the $B = 0$ curve. The shapes of the curves are independent of the length of the part of the probe that is parallel to the magnetic field, provided that it is greater than a minimum value that varies with pressure. The results in all cases are relatively symmetrical about the tube axis except for a general tilt--perhaps due to a remnant effect of the radial stem of the "dogleg" probe. Perturbations are still visible very close to the tube walls. At magnetic fields greater than B_c, the fields at which the columns changed from azimuthally symmetric to helical discharges, the distributions are not particularly meaningful.

In order to remove the collecting area still further from any possible radial asymmetric effects, the geometry shown in Fig. 8 was used. Anodized aluminum wires 0.25 mm in diameter with a 1-mm-long bare spot as the collecting area were used. (Problems of sag due to heating of the wire in the discharge precluded the use of this type of probe in the 300-cm tube.) The

wall probes were actually located along a diameter rotated 90° from the positions indicated in Fig. 8 so that the bare portion of the anodized wire did not approach them. Measurements of the axial electric field as the anodized wire probe was moved about in the discharge showed perturbations that were less than 5% of the magnitude of the field. A second anodized wire 0.25 mm in diameter, parallel to the tube axis and movable along a diameter perpendicular to the motion of the probe wire, was installed in the system depicted in Fig. 8. The radial potential was monitored while this perturbing wire was moved about the discharge; we found that the radial potential was not altered by more than 5% by the presence of the second wire.

Some of the results obtained with these probes are given in Figs. 9 to 11. Once again, the curves at and above B_c are not easily interpreted because they are time averages of the potentials in unstable discharges.

IV. DISCUSSION

A comparison of the data from the dogleg probe in the long discharge tube and the axial probe in the short tube--e.g. Figs. 6 and 10 at 0.6-mm-Hg pressure and Figs. 7 and 11 at 0.9-mm-Hg pressure--shows that the results obtained with these two geometries are nearly identical. There are two minor exceptions: The curve slopes are different when the probing area is within a few millimeters of the tube wall, and they are quite different when the magnetic fields are so large that the discharges are unstable. The latter fact is probably due to the very different tube and electrode geometries. The general agreement between results obtained with these two probe geometries, and the demonstration in the short tube that a second axial probe perturbs the measurements only in a minor way provide a measure of confidence in the technique.

To compare the experimental results with theory, it is necessary to correct the curves for sagging of the probes when they are heated in the discharges, and, more important, to make an assumption about the ion temperature. As an example, consider the case shown in Fig. 9. The observed maxima do not occur exactly at the center of the tube; the probe position is indicated on the micrometer screws. Near the center, the probe wire was observed to sag about 2 mm when the discharge was turned on, whereas no deflection was noted when the probe was near the tube walls. If we make the crude assumption that the sag is proportional to the charged-particle density, then the effect can be unfolded from the experimental data to give symmetrical curves--examples of which are shown in Fig. 12. As data on the actual sag vs position do not exist, we can use these examples only as a semiquantitative argument for the explanation of the observed asymmetries.

Also shown in Fig. 12 are sample potential curves calculated from Eq. (5). For this case, T_- was measured to be 3.2 eV at B = 0 and 2.9 eV at B = 472 G; the mobilities were obtained from ref. 13. The ratio T_+/T_- is not known but is generally thought to be in the range 10^{-2} to 10^{-1}. We see from Fig. 12 that $T_+/T_- = 10^{-2}$ gives a reasonably good fit except in the region close to the tube wall. This general conclusion appears to hold for our range of pressures. No examples of a reversal in the radial field were obtained below B_c.

There is little published literature on potential measurements in a positive column in a magnetic field. The straight radial probe measurement of Bickerton and von Engel[10] is at a lower pressure than we used, but the resultant asymmetries are similar to those that we found with straight probes. Von Gierke and Wöhler have reported[14] measurements in a 3-cm-radius tube with a radially movable probe that consisted of two 2-mm-diameter probes at a fixed separation of 1 cm. We would expect appreciable perturbation of the potential by the probe, but no data are given

for finite magnetic fields less than the critical field for macroscopic instability. Probe measurements in other types of discharge, e.g. reflex (PIG) discharges,[15, 16] are not directly comparable.

Ecker et al.[17] have calculated the perturbations caused by a probe in a positive column. Unfortunately, no quantitative comparison with our experiment is possible at this time because (1) the calculations do not include the effects of an axial magnetic field, and (2) an unknown quantity α is carried as a parameter. (α includes, for example, the ratio of the number of charged particles returned to the plasma to the number entering the probe sheath from the plasma). Qualitatively, it is apparent from their theory that large perturbations can be introduced by a radial probe stem-- in agreement with the effects which we have observed.

It is interesting to note that a qualitative comparison of the time-averaged potential profiles in quiescent uniform discharges (Figs. 5 and 9) and in discharges containing moving striations (Figs. 6, 7, 10, and 11) reveal no effects that can be attributed to striations.

V. CONCLUSIONS

The radial stem of an insulated probe can seriously perturb the radial potential distribution in a positive column in an axial magnetic field. Figure 3 is an especially bad example; the perturbations are smaller at higher pressures or with smaller-diameter probes. When more reasonable probe geometries are used, the radial potential distributions can be explained by the classical theory of the column; in this case we do not find minima in the U(r) vs r curves that would, according to the Ecker theory,[8] suggest the presence of enhanced diffusion.

There is no evidence for Simon diffusion, even in short tubes at low pressures, i.e., where Eq. (8) was not properly satisfied. This is not surprising because Eq. (8) was not violated severely, and the magnetic field lines crossed the glass walls of the discharge tube rather than the metallic conductors assumed by Simon. (There is, however, good evidence that insulating surfaces behave like conductors when they are bombarded by plasma with a sufficiently high energy density.[18])

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Figure Captions

Fig. 1. The ambipolar radial potential distribution from the theory of Ecker[8] plotted as a function of the relative radial distance r/R for values of the parameter $q = \mu_+ \mu_- B^2$; $\sigma_{0+} + \sigma_{0-} = 5$; $T_-/T_+ = 10$.

Fig. 2. The primary experimental arrangement (long-tube system).

Fig. 3. Potential with respect to wall probe vs radius. He gas at 0.2 mm in 55-mm-i.d. tube. Magnetic field in gauss as indicated. Curves have been normalized to center. $B_c = 760$ G is the field at which the helical instability develops.

Fig. 4. Details of probe arrangement in long-tube system, using 0.25-mm-diam anodized aluminum dogleg probe.

Fig. 5. Radial potential U(r) vs distance of probe tip from tube wall; 0.3 mm Hg, He gas, I = 200 mA. Dogleg probe (Fig. 4) in 300-cm-long tube, R = 2.75 cm. Magnetic field B in gauss. B_c is the magnetic field at which the helical instability develops.

Fig. 6. U(r)-vs-d curves; He gas, 0.6-mm Hg, I = 200mA. Probe and tube geometry is indentical with Fig. 5.

Fig. 7. U(r)-vs-d curves; He gas, 0.9-mm Hg, I = 200mA. Probe and tube geometry is identical with Fig. 5.

Fig. 8. Secondary, short-tube system. The anodized aluminum wire was movable along a diameter for radial potential measurements.

Fig. 9. U(r)-vs-d curves; He gas, 0.2-mm Hg, I = 200 mA. Probe and tube geometry as shown in Fig. 8; R = 2.75 cm.

Fig. 10. U(r)-vs-d curves; He gas, 0.6-mm Hg, I = 200 mA. Probe and tube geometry as shown in Fig. 8; R = 2.75 cm.

Fig. 11. U(r)-vs-d curves; He gas, 0.9-mm Hg, I = 200 mA. Probe and tube geometry as shown in Fig. 8; R = 2.75 cm.

Fig. 12. Comparison of experimental results and theory [Eq. (5)] for He at 0.2-mm Hg and I = 200 mA. The probe and tube geometry are shown in Fig. 8. The data have been corrected for probe sag as described in the text; this correction is too small to indicate separately in the B = 472 -G case.

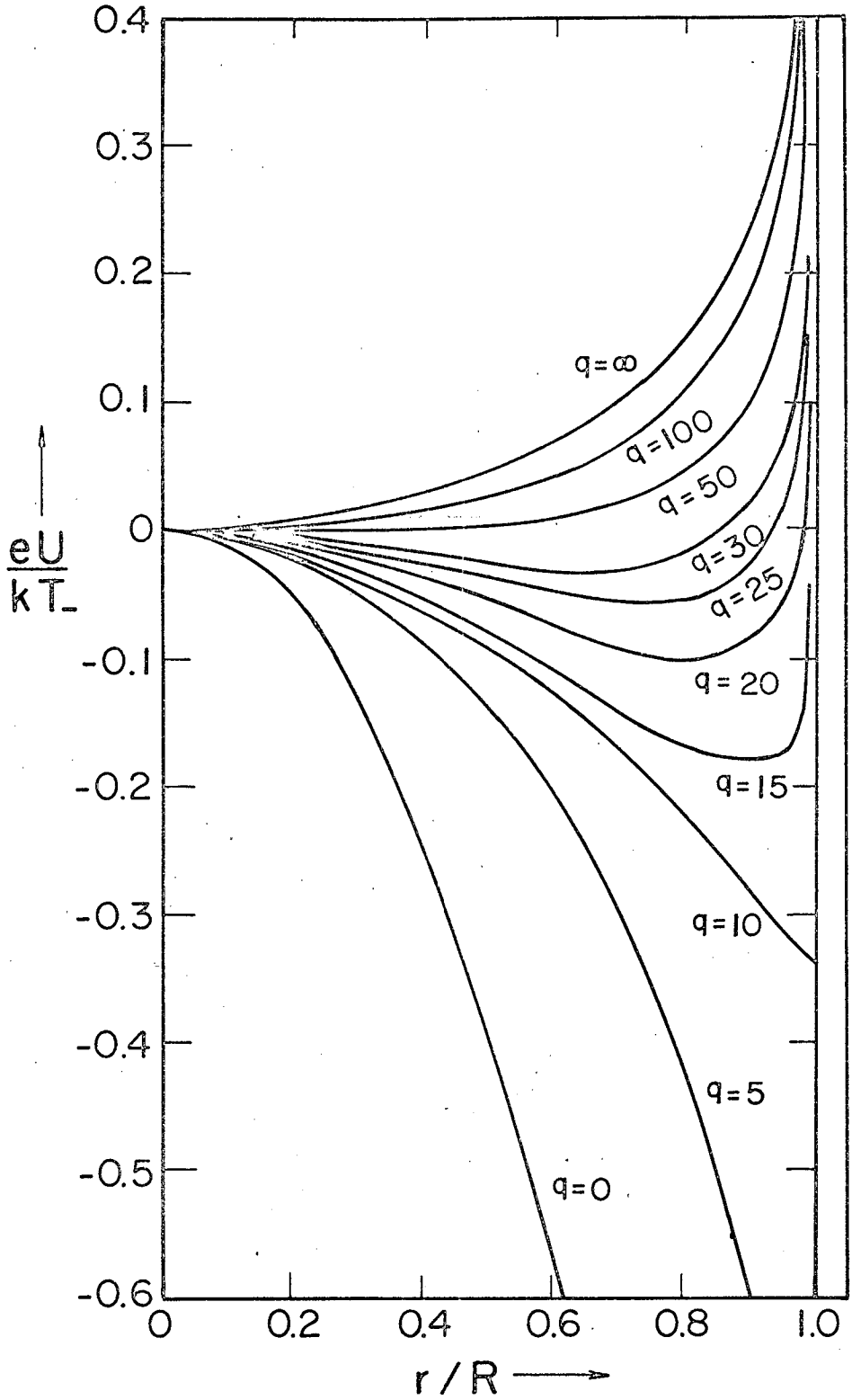

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Fig. 1

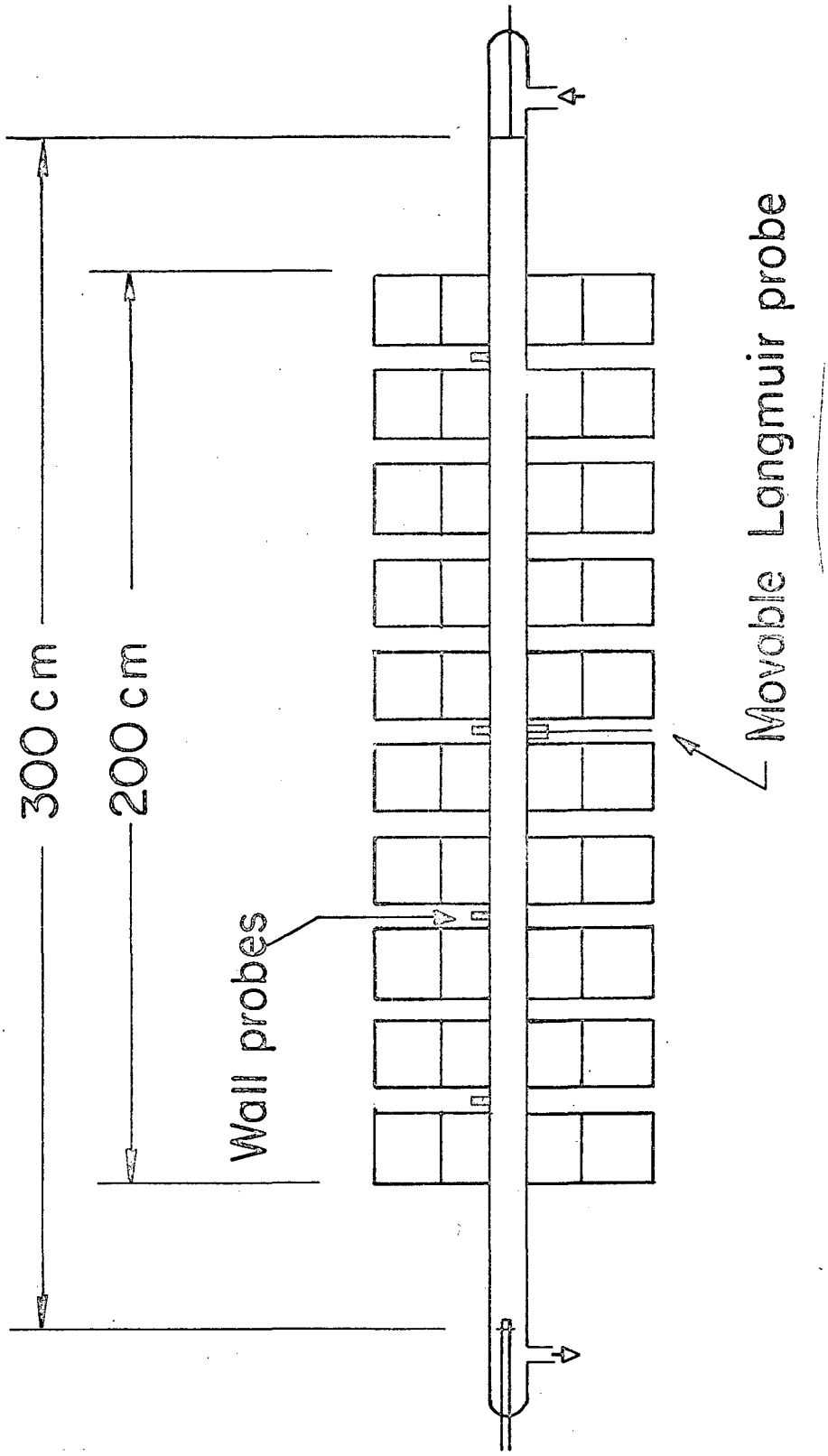

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Fig. 2

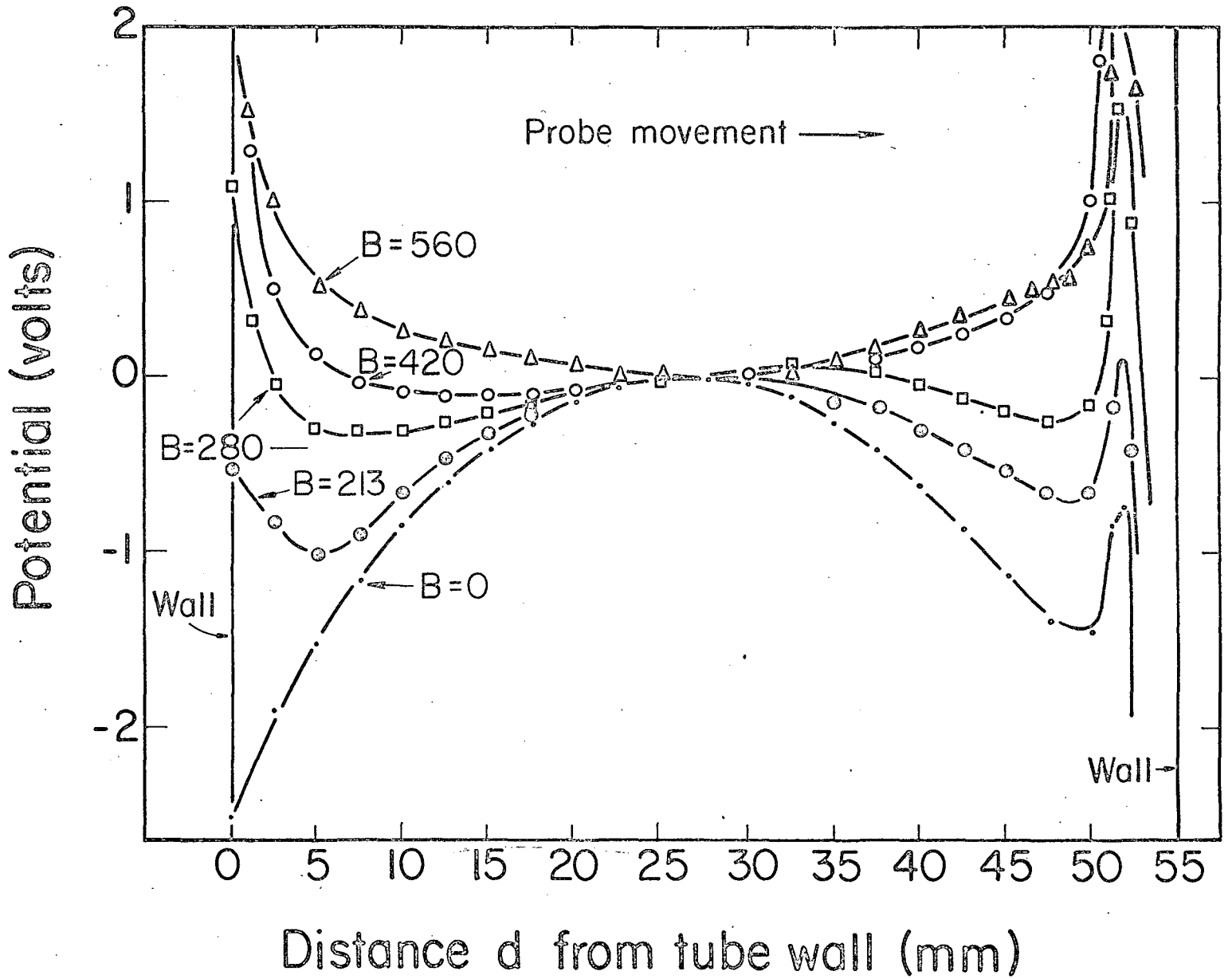

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Fig. 3

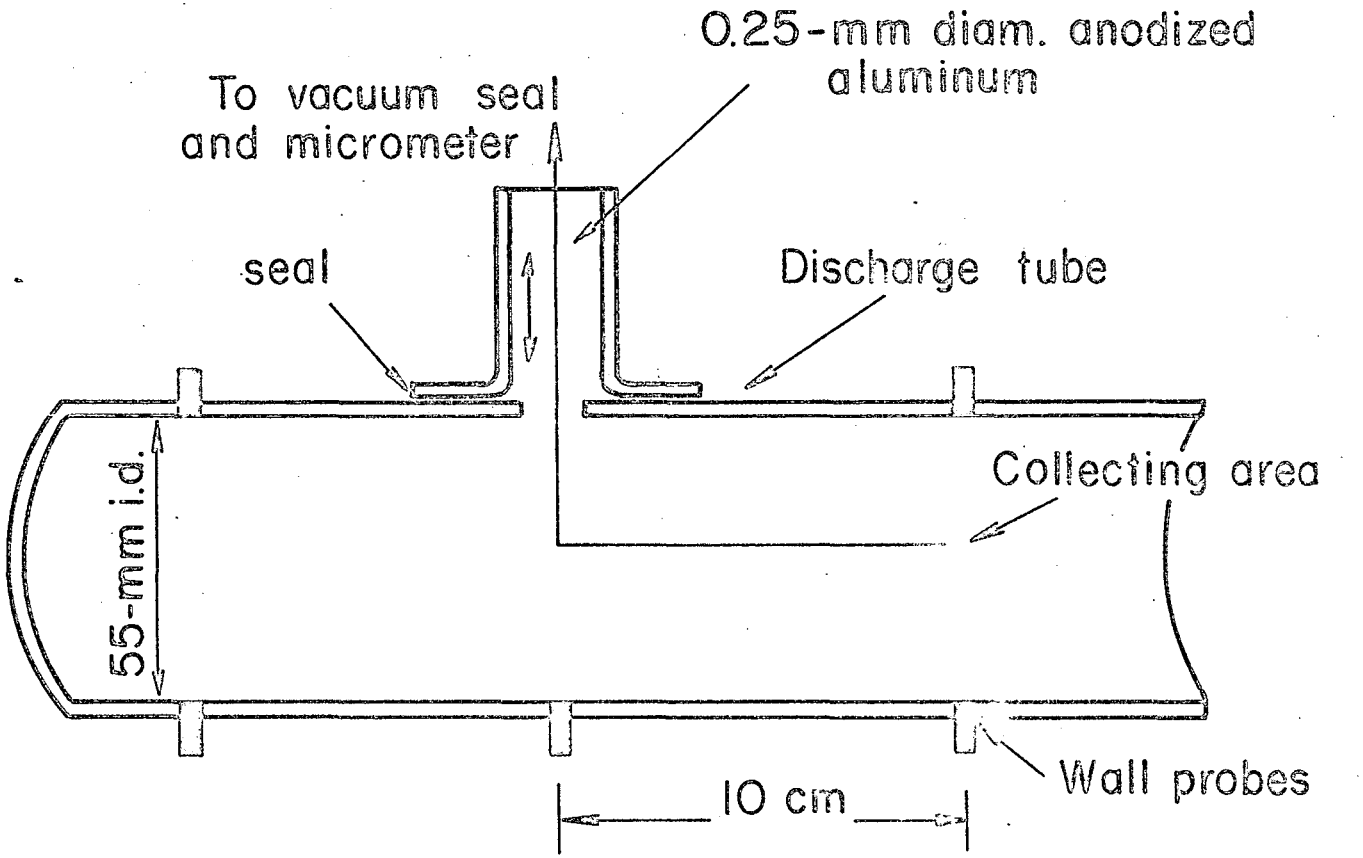

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Fig. 4

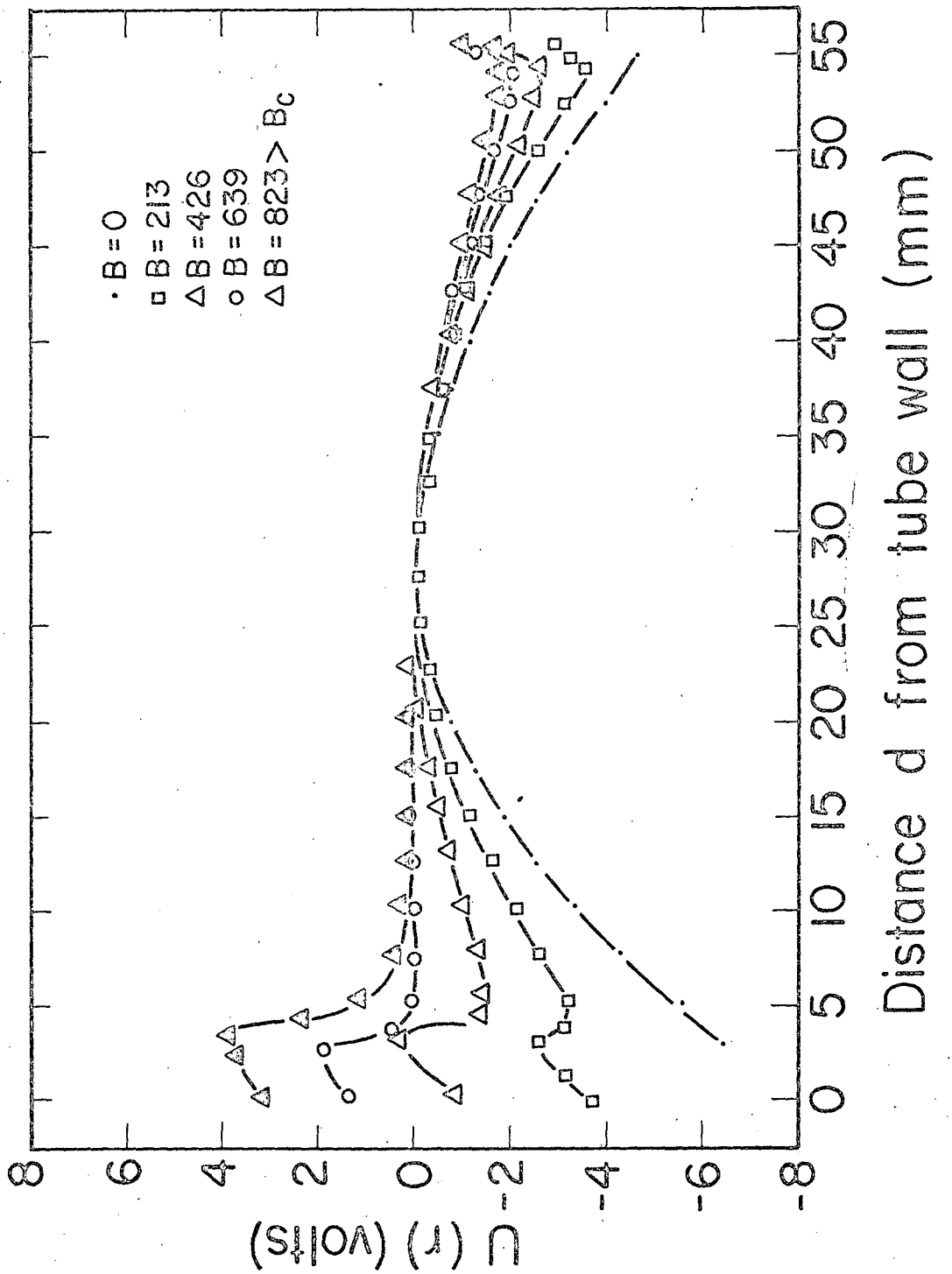

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Fig. 5

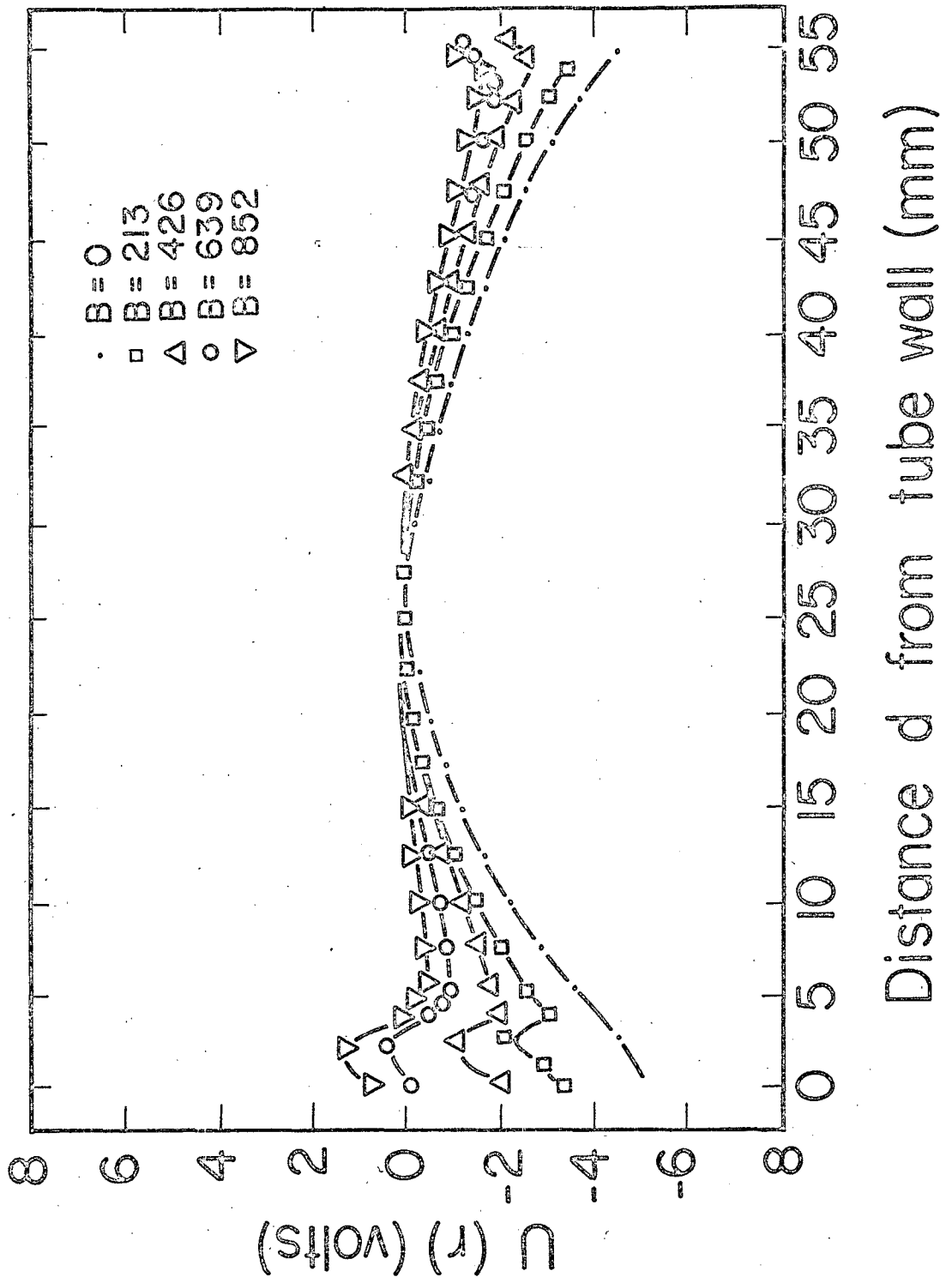

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Fig. 6

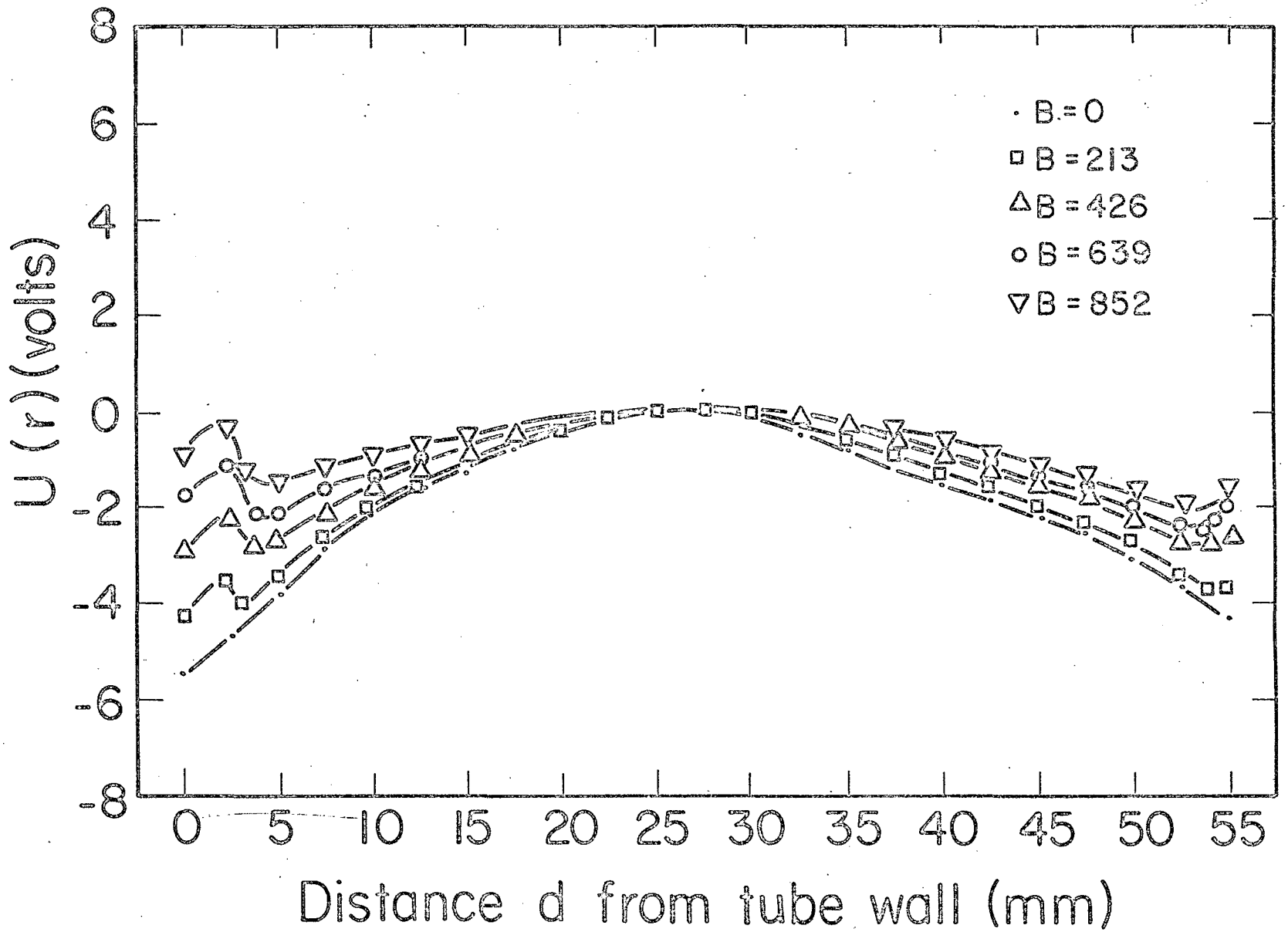

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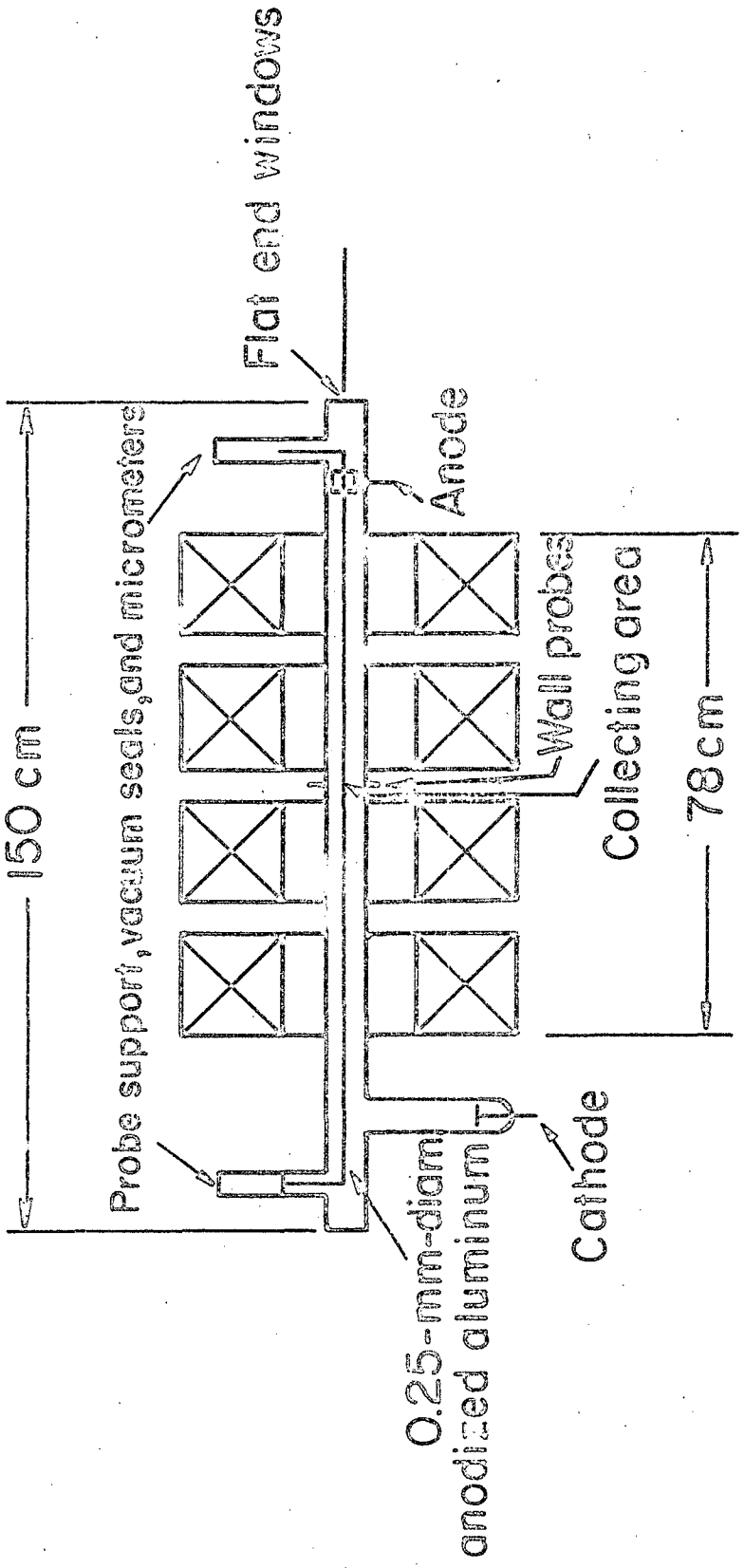
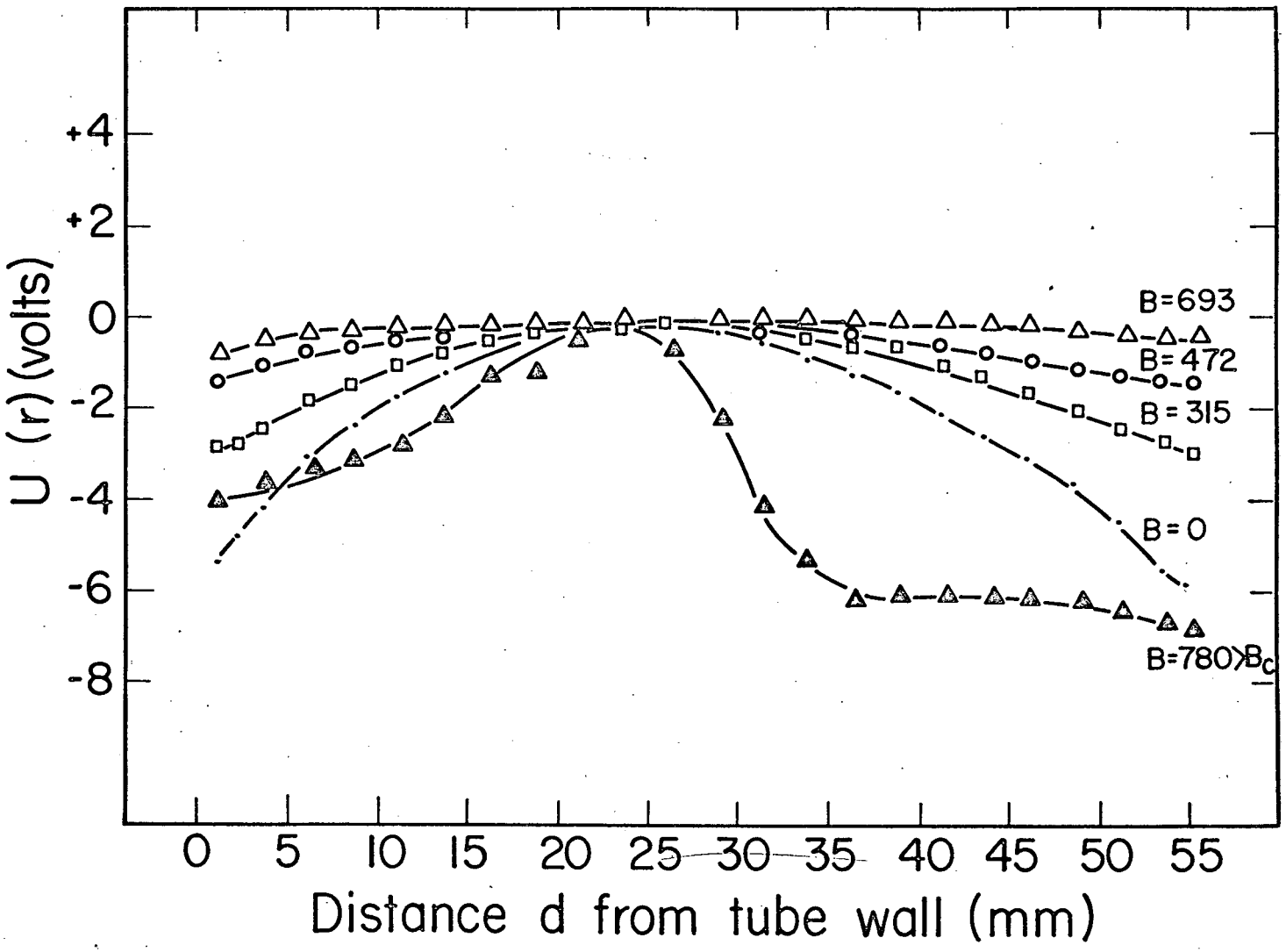
Fig. 7



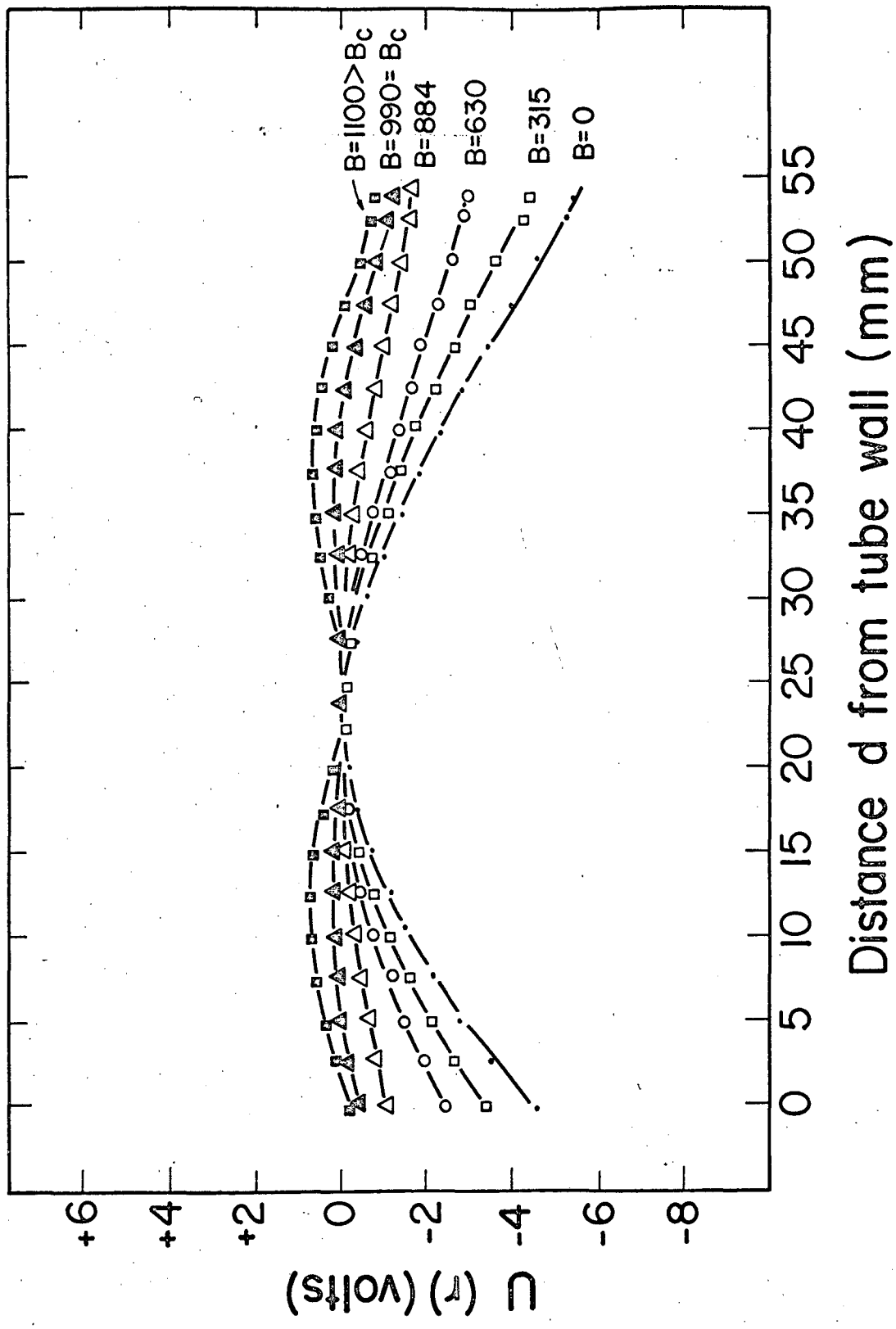
MU-22939

Fig. 8



MU-22926

Fig. 9



MU-22932

Fig. 10

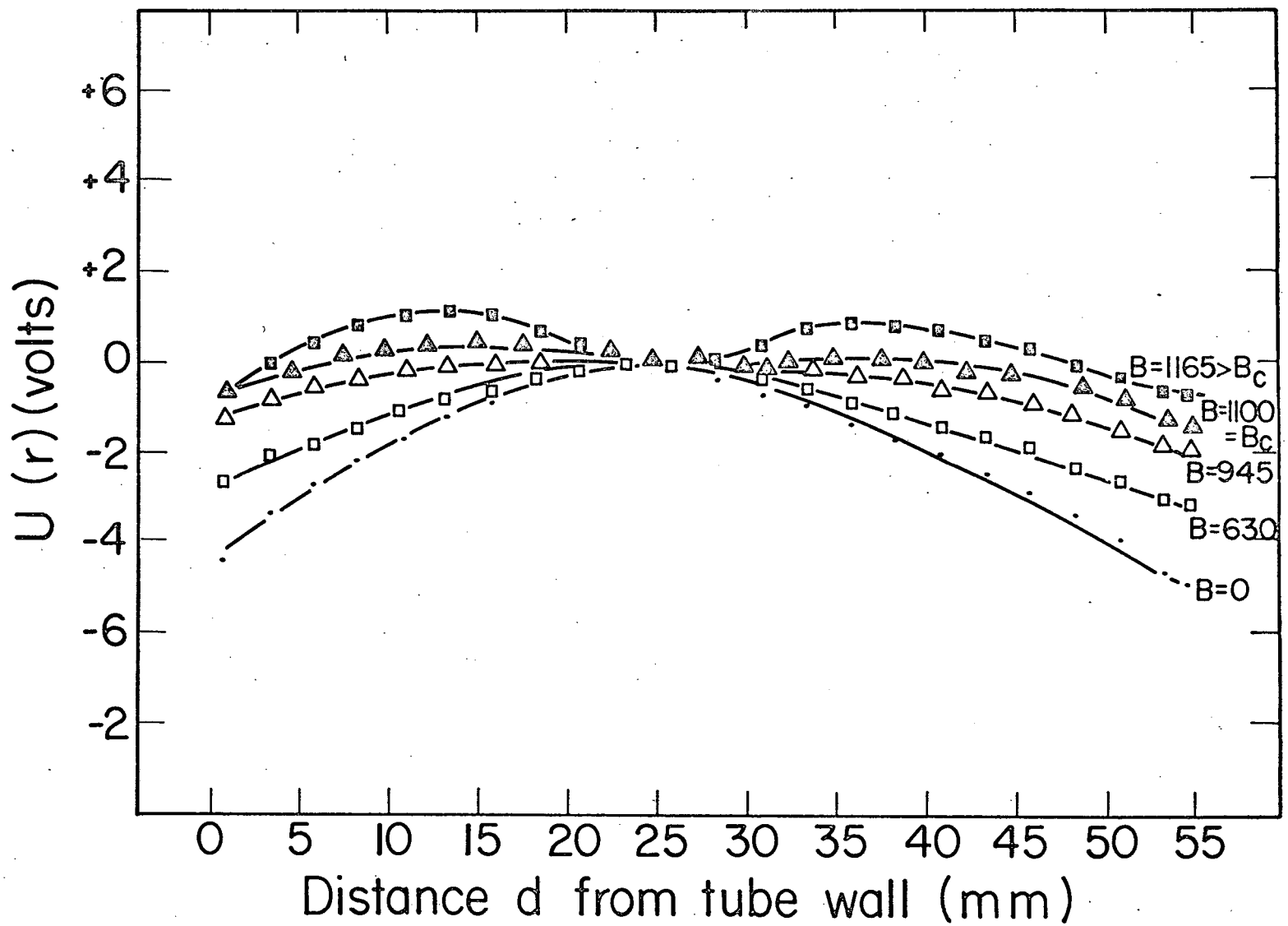


Fig. 11

MU-22935

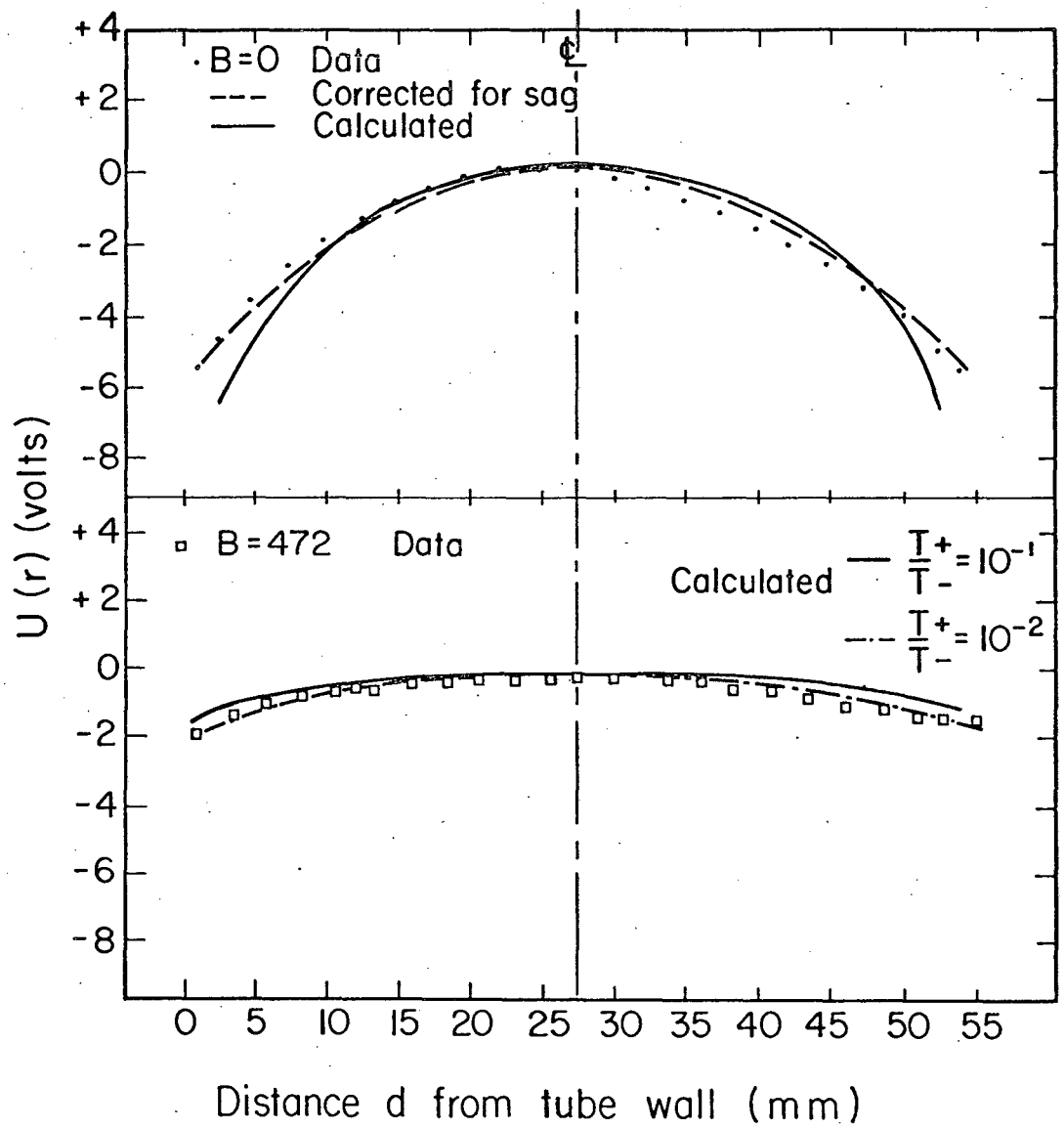


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Fig. 12