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Abstract

A multiple pseudowave — or a series of fast ion bursts — is generated when a short negative voltage pulse is placed on a transparent grid immersed in a plasma. The phenomenon resembles, but is not, a damped wave train. We show, using a single-particle model, that multiple pseudowaves can be explained in terms of ions trapped and oscillating in the ion sheath formed around the grid by the negative voltage pulse. A pulsed grid used in this manner constitutes a simple diagnostic technique for measuring plasma density.

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Recently, we reported that it is possible to excite an energetic burst of ions by placing a time-varying potential on a transparent grid immersed in a plasma.[1] We called such an ion burst a pseudowave. In those experiments we found when we removed a large, essentially dc, negative voltage from a grid that a single energetic burst of ions would be shot out into the plasma. We now find that if a sufficiently narrow negative square pulse is placed on such a grid that several discrete ion bursts are accelerated into the plasma.[2] Below, we show both graphically and mathematically how multiple pseudowaves can be explained in terms of ions trapped and oscillating in the ion sheath formed around the grid by the negative voltage pulse.

Figure 1 shows the apparatus used in the experiment. A xenon plasma was generated in a 5-liter glass cross by ionizing collisions between energetic electrons from the electron gun and the background gas atoms, a method being similar to that described previously.[1,3] By this technique, in a xenon gas at a pressure of about one micron, we generate quiescent plasmas having densities of 10^8-10^{10} particles cm^{-3} and electron temperatures of approximately 1 eV. The gas pressure and ion density are sufficiently low that over short distances the ions can be considered to be collisionless. The pseudowaves are generated at the nearly transparent tungsten-mesh transmitter grid by placing a large negative square-pulse voltage of variable width on the grid. The pseudowave signal then propagates through the plasma and is detected by the small positively biased wire probe which observes a burst of electrons accompanying the ion burst. This electron collection technique greatly enhances the sensitivity of a probe used to study ion density fluctuations.[4] The

pseudowave signal appears as a voltage across the 1-kΩ small resistor which is amplified, and then viewed on an oscilloscope.

An important point is that electron neutralization of the ion burst is essential for the burst's propagation. If the bursts were unneutralized, space-charge potentials comparable to the negative voltage pulse on the grid would immediately explode the burst. Thus, an "ion burst," or pseudowave, is a collective phenomenon whose properties in many respects are similar to those of a bona fide electrostatic plasma wave.

Figure 2 shows the qualitative behavior of the discrete structure of the pseudowave signal as a function of pulse width. In this series of photographs nothing was varied except the pulse width. In each case the upper trace shows the 160-V negative voltage pulse, while the lower trace shows the received pseudowave signal. From the figure two main features of the received signals can be observed: the first is that as the driving pulse is made wider and wider, the number of bursts increases until finally they begin to overlap and all structure is lost; the second feature is that, while the number of bursts gets larger and larger as the pulse gets wider and wider, each individual burst is moving toward some shortest propagation time, indicating a "saturation" velocity. First, we show graphically why, qualitatively, multiple structure should be expected in the first place and, secondly, why it should exhibit these two features. Based on the graphical model, we then calculate the velocity properties of the bursts, using a non-harmonic potential well.

Figure 3 shows the graphical model for multiple pseudowave generation. Here we represent a grid in a plasma by the vertical dashed line. Consider, now, a negative potential to be suddenly applied to the grid. The ions will suddenly find themselves at rest at various locations in

the well, as shown schematically in Fig. 3(a). Ions are at the bottom of the well when they are at the grid plane and are at the edge of the well when at the maximum distance shown from the grid. Thus, the horizontal displacement from the grid gives not only physical position but also depth of the ion in the well. In actuality there would be ions at all points both inside and outside the well and on both sides of the grid; however, for simplicity we show here only a few representative ions on only one side of the grid. The ions shown outside the well are important since they can diffuse into the well at later times. The ions which are trapped inside the well will oscillate in the well as long as the negative voltage is sustained, each ion at its own characteristic frequency. At some time later their profile will be transformed into a smooth curve such as shown in Fig. 3(b). The ions at A, C, and E have returned to their initial depths in the well and have zero velocity. The ions at B, D, and F are at the bottom of the well and have a larger velocity than ions immediately on either side which are either still falling into the well or else climbing out. Thus, if we suddenly remove the voltage pulse from the grid, these ions will continue out into the plasma with their full velocity and will constitute the leading edges of multiple ion bursts such as we saw in Fig. 2. If we look at slightly longer times then particles located higher up in the well, just above F for example, will have had time to reach the grid, so that the point F will have moved upward. Correspondingly, all the other points — A, B, C, D, and E — will have moved higher. Continuing this line of reasoning, it becomes obvious that the longer the negative voltage pulse stays on the grid, the more wiggles the particle profile will have and thus the

more ion bursts that will be seen, until finally their structure begins to overlap and form a smooth signal such as seen in Fig. 2(d). And since the intersection points all move upward, it is seen that each burst will approach the limiting velocity given by setting the ion kinetic energy equal to the total eV of the potential well. A second ion-profile curve, which is just the mirror image of the one shown, results when ion motion due to ions trapped on the other side of the grid is considered. It is interesting to note that a multiple pseudowave is a form of plasma echo in the sense that information concerning the formation of the ion sheath around the grid can be stored for long times in the trapped ions and then recovered upon removal of the negative voltage.

Figure 4 demonstrates an alternative more sophisticated method of presenting the information contained in Fig. 3. In Fig. 4 we, again, show particle profiles of representative particles at time equal to zero and at two successively later times, relative to the turning on of the negative voltage pulse; however, we now show the profiles using the more conventional phase-space diagram. Also, we show profiles for ions on both sides of the grid. The intersections of the spiralling arms of the particle profiles in Figs. 4(b), 4(c) with the velocity axis show quite clearly the origin of the multiple pseudowaves; two bursts and four bursts of ions, respectively, would be emitted from the sheath region on each side of the grid if the negative voltage pulse were to be suddenly removed. Figure 4 shows that as the ions are allowed to oscillate longer and longer in the well (i.e., as the negative voltage pulse is made longer and longer), the spiral structure "unwinds" resulting in a larger number of intersections with the v-axis (i.e., more bursts), with

each intersection asymptotically approaching a $v_{max} = \sqrt{\frac{2\ eV_o}{m_1}}$, where V_o is the total depth of the well. The qualitative "unwinding" behavior of the spiral structure with time, as well as the qualitative time behavior of the smooth curve shown in Fig. 3, depends upon the well having the property that the electric field either stays constant or decreases monotonically with distance from the grid. This would seem to be the case for any physically reasonable sheath resulting from the plasma's shielding itself against external electric fields. Note that the outer fold of each arm in Fig. 4 is always tied to the sheath edge; this could be due both to the continual influx of ions from outside the well and to the continuous generation of ions in the edge of the well. Also, a potential well of the form used in the calculation below would predict this behavior, as the acceleration of an ion near the edge of the well is very small.

We have made a simple calculation for the motion of an ion in a non-harmonic potential well, such as shown schematically in Fig. 5. This is the potential distribution in the so-called transient sheath which is formed when a surface in contact with a plasma is driven suddenly negative,[5] and is a good first approximation to the situation for a short negative pulse on a transparent grid. The equation for the well is

$$V = -V_o \left(\frac{|x| - |x_o|}{x_o} \right)^2 , \tag{1}$$

where $\pm x_o$ are the edges of the well and $|x| \leq |x_o|$. The equation of motion of an ion in the well is

$$\frac{d^2x}{dt^2} = \alpha \left(|x| - |x_o| \right) , \tag{2}$$

where, it turns out, $\alpha = \omega_{pi}^2$. Solving Eq. (2) for $\frac{dx}{dt}$, using the initial condition that the ion starts from rest, and evaluating at the center of the well gives the velocity of the ion as

$$v = v_{max} \tanh\left(\omega_{pi}\, \tau\right) \quad , \tag{3}$$

where $v_{max} = \left(2\, eV_o/m_i\right)^{\frac{1}{2}}$ is the velocity of an ion falling completely into the well, and τ is the time of acceleration of the ion in the well (i.e., the width of the negative voltage pulse). Equation (3) applies only to the first, most energetic burst of ions coming out of the sheath, i.e., to ions which have made only $\frac{1}{2}$ transit in the well during the time τ. The ions which constitute the leading edge of the second ion burst, see Fig. 3, will have made $1\frac{1}{2}$ transits in the well during the time τ, so that their acceleration time in the well from a zero-velocity point to the grid will be only $\tau/3$. Similarly, the ions of the third burst will have made $2\frac{1}{2}$ transits, so that their effective acceleration time is $\tau/5$. So that, in general, the effective acceleration time of the nth burst will be $\tau/(2n - 1)$. Thus, Eq. (3) can be modified to encompass the velocities of all the bursts by substituting $\tau/(2n - 1)$ for τ:

$$v_n = v_{max} \tanh\left(\frac{\omega_{pi}}{2n - 1}\, \tau\right) \quad , \tag{4}$$

where $n = 1, 2, 3, \ldots$ is the order (in velocity) of the nth ion burst in the multiple pseudowave.

Figure 6 shows a quantitative comparison of the theoretical pseudowave velocities, as predicted by Eq. (4), and the normalized experimentally observed burst velocities. Only the first eight bursts are shown since, experimentally, the signal amplitudes became progressively smaller

and more difficult to observe as the order of the ion burst increases. This is because, primarily, of grid absorption of the ions which would have contributed to the higher-order bursts. The ions in an eighth-order burst, for example, have traversed the grid plane eight times. Since the normalizing factor, ω_{pi}, for τ refers to the plasma density inside the sheath, we have allowed this to be a free parameter and have chosen the value which optimizes the agreement between experiment and theory. The value chosen for ω_{pi} here gave an ion density in the sheath which is approximately a factor of 2 less than that measured just outside the sheath using an ordinary Langmuir probe. Considering the fact that our simple model does not take collective effects into account, we feel that the agreement between experiment and theory is remarkably good. The model also does not allow for plasma absorption by the grid and the resulting expansion of the sheath, which undoubtedly is occurring at the longer times where experiment and theory are seen to agree less well. Both the decrease in ion density in the sheath and the expansion of the sheath are in directions which would improve agreement between experiment and theory, if taken into account.

Allowing ω_{pi} to be a free parameter permits a pulsed gridded probe, used in the manner discussed here, to be used as a simple diagnostic tool for measuring plasma density. Not only is the technique probably valid at much lower densities where Langmuir probe measurements become ambiguous,[6] but the technique can probably be used to measure ion densities in magnetically supported plasmas of simple geometry (by propagating the pseudowaves along the field) where, again, Langmuir probe measurements are difficult to interpret. Note that the theoretical curves in Fig. 6 constitute a

universal set so that new curves do not have to be drawn for each experiment. Also, for diagnostic purposes, the velocity variation with τ of only one ion burst would be required, not several as shown in Fig. 6.

In summary, we have discovered experimentally that a narrow negative voltage pulse placed on a grid in a plasma gives rise to a series of energetic ion bursts which free-stream out into the plasma but require electron-neutralization for their existence. We have demonstrated on a single-particle basis that the observed basic properties of these so-called multiple pseudowaves can be explained by ions trapped and oscillating in the potential well formed at the grid by the negative voltage pulse. Since information concerning the formation of the ion sheath around the grid remains stored in the trapped ions for the duration of the voltage pulse and then is recovered upon the removal of the pulse, multiple pseudowaves represent a form of plasma echo. Using a grid in this manner represents a particularly simple means for measuring plasma density. The technique would appear to work equally well for low densities where Langmuir probe measurements are no longer valid,[6] and also to be valid for measuring plasma density in magnetically supported plasmas of simple geometry.

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FIGURE CAPTIONS

1. Schematic of the apparatus used to study multiple pseudowaves. A quiescent plasma is produced by ionizing collisions between background xenon atoms and a diffuse spray of energetic electrons from the electron gun at the left. The pseudowaves are generated at the transparent transmitter probe, propagate through the plasma, and are detected by the biased receiver probe.

2. Multiple pseudowave data exhibiting the qualitative dependence of the pseudowave structure upon the negative voltage pulse width. The upper trace in each photo shows the −160 volt pulse placed on the transparent gridded transmitter (vertical scale = 50 V/cm), while the lower trace shows the received signal at the biased receiver probe. Sweep scale is 2 μsec/cm; transmitter-receiver separation was 6 cm.

3. A simple model showing schematically the origin of the multiple structure of pseudowaves for a narrow negative voltage pulse. Based on the concept of ions trapped and oscillating in the potential well at the grid, the model accurately predicts qualitatively the observed dependence of the pseudowave structure on pulse width. (a) Profile of representative ions trapped in the well just at the time the voltage pulse is applied; (b) Profile of the ions at a later time. Ions at B, D, and F would constitute the leading edges of separate ion bursts if the pulse were suddenly removed at the time shown.

4. A phase-space representation of the generation of multiple pseudowaves. (a) Profile of representative ions both inside and outside the well and on both sides of the grid at the time the negative potential is applied; (b) Profile of the ions at a later time. Each intersection of the spiralling arms with the velocity axis would, if the negative pulse were suddenly removed, correspond to the leading edge of an ion burst. As time increases the spiral structure "unwinds," increasing the number of ion bursts, as observed in (c), with each burst approaching the limiting velocity of the outermost intersection. For the case shown in (c) there would be four ion bursts emitted on each side of the sheath.

5. Schematic representation of the non-harmonic potential well used in the calculation of the velocity properties of ions trapped in the ion sheath around a negatively pulsed transparent grid in a plasma.

6. A quantitative comparison of the experimentally observed variation of ion bursts' velocities with pulse width and the velocities predicted by Eq. (4) for the conditions of the experiment. Here we have plotted normalized pseudowave velocity versus normalized pulse width for the first eight bursts. By allowing ω_{pi} to be a free parameter and choosing the value which optimizes the agreement between experiment and theory, a pulsed grid exciting multiple pseudowaves becomes a simple diagnostic tool for measuring plasma density; here a plasma density approximately a factor of two lower than the value of 2×10^9 cm^{-3} as measured by a Langmuir probe located immediately outside the grid sheath was found. Note that the theoretical curves constitute a universal set for our sheath profile and need not be calculated for each experiment.

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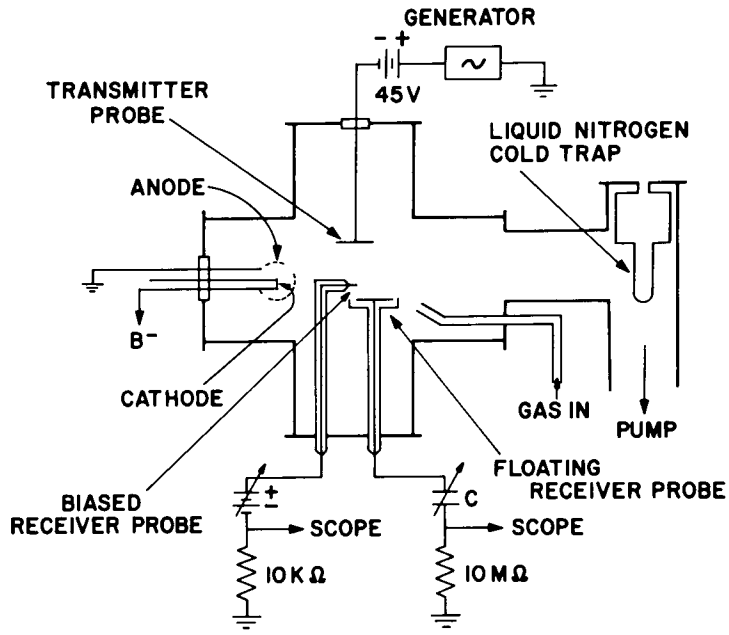

Fig. 1.

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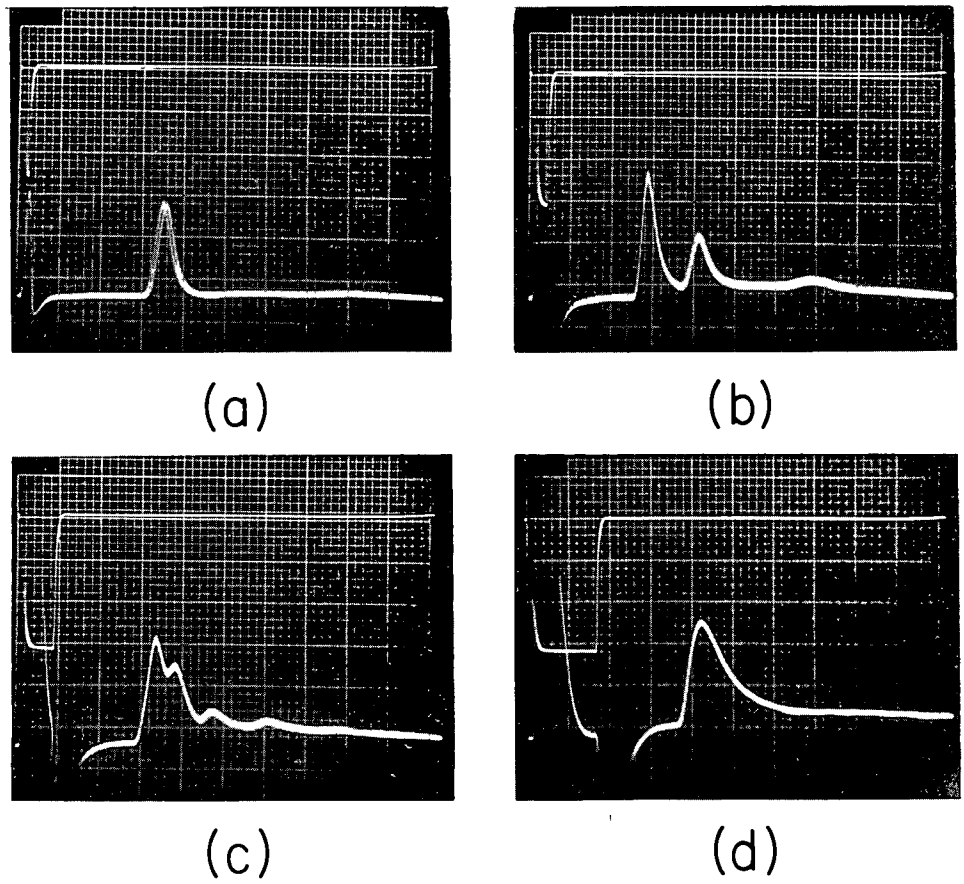

Fig. 2.

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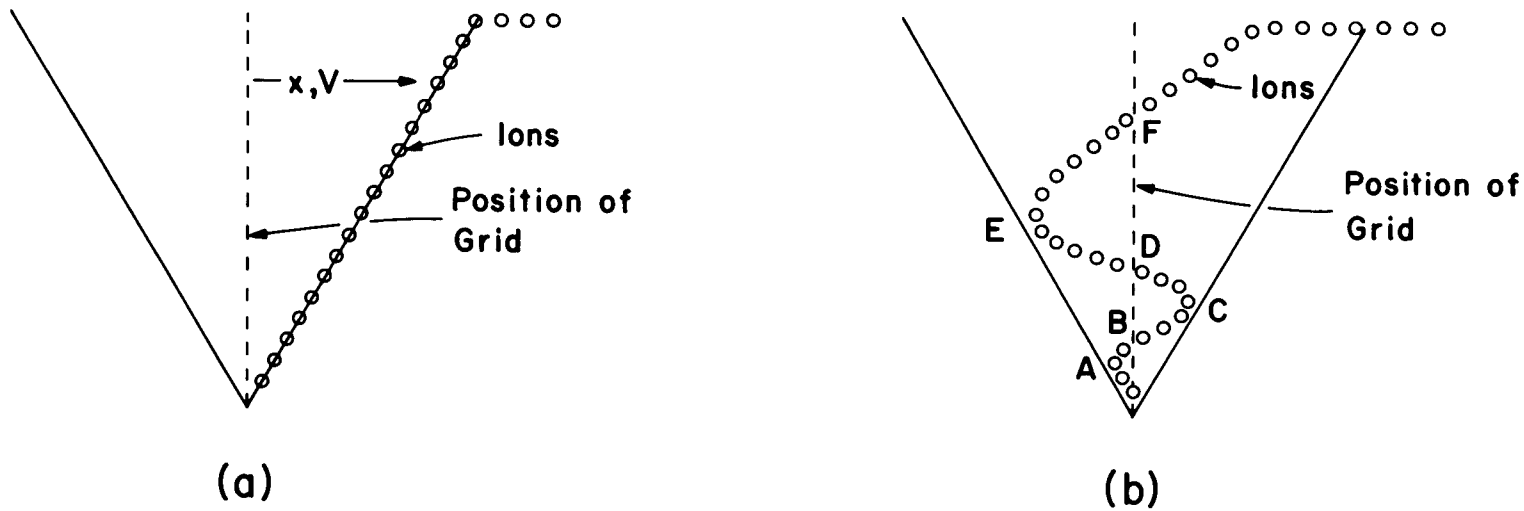

Fig. 3.

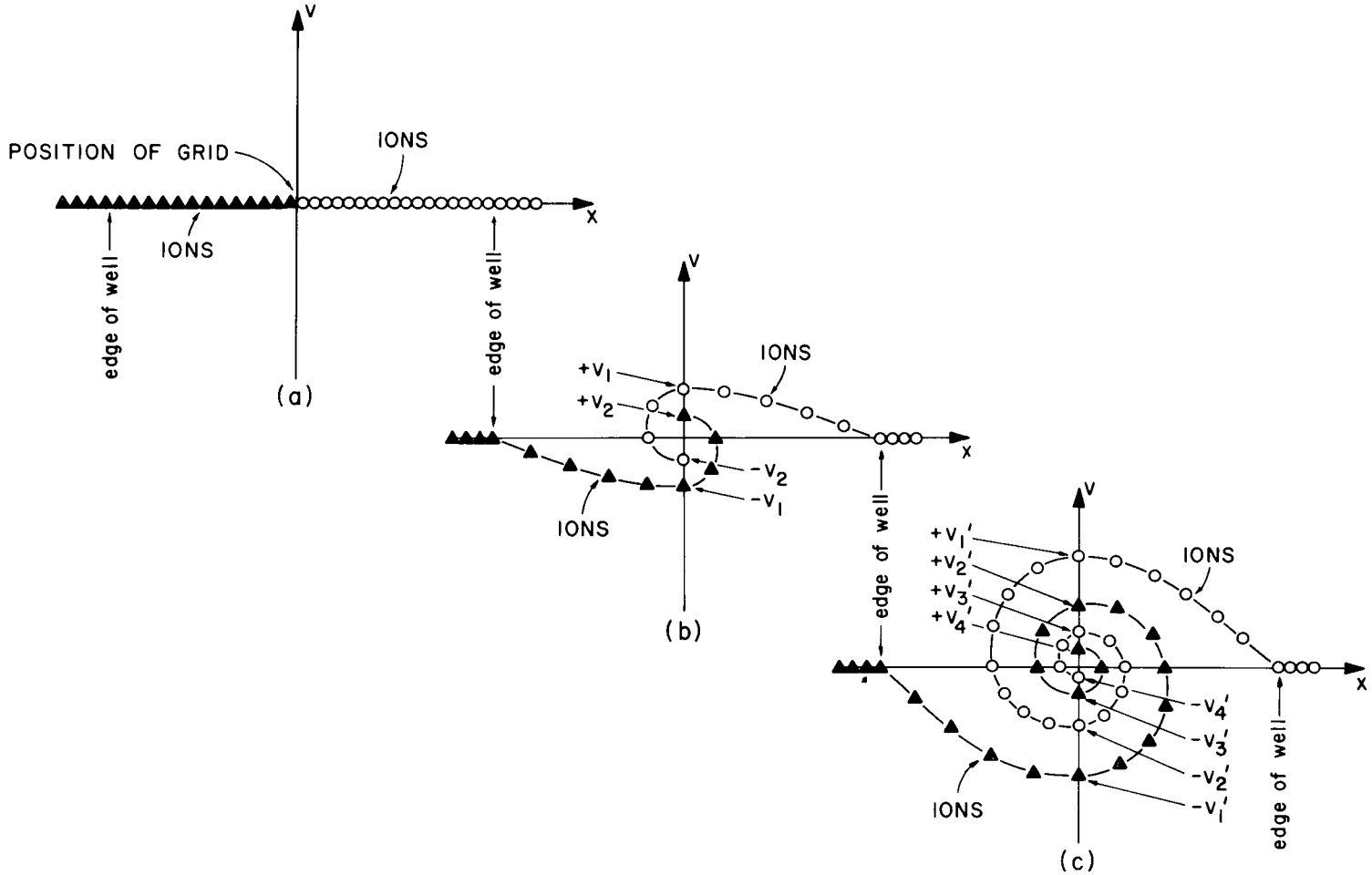
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Fig. 4.

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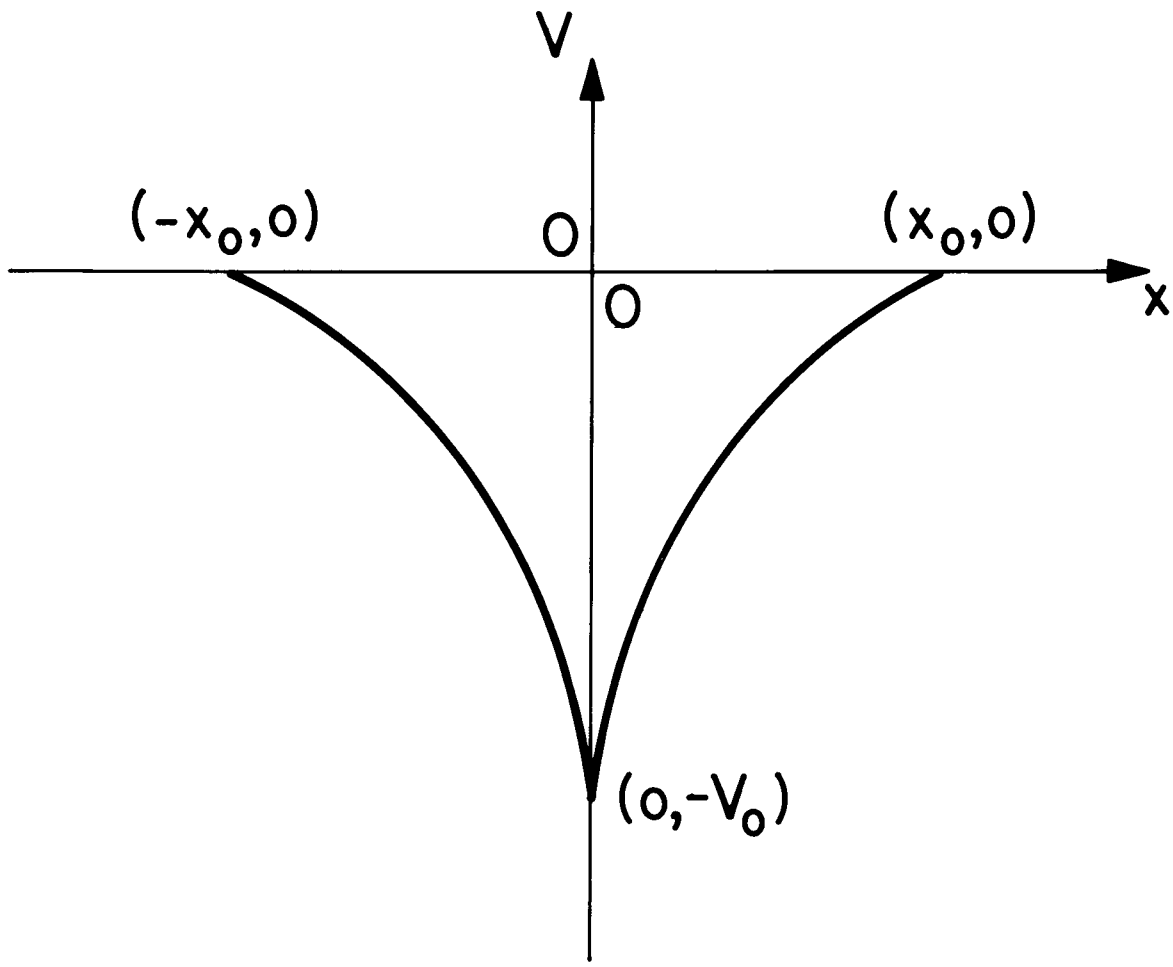

Fig. 5.

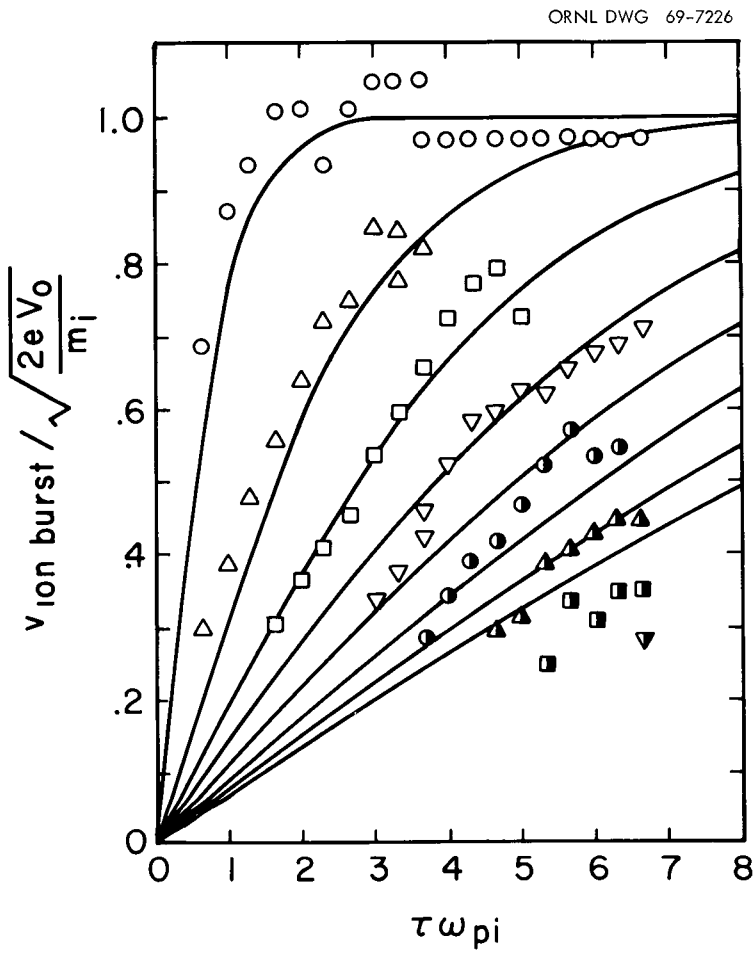
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Fig. 6.