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ANOMALOUS DC RESISTIVITY AND DOUBLE LAYERS IN THE AURORAL IONOSPHERE

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Abstract

There are at least four candidate instabilities which might account for anomalous dc resistivity in the auroral ionosphere. These are: the ion-acoustic instability, the Buneman instability, the ion-cyclotron instability and double layers. We report here results of computer simulations of these four instabilities which suggest that double layers are most likely to be responsible for resistivity in the auroral zone.

The polar magnetosphere-ionosphere interface is characterized by field-aligned currents connecting regions of plasma with vastly different particle density and energy. Observational and theoretical studies indicate that parallel and perpendicular electric fields exist in the region.[1] It would not be surprising to find micro-instabilities there which grow to significant amplitude and lead to resistivity and particle acceleration. Although the "boundary" conditions in this region are not well known, particularly particle distribution functions, it would seem useful to study these micro-instabilities in a simplified, but more controllable form. If their behavior and effect under these conditions are known, then additional complexity and reality can be built into the model with some hope of producing results which can be compared with experimental observations.

The contents of this paper are therefore a summary of our work in simulating several instabilities in simple configurations. From these results, one can then say something about what physics might still be missing from a simulation model which explains physical observations. In a sense, we are presenting only a progress report in a larger ongoing program aimed at matching simulation with the physical world.

We are concerned with electrostatic instabilities and waves which appear in a current carrying plasma with a possible field aligned electric field in which both particle species initially have Maxwellian distribution functions. When $v_d < v_e$ and $T_i << T_e$, we expect ion acoustic waves to grow and produce d-c resistivity. As v_d exceeds the electron thermal speed, the Buneman instability will arise for all ion temperatures.[2] In the presence of a strong magnetic field, $\omega_{ce} \approx \omega_{pe}$, ion-cyclotron waves will grow.[3] There is also the possibility of double layers, either with or without a magnetic field present.[4] We find that significant resistivity occurs as a result of ion-acoustic and Buneman instability and of double layers, but not ion-cyclotron waves directly. The former effects give rise to large changes in electron and ion distribution functions. Figure 1 shows the regimes of these instabilities as determined by the results of computer experiments in our simplified configurations (uniform, periodic).

The Model

A standard electrostatic particle code was used throughout. An arbitrary strength, uniform magnetic field could be applied in any direction relative to the coordinate axes. The bulk of the calculations were done with periodic boundary conditions on the fields and particles. However, some runs were done in a convective system where the potential was held fixed at two boundaries and particles striking these walls were collected. New particles could then be injected at the boundaries with any desired distribution function. In this configuration, heat could be continually drained from the system by particle convection. A fixed or time-varying potential could be placed across the boundaries of this system to accelerate electrons or maintain a constant current. In the periodic system, a uniform electric field could also be applied.

Ion-Acoustic Turbulence

It is well known that electrons drifting through an ion background will excite ion-acoustic waves which, if the ions are cold enough, will grow to large amplitude. The threshold drift velocity for growth is predicted from theory to be only several times the ion sound speed $v_e/\sqrt{M_i/m_e}$. It has been found from simulations, that drift velocities must exceed roughly $v_e/3$ to produce a significant level of ion wave fluctuations. When $v_d > v_e/3$, modification of the electron distribution function is easily observed as is an enhanced level of dc resistivity. The ion-acoustic waves produced in such a system are characterized by a large angular spectrum of modes. Although each mode saturates at a fairly low level, taken as whole they can produce ion fluctuation levels of 3%-5%, particularly for drift velocities exceeding $v_e/2$. The drifting electrons then scatter off these ion-fluctuations, leading to an anomalously high effective collision frequency in the several x 10^{-3} ω_{pe} range. The effect on the electron distribution function is to first flatten it, then slow it towards low velocities so that the peak appears very near $v = 0$. The high velocity tail then runs away (in the presence of an externally applied field) at nearly the free acceleration rate since fast electrons do not match well the parallel components of the ion wave phase velocity. Figure 2 is a plot of a typical electron distribution function showing the skewing of the peak and the runaway tail due to the presence of ion-acoustic turbulence.

The wide angular spread of the ion modes suggests that the level of ion-acoustic turbulence in a one-dimensional system would be much smaller, producing a low level of resistivity. One-dimensional simulations show this to be true, giving one to two orders of magnitude lower resistivity than is found in two-dimensional systems.

In a magnetized system with a uniform magnetic field parallel to the direction of drift, the level of ion waves excited is reduced, more so as the field increases. For instance when $\omega_{ce} = \omega_{pe}$, the wave amplitude is less than half of the equivalent unmagnetized value. The anomalous resistivity resulting from the ion turbulence decreases rapidly as magnetic field strength increases. Figure 3 shows the variation of measured resistivity in four 2-d runs with $v_d = v_e$. The magnetic field increases from $\omega_{ce} = 0$ to $\omega_{ce} = 2\omega_{pe}$. The resistivity varies over almost an order of magnitude in these four runs.

Buneman Instability

When the electron drift exceeds roughly 1.3 v_e, the Buneman instability takes over. This instability is a hydrodynamic type instability which is almost insensitive to ion temperature and magnetic field strength. It leads to high resistivity and rapid electron heating. Because the unstable waves are bunched around the drift direction, a one-dimensional or magnetized system will exhibit this instability as strongly as a multi-dimensional or unmagnetized system.

This instability effectively places an upper limit on the relative electron-ion drift in a Maxwellian plasma. Because resistivity rapidly increases with drift, v_d/v_e is effectively limited to the order of 1.5.

Ion-Cyclotron Waves

Because of the presence of a magnetic field and the likelihood that the ion temperature equals or exceeds the electron temperature in the magnetosphere, ion-acoustic waves may not provide the principal resistivity mechanism there. It has been shown that ion cyclotron waves are excited by relative electron-ion drift in a magnetized plasma. The question is whether these waves will lead to large enough ion density variations to produce resistivity.

We have found that in order to excite large amplitude ion-cyclotron waves in a uniform plasma, electron drift must exceed the Buneman limit. Not surprisingly, Buneman resistivity overshadows any due to ion-cyclotron waves. In a run in which $v_d = 2v_e$ initially and in which subsequently the current is kept constant by the application of an external electric field, the Buneman instability grows rapidly to saturation producing a peak in resistivity. Figure 4a shows a time history of electrostatic field energy in this run. The rapid growth of the Buneman instability can be seen. There is rapid electron heating so that v_d/v_e declines, quenching the instability. Figure 4b shows the parallel electron temperature history for the same run. Meanwhile, ion-cyclotron waves are growing to large amplitude. They persist throughout the remainder of the run, although they seem to be weakly driven. This is apparently the case since v_d/v_e is now only of order unity. The modes are nearly perpendicular to the magnetic field and occur as the first three or four harmonics of the ion cyclotron frequency. The resistivity declines late in the run an order of magnitude from its peak value. Even this value is possibly attributable to residual Buneman induced resistivity. Figure 5 shows a plot of a potential surface taken during the Buneman instability phase of this run. Electron drift and magnetic field direction is nearly perpendicular to the horizontal axis. Figure 6 shows a similar plot later in the run when the

Buneman waves have died down and ion-cyclotron waves are fully developed. The model was arranged to favor an axis aligned ion-cyclotron mode.

Figure 7 shows a potential surface plot for a similar run in which the drift and magnetic field were aligned with the horizental axis. Ion-cyclotron waves can be seen propagating obliquely to the horizontal axis. The limited angular spectrum can be inferred from this plot.

In order to assess the level of resistivity due to ion-cyclotron waves alone, we performed a series of one-dimensional calculations in which the mode vector was at a large angle (85°) from the magnetic field and drift direction. This prevents the Buneman instability from growing while allowing ion-cyclotron modes to grow freely. Drift velocities between 1.5 v_e and 3 v_e were used. Anomalous collision frequencies bebetween 10^{-3} and 10^{-4} ω_{pe} were measured. Even this must be taken as an upper limit since there was some evidence of off angle Buneman waves. Ion density variations of order 10% were seen. Figure 8 shows a plot of anomalous collision frequency as a function of drift velocity measured in these one-dimensional runs.

The feeble resistivity observed must at least in part be due to the restricted mode spectrum characteristic of ion-cyclotron waves in this system. Unlike ion-acoustic waves, ion-cyclotron waves do not have a large angular spectrum. The waves do not steepen in saturation as ion-acoustic waves do, producing a smaller density variation.

Double Layers

Double layers are non-neutral regions in a current carrying plasma across which there can be a large potential jump. Electrons are accelerated across this jump and downstream are thermalized by electron-electron two stream turbulence, providing a mechanism for converting $\underline{E} \cdot \underline{J}$ work into thermal energy.

Double layers are formed and driven by the drifting electron component at small negative charge perturbations. As shown by Hasegawa and Sato,[5] there is a self consistent solution to Poisson's equation and the Vlasov equation in a non-drifting plasma in which a negative potential well exists of depth less than the electron thermal potential. If now the electrons are given a drift across such a local structure, reflected electrons upstream will have greater density than trapped electrons downstream causing a net potential jump across the structure. This double layer is driven by electron drift energy. In one-dimensional simulations it is seen that a small negative potential disturbance will form moving in the direction of electron drift at nearly the sound speed. As it grows in amplitude, it decelerates. It becomes stationary or nearly stationary as it reaches maximum amplitude at which time there is a fully developed hole in ion phase space. As it decays into an ion-acoustic solitary wave, it again picks up speed, usually in the direction opposite to the electron drift. It then disappears as it reaches the ion sound speed. Its lifetime as a nearly stationary double layer can vary considerably, up to many hundreds of plasma periods.

The above described double layer is a current driven instability in which the potential jump cannot greatly exceed the electron thermal energy, assuming that the drift of incoming electrons will be limited to roughly their thermal speed by ion acoustic or Buneman instabilities. The ion phase space has a hole in it caused by the potential dip and ions are trapped because [illegible] ions accelerated upstream across the jump do not gain sufficient energy to free stream upstream once they have passed the potential dip. Figure 9 shows an example of double layers formed in one-dimensional computer simulations. Shown are plots of ion phase space and time averaged electrostatic potential for several instants of time. One can see the negative potential dip in front of the potential jump.

Suppose now that an external potential drop is applied across the plasma which contains the double layer.[6] The neutral plasma will exclude the applied field and force it to appear solely in the non-neutral double layer regions. If this potential exceeds several kT_e/e, the ions accelerated upstream by the jump will become untrapped and stream upstream freely past the original potential dip. The dip itself will disappear because the fractional change in ion density through the dip will be small due to the high ion entrance velocity. There will be less excess negative charge there, and therefore a smaller dip. Since the double layer is now field driven, the dip which allowed a current driven double layer to form is not necessary and in fact disappears when the potential jump becomes large enough. Now the ion and electron phase space plots are near mirror images of each other, with ions beaming upstream of the double layer. Figure 10 shows a plot of ion phase space for a one-dimensional simulation of a field driven double layer across which there is a potential drop of [illegible] kT_e/e. Notice that ions are not trapped and freely stream to the left against the electron drift direction.

In one-dimensional simulations, double layers are seen to form spontaneously with drift velocities as low as [illegible] v_e, particularly in very long systems. There is a bootstrapping mechanism in one dimension due to the fact that fields do not decay with distance as in two and three dimensions. If the boundary conditions are fixed potential or periodic, a potential jump will create a decelerating field elsewhere which will extract energy from global electron drift and feed it into the double layer.

In multidimensional simulations, double layers do not as readily form. This is because they form locally and only become one-dimensional by spreading sideways as they grow. The local potential dip does not tend towards a potential jump because the excess negative charge upstream can be deflected sideways and dissipate. Also, the retarding field generated by a jump only extracts drift energy from electrons locally since fields fall off with distance.

If a one-dimensional density perturbation is applied as an initial condition, upstream excess electrons cannot be deflected sideways (there is no transverse E) and fields again do not fall of with distance. It is observed that double layers under such conditions form more readily in two-dimensional simulations.

If the plasma is magnetized, a double layer growing from a local perturbation will not spread sideways and become one-dimensional. Instead, it remains local with a transverse width roughly twice its length. These local double layers form more easily in a magnetized plasma because ion-acoustic turbulence is suppressed with far less electron heating as a result.

In convective systems, where particles leave and new ones are injected at the boundaries, field driven double layers form easily at the entrance boundary where a sheath acts as an initial perturbation. The double layer moves downstream and leaves the system. As it disappears, a new one forms at the entrance plane. Figure 11 shows a 2-d simulation of a field driven double layer in which a potential of 1 KT_e is applied across a system [illegible] Debye lengths long. In the presence of a magnetic field, large amplitude ion-cyclotron waves are excited just downstream of the double layer where the electrons are beaming with high velocity. The ion-cyclotron waves then propagate downstream but nearly obliquely to the magnetic field. Although the grow to large amplitude, they apparently do not affect the double layer significantly.

Resistivity

As suggested in preceeding paragraphs, ion-acoustic turbulence, double layers and the Buneman ion-electron instability all can produce large resistivity in current carrying plasmas. Of the four instabilities discussed, the ion-cyclotron instability produces by far the lowest resistivity. Figure 12 shows the anomalous collision frequency measured in a number of two-dimensional runs as a function of electron drift velocity. In all cases, the plasma was unmagnetized with $T_i << T_e$. Double layers formed in some of the runs at the higher drift velocities.

Conditions in the auroral zone may not lead to excitation of all these modes since each has drift, temperature, or magnetic field requirements for its existence which may not be met there. Ion-acoustic waves require low temperature ions and low magnetic fields. The ion-cyclotron and Buneman instabilities require electron-ion drift velocities exceeding the electron thermal speed. Double layers are relatively insensitive to magnetic field strength and ion-electron temperature ratio although they apparently do need a perburbation from which to grow.

It is thought that ion temperature in the auroral zone is comparable to electron temperature. That and the presence of a magnetic field suggests that ion-acoustic waves will not be driven to large amplitude and will produce little resistivity. The two best candidates for the production of auroral zone resistivity are double layers and the Buneman instability. Both occur when electron drift is comparable to the electron thermal speed. Because both can account for large resistivity, electron drift driven by external fields will not much exceed the electron thermal velocity.

In situations where the instability is driven by large external potential drops (such as are found in the auroral zone), simulations have shown that double layers will dominate over the other three candidates. Once formed, they absorb most of the potential drop so that electron drift remains at or below the thermal speed except near the double layer. Downstream, after the beam electrons become thermalized by electron-electron two stream effects, their temperature may be quite high.

It should be mentioned that the form of double layers in the auroral ionosphere may be quite different from that suggested by simulations reported here. The particle distribution function applicable as boundary conditions are most likely quite different there and could cause much more extended double layer like structures almost unrecognizable as being related to the more classical form reported here. Whatever their form, double layers can very efficiently convert beaming energy into thermal energy, leading [illegible] of resistivity.

References

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2. O. Buneman, Phys. Rev., 115, 503 (1959).
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Figure Captions

Fig. 1. Regions at which various instabilities will be found as a function of v_d/v_e, the electron drift and ω_{ce}/ω_{pe}, the magnetic field strength.

Fig. 2. The effect of ion-acoustic resistivity on the electron distribution function. Initially a drifting Maxwellian, the peak has skewed towards zero velocity while the tail has extended, indicating runaway electrons.

Fig. 3. The effect of magnetic field strength on ion-acoustic resistivity. Shown is a plot of effective collision frequency normalized to ω_{pe} as a function of ω_{ce}/ω_{pe}. In all runs, the electron drift was maintained at $v_d = v_e$. The mass ratio was 100 and T_i/T_e was 0.05.

Fig. 4. A two-dimensional simulation of ion-cyclotron wave excitation in which $v_d = 2v_e$, $\omega_{ce} = 2\omega_{pe}$ and $T_i = T_e$. The mass ratio was 1000. (a) The field energy (normalized to electron thermal energy) as a function of time with $\omega_p dt = 0.3$. The Buneman instability rapidly saturates and heats electrons. The heated electrons reduce v_d/v_e which largely kills the instability. Later, ion-cyclotron waves grow to large amplitude. (b) A time history plot of parallel electron temperature. One can readily see the heating effect of the Buneman instability. The perpendicular electron temperature slowly increases by 50% during the run as parallel thermal energy is isotropized.

Fig. 5. A potential surface plot of the run of Fig. 4 during the early time when Buneman waves are strongest. Electron drift and magnetic field are away from the viewer but at a slight angle (5°).

Fig. 6. A similar potential surface later in the run when ion-cyclotron waves have reached large amplitude.

Fig. 7. A potential surface plot for a run in which an angular spectrum of ion-cyclotron waves is allowed. Several modes are present but nearly perpendicular to the magnetic field which is along the horizontal axis here.

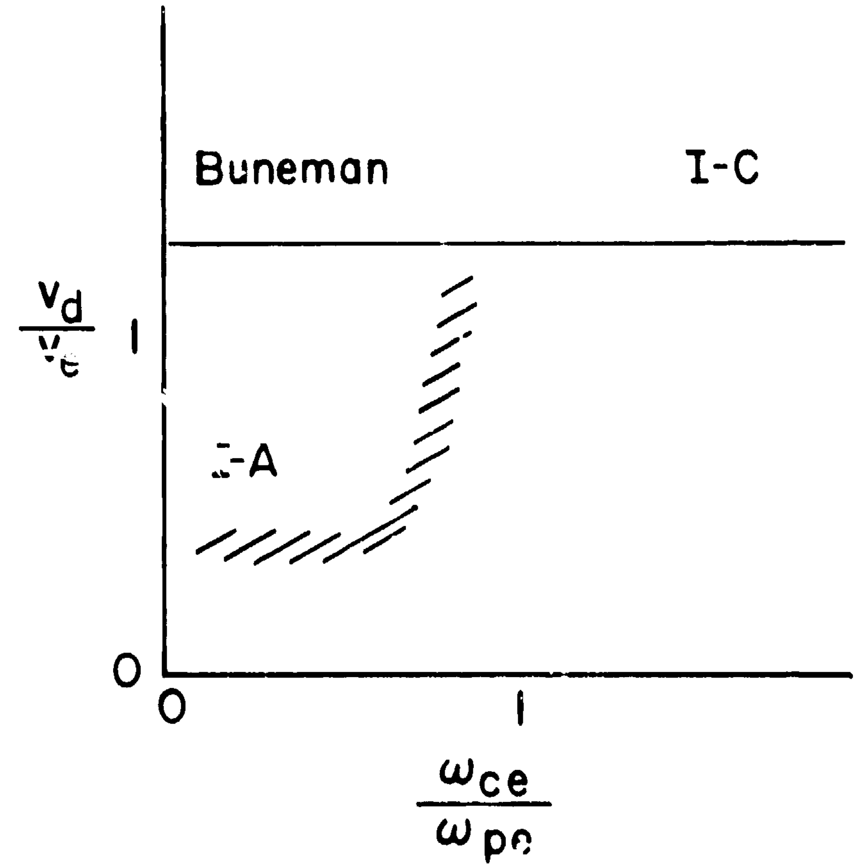
Fig. 8. Anomalous collison frequency in several 1-d runs due to ion-cyclotron waves.

Fig. 9. Results of 1-d spatially periodic simulations of current driven double layers. Electron drift is to the right. (a) Ion phase space and electrostatic potential at time $\omega_{pe}t = 240$, (b) Similar plots at $\omega_{pe}t = 360$. One can easily see a potential dip followed by a jump near the right hand side.

Fig. 10. Ion phase space for a field driven double layer. Notice how the ions are not trapped but stream freely to the left (upstream).

Fig. 11. A 2-d simulation of a field driven double layer. The double layer is one-dimensional (planar) because it was launched from the left boundary which itself is flat.

Fig. 12. A plot of anomalous collision frequency as a function of drift for a number of simulations in which ion-acoustic turbulence was seen. For runs at the larger drifts, double layers formed. One can see the rapid increase as electron drift exceeds the thermal speed. Shown are runs with two different mass ratios (100 and 2000). The electrons were cooled artificially in some runs to better approximate steady state conditions in a convective system.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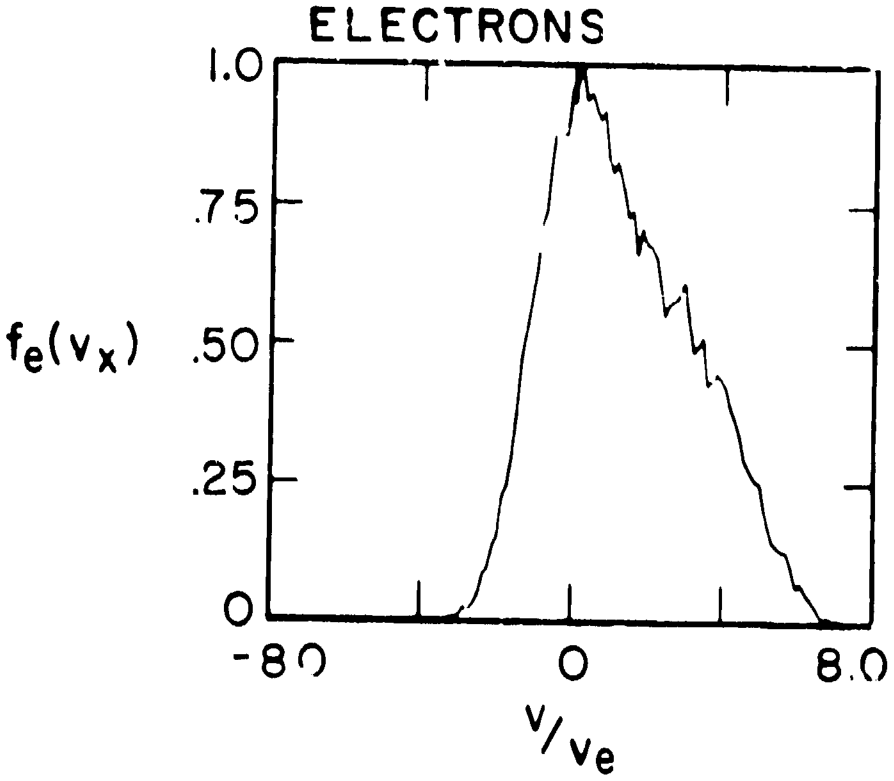
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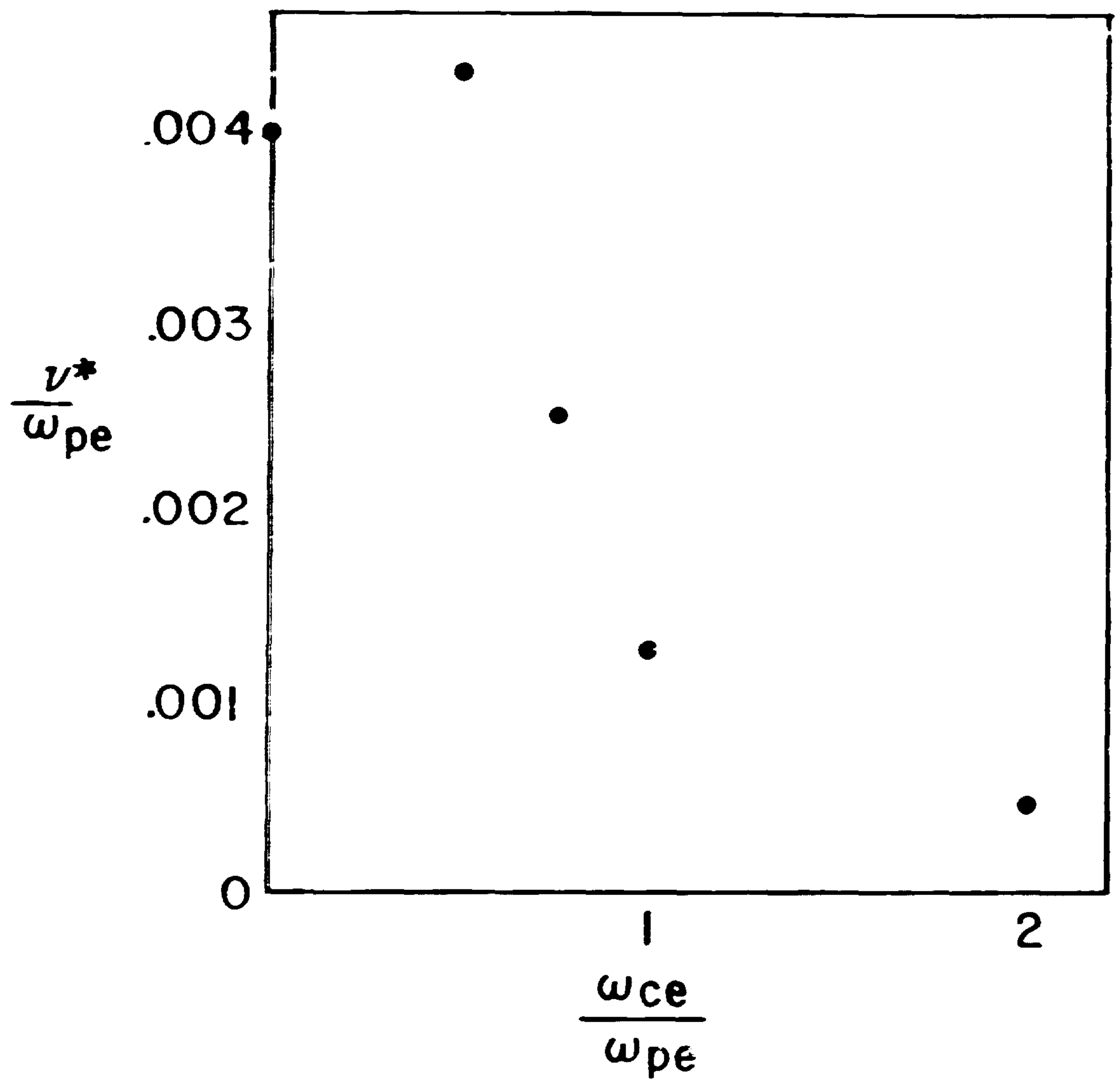
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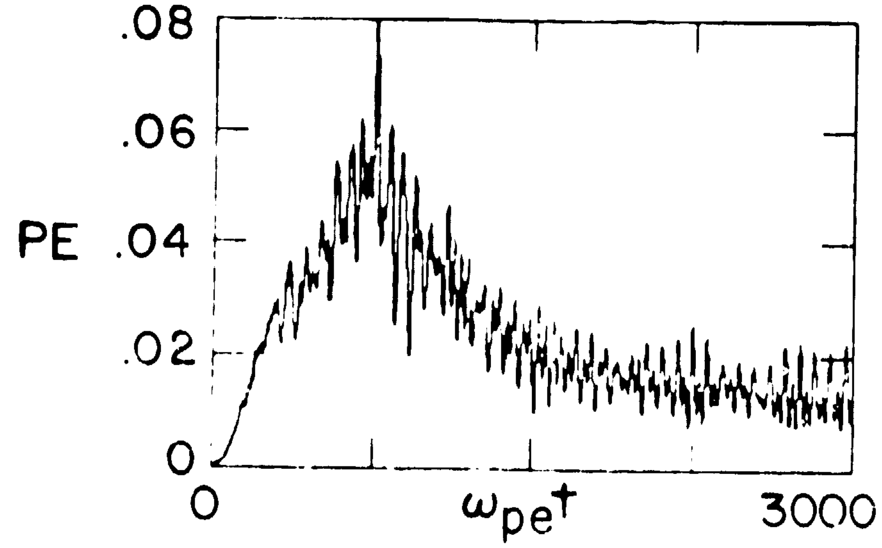
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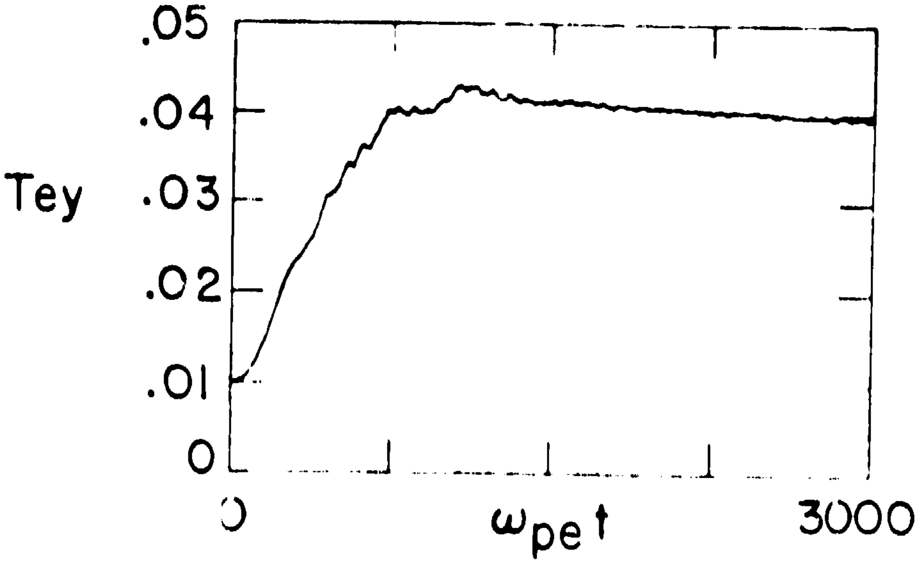
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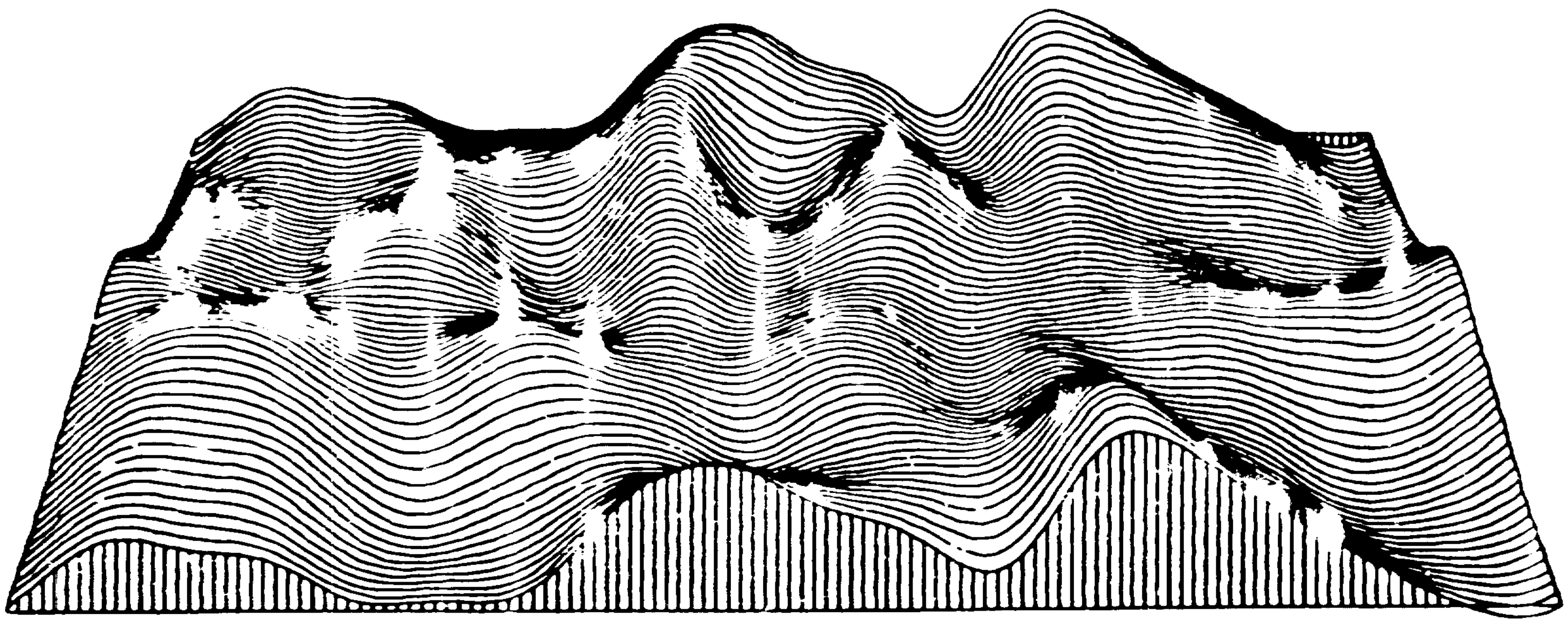

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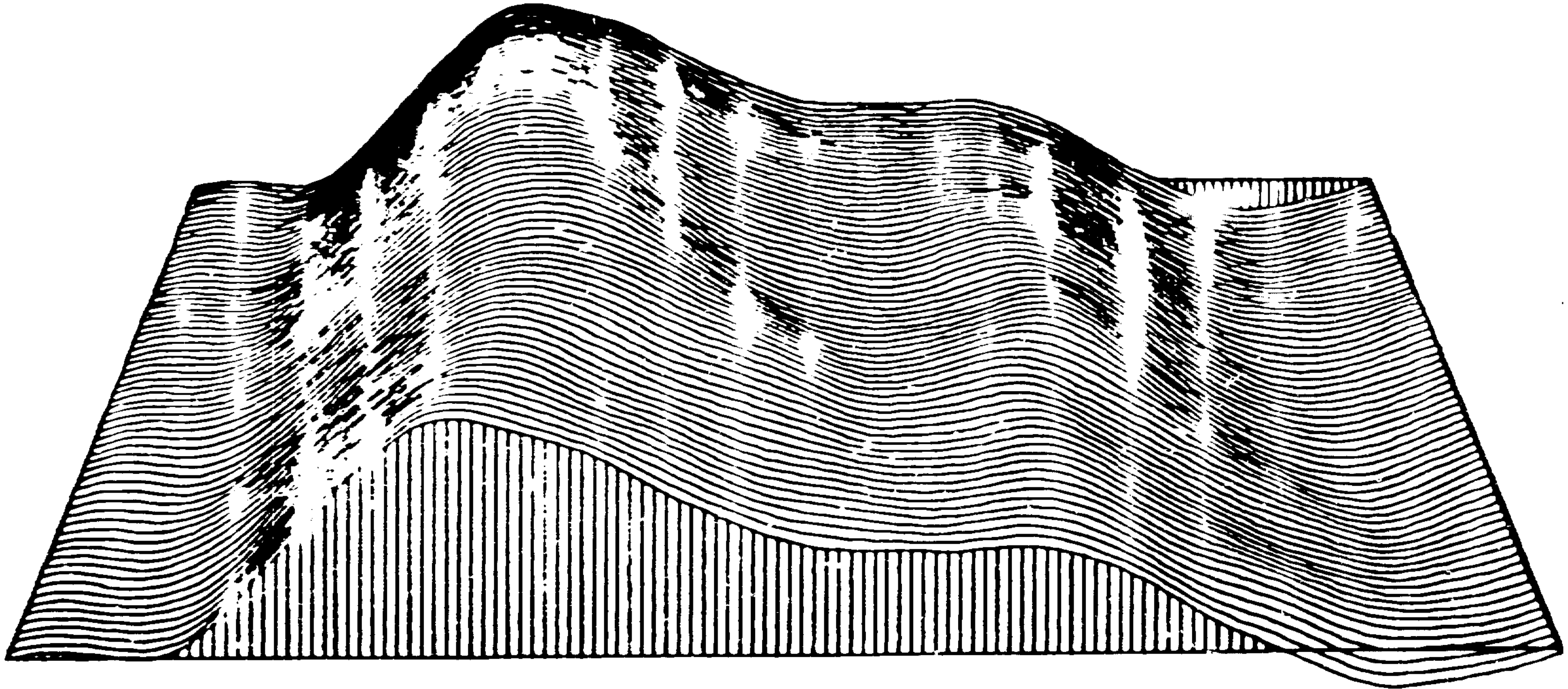

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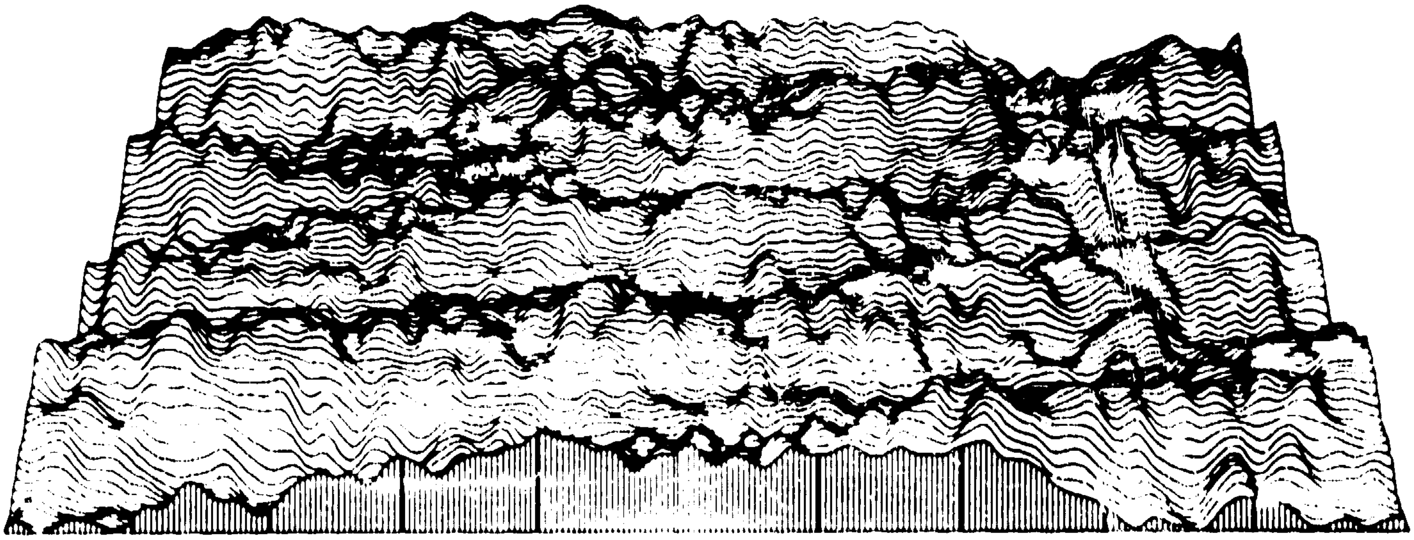

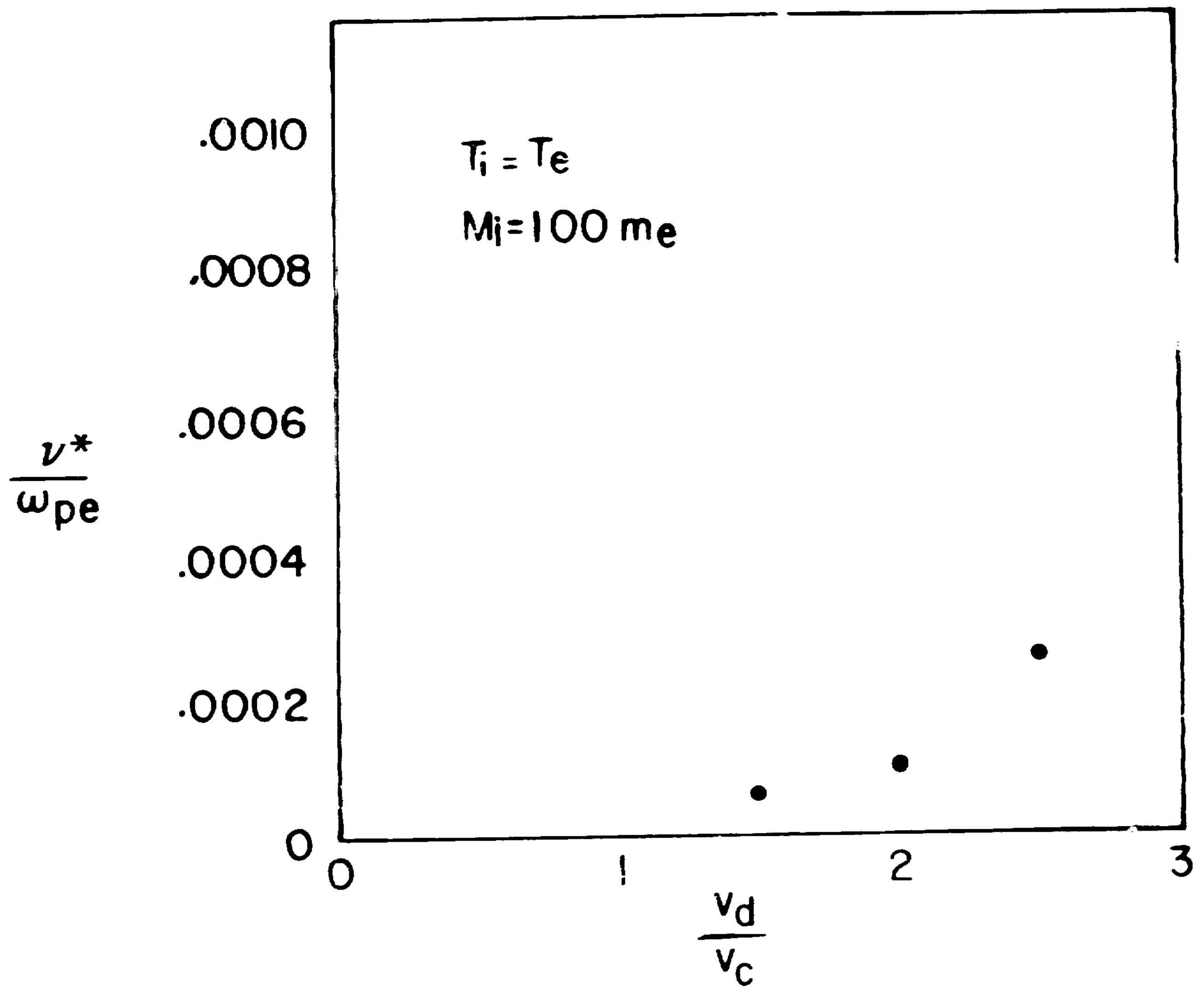
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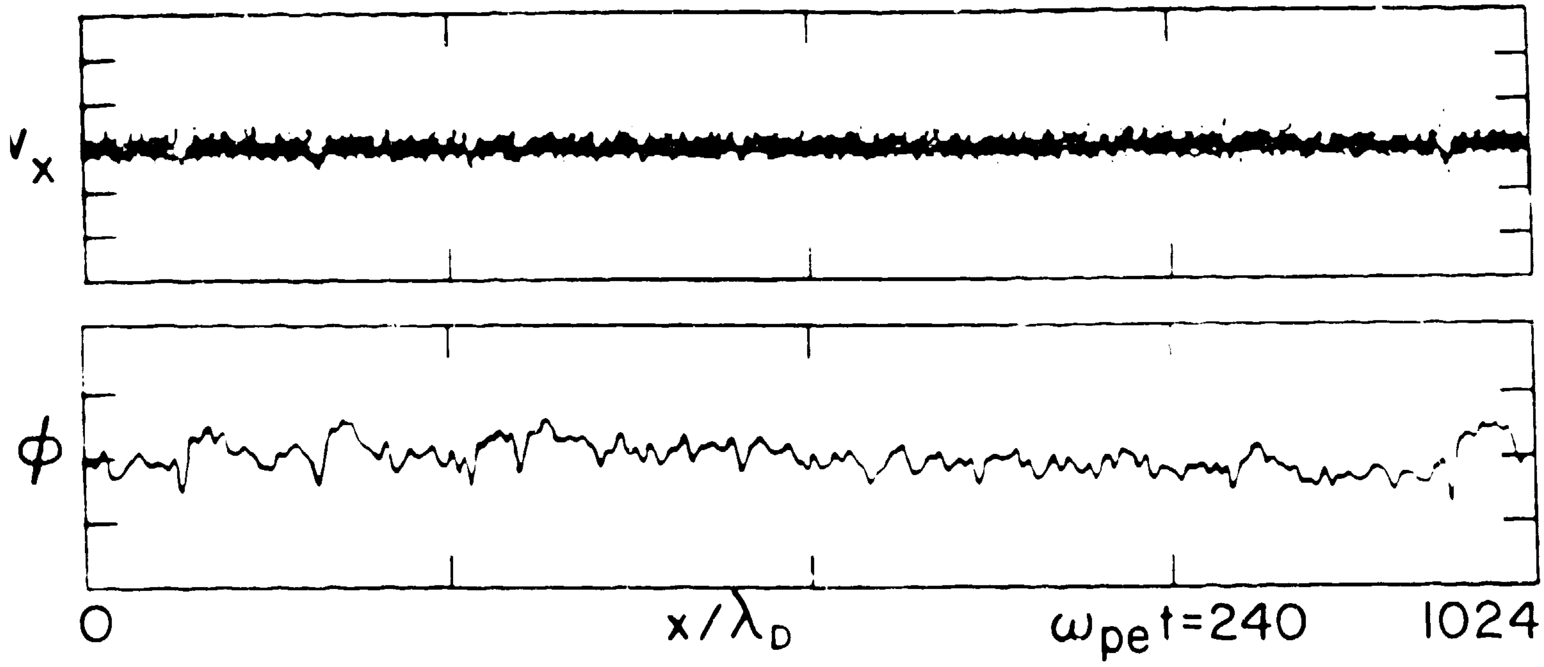
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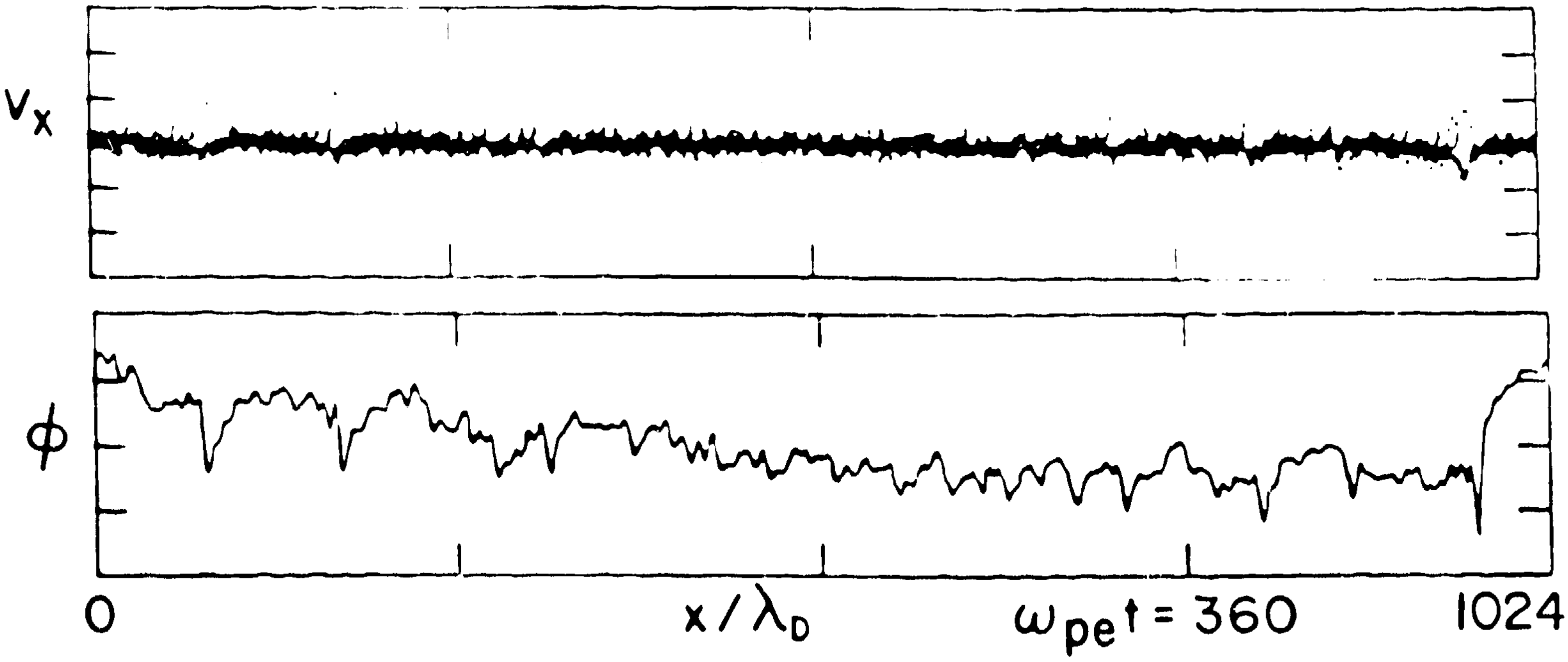
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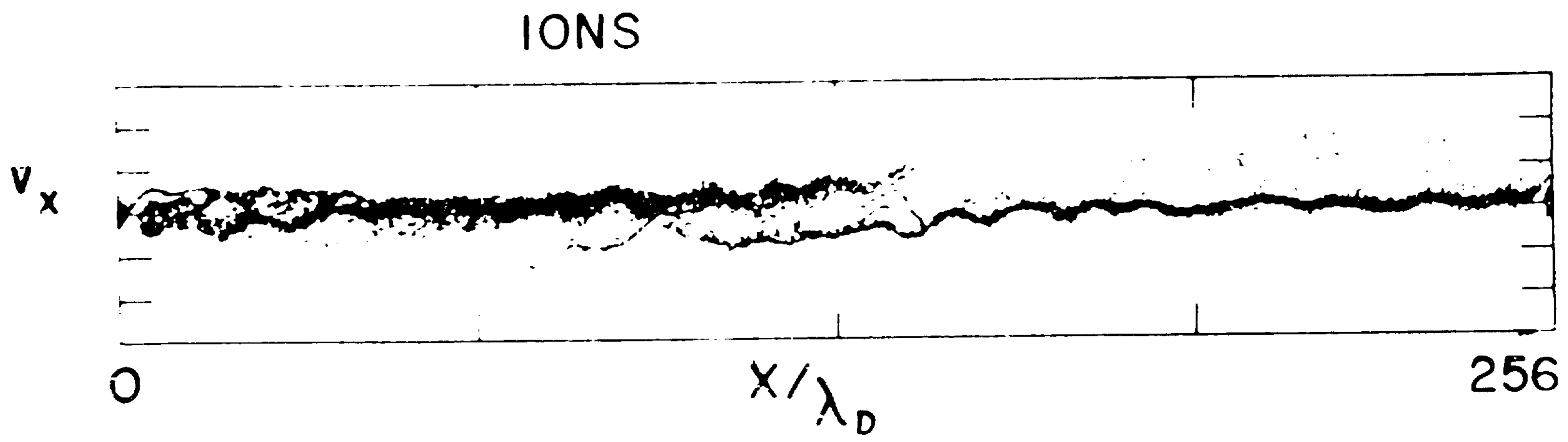
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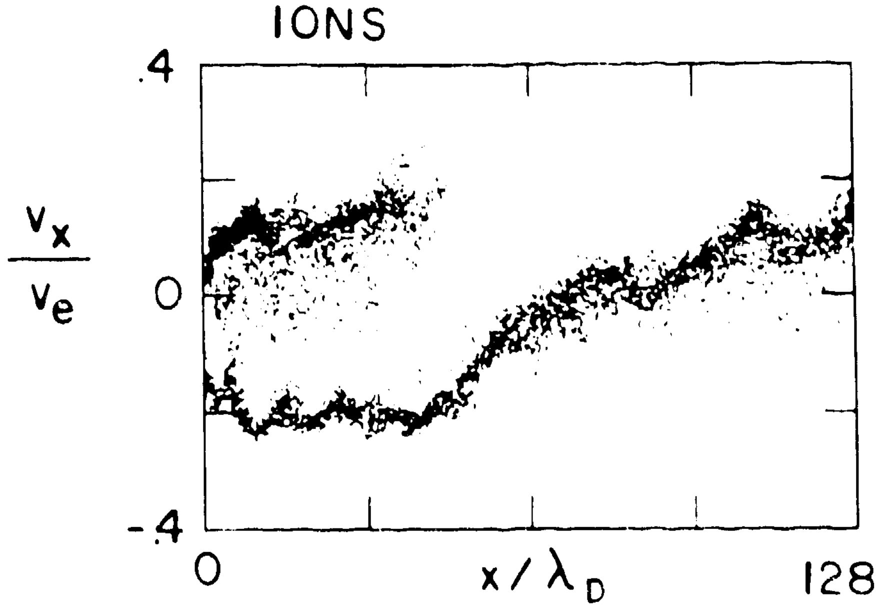
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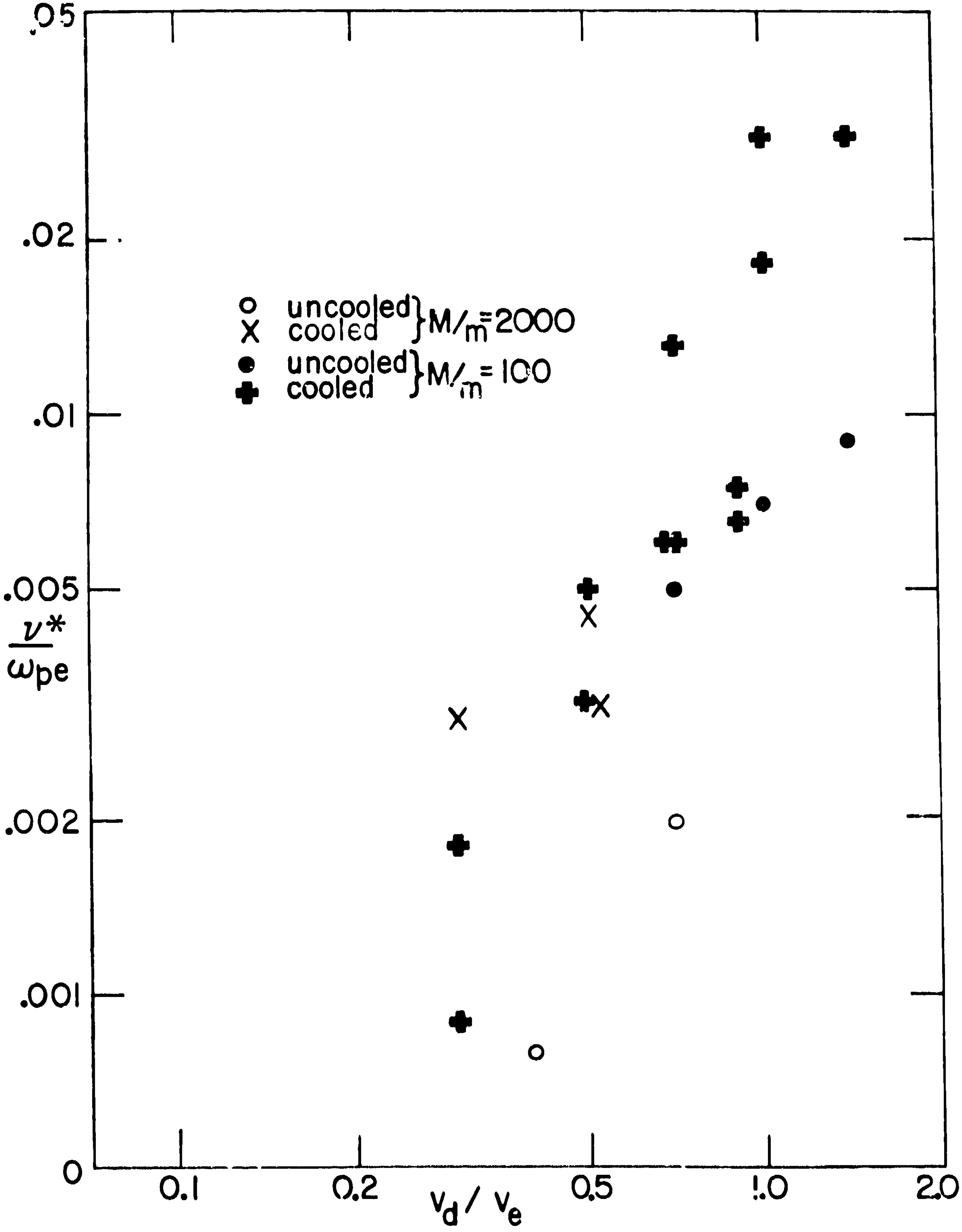

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