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AUTHOR(S): J. Birn, K. Schindler

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Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# Large Scale Instabilities and Dynamics of the Magnetotail Plasma Sheet

J. Birn (Los Alamos National Laboratory,
Los Alamos, NM 87545, USA)

K. Schindler (Ruhr-Universität Bochum, 4630 Bochum 1, FRG)

## Abstract

We review the stability properties of the magnetotail current sheet against large scale modes in the framework of ideal MHD, resistive MHD, and collisionless Vlasov theory. It appears that the small deviations from a plane sheet pinch (in particular a magnetic field component normal to the sheet) are important to explain the transition of the tail from a quiet stable state to an unstable dynamic state. It is found that the tail is essentially stable in ideal MHD, but unstable in resistive MHD, while both stable and unstable configurations are found within collisionless theory. The results favor an interpretation where the onset of magnetotail dynamics leading to a sudden thinning of the plasma sheet and the ejection of a plasmoid is caused by the onset of a collisionless instability that either directly leads to the growth of a collisionless tearing mode or via microscopic turbulence to the growth of a resistive mode. The actual onset conditions are not fully explored yet by rigorous methods. The onset may be triggered by local conditions as well as by boundary conditions at the ionosphere or at the magnetopause (resulting from solar wind conditions).

## 1. Introduction

The geotail plasma sheet is certainly the best studied example of a current sheet in space plasmas. Since current sheets, their formation and break up, are usually considered as of eminent importance for a variety of dynamic eruptive processes in space as well as in laboratory plasmas, it is worthwhile to study the stability properties of this best known example in considerable detail. While the general existence of the tail current sheet is a manifestation of its overall stability, its occasional unstable behavior is probably most clearly demonstrated by the sudden and drastic thinning that occurs close to the onset of a substorm expansive phase and by the later thickening associated with the onset of substorm recovery (Hones, *et al.*, 1984b). The statistic evidence as well as individual current sheet observations clearly show that the observed effects near substorm onset are due to thinning to probably less than one-tenth of the average sheet thickness during quiet times (e.g., Fairfield *et al.*, 1981, McPherron and Manka, 1985). The timescale of this process is apparently not directly related to an external change. The thinning and later thickening is observed at distances from around 15 $R_E$, covered by the VELA and ISEE satellites, up to at least about 35 $R_E$ downtail as covered by the IMP satellites. At much larger distances of around 200 $R_E$ as explored by ISEE 3 the consequences of the near-earth thinning seem to be the passage of a thick plasmoid, which is considered as a severed part of the near earth plasma sheet (Hones *et al.*, 1984a), roughly 30 minutes after substorm onset.

These observations seem to clearly suggest the existence of a large-scale instability involving a major portion of the tail current sheet and possibly related to changes of magnetic topology which would allow for the severance of a part of the plasma sheet that was originally magnetically connected with the earth. In this paper we will review our present knowledge of the stability properties of the tail current sheet concentrating on large scale modes. After a short presentation of stability tools in Section 2, we will start in Section 3 with instabilities of a one-dimensional sheet pinch because the tail current sheet resembles such a pinch to a high degree. We will see, however, that in particular the transition from stability to instability and the dynamic changes in the nonlinear evolution of the tail cannot be understood without taking the more realistic two dimensional (or even three-dimensional) geometry into account. This will be discussed in Section 4. While these two sections basically follow a classical stability analysis disregarding boundary effects, Section 5 will be concerned with modifications primarily associated with boundaries but also with details of the plasma population that can possibly lead to triggering or enhancement of the growth of the instabilities.

We would like to stress that we do not intend to give a complete review of all relevant papers but rather want to illuminate typical results by selected examples of the literature.

## 2. Stability Tools

Linear stability properties are usually studied by variational approaches or by a classical perturbation method studying small perturbations of an equilibrium or quasi-equilibrium. By quasi-equilibrium we mean configurations that may change slowly (as compared to the growth of the instabilities of interest) due to either external forces or an internal process such as diffusion. This concept is particularly useful within resistive magnetohydrodynamics where the requirement of an exact equilibrium,

$$\nabla \cdot \mathbf{E} = \nabla \cdot (\eta \mathbf{j}) = 0$$

is often too restrictive (e.g., Barston, 1972). The nonlinear evolution is most often studied by a numerical integration of the dynamic equations.

We do not want to go into detail about linear perturbation theory and numerical integration. Both methods are straightforward in principle, although they may become very tricky in details. We would like, however, to make a few comments about the existing variational methods because they seem to shed some light on an underlying "free energy" concept and on different stabilizing effects due to certain restrictions on particle or fluid motion.

Variational principles have been derived within the framework of ideal MHD (Bernstein *et al.*, 1958), resistive MHD (Tasso, 1975), and Vlasov theory (Laval *et al.*, 1966, Schindler, 1966, Schindler *et al.*, 1973). With the exception of the ideal MHD criterion these principles are restricted to a spatial dependence on two coordinates only, both for the equilibrium and the perturbations. We will therefore restrict our discussion to this case keeping in mind that the derived instability thresholds may be sufficient for instability only.

The interesting feature of these variational principles is that they can all be written in the form

$$\delta^2 W = \delta^2 F + \delta^2 Q > 0 \quad \text{necessary for stability} \tag{1}$$

where $\delta^2 F$ is common for all cases while $\delta^2 Q$ is different for the different models but generally positive (Schindler *et al.*, 1982). The term $\delta^2 F$ is the second variation of a functional $F$ given by

$$F = \int \left( \frac{(\nabla A)^2}{2\mu} - P(A) \right) d\,r \tag{2}$$

using a constraint that keeps the function $P(A)$ fixed (for more details see also Schindler and Birn, 1986). One finds

$$\delta^2 F = \frac{1}{2\mu_o} \int \left[ |\nabla A_1|^2 - \mu_o \frac{dJ_o}{dA_o} |A_1|^2 \right] dx dz \tag{3}$$

where it is assumed that $y$ is the ignorable coordinate expressing the magnetic field by $\mathbf{B} = \nabla A(x,z) \times \mathbf{y}$, ignoring also, for simplicity, the magnetic field component $B_y$. In Equation (3) we have also used the equilibrium condition

$$J_o = -\frac{1}{\mu_o} \nabla^2 A_o = \frac{dP(A_o)}{dA_o} \tag{4}$$

which can be derived from the first variation of (2). For the explicit form of the additional positive terms $\delta^2 Q$ we refer to Schindler *et al.* (1983). A dynamic model that keeps the pressure fixed on perturbed field lines (as identified by the value of $A$) is the most unstable one, while other constraints add stabilizing terms. In the case of ideal MHD this most unstable case corresponds to isobaric variations where the pressure stays constant in a moving fluid element.

## 3. Stability of a Plane (One-Dimensional) Current Sheet

The stability of a plane sheet pinch within ideal MHD is well known (a proof is given for example by Schindler *et al.*, 1983, unfortunately we do not know the first published proof). It is the major reason why the magnetotail plasma current sheet keeps existing to distances well beyond 200 $R_E$.

Nonideal effects generally destabilize the current sheet. The linear instability of the plane sheet pinch has been first shown within resistive MHD by Furth *et al.* (1963) and within collisionless Vlasov theory by Furth (1962) and later through variational approaches by Laval *et al.* (1966) and Schindler (1966). The most relevant unstable modes, called tearing modes, are symmetric with respect to the symmetry plane of the sheet pinch. Because nonideal effects are important only in a thin layer around the symmetry plane (where $\mathbf{B} = 0$ or at least $\mathbf{k} \cdot \mathbf{B} = 0$, where $\mathbf{k}$ is the wave vector parallel to the sheet) the modes are essentially identical in resistive MHD and collisionless theory. They produce localized thinning and the growth of magnetic islands with fast flow from the thinning regions into the island regions. This is illustrated by Fig. 1 showing results from a resistive MHD simulation by Biskamp (1982).

At this point we may also stress two important stability limits valid for both the collisional (i.e., resistive) and the collisionless regime. Tearing modes are stable for $kL \geq 1$ where $L$ is the characteristic scale of the current sheet (defined e.g., by a variation of the main magnetic field component $B_x \propto \tanh(z/L)$).

and wall stabilization becomes important if a solid conducting wall is present parallel to the sheet at a distance close to $L$. These conditions impose certain minimum requirements on the size of numerical simulation boxes if unstable tearing modes are to be treated.

The instability of the collisionless sheet pinch was used by Coppi *et al.* (1966) to explain auroral activity. The problem with this interpretation, however, is that it does not explain the transition from stability to instability because the one-dimensional sheet pinch is always unstable within collisionless Vlasov theory. One therefore has to look for stabilizing effects and their possible overcoming. One line of thought that involves the more refined geometry of the sheet including a small normal magnetic field component will be discussed in the following section. A possible alternative is to look for the nonlinear evolution of the tearing instabilities, saturation mechanisms and their possible overcoming.

The nonlinear growth of resistive tearing modes has been studied with analytical and numerical methods. While shorter wavelength modes may saturate at a relatively low level (White *et al.*, 1977) or exhibit a reduced (algebraic instead of exponential) growth (Rutherford, 1973), larger wavelengths are found to grow to finite size with magnetic island widths comparable to the sheet thickness (e.g., Biskamp, 1982; see Figure 1; Steinolfson and VanHoven, 1984).

Nonlinear results within the collisionless regime seem less certain. Numerical simulations suffer from the fact that electron contributions are either neglected or are treated within unrealistic parameter regimes characterized by high electron/ion mass ratios, a limited sheet thickness of a few electron Debye lengths, and integration times of hundreds of electron plasma oscillation times only.

Using analytic estimates, Drake and Lee (1977) predict the transition of collisionless tearing modes into a "semi-collisional" regime characterized by electron diffusion, where the growth becomes algebraic similar to the resistive results of Rutherford (1973). Their approach, however, excludes also the very long wavelengths. A more speculative approach by Galeev *et al.* (1978) predicts the transition into an explosive growth. A similar result was found from numerical simulations by Terasawa (1981) considering, however, only one particle component, while Katanuma and Kamimura (1980) have found only an algebraic growth.

From the linear and nonlinear stability results for a plane one-dimensional current sheet it is not obvious how the transition from a quiet stable plasma sheet to a dynamic unstable state can be accomplished. Promising models can, however, be based on the results discussed in the following section which include the effects of the actual geometry of the geotail.

## 4. Stability of the (2D or 3D) Magnetotail Current Sheet

Although the magnetotail plasma sheet resembles a plane current sheet to a good degree of approximation, the slight differences are apparently quite important for its stability properties and dynamic behavior. These properties are demonstrated by Figure 2 which shows magnetic field lines of a self-consistent equilibrium model of the quiet tail similar to those obtained by Birn (1979). The most important difference from a plane current sheet, as far as stability is concerned, is the presence of a magnetic field component $B_z$ perpendicular to the sheet, which is positive in the center of the sheet and becomes negative in the lobes producing closed field lines within the plasma sheet and flaring of the lobes. While the presence of $B_z \neq 0$ at the center of the plasma sheet has an important stabilizing effect, as we will discuss below, the change of the sign of $B_z$ near the plasma sheet/lobe boundary is in fact a feature necessary to allow for instability. It is the consequence of a general criterion that a (2-D) plasma configuration is stable, if any Cartesian magnetic field component can be found which does not change sign within a closed area (Schindler, 1970; Birn *et al.*, 1975). The presence of $B_z \neq 0$ is closely related to variations with $x$ along the tail axis, since the $j_y \times B_z$ force is typically balanced by a pressure gradient $\partial p/\partial x$.

Other features that involve a $y$ dependence across the tail are a flaring of field lines in that direction also and the plasma sheet thickening towards the tail flanks which is also related to an increase of $B_z$ with $|y|$.

No rigorous ideal MHD stability analysis has been done for such a two- or three-dimensional tail configuration. The numerical MHD simulations of Birn (1980) and Birn and Hones (1981), however, indicate stability, as in the one-dimensional case.

A stability analysis within resistive MHD, similar to that of Furth *et al.* (1963), has been performed by Janicke (1980) for a two-dimensional (i.e., $x$ and $z$ dependent) quasi-equilibrium. In the wave length regime $L_z \ll \lambda \ll L_x$, where $L_z$ and $L_x$ denote the characteristic length scales for variations of the equilibrium with $z$ and $x$, respectively, he found no change of the tearing growth rates although the eigenmodes became affected by the presence of $B_z$. The nonlinear evolution in the resistive regime was studied via numerical simulation by Birn (1980) in the 2D and Birn and Hones (1981) in the 3D case. The transition from stability to instability was accomplished by a sudden occurrence or increase of resistivity. The growth of tearing instabilities developed out of an initial slow diffusion. These simulations produced features such as plasma sheet thinning in the near tail, the formation and tailward ejection of a plasmoid, whose size was limited in the y-direction, consistent with observations and empirical substorm models (e.g., Hones, 1971). Results from Birn and Hones (1981) are shown in Figures 3 and 4.

While a resistive model may be applicable to the unstable evolution, a discussion of the stability transition requires collisionless theory. Schindler (1974) first considered the role of the normal component in a stability analysis of two-dimensional equilibria. He found a transition from stability to instability when ions became nonadiabatic in the center of the plasma sheet with a stability criterion involving the product $B_z L_z^{5/2}$. Destabilization thus occurs not only by a reduction of $B_z$ but also by a compression of the plasma sheet (i.e., a reduction of $L_z$). Schindler's analysis, however, neglected the stabilizing effect from electron contribution to the term $\delta^2 Q$ in equation (1). A more detailed, yet still not fully rigorous treatment by Galeev and Zelenyi (1976) confirmed Schindler's results but also gave a more restricted unstable regime which required a scale length $L_z$ below a few times the ion Larmor radius. A rigorous $WKB$ approach in the wavelength regime $L_z \ll \lambda \ll L_x$ predicted general stability (Lembège and Pellat, 1982). Goldstein and Schindler (1982), however, showed by numerical evaluation of the full variational integral including all stabilizing terms, that unstable solutions exist in the regime where $\lambda \approx L_x$, i.e., for large wavelengths of the order of tens of earth radii. Figure 5, taken from that paper shows that a stability transition exists even in the regime where electrons are adiabatic. The actual stability properties result from several contributions to the energy principle (1). The term $\delta^2 F$ is negative for any reasonable plasma sheet configuration which is a necessary requirement for an instability to be possible. Stabilizing effects that appear in different contributions to $\delta^2 Q$ are due to restrictions of the accessible phase space for each particle species and to electrostatic potentials resulting from charge separation effects. The configuration is unstable if the minimum of $\delta^2 W = \delta^2 F + \delta^2 Q$ becomes negative. The finite element representation of trial functions in the variational integral was somewhat coarse such that the transition parameters may not be very accurate. A more refined analysis, however, can only expand the unstable region.

The results from numerical particle simulations starting from 2-D equilibrium (Hamilton and Eastwood, 1982; Swift, 1983) are not yet conclusive. They suffer not only from the limitations in space and time mentioned in the previous section, but also from the fact that initial configurations did not include the flaring of the lobes which is necessary for instability of a closed system.

## 5. Refinements

The results discussed in the previous two sections were based essentially on the classical (linear or nonlinear) stability concept where it is assumed that perturbations of the equilibrium (or quasi-equilibrium) vanish at the boundaries of a given box. Since the magnetotail is obviously not enclosed by a solid box and it is impossible to treat the infinite problem, it is important to look for refinements which result from widening the boundary conditions. Variational principles typically are no longer valid for generalized boundary conditions. We must therefore rely largely on numerical results based on some ad hoc assumptions and on more speculative arguments.

Two ways are suggested in which the ionosphere might influence the onset and or the growth rate of a collisionless tearing mode. (1) The stabilizing space charges in the magnetotail could be discharged by field-aligned currents closing through the ionosphere (Goldstein and Schindler, 1978; Swift, 1986). This would imply a control of ionospheric resistivity over the onset of a tail tearing mode and a close relation of the occurrence of sheets of field-aligned currents with this onset. (2) The presence of heavy ions (e.g., oxygen of ionospheric origin) can lower the threshold for the onset of an ion-tearing mode (Baker *et al.*, 1982). Since $O^+$ ions are pulled out from the ionosphere preferably in the pre-midnight sector, this can be related to an east-west asymmetry of the occurrence of substorms.

The most important role of the solar wind boundary conditions can be ascribed to a growth phase of magnetospheric substorms (McPherron, 1973). The gradual deformation of the tail (e.g., stretching and compression of the plasma sheet resulting from addition of magnetic flux from the front side magnetosphere to the tail) either directly pushes the tail plasma sheet beyond a certain stability threshold (as modeled within resistive MHD by Sato and Hayashi, 1979, or Ugai, 1980) or brings it into a "metastable" state (Schindler and Birn, 1986) which might be subject to unstable ion-tearing modes but is stabilized by electron effects. A destabilization and the onset of the ion-tearing mode could then result from ionospheric discharging or an occurrence of fluctuations scattering the electrons anywhere along the field lines (Coroniti, 1980). After the onset of a tearing instability the influence of driving fields at the boundary is probably less important. Computer results within resistive MHD show that the major effect is to modify the tearing growth by changing the relevant scales such as plasma sheet width and a typical Alfvén wave travel time (Birn and Schindler, 1986). Continuous driving, however, may also be responsible for repetitive ejection of plasmoids (Lee *et al.*, 1985).

In addition to boundary effects, one might consider modifications due to local properties of the plasma population. Such properties might, of course, also be related to boundary effects (as for instance the above discussed role of heavy ions). We mentioned already that the presence of fluctuations scattering the pitch angles of electrons, can considerably destabilize (Coroniti, 1980). There are several ways how such fluctuations could be generated. An obvious way is the onset of micro instabilities not necessarily in the center of the plasma sheet. An alternative would be the resonant absorption of waves generated, e.g., near the magnetopause (Goertz and Smith, 1986).

Anisotropies of the ion distribution can lead to an increased growth rate of the collisionless tearing mode (Chen *et al.*, 1986; Ambrosiano *et al.*, 1986). The presence of plasma flow (beams) can also influence stability and growth rates. Fast beams near the plasma sheet/lobe interface can generate Kelvin-Helmholtz instability, i.e., ideal MHD surface modes. To produce an effect on the body of the plasma sheet these modes have to penetrate to the center of the plasma sheet and to interact with the modes from the opposite surface. Such an interaction seems more likely to lead to an enhanced antisymmetric flapping mode than to a sausage type mode, although to our knowledge a rigorous analysis has not been done. There is, however, a destabilizing effect of the plasma flow on resistive tearing modes (e.g. Paris and Sy, 1983) that seems also to exist in the collisionless limit (Lakhina and Schindler, 1986).

## 6. Summary and Discussion

The most dramatic dynamic behavior of the geomagnetic tail is the sudden thinning in the tail region from about 15 $R_E$ to more than 30 $R_E$ distance which is apparently related to effects in the distant tail identified as plasmoid ejections and also a cause of auroral activity. This dynamic behavior is most likely the result of a large scale instability that may or may not be triggered externally but proceeds on an intrinsic time scale. Since the tail current sheet is stable within ideal MHD, the instability must involve nonideal effects, e.g., resistivity or particle inertia effects. Its appearance should be that of a tearing mode which involves the formation of magnetic islands (in a more realistic 2-D or 3-D geometry, however, first at an advanced stage of the evolution).

Our present limited knowledge of the stability of current sheets allow the following suggestions for the transition from stability to large-scale instability, which are discussed in several places in the literature:

In all cases we must assume that during the quiet stage the collisionless tearing instability is stabilized by the presence of a sufficiently large normal magnetic field component $B_z$ or has saturated at a sufficiently low level not effecting the average large scale geometry. It is conceivable that the former holds in the near tail up to the distance of the suggested "quasi-steady distant neutral line" while the latter is the case beyond that distance. A destabilization might occur through one of the following mechanisms which may be neither exclusive nor complete:

(a) A gradual change of magnetotail conditions (e.g., stretching or compression as suggested to be characteristic of the substorm growth phase; McPherron, 1973) leads to the onset of a microinstability which generates turbulence and thereby an effective resistivity that allows a large scale resistive tearing mode to grow as simulated, e.g., by Birn (1980) and Birn and Hones (1981). The problem with this concept is that an appropriate microinstability has not yet been identified. Current driven instabilities typically require too narrow a current sheet; the lower hybrid drift instability (Huba *et al.*, 1977) can be exited for thicker sheets, however, near the plasma sheet boundary. It does not penetrate into the center where the resistivity is needed unless the plasma sheet becomes sufficiently thin (of the order of a typical ion Larmor radius of a few hundred kilometers).

(b) A gradual stretching of the tail reduces $B_z$ until the threshold for a collisionless tearing instability is exceeded, which grows to finite amplitude. Although such a transition is shown to exist in principle (Goldstein and Schindler, 1982), it is not yet proven rigorously that the parameters at the transition point are realistic nor that the growth after the transition is fast enough.

(c) A gradual externally driven process as in (a) and (b) brings the tail current sheet into a stage that is unstable to an ion-tearing mode but stabilized by electron effects as discussed in Section 4. There are several possibilities for a destabilization of these electron effects. (1) The stabilizing electrostatic potentials could be discharged at the ionosphere (Goldstein and Schindler, 1978, Swift, 1986). This process would closely associate the onset of the unstable evolution with the build-up of sheets of field-aligned currents. (2) A loading of field lines with heavy ions of ionospheric origin could make the onset criterion for an ion tearing mode less stringent (Baker *et al.*, 1982). (3) A sudden onset of fluctuations leading to pitch angle scattering of electrons would also destabilize (Coroniti, 1980). In contrast to the resistive model (a), this scattering need not happen near the center of the plasma sheet but could occur anywhere along a field line, in particular also near the boundary of the plasma sheet which seems to be more easily subject to microinstabilities due to strong gradients and beaming of particles. The fluctuations may also result from the resonant absorption of an externally generated wave field (Goertz and Smith, 1986) instead of from a local microinstability.

These possibilities show that the instability although relying on nonideal effects in the center of the plasma sheet might actually be triggered not only by conditions in the center, but as well by conditions near the plasma sheet/lobe boundary, at the ionosphere, or in the external (magnetopause, magnetosheath) region, i.e., by the solar wind

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## Figure Captions

Figure 1. Results from a resistive MHD simulation by Biskamp (1982) showing the time evolution of the magnetic field configuration.

Figure 2. Self-consistent magnetotail equilibrium showing magnetic field lines in the northern dusk sector of the tail and the width of the plasma/current sheet (hatched region). Length values are normalized by the scale length $L_z$ equal to the characteristic half-thickness of the plasma/current sheet at the near earth (left) side at local midnight ($y = 0$).

Figure 3. Results from a three-dimensional resistive MHD simulation of magnetotail dynamics by Birn and Hones (1981) showing magnetic field lines in the midnight meridian plane. Length values are normalized as in Figure 2.

Figure 4. Velocity vectors and magnetic neutral lines (dotted lines) in the equatorial plane in the 3-D computer simulation of Birn and Hones (1981).

Figure 5. Results from a numerical analysis of tail stability using Vlasov theory by Goldstein and Schindler (1982) showing different contributions to the energy integral in Equation (1) as a function of the normalized electron Larmor radius $\epsilon$. (a) the term $\delta^2 F$, normalized to 1, (b) the sum of (a) and the ion contribution to $\delta^2 Q$, (c) the sum of (b) and the electron contribution, and (d) the total sum $\delta^2 W$ including also an electrostatic potential term.

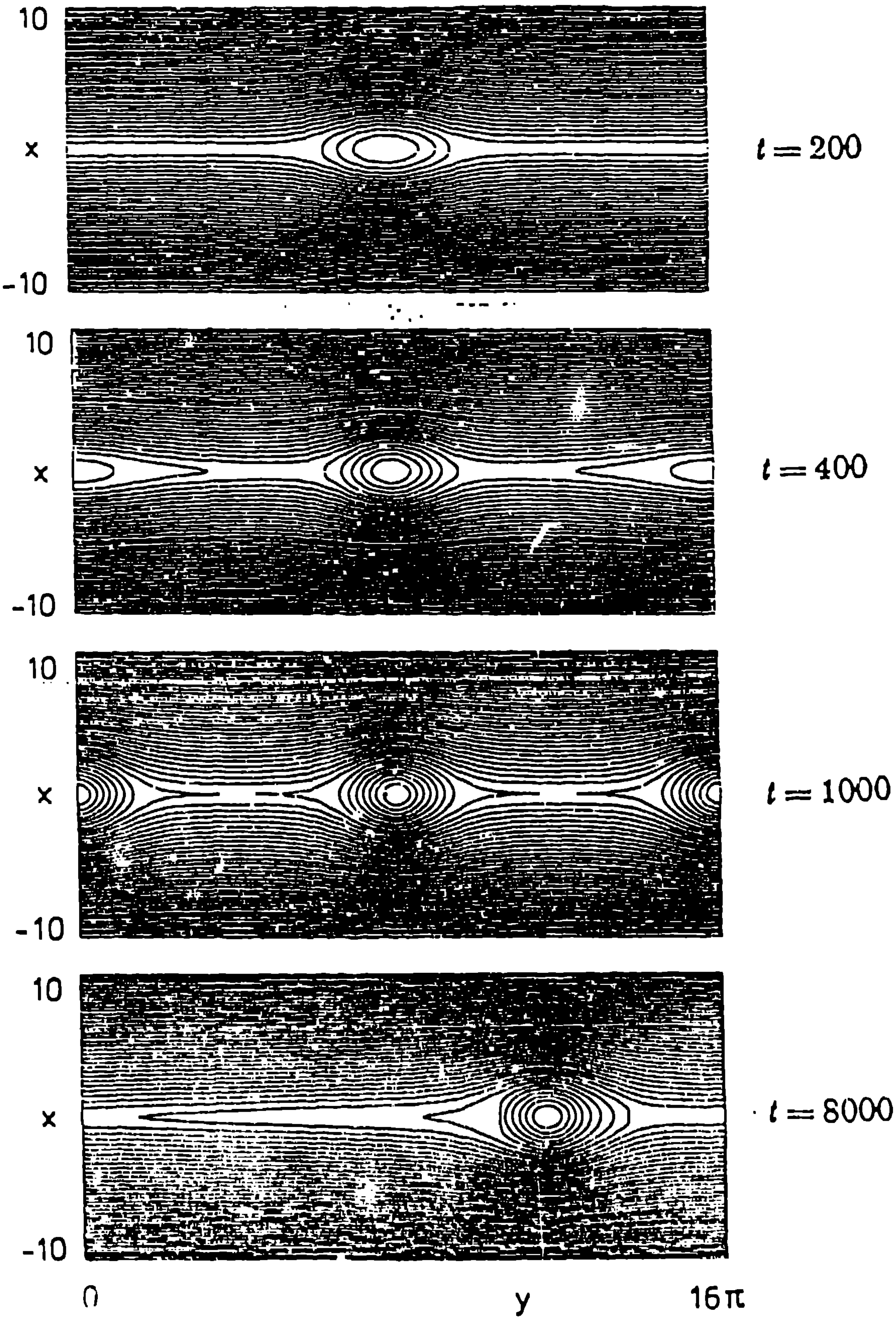



Fig. 1

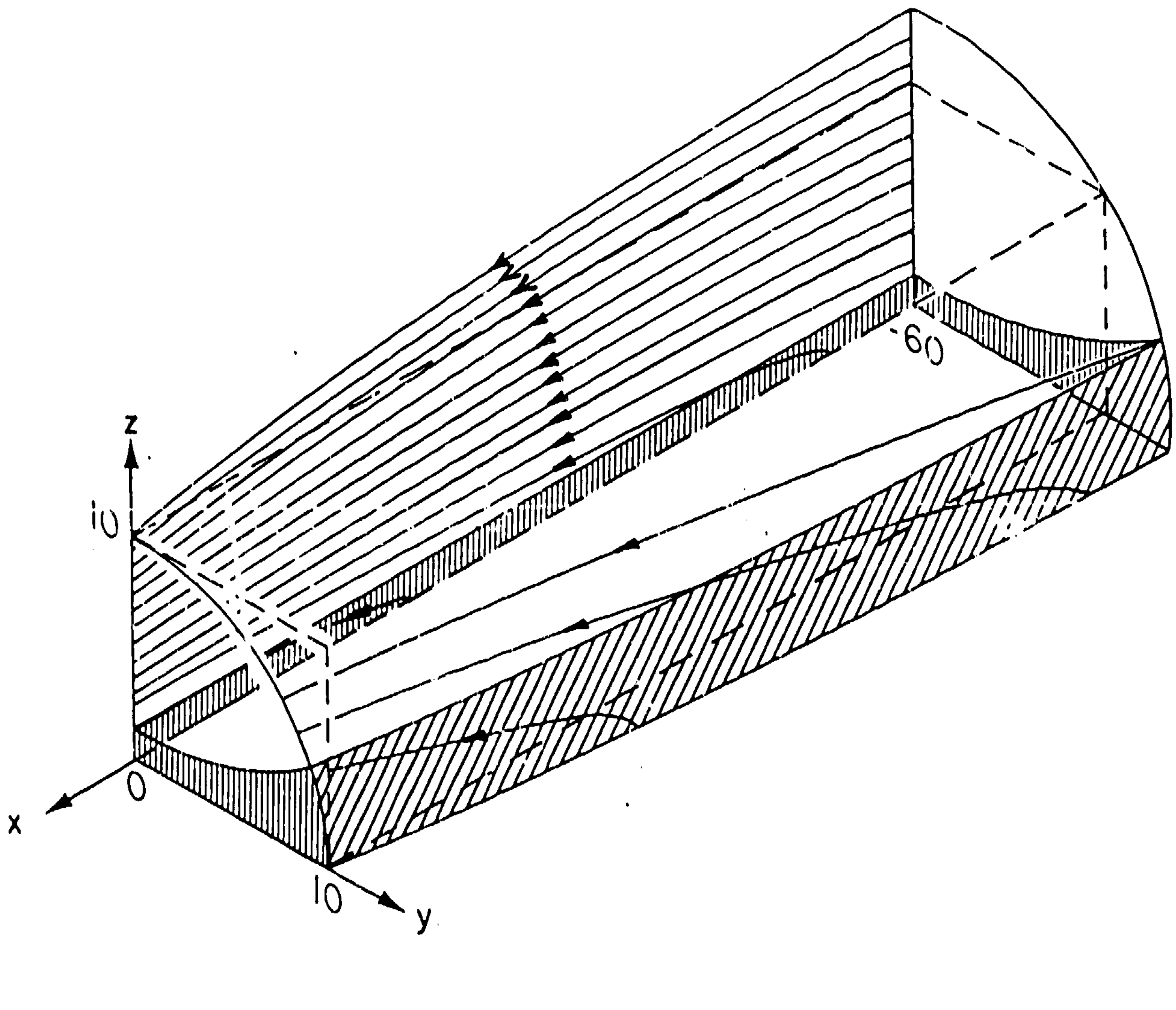
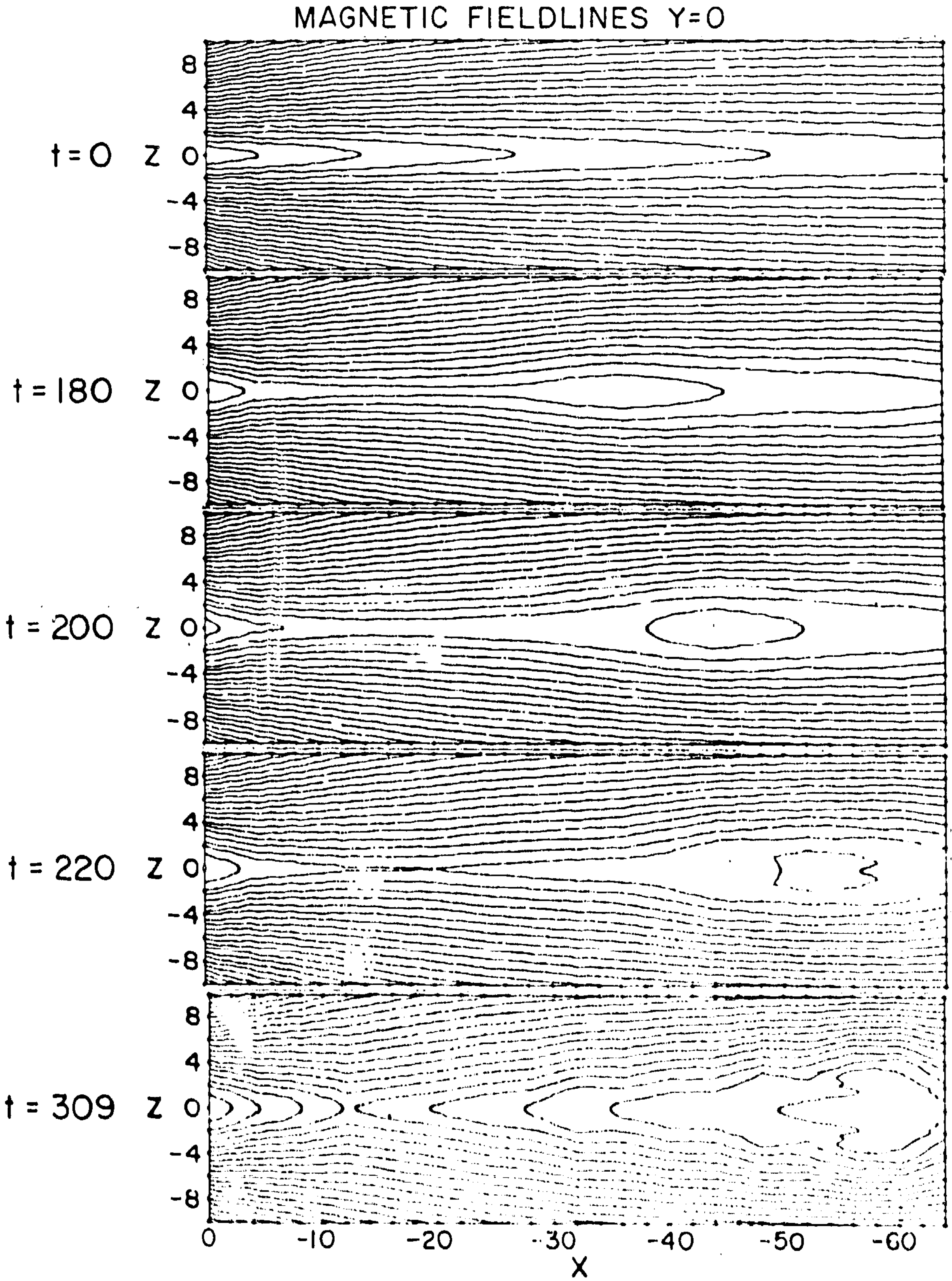



Fig. 2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t=200
t=220
t=309
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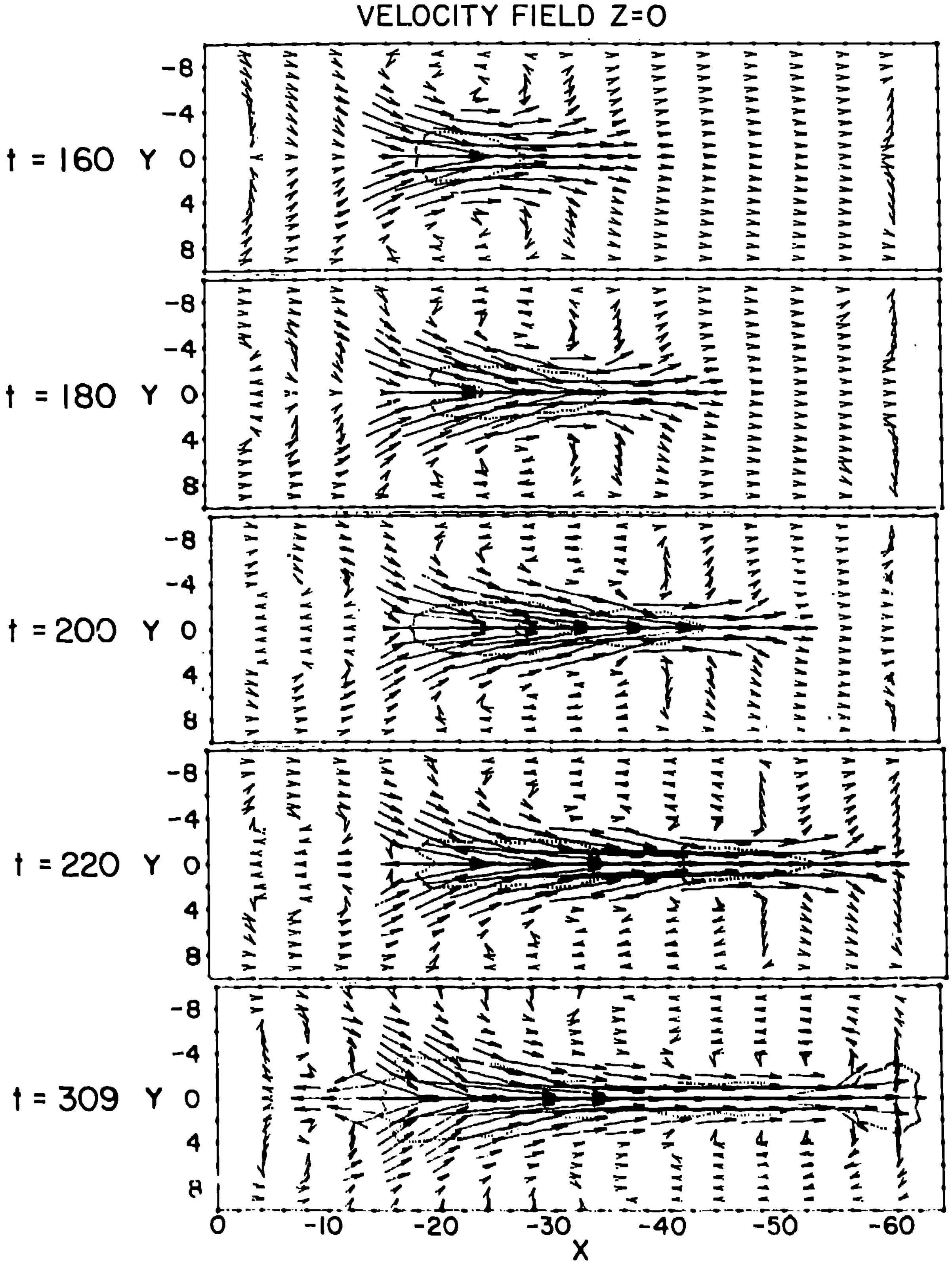
-20
-30
-40
-50
-60
X

Fig 3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t = 180 Y
t = 200 Y
t = 220 Y
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0
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-20
-30
-40
-50
-60
X

Fig. 4

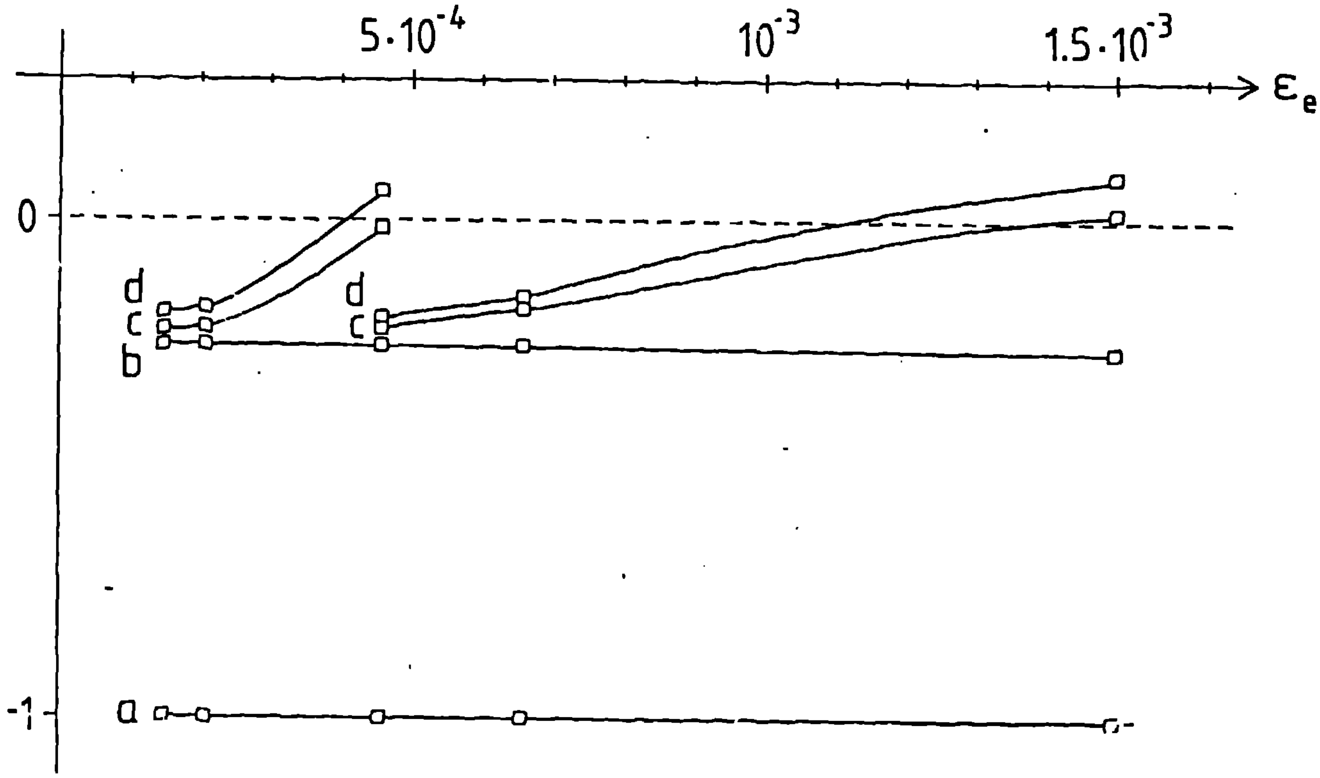


Fig. 5