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Slab Model Analysis of Magnetic and Collisional Viscosity Effects on the First Generation of Nuclear Structure

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We postulate a simple model of the freezing scale in nuclear plumes, whose success depends strongly on the high M ratios of nuclear plumes, and on the existence of some mechanism which causes the slab growth rate $\gamma(k)$ to be sharply peaked when regarded as a function wavenumber k. Although the model derivation is quite different from that of the JAYCOR model, the only significant difference in implementation is the use of growth rates valid for all gradient scale lengths, rather than for just the asymptotic long wavelength limit. We note that this model is only two dimensional, and hence does not address three dimensional effects, which may be important.

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CONTENTS

SLAB MODEL ANALYSIS OF MAGNETIC AND COLLISIONAL VISCOSITY EFFECTS ON THE FIRST GENERATION OF NUCLEAR STRUCTURE

I. INTRODUCTION

Our goal in this paper is to postulate a simplified model of the structure formation process in the late time nuclear environment. To the extent that this model is valid, the specification of the freezing scale in the nuclear case is reasonably simple both conceptually and computationally. As in the case with any theory, its success depends critically on its assumptions, and we ask the reader to examine our hypotheses with a critical eye.

In effect, we are going to argue that we can use one-dimensional linear stability analysis to predict the freezing scale in the late-time multidimensional nonlinear evolution of a nuclear plume. In this respect our view is quite similar to that of the JAYCOR freezing model [Glassman and Sperling, 1987]. The present arguments differ from those used by JAYCOR in two key respects: (1) the success of the model relies on the shielding properties of multidimensional high M clouds, rather than a hoped-for proportionality between one-and two-dimensional stability analysis scale sizes; and (2) we find that the long wavelength limit is often not appropriate for the range of nuclear parameters we expect. Only this last point has any effect on the model itself, and it is fair to say that the only structural difference between the model we propose here and that of JAYCOR is our use of routines which solve the full stability problem for the actual expected density gradients, rather than for the asymptotic long wavelength limit. Thus changing a piece of software which implements the present JAYCOR model to the model we propose here would simply involve changing the routines which calculate growth rates to our routines, or better yet, to a table look-up based on a one-time parameter search with our routines.

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In concise form our postulated model is as follows:

1. The one-dimensional slab mode is appropriate for the linear regime during the first generation of nuclear structure (see Section II).

2. Due to the high M ratio of a nuclear plume, and to the scale sizes of the neutral wind relative to k_m^{-1} (see below), the first generation of nuclear structure is the last (see Sec. III).

3. If k_m is the wavenumber for which the growth rate $\gamma(k)$ maximizes, and if the maximum in γ is sufficiently narrow about k_m, then the nonlinear "blobs" associated with the first generation of nuclear structure are dominated by a scale size k_m^{-1} (see Section IV).

4. It follows from (1) - (3) that the freezing scale is given by k_m^{-1}

In Section II we make the case for the use of one-dimensional slab linear stability analysis to model the behavior of a two dimensional nuclear plume. In Section III we make the case for the first generation of nuclear structure being the last. In Section IV we show numerically generated curves of the growth rate γ for a range of expected nuclear parameters, and show that when the function $\gamma(k)$ has a sufficiently narrow maximum at wavenumber k_m, then the structure scale size at the end of the first generation of structure will be dominated by k_m^{-1}. Combining this with the results of Section II, we conclude that the freezing scale is simply k_m^{-1}. In Section V we show the results of some two-dimensional nonlinear numerical simulations, which verify what we have concluded in the previous sections. We also address in this section the question of the sensitivity of our conclusions to the size of the seed perturbations that are assumed to exist in all real-world nuclear plumes. In Section VI we state our conclusions, and try to place this model in perspective by enumerating those things which may limit its applicability. The physics and basic equations used here are given in Zalesak et al. (1988) along with the linearized equations used in the stability analysis.

II. THE CASE FOR USING ONE-DIMENSIONAL GROWTH RATES

Consider a nuclear plume at the beginning of the late-time environment (Fig. 1). We assume that the overall cross-field diameter of the plume is tens or hundreds of kilometers, with edge gradient scale lengths in the kilometer range, certainly no shorter than 100m, and that the ratio M of integrated Pedersen conductivity inside the plume to outside the plume is very large (100 or greater). The two primary drivers for structure are (1) a component of the neutral wind more or less uniform and imposed on the plume externally, and (2) those components of the neutral wind which are internal to the cloud, i.e. a radial neutral wind or at least one which has substantial variation over the diameter of the plume (see Fig. 1).

We know that the external component of the wind will not be effective in producing structure, due to the large M of the cloud. The cloud will simply produce polarization electric fields ("shielding") which allow it to drift at the field-line-weighted neutral wind velocity, reducing the field-line-weighted slip velocity and driving the growth rates to near zero [McDonald et al., 1981]. The plume will steepen on one side as a result of this process however. Thus we argue that it is the internal winds which have the only real chance of producing structure in the nuclear plume, since shielding cannot take place in the internal wind geometry, and further, that to the degree that this internal wind component is well approximated by a radial wind, the structuring process is well described by a slab model analysis (see Fig. 2).

It remains to specify the gradient scale lengths and slip velocities to be used in the slab analysis. In Fig. 1 we show the range of possibilities that we consider to be most likely. In Fig. 1a we show a reasonably symmetric nuclear plume located near the center of a radial neutral wind field associated with a burst. Since the raw wind speeds are expected to be quite high near this point, and since the radial geometry yields little or no shielding, we expect the slip velocities to be large. Further, since no shielding means no steepening either, we expect the gradient scale lengths to be large. Assuming that structuring does not take place at this time, a little while later we expect the plume to appear as in Fig. 1b. The small external component of the neutral wind has translated the entire cloud away from the neutral wind center, reducing the raw neutral wind speed and also its internal component, thus giving smaller slip velocities. However the translation has also given rise to a steepening on one side, thus giving smaller gradient scale lengths. Fig. 1c just continues the arguments advanced to justify Fig. 1b, with still smaller slip velocities and gradient scale lengths. Thus we conclude that we can span the range of realistic possibilities by pairing small gradient scale lengths with small slip velocities, and large gradient scale lengths with large slip velocities. Note, however, that this raises the distinct probability that the long wavelength limit will not always be appropriate for the slab stability analysis, and that finite gradient scale lengths will have to be part of the analysis.

III. THE CASE FOR THE FIRST GENERATION OF NUCLEAR STRUCTURE BEING THE LAST

The above simply argues that a slab analysis is sufficient to predict the first generation of structure in a nuclear environment. In order to fully argue the case for using slab analysis to predict the late-time freezing scale, we must also make the case for the first generation of nuclear structure being the last. This we do as follows.

Consider the cases shown in Fig. 1. We shall assume that the scale lengths associated with the divergent part of the neutral flow field are approximately equal to those of the large unstructured plume, on the order of tens or hundreds of kilometers, since both evolved from the same or a similar burst. Thus when structuring takes place, generating kilometer or sub-kilometer scale plasma structures, the neutral wind field will now appear to be almost totally externally imposed to these new, much smaller structures. Thus the structuring event itself will have given rise to a sudden and substantial drop in the internal wind component. We now argue simply that this sudden drop has put these new small-scale structures in a regime where even the smallest of dissipation mechanisms will inhibit bifurcation. Thus structuring ceases after the first generation.

IV. LINEAR ANALYSIS FOR NUCLEAR PARAMETERS

In this section we attempt to span the range of possible nuclear parameters and compute the growth rate $\gamma(k)$ for all relevant values of wavenumber k, based on the conclusions of the previous sections. We shall be looking for the situations where $\gamma(k)$ is a strongly peaked function of k, since in this case we can argue that at the end of the first generation of structure, the resultant nonlinear evolution will be dominated by scale sizes of order k_m^{-1}, where k_m is the wavenumber for which $\gamma(k)$ maximizes.

Rather than try to present the detailed argument now, let us present a few calculations of linear growth rates for nuclear parameters and use these as models for our arguments. The geometry we shall work with is shown in Fig. 2. We have a driver modeled as a neutral wind blowing through the edge of a plume. This is meant to represent a small pie-slice of a radial wind blowing outward into a transition region between the plume interior electron density $n_<$ and the ambient electron density $n_>$.

We must choose the following parameters when performing a linear slab analysis.

1) $n_>$, the electron density outside the plume,
2) $n_<$, the electron density inside the plume,
3) the functional dependence n(x) in the transition between $n_>$ and $n_<$,
4) the neutral wind slip velocity U,
5) The ion-neutral collision frequency ν_{in},
6) The ion species (e.g. O^+, $B_a{}^+$), and
7) the ion temperature T_i.

For the calculations we present, we have chosen the following as being representative of the nuclear plume case:

1) $n_> = 10^5$,
2) $n_< = 10^8$,
4) the ion species is O^+,
3) n(x) is a hyperbolic tangent with scale length L,
5) the ion temperature T_i = 0.1 ev,
6) three calculations were done, in accordance with the arguments advanced in Section II:

L) large L, large U : L = 1 km, U = 1 km/sec
M) moderate L, moderate U: L 100m, U = 100 m/sec
S) small L, small U : L = 20m, U = 20 m/sec,

7) for each of those three calculations, three ν_{in} values were used, meant to span the altitude range from low to high: $\nu_{in} = 10.0$, 1.0, $0.1\ s^{-1}$, and

8) the physics included are ion-neutral collisions, ion inertia, magnetic viscosity, and ion collisional viscosity. A detailed description of the physics and the numerical solutions of the linearized equations is found in Zalesak et al., 1988.

Calculations L, M, and S are shown in Figs. 3, 4, and 5 respectively. In each plot is shown the growth rate γ as a function of the wavenumber k, for each of the three values of ν_{in}.

Let us pick a particular growth curve, that of calculation M (Fig. 4) for $\nu_{in} = 1.0$. Suppose we assume that our initial condition consists of the slab itself plus a small amplitude white noise perturbation. The curve peaks at $k = k_m \sim 20\ km^{-1}$, with growth rates at $k = 10\ km^{-1}$ and $k = 30\ km^{-1}$ lower by a factor of about 1/6. All these modes will grow, but at different rates. If we postulate that the initial normalized amplitude of each mode, $\delta n/n$, is $\sim 10^{-6}$, then it will take 13.8 growth times for a mode to reach $\delta n/n = 1$. Now consider two modes whose growth rates differ by 1/6. By the time the faster growing of the two had reached $\delta n/n = 1.0$, the slower growing one would have achieved only $\delta n/n = 0.1$. Thus we would expect the spectrum at the transition to nonlinear ($\delta n/n = 1$) to be strongly peaked at $k_m = 20\ k_m^{-1}$. If we further argue that these fingers are now two-dimensional structures and high M and hence virtually immune to further bifurcation, then we conclude that the freezing scale is k_m^{-1}.

Note, however, that not all of the curves shown display this property of being strongly peaked functions of k. In general for larger L and for larger ν_{in}, the maximum is less strongly peaked, and indeed may be nonexistent. In these cases we expect our model to break down.

V. TWO-DIMENSIONAL NONLINEAR SIMULATIONS

In this section we take one of the initial conditions considered in the previous sections, the case of $L = 100$ m, $U_n = 100$ m/sec, $\nu_{in} = 1.0$ s^{-1}, which yields a reasonably peaked profile $\gamma(k)$, and put our ideas to the test. We seed our initial profile with a white noise, random phase initial perturbation in the x direction, in effect seeding all k's with the same level of fluctuation. We then let the perturbed slab evolve in time using a fully two dimensional nonlinear numerical simulation code, to see if a preferred freezing scale does arise out of the noise at late times. The curve for $\nu_{in} = 1.0$ s^{-1} in Fig. 4 shows that the peak in the growth rate occurs for $k \sim 20$ km^{-1}. Thus we expect a wavelength of about 300 m to dominate at late times. The grid used in the code was 1200 m wide in the x-direction, with periodic boundary conditions assumed. Thus we expect approximately four major fingers of plasma to emerge from the slab at late times.

We have run the calculation at two different levels of fluctuation. The fluctuation was applied by initially displacing the plasma a distance δy in y, where δy is a white noise random phase function of x. In calculations A and B we took the mean δy to be 10^{-3} L and 5×10^{-2} L respectively. Obviously we are trying to ascertain the effect of fluctuation level on our results, since the logic we have used in section IV would argue that the late-time spectrum would be less dominated by $\lambda \sim 300$ m for the high fluctuation case.

In Fig. 6 we show the isodensity contours for the initial conditions for calculation A. Note that the perturbation level is sufficiently low as to make the perturbations almost undetectable on the plot. In Fig. 7 we show calculation A after 10.67 sec of evolution. Note that there are indeed 3-4 major fingers of plasma, as the present model would predict.

In Fig. 8 we show the initial conditions for calculation B. Note that the perturbation is now easily visible to the eye. In Fig. 9 we show calculation B after 3.56 sec of evolution. Despite the presence of high frequency structure, the morphology is still dominated by approximately four major fingers of plasma. Thus even when the perturbation levels are reasonably high, the model advanced here may be acceptable.

VI. CONCLUSIONS

We have postulated a simple model of the freezing scale in nuclear plumes, whose success depends strongly on the high M ratios of nuclear plumes, and on the existence of some mechanism which causes slab growth rates $\gamma(k)$ to be sharply peaked functions of k. Although the results examined here rely on the η_3 and η_1 terms in Braginskii's stress tensor, this need not be the case. The final model is similar to the JAYCOR model in the sense that the freezing scale is taken to be proportional to k_m^{-1} where k_m is the wavenumber for which $\gamma(k)$ maximizes. However, the derivation is different and, we think, rests on more solid theoretical ground. It is also clearer, making the limitations of the model more apparent. Using numerical simulations, we conclude that the model has a reasonable chance of working in the nuclear case, with the caveat that the long-wavelength limit may not always be the appropriate model for the slab growth rates.

ACKNOWLEDGMENTS

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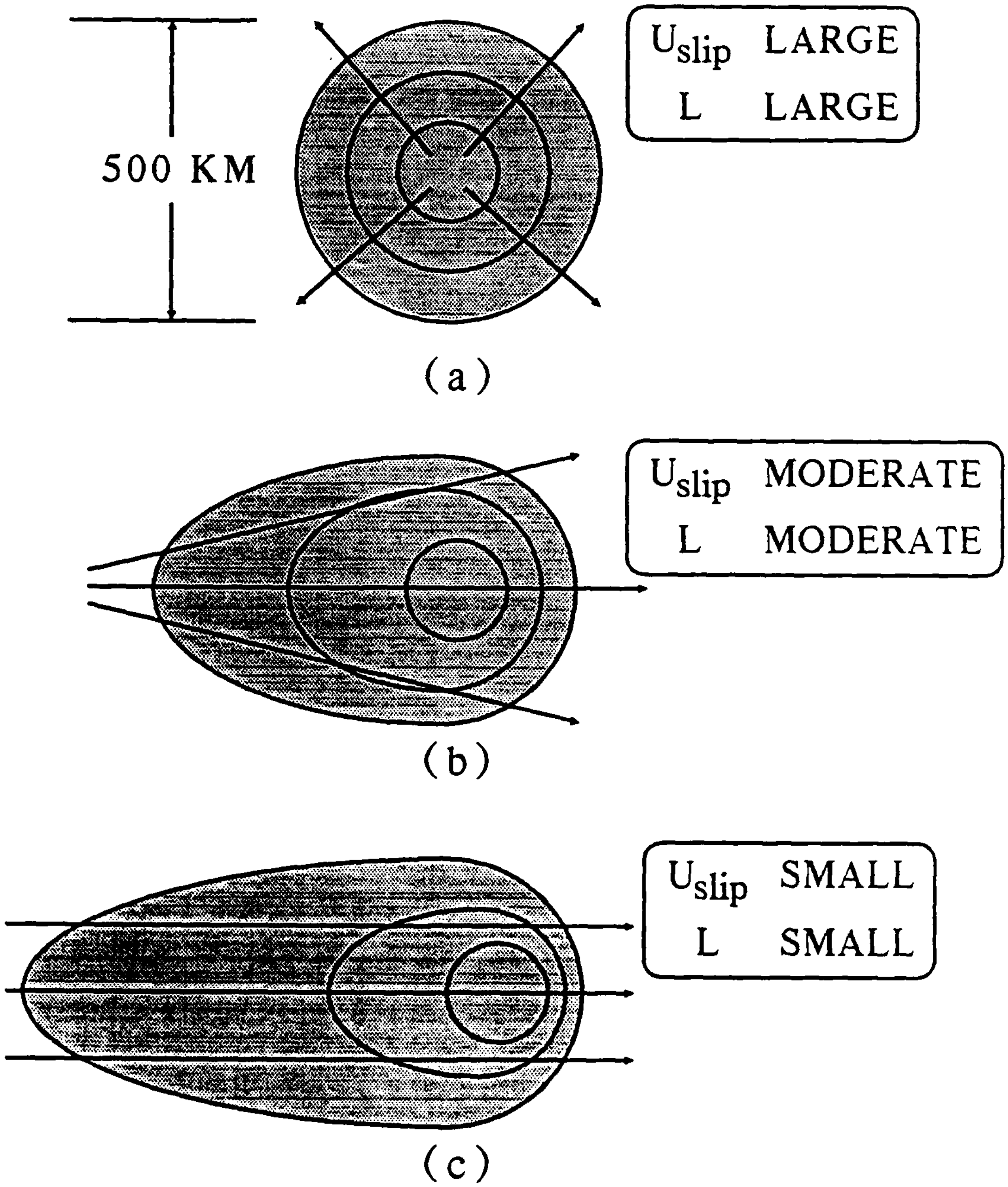

Fig. 1. Range of possibilities for the morphology of a nuclear plume perpendicular to the magnetic field, during the late-time regime. The arrows denote neutral wind direction. The possibilities are (a) L Large, U_{slip} large, steepening small; (b) L moderate, U_{slip} moderate, steepening moderate; and (c) L small, U_{slip} small, steepening large. See text for reasoning.

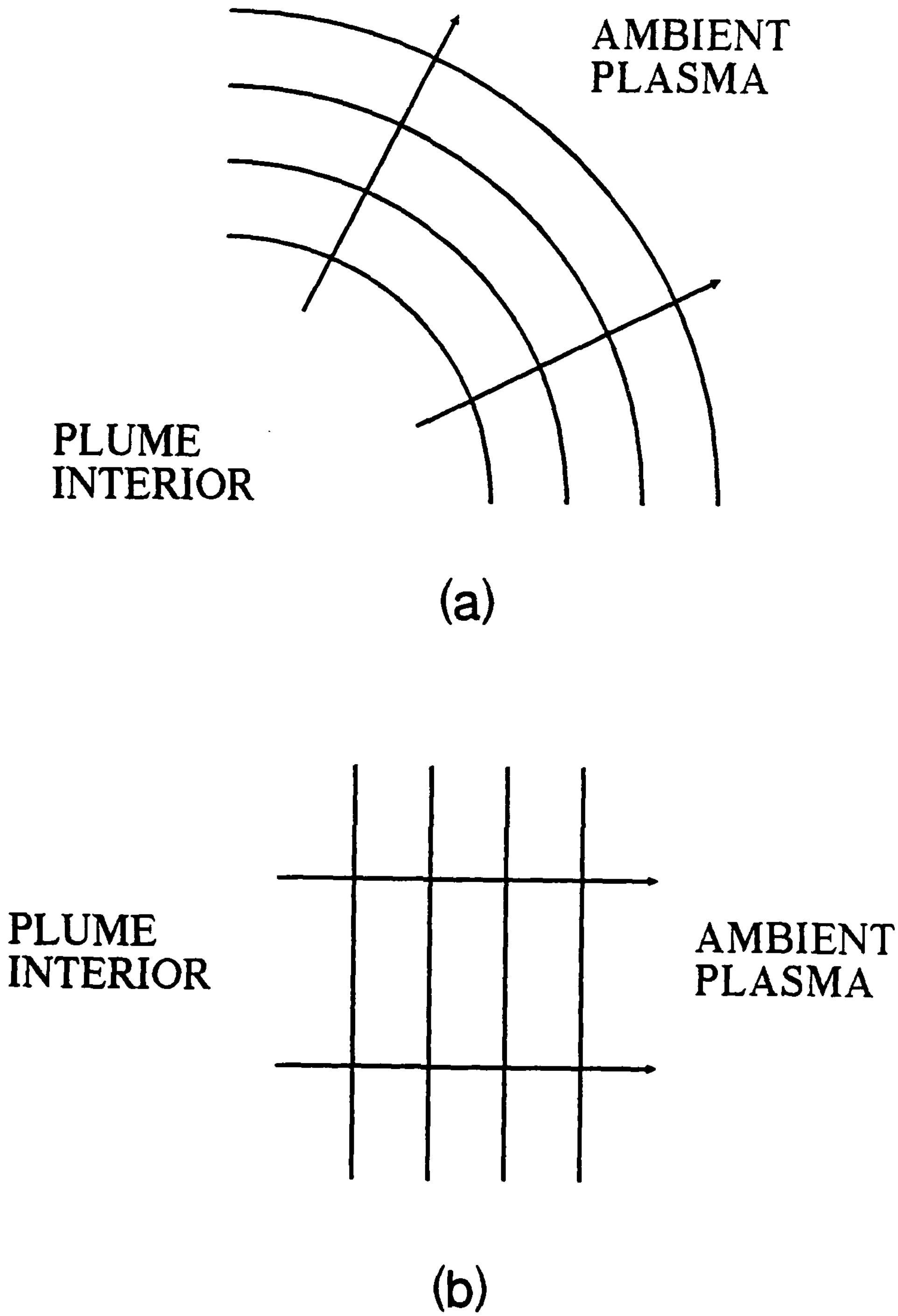

Fig. 2. Approximating a radial wind component acting outward on a curved cloud edge segment (a) as a uniform wind acting on a slab (b).

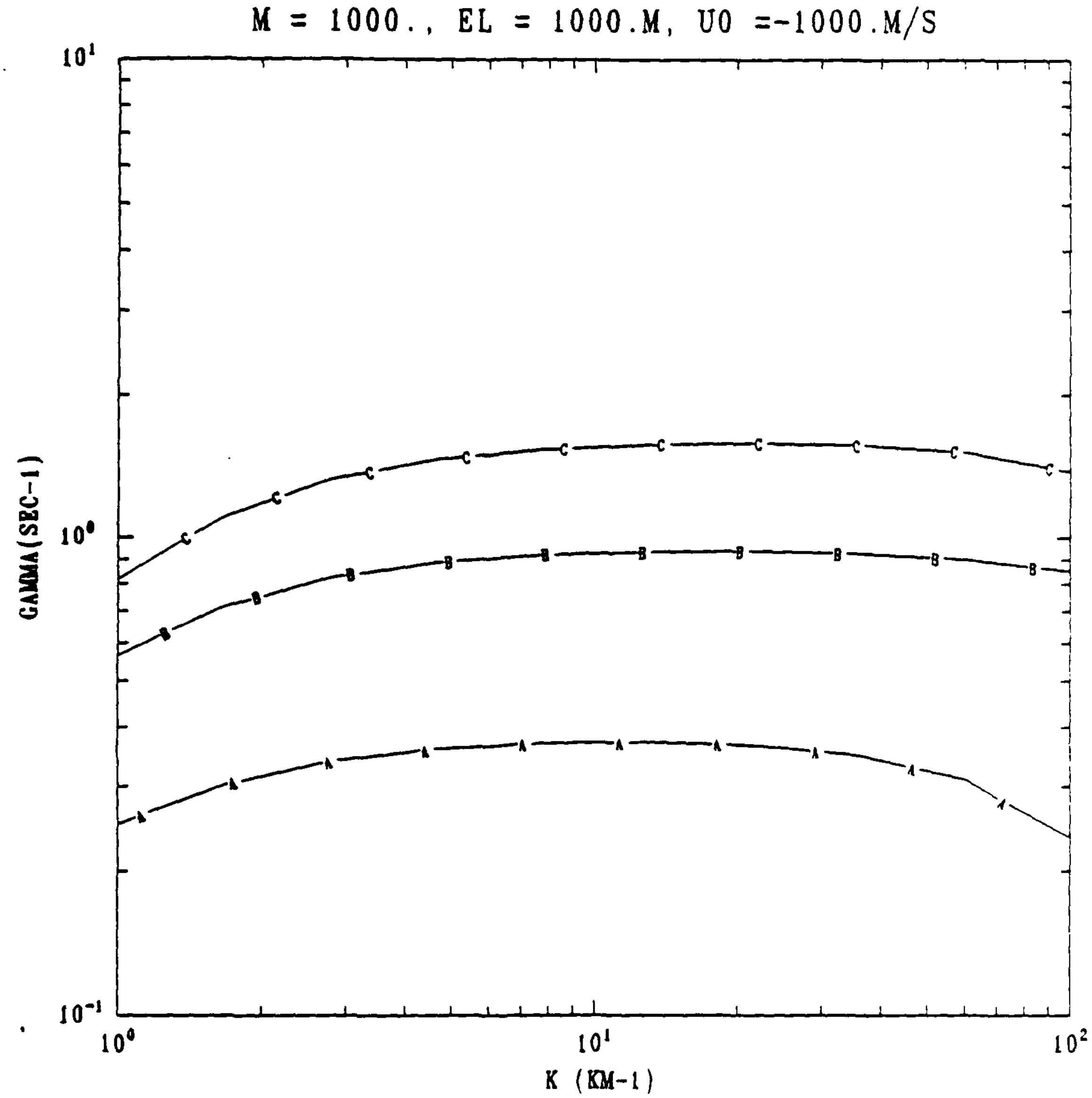

Fig. 3. Plots of γ vs k for the case of $n_{>} = 10^5$, M = 1000, U_n = -1000 m/s, using a hyperbolic tangent density profile and L = 1000 m. Curves A, B, and C refer to ν_{in} = 0.1, 1.0, and 10.0 s^{-1} respectively. (Calculation L)

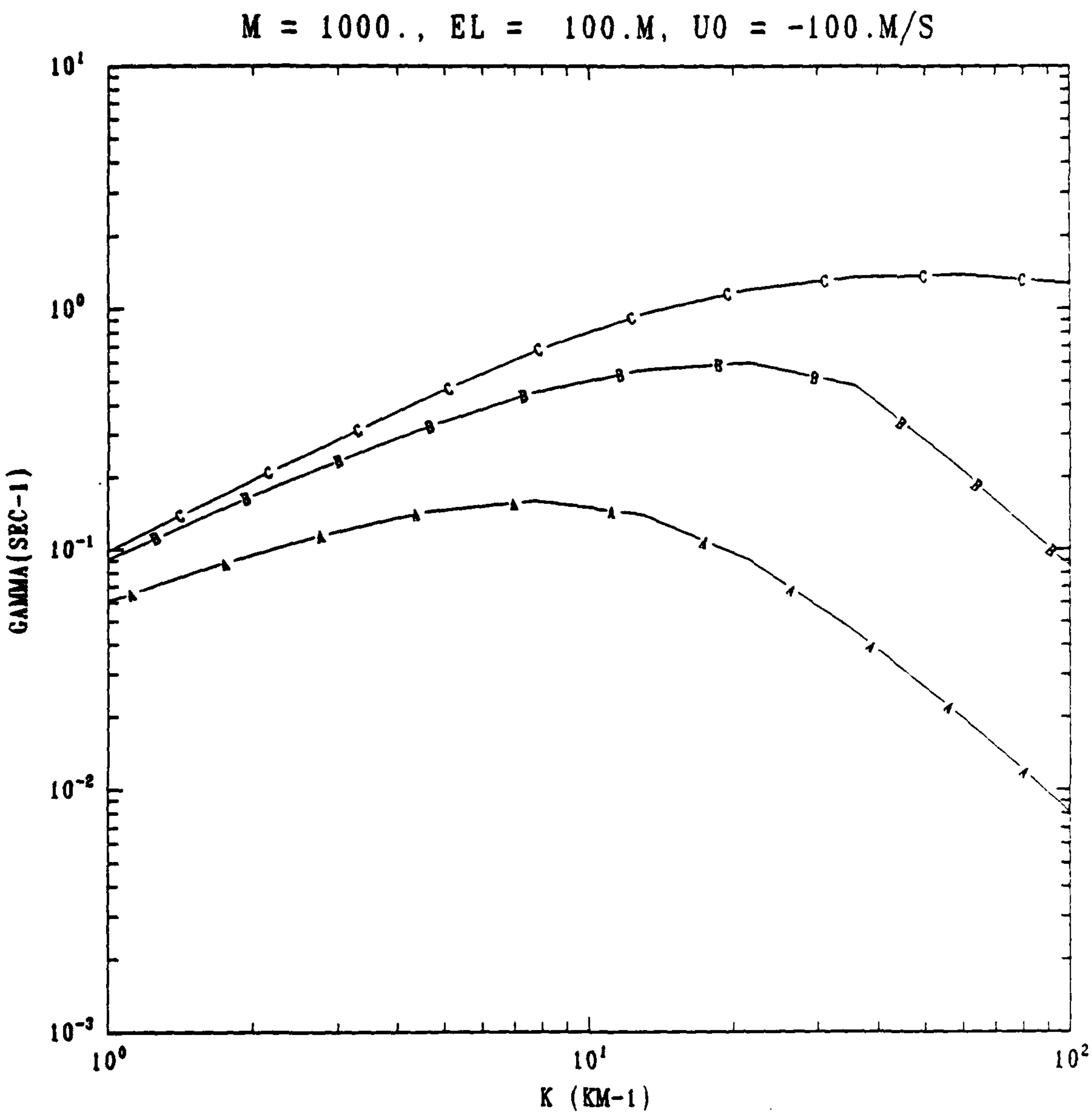

Fig. 4. As in Fig. 3 but for U_n = -100 m/s and L = 100 m. (Calculation M)

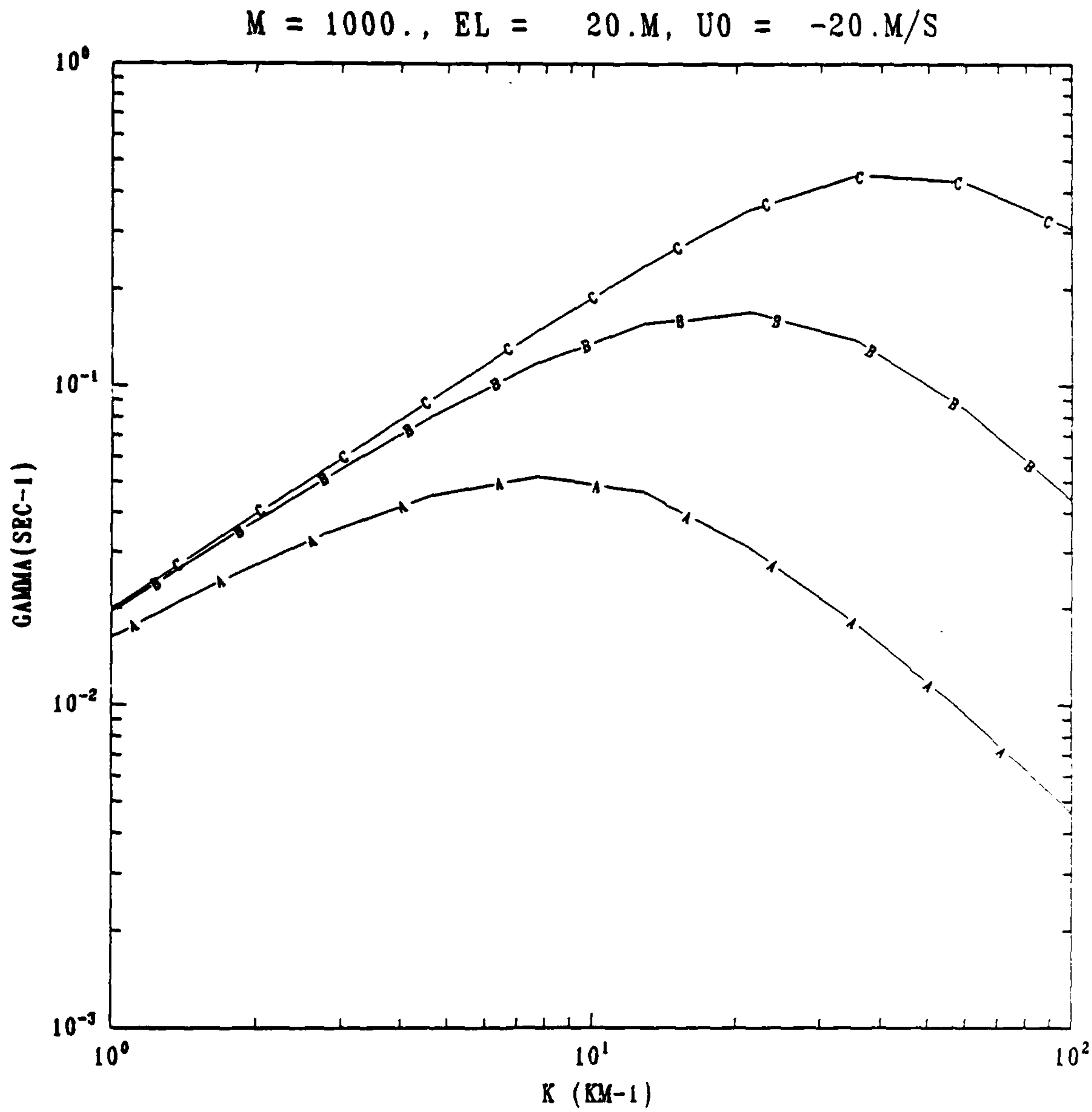

Fig. 5. As in Fig. 3 but for U_n = -20 m/s and L = 20 m. (Calculation S)

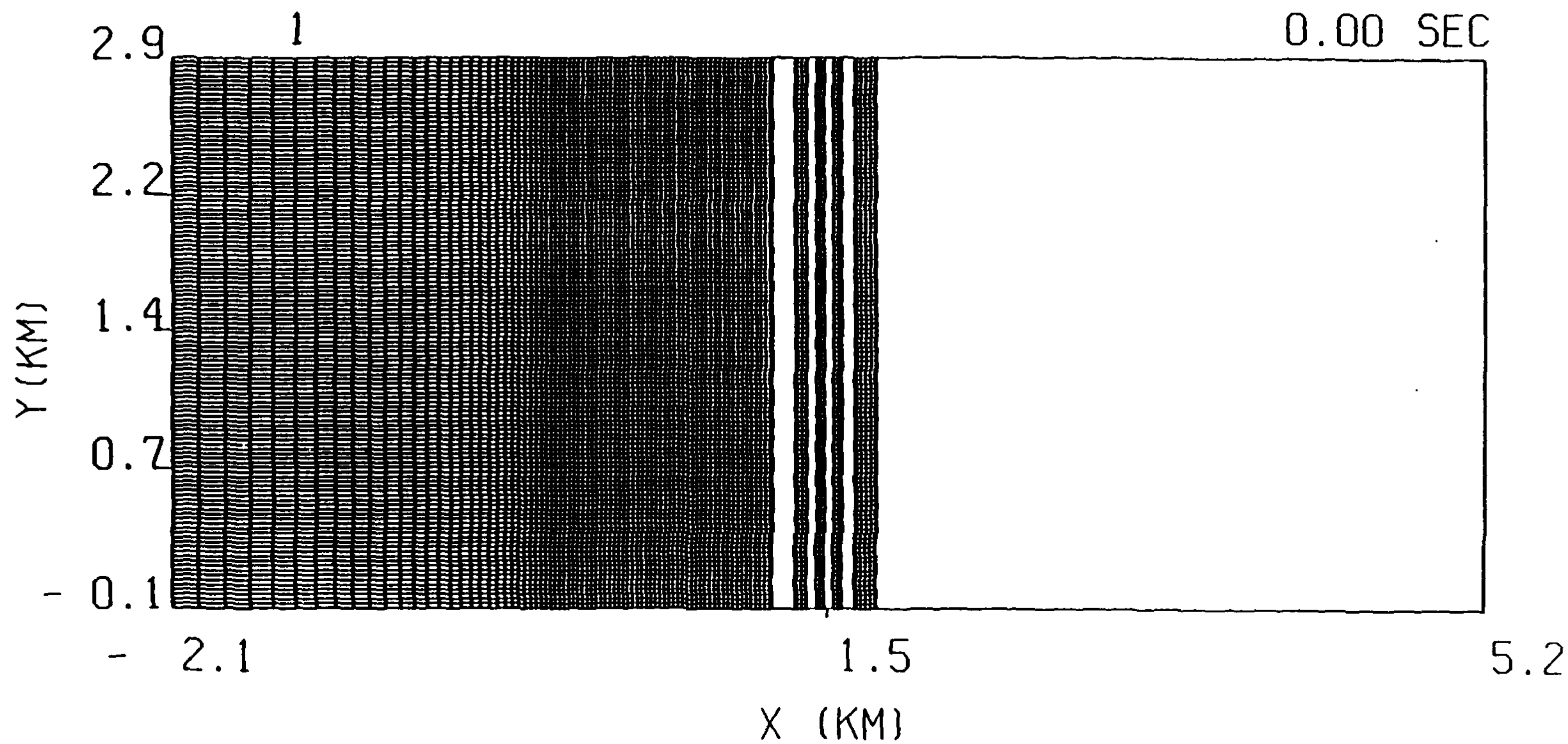

Fig. 6. Initial conditions for calculation A. Shown are evenly spaced isodensity contours of n from 10^5 to 10^8. Cross-hatching is used between alternate pairs of contour lines for clarity. The 180 x 120 mesh is stretched away from the center in x, where the grid size is 10 m in both directions. A small initial random perturbation has been applied (see text).

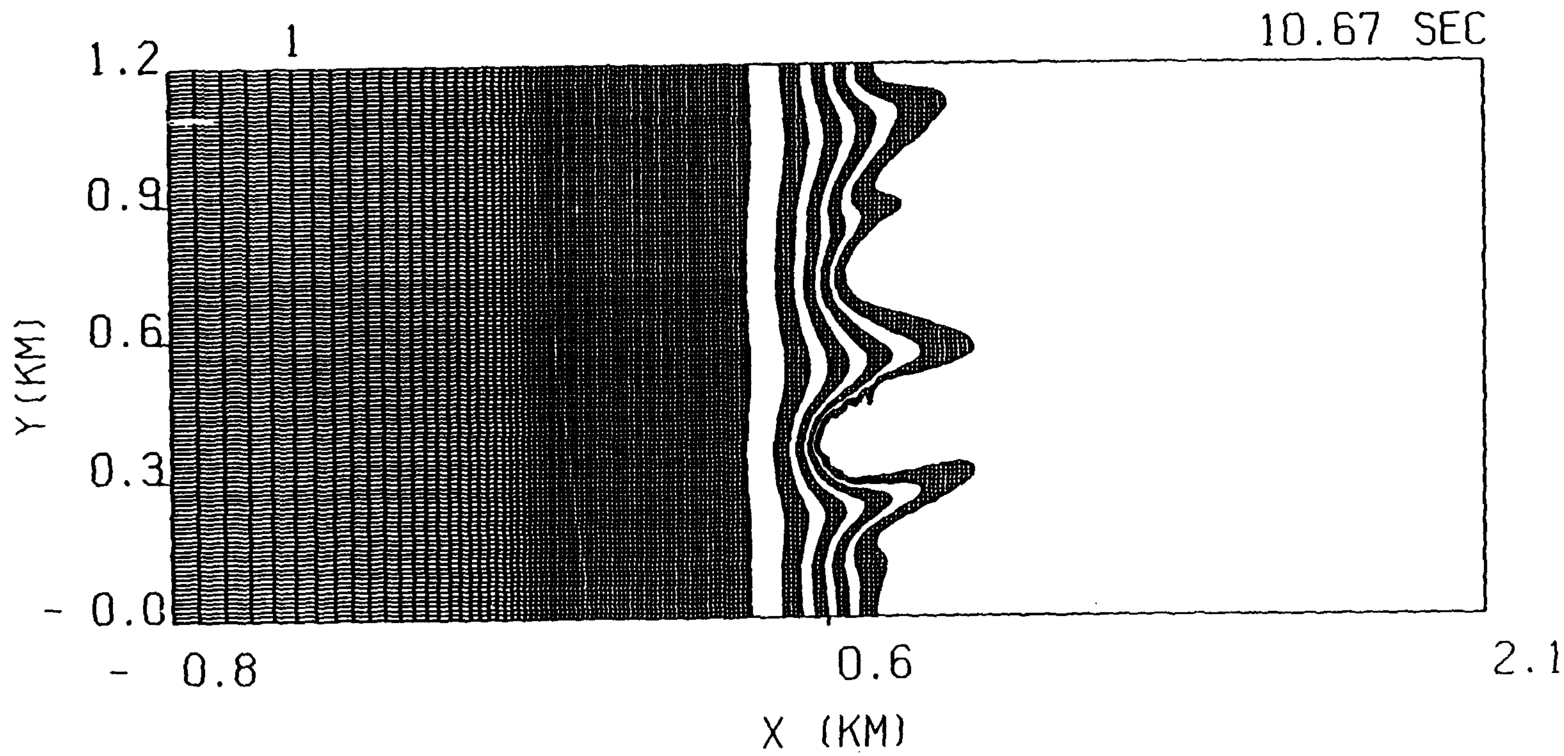

Fig. 7. Plasma configuration at 10.67 sec corresponding to the initial conditions in Fig. 6.

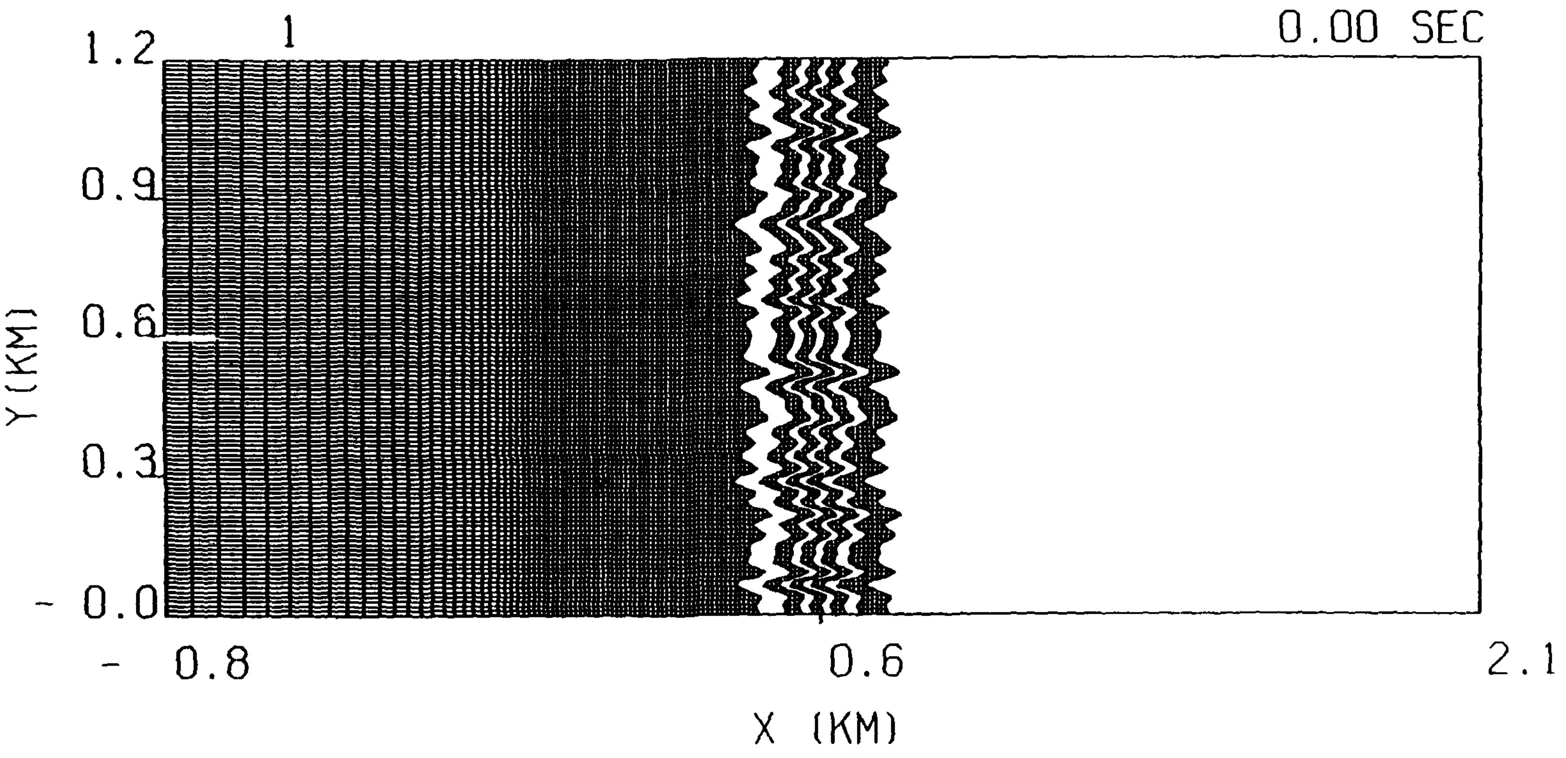

Fig. 8. As in Fig. 6, but for calculation B, where the initial random perturbation is fifty times larger.

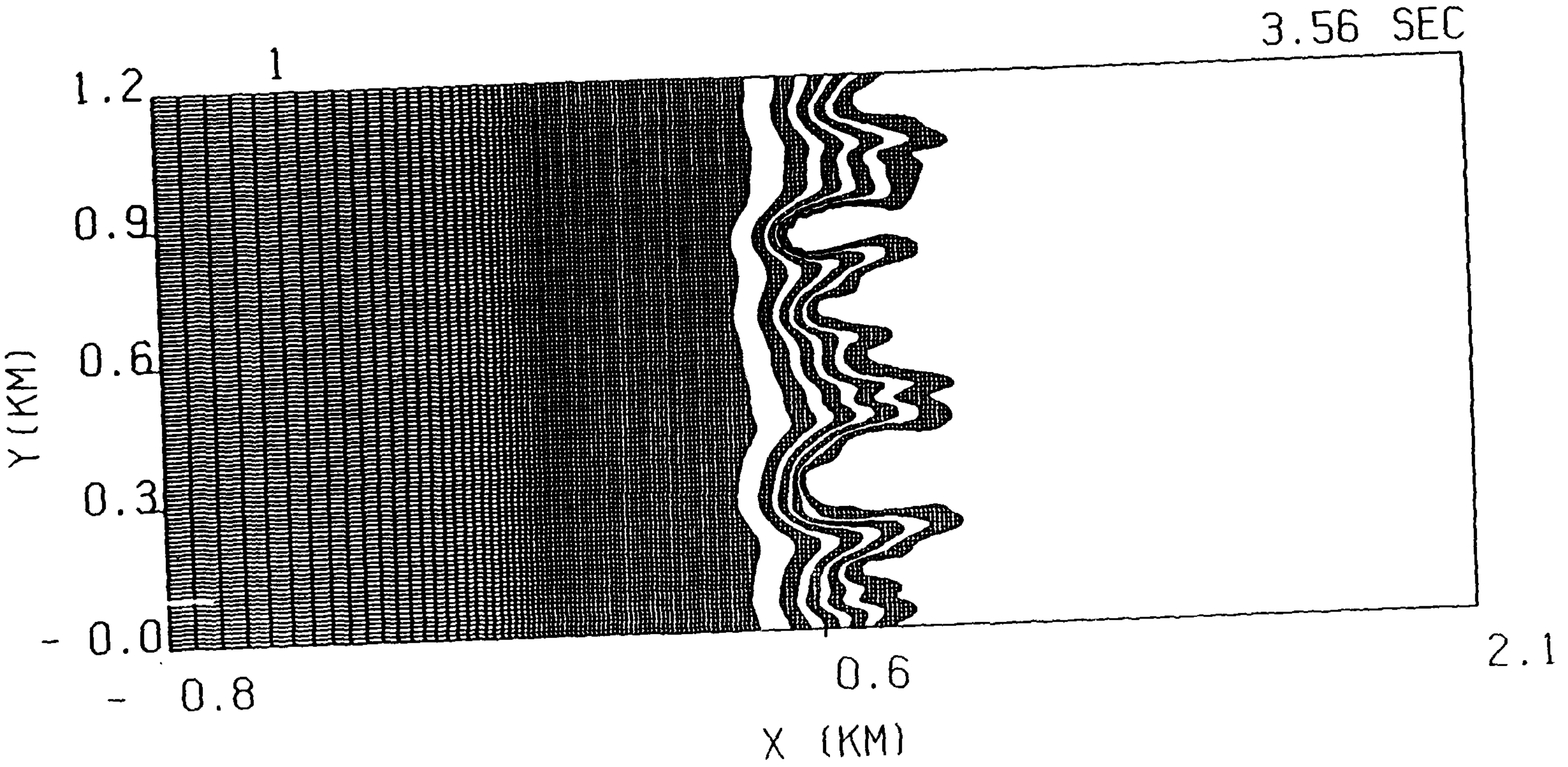

Fig 9. Plasma configuration at 3.56 sec corresponding to the initial conditions in Fig. 8.

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