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The control of the plasma vertical position in tokamak configurations and the positioning of magnetic, pick-up loops are considered. The equilibrium problem for a plasma with free-boundary is solved using the inverse-variable technique. Circuit equations for eddy currents in the vacuum vessel, eddy currents in structures, and currents in active coils coupled with the plasma equilibrium and transport equations are solved. The influence of the location of pick-up coils on control of the plasma vertical position is examined. It is shown that there are geometrical arrangements of the magnetic loops such that the plasma vertical position can not be controlled using a conventional control law (this is regardless of the resistivity of the passive conductors and the gain value in the control system). An explanation of this phenomenon is given. A new control law is proposed such that plasma control is possible with general positioning of the magnetic loops. Our conclusions should be important for the operation of ignition tokamaks, where elongated, high-current plasmas have to be stabilized with magnetic loop positioning subject to severe constraints.

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Introduction

Many present day tokamaks (e.g.: JET, D-III-D, PBX, etc.) have elongated plasma shapes and operate in divertor regimes. The next generation tokamaks (e.g.: ITER), will be high-elongation devices. It is well known that elongated tokamak plasmas are unstable to axisymmetric vertical displacements. Vacuum vessel or passive conductors can stabilize the fast plasma motion. For stabilization of the slow plasma motion and position control, an active feedback control system is utilized. The plasma vertical position and displacement velocity are input parameters to the control system. The voltage applied to the active coils is one of the output parameters.

In many tokamaks the plasma position and velocity are determined by magnetic pick-up loops. Usually it is considered that the change in the poloidal flux through each loop is proportional to the plasma displacement and the induced voltage on each loop is proportional to the plasma speed. To determine the mode's growth time under passive stabilization, the pick-up coils can be located at any position. However, when a feedback system is added the situation changes dramatically. The positions of the pick-up coils become important and only an adequate location of the coils leads to control of the plasma's position.

An explanation of this phenomenon based on the change in the plasma shape is given in Ref.[1]. Here we suggest a different mechanism to explain this effect. In this paper the influence of the pick-up coils location on the possibility to control the plasma vertical position is studied. A simple modification of the standard control system is suggested which enables to control the plasma with any position of pick-up coils.

The numerical simulations are carried out in the IGNITEX [2-5] configuration for two different cases: a) with very high resistivity of the poloidal field (PF) coils (i.e. neglecting the influence of the PF coils), and b) with the real resistivity of PF coils. A $1-\frac{1}{2}$ D equilibrium-transport code (DINA) [6] has been used to model the evolution of a plasma with free-boundary coupled to the currents in the vacuum vessel, passive conductors, and active-control coils.

The plasma displacement model

The evolution of a free-boundary tokamak plasma in external, changing magnetic fields is modelled using the code DINA [6]. The equilibrium problem in 2-D geometry coupled with the system of 1-D transport equations obtained by averaging on the magnetic surfaces are solved. The eddy currents induced in the vacuum vessel and in the poloidal field coils are evaluated. The plasma parameters (current, temperature, density, poloidal flux, toroidal flux, etc.) are obtained. The vacuum vessel, the passive coils, and the active control coils are described by circuit equations of the form:

$$L_j \dot{I}_j + \sum_{k \neq j}^{M} M_{jk} \dot{I}_k + \tilde{R}_j I_j + \dot{\Psi}^j_{pl} = V_j \,, \tag{1}$$

where L_j is the self-inductance of the j^{th} filament; M_{jk} is the mutual inductance between the k^{th} and j^{th} filament; I_j is the current on the j^{th} filament; $\tilde{R}_j$ is the resistance of the j^{th} filament; Ψ^j_{pl} is the poloidal flux produced by the plasma on the j^{th} filament; and, V_j is voltage on the j^{th} filament.

To exclude the symmetric contribution of the PF coils and the plasma current, an up-down, symmetric pair of pick-up coils are employed. The difference of fluxes through the upper and lower loops is used to determine the plasma position. In what follows, the "flux" ψ, refers to the difference of magnetic flux through the pick-up loops. Here we assume that the control voltage applied to the active coils is proportional to the flux and has the simple form:

$$v = -g(\psi - \psi_{ref}) \,, \tag{2}$$

where ψ_{ref} is an imposed reference flux and g is the gain on the active coil. The flux through the pick-up loops has the form:

$$\psi = \psi_{ps} + \psi_{act} + \psi_{pl} \tag{3}$$

where ψ_{ps}, ψ_{act}, and ψ_{pl} are the fluxes produced by the eddy currents induced in the vacuum vessel and the passive conductors, by the currents in the active control coils, and by the plasma current, respectively.

Analysis of the the Control of Vertical Displacements of the Plasma Discharge

The poloidal field system configuration and the positions of the active coils and pick-up loops considered here are shown in Fig.1. A number of different positions of the pick-up loops are analyzed. Each position is denoted by a number as shown in Fig.1. In the simulations, the resistivity of the active coils is the resistivity of copper at room temperature (ρ_c) and the reference flux is $\psi_{ref} = 3 \times 10^{-2}$vs.

First we study a case in which the resistivity of the PF coils is artificially increased to $\rho_{pf} = 10^6 \times \rho_c$. This is equivalent to neglecting the effect of the PF coils in the calculation. The simulation is organized as follows:

a) a location of pick-up loops is selected.

b) the resistivity of the vacuum vessel is fixed.

c) the plasma time response to a step-control signal for different gain values is obtained.

d) the resistivity of the vacuum vessel is changed and step c) is repeated.

e) the calculation is repeated for various locations of the pick-up loops.

The values of resistivity considered for the vacuum vessel are: $10\rho_c$, $100\rho_c$ and $1000\rho_c$ (this permits the analysis of several vacuum vessel materials and break configurations).

It is found that there are some locations of the pick-up loops for which the plasma position can not be controled regarless of the values of the gain and the resistivity of the vacuum vessel. The plasma response to a step-control signal with the pick-up loops located at point 1 (see Fig.1) is shown in Fig.2 for three vacuum vessel resistivity values. In Fig.2-a (with $\rho_v = 10 \times \rho_c$ and $g = 40V/\psi_{ref}$) it is shown that the plasma oscillates aroun the midplane with increasing amplitude. The period of the oscillations is a 100 ms. In Fig.2-b, (with $\rho_v = 100 \times \rho_c$ and $g = 45V/\psi_{ref}$) the period of oscillation is smaller than in case a) and the amplitude increases at a faster rate. In Fig.2-c (with $\rho_v = 1000 \times \rho_c$ and $g = 90V/\psi_{ref}$) the period of oscillation is a few ms and the amplitude increases rapidly. In these simulations the relation $|\psi_{ps}| > |\psi_{act}| > |\psi_{pl}|$ is satisfied (Fig.3).

There are positions of the pick-up loops for which the plasma can be controlled (that is, for any value of the vacuum vessel's resistivity we can find a gain value such that the plasma is stabilized). This is the case of position 2 (see Fig.1). The plasma response to a step-control signal with the pick-up loops located at point 2 is presented in Fig.4. In Fig.4-a (with $\rho_v = 10 \times \rho_c$ and $g = 40V/\psi_{ref}$) the plasma approaches without oscilations the reference position $z_{ref} = 0.14\ cm$ with a response time $\tau_r = 400\ ms$. Changing the resistivity of the vacuum vessel to $\rho_v = 100 \times \rho_c$ reduces the response time to $\tau_r = 40\ ms$. In this case the plasma has as reference position $z_{ref} = 0.135\ cm$ and as gain $g = 45V/\psi_{ref}$. Fig.4-b shows a plasma which becomes stable very rapidly. In this case it is observed that the relation $|\psi_{ps}| < |\psi_{act}|$ holds (Fig.5).

From this analysis we conclude that, in terms of the location of pick-up loops, there are two possible cases. In the first case the relation $|\psi_{ps}| > |\psi_{act}| > |\psi_{pl}|$ holds (for any vacuum vessel resistivity and for any gain) throughout the plasma response to the control signal. In this case the plasma vertical position can not be controlled. In the second case the relation $|\psi_{ps}| < |\psi_{act}|$ is satisfied and the plasma can be controlled.

There are locations of the pick-up loops for which the relation $|\psi_{ps}| > |\psi_{act}| > |\psi_{pl}|$ holds for any resistivity of the passive conductors. In this case plasma can not be controlled for any value of the gain. In a first sight it would seem that in this case, for the "best" control we should simply reduce $|\psi_{ps}|$ by increasing the resistivity of passive conductors. Unfortunately, this leads to a decrease in the passive mode growth time and to a fast plasma motion. Then a fast change of the current in the active coils is required. This leads to a increase of the induced current in the passive conductors and to a increase in the value of $|\psi_{ps}|$. To show that this depends on the value of the eddy current in the passive conductors (induced by the changing flux of the control coils), we exclude the influence of the active coils on the passive conductors by assuming that the mutual inductance (M_{ij}) between the active coils and the passive conductors is zero. The results of the simulation with $M_{ij} = 0$ for an initially unstable plasma (Fig.2-b) are given in Fig.6. It is seen that plasma motion is stabilized.

For improved plasma control we propose here a new control law:

$$v = -g(\psi - \psi_{ref}) \quad \text{with}$$
$$\psi = \psi_{pl} + \psi_{ps} + (1+\alpha)\psi_{act}\,, \tag{4}$$

where α is the stability coeficient (> 0). The value of α is choosen so that $|\psi_{ps}| <$

$(1+\alpha)|\psi_{act}|$. The results of our simulations show that a "good" α value is such that

$$|\psi_{ps}| < (1+\alpha)|\psi_{act}| < 2|\psi_{ps}| \, .$$

The simulation for a previously unstable plasma (given in Fig.2-b) is repeated with $\alpha = 2$ in Fig.7. It is seen that the plasma becomes stable and the results are similar to those of Fig.6. The parameter α compensates for the flux of the eddy currents in the passive conductors which are induced by the changing active coil currents.

Next we consider the IGNITEX configuration with the actual resistivity of the PF coils. The pick-up loops are located at point 3 (Fig.1). The plasma response to a step-control signal with gain $g = 100V/\psi_{ref}$ is shown in Fig.8-a. It is seen that the plasma is not stabilized. Using our new voltage control law with $\alpha = 0.5$ the plasma can be controlled with a short response time $\tau_r = 20\ ms$. The plasma time response to a step-control signal with a gain $g = 100V/\psi_{ref}$, is shown in Fig.8-b ($\alpha = 0.5$). We can see that plasma is controlled rapidly and is kept at the reference position $z_{ref} = 0.085\ cm$. The control of the plasma vertical position is made possible by with the use of the control law proposed here (Eq.4). An analitical analysis of a symple system (the plasma column is represented by a single filament) is given in an Appendix to this paper. This analysis helps to explain the influence the positioning of the magnetic pick-up loops on plasma control.

Conclusions

It has been studied numerically, and shown analitically for a simplified system, that the location of pick-up loops is fundamental in the problem of plasma vertical position control. As a result of our simulations it is found that there exist locations of the pick-up loops such that the plasma can not be controlled regardless of the resistivity of the passive conductors and the gain value of control system. An explanation of this effect has been given here. It is shown that this is due to the influence of the change in flux produced by the active coils on the passive conductors (and vacuum vessel). A simple modification of the standard voltage control law has been proposed. This makes possible to control the plasma position with any location of the pick-up loops. These results will be important for the operation of ignition tokamaks, where elongated, high-current plasmas have to be stabilized with magnetic loop positioning subject to severe constraints.

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Figure captions

Fig.1. Poloidal field coil system. Locations of the active control coils and pick-up loops.

Fig.2. Plasma response to control input signal with control law $v = -g(\psi - \psi_{ref})$ (pick-up loops are at point 1 (Fig.1)).

a) $\rho_v = 10 \times \rho_c$, $g = 40V/\psi_{ref}$

b) $\rho_v = 100 \times \rho_c$, $g = 45V/\psi_{ref}$

c) $\rho_v = 1000 \times \rho_c$, $g = 90V/\psi_{ref}$

Fig.3. Time dependence of the poloidal fluxes through pick-up loops (pick-up loops at point 1 (Fig.1)).

A total flux

B plasma flux

C vacuum vessel flux

D active coil flux

a) $\rho_v = 10 \times \rho_c$, $g = 40V/\psi_{ref}$

c) $\rho_v = 1000 \times \rho_c$, $g = 90V/\psi_{ref}$

Fig.4. Plasma response to control input signal with control law $v = -g(\psi - \psi_{ref})$ (pick-up loops at point 2 (Fig.1)).

a) $\rho_v = 10 \times \rho_c$, $g = 40V/\psi_{ref}$

b) $\rho_v = 100 \times \rho_c$, $g = 45V/\psi_{ref}$

Fig.5. Time dependence of the poloidal fluxes througn pick-up loops (pick-up loops at point 2 (Fig.1)).

A total flux

B plasma flux

C vacuum vessel flux

D active coil flux

a) $\rho_v = 10 \times \rho_c$, $g = 40V/\psi_{ref}$

b) $\rho_v = 100 \times \rho_c$, $g = 45V/\psi_{ref}$

Fig.6. Plasma response to control input signal with control law $v = -g(\psi - \psi_{ref})$ (pick-up loops at point 1 (Fig.1)). The influence of the flux produced by the active coils on vacuum vessel has been excluded.

$\rho_v = 100 \times \rho_c$, $g = 45V/\psi_{ref}$

Fig.7. Plasma response to control input signal with control law $v = -g(\psi - \psi_{ref})$ (pick-up loops at point 1 (Fig.1)). Stability coefficient $\alpha = 2$.

$\rho_v = 100 \times \rho_c$, $g = 45V/\psi_{ref}$

Fig.8. Plasma response to control input signal with control law $v = -g(\psi - \psi_{ref})$ (pick-up loops at point 4 (Fig.1)). The resistivity of the PF coils is equal to the resistivity of the copper at room temperature.

a) Stability coeficient $\alpha = 0$, $\rho_v = 100 \times \rho_c$, $g = 100V/\psi_{ref}$

b) Stability coeficient $\alpha = 0.5$, $\rho_v = 100 \times \rho_c$, $g = 100V/\psi_{ref}$

Appendix

We consider the rigid displacement model [5] in the simple case of one passive conductor element, one active control coil and one pick-up loop. It is shown here that there exists a position of the active coil, the passive conductor, and the pick-up loop such that the plasma vertical position can not be controlled regardless of the resistivity of the passive conductors and the gain value in the feedback system.

An axisymmetric vertical plasma displacement can be described by a system of equations which includes: force balance, circuit, and voltage control law. The plasma is modelled by a single rigid filament. The plasma motion equation in the rigid displacement approximation is

$$m\ddot{z} = -\frac{dB_r}{dz}\frac{2\pi R_p}{c}I_p z - \sum_{j=1}^{2} B_j I_p \frac{2\pi R_p}{c} I_j\,,$$

where m is the plasma mass; c is the speed of light; R_p is the major radius of plasma filament; B_r is the external radial magnetic field on the plasma filament; B_j is the radial magnetic field produced by induced and active coil unit currents on the plasma filament; I_p and I_j are the currents in the plasma and the external filament, respectively; z is the plasma displacement; and, $\ddot{z}$ is the plasma acceleration. We define:

$$S_b = -\frac{dB_r}{dz}\frac{2\pi R_p}{c}I_p\,,$$

$$S_j = -B_j I_p \frac{2\pi R_p}{c}\,, \quad \text{and}$$

$$S_j^M = I_p \frac{\partial M_{pj}}{\partial z}\,.$$

Denoting the active coil by the index 1 and the passive coil by the index 2, the plasma motion and the circuit equations can be written as

$$m\ddot{z} = S_b z + \sum_{j=1}^{2} S_j I_j\,,$$

$$L_1\dot{I}_1 + M\dot{I}_2 + R_1 I_1 + S_1^M \dot{z} = V\,, \quad \text{and}$$

$$L_2\dot{I}_2 + M\dot{I}_1 + R_2 I_2 + S_2^M \dot{z} = 0\,,$$

where L_j is the self-inductance of the j^{th} filament; M is the mutual inductance between the active coil and the passive conductor filaments; R_j is the resistance of the j^{th} filament; M_{pj} is the mutual inductance between the j^{th} filament and the plasma filament; and, V is the voltage on the active coil.

The stability of the system is determined by the character of the voltage applied to the feedback control coil. A standard control law is given by:

$$V = -g(\psi_{pl} + \psi_{ps} + \psi_{act}), \quad \text{or}$$

$$V = -g(S^M z + M_1 I_1 + M_2 I_2),$$

where $S^M = d\psi_{pl}/dz$; M_1 is the mutual inductance between the active coil and the pick-up loop; and M_2 is the mutual inductance between the passive conductor and the pick-up loop.

The system of equations can be expressed in matrix form as:

$$\hat{B}\dot{\vec{x}} = \hat{A}\vec{x}, \tag{1}$$

where $\vec{x} = \{z, \dot{z}, I_1, I_2\}$.

The Laplace transform of Eq.(1) is

$$\lambda B\vec{x} = A\vec{x}. \tag{2}$$

Denoting by λ_j and $\vec{u}_j$ the j^{th} eigenvalue and eigenvector, respectively, the general solution of the system can be written as

$$\vec{x}(t) = \sum_k c_k \vec{u}_k e^{\lambda_k t}, \tag{3}$$

where c_k are general coefficients. The quantities λ_j and $\vec{u}_j$ have usually complex values. For plasma stability it is necessary that the real parts of all eigenvalues be negative.

Equation (2) is a polinomial of fourth order in λ:

$$a_4\lambda^4 + a_3\lambda^3 + a_2\lambda^2 + a_1\lambda^1 + a_0 = 0 \tag{4}$$

with:

$$
\begin{aligned}
a_4 &= m(L_1L_2 - M^2)\,,\\
a_3 &= m\{L_2R_1 + L_1R_2 + g(L_2M_1 - MM_2)\}\,,\\
a_2 &= m(R_1 + gM_1)R_2 + S_1S_1^ML_2 + S_2S_2^ML_1 - S_1S_2^MM - S_2S_1^MM - S_b(L_1L_2 - M^2)\,,\\
a_1 &= S_1S_1^MR_2 + S_2S_2^MR_1 - S_b(L_2R_1 + L_1R_2) + \\
&\quad g(S_2S_2^MM_1 - S_1S_2^MM_2 + S_1S^ML_2 - S_2S^MM - S_bL_2M_1)\,, \quad \text{and}\\
a_0 &= g(S_1S^M - S_bM_1)R_2 - S_bR_1R_2\,.
\end{aligned}
$$

For stability the coefficients must satisfy the Routh-Gurvit's criterion [7], i.e, the following numbers should have all the same sign:

$$a_4; \quad a_3; \quad a_2 - \frac{a_4a_1}{a_3}; \quad a_1 - \frac{a_3a_0}{a_1}; \quad a_0\,.$$

Since $a_3a_0/a_1 \sim m \ll a_1$ the fourth term is: $a_1 - a_3a_0/a_1 \approx a_1$.

The first term a_4 is positive for all values of L_1, L_2 and M, because the mutual inductances are smaller than the self-inductances. This imposes the requirement that all the other terms must be positive. We first consider the second term a_3. From the condition that $a_3 > 0$ it follows that:

$$L_2R_1 + L_1R_2 + g(L_2M_1 - MM_2) > 0\,,$$

that is,

$$MM_2 - L_2M_1 < \frac{L_2R_1 + L_1R_2}{g}$$

or,

$$M_2 < L_2\frac{M_1}{M} + \frac{L_2R_1 + L_1R_2}{Mg}\,. \tag{5}$$

This relation requires that the mutual inductance between the passive conductors and the pick-up loops must be less than a given value. If the inverse relation

$$M_2 > L_2\frac{M_1}{M} + \frac{L_2R_1 + L_1R_2}{Mg}$$

holds, then the system is unstable.

Suppose that the system is unstable. Then, we consider changes which can stabilize the system: increased resistivity (R_1 or R_2) or decreased gain (g). The value of g is limited by:

a) $g > \frac{S_b R_1}{S_1 S^M - S_b M_1}$, from $a_0 > 0$ assuming $S_1 S^M - S_b M_1 > 0$

b) $g > \frac{S_1 S_1^M R_2 + S_2 S_2^M R_1 - S_b(L_2 R_1 + L_1 R_2)}{S_2 S_2^M M_1 - S_1 S_2^M M_2 + S_1 S^M L_2 - S_2 S^M M - S_b L_2 M_1}$ from $a_1 > 0$ assuming that the denominator is positive.

An increase in the resistivities (R_1 or R_2) does not stabilize the system. Increasing R_1 leads to increasing g_{min} from the first inequality. Increasing R_2 leads to increasing g_{min} from the second inequality. These two changes result in an increased gain and thus, the term $\frac{L_2 R_1 + L_1 R_2}{Mg}$ in Eq.(5) remains unchanged.

The relation $S_1 S^M - S_b M_1 > 0$ results in limitations on the derivative of the radial component of the external magnetic field, S_b, and the plasma elongation. The assumption b) also restricts the plasma elongation. Particularly, if the relation

$$S_b > \frac{S_2 S_2^M M_1 - S_1 S_2^M M_2 + S_1 S^M L_2 - S_2 S^M M}{L_2 M_1}$$

holds, the plasma can not be stabilized.

Therefore, it has been shown that there are locations of the passive conductor and the active control coil such that the plasma vertical position can not be controlled regardless of the passive conductor resistivity and the gain in the feedback control system. In addition, there is a limitation for plasma stability on the derivative of the radial component of the external magnetic field and then on plasma elongation.

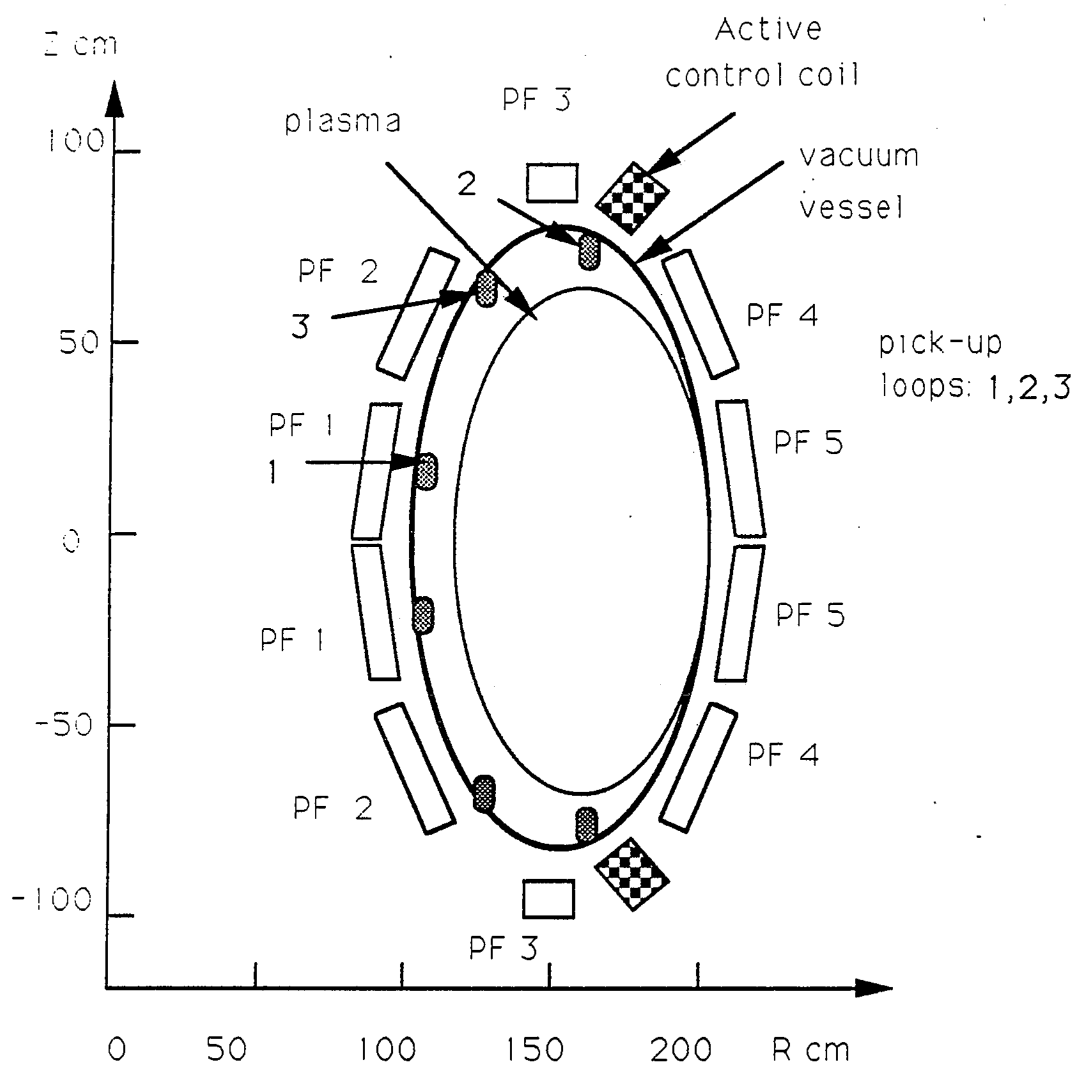
Z cm
100
50
0
-50
-100
0
50
100
150
200
R cm
Active
control coil
vacuum
vessel
plasma
PF 3
2
PF 2
3
PF 4
pick-up
loops: 1,2,3
PF 1
1
PF 5
PF 1
PF 5
PF 4
PF 2
PF 3

Fig.1

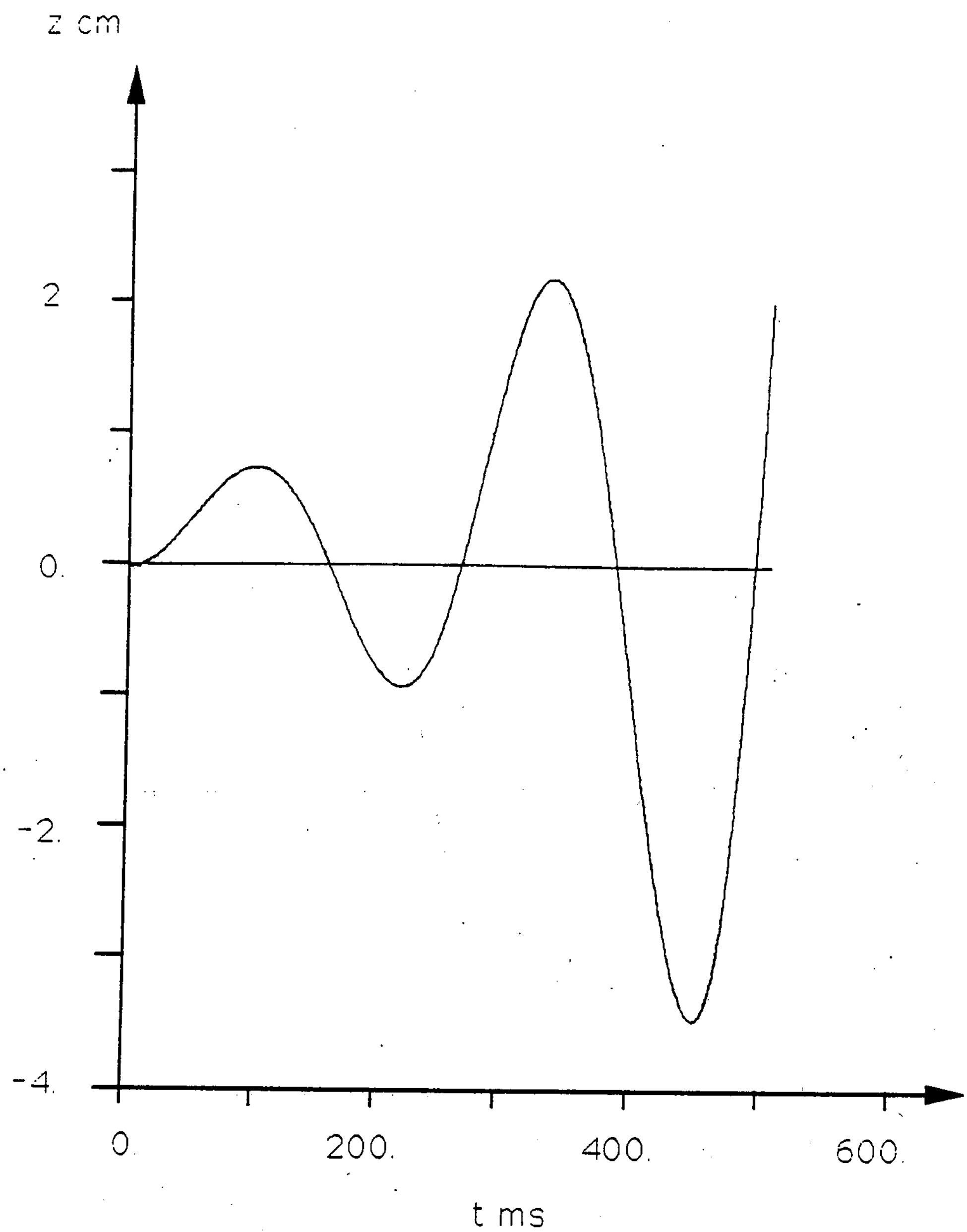

Fig.2-a

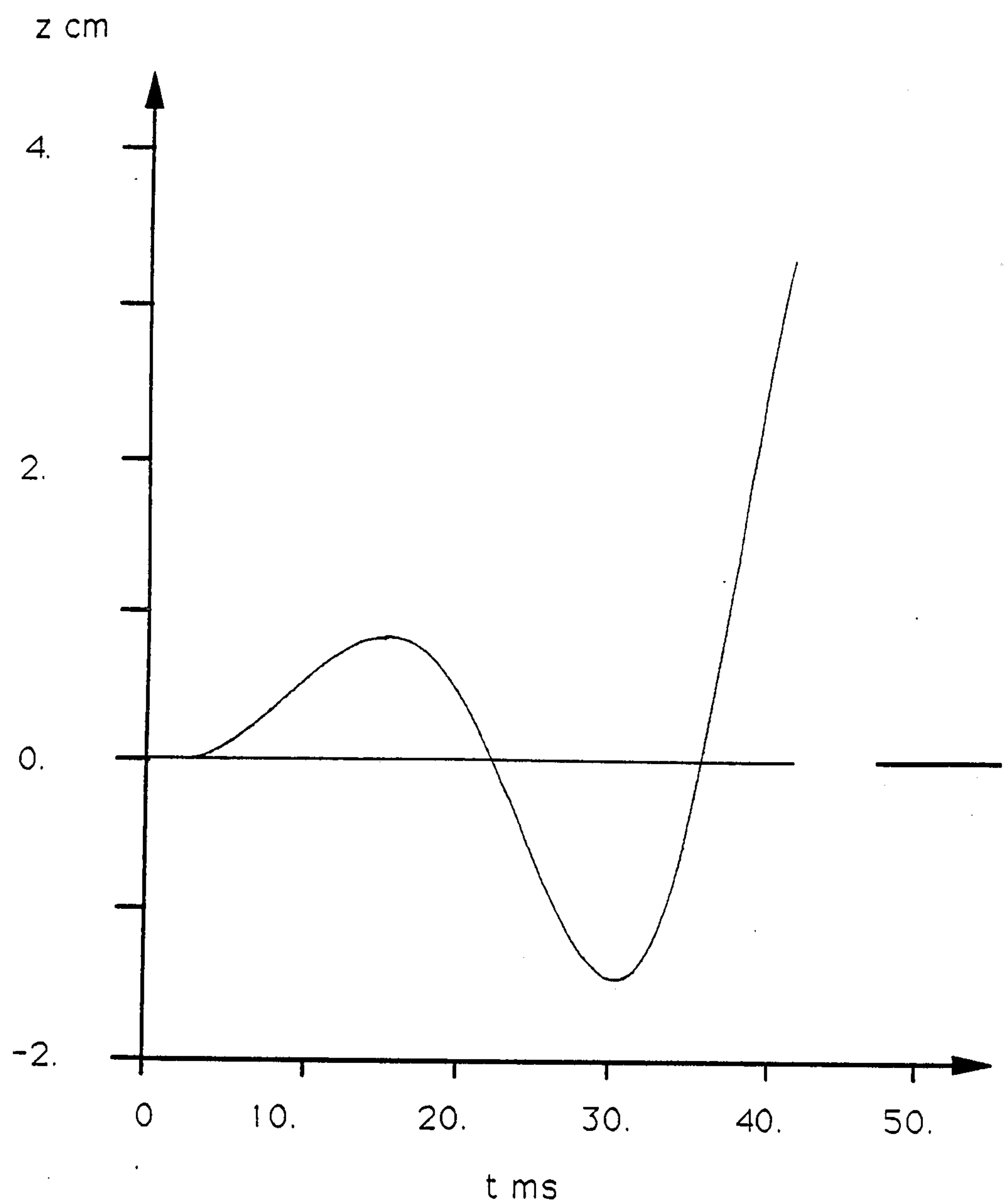

Fig.2-b

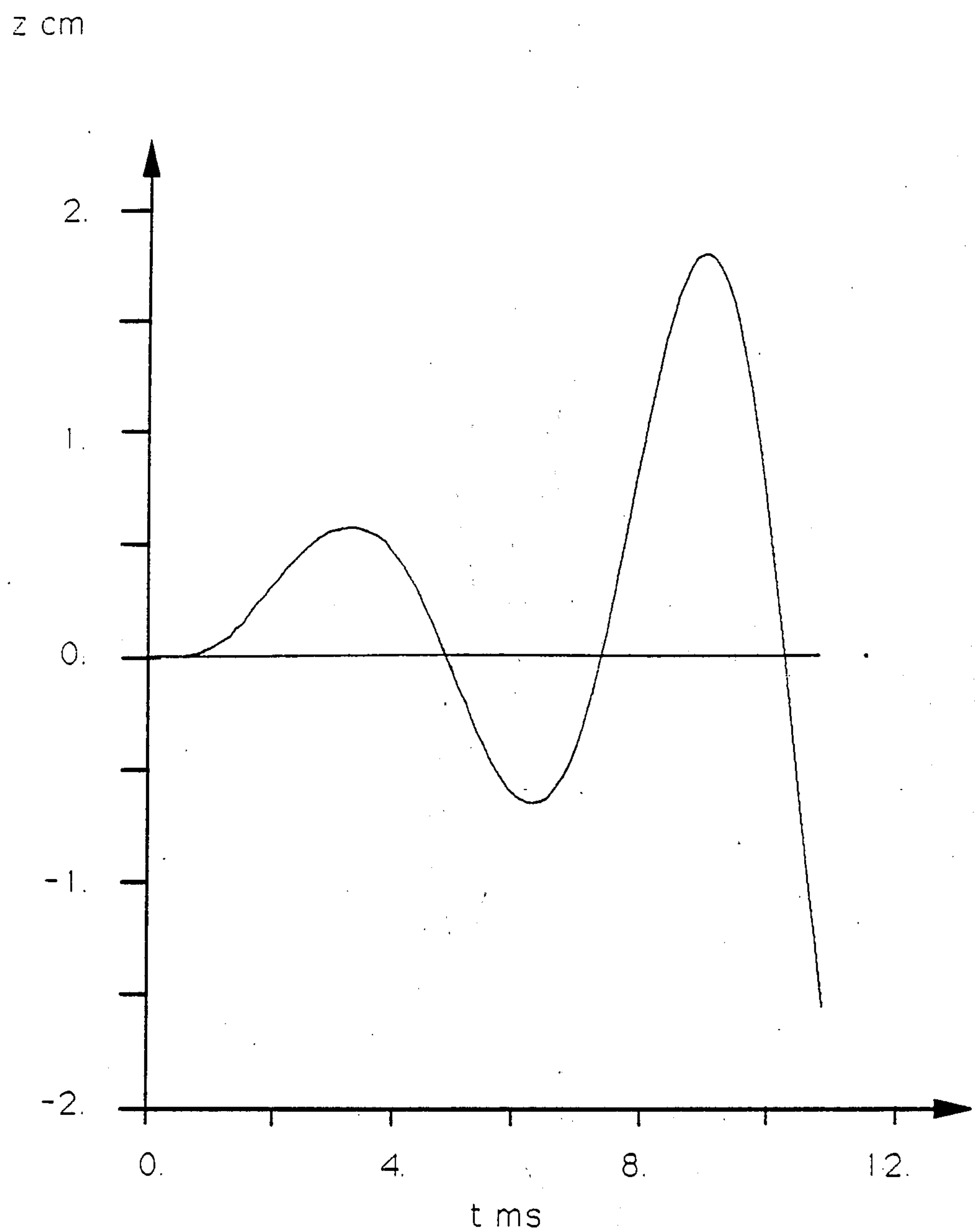

Fig.2-c

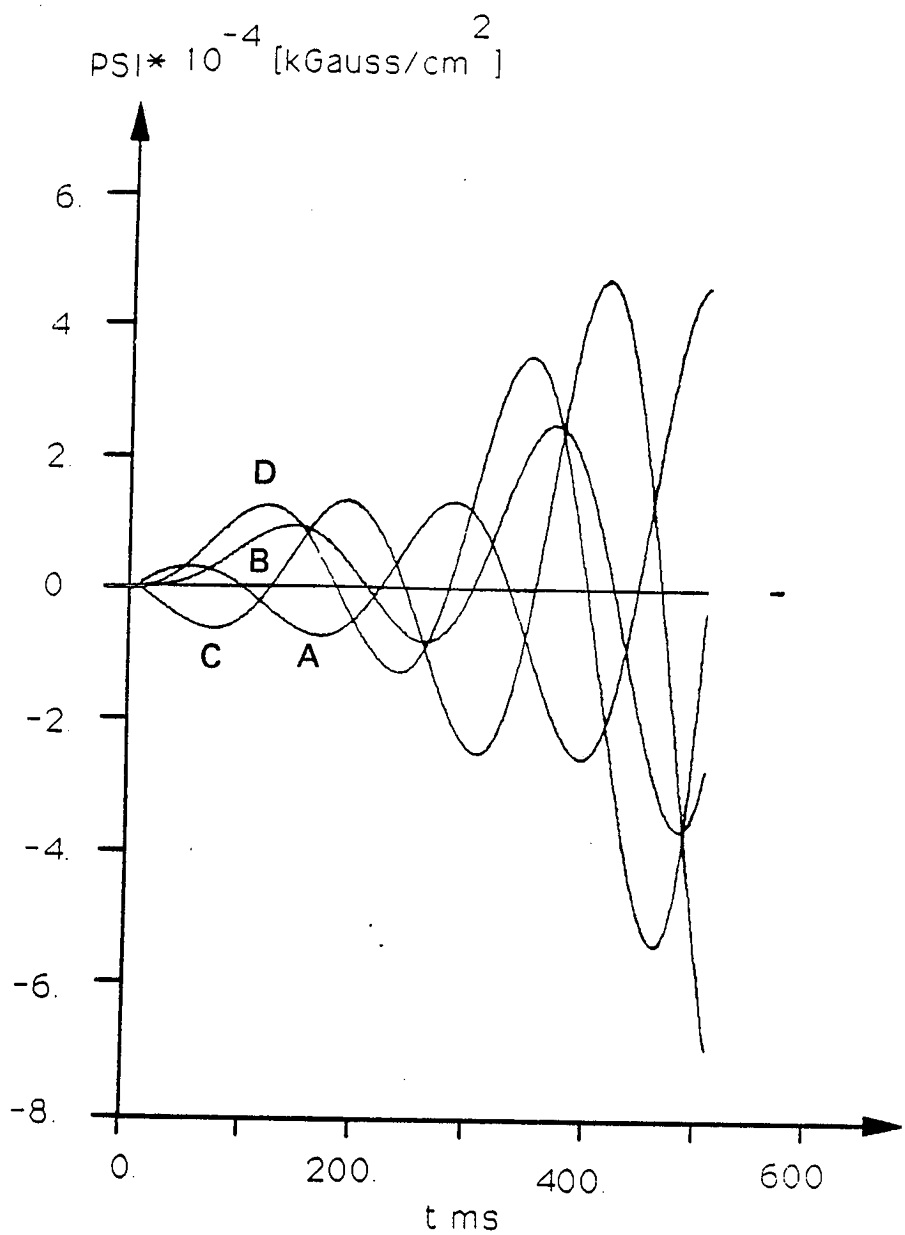

Fig.3-a

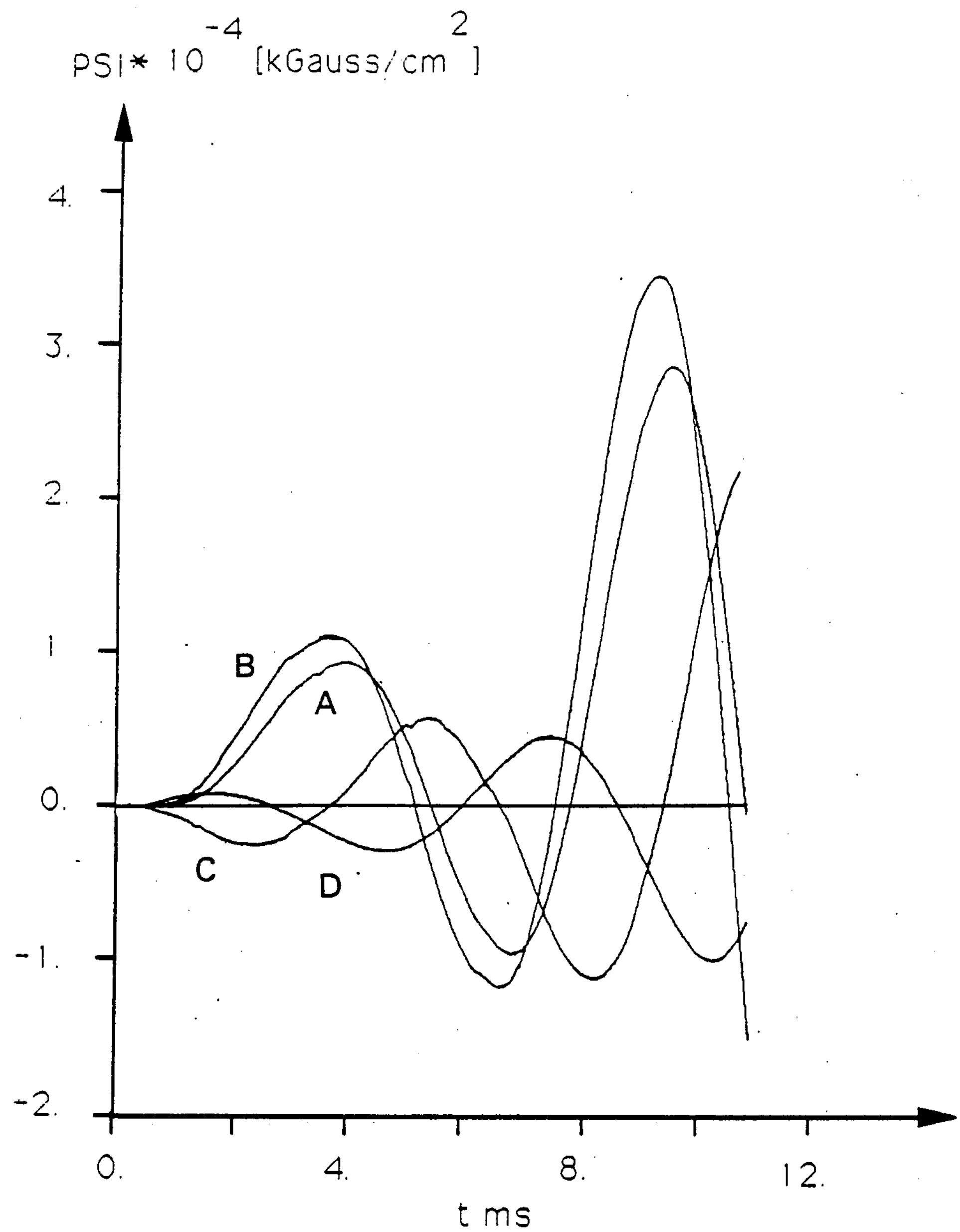

Fig.3-b

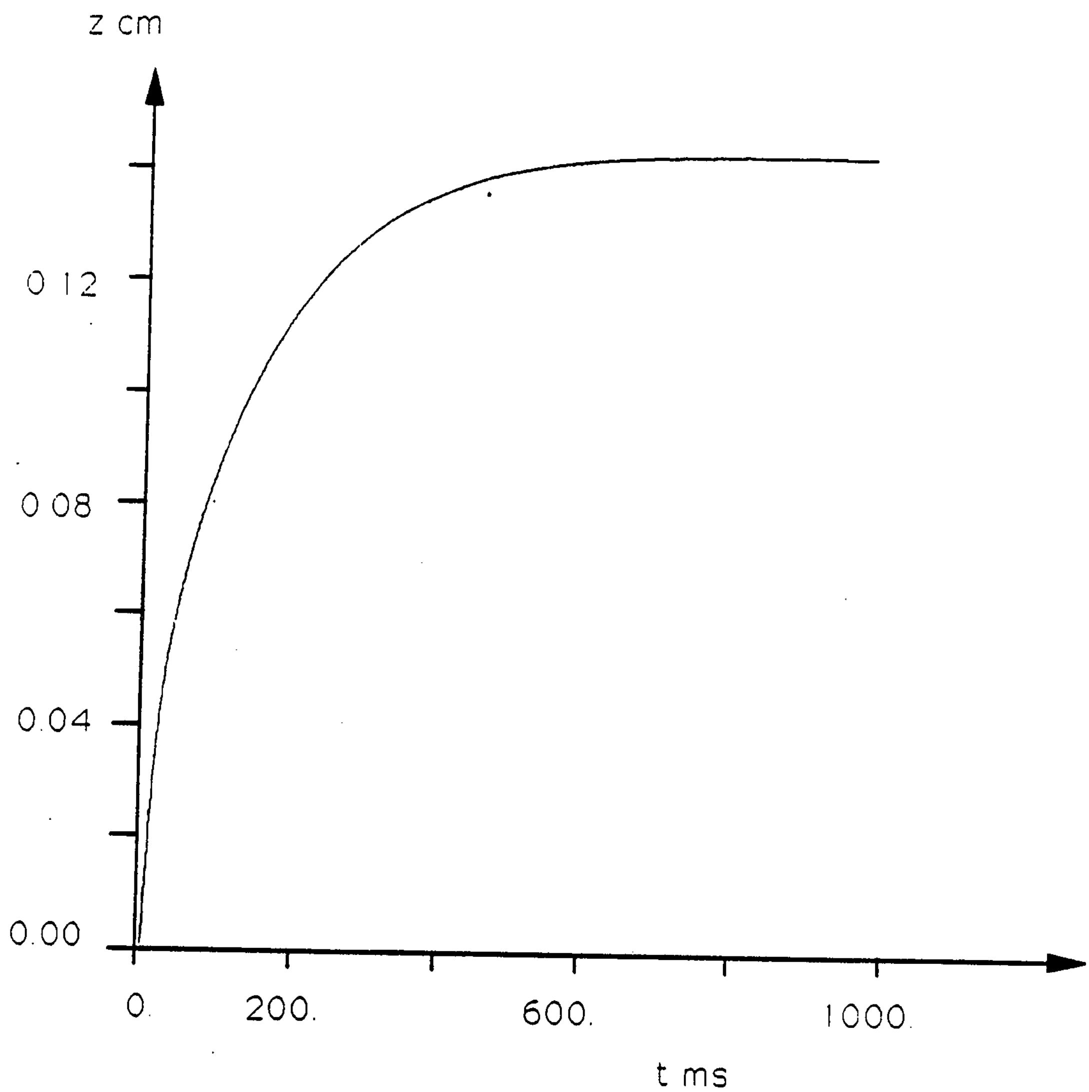

Fig.4-a

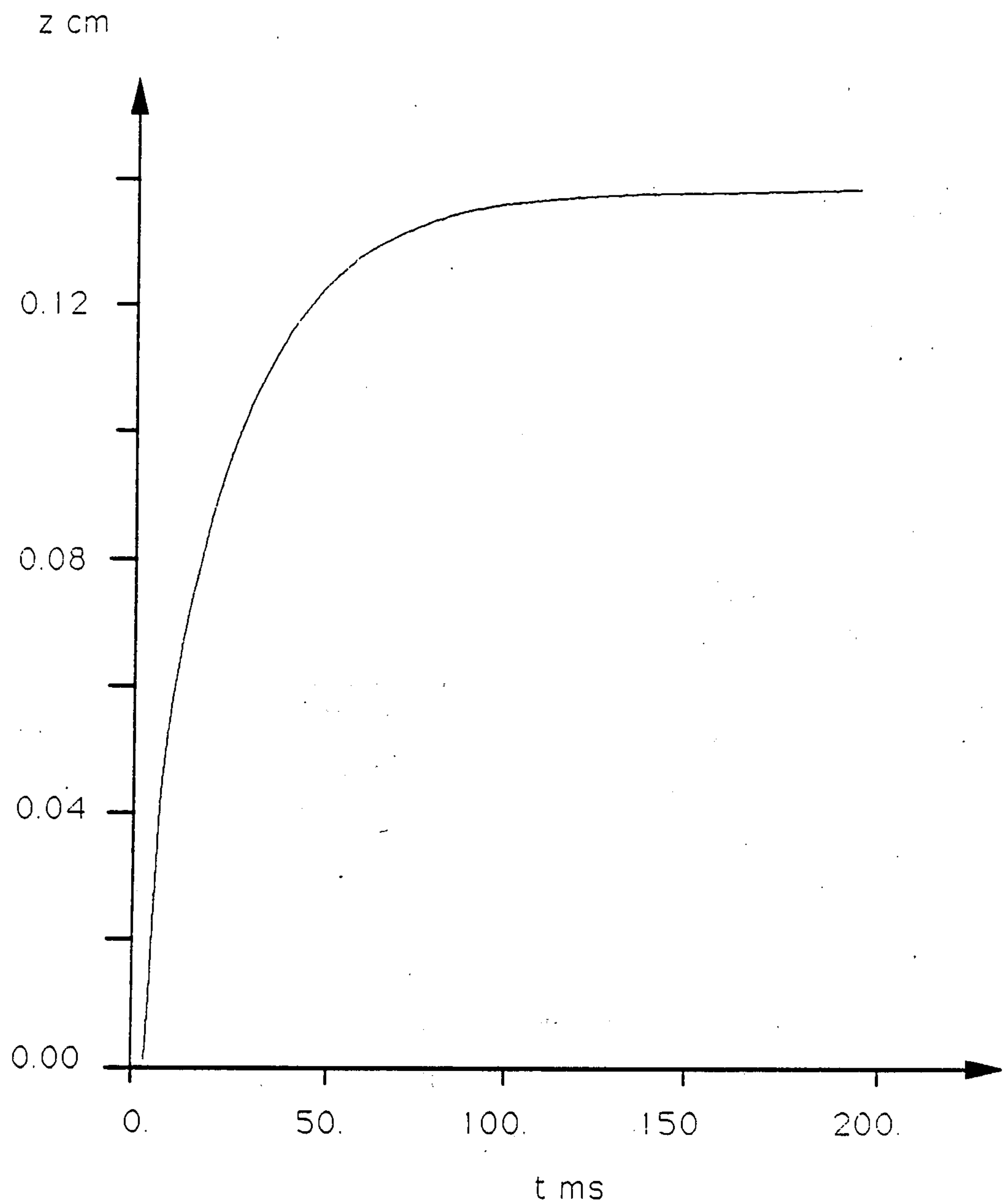

Fig.4-b

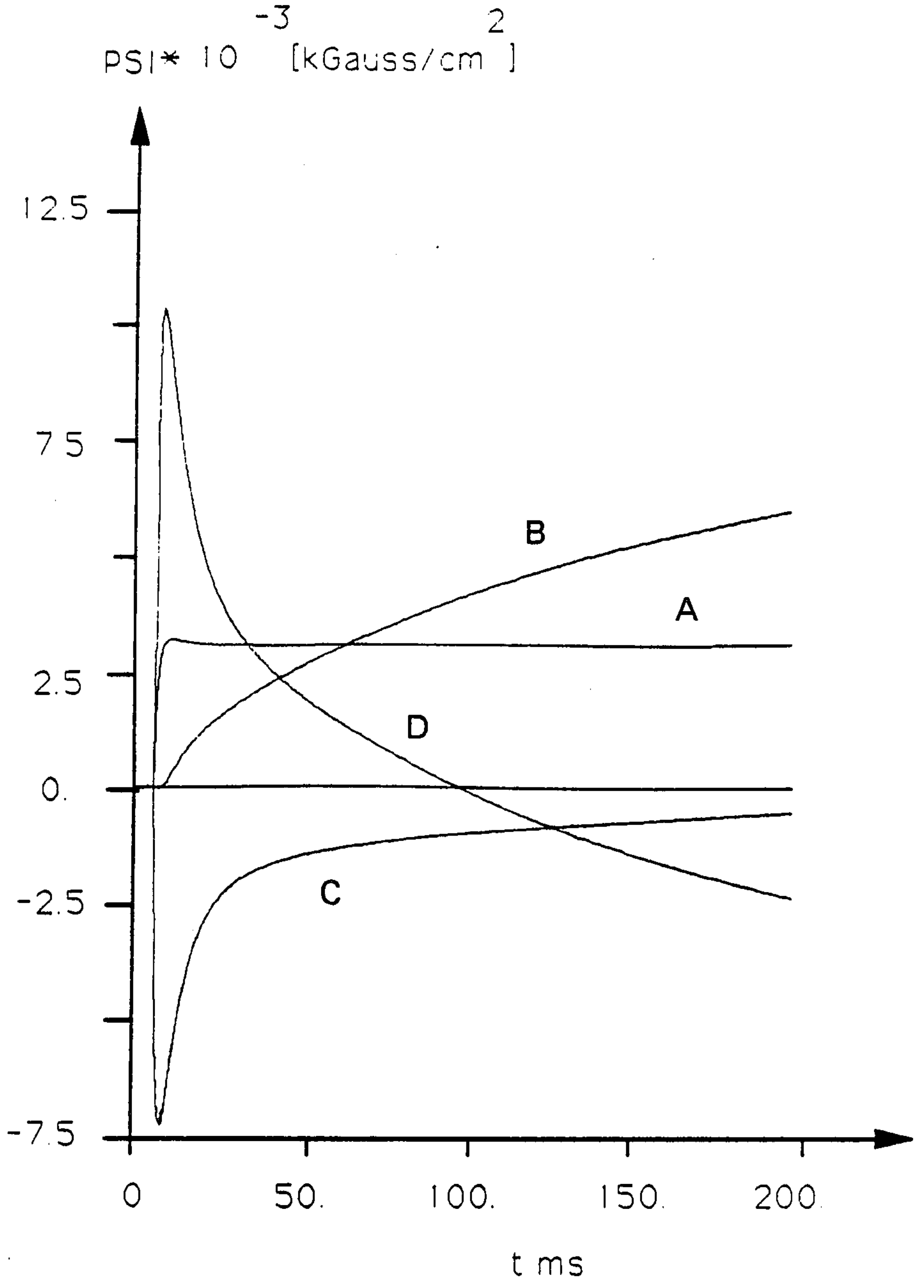

Fig.5-a

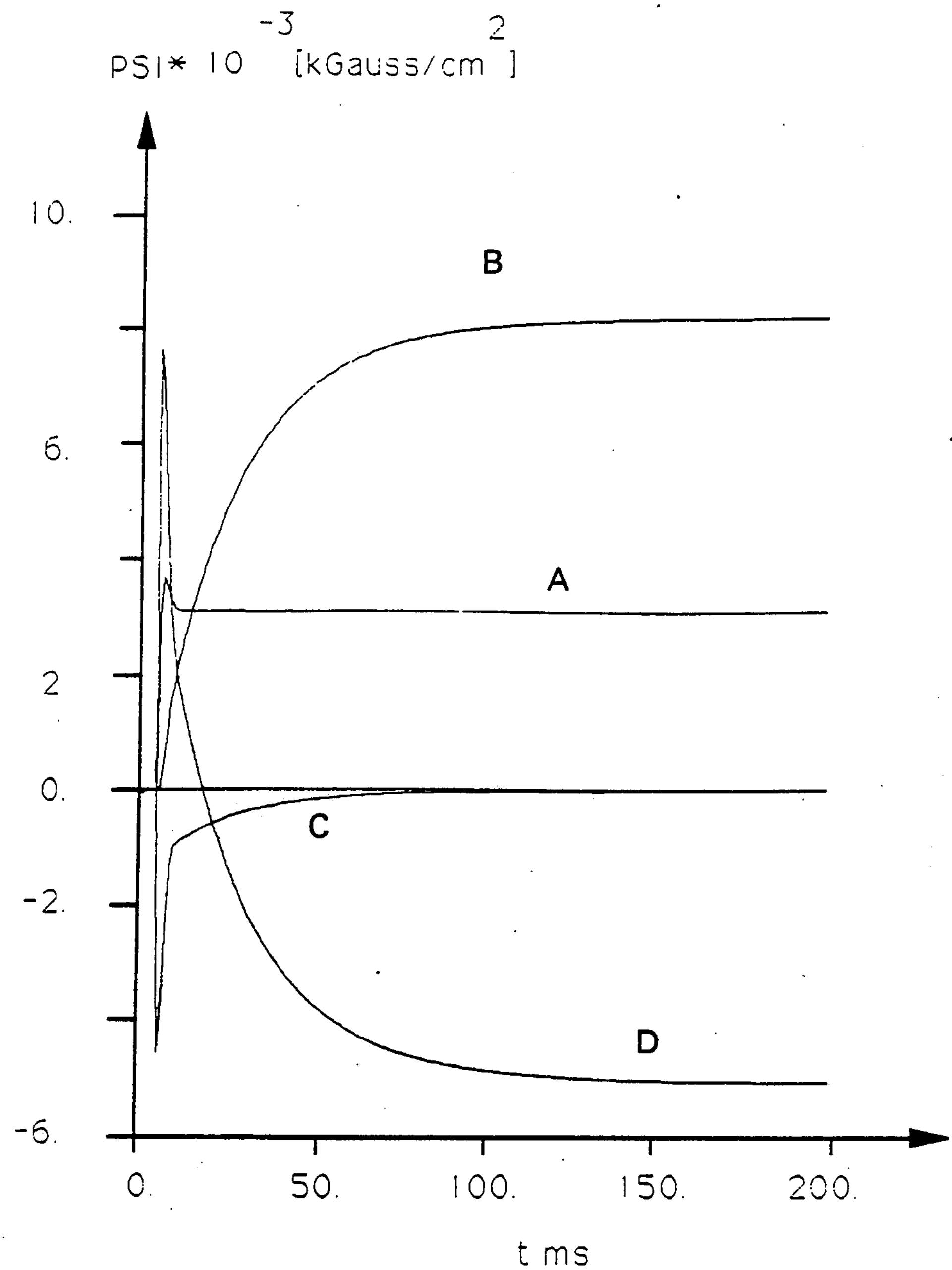

Fig.5-b

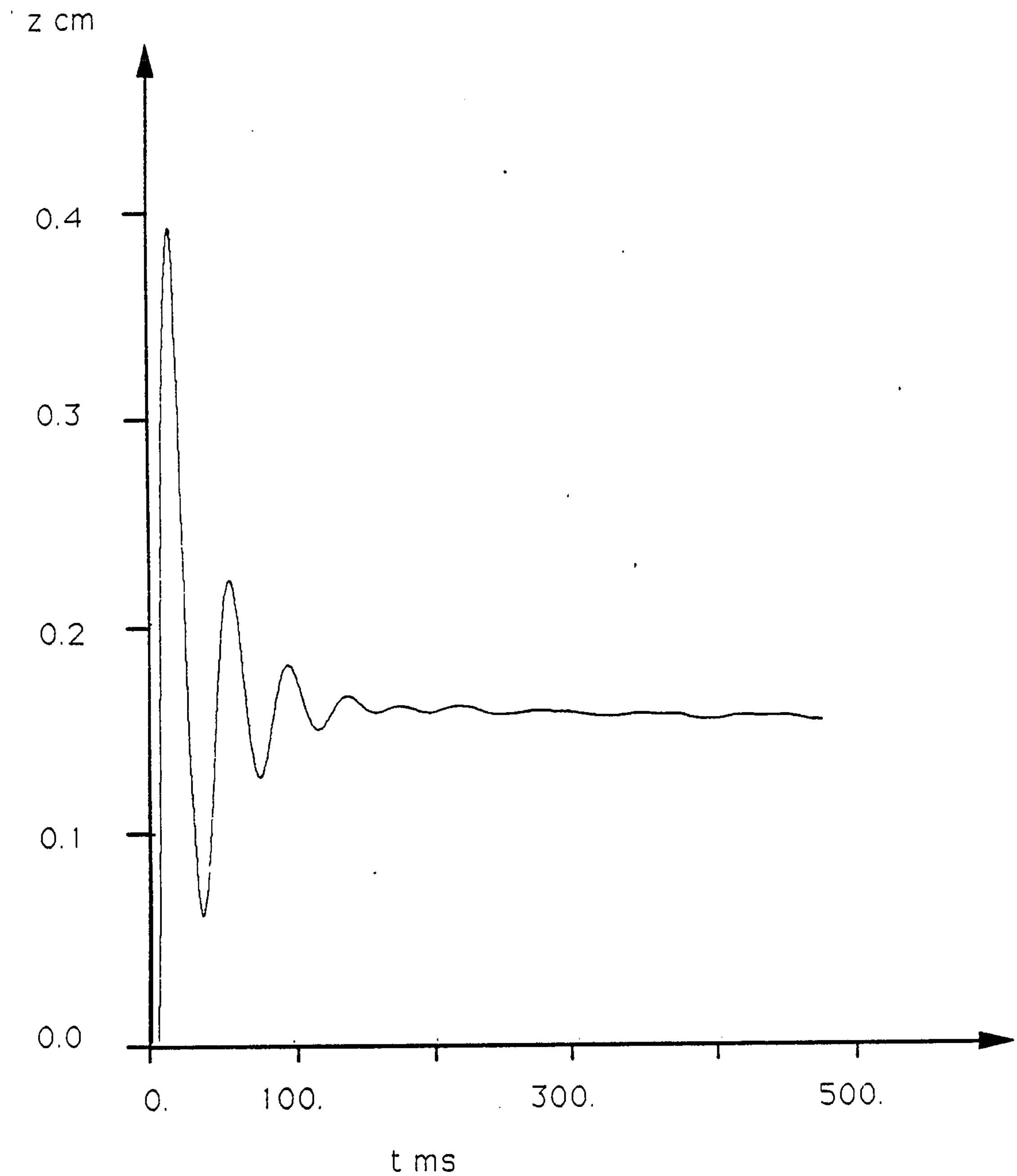

Fig.6

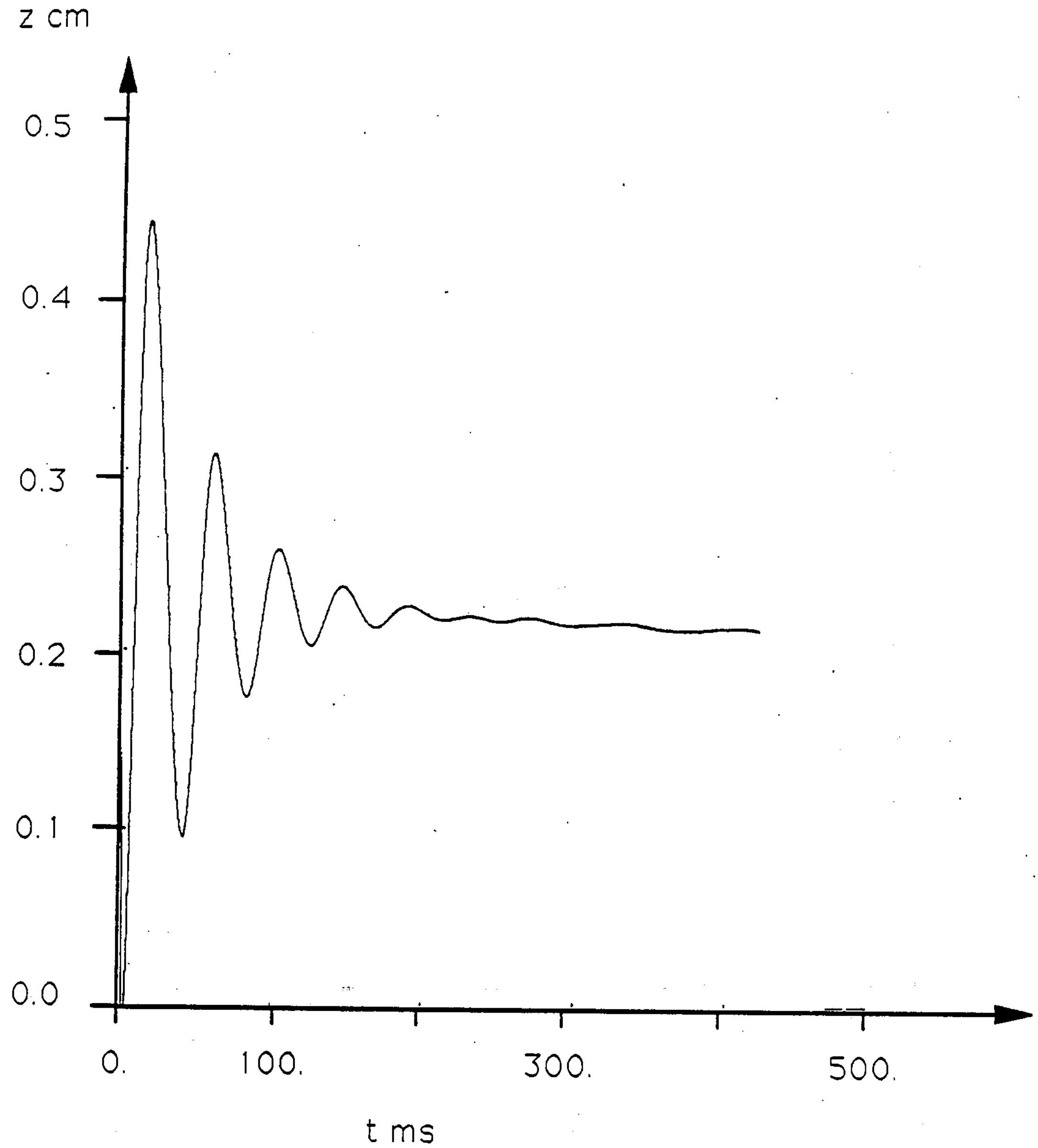

Fig.7

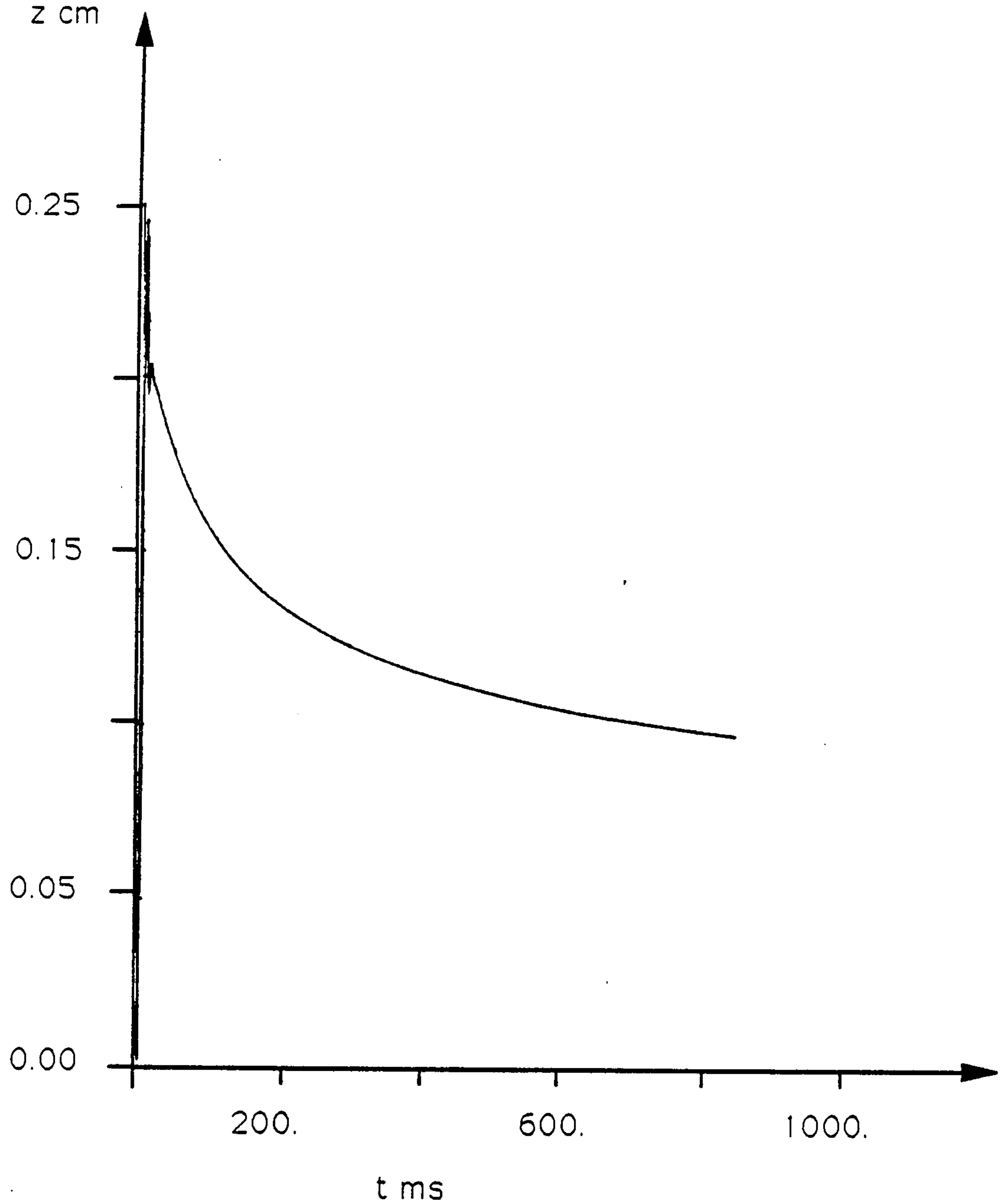

Fig.8-a

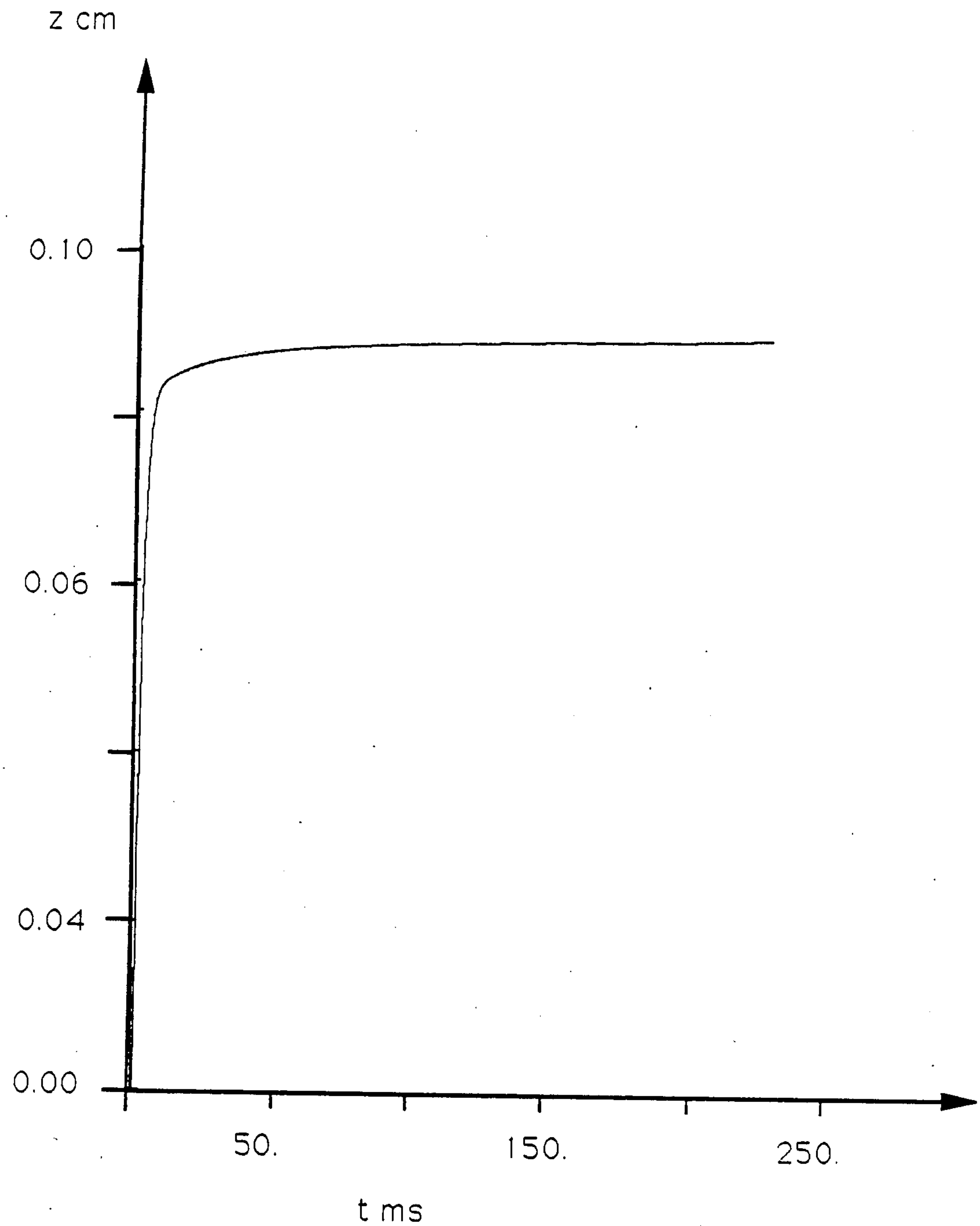

Fig.8-b