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CONTROL OF PLASMA DRIFT IN THE THETATRON

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ABSTRACT

The linear theta pinch drifts laterally with an acceleration directly proportional to the magnetic field gradient and temperature; for example, a magnetic field gradient of only one gauss in 100 kilogauss causes a 1 keV plasma to drift to the wall of a 10 cm diameter tube in 100 μsecs. Four main sources of magnetic field gradient are proposed and examined experimentally; the coil end, the collector shape, the collector-coil discontinuity and the plasma influence. The magnetic field gradient may be controlled by sectionalizing the coil at regular intervals, or by a tab between the coil and collector or, more conveniently, by the use of an 'inductive lens'.

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I INTRODUCTION

It is common practice in theta pinch experiments for the rapidly varying magnetic field which compresses the plasma to be generated by a single turn coil fed by low inductance plates which are termed the collector. Recent observations [1,2] of the plasma have revealed a radial drift which, if uncorrected, represents a serious limitation on containment of the plasma. The drift is caused by a magnetic field gradient (∇ B) producing a pressure difference across the plasma and consequently an acceleration perpendicular to the field lines:

$$\ddot{r} = -\frac{\mu}{nAM}\nabla B ,$$

where μ is the magnetic moment per cm of plasma, n is the density of ions, A is the plasma area and M is the mass of the ions. If B_T is the field trapped in the plasma and B is the external field, $\mu = A(B - B_T)/4\pi$. Eliminating n by using the pressure balance equation $B^2 - B_T^2 = 16\pi n K T$ (in which we assume thermal equilibrium between ions and electrons) gives

$$\ddot{r} = \frac{4KT}{M}\cdot\frac{1}{B}\cdot\frac{dB}{dr}\cdot\left(1+\frac{B_T}{B}\right)^{-1} .$$

Often the trapped field in theta pinch plasmas is small compared to the external field and

$$\ddot{r} = \frac{4KT}{M}\cdot\frac{1}{B}\,\frac{dB}{dr} . \qquad \ldots (1)$$

Equation (1) shows that in order to check the drift the magnetic field gradient must be closely prescribed. For example, radial confinement of a 1 KeV plasma for 100 µsecs in a tube of 10 cm diameter demands a magnetic field variation of less than one gauss in a 100 kilogauss.

The first part of the present paper analyses the principal sources of magnetic field gradient and describes the use of an 'inductive lens' as a technique of control. The second part gives experimental results for a plasma with negligible trapped field illustrating the various sources and the inductive lens technique.

II SOURCES OF MAGNETIC FIELD GRADIENT

Conventionally the theta pinch magnetic field is generated by a single turn coil fed assymetrically by a pair of large flat closely spaced plates called the collector. An ideal coil, infinitely long and with a uniform current density, produces a uniform field and in practice magnetic field gradients arise because of the finite length of the coil. Although it is difficult to make an exact calculation of the gradient of magnetic field in a finite coil, one may differentiate four principal sources of magnetic field gradient: the end effect, the collector shape, the collector-coil discontinuity and the plasma influence. The end effect provides a stabilizing force whereas the other three sources lead to drift.

End Effect

At the ends of the coil the magnetic field lines diverge so as to produce the axisymmetric magnetic field gradient illustrated in Fig.1. Since the magnetic field decreases towards the coil axis there is a force which tends to retain the plasma on the coil axis.

In order to find how far into the coil the end effect extends, we have used a resistive analogue[3] to determine approximately the field pattern. Fig.1 presents the magnetic field (H) as a function of radius (r) at various distances (x) from one end of the coil with aspect ratio four; the radius and distances are normalized to the coil radius (a). The curves show a decrease in the ratio of the magnetic field on the axis at the end plane of the coil to the magnetic field at the centre plane (H_∞) of 23%. The decrease falls off rapidly for points inside the coil; for example at one coil radius from the end the decrease is only 1% and theoretically far from the end the decrease falls off in proportion to $\exp(-3.83x/a)$.

The end effect is also influenced by distortion of the magnetic field lines due to non-uniformities of the coil metal thickness in the theta direction or the presence of metal outside the coil which may carry induced currents. These move the axis of minimum magnetic field from the coil axis.

Collector Shape

Generally collector plates are shaped in such a way as to produce highly convergent current paths because they are required to connect a large number of coaxial cables to the theta pinch coil with the minimum circuit inductance. This is illustrated in Fig.2(a) for a section of a toroidal system where the field decreases inversely as the distance from the centre and a strong magnetic field gradient is produced. For example, in a 10 cm diameter 40 cm long coil on a collector with a 45 degree angle the change in magnetic field across the diameter is 20 kilogauss in 100 kilogauss. In contrast to the end effect this magnetic field gradient is not symmetrical about the coil axis and results in a drift force. As the magnetic field gradient is directed away from the collector, the direction of drift is towards the collector.

The situation is more complicated when a straight coil is attached to a convergent collector Fig.2(c). An understanding may be gained by considering the symmetry condition, shown in Fig.2(b) that at the coil surface opposite the junction of the coil and collector the current flow lines are parallel to one another so that the magnetic field line is straight. It follows that the magnetic field gradient at the coil surface opposite the junction is zero and magnetic field gradients in other parts of the coil are appreciably less than with the toroidal coil. With a straight coil the inductance of the collector is important. Since flux is conserved, some of the magnetic field lines that pass through the end of the coil must bend into the gap between the collector plates when magnetic field gradients assymetric about the coil axis are present. Therefore the larger the gap (and therefore the collector inductance), the larger the magnetic field gradients that develop.

Many collectors have a rectangular geometry with the coil connected at the mid point of the long side. This allows extremely convergent current paths and is the predominant reason for the normally observed drift towards the collector.

Collector-coil Discontinuity

This source arises because a small fraction of the current flows on the outside of the collector to support the external magnetic field. The fraction depends on the ratio of separation to width of the conductors (h/b) and a theoretical graph[3] for a parallel sided transmission line collector is shown in Fig.3. For the coil, the fraction is a function of the coil aspect ratio.

At the collector-coil discontinuity, the effective value of h/b suddenly increases, and there is a corresponding increase of external current. Since current is conserved this occurs as the transfer of current from inside the collector to outside the coil, as illustrated in Fig.3. Therefore some current diverges from the centre plane of the system and a resultant magnetic field gradient is directed towards the collector, producing a drift away from the collector.

Measurements with a resistive analogue[3] shows that at the junction between a transmission line collector and a coil where h/b increases from 1/200 to 1/4 (typical values of interest) the external current changes from 1% to 15%* (these numbers agree with magnetic probe measurements on a practical coil). This corresponds to a change of about 14 kG in 100 kG across the coil diameter. Because the collector plate separation is always much less than the coil diameter the transfer current, and so the drift force, is practically independent of the plate separation.

Plasma Influence

The plasma shape itself modifies the magnetic field gradient because it determines the relative inductance of different regions of the coil. The effect is illustrated in Fig.4 which shows a spindle-shaped plasma whose diameter is much greater at the centre of the coil than at its ends. It follows that the central region of the coil will have a relatively smaller inductance than regions

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*Note that this implies a 15% error in magnetic field calculated from the commonly used ideal formula $B = \frac{4\pi I}{L}$, where I is taken as the total current.

elsewhere so that current will tend to converge towards the centre. This results in a magnetic field gradient so as to induce drift towards the collector.

The most common sources of non-uniform plasma diameter are the axial contraction of the plasma[4] and losses of plasma at the ends of the coil[5]. Both these would lead to convergent current flow and thus enhance the drift of plasma towards the collector. Stabilization against drift of a non-uniform plasma by image forces may occur when the plasma approaches the conducting wall of the coil[8].

III CONTROL OF PLASMA DRIFT

Near the ends of the coil stabilization is produced by the end effect. This indicates a method of controlling plasma drift by sectionalizing the coil[6] at regular intervals along the length thereby producing a series of end effects. The sections must be sufficiently small compared to the coil diameter for the magnetic field lines to bend into the slots between the section and cause a minimum in the field on the axis. The advantage of this system is that a definite minimum in magnetic field and axis of stability is produced, but there is the disadvantage that the field lines at the slot are convex towards the plasma, which may allow the growth of flute instabilities. It is possible that if the axisymmetric gradients required to avoid the drift are not too great, finite Larmor orbit damping[7] may prevent the flutes.

The magnetic field gradients due to the collector shape can be reduced by adding a parallel sided transmission line (called a 'tab') between the coil and collector. This allows space for the current lines to become uniform. A long tab is undesirable because it increases circuit inductance and the minimum length required to avoid drift must be found by trial and error. This may be difficult with the large massive collector systems used in long period high magnetic field experiments. A more precise and convenient control of the field gradient is obtained by incorporating what we term an 'inductive lens' between the collector plates and the coil.

In essence, the inductive lens is a section of the collector which has an increased inductance and a curved interface. Its inductance varies across the width of the collector in such a way as to correct the convergence of the current paths in the coil.

Fig.5 shows a convergent collector feeding a short length of parallel-sided transmission line incorporating a lens which, by forcing current away from the centre of the collector, straightens the current flow lines on the inner surface of the coil. We refer to the curved region as a lens in order to suggest an analogy with optical refraction. The strength of the lens is determined by the curvature of the inductive interface together with the ratio of insulator thickness at the lens plate to just after the plate which plays a role analogous to that of a refractive index. The analogy with refraction of light ray is loose since in the inductive case the inductance of the lens itself depends on the distribution of the current it is designed to modify, i.e. the problem is a non-linear one. The deflection of the current paths is further determined by the need to satisfy boundary conditions at the edges of the collector and at the line of symmetry on the inner surface of the coil opposite the collector.

In practice the required lens shape can be found empirically by trial and error. By providing several pieces of conducting material whose surfaces have varying degrees of positive and negative curvature a series of lenses can be tested rapidly. It is not necessary that the lens have a simple radius of curvature; clearly the lens may be provided with a more complex shape in order to straighten a complex current pattern.

IV DRIFT EXPERIMENTS

Experiments were made to verify the four sources of magnetic field gradient and investigate methods of controlling the drift. The plasma position was measured by an image converter streak camera using a 10 μsec time base. To avoid confusion caused in axial pictures by different amounts of drift at different positions along the plasma length, radial pictures were taken. For this purpose the plasma was observed perpendicular to its axis through a thin slot at the coil centre plane. Since this was a plane of symmetry it did not intersect the axial currents associated with the field gradients and so the slot did not disturb the current distribution (see Fig.2(b)).

A hydrogen plasma was formed in a quartz tube of 4.6 cm internal diameter. It was preheated by discharging axially a 1 μF, 40 kV capacitor via a damping resistor; this generated a unidirectional pulse of current of 10 kA peak which heated the plasma sufficiently to prevent field diffusion. This formed a plasma in which the trapped magnetic field was much smaller than the external magnetic field[6] when the theta pinch bank was initiated 10 μsec later.

The theta pinch magnetic field was produced in a 5.6 cm diameter coil by a 42 μF, 42 nH, 38 kV capacitor bank connected via 56 cables to the long side of a rectangular collector 152 × 36 cm. The coil was attached at the centre of the side opposite the cables. In order to avoid complications due to trapped field all experiments were made on the first half cycle plasma except for that demonstrating the plasma shape effect which required the reversed trapped field occurring on the second half cycle.

End Effect

Fig.6 shows a comparison of the drift at the centre-plane with the drift at the end of a 60 cm long coil. The vertical lines on the photographs are electrical interference on the image convertor. For clarity the drift measured from the photographs is plotted in the graphs. These show that the drift at the coil end has less acceleration and less than half the amplitude of the drift at the centre. This illustrates the stabilizing effect at the ends, and that the plasma was bow shaped.

Collector Shape

The rectangular shape of the collector produces a highly convergent current distribution. Fig.7 shows the drift at the centre plane for 20 cm, 40 cm and 60 cm coil lengths.

Because of the high convergence of the currents, the magnetic field gradient is directed away from the collector, and the drift is towards the collector. Since the end effect tends to stabilize the plasma at the axis and the collector shape effect produces a drift towards the collector, the combined effect is to create a minimum of magnetic field away from the coil axis towards the collector. The plasma, which is defined initially by the wall of the discharge tube (coaxial with the coil), implodes towards the coil axis, then later drifts to the stable axis of minimum magnetic field.

With shorter coils the end effect becomes more dominant and the stable axis moves towards the coil axis. This is demonstrated by comparing the curves for the three lengths of the coil: the 60, 40 and 20 cm coils have stable axis 1.4, 1.0 and 0.4 cm from the coil axis respectively.

The influence of the collector inductance was investigated by varying the gap between the collector plates. With the 40 cm long coil an increase in the gap width from 0.10 cm to 0.58 cm resulted in the stable axis moving from 1.4 cm from the coil axis to outside the tube causing the plasma to collide with the wall. This is shown in Fig.8.

Collector-coil Discontinuity

This is shown in Fig.9 for an experiment using a parallel sided transmission line to feed current to the coil[9]. The coil length was 30 cm, diameter 5.4 cm and slot width 0.15 cm. As predicted the plasma drifted away from the collector. The end effect again combined with the drift source and formed a stable axis. Note that the plasma tends to oscillate about the final axis of equilibrium due to its inertia. This oscillation is particularly common with high temperature plasmas which, by equation (1), have a high drift acceleration.

The axis of stability was 0.1 cm from the coil axis at the centre plane of the coil. This position was much closer to the coil axis than that associated with the collector shape source of magnetic field gradient. This may be because both the collector-coil discontinuity and end effect are associated with the finite length of the coil and the end effect dominates. Another reason for such a small drift away from the collector is the boundary condition that the magnetic field line at the coil surface opposite the collector-coil junction must be straight. This implies that the magnetic field lines can bend less easily when they are concave towards the boundary, than when they are convex towards the boundary.

The effect of the magnitude of the gap between the collector plates on the collector-coil discontinuity source was measured by using two separations of the transmission line. A different coil, 23.5 cm long and 5.6 cm diameter, was used and the drift was again measured at the centre plane of the system. With an 0.1 cm gap the maximum drift was 0.1 cm from the coil axis away from the collector-coil junction, but with an 0.6 cm gap the drift was 0.4 cm from the coil axis towards the collector-coil junction. This is explained by the end effect in the transmission line itself combining with the coil end effect and over-coming the effect of the collector-coil discontinuity source of magnetic field gradient.

It is clear that, in principle, by suitable choice of the collector geometry, the drift away from the collector due to the collector-coil discontinuity can be made just to cancel the drift towards the collector due to the collector shape. However, these experiments show that in practice only slightly convergent collector shape effects can be corrected and generally the end effect and collector shape sources dominate the collector-coil discontinuity source of drift.

Plasma Influence

The bending of the current paths caused by a non-uniform distribution of plasma along the coil length can produce complicated drifts with reversed trapped field plasmas.

Fig.10 shows the drift with a reversed trapped field plasma taken on the second half cycle of the discharge. The system included an inductive lens which would cause a cylindrical plasma to drift away from the collector. At the start of the discharge the plasma was cylindrical and the drift was away from the collector, but, at about 1.5 μsec, axial contraction[4] caused the plasma to become shorter, the collector current to become convergent and the drift was reversed. Later at 3 μsec, the reversed field dissipated, the plasma again became cylindrical and the drift away from the collector was resumed.

V EXPERIMENTAL DEMONSTRATION OF DRIFT CONTROL

The reduction of plasma drift by sectionalizing the coil at regular intervals is shown in Fig.11. The sections were 0.5 cm wide and 0.5 cm apart in a coil 60 cm long and 5.6 cm in diameter. The slotting moved the axis of stability from 1.4 cm to 0.6 cm away from the tube axis, and although the drift was not completely eliminated, it was considerably reduced.

The effect of introducing a tab between the coil and collector is shown in Fig.12. The coil length and tab depths were both 40 cm. The curves show that the rapid drift to a stable axis about 1 cm towards the collector was eliminated (and even slightly reversed by the collector-coil discontinuity effect) with a tab.

In order to demonstrate the control of plasma drift with inductive lenses various shaped metal plates were inserted in the collector-tab-coil system. The results with a 40 cm long coil are shown in Fig.13. Lens 1 produced a divergent current which, in order to satisfy the boundary conditions at the coil became convergent again over the coil. Thus the drift was towards the collector and, with the end effect, produced an axis of stability 1.4 cm from the coil axis. Conversely, lens 2 produced a convergent current which diverged at the coil producing a drift away from the collector and an axis of stability 0.6 cm from the coil axis. With no lens the drift was slightly away from the collector owing to the collector-coil discontinuity.

CONCLUSIONS

We have shown that many of the theta pinch drift characteristics may be explained by separating the sources of magnetic field gradient into the effects of the coil ends, collector shape, collector-coil discontinuity and plasma influence. When the trapped magnetic field in the plasma is small the effects of the coil ends and collector convergence generally dominate to produce an axis of stability displaced from the coil·axis towards the collector. Control of the axis of stability may be achieved by sectionalizing the coil, introducing a tab or using an inductive lens.

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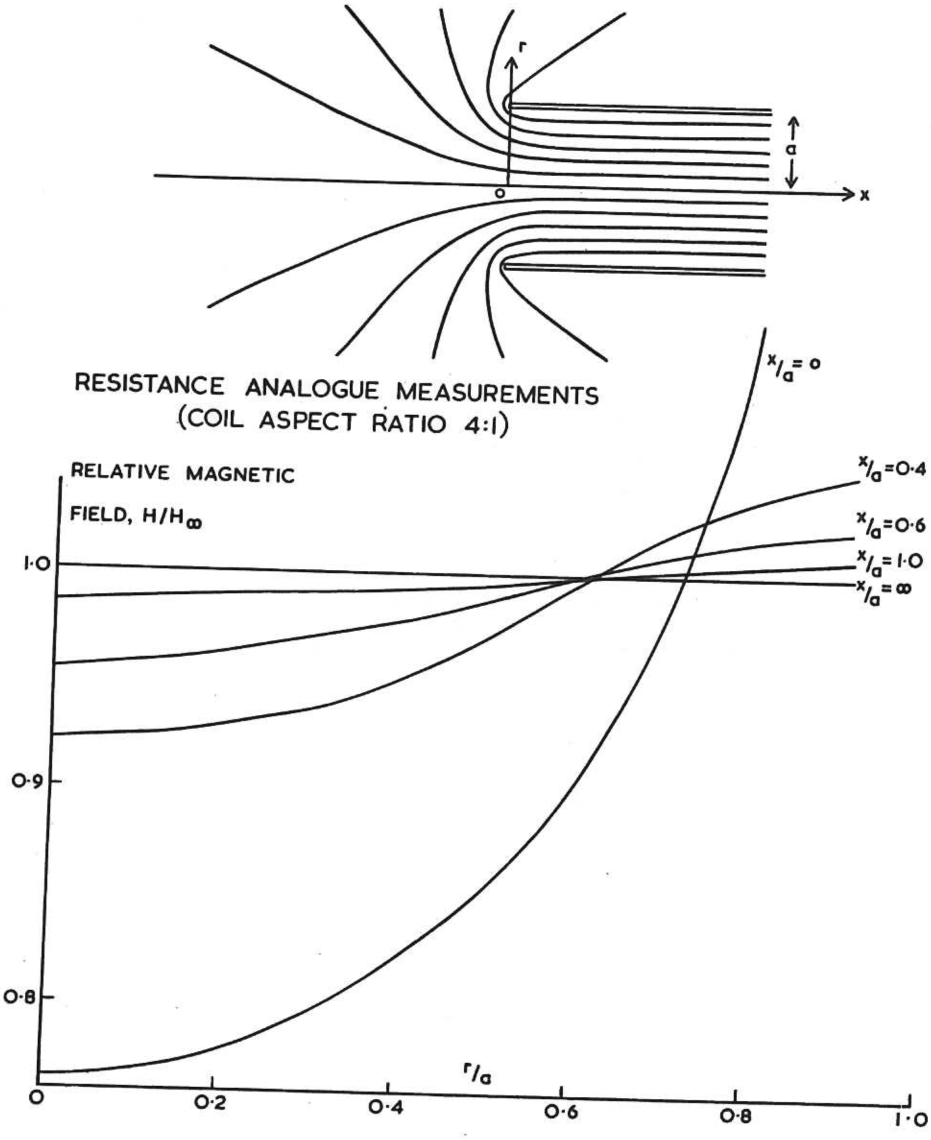
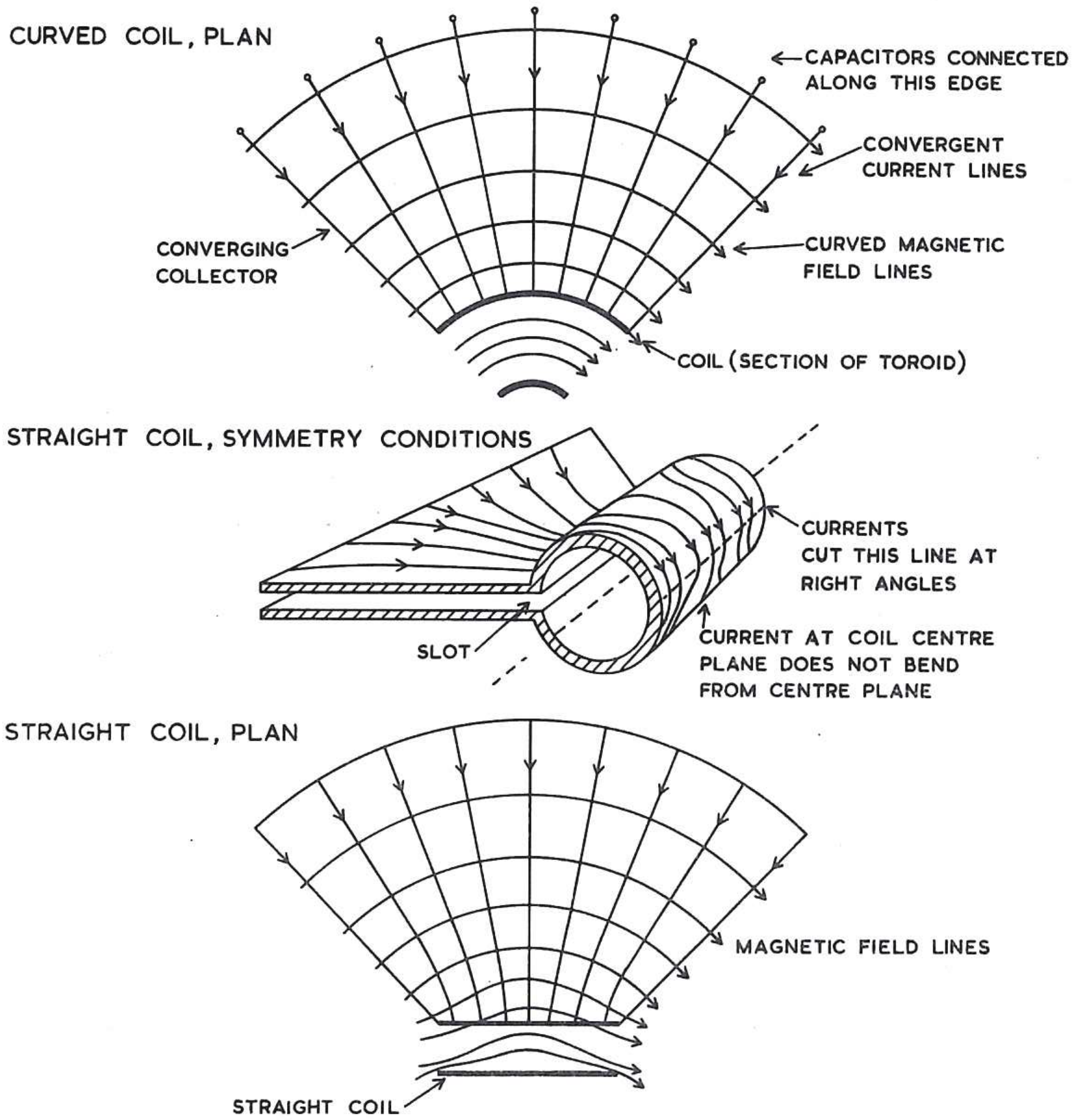


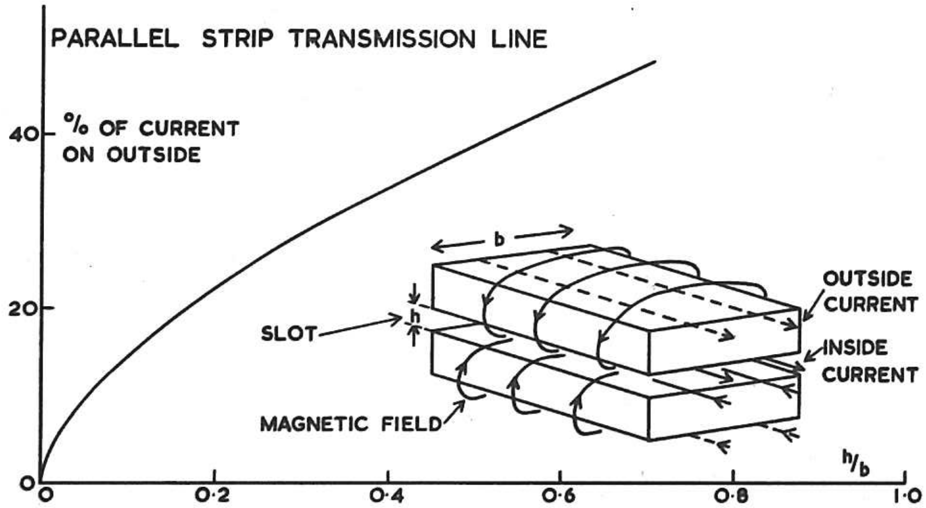
CLM-P46 Fig. 1
Source of field gradient A: end effect


CURVED COIL, PLAN

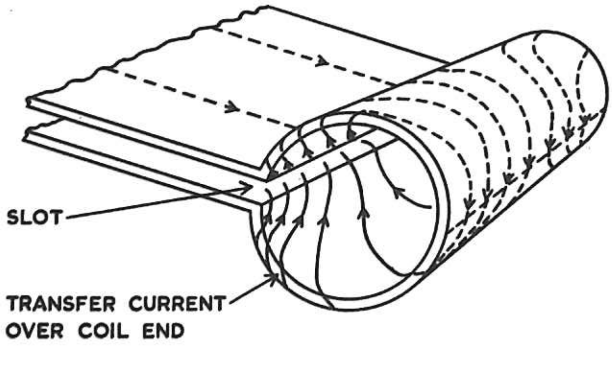
STRAIGHT COIL, SYMMETRY CONDITIONS

STRAIGHT COIL, PLAN

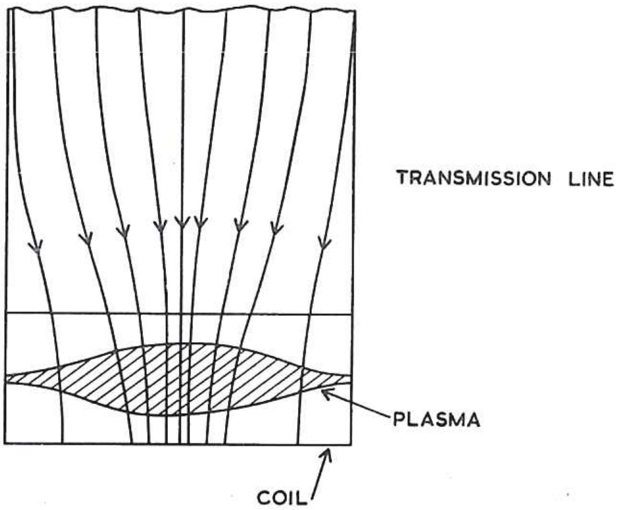
CLM-P46 Fig. 2
Source of field gradient B: collector shape



TRANSFER OF CURRENT FROM INSIDE LINE TO OUTSIDE COIL

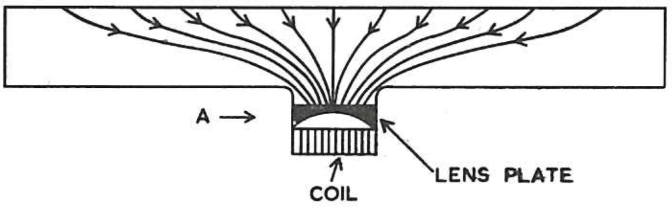


CLM-P46 Fig. 3
Source of field gradient C: collector-coil discontinuity effect

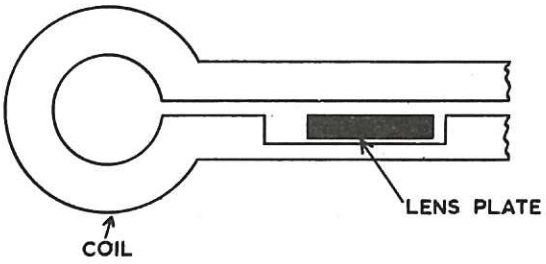


CLM-P 46 Fig. 4
Source of field gradient D: plasma influence

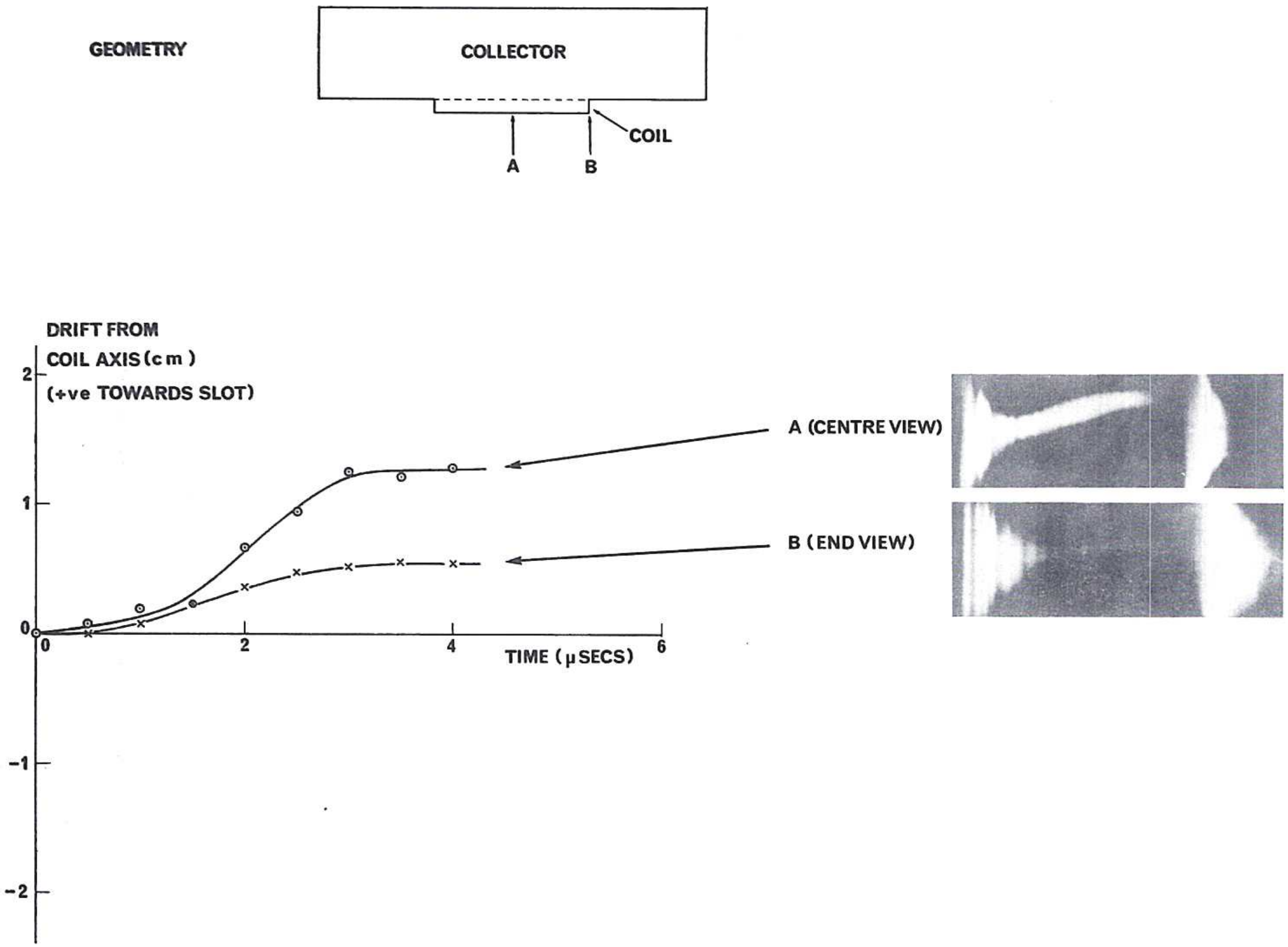
PLAN



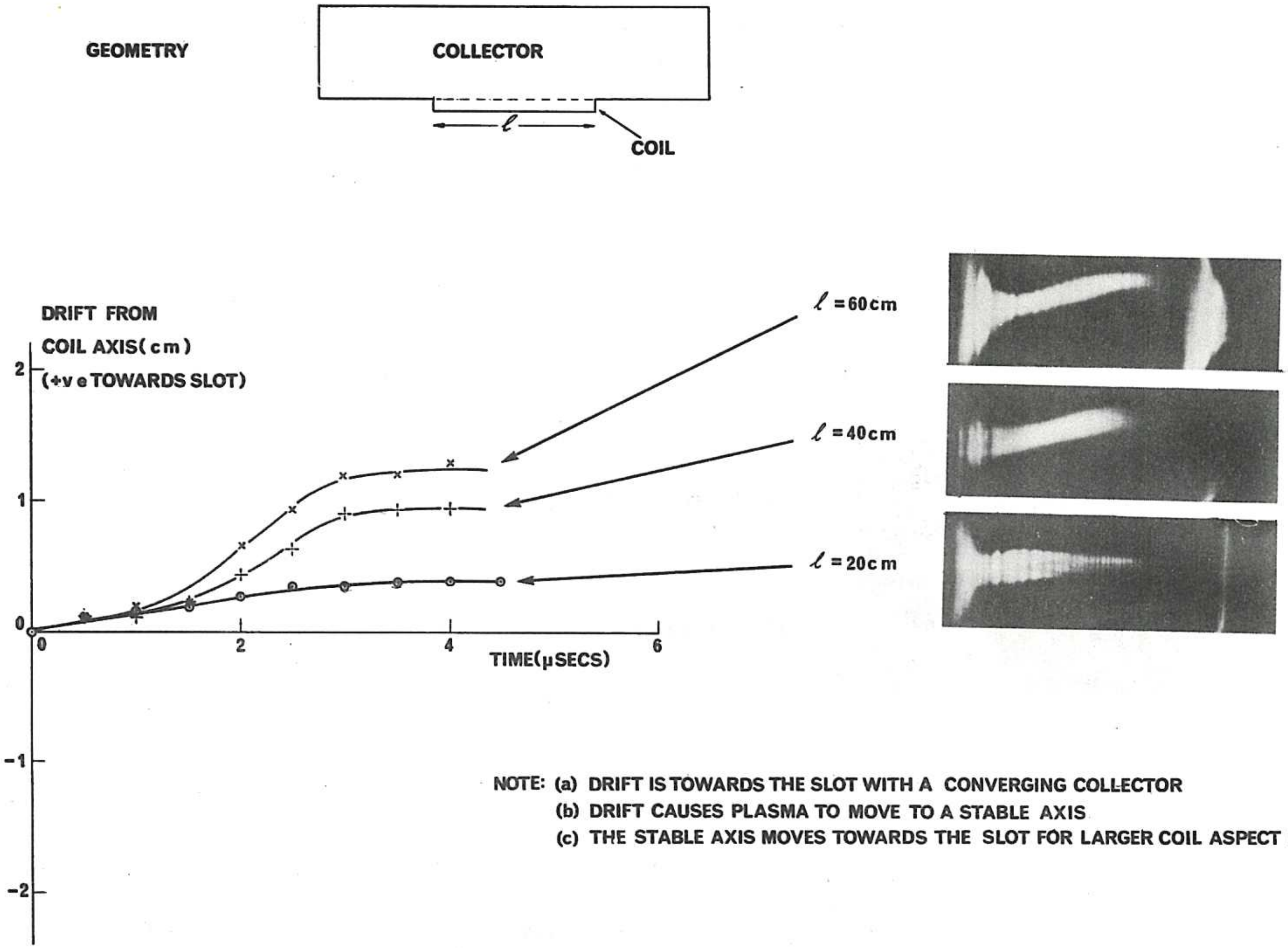
ELEVATION (VIEW ON ARROW A)



CLM-P46 Fig. 5
Drift adjustment with an inductive lens

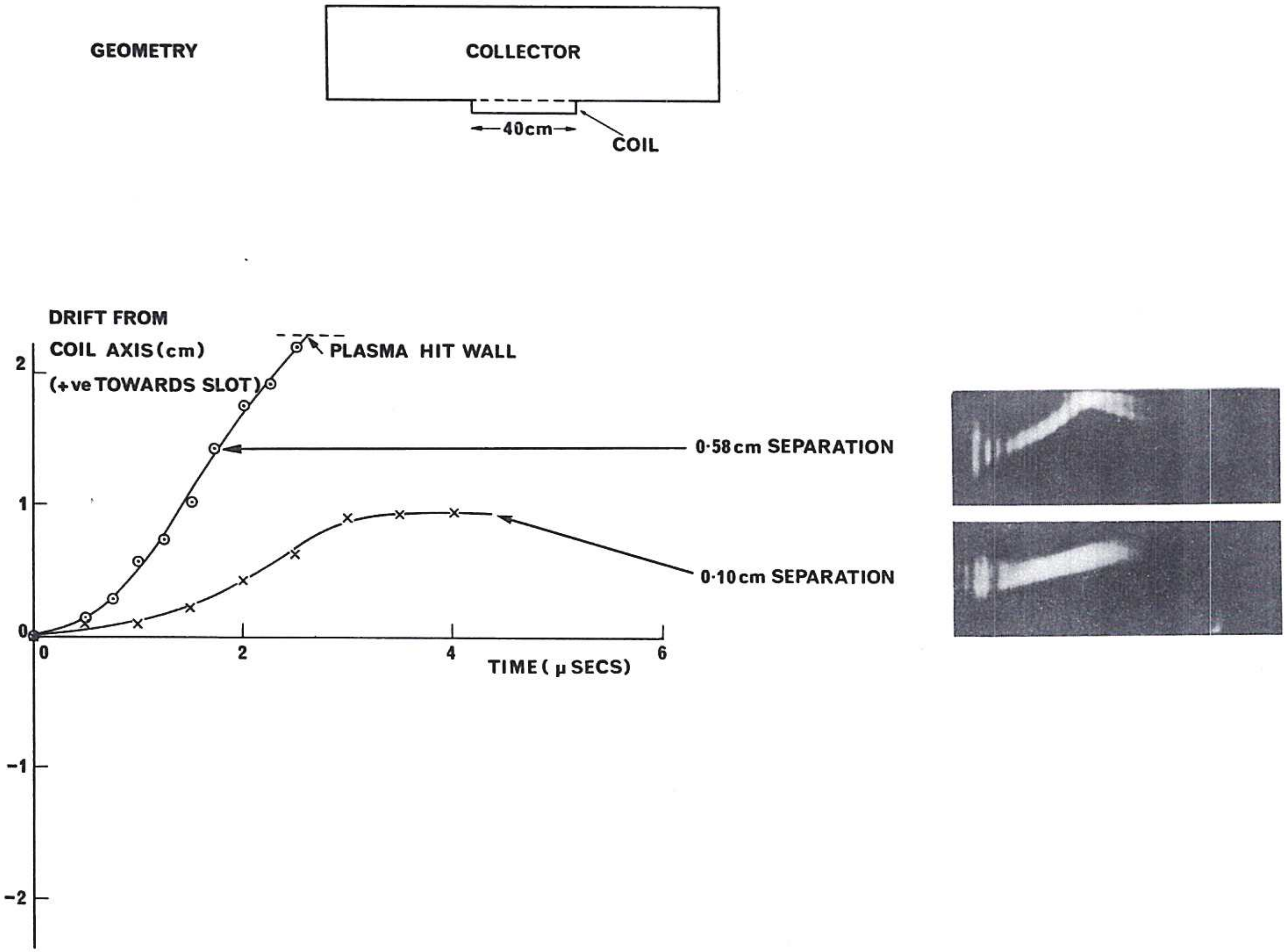


CLM-P 46 Fig. 6
Plasma drift showing end effect

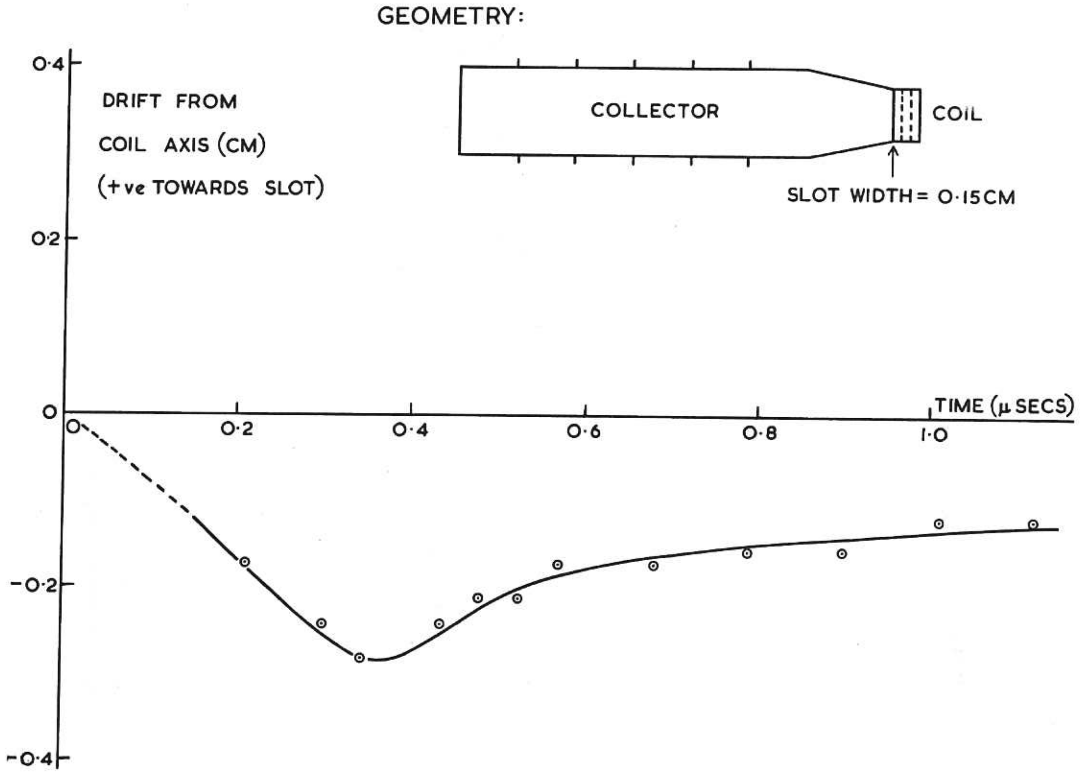


NOTE: (a) DRIFT IS TOWARDS THE SLOT WITH A CONVERGING COLLECTOR
(b) DRIFT CAUSES PLASMA TO MOVE TO A STABLE AXIS
(c) THE STABLE AXIS MOVES TOWARDS THE SLOT FOR LARGER COIL ASPECT RATIOS

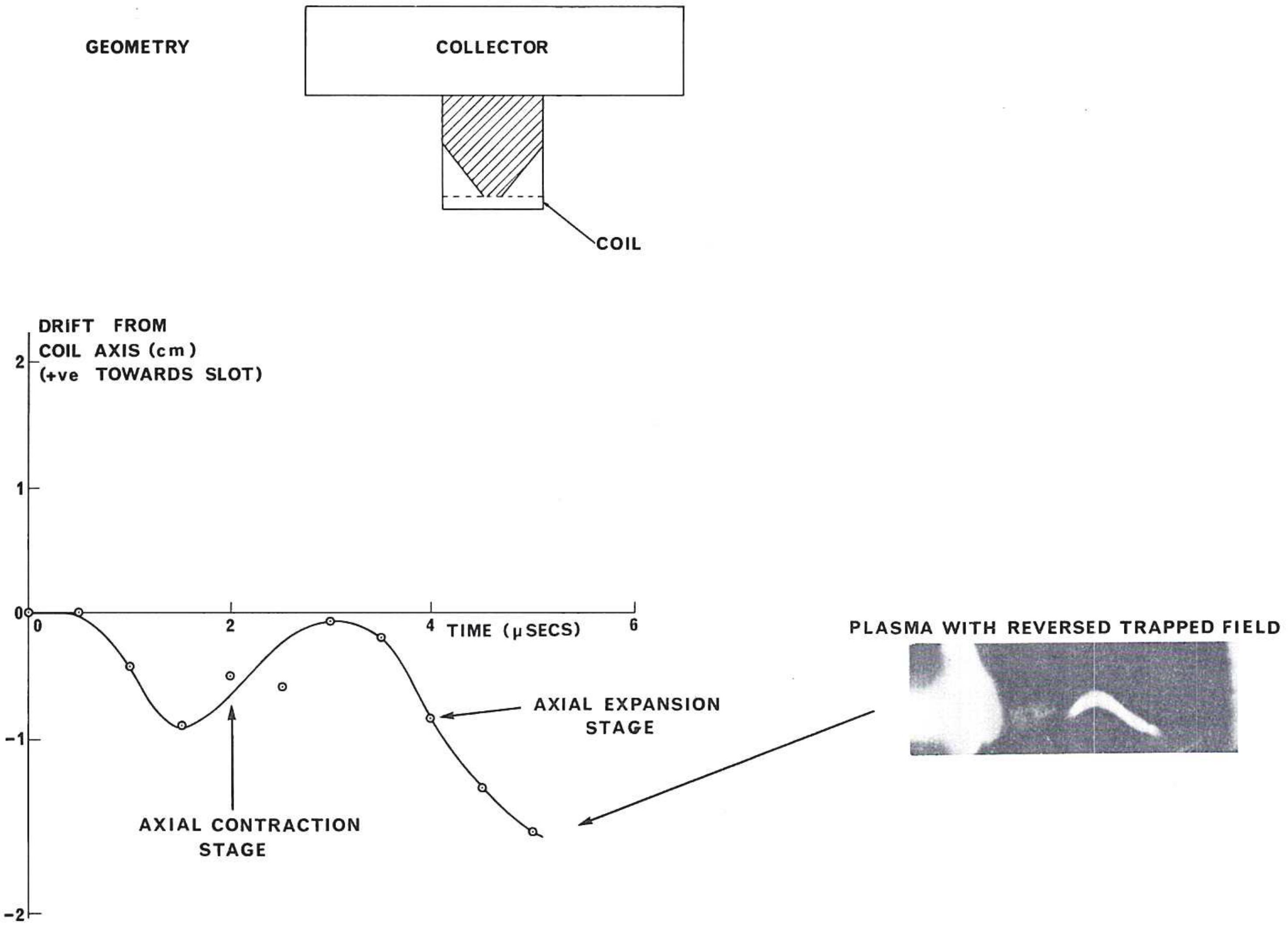
CLM - P 46 Fig. 7
Plasma drift showing end effect and collector shape influence



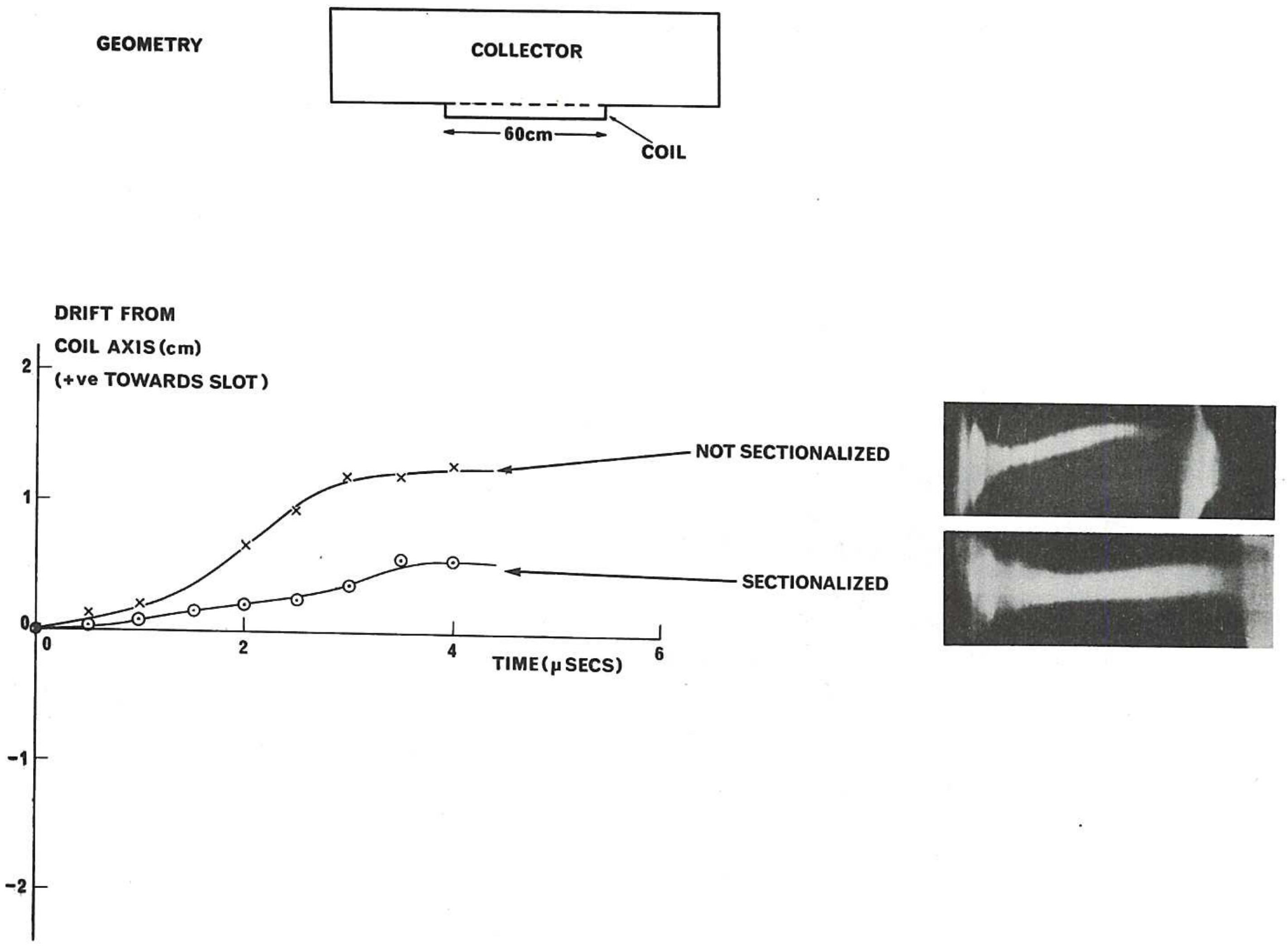
CLM-P 46 Fig. 8
Influence of collector plate separation on plasma drift



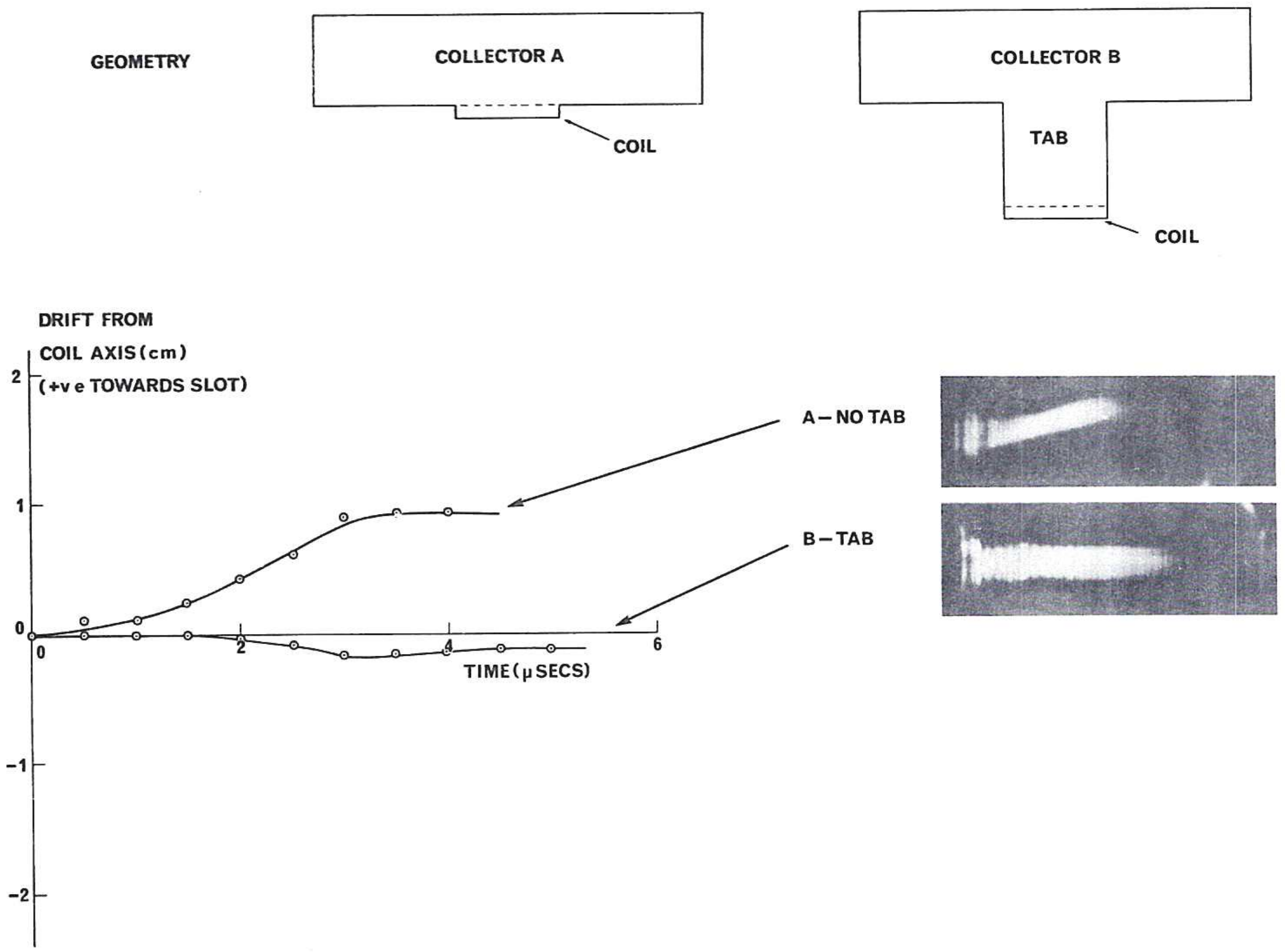
CLM - P 46 Fig. 9
Plasma drift showing collector-coil discontinuity effect
(Garching theta pinch)



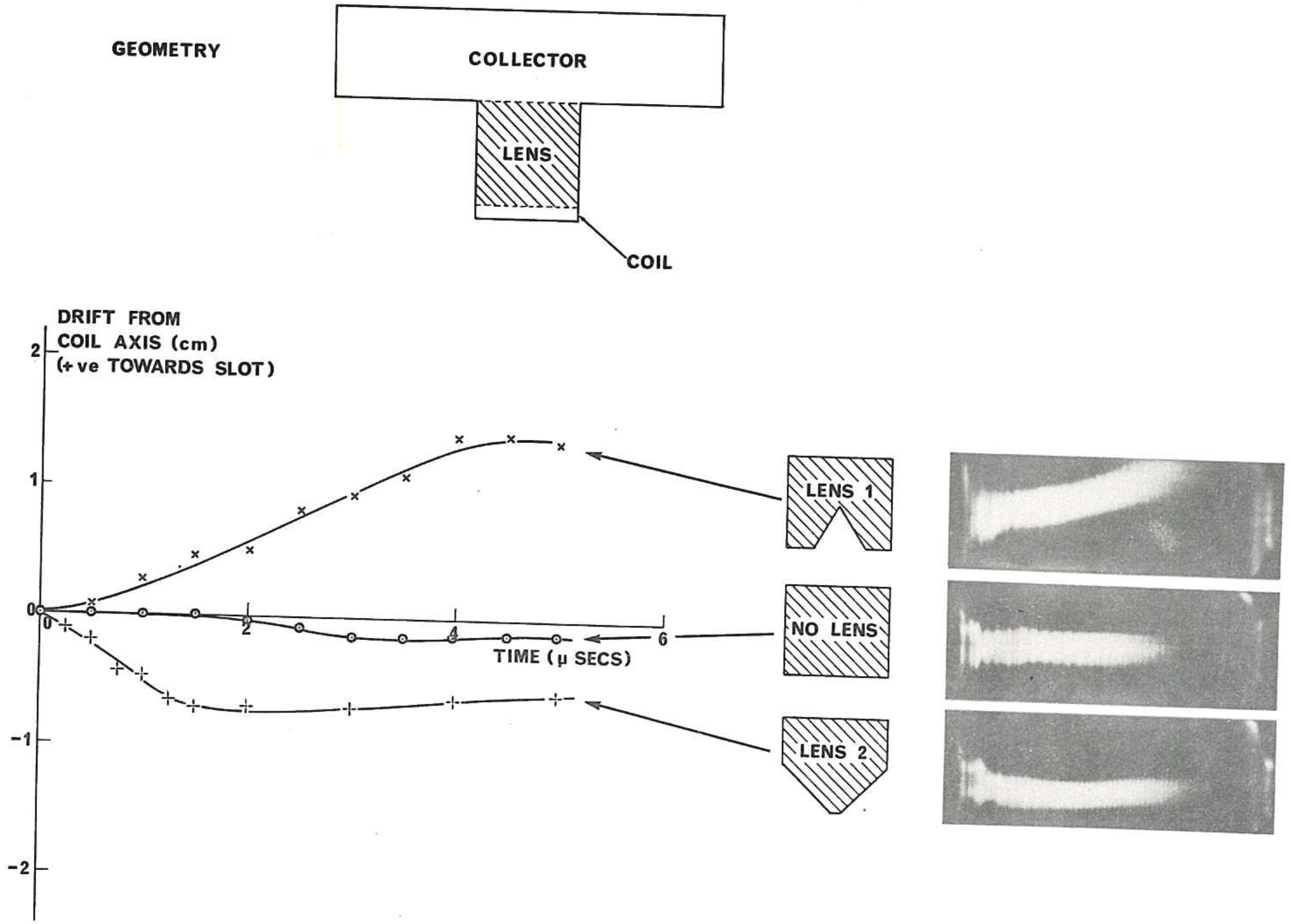
CLM-P 46 Fig. 10
The effect of plasma shape on the drift



CLM-P 46 Fig. 11
Reduction of plasma drift by using a sectionalized coil



CLM-P 46 Fig. 12
Removal of plasma drift by using a tab



CLM-P 46 Fig. 13
Control of plasma drift with an inductive lens