EXPERIMENTAL STUDY OF AXISYMMETRIC INSTABILITY OF INVERSE DEE AND SQUARE TOKAMAK EQUILIBRIA

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ABSTRACT

Dee and square shaped equilibria are observed by experimentally mapping out the magnetic flux plot as a function of time in a tokamak with a 4-null poloidal divertor. Inverse dee equilibria are observed to be unstable to the vertical MHD axisymmetric instability on a time scale ~ 100 poloidal Alfvén times. Square equilibria are stable on the time scale available for observation. Instability growth is apparently slowed by field shaping hoop and wall passive stabilization.

Tokamaks with non-circular cross sections (such as dee's and ellipses) are advantageous with respect to q limited MHD modes (e.g. ideal and resistive kink modes). However, elongation introduces instability to axisymmetric displacements (with toroidal mode number n=0) to which circles are neutrally stable. The poloidally asymmetric placement of external currents necessary to establish a non-circular equilibrium in turn creates destabilizing forces on the plasma current. The importance of these modes has given rise to a farily large amount of linear theory--mostly for idealized displacements of ideal analytic equilibria (see, for example, references 1-4). Recently, non-linear evolution of the instability has been followed numerically.[5,6] Axisymmetric displacement of dee and elliptical plasmas has been deduced in a few previous experiments from magnetic probes external to the plasma. Plasma shapes have been inferred from equilibrium computer codes using external experimental signals as input.

Here we present the first direct experimental observation of the stability to axisymmetric modes of square and dee-shaped equilibria in a 4-null poloidal divertor configuration. The equilibria are verified by mapping out the magnetic field in the plasma as a function of time. The stability of these equilibria to axisymmetric modes is determined by studying the evolution of these experimental flux plots. We have found that dee and square shaped equilibria experimentally exist. Increasingly dee-like equilibria appear to be increasingly unstable, with growth times (i.e., time for plasma to displace a finite distance) on the order of 100 poloidal Alfvén times. The instability is slowed from the Alfvén MHD time scale by passive stabilization from the hoops and walls.

These experiments were performed on the Wisconsin Tokapole. The Tokapole has a vacuum magnetic flux plot of an Octupole (Fig. 1a) which provides vertical and horizontal fields to center the discharge. When plasma current is driven toroidally through the octupole null, a tokamak with four poloidal divertors is generated (Fig. 1b). By varying the placement of the internal rings, we can change the shape of the tokamak separatrix from outside 'dee' to square (Figs. 3a,b,c).

The machine has an iron-cored, square cross section (44 × 44 cm) toroidal chamber made out of aluminum. A soak in time of approximately 15 msec through the wall eliminates bumpiness in the toroidal magnetic field ($\leq$ 5 kG) on the time scale of our experiment. The major radius is 50 cm and the four octupole hoops, made of a chromium-copper alloy, are placed near each corner (Fig. 1). Typical electrical characteristics of the discharge are shown in Figure 2. A normal discharge lasts approximately 4 msec with peak toroidal currents of 40 kA. The peak electron temperature $\sim$ 100 eV (surmised from modeling of the time evolution of different sets of impurity lines, e.g. OI – OVI) and the electron density $\sim 10^{13}$ cm^{-3} (measured by microwave interferometry and Langmuir probes). The ion temperature is approximately 20 eV (measured through Doppler broadening of He II). The current distribution is fairly uniform inside the separatrix (measured by Rogowskii loops and inferred from experimental flux plots) with the safety factor q near 1 on axis and slightly higher near the separatrix. Temperatures are sufficiently low that probes can be inserted into the plasma with little or no observable effect, and detailed information on such parameters as plasma current, electric field, magnetic field, and pressure can be obtained. The reproducibility of the plasma allows us to plot out the above parameters as a function of space and time.

Extremely important to this study is the special ability to produce experimental flux plots. We are able to adjust the vertical positions of the internal hoops by ± 5 mm enabling us to experimentally verify the existence of a range of poloidal divertor equilibria and to study their axisymmetric stability.

Axisymmetric instabilities were observed in the form of a non-rigid vertical shift of the plasma. The deeness is varied by moving our hoops, which exert attractive forces on the plasma. Three cases are studied. Case A (Fig. 3a) has the outside hoops moved closer together yielding an inverse dee equilibrium. Case B (Fig. 3b) with the inside hoops moved closer together gives roughly a square equilibrium. The intermediate case C (Fig. 3c) with inside and outside hoops at the same height yields a slightly inverse dee equilibrium. Figure 4 illustrates the vertical motion of the central magnetic axis in the three cases. These figures indicate that in cases A and C the magnetic axis moves vertically upward, with case A starting slightly earlier. In case B the magnetic axis only moves horizontally as the plasma current magnitude changes. Thus we see cases A and C (deeish equilibria) are unstable but that case B (square) is stable on the time scale of the experiment. In agreement with analytical Solv'ev equilibira,[1,5,10] we find the inner surfaces of the flux plot to be elliptical. In addition, we find the deeness, or triangularity, of the equilibrium to be an increasing function of ellipticity.

All references have predicted that conducting walls and external coils will slow down the growth rate through passive stabilization. Jardin[6], predicts that the growth time is shortened to the L/R time of the wall and field shaping coils. Since we presently have no programmable vertical field, the slowing of the instability to 100 poloidal Alfvén times is a good indication of passive stabilization. Although the difference in stability between the square and dee is easily distinguishable, the difference in stability between cases A and C are eclipsed by the passive stabilization. However in case A, as mentioned before, the plasma begins vertical motion earlier in time, possibly indicating it is more unstable than case C (a less deeish case). The L/R times of the hoops, walls, and plasma are approximately 20 msec, 15 msec, and 100 μsec respectively. The rough equality of the plasma L/R time scale and the growth time scale suggests that the passive stabilization may be limited by the conductivity of the plasma.

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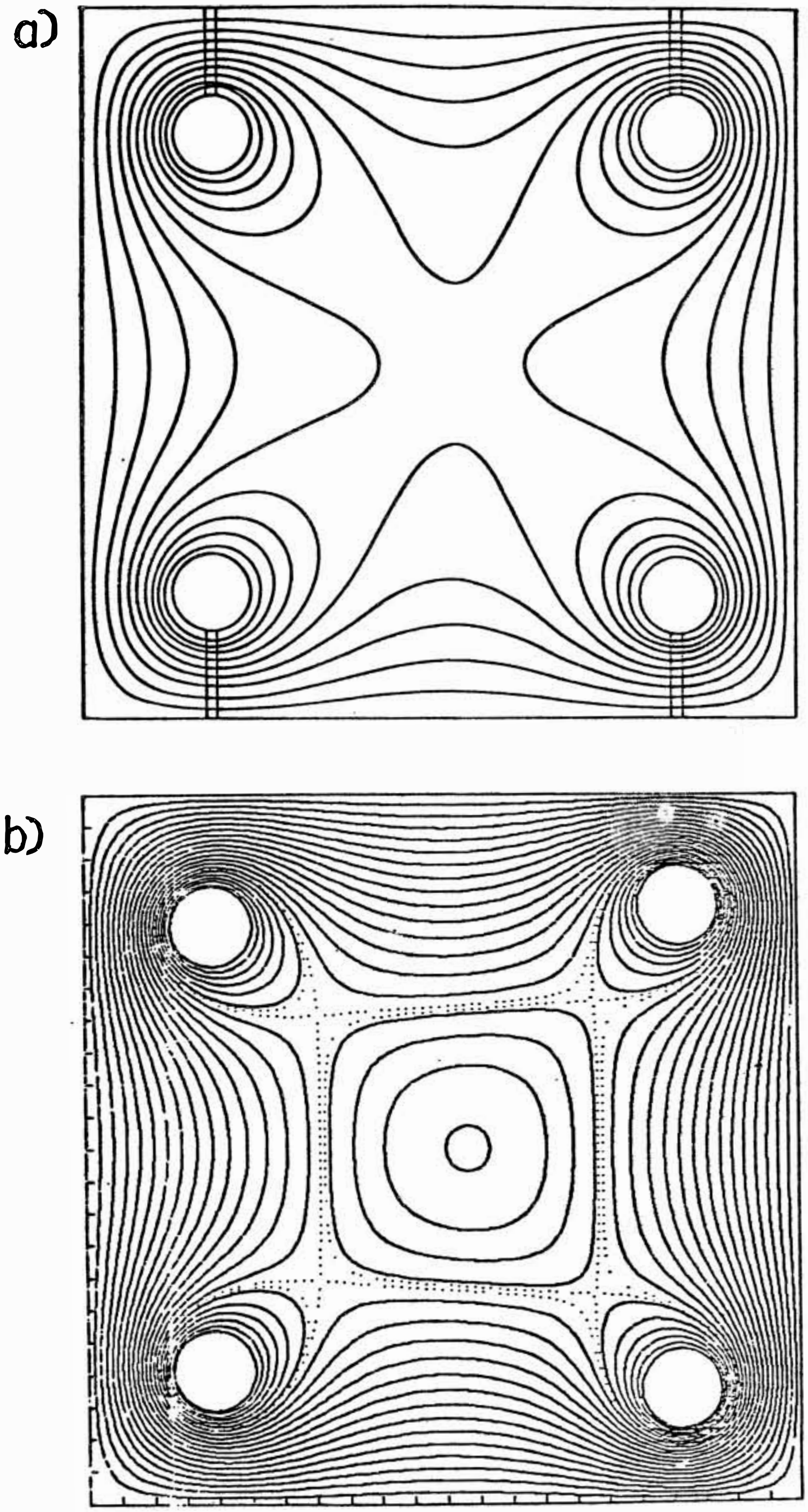

Fig. 1. Numerical flux plots (major axis to left). (a) Without plasma. (b) With plasma (hoops in case B position).

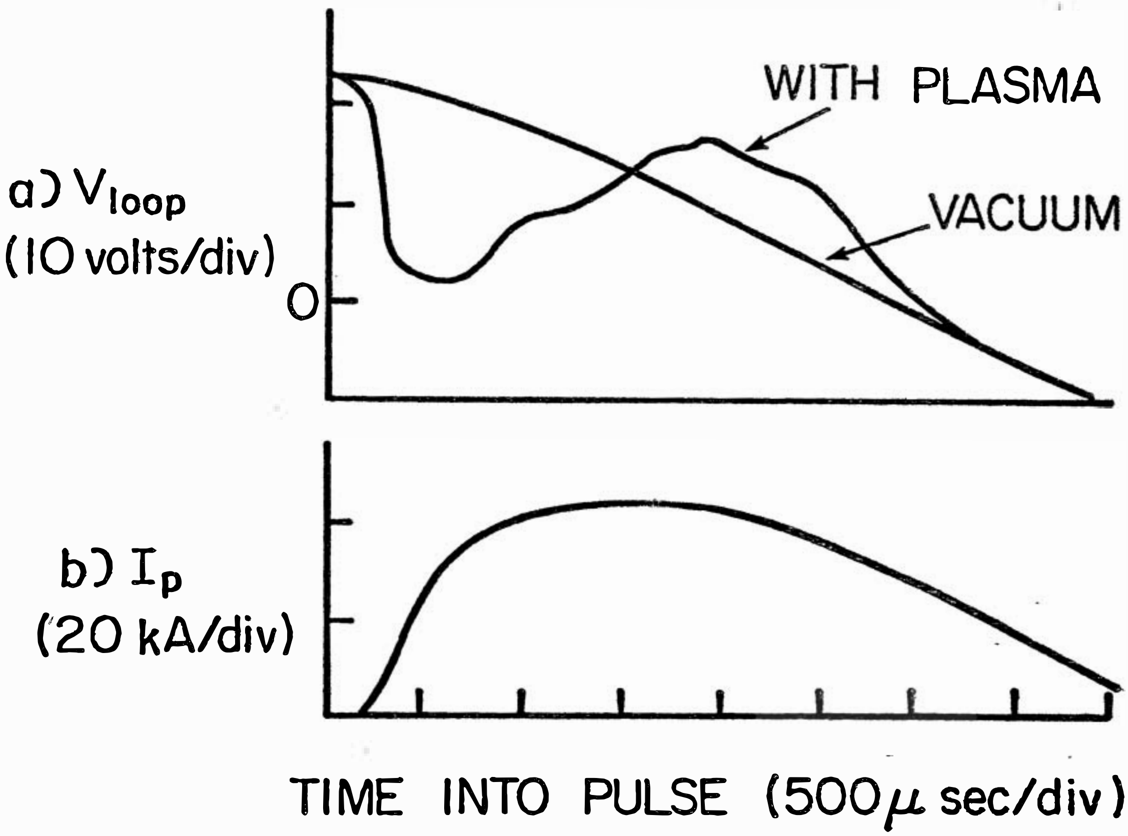

Fig. 2. Electrical characteristics. (a) Hoop voltage at machine center with and without plasma. (b) Plasma current.

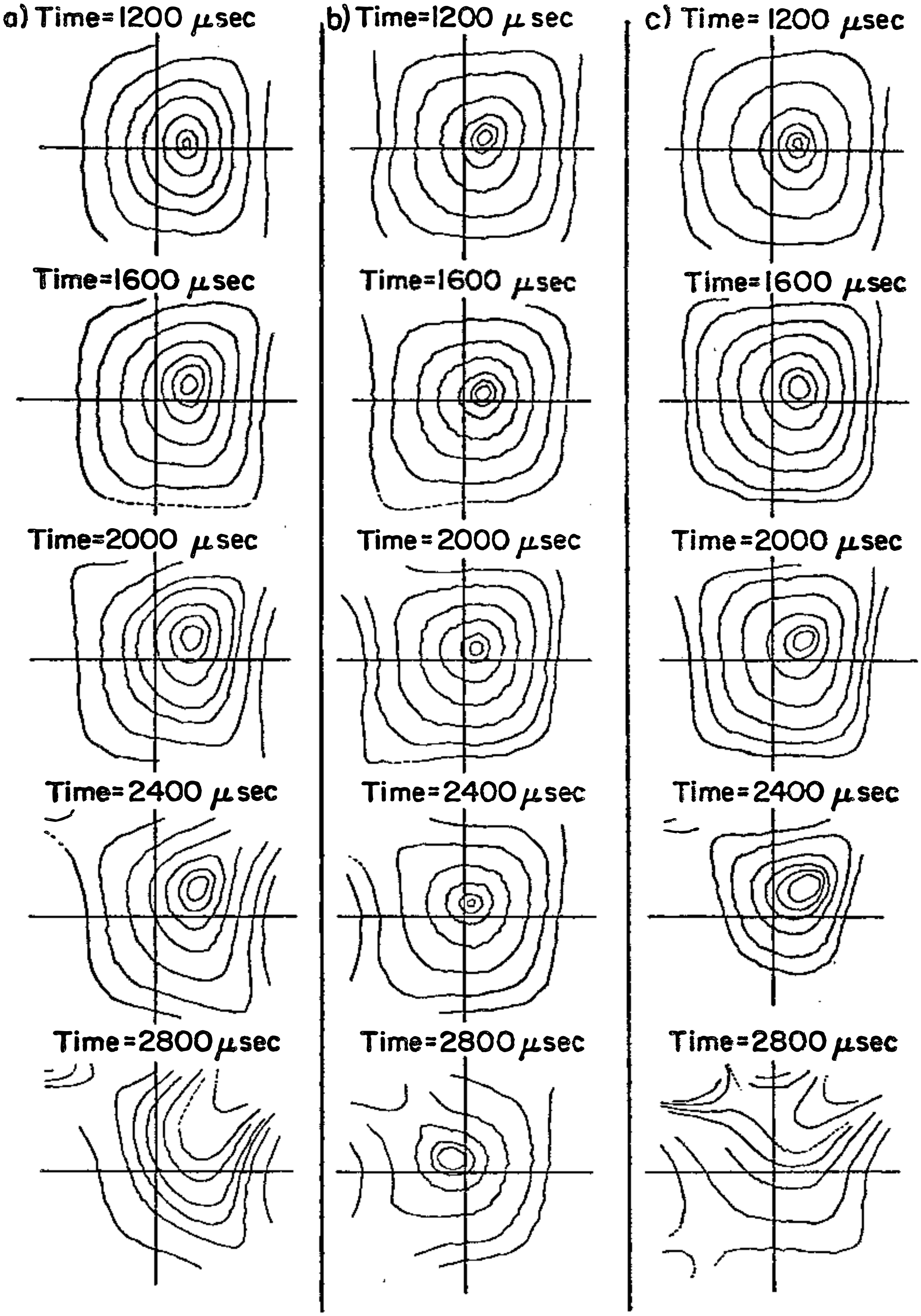

Fig. 3. Time evolution of experimental flux plots mapped out with magnetic probes. Only the area iside the initial separatrix is shown. (a) Case A. (b) Case B. (c) Case C.

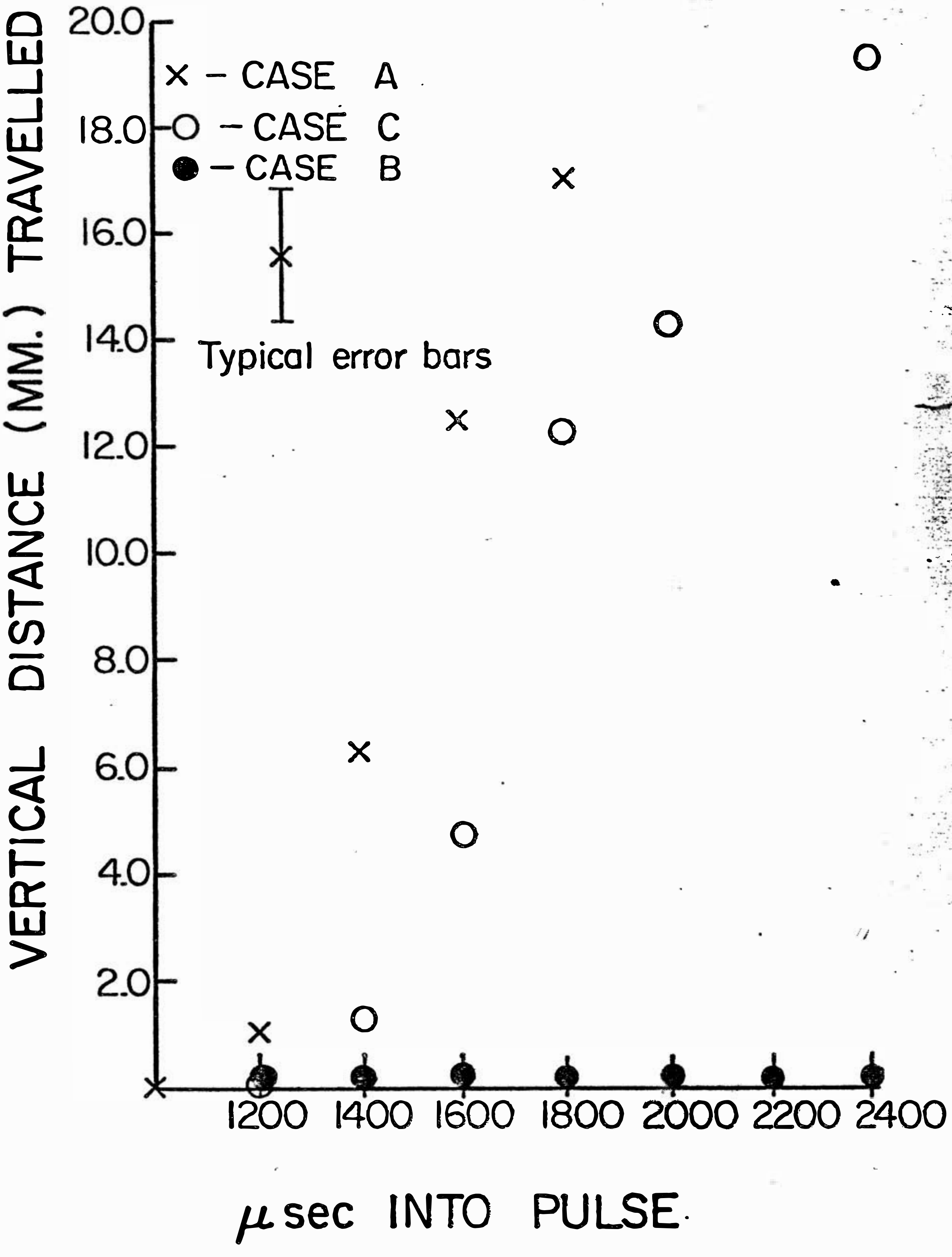

Fig. 4. Vertical position of the magnetic axis as a function of time. Note—case B moves only horizontally.