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B. Feinberg, B.G. Vaucher, R.S. Shaw and M.C. Vella

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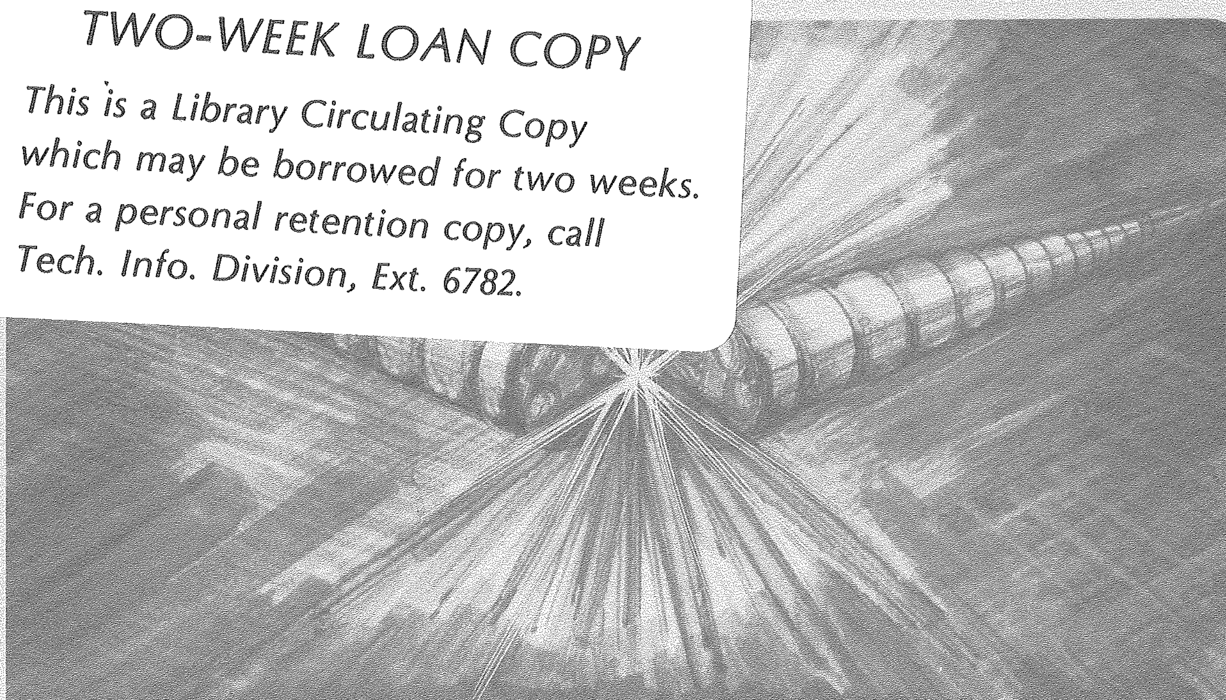

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Anomalous Toroidal Field Penetration in Tormac V*

B. Feinberg, B. G. Vaucher+, R. S. Shaw,
and M. C. Vella

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

Magnetic field penetration into a cool, collisional, magnetized plasma has been investigated in Tormac V. Magnetic probe and laser interferometer studies reveal anomalous penetration of the applied toroidal field into a plasma with an initial parallel bias toroidal field. The applied poloidal field, however, formed a well-defined magnetic front which was effective at sweeping up particles. Strong shear in the vacuum magnetic field does not inhibit the apparent decoupling of the applied toroidal field from the applied poloidal field.

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+ Present address: Department of Physics, University of Fribourg, Switzerland, and supported by the Swiss National Science Foundation.

I. Introduction

Tormac V, like other recent Tormac experiments,[1] has a bicusp geometry with both toroidal and poloidal cusp components. The toroidal component is strong at small major radius while the poloidal component is dominant at large major radius. Confinement scaling depends in part on the adiabatic invariance of the magnetic moment[2], which, in a bicusp, necessitates a toroidal stuffing field parallel to the toroidal component of the cusp field. Startup requires the formation of a sheath between the cusp field and the central plasma.

In this experiment the stuffing field is provided by a relatively weak toroidal bias field introduced before ionization. After preionization, the rapidly rising cusp field ionizes the remaining gas and heats the plasma, forming a dense, cool, and collisional plasma.[3] Magnetic probe and laser interferometer studies have revealed anomalously fast penetration of the plasma by the toroidal component of the cusp field, similar in character to phenomena observed in parallel bias theta pinch experiments.[4,5] In contrast, the poloidal field component formed a well-defined front moving at several centimeters per microsecond which was effective at sweeping up particles. The high shear vacuum magnetic configuration did not inhibit the decoupling of the poloidal and toroidal components of the cusp field. When the bias field was reversed with respect to the toroidal component of the cusp, toroidal field penetration was similar in character to poloidal penetration, which was unaffected by the reversal. These results suggest intrinsic difficulties with startup, and perhaps equilibrium, in the stuffed bicusp geometry.

II. Experimental Configuration

Tormac V is a toroidal device with a 30 cm major radius and an equivalent aspect ratio of 3, built to test containment in the Tormac bicusp magnetic field configuration.[3] The vessel cross section, vacuum cusp poloidal flux surfaces, and $|B|$ surfaces are illustrated in Fig. 1. The $|B|$ surfaces include both the toroidal and poloidal field components of the cusp. Both cusp field components are provided by a single set of windings. Each individual winding has sections which provide poloidal field, and sections which provide toroidal field, resulting in one series coil for both poloidal and toroidal field components.

The experimental sequence is as follows. First, the vacuum chamber is filled with H_2 to a pressure of 10 mTorr. A slow, pulsed toroidal bias field of $\lesssim$ 600 G is next applied. At peak field, the preionizer is fired, inducing a peak toroidal plasma current of 70 kA oscillating at 50 kHz. After 20 μsec this produces a partially ionized plasma with a density $\langle n \rangle \sim 5 \times 10^{14}$ cm^{-3} and a temperature $T_e < 5$ eV at a major radius R ~ 35 cm. The main bicusp containment coils are then energized with a 12 μsec risetime, resulting in a magnetic well centered at a major radius of 30 cm with a magnitude of 3 kG at the B surface with a minor radius of 10 cm. A mean plasma density $\langle n \rangle \sim 10^{15}$ cm^{-3} is measured with a He-Ne laser interferometer, and an electron temperature Te ~ 5-10 eV is measured by Thomson scattering.[3]

A magnetic probe was inserted at the midplane port to scan the vessel in major radius, and also was inserted at a side port at a radius of 31 cm to scan in the axial direction. The probe consisted of two 20 turn coils of #37 (5 mil) wire, 3 mm in diameter, mounted 2 cm apart, and encased in a 5mm diameter quartz tube. Measurements of both toroidal and poloidal field components were obtained by rotating the probe. Inserting the probe at the midplane allowed measurements of the toroidal field and the axial component of the poloidal field, while inserting the probe at a major radius of 31 cm allowed measurements of the toroidal field and the radial component of the poloidal field. Calculations of the boiloff time for quartz in a plasma with the measured temperature and density indicate that the observation time was short compared with the boil-off time,[6] so that the probe measurements should be accurate for all times of interest.

The magnetic probe was calibrated using a pulsed Helmholtz coil which determined the magnetic axis and the effective area-turns of the probe coils. During each experimental run the coils were rotated by 180° to ensure that electrostatic pickup was not influencing the probe signal. The signal was found to invert, indicating that it was magnetic in origin, not electrostatic. A passive integrator with an RC time constant of 100 μsec, much longer than the times of interest, was used to integrate the probe signals.

Radial and axial scans were made under two conditions. In the first case, the standard Tormac operating condition with parallel bias, the toroidal bias field was in the same direction as the toroidal component of the cusp containment field. For comparison, a second "reversed bias" case was used, with the toroidal bias field antiparallel to the cusp toroidal component. In both cases toroidal and poloidal field components were measured, at the midplane as a function of major radius, and at a radius of 31 cm as a function of axial position.

Laser interferometry was used to determine the plasma line density. A feedback stabilized He-Ne laser interferometer was mounted to measure the line density along the axial direction.[7] Scans of line density were taken as a function of major radius, for both the parallel and reverse bias cases.

III. Magnetic Field Measurements

Magnetic probe traces typical of the toroidal field in the standard, parallel bias bicusp configuration are shown in Fig. 2. In the case shown, the probe coils were located on the midplane at major radii of 22 and 24 cm. No significant difference between the vacuum and plasma shots is evident. There was no evidence of formation of a toroidal field step whether the probe was inserted radially from the outside of the vessel or axially from the side of the vessel. The penetration speed of the toroidal field cannot be resolved accurately from traces similar to Fig. 2, but a speed of at least 30 cm/μsec is evident.

Typical magnetic probe traces of the poloidal field are shown in Fig. 3 for the parallel bias configuration. The probe coils were located at major radii of 38 and 40 cm, where the poloidal field is relatively strong. In comparison with the vacuum shot a sharp field rise, indicated by an arrow, is evident after a delay of 1.3 μsec. The arrival time of this poloidal field jump is plotted as a function of major radius, R, in Fig. 4A, and as a function of axial position, Z, in Fig. 4B. The poloidal field propagates radially inward with a speed of about 7 cm/μsec, and axially toward the midplane at about 18 cm/μsec. The radial component of the poloidal field is small near the midplane, resulting in large measurement errors near $Z = 0$.

As a check the toroidal bias field was reversed with respect to the toroidal component of the cusp field. Magnetic probe traces of the toroidal field are shown in Fig. 5, for major radii of 23 and 25 cm. In this reverse bias configuration, the plasma shot exhibits a noticeable delay compared with the vacuum shot, with a sharp reversal in toroidal field after 9 μsec. This contrasts markedly with the behavior observed in the parallel bias case, Fig. 2. The arrival time of the reverse bias toroidal field as a function of R and Z is shown in Fig. 6A and 6B. The toroidal field moves outward in major radius at ~ 6 cm/μsec, and axially toward the midplane at ~ 3 cm/μsec, comparable to the propagation speeds of the poloidal field. The behavior of the poloidal field propagation was unaffected by the reversal of the toroidal bias field.

IV. Density Measurements

Measurements were made of the axial line density versus time, at various major radii using a He-Ne laser interferometer. The purpose of these measurements was to look for evidence of the formation of a density step associated with the step in the cusp magnetic field. Fig. 7 shows a typical oscilloscope trace of the interferometer signal. The line density is proportional to the arcsine of the voltage, for phase changes less than $\pi/2$.

For the standard parallel bias case, the arrival time of the density step is plotted as a function of major radius in Fig. 8. The increase in density starts at large major radius and moves toward small major radius. No evidence is seen of a density front moving outward from small major radius.

Figure 9 shows the time of the density rise versus major radius for the reverse bias case. In contrast with the parallel bias case there is evidence of a density front moving outward from small major radius. The density front which moves inward from large radius, associated with the strong poloidal field, is substantially unaffected by the direction of the bias field.

V. Discussion

Significant differences were observed in the penetration of the toroidal and poloidal components of the Tormac V bicusp field. The toroidal and poloidal field components appear to decouple and exhibit independent penetration characteristics. This behavior was verified by reversing the bias field and observing that only the toroidal-field penetration was affected.

With the required parallel bias, or stuffing toroidal field, the toroidal component of the bicusp was observed to penetrate the plasma anomalously rapidly. This conclusion is based on the similarity of the magnetic probe signals with and without plasma, and the absence of a discernable density step at small major radius. Although the mechanism has not been identified, the time scale for toroidal field penetration is much faster than either the classical resistive penetration-time or the sound time, given the known plasma parameters. Viscous damping due to the background neutral gas cannot account for the observed penetration. The observed behavior contrasts sharply with the behavior of both the poloidal component of the cusp field, and the toroidal component under reversed bias conditions.

Penetration of the poloidal component of the bicusp was qualitatively unaffected by the direction of the toroidal bias field. A distinctive step in the magnetic probe signal was observed moving toward the center of the vessel from the strong poloidal field region at a speed of several centimeters per microsecond, roughly consistent with the sound speed. An associated density step was also observed, with the interferometer, to propagate in from large major radius, where the poloidal field is dominant. This step is interpreted as both ionization and particle pickup by the poloidal field.

As a check, the toroidal bias field was reversed with respect to the toroidal component of the bicusp. A jump in the toroidal magnetic probe signal, similar to the poloidal field step was observed. This step moved outward from small major radius, and axially toward the midplane at a propagation speed of several centimeters per microsecond. At small major radius an associated density jump was also observed to move outward from the inner wall. This check would appear to rule out probe effects or some peculiarity of the vessel design as an explanation of the parallel bias results. Since the electron temperature in Tormac V was relatively insensitive to the direction of the toroidal bias field, significant changes in classical plasma conductivity are ruled out.

Related phenomona have been observed in a number of theta pinch experiments. A marked difference in behavior has been noted between the case with a bias field parallel to the compressing field, and with a bias field antiparallel to the compressing field.[4,5] These experiments have shown an initial rapid diffusive penetration of the plasma in the parallel bias case with very little particle compression, in spite of the values of dB/dt 10 to 100 times greater than in Tormac V. When the bias field was reversed, all of these experiments showed rapid formation of a magnetic piston, with a sharp step in the field and good particle sweepup. These results are qualitatively similar and consistent with the toroidal field results in Tormac V.

One experiment[4] used the measured magnetic penetration velocities and the magnetic field scale length to get an effective collision frequency. Making the usual fluid assumptions and assuming the magnetic diffusion speed is much greater than the mass motion results in an effective resistivity

$$\overline{\eta} = 4\pi \ \delta \ v/c^2$$

where δ is the magnetic field scale length and v is the diffusion velocity (all units are Gaussian). The effective collision frequency, normalized to the plasma frequency is

$$\overline{\nu}/\omega_{pe} = v \ \omega_{pe} \ \delta/c^2$$

For Tormac V the effective collision frequency is found to be $\overline{\nu}/\omega_{pe} \gtrsim .4$ for the parallel bias toroidal field case, which compares to a $\nu/\omega_{pe} \sim .15$ for the parallel bias theta pinch experiment.

One can use the difference between the magnetic piston speed and the mass motion to get a magnetic diffusion speed for the antiparallel bias case. In both the theta pinch experiment[4] and Tormac V the effective collision frequency was reduced by an order of magnitude with antiparallel bias.

A comparison can also be made between the effective resistivity for the poloidal field penetration and for the toroidal penetration in the parallel bias case. The effective resistivity is almost one order of magnitude greater for toroidal penetration than for poloidal, and thus the plasma behaves as if there were a highly anisotropic resistivity. The fact that the vacuum field is highly sheared does not inhibit this effect.

Propagation of magnetic field steps orthogonal to an initial bias field has also been previously investigated.[8] A plasma was created with an initial axial bias field B_z, after which a fast z-pinch was applied.Rapid formation of a magnetic piston and substantial compression of the initial bias field was observed. These results are consistent with the observation of the formation of a magnetic step and good particle pickup for the poloidal component of the cusp field in Tormac V.

VI. Conclusion

Measurements have been made of the behavior of the magnetic field and line density in the Tormac bicusp. With the parallel bias toroidal field (i.e., stuffing field) required for Tormac confinement scaling, the toroidal component of the cusp field is observed to penetrate the plasma anomalously fast. The presence of anomalous phenomena in such a collisional plasma is somewhat surprising, and may indicate intrinsic difficulty with startup and equilibrium in the bicusp geometry. Similar phenomena have been observed in parallel bias theta pinch experiments[4,5] with considerably more energy available per particle and a field rise time short compared to an Alfven transit time. This would appear to rule out the simple cure of more energy or fast rise, even though the underlying physical mechanism remains experimentally unclear. Although a well-defined magnetic piston can be obtained in a reverse bias theta pinch[4,5] this option is ruled out for Tormac startup, since the presence of a field null appears incompatible with the existence of the adiabatic invariant upon which Tormac scaling is based.[2]

The poloidal component of the cusp is perpendicular to the toroidal bias field, and appears unaffected by the bias direction. Sharp poloidal field jumps and an associated density compression have been observed. This is consistent with previous results[8] and suggests that some of the startup problems encountered in this bicusp experiment could be alleviated with a higher order cusp, e.g., a quadrupole, in which the compressing cusp field is everywhere perpendicular to the toroidal bias field.

Small, collisional higher order toroidal cusp experiments have been reported[9], and the problem of shock heating a higher order toroidal cusp has been studied in detail.[10]

Acknowledgments

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Figure Captions

Fig. 1a Cross section of the Tormac V vacuum vessel. The lines labeled 1-7 represent interferometer lines of sight. Magnetic probes were inserted through the ports.

Fig. 1b Cross section of the vacuum poloidal flux surfaces for Tormac V. The dark line represents the vacuum vessel.

Fig. 1c Cross section of the vacuum magnetic field intensity for Tormac V, including both poloidal and toroidal field components. The dark line represents the vacuum vessel.

Fig. 2 Magnetic probe signals for the toroidal field in the parallel bias case. The upper and lower traces are for radii of 22 and 24 cm respectively. A vacuum shot is shown in the upper picture and a plasma shot is shown in the lower picture. The arrows represent the arrival times of the magnetic field.

Fig. 3 Magnetic probe signals for the poloidal field in the parallel bias case. The upper and lower traces are for radii of 38 and 40 cm respectively. A vacuum shot is shown in the upper picture and a plasma shot is shown in the lower picture. The arrows represent the arrival times of the magnetic field.

Fig. 4a Arrival time of the poloidal magnetic field at different major radii along the midplane, for the parallel bias case.

Fig. 4b Arrival time of the poloidal field at a major radius of 31 cm as a function of axial position, for the parallel bias case.

Fig. 5 Magnetic probe signals for the toroidal field in the antiparallel bias case. The upper and lower traces are for radii of 23 and 25 cm respectively. A vacuum shot is shown in the upper picture and a plasma shot is shown in the lower picture. The arrows represent the arrival times of the magnetic field.

Fig. 6a Arrival time of the reverse bias toroidal field at different major radii along the midplane.

Fig. 6b Arrival time of the reverse bias toroidal field at a major radius of 31 cm as a function of axial position.

Fig. 7 Laswer interferometer signal at a major radius of 23 cm for the reverse bias case. The left-hand arrow shows the time of cusp firing and the right-hand arrow shows the arrival time of the density increase.

Fig. 8 Arrival time of the density increase as a function of major radius for the parallel bias case.

Fig. 9 Arrival time of the density increase as a function of major radius for the antiparallel bias case.

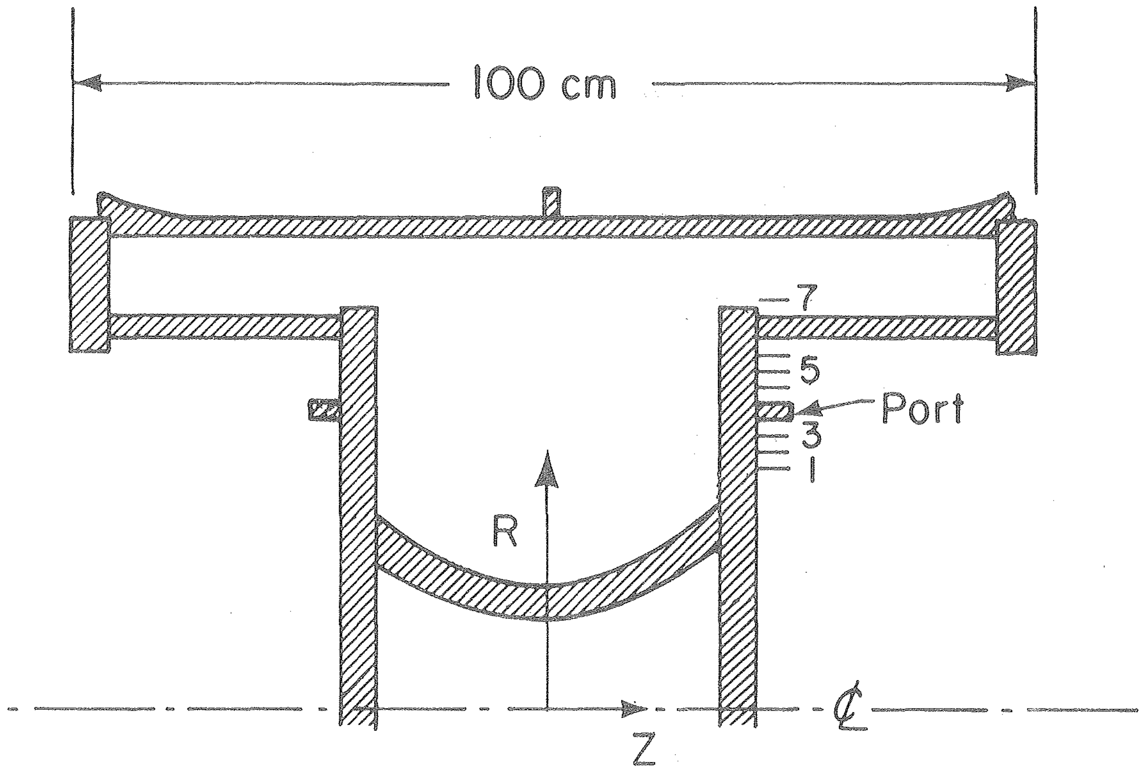

Fig. 1a

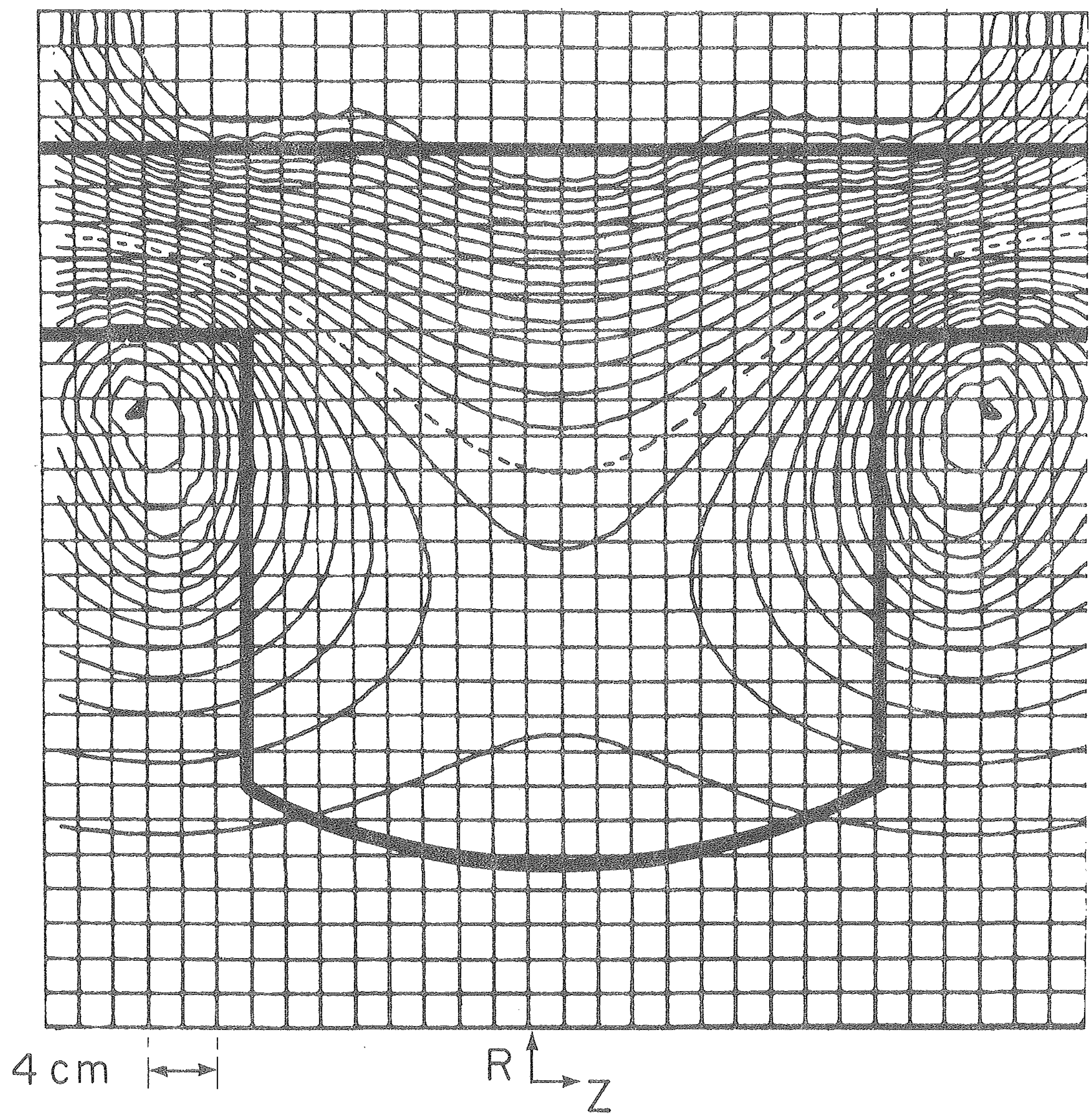

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Fig. 1b

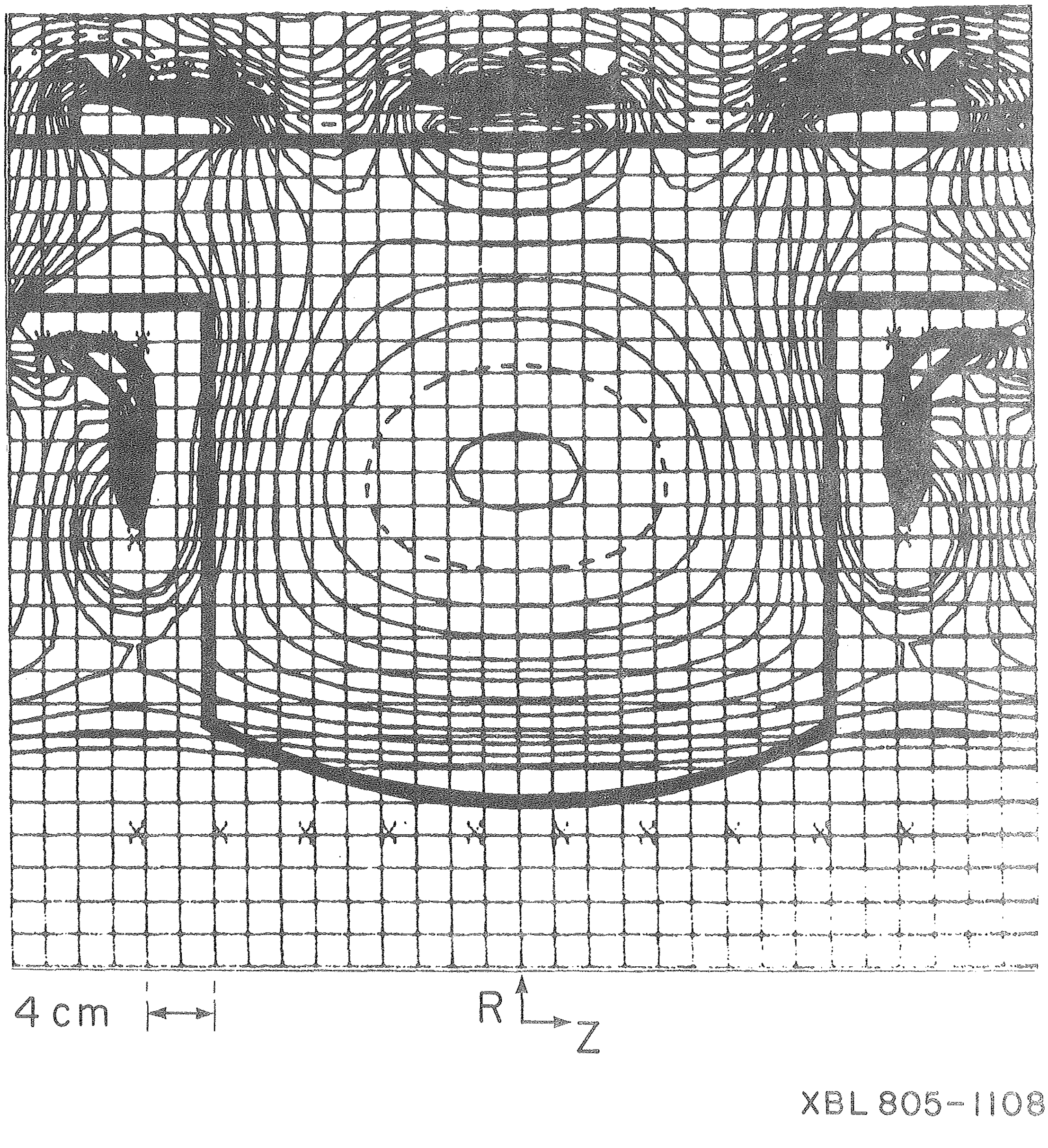
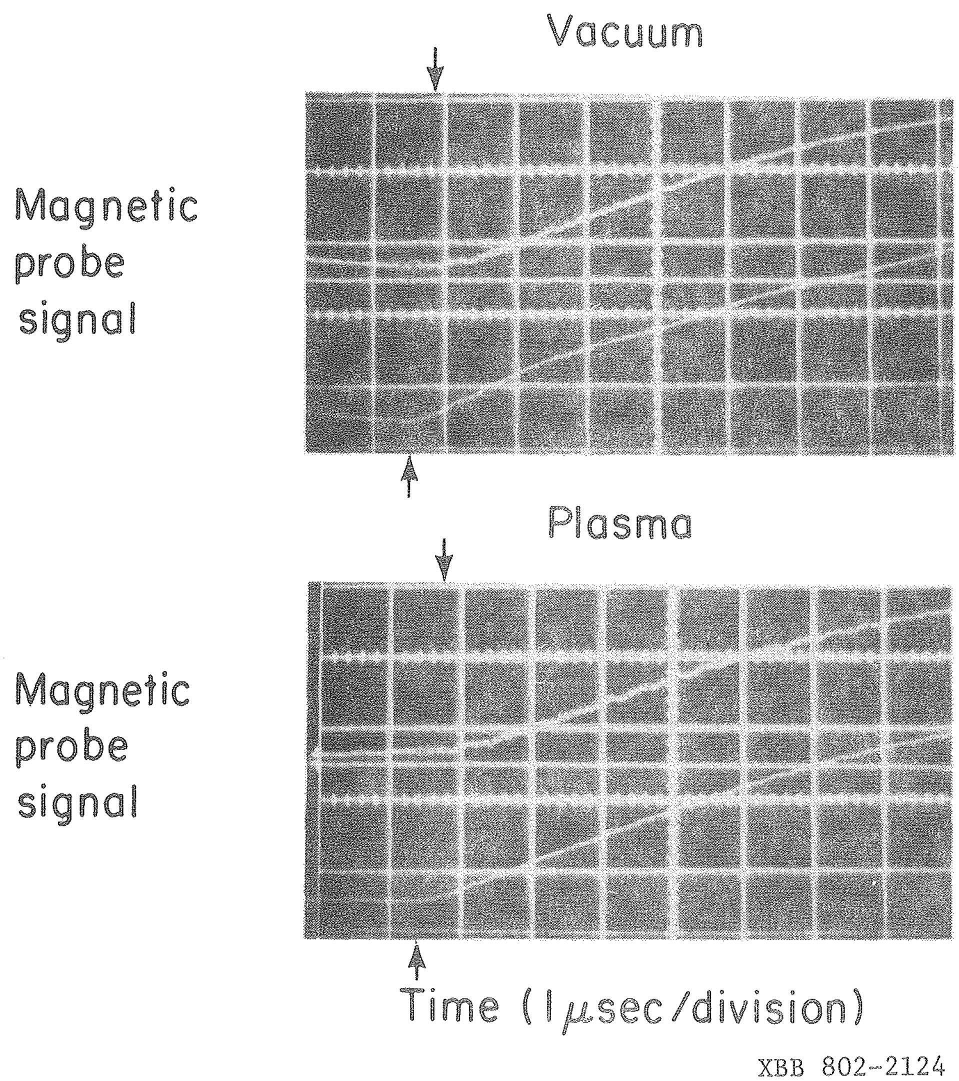


Fig. 1c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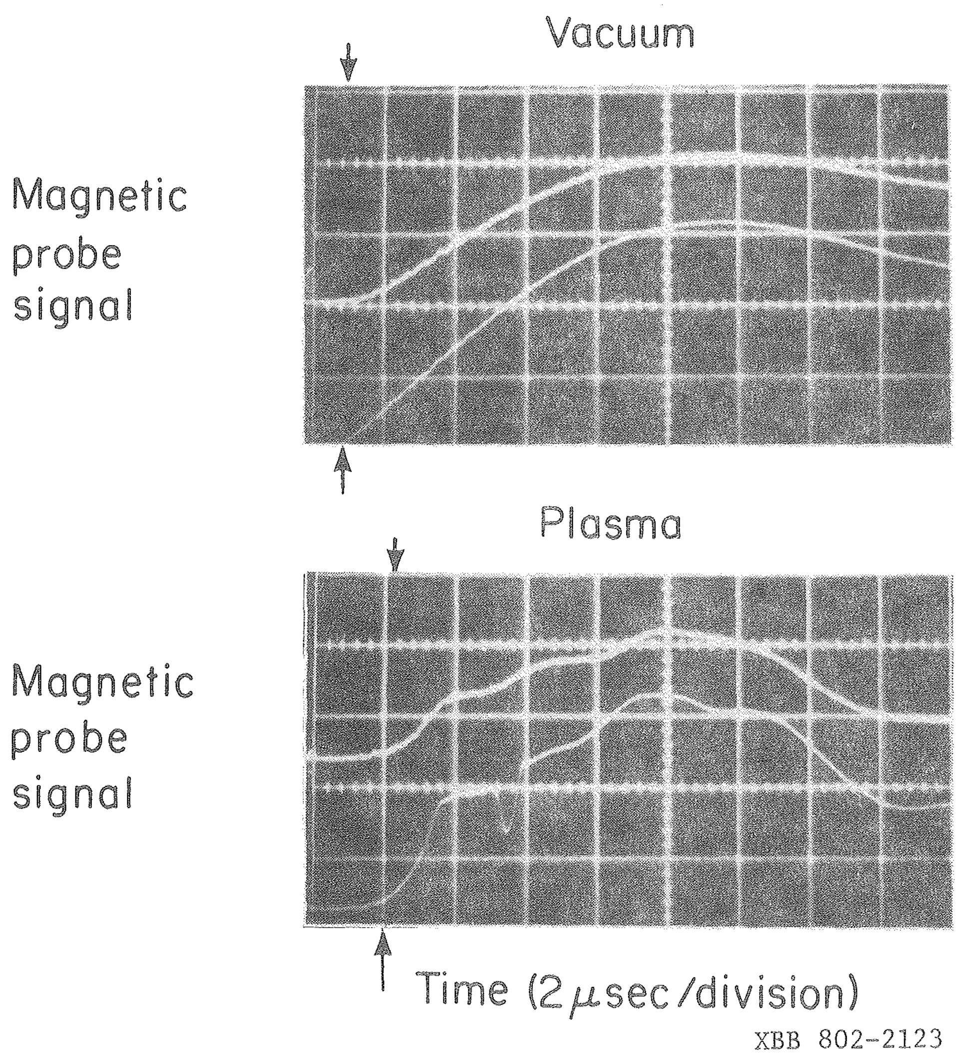
Magnetic probe signal
Plasma
Magnetic probe signal
Time (1 μsec/division)
XBB 802-2124

Fig. 2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Magnetic probe signal
Plasma
Magnetic probe signal
Time (2μsec/division)
XBB 802-2123

Fig. 3

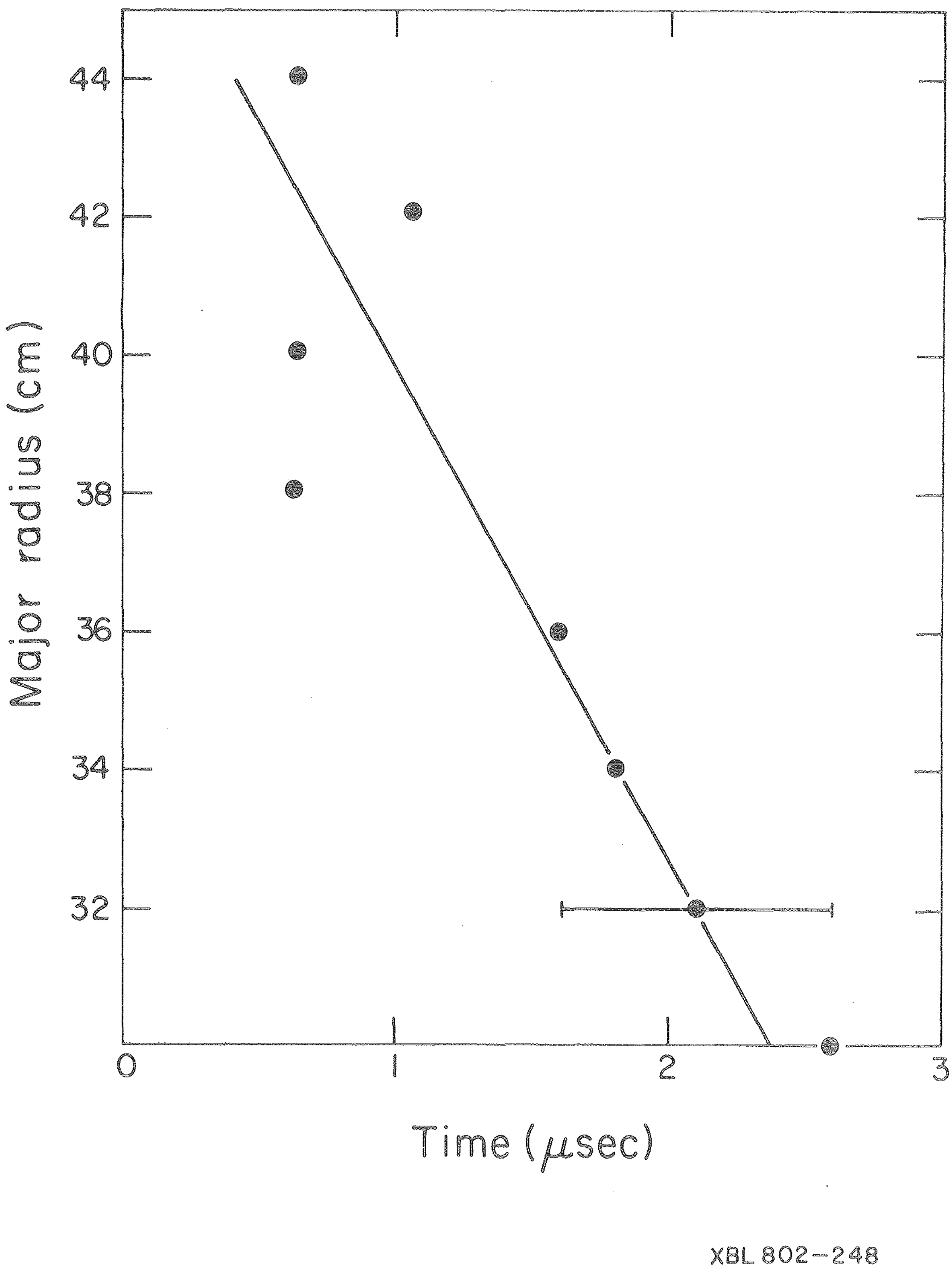
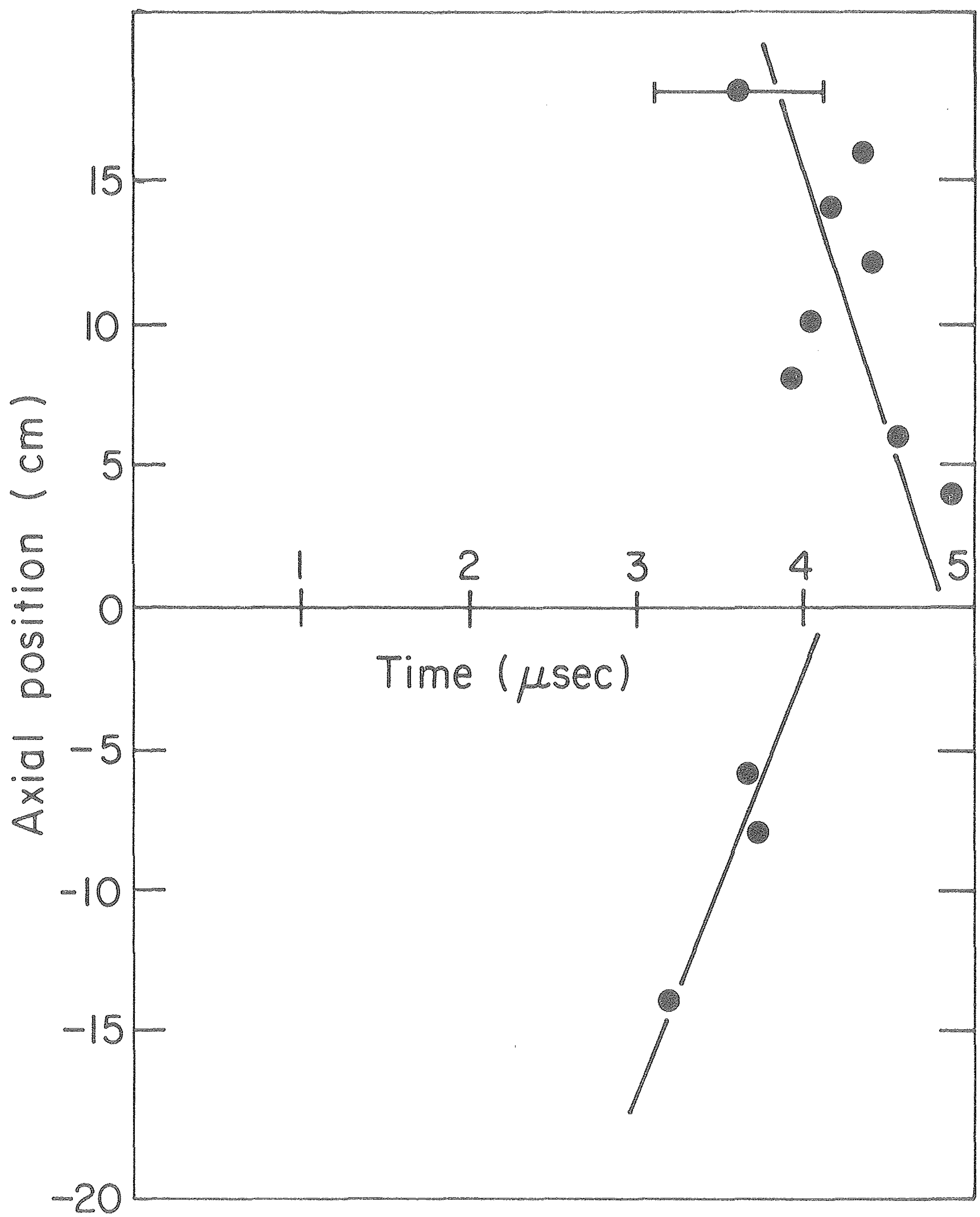
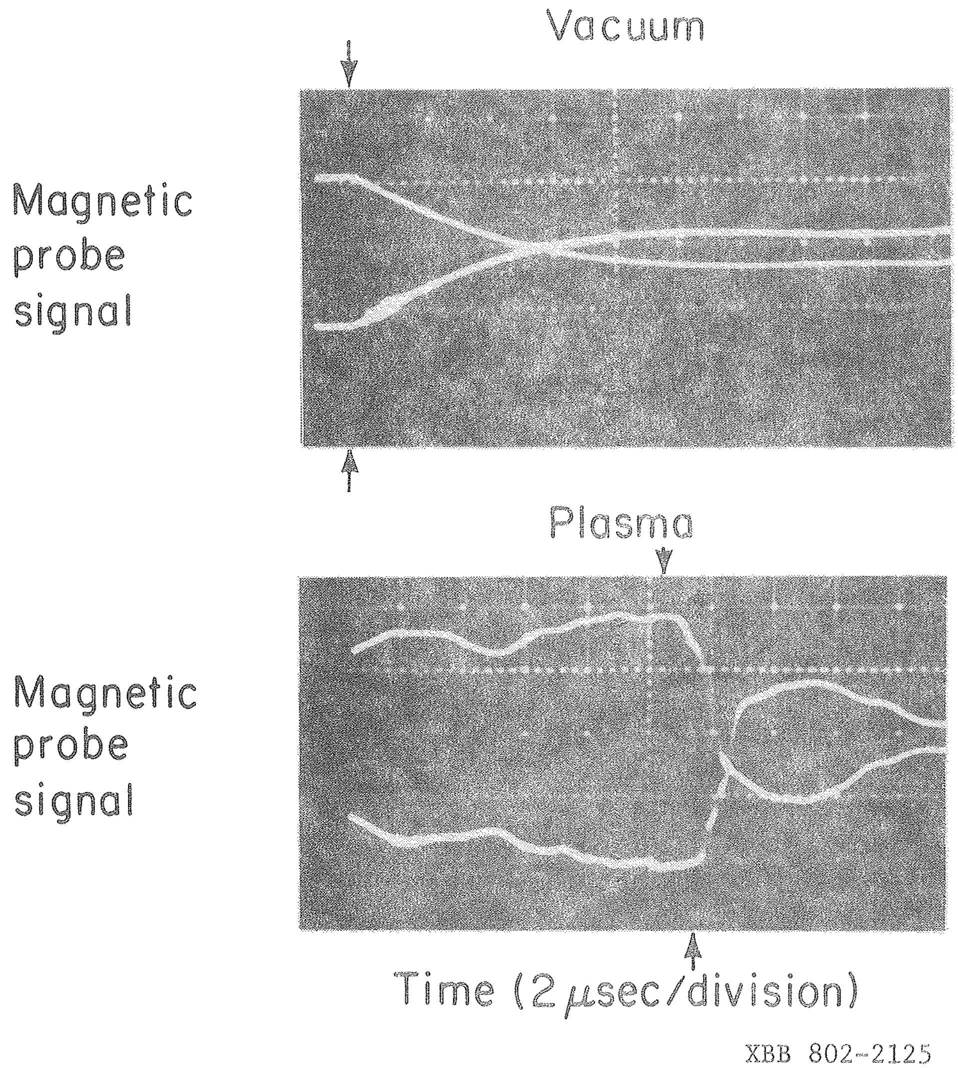


Fig. 4a



XBL 802 - 246

Fig. 4b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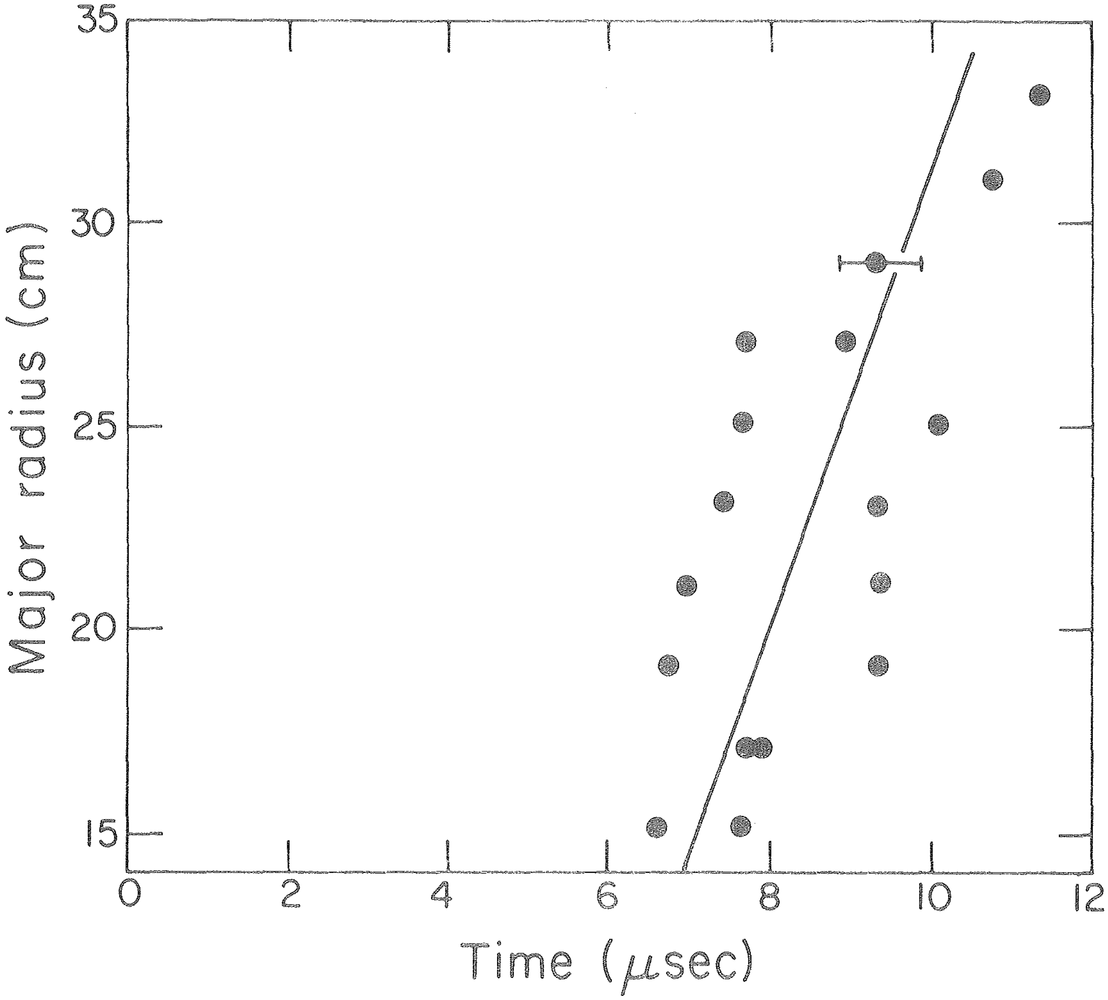
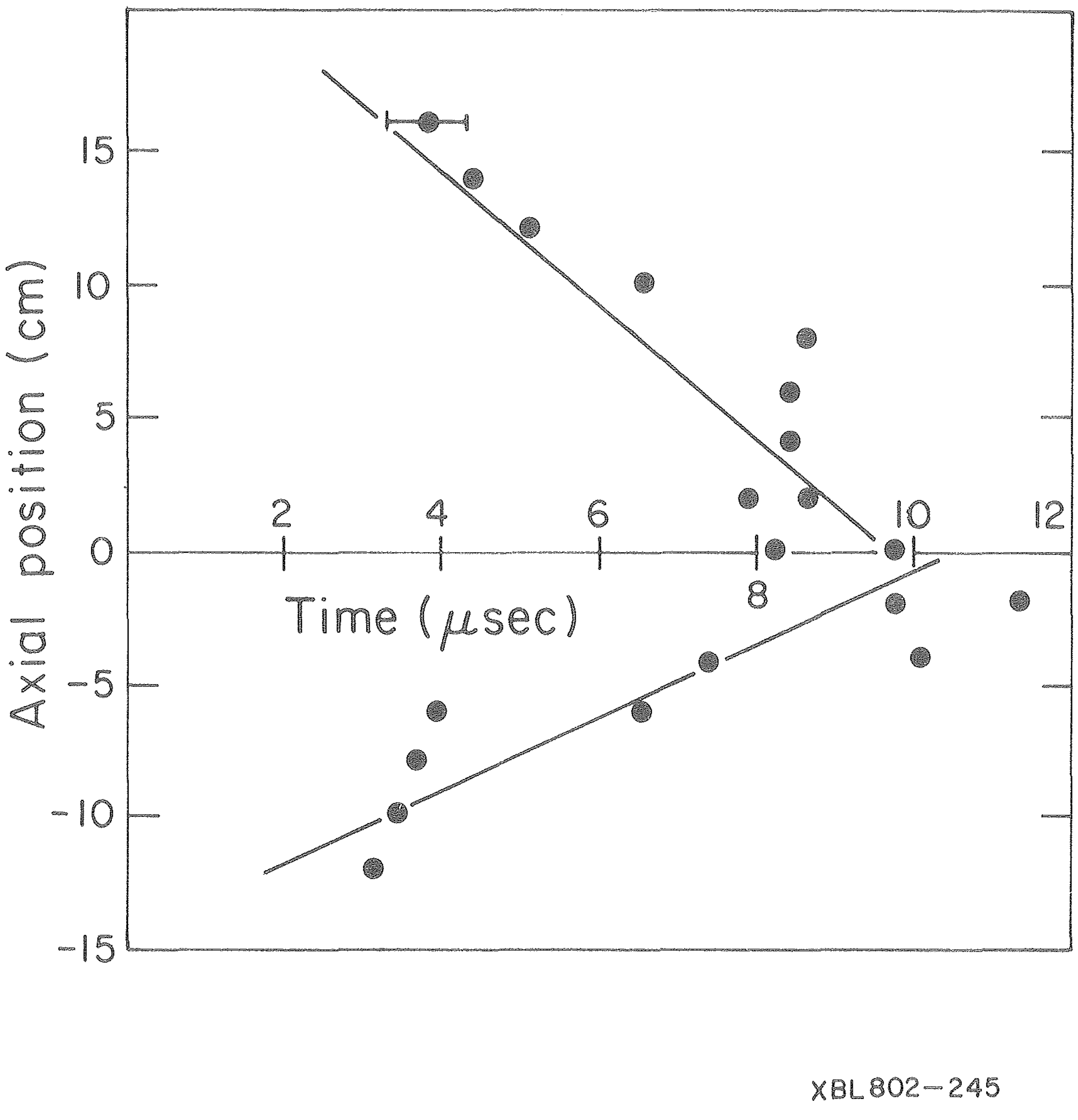
Plasma
Magnetic probe signal
Time (2 μsec/division)
XBB 802-2125

Fig. 5



XBL 802-247

Fig. 6a


Axial position (cm)
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5
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-5
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6
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10
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Time (μsec)
XBL 802-245

Fig. 6b

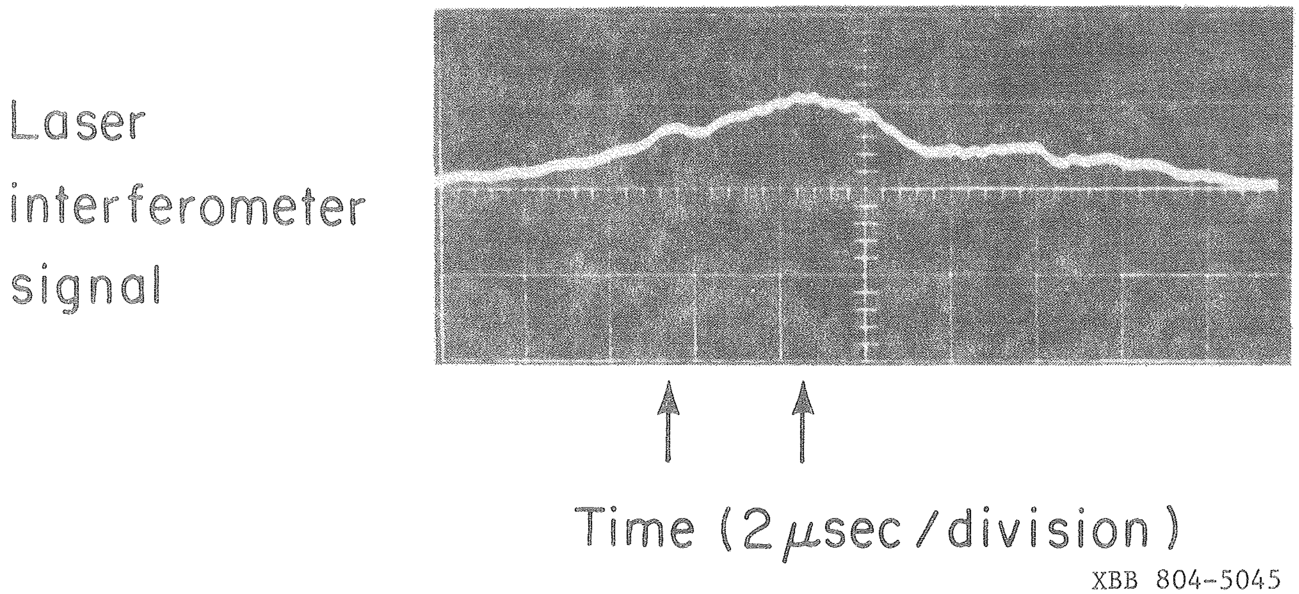
Laser
interferometer
signal
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Fig. 7

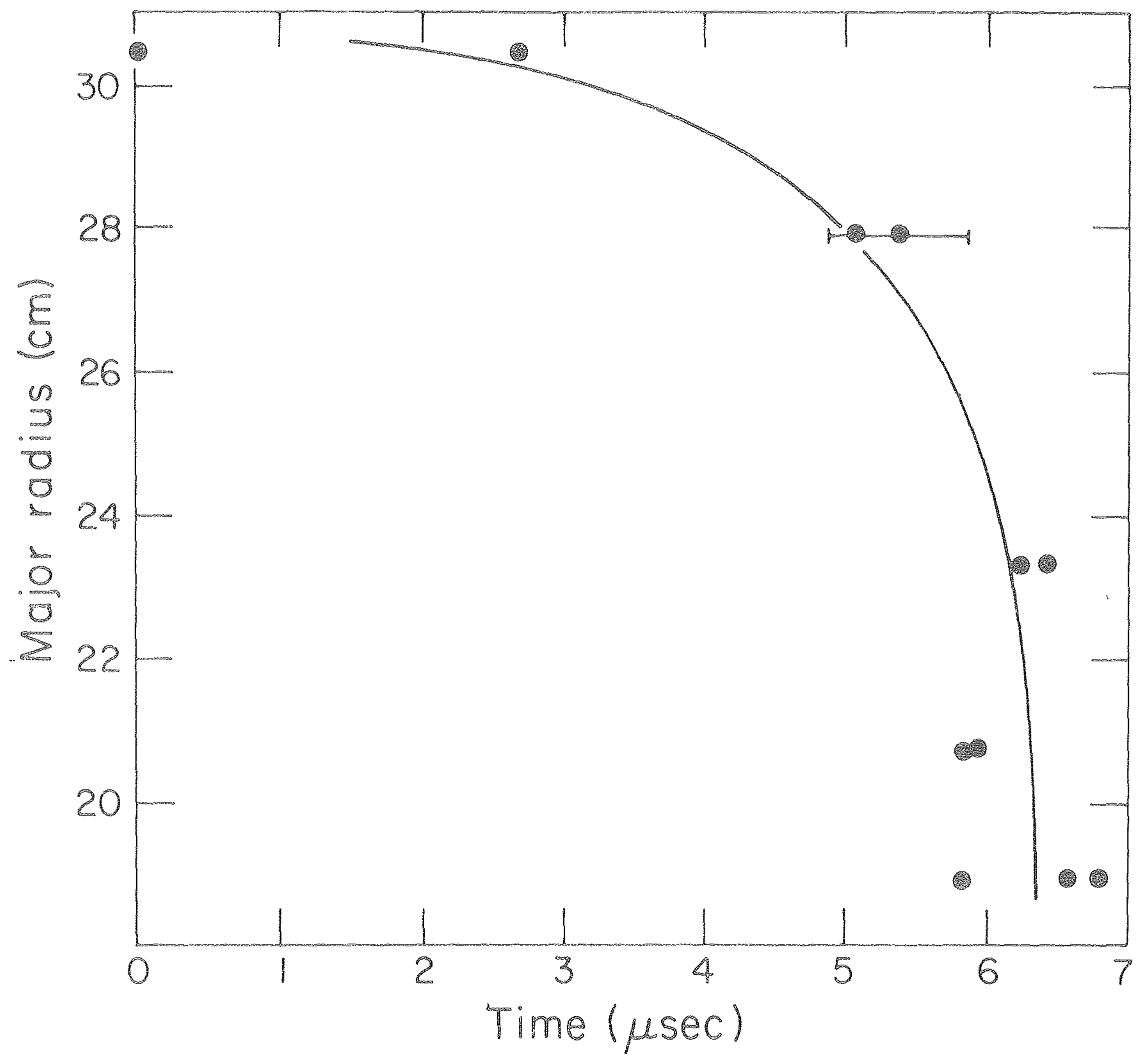

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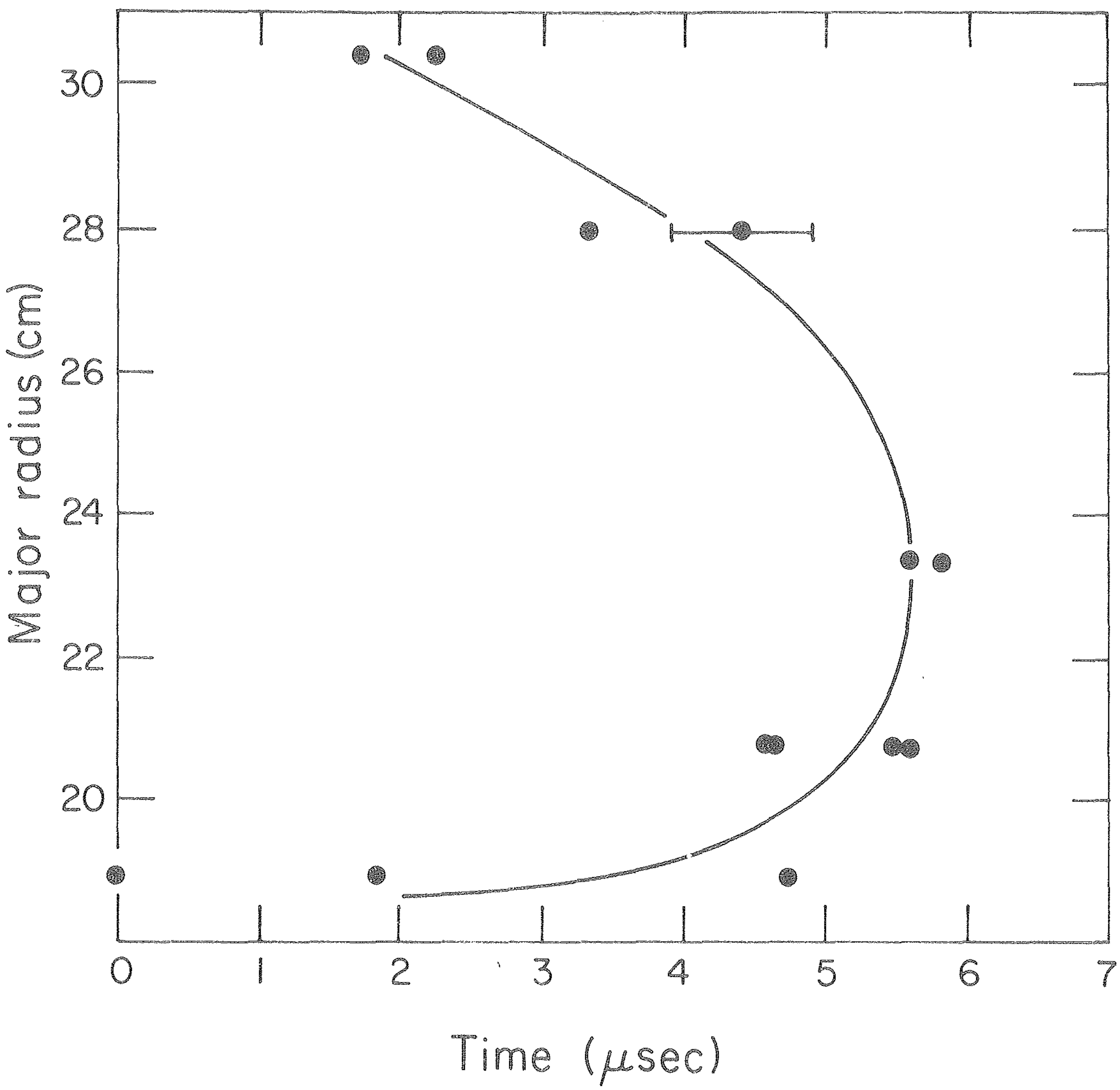
Fig. 8



XBL 802-243

Fig. 9