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In this paper we report our initial results on the formation of compact toroidal plasmas in an oblate shaped metallic flux conserver similar to that used previously by Jarboe, et al[1] at Los Alamos Scientific Laboratory. A schematic of the experimental apparatus is shown in Fig. 1. The plasma injector is a coaxial plasma gun with solenoid coils wound on the inner and outer electrodes. The electrode length is 100 cm, the diameter of the inner (outer) electrode is 19.3 cm (32.4 cm). Deuterium gas is puffed into the region between electrodes by eight pulsed valves located on the outer electrode 50 cm from the end of the gun. The gun injects into a cylindrically symmetrical copper shell (wall thickness = 1.6 mm) which acts as a flux conserver for the time scale of experiments reported here. The copper shell consists of a transition cylinder 30 cm long, 34 cm in diameter, a cylindrical oblate pill box 40 cm long, 75 cm in diameter and a downstream cylinder 30 cm long, 30 cm in diameter. The gap between the gun and transition cylinder is 6 cm. An axial array of coils outside the vacuum chamber can be used to establish an initial uniform bias field.

Axial and radial arrays of probes shown in Fig. 1 are used for measurements of internal magnetic field profiles. A He-Ne (6328Å) interferometer has been used to measure line density. Photographs of the gun discharge have been taken with a framing camera. Recently we have added a number of additional diagnostics; bolometer, VUV spectrometer, collimated secondary electron emitting diode, radial Langmuir probe, radial piezoelectric pressure probe, PIN diodes, 2 mm microwave interferometer and magnetic loops on the outside of the flux conserver.

We will first summarize qualitatively the main results obtained with the apparatus in Fig. 1 and then follow with detailed examples from the experiment. Initially a uniform bias field (which may be zero) is established in the flux conserver. The inner electrode solenoid is pulsed on to produce a relatively strong field inside the inner electrode, a radial field at the end of the gun and a return field in the gap between gun electrodes. The vacuum field strength of the inner electrode solenoid falls off rapidly with increasing distance from the end of the gun — decreasing from several kilo Gauss at the end of the gun to less than 100 Gauss at the center of the transition region of the flux conserver shown in Fig. 1. The gun discharge is initiated and the j x B force axially elongates the inner

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solenoid field lines until the volume of the transition region and flux conserver are filled with plasma currents and several kilo Gauss magnetic fields. The field strength in the transition region then decays rapidly to zero while persisting for a much longer time in the oblate region of the flux conserver. From this we infer that some of the elongated field lines have undergone reconnection and resulted in formation of an isolated closed flux surface toroidal plasma in the oblate region of the flux conserver. With zero initial bias flux, the major axis of the toroidal plasma is along the symmetry axis of the experiment and the magnetic axis encircles the symmetry axis. Toroidal and poloidal magnetic field components are present in a nearly force free configuration analogous to "Taylor states" for the reversed field pinch.(2) As the bias flux (with orientation opposing the inner electrode solenoid field) is increased from zero, the radius of the magnetic axis shrinks until a critical ratio of bias flux to closed field line poloidal flux is reached. Above this ratio, the oblate shape of the flux conserver is no longer effective for stabilizing the $n = 1$ tilting mode(3) and the major axis of the toroidal plasma flips.

We now turn to the detailed discussion of experimental results. Figures 2, 3 and 4 show the plasma gun discharge characteristic and magnetic field profiles for a particular shot. For this shot, the initial bias field in the flux conserver was zero, the inner electrode flux was 1465 $kG\text{-}cm^{-2}$ and the outer electrode solenoid was shorted, producing a return field 1.4 kG in the gap between electrodes. The gun discharge capacitor bank (232 μF) was charged to 30 kV. The total gas fill in the eight gas valve plenum chambers was 29 Torr-$ℓD_2$. The discharge was initiated 225 μs after opening the gas valves. The gun discharge current reaches a peak value 830 kA and falls to 650 kA when plasma begins to leave the gun muzzle (inferred from downstream magnetic signals). The initial magnetic pulse propagates axially with a velocity 5×10^7 cm/sec. Profiles of the B_z component of magnetic field along the symmetry axis are shown in Figure 3 at $t = 6$ μsec and 36 μsec after plasma leaves the gun. An outline of the axial locations of the gun and flux conserver is also shown in Figure 3. At 6 μsec the peak amplitude of magnetic signal extends back into the center of the transition region indicating elongation of field lines from the inner electrode solenoid. At 36 μs the field in the transition region has decayed to zero while fields of 6.5 kG persist in the oblate region of the flux conserver. For reference the vacuum field on the symmetry axis due to the inner electrode solenoid of the gun is 5.0 kG at the gas valves, 2.5 kG at the gun muzzle and .05 kG at the position of the first probe measurement in Figure 3. The profile at $t = 36$ μs in Figure 3 is asymmetrical with respect to $z = 0$ because of insertion of a truncated 45° cone in the exit cylinder of the flux conserver. As will be discussed below this cone has some influence on stabilizing the tilting instability when bias flux is added to the flux conserver. Radial profiles of B_z and B_x at $z = 0$ cm are shown in Figure 4. These profiles have the symmetry expected for a toroidal plasma with major axis along the symmetry axis of the flux conserver and magnetic axis at a radius $R_o = 22 - 24$ cm (B_z = poloidal component, B_x = toroidal component). The B_z component is 5 kG maximum at $y = 0$ cm, is zero at $y = \pm 23$ cm, and reverses sign near the flux conserver wall. Within experimental error the net B_z flux inside the copper shell at $r = 37.5$ cm is zero, as expected for a flux conserving boundary. The B_x component is zero at $y = 0$, reaches a peak value 4 kG and has opposite polarity above and below the symmetry axis. Taken together

Figures 3 and 4 are evidence that a toroidal closed field line plasma has been formed in the oblate region of the flux conserver and is detached from the plasma gun electrodes.

From the magnetic profiles in Figure 4 we estimate the following; toroidal current, I_{tor} = 175 kA, poloidal current I_{pol} = 260 kA, poloidal flux ϕ_{pol} = 3800 kG-cm^2, toroidal flux 1000 kG-cm^2, poloidal field energy W_{pol} = 3.7 kJ, toroidal field energy 1.7 kJ.

Figure 5 illustrates the time behavior of magnetic signals at two positions on the symmetry axis for the experimental conditions of Figures 2 to 4. The probe in Figure 5 (a) is at the center of the transition region near where reconnection occurs and the plasma becomes detached from the gun discharge. The probe in Figure 5 (b) is at the center of the oblate region of the flux conserver. Ten microseconds after the first appearance of signals the field in the transition section has dropped to zero while the field in the oblate section is at its maximum value 8.6 kG and then decays nearly linearly to zero. The time τ_B for the signal in Figure 5 (b) to decay to $\frac{1}{e}$ of its peak value is about 110 μsec.

He-Ne interferometer measurements of plasma line density have been made along horizontal lines of sight just above the probe positions shown in Figure 5 — i.e. at the center of the transition section and center of the oblate section of the flux conserver. For the conditions of Figures 2 to 5 the peak line density at the center of the transition section is 6×10^{16} cm^{-2} and at the center of the oblate section is 1.7×10^{17} cm^{-2}. At the center of the oblate section this corresponds to a chord average electron density n_e = 2.2×10^{15} cm^{-3}. The line density decays much more slowly and with different time behavior than the magnetic signals shown in Figure 5. Roughly plasma density decays to zero in the transition region in ~ 200 μsec and in the oblate region in ~ 500 μsec. There is no apparent abrupt change in line density in the transition region when reconnection occurs.

Measurements of plasma thermal pressure with a piezo electric crystal coupled to a quartz acoustic delay line inserted in the plasma give an upper limit $P = n_i kT_i + n_e kT_e < 10^4$ Joules/m^3. For $n_e = 2. \times 10^{15}$ cm^{-3} and $n_i \approx n_e$ this gives an upper limit on plasma temperature $T_i = T_e < 15$ eV. For $\bar{B}$ = 5 kG the corresponding local plasma beta is less than 10% and we conclude that the plasma configuration is essentially force free. The profiles in Figure 4 are in agreement with 2-D equilibrium calculations of pressureless force free equilibria.(4)

We have taken some data with an axial bias field opposing the field in the inner electrode of the plasma gun. Figures 6 and 7 indicate, first schematically and then with experimental data, a particular case where the plasma is initially formed with its major axis along the symmetry axis and then rotates 90° about the vertical axis. In this particular case the bias field was 200 G and the ratio of bias flux trapped in the flux conserver to closed poloidal flux in Figure 7 (a) is 0.23. The plasma begins to rotate almost immediately after the snapshot of Figure 7 (a) until the profiles in Figure 7 (b) are obtained 30 sec later. Oscilloscope photographs of B_z at the center of the flux conserver indicate that after an additional 40 μsec the plasma has rotated 180° and then decays with $\tau_{\bar{B}}$ = 70 μs. The data in

Figure 7 were obtained without the 45° cone placed in the exit cylinder of the flux conserver, as sketched in Figure 2. If the cone is in place the plasma decays without tilting for a bias field of 100 G. When the bias field is raised to 200 G the plasma tilts after a delay of 130 μs instead of beginning to tilt almost immediately after formation as in Figure 7.

At the present time our measurements do not identify the factors responsible for the field decay rate τ_B = 110 μsec. For resistive decay of poloidal flux we can calculate the decay time τ_η of the lowest energy force free normal mode in a cylindrical flux conserver[5]

$$\tau_\eta = \frac{\mu_o R^2}{\eta} \frac{1}{\left[14.7 + \left(\frac{\pi R}{L}\right)^2\right]}$$

where η = plasma resistivity, R = radius of flux conserver = .375 m and L = length of flux conserver = .40 m. For Z = 1 the classical resistivity is given by

$$\eta = \frac{.51 \times 10^{-4} \, \ell n\Lambda}{T_e \, (eV)^{3/2}} \text{ ohm-m}$$

where

$$\ell n\Lambda = 24 - \log \frac{n_e \, (cm^{-3})^{1/2}}{T_e \, (eV)} .$$

Inserting T_e = 15 eV, which is an upper limit from the pressure measurements, and $n_e = 2 \times 10^{15}$ cm^{-3} gives $\tau_\eta \approx$ 950 μs or a decay anomaly of approximately 9. For T_e = 4 eV we get $\tau_\eta \approx$ 130 μs, approximately in agreement with the experiment.

We would like to thank the Los Alamos plasma gun group for many helpful discussions related to the work reported in this paper.

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EXPERIMENTAL CONFIGURATION

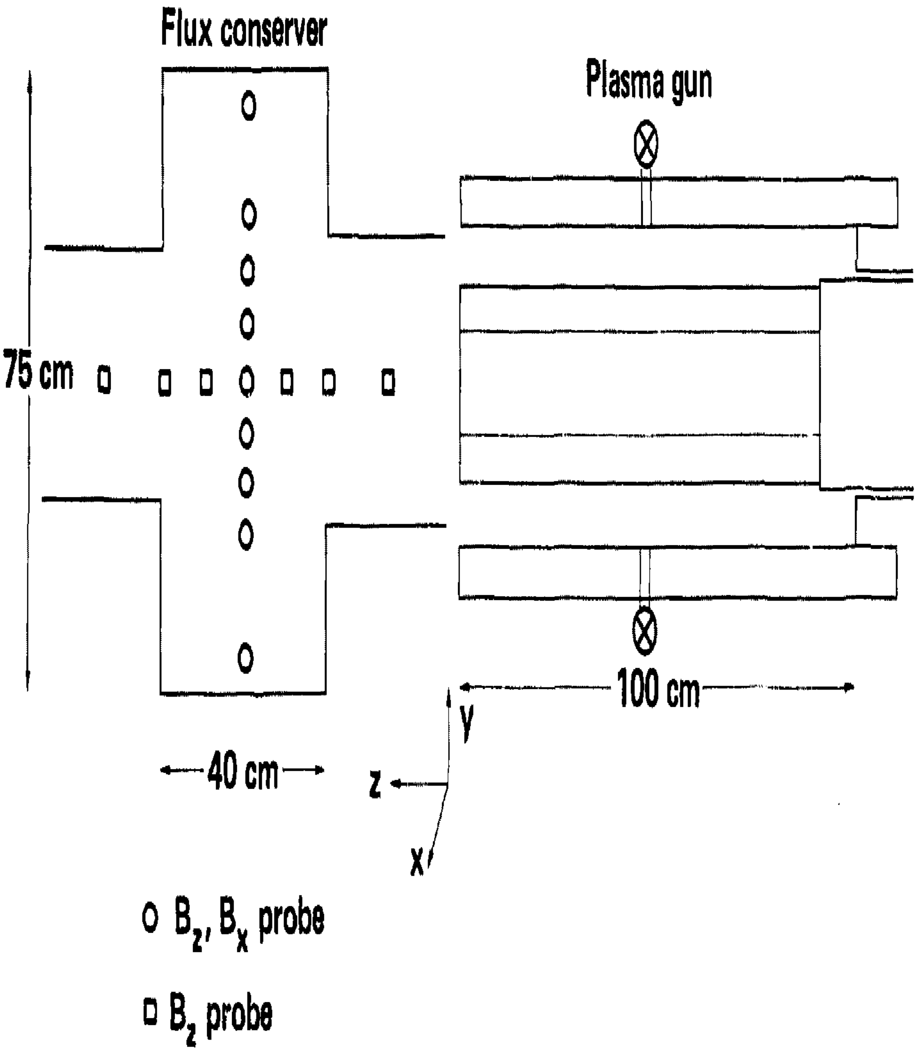


FIGURE 1

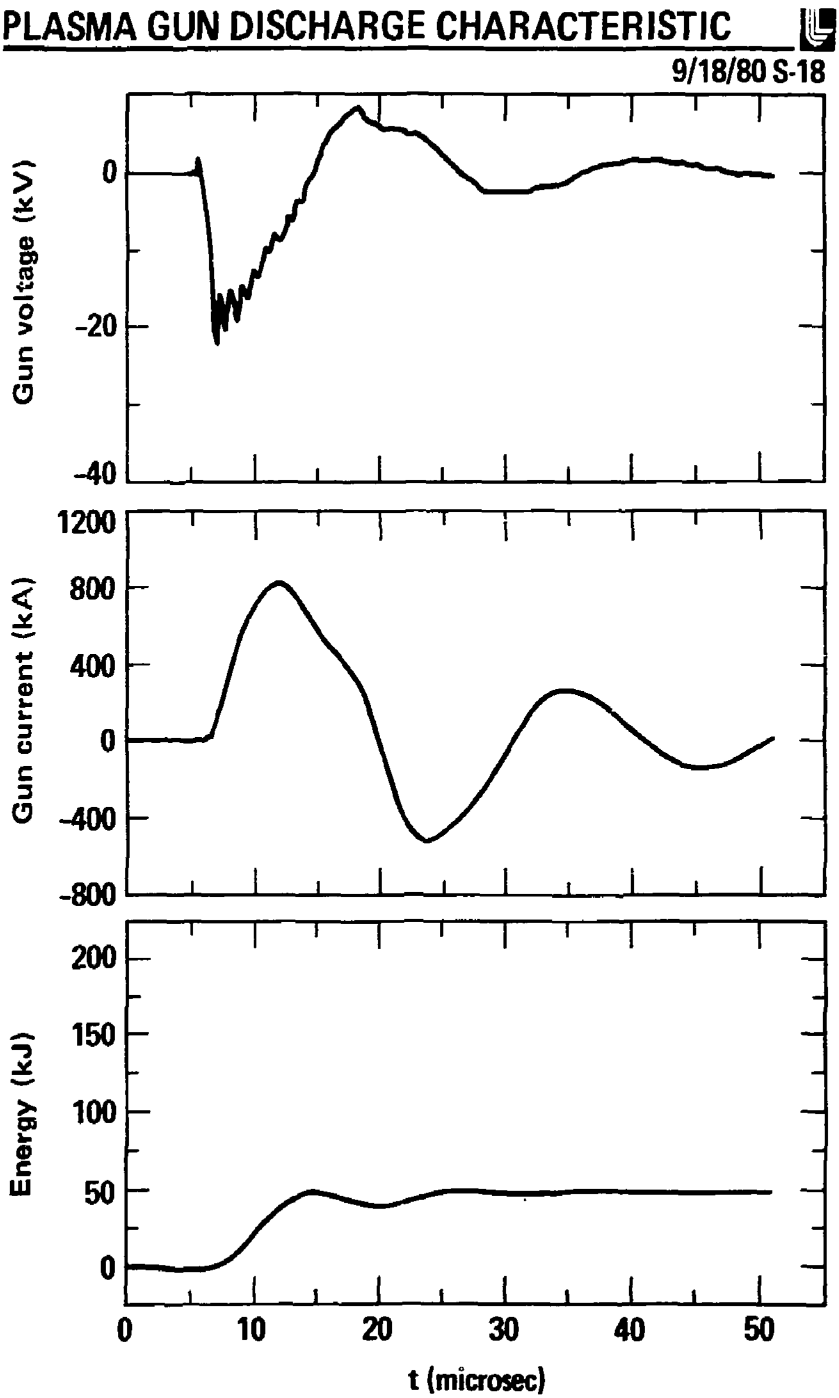

PLASMA GUN DISCHARGE CHARACTERISTIC
9/18/80 S-18
Gun voltage (kV)
0
-20
-40
Gun current (kA)
1200
800
400
0
-400
-800
Energy (kJ)
200
150
100
50
0
0
10
20
30
40
50
t (microsec)

FIGURE 2

MAGNETIC FIELD PROFILES ON THE FLUX CONSERVER AXIS

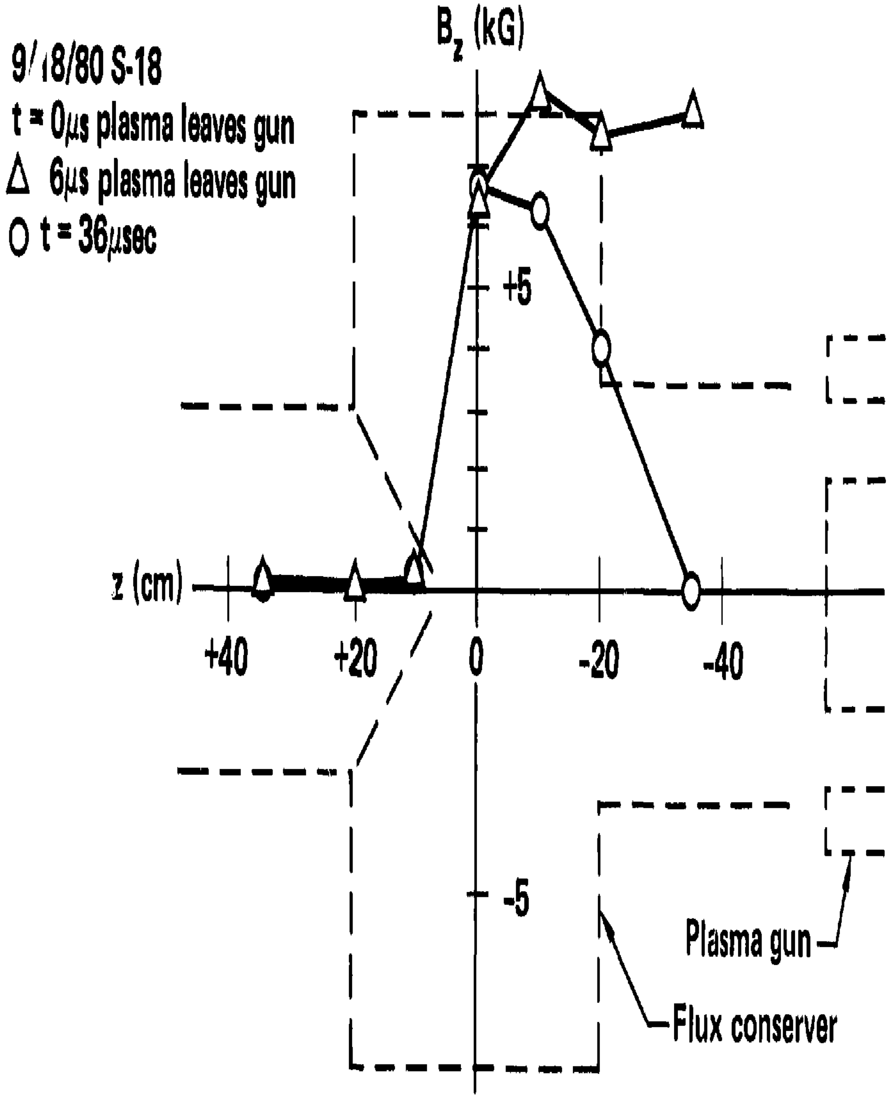


FIGURE 3

VERTICAL PROFILES OF B_z AND B_x IN THE FLUX CONSERVER MIDPLANE

9/18/80
S-18
t=26μs

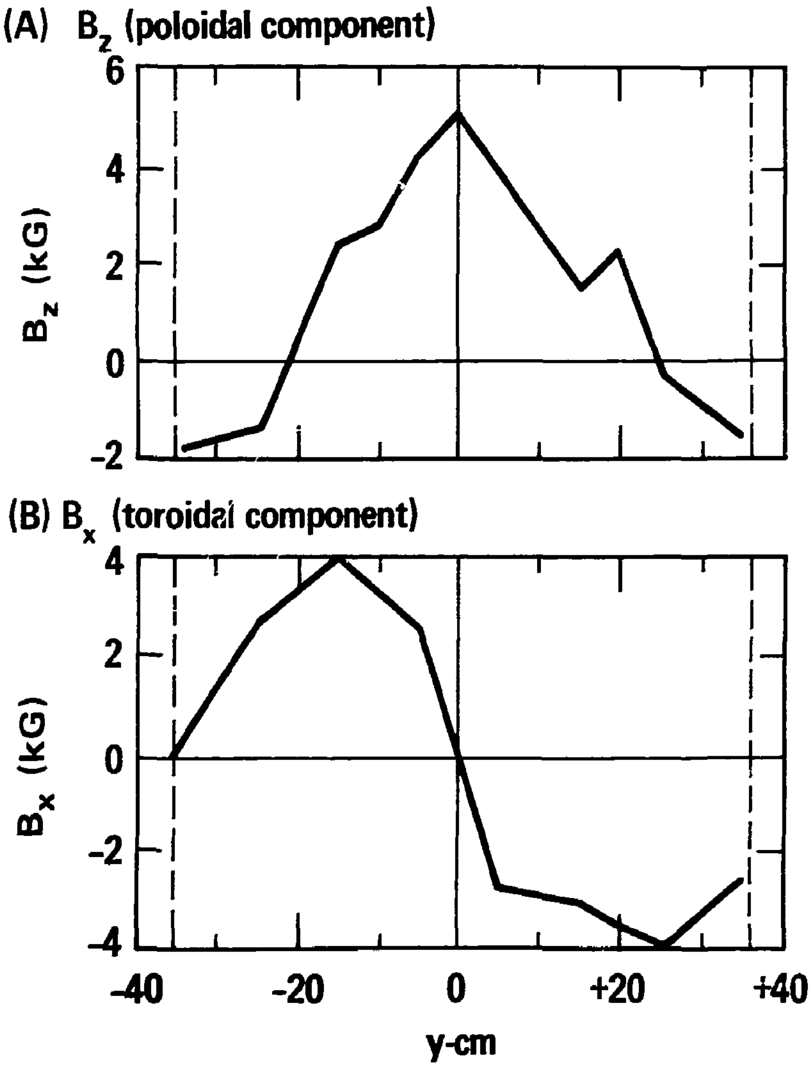
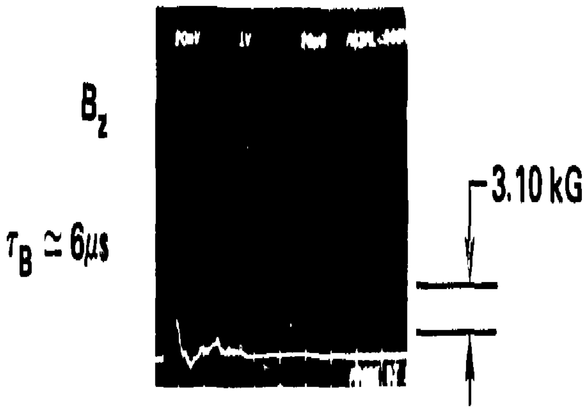


FIGURE 4

ILLUSTRATION OF DECAY OF MAGNETIC FIELD AT TWO AXIAL LOCATIONS

9/15/80 S-28

(A) Center of transition region (Z = 22 cm from the plasma gun)



(B) Center of flux conserver (Z = 57 cm from the plasma gun)

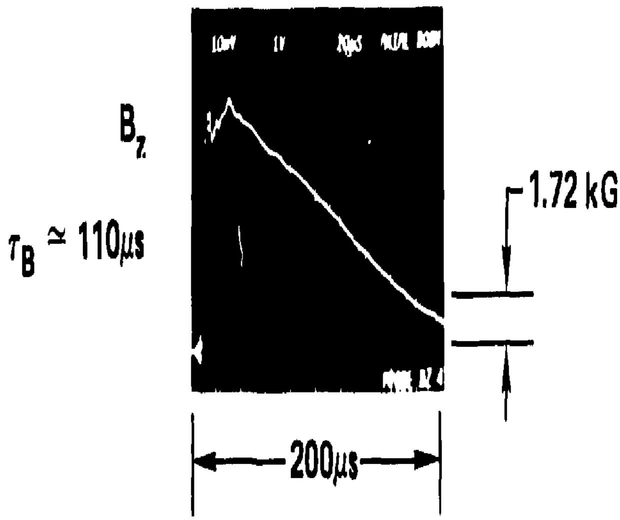


FIGURE 5

SCHEMATIC OF PROBE SIGNATURE FOR 90° ROTATION ABOUT PROBE AXIS

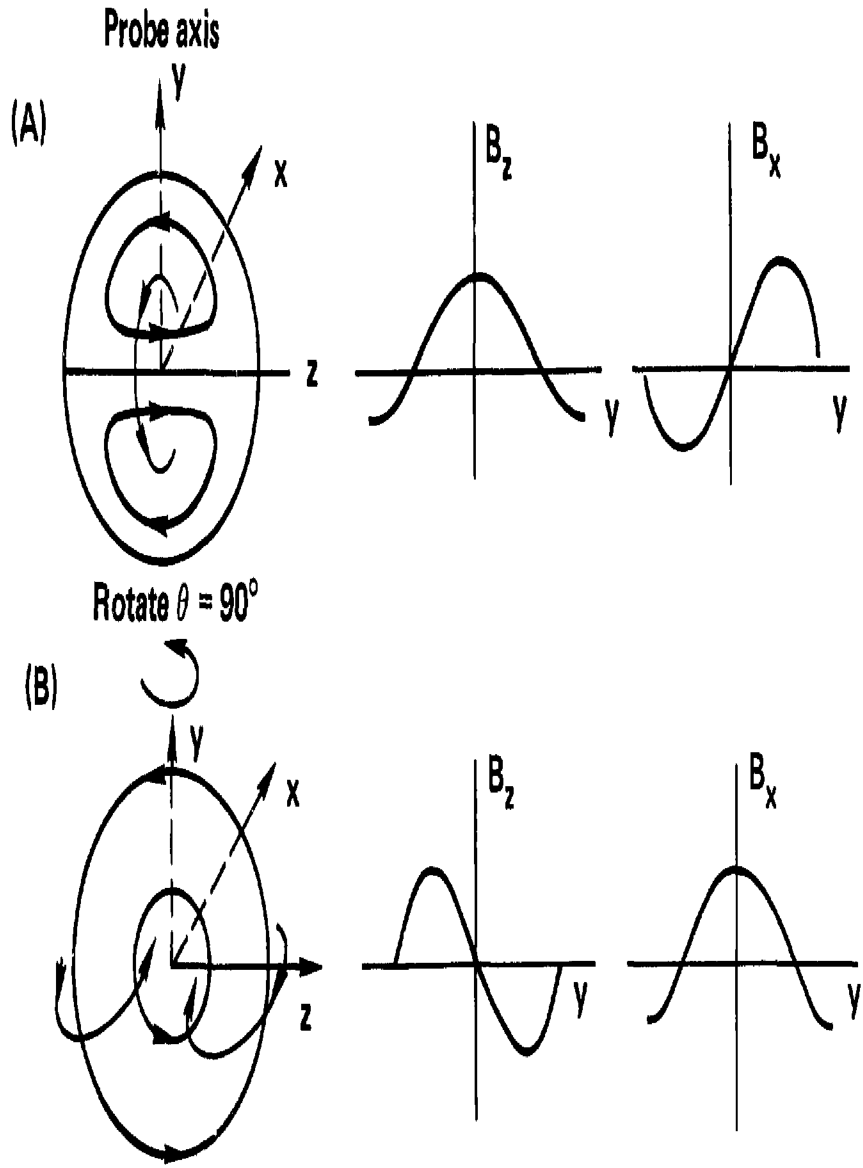


FIGURE 6

EXAMPLE OF BIAS FLUX INDUCED TILTING

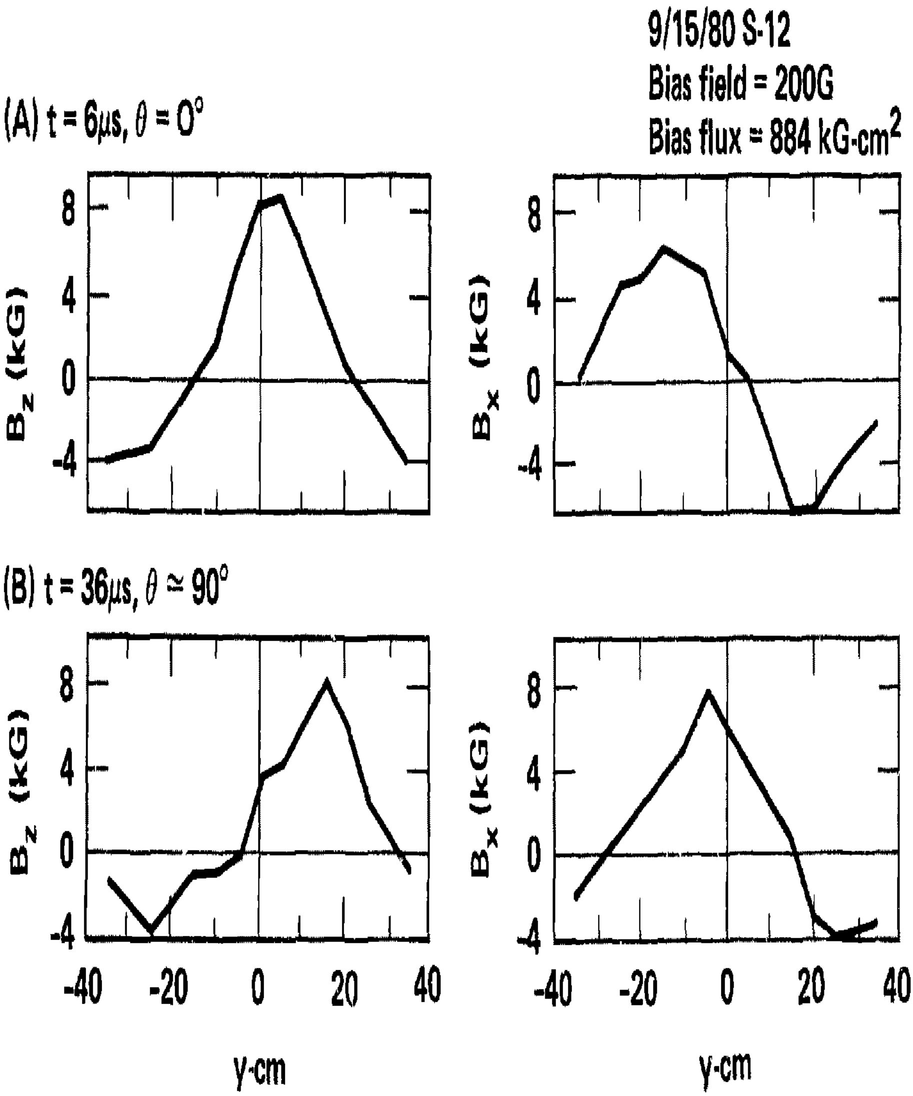


FIGURE 7