Motion of a Compact Toroid inside a Cylindrical Flux Conserver

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Compact toroids have been generated in a cylindrical resistive flux conserver. They are observed to rotate so that their major axis is perpendicular to the axis of the flux conserver. Subsequently they remain stationary and their magnetic fields decay with a time constant of about 100 μs. This is the first observation of the predicted tipping mode and its saturation when no external fields are present. The compact toroids contain toroidal fields and are initially prolate in shape.

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A compact toroid (CT) is a toroidal magnetic-plasma-containment geometry in which no conductors or vacuum-chamber walls pass through the hole in the torus. This property could simplify the construction and maintenance of fusion reactors. For example, it allows the reacting plasma to be transported. A CT could contain poloidal and toroidal field components. CT's have been created with and without the use of toroidal field by pinch techniques.[1-3] This publication reports the motion of CT's generated inside a prolate metal cylindrical shell. The important observations are the following: (a) These CT's are unstable to the predicted tipping mode,[4] and the mode saturates when the major "axis" of the now distorted compact "toroid" is perpendicular to the axis of the flux conserver. (See Fig. 1.) (b) They have little or no axial motion within the flux conserver. (c) After the saturation of the tipping mode they appear to be stable with magnetic field lifetimes of about 100 μs.

The CT's are generated utilizing in part a technique pioneered by Alfvên *et al.*,[5] and extended by us to a higher-temperature fully ionized plasma regime. Recent interest in this method of CT generation was stimulated by C. Hartman of Lawrence Livermore Laboratory, where experiments utilizing a similar approach are also being pursued in the Beta-II Facility. In the present experiment a coaxial plasma gun has a solenoidal coil placed inside the inner electrode. This coil produces axial magnetic field inside the inner electrode which diverges at the gun muzzle becoming radial. When the gun is fired, the highly conductive emerging plasma stretches the radial field lines in the axial direction away from the gun. These elongated field lines reconnect behind the plasma forming the closed poloidal field of the CT, with the magnetic field generated by the gun current becoming the embedded toroidal field.

Before it tips the major axis of the CT coincides with the axis of the coaxial gun.

We have observed the generation and tipping of these CT's when they are formed in a 0.46-m-diam, 1.2-m-long, 1.6-mm-thick stainless steel, quasi-flux-conserving shell (L/R time ~ 300 μs) placed 0.13 m from the gun muzzle. The length of the gun is 0.70 m and the inner and outer electrodes have radii of 0.10 and 0.15 m, respectively. For the observations reported here, the total D_2 gas puffed into the gun with a fast valve is 0.57 Torr·liter. About 150 μs after the gas is puffed, the gun is energized with a 37-μF capacitor bank charged to 45 kV. About 2 μs after the initiation of the discharge the gas current peaks with a value of 0.8 MA, and falls to about one-third of this value at 3.5 μs when the plasma current sheath reaches the gun muzzle. The gun ab-

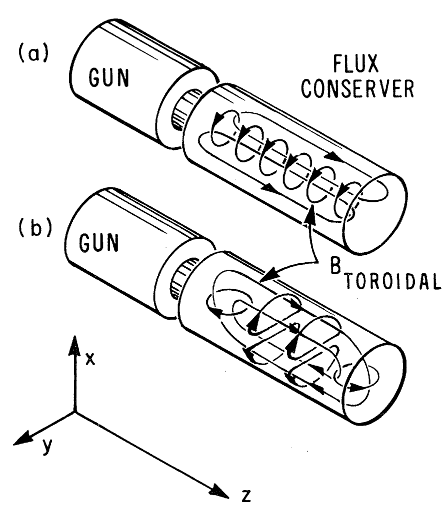

FIG. 1. Schematic of the CT's orientation and shape (a) before and (b) after its major axis rotates by 90°. Note the directions of x, y, and z.

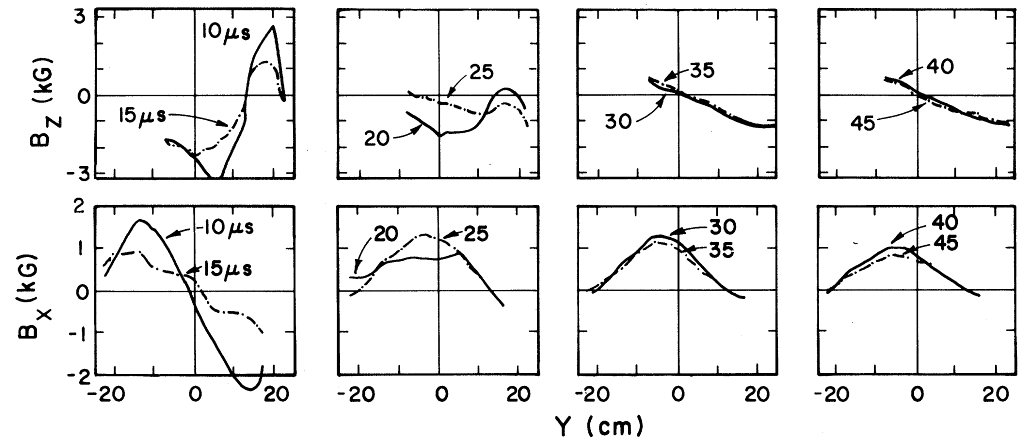

FIG. 2. B_x and B_z vs y at various times. These data are consistent with that produced by a CT which tips as shown in Fig. 1. The data at 10 μs correspond to Fig. 1(a) and the data after 30 μs correspond to Fig. 1(b). Note that these data are taken 0.27 m from the center of the racetrack as shown by the asterisk in Fig. 3.

sorbs more than 80% of the initial energy in the capacitor bank during the first 2.5 μs of the discharge. The addition of an axial magnetic "bias" field between the gun electrodes allows it to be operated with much smaller gas loads and makes the gun more reliable than without this field. The lower density and puff gas filling are factors which contribute to the production of CT's which are disconnected from the gun and which have lifetimes several times longer than previously achieved.

In the flux-conserver region the diagnostics employed were magnetic probes, spectroscopic observation of C V radiation, and an infrared interferometer. When the plasma emerges from the gun muzzle, the probes sense a magnetic disturbance which propagates into the resistive flux-conserving shell at a velocity of about 10^6 m/s. For low values of axial flux inside the inner electrode of the gun the plasma pushes the plasma-magnetic-field configuration completely through the shell and out the other end, whereas for high flux values the configuration hardly leaves the gun. For an intermediate value (~0.015 Wb) used for the data reported here the disturbance propagates into the flux conserver and nearly stops, then reconnection and tipping occur and the configuration remains with little or no axial motion.

A set of 20 B-field probes (pickup coils) in one quartz jacket (holder) is located 0.49 m from the gun muzzle. The probes are located on a diameter of the flux conserver which is parallel to the y axis. (The coordinate system is defined in Fig. 1.) By rotating this set of probes we can measure either B_z or B_x, at 20 y positions simultaneously. These measurements (see Fig. 2) show an overall change in the magnetic field profile occurring over a period of roughly 15 μs starting 10 μs after the gun fires. These data are interpreted as follows: The CT is generated with its major axis parallel to the z axis, [Fig. 1(a)]. The axis of the CT then rotates by 90° to make a more "oblate" racetracklike CT [Fig. 1(b)]. This tipping of a prolate CT has been predicted.[4] For the data presented in this paper, the major axis of the CT rotates in the y-z plane and is parallel to the y axis at the end of the rotation as shown in Fig. 1(b). Figures 1 and 3 should be helpful in understanding the data of Fig. 2.

Figure 3 shows some data from other groups of probes (in three jackets) that have three orthogonal coils at each location so that all components of $\vec{B}$ can be measured simultaneously. These probes and their jackets are in the x-z plane. The probe (coil) locations are indicated in Figs. 3 and 4 by the plusses. The data for Figs. 2 and 3 came from shots which were not typical in that rotation occurred very late. On most shots the field profile has the signature of a rotated toroid very early in time and a prolate CT field structure is not observed. Figure 4 shows data for this this more typical case with more probes being used than in Fig. 3. The data shown in Fig. 3 are consistent with the interpretation of the stopping of a prolate CT and its subsequent rotation of 90°, whereas Fig. 4 shows a rotated CT almost from the beginning. Although the time history varies from shot to shot, the axis of the toroid always ends up perpendicular to the axis of the flux con-

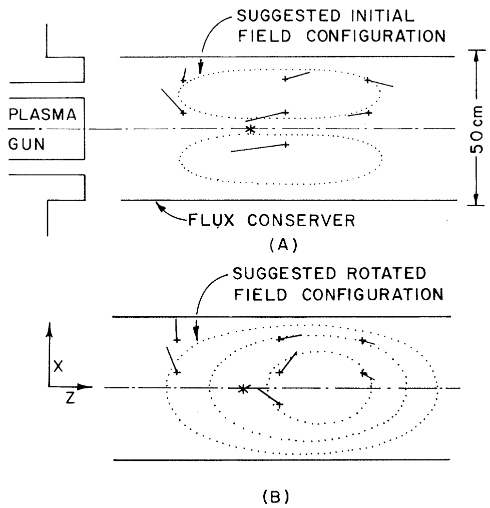

FIG. 3. Magnetic field data from seven multidirectional probes which are in the x-z plane. The plus is the probe location and the line pointing away from it is a vector representation of the component of $\vec{B}$ in the x-z plane. (a) The poloidal fields 15 μs after the initiation of the gun discharge are consistent with a prolate CT. See Fig. 1(a). (b) These final fields (t = 27 μs) are the "toroidal" fields after the CT rotates by 90° and becomes racetrack shaped. See Fig. 1(b). The asterisk represents the position of the jacket (orthogonal to the plane of the figure) of the set of 20 probes which was used to obtain the data of Fig. 2.

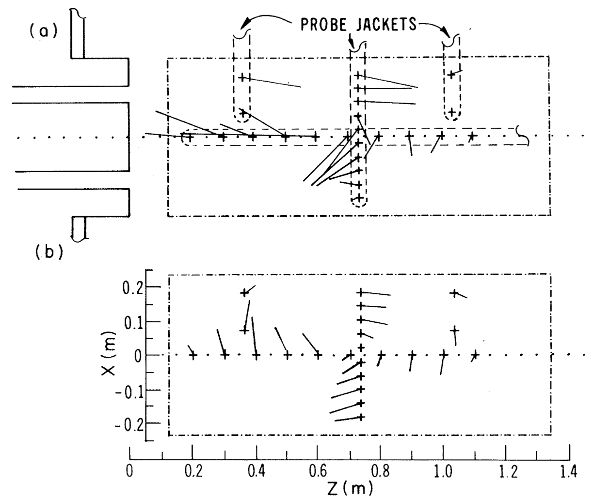

FIG. 4. These typical magnetic-probe data show the toroidal field (a) 5 μs and (b) 45 μs after the gun is fired. This is the same plane as shown in Fig. 3, but more probes are used here.

server. The azimuthal direction of the axis of the final configuration in the x-y plane tends to be the same unless all symmetry-destroying objects such as probe jackets are removed from the flux conserver. In that case the azimuthal direction appears random. From the probes shown in Fig. 4 we can get profiles of B_z, B_y, and B_x for various times. These are shown in Fig. 5, which also shows the poloidal fields (B_y). From these data the poloidal flux is estimated to be about two-thirds of that initially inside the inner electrode of the gun. Once the final configuration is reached it appears to be magnetohydrodynamically stable and the fields decay with a time constant dependent upon the number of probe jackets in the flux conserver. Flux loops on the outside of the flux conserver show that the motion of the CT remains the same when the internal probes are removed. However, the magnetic-field decay time increases from 40 to 100 μs.

To measure the electron density and temperature of the plasma interferometry and spectroscopy are used. With a double-pass 3.4-μm HeNe interferometer it was determined that the average density on a diameter at the midplane of the flux conserver is about $10^{14}/\text{cm}^3$. The time history of the density is similar to that of the magnetic fields. On most shots CV radiation is observed for over 150 μs with all probes removed, which implies that electron temperatures of over 70 eV exist throughout much of the CT's life.

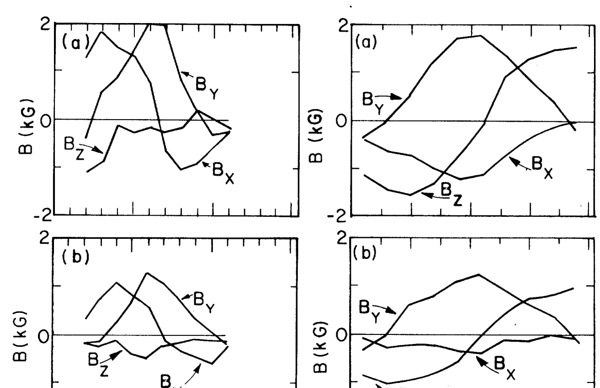

FIG. 5. Magnetic field profiles on the axis and across the midplane of the flux conserver at (a) 25 μs and (b) 45 μs after the gun is fired. The probe locations are shown in Fig. 4. B_y is out of the plane of the paper and hence not shown in Fig. 4. It is in the direction of the poloidal field. Axial distance is measured from the gun muzzle.

A compact-toroidal plasma configuration is generated in a prolate cylindrical resistive flux conserver with use of a magnetized coaxial plasma gun. If the initial poloidal field strength of the magnetized gun is adjusted appropriately the configuration is observed to stop within the flux conserver. In a few cases the toroid stops oriented with its major axis parallel to the axis of the plasma gun and the flux conserver, but then rotates so that its axis is orthogonal to the original axis of symmetry. This tipping mode has been predicted.[4] In most cases the stopped toroid is first observed in an already rotated configuration. After this rotation, the deformed toroid appears to be magnetohydrodynamically stable and decays away with about a 100-μs time constant. C V radiation is observed throughout the lifetime of the magnetic field structure. Interferometric measurements show an initial value of about 10^{14} cm^{-3} and a lifetime for the plasma density similar to the magnetic field lifetime.

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