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TITLE: PRODUCTION OF FIELD-REVERSED CONFIGURATIONS WITH A MAGNETIZED COAXIAL PLASMA GUN

MASTER

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Production of Field-Reversed Configurations With a Magnetized Coaxial Plasma Gun

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ABSTRACT

We have generated compact toroids which can be made to come to rest 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 appear to remain stationary and decay with a time constant of about 100 μs. We have also generated compact toroids in an oblate geometry which remain aligned with the axis of the flux conserver and decay with a time constant of 150 μs. The magnetic field reconnection time for compact toroid formation is measured in the latter case to be much shorter than the decay time.

A compact toroid is a toroidal magnetic plasma containment geometry, in which no conductors or vacuum chamber walls pass through the hole in the torus. This latter property could ease the constraints upon the construction and maintenance of a reactor. For example, it would allow the reacting plasma

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to be translated. A compact toroid could contain both poloidal and toroidal field components. Compact toroids created without the use of toroidal field have been observed in experiments.[1-2] This paper reports the production of compact toroids with toroidal field utilizing in part a technique pioneered by Alfven et al,[3] but extended by us to a higher temperature fully ionized plasma regime. In the present experiment a solenoidal coil is placed inside the inner electrode of a coaxial plasma gun. This coil produces axial magnetic field inside the inner electrode which diverges and becomes a largely radial field in front of the gun muzzle. When the gun is fired, the 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 compact toroid, while the magnetic field generated by the gun current becomes the embedded toroidal field. The major axis of the compact toroid will then coincide with the axis of the coaxial gun.

The length of the coaxial gun used in our experiments is 0.70 m, and its inner and outer electrodes have radii of 0.10 m and 0.15 m respectively. For the results reported here, the total D_2 gas puffed into the gun with a fast valve is 0.75 cm^3 atm. 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 current peaks with a value of 0.8 MA, and it reverses in about 4.5 μs. The gun current has fallen to about one-third of its peak value at 3.5 μs when the plasma current sheath reaches the gun muzzle. The gun absorbs almost all of the initial energy in the capacitor bank during the first 2.5 μs of the discharge. The addition of a magnetic "bias" field between the gun electrodes parallel to the axis of the gun allows it to be operated with much smaller gas loads and makes the gun discharges more reproducible.

Using this magnetized plasma gun we have produced compact toroids in two different flux conservers. The first is a stainless steel cylinder which is 0.46 cm in diameter, 1.2 m long, and 1.6 mm thick. Both ends are open. This cylinder is aligned to be coaxial with the plasma gun, and it is placed 0.13 m from the muzzle. To make measurements in this flux conserver we have employed as diagnostics: magnetic probes, spectroscopic observation of CV radiation, and an infrared interferometer. When the plasma emerges from the gun muzzle, the magnetic probes sense a disturbance which propagates at a velocity of about 10^6 m/s into the resistive flux conserving shell. For low values of initial 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 barely leaves the gun. For an intermediate value of 0.015 Wb, which was used for the data reported here, the disturbance propagates into the flux conserver and essentially stops; then, within the accuracy of our measurements, reconnection occurs and the configuration remains with little or no axial motion. The compact toroids generated in this flux conserver are observed to rotate so that the axis of the compact toroid is perpendicular to the axis of the flux conserver.[4] See Fig. 1. This tipping has been predicted from a δW calculation which shows that prolate compact toroids are unstable to tipping.[5] After rotation the compact toroid assumes a racetrack shape which is oblate-like. Figure 2 shows the magnetic field on axis and also on a diameter at the midplane of the flux conserver. These data are consistent with a rotated compact toroid where the quantities labeled B_z and B_r are two components of the toroidal field and B_θ is the poloidal field. The poloidal flux can be estimated from these data to be two-thirds of that which was put on the gun initially. Flux loops placed on the outside surface of the flux conserver show that the motion of the compact toroid remains the same when the

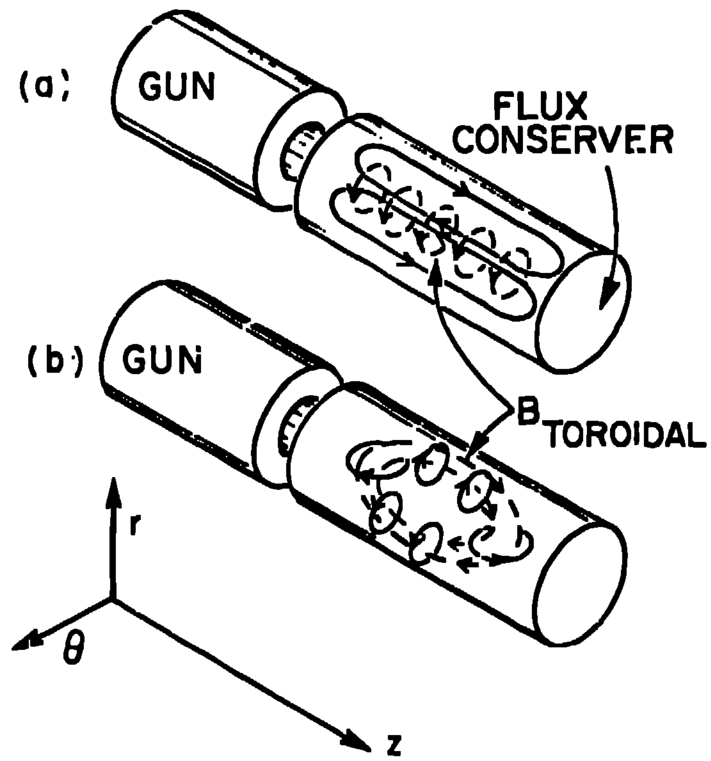

Fig. 1.
Schematic of the compact toroid's positions before and after its major axis rotates 90°.

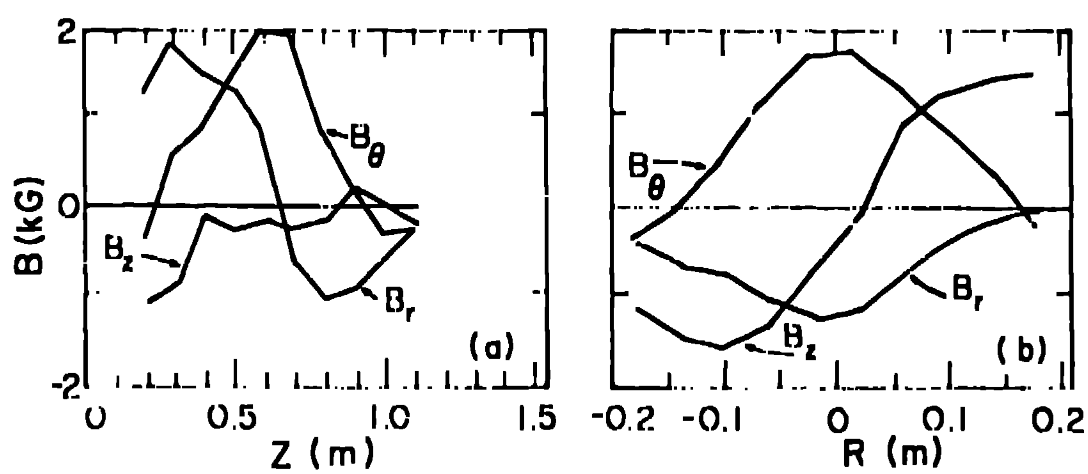

Fig. 2.
Magnetic field profiles on the axis and across the midplane of the prolate flux conserver at 25 μs after the gun is fired.

internal probes are removed. However, the magnetic field decay time increases from 40 μs to 100 μs.

Using a double-pass 3.4-μm HeNe interferometer we have determined that the average density on a diameter at the midplane of the flux conserver is about $10^{14}/cm^3$. The time history of the density is similar to that of the magnetic fields. We observe the existence of CV radiation for over 150 μs if all probes are removed, which implies that there are electron temperatures of over 70 eV throughout much of the compact toroid's life.

We have produced compact toroids when an initial axial magnetic "guide" field was established within the cylindrical stainless steel flux conserver. In the presence of this field the compact toroid was still observed to rotate as described above. However, the characteristic decay time of the magnetic field configuration was only 10–15 μs, i.e., much shorter than comparable conditions without the guide field. We speculate that the rapid destruction in the guide field case is due to reconnection of magnetic field lines in the high shear regions which occur after the toroid rotates, opening previously closed field lines.

In an attempt to stabilize the tipping of compact toroids produced by the magnetized gun, we have generated compact toroids in a second flux conserver having an oblate region incorporated in its geometry. This flux conserver is made of 0.8-mm-thick copper, and a cross section of it is shown in Fig. 3. The plasma from the magnetized gun is injected from the left through the 0.34-m-diameter entrance cylinder into the confining region. With this geometry the tipping no longer occurs and the configuration is stable throughout its life time. We also tried a 0.46-m diameter entrance cylinder and found that the compact toroid still tipped. With the elimination of the complication of tipping, three distinct time scales emerge. The first (~ 1 μs) is the time required to fill the flux conserver with magnetic field and plasma. The second (~ 12 μs) is the time for the decay of the fields in the entrance cylinder. Figure 4a shows this decay. We interpret this decay as being due to field line reconnection which is completed in about 30 μs. The third time (~ 150 μs) is the characteristic time for the decay of the fields in the flux conserver measured after reconnection has occurred. Figure 4b shows this decay. It is interesting to observe that the three time scales 1 μs, 12 μs, and 150 μs have the proper relative values to be an Alfven time, a resistive tearing time, and a resistive decay time respectively.[6]

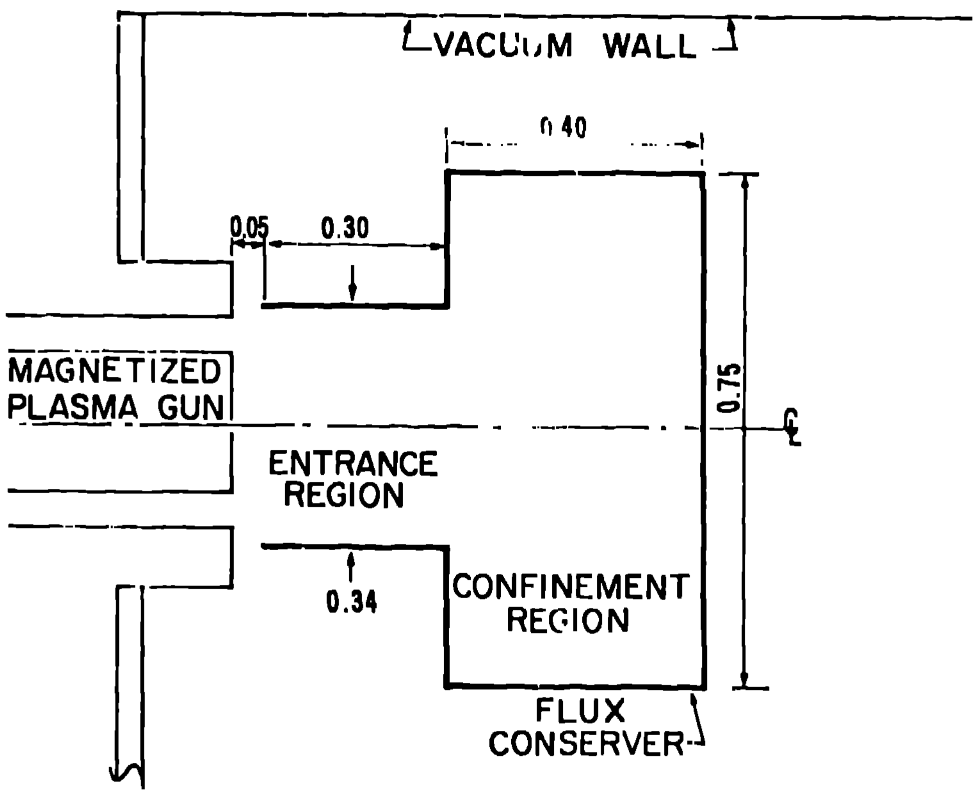

Fig. 3.
Schematic of the geometry for creating a stable compact toroid. It is axially symmetric with dimensions given in meters.

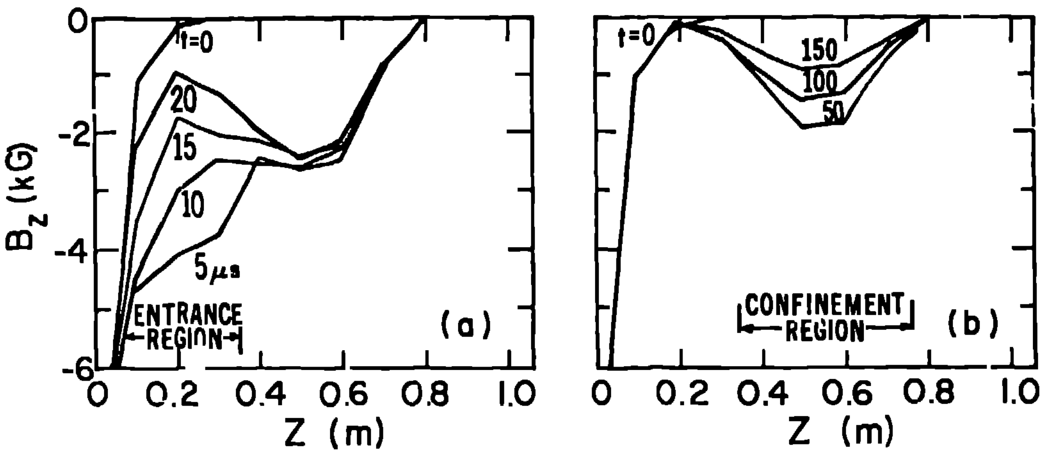

Fig. 4.
Plots of the axial component of the magnetic field on axis at various times. Figure 4a shows plots at various times during the decay of the field in the entrance cylinder. The time elapsed between plots is 5 μs. Figure 4b shows plots at various times during the decay of the compact toroid and the time between plots here is 50 μs. The gun discharge is initiated at t=0 and the plot labeled t=0 shows the value of the axial component of the magnetic field in this region due to the coils which supply the initial axial flux for the plasma gun.

Figures 4b and 2a illustrate the dramatic differences in the fields on the axis of the flux conserver for the stable and rotated toroid. If it does not tip then one expects to have only B_z on axis as is the case in Fig. 4b (the peak transverse components are measured to be less than 15% of the peak B_z and are not shown). When the compact toroid rotates 90° one then expects to have only transverse components on axis. Fig. 2a shows the transverse components (B_θ and B_r) to be much larger than B_z. Thus, the measurement of all components of the magnetic fields on the axis of the flux conserver is a powerful means of determining the extent of tipping.

CONCLUSION

A compact toroidal plasma configuration is generated in a cylindrical resistive flux conserver using 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. For a straight cylindrical flux conserver the axis of the toroid is observed to rotate so that it is orthogonal to the original axis of symmetry. After this rotation, the deformed toroid appears to be MHD stable and decays away with about a 100-μs time constant. CV 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. When a compact toroid is generated in an oblate flux conserver under proper conditions it does not tip as verified by the fact that the transverse fields on axis are small compared to the axial field. In this stable case the reconnecting time (12 μs) can be observed and it is much shorter than the decay time of the fields of the compact toroid (150 μs).

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