As seen in Fig. 1(a), the diabatic signal does indeed increase as the value of n increases. In addition, both ionization features are evident at slew rates differing by a factor of 2 from that used to obtain the data in Fig. 1.

When both lasers are polarized parallel to the direction of the electric field, then theoretically no $|m_l|=2$ can be produced and, in this case, we observe a dramatic decrease in the signal obtained at the diabatic threshold. In view of this test, and since the probability for diabatic passage in a given field slew rate is larger for $|m_l|=2$ states than for $|m_l|=1$ or $|m_l|=0$ states, we conclude that the diabatic high-field peak is due primarily, if not wholly, to $|m_l|=2$.

The signal at electric fields between the adiabatic threshold and the diabatic threshold is attributed to a combination of adiabatic and diabatic passage through level crossings. As n increases, the ratio of this intermediate signal to the diabatic signal drops rapidly.

These measurements demonstrate, for the first time, the passage of highly excited atoms from low electric fields to ionizing electric fields along predominantly diabatic paths. Clearly, it is important to account for the possibility of diabatic thresholds whenever one observes atomic states of high n using field ionization.

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Formation of a Spheromak Plasma Configuration

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A compact, toroidal configuration of magnetized plasma is produced by a combination of Z- and θ-pinch discharges. A paramagnetic toroidal field is produced by currents circulating in the plasma on closed flux surfaces.

We report here our initial results on the formation of a plasma confinement configuration with the generic name of spheromak.[1,2] This compact toroidal configuration has both toroidal (B_φ) and poloidal (B_r, B_z) magnetic field components with the toroidal field maintained by circulating plasma currents rather than by an external coil through the toroidal hole, as in a tokamak. Configurations of this type were first studied theoretically in an astrophysical context.[3,4] Related laboratory experiments involving plasma guns,[5,6] electron beams,[7] and pinches[8] have been performed. Our experiment, called paramagnetic spheromak (PS-1), makes use of Z- and θ-pinch techniques to produce a prolate spheroid configuration. The results show, for the first time, that it is possible to establish the desired closed poloidal flux surfaces with a stabilizing paramagnetic toroidal field (i.e., with the peak magnitude of B_φ near the magnetic axis).

Figure 1 illustrates the formation phase. We start with a cylindrical deuterium gas column of radius 11.4 cm and a pressure of 15 mTorr. The column contains an axial bias magnetic field ($-B_z$) produced by I_φ currents[9] in an external, single-turn mirror coil with a mirror ratio of 1.1. The bias field is produced by a 20-kV, 18-μF capacitor bank capable of producing fields with magnitude up to 8 kG. Typically fields of 4 kG are used. The field rises in 3 to 5 μsec (depending on the external inductance) and is clamped. Following this a Z-directed current shell is produced by discharging a second capacitor bank (30 μF, 10–20 kV) between two annular electrodes with a radius of 7.6 cm located at the ends of the coil. The I_z current rises to a peak value of about 150 kA in 4 μsec. The I_z circuit creates an annular shell of plasma and a slight

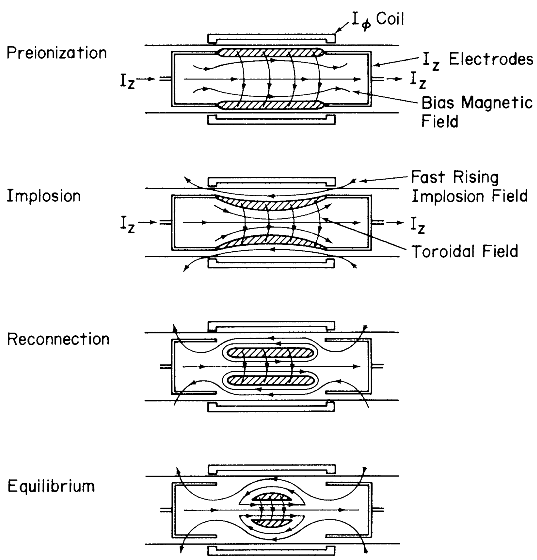

FIG. 1. The formation phase of the configuration.

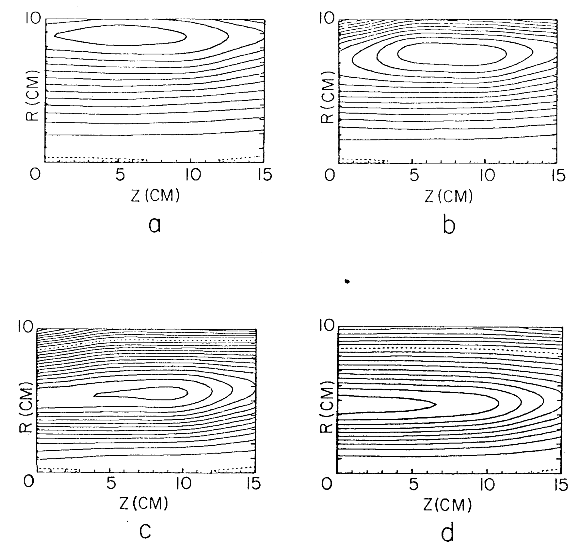

FIG. 2. Surfaces of constant magnetic flux after the start of the fast-rising reversed B_z field. The surfaces obtained from magnetic-probe data map of one half of the (R, Z) plane. The change in flux function between adjacent curves is 10 kG $\cdot$ cm^2. The dashed line is the separatrix between surfaces closing around the plasma and those closing externally: (a) $t = 0.6$ μsec, (b) 1.1 μsec, (c) 1.6 μsec, and (d) 2.0 μsec.

pinching of the plasma column with compression of the initial B_z flux. Finally, the last capacitor bank is discharged into the I_φ mirror coil creating a fast-rising reversed B_z field on the outer edge of the column. The fast B_z bank (40 kV, 8 μF) produces a 10-kG field rising in 1.5 μsec and decaying to 5 kG in 40 μsec. This further compresses and heats the plasma annulus. Because plasma exists at larger radii during the preionization and early compression phase some of the B_φ flux is trapped and compressed radially by the reversed B_z field. The mirror coil causes the plasma to be compressed axially as well as radially. Based on previous θ-pinch experiments[10] it is expected that field line reconnection will take place at the ends allowing some current to circulate within the plasma on closed flux surfaces. The previous θ-pinch experiments, however, did not have a toroidal field component. How this will affect the reconnection process is not precisely known.

Detailed information on the structure of the magnetic surfaces, as well as the toroidal field produced by the poloidal current, was obtained with use of a two-coil probe that simultaneously measured B_z and B_φ at one spatial position as a function of time. On successive shots the probe is moved to different positions allowing spatial dependencies of the field to be determined for different times during the discharge. The probe is inserted from one end through the toroidal hole to measure the field at every 0.5 cm along the radius in four different planes at $Z = 0, 5, 10$, and 15 cm ($Z = 0$ is the midplane and $Z = 15$ cm is the end of the coil). These data have been used in two ways: (a) to produce contour plots of the poloidal magnetic flux and (b) to calculate the poloidal current.

The poloidal flux function is useful for describing magnetic configurations.[11] In the present context we define the flux function as

$$\psi(R, Z) = \int_0^R B_z(r, Z) r \, dr.$$

Using the measured field values, we calculate the flux in the half (R, Z) plane for different times during the implosion. In Fig. 2 we show curves of constant magnetic flux for several times after the start of the fast reversing field. Each contour is 10 kG $\cdot$ cm^2 different from the adjacent contour. In the figure representing $t = 0.6$ μsec we see that surface closure has already occurred in the plasma and that an island structure has formed. Assuming symmetry about the $Z = 0$ midplane we see that initially a double toroidal island structure forms. By 1.8 μsec the two islands have coalesced to form a single island. At 2 μsec the desired closed flux surfaces are centered about $R = 5$ cm.

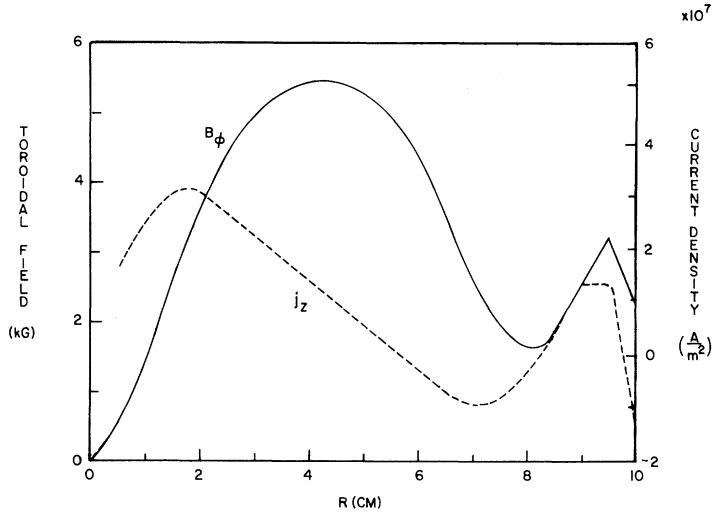

FIG. 3. Radial profile, in the $Z=0$ midplane, of the toroidal magnetic field (solid line) obtained by a polynomial fit to probe data and a calculated profile of the poloidal current density (dashed line).

In Fig. 3 we show a radial profile of the toroidal component of the magnetic field in the $Z=0$ midplane at $t=2$ μsec. This figure shows a large paramagnetic maximum near the center of the magnetic island. Calculating the poloidal current density, j_z, using Maxwell's curl equation and assuming axisymmetry, we find that a reversed (from the initial positive-polarity external current) current has been produced at radii greater than 5.5 cm. This means that some current is circulating internally on the flux surfaces.

Framing-camera photographs of the plasma have been taken from one end of the cylinder with 0.1-μsec resolution. In these photographs the plasma annulus is seen moving radially inward with no apparent gross instability. In addition, the plasma ring appears to be axisymmetric. The plasma is observed to continue moving inward even after the peak of the driving field at 1.5 μsec. The plasma moves inward compressing the trapped flux on the axis until the magnetic pressure is sufficient to stop the motion (at $t\simeq 2$ μsec). Eventually the plasma comes to rest with the center of the annulus at a radius of about 4.5 cm. This motion implies that the plasma does not pass through a succession of static equilibria but instead involves a substantial amount of flow kinetic energy which is available for conversion to thermal energy. The velocity of the luminous plasma front corresponds to individual deuteron energy of 0.5 to 1 keV.

An estimate of the ion temperature was obtained by observing the width of various spectral lines and comparing the observed widths with Doppler profiles. We observed the deuterium Balmer lines D_α and D_β as well as carbon impurity lines from C III, C IV, and C V. All carbon line measurements are made looking along the Z axis at the full tube diameter. This means we see only the axial temperature integrated over the radius as well as the Z direction. The C III linewidth gives a temperature of 190 eV at 2 μsec. The Gaussian shape of the line indicates rapid thermalization by Joule heating and/or relaxation of radial motion. The Balmer lines were observed both radially and axially and both measurements give a temperature approximately 50% higher than the carbon lines. In addition to the temperature the radial measurements of D_α at early times ($t\simeq 1.0-2.0$ μsec) show non-Gaussian "bumps" which if interpreted as directed radial motion correspond to a deuteron energy of 800 eV. Because of the complexity of the energy transfer process between the different species as well as the possibility of turbulent Stark broadening for the Balmer lines we do not at this time understand the difference in temperatures obtained from the different lines. Even though no attempt has been made at optimizing the heating rate, it is clear that the presence of the B_φ field and the subsequent reduction in compression over that of a pure θ pinch has not eliminated the nonadiabatic ion heating processes of the θ pinch.

Interferometer measurements using the 6328-Å He-Ne laser line give an electron density of 3

$\times 10^{15}$ cm^{-3} at $t=2$ μsec along a line at $R=5$ cm (assuming a 30-cm path length). Electron temperature measurements, by ruby-laser Thomson scattering, give 30 eV at the same space-time point. If we define β as the particle pressure on the magnetic axis divided by the externally applied magnetic pressure we find $\beta=0.4$ at $t=2$ μsec.

Finally, we have observed the radial profile of the electron density at late times. We see that the toroidal plasma has remained intact for 30 μsec, corresponding to ~ 40 Alfvén transit times from the end of the coil to the center. At this time the density has dropped to about half its initial value. No evidence of gross instability is seen.

In summary, we have observed the formation of a toroidal magnetic configuration with closed surfaces formed by a pinch-implosion technique. Toroidal and poloidal magnetic fields as well as ion temperatures have been measured. In the future we plan to install the necessary circuitry to prolong the B_z field and to study lifetimes on the magnetohydrodynamic and diffusion timescales.

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Ordinary-Mode Fundamental Electron-Cyclotron Resonance Absorption and Emission in the Princeton Large Torus

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Fundamental electron-cyclotron resonance damping for 4-mm waves with ordinary polarization as well as blackbody emission is measured along the midplane of the plasma in the Princeton Large Torus. Optical depths obtained from the data are in good agreement with those predicted by hot-plasma theory. The use of ordinary-mode fundamental electron-cyclotron resonance heating in existing and future toroidal devices is supported by these results.

In fusion research there is considerable interest in understanding and utilizing wave absorption and emission near the electron-cyclotron frequency, f_{ce}, and its harmonics.[1] In the Model-C Stellarator, the extraordinary-mode absorption measurements near $2f_{ce}$ were successfully used, not only to measure T_e but also to study the details of the electron velocity distribution function.[2] However, the recent development of powerful millimeter microwave sources (i.e., gyratrons) has stimulated considerable interest in wave absorption near f_{ce} since a clear understanding of the absorption process can prescribe the proper conditions for efficient application of electron-cyclotron resonance (ECR) heating in tokamaks. The primary schemes for ECR heating of tokamak plasmas are (1) as a general method of heating the bulk electrons, and (2) as a specific method of controlling the T_e profile with spatially localized heating with beneficial conse-

