Quasistatic Formation of the Spheromak Plasma Configuration

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A novel method for creating the spheromak configuration has been proposed and verified experimentally. The scheme is based on a transfer of poloidal and toroidal magnetic fluxes into a plasma from a "flux core." We present the first experimental verification of this quasistatic ($\tau_{\text{Alfvén}} \ll \tau_{\text{form}} < \tau_{\text{diff}}$) formation scheme, which is suitable for future scaleup to fusion-reactor parameters.

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The spheromak configuration is characterized by magnetic field lines that are closed (as in a tokamak) and by a coil-blanket topology that does not link the plasma (as in a mirror machine).[1-3] The magnetic field configuration of the spheromak includes both toroidal and poloidal components, but the toroidal component is maintained entirely by plasma currents and, therefore, vanishes outside the plasma. There are no external toroidal-field coils. The outward pressure of the toroidal field and of the plasma is balanced by the inward pressure of the poloidal pinch field.

The experimental realization of the spheromak configuration, a "compact toroid with toroidal field," has followed two main lines of approach to date: the coaxial plasma-gun scheme[3] and the field-reversed θ pinch with center-column discharge.[4] These are both "dynamic" schemes, occurring on a time scale comparable to the Alfvén-wave transit time ($\tau_{\text{Alfvén}}$), and involving the passage of large plasma currents through electrodes.

The attractiveness of the spheromak as a fusion-reactor concept would be enhanced by a slow-formation scheme in which the required forming power could be kept moderate even for reactor plasma parameters. The elimination of electrodes would also be a favorable development. The S-1 program[5] is designed to demonstrate an appropriately slow (quasistatic) and electrodless formation scheme. The present communication describes results from the Proto S-1 device, the first experimental demonstration of this type of approach.

The S-1 scheme of Fig. 1 was developed in the course of extensive two-dimensional (2D) resistive magnetohydrodynamic (MHD) simulations.[6-8] An initial poloidal field is generated by toroidal current inside a ring-shaped (toroidal) flux core, and is weakened on the small-major-radius side of the core by the superposition of an externally

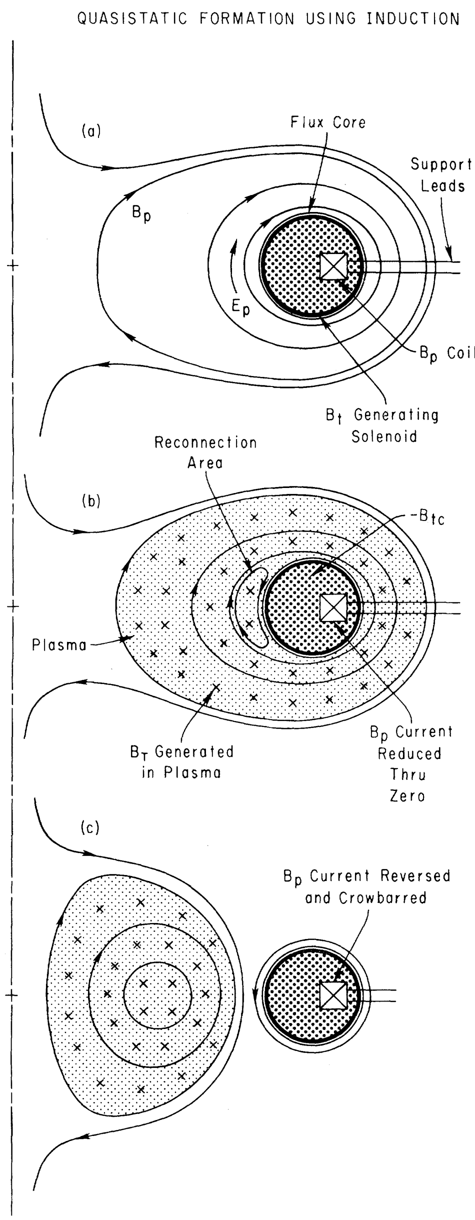

FIG. 1. (a)–(c) S-1 spheromak formation scheme.

generated vertical field. The core also contains a toroidal solenoid, which generates a toroidal-field flux (Φ_{TF}) on its interior. When the toroidal solenoid is energized, it induces (by $d\Phi_{TF}/dt$) a poloidal current in a sleeve-shaped plasma surrounding the ring. The associated toroidal field distends the poloidal-field sleeve, stretching it towards the magnetic axis where the poloidal field is weakest. While the toroidal core current is reduced through zero and "crowbarred" at a negative value, an increasingly large toroidal current is induced in the plasma. Magnetic reconnection of the poloidal field then occurs, on a time scale that is slow compared with the dynamic time $\tau_{\text{Alfvén}}$, but rapid compared with the resistive diffusion time τ_{diff}, and a separated plasma toroid is created on the small-major-radius side of the flux core. This toroid, the desired spheromak configuration, is held in subsequent equilibrium by the externally generated steady-state vertical field.

The machine configuration and the main components of the Proto S-1 device are scaled down ($\frac{1}{8}$) versions of the main S-1 device,[5] which will be completed at the end of 1982. The flux core of a 15-cm major radius and a 3-cm minor radius contains the poloidal-flux (PF) coil (three-turn toroidal winding) and the toroidal-flux (TF) coil (40-turn poloidal winding). The core is covered by 3-mm-thick metallic liner (stainless steel), which provides a vacuum enclosure around the core and also tends to symmetrize the induced fields during the initial breakdown stage. The core is powered by two sets of electrical leads. The externally generated dc vertical field is $\lesssim 1$ kG. The PF and TF coils are driven by fast capacitor banks.

The timing of the coil currents in the flux core is shown in Fig. 2. The plasma is created through a breakdown process induced by the TF current. Framing-camera observations show that a few microseconds after the initiation of the TF current a plasma sleeve is created around the core, which then expands on its small-major-radius side and finally transforms into a localized plasma in the intended spheromak equilibrium position. Many plasma discharges have been made in H_2, He, and Ar gases with best results obtained by filling the vacuum vessel with 20–50-mTorr helium gas.

For a conclusive demonstration of the spheromak formation, the time evolution of the magnetic fields has been measured directly by movable magnetic probes (2 mm diameter, 20-turn loops).

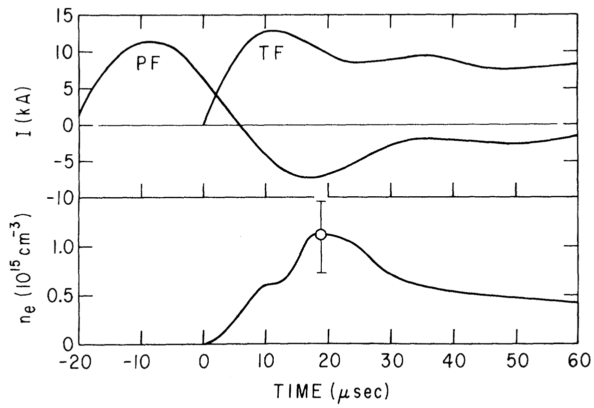

FIG. 2. Time evolution of current in one turn of PF (three-turn) and TF (40-turn) coils and plasma density at $R=6$ cm and $Z=0$. The vacuum field outside the core is expected to be phase shifted (for PF, 6–7 μsec; for TF, 2 μsec) because of induced liner currents.

The success of this method is due to the excellent reproducibility of the field configuration (within 5% deviation). Figure 3 depicts the evolution of the toroidal and poloidal magnetic fields at the midplane. The spheromak equilibrium configuration with the poloidal field reversing as a function of major radius R and the toroidal field vanishing at the plasma edge is established 12–14 μsec after the start of the plasma discharge (TF current start). This fully formed configuration remains intact for about 12 μsec. Figure 4(a) shows the measured contours of the toroidal field in a poloidal plane at $t=16$ μsec.

Following the establishment of the desired configuration, the spheromak plasma assumes an equilibrium, while the poloidal and toroidal fluxes trapped in the plasma are decaying by resistive diffusion. At about $t=26$ μsec, the sudden appearance of a nonuniformity in the framing-camera pictures suggests the onset of a nonaxisymmetric instability.

The plasma density and temperature have been monitored by double Langmuir probes (voltage swept) and CO_2-laser interferometry. For helium discharges, the central density, measured at $R=5$ cm and $t=16$ μsec, is $(1.2\pm0.6)\times10^{15}$ cm^{-3}, and the central temperature reaches its highest value 25 ± 5 eV at $t=15$–18 μsec.

We have performed a computer simulation for the present spheromak formation experiment by a resistive, 2D axisymmetric MHD code.[7] We look for solutions with slowly changing boundary conditions and small mass flow. The reduced MHD equations used are a finite-β generalization of those described in detail in Ref. 7.

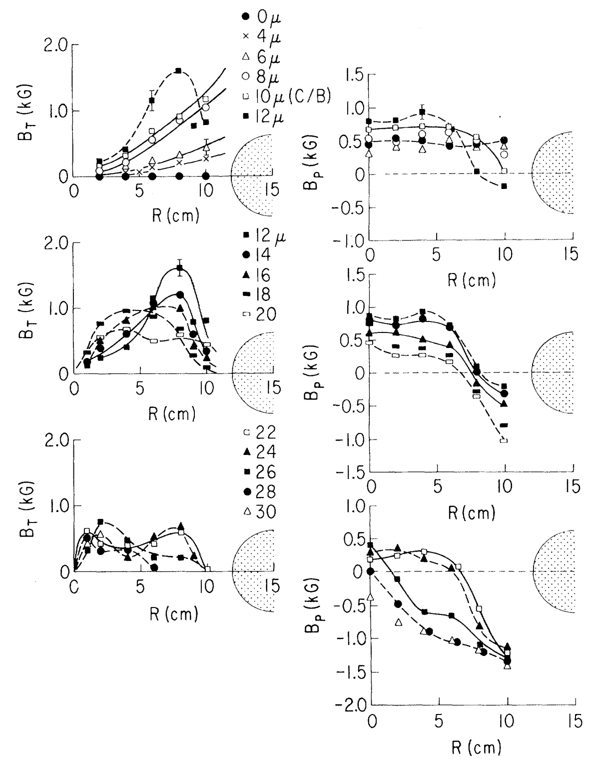

FIG. 3. Time evolution of the magnetic field at the midplane: Toroidal field (left) and poloidal field (right). $t = 0$ corresponds to TF current start. TF and PF currents are crowbarred at $t = 10$ μsec and $t = 12$ μsec, respectively.

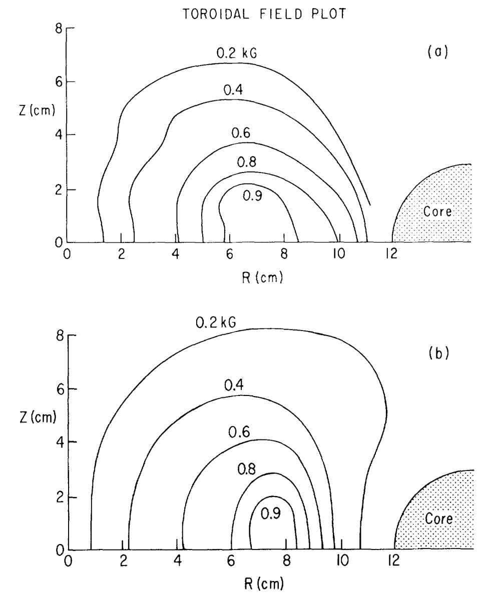

FIG. 4. (a) Measured toroidal-field contours at $t = 16$ μsec. Symmetry with respect to major axis was checked to be satisfactory. (b) Result from the simulation at the same time.

Magnetic boundary conditions require information about the poloidal-flux function ψ and the toroidal-field function $g = RB_\varphi$ at the plasma boundary. These functions are related to the tangential electric field at the core by Faraday's law,

$$\partial\psi/\partial t = R^2 \nabla\varphi \cdot \vec{E}, \quad \partial g/\partial t = R^2 \nabla \cdot (\nabla\varphi \times \vec{E}).$$

The tangential electric field is determined self-consistently by the simultaneous solution of electric-circuit equations, taking into account the presence of a resistive metallic liner.

Figure 4 presents experimental and theoretical toroidal-field contours at $t = 16$ μsec. The time evolution of the toroidal and poloidal magnetic fields was also simulated (Fig. 5). The initial plasma distribution was modelled to be uniform at 6×10^{14} cm^{-3} and 3 eV. Impurity radiation was included, with a uniform mix of (1–5)% oxygen. The peak temperature and density vary from 10 to 30 eV and from 1×10^{15} to 2×10^{15} cm^{-3}, respectively, depending on initial conditions. The qualitative agreement between the data and the simulation during the first 20 μsec is excellent. Some quantitative discrepancies are explainable by uncertainties in the initial density distribution, concentration of impurities, and the nonphysical assumption in the computer code that the flux core remains a constant-flux surface. We observe some larger discrepancies after 20 μsec, due to the development of nonaxisymmetric motion in the experiment, which has no counterpart in the 2D simulation.

In conclusion, the feasibility and effectiveness of the quasistatic S-1 spheromak formation scheme

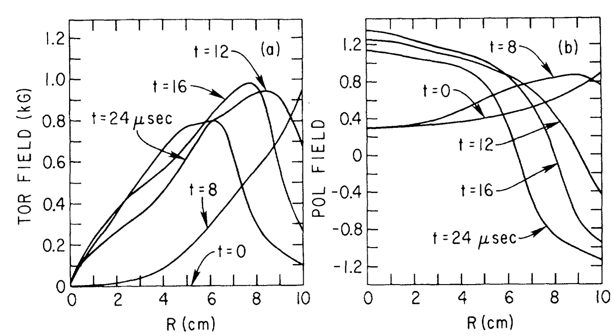

FIG. 5. Simulated evolution of (a) toroidal field and (b) poloidal field, for an initial plasma density of 6×10^{14} cm^{-3} with 5% oxygen.

have been verified experimentally. The resultant spheromak configuration lasts about 15–20 μsec ($10^2 \tau_{\text{Alfvén}}$), which is significantly long, since the classical magnetic diffusion time of the plasma (T_e =20 eV) is expected to be of the same order (50 μsec). With use of about $\frac{1}{4}$ to $\frac{1}{3}$ of the flux change from the core, the maximum toroidal and poloidal plasma currents are found to be roughly 20 and 50 kA, respectively. Larger experiments in the S-1 program are expected to provide more detailed information on the MHD stability and transport characteristics of the spheromak configuration.

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