Slow Formation and Sustainment of Spheromaks by a Coaxial Magnetized Plasma Source

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Two steps have been taken towards determining if the flux absorption and relaxation properties of a spheromak will allow dc-powered electrodes to form and sustain a steady-state spheromak. Without changing the physical properties of the spheromak, the formation time was increased from an Alfvén time to a tearing time, reducing the coaxial source power from ~ 10 GW to ~ 500 MW. With use of ~ 50 MW, spheromaks were formed and then sustained at constant density and field for 1 ms, much longer than a magnetic-energy decay time.

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A spheromak[1] is a toroidal magnetic fusion configuration having comparable toroidal and poloidal magnetic fields and having no material topologically linking the hole in the torus. Some potential reactor advantages of this confinement concept are simply connected fusion blanket and coil structures, high power density, and small size. Spheromaks have been successfully generated by a variety of formation schemes, by use of either electrodes,[2-4] induction,[5,6] or both.[7,8] Spheromaks drawing direct current (dc) from electrodes that continuously inject magnetic helicity[9] to sustain the plasma might operate in steady state,[10,11] which would enhance the concept's reactor potential.

Previously spheromaks have been formed in the compact toroid experiment (CTX) at Los Alamos with a magnetized coaxial source injecting plasma into a conducting shell called a flux conserver (see Fig. 1). This method used high electrical power on a short (Alfvén transit) time scale.[2] One important step towards dc operation is to lower the power required for forming the spheromak. This Letter reports that spheromaks can be formed with use of the same source with electrodes, but on much slower (resistive tearing or reconnection) time scales, as has been done inductively.[6] This observation that magnetic helicity can be injected on a reconnection time scale with electrodes suggested the extension of the concept to continuous injection and absorption of helicity in order to reflux the poloidal and toroidal fields

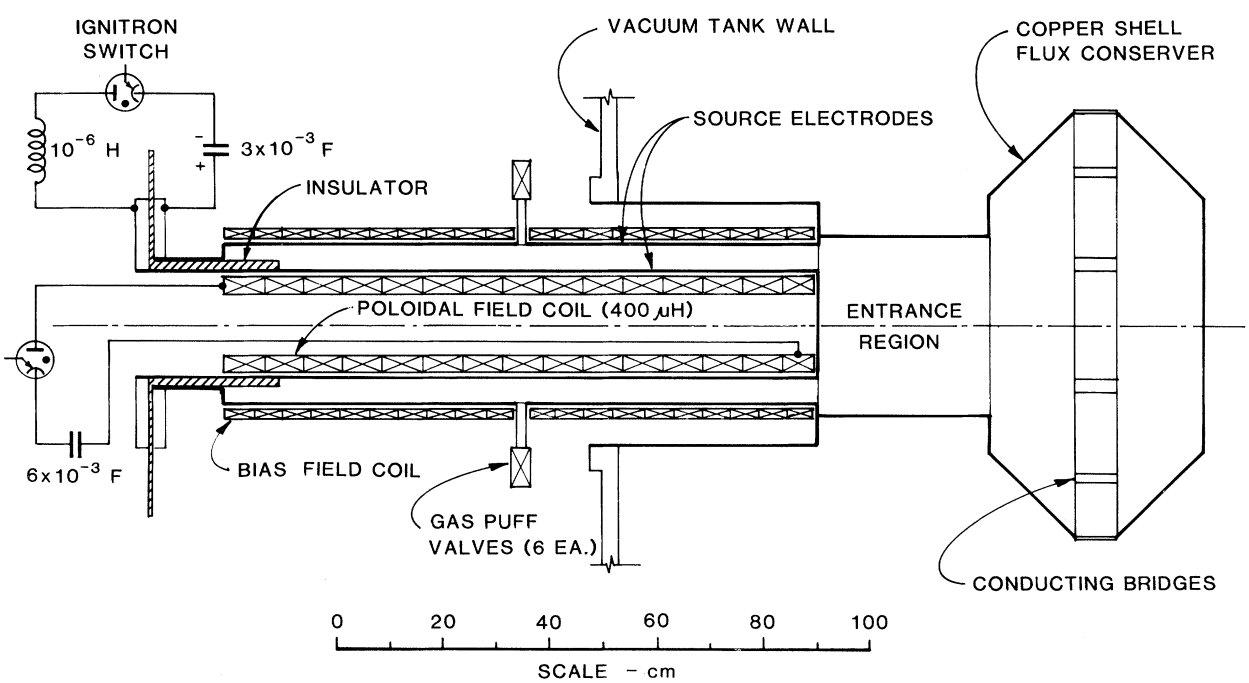

FIG. 1. Scale drawing of the magnetized coaxial source and flux conserver, and schematic of the electric circuit.

in the spheromak which are resistively decaying. This extension was tested by further increasing the helicity injection time, and constant magnetic field and density have been sustained for over 1 ms, a time much longer than the magnetic energy decay time. These demonstrations, of slow formation at reduced power, and of sustainment for periods much longer than a resistive decay time, are important steps toward the use of dc power to produce and maintain a steady-state spheromak.

The use of electrodes with dc power to reflux steady-state spheromaks eliminates the need for rf current drive, beam injection, or sequential pulsed merging of individually formed spheromaks.[12] Electrodes are often presumed to be always unacceptable sources of impurities. However, so far there is no evidence that nonelectrode spheromak experiments are any cleaner or hotter than magnetized coaxial source experiments. As the operation time of a coaxial source is lengthened the production of low-Z impurities may be reduced as in other steady-state experiments,[13] while the production of metal electrode impurities may remain very small as in magnetoplasmadynamic arcs.[14]

The slow formation and sustainment can be understood as an application of a minimum-energy principle. Spheromak equilibria are experimentally observed to be close to that specified by one such principle.[3-5] This principle says that the plasma and magnetic fields within a conducting boundary relax to a state of minimum energy under the constraint of conserved helicity.[15] Experimental observations suggest the usefulness of viewing the production of spheromaks by a magnetized coaxial source as being a process involving the injection of plasma and magnetic helicity from the source into the flux conserver,[3] with subsequent relaxation to the minimum-energy, conserved-helicity state on a time scale much shorter than the resistive decay time. The magnetic fields and therefore helicity of the spheromak decrease with time as a result of resistive decay. The sustainment process, then, involves the continual injection of helicity from the source for times long compared to a resistive decay time so that a steady state is reached in which the Ohmic losses of helicity are balanced by its injection rate. In the CTX experiment the helicity[9] is generated in the source by the electrode voltage causing toroidal flux to flow into the interelectrode region and to become linked with the temporally constant poloidal flux created by the solenoid coil.

In the fast mode the source, operating at 40–50 kV, uses 40–60 kJ of energy in about 4 μs (10–15 GW). Such high power levels imply that extrapolating this mode of generation to a reactor would be difficult. The source was then operated with a capacitor bank which supplied $\frac{1}{5}$ the voltage (7–10 kV) and $\frac{1}{3}$ the current (100–200 kA), but on ~15 times the time scale. In the fast case the plasma and field are injected in 3–6 μs (about the Alfvén transit time); in the slow case they build up for ~60 μs (about a resistive tearing time). The slow mode uses capacitor banks which deliver 25–30 kJ in 50 μs (0.6 GW), a reduction in power by a factor of about 15–25.

The spheromaks formed in both cases are almost identical. Figure 2 shows the average magnetic field and line-integrated electron density in the fast and slow cases. With the slow formation the configuration takes about 100 μs longer to set up. The initial magnetic field is higher in the slow mode, but both cases decay in a very similar manner. These slow-source–generated spheromaks have greater than 40-eV temperatures (measured with multipoint Thomson scattering[16]) and last over 950 μs. The coaxial source is thus forming spheromaks (confirmed with a radial magnetic probe array[17]) on the same slow time scale as induction methods currently used.[6]

The capacitance and energy of the source bank was doubled and a 10-μH inductor was added to the source circuit. These changes resulted in a long current pulse, with the source injecting plasma and magnetic field for over 250 μs. The pulse length of the coaxial source has been increased even further by adding more inductance to half

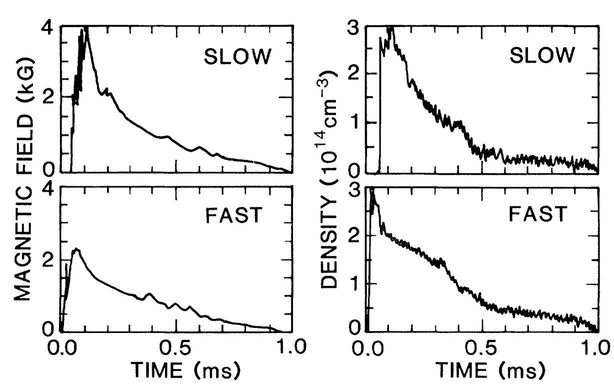

FIG. 2. Density from a midplane-diameter interferometer, and magnetic field on the geometric axis 13 cm from the midplane, in representative discharges formed by fast and slow modes. The peak magnetic field is about twice this measured field.

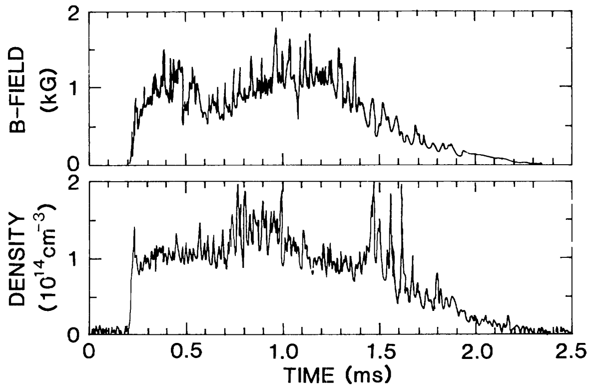

FIG. 3. Magnetic field and density (measured as in Fig. 2) in a two-bank sustained discharge. The second bank was triggered 500 μs after the first.

of the bank and delaying the triggering of this half by 300 to 500 μs (two-bank mode). Figure 3 illustrates that the two-bank operation of the source maintains the magnetic field and density at nearly constant values for over 1 ms. This time is much longer than the magnetic-energy decay time, which is 0.1–0.3 ms for these plasmas. Figure 4 shows magnetic field radial profiles taken with multiple probes during sustained two-bank operation. Such magnetic field measurements show that spheromaks[17] are generated early in time and maintained against resistive decay throughout the sustained operation by source currents and fluxes which are only a fraction of the currents and fluxes in the spheromak. At the later time in Fig. 4 the poloidal current in the spheromak is 2.1 times the current flowing in the source, while the poloidal flux of the spheromak is 3.8 times more than that of the magnetized source. These values are lower bounds on the actual ratios of plasma current and closed poloidal flux in the spheromak to the smaller currents and fluxes connecting to the source.

Figure 5 illustrates how the power requirements have been reduced and the energy injection time increased in going from the fast to the slow, long-pulse, and two-bank modes. The Ohmic power densities at 1.4 kG average magnetic field and 40 eV temperatures, with $Z_{eff}=1$ and twice Spitzer resitivity assumed, are ~10 W cm^{-3}. If one assumes that the efficiency of the sustainment process[11] is 25%–50%, then dc powers of 5–10 MW may be able to sustain a spheromak of volume 2×10^5 cm^3 at these temperatures and fields. As temperatures increase the Ohmic losses should decrease, and reactor plasmas might be sustained with reasonable power levels.

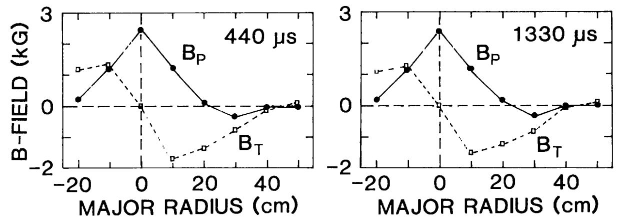

FIG. 4. Magnetic field radial profiles for a sustained spheromak at two times in a single discharge, formed with the same conditions as that of Fig. 3. Note that the positive and negative portions of the poloidal flux do balance.

In the CTX experiment, spheromaks have now been formed by a coaxial source on slow (resistive tearing) time scales with a corresponding reduction in power requirements. Further, the coaxial source has sustained the magnetic field and density of the spheromak for over 1 ms, a time long compared to the magnetic-energy decay time. A magnetized coaxial source injecting plasma and magnetic helicity into a conducting flux conserver at low powers with simple capacitor-bank technology is thus an effective means of creating quasistatic, stable, and sustained spheromaks. The observed slow formation and the observed sustained operation are important steps towards making a steady-state spheromak driven by dc power.

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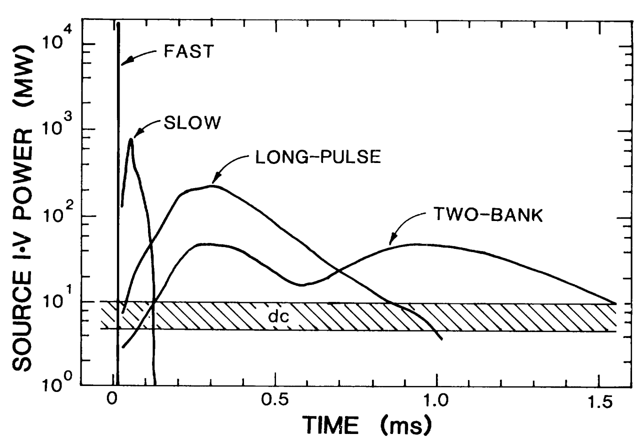

FIG. 5. Current-voltage product power in different modes. The dc power is an estimate, while the other modes have been achieved.

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[17]An operational definition used to determine if a spheromak is present is to see if the direction of the poloidal magnetic flux changes sign as a function of major radius (R) near where $B_T R$ is maximum.