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TITLE: STEADY-STATE SPHEROMAK

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ABSTRACT

A major effort is being made in the national program to make the operation of axisymmetric, toroidal confinement systems steady state by the application of expensive rf current drive. Described here is a method by which such a confinement system, the spheromak, can be refluxed indefinitely through the application of dc power.

As a step towards dc sustainment we have operated the present CTX source in the slow source mode with a longer power application time (~ 0.1 ms) and successfully generated long-lived spheromaks. If the erosion of the electrodes can be controlled as well as it is with MPD arcs then dc operation should be very clean. If only a small fraction (~ 10% for an experiment) of the poloidal flux of the spheromak connects to the source then the dc sustainment can be very efficient. The amount of connecting flux that is necessary for sustainment needs to be determined experimentally.

STEADY STATE SPHEROMAK

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I. INTRODUCTION

A major effort is being made in the national program to make the operation of axisymmetric, toroidal confinement systems steady state by the application of expensive rf current drive. Described here is a method by which such a confinement system, the spheromak, can be refluxed indefinitely through the application of dc power.

Presently, spheromaks are generated by pulsed techniques. For coaxial source produced spheromaks the generation process, gross behavior, and magnetic field profiles are in qualitative agreement with Taylor's minimum energy principle.[1] This principle states that a plasma-laden magnetic field configuration enclosed within a flux-conserving boundary will go to the minimum energy state allowed by the boundary conditions subject to the constraint that the magnetic helicity is conserved. Helicity has the dimensions of magnetic flux squared and is a measure of linkage of flux with flux.[2] This minimum energy principle was applied by J. B. Taylor to explain the remarkable phenomenon of self-reversal of the toroidal field in the Zeta reversed field pinch experiment.

In order to maintain a spheromak continuously both its toroidal and poloidal flux must be maintained against resistive diffusion. An important consequence of the Taylor principle is that the boundary conditions imposed by the geometry and the amount of helicity present determine the magnetic field profiles. Thus, if the boundary conditions are chosen properly and a dc source of helicity is provided continuously refluxed spheromaks should be possible. Proper boundary conditions are known from experience with pulse-generated spheromaks.

When dc power is used to sustain a spheromak the source of power must be applied by electrodes. The electrodes must be configured so that the toroidal flux coming from the electrodes ($\dot{\phi}_t = V$) links some poloidal flux ϕ_p. (See Fig. 1.) V is the voltage applied to the electrodes. The helicity is supplied at a rate of $2V\phi_p$.[2]

II. SLOW SOURCE MODE

Four important time scales in the formation and sustainment of a spheromak are the Alfvén time t_A, the resistive tearing or reconnection time t_t, the magnetic decay time t_B, and the system impurity cleanup time t_C. In most of the results reported to date, the spheromak is generated with a power application time comparable to t_A ($\approx$ 2 μs). Figure 2 shows some results of generating a spheromak using a power application time of about the reconnection time t_t in CTX. The voltages at the gun are about an order lower and the generation time ($\approx$ 60 μs) is over an order longer than in the fast t_A generation time. The spheromaks generated on the t_t

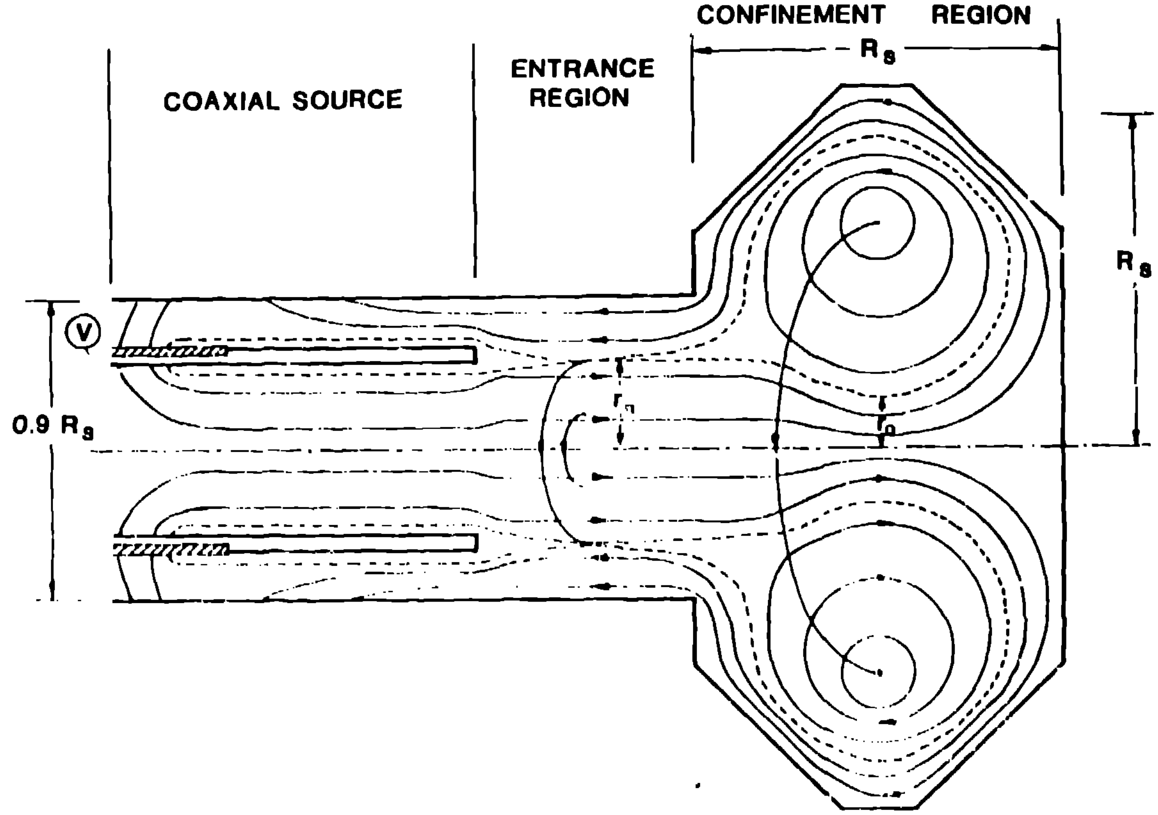

Fig. 1.
Schematic of steady state spheromak.

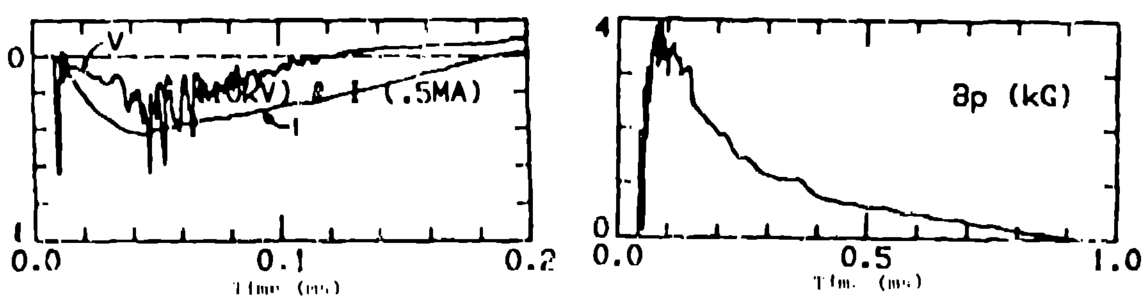

Fig. 2. Slow source formation.
The current and voltage vs time of the source and the poloidal field (B_p) vs time of the spheromak. The scales for I and V are 500 kA full scale and 10 kV full scale.

time scale are similar to the one generated on the faster time scales and have total lifetimes of about 1 ms. The obvious next experiment (which should be fairly simple due to the flexibility designed into the CTX experiment by Rulon Linford and Art Sherwood) is to lengthen the power application time to a few τ_B (~ 1 ms). This should test the concept of dc sustainment. Increasing the power application time scales to τ_t and τ_B may not help the impurity situation and could even be detrimental because of the longer time impurity transport from the source. However, a real gain in cleanliness will probably be realized when the spheromaks are sustained for times long compared to τ_C. For the Elmo Bumpy Torus τ_C is about 5 minutes.

III. IMPURITY CONSIDERATIONS

In pulsed discharges where electrodes are used impurities can be a problem. In the past, impurity problems from such discharges were important factors in the demise of many concepts utilizing electrodes. The application of modern cleaning techniques and vacuum technology can substantially reduce these problems as we have seen during the history of the coaxial source generated spheromaks. However, when electrodes are used continuously, such as in vacuum tubes, Q-machines, and MPD arcs, impurities become less of a problem.

The hollow cathode MPD arc[3] has a geometry similar to the coaxial helicity generator shown in Fig. 1. A rule of thumb for the MPD arc is that the input gas supplied must provide the charge carriers for the input current. MPD arcs of a few centimeters size have operated several tens of hours (passing thousands of moles of gas) showing little erosion (a small fraction of a mole). This demonstrates that the erosion problems have been controlled at least to the point where electrode material contamination is negligible. Also, the large volume of gas flowing through the system will rapidly remove any other contaminants provided a clean pumping system is used. Thus, if the erosion problems can be solved, as they have been with MPD arcs, the plasma from the source should be pure. The high gas flow rates associated with this type of source should tend to maintain a clean gas blanket around the spheromak, providing a clean source for recycling of particles.

IV. EFFICIENCY OF DC SUSTAINMENT

There are two sources of inefficiency considered in this section: the mismatch of the source with the spheromak and the energy loss due to ohmic heating of the source and entrance region. In the first subsection the mismatch loss will be treated. The second subsection will add heat loss based on classical resistivity and thermal conductivity.

A. Match Efficiency

Helicity is transferred with high efficiency (assumed 100%) from the source to the spheromak. Energy flows from the source with the helicity. When the helicity is absorbed by the spheromak the energy of the spheromak is increased. The Taylor minimum energy principle dictates that the energy gained by the spheromak is less than that flowing from the source. Thus there is a loss of energy in the process. A very useful concept in considering this process is the ratio of the helicity to energy. This ratio has the units of inductance. The magnetic field profiles for the

Taylor minimum energy state of an oblate spheromak (in a right circular cylinder of radius R_s and length ℓ) are well known.[4] These profiles yield a helicity per unit energy of $L_{HE} = 2\mu_o/\sqrt{K_{rs}^2 + K_z^2}$ where $K_{rs} = 3.83/R_s$, $K_z = \pi/\ell$, and μ_o is the magnetic permeability of free space. The match efficiency then is simply the L_{HE} of the source divided by that of the spheromak. To estimate this loss I will assume that the field profiles in the entrance region adjacent to the source are those given by the Taylor principle for a fully reversed RFP. The source L_{HE} then has the same form as that of the spheromak with ℓ going to ∞ and R_s going to R_w. R_w is the radius of the entrance region. Thus the efficiency is $\epsilon_m = \sqrt{(K_{rs}^2 + K_z^2)}/K_{rw}^2$. For the geometry of Fig. 1 $\epsilon_m = 0.6$.

B. Adding Ohmic Losses

Efficient current drive, by this method, means that the ηj^2 losses in the entrance region must be smaller than the ηj^2 losses in the spheromak. One advantage of this method of steady state sustainment over the Bumpy Z-Pinch[5] is that a larger fraction of the inevitable power loss from the spheromak will be diverted to heat the entrance region (and lower its resistance) since the driven layer surrounds the entire spheromak. The value of j^2 in the entrance region relative to that of the spheromak scales as $(r_o/r_n)^4$. (See Fig. 1.) This effect and the temperature of the spheromak dominate the efficiency.

Acceptable (Eff ≃ 50%) maximum values for r_o/r_n can be found by solving the parallel heat flow problem with classical resistivity and heat conductivity. These types of estimates show that r_o/r_n must be less than about 1/10 for a reactor ($B_{wall} \simeq 5$ T, $T_e = 5000$ eV) and less than about 1/3 for an interesting experiment ($B = 0.2$ T, $T_e = 100$ eV). Whether or not these values are large enough for sustainment depend on the absorption rates for the helicity. The amount of excess helicity available for absorption compared to the amount the spheromak has is proportional to $(r_o/R_s)^4$. Thus r_o must be large enough for sustainment yet small enough so that the sustainment is efficient. That there is an operating window needs to be shown experimentally. The smallness of r_o will be a good measure of success for dc current drive.

V. SUMMARY

As a step towards dc sustainment we have operated the present CTX source in the slow source mode with a longer power application time (~ 0.1 ms) and successfully generated long-lived spheromaks. If the erosion of the electrodes can be controlled as well as it is with MPD arcs then dc operation should be very clean. If only a small fraction (~ 10% for an experiment) of the poloidal flux of the spheromak connects to the source then the dc sustainment can be very efficient. The amount of connecting flux that is necessary for sustainment needs to be determined experimentally.

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