Injection and Sustainment of Plasma in a Preexisting Toroidal Field Using a Coaxial Helicity Source

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The spheromak device SPHEX has been modified by adding a current-carrying rod along the geometric axis, providing a preexisting toroidal field. We show that plasma can be successfully injected into such a field from a helicity source; the field assists plasma ejection from the gun and improves the coupling between gun and plasma, so that T_e, T_i, and the toroidal current all increase with rod current. The mechanism of plasma sustainment appears to be the same as that of the spheromak. These results represent a step towards the achievement of steady-state tokamak operation.

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SPHEX is a gun-injected spheromak device similar to the Compact Toroid Experiment (CTX) [1] at the Los Alamos National Laboratory; it is described in the preceding Letter [2], which presents results suggesting the outline of a relaxation mechanism involving a large-scale coherent mode of oscillation which, we believe, drives the toroidal current in the plasma.

In this paper we describe the modification of SPHEX in which the plasma is injected into a pre-existing toroidal field. This is generated by a current-carrying rod placed along the geometric axis of both the gun and the flux conserver (see Fig. 1 of Ref. [2]). This configuration was suggested by results from the Heidelberg HSE experiment [3]; a similar scheme has been proposed [4] to sustain a tokamak discharge by helicity injection. Our results (presented briefly in Ref. [5]) show for the first time that a coaxial helicity source can form and sustain a plasma in an externally generated toroidal field; although it is not clear that our configuration can properly be described as a tokamak, our results suggest that sustainment in a tokamak regime may be possible.

In an ideal spheromak configuration the toroidal field vanishes at the wall but the safety factor q does not [6]; in fact, in a closed spheromak it varies by $< 20\%$ over the radius. We expected that because of the tight aspect ratio and strong toroidicity, the addition of toroidal field might lead to a significant shear even at modest rod currents. We have therefore studied numerically the effects of toroidal field on force-free equilibria described by $\mathbf{\nabla}\times\mathbf{B}=\mu\mathbf{B}$, both for constant μ (the relaxed state [7]) and for $\mu=\mu_w+c\psi/\psi_G$, where ψ is the poloidal flux coordinate, ψ_G is the gun solenoid flux, and μ_w is the value of μ at the wall. This form has been used to describe spheromak equilibria in CTX [8]; with $\psi=0$ at the wall, a driven spheromak has $c<0$, the relaxed state $c=0$, and a decaying plasma $c>0$ [8]. Solutions are obtained [9] by the SOR (successive over-relaxation) method applied to the corresponding Grad-Shafranov equation (linearized when μ is not a constant). We have so far studied the driven or relaxed cases, $c\leq 0$.

We first consider spheromaklike solutions with $I_R=0$. Figure 1(a) shows a typical set of flux surfaces. Since this system has flux entering and leaving through the electrodes, it includes a separatrix dividing the field into regions of "short open flux," "long open flux," and "closed flux" [10]; these regions meet at an X point in the entry region. The q profile, shown in Fig. 2, falls slowly towards the wall as expected [7], but rises sharply at the separatrix, where the X point leads to a logarithmic singularity. The main effect of the toroidal field of the rod is to suppress the short open flux; as I_R increases, a new small region of closed flux forms outside the X point, and then interacts with the X point so that the closed flux surfaces penetrate the entry region. Eventually the X point may disappear, as shown in Fig. 1(b). The q profile is little changed over most of the closed flux (Fig. 2); q does rise near the wall, but only on flux surfaces which penetrate the entry region, and the exact form is governed by details of the field there, including the presence or absence of an X point. These details will not be

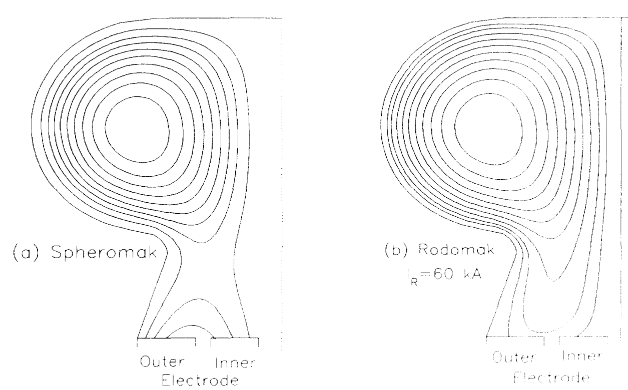

FIG. 1. Poloidal cross sections of flux surfaces in calculated equilibria for $\mu_w=14$ m^{-1}, $c=-1$ m^{-1}, and $\psi_G=3.2$ mWb: (a) spheromak; (b) rodomak with $I_R=60$ kA.

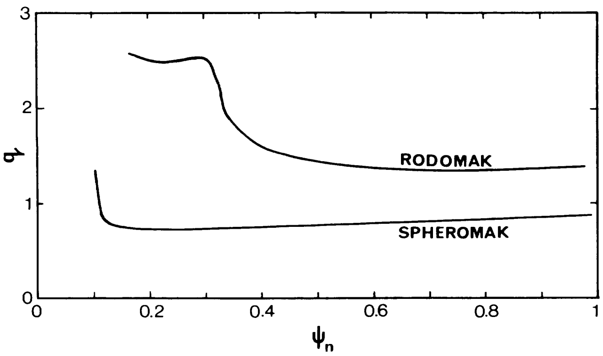

FIG. 2. Safety factor q as a function of normalized poloidal flux ψ_n for the configurations shown in Fig. 1; $\psi_n=0$ at the wall and 1 at the magnetic axis (q is not defined on the open flux of the spheromak).

well described by our simple model; for example, it does not include the current loss to the wall described in Ref. [2]. The calculations should, however, be applicable to the bulk of the plasma in the flux conserver; they show that a toroidal field at the levels we have considered does not increase the shear substantially. To conform with our experimental parameters, we have considered only cases in which μ_w exceeds μ_e, the spheromak eigenvalue [2]; we suspect that truly tokamaklike configurations with significant shear will be obtained only when the average μ is less than μ_e (for example, the tight-aspect-ratio tokamak START [11], with similar plasma dimensions, operates at $\mu\approx 3\ \mathrm{m}^{-1}$). It is not yet clear that a relaxation process will operate at μ values so far below the eigenvalue.

Some of the results can usefully be compared with experiment. For example, the current amplification factor A (the ratio of toroidal circulating current to gun current) is predicted to increase substantially with I_R; for a typical case ($\mu_w=14\ \mathrm{m}^{-1}$, $c=-1\ \mathrm{m}^{-1}$), $A\approx 2$ at $I_R=0$ and rises to 5.7 for $I_R=I_G$. As is suggested by Fig. 1, the magnetic axis position is predicted to be very nearly independent of I_R.

We now describe the experimental results. The rod is powered by two 815-μF capacitors, transformer coupled to allow either sense of current; it can carry current I_R up to 60 kA, about equal to the gun current I_G in normal operation. The rod current returns through the flux conserver. Figure 3 shows the gun current I_G, rod current I_R, gun voltage V, and poloidal field B_θ at the equator [2] for a typical discharge. The rod current pulse is rather short with the present circuit, but the current is well established at the time of plasma ejection from the gun, which occurs when I_G reaches a critical value I_{Gc}. In the spheromak mode, I_{Gc} is proportional to the solenoid flux ψ_G, as shown in Fig. 4, defining a critical value μ_{Gc} of $\mu_G=\mu_0 I_G/\psi_G$ (we evaluate ψ_G at the center of the solenoid, assuming that the emerging plasma sweeps up all of this flux). The results shown in Fig. 4 give

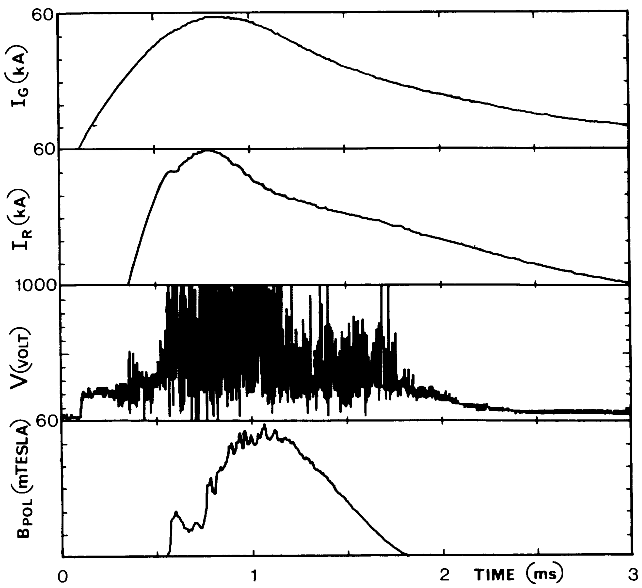

FIG. 3. The history of a typical shot: I_G, gun current; I_R, rod current; V, gun voltage; B_{pol}, equatorial poloidal field at the wall.

$\mu_{Gc}=\mu_{c0}\approx 23\ \mathrm{m}^{-1}$. This value is set by force balance at the gun muzzle; for ejection, the internal azimuthal field $B_{\theta G}$ of the gun current must exceed the external radial field B_r from the solenoid. In the rodomak mode, the internal field becomes $B_{\theta G}+B_{\theta R}$ and the external field $(B_r^2+B_{\theta R}^2)^{1/2}$, where $B_{\theta R}$ is the rod field. Thus, ejection is aided when the rod and gun currents are in the same sense. It is straightforward to show that $\mu_{Gc}=(\mu_{c0}^2+\mu_R^2)^{1/2}-\mu_R$, where $\mu_R=\mu_0 I_R/\psi_G$; this expression agrees well with the experimental results shown in Fig. 5. Thus, it is easy to set up a "tokamaklike" configuration with $I_R>0$ as in Fig. 1, but more difficult to produce the alternative "reversed-field-pinch-like" configuration with $I_R<0$; further results are therefore given for $I_R\geq 0$ only.

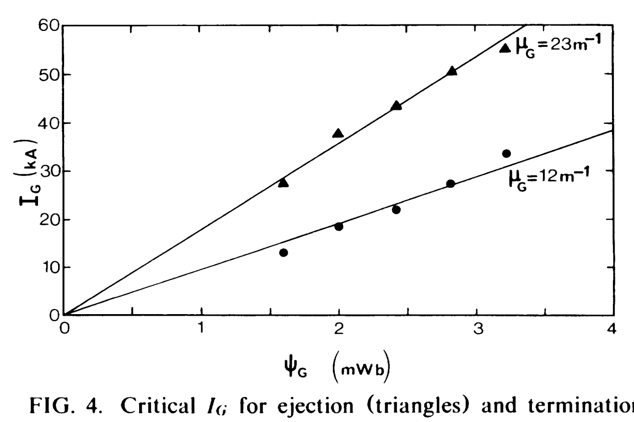

FIG. 4. Critical I_G for ejection (triangles) and termination (circles) as a function of solenoid flux ψ_G for the spheromak. The straight lines define values of $\mu_G=\mu_0 I_G/\psi_G$ of 23 and 12 m^{-1} for ejection and termination, respectively.

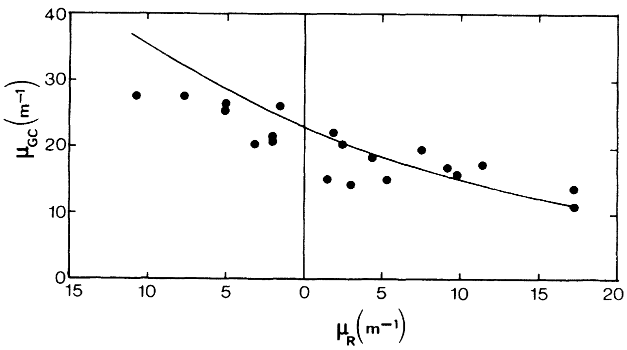

FIG. 5. Plasma ejection in the rodomak: the critical value of μ_G for plasma ejection as a function of $\mu_R \equiv \mu_0 I_R/\psi_G$. The solid curve is the theoretical expression given in the text.

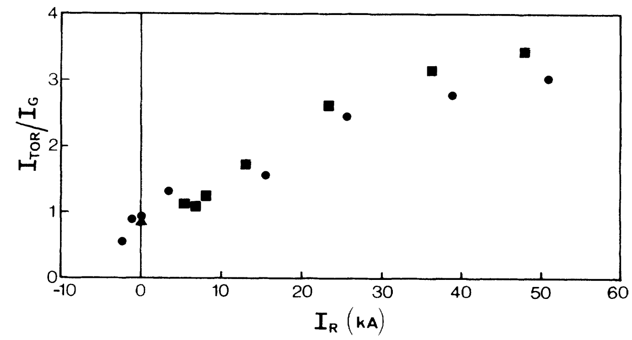

FIG. 6. The current amplification factor $A = I_{tor}/I_G$ as a function of rod current I_R for $I_G = 60$ kA and $\psi_G = 3.2$ mWb (circles) and 4.8 mWb (squares). For $I_R = 0$ the plasma will not eject at $\psi_G = 4.8$ mWb.

Also, it can be shown that plasma ejection at $\mu \approx 3$ m^{-1} would require $I_R/I_G > 10$, which cannot be attained in the present experiment.

After ejection the plasma persists until I_G falls to a second lower critical value, also plotted in Fig. 4. The corresponding value of μ_G is about 12 m^{-1}. This agrees well with theory [9] which shows that the spheromak can only be maintained if $\mu_G \gtrsim \mu_e = 11.1$ m^{-1}, the spheromak eigenvalue.

In addition to the diagnostics described in Ref. [2], we have used four poloidal field coils mounted on the central rod, and five on a "line of longitude" at the wall, to approximate a Rogowski loop measuring the toroidal current I_{tor}. From this we determine the current amplification ratio I_{tor}/I_G as a function of I_R for fixed $I_G = 60$ kA; Fig. 6 shows the results, which are very similar to the trend of the numerical simulations. However, the magnetic axis radius R appears to change systematically with I_R, as shown in Fig. 7, and this disagrees with the simulations.

These measurements do not determine the q profile, but we can estimate q at the magnetic axis assuming, as the simulations suggest, that the limiting flux surfaces are circular in cross section. Then $q_{axis} = rB_\phi/RB_\theta$, where r is measured from the magnetic axis, and it is easy to show that $q_{axis} \approx 2/\mu R$. As Fig. 7 shows, $q_{axis} \approx 1$ for $I_R \lesssim 45$ kA; the increase at 60 kA is related to the magnetic axis shift. For CTX [8], $q_{axis} = 1$ was the threshold for the appearance of the $n = 1$ mode which, we propose [2], drives the spheromak toroidal current.

The electron temperature T_e, measured with a Langmuir probe [2], increases systematically with I_R from about 12 eV for the spheromak to 25–30 eV for $I_R = 45$ kA. It can be shown, however, that this does not necessarily imply any improvement in energy confinement; the electron energy replacement time, defined locally at the magnetic axis, is about 10 μsec and shows no significant change with rod current. This suggests that the electrons are radiation dominated, which is not unexpected.

However, the rod current clearly improves the coupling of energy from the gun to the plasma, and this is in turn reflected in the impedance presented to the driving circuit by the gun. The inductive energy store [2] acts as a current source, and the gun voltage measures the impedance directly. The gun voltage trace in Fig. 3 comprises a "pedestal" $V_0 \approx 100$–200 V which lasts throughout the discharge (which we interpret as the electrode sheath voltage) with a sharp rise V_G superimposed at the instant of plasma ejection. For the spheromak, V_G is typically 300 V, corresponding to an impedance of ~ 5 mΩ; for the rodomak, V_G increases with I_R to 700 V at $I_R = 60$ kA. (This result agrees qualitatively with a prediction due to Jarboe [4], but the experimental values are a factor of 10 larger.)

Figure 8 shows the dependence of the electron temperature T_e, the ion temperature T_i (from Doppler broadening of a C III line [2]), the apparent temperature T_{tail} of the high-energy particles seen by the neutral-particle analyzer [2], and the gun voltage V as functions of I_R. All these quantities increase roughly in parallel (apart from the initial fall in T_i). Thus, the main features of the

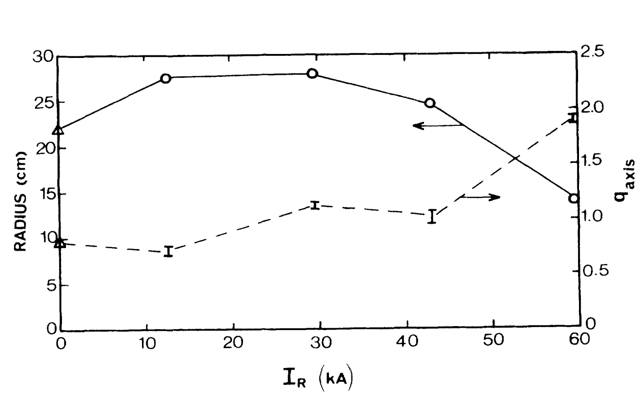

FIG. 7. The effect of rod current on magnetic structure, for $I_G = 60$ kA and $\psi_G = 4.8$ mWb. Left-hand scale: magnetic axis radius R; right-hand scale: safety factor q_{axis}. Triangles: values for the spheromak ($I_R = 0$) at $\psi_G = 3.2$ mWb.

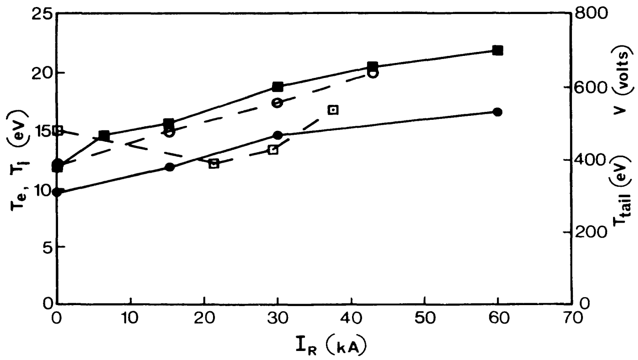

FIG. 8. The gun voltage V (■), electron temperature T_e (○), ion temperature T_i (⊡), and high-energy particle "temperature" T_{tail} (●) as functions of rod current I_R. Dashed lines and open symbols refer to the left-hand scale; solid lines and solid symbols to the right-hand scale. For $I_R = 0$, $\psi_G = 3.2$ mWb; otherwise $\psi_G = 4.8$ mWb.

spheromak [2] are qualitatively reproduced in the rodomak. The division into "column" and "annulus" suggested in Ref. [2] still appears in the equatorial potential profile, though the boundary is less well defined; and the 20-kHz $n=1$ mode has a similar phase variation to that in the spheromak, and an increased amplitude consistent with the greater power flow in the system.

In conclusion, we have shown that a magnetized Marshall gun can inject a toroidal plasma into a preexisting toroidal field, and that the field assists ejection of the plasma from the gun. The toroidal field also markedly improves the coupling of energy from the gun to the plasma, and as a result the toroidal current rises and T_e and T_i both increase; however, the plasma is governed by the same basic process that we have suggested in Ref. [2] for the spheromak, and there is no evidence that energy confinement is improved.

We have shown that theoretical relaxed and partially relaxed equilibria show less change in the q profile than we had expected; however, it is not clear how relevant these equilibria are to the observations, since the measured field configurations show magnetic axis shifts not reproduced by the theory.

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