Power Flow in a Gun-Injected Spheromak Plasma

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We describe results from the gun-injected spheromak device SPHEX, which show that the power required to sustain the plasma is initially deposited in a column, about 8 cm in radius, along the geometric axis of the device, and is transmitted from the column to the remainder of the plasma by a radially propagating oscillation at about 20 kHz. These results are relevant to the process of relaxation in spheromak systems.

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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, in which a magnetized Marshall gun generates a toroidal plasmoid, containing both toroidal and poloidal magnetic fields, which after ejection from the gun sets up a spheromak equilibrium in a vessel with conducting walls, the "flux conserver"; the plasma is then sustained as long as the gun is driven [1]. The formation of the spheromak involves the exchange of toroidal and poloidal flux characteristic of magnetic relaxation [2]; in a driven system, relaxation can be regarded as continuing during plasma sustainment if the relaxation time is shorter than the decay time of magnetic helicity [2]. Sustainment has therefore often been discussed in terms of "helicity injection" [3]; in the present work we supplement this by investigating the energy flow which must also be present for plasma sustainment.

The dimensions of SPHEX are similar to those of CTX. The flux conserver is a solid copper shell 5 mm thick, enclosing a plasma volume of 0.25 m^3; openings are reduced to the minimum compatible with vacuum pumping and diagnostic access. The internal surface is smoothly contoured to reduce differential flux penetration [4,5]; its outline is shown in Fig. 1. The gun is 1 m long, with inner and outer electrode diameters 23 and 33 cm; hydrogen gas is admitted through six fast-acting puff valves [6] placed midway along the length. The device is powered by a 7.9-mF capacitor bank storing up to 250 kJ, with a 40-μH inductor as intermediate energy store, driving a gun current of up to 100 kA. Diagnostics include a CO_2 interferometer, magnetic pickup coils in wall arrays and on insertable probes, Langmuir probes, a 1-m monochromator, and a neutral-particle analyzer (NPA).

In this paper we report measurements of the potential distribution in the plasma and of the properties of a large-scale $n=1$ mode like that seen on CTX [7]; we also report observations of the ion energy distribution showing that it extends to surprisingly high energy. On the basis of these observations we propose a description of the power flow associated with relaxation and plasma sustainment. A preliminary account of this work has appeared in Ref. [8]. All the observations reported refer to the period of spheromak sustainment, typically about 400 μsec around peak gun current.

First we describe briefly the plasma properties, for standard operating conditions with a gun current $I_G=60$ kA and a gun solenoid flux of $\psi_G=3.2$ mWb. Figure 2 shows the history of a typical discharge, showing I_G, the gun voltage V, the line-of-sight average density from the interferometer, and the equatorial poloidal field at the flux-conserver wall. Allowing for the lower bank energy and gun current, the results are generally consistent with those of CTX. The electron temperature T_e is measured with a floating double Langmuir probe, driven by a 5-kHz ac voltage of up to 100-V amplitude to give complete current-voltage characteristics during each shot. The results show that T_e increases from 10 eV at the wall to 14 eV at the geometric axis; the density has a hollow profile, so that the value at the magnetic axis, about 2.6×10^{19} m^{-3}, is less than the line-of-sight average shown in Fig. 2. Insertable magnetic probe measurements show that the poloidal flux ψ_{pol} in the flux conserver exceeds ψ_G; the ratio is about 4.7, more or less independent of operating

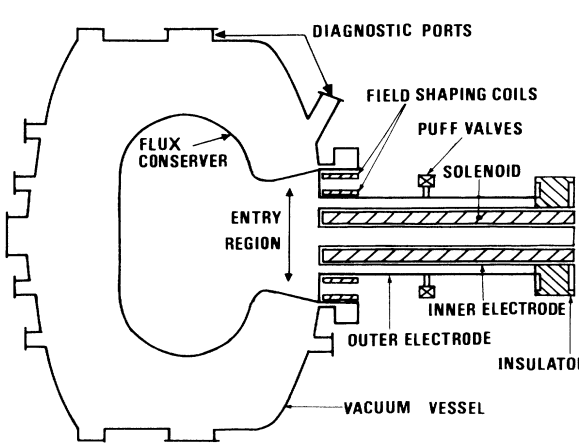

FIG. 1. Schematic cross section of SPHEX. The purpose of the field shaping coils is discussed in Ref. [4].

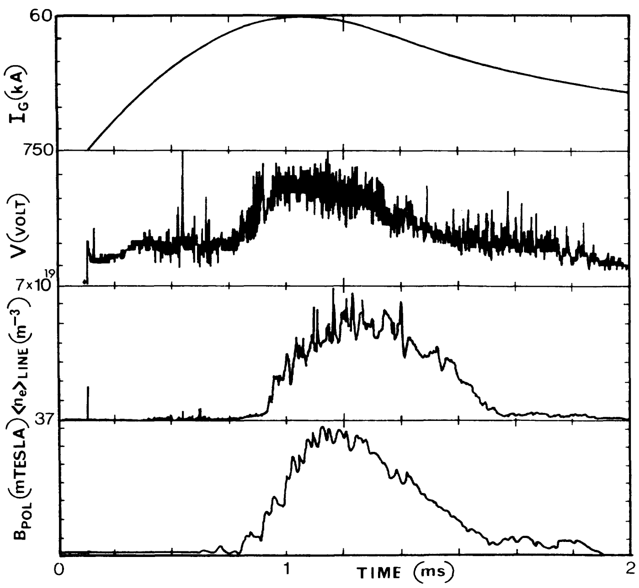

FIG. 2. This history of a typical shot, showing the gun current I_G, the gun voltage V, the average electron density as determined from the interferometer, and the equatorial poloidal magnetic field at the wall B_{pol}.

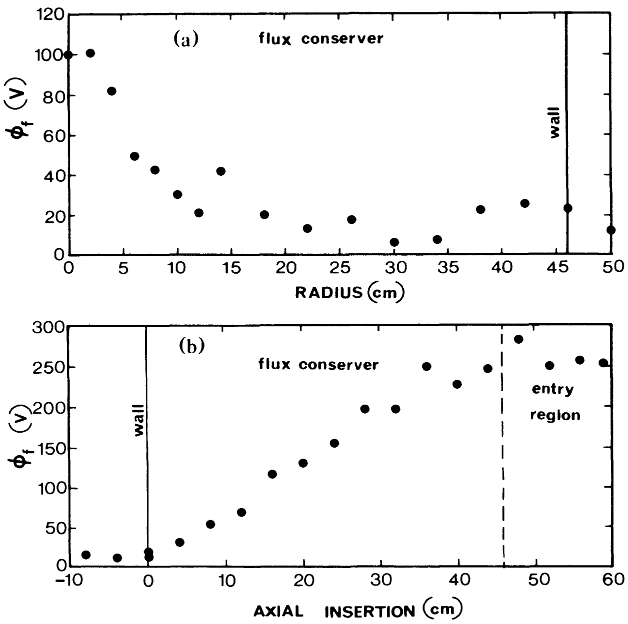

FIG. 3. Profiles of floating potential ϕ_f: (a) along the equatorial radius; (b) along the geometric axis.

conditions. This flux amplification confirms that the relaxation process operates in SPHEX.

Figure 3 shows floating potential profiles measured (a) along an equatorial radius and (b) along the geometric axis of the flux conserver and entry region (see Fig. 1). On the basis of these results we distinguish two regions of the plasma: the *central column* (the column) in which there is a large dc electric field, and the surrounding *toroidal plasma* (the annulus) where the potential is almost constant. The column is about 8 cm in radius, and magnetic probe measurements show that it carries about 50% of the gun current; it continues into the entry region to the central gun electrode. From Fig. 3 the electric field in the column is about 600 V/m, though the Spitzer resistivity for $T_e = 14$ eV and $Z_{\rm eff} \approx 1.5$ would give only about 40 V/m. In the entry region the field is much less and may be consistent with the Spitzer value; the maximum potential is close to the gun voltage, allowing for the sheath potential drop. The total power deposited in the central column is about 7.9 MW, and of this the Spitzer resistance can account for only 0.7 MW. The power required to maintain the current in the annulus is difficult to estimate precisely, but is of the order of 2 MW. The obvious conclusion is that some of the anomalous power deposited in the column is transmitted to the annulus to drive the toroidal current and maintain the spheromak structure.

This raises at least three questions: (1) What process transmits the power? (2) How is it driven in the central column? (3) How is the power flow coupled to the current drive in the annulus? Answers to these questions will describe the sustainment process in SPHEX. We shall propose an answer to the first question and describe observations relevant to the second.

A prominent feature of all the probe signals is a quasiregular oscillation at about 20 kHz. The phasing of the oscillation in an equatorial array of wall coils shows it to be an $n=1$ mode, and it can be identified with the $n=1$ mode observed in CTX [7]. Insertable magnetic probe studies show that it is highly coherent over the entire plasma; the amplitude on all components increases towards the geometric axis, and there is a systematic shift of phase with radius, shown in Fig. 4. This is clearly not a normal mode of the system; it cannot be identified with either the "tilt" or the "shift" mode, for example. Over the range 5–25 cm from the geometric axis in particular, the combination of monotonic phase change with decreasing amplitude suggests that it carries a radial flow of power which is absorbed in the annulus. It is difficult to calculate the power flow from these results alone, however, and we have instead used a probe containing two orthogonal magnetic-field coils and four Langmuir probe tips, to measure simultaneously the electric- and magnetic-field components required to determine the radial component of the Poynting vector, $P_r = \langle (E_t B_p - E_p B_t) \rangle / \mu_0$, where suffixes t and p denote toroidal and poloidal components, respectively. The results shown in Fig. 5 confirm that the mode carries an outward power flow with a maximum of 10 MW/m^2 at the interface between column and annulus, falling to zero beyond about 18 cm. (Thus, some other process is required to redistribute the power over the bulk of the annulus.) We have not yet measured the spatial distribution of this power flow away from the equatorial plane, but assuming P_r to be uniform

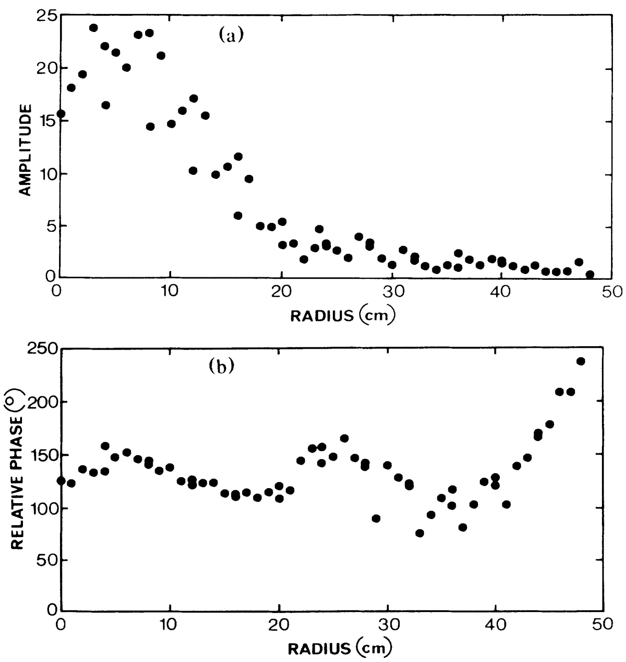

FIG. 4. The B_r component of the $n=1$ mode along the equatorial radius, in relation to a reference poloidal field coil at the wall on which the mode is clearly defined: (a) the amplitude of the cross-power spectral density, proportional to the mode amplitude; (b) the relative phase.

over the interface gives a total flow of about 2.5 MW, sufficient to drive the current in the annulus.

We now describe a feature of the magnetic-field configuration which has not been noticed in previous work on gun-injected spheromaks. At the equator, the toroidal field at the wall, though small, is definitely nonzero. The measured field is approximately uniform around the equator, and shows that a net current equal to about 50% of the gun current passes through the equatorial plane —equal to the estimated column current. This current must flow to the front (flat) face of the flux conserver, which is electrically continuous with the outer gun electrode. Similar measurements with wall coils at other locations show that most of the remaining gun current reaches the flux conserver near its junction with the entry region; measurements in the entry region itself confirm that at most 10% of the current returns to the outer electrode through the plasma. Some flow of current to the flux conserver is expected, through the effects of differential flux diffusion into the wall [4], but the calculated flux loss, confirmed by flux loop measurements, would account for at most a few percent of the input current [5]. Therefore, the current must cross the magnetic field to reach the flux conserver.

We propose that this cross-field current flow is part of the process driving the $n=1$ mode. The anomalous resistance shows that the mode must be coupled directly to the plasma current and is not driven by the pressure.

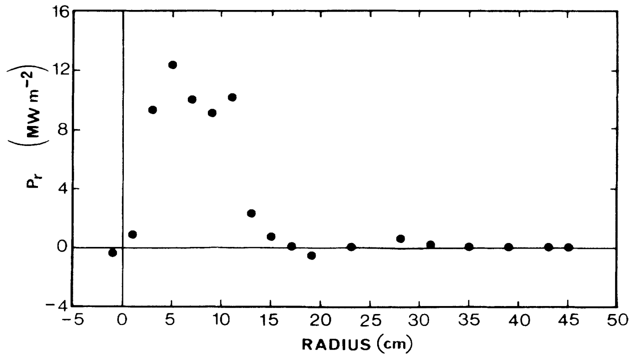

FIG. 5. The radial component of the Poynting vector along the equatorial radius.

Anomalous resistance to current flow parallel to the mean field generally occurs only if the drift speed exceeds a critical value, which in our case (since $T_i > T_e$, see below) would be the electron thermal speed; this would lead to a two-stream instability rather than a large-scale MHD-type mode. Although we cannot yet suggest the mechanism, it seems plausible that to couple to such a mode the current must flow across the magnetic field.

The ion temperature T_i has been estimated from the Doppler broadening of the spectral line of C III at 2296 Å; it is in the range 15–20 eV, rather larger than T_e. The NPA neutral-particle spectrum shown in Fig. 6 may be consistent with this result at low energy, but its most prominent feature is a long and apparently Maxwellian tail extending to at least 2.5 keV (thus greatly exceeding even the largest spikes seen on the gun voltage trace); the corresponding temperatures are about 300 eV for a line of sight along an equatorial diameter and about 200 eV for a tangential view passing close to the magnetic axis. (The operation of the NPA and the interpretation of the spectra are described in Ref. [9].) These results show that high-energy particles are found throughout the plas-

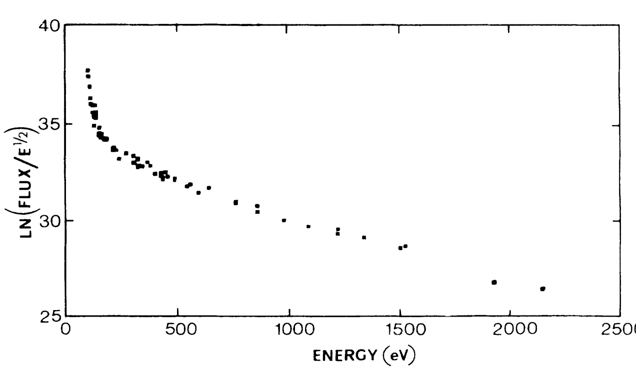

FIG. 6. A typical neutral-particle spectrum. The ordinate is $\ln(F/E^{1/2})$, where F is the neutral-particle flux (particles/sec sr) and E is the energy in eV; for a Maxwellian distribution, the plot is a straight line with a gradient equal to the inverse temperature. In this case the apparent temperature is about 300 eV.

ma, not only in the central column. Although in principle the impurity and hydrogen ion temperatures could be different, it seems more plausible to interpret the spectroscopic and NPA results together in terms of a two-temperature ion energy distribution.

Spectroscopic observations of the Doppler shift of the C III light along a tangential line of sight show that the plasma is rotating in the same sense as the $n=1$ mode but much more slowly: The rotation frequency is about 1 kHz. The sense of rotation reverses with the solenoid field.

It is possible to short out the gun voltage during the pulse, removing the current drive. The plasma parameters then behave in two distinct ways: The density and rotation speed, together with T_e and T_i and the overall magnetic field, decay with a time scale of 200 μsec or longer, while the $n=1$ mode, the net plasma current across the equatorial plane, and the high-energy neutral flux all disappear in 50 μsec or less. (We have not so far observed the $n=2$ mode seen in decaying plasmas in CTX [7].) On the basis of these time constants we estimate that the power W_i required to maintain the bulk ion energy is about 0.1 MW, while for the high-energy component the corresponding figure is $W_{\text{tail}}=7.5\epsilon$ MW, where ϵ is the fraction of ions in the tail. From the absolute flux of fast neutrals and the estimated neutral concentration in the plasma, we find that $\epsilon < 1\%$; thus the total ion power $W_i + W_{\text{tail}} < 0.2$ MW.

The cross-field current flow exerts a torque on the central column of the order of 10 N m, and from the potential distribution in Fig. 3(a) we find the rotation frequency of the central column to be about 40 kHz, much greater than that of the annulus; and if we estimate the torque T_{ann} on the annulus from $T_{\text{ann}}=M/\tau$, where M is the angular momentum and τ the decay time after removing the drive, we find a value less than 0.03 N m. Thus, in contrast to the energy flow, there is little coupling of angular momentum from the column to the annulus.

In conclusion, we have described observations in the SPHEX spheromak which suggest that the mechanism of relaxation involves a radial power flow carried by a global $n=1$ mode; that this mode is coupled to the current flow in the central column and is responsible for the non-Spitzer resistance; and that it is capable of driving toroidal current in the annulus. The possible implications for current sustainment in toroidal systems are obvious.

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