Observations of the Magnetohydrodynamic Dynamo Effect in a Spheromak Plasma

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(Received 19 November 1992)

We present measurements of the magnetohydrodynamic "dynamo" due to correlated fluctuations of velocity and magnetic field in the SPHEX spheromak. We show that there are both single-mode and turbulent dynamo processes present, although the single-mode process is in this case an "antidynamo" opposing the externally applied electric field. The size of the turbulent dynamo at the magnetic axis is close to that required to drive the toroidal current there.

PACS numbers: 52.55.Hc

It has been known for some time that in many magnetic plasma confinement systems the plasma current cannot be driven everywhere by the externally applied electric field alone; for example, in a reversed-field pinch (RFP) the current outside the reversal surface is opposed to the external electric field, and in a spheromak such as CTX [1] or SPHEX [2] the current at the magnetic axis is orthogonal to the driving field. (In the SPHEX experiments described in this paper there is a steady current density of about 500 A/m^2 at the magnetic axis, even though it forms a closed loop with constant flux linkage in the steady state.) These systems are seen to exemplify the theory of magnetic relaxation [3], according to which the configuration should relax to a state of minimum energy subject to the conservation of magnetic helicity. In practice the observed configurations are not fully relaxed, but are maintained by an external energy source in a steady state whose energy is larger than the minimum value. Nevertheless the observed configurations are qualitatively similar to the relaxed states predicted by the theory, but this does not explain how the current is driven. Three theories have been proposed: the tangled discharge model or TDM [4], the magnetohydrodynamic (MHD) dynamo [5,6], and the kinetic dynamo theory or KDT [7]. In MHD dynamo theories the current drive is attributed to the effect of fluctuations through the $\langle \mathbf{v}\times\mathbf{b}\rangle$ term in Ohm's law (where $\mathbf{v}$ and $\mathbf{b}$ are the fluctuating parts of the velocity and magnetic field in the plasma), and it has recently been shown [8] that the same is true for the TDM; on the other hand, the KDT relies on an effective nonlocal conductivity due to current diffusion arising from magnetic fluctuations.

An essential feature of all these theories is that the magnetic field fluctuations form a broadband spectrum of turbulence. It has also been suggested that current can be driven, again through a nonvanishing $\langle \mathbf{v}\times\mathbf{b}\rangle$, by the propagation of a single-mode Alfvén-type wave through the plasma; however, a net current drive can occur only for an elliptically polarized damped wave, since in an undamped or plane wave $\mathbf{v}$ and $\mathbf{b}$ are in phase and parallel [9,10]. We shall call this the "single-mode" dynamo to distinguish it from the "turbulent" dynamo models discussed above.

It is of obvious significance to measure $\langle \mathbf{v}\times\mathbf{b}\rangle$ in a range of plasma conditions where dynamo effects are expected, and compare the results with the various theories. Recent measurements in an RFP [11] have suggested that $\langle \mathbf{v}\times\mathbf{b}\rangle$ is zero within experimental error, with an upper limit much less than the required current drive; it is concluded that the KDT must be the appropriate description in this case. However, we now present results from SPHEX which for the first time show that $\langle \mathbf{v}\times\mathbf{b}\rangle$ is nonzero, and of the right magnitude to drive the current. We shall show that both single-mode and turbulent dynamos are present, although the former forms an "antidynamo" opposing the applied electric field [12].

The plasma in SPHEX [2] can be divided into the *central column*, comprising the open flux linked with the central electrode of the magnetized Marshall gun, and the surrounding toroidal *annulus* containing the closed toroidal flux. The current in the column is driven directly by the electric field from the gun; that in the annulus is driven indirectly through a global $n=1$ oscillation at a frequency of about 20 kHz, which transports energy outwards from the column [2] (this oscillation, probably due to instability of the central column, is present throughout the plasma, but the associated Poynting flux is significant only in the column and the first few cm of the annulus). For the present measurements, the gun current was 60 kA, the plasma pulse length about 1 msec, the density about 4×10^{19} m^{-3}, and the electron temperature about 20 eV. At the magnetic axis the current density $j_\parallel \approx 500$ A/m^2, and $\eta j_\parallel \approx 10$ V/m even though $E_\parallel = 0$ in the steady state. In the column, however, the measured $E_\parallel \approx 500$ V/m is much greater than $\eta j_\parallel \approx 40$ V/m. (The subscript $\parallel$ denotes a component parallel to the mean magnetic field; η is estimated from the electron temperature determined using Langmuir probes [2], and we take $z_{\text{eff}} \approx 1.5$.)

We measure the parallel component of the dynamo field $E_{d\parallel} = \langle \mathbf{v}\times\mathbf{b}\rangle\cdot\mathbf{B}/B$, where $\mathbf{B}$ is the mean magnetic field. Substituting $\mathbf{v}=\mathbf{v}_\parallel+\mathbf{E}\times\mathbf{B}/B^2$ (valid provided that $\eta|\tilde{j}|\ll|\tilde{E}|$, which is satisfied in our case) we obtain $E_{d\parallel} = (\langle \mathbf{E}\cdot\mathbf{b}\rangle - \langle \tilde{E}_\parallel \tilde{b}_\parallel\rangle)/B$. Thus we require simultaneous

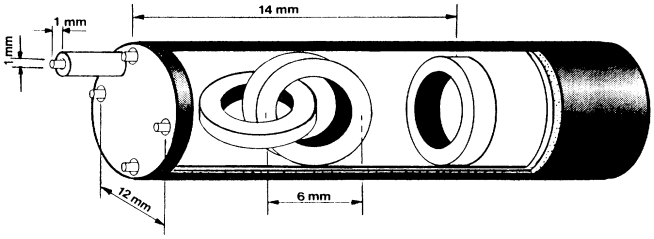

FIG. 1. Arrangement of coils and Langmuir probe tips in the probe.

measurements of all components of **E** and **B**. Figure 1 shows the probe assembly; the Langmuir tips are of platinum, 1 mm in diameter and 1 mm long, while the magnetic coils have 36 turns wound on formers 6 mm in diameter. The length from the furthest Langmuir tip to the innermost coil is 26 mm. Tips are connected in pairs through transformers to give the voltage differences and hence the corresponding electric field components; the signals from the magnetic coils are integrated electronically. The frequency response of all circuits extends to at least 100 kHz, and there is no significant phase shift up to 60 kHz apart from a fixed constant time delay of 2.6 μsec due to the transformers, which is removed in data processing. A set of traces from a typical shot is shown in Fig. 2.

The measurements were made along two traverses shown in Fig. 3: one ("radial") along the equatorial radius and a second ("axial") parallel to the geometric axis at a radius of 20 cm. Neither passes exactly through the magnetic axis, which is at a radius of 27 cm and 2 cm in front of the equatorial plane, and in general the magnetic field will not be exactly normal to the probe stem. At each position, therefore, we rotate the probe about the stem until one component is zero as seen in the reference frame of the probe, a Cartesian system with the z axis along the probe stem. If $B_y=0$, $E_{d\parallel}$ is given by the following expression:

$$E_{d\parallel}=B^{-1}(\langle\tilde{E}_x\tilde{b}_x\rangle\sin^2\theta+\langle\tilde{E}_y\tilde{b}_y\rangle+\langle\tilde{E}_z\tilde{b}_z\rangle\cos^2\theta-R_{xz}\sin\theta\cos\theta)\ ,$$

where $R_{xz}=\langle\tilde{E}_x\tilde{b}_z\rangle+\langle\tilde{E}_z\tilde{b}_x\rangle$, and $\sin\theta=B_z/B$.

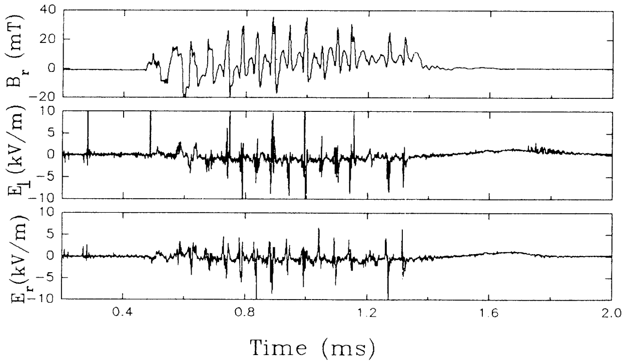

FIG. 2. A typical set of traces from the probe, showing electric and magnetic fields and the Spheromak gun current.

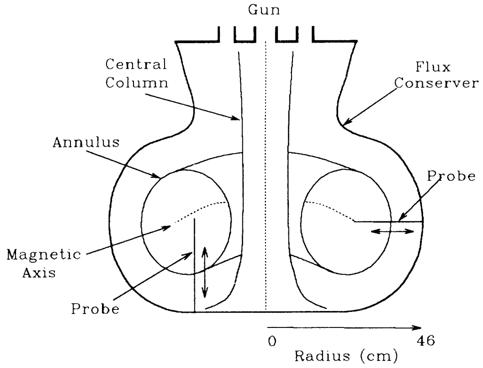

FIG. 3. Cross section of SPHEX to show the probe traverses used in the measurements.

The results are averaged over the period of sustainment at peak spheromak magnetic field strength, between 0.8 and 1.2 msec, and over a set of 6 shots at each position. Figure 4 shows the results from the radial traverse; near the central column we can be certain that **B** is normal to the probe stem, and the expression simplifies to $E_{d\parallel}=(\langle\tilde{E}_y\tilde{b}_y\rangle+\langle\tilde{E}_z\tilde{b}_z\rangle)/B$. At the axis the two averages are equal as required by symmetry, but elsewhere the

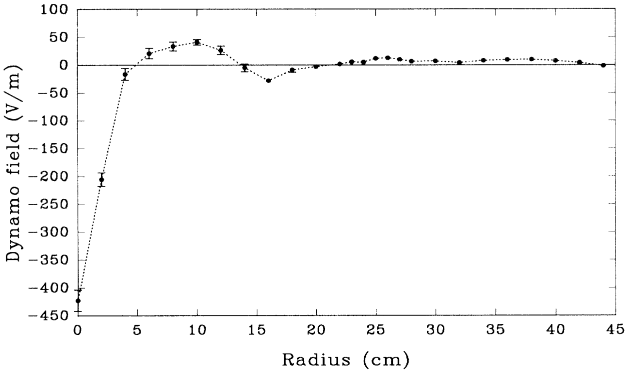

FIG. 4. $E_{d\parallel}$ measured along the equatorial radius, to show the peak at the geometric axis in the central column.

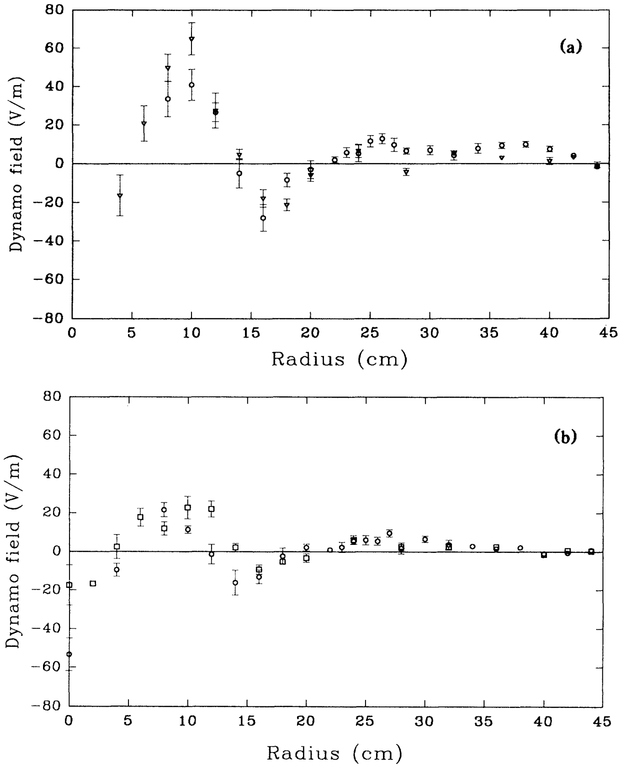

FIG. 5. As in Fig. 4, but on a larger scale to show the variation in the annulus: (a) unfiltered; (b) with the 20 kHz mode and its harmonics filtered out. Triangles, squares, and circles represent independent sets of results.

second term dominates, i.e., that derived from the radial components in the spheromak frame. The sense of $E_{d\parallel}$ is opposite to the applied electric field at the axis: This is therefore the "antidynamo" mentioned above. With $E_{d\parallel}=-425\pm20$ V/m and $E_\parallel\approx480\pm30$ V/m we have $E_\parallel+E_{d\parallel}=55\pm40$ V/m, in good agreement with the estimated value of $\eta j=40$ V/m quoted above. Away from the central column the values are much smaller, of the order of 10-30 V/m, and are shown in Fig. 5 on a larger scale. The experimental errors are derived from the standard deviation of the results over the sets of shots at each position; both the size of the errors and the consistency of the results confirm their significance. In Fig. 6 we show the results obtained from the axial traverse; the values from the two traverses are consistent at the crossover point. Near the magnetic axis, the values are clearly positive, the sense required for current drive. From Fig. 5 the dynamo field averaged over the region near the axis is about 10 V/m, and this compares well with the estimated current drive $\eta j\approx9$ V/m for $T_e\approx20$ eV.

In Fig. 5(a) we show unfiltered results, while Fig. 5(b) shows results with the $n=1$ mode and its harmonics filtered out to leave only the incoherent background. In the central column the result is clear: The antidynamo is

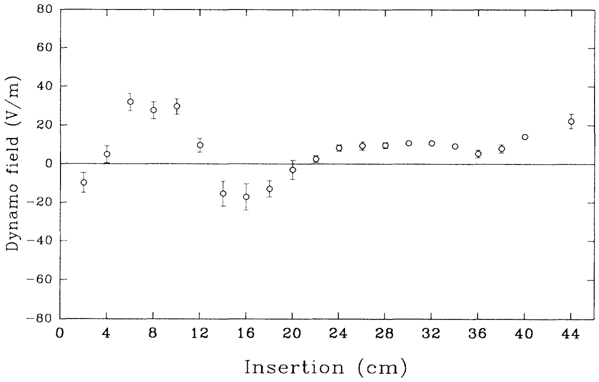

FIG. 6. $E_{d\parallel}$ along the traverse parallel to the geometric axis.

generated entirely by the $n=1$ mode. In the annulus, the first impression is that the mode and the background contribute roughly equally; however, this is misleading. Since the total signal length in one shot is only 0.4 msec, the resolution of the Fourier transform is 2.5 kHz; the filtering of the mode requires the removal of Fourier components covering at least 5 kHz at each harmonic, and in fact we remove 3 components in every 8 throughout the spectrum. Since in broadband turbulence each Fourier component is expected to contribute independently, to obtain the true contribution of the background we should increase the values shown by a factor of $\frac{8}{5}$. The results are then consistent with the conclusion that the dynamo in the annulus derives from the background only. In principle the results should also be corrected for the loss of coherence over the distance spanned by the coils and tips in the probe; however, the 20 kHz mode is globally coherent [2], while a separate measurement has shown that the background coherence is at least 0.9 over this distance [13], so no correction has been made.

The distinction between single-mode and turbulent dynamo effects can also be seen in the cross correlations of $\tilde{E}_r$ and $\tilde{b}_r$, shown in Fig. 7. At the geometric axis (solid curve) the coherence is high and clearly shows the 20 kHz $n=1$ mode, with a phase shift between $\tilde{E}$ and $\tilde{b}$; because this is an antidynamo the phase shift is in the sense required for growth of the mode rather than damping, and this is the mechanism whereby the mode is coupled to the external field to absorb the energy required to drive the annulus. On the other hand, the broken curve, measured at the magnetic axis, shows low coherence with no obvious systematic phase shift; this is consistent with the general picture of MHD turbulence in an RFP plasma [14].

The MHD dynamo can only act to redistribute current driven by an applied electric field, and therefore regions of positive current driven by the dynamo must be associated with regions of negative drive [8]. For example, in an RFP it is understood that the dynamo opposes the applied electric field near the axis and drives positive

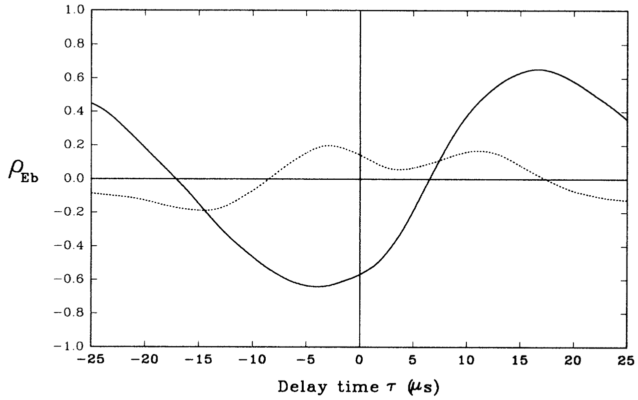

FIG. 7. Cross-correlation functions of $\tilde{E}_r$ and $\tilde{b}_r$ at the geometric axis (solid line) and at the magnetic axis (dotted line).

current around and beyond the field reversal surface. This pattern is inverted in the spheromak because the external field is applied in a different way. The surprisingly complex spatial variation of the dynamo field can be understood by noting that the column and annulus are distinct entities, coupled only by the Poynting flux of the $n=1$ mode. Within the annulus ($\geq$ 10 cm from the axis) the power inflow due to the $n=1$ mode [2] is absorbed within a few cm, but the resulting current drive must be distributed throughout the remaining part of the annulus. This is the role of the dynamo, and so a positive drive near the axis must again be balanced by a negative drive at the edge. There is evidently a second independent turbulent dynamo in the column, which presumably acts to redistribute the current drive within it, and therefore also has both positive and negative regions.

Clearly, the actual current drive process at the edge of the annulus awaits identification. We have suggested [15] that it may be due to correlated fluctuations of electric field and conductivity, but this suggestion remains to be tested. In conclusion, we have shown that the MHD dynamo $\langle \mathbf{v}\times\mathbf{b}\rangle$ is nonzero in the SPHEX plasma, and we have identified three independent dynamo processes: a single-mode antidynamo process in the central column opposing the applied electric field, and two apparently independent turbulent processes in the column and the annulus. The turbulent processes show both negative and positive regions, since they operate to redistribute the effect of an external current drive. Turbulent and single-mode processes are distinguished by the form of the cross correlation between electric and magnetic field fluctuations. At the magnetic and geometric axes the measured dynamo is close to that required by Ohm's law.

The SPHEX project is supported by the Science and Engineering Research Council. A. al-Karkhy is grateful to the Iraqi Government for studentship support. We acknowledge technical assistance from P. Brierley and T. Haslam, and are grateful to AEA Technology (Culham Laboratory) for the loan of equipment.

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