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THE FLUCTUATION INDUCED HALL EFFECT

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The fluctuation induced Hall term, $<\tilde{J} \times \tilde{B}>$, has been measured in the MST reversed field pinch. The term is of interest as a possible source of current self-generation (dynamo). It is found to be non-negligible, but small in that it can account for less than 25% of the dynamo driven current.

The spontaneous self-generation of current in a plasma is a phenomenon observed in many situations, including reversed field pinch (RFP), tokamak, and astrophysical plasmas. If the current is not fully produced by an applied electric field, an additional current drive mechanism must be present. This self-generation of current and magnetic field is often referred to as a dynamo effect. In the reversed field pinch a significant portion of the equilibrium current is not produced by the applied electric field. In the tokamak, self-generation of current occurs during a sawtooth crash which spontaneously redistributes the plasma current. In situations such as these, as well as in the astrophysical dynamo, current is believed to be driven by fluctuations.

The equilibrium, or mean, current $<J>$ is described through the mean-field Ohm's law which, including the Hall term, can be written as

$$<E> = \eta<J> + <\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}> + \frac{<\tilde{\mathbf{J}} \times \tilde{\mathbf{B}}>}{n_0 e} \qquad (1)$$

where <> denotes an ensemble average, tilde denotes a fluctuating quantity (in space and time), <E> is the applied electric field, n_0 is the electron density, **v** is the fluid velocity, and η is the resistivity. A manifestly strong dynamo effect occurs in the edge of the reversed field pinch where $<E> \ll \eta<J>$ (in fact on the reversal surface <E> = 0), and hence the fluctuation terms in Ohm's law are likely sources for current drive.

The $<\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}>$ term has been considered as the cause for both the RFP and astrophysical dynamo. It has been demonstrated in MHD theory and computation that tearing modes produce a $<\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}>$ effect which produces and sustains reversal in the RFP.(1) The same effect likely alters, in part, the current density profile in a tokamak during tearing mode activity, as occurs with a Mirnov oscillation, sawtooth crash, or disruption. However, the strength of the $<\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}>$ effect in experiment has not been generally determined (although a recent Langmuir probe inference of the term in the Repute RFP indicated that it is small in that device(2)).

The last term in the above Ohm's law, the fluctuation induced Hall term, is another possible dynamo source. In the MST reversed field pinch device we have measured the Hall term in the outer 20% of the plasma. It cannot be dismissed a priori as a small effect; the magnitudes of $\tilde{\mathbf{J}}$ and $\tilde{\mathbf{B}}$ are individually large, such that if they are highly correlated the Hall dynamo would be able to account for the entire dynamo effect. In addition, a nonlinear resistive MHD computation suggests that the term could be significant.[3] However, the computation was not conclusive since the Hall effect was observed to depend upon the choice of viscosity (which is needed in the code for numerical stability). We find that in MST, despite the large current and field fluctuations, the Hall term is a small, although nonzero, effect.

For these experiments the MST device (minor radius = 0.5 m, major radius = 1.5 m) is operated at low plasma current, $I_p \approx 210$ kA (reduced from a maximum of about 600 kA), with a subsequently reduced central electron temperature $T_e(0) \approx 130$ eV, line averaged electron density $\overline{n} \approx 0.7 \times 10^{13}$ cm^{-3}, field reversal parameter $F \approx -0.15$, and pinch parameter $\theta \approx 1.85$. The current is low so that probes may be inserted into the edge (to r = 0.42 m). The current density (and magnetic field) are measured with a movable array of pickup coils, taking appropriate spatial differences to approximate curl **B**.[4] The coils are situated in a fork configuration, with two poloidal, four toroidal, and two radial coils distributed within two parallel tubes which are mounted on a common movable stalk for insertion within the plasma. The tubes are 0.9 cm in diameter and are separated by 1.7 cm. The coils, with 0.2 cm radii, have separations between 0.5 cm and 1.7 cm, providing wavelength resolution adequate for the frequency range of measurement. Inaccuracy in the coil calibration and alignment yields errors in the equilibrium current density of typically 2% and in fluctuating current density of up to 10%.

The component of the Hall term of interest for the dynamo is that parallel to $\langle \mathbf{B} \rangle$. In the RFP edge, where the magnetic field is dominantly poloidal, the parallel component of $\langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle$ is given by

$$< \tilde{J} \times \tilde{B} >_{\parallel} \approx < \tilde{J}_{\phi} \tilde{B}_r > - < \tilde{J}_r \tilde{B}_{\phi} > \quad (2)$$

where r and ϕ denote minor radial and toroidal directions. The current density components are further decomposed as

$$\tilde{J}_{\phi} = \frac{\partial \tilde{B}_{\theta}}{\partial r} - \frac{1}{r}\frac{\partial \tilde{B}_r}{\partial \theta}, \quad \tilde{J}_r = \frac{1}{r}\frac{\partial \tilde{B}_{\phi}}{\partial \theta} - \frac{1}{R}\frac{\partial \tilde{B}_{\theta}}{\partial \phi} \quad (3)$$

Using eqn (3) in eqn (2) yields

$$< \tilde{J} \times \tilde{B} >_{\parallel} \approx < \frac{\partial \tilde{B}_{\theta}}{\partial r} \tilde{B}_{\phi} > - \frac{1}{r} < \frac{\partial \tilde{B}_r}{\partial \theta} \tilde{B}_{\phi} >$$
$$- \frac{1}{r} < \frac{\partial \tilde{B}_{\phi}}{\partial \theta} \tilde{B}_{\phi} > + \frac{1}{R} < \frac{\partial \tilde{B}_{\theta}}{\partial \phi} \tilde{B}_{\phi} > \quad (4)$$

All the terms in eqn (4) are measured with the magnetic coil array. Averages are computed from an ensemble of 400 time records of 500 μsec duration, accumulated from 100 different, but reproducible, discharges. The first two terms (corresponding to $< \tilde{J}_{\phi} \tilde{B}_r >$) are about five times larger that the last two terms (corresponding to $< \tilde{J}_r \tilde{B}_{\phi} >$).

Displayed in figure 1 are the magnitude and phase of $< \tilde{J} \times \tilde{B} >_{\parallel}$ at r = 0.46 m. We see that the signals are substantially correlated (coherence ≈ 0.4), but that the ensemble-averaged phase difference between $\tilde{J}$ and $\tilde{B}$ is close to $\frac{\pi}{2}$ for frequency below 50kHz. The power spectra of $\tilde{J}$ and $\tilde{B}$ indicate more than 90% of the fluctuating power is from the f < 50kHz range. The net result is that $\frac{<\tilde{\mathbf{J}} \times \tilde{\mathbf{B}}>_{||}}{ne} \approx 0.48 \pm 0.13$Volts/m. To evaluate the significance of this term we compare it to the $\eta<J>$ term in eqn (1). The measured $<J>_{||}$ is 20 A/cm^2. We estimate η by assuming classical resistivity with T_e = 30 eV, measured from Langmuir probes, and Z_{eff} = 1. This yields $\eta<J>_{||} = 2.25 \pm 0.15$Volts/m, which is four to five times larger than the Hall term. Since Z_{eff} is not measured and may be greater than unity, we conclude that the Hall dynamo can account for at most about 20% - 25% of the dynamo effect.

In conclusion, we have measured the fluctuation induced Hall effect, which is a possible dynamo mechanism. We find that this term is non-negligible in the reversed field region of the RFP. However, it drives less than 25% of the total current, and thus is not the dominant dynamo mechanism. The upper bound is provided by the assumption that Z_{eff} =1. The contribution is less than 25% if Z_{eff} exceeds unity. A qualification on the conclusion is that fast electrons might carry a significant portion of the current in MST,(5) as has also been observed elsewhere.(6) The electrical resistivity might then not be given accurately by the Spitzer value. An improved comparison between the measured Hall term and the friction term $\eta<J>_{||}$ would benefit from an accurate determination of the local resistivity through measurement or calculation from a measured distribution function.

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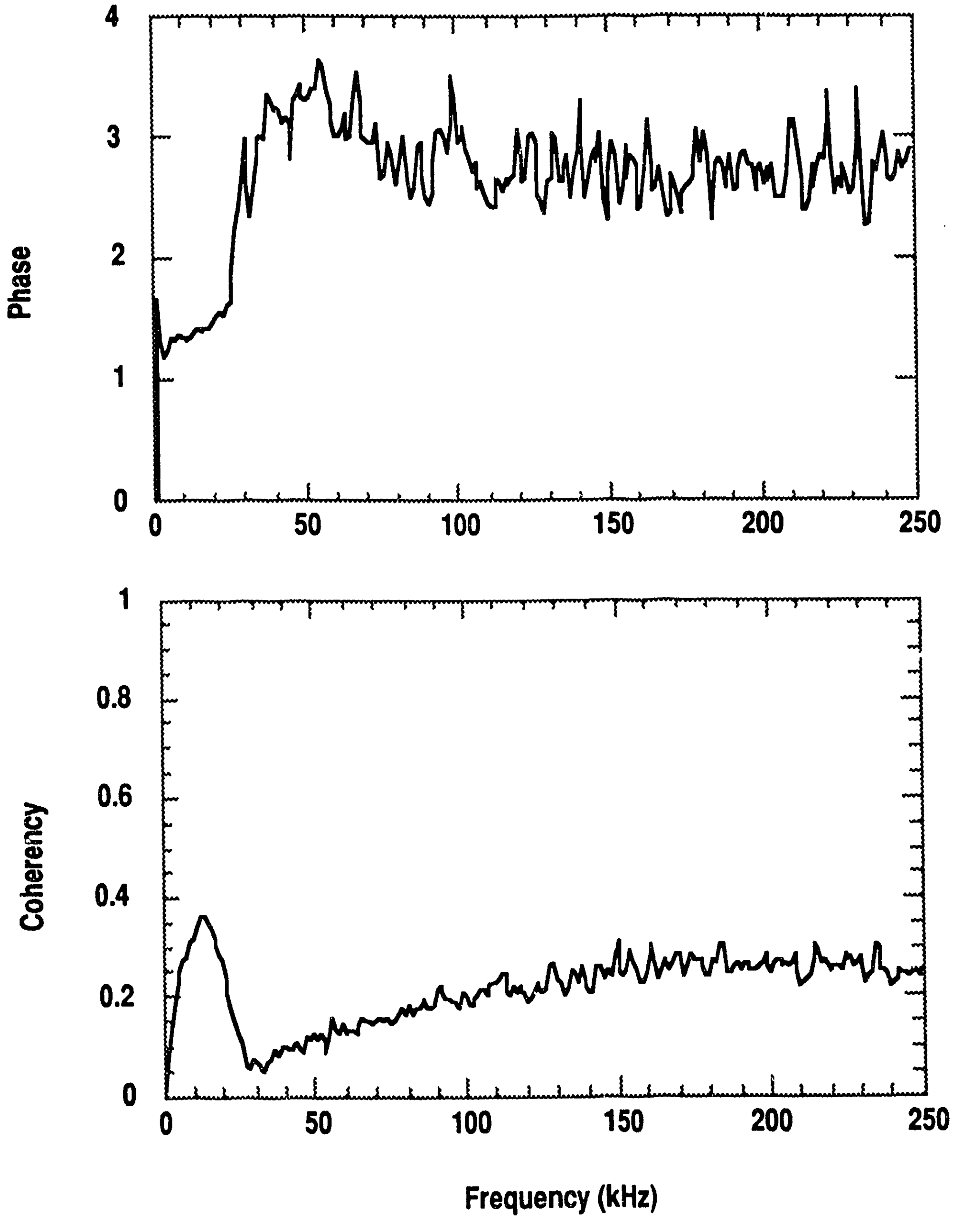

Fig. 1 The cross-coherence (normalized cross-power) and cross-phase of <j x B>II from the multi-coil probe measurement.

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