AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

Conservation of Magnetic Helicity during Plasma Relaxation

H. Ji, S.C. Prager, and J.S. Sarff

Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

(July 8, 1994)

Abstract

Decay of the total magnetic helicity during the sawtooth relaxation in the MST Reversed-Field Pinch is much larger than the MHD prediction. However, the helicity decay (3-4%) is smaller than the magnetic energy decay (7-9%), modestly supportive of the helicity conservation hypothesis in Taylor's relaxation theory. Enhanced fluctuation-induced helicity transport during the relaxation is observed.

PACS numbers: 52.30.Jb, 52.25.Gj, 52.55.Hc

MASTER

Typeset using REVTeX

Magnetic helicity [1] is a measure of the “knottedness” of magnetic field. It is an invariant within a flux tube in a perfectly conducting plasma. In 1974 Taylor conjectured [2] that in a “slightly” resistive plasma the *total* helicity is well-conserved during plasma relaxation in which the magnetic energy decays toward a minimum-energy state. This well-known hypothesis has been successful [2] in explaining magnetic structures in laboratory plasmas, such as the reversed-field-pinch (RFP), spheromak, and multipinch. It has also been applied to relaxation in tokamak [3,4], magnetospheric [5], and solar [6] plasmas. The conjecture has been extended theoretically [7] and studied through nonlinear MHD computations [8–11]. However, to our knowledge, this rather well-accepted conjecture has never been tested experimentally.

In this Letter, we report an experimental investigation of the magnetic helicity and energy evolution during plasma relaxation in the Madison Symmetric Torus (MST) RFP. The test of Taylor’s conjecture is possible since relaxation occurs in MST as events which are discrete in time (corresponding to the $100\mu\text{s}$ crash phase of a sawtooth oscillation). We find that during the relaxation event the magnetic helicity decreases by 3-4%, while the magnetic energy decreases by 7-9%. Hence, the helicity conservation conjecture is modestly well-satisfied in that the helicity decay is half the energy decay. However, the helicity decay is far greater than expected from simple resistive MHD arguments.

The gauge-invariant definition of the total helicity in a toroidal plasma is given by [12]

$$\begin{aligned} K &\equiv \int \mathbf{A} \cdot \mathbf{B} dV - \Phi_\phi(a)\Phi_\theta(a) \\ &= \int [\mathbf{A} - \mathbf{A}_\phi(a)] \cdot \mathbf{B} dV, \end{aligned}$$

where $\mathbf{A}$ is the vector potential, $\mathbf{B}$ is the magnetic field, $\Phi_\phi(a)$ is the total toroidal flux, $\Phi_\theta(a)$ is the external poloidal flux threading the central hole of the torus, $\mathbf{A}_\phi(a) = \Phi_\theta(a)/(2\pi R)$ (R is the major radius) is the toroidal component of $\mathbf{A}$ at the plasma surface $r = a$, and the integration is over the plasma volume. Taylor evaluated [2] a relaxed state by minimizing the magnetic energy $W = \int (\mathbf{B}^2/2\mu_0) dV$, subject to the constraint of constant helicity. The resulting magnetic field satisfies the equation $\nabla \times \mathbf{B} = \lambda \mathbf{B}$, where the current to field ratio

$\lambda \equiv \mu_0 \mathbf{j} \cdot \mathbf{B} / B^2$ is a spatial constant. The Bessel function solutions to this equation (often referred as the Bessel Function Model, or BFM) approximate well the measured fields in the RFP, except that in experiments λ falls to zero at the plasma boundary and the plasma pressure is finite.

The MST [13] is a large RFP device ($R = 1.50\text{m}$, $a = 0.52\text{m}$) with plasma current I_p up to 700kA. The plasma is surrounded by a 5 cm-thick aluminum shell with one toroidal and one poloidal gap. The shell also acts as the vacuum vessel and a single-turn toroidal field coil. Magnetic energy and helicity enter through the gaps across which nonzero voltages occur.

Sawtooth oscillations [14] in MST consist of a fast crash phase and a slow recovery phase. The plasma rapidly relaxes towards its minimum energy state during the crash within 0.2 ms. This can be illustrated by changes in two dimensionless parameters: the reversal parameter $F \equiv B_\phi(a)/(\Phi_\phi/\pi a^2)$ and the pinch parameter $\Theta \equiv B_\theta(a)/(\Phi_\phi/\pi a^2)$. Figure 1 illustrates time-evolution of the plasma current I_p , $\Phi_\phi(a)$, F , Θ and $V_\theta(a)$ over a sawtooth oscillation. I_p and $\Phi_\phi(a)$ increase (by 1-2% and 9-10%, respectively) while F and Θ decrease during the crash. The increase in toroidal flux identifies the sawtooth crash as a “dynamo” field-generation event. The voltage across the toroidal gap in the shell, $V_\theta(a)$, is employed as a trigger for the sawtooth ensemble averaging and as a time reference throughout the paper. In Fig.2, the trajectory in an $F - \Theta$ diagram approaches the minimum energy state (BFM curve) during the crash.

The important question here is whether the total helicity is conserved during the relaxation. Calculation of W and K requires knowledge of radial profiles of the toroidal field $B_\phi(r)$ and poloidal field $B_\theta(r)$. The vector potential $A_\phi(r) - A_\phi(a)$ and $A_\theta(r)$ then can be obtained by integrating $\mathbf{B} = \nabla \times \mathbf{A}$ over the radius. Note that W and K are dominated by their mean-field values ($\mathbf{B}_0^2$ and $\mathbf{A}_0 \cdot \mathbf{B}_0$) since contributions from fluctuations $\widetilde{\mathbf{B}}^2$ and $\widetilde{\mathbf{A}} \cdot \widetilde{\mathbf{B}}$ are smaller by a factor of 10^{-4} .

Lacking measurement of the magnetic field profiles, we deduce the profiles (and hence energy and helicity) from other measured quantities by employing equilibrium models. We

find that the changes of K and W during a sawtooth crash can be accurately determined. Let us first consider the “ α -model ” [15] which assumes $\lambda = \lambda_0[(1 - (r/a)^\alpha]$ in $\nabla \times \mathbf{B} = \lambda \mathbf{B} + (\beta_0/2B^2)\mathbf{B} \times \nabla p$ where $\beta_0 (\equiv 2\mu_0 p(0)/B^2(0))$ is the central beta (p is the plasma pressure). Every set of α , $\Theta_0 (\equiv \lambda_0 a/2)$, and β_0 with a specific pressure profile gives an unique prediction for F , Θ and the central poloidal beta $\beta_{\theta 0} (\equiv 2\mu_0 p(0)/B_\theta^2(a))$. Since F , Θ , and $\beta_{\theta 0}$ are measured quantities, it is possible to deduce the corresponding α , Θ_0 and β_0 . However, this inverse mapping problem is not trivial. To overcome the difficulty, we have developed an Artificial Neural Network (ANN) [16] to perform the inverse mapping. The network was trained by a training table created by the forward mapping using the Error Backward Propagation technique [16]. A well-trained ANN maps $(F, \Theta, \text{ and } \beta_{\theta 0})$ to $(\alpha, \Theta_0, \text{ and } \beta_0)$ space with negligible errors. The dotted lines in Fig.1 represent values of F and Θ after one inverse mapping via ANN and one forward mapping. Negligible departure from the original F and Θ indicates good performance of the ANN.

From the dimensionless parameters $(\alpha, \Theta_0, \text{ and } \beta_0)$ and one dimensional parameter, say $\Phi_\phi(a)$, the helicity K and energy W can be obtained. The results with a parabolic pressure profile $p = 1 - (r/a)^2$ over the ensemble-averaged sawtooth oscillation are shown in Fig.3. The results with other pressure profiles such as $p = [1 - (r/a)^2]^2$ give negligible differences. Both K and W decrease during the sawtooth crash, but the drop in W (by $\simeq 8\%$) is considerably larger than in K (by $\simeq 3\%$).

In order to determine the dependence of the above finding on the equilibrium model, three other models have been examined: the Modified Bessel Function Model (MBFM) [17], a smoothed MBFM, and the “ 2λ -model”. In the MBFM, the λ profile has a cutoff radius $r_b \leq a$ with in which λ is flat as in the BFM, while λ falls off linearly to zero as the radius increases from r_b to a . However, the artificial cutoff at $r = r_b$ leads to an unphysical discontinuity in the current density profile. The smoothed MBFM has a rounded λ profile at $r = r_b$, providing a physically reasonable model. In both the MBFM and smoothed MBFM, the free parameters are r_b , Θ_0 , and β_0 . On the other hand, the 2λ -model uses the λ value at the center, the λ value at $r/a = 0.8$, and β_0 as free parameters; it allows hollow λ

profiles, unlike the other models. The ANN again is trained for these three models with the parabolic pressure profile, which is typical in the experiments. (Our conclusion is insensitive to pressure profile as in α -model.) Table I compares results from all four models. Although there are small deviation between models, we can conclude that the helicity decreases by 3-4% while the energy decreases by 7-9% during the sawtooth crash, insensitive to the equilibrium models. The correction from toroidicity is approximated from the θ -average of $2(\Lambda a \cos \theta / R)^2$ where Λ is the poloidal field asymmetry factor. From the measured Λ of $\simeq -0.1$ [18], the toroidal correction is about 0.1%.

The change in W is in good accord with Taylor's theory. Given the helicity and toroidal flux ($K, \Phi_\phi(a)$), one can calculate the energy of the minimum energy state, $W_{\min}$, from the BFM. We find that W approaches closely $W_{\min}$ during the crash, i.e., the excess energy $(W - W_{\min})/W_{\min}$ decreases from 4% before the crash to 1% afterward (Fig.3). The measured change of K of 3-4% adheres less to the Taylor theory which assumed that K is invariant. However, the change in K is indeed less than that of W (by a factor of two).

Another way to quantify the difference in dissipation rates is to compare the confinement times of the helicity and energy. Balance equations for K and W in a plasma bounded by a shell (with cuts) are given by

$$\frac{dK}{dt} = -2 \int \mathbf{E} \cdot \mathbf{B} dV + 2\Phi_\phi(a)V_\phi(a) \quad (1)$$

$$\frac{dW}{dt} = - \int \mathbf{E} \cdot \mathbf{j} dV + I_\phi V_\phi(a) + I_\theta V_\theta(a), \quad (2)$$

where $\mathbf{E}$ is the electric field, $I_\phi \equiv I_p$, and $I_\theta \equiv 2\pi R B_\phi(a)/\mu_0$. In the right-hand side of the above equations, the integral terms are dissipation terms and the others are input terms. Then we can define the confinement times for the helicity $\tau_K = K/[2\Phi_\phi(a)V_\phi(a) - dK/dt]$ and for the magnetic energy $\tau_W = W/[I_\phi V_\phi(a) + I_\theta V_\theta(a) - dW/dt]$. Between the crashes $\tau_K (\simeq 21\text{ms})$ is comparable to $\tau_W (\simeq 25\text{ms})$, but during the crash $\tau_K (\simeq 4.6\text{ms})$ is longer than $\tau_W (\simeq 2.5\text{ms})$ by a factor of two.

Spatial information on the helicity and energy is useful to understand the transport properties. Figure 4 shows the helicity and energy content per unit radial length before and

after the crash. The magnetic energy largely dissipates at the center with little increase at the edge while the helicity apparently is transported from the center to the edge rather than dissipated locally during the crash. This phenomenologically explains why the helicity is better conserved than energy.

Helicity transport is confirmed by local measurements of helicity flux due to fluctuations at the edge in MST. The balance equation for helicity in the annular region of $b \leq r \leq a$, K_{ab} , can be written as

$$\frac{dK_{ab}}{dt} = -2 \int_b^a \eta \mathbf{j}_0 \cdot \mathbf{B}_0 dV + S_K + 2 \int < \tilde{\phi} \tilde{B}_r > dS_b, \quad (3)$$

where the helicity injection term S_K is given by $2\Phi_\phi(a)V_\phi(a) - \Phi_\phi(b)V_\phi(b) - \Phi_\phi(b)V_\phi(a) + \Phi'_\theta(b)V_\theta(b)$ ($\Phi'_\theta(r)$ is the poloidal flux between radius r and a), S_b is the surface area at $r = b$, and only the classical dissipation through η is included. The last term represents helicity transport across $r = b$ by correlation between fluctuations in plasma potential $\tilde{\phi}$ and radial field $\tilde{B}_r$ associated with dynamo activity. (Another helicity flux term $2 \int < \tilde{A}_\theta (d\tilde{A}_\phi/dt) > dS_b$ is small.)

The fluctuations $\tilde{\phi}$ and $\tilde{B}_r$ have been measured simultaneously in the outer 5 cm region of MST using a probe [19] which incorporates both Langmuir probes and magnetic pickup coils. The measured fluctuation-induced helicity flux $< \tilde{\phi} \tilde{B}_r >$ across the surface $r = b (= a - 5\text{cm})$ shows that the helicity is continuously transported to the edge between crashes and its activity is enhanced during the crash (Fig.5). Because the profiles of field, current density, and electron temperature (thus the resistivity η with an estimated Z_{eff}) have been measured as functions of time during the entire sawtooth oscillation at $b \leq r \leq a$, it is possible to predict the helicity flux needed to balance the edge dissipation by Eq.(3). The predicted helicity flux is also shown in Fig.5 as a dotted line. Excellent agreement between the prediction and measurement supports the picture that the dynamo fluctuations continuously transport helicity from the center to the edge and that the transport is largely enhanced during the crash. Also, since the surface loss term [20] has been omitted in Eq.(3), the agreement implies that edge helicity dissipation, such as from limiters, is not important

in MST, unlike some other experiments [20].

The total helicity is predicted by MHD theory to be better conserved than we observe experimentally. The helicity balance (Eq.(1)) can be rewritten as

$$\frac{dK}{dt} = -2 \int \eta \mathbf{j}_0 \cdot \mathbf{B}_0 dV + 2\Phi_\phi(a)V_\phi(a) + 2 \int \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle \cdot \mathbf{B}_0 dV \quad (4)$$

where the mean-field Ohm's law $\mathbf{E}_0 + \mathbf{v}_0 \times \mathbf{B}_0 + \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle = \eta \mathbf{j}_0$ has been used ($\mathbf{v}$ is the flow velocity). The first two terms in the R.H.S. of Eq.(4) remain essentially unchanged during the crash. The last term has been predicted [21] to be small compared to the other two terms, as confirmed in MHD simulation [10], and to scale with resistivity as

$$2 \int \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle \cdot \mathbf{B}_0 dV \simeq -2 \int \langle \eta \tilde{\mathbf{j}} \cdot \tilde{\mathbf{B}} \rangle dV.$$

Since $\tilde{j}/j_0 \leq 1$ and $\tilde{B}/B_0 \sim 3\%$ in MST, this term yields a helicity change of $\lesssim 0.03\%$, which is smaller than the observed helicity change by two orders of magnitude. This analytic estimate is consistent with MHD computation which displays sawtooth relaxations. In the computation, the helicity drops by $\sim 6\%$ [11] during a sawtooth crash. However, the Lundquist number S ($\propto \eta^{-1}$) used in the simulations is 3×10^3 , 200 times smaller than that in MST. Therefore, the projected helicity change during a sawtooth crash in MST is 200 times smaller, i.e. 0.03% . Hence, the helicity should be well conserved in our experiments.

The helicity dissipation of 3-4% during the MST sawtooth crash implies the existence of a dissipation mechanism larger than that predicted by a simple Ohm's law. Table II lists all three terms in Eq.(1) and Eq.(2) between and during the crashes. Dissipation terms are enhanced by a factor of 4 for K and a factor of 10 for W during the crash, while the input terms remain essentially unchanged. Since dissipation at the edge is measured to be classical, the anomalous dissipation must occur at inner region. Possible candidates to explain the enhanced helicity dissipation during the crash can be inferred by inserting the generalized Ohm's law [22] $\mathbf{E} = \eta \mathbf{j} - \mathbf{v} \times \mathbf{B} + \mathbf{j} \times \mathbf{B}/en - \nabla P_e/en$ into the helicity dissipation term to yield $\mathbf{E} \cdot \mathbf{B} = -\nabla P_e \cdot \mathbf{B}/en + \eta \mathbf{j} \cdot \mathbf{B}$. The first term includes helicity dissipation due to fluctuations in the diamagnetic drift $-\langle \nabla \tilde{P}_e \cdot \tilde{\mathbf{B}} \rangle /en$. Its ratio to the second term can be written

as $(k\tilde{T}_e/e\eta j)(\tilde{B}/B_0)$ where the density fluctuations are assumed to be small. For MST parameters ($\eta j \sim 1\text{V/m}$, $k = n/R$ where $n \sim 5$, $\tilde{T}_e \sim 20\text{eV}$ and $\tilde{B}/B_0 \sim 3\%$) this ratio is $\lesssim 2$. Therefore, the enhanced fluctuations in the diamagnetic drift and magnetic field during the crash may account for the anomalous helicity dissipation. Another form of the first term is $-\partial/\partial r < \tilde{P}_e \tilde{B}_r > /en$ where $< \tilde{P}_e \tilde{B}_r >$ can be identified as electron momentum flux due to magnetic fluctuations, possibly related to the kinetic dynamo mechanism [19]. In fact, magnetic fluctuation induced particle [23] and energy [24] transport are large near the core plasma in MST. Other possible mechanisms of anomalous helicity dissipation may result from the kinetic modifications in the Ohm's law due to the fast electrons [23]. On the other hand, the magnetic energy dissipation term can be rewritten as $\mathbf{E} \cdot \mathbf{j} = -(\mathbf{v} \times \mathbf{B}) \cdot \mathbf{j} - \nabla P_e \cdot \mathbf{j} / en + \eta j^2$. The first term on the R.H.S. can be expressed as $(\rho/2)d\mathbf{v}^2/dt + \mathbf{v} \cdot \nabla p$ where ρ is the mass density and the force balance equation $\rho d\mathbf{v}/dt = -\nabla p + \mathbf{j} \times \mathbf{B}$ has been used. Apparently, the magnetic energy can be dissipated to kinetic energy.

In summary, the first experimental test of Taylor's helicity conservation hypothesis has been performed during the sawtooth relaxation in the MST RFP plasma. It is found that the change in the total magnetic helicity is far larger than MHD prediction. However, the relatively smaller decay of helicity (3-4%), compared to the decay of magnetic energy (7-9%), modestly supports the essence of the hypothesis in Taylor's relaxation theory. Enhanced transport of helicity, rather than local dissipation during the crash, phenomenologically explains its weaker decay, confirmed by a direct experimental observation of helicity flux due to the dynamo fluctuations. The fact that decay ratio of energy to helicity is a factor of two instead of orders of magnitude, indicates that helicity conservation is only a rough approximation. Detailed mechanisms for anomalous helicity dissipation during relaxation await for further investigations.

One of the authors (H.J.) deeply thanks Profs. K. Itoh and S.I. Itoh for their encouragement and Prof. Z. Yoshida for valuable discussions. The authors are grateful to MST group members, particularly Dr. A. Almagri, Dr. I.H. Tan, and Dr. M. Stoneking, for their

experimental contributions. This work was supported by the U.S. Department of Energy.

REFERENCES

- [1] H.K. Moffatt, J. Fluid Mech. **35**, 117(1969).
- [2] J.B. Taylor, Phys. Rev. Lett. **33**, 1139(1974); Rev. Mod. Phys. **58**, 741(1986).
- [3] B.B. Kadomtsev, in *Plasma Phys. Control. Nucl. Fusion Research*(IAEA, Vienna, 1977), Vol. I, p.555; F.L. Waelbroeck, Phys. Fluids, **B1**, 2372(1989).
- [4] A.H. Boozer, Phys. Fluids, **29**, 4123(1986); Plasma Phys. Control. Fusion, **36**, 825(1994).
- [5] Y. Song and R.L. Lysak, J. Geophys. Res., **94**, 5273(1989).
- [6] M.A. Berger, Geophys. Astrophys. Fluid Dyn., **30**, 79(1984).
- [7] For example, A. Bhattacharjee, R.L. Dewar, and D.A. Monticello, Phys. Rev. Lett., **45**, 347(1980); J.W. Edenstrasser and W. Schuurman, Phys. Fluids, **26**, 500(1983); R. Horiuchi and T. Sato, Phys. Fluids, **31**, 1142(1988); Y. Kondoh, J. Phys. Soc. Jpn., **58**, 489(1989).
- [8] R. Horiuchi and T. Sato, Phys. Rev. Lett., **55**, 211(1985).
- [9] J.P. Dahlburg, D. Montgomery, G.D. Doolen, and L. Turner, Phys. Rev. Lett., **57**, 428(1986).
- [10] Y.L. Ho, Ph.D thesis, University of Wisconsin(1988).
- [11] K. Kusano and T. Sato, Nucl. Fusion, **30**, 2075(1990).
- [12] M.K. Bevir and J.W. Gray, in *Proceeding of the Reversed-Field Pinch Theory Workshop*, Los Alamos 1981, Report No. LA-8944-C.
- [13] R.N. Dexter, *et al.*, Fusion Technol. **19**, 131(1991).
- [14] S. Hokin, *et al.*, Phys. Fluids, **B3**, 2241(1991).
- [15] V. Antoni, *et al.*, Nucl. Fusion, **26**, 1711(1986).

- [16] B. Müller and J. Reinhardt, *Neural Network*, (Springer-Verlag, Berlin Heidelberg, 1990).
- [17] J.W. Johnston, *Plasma Phys.*, **23**, 187(1981).
- [18] A.F. Almagri, *et al.*, *Phys. Fluids*, **B4**, 4080(1992).
- [19] H. Ji, *et al.*, *Phys. Rev. Lett.*, in press.
- [20] H.Y.W. Tsui, *Nucl. Fusion*, **28**, 1543(1988).
- [21] E. Hameiri and A. Bhattacharjee, *Phys. Fluids*, **30**, 1743(1987).
- [22] L. Spitzer, Jr., *Physics of Fully Ionized Gases* (2nd Revised Edition), (Interscience Publishers, New York, 1962), p.28.
- [23] M. Stoneking, *et al.*, *Phys. Rev. Lett.*, in press.
- [24] G. Fiksel, *et al.*, *Phys. Rev. Lett.*, **72**, 1028(1994).

TABLES

TABLE I. Comparison of helicity K , energy W and their decays during a sawtooth crash for four different equilibrium models.

model	$K_{t=0}(\text{Wb}^2)$	$W_{t=0}(\text{kJ})$	$\Delta K/K(\%)$	$\Delta W/W(\%)$
α -model	0.0229	47.9	-3.2	-7.7
MBFM	0.0225	46.8	-3.1	-7.7
smoothed MBFM	0.0227	47.3	-3.0	-7.6
$2 - \lambda$ model	0.0225	46.9	-4.0	-8.5

TABLE II. Comparison of all terms in the helicity and energy balance equations, Eq.(1) and Eq.(2), between and during the sawtooth crash.

	$\dot{K}$ (Wb ² /s)	$-2 \int \mathbf{E} \cdot \mathbf{B} dV$ (Wb ² /s)	$2\Phi_\phi V_\phi$ (Wb ² /s)	$\dot{W}$ (MW)	$-\int \mathbf{E} \cdot \mathbf{j} dV$ (MW)	$I_\phi V_\phi + I_\theta V_\theta$ (MW)
between crash	0.4	-1.1	1.5	1.7	-1.9	3.6
during crash	-3.3	-4.9	1.6	-16.2	-19.0	2.8

FIGURES

FIG. 1. Ensemble-averaged plasma current I_p , toroidal flux $\Phi_\phi(a)$, pinch parameter Θ , reversal parameter F , and voltage across the toroidal gap in the shell $V_\theta(a)$ during one sawtooth cycle. The ensemble consists of 150 sawtooth oscillations. The dotted lines represent values of F and Θ after one inverse mapping via ANN and one forward mapping (see main text).

FIG. 2. Plasma trajectory during one sawtooth cycle. The BFM (Bessel Function Model) curve is the locus of predicted minimum energy states.

FIG. 3. The magnetic helicity K , magnetic energy W , and “excess energy” $(W - W_{\min})/W_{\min}$ during one sawtooth cycle. $W_{\min}$ is energy predicted by the BFM with a given K and $\Phi_\phi(a)$. Also shown is $V_\theta(a)$ as a time reference.

FIG. 4. Radial profiles of the helicity and energy per unit radial length before (solid line) and after (dotted line) the crash.

FIG. 5. Comparison between the measured fluctuation-induced helicity flux (dotted line) and the prediction (solid line) from local helicity balance at $r = a - 5\text{cm}$.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

DATE

FILMED

9 / 7 / 94

END