PPPL-2279

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AMPLIFICATION OF S-1 SPHEROMAK CURRENT
BY AN INDUCTIVE CURRENT TRANSFORMER

By

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NOVEMBER 1985

PLASMA
PHYSICS
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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CNO-3073

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Abstract

We attempt to predict the consequences of adding an inductive current transformer (OH Transformer) to the present S-1 Spheromak experiment. Axisymmetric modeling with only classical dissipation shows an increase of toroidal current and a shrinking and hollowing of the current channel, conserving toroidal flux. These unstable profiles will undergo helical reconnection, conserving helicity $K = \int \vec{A} \cdot \vec{B} \, d\tau$ while increasing the toroidal flux and decreasing the poloidal flux so that the plasma relaxes toward the Taylor state. This flux rearrangement is modeled by a new current viscosity term in the mean-field Ohm's law which conserves helicity and dissipates energy.

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1. Introduction

It is now an established experimental fact that flux conversion between poloidal and toroidal fields plays an important role in compact torus (CT) and reversed-field pinch (RFP) laboratory experiments. The dynamo action in the RFP is probably the most familiar manifestation of this phenomena.¹ Flux conversion also occurs in the CT sustainment experiments^{2,3} and, in general, occurs during any plasma relaxation in which unstable plasma profiles evolve toward a stable minimum energy state.

It has been found that the present plasma formation phase^{4,5} in the S-1 Spheromak makes use of flux conversion in that detailed programming of the relative voltages and the timing of the capacitor bank discharges into the toroidal and poloidal windings of the flux core is not necessary.⁶ The forming plasma is observed to adjust itself to stay near a stable minimum-energy equilibrium state.

It has further been found that this equilibrium state is nearly characterized by a single internal parameter, the plasma helicity K . The helicity has been observed to decay on a time scale much longer than the time scale over which the individual poloidal or toroidal fluxes change, or over which the plasma magnetic energy decays. This observation is consistent with and is, in fact, the basis of the Taylor theory¹ of plasma relaxation. The important quantity characterizing the formation or sustainment of the spheromak plasma in S-1, then, is the amount or rate of helicity injected into the plasma by the flux core and the other external circuits.

In this note we demonstrate that supplementary helicity can be injected into the S-1 plasma by way of an ohmic heating (OH) transformer, very much like what is done in an air core tokamak. The OH transformer provides a relatively easy and inexpensive means of approximately doubling the toroidal current in the S-1 device.

In the following sections, we derive the appropriate expressions for helicity and helicity injection rates in axisymmetric geometry. We then apply these to calculate the helicity injection rates of the existing flux core and the proposed OH transformer in the S-1 experiment.

If we regard the axisymmetric magnetic fields as "mean fields," about which there are small amplitude nonaxisymmetric fluctuations, the turbulent relaxation processes can be modeled by a new term⁷⁻¹⁰ in the mean-field Ohms law which allows flux conversion but conserves global helicity and always dissipates energy. We have implemented this new term in an existing 2-D computer code⁵ that simulates the formation phase of the S-1 Spheromak experiment. This term then allows quantitative estimates of the actual effect of the proposed OH transformer and includes both flux conversion and 3-D relaxation effects.

II. Helicity in Axisymmetric System

The magnetic helicity associated with a simply connected volume of plasma V is defined by¹

$$K_{SC} = \int_V \vec{A} \cdot \vec{B} \, d\tau \quad , \quad (1)$$

where $\vec{A}$ is the vector potential associated with the magnetic field $\nabla \times \vec{B} = \vec{A}$ having the property that the line integral of $\oint \vec{A} \cdot d\vec{l}$ around any closed curve is equal to the magnetic flux contained by that curve.¹¹ When the domain of interest is not simply connected, the definition of helicity must change to remain physically meaningful. In particular, when a toroidal plasma is wrapped around an axisymmetric flux core with toroidal flux Φ_C and poloidal flux χ_C , fig. 1, and is bounded by a limiter with poloidal flux χ_L and plasma toroidal flux Φ_L , Fig. 2, the correct definition of helicity is¹²

$$K = \int_V \vec{A} \cdot \vec{B} \, d\tau - x_c \phi_c - x_2 \phi_2 \quad (1a)$$

Here the integral is over the plasma region only. This definition will be shown to lead to expressions for helicity and helicity injection rates that are independent of the initial values of the toroidal flux in the flux core and the poloidal flux at the limiter.

In an axisymmetric system, we can construct an explicit form for the vector potential $\vec{A}$ having the line integral property as well as the gauge condition $\nabla \cdot \vec{A} = 0$ as follows:

$$\vec{A} = \frac{1}{2\pi} \chi \nabla \phi + \nabla \phi \times \nabla a \quad (2)$$

Here (R, ϕ, Z) form a cylindrical coordinate system, χ is the poloidal magnetic flux, and a is a stream function associated with the toroidal magnetic field. In terms of these functions, we can calculate the magnetic field as the sum of a poloidal piece $\vec{B}_p$ and a toroidal piece $\vec{B}_T$

$$\vec{B} = \frac{1}{2\pi} \nabla \chi \times \nabla \phi + g \nabla \phi \quad (3)$$

the poloidal magnetic flux

$$\chi = \int \vec{B} \cdot \hat{n} \, dS = \frac{1}{2\pi} \int \nabla \chi \times \nabla \phi \cdot \hat{Z} \, 2\pi R \, dR \quad (4)$$

and the toroidal magnetic flux

$$\phi = \frac{1}{2\pi} \int \vec{B} \cdot \nabla \phi \, d\tau = \frac{1}{2\pi} \int \frac{1}{R^2} g \, d\tau = \oint dz \, \frac{1}{R} \hat{n} \cdot \nabla a \quad (5)$$

Here, $g \equiv \Delta^* a \equiv R^2 v \cdot R^{-2} \nabla a$, the area of integration in Eq. (4) is an axisymmetric disk extending from the symmetry axis $R = 0$ to the magnetic surface with label χ , and the line of integration in Eq. (5) is a loop around the minor cross section within the surface with label χ .

The helicity can now be calculated using Eqs. (1a) through (5):

$$K = 2 \left(\int \chi \, d\phi - \chi_g \phi_g \right), \quad (6)$$

where the integral is over the plasma volume, $d\phi \equiv (2\pi R^2)^{-1}$, $\Delta^* a \, d\tau$ is the toroidal flux associated with the volume element $d\tau$, and, as before, χ_g and ϕ_g are the values of poloidal and toroidal magnetic flux at the plasma limiter. This agrees with the corrected form of Eq. (13) in Ref. 12, and it clearly has the properties that the helicity is invariant under the transformation $\chi \rightarrow \chi + \text{constant}$ and $K = 0$ when $\phi_g = \int d\phi = 0$.

III. Time Rate of the Change of Helicity

The induction equation for the magnetic field evolution

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}, \quad (7)$$

and a general form of Ohm's law,

$$\vec{E} + \vec{v} \times \vec{B} = \vec{R}_d, \quad (8)$$

where $\vec{R}_d$ contains all the dissipative or nonideal terms, imply an evolution equation for the helicity density

$$\frac{\partial}{\partial t} \vec{A} \cdot \vec{B} = \nabla \cdot (\vec{A} \times \vec{E} - \vec{B} \nabla \psi) - 2 \vec{R}_d \cdot \vec{B} \quad , \quad (9)$$

where ψ is the single-valued potential associated with the electric field $\vec{E}$,

$$\vec{E} = - \frac{\partial \vec{A}}{\partial t} - \nabla \psi \quad . \quad (10)$$

Integrating Eq. (9) over the plasma volume and using Eq. (1a) yields an expression for the time rate of the change of helicity in the plasma volume

$$\frac{\partial K}{\partial t} = -2 \left(\chi_c \frac{\partial \Phi_c}{\partial t} + \Phi_c \frac{\partial \chi_c}{\partial t} \right) - 2 \int \vec{R}_d \cdot \vec{B} \, d\tau \quad , \quad (11)$$

where the term involving χ_c and Φ_c is only present if the plasma encloses the flux core as in Fig. 1(a). The term in parentheses in Eq. (11) describes helicity injection or helicity extraction from the system, while the volume integral normally describes helicity decay due to dissipation.

IV. Helicity Injection With Flux Core

We now use Eqs. (6) and (11) to calculate the helicity injected into the S-1 plasma via the flux core. The initial configuration, immediately after preionization and before the flux core swing, is shown in Fig. 1(a). The flux core contains initial toroidal flux $\Phi_c(0)$ and has initial poloidal flux $\chi_c(0)$, but the plasma contains no toroidal flux. From Eq. (6), the initial helicity associated with the plasma volume bounded by the flux core boundary $\chi = \chi_c$ and the separatrix surface $\chi_s = 0$ is given by

$$K_i = 0 \quad . \quad (12)$$

After the flux swing, χ_0 remains zero so that the final helicity is

$$K_f = 2 \int \chi \, d\phi \quad , \quad (13)$$

where the integral is inside the volume in Fig. 1(b) which is bounded by the surface $\chi = \chi_0 = 0$. Ignoring the dissipative term, we can calculate the helicity injection rate of the flux core by evaluating Eq. (11) during the flux swing. Since $\chi_0 = 0$, this yields

$$\frac{\partial K}{\partial t} = -2\chi_c \frac{\partial \phi_c}{\partial t} \quad . \quad (14)$$

Integrating Eq. (14) from the initial time $t_i = 0$ to the final time t_f yields

$$K_f - K_i = -2 \int_0^{t_f} \chi_c(t) \frac{\partial}{\partial t} \phi_c(t) \, dt \quad . \quad (15)$$

Combining Eq. (15) with Eq. (12) yields an expression for the final helicity

$$K_f = \int_0^{t_f} \dot{K}_{INJ} \, dt \quad , \quad (16)$$

where the helicity injection rate is

$$\dot{K}_{INJ} = -2\chi_c(\tau) \frac{\partial}{\partial \tau} \phi_c(\tau) \quad . \quad (17)$$

We see that expressions (12) and (13) for the initial and final helicity and that expression (17) for the helicity injection rate are independent of the initial value of toroidal flux in the flux core $\phi_c(0)$ as required.³

V. Helicity Injection With Ohmic Heating Transformer

We next calculate the helicity injection rate after the initial plasma has been fully formed and is separated from the flux core, and the plasma is limited on its small major radius side by an OH transformer that undergoes a flux swing (see Fig. 2). If we again assume dissipative processes to be negligible, the helicity injection rate from Eq. (11) is given by

$$\frac{\partial K}{\partial t} = -2\phi_z \frac{\partial \chi_z}{\partial t} \quad (18)$$

Since the total plasma toroidal flux ϕ_z remains approximately conserved during the transformer swing, Eq. (18) can be integrated to yield the incremental gain in helicity

$$\Delta K = -2\phi_z \Delta \chi_z \quad , \quad (19)$$

where $-\Delta \chi_z$ is the total flux swing (in volt-sec) for the transformer. The total helicity in the plasma after the transformer swing is given by

$$K = 2 \left(\int \chi \, d\phi - \chi_z \phi_z \right) \quad , \quad (20)$$

where the integral is over the plasma volume, and χ_z and ϕ_z are the values of the poloidal and toroidal flux at the limiter after the flux swing.

VI. Mean-Field Description of Turbulent Relaxation

If one assumes only classical axisymmetric processes, the plasma profiles obtained after the transformer flux swing are generally found to be

unstable to nonaxisymmetric perturbations of the tearing mode type. We postulate that the effect of these instabilities is to induce small amplitude MHD fluctuations which allow magnetic reconnection while conserving the global helicity. The axisymmetric magnetic field is then interpreted as a "mean-field," averaged over these fluctuations.

The 2-D MHD equations for the evolution of the mean fields are very similar to those for the axisymmetric fields, with the important exception of a new term appearing in the mean-field Ohm's law. We take the dissipative term $\vec{R}_d$ appearing in the Ohm's law, Eq. (8), to be of the form⁷

$$\vec{R}_d = \eta \vec{J} - \frac{\vec{B}}{B^2} \cdot \nabla \cdot \left[\lambda \nabla \left(\frac{\vec{J} \cdot \vec{B}}{B^2} \right) \right] \quad , \quad (21)$$

where the first term on the right-hand side of Eq. (21), $\eta \vec{J}$, is the classical ohmic dissipation term, while the second term, containing the coefficient λ , describes the effect of 3-D turbulent relaxation on the mean fields. By substituting Eq. (21) into the helicity conservation Eq. (11), we see that the new term containing λ can be integrated to become a surface term and, thus, only transports and does not dissipate helicity. It can also be shown that for $\lambda > 0$ this term will always dissipate energy and, thus, will not violate any thermodynamic inequalities. Physically, the parameter λ is the coefficient of electric current viscosity.⁹

What is the effect of the new term containing λ on the plasma profiles? Clearly, since this term multiplies the highest derivatives of the current, it will tend to smooth out current distributions into more stable profiles. But since the OH transformer adds only poloidal flux and does not directly increase the toroidal flux, we ask whether this term can increase the global toroidal flux in the plasma.

From Eqs. (5) and (7), we have for the time rate of the change of toroidal flux in the plasma

$$\frac{\partial \Phi}{\partial t} = \frac{1}{2\pi} \int d\tau \nabla \cdot (\vec{\nabla} \Phi \times \vec{E}) = - \oint \vec{E} \cdot d\vec{L} \quad (22)$$

$$= - 2\pi n g' \oint dL B_\rho + \frac{\partial}{\partial \chi} \oint \frac{dL}{B_\rho} \lambda \nabla \chi \cdot \nabla \left(\frac{\vec{J} \cdot \vec{B}}{B^2} \right) , \quad (23)$$

where Eqs. (8) and (21) were used in obtaining Eq. (23) and $B_\rho = (2\pi)^{-1} \nabla \chi \times \nabla \Phi$. If we use the force free condition that $p' = 0$ at the plasma boundary, Eqs. (22) and (23) simplify to

$$\frac{\partial \Phi}{\partial t} = - 2\pi n g' \oint dL B_\rho + 2\pi \frac{\partial}{\partial \chi} \left(\lambda g'' \oint dL R^2 B_\rho \right) , \quad (24)$$

where the right-hand side is evaluated at the plasma/vacuum boundary and primes denote derivatives with respect to the poloidal flux χ .

We note here that if the current viscosity term λ goes smoothly to zero at the boundary so that λ and $\lambda' = 0$ there, as we assume, then the second term on the right in Eq. (24) will not contribute to net toroidal flux increase in the plasma. Instead, the first term on the right, which normally tends to decrease the toroidal flux in a paramagnetic plasma, must change sign due to λ being nonzero in the plasma interior. For this to happen, the plasma must become locally diamagnetic near the boundary.

VII. Computational Results

Here we describe the results of several simulations performed using the Princeton Toroidal Simulation Code¹³ (PTSC) in which we model the current amplification caused by the proposed OH transformer flux swing in the S-1 device. The PTSC is a free-boundary axisymmetric, or mean-field, time dependent resistive MHD code. We begin the simulations after the flux-core formation process is complete, and just as the OH transformer flux swing is to start.

The initial configuration is illustrated in Fig. 3. A spheromak plasma, fully separated from the flux core, sits at a major radius of $R = 0.56$ m and rests on an inside limiter at $R = 0.25$ m. The plasma has an initial toroidal current of 500 kA and an initial toroidal flux of $\Phi = 0.0773$ webers. The initial current distribution is described by $\vec{J} = \mu \vec{B}$ with μ constant. The initial temperature in the plasma decreases linearly in χ from 350 eV in the center to 0.2 eV at the edge, with a constant density of 0.7×10^{19} . This corresponds to an initial plasma β of 0.5%. The resistivity is taken to be classical Spitzer so that the initial plasma resistance is 5×10^{-6} Ohm-m. The initial plasma helicity, calculated from Eq. (6), is 0.0236.

At time $t = 0$, the OH transformer and the fast equilibrium field coils are ramped to their final values of current over a time period of 10^{-4} sec as indicated in Table I. In case I, we model the plasma with a classical Ohm's law, i.e., we set $\lambda = 0$ in Eq. (21) so that no flux conversion will occur. In cases II-IV, we repeat the identical calculation but with $\lambda \neq 0$ to model turbulent relaxation during the transformer flux swing. The specific form of $\lambda(\chi)$ used is

$$\lambda(\chi) = \lambda_0 (1 - \chi^4) \quad , \quad (25)$$

where $\tilde{\chi}$ is a linear function of the poloidal flux χ which goes to zero at the magnetic axis and to 1.0 at the plasma flux surface containing 0.9 of the poloidal flux between the magnetic axis and the plasma limiter surface. Beyond this 0.9 surface and into the vacuum we have $\lambda = 0$. This assures that both λ and $\lambda' = 0$ at the limiting $\chi = \chi_L$ surface and, thus, flux conversion is confined to the interior of the plasma. We find the actual results to be relatively insensitive to this value of 0.9. In the calculation reported here, $\lambda_0 = 0.06, 0.12, 0.24$ and 0.96 times η_{50} was used, where η_{50} is the Spitzer resistivity associated with a 50 eV plasma.

In Fig. 4 we plot the final contours and midplane profiles of (a) the poloidal flux function $\psi = -\chi/2\pi$, (b) the toroidal current, and (c) the toroidal field function $g = RB_T$. We see, in Fig. 4(a), that a separatrix moves in from the top and bottom small major radius side and limits the plasma, acting as a natural divertor. Figures 4(b) and 4(c) show that with only classical processes the current channel shrinks while forming a skin with steep gradients around the initial $\chi = \chi_L(0)$ surface. From Fig. 4(c) we see that the plasma volume with nonzero toroidal field also shrinks with the toroidal field strength being amplified in the center. The total plasma toroidal flux is exactly conserved during the flux swing, while the poloidal flux at the limiter decreases by 0.45 webers. The toroidal plasma current has increased from 500 kA to 975 kA while the internal inductance $\mathcal{L}_1/2 \equiv \int B_p^2 cV/RIp^2$ has increased from 0.432 to 0.825. Thus, from Eq. (19), the plasma helicity increases by an amount $\Delta K = -2 \Phi_L \Delta\chi_L = 0.07$. In Fig. 5(a) we again illustrate the current peaking and skin effect that occurs by plotting the toroidal current midplane profiles at several times. Similar profile plots of the safety factor q versus the poloidal flux function ψ are shown in Fig.

5(b). We see that the q profile is nearly conserved in the central portion of the plasma, indicating that resistivity is not important there. Outside the initial $\chi = \chi_0(0)$ surface, the q profiles undergo some oscillations and go smoothly to zero along with their derivatives at the instantaneous plasma boundary $\chi = \chi_0(t)$.

The results of case III, which has the flux conversion term $\lambda \neq 0$ given by Eq. (25), are shown in Figs. 4(d), (e), (f) and in Figs. 5 (c) and (d). We see that while the flux surface contours look very similar to the previous case, the toroidal current and toroidal field function profiles are quite different, being markedly smoother and less peaked. The q profile in Fig. 5(d) is markedly different than that of 5(b), having decreased in the center and being more broad. It is interesting to note that q becomes negative out near the edge, as it must for the net toroidal flux in the plasma to increase according to the reasoning following Eq. (24). We see from Table II that the toroidal flux in the plasma for case III has increased some 27% due to the flux conversion term, while the total toroidal current has increased 95% to the same final value as obtained in case I.

We see from Table II that the final values of the plasma current and helicity are relatively independent of the coefficient λ_0 . The value of the toroidal flux Φ_θ in the plasma after the OH transformer flux swing clearly increases with increasing λ_0 , although its dependence is relatively weak. Similarly, the internal inductance $l_i/2$ decreases with increasing λ_0 . The poloidal flux difference between the magnetic axis and the limiter $\chi_m - \chi_0$, decreases with λ_0 for large enough λ_0 , as the new dissipative term in Eq. (21) begins to act at the magnetic axis to reduce χ_m . This is a consequence of the new flux-conversion term in Ohm's law acting to convert excess poloidal flux into toroidal flux.

VIII. Summary and Conclusions

The center OH transformer appears to provide an attractive and feasible means of quadrupling the plasma helicity and doubling the toroidal current in the S-1 Spheromak experiment. If the plasma evolves due to purely classical axisymmetric processes, this additional toroidal current, unaccompanied by additional toroidal flux, will cause the plasma to become unstable to resistive tearing instabilities. We postulate that these instabilities occur, causing rearrangement of the plasma current profiles and the conversion of some poloidal flux into toroidal flux, but conserving the net helicity of the configuration. Thus, it is the amount of helicity injected rather than the amount of toroidal or poloidal flux added that is of primary importance. There is a growing experimental basis for this conjecture, both in the S-1 experiment and in the Los Alamos National Laboratory CT experiment.

We have modeled the helicity conserving plasma relaxation by a new term in Ohm's law that acts only on the mean (axisymmetric) fields. It is interesting to note that 2-D axisymmetric simulations including this term predict that the total toroidal flux in the plasma should increase during the OH transformer flux swing. From Table II, however, we see that this increase is not totally at the expense of the poloidal flux difference between the magnetic axis and the limiter, but is also a consequence of the helicity being conserved and the toroidal flux increasing and redistributing itself relative to the poloidal flux.

Acknowledgments

We wish to gratefully acknowledge several useful conversations and continuing encouragement from Drs. A.H. Boozer, R.A. Ellis, Jr., and Prof. H.P. Furth. We thank Dr. J.L. DeLucia for his expert computational assistance.

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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Table I.

Coil Currents.

R(m)	Z(m)	I _{INIT} (kA)	I _{FINAL} (kA)
0.8	±1.05	-322	-322
1.51	±0.750	-281	-281
1.80	±0.278	218	218
1.0	0.0	-70	-70
0.8	±0.4	0.0	-400
3.2	Z ≤ 0.4	0.0	-3300

Table II.

Results of Simulation.

<u>INITIAL VALUES</u>		<u>FINAL VALUES</u>				
		<u>I</u>	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>
λ_o		0	$0.06n_{50}^{(a)}$	$0.12n_{50}$	$0.24n_{50}$	$0.96n_{50}$
I_p	500 kA	975 kA	963 kA	976 kA	997 kA	1030 kA
K	0.0236	0.092	0.098	0.101	0.103	0.102
ϕ_L	0.0773	0.0764	0.0898	0.0973	0.106	0.116
$x_m - x_L$	0.253	0.703	0.738	0.738	0.724	0.62
$z_i/2$	0.432	0.825	0.827	0.794	0.743	0.60

(a) Note: $n_{50} \approx n_{\text{Spitzer}}$ ($T = 50$ eV)

Figure Captions

- FIG. 1. Flux core spheromak showing magnetic configuration (a) before transformer swing and (b) after transformer swing. Spheromak plasma fills the volume inside the contour $\chi = 0$ and outside the flux core.
- FIG. 2. Magnetic configuration (a) before transformer swing and (b) after transformer swing.
- FIG. 3. Initial contours and midplane profiles of (a) poloidal flux function $\psi = -\chi/2\pi$, (b) toroidal field function $g = RB_T$, (c) toroidal current $\mu_0 J_T$.
- FIG. 4. Final contours and midplane profiles of (a) poloidal flux function, (b) toroidal current, and (c) toroidal field function for case I with $\lambda = 0$. Figures (d), (e), and (f) are same profiles for case III with $\lambda \neq 0$.
- FIG. 5. Profiles of (a) toroidal current vs major radius and (b) safety factor vs poloidal flux function for case I at times 0, 68, 94, 112, and 129 usec. Figures (c) and (d) are the same for case III.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

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