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# STEADY-STATE OPERATION OF SPHEROMAKS BY INDUCTIVE TECHNIQUES

By

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ABSTRACT

A method to maintain a steady-state spheromak configuration inductively using the S-1 Spheromak device is described. The S-1 Spheromak formation apparatus can be utilized to inject magnetic helicity continuously (C.W., not pulsed or D.C.) into the spheromak configuration after equilibrium is achieved in the "linked" mode of operation. Oscillation of both poloidal- and toroidal-field currents in the flux core ($\psi$-$\phi$ Pumping), with proper phasing, injects a net time-averaged helicity into the plasma. Steady-state maintenance relies on flux conversion, which has been earlier identified. Relevant experimental data from the operation of S-1 are described. Helicity flow has been measured and the proposed injection scheme simulated. In a reasonable time practical voltages and frequencies can inject an amount of helicity comparable to that in the initial plasma. Plasma currents can be maintained or increased. This pumping technique is similar to F-$\Theta$ Pumping of a Reversed-Field-Pinch but is applied to this "inverse-pinch" formation.

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# I. INTRODUCTION

Steady-state or long-pulse operation of a fusion reactor has many advantages over pulsed operation. The possibility for steady-state operation of spheromaks has relied so far on one of a number of unproven schemes: radio-frequency current drive, beam injection, or merging[1] of newly created spheromaks with previously established, but decaying, ones. Steady-state spheromak drive has been proposed[2,3] by use of electrodes, as well.

The S-1 Spheromak induction technique[4] lends itself not only to the formation of spheromaks, but also to the inductive sustainment of a steady-state spheromak. The S-1 formation apparatus can be utilized to inject magnetic helicity $K = \int \underline{A} \cdot \underline{B}\, dV$ into the spheromak configuration after equilibrium is achieved in order to maintain or increase plasma currents. This steady-state inductive operation has been made possible by three recent developments. The first is the positive identification[5] of flux conversion processes and relaxation phenomena in the S-1 Spheromak plasma. These phenomena are consistent with the spontaneous approach to a Taylor state.[6] Relaxation is an essential requirement for steady-state drive. The plasma is relied on to assimilate properly the fluxes input to it to maintain adequate profiles. A second development is the favorable stability afforded by operation in the "linked" mode;[7] the spheromak is not completely detached from the core, so some poloidal magnetic flux links both the plasma and the core. This minimal linkage provides the coupling to external circuits needed for continuously driving the plasma currents. The third development is the proposal of F-Θ Pumping[8-11] in RFP devices. There is a significant similarity between operation of Reversed-Field-Pinch poloidal- and toroidal-field circuits and operation of the S-1 Spheromak "inverse-pinch" circuits.

The combination of these developments allows sustainment of spheromaks via access to only the outermost flux surfaces. The spheromak configuration can be maintained in a highly stable and controlled fashion. The method described below eliminates the restriction to pulsed spheromak plasmas or the use of electrodes for steady-state operation, and, therefore, is a reactor-relevant formation and sustainment method. The inductive formation and equilibrium of these spheromaks have already been experimentally tested and proven[4] so that only the steady-state drive technique needs testing.

The purposes of this report are to describe this new method of maintaining a steady-state spheromak plasma configuration by inductive techniques, to present the pertinent experimental data from the S-1 Spheromak device, and to describe a simple simulation of the steady-state drive.

## II. STEADY-STATE TECHNIQUES

This continuous (C.W.) method injects magnetic helicity from the flux core into the already formed spheromak configuration by appropriately oscillating the currents in the poloidal- and toroidal-field circuits (Fig. 3a). This method requires the spheromak to be operated in the linked mode; that is, the spheromak would be formed in the same manner as usual, but would not be completely detached from the core (Fig. 1). Hereafter, an oscillation of both poloidal- and toroidal-field currents in the core commences. A net helicity is injected from the core into the plasma on an average over a period of oscillation. The phasing is chosen to maximize the average helicity input rate. This $\psi$-$\phi$ Pumping works because of the nonlinear behavior of the magnetics. It is analogous to what RFP researchers call F-$\Theta$ Pumping.

This pumping technique has two immediate advantages over some of the other pulsed techniques: the injection is continuous and controllable; and it operates in the stable linked mode. Without a stabilizing system or method, plasmas either tilt or shift after completely detaching, depending on the equilibrium field shape. Increased stability against tilting and shifting has been demonstrated[7] by not fully detaching the spheromak from the core. The linked mode provides both a very stable plasma and the necessary coupling between the plasma and core.

## III. HELICITY INJECTION

### A. Basic equations for S-1 Spheromak topology

It can be shown that the proper definition of the magnetic helicity for the linked spheromak topology is

$$K \equiv \int \underline{A} \cdot \underline{B}\, dV - \psi\phi \quad . \tag{1}$$

This ensures that the helicity is gauge invariant. $\underline{A}$ is the vector potential; $\underline{B} = \nabla \times \underline{A}$ is the magnetic field vector. The integral is over the plasma volume. The magnetic fluxes $\psi$ and $\phi$ are defined by

$$\psi = \int \underline{A} \cdot \underline{d\ell}_\phi \tag{2}$$

and

$$\phi = \int \underline{A} \cdot \underline{d\ell}_\theta \; ,$$

where the line integrals of the vector potential are taken the long and the short way around the flux core, respectively.

The plasma has the two surfaces $S_1$ and $S_2$ to consider in the linked mode, as is shown in Fig. 1. The surface $S_1$ between the plasma and the core can be considered a constant flux surface. This is experimentally true for several reasons. First, the flux core poloidal field system and the equilibrium field system are designed so that, at the moment the plasma is initiated, the vacuum poloidal flux intercepting the core surface is minimized. Second, there is an aluminum shell, with poloidal and toroidal cuts, embedded in the core between the surface and the coils; this smooths field ripple and maintains a more nearly constant flux surface at the core surface throughout the discharge. Hence, $\underline{B} \cdot \underline{dS} = 0$ on $S_1$. The surface $S_2$ is defined by the outermost poloidal field line enclosing the plasma so that $\underline{B} \cdot \underline{dS} = 0$ identically.

The time dependence of K is obtained by taking the time derivative of Eq. (1):

$$\frac{\partial K}{\partial t} = \int \left[\frac{\partial \underline{A}}{\partial t} \cdot \underline{B} + \underline{A} \cdot \frac{\partial \underline{B}}{\partial t}\right] dV + \int \left(\underline{A} \cdot \underline{B}\right) \underline{v} \cdot \underline{dS} - \frac{\partial}{\partial t} (\psi\phi) \ . \qquad (3)$$

The remainder of this section is devoted to reformulating this expression for $\partial K/\partial t$ using ohmic loss terms and the fluxes and voltages associated with the core.

Using Faraday's Law, Eq. (3) becomes

$$\frac{\partial K}{\partial t} = - \int \left[\underline{B} \cdot \left(\underline{E} + \nabla\Theta\right) + \underline{A} \cdot \nabla \times \underline{E}\right] dV + \int \left(\underline{A} \cdot \underline{B}\right) \underline{v} \cdot \underline{dS} - \frac{\partial}{\partial t} (\psi\phi) \ , \qquad (4)$$

where $\theta$ is a scalar potential. The term in $\underline{B} \cdot \nabla\theta$ is zero because $\underline{B} \cdot \underline{dS} = 0$ on both plasma surfaces:

$$\int \underline{B} \cdot \nabla\Theta \, dV = \int \nabla \cdot (\Theta \underline{B}) \, dV = \int \Theta \, \underline{B} \cdot \underline{dS} \, . \tag{5}$$

The first integral in Eq. (4) can be rewritten using a vector identity and Gauss' Theorem, so that

$$\frac{\partial K}{\partial t} = -2 \int \underline{E} \cdot \underline{B} \, dV + \int \left(\underline{A} \times \underline{E}\right) \cdot \underline{dS} + \int \left(\underline{A} \cdot \underline{B}\right) \underline{v} \cdot \underline{dS} - \frac{\partial}{\partial t} \left(\psi\phi\right) \, . \tag{6}$$

The third integral on the right-hand side of Eq. (6) can be rewritten by use of a vector identity as $\int \left\{\underline{A} \times \left(\underline{v} \times \underline{B}\right) + \left(\underline{A} \cdot \underline{v}\right)\underline{B}\right\} \cdot \underline{dS}$, so that

$$\frac{\partial K}{\partial t} = -2 \int \underline{E} \cdot \underline{B} \, dV + \int \underline{A} \times \left(\underline{E} + \underline{v} \times \underline{B}\right) \cdot \underline{dS} + \int \left(\underline{A} \cdot \underline{v}\right) \underline{B} \cdot \underline{dS} - \frac{\partial}{\partial t} \left(\psi\phi\right) \, . \tag{7}$$

The third integral in Eq. (7) is zero as $\underline{B} \cdot \underline{dS} = 0$. The surface integral of $\underline{A} \times (\underline{v} \times \underline{B})$ is zero at the core surface as $\underline{v}$ is parallel to the surface.

The second integral over surface $S_2$ can be shown to be negligible. Using Ohm's law, this integral is just

$$\int_{S_2} \underline{A} \times \left(\underline{E} + \underline{v} \times \underline{B}\right) \cdot \underline{dS} = \int_{S_2} \underline{A} \times \eta \, \underline{j} \cdot \underline{dS} \, . \tag{8}$$

However, $\underline{j}$ and $\underline{A}$ are nearly, if not exactly, parallel on $S_2$ since the plasma is expected to be maintaining a force-free state. The vector potential $\underline{A}$ is only poloidal on $S_2$, and the only current, if any, expected on the outer surface for reasonable discharges would be poloidal. The same integral over surface $S_1$ is nonzero since there exist both poloidal and toroidal components of both $\underline{j}$ and $\underline{A}$ on $S_1$. The plasma is being driven through the $S_1$ surface. Hence, we get

$$\frac{\partial K}{\partial t} = -2 \int \underline{E} \cdot \underline{B}\, dV + \int_{S_1} \underline{A} \times \underline{E} \cdot \underline{dS} - \frac{\partial}{\partial t} (\psi\phi) \tag{9}$$

$$= - 2 \int \underline{E} \cdot \underline{B}\, dV + \dot{\psi}\, \phi - \psi\dot{\phi} - \frac{\partial}{\partial t} (\psi\phi) \tag{10}$$

$$= - 2 \int \underline{E} \cdot \underline{B}\, dV - 2\psi\dot{\phi}\ . \tag{11}$$

B. Helicity loss term

The first term in Eq. (11) can be rewritten using Ohm's law, $\underline{E} + \underline{v} \times \underline{B} = \eta\underline{j}$, as

$$-2 \int \underline{E} \cdot \underline{B}\, dV = -2 \int \eta\underline{j} \cdot \underline{B}\, dV. \tag{12}$$

Assuming force-free fields so that $\nabla \times \underline{B} = \mu\underline{B}$, then $\underline{j} = \mu\underline{B}$. The first term in Eq. (11) becomes $-(2/\mu) \int \eta j^2\, dV$. This term is simply the decrease in helicity due to ohmic losses.

During early times when the plasma is forming around the core, the magnitude of this loss term $-2\int \underline{E}\cdot\underline{B}\,dV$ must be smaller than that of the helicity input term $-2\psi\dot{\phi}$ in order for helicity to be built up in the plasma. This loss term can be estimated[12] as follows. Since $\underline{E}\cdot\underline{B} = \eta\underline{j}\cdot\underline{B}$ and the resistivity is low except near the plasma edge, the volume over which this integral is significant becomes a shell around the core, so that

$$-2\int \underline{E}\cdot\underline{B}\,dV \approx -2\delta\int \underline{E}\cdot\underline{B}\,dS = -2\,\delta\int (E_\phi B_\phi + E_\theta B_\theta)dS\ , \tag{13}$$

where

$$\begin{aligned} E_\phi &\approx -\frac{\dot{\psi}}{2\pi R_c}\ , \\ E_\theta &\approx -\frac{\dot{\phi}}{2\pi a_c}\ , \\ B_\phi &\approx -\frac{\phi}{\pi a_c^2}\ , \\ B_\theta &\approx \frac{\psi}{\pi R_c^2} \end{aligned} \tag{14}$$

and where $R_c$ and $a_c$ are the major and minor radii of the flux core, respectively, and $\delta$ is some effective skin depth. Substituting Eq. (14) into (13):

$$-2\int \underline{E}\cdot\underline{B}\,dV \approx 4\delta\ \left(\frac{-\dot{\psi}\phi}{a_c} + \frac{\dot{\phi}\psi}{R_c}\right)\ . \tag{15}$$

This is small compared to the input term if $2\delta/a_c \ll 1$. Since the plasma width around the core is experimentally already smaller than the core radius, $\delta$ also has to be smaller than $a_c$, and the inequality can easily be satisfied.

C. Helicity input term

The second term in Eq. (11) can be written as

$$\left(\frac{\partial K}{\partial t}\right)_{in} = 2\Psi\dot{\Phi}\,, \tag{16}$$

where $\Phi$ is the experimentally measured toroidal flux inside the core and $\Psi$ is the experimentally measured poloidal flux between the device axis and the core surface. This sign convention is chosen to conform to that used to display the experimental data below and also to make the plasma helicity a non-negative quantity.

It turns out that it is the poloidal flux and toroidal flux change which contribute to the helicity in the S-1 induction scheme, whereas it is the toroidal flux and poloidal flux change which contribute in the RFP technique. This is due to the "inverse-pinch" topology of the S-1 technique.

Combining Eqs. (11), (12), and (16) results in

$$\frac{\partial K}{\partial t} = -2 \int \eta \underline{j} \cdot \underline{B}\, dV + 2\, \Psi\, \dot{\Phi}\,. \tag{17}$$

Steady state requires $\partial K/\partial t = 0$, or

$$2 \int \eta\, \underline{j} \cdot \underline{B}\, dV = 2\, \Psi\dot{\Phi}\,, \tag{18}$$

wherein the helicity injection just compensates for the ohmic losses.

D. Linked requirement for basic equilibrium "target" plasma

In order to have a nonzero helicity input, the right-hand side of Eq. (16) must be nonzero. This means $\Psi$ must be nonzero, or some poloidal flux must link both the plasma and the core.

E. Programming of $\Psi$ and $\Phi$

The right-hand side of Eq. (16) involves both the poloidal- and toroidal-field circuits. This scheme to inject helicity involves oscillation of both circuits around some equilibrium values, with the proper phasing, so that the time average $\langle 2\Psi\dot{\Phi}\rangle_t > 0$.

Helicity input requires

$$2\Psi\dot{\Phi} > 0 \; . \tag{19}$$

Let the flux functions during the steady-state drive phase be

$$\Psi = \Psi_0 + \Psi_1 \cos \omega t \tag{20}$$

$$\Phi = \Phi_0 + \Phi_1 \cos(\omega t + \delta) \; ,$$

where $\delta$ is some phase shift. Substitution of Eq. (20) into Eq. (19) and averaging over time results in

$$\langle 2\Psi\dot{\Phi}\rangle_t = -\omega\Psi_1\Phi_1 \sin\delta \; . \tag{21}$$

This average is a maximum when $\sin\delta = -1$, or when $\delta = -\pi/2$. Then the maximum average helicity input rate is

$$\langle\frac{\partial K}{\partial t}\rangle_{in,max} = \omega\, \Psi_1 \Phi_1 \ . \tag{22}$$

The resulting flux functions during the steady-state drive phase are therefore

$$\begin{aligned} \Psi &= \Psi_0 + \Psi_1 \cos\omega t \\ \Phi &= \Phi_0 + \Phi_1 \cos\left(\omega t - \frac{\pi}{2}\right) , \end{aligned} \tag{23}$$

as shown in Fig. 3a. The maximum average helicity input rate relative to the peak-to-peak swing of the helicity input rate is

$$\frac{\langle\partial K/\partial t\rangle_{in,max}}{(\partial K/\partial t)_{p-p}} = \frac{1}{2}\,\frac{(\Psi_1/\Psi_0)^2}{(\Psi_1/\Psi_0)^2 + (\Psi_1/\Psi_0) + 1/4} \tag{24}$$

and is increased when $\Psi_1/\Psi_0$ is increased. The ratio $\Psi_1/\Psi_0$ cannot be greater than one, otherwise the plasma is no longer coupled to the core during part of a cycle.

Higher pumping frequencies are better, but a limit is set by the skin time of the flux core liner. With higher frequencies, there is also a practical upper voltage limit for the power supplies and coil systems. Higher modulation in the toroidal flux is also better. The normalized helicity input rate $\dot{K}/K$ should be larger than the inverse classical diffusion time but smaller than the inverse relaxation time in order for the plasma to assimilate the input flux into a relaxed state before the configuration decays.

## IV. EXPERIMENTAL RESULTS AND SIMULATED STEADY-STATE DRIVE

The experimental results from a typical linked discharge in S-1 are shown in Fig. 2a-c. The fluxes and voltages are obtained[5] from wire loops embedded in the core just beneath the surface. The fact that the poloidal flux does not return to zero indicates that the spheromak plasma is still coupled to the flux core as in Fig. 1. The resulting rate of helicity input from the core

$$\left(\frac{\partial K}{\partial t}\right)_{in} = 2\Psi\dot{\Phi} \tag{25}$$

and the resulting helicity are shown in Fig. 2b. Injected helicity reaches a constant value approximately 0.3 msec after the plasma is initiated. The resulting experimentally measured toroidal plasma current and flux are shown in Fig. 2c.

The same discharge is used to represent, or model, the first 0.6 msec of a continuously driven spheromak (Fig. 3). Then the poloidal flux is modulated with $\Psi_1/\Psi_0 = 0.68$ and the toroidal flux with $\Phi_1/\Phi_0 = 0.21$ (Fig. 3a). The resulting peak voltages are on the order of 1 kV and 0.25 kV, respectively. This $\psi$-$\phi$ Pumping may be understood as follows. Toroidal flux is inductively transferred to the plasma during that part of the cycle for which there is a relatively large coupling ($\Psi$ large) between plasma and core, so a relatively large amount of helicity is added. Toroidal flux is inductively removed from the plasma during that part of the cycle for which there is a relatively small coupling ($\Psi$ small) between plasma and core, so a relatively small amount of helicity is extracted. The input helicity increases nearly linearly in time at a rate of approximately 6.67 volt$^2$sec$^2$ per msec for this case. The helicity doubles from its value before $\psi$-$\phi$ Pumping in approximately 4.5 msec. (No losses are considered in this computation.) There is evidence[5] of relaxation times in S-1 on the order of 50 μsec. The requirement that the characteristic helicity input time be larger than the relaxation time but comparable or shorter than the diffusion time can easily be satisfied with further optimization and/or hotter plasmas.

## V. CONCLUSIONS AND DISCUSSION

By coupling the spheromak to a flux core, we have transformed a singly connected configuration into a doubly connected one, wherein the $[(\underline{A} \times \underline{E}) \cdot \underline{dS}]$ contribution to helicity injection can be made large and inductive current drive in spheromaks can become practical. This $\Psi/\Phi$ Pumping can be used to either maintain or increase the plasma helicity (plasma currents).

There is no guarantee that relaxations will completely integrate the fluxes into proper profiles, especially for very hot plasmas ($T \gg 100$ eV). Flux conversion seems to work particularly well during formation as the flux is being added to the outermost, cold surfaces of the plasma. The interior of the plasma may not relax as well. Further investigation of higher-temperature spheromaks is necessary.

## ACKNOWLEDGMENTS

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## FIGURE CAPTIONS

FIG. 1 Flux surfaces of an inductively formed spheromak without complete detachment from flux core. The shaded portion indicates the plasma volume. This is called a linked discharge.

FIG. 2-a Time histories of fluxes and voltages for a typical, inductively formed spheromak in the linked mode. From top-to-bottom: the poloidal flux $\Psi$ coupled by the flux core, the toroidal flux $\Phi$ inside the flux core, the associated time derivatives of these fluxes.

FIG. 2-b The rate of helicity injection $(\partial K/\partial t)_{in} = 2\Psi\dot{\Phi}$ and the resulting net input helicity $\int_0^t 2\Psi\dot{\Phi}\, dt$ as a function of time.

FIG. 2-c Resulting experimentally measured plasma toroidal current and flux for this discharge.

FIG. 3-a Time histories of fluxes and voltages for the same inductively formed spheromak as above, but an oscillation of poloidal and toroidal fluxes is initiated at time 0.6 msec into the discharge in order to supply helicity continuously.

FIG. 3-b The helicity input rate and resulting net input helicity for $\psi$-$\phi$ Pumping. Note that the helicity input doubles in about 4.5 msec with pumping.

#84X0146

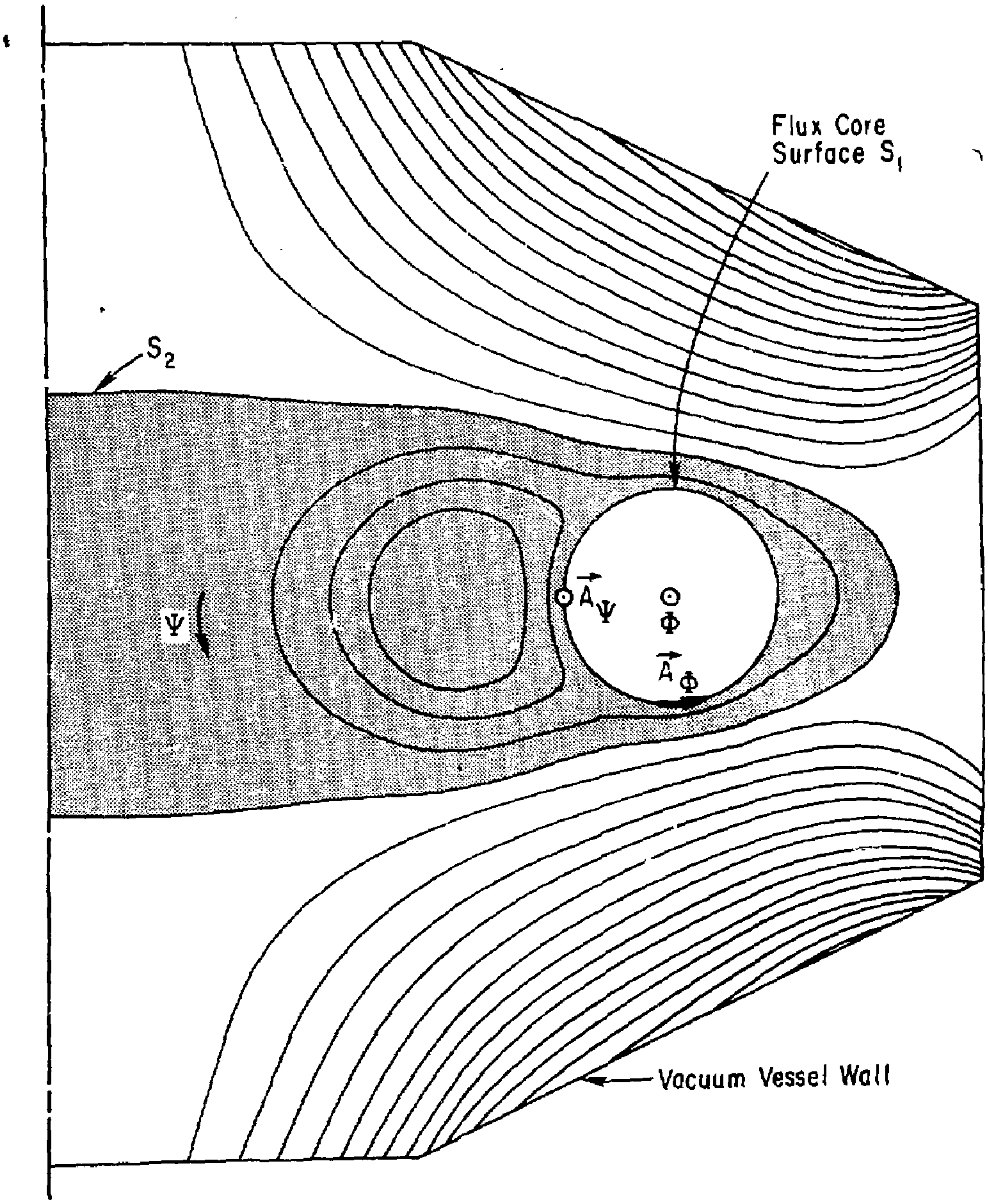
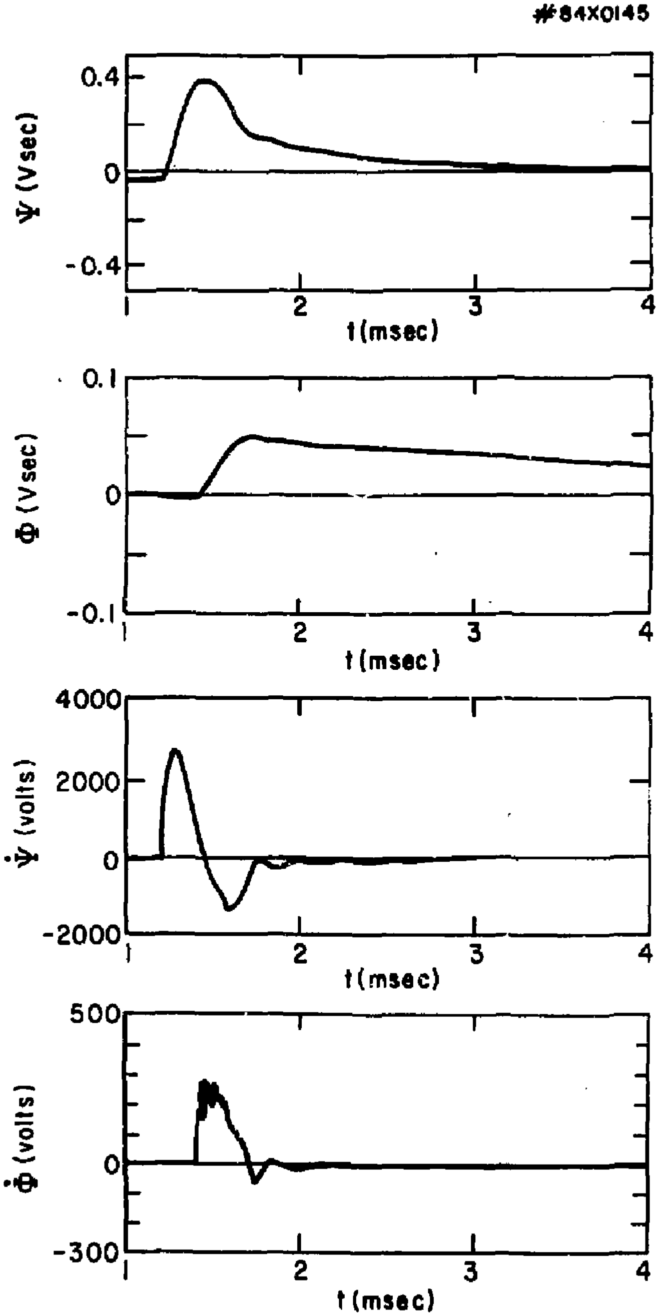



Fig. 1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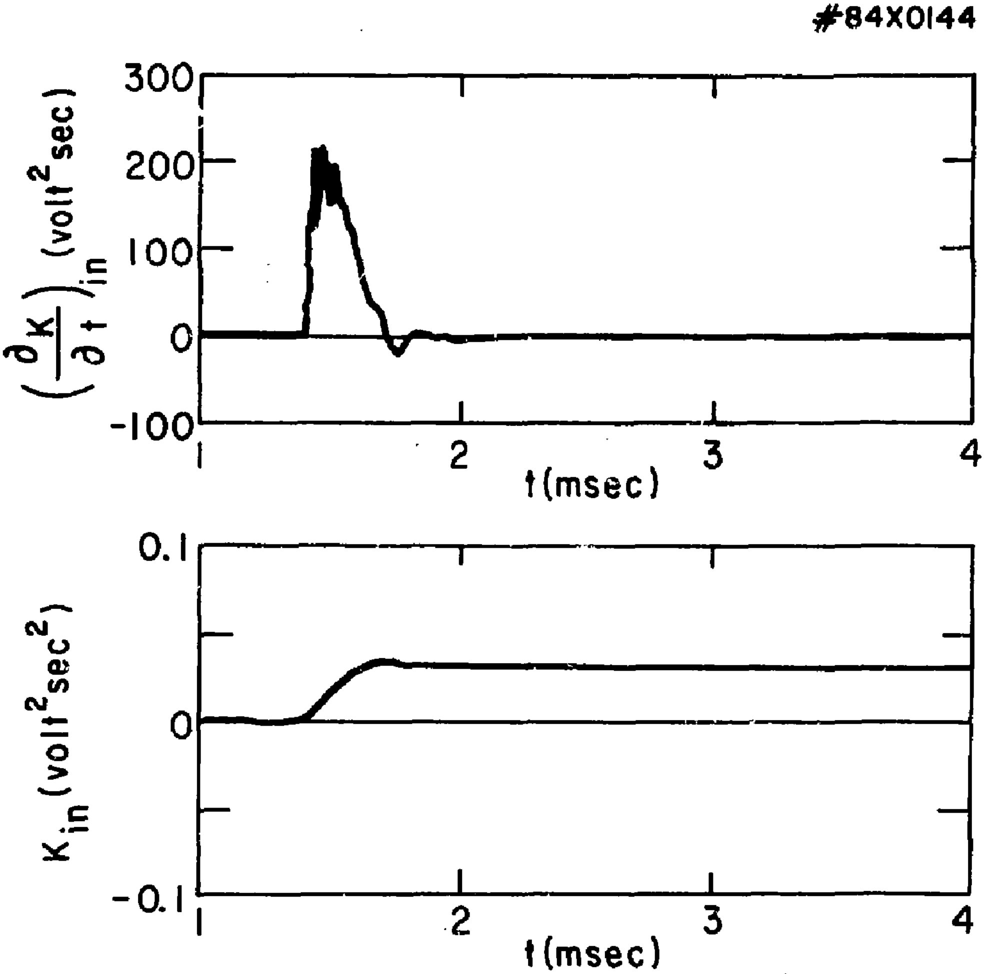
Φ (Vsec)
t (msec)
4000
2000
0
-2000
Ψ̇ (volts)
t (msec)
500
0
-300
Φ̇ (volts)
t (msec)

Fig. 2a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2
3
4
t(msec)
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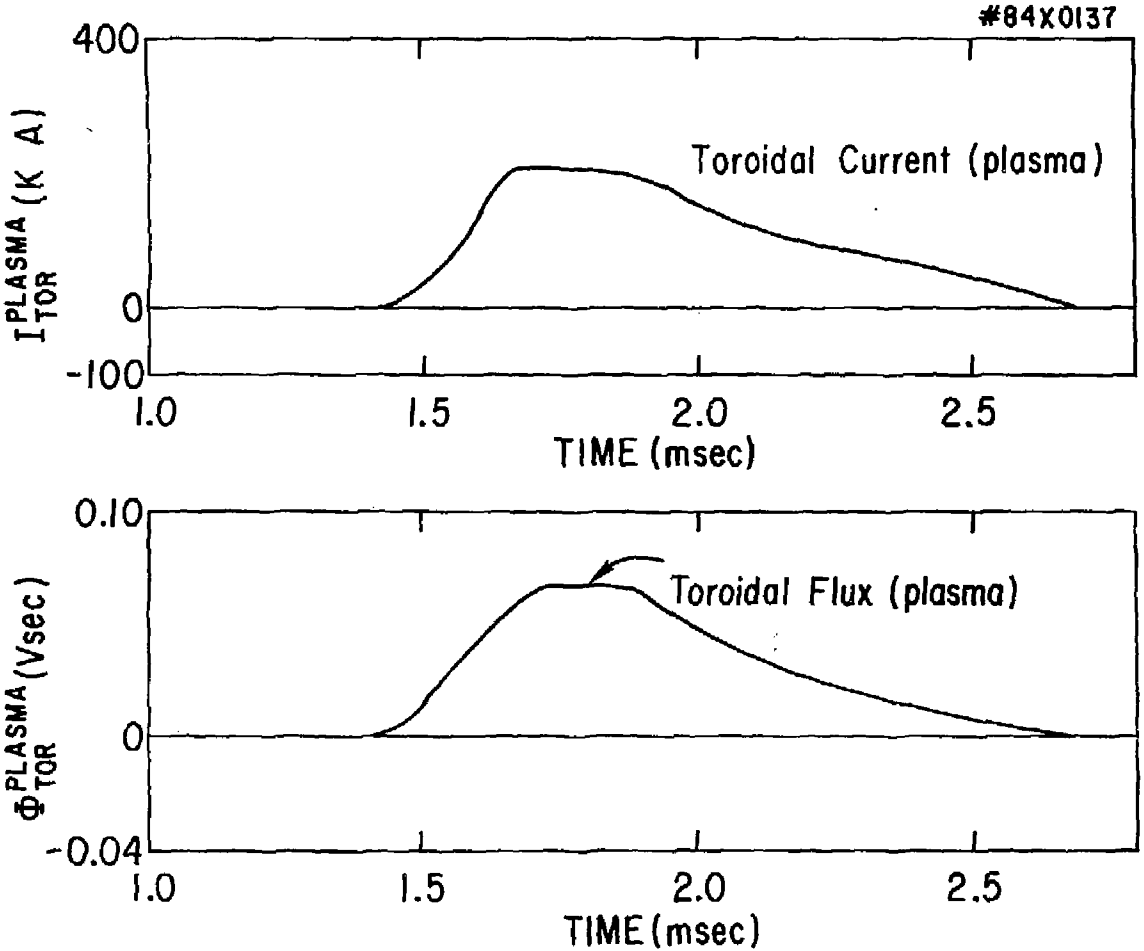
0
-0.1
Kin (volt²sec²)
1
2
3
4
t(msec)

Fig. 2b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1.5
2.0
2.5
TIME (msec)
0.10
0
-0.04
$\Phi_{TOR}^{PLASMA}$ (Vsec)
Toroidal Flux (plasma)
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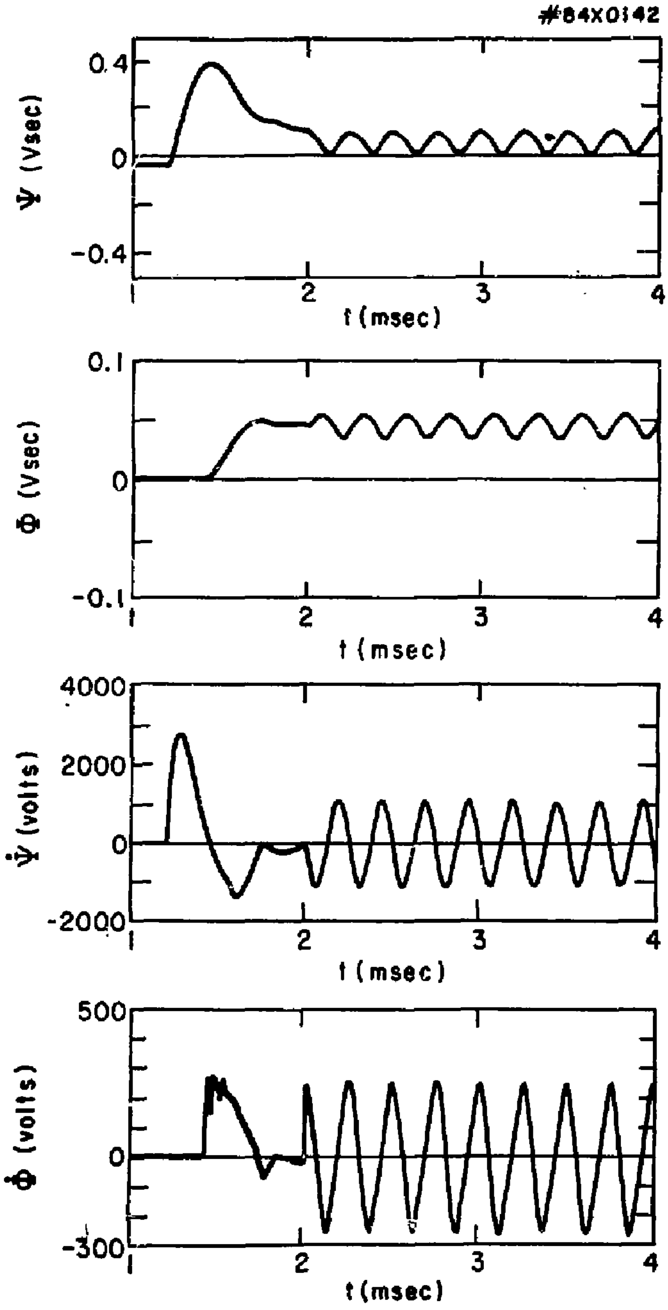
1.5
2.0
2.5
TIME (msec)

Fig. 2c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t (msec)
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0
-2000
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t (msec)
500
0
-300
Φ̇ (volts)
t (msec)

Fig. 3a

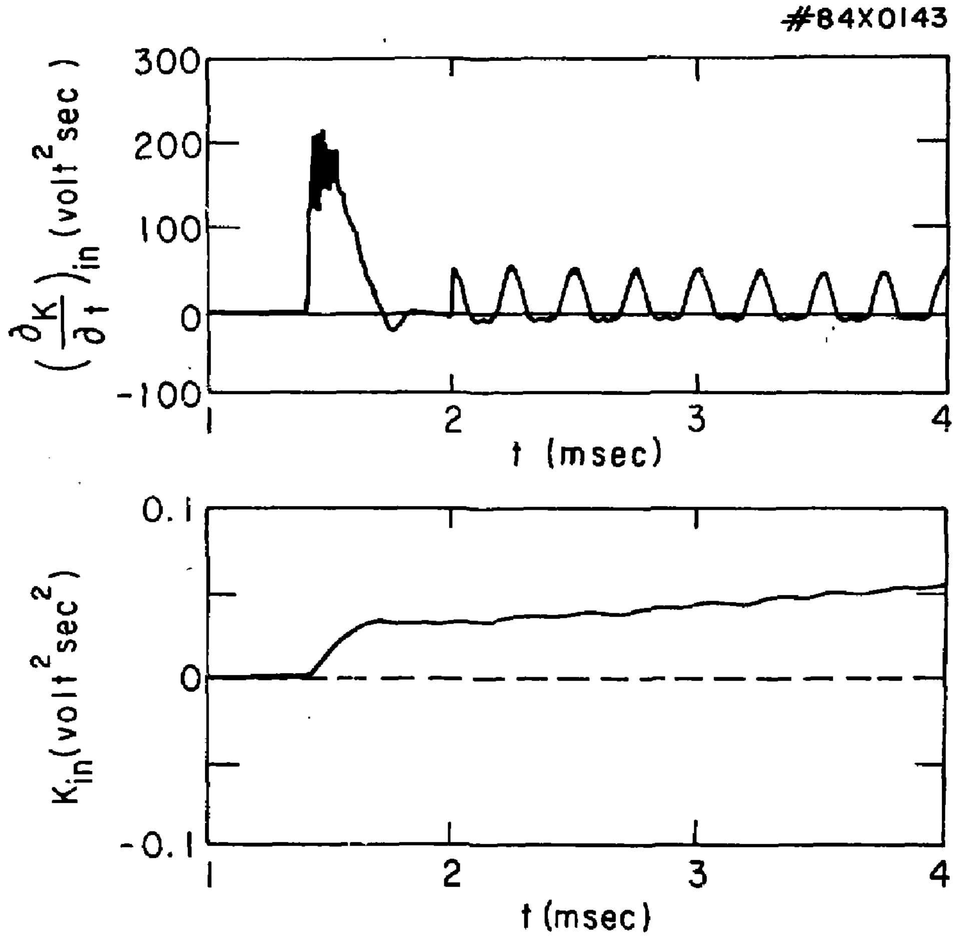


Fig. 3b

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