PPPL-2066

UC20-A,D,F

PPPL-2066

I-23347

192
10/5/85
JMD
②

(25) 2-1341-2

MAGNETIC FLUX CONVERSION AND RELAXATION TOWARD A
MINIMUM-ENERGY STATE IN S-1 SPHEROMAK PLASMAS

By

A. Janos

SEPTEMBER 1985

MASTER

PLASMA
PHYSICS
LABORATORY

MAGNETIC FLUX CONVERSION AND RELAXATION TOWARD A
MINIMUM-ENERGY STATE IN S-1 SPHEROMAK PLASMAS

PPPL--2066

A. Janos

DE86 000313

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

S-1 Spheromak currents and magnetic fluxes have been measured with Rogowski coils and flux loops external to the plasma. Toroidal plasma currents up to 350 kA and spheromak configuration lifetimes over 1.0 msec have been achieved at moderate power levels. The plasma formation in the S-1 Spheromak device is based on an inductive transfer of poloidal and toroidal magnetic flux from a toroidal "flux core" to the plasma. Formation is programmed to guide the configuration into a force-free, minimum-energy Taylor state. Properly detailed programming of the formation process is found not to be essential since plasmas adjust themselves during formation to a final equilibrium near the Taylor state. After formation, if the plasma evolves away from the stable state, then distinct relaxation oscillation events occur which restore the configuration to that stable state. The relaxation process involves reconnection of magnetic field lines, and conversion of poloidal to toroidal magnetic flux (and vice versa) has been observed and documented. The scaling of toroidal plasma current and toroidal magnetic flux in the plasma with externally applied currents is consistent with the establishment of a Taylor state after formation. In addition, the magnetic helicity is proportional to that injected from the flux core, independent of how that helicity is generated.

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

I. INTRODUCTION

A spheromak¹ is a toroidal magnetic confinement configuration for plasmas. The toroidal magnetic field in the plasma is sustained entirely by poloidal plasma currents, thereby eliminating the need to link the plasma topologically. It has been possible to create²⁻⁵ these configurations with poloidal- and toroidal-field profiles which satisfy the equations for force-free fields: $\nabla \times \underline{B} = \lambda \underline{B}$. Agreement between experiment and theory was confirmed predominantly by identification of the experimental equilibria's profiles with the lowest-energy, force-free eigenmodes predicted by theory.²⁻⁷ Experimental profiles were obtained from magnetic probes inserted into and around the plasmas.

An important observation in spheromak experiments is the tendency for plasmas to relax toward the force-free, minimum-energy Taylor state.⁸ Relaxation was first evidenced in laboratory experiments with magnetized-coaxial-gun-generated plasmas wherein spheromak-like configurations were produced.⁹ Amplification of the poloidal magnetic flux input to a plasma discharge was witnessed as well.¹⁰ Relaxation later was seen to be operative when plasmas with spheromak profiles were produced by a variety of formation techniques.²⁻⁵ J.B. Taylor successfully explained many experimental observations of the closely related reversed-field pinch¹¹ (RFP) by proposing that plasmas inside a conducting boundary relax to an equilibrium of minimum magnetic energy, subject to the constraint of conservation of total magnetic helicity,^{12,13} over a time scale which is short compared to a resistive decay time. Magnetic helicity measures the linkage of magnetic field lines. It is defined for the case of a simply connected, closed magnetic field configuration with a boundary through which no magnetic flux penetrates by $K = \int \underline{A} \cdot \underline{B} \, dv$, where $\underline{B} = \nabla \times \underline{A}$ is the magnetic field and $\underline{A}$ is the vector

potential. This principle is helpful in understanding the formation of spheromaks. It was shown with magnetized-coaxial-gun-generated spheromaks which were shot into a close-fitting flux conserver container that the amount of poloidal magnetic flux in the spheromak configuration after formation could be predicted from the total magnetic helicity injected from the gun (taking into account reasonable losses), independent of how that magnetic helicity was generated.⁴ This supported the plasma's ability to assimilate arbitrary poloidal and toroidal magnetic fluxes into a spheromak configuration by magnetic reconnection. Indication of a plasma's ability to maintain a force-free, minimum-energy state after formation was suggested by disturbances of the magnetic field during decay in other magnetized-coaxial-gun experiments.¹⁴

Relaxation is found to be operative in the free-boundary spheromak plasmas created in the S-1 device during and after formation, and is a strong mechanism which tries to return the plasma to a force-free, minimum-energy state even under extreme conditions.¹⁵ The plasma formation in the S-1 Spheromak device^{7,16} is based on an inductive transfer of poloidal and toroidal magnetic fluxes from a toroidal "flux core" to the plasma. Formation is programmed to guide the forming spheromak toward a force-free, minimum-energy Taylor state. Properly detailed programming of the formation process is found not to be essential since plasmas adjust themselves during formation to a final equilibrium near the force-free, minimum-energy Taylor state. This is true even in cases where the applied currents in S-1 are expected to produce a configuration far from the Taylor state if the magnetic fluxes are transferred directly into the plasma. The final state is independent of initial conditions and is insensitive to the details of the formation process. If the plasma evolves after formation away from the stable state, then distinct and sudden relaxation oscillation events occur which restore the

configuration to that stable state. The relaxation process involves reconnection of magnetic field lines, and conversion of magnetic flux¹⁵ from the poloidal field to the toroidal field (and vice versa) is observed both during and after formation of the spheromak configuration.

The ratio of the toroidal plasma current (poloidal magnetic flux) to the toroidal magnetic flux in the plasma, I/Φ , is useful for studying relaxation phenomena both experimentally and theoretically. The Taylor state is characterized by the force-free condition $j = (\lambda/\mu_0) B$, where λ (m^{-1}) is a constant independent of position, j (A/m^2) is current density, and B (Tesla) is magnetic field. If λ is constant independent of position, then λ/μ_0 also equals I/Φ by simple integration; otherwise, I/Φ can be treated as some average value of λ . I/Φ is also proportional to the pinch parameter $\theta \equiv B_p/B_o$ ($= 2I/aB_o$ in Gaussian units) of RFP research through a simple geometric factor involving the plasma size, where B_p is poloidal magnetic field at the plasma edge, B_o is toroidal magnetic field, and a is plasma radius.

S-1 Spheromak plasmas adjust themselves midway through formation such that the ratio I/Φ assumes the same value after formation independent of initial conditions (such as voltages on separate capacitor banks which energize the poloidal- and toroidal-field coils used for forming the spheromak). The experimental value of I/Φ is in a range commensurate with that theoretically predicted on the basis of a force-free, minimum-energy state Taylor equilibrium. In some cases, the toroidal magnetic flux in the plasma is observed to exceed the toroidal magnetic flux in the flux core, giving clear evidence of conversion of poloidal to toroidal magnetic flux.¹⁵ This I/Φ ratio is usually maintained for the duration of a discharge. If a plasma evolves after formation such that I/Φ deviates too far from that for the Taylor state, then relaxation oscillations restore I/Φ to the acceptable

range. These relaxations are often preceded by precursor oscillations in the toroidal plasma current and toroidal magnetic flux in the plasma. The time behavior of I/Φ in S-1 is, in fact, very similar to that of Φ in RFP discharges. A constant value of I/Φ is quickly attained during formation and is maintained for the duration of a discharge.

The experimental values of I/Φ for S-1 lie between 2.5 and 3.5 MA/Vsec for the discharges investigated. These values agree with those from spheromak models, which predict a unique value for a given spheromak configuration. In particular, experimental I/Φ values agree with theoretical estimates based on a classical, spheromak configuration model,⁷ which is a force-free, minimum-energy state.

An experiment was performed to test the limits of the plasma's ability to relax to a stable equilibrium under differing initial conditions. In the flux core, externally applied currents which produce the poloidal and toroidal magnetic fields were driven in an attempt to force the plasma away from the Taylor state during formation. It was found that both the toroidal plasma current and the toroidal magnetic flux in the plasma varied with a change in either current. Relaxation by means of conversion of poloidal to toroidal or toroidal to poloidal magnetic flux in S-1 Spheromak plasmas was identified as having maintained the proper magnetic flux distribution between the poloidal and toroidal fields so that the same final I/Φ value was obtained under a wide range of initial conditions.

The scaling of the toroidal plasma current and toroidal magnetic flux in the plasma with the two externally applied currents in the flux core is consistent with the establishment of a Taylor state after formation. In addition, the magnetic helicity is proportional to that injected by the applied currents in the flux core, regardless of how that helicity was produced by those currents.

The S-1 Spheromak device has been operated in two modes⁷ which differ in whether or not there is common poloidal magnetic flux linking both the spheromak and the flux core. These operation modes affect the general behavior of the relaxation phenomena after formation: the frequencies and growth rates of the precursor oscillations are reduced, and greater oscillation amplitudes can be tolerated, when some common poloidal magnetic flux links both the plasma and the flux core. The S-1 device, the basic formation process, and diagnostics for S-1 magnetics are described in Sec. II. The overall behavior of the plasma is discussed in Sec. III. Relaxation is discussed in more detail in Sec. IV.

The results in this paper are derived from data acquired before the installation of passive stabilization coils or conductors.

II. EXPERIMENTAL APPARATUS

A. S-1 Device

The major components of the S-1 device¹⁶ (Fig. 1) are the vacuum vessel, the equilibrium field coils, and the flux core, which contains the poloidal- and toroidal-field coils. All three magnetic field systems are separately controlled.

The equilibrium field (EF) system provides a steady-state field, nearly uniform over the volume where the final spheromak resides and parallel to the device axis, to hold the toroidal plasma current in major radius force balance. The EF coils are outside the vacuum vessel and are powered by motor-generator sets providing constant current throughout the duration of a discharge. The various coils of this system can be reconfigured to provide different shapes of the field (EF modes) to optimize the equilibrium and stability of the final plasma. Results described in this paper are not dependent on the EF mode.

The spheromak magnetic configuration is created by inducing plasma currents from external circuits. In order to induce poloidal plasma currents (which create the plasma's own toroidal magnetic field) as well as toroidal plasma currents, two sets of coils are inserted into a torus, or flux core, and the plasma is formed outside the flux core. The S-1 flux core has a major radius of 1 m and a minor radius of 0.19 m. During formation, the spheromak is detached from the flux core by reconnection of poloidal field lines. The toroidal-field (TF) coil system consists of 90 turns of conductor in a toroidal solenoid. The poloidal-field (PF) coil system consists of six toroidal conductors passing through the toroidal-field solenoid. Both systems are segmented into six separate coils and can be reconfigured into various parallel and series combinations, permitting spheromak formation time scales of 0.1, 0.2, 0.3, or 0.6 msec. Spheromaks have been formed on all these time scales, but the results reported herein are from operation with 0.3 msec formation time only. The poloidal- and toroidal-field coil systems are powered by separate capacitor banks, having energies of up to 0.48 MJ each at a maximum voltage of 20 kV. Typical operating conditions were with equal voltages on the poloidal- and toroidal-field capacitor banks ($V_{PF} = V_{TF}$). Both circuits are underdamped and are, therefore, crowbarred at appropriate times after formation.

No stabilization conductor systems were utilized in these studies. The vacuum vessel was the nearest conductor wall, with time constants on the order of 10-20 msec. A passive Figure-8 coil system⁷ for stabilization of rigid-body $n = 1$ modes was added later.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

B. Formation

Currents in the poloidal- and toroidal-field coils are programmed to induce toroidal and poloidal currents simultaneously. The formation process proceeds as follows. Initially, a steady-state poloidal equilibrium field is generated to support the final plasma equilibrium. A poloidal magnetic field generated by a toroidal current inside the flux core is pulsed on. The superposition of these two fields creates a field weaker on the small major radius side of the core. A toroidal solenoid inside the core is then pulsed on at time $t = 0$, and a plasma discharge is initiated. The increasing toroidal magnetic flux in this solenoid induces a poloidal current in a toroidally concentric plasma surrounding the core. The associated toroidal magnetic field distends the plasma, stretching it toward the device axis where the poloidal magnetic field is weakest. Simultaneously, the toroidal current in the core is reduced to induce a toroidal current in the plasma. Magnetic reconnection of the poloidal field occurs and a plasma toroid, the desired spheromak configuration, is created. Currents in the pulsed poloidal- and toroidal-field systems are then crowbarred.

C. Diagnostics for S-1 Magnetics

Currents and magnetic fluxes associated with the plasma alone and also with external circuits have been measured with Rogowski coils and flux loops external to the plasma. These diagnostics are especially compatible with the S-1 scheme of spheromak formation since the plasma does not come into strong contact with them, yet the currents, magnetic fluxes, magnetic helicity, and equilibrium parameters are accounted for at all times during the formation, equilibrium, decay, and termination of the plasma.

Figure 1 shows the diagnostics for magnetics inside the S-1 device. A Rogowski coil and toroidal-flux loop encircle both the plasma volume and the flux core by running down the device axis. Another Rogowski encircles just the flux core. Toroidal- (and poloidal-) flux loops are also built into the flux core and are located just beneath the flux core surface. The toroidal plasma current and toroidal magnetic flux in the plasma, therefore, can be obtained by subtracting the signals in two pairs of coils. The poloidal-flux loop measures the net poloidal magnetic flux linking the core.

The toroidal plasma current and toroidal magnetic flux in the plasma, and the poloidal flux, can then be used to derive further quantities, the most important of which are the ratio of toroidal plasma current to toroidal magnetic flux in the plasma, the magnetic helicity flow, and the input power to the plasma.

The toroidal-flux loops enable a toroidal-flux inventory and measure the actual breakdown voltage. The poloidal-flux loops allow determination of the maximum possible poloidal magnetic flux captured by the spheromak and the degree of detachment. In addition, the pair of poloidal-flux loops can be used to determine the amount of magnetic flux intercepting the core liner, the resistive metallic cover on the flux core. Finally, these loops allow measurement of liner characteristics, including induced currents and effective time constants.

Figure 2 shows the actual Rogowski coils and flux loops installed in the S-1 device. The view is from one of the four-foot end flanges. The Rogowski coils are covered by stainless steel tubing of 6.35 mm outer diameter and 0.13 mm wall thickness. The large toroidal-flux loop encircling both the plasma and core is covered by a stainless steel tubing of 1.83 mm outer diameter and 0.23 mm wall thickness. The poloidal- and toroidal-flux loops for the core are actually inside the core just beneath the liner surface.

The signals from these diagnostics are all processed in a similar fashion. They are first reduced by voltage dividers immediately outside the device. Intermediate-level signals are then transferred via twisted-pair cables to additional dividers, fast differential amplifiers, and finally 1 MHz analog-to-digital converters. Digitized information is held in memory until read out by a computer system after a plasma shot. Integrations are done through software to avoid problems inherent in the noisy environment. Figure 3 shows block diagrams of typical diagnostics, while Fig. 4 shows the circuits of typical diagnostics in detail.

The magnetic field profiles of the spheromak were also measured with a movable multicoil magnetic probe inserted into the plasma. The time evolution of magnetic field profiles in major radius, R , is obtained on a single shot for fixed z (distance along the device axis) and ϕ (toroidal angle).

III. GLOBAL EQUILIBRIUM AND STABILITY

A. Plasma Parameters

The S-1 Spheromak device was operated under limited conditions for these experiments. Higher power level, lower density, and lower impurity level regimes were not yet explored. Experiments were performed with the device operating up to moderate (60% maximum) power levels. Toroidal plasma currents of up to 350 kA were obtained. The peak toroidal magnetic field inside the plasma due to poloidal plasma currents was as high as 3 kG. Spheromak configuration lifetimes have exceeded 1.0 msec. The major radius of the plasma ranged from 0.40 to 0.65 m and the minor radius from 0.25 to 0.45 m. Plasma electron densities ranged from 0.6 to $4.0 \times 10^{14} \text{ cm}^{-3}$ for H_2 and He neutral-gas fill pressures from 1 to 10 mtorr. Typical fill pressure was 2.2 mtorr. (All the data presented here are for H_2 discharges unless He

is explicitly noted as the operating gas.) Peak electron temperatures of up to 45 eV were measured for plasma currents below 200 kA. Typical midplane profiles of poloidal and toroidal magnetic fields as a function of time are shown in Fig. 5.

B. Detached and Linked Spheromak Operation Modes

Two representative discharge modes were investigated. The "detached" mode operated with the spheromak configuration completely detached from the core so that there was no common poloidal magnetic flux linking both the spheromak and the flux core; the flux core was outside the separatrix in this mode. The "linked" mode (Fig. 6) was essentially an earlier picture of the soon-to-be detached configuration where there was still some common poloidal magnetic flux linking both the spheromak and the flux core; the flux core was still inside the separatrix in this mode.

The dependence of the poloidal flux function, defined by $\Psi(R,t) = \int_0^R 2\pi R B_z(R,t) dR$, on major radius R is shown in Fig. 7-a for three representative times during the discharge cycle. The net poloidal magnetic flux linking the flux core, which is measured by the value of the poloidal flux function at the inside major radius ($R = 80$ cm) of the flux core, determines if the magnetic configuration is detached [$\Psi(R = 80 \text{ cm}) < 0$] or linked [$\Psi(R = 80 \text{ cm}) > 0$] to the core and by how much. A flux loop is located in the S-1 flux core near $R = 80$ cm so that $\Psi(k = 80 \text{ cm}, t)$ is measured.

Figure 7-b shows $\Psi(R = 80 \text{ cm})$ as a function of time during a discharge cycle. Seconds before the plasma discharge is initiated, the equilibrium field is energized, creating a negative poloidal magnetic flux. Hundreds of microseconds before the plasma discharge is initiated, the poloidal-field coil is energized, creating a net positive poloidal magnetic flux. At $t = 0$ (when

net poloidal magnetic flux is maximum), the plasma discharge is initiated. As the current in the poloidal-field coil decreases, inducing a toroidal plasma current, poloidal magnetic flux around the flux core reconnects to create an increasingly more detached spheromak configuration, thereby reducing $\Psi(R = 80 \text{ cm})$. Complete detachment occurs at time t_p , when $\Psi(R = 80 \text{ cm}) = 0$. The current in the poloidal-field coil is crowbarred after this time. If the current is crowbarred before t_p , $\Psi(R = 80 \text{ cm})$ does not swing negatively and a net poloidal magnetic flux remains linked around the flux core (Fig. 6). (Comparison of the poloidal magnetic flux linked by flux loops on the inside and outside major radius sides of the flux core indicates that most of the flux passes around the core and a negligible amount intercepts and passes through the flux core itself.)

In the absence of a nearby conducting wall or stabilizing coil, a spheromak is predicted to be unstable to rigid-body $n = 1$ MHD modes of the tilt, shift, or axial translation type depending on the shape of the EF field. It was found that detached spheromaks were unstable to shifting and tilting; a finding which resulted in lifetimes on the order of 0.2 msec. The shift or tilt direction was random on a shot-to-shot basis. Shift velocities were on the order of 0.5 to $1.0 \times 10^6 \text{ cm/sec}$ or greater. Maximum plasma currents were achieved in this mode since the full flux-swing capability of the poloidal field system was utilized. The approximate scaling of toroidal plasma current with capacitor voltage, with equal voltages on the poloidal- and toroidal-field banks, is 0.4 MA/kV .

The linked mode was more stable. The plasma shifted but the velocity was an order of magnitude slower. This mode yielded the longest lifetimes (up to 1.5 msec).

Figure 8 shows data from a typical, long-lived linked discharge. The time evolution of the net poloidal magnetic flux linked by the flux core [$\Psi(R = 80 \text{ cm})$] is similar to that in Fig. 7, except that it does not swing negatively, indicating that this is a linked discharge.

This shot is a good representative discharge since a number of features of the toroidal plasma current and toroidal magnetic flux in the plasma is evident in it. These features and their relation to relaxation and flux conversion are discussed in detail in Sec. IV.

IV. RELAXATION PHENOMENA AND MAGNETIC FLUX CONVERSION

A. Toroidal Magnetic Flux

S-1 Spheromak plasmas can be produced with a toroidal magnetic flux which significantly exceeds the toroidal flux generated in the flux core. For the discharge in Fig. 8, the formation period lasts until $t = 0.3 \text{ msec}$; however, the toroidal magnetic flux in the plasma becomes greater than the toroidal flux in the flux core midway through ($t = 0.15 \text{ msec}$) the formation phase, and this condition lasts well past formation (until $t = 0.62 \text{ msec}$). The toroidal magnetic flux in the plasma becomes as much as 40% greater than that in the flux core for this discharge.

A simple circuit model of inductive coupling cannot account for this enhancement. It is instructive to look at the time derivative of the total (plasma minus flux core) toroidal magnetic flux (Fig. 9). The inductively driven plasma is expected to "snort out" the induced voltage from the toroidal-field coil system, or at least reduce it somewhat. In fact, the polarity of this voltage reverses, between $t = 0.06$ and $t = 0.4 \text{ msec}$, from that due to the toroidal-field coil alone; that is, there is more toroidal magnetic flux generated in the plasma than there is reverse-polarity toroidal flux generated in the core.

Major radius compression of the plasma from the core radius to the final equilibrium radius also cannot explain this enhancement since, at best, toroidal magnetic flux is expected to be conserved, neglecting any flux conversion processes. Adiabatic compression of a spheromak plasma is expected¹⁷ to follow the scaling laws derived for "Type-A" compression, as described by Furth and Yoshikawa.¹⁸ The toroidal current would scale as $I \propto R^{-1}$, where R is the major radius. It is experimentally observed that the peak toroidal current in the plasma can be greater than that in the flux core. For the discharge in Figs. 8 and 9, the peak toroidal current in the plasma is approximately 5% greater than that in the flux core. This increase in toroidal current may be due to the major radius compression of the toroidal current as it leaves the flux core and enters the plasma at smaller major radius. The change in the time derivative of the toroidal plasma current at $t = 0.43$ msec may be due to the end of the compression phase.

A combination of compression and magnetic flux conversion may explain how both the toroidal current and toroidal magnetic flux in the plasma can be greater than the toroidal current and toroidal magnetic flux in the flux core, respectively. The total toroidal current can increase during formation because of major radius compression, even though the poloidal magnetic flux is being lost due to resistivity and conversion to toroidal magnetic flux. The toroidal current increase is small, however, and may be due to these two loss channels. However, conversion of only a small relative amount of poloidal magnetic flux can effect a relatively large gain in toroidal magnetic flux. The poloidal field constitutes a very large reservoir of flux compared to that of the toroidal field - almost an order of magnitude larger. The swing of the poloidal flux linked by the core is 0.25 Vsec. The swing of the toroidal flux inside the core is 0.04 Vsec, while the toroidal flux in the plasma reaches

0.06 Vsec. Therefore, the increment of toroidal flux in the plasma over the toroidal-flux swing in the core represents only 8% of the poloidal-flux swing.

B. I/Φ (Experimental) and Relaxation Oscillations

It is evident that the toroidal plasma current I and toroidal magnetic flux in the plasma Φ have very similar time histories (Fig. 8). This is so for most discharges, and it holds true even though I and Φ individually vary dramatically. The ratio I/Φ quantifies the similarity (Fig. 8) in that it remains nearly constant over time. This is further evidence of flux conversion processes.

I/Φ is a global measurement of λ/μ_0 , where λ is defined by the force-free condition $\underline{j} = (\lambda/\mu_0)\underline{B}$. Integrating over the minor cross section of the plasma yields $I/\Phi = \langle\lambda\rangle/\mu_0$, where $\langle\lambda\rangle$ is an average value. This $\langle\lambda\rangle$ is proportional to the pinch parameter θ of RFP research through the size of the plasma. In the infinite aspect ratio limit, this size factor is simply the minor radius a . Letting $B_0 = \langle B \rangle = \Phi/\pi a^2$, a simple relation between I/Φ and θ is

$$\frac{I}{\Phi} \text{ (MA/Vsec)} = \frac{5}{\pi} \frac{\theta}{a \text{ (m)}}, \text{ or}$$

$$\frac{I}{\Phi} \text{ (MA/Vsec)} = 1.59 \frac{\theta}{a \text{ (m)}}.$$

Experimentally, it is difficult to associate I/Φ with a spheromak pinch parameter since a is difficult to measure and is not as well defined as in a

large aspect ratio RFP. In an RFP, it is easy either to measure θ , or to measure I/ϕ and determine θ from $\theta = \lambda a/2$. I/ϕ can nevertheless be compared with experimental results of other spheromaks and RFP's.

The time evolution of I/ϕ for three typical linked discharges is shown in Fig. 10. Discharges are initiated at $t = 0$. This ensemble defines a range in I/ϕ between the limits of 2.5 and 3.5 MA/Vsec, wherein the discharges are quiescent, showing no sudden changes in magnetic quantities. The attainment of a Taylor state after formation is supported¹⁹ by measurements made internal to the plasma, showing λ profiles which are nearly uniform over the plasma volume and q profiles in agreement with theoretical predictions.

It is interesting that the value of I/ϕ for the final equilibrium (final equilibrium value) is attained very early in the formation phase. The I/ϕ values in Fig. 10 reach their final equilibrium values less than 0.1 msec after the initiation of discharge, even though the formation takes up to 0.3 msec to complete. Since the spheromak is not developed substantially at such an early time, the constant I/ϕ is representative of the minimum-energy state of the linked discharge.

I/ϕ has a tendency to deviate slowly from its final equilibrium value. If I/ϕ deviates too far from the limits in Fig. 10, then the plasma either quickly relaxes, restoring I/ϕ to its original value, or the plasma terminates. The number of times a discharge shows relaxations depends on the programming of the formation process (bank voltages, timing, etc.).

In Fig. 10, the solid line is for the previously discussed long-lived discharge (Fig. 9). The I/ϕ for the discharge indicated by short dashes first overshoots the upper limit and then the plasma relaxes so that I/ϕ is again within the limits. I/ϕ then slowly rises until it nears the upper limit and then the plasma relaxes again, a pattern which repeats twice more until the

plasma is decayed. These sudden drops in I/Φ are called relaxation oscillations. Times scales for relaxation are on the order of 50 μ sec.

The I/Φ for the discharge indicated by the long dashes also overshoots the upper limit of I/Φ at first, and then the plasma relaxes so that I/Φ is again in the allowed range. Thereafter, it increases until it exceeds the upper limit. For some reason, the plasma does not relax as usual. In this case, I/Φ rises rapidly and the plasma terminates shortly thereafter. This event is called a sudden termination.

I/Φ has a tendency to increase rather than decrease over time. This can be attributed to several causes. First, the toroidal magnetic flux in the plasma Φ is maintained by poloidal plasma currents. Since these currents are closer to the edge of the plasma and thus in a colder region than the toroidal plasma currents, they are expected to decay faster, leading to an increase in I/Φ and a departure from the Taylor state. Second, I/Φ is inversely proportional to the plasma size. As plasma currents decay, the constant equilibrium field moves the plasma to smaller major radius. The I/Φ for a highly detached discharge (Fig. 11) assumes a value between 2.5 and 3.5 MA/Vsec during formation while the plasma is still linked to the core. As the plasma detaches, the I/Φ value rises. Hence, the slow time behavior may simply track the plasma size. The change in I/Φ due to size dependence does not directly imply a departure from the Taylor state. The reason the plasma in Fig. 11 quickly terminates is that, once detached, it is shift unstable.

The time evolution of I/Φ for the stable linked modes behaves very similarly to that of θ for HBTX discharges²⁰ of the stabilized Z-pinch type (that is, not reversed-field type), as shown in Fig. 12. The θ first overshoots its final equilibrium value, and then there is rapid relaxation of θ to an approximate equilibrium value of 1.5 to 2. This value is maintained

for the remainder of the discharge ($\approx 40 \mu\text{sec}$). Theoretically, θ is not expected to be a constant during relaxation. The similarity between spheromak and RFP relaxation phenomena is thus made more evident.

C. I/Φ (Theoretical)

Experimentally measured I/Φ can be compared to model and theory calculations to understand more fully the state toward which the plasma relaxes. The I/Φ ratio is a unique constant for each given spheromak equilibrium configuration.

A simple comparison can be made using the classical spheromak model with the $n=0$, $m=1$ terms of the analytical expansion solution¹ of the spheromak equilibrium in spherical coordinates. The force-free currents and fields are related by

$$j = \frac{k_0}{\mu_0} B ,$$

where λ becomes k_0 , and

$$k_0 = \frac{4.493}{r_c}$$

is constant over the plasma volume with r_c the radius of the separatrix sphere (Fig. 13). This can be integrated over the plasma minor cross section to yield

$$\frac{I}{\Phi} \text{ (MA/Vsec)} = \frac{3.58}{r_c \text{ (m)}} .$$

Taking $r_c = 1.2$ m for the linked mode in the S-1 device, I/Φ becomes 2.98 MA/Vsec, in quantitative agreement with the experimental values between 2.5 and 3.5 MA/Vsec. The theoretical I/Φ value versus r_c is shown in Fig. 13. It should be emphasized that this model is for a force-free, minimum-energy state.

Another comparison is offered by the more empirical model of Katsurahi and Yamada.¹⁸ For I/Φ , this model yields the expression

$$\frac{I}{\Phi} \text{ (MA/Vsec)} = \frac{2}{\mu_0} \frac{\gamma + 1}{\sqrt{2\gamma + 1}} \frac{1}{a(\text{m})}, \quad \text{or}$$

$$\frac{I}{\Phi} \text{ (MA/Vsec)} = 1.59 \frac{1}{a(\text{m})} \frac{\gamma + 1}{\sqrt{2\gamma + 1}},$$

where γ is a parameter specifying the peaking of the toroidal plasma current density j_t and toroidal magnetic field B_t profiles:

$$j_t(r) = j_{t0} \left[1 - \left(\frac{r}{a} \right)^2 \right]^\gamma$$

$$B_t(r) = B_{t0} \left[1 - \left(\frac{r}{a} \right)^2 \right]^\gamma,$$

where r is the minor radius. The parameter γ is approximately 1 for aspect ratio $A \approx 2$, and is approximately 1.3 for $A \gg 1$. The toroidal plasma current I is derived from force-balance considerations to be

$$I = \frac{2\pi}{\sqrt{2\gamma + 1}} \frac{aB_{to}}{\mu_o},$$

and Φ is simply $\int_0^a B_t(r) 2\pi r dr$.

The I/Φ versus γ is shown in Fig. 14. The I/Φ value agrees with experiment for low aspect ratios and minor radii greater than 0.4 m.

D. Precursor Oscillations

Relaxation oscillations and sudden terminations are usually preceded by current and flux oscillations of well-defined frequency and growth rate. Again, there appears to be a threshold for these precursor oscillations; that is, they occur only if I/Φ deviates too far from values associated with a Taylor state.

Figure 15 shows a discharge containing relaxation oscillations and associated precursor oscillations. Oscillations develop on the toroidal plasma current and flux soon after initiation of the discharge. These oscillations are emphasized in the time derivative of the current which shows the oscillations growing until a sudden jump occurs at 0.27 msec. (Superimposed on these precursor oscillations are much higher frequency fluctuations.) The time derivative of the current during these oscillations is large compared to normal levels for well-behaved, long-lived discharges (Fig. 9). The jump coincides with a sudden and substantial decrease in current. I/Φ also decreases. This event is a relaxation. The plasma recovers in this case and the oscillations disappear. However, the oscillations start to grow again until another relaxation occurs at $t =$

0.55 msec, followed by a third relaxation that occurs shortly thereafter, by which time the plasma has decayed substantially.

Figure 16 shows a discharge which suffers from a sudden termination preceded by precursor oscillations. In this case, the oscillations are so large that they easily are seen on the toroidal plasma current.

Figure 11 for a detached discharge also exhibits these oscillations, clearly evident on both the toroidal plasma current and flux and their derivatives.

The frequency of these precursor oscillations (Fig. 17a) ranges from 10 to 40 kHz. The frequency usually decreases over time as a relaxation approaches. There is a possible linear dependence on bank voltage. The frequency of the oscillations in the linked mode is typically half that in the detached mode.

The growth rate of the precursor oscillations (Fig. 17b) ranges from 0.01 to 0.05 μsec^{-1} (corresponding to growth times from 20 to 100 μsec). The growth rate in the linked mode is typically half that in the detached mode.

The peak-to-peak amplitudes of the current oscillations (Fig. 17c) relative to the average current, $\Delta I/I$, can be as high as 25% in the detached mode before the plasma terminates. The linked mode can sustain amplitudes up to 50% before plasma termination or relaxations.

In the linked mode, oscillations usually cease after a relaxation occurs, but can start up again. Sometimes the oscillations gradually disappear. In the detached mode, oscillations usually lead to a termination.

Since the precursor oscillations involve the total toroidal plasma current and flux, they are global $m = 0$ modes where m is defined by the functional dependence $e^{im\theta}$ of a perturbation of the equilibrium on poloidal angle θ . Possible explanations for the existence of $m = 0$ modes (in RFP's)

were summarized by H.A.B. Bodin.²¹ The oscillations of the current in S-1 may be driven by the changing plasma inductance caused by quasilinear effects or reconnection effects modifying the equilibrium profile.

E. Relaxation Experiments

Based on the preceding results, experiments were devised that demonstrated dramatic relaxation effects during formation.

Discharges were set up under typical operating conditions of equal voltages, V_{PF} and V_{TF} , on the poloidal- and toroidal-field capacitor banks, respectively. A reference case of $V_{PF} = V_{TF} = 8$ kV was chosen. Plasma currents and fluxes were measured. It was already established that such conditions yielded an equilibrium after formation that was close to the Taylor state.

During formation, an attempt was then made to force the plasma away from the Taylor state by varying on a shot-to-shot basis one of the two bank voltages, keeping the other fixed.

Increasing or decreasing V_{PF} (toroidal current in the flux core) while holding V_{TF} (toroidal flux in the flux core) fixed caused the toroidal plasma current I to increase or decrease, respectively (Fig. 18a-top). This result is not surprising. What is interesting is that the toroidal flux in the plasma ϕ also increased or decreased in a similar fashion (Fig. 18a-bottom). This latter behavior is not possible if the core/plasma system is modeled as a simple inductive circuit, but is possible through conversion of magnetic flux.

The opposite experiment was executed. Increasing or decreasing V_{TF} (toroidal flux in the flux core) while holding V_{PF} (toroidal current in the flux core) fixed caused the toroidal flux in the plasma to increase or

decrease, respectively (Fig. 18b-top), as expected; however, the toroidal plasma current increased or decreased in a similar fashion (Fig. 18b-bottom). Again, this is possible through conversion of magnetic flux.

In both cases, the change in the "secondarily driven" flux was proportionally slightly less than that of the "primarily driven" flux, as is to be expected if conversion is taking place. During these experiments, the equilibrium field was changed on a shot-to-shot basis to reflect the changes in toroidal plasma current. The results were not sensitive to the exact setting of the equilibrium field.

In summary, the toroidal plasma current I and toroidal magnetic flux in the plasma Φ increase or decrease with an increase or decrease, respectively, in either the poloidal-field bank voltage V_{PF} or the toroidal-field bank voltage V_{TF} so that I/Φ assumes the same final equilibrium value midway through the formation. This value is then maintained for the duration of the discharge. The results of these experiments are consistent with the observation that the discharges with highest magnetic fields and longest lifetimes are those with $V_{PF} = V_{TF} = V_0$, where V_0 is an arbitrarily chosen maximum limit on the operating voltages of the poloidal- and toroidal-field capacitor banks, all other device parameters held constant.

The toroidal plasma current and toroidal magnetic flux in the plasma both show a square-root dependence on the voltage that is varied on a shot-to-shot basis. This scaling of I and Φ can be explained as follows.

The formation of the spheromak configuration can be considered in terms of an injection of magnetic helicity K from the flux core into the plasma. The injection rate of magnetic helicity from the flux core is proportional to the product $\psi_{core} \dot{\Phi}_{core}$, where Φ_{core} is the toroidal magnetic flux inside the flux core and ψ_{core} [called $\Psi(R = 80 \text{ cm})$ above] is the poloidal magnetic flux

linked by the flux core.²²⁻²⁴ ψ_{core} and $\dot{\phi}_{\text{core}}$ are, in turn, directly proportional to the externally driven currents in the poloidal- and toroidal-field circuits in the flux core or, equivalently, the voltages on the capacitor banks for the poloidal- and toroidal-field circuits.

With respect to the above flux conversion experiments, the injected magnetic helicity would be proportional to V_{varied} , the bank voltage which is varied from shot to shot. During the plasma's relaxation toward a Taylor state, K is conserved. In the resultant spheromak, K is proportional to the product $\Psi\phi$ of poloidal and toroidal magnetic fluxes, or to I^2 or ϕ^2 since $\Psi=LI$ and $I/\phi = \text{constant}$. Hence, I or ϕ is proportional to $(V_{\text{varied}})^{1/2}$. With this simple treatment, I and ϕ are plotted against $(V_{\text{varied}})^{1/2}$ in Figs. 19a and b. A good fit to a square-root dependence is evident for the case where V_{PF} is varied. The fit of I and ϕ to a square-root dependence on V_{TF} is good only for intermediate values of V_{TF} . The extremely low voltage points represent a significant departure from the typical spheromak configuration because the equilibrium field was not adjusted sufficiently to compensate for the lower toroidal plasma current. It is very interesting that the proportionality factors for the I - (or ϕ -) dependence on the square root of the varied voltage are the same (within experimental error) whether V_{PF} or V_{TF} is varied.

F. High-Frequency Fluctuations

High-frequency fluctuations of 100-200 kHz frequency are almost always present in the plasma current during formation, but cease afterwards. These fluctuations are most evident in the time derivative of the plasma current. Similar frequencies are observed with local magnetic diagnostics that are internal and external to the plasma. These fluctuations may be due to small-scale, turbulent, flux conversion processes necessary for adjustment to a Taylor state.

V. SUMMARY

Conversion of magnetic flux in the S-1 Spheromak from the poloidal field to the toroidal field (or vice versa) by magnetic reconnection processes is driven by the plasma itself so that the equilibrium approaches a force-free, minimum-energy Taylor state during formation, independent of the initial conditions or details of the formation process. After formation, the ratio of the toroidal plasma current to toroidal magnetic flux in the plasma (the spheromak's pinch parameter), I/Φ , agrees with that expected for a force-free, minimum-energy configuration. The Taylor state then is maintained for the duration of the plasma lifetime, a fact which is nicely evidenced by the I/Φ ratio that is constant over time. If the equilibrium deviates after formation (through dissipative or diffusion processes, for example), then the Taylor state is reestablished through discrete and sudden flux exchange events (herein called relaxation oscillations). Oscillations preceding these relaxations are observed in the toroidal plasma current and toroidal magnetic flux in the plasma (herein called precursor oscillations).

The individual scaling of toroidal plasma current and toroidal magnetic flux in the plasma with externally applied currents in the poloidal- and toroidal-field circuits is consistent with the establishment of a Taylor state after formation. In addition, the magnetic helicity is proportional (not equal, due to resistive losses) to the helicity injected from the flux core, regardless of how the helicity was produced by those currents.

It is clear that the plasma's ability to adjust itself to a constant I/Φ state independent of the applied voltages and timings makes the programmed formation a nonsensitive task. The efficiency of formation may, however, depend on the programming, and a carefully programmed formation of the

Spheromak may be beneficial. Recently, strong evidence has been found²⁵ suggesting that globally coherent magnetic field fluctuations (modes) of low n -number ($2 \leq n \leq 5$) play an essential role in relaxation of S-1 Spheromak plasmas toward the Taylor state during formation. Experimental observations and comparison with theory suggest that the modes can provide a means for relaxation [namely a (large) redistribution of magnetic flux], since they become resonant modes and are resistive MHD unstable. The time evolution of the total poloidal flux and the total toroidal flux in the plasma, as measured with probes in the plasma, shows that there is a sudden, relative to the formation time, (and sometimes large) exchange of fluxes when these modes are present midway through formation. After formation, a quiescent equilibrium near the Taylor state is obtained. The mechanisms by which relaxation takes place are significant because of their possible influence on the confinement of energy and particles in the plasma.

Flux conversion is important not only for relaxation of these plasmas toward a stable Taylor state, but also for sustainment²⁶ of these spheromak discharges. Sustainment describes any method of actively driving plasma currents to either extend the plasma lifetime, maintain a steady-state discharge, or increase plasma currents. Relaxation is necessary to assure that stable equilibria are maintained as magnetic flux is added to the plasma. Spheromaks have been maintained by use of electrodes for much longer than a resistive decay time.²⁷ Because relaxation is observed to be such a strong mechanism in S-1 Spheromak plasmas, inductive formation and sustainment are now considered possible by use of a flux core or other induction coils.²²⁻²³ Sustainment would greatly improve the prospects for making high-powered spheromak fusion devices.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Contract No.
DE-AC02-76CHO3073.

REFERENCES

- ¹M.N. Bussac et al., in Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978 (IAEA, Vienna, Austria, 1979), Vol. III, 249; H.P. Furth, J. Vac. Sci. Technol. 18, 1073 (1982).
- ²G. Goldenbaum et al., Phys. Rev. Lett. 44, 393 (1980).
- ³M. Yamada et al., Phys. Rev. Lett. 46, 188 (1981).
- ⁴W.C. Turner, G.C. Goldenbaum, E.H.A. Granneman, J.H. Hammer, C.W. Hartman, D.S. Probe, and J. Taska, Phys. Fluids 26, 1965-1986 (1983).
- ⁵J. Jarboe et al., Phys. Rev. Lett. 45, 1264 (1980).
- ⁶G.W. Hart, C. Chin-Patt, A.W. DeSilva, G.C. Goldenbaum, R. Hess, and R.S. Shaw, Phys. Rev. Lett. 51, 1558-1561 (1983).
- ⁷M. Yamada et al., in Proceedings of the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, London, UK, 1984 (IAEA, Vienna, Austria), IAEA-CN-44/D-III-3, p. 535.
- ⁸J.B. Taylor, in Proceedings of the Third Topical Conference on Pulsed High β Plasmas, IAEA Culham Laboratory, U.K., 1975, p. 59; J.B. Taylor, Phys. Rev. Lett. 33, 1130-1141 (1974).

- ⁹W.H. Bostick, Phys. Rev. 104, 292 (1956).
- ¹⁰H. Alfvén, L. Lindberg, and P. Mitlid, J. Nucl. Energy, Part C: Plasma Phys., 1, 116 (1960); L. Lindberg and C. Jacobsen, Astrophys. J. 133, 1043 (1961).
- ¹¹H.A.B. Bodin and A.A. Newton, Nucl. Fusion 20, 1255 (1980), and references therein.
- ¹²L. Woltjer, Proc. Nat. Acad. Sci. 44, 469 (1958).
- ¹³D.R. Wells and J. Norwood Jr., J. Plasma Phys. 3, 21 (1969); E.E. Nolting, P.E. Jindra, and D.R. Wells, J. Plasma Phys. 9, 1 (1973).
- ¹⁴H.P. Furth, Nucl. Instrum. Methods 207, 93 (1983).
- ¹⁵A. Janos, in Proceedings of the Sixth U.S. Symposium on Compact Toroid Research and the Fifth U.S.-Japan Joint Symposium on Compact Toroid Research, Princeton, New Jersey, Feb. 1984, pp. 97-102.
- ¹⁶R. Ellis, Jr., A. Janos, J. Joyce, and M. Yamada, in Proceedings of the Fifth Symposium on the Physics and Technology of Compact Toroids, Bellevue, Washington, Nov. 1982, pp. 39-45.
- ¹⁷M. Katsurahi and M. Yamada, Nucl. Fusion 22, 1407-1419 (1982).
- ¹⁸H.P. Furth and S. Yoshikawa, Phys. Fluids 13, 2593-2596 (1970).

- ¹⁹G. Hart, A. Janos, D.D. Meyerhofer, and M. Yamada, Princeton Plasma Physics Laboratory Report No. PPPL-2257, August 1985.
- ²⁰E.P. Butt et al., in Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974 (IAEA, Tokyo, Japan, 1975), Vol. 3, pp. 417-429.
- ²¹H.A.B. Bodin, in Proceedings of the International Conference on Plasma Physics, Lausanne, Switzerland, 1984 (Commission of the European Communities, Brussels, 1984), Vol. 1, p. 417.
- ²²A. Janos, in Proceedings of the Sixth U.S. Symposium on Compact Toroid Research and the Fifth U.S.-Japan Joint Symposium on Compact Toroid Research, Princeton, NJ, 1984, pp. 103-108.
- ²³A. Janos and M. Yamada, Fusion Technol. (in press); A. Janos, Princeton Plasma Physics Laboratory Report No. PPPL-2095R, April 1984.
- ²⁴J.M. Finn and T.M. Antonsen, Jr., University of Maryland Plasma Preprint UMLPF #85-021, December 1984.
- ²⁵A. Janos, G.W. Hart, C.H. Nam, and M. Yamada, Phys. Fluids (in press); Princeton Plasma Physics Laboratory Report No. PPPL-2214 (May 1985).
- ²⁶M.K. Bevir and J.W. Gray, "Relaxation, Flux Consumption and Quasi Steady-State Pinches," in Proceedings of the Reversed-Field Pinch Theory Workshop, Los Alamos National Laboratory, Los Alamos, NM, 1980, p. 239, LA-8944-C.
- ²⁷T.R. Jarboe et al., Phys. Rev. Lett. 51, 39 (1983).

FIGURE CAPTIONS

- Fig. 1 Schematic of the cross section of the S-1 Spheromak device showing vacuum vessel, equilibrium field coils, flux core, and locations of magnetic flux loops and current Rogowskis.
- Fig. 2 Actual loops and Rogowskis installed in the S-1 device.
- Fig. 3 Block diagrams of typical diagnostics systems.
- Fig. 4 Detailed circuit diagrams of typical diagnostics systems.
- Fig. 5 Typical midplane profiles of the spheromak's poloidal and toroidal magnetic fields as a function of time for a discharge lasting over 0.7 msec.
- Fig. 6 Magnetic 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. 7 Time evolution of (a) radial profiles of poloidal magnetic flux Ψ and (b) poloidal magnetic flux linking the flux core, $\Psi(R = 80 \text{ cm})$, during the production of an inductively formed S-1 spheromak plasma. The magnetic configuration is "detached" from the core at time $t = t_p$.

Fig. 8 Typical, long-lived linked discharge. ψ_{core} is the total poloidal magnetic flux linking the core. The ratio of toroidal plasma current to toroidal magnetic flux in the plasma, I/Φ , is nearly constant even though individually I and Φ vary dramatically. Also, the toroidal magnetic flux in the plasma is $\approx 40\%$ greater than that in the flux core.

Fig. 9 Same as Fig. 8, but including total toroidal currents, total toroidal magnetic fluxes, and time derivatives.

Fig. 10 I/Φ versus time for three different discharges exhibiting 1) long-lived linked mode, 2) relaxation oscillations, and 3) sudden termination.

Fig. 11 Highly detached discharge.

Fig. 12 RFP pinch parameter θ versus time for HBTX discharges of the stabilized-pinch (not RFP) type.¹⁹

Fig. 13 The theoretical value of I/Φ versus separatrix radius r_c for the classical spheromak model.

Fig. 14 The value of I/Φ versus minor radius a and peaking factor γ for the model of Katsurahi and Yamada.¹⁷

Fig. 15 Discharge showing relaxation oscillations and associated precursor oscillations.

Fig. 16 Discharge showing sudden termination and associated precursor oscillations.

Fig. 17 Dependence of precursor oscillations on capacitor bank voltage for the detached and various linked modes: a) frequency, b) growth rate, c) relative amplitude.

Fig. 18 Both toroidal plasma current (poloidal flux) and toroidal magnetic flux in the plasma increase or decrease with an increase or decrease, respectively, in either the poloidal-field bank voltage V_{PF} or the toroidal-field bank voltage V_{TF} .

(a) If V_{PF} (toroidal current in the flux core) is increased or decreased with V_{TF} (toroidal flux in the flux core) fixed, both I (toroidal plasma current) (top) and Φ (toroidal flux in the plasma) (bottom) increase or decrease, respectively.

(b) If V_{TF} (toroidal flux in the plasma) is increased or decreased with V_{PF} (toroidal current in the flux core) fixed, both Φ (toroidal flux in the plasma) (top) and I (toroidal plasma current) (bottom) increase or decrease, respectively.

Fig. 19 Toroidal plasma current and toroidal magnetic flux in the plasma versus square root of a) poloidal-field bank voltage and b) toroidal-field bank voltage. Open circles denote equilibrium field was not appropriately adjusted.

Fig. 1

Fig. 2

● POLOIDAL FLUX LOOP

● TOROIDAL FLUX LOOP
● ROGOWSKI

Fig. 3

Fig. 4

#84X0371

Fig. 5

#84X0146

Fig. 6

85X0641

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

#84X0323

Fig. 12

Fig. 14

#84X1828

Fig. 15

#84X1829

Fig. 16

Fig. 17a

Fig. 17b

Fig. 17c

Fig. 18a

Fig. 18b

Fig. 19a

Fig. 19b

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austr Nat'l Univ, AUSTRALIA
Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
Prof. I.R. Jones, Flinders Univ., AUSTRALIA
Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
Prof. F. Cap, Inst Theo Phys, AUSTRIA
Prof. Frank Verheest, Inst theoretische, BELGIUM
Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
Dr. P.H. Sakanska, Univ Estadual, BRAZIL
Dr. C.R. James, Univ of Alberta, CANADA
Prof. J. Teichmann, Univ of Montreal, CANADA
Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
Prof. S.R. Sreenivasan, University of Calgary, CANADA
Prof. Tudor W. Johnston, INRS-Energie, CANADA
Dr. Hannes Barnard, Univ British Columbia, CANADA
Dr. M.P. Bachynski, MEB Technologies, Inc., CANADA
Chalk River, Nucl Lab, CANADA
Zhengwu Li, SW Inst Physics, CHINA
Library, Tsing Hua University, CHINA
Librarian, Institute of Physics, CHINA
Inst Plasma Phys, Academia Sinica, CHINA
Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
The Librarian, Culham Laboratory, ENGLAND
Prof. Schatzman, Observatoire de Nice, FRANCE
J. Radet, CEN-EP6, FRANCE
AM Dupas Library, AM Dupas Library, FRANCE
Dr. Tom Muai, Academy Bibliographic, HONG KONG
Preprint Library, Cent Res Inst Phys, HUNGARY
Dr. S.K. Trehan, Panjab University, INDIA
Dr. Indra Mohan Lal Das, Banaras Hindi Univ, INDIA
Dr. L.K. Chavda, South Gujarat Univ, INDIA
Dr. R.K. Chhajlani, Vikram Univ, INDIA
Dr. B. Dasgupta, Saha Inst, INDIA
Dr. P. Kaw, Physical Research Lab, INDIA
Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
Prof. S. Cuperman, Tel Aviv University, ISRAEL
Prof. G. Rostagni, Univ Di Padova, ITALY
Librarian, Int'l Ctr Theo Phys, ITALY
Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
Biblioteca, del CNR EURATOM, ITALY
Dr. H. Yamato, Toshiba Res & Dev, JAPAN
Dirsc. Dept. Lg. Tokamak Dev. JAERI, JAPAN
Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
Research Info Center, Nagoya University, JAPAN
Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
Prof. Sigeru Mori, JAERI, JAPAN
Library, Kyoto University, JAPAN
Prof. Ichiro Kawakami, Nihon Univ, JAPAN
Prof. Satoshi Itoh, Kyushu University, JAPAN
Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
Tech Info Division, KAERI, KOREA
Bibliotheek, Fon-Inst Voor Plasma, NETHERLANDS
Prof. B.S. Liley, University of Waikato, NEW ZEALAND
Prof. J.A.C. Cabral, Inst Superior Tecn, PORTUGAL
Dr. Octavian Petrus, ALI GUZA University, ROMANIA
Prof. M.A. Hellberg, University of Natal, SO AFRICA
Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
Fusion Div. Library, JEN, SPAIN
Prof. Hans Wilhelmsson, Chalmers Univ Tech, SWEDEN
Dr. Lennart Stenflo, University of UMEA, SWEDEN
Library, Royal Inst Tech, SWEDEN
Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
Dr. V.T. Tolck, Kharkov Phys Tech Ins, USSR
Dr. D.D. Ryutov, Siberian Acad Sci, USSR
Dr. G.A. Eliseev, Kurchatov Institute, USSR
Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
Institute Gen. Physics, USSR
Prof. T.J.M. Boyd, Univ College N Wales, WALES
Dr. K. Schindler, Ruhr Universitat, W. GERMANY
Nuclear Res Estab, Julich Ltd, W. GERMANY
Librarian, Max-Planck Institut, W. GERMANY
Bibliothek, Inst Plasmaforschung, W. GERMANY
Prof. R.K. Janey, Inst Phys, YUGOSLAVIA