Relaxation Oscillations and Toroidal-Current Regeneration in a Helicity-Driven Spheromak

M. Nagata, T. Kanki, T. Masuda, S. Naito, H. Tatsumi, and T. Uyama

Department of Electrical Engineering, Himeji Institute of Technology, Shosha, Himeji, Hyogo 671-22, Japan

(Received 15 September 1993)

During the sustained phase of spheromak operation in the flux amplification compact toroid device, detailed observations were made on the discrete relaxation and toroidal current regeneration events that occurred throughout a typical quasiregular cycle. Measurements indicate that over such a cycle there appears to be a global self-organizing phenomenon which involves both the collapse and subsequent recovery of the closed flux surfaces. At the point of recovery, the partially relaxed state is characterized by a value of λ on the central region which is greater than that on the edge region.

PACS numbers: 52.55.Hc, 52.30.Jb, 52.35.Py

Numerous experiments have been performed to observe the magnetohydrodynamic (MHD) relaxation phenomena during the resistive decay [1–3], formation [4], and sustainment [1,5,6] processes of spheromak plasmas. The sustainment of a spheromak plasma is effectively achieved by the continual injection of poloidal current from a dc helicity injector so that a steady-state toroidal plasma current is maintained through the "Taylor-type" relaxation process [7,8]. This relaxation or self-organizing process arises during helicity injection and is associated with a current redistribution (the inward diffusion of the externally injected edge current) which leads to the attainment of relaxed states characterized by a peaked current profile. The attractive possibility of maintaining a toroidal current distribution by means of a dc helicity injector motivates our particular investigation into the detailed MHD behavior associated with the quasiregular oscillatory nature of the relaxation events.

In our flux amplification compact toroid (FACT) experiments we have successfully demonstrated the sustainment of a "flux-core" spheromak, which has open field lines, by dc helicity injection using an additional cathode electrode [5]. Simultaneously, we have observed the intrinsic, globally coherent oscillations likewise observed in the compact toroid experiment device [1] and the gun-injected spheromak device (SPHEX) [6]; these oscillations are considered to be the important common phenomena occurring in the sustainment phase of spheromaks. However, details concerning how such oscillations are associated with the relaxation mechanism required for plasma sustainment by dc helicity injection remain unclear. With a view to answering this problem, we have investigated the temporal behavior of the internal magnetic structure during one cycle of the observed oscillations. This led to the present Letter which describes experimental observations confirming that the configuration is apparently destroyed and then effectively reconstructed during the regeneration of the toroidal current by the relaxation process. Contrary to expectation, our experimental results showed that the observed relaxation drives the configuration towards a partially relaxed state [9] with a higher λ ($\equiv \mu_0 I_t/\Psi_t$, where I_t is the toroidal current and Ψ_t is the toroidal flux) on the central region than on the edge region. The experimental description concerning the FACT device is presented in Ref. [5].

Figure 1 shows typical discharge wave forms of the toroidal plasma current I_t, toroidal flux Ψ_t, C III spectral line radiation measured along the line of sight through the core region, and the poloidal magnetic field B_p on the midplane and the symmetric axis, where $t=0$ ms corresponds to firing time of the magnetized coaxial gun. Note that several discrete I_t generation events ($\Delta I_t/I_t > 16\%$) have been observed during sustainment. These large-scale toroidal current generation events are suggestive of dynamo-type behavior. The experimental evidence indicates that these events are linked to the current conversion process of the injected poloidal current along the long open bias flux. The C III impurity line radiation shows a corresponding sawtooth behavior which seems to suggest that anomalous outward particle transport is also associated with these events. The oscillations of the B_p signal shown in Fig. 1 are observed throughout the entire

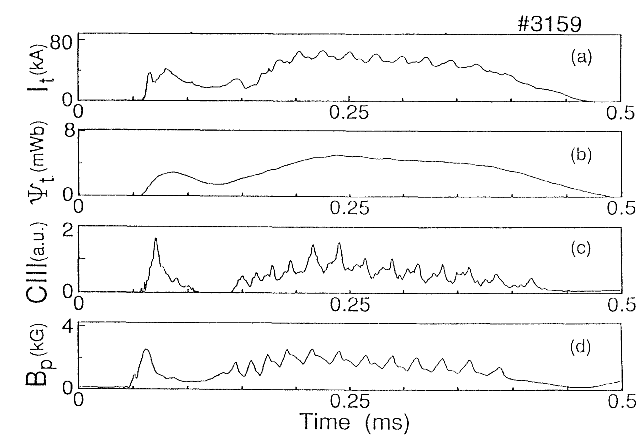

FIG. 1. Temporal evolutions of a typical single-shot discharge in which discrete dynamo events are seen: (a) toroidal current I_t; (b) toroidal flux Ψ_t; (c) C III spectral line intensity (4647 Å); (d) the poloidal magnetic field B_p at $R=0$ m on the midplane of the flux conserver.

0031-9007/93/71(26)/4342(4)$06.00

plasma region.

In order to examine in detail the internal magnetic structure formed during a single shot we used a two-dimensional magnetic probe array of pickup coils that was located in a poloidal plane (R-Z) of the flux conserver (FC). Tests revealed that this probe did not significantly change the plasma activity and the magnetic field profiles. From the two-dimensional magnetic field data obtained, it was possible to derive the amplitude of the poloidal magnetic flux Ψ_p. Figure 2(a) shows the resulting temporal evolution of Ψ_p and I_t during a time scale ($\Delta t = 0.070$ ms) corresponding to three cycles of the I_t current oscillations. These quasiperiodic oscillations are apparent for the Ψ_p data as well. At a peak of I_t, it is observed that Ψ_p also reaches a maximum value. Indeed, the oscillations of Ψ_p and I_t are found to be very well correlated. Thus, the self-generation of I_t produces a flux amplification of Ψ_p. We found from the two-dimensional poloidal flux contours that ordered magnetic flux surfaces were apparently formed at the beginning of a cycle at the peak of I_t. Once I_t has decayed, the spheromak deviates from the axisymmetric configuration and then undergoes the relaxation which may cause the destruction of the nested closed flux surfaces. The wave forms of Ψ_t,I_t and the cathode electrode voltage V_c of the helicity injector are displayed in Fig. 2(b). Despite the small amplitude of oscillations of Ψ_t, it appears that they are certainly out of phase with respect to I_t, indicating a conversion from the externally injected poloidal current to toroidal plasma current. The cathode voltage V_c is observed to enhance throughout this relaxation process. The reason for this is not clear, however, especially since I_t is effectively increased by the action of helicity injection which occurs at a rate of $2V_c\Psi_v$, where Ψ_v is the bias vacuum flux.

In order to analyze the structure of the toroidal mode (n) of the observed magnetic oscillations, we employed a toroidal mode diagnostic coil array which consists of eight B_z coils distributed toroidally at equal angles over 360° and at a major radial position of $R = 0.124$ m. Figure 3 shows typical temporal evolutions of the n-mode amplitudes ($n = 0$–3) and the $n = 1$ phase. The $n = 0$ mode is primarily composed of the unperturbed axisymmetric poloidal field of the sustained plasma. Importantly, it should be noted that large-amplitude oscillations occur for both the $n = 0$ and $n = 1$ modes and the latter is characterized by the largest amplitude. The periodic oscillations for the modes $n = 2$ and $n = 3$ have, by comparison, much smaller amplitudes. Also of interest is the observation that the oscillations in $n = 1$ are out of phase with those of $n = 0$, which suggests that the cyclic excitation of the $n = 1$ mode is probably triggered by the corresponding decay of the $n = 0$ mode. Additionally, the increase in the mode amplitude of $n = 0$ corresponds very well with the increase in I_t. Regarding the poloidal mode number (m), we can guess from the displacement of the closed poloidal flux contours that it is $m = 1$. The phase of $n = 1$ shows that this mode rotates toroidally at a frequency ≈ 33–39 kHz which is commensurate with the $\mathbf{E} \times \mathbf{B}$ drift applied by the cathode voltage.

Figure 4 shows the typical time evolution during one relaxation cycle of the safety factor profile q, as calculat-

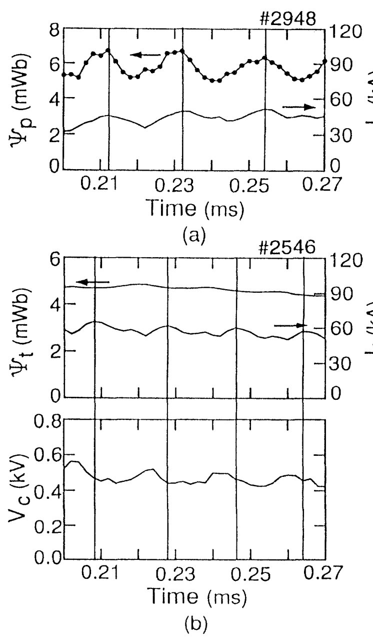

FIG. 2. Temporal evolutions of the poloidal flux Ψ_p and the toroidal current I_t (a), the toroidal flux Ψ_t,I_t and the cathode voltage V_c (b) during the cycles of the relaxation oscillation.

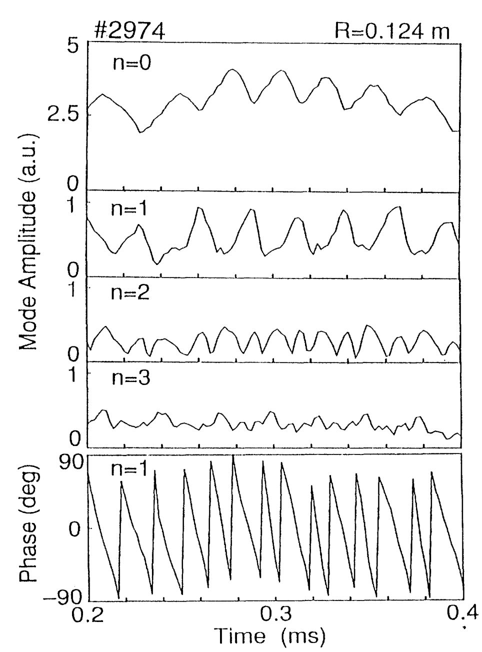

FIG. 3. Temporal evolution of the toroidal modes ($n = 1$–3) and the phase of the $n = 1$ mode.

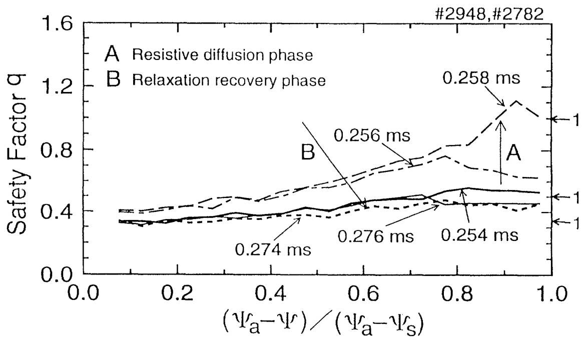

FIG. 4. Temporal evolution of the q profiles as derived from the two-dimensional Ψ_p and B_t data of the two different and reproducible discharges.

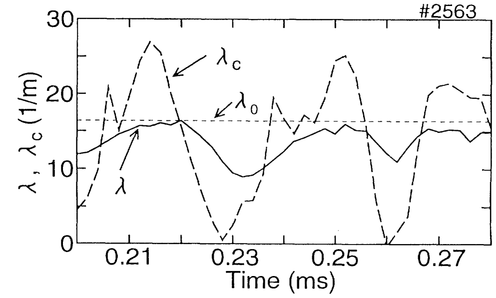

FIG. 5. Temporal evolution of the whole λ and the central λ_c during the cycles of the relaxation oscillation.

ed from $q \equiv \Delta\Psi_t/\Delta\Psi_p$, and obtained from two reproducible shots, where $\Delta\Psi_t$ is the difference in toroidal flux between two nearby poloidal flux surfaces Ψ_p and $\Psi_p + \Delta\Psi_p$. We note that q is only defined on the closed flux surfaces. The resultant q profile is therefore shown as a function of normalized poloidal flux $\tilde{\Psi} \equiv (\Psi_a - \Psi)/(\Psi_a - \Psi_s)$, where $\Psi \equiv \Psi_p$, Ψ_s is the value of Ψ at the separatrix, and Ψ_a is the value ($\sim$6.2 mWb) of Ψ at the magnetic axis ($R \sim 0.2$ m). At the magnetic axis $\tilde{\Psi} = 0$ and at the separatrix $\tilde{\Psi} = 1$. The absolute value of Ψ_s ($\sim$2.2 mWb) is estimated from the contours of Ψ_p and appears to be almost constant over time. The q profiles approximately correspond to the variations of Ψ_p [Fig. 2(a)]. At times $t = 0.254$, 0.274, and 0.276 ms the toroidal current I_t is almost peaked while the corresponding q profiles at those times are, for the most part, relatively flat ($1/3 < q < 1/2$) with only a slight rise occurring in the vicinity of the separatrix. We note that at this time the configuration is almost an axisymmetric state. The q value at the separatrix, q_s, begins to increase due to the resistive diffusion of the toroidal current concentrated mainly in the closed flux surfaces region. As this q_s "rising process" proceeds, a tokamaklike profile occurs and, consequently, q_s rises above the rational ratio of 1/1 at $t = 0.258$ ms. Immediately after, the entire central region of the q profile is observed to abruptly rise to a value greater than 1/1. However, we cannot accurately represent the q profile during the collapse of the closed magnetic surfaces and the subsequent loss of axisymmetry owing to the very dependence of q on the assumption of axisymmetry. Thereafter, MHD relaxation begins to recover the q profile to its original relaxed state, as shown by Fig. 4.

We have directly measured the λ_c ($\equiv \mu_0 I_{tc}/\Psi_{tc}$, where I_{tc} is the toroidal current and Ψ_{tc} is the toroidal flux, respectively) on the central region (within a minor radius $a = 0.05$ m) by using a Rogowski loop and a flux loop in order to compare with the λ value ($\equiv \mu_0 I_t/\Psi_t$) for the whole region. Figure 5 shows that λ_c rises above λ during the process of I_t generation and indicates that the centrally peaked current distribution is being established on account of the rapid inward current flow from the outer edge (higher λ) region. The collapse of the closed flux surfaces causes the λ profile to become hollow since I_{tc} and hence λ_c both vanish. From Ref. [9], we would reasonably expect that the λ value does not exceed the eigenvalue ($\lambda_0 = 16.4$ m^{-1}) as determined from the shape of the FC. The approximate safety factor derived on the basis of circular cross-section flux surfaces is $\langle q \rangle$ ($\equiv 2/\lambda_c R$), which, in the relaxed state, with a measured value of λ_c in the range 21–26 m^{-1}, yields $\langle q \rangle$ to be 0.39–0.48. This value agrees well with the range $1/3 < q < 1/2$ as depicted in Fig. 4.

This one-cycle oscillation event ($\Delta t \sim 0.02$ ms) occurring in the plasma during dc helicity injection can be classified as having an initial resistive diffusion phase and a subsequent MHD relaxation phase (collapse and recovery; $\Delta t \sim 0.015$ ms). The configuration's deviation from the initial stable state is caused by the resistive dissipation of the toroidal current I_t on the closed flux surfaces region. This resistive decay is attributable to the increase in q_s. The value of q_s exceeds the rational ratios of 1/2 and 1/1, which consequently excites the modes of $m = 1/n = 2$ and $m = 1/n = 1$. Next, the magnetic surfaces are deformed helically by the development of the dominant $m = 1/n = 1$ kink mode, and the subsequent magnetic reconnection destroys the original flux surfaces and abruptly raises the entire q profile. This physical picture is believed to demonstrate the basic features of Kadomtsev's reconnection model [10]. In the relaxation collapse phase, the plasma current, concentrated on the central region, anomalously moves to the open flux region leading to a drastic reduction there which causes the current density profile to change from peaked to hollow ($\lambda > \lambda_c \sim 0$). At the other extreme, in the relaxation recovery (the flux amplification) process, the high q profile or the low λ_c value returns to its original profile or value; i.e., the injected current on the open field lines is transported towards the central core region ($\lambda_c > \lambda \sim \lambda_0$). It appears that the open field lines along the geometric axis helically deform giving rise to the possibility of significant inward current transport and poloidal flux amplification [11].

In conclusion then, we have found that the dynamics of a helicity-driven spheromak is dominated by a MHD process incorporating the resistive field diffusion and subsequent MHD relaxation. The periodically observed relaxation mechanism returns the configuration to the partially relaxed state with the higher λ on the central region.

The authors are grateful to R. G. Kenny for many valuable discussions.

[1] S. O. Knox *et al.*, Phys. Rev. Lett. **56**, 842 (1986).
[2] T. Uyama *et al.*, Nucl. Fusion **27**, 799 (1987).
[3] Y. Ono *et al.*, Phys. Rev. Lett. **61**, 2847 (1988).
[4] A. Janos *et al.*, Phys. Rev. Lett. **55**, 2868 (1985).
[5] M. Nagata *et al.*, J. Phys. Soc. Jpn. **60**, 3203 (1991).
[6] P. K. Browning *et al.*, Phys. Rev. Lett. **68**, 1718 (1992).
[7] J. B. Taylor, Rev. Mod. Phys. **58**, 741 (1986).
[8] T. R. Jarboe *et al.*, Phys. Rev. Lett. **51**, 39 (1983).
[9] D. A. Kitson and P. K. Browning, Plasma Phys. Controlled Fusion **32**, 1265 (1990).
[10] B. B. Kadomtsev, Fiz. Plazmy **1**, 710 (1975) [Sov. Plasma Phys. **1**, 389 (1975)].
[11] K. Katayama and M. Katsurai, Phys. Fluids **29**, 1939 (1986).