Observation of a New Toroidally Localized Kink Mode and Its Role in Reverse-Field–Pinch Plasmas

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A new type of toroidally localized kink instability, which we named the "slinky mode," was observed in a reverse-field–pinch plasma in the OHTE device. It is found that the slinky mode is the result of the phase locking of several internal kink modes due to nonlinear coupling and is an effective way to approach the Taylor relaxed state.

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Reverse-field pinches (RFP's) were successfully operated in the OHTE device with the resistive shell, and discharges were sustained over 10 ms, much longer than the resistive-shell time constant of 1.5 ms. Global plasma characteristics with the resistive shell were very similar to those obtained with the conducting shell.[1] Since the linear MHD theories predict that RFP plasmas are unstable with a resistive shell and that unstable modes grow on the resistive-shell time scale,[2-4] magnetic fluctuations were studied in detail. A new type of toroidally localized kink instability was observed. In this Letter we report characteristics of the instability and its role in RFP discharges.

The OHTE device has a major radius of 1.24 m and a plasma radius of 0.183 m. The resistive shell is placed at a minor radius of 0.200 m. The details of the device and the operation mode are described elsewhere.[1] In order to investigate detailed MHD behavior of the plasma, an array of 128 pickup loops, 32 toroidally by 4 poloidally, was installed at a minor radius of 0.255 m. Each pickup loop spans 11.25° toroidally by 90° poloidally, and together they cover the entire torus. The pickup loops measure time derivatives of radial magnetic fluxes.

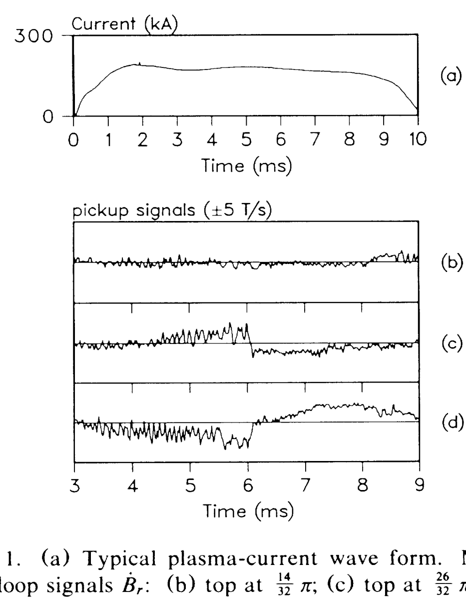

FIG. 1. (a) Typical plasma-current wave form. Magnetic pickup-loop signals $\dot{B}_r$: (b) top at $\frac{14}{32}\pi$; (c) top at $\frac{26}{32}\pi$; (d) top at $\frac{28}{32}\pi$.

Figure 1 shows a typical plasma-current wave form at about 180 kA and some magnetic loop signals. Most of the pickup-loop signals are reasonably quiet, as represented by the top-pickup-loop signal $\dot{B}_r$ at the toroidal location of $\frac{14}{32}\pi$ [Fig. 1(b)]. The spectrum of the high-frequency fluctuations covers 3–50 kHz with a broad peak around 10 kHz as typically observed in RFP plasmas. Besides the high-frequency fluctuations, occasional slow, aperiodic, toroidally localized behavior was found as shown in Figs. 1(c) and 1(d) for the $\dot{B}_r$ signals of the top pickup loops at $\frac{26}{32}\pi$ and $\frac{28}{32}\pi$. Similar signals are recorded by the outside pickup loops at $\frac{25}{32}\pi$ and $\frac{27}{32}\pi$ and the bottom pickup loops at $\frac{24}{32}\pi$ and $\frac{26}{32}\pi$, respectively. These exhibit a toroidally localized kink instability starting at about 4 ms into the discharge with a growth time of about 1 ms ($\simeq$resistive-shell time). Its toroidal extent is limited to approximately one period ($\simeq$0.5 m long) corresponding to $n \simeq 16$. It has the same helical handedness as the internal magnetic field lines. The

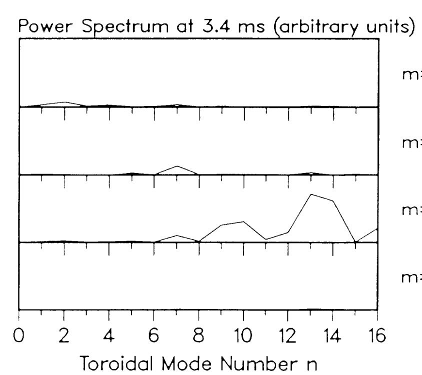

FIG. 2. Example of mode power spectra for $m = +1, 0, -1$, and ± 2 when a slinky mode exists.

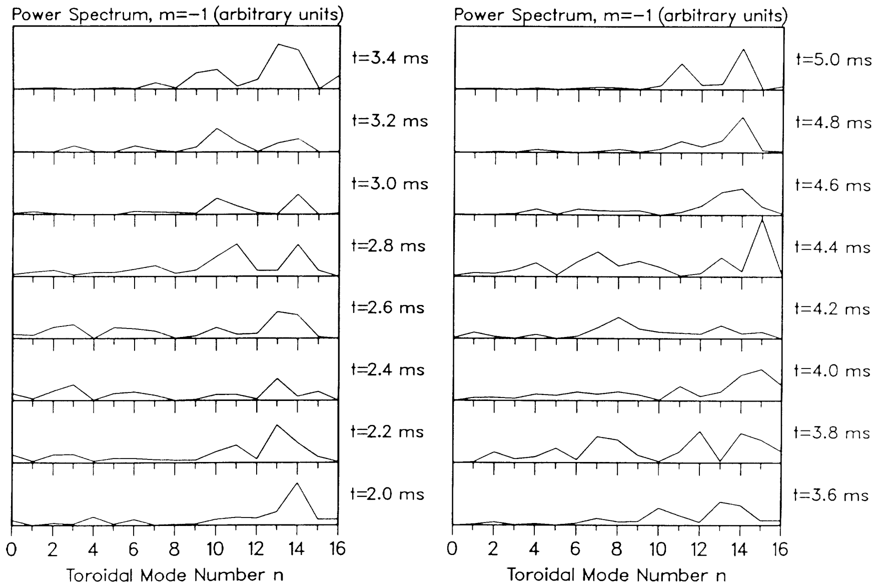

FIG. 3. Mode power spectra for $m=-1$ at various times.

plasma shape with this mode is analogous to the kink when the spring toy "Slinky" is twisted. Thus, we named it the "slinky" mode.

An interesting and important feature of the slinky mode is that it suddenly stops growing, as seen at 6 ms in the example, and self-heals. Apparently, slinky modes arise randomly in time and toroidal location. On the average, one slinky mode was observed in a 10-ms discharge, but sometimes two were seen in a discharge.

The 128 pickup-loop signals were low-pass filtered and then Fourier analyzed. The result indicates that $m=-1$ is the dominant poloidal mode when a slinky mode exists as shown in Fig. 2. The analysis of toroidal mode numbers indicates that the dominant modes are $10 \lesssim n \lesssim 16$. However, because of the finite number of pickup coils, modes with $n > 16$ could also have contributed. The amplitudes of various n modes vary from time to time or from shot to shot, and no clear pattern has been found. However, it has been observed that their individual amplitudes do not increase by much even when a slinky mode develops, as illustrated in Fig. 3. In this example, the slinky mode begins at around 2 ms and is fully developed at around 3.4 ms. It suddenly starts decaying at around 4 ms and is gone by 5 ms.

Therefore, their phase relationship was examined as a possible mechanism for the slinky mode. Figure 4 shows normalized Fourier modes for $m=-1$ with $10 \le n \le 16$ plotted along the toroidal angle ϕ. Just before the beginning of the slinky mode (2 ms) the phases are random. However, all the phases are locked and all the modes with the above-mentioned n values add up near $\phi=0.6$, when the slinky mode fully develops at 3.4 ms. The phase locking is lost when the sudden decay has started at 4 ms. It should be noted that if those modes are all independent, the probability of our observing a slinky mode in a shot is about one out of a million.

Figure 5 shows the Fourier-mode argument $n\phi+\alpha_n$ [mod(2π rad)] for the $m=-1$ mode at $\phi=0.6$ as a function of the discharge time. The arguments for $1 \le n \le 7$ are always random as shown in Fig. 5(a). On the other hand, the phase locking is clearly observed around 3.5 ms for $8 \le n \le 15$ [Fig. 5(b)]. The modes with $n=10$ and 11 are locked together from the beginning, and the modes with $n=12$–15 join the phase locking in ascending order. However, the $n=9$ mode joins fairly late and the $n=8$ mode joins last.

In order to investigate effects of the slinky mode, it was modeled as a free-boundary pressureless plasma

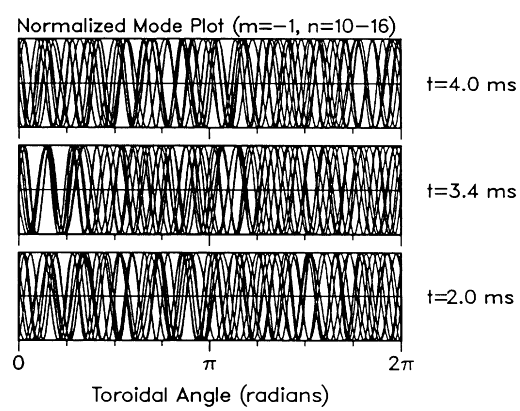

FIG. 4. Phases of the $m=-1$ modes with $10 \le n \le 16$ vs toroidal angle ϕ.

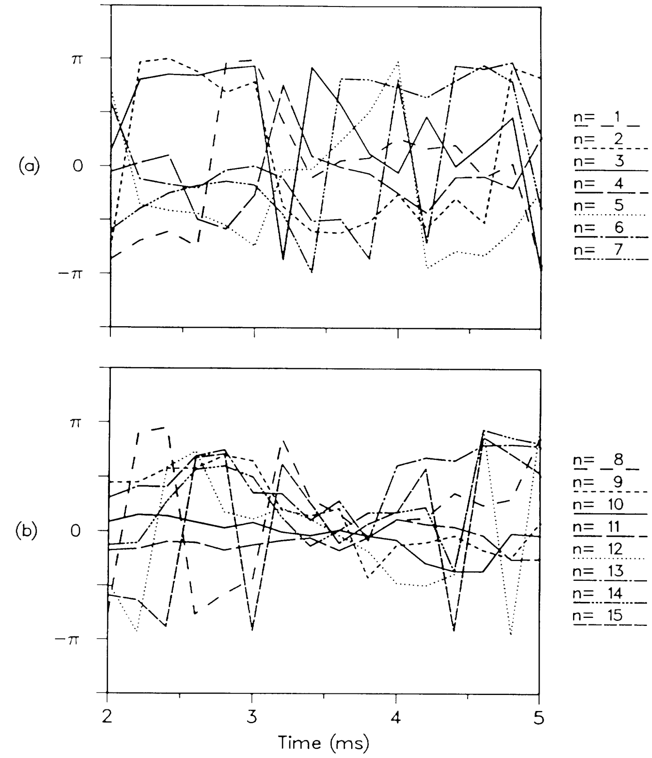

FIG. 5. Fourier-mode argument [mod(2π rad)] for the $m=-1$ mode at $\phi=0.6$ vs time. (a) $1\leq n\leq 7$ and (b) $8\leq n\leq 15$.

equilibrium with the measured pickup signals as the boundary conditions. It was assumed that $\mu\equiv j_{\parallel}/B$ is a constant throughout the deformed plasma column. When a group of field lines originally at the same radius with different azimuthal positions were traced through the slinky mode, we found general characteristics as shown in Fig. 6. The field lines outside the field-reversal layer (dashed line) all come back to the original radius.

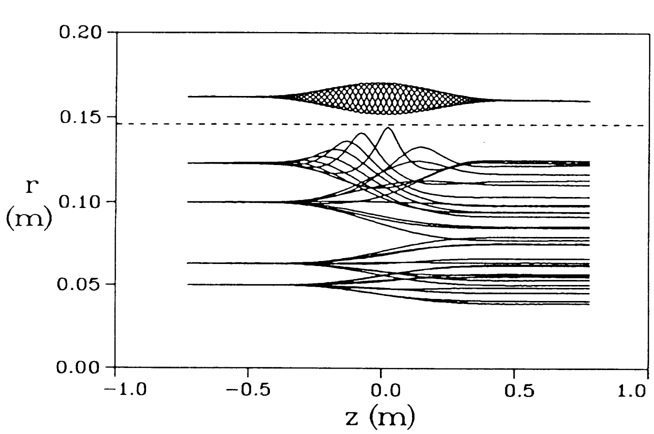

FIG. 6. Field line traces through the slinky mode simulated in the code.

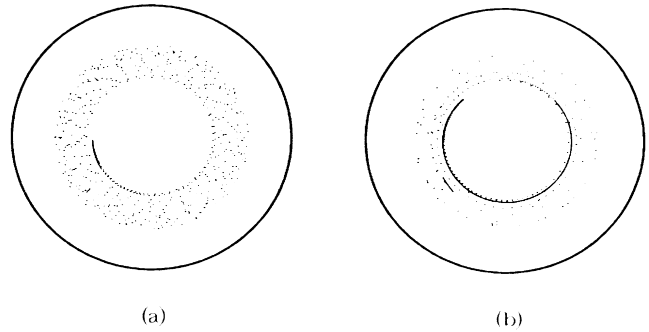

FIG. 7. Cross-section view of 540 field lines, originally at $r=10$ cm, traced once around the torus: (a) with a slinky mode (phase locking); (b) without phase locking.

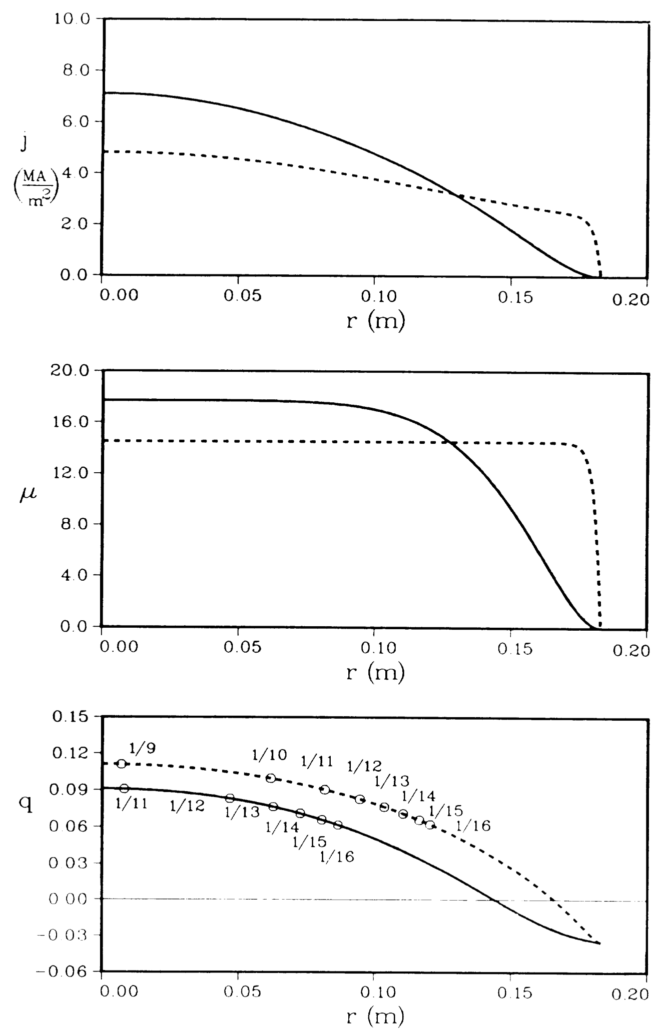

FIG. 8. Modeled j, μ, and q profiles before and right after the development of the slinky mode (solid lines and dashed lines, respectively).

However, the field lines inside the reversal layer end up at different radii and mix up. This is because they have the same handedness as the slinky mode and are pitch resonant as they traverse it. Therefore, creating a slinky mode is an effective way of stochastically mixing internal field lines. Figure 7 illustrates the effectiveness of the field-line mixing. 540 field lines originally at the same radius were traced once around the torus and plotted in the cross-section plane. Figure 7(a) shows the case with a slinky model, i.e., a number of $m=-1$ modes with different n values are phase locked together at one toroidal location, while in Fig. 7(b) the same $m=-1$ modes exist, except that their phases are all random. It is clear that the level of field-line stochasticity is much higher with the slinky mode.

These observations lead to the following interpretation of the slinky behavior. The current distribution of an RFP plasma tends to peak in the middle because of Ohmic heating and edge current dissipation. This causes current-driven MHD instabilities. In particular, $m=-1$ resistive internal kink modes with $n \gtrsim 11$ are unstable since they have resonance field lines as illustrated on the q profile (solid line) in Fig. 8. The q profile is a typical solution generated by a plasma equilibrium code, consistent with the observed plasma current and edge toroidal field. The corresponding current density j and $\mu \equiv j_{\parallel}/B$ profiles are also shown as solid lines in Figs. 8(a) and 8(b). When these $m=-1$ modes grow, an adjacent mode couples to the resonant mode and the phase locking occurs. First, the $n=10$ mode locks its phase to the $n=11$ resonant mode, and then the $n=12$–15 modes, sequentially, couple one after another. This forms a slinky mode and the field lines are effectively mixed up. Once the field-line mixing takes place, the j profile flattens as indicated by the dashed curves in Fig. 8. Here, the fact that the plasma current and edge toroidal field remained unchanged throughout the slinky-mode development is used as a constraint in the code simulation. The flattened j profile brings the central q value up and the $n=9$ mode becomes a resonant mode and joins the phase locking. Finally, the adjacent $n=8$ mode also couples. By this time, the μ profile ($\mu \equiv j_{\parallel}/B$) is very close to that of the Taylor relaxed state[5] and the plasma is stabilized. The whole process repeats as the current distribution starts peaking again because of Ohmic heating and edge current dissipation.

In conclusion, a new type of toroidally localized kink instability (slinky mode) was observed in an RFP plasma. The slinky mode is the result of the phase locking of several internal kink modes due to nonlinear coupling. By the formation of the slinky mode, the plasma quickly approaches the Taylor relaxed state and self-heals before a catastrophe occurs.

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