Studies of Internal Disruptions and $m = 1$ Oscillations in Tokamak Discharges with Soft–X-Ray Techniques*

S. von Goeler, W. Stodiek, and N. Sauthoff
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 11 July 1974)

Fluctuations in x-ray intensity from the ST tokamak show a characteristic sawtooth behavior. This behavior is identified as an internal disruption. The internal disruptions are preceded by growing sinusoidal $m=1$, $n=1$ oscillations. The properties of these oscillations are compared with predictions for the $m=1$ internal kink mode.

Investigation of the continuous soft–x-ray emission from the hot central core of the ST tokamak has been undertaken in an attempt to study the stability properties of a tokamak plasma. Figure 1 shows the experimental arrangement. An "image" of the plasma column was formed by a slot aperture and the x-ray emission from different regions of the plasma transmitted through 1- and 3-mil Be foils was measured with silicon surface-barrier detectors, of 200 μm fully depleted thickness, which are movable in the image plane. The detectors are sensitive between 3 and 13 keV. The spatial resolution at the plasma center is about 2 mm; the frequency resolution, up to 1 MHz.

The radiation is produced by the thermal part of the plasma electrons and consists predominantly of the recombination-radiation continuum of the partly ionized oxygen and iron impurities.[1] The radiation intensity is therefore a function of the electron density and temperature and of the impurity concentration. The x-ray fluctuations are caused by a fluctuation in either of these quantities, but predominantly by temperature fluctuations.

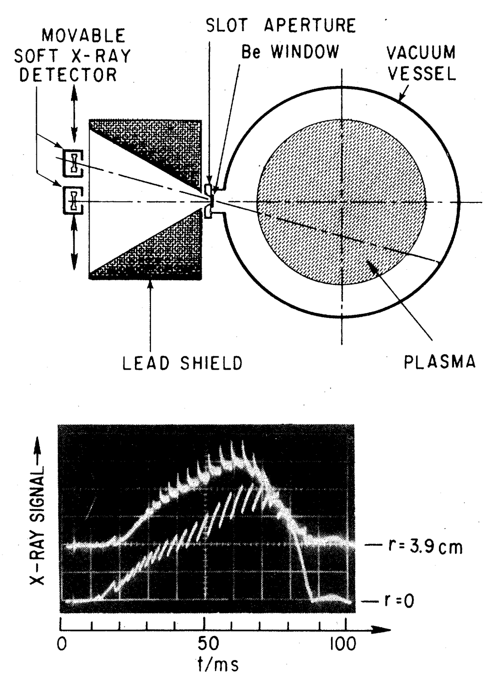

FIG. 1. Experimental arrangement of x-ray detectors. The x-ray traces exhibit internal disruptions.

The oscillograms of the x-ray emissions, shown in Fig. 1, are typical for high-density discharges in the ST tokamak. The traces exhibit a "sawtoothlike" oscillation. The sawtooth is "inverted," showing a fast rise and a slow exponential drop, if one scans a small distance away from the center of the column (e.g., trace marked $r=3.9$ cm). Similar sawtooth oscillations seem to be present also in the T-4 tokamak[2] (Ref. 2, Fig. 7) and have also been seen on the ATC tokamak.[3] We will show that they have the features of internal disruptions preceded by $m=1$ oscillations.

In Fig. 2 we plot radial scans of various quantities for a typical high-density discharge in the ST tokamak. In Fig. 2(a) are shown electron temperature and electron density, as derived from Thomson scattering of laser light. Assuming that the discharge is nearly stationary and that the impurity concentration is uniform across the column $[Z_{\rm eff}(r) = \text{const}]$,[1] we can calculate the current density and the safety factor $q(r)$ as a function of radius: q is roughly 0.8 in the center of the plasma [Fig. 2(b)] and reaches a value of 1.0 at $r \approx 2$ cm. There is, of course, some uncertainty in these values for q because the above-mentioned assumptions may not hold. Figure 2(c) shows the measured relative sawtooth amplitude $\Delta\tilde{A}/A$. The sawtooth amplitude has a node, which occurs at the $q=1$ point. Outside this node, the sawtooth is "inverted." The amplitude is very small for radii $r>4$ cm. Simultaneous measurement of the sawtooth at different radii and at different locations around the torus shows that the

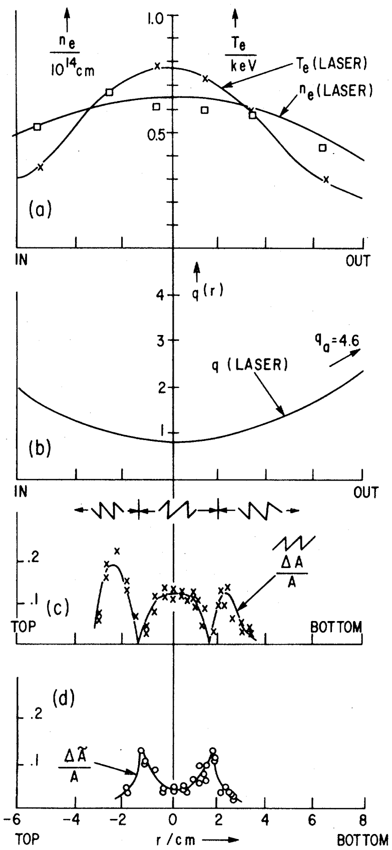

FIG. 2. Radial profiles of (a) electron temperature and density from laser data, (b) the safety factor $q(r)$ from laser data, (c) amplitude $\Delta\tilde{A}$ of the internal disruption (sawtooth), and (d) amplitude $\Delta\tilde{A}$ of the sinusoidal $m=1$ oscillations preceding the step.

sudden break of the sawtooth occurs at the same time everywhere. This indicates that the sawtooth behaves like an $m=0$, $n=0$ mode, i.e., an expansion in minor radius of the central region of the plasma column or "internal disruption."

Inside the $q=1$ surface the plasma temperature profile sharpens, until at the time of the sawtooth break it becomes unstable and enhanced transport occurs through the $q=1$ surface. The electron-temperature profile flattens, causing a decrease inside and increase just outside the $q=1$ surface. The increase dies off exponentially during the linear reheating of the central part.

In the ST tokamak, internal disruptions have been observed in high-density discharges near the high-pressure instability limit and at low densities near the electron runaway regime. (Intermediate is a region where $m=2$ oscillations occur near the $q=2$ surface of the plasma column, which will be described in another paper.) In the low-density region, the amplitude of the sawtooth is 3 to 10% and the frequency is 2 kHz. In the high-density regime the amplitude is larger, 5 to 30%, and the frequency smaller, 700 to 200 Hz.

Each internal disruption is preceded and probably caused by a growing sinusoidal kink-mode oscillation. Its amplitude $\Delta\tilde{A}$ is shown in Fig. 2(d). The amplitude $\Delta\tilde{A}$ is very small in the center of the column, has a maximum close to the $q=1$ surface, and vanishes abruptly outside the $q=1$ surface. Figure 3 illustrates the method for determining the m number of the mode. Two detectors look (a) slightly below and above the center of the column and (b) slightly off center at right angles. From the phase relation it follows that the oscillation is an $m=1$ mode. Similar measurements, placing detectors around the torus, show that it is also an $n=1$ mode. Since in Fig. 3(b) the top trace precedes the bottom trace, the mode propagates in the direction of the electron diamagnetic drift. The frequency ν of the waves is close to $\nu^* = (1/2\pi r)(kT/eB)p^{-1}dp/dr$ as determined from the laser temperature and density at the $q=1$ surface; it should be pointed

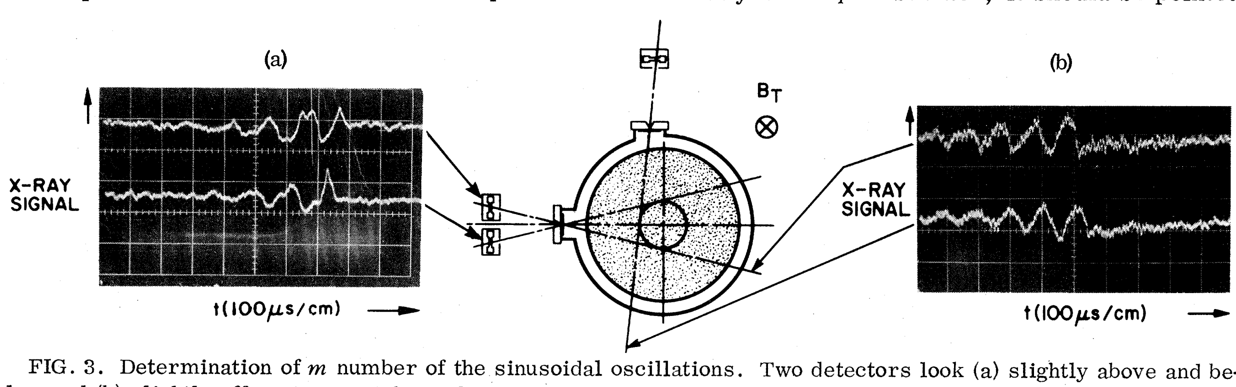

FIG. 3. Determination of m number of the sinusoidal oscillations. Two detectors look (a) slightly above and below and (b) slightly off center at right angles through the column. The pictures are from different shots. Case (b) shows that the waves go in the direction of the electron diamagnetic drift (i.e., the toroidal field vector B_T points into the plane of the picture).

out, however, that no correction for $E\times B$ drifts has been made, because the plasma potential is not known for these discharges.

Attempts were made to compare the experimental results with the predictions for the $m=1$ internal kink mode.[4,5] Pictures like Fig. 3 suggest an experimental growth rate $\gamma\approx 3\times 10^3$ sec^{-1}. The theoretical linear growth rate depends on the exact radial dependence of q. For parabolic temperature profiles (n_e = const, $j\sim T_e^{3/2}$) we derive from Eq. (13) of Ref. 5

$$\gamma_{\text{theor}}=\tfrac{2}{3}\pi(v_{\text{A}}/R)(\beta_{z0}+\tfrac{1}{2}r_s^{\,2}/R^2),$$

where v_{A} is the Alfvén velocity, R the major radius, β_{z0} the toroidal β in the center of the column, and r_s the radius of the singular surface ($q=1$). This formula gives a value of γ_{theor} equal to 2×10^4 sec^{-1}, which is larger than the experimental growth rate by a factor of about 7.

We can also compare the radial profile of the oscillation amplitude [Fig. 2(d)] with the prediction for the internal kink mode, i.e., displacement ξ = const for $r<r_s$ and $\xi=0$ for $r>r_s$. The x-ray signal is the integral over the x-ray sources along a line of sight. To obtain the x-ray radial profile a set of scans at different lines of sight have been inverted. Without going into the details, we state that the shape of the profile is in reasonable agreement with the theoretical prediction. The experimental displacement ξ, however, seems to be larger than the predicted nonlinear displacement of Ref. 5 by approximately an order of magnitude. Experimentally we obtain $\xi/r_s\approx 0.2$. It should be pointed out that resistivity is not included in the present theory and that it is likely that a tearing-mode version of this instability exists (Ref. 5, p. 1899) which might lead to smaller growth rates and larger displacements.

The technical assistance of W. Mycock and the ST tokamak operating crew is gratefully acknowledged. We thank Dr. K. Bol, Dr. H. P. Furth, and Dr. P. Rutherford for valuable discussions.

*This work was supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3073.

[1]S. von Goeler, W. Stodiek, H. Eubank, H. Fishman, S. Grebenshchikov, and E. Hinnov, "Thermal X-Ray Spectra and Impurities in the ST Tokamak" (to be published).

[2]V. A. Vershkov, C. E. Lisenko, I. B. Semenov, and A. T. Scherbac, Kurchatov Institute Report No. IAE-2291, 1973 (unpublished), and Princeton University Plasma Physics Laboratory Report No. MATT-TRANS-112, 1974 (unpublished).

[3]R. R. Smith, Princeton University Plasma Physics Laboratory Report No. TM-273, 1974 (unpublished).

[4]V. D. Shafranov, Zh. Tekh. Fiz. 40, 241 (1970) [Sov. Phys. Tech. Phys. 15, 175 (1970)].

[5]M. N. Rosenbluth, R. Y. Dagazian, and P. H. Rutherford, Phys. Fluids 16, 1894 (1973).

Adiabatic Compression of Plasma Vortex Structures*

D. R. Wells, E. Nolting, F. Cooke, Jr., J. Tunstall, P. Jindra, and J. Hirschberg
Department of Physics, University of Miami, Coral Gables, Florida 33124

(Received 3 June 1974)

Plasma vortex structures generated by conical theta-pinch guns have been successfully compressed and amplified by secondary adiabatic compression. A pair of vortex rings meet at the center of a primary magnetic mirror. A secondary mirror starts to compress them as soon as the collision has occurred. Peak ion temperatures of 170 eV have been obtained at an $n\tau$ of 10^{12} sec/cm^3 by utilizing a capacitor bank that stores 250 kJ.

Over the past fourteen years, an extensive series of experiments concerned with naturally occurring stable plasma states has been performed.[1-6] We have intensively studied, both theoretically and experimentally, a whole new field of plasma physics concerned with the problem of production, heating, and application of these states.

A theory has been developed which predicts a spectrum of naturally occurring stable states.[5,7,8] The particular stable state studied at the University of Miami consists of a closed plasma structure produced by conical theta-pinch guns. This state is the force-free collinear vortex ring or spheroid first described by Wells.[1,2]

It has been shown elsewhere that, by variation-

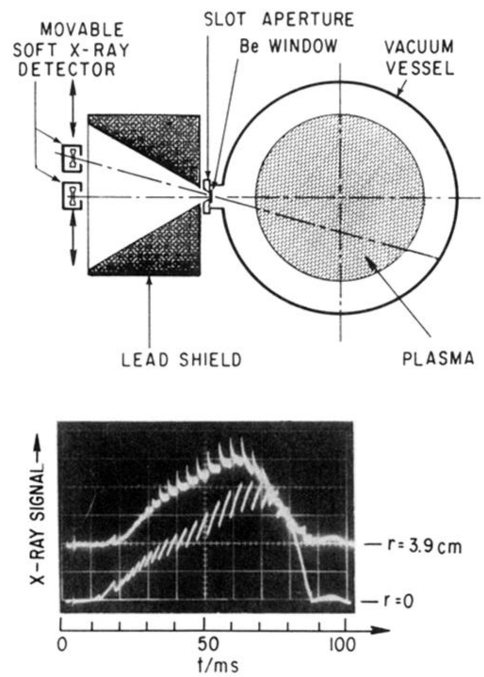

FIG. 1. Experimental arrangement of x-ray detectors. The x-ray traces exhibit internal disruptions.

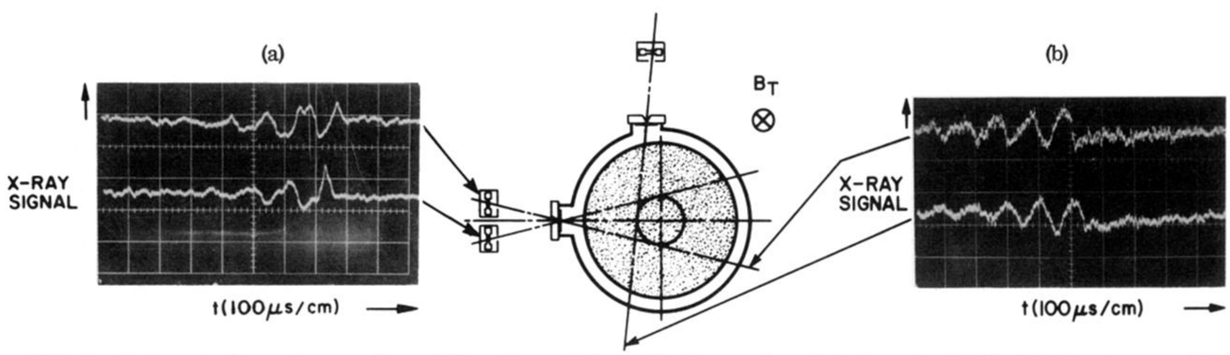

FIG. 3. Determination of m number of the sinusoidal oscillations. Two detectors look (a) slightly above and below and (b) slightly off center at right angles through the column. The pictures are from different shots. Case (b) shows that the waves go in the direction of the electron diamagnetic drift (i.e., the toroidal field vector B_T points into the plane of the picture).