SUCCESSOR OSCILLATIONS OF INTERNAL DISRUPTIVE
INSTABILITIES IN THE PLT TOKAMAK

N. R. Sauthoff, S. von Goeler*, D. R. Eames, and W. Stodiek

Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544 USA

ABSTRACT

The experimentally observed persistence of the $m=1$ mode following an internal disruption is described. The hot central region appears to spiral outward, being "pared" by interception with the radius of $q=1$ (as deduced from the radial extent of the $m=1$ mode). The outward motion of the axis can be arrested and the surviving helical filament can subsequently spiral inward, rather than being annihilated as expected from nonlinear resistive internal kink mode simulations.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

*Present address: Max Planck Institut fur Plasmaphysik

fig

I. INTRODUCTION

Attempts have been made to explain "sawtooth" oscillations of the central electron temperature^[1] on the basis of resistive internal kink modes.^[2,3,4,5] This model has invoked the growth of an $m=1$ island and the motion of the hot center toward the X-point where the energy is transported to the outer half of the island created by the reconnection of a hot inner and a cold outer flux surface. In the conventional simulation without diamagnetic effects^[2] complete reconnection annihilates the hot central peak and the heat diffuses over an annular region near the $q=1$ surface. Previous experimental attempts at confirmation have been based on the growth rate of the emissivity fluctuation and the repetition time of the sawtooth (which is presumed to be related to the onset of an explosive growth phase due to the evolution of the shear at the singular surface).

In PLT with neutral beam injection the agreement between theory and experiment is not as simple as that in ORMAK^[3,4] and TOSCA;^[5] the repetition time expands from ~5-10 ms without injection to ~20-40 ms with 400 kW injection.^[6,7] In ORMAK the extension of the period was related to a fourfold increase in the radius where $q=1$, whereas in PLT the resonant surface does not move more than ~20% (remaining at 8-10 cm). The greater breadth of the heat deposition profile or modified ordering of time scales might afford explanations for the slower increase of growth rate within the tearing mode model.

In this paper we present information on the evolution of $m=1$

modes, bursts of which can either be correlated with internal disruptions or seemingly merely decay without disruption.

II. EXPERIMENTAL OBSERVATION AND SIMULATION

Figure 1 shows signals of line-integrated x-ray emissivities from detectors viewing horizontally at the listed tangent radii near the time of a sawtooth drop at 483.20 ms. In this high-temperature ($T_e \sim 3.0$ keV), low-density ($\bar{n}_e \sim 2.4 \times 10^{13} \text{ cm}^{-3}$) discharge with neutral beam injection (400 kW) in the direction opposite the plasma current (460 kA), the plasma rotated in the toroidal direction so as to enhance the real part of the frequency to ~ 17 kHz, permitting more detailed analysis of the internal disruption, which more typically occurs in a time comparable to the rotation period. The $m=1$ oscillations at fundamental rotation frequency ω are visible on the ± 8 cm traces until 483.10 ms after which a more complex double-peaked structure is evident; a slightly phase-shifted 3ω perturbation complicates the interpretation but is likely unimportant as it is absent in other cases.

The central trace exhibits dominantly 2ω behavior since the "hot spot" passes within view (i.e., along the line of sight) twice per revolution. An illustration of this interpretation is given in Figure 2, where a large emitter with parabolic source strength (i.e., $\epsilon(r) \sim 1-r^2/a^2$) is modeled to rotate about a point, giving the projected trajectory of the center as $y(t) = \cos(\omega t)$.

At outer radii, a near-sinusoidal oscillation at frequency ω is seen, corresponding to the observed point moving along the steep

emission profile as the peak approaches and recedes. Looking through the center of rotation (i.e., $r=0$) the peak emission is viewed twice per cycle, giving a 2ω signal. Away from the center of rotation but within the range of the excursion of the emission peak a double-peaked line-integral signal is measured. In this case the peaks are unequally spaced temporally, as the peak is executing a sinusoidal projected trajectory and passes the detector's position only at fixed phases; the relative minima between the unequally-spaced peaks differ in magnitude since the peak moves further from the detector when it is located on the opposite side of the center, thus placing the observation point in a region of diminished emissivity.

The central oscillation in Figure 1 exhibits a constant maximum prior to disruption, corresponding to the repetitive view of the displaced hot center; the progressive decrease of the minimum of the oscillation is due to an increase of the displacement and a resultant excursion to regions of lower emissivity. This is graphically illustrated in Figures 3 and 4, where the source is modeled to execute a spiral trajectory. Figure 3 shows the progressive shift of the emitter away from the center of rotation; Figure 4 shows the line integrals for the projected center trajectory indicated by the dotted line, for the case of a large emitter (i.e., neglecting edge effects). Again, sinusoidal oscillations at ω and 2ω are observed at large radii and through the center of rotation respectively; at small, nonzero radii the double-peaked shape is seen whenever the central excursion exceeds the tangent radius of the detector, giving a direct measure of the central

displacement; hence, the magnitude of the central displacement can be determined directly by assuming a rotation of the peak such that the projected radii of the peak at the intensity maxima equal the tangent radii of the detectors. Using this technique, a displacement less than 4 cm is found at 483.13 ms, near 8 cm between 483.15 and 483.20 ms, and 9-10 cm from 483.21 to 483.27 ms. The commencement of the reduction of the peak emissivity as seen at the center (where the effects of the 3ω component should be less prominent) coincides with the approach of the peak emissivity region to the outer radius of the normal mode (near 10 cm) and presumably the radius of $q=1$.

An inward spiral trajectory of the peak after disruption is shown in the relatively small sawtooth of Figure 5, which was seen in a lower temperature (0.9 keV), higher density ($\bar{n} \sim 6 \times 10^{13} \text{ cm}^{-3}$) discharge with no neutral beam injection. The displacement increases from ~ 2 cm at 502.8 ms to ~ 5 cm at 503.35 and ~ 6 cm at 503.8 ms; the peak emissivity region then spirals inward from ~ 5 cm at 505.0 ms to ~ 4 cm at 505.6 ms and ~ 3 cm at 505.9 ms. The disturbance of the outer radii beyond the limit of the initial mode at ~ 8 cm indicates that near the time of disruption the peak region creates a localized protrusion into the previously concentric circular surfaces. The flatness of the traces between peaks following the disruption indicates the absence of the peaked emissivity region along that line of sight; this effect is shown in the simulation of Figure 6, where a small emitter is modeled to spiral outward. When the magnitude of the excursion exceeds the distance between the tangent position of the detector and the

edge of the centered emitter then the emitter disappears from view and the resultant waveforms exhibit flatness at their minima. At detector positions larger than the radius of the small emitter, the approach of the peak can give "spikes" on an otherwise flat waveform. Using the double-peaked structures to determine the position of the center and the commencement of the flatness to indicate the edge of the peak, the radial dimension of the peaked emitting region in Figure 5 can be found to be ~ 4 cm. The onset of disruption at ~ 503.4 ms coincides with the near interception of the radius of the innermost previously undisturbed surface by the center of the peak.

The drop in the sawtooth around 503.3 ms (when the peak is near ~ 5.3 cm) resembles scrape-off of the periphery of the rotating structure, as the successor spikes are of much narrower spatial scale. This scenario is illustrated by the sequence in Figure 7, where the rotating emitting region is modeled to move outward while being "pared" at some fixed radius after which the "shaving" is terminated and the emitter continues to move outward, intruding on the previously unperturbed region.

After reaching some maximum displacement, the trimmed emitter returns to the center of rotation. Figure 8 exhibits the line-integral signals corresponding to the source evolution shown in the previous Figure 7. Visible are exaggerated features of the experimentally observed waveforms.

Figure 9 shows a burst of $m=1$ activity of roughly 7 ms duration which allows the equilibrium to return to nearly its initial state without disruption; the maximum excursion was ~ 3 cm,

which was considerably less than the radial extent of the mode.

The dichotomy of the outcomes of bursts of $m=1$ activity may be related to the extent of the radial excursion of the magnetic axis. If the axis approaches the radius of $q=1$, energy is lost from the center, whereas if the mode decays prior to interaction at $q=1$, considerably less central transport results.

III. DISCUSSION

The persistence of the central region of peaked emissivity through the internal disruption and the subsequent inward spiral of the pared filament illustrates the inadequacy of the traditional model in explaining the final stages of the sawtooth in some circumstances. A mechanism which limits the extent of reconnection seems to be capable of arresting the outward motion of the magnetic axis toward the X-point and restoring the surfaces to their original topology, rather than permitting the annihilation of the primal axis.

IV. ACKNOWLEDGEMENTS

The authors express their indebtedness to Dr. D. Monticello and R. White for trenchant theoretical discussion, and especially to the late Dr. Bruce Waddell, two of whose last efforts were considerations of partial reconnection and the modifications of the sawtooth repetition rate mentioned in this paper.

This work was supported by the U.S. Department of Energy Contract No. EY-76-C-02-3073.

References

1. VON GOELER, S., STODIEK, W., and SAUTHOFF, N., Phys. Rev. Lett. 33, 1201 (1974).
2. WHITE, R. B., MONTICELLO, D. A., ROSENBLUTH, M. N., and WADDELL, B. V., Berchtesgaden IAEA Conference, Paper I, 569 (1976).
3. WADDELL, B. V., JAHNS, G. L., CALLEN, J. D., and HICKS, H. R., Nucl Fus. 18, 735 (1978).
4. JAHNS, G. L., SOLER, M., WADDELL, B. V., CALLEN, J. D., and HICKS, H. R., Nucl. Fus. 18, 609 (1978).
5. MCGREGOR, K., and ROBINSON, D., C., Nucl. Fus. 19, 505 (1979).
6. SAUTHOFF, N. R., VON GOELER, S. EAMES, D. R., and STODIEK, W., Bull. Am. Phys. Soc. 23, 830 (1978).
7. TAIT, G. D., BOYD, D., and BRETZ, N., *ibid.*, 774 (1978).

793108

Fig. 1. Experimentally observed line-integrated x-ray emissivities along chords vertically displaced by 4 cm, showing precursor and successor oscillations of an internal disruption.

793159

Fig. 2. Simulated line-integrated emissivities for a large emitter displaced by 10 cm from the center of rotation. Dotted line indicates temporal evolution of projected radius of the center of the emitter. Double frequency components are apparent on detectors with tangent radii inside the region of central excursion.

CONSTANT-SIZE EMITTER
GROWING DISPLACEMENT

Fig. 3. Model of the outward motion of the emitter. Rotation about the original center has been suppressed.

793162

793161

Fig. 4. Projections of the emission and the trajectory of the peak of emissivity for a rotation of the outwardly moving emitter of previous figure. The onset of the double-peaked waveform at the interception of the displacement and the tangent radius of the detector is apparent.

793109
 Fig. 5. Experimentally observed line-integrated x-ray emissivities during an internal disruption, illustrating the survival and inward spiral trajectory of the pared filament after disruption.

793158
Fig. 6. Simulation of the effects of finite size for an outwardly spiraling emitter.

Shrinking Emitter With Finite Minimum Size

INTERNAL DISRUPTION PARTIAL RECONNECTION

793164

Fig. 7. Model for internal disruption, illustrating the outward motion of the hot center with "scrape-off" at some radius, followed by the continued progression and subsequent recession of the original central region after termination of the "peeling."

793160

Fig. 8. Simulated projected emissions and central trajectory for the model illustrated in the previous figure, including rotation.

793110

Fig. 9. Experimentally observed line-integral emissions for a burst of $m = 1$ activity, seemingly without disruption.

EXTERNAL DISTRIBUTION IN

ALL CATEGORIES

R. Askew, Auburn University, Alabama
 S. T. Wu, Univ. of Alabama
 Geophysical Institute, Univ. of Alaska
 G. L. Johnston, Sonoma State Univ., California
 H. H. Kuehl, Univ. of S. California
 Institute for Energy Studies, Stanford University
 H. D. Campbell, University of Florida
 N. L. Oleson, University of South Florida
 W. M. Stacey, Georgia Institute of Technology
 Benjamin Ma, Iowa State University
 Magne Kristiansen, Texas Tech. University
 W. L. Wiese, Nat'l Bureau of Standards, Wash., D.C.
 Australian National University, Canberra
 C. N. Watson-Munro, Univ. of Sydney, Australia
 F. Cap, Inst. for Theo. Physics, Austria
 Ecole Royale Militaire, Bruxelles, Belgium
 D. Palumbo, C. European Comm. B-1049-Brussels
 P. H. Sakanaka, Instituto de Fisica, Campinas, Brazil
 C. R. James, University of Alberta, Canada
 T. W. Johnston, INRS-Energie, Varennes, Quebec
 H. M. Skarsgard, Univ. of Saskatchewan, Canada
 Librarian, Culham Laboratory, Abingdon, England (2)
 A. M. Dupas Library, C.E.N.-G, Grenoble, France
 Central Res. Inst. for Physics, Hungary
 R. Shingal, Meerut College, India
 A. K. Sundaram, Phys. Res. Lab., India
 M. Naraghi, Atomic Energy Org. of Iran
 Biblioteca, Frascati, Italy
 Biblioteca, Milano, Italy
 G. Rostagni, Univ. Di Padova, Padova, Italy
 Preprint Library, Inst. de Fisica, Pisa, Italy
 Library, Plasma Physics Lab., Gokasho, Uji, Japan
 S. Mori, Japan Atomic Energy Res. Inst., Tokai-Mura
 Research Information Center, Nagoya Univ., Japan
 S. Shioda, Tokyo Inst. of Tech., Japan
 Inst. of Space & Aero. Sci., Univ. of Tokyo
 T. Uchida, Univ. of Tokyo, Japan
 H. Yamato, Toshiba R. & D. Center, Japan
 M. Yoshikawa, JAERI, Tokai Res. Est., Japan
 N. Yajima, Kyushu Univ., Japan
 R. England, Univ. Nacional Auto-noma de Mexico
 B. S. Liley, Univ. of Waikato, New Zealand
 S. A. Moss, Saab Univas Norge, Norway
 J. A. C. Cabral, Univ. de Lisboa, Portugal
 O. Petrus, A.L.I. CUZA Univ., Romania
 I. de Villiers, Atomic Energy Bd., South Africa
 A. Maurech, Comisaria De La Energy y Recursos
 Minerales, Spain
 Library, Royal Institute of Technology, Sweden
 Cen. de Res. En Phys. Des Plasmas, Switzerland
 Librarian, For-Instituut Voor Plasma-Fysica, The
 Netherlands
 V. E. Golant, A.F. Ioffe Physical-Tech. Inst., USSR
 B. B. Kadomtsev, Kurchatov Inst. of Atomic Energy,
 USSR
 The Kharkov Physical-Tech. Inst., USSR
 M. S. Rabinovich, Academy of Sci., USSR

ADDITION TO THE 1979

Heidelberg, Stuttgart, West Germany
 R. D. Buhler, Univ. of Stuttgart, West Germany
 Max-Planck-Inst. fur Plasmaphysik, W. Germany
 Nucl. Res. Estab., Jülich, West Germany
 K. Schindler, Inst. Fur Theo. Physik, W. Germany

EXPERIMENTAL THEORETICAL

M. H. Brennan, Flinders Univ. Australia
 H. Barnard, Univ. of British Columbia, Canada
 S. Screenivasan, Univ. of Calgary, Canada
 J. Radet, C.E.N.-B.P., Fontenay-aux-Roses, France
 Prof. Schatzman, Observatoire de Nice, France
 S. C. Sharma, Univ. of Cape Coast, Ghana
 R. N. Aiyer, Laser Section, India
 B. Buti, Physical Res. Lab., India
 L. K. Chavda, S. Gujarat Univ., India
 I. M. Las Das, Banaras Hindu Univ., India
 S. Cuperman, Tel Aviv Univ., Israel
 E. Greenspan, Nuc. Res. Center, Israel
 P. Rosenau, Israel Inst. of Tech., Israel
 Int'l. Center for Theo. Physics, Trieste, Italy
 I. Kawakami, Nihon University, Japan
 T. Nakayama, Ritsumeikan Univ., Japan
 S. Nagao, Tohoku Univ., Japan
 J. I. Sakai, Toyama Univ., Japan
 S. Tjøtta, Univ. I Bergen, Norway
 M. A. Hellberg, Univ. of Natal, South Africa
 H. Wilhelmson, Chalmers Univ. of Tech., Sweden
 Astro. Inst., Sonnenborgh Obs., The Netherlands
 N. G. Tsintsadze, Academy of Sci GSSR, USSR
 T. J. Boyd, Univ. College of North Wales
 K. Hubner, Univ. Heidelberg, W. Germany
 H. J. Kaeppler, Univ. of Stuttgart, West Germany
 K. H. Spatschek, Univ. Essen, West Germany

EXPERIMENTAL ENGINEERING

B. Grek, Univ. du Quebec, Canada
 P. Lukac, Komenského Univ., Czechoslovakia
 G. Horikoshi, Nat'l Lab for High Energy Physics,
 Tsukuba-Gun, Japan
 V. A. Glukhikh, D.V. Efremov Sci.
 Res. Institut. of Elect. App., USSR

EXPERIMENTAL

F. J. Paoloni, Univ. of Wollongong, Australia
 J. Kistemaker, For Inst. for Atomic
 & Molec. Physics, The Netherlands

THEORETICAL

F. Verheest, Inst. Vor Theo. Mech., Belgium
 J. Teichmann, Univ. of Montreal, Canada
 T. Kahan, Univ. Paris VII, France
 R. K. Chhajlani, India
 S. K. Trehan, Panjab Univ., India
 T. Namikawa, Osaka City Univ., Japan
 H. Narumi, Univ. of Hiroshima, Japan
 Korea Atomic Energy Res. Inst., Korea
 E. T. Karlson, Uppsala Univ., Sweden
 L. Stenflo, Univ. of UMEA, Sweden
 T. R. Saraf, New Univ., United Kingdom