PPPL-2023

FISHBONES AND INTERNAL KINKS

H. Strauss*, W. Park, D. Monticello, R. Izzo,
R. White, K. McGuire, J. Manickam, and R. Goldston

PPPL--2023

DE83 016331

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08544

July 1983

ABSTRACT

The internal-kink mode, combined with neutral-beam heating and beam losses, appears to be responsible for the fishbone soft X-ray oscillations in PDX. Nonlinear simulations of both ideal and resistive kinks are presented and shown to be consistent with experimental observations. The internal kink may also be important in low-beta internal disruptions.

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available copy to permit the broadest possible availability.

*Permanent address: Courant Institute of Mathematical Sciences, New York University, New York, NY 10012

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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Fishbones^{1,2} are soft X-ray signals observed during high neutral beam power experiments in PDX. The temperature and magnetic fluctuations appear to be produced by internal kink modes, in conjunction with an anomalous loss of beam particles, caused by the magnetic perturbations.³ The experimental results and the beam loss mechanism, a resonant trapped particle drift effect, are described in detail in Refs. 1 and 3. The present report concentrates on the finite beta stability and nonlinear evolution of the internal kink mode.

The numerical results described here give the following picture of the role of the internal kink mode in the experiment. The internal kink is unstable in a range $q_c < q_0 < 1$, with growth rate increasing with beta in the regime of interest, where q_0 is the inverse rotational transform at the magnetic axis. Initially, q_0 is greater than unity. Due to the beam heating and the usual tokamak thermal instability, beta increases and q_0 falls below unity, so that the plasma becomes internal kink unstable. During the nonlinear motion, part of the beam is ejected, roughly balancing the injection rate, and a dynamic equilibrium is set up. Finally, q_0 drops below the unstable range for the internal kink, and the slower resistive kink occurs, reconnecting and returning the plasma near its initial state with $q_0 > 1$. The reconnection is observed as the well-known soft X-ray sawtooth.^{1,4,5} The whole process is then repeated. Experimentally, several soft X-ray bursts, occur between sawteeth.¹ These bursts are called fishbones. The occurrence of fishbones, as a function of beta and q_0 , is correlated with internal kink instability.² The computations of internal kink stability were made with the PEST code, using profiles similar to the measured ones. The linear growth rates were consistent with the fishbone rise time.⁶

Nonlinear computations of the internal kink mode were performed with the HIB large aspect ratio, high beta tokamak⁷ code. The ordering in beta and

aspect ratio are not well-justified for PDX, but the numerical results appear qualitatively correct. Figure 1 shows HIB linear stability results, for a class of equilibria, generated from axial current and pressure profiles of the form

$$J_z = 2\epsilon B_0 / (q_0 a) [1 - (z/a)^2]$$

$$P = 1/2 \beta B_0^2 [1 - (r/a)^2]^2$$

where a is the radius of the conducting, fixed boundary, $\epsilon = a/R$, where R is the major radius, and B_0 is the magnetic field strength. The effects of rotation are neglected. The figure shows contours of constant growth rate, with no contours plotted for stable modes. The vertical axis is $\beta_p \epsilon = \beta q_0^2 / \epsilon$, and the horizontal axis is nq_0 , where n is the toroidal mode number, plotted logarithmically to emphasize the region below $nq_0 = 1$. The internal kink modes, with $nq_0 < 1$, are clearly separated from the ballooning modes, with large nq_0 . The internal kink modes, like the ballooning modes, have a threshold in beta.⁸⁻¹⁰ However, the stability at low beta in Fig. 1 may be an effect of resolution, since the code cannot measure accurately growth rates of order $10^{-3} c_A / q_0 R$, where $c_A = B_{0p}^{-1/2}$, the Alfvén speed. Typical internal kink growth rates are of order $10^{-2} c_A / q_0 R$, while ballooning growth rates are of order $10^{-1} c_A / q_0 R$. In general, the high beta tokamak ordering is not adequate^{11,12} to describe correctly internal kinks for $\beta \sim \epsilon^2$. However, in the beta range of interest, near the threshold for ballooning modes, the high beta ordering has been found reasonably reliable.⁷

To attempt to model the beam heating and perturbation dependent beam losses, the pressure equation was taken of the form

$$\frac{d}{dt} P = \gamma_h P + \kappa_{\perp} v^2 P + \kappa_{\parallel} (B \cdot \nabla)^2 P / B_0^2$$

where γ_h is the heating rate, $\kappa_{\parallel}$ is the parallel thermal conductivity (with density taken constant); and the perpendicular thermal conductivity has the form

$$\kappa_{\perp} = \kappa_{\perp 0} + \kappa_{\perp 1} \langle |\nabla \tilde{A}_z|^2 \rangle$$

where $\kappa_{\perp 0}$, $\kappa_{\perp 1}$ are constants, $\tilde{A}_z$ is the part of the toroidal vector potential for which the average over toroidal angle vanishes, and the bracket denotes an average over angle. The nonlinear term is proportional to the squared perturbed magnetic field, and might be obtained by a perturbative treatment of the parallel thermal conductivity term.¹³ The precise form of this term is not important, merely the fact that it increases with the size of the magnetic perturbations. The most likely explanation of the beam loss is not really a diffusion process at all, but a resonant $\vec{E} \times \vec{B}$ drift of trapped beam ions in the perturbed magnetic field.³ However, despite the limitations of the present model, it appears to describe the essentials of the heating and loss process.

In nonlinear computations, γ_h and $\kappa_{\perp}$ were chosen roughly in balance, so that if $\kappa_{\perp 1} = 0$, γ_h would raise the pressure by about 10% during a nonlinear oscillation, consistent with experiment. The constants $\kappa_{\perp 0}$ and $\kappa_{\perp 1}$ were typically $\kappa_{\perp 0} = 10^{-5} \epsilon a c_A / q_0$, and at the maximum nonlinear excursion $\kappa_{\perp 1} \sim 10 \kappa_{\perp 0}$. The parallel thermal conductivity, necessary to restore the plasma to approximate equilibrium with $B \cdot \nabla P \approx 0$ was typically $\kappa_{\parallel} \sim 10^{-1} q_0 R c_A$.

Figure 2 shows equilibrium contours of the pressure, with $\beta_p \epsilon = 0.2$, and

the profiles mentioned earlier. With $nq_0 = 0.9$, the internal kink growth rate is $0.03 c_A/(q_0 R)$. Figure 3 shows a nonlinear $nq_0 = 0.9$ internal kink mode, near saturation, with the pressure model described above. The cross section is shown in a plane constant toroidal angle. The plasma "bounces" off the $q = 1$ rational surface and returns toward the initial state. Figure 4 shows the position of the magnetic axis in the same plane as Fig. 3, as a function of time. The axis undergoes a nonlinear oscillation around the initial state. The nonlinear motion produces pressure fluctuations consistent with the fishbone soft X-ray measurements.

The transport terms in the pressure equation, besides helping to model the heating and loss, tend to reduce the amplitude of the nonlinear oscillations, since a large amplitude driven loss reduces the instability driving term. This, of course, is a great aid to numerical computation, since a saturated state of the internal kink mode without loss terms has a singular structure,¹⁴ which requires special techniques¹⁵ to resolve. It has so far not been possible to follow a bounce numerically without transport terms.

In the nonlinear computation described above, a resistivity $\eta = 10^{-6} \epsilon c_A/q_0$ was included, and evidently did not cause reconnection. At higher beta, with higher growth rate, reconnection did not occur even with $\eta = 10^{-5} \epsilon c_A/q_0$. Hence, as long as the bounce time scale is shorter than the reconnection time scale, reconnection is inhibited. When q_0 is sufficiently low, the internal kink is stable, and only the resistive kink can be unstable. At $\beta_p \epsilon = 0.2$, this occurs when $nq_0 < 0.75$. Figure 5 gives an example of a nonlinear resistive kink, with $\beta_p \epsilon = 0.2$, $nq_0 = 0.8$, $\eta = 10^{-5} \epsilon c_A/q_0$, showing pressure contours. The effect of reconnection gives a strikingly different picture from Fig. 3.

In summary, the role of the internal kink in high beta PDX discharges has

been elucidated. The nonlinear motion of the internal kink mode combined with a nonlinear pressure loss can lead to oscillations that are similar to the experimentally observed fishbones. The amplitude of the computed magnetic fluctuations is sufficient, according to Ref. 3, to produce the experimentally observed loss of beam particles.

Our computations have not included the mode rotation, which produces the fishbone fine structure. The rotation frequency appears to be due to the toroidal precession of the energetic beam particle banana orbits.^{3,16}

The present calculations are not valid for $\beta \sim \epsilon^2$, but we conjecture that at low beta, similar effects occur. The internal kink has been calculated to be unstable for $\beta_p > 0.3$, in a range of q_0 similar to that found here. If the internal kink is unstable at low beta, it would prevent reconnection until q_0 drops sufficiently low to stabilize the mode. The plasma would then reconnect abruptly, once q_0 falls below the critical value. The "precursor oscillations" to the sawtooth may be low amplitude internal kinks. Nonlinear internal kink modes,⁵ besides producing fishbone, may thus also play an important role in low beta internal disruptions. We plan to test this hypothesis, and include finite ϵ effects, using a more accurate numerical code.¹²

ACKNOWLEDGMENTS

This work supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

REFERENCES

- ¹ K. McGuire et al., Phys. Rev. Lett. 50, 891 (1983).
- ² D. Johnson et al., in Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (in press).
- ³ R. B. White, R. J. Goldston, K. McGuire, A. H. Boozer, D. A. Monticello, and W. Park, Princeton Plasma Physics Laboratory Report No. PPPL-1992, 1983; Phys. Fluids (to be published).
- ⁴ S. von Goeler, W. Stodiek, and N. R. Sauthoff, Phys. Rev. Lett. 33, 1201 (1974).
- ⁵ R. B. White, D. A. Monticello, M. N. Rosenbluth, and B. V. Waddell, Phys. Fluids 20, 800 (1977).
- ⁶ D. A. Monticello, Bull. Am. Phys. Soc. 27, 986 (1982).
- ⁷ H. R. Strauss, W. Park, D. A. Monticello, R. B. White, S. C. Jardin, M. S. Chance, A. M. M. Todd, and A. H. Glasser, Nucl. Fusion 20, 628 (1980).
- ⁸ M. N. Bussac, R. Pellat, D. Edery, and J. L. Soule, Phys. Rev. Lett. 35, 1638 (1973).
- ⁹ W. Kerner, R. Gruber, and F. Trogen, Phys. Rev. Lett. 44, 536 (1980).
- ¹⁰ S. Tokuda, T. Tsunematsu, M. Azumi, T. Takizuka, and T. Takeda, Nucl. Fusion 22, 661 (1982).
- ¹¹ G. B. Crew and J. J. Ramos, Phys. Rev. A26, 1149 (1982).
- ¹² R. Izzo, D. A. Monticello, H. R. Strauss, W. Park, J. Manickam, R. C. Grimm, and J. DeLucia, Phys. Fluids (to be published).
- ¹³ R. D. Hazeltine, and H. R. Strauss, Phys. Rev. Lett. 37, 102 (1978).
- ¹⁴ M. N. Rosenbluth, R. Y. Dagazian, and P. H. Rutherford, Phys. Fluids 16, 1894 (1973).

- 15 W. Park, D. A. Monticello, R. B. White, and S. C. Jardin, Nucl. Fusion 20,
1181 (1980).
- 16 M. N. Rosenbluth (private communication).

FIGURE CAPTIONS

FIG. 1. Contours of constant growth rate γ in $\beta_p \epsilon$, nq_0 plane. The horizontal axis is logarithmic to emphasize $nq_0 < 1$. Ballooning modes, with $nq_0 > 1$, have large growth rates compared to internal kinks, with $nq_0 < 1$.

FIG. 2. Pressure contours of an equilibrium with $\beta_p \epsilon = 0.2$.

FIG. 3. Pressure contours in a poloidal plane, near nonlinear saturation of internal kink.

FIG. 4. Position of the magnetic axis in the same plane as the previous figure, as a function of time, showing a complete nonlinear oscillation. Figures 2 and 3 correspond to the initial and final positions of the axis.

FIG. 5. Pressure contours during reconnection of resistive kink with $nq_0 = 0.8$.

#83T0195

Fig. 1

#83TCI98

Fig. 2

#83T0197

Fig. 3

Fig. 4

#83T0199

$$nq_0 = 0.8$$

Fig. 5

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austro 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. C. Cao, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. C. Petrucci, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakenaka, Univ Estadual, BRAZIL
 Dr. C.P. James, Univ of Alberta, CANADA
 Prof. J. Telchewski, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Greenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Bernard, Univ British Columbia, CANADA
 Dr. W.P. Bachynski, MPB Technologies, Inc., CANADA
 Zhongguo Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, SW Inst Physics, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Redet, CEN-BP6, FRANCE
 AN Dupes Library, AM Dupes Library, FRANCE
 Dr. Tom Muai, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. A.K. Sundaram, Physical Research Lab, INDIA
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra, Mohan Lal Das, Benares Hindu Univ, INDIA
 Dr. L.K. Chavda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Mera, INDIA
 P. Kew, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rossetti, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Ciella De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sideru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. Enoland, Ciudad Universitaria, MEXICO
 Bibliotheek, Fon-inst Voor Plasma, NETHERLANDS
 Prof. B.S. Lilov, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Calais, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Dr. R. Jones, Nat'l Univ Singapore, SINGAPORE
 Prof. M.A. Mollera, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Dr. J.A. Tadie, IFN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weise, Nat'l Bur Stand, USA
 Dr. W.M. Steacy, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Prof. Norman L. Olsson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Prof. Magna Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. M.S. Rabinovich, Lebedev Physical Inst, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Kneopler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY