vide fresh stimulus for theoretical development. Experimental work is continuing on alkali and rare-gas systems.

This work is supported by the Office of Naval Research under Contract NOO14-78C-0823.

[(a)]Permanent address: Institut d'Electronique Fondamentale, Bât. 220, Université de Paris, Faculté d'Orsay, F-91405 Orsay, France.

[1]T. F. George, I. H. Zimmerman, P. L. DeVries, J. M. Yuan, K. S. Lam, J. C. Bellum, H. W. Lee, M. A. Slutsky, and J. T. Lin, in *Chemical and Biochemical Applications of Lasers*, edited by C. B. Moore (Academic, New York, 1979), pp. 253–354.

[2]A. M. F. Lau, Phys. Rev. A 18, 172 (1978), and references cited therein.

[3]S. Yeh, P. R. Berman, Phys. Rev. Lett. 43, 848 (1979).

[4]R. W. Falcone, W. R. Green, J. C. White, J. F. Young, and S. E. Harris, Phys. Rev. A 15, 1333 (1977).

[5]W. R. Green, J. Lukasik, J. R. Willison, M. D. Wright, J. F. Young, and S. E. Harris, Phys. Rev. Lett. 42, 970 (1979).

[6]P. L. Cahuzac and P. E. Toschek, Phys. Rev. Lett. 40, 1087 (1978).

[7]A. V. Hellfeld, J. Caddick, and J. Weiner, Phys. Rev. Lett. 40, 1369 (1978).

[8]A. M. F. Lau, Phys. Rev. Lett. 43, 1009 (1979).

[9]J. Weiner, J. Chem. Phys. 72, 2856 (1980).

[10]T. B. Lucatorto and T. J. McIlrath, Phys. Rev. Lett. 37, 428 (1976).

[11]P. Polak-Dingels and J. Weiner, to be published.

[12]J. N. Bardsley, B. R. Junker, and D. W. Norcross, Chem. Phys. Lett. 37, 502 (1976).

[13]C. J. Cerjan, K. K. Docken, and A. Dalgarno, Chem. Phys. Lett. 38, 401 (1976).

[14]K. Kirby-Docken, C. J. Cerjan, and A. Dalgarno, Chem. Phys. Lett. 40, 205 (1976).

[15]A. Herrmann, S. Leutwyler, E. Schumacher, and L. Wöste, Helv. Chim. Acta. 61, 453 (1978).

[16]D. L. Feldman, Ph.D Thesis, Columbia University, University Microfilm Int. Ann Arbor, Michigan, 1978 (unpublished).

[17]W. Demtröder and M. Stock, J. Mol. Spectrosc. 55, 476 (1975).

[18]P. Kusch and M. M. Hessel, J. Chem. Phys. 68, 2591 (1978).

# Major Disruptions in the TOSCA Tokamak

K. M. McGuire
*Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540*

and

D. C. Robinson
*EURATOM–United Kingdom Atomic Energy Authority Fusion Association, Culham Laboratory, Abingdon, Oxon OX14 3DB, United Kingdom*

(Received 27 December 1979)

The major disruption has been studied in detail on the TOSCA tokamak with the use of approximate helical coils. The $m=3$, $n=2$ and $m=5$, $n=3$ modes have been clearly observed for the first time before a major disruption. The amplitude of the $m=2$, $n=1$ mode at the rational surface is about 4% and the $m=3$, $n=2$ mode amplitude ~4.5% before a major disruption. When the $m=2$, $n=1$ and $m=3$, $n=2$ approximate helical coils are energized with large coil currents, a major disruption occurs.

PACS numbers: 52.55.Gb

Further improvements of plasma parameters in present-day tokamak devices are limited by the major disruption.[1] In the next generation of tokamaks, the major disruption can be a severe problem because large forces and voltages are generated by the sudden decrease in plasma current following the disruption. An understanding and a means of controlling this dangerous instability is therefore very important for the future of the tokamak device.

TOSCA is a small air-core tokamak, which can produce noncircular plasmas.[2] The major radius of the vacuum vessel is 30 cm and the minor radius 10 cm. Central electron temperatures of 300 eV and central electron densities of $3\times10^{13}$ cm$^{-3}$ are routinely obtained, with a plasma current of 12 kA, a loop voltage of 2.5 V and a safety factor at the edge of the plasma, $q_a$, of 3.5.

A series of large saddle coils were used to detect the helical radial field perturbations produced by different instabilities. For the perturbations with poloidal mode number $m=3$ and toroidal mode number $n=2$ each quadrant of the torus was fitted with six windings which are positioned to produce an accurate hexapole field in the torus with an aspect ratio of 3. Each pair of windings is then connected to form a loop or saddle coil which is then connected to the saddle coil on the next quadrant at a poloidal angle of 60° to the first. Twelve saddle coils are connected in this way so that they have no net helicity and an effective coil area of $\sim 1\ m^2$. Four such saddle coils on two halves of the torus suffice to detect and generate a perturbing field with $m=2$ and $n=1$. The coils were used in two ways, first as passive coils to detect particular mode structures and second, as active coils to produce a helical radial field which results in the formation of magnetic islands with the same toroidal structure as the coil.

The winding performance was checked by measuring the azimuthal variation of the poloidal field generated by the coils and comparing this with 3D magnetic field computations: The agreement was good. The helical fields penetrate through the vacuum vessel and into the plasma in a few 100 $\mu$s for the plasma parameters in this experiment.

With use of the approximate $m=3$, $n=2$, $n=1$ coils, the major disruption was studied in detail. A high-frequency mode was detected on the $\frac{3}{2}$ coil[3] with large amplitude just before the major disruption. This mode is shown in Fig. 1 along with the $\frac{2}{1}$ mode. The amplitude of the $\frac{2}{1}$ mode reaches a value with $\tilde{B}_r/B_\theta \approx 4\%$ before the disruption, (assuming $q=2$ at 6 cm, and $\tilde{B}_r$ is the perturbed radial field). It has previously been established from probe measurements that the $\frac{2}{1}$ mode is a resistive tearing mode.[4] During the last 40 $\mu$s the $\frac{3}{2}$ mode grows rapidly in amplitude and reaches a level with $\tilde{B}_r/B_\theta \approx 4.5\%$ (assuming $q=\frac{3}{2}$ at 4 cm). The $H_\alpha$ light emission is shown, and it is clear that the level does not change before the disruption provided the plasma is well centered. The central channel of a soft x-ray array is also shown in the figure. The x-ray emissivity starts to fall when the $m=2$ amplitude reaches 2% ($\tilde{B}_r/B_\theta \sim 2\%$), and the $m=2$ mode is clearly observed. This soft x-ray signal is filtered to give frequencies between 10–100 kHz only. Detailed investigation of the soft x-ray signals also reveals the presence of the $\frac{3}{2}$ mode.

The general characteristics of the $\frac{3}{2}$ mode are demonstrated in Fig. 1. The frequency of the $\frac{3}{2}$ mode is about twice the frequency of the $\frac{2}{1}$ mode (this has a frequency of about 50 kHz which is close to the electron diamagnetic drift frequency). The growth rate of the $\frac{3}{2}$ mode is approximately three times faster than the $\frac{2}{1}$ mode. The amplitude of the $\frac{3}{2}$ mode decreases about 10 $\mu$s before the disruption which appears to be correlated

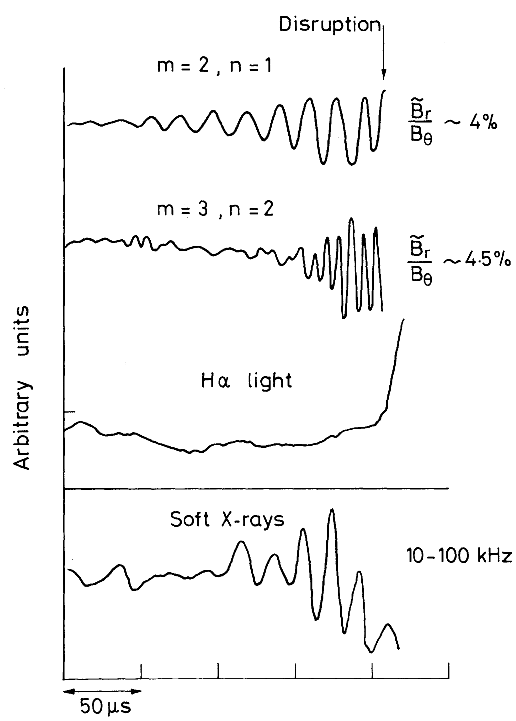


FIG. 1. Evolution of the $m=2$, $n=1$ and $m=3$, $n=2$ modes at a major disruption, together with the $H\alpha$ light and the soft x-ray central channel emission. The arrow indicates the time of disruption.

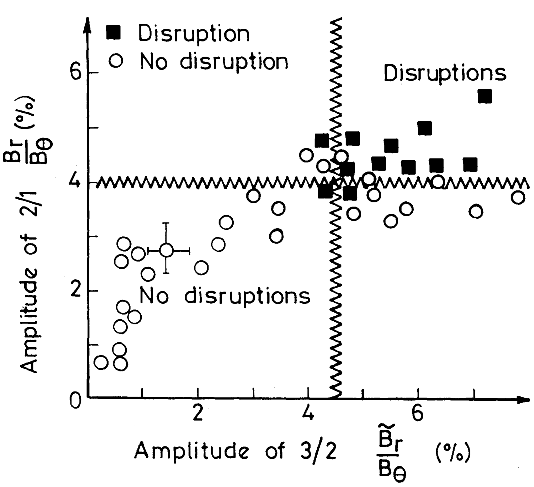


FIG. 2. The amplitudes of the $\frac{2}{1}$ and $\frac{3}{2}$ modes necessary for a major disruption.

with the presence of other modes. Further investigations have shown that modes with $m=5$ and $n=3$ and also $m=8$, $n=3$ are present in the last 10 $\mu$s before the major disruption. The strength of the disruption is correlated with the higher mode number activity. No doubt other modes may be present seeming to indicate that the plasma is turbulent for a short time before disruption. Such activity will permit free magnetic reconnection to occur and the configuration to relax towards a lower or minimum magnetic energy state.

Figure 2 indicates the size of the $\frac{3}{2}$ and $\frac{2}{1}$ radial field perturbations associated with a major disruption. This figure can be used to calculate the size of the magnetic islands present at disruption but care must be exercised because different discharges may possess different current profiles. It is clear from the experiments that when the $\frac{2}{1}$ mode exceeds a certain amplitude, a $\frac{3}{2}$ mode is generated and this may lead to a major disruption. For a major disruption the critical amplitude of the $\frac{2}{1}$ mode is $\tilde{B}_r/B_\theta \approx 4\%$ and of the $\frac{3}{2}$ mode is $\tilde{B}_r/B_\theta \approx 4.5\%$. For any reasonable current profile these values of $\tilde{B}_r/B_\theta$ imply that the resultant magnetic islands have overlapped.

The $\frac{2}{1}$ and $\frac{3}{2}$ modes are always observed before a soft or major disruption for circular, triangular, and elliptical plasmas. For triangular and elliptical plasmas the amplitude of the $\frac{2}{1}$ and $\frac{3}{2}$ modes are somewhat different from those shown in Fig. 2, but the general pattern of the $\frac{2}{1}$ and $\frac{3}{2}$ mode production and interaction is the same as for circular plasmas.

A recent theory[5] suggests that the $\frac{2}{1}$ and $\frac{3}{2}$ modes may play an important part in the disruptive process. The disruptive instability is thought to be produced by a large $\frac{2}{1}$ magnetic island, which may interact with the $\frac{3}{2}$ island or with the limiter (or cold gas).[6,7]

Because of the possible importance of the $\frac{3}{2}$ mode in the disruptive process on the TOSCA device, it was considered essential to test whether a major disruption could be produced by activating the external saddle coils. When both the $\frac{2}{1}$ and $\frac{3}{2}$ coils are activated, at different times to allow for the different field penetration times, with large coil currents, ($I_{m=2}=3$ kA, $I_{m=3}=4$ kA, $I_p=12$ kA), a major disruption occurs depending on the position of the plasma. The quadrupole and hexapole fields are only accurate if the plasma is well centered in the vacuum vessel, so the resultant island sizes are sensitive to plasma position. A feature of these artificially produced disruptions is that they occur very rapidly and the larger the growth rate of the modes the more severe the disruption. Growth times down to 25 $\mu$s for the $\frac{2}{1}$ mode have been measured. When both the $\frac{3}{2}$ and $\frac{2}{1}$ coils are activated together they are 70% effective in producing a major disruption, the remaining 30% are soft disruptions. The $\frac{2}{1}$ coil alone is 50% effective.

From the attempts to produce a major disruption, a stabilization of the $\frac{2}{1}$ mode was observed when the $\frac{2}{1}$ coil alone was activated with low coil current.[4] The major disruption on the TOSCA device can also be delayed by activation of this $\frac{2}{1}$ coil.[8] Production of major disruptions with these helical coils shows that it is easier to obtain a major disruption with both the $\frac{2}{1}$ and $\frac{3}{2}$ coils activated together. Field line tracing calculations for the actual equilibria with the appropriate helical windings show large distorted magnetic islands with large ergodic regions.

A study of disruptions caused by interaction of the plasma with the vacuum vessel wall either associated with incorrect vertical field control or positional instabilities has been made. It was observed that the effect of the plasma touching the walls was to increase the $\frac{2}{1}$ and $\frac{3}{2}$ mode activity promoting the tendency to disrupt. The $H_\alpha$ and 3845-Å impurity light did not increase dramatically until after the negative voltage spike occurred. A double Langmuir probe was also used to detect activity at the plasma boundary. The probe did not detect any significant change until after the disruption. From these experiments, it appears that the major disruption is due to mode interaction or overlap of mangetic islands.

These experiments show that the soft or major disruption is associated with a growing $m=2$, $n=1$ mode which, at a critical amplitude, leads to the rapid growth of an $m=3$, $n=2$ mode. This occurs for circular, elliptical and triangular cross-sectioned plasmas. The production of a rapid, more severe major disruption is possible by the creation of magnetic islands with mode numbers $\frac{2}{1}$ and $\frac{3}{2}$. A study of the interaction of the plasma with the wall shows that the disruption is due to an internal interaction in the plasma. The detection of the $\frac{3}{2}$, $\frac{2}{1}$ and the observation of $\frac{5}{3}$ and $\frac{8}{3}$ modes just before disruption indicates that the internal interaction involves many modes of different helicity.

[1]B. B. Kadomtsev, Fiz. Plazmy 1, 710 (1975) [Sov. J. Plasma Phys. 1, 389 (1975)].

[2]K. M. McGuire, D. C. Robinson, and A. J. Wootton, in *Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978* (International Atomic Energy Agency, Vienna, 1979), Vol. 1, p. 339.

[3]K. M. McGuire and D. C. Robinson, in *Proceedings of the Ninth European Conference on Controlled Fusion and Plasma Physics, Oxford, England, 1979* (European Physical Society, Geneva, 1979), Vol. 1, p. 93.

[4]D. C. Robinson and K. M. McGuire, Nucl. Fusion 19, 115 (1979).

[5]B. V. Waddell, B. Carreras, H. R. Hicks, and J. A. Holmes, Phys. Fluids 22, 896 (1979).

[6]R. B. White, D. A. Monticello, and M. N. Rosenbluth, Phys. Rev. Lett. 39, 1618 (1977).

[7]R. Pollard, M. Turner, A. Sykes, and J. A. Wesson, Max-Planck-Institut für Plasmaphysik, Garching, Report No. IPP-III/51, 1979 (unpublished).

[8]F. Karger *et al.*, in *Proceedings of the Eighth European Conference on Controlled Fusion and Plasma Physics, Prague, Czechoslovakia, 1977* (European Physical Society, Geneva, 1978), Vol. 1, p. 3; K. Bol *et al.*, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, 1975), Vol. 1, p. 83.

# Time-Resolved X-Ray Spectroscopy of Laser-Produced Plasmas

M. H. Key,[(a)] C. L. S. Lewis, J. G. Lunney, A. Moore, and J. M. Ward
*Queen's University of Belfast, Belfast 1, Northern Ireland*

and

R. K. Thareja
*University of Strathclyde, Glasgow G1 1XW, Scotland*
(Received 31 December 1979)

X-ray emission spectra, produced by irradiation of neon-filled aluminum-coated glass microballoon and plane aluminum targets, with 100-ps Nd-glass laser pulses, have been time resolved with an x-ray streak camera. The time evolution of the Ne X $L\alpha$ and Si XIII $1^1S_0$-$3^1P_1$ linewidths has been recorded. The implosion delay time of microballoon targets and the emission histories of the Al XIII $1^1S_0$-$2^1P_1$ line and its satellites from plane targets have been measured.

PACS numbers: 52.70.-m, 32.30.Rj, 52.50.Jm

Analysis of x-ray emission spectra from laser-produced plasmas has been widely used in diagnosing the plasma parameters.[1-5] Spectra have been either time and space integrated or, more recently, space resolved, e.g., down to a scale of 10 $\mu$m.[4] Development of x-ray streak cameras has made time resolution of spectra possible, in principle, with a resolution down to[6] ps and x-ray continua have been studied in this way.[7] In practice sensitivity restricted the study of dispersed spectra until a high-sensitivity CsI photocathode became available.[8]

We report here results which show the time-resolved line shapes of Ne X $L\beta$ and Na XI $L\alpha$ in glass microballoon implosions and the time-resolved line shapes and intensities of Si XIII $1^1S_0$-$3^1P_1$ and its satellites in surface ablation plasmas.

Experiments were performed with a Nd-glass laser and focusing was by $f/1$ lenses.[8] Spectra were recorded with the apparatus shown in Fig. 1 with typically $L = 20$ cm.[8] Temporal resolution in each case was limited by instrumental sensitivity. Table I lists the laser pulse and instrumental parameters for the three cases discussed

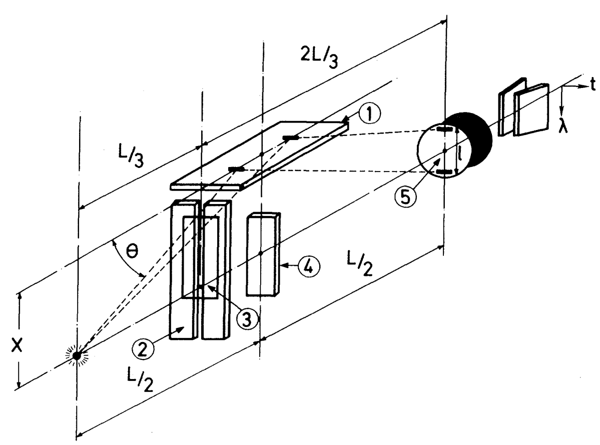


FIG. 1. Experimental arrangement for recording streaked spectra: (1) crystal of thallium-acid-phthalate (TlAP) or pentaerythritol (PET), (2) adjustable entrance slit, (3) beryllium filter, (4) baffle, and (5) CsI photocathode.