NUCLEAR FUSION 18 12 (1978)

RADIAL TRANSPORT OF HIGH-ENERGY RUNAWAY ELECTRONS IN ORMAK

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ABSTRACT. The transport of high-energy runaway electrons near the outside of a low-density ORMAK discharge is investigated by measuring the flux of runaways to the outer limiter during and after an inward shift of the plasma column. The experimental results are interpreted through a runaway confinement model which includes both the classical outward displacement of the runaway orbit with increasing energy and an additional runaway spatial diffusion coefficient which simulates an unspecified source of anomalous transport. Diffusion coefficients in the range $D \cong 10^2 - 10^4$ cm·s^{-1} are found under various discharge conditions indicating a significant non-collisional runaway transport near the outside of the discharge, particularly in the presence of MHD instability.

INTRODUCTION

Runaway electrons can be useful as a natural probe of the single-particle confinement properties of tokamaks. One overall measure of this confinement is readily given by the maximum observed runaway energy. For example, the existence of a substantial number of 10-MeV electrons in ORMAK [1,2] directly implies that these particles can be accelerated freely and contained for nearly the duration of the discharge ($\gtrsim$ 50 ms). In this case, it is of interest to see whether the radial transport of these runaways agrees in detail with the classical collisionless-particle model as calculated for an ideal (quiescent) tokamak field structure, since any departure from this ideal behaviour directly indicates the presence of an anomalous transport mechanism which may eventually be related to the well-known anomaly in the tokamak's electron energy confinement.

In this paper, we describe an experiment in which high-energy runaway transport was measured by monitoring the flux of runaways to the outer edge of the limiter during and after a programmed inward shift of the plasma column. It was found that the classical model must be supplemented by a runaway diffusion coefficient $D \cong 10^2 - 10^4$ cm^2·s^{-1} in order to explain the observed radial movement of these runaways near the outside of the discharge.

Runaway electron confinement has been studied on several tokamak devices in recent years. On the ST [3] and Pulsator [4] machines a plasma bremsstrahlung technique was used to measure the runaway population below about 1 MeV, and the analysis of these results indicated that this group of runaways could be characterized by a confinement time τ_R comparable to the thermal electron particle confinement time $\tau_P = 5-20$ ms. On the LT-3 tokamak, runaway confinement was studied by means of movable probes inserted into the discharge [5,6], and a runaway diffusion model was developed through which a diffusion coefficient of up to $D \cong 10^4 - 10^5$ cm^2·s^{-1} could be used to describe their observations of rapid runaway loss. Each of these experiments, therefore, indicated that a group of relatively low-energy runaways could experience a substantial non-collisional transport, but the physical mechanism responsible for this transport was not isolated.

On the other hand, the observation of high-energy ($\approx$ 10 MeV) electrons in ORMAK, TFR [7], and PLT [8] implies that $\approx$ 10–100 A of runaway current

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can be confined for times much longer than the overall electron energy containment time ($\tau_E < 5$ ms in ORMAK low-density discharges). This good confinement of high-energy runaways has in some cases been shown to be *consistent* with the behaviour expected for classical collisionless-particle orbits [1], but since these runaways have been detected only after they have left the discharge (and intersected the limiter), a conclusive analysis of the internal radial transport has not yet been achieved.

In particular, the observation of free-fall acceleration of runaways intersecting the limiter may also be partially consistent with a diffusive runaway transport model in which an exponentially small population of high-energy runaways persists in the discharge after $t \gg \tau_R$. This model would imply, however, that for a steady-state situation the *total* runaway population would be much larger than the observed 10–100 A constituting the highest energy component. Again, lack of knowledge concerning the internal runaway distribution function and runaway production rates has made a direct check of this diffusive model of confinement very difficult.

This situation prompted a search for a method by which runaway transport could be measured directly without reference to runaway production rates or to overall runaway confinement in the discharge. The experiment described here used an adaptation of the limiter bremsstrahlung technique to measure the transport of high-energy runaways across a known distance near the outside of the discharge, as described in Section 2 of this paper. The experimental results leading to an estimate of the runaway diffusion coefficient are described in Section 3, and in Section 4 we review some of the possible mechanisms for the observed deviation from the collisionless orbit model. In the last section we discuss the relationship between the results of this experiment and those of other runaway confinement studies.

2. PLASMA SHIFT EXPERIMENT

The present work is based on previous studies of the confinement of high-energy runaways in normal low-density ORMAK discharges [1, 2]. The new feature of this experiment involves a sudden inward shift of the plasma column which enables the subsequent outward movement of the runaways to be directly compared with the predictions of the classical (diffusionless) single-particle drift orbit model.

The high-energy runaway behaviour in low-density ORMAK discharges without an inward plasma shift was described previously [1]. A collimated NaI hard-X-ray bremsstrahlung detection system was used to show that the maximum runaway energy observed at the outer limiter increases at nearly the free-fall rate, such that the overall pattern of runaway loss can be interpreted on the basis of a collisionless drift orbit model. In this model the runaway confinement is determined by the displacement d_γ of the runaway drift surface from the magnetic flux surfaces:

$$\frac{d_\gamma}{r_L} \cong 0.73\, \frac{r_L}{2R_0}\, \frac{I_A}{I}, \quad \text{for } d_\gamma \leqslant r_L/2 \tag{1}$$

where r_L is the limiter radius, R_0 the major radius of the torus, $I_A \cong 17\beta\gamma$ the Alfvén current (in kA) corresponding to a runaway kinetic energy $E = (\gamma - 1)m_0c^2$, and I is the total plasma current (Assuming $I_{\text{runaway}} \ll I$, and a typical low-density ORMAK current profile [1]). The quantities β and γ are the usual relativistic factors. The runaway drift orbit intersects the outer limiter when

$$r_0 + d_\gamma + d_p = r_L \tag{2}$$

where r_0 is the minor radius of the runaway orbit *at intersection with the outer limiter* and d_p is the shift of the outer magnetic flux surfaces from the minor axis of the torus. Note that a diffusive behaviour may be incorporated in this model by allowing the runaway orbit minor radius r_0 to vary over time in a random manner, presumably owing to the effects of perturbing electric or magnetic fields.

The present experiment was designed to measure directly the radial motion of runaways, as shown schematically in Fig.1. A low-current ($I \cong 75$ kA, $B_T = 12$ kG), low-density ($\bar{n}_e \cong 0.5 \times 10^{13}$ cm^{-3}) ORMAK discharge is allowed to evolve normally for about 60 ms, at which time a programmed increase in the vertical field over a period of 10 ms produces an inward shift of the plasma column. During this well-controlled and reproducible shift the plasma current is adjusted to remain constant, the loop voltage varies as shown in the figure, and in most cases the MHD activity (as monitored by $\dot{B}_P$ pick-up loops) remains unchanged. This inward shift of < 4 cm is small enough so that the overall shape of the temperature and density profiles also remains constant during and after the shift. The plasma position d_p was monitored in the usual way using in/out B_P field measurements. The X-ray flux

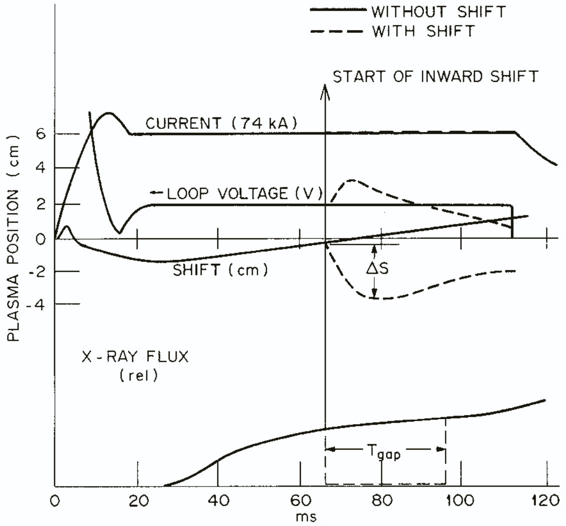

FIG.1. Basic concept of the plasma shift experiment. The measured behaviour of plasma position, loop voltage, and current is shown for a 3.5-cm inward plasma shift. The gap in the hard-X-ray flux at the outer limiter, T_{gap}, is expected on the basis of a diffusionless drift orbit model of runaway confinement.

at the inner limiter was not monitored during these experiments; however, previous results for normal discharges without an inward shift have indicated a negligible runaway flux at the inner limiter.

The runaway behaviour expected in this situation on the basis of the (diffusionless) drift orbit model is shown schematically at the bottom of Fig.1. The inward shift Δs of the plasma current distribution should pull all runaway orbits away from the outer limiter so that the hard-X-ray flux monitored by the collimated detector should fall to zero just after the inward shift. *If* then the plasma is held constant at its new position, these runaways should re-appear at the outer limiter only after they have gained enough additional energy so that the displacement d_γ has increased by Δs. The hard-X-ray flux pattern due to runaways striking the outer limiter should therefore have a "gap" of duration T_{gap}, where

$$T_{gap} = \Delta s \Big/ \frac{d}{dt}\,(d_\gamma) \qquad (3)$$

For I = 75 kA and an average loop voltage of 2V, we find from Eq.(1) (assuming runaway free-fall acceleration), that $d(d\gamma)/dt = 120\ \mathrm{cm \cdot s^{-1}}$. Thus, for a typical shift of $\Delta s = 2$ cm, we expect $T_{gap} = 17$ ms. This is shown schematically by the dotted line at the bottom of Fig.1. Of course, the outward orbit displacement $d_\gamma \cong 5$ cm is large enough for these high-energy runaways that the inward plasma shift should not cause the drift orbits to intersect the inner limiter.

3. EXPERIMENTAL RESULTS

In Fig.2, we show an example of the actual behaviour of the hard-X-ray flux to the outer limiter after inward plasma shifts of Δs = 1.7 and 3.5 cm. The observed gaps in the flux last longer for the larger plasma shifts, as expected on the basis of Eq.(3), but there are evidently some X-rays appearing during T_{gap}, which we attribute to an anomalous diffusion in minor radius of the outer runaway orbits.

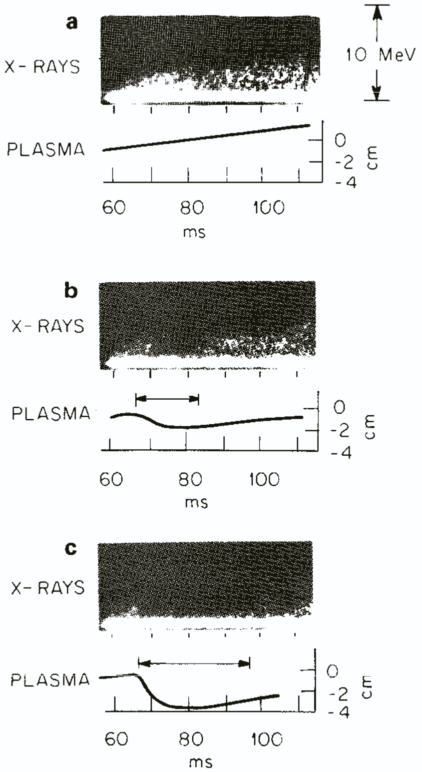

FIG.2. Effect of plasma position shift on scintillator pulse patterns. Photos showing typical patterns of X-rays observed at the outer limiter with (a) no inward shift (top), (b) 1.7-cm inward shift (middle), and (c) 3.5-cm inward shift (bottom). Arrows indicate gaps expected on the basis of diffusionless drift orbit theory.

An analysis of such scintillator pulse spectra shows [2] that in this experiment the energy spectrum versus time of X-rays striking the limiter (which correspond to a runaway energy spectrum $E \approx 5-10$ MeV) is similar with and without shift. Thus the X-ray gap due to the inward shifts can be most clearly isolated by normalizing the scintillator count rates for shifted discharges such as those in Figs 2b and c to those measured for unshifted discharges such as those shown in Fig.2a. In this way the normalized X-ray flux versus time gives a rough measure of the relative high-energy runaway flux to the limiter during the shift. Spectrum analysis of these pulse patterns also shows that the maximum runaway energy increases at nearly the free-fall rate in these cases, as would be expected for the loss of a group of collisionless electrons born at the same time early in these discharges.

Although flux patterns such as those in Fig.2 clearly show a rather diffuse gap compared to the prediction of the diffusionless model (see Fig.1), we proceeded to compare the experimental values for T_{gap} with those calculated on the basis of Eq.(3). To do this, we arbitrarily defined the experimental T_{gap} to be the interval between the beginning of the inward plasma shift and the time when the normalized X-ray flux returns to 50% of the value it had before the shift (diffusive effects smooth out the structure of the X-ray flux versus time without strongly affecting this experimental T_{gap}). The drift orbit model predictions of T_{gap} were calculated using the actual measured plasma position versus time (i.e. including the outward plasma movement such as shown in Fig.1), plus the outward drift orbit movement $d(d_\gamma)/dt$ based on the assumption of runaway free-fall acceleration in the measured loop voltage (which changes due to the varying applied vertical field). That is, the calculated time T_{gap} is defined to be the interval between the beginning of the inward shift and the time at which the combination of outward drift orbit movement due to free-fall energy gain and the outward movement due to the plasma motion would have brought the edge of the original runaway distribution back to the outward limiter.

A comparison between experiment and theory for several trials of this experiment is shown in Fig.3, each point representing an average over a series of about 5 similar discharges. Calculated T_{gaps} are within ± 20% of the line shown. This agreement is fairly good, especially considering the fact that there are not adjustable parameters involved in the analysis. This agreement may be taken as a semi-quantitative confirmation of the basic orbit displacement effect of Eq.(1).

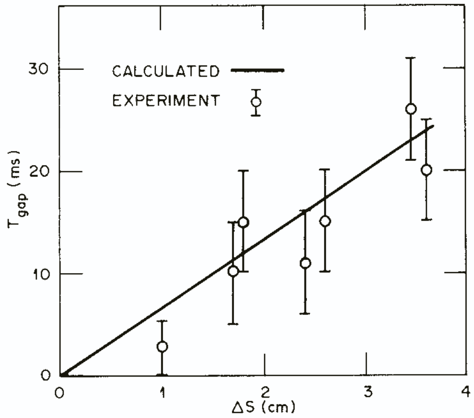

FIG.3. Comparison of T_{gap} from theory and experiment. The experimental points are obtained from analysis of the X-ray flux versus time patterns, such as those of Figs 2b and c.

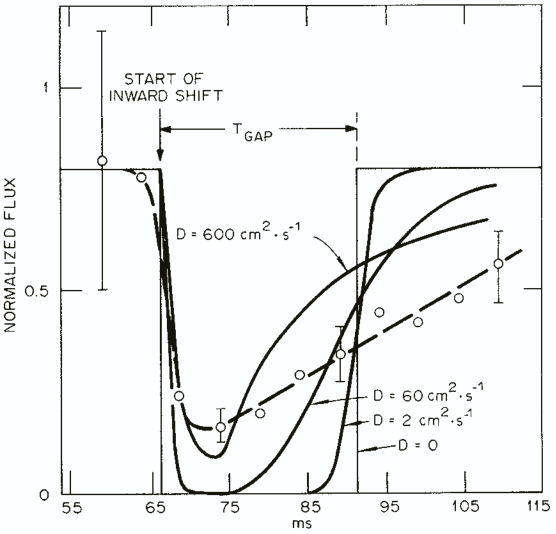

FIG.4. Estimation of diffusion coefficient from the flux-versus-time pattern. The simplified diffusion model described in the text has been used to determine an order-of-magnitude value $D \approx 10^2\ cm^2 \cdot s^{-1}$ for this series of 19 discharges with a 3.5-cm inward shift. Error bars represent the RMS shot-to-shot variation during this series.

However, this result by itself can also be interpreted in terms of a diffusive model in which $T_{gap} \approx (\Delta S)^2/4D$ with $D \approx 100\ cm^2 \cdot s^{-1}$.

An example of a normalized X-ray flux pattern versus time is shown in Fig.4. These data were used to deduce the experimental $T_{gap} \approx 26$ ms for this 3.5-cm-inward-shift case (Fig.3), and it is clear that the gap is much less sharply defined than would be expected from the diffusionless model. We therefore introduced an ad-hoc diffusion coefficient into the orbit model in order to better match the observed runaway flux versus time at the outer limiter.

A one-dimensional diffusion equation can be written for the local density n(x,t) of runaways near the outside of the discharge:

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - V(t)\frac{\partial n}{\partial n} \qquad (4)$$

Here D is a particle diffusion coefficient (taken to be independent of the distance x from the outer limiter), and V(t) is the velocity with which the runaway distribution moves as a whole due to the sum of the orbit displacement effect (Eq.(1)) and the imposed plasma shift $d_p(t)$. The shift experiment is modelled by assuming: (a) an absorbing boundary at the outer limiter, n(0,t) = 0; (b) an initial condition n(x,0) corresponding to the runaway spatial distribution just before the inward shift (x > 0 toward the plasma); and (c) a V(t) which takes into account the outward orbit movement $d(d_\gamma/dt)$ and the shifting plasma position versus time (such as that shown in Fig.1). With such a model, the runaway flux to the limiter $D(\partial n/\partial x)_{x=0}$ can be calculated and compared to the flux versus time pattern from the experiment. It should be noted that this approximate model treats only the runaway movement near the outside of the discharge ($\Delta S \ll r_L$), and that it is valid only for $\Delta S < d_p + d_\gamma$ such that the runaway distribution is not shifted into the inner limiter.

Since in the unshifted discharges the flux of runaways to the limiter during the steady state has been seen to be fairly constant in time [1], we assumed an initial condition, $n(x,0) = n_0(1-\exp(-V_0 x/D))$, which is the stationary solution of Eq.(4) for the case when $V_0 \propto d(d_\gamma)/dt$ constant (for a constant loop voltage). For the 3.5-cm-shift case, V(t) was chosen so as to move the runaway distribution as a whole inward by 3.5 cm over 0 < t < 8 ms (roughly following the plasma motion shown in Fig.1), and then back outward so as to return to its initial position after the experimentally observed T_{gap} = 26 ms (both shifts at constant velocity). Thus for D = 0, the calculated flux to the limiter versus time shows a sharp gap (Fig.4), which would correspond to a pattern expected from the diffusionless drift orbit model.

For D > 0 the flux versus time was calculated numerically, and some results for this 3.5-cm-shift case are shown by the curves in Fig.4. The diffusive behaviour can be seen in the non-zero flux during the start of the inward shift (when the runaways are still near the outer limiter) and in the more gradual return of the flux to its steady-state value near t ≈ 26 ms. In this case we deduce that the data are best fitted by including into the orbit model a diffusion coefficient $D \approx 100\ \mathrm{cm^2 \cdot s^{-1}}$ for runaway confinement. We should stress that the uncertainties in the assumed n(x,0), V(t) and in the experimental data make this an order-of-magnitude estimate only. We note, incidentally, that the classical diffusion expected from Coulomb collisions for untrapped ≈ 5-MeV electrons is roughly $D \cong \rho_{tor}^2\ \nu_e \lesssim 1\ \mathrm{cm^2 \cdot s^{-1}}$, where ρ_{tor} is the runaway gyroradius evaluated in the toroidal field, and ν_e is the effective collision frequency for 90° scattering.

The rather small runaway diffusion implied by the analysis of Figs 3 and 4 can be contrasted with the behaviour observed in several cases in which *no* clear gap appeared in the X-ray flux after an inward plasma shift of up to ≈ 6 cm. In some of these cases, it was noticed that an inward shift triggered the growth of MHD instability in the discharge, such that an increased level of m = 2 activity during the first 5 ms of the inward shift actually coincided with an *increase* in the normalized X-ray flux during this time. This indicates an enhanced runaway diffusion due to the MHD activity. In other discharges, there was no observed enhancement of the MHD activity even though there was no clear X-ray gap, possibly indicating the presence of another source of anomalous diffusion in these cases. Since the runaways at the outside of these discharges were observed to diffuse outward faster than the plasma shifted inward, these results imply that the diffusion must have been particularly strong, i.e. $D \gtrsim V_{inward} \times \Delta s \approx (6\ \mathrm{cm}/10\ \mathrm{ms}) \times (6\ \mathrm{cm})$, or $D \approx 10^3 - 10^4\ \mathrm{cm^2 \cdot s^{-1}}$. These high-D cases were observed in about ten discharges on different dates than those cases of low-D analysed above, but no systematic cause for this difference was noticed (i.e. I, n_e and V were the same).

4. POSSIBLE MECHANISMS FOR RUNAWAY DIFFUSION

There are at least four distinct mechanisms which could allow non-collisional diffusion of runaways near the outside of the ORMAK discharge: (a) drift orbit deflections due to static magnetic field perturbations from finite coils or stray fields [9, 10]; (b) magnetic ergodicity due to low-frequency MHD instabilities with

$f \approx 10$ kHz [5, 11, 12]; (c) electrostatic or magnetic turbulence associated with drift waves with $f \cong 100$ kHz [13]; and (d) scattering by high-frequency RF or microwave radiation due to instabilities near the electron or ion plasma or electron cyclotron frequencies [14].

Of particular interest for general tokamak transport studies is the possibility that a magnetic "flutter" associated with drift wave turbulence [15] may allow a substantial runaway diffusion. Such drift wave activity was recently observed to be localized near the limiter in Alcator [16]. This possibility has not been directly tested on Ormak, but a theoretical model [15] which reproduces the observed anomaly in electron heat conduction indicates an expected *low-energy* runaway diffusion coefficient in the range of $10^2 - 10^4$ cm$^2\cdot$s^{-1}.

Another interesting possibility is that an instability of the runaway tail itself [17] may lead to high-frequency radiation which causes a diffusion of these high-energy runaways. An indication of such an instability was, in fact, observed after 76 ms during the series documented in Figs 3 and 4 but its relationship to the observed runaway diffusion is, at present, uncertain.

5. CONCLUSIONS

This experiment measured the movement of high-energy runaways across the outside of a low-density ORMAK discharge, and the results were interpreted in terms of a runaway confinement model with an anomalous (non-collisional) diffusion coefficient $D = 10^2 - 10^4$ cm$^2\cdot$s^{-1} for these particles. The mechanism responsible for this diffusion has not been isolated.

Such a diffusive runaway transport will be comparable to the orbit displacement effect [1, 2] over radial distances Δx such that $\Delta x \approx D/(d/dt)\,(d_\gamma)$; i.e. for $D = 100$ cm$^2\cdot$s^{-1} we have roughly $\Delta x = 1$ cm. This diffusion rate should, therefore, significantly affect the confinement of high-energy runaway orbits only when these orbits are within a few centimetres of the limiter. It cannot be concluded, however, that an observed $D > 10^3$ cm$^2\cdot$s^{-1} implies $\Delta x \approx 20$ cm, since D has not been measured for the plasma interior. It is possible that the less than free-fall energy gain observed at the outer limiter in some cases in ORMAK can be attributed to an enhanced runaway loss rate from the plasma interior, yet without an independent knowledge of the runaway density profile n(r), the diffusion coefficient D(r) cannot be evaluated. Thus, these results do not allow us to make any statement about the radial (or energy) dependence of the runaway diffusion coefficient.

Our experimental results are, therefore, consistent with the possibility that the runaway diffusion coefficient increases with radius [5] such that the anomalous transport would be an edge rather than a bulk plasma phenomenon. The results are also consistent with an increased diffusion rate for higher-velocity, non-relativistic runaways [6], although they may be more closely related to a recent result showing a runaway energy life-time which increases with energy in the range 200 eV–60 keV [18]. We also note that the cases of high D during enhanced MHD activity appear similar to that observed in ATC (12), although, in our case, the observed diffusion was an edge rather than a bulk phenomenon.

Beyond their potential usefulness in defining the anomalous transport processes in present-day tokamaks, these results can also have some implications for the operation of future devices as well. The existence of high-energy runaway diffusion may allow the gradual removal of runaways created during the start-up phase of large tokamaks, thus avoiding the acceleration of these particles to energies approaching 100 MeV. On the other hand, the confinement properties of high-energy runaways may be similar to those of fast-injected ions (or alpha-particles) with similar values of orbit displacement, such that enhanced fast-ion losses might be anticipated near the plasma edge. Finally, such evidence for a non-collisional loss mechanism may need to be taken into account in analysing physical processes involving the plasma edge, i.e. those of impurity transport, RF heating, or magnetic divertor design.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the support received for this work from J.F. Clarke and L.A. Berry; from our collaborators H.E. Knoepfel and D.A. Spong; and from the ORMAK group as a whole. Helpful comments on runaway diffusion have also been received from J.D. Callen, G. Fussman, J.A. Rome and J.D. Strachan.

REFERENCES

[1] KNOEPFEL, H., ZWEBEN, S.J., Phys. Rev. Lett. **35** 20 (1975) 1340.

[2] ZWEBEN, S.J., An Investigation of High Energy Runaway Electron Confinement in the Oak Ridge Tokamak, PhD Thesis, Cornell University, Ithaca, New York (1977); published as ORNL/TM-6030, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1977).
[3] VON GOELER, S., STODIEK, W., SAUTHOFF, N., SELBERG, H., in Toroidal Plasma Confinement, Proc. 3rd Int. Symp., Paper B25 (1973).
[4] SESNIC, S., FUSSMAN, G., Runaway Bremsstrahlung in Pulsator Tokamak, Max Planck Institut für Plasmaphysik, Report IPP29 (August 1976).
[5] HUTCHINSON, I.H., MORTON, A.H., Nucl. Fusion **16** (1976) 447.
[6] STRACHAN, J.D., Nucl. Fusion **16** (5) (1976) 743.
[7] TFR GROUP, Nucl. Fusion **16** (3) (1976) 473.
[8] STRACHAN, J.D., Nucl. Fusion **17** (1) (1977) 141.
[9] MATSUDA, S., Influence of the Minor Periodicity on Magnetic Island Formation in Tokamaks, ORNL/TM-5114, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1976).
[10] ROME, J.A., Effects of Magnetic Field Errors in ORMAK, ORNL/TM-3880, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1972).
[11] FINN, J.M., Nucl. Fusion **15** (1975) 845.
[12] BOYD, D.A., STAUFFER, F.J., TRIVELPIECE, A.W., Phys. Rev. Lett. **37** (1975) 98.
[13] MAZZUCATO, E., Phys. Rev. Lett. **36** 14 (1976) 792.
[14] ALIKAEV, V.V., RAZUMOVA, K.A., SOKOLOV, Yu.A., Sov. J. Plasma Phys. **1** 4 (1975) 303.
[15] CALLEN, J.D., Phys. Rev. Lett. **39** (1977) 1540; see also RECHESTER, A.B., ROSENBLUTH, M.N., Phys. Rev. Lett. **40** (1978) 38.
[16] SLUSHER, R.E., SURKO, C.M., Phys. Rev. Lett. **40** 6 (1978) 400.
[17] LIU, C.S., MOK, Y.C., PAPADOPOULOS, K., ENGELMANN, F., BORNATICI, M., Phys. Rev. Lett. **39** 11 (1977) 701.
[18] ALIKAEV, V.V., BOBROVSKII, G.A., POZNYAK, V.I., RAZUMOVA, K.A., SANNIKOV, V.V., SOKOLOV, Yu.A., SHMARIN, A.A., Sov. J. Plasma Phys. **2** 3 (1976) 212.

(Manuscript received 13 April 1978
Final version received 9 August 1978)