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High Energy Runaway Orbits in the Presence of $m = 2$ Magnetic Islands

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MASTER

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OF $m = 2$ MAGNETIC ISLANDS

S. J. Zweben, B. V. Waddell, D. W. Swain,
and H. H. Fleischman

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ABSTRACT

A guiding center computer code is used to map out trajectories of collisionless runaway electrons in the presence of $m = 2$ magnetic islands in a tokamak. Low energy runaway drift surfaces follow closely the perturbed poloidal magnetic flux surfaces, as expected. Higher energy runaway orbits are seen to retain an $m = 2$ structure even though the drift surfaces are shifted considerably outward from the magnetic flux surfaces. The size of the island structure in the drift surfaces decreases as the outward shift becomes larger than the island width. Trapped particle orbits are apparently unaffected by the presence of the island. Little or no ergodicity of the particle orbits has been observed in this model, although a coupling of the $m = 2$ island with the $m = 1$ outward shift can produce an $m = 3$ structure in the particle drift surfaces.

1. INTRODUCTION AND REVIEW

The purpose of this report is to display the effect of magnetic islands on the single-particle orbits of high energy runaways in a tokamak. High energy (<10 MeV) runaway orbits are characterized by a substantial shift of the particle drift surfaces from the magnetic flux surfaces,¹ so it is not obvious that these orbits are perturbed by islands in the same way as are low energy (unshifted) runaway orbits.² Besides being useful in the study of runaway confinement, such calculations may have application to the study of the confinement of high energy (neutral beam injected) ions and fusion-produced α 's, since these particles are also fairly collisionless and can have large orbit shifts.

There have been several experimental indications that runaway orbits in tokamaks can be perturbed by magnetohydrodynamic (MHD) activity. In ORMAK, a correlation between hard x-ray emission (due to runaway impact with the limiter) and MHD pickup loop activity has been repeatedly observed.^{2,3} An enhanced diffusion of low energy runaways has been attributed to MHD activity in ATC⁴ and in the current-rise phase of the LT-3.⁵ Perhaps the most interesting observations have been made on the Pulsator device,⁶ in which periodic runaway losses in the predisruptive phase have been directly attributed to the influence of rotating $m = 2$ islands on the high energy (~ 8 MeV) runaways. In this last experiment it was noticed that all runaways were lost prior to the main disruptive voltage spike, and this was interpreted in terms of outward-shifted runaway orbits which intersected the limiter before the $m = 2$ island itself. No calculations of the high energy runaway orbits were presented in the Pulsator paper, however.

Nearly all theoretical work on particle orbits in the presence of islands has concentrated on the case of low energy particles which can be assumed to follow magnetic field lines. It was shown by Chrisman, Clarke, and Rome² that helical sheet-current perturbations on rational surfaces can produce islands in the flux surfaces (which are coincident with zero-energy runaway drift surfaces), such that the early ORMAK observations of hard x-ray/MHD correlations could be related to the effect of these islands on runaway confinement. They noted that drift surfaces for

nonzero energy runaways are slightly deformed and displaced, but gave no details of this behavior. They also noted that the interaction between large $m = 2$ island perturbations and the $1/R$ ($m = 1$) toroidal field can lead to a breakup of the magnetic surfaces.

Finn⁷ has extended the study of magnetic surface breakup to include the interaction between $m = 2$ and $m = 3$ islands, as well as the interaction between the $m = 2$, $n = 1$ mode and the $m = 1$, $n = 0$ toroidal structure of the tokamak. He has found that perturbed currents of a few percent are needed in order to produce a large-scale field line ergodicity which he speculates may cause the disruptive instability. The onset of magnetic surface breakup (ergodicity) was also shown to be sensitive to the assumed current profile.

Matsuda⁸ has studied the formation of magnetic islands due to non-axisymmetric external current perturbations. Although such stationary island structures are probably not related to the periodic runaway losses observed in the experiments, their influence on runaway confinement in future devices (i.e., with divertor or ripple coils) may be significant.

In the following analysis the magnetic islands are assumed to be stationary on the time scale of a runaway transit (the toroidal transit time is ~ 20 ns for relativistic electrons in ORMAK). The runaway drift surfaces should therefore remain locked in phase with respect to slowly rotating (~ 5 kHz) islands such as those which apparently cause the observed B_p magnetic oscillations.² The effects of a growing or turbulent island structure have not been considered in the present work.

2. GUIDING CENTER CODE

We used a guiding center computer code to follow the high energy runaway orbits. The following simplified set of guiding center equations was employed⁹ (see Fig. 1):

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Fig. 1. Geometry for guiding center code showing the cylindrical coordinate system with periodicity $2\pi R_0$ along the "toroidal" direction z .

$$\left\{ \begin{array}{l}
 \text{(a)} \quad \frac{dx}{dt} = v_z \left(\frac{B_x}{B_o} \right) \frac{R_o}{R} \\
 \text{(b)} \quad \frac{dy}{dt} = v_z \left(\frac{B_y}{B_o} \right) \frac{R_o}{R} - \frac{\gamma}{\Omega_o R_o} \left(v_z^2 + v_\perp^2/2 \right) \\
 \text{(c)} \quad \frac{dz}{dt} = v_z \\
 \text{(d)} \quad \frac{d(\gamma m v_z)}{dt} = eE - \frac{M}{\gamma} \frac{\partial B}{\partial S} \\
 \text{(e)} \quad \frac{d(\gamma m_o c^2)}{dt} = eE v_z, \quad (1)
 \end{array} \right.$$

where

$$\frac{v}{c} = \sqrt{1-1/\gamma^2} \quad \text{and} \quad \begin{cases} v_z = v \cos \xi \\ v_\perp = v \sin \xi \end{cases} \quad \text{with } \xi = \text{pitch angle}$$

S = arc length,

E = toroidal electric field,

and

$$M = \frac{(\gamma m_o v_\perp)^2}{2B_o} \quad \text{is the runaway magnetic moment.}$$

The toroidal geometry is approximated by a periodic cylindrical system (periodicity $2\pi R_o$) in which the axial field is $B_z = B_o R_o / R$, and the tokamak poloidal field $B_p^2 = B_x^2 + B_y^2$ is chosen to be cylindrically symmetric in the absence of the island. Orbits calculated using a $B_z =$ constant geometry are generally quite similar to those using a $B_z \propto 1/R$.

Equations 1(a)-(c) represent the particle motion along a magnetic field line, but with a vertical drift $v_d = (\gamma/\Omega_o R_o) (v_z^2 + v_\perp^2/2)$ added to simulate the usual ∇B and centrifugal drifts of a tokamak (note that the $1/R$ dependence of B_z cancels out to first order here). Equation 1(d) gives the change in parallel velocity due to an applied toroidal electric field E with the usual $1/R$ mirroring force added on to form trapped particle

orbits when the magnetic moment M is large enough. The term $\partial B/\partial S$ is simplified to be $(B_x/B)(\partial B/\partial x) = -B_o/R$, so that the mirroring force reduces to $(\gamma m_o v_{\perp}^2/2R_o)(B_x/B_o)$. Equation 1(e) gives the change in particle energy in the applied electric field.

The only thing left to be specified is the toroidal current distribution which determines the unperturbed poloidal fields. We have taken

$$q = \frac{B_o}{B_p} \frac{r}{R_o} = \frac{m}{nC_1} [1 + (r/r_o)^2] \quad (2)$$

to define B_p , where r_o is a parameter which determines the effective width of the current channel, and $C_1 = 1 + (r_s/r_o)^2$, where r_s is the radius of the singular surface (m,n) . Normalizing all radii to the limiter radius a , we have typically for $m = 2$, $n = 1$, $\hat{r}_o = r_o/a = 0.8$, $\hat{r}_s = r_s/a = 0.6$; thus $q(a) \cong 4$ and $q(o) = 1.6$.

This set of five coupled differential equations has been solved numerically using a well documented and reliable computer code ODE (Ordinary Differential Equations). This code has been used previously for a similar application.¹⁰

Some examples of particle orbits (without islands) computed in this way are shown in Fig. 2. Each dot represents the puncture of a fixed toroidal cut ($z = \text{constant}$) by the particle guiding center. The plasma edge is shown by the heavy circle. The equations can be seen to reproduce the two basic features of tokamak particle orbits: (a) high energy, low magnetic moment electrons are displaced from the magnetic axis by an amount $d_y/a \cong 3.4 E(\text{MeV})/I(\text{kA})$ for this current profile¹ and (b) high magnetic moment particles form trapped particle (banana) orbits. In this code each orbit is defined by choosing an initial position, a total energy, and a pitch angle ξ (an orbit with 50 punctures can be computed in less than 30 sec on the PDP-10). Orbits such as these have been followed for many hundreds of punctures without a noticeable wandering from the initial drift surfaces.

Fig. 2. Typical particle orbits calculated in the absence of the $m = 2$ island. Cases 2(a)-(c) represent a runaway with $M = 0$ of energy 5, 20, and 35 MeV, respectively ($I = 200$ kA). Case (d) is a trapped particle with $E = 3$ MeV and $\xi = 70^\circ$. The unperturbed current profile for these cases is specified by $r_s = 0.6$ and $r_o = 0.8$ (see Eq. 2).

3. $m = 2$ ISLAND PERTURBATION

An $m = 2$ magnetic island has been included into the code by adding to Eq. (1) the perturbed poloidal fields B_{x1} and B_{y1} due to the island. Since these $m = 2$, $n = 1$ fields are much smaller than B_0 , no change in the particle drift velocity v_d has been made; the effect of the island therefore comes entirely through the tendency of the guiding center to follow the perturbed magnetic field line.

The perturbed fields are obtained from an analytic fit to a saturated $m = 2$ island structure as calculated by Waddell with the MASS code.¹¹ A helical flux function ψ is defined in a cylindrical coordinate system.

$$\begin{cases} B_r = \frac{1}{r} \frac{\partial \psi}{\partial r} \\ B_\theta = -\frac{\partial \psi}{\partial r} - \frac{kr}{m} B_z & k \equiv n/R_0 \\ B_z = \text{constant} \end{cases} \quad (3)$$

It is easy to verify that the unperturbed field given by Eq. (2) can be written in terms of a normalized $\hat{\psi}_0 = \psi_0 / (a^2 k B_z / m)$ and a normalized $\hat{r} = r/a$ as follows:

$$\hat{\psi}_0(\hat{r}) = C_3 \ln [1 + (\hat{r}/\hat{r}_0)^2] - \frac{1}{2} \hat{r}^2 + C_2 ,$$

where

$$C_3 = \frac{1}{2} \hat{r}_0^2 [1 + (\hat{r}_s^2/\hat{r}_0^2)] , \quad (4)$$

and

$$C_2 = -C_3 \ln (1 + \hat{r}_0^{-2}) + \frac{1}{2} .$$

The perturbed helical flux $\hat{\psi}_1(r, \theta, z)$ for the island has been taken to be:

$$\hat{\psi}_1 = C_4 \hat{r}^2 \exp[-(\hat{r} - \alpha \hat{r}_s)^2 / \hat{w}^2] (1 - \hat{r}) \cos(2\theta + kz) , \quad (5)$$

where $\hat{w}$ is the normalized width of the island, and

$$C_4 = \frac{\hat{w}}{16f(\hat{r}_s, \hat{w})} \left[\frac{(\hat{r}_s/\hat{r}_0)^2}{1 + (\hat{r}_s/\hat{r}_0)^2} \right] \quad (6)$$

with

$$f(\hat{r}_s, \hat{w}) = \hat{r}_s^2 \exp\left(-\frac{r_s^2}{\hat{w}^2}\right) (1 - \hat{r}_s) . \quad (7)$$

The island is therefore specified by choosing $\hat{r}_0$ (the radius of the $m = 2$ singular surface), $\hat{w}$ (the width of the island), and α (a parameter which slightly affects the centering of the flux surfaces within the island). It can be checked that $\vec{B} \cdot \nabla \hat{\psi} = 0$; thus, a magnetic field line lies on a helical flux surface of constant $\hat{\psi}$.

The perturbed magnetic fields $\vec{B}_1(r, \theta)$ corresponding to this island can be found through Eq. (3):

$$\begin{aligned} B_{r1}(\hat{r}, \theta, z) &= \frac{1}{\hat{r}} \frac{\partial \hat{\psi}_1}{\partial \theta} = C_4 (1 - \hat{r}) \hat{r} \exp\left[\frac{-(\hat{r} - \alpha \hat{r}_s)^2}{\hat{w}^2}\right] 2 \sin(2\theta + kz) \\ B_{\theta 1}(\hat{r}, \theta, z) &= \frac{-\partial \hat{\psi}_1}{\partial \hat{r}} = C_4 \{ \hat{r}^2 (1 - \hat{r}) [-2(\hat{r} - \alpha \hat{r}_s)/\hat{w}^2] + 2\hat{r} - 3\hat{r}^2 \} \quad (8) \\ &\quad \cdot \exp[-(\hat{r} - \alpha \hat{r}_s)^2/\hat{w}^2] \cos(2\theta + kz) . \end{aligned}$$

Finally, the components B_{x1} and B_{y1} used by the guiding center code can be obtained from:

$$\begin{aligned} B_x &= (B_p + B_{\theta 1}) \left(\frac{-y}{r} \right) + B_{r1} \left(\frac{x}{r} \right) \\ B_y &= (B_p + B_{\theta 1}) \left(\frac{x}{r} \right) + B_{r1} \left(\frac{y}{r} \right) , \end{aligned} \quad (9)$$

where B_p is the unperturbed poloidal field given by Eq. (2).

This island perturbation corresponds to a normalized perturbed current $\hat{J}_z$ which can be calculated through:

$$\hat{J}_z = \frac{\mu_0 J_z}{kB_z/m} = -\frac{1}{\hat{r}} \frac{\partial}{\partial \hat{r}} \left(\hat{r} \frac{\partial}{\partial \hat{r}} \hat{\psi} \right) + \left(\frac{1}{\hat{r}} \right)^2 \frac{\partial^2 \hat{\psi}}{\partial \theta^2}. \quad (10)$$

The perturbation is such that the current profile is flattened near the $q = 2$ surface; thus the island corresponds to a dipole-like current perturbation, as opposed to the islands of Refs. 2 and 7 which were calculated using sheet current models.

4. RESULTS FOR $m = 2$ ISLANDS

Low energy particle drift surfaces for typical $m = 2$ island are shown in Fig. 3(a). These surfaces are nearly identical with magnetic flux surfaces (i.e., ψ contours), since for $v_d \rightarrow 0$ and $M = 0$ the particles follow magnetic field lines according to Eq. (1). The island structure is qualitatively similar to those shown in Refs. 2 and 7, except for the asymmetry around $x = 0$ due to our choice of $B_z \propto 1/R$. For $B_z = \text{constant}$ the islands are symmetric, similar to the direct plot of ψ contours in Fig. 3(b).

As in the case without islands, these particle orbits can be followed for many hundreds of toroidal transits without an appreciable deviation from the initial drift surfaces. Thus there appears to be little or no ergodicity in this model, even though the $m = 2$, $n = 1$ symmetry is mixed with an $m = 1$, $n = 0$ toroidal field.

In Fig. 4 we show the typical behavior of high energy, zero magnetic moment particles. The high energy drift surfaces are all shifted outward from the axis as in Fig. 1, and the island structure in the drift surfaces is retained even when the shift $d_Y \propto E$ is comparable to the width of the island (w). As the particle energy is increased the islands in the particle drift surfaces gradually shrink; thus only when $d_Y \gtrsim w$ does the particle lose the resonance necessary to form an island. It is somewhat surprising that both lobes of the island can appear at $x > 0$, but a check of the toroidal mode structure showed that indeed these distorted drift surfaces have the same $m = 2$, $n = 1$ structure as the flux surfaces.

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Fig. 3. Low energy particle drift surfaces with the $m = 2$ island. The particle orbit in Fig. 3(a) can be seen to be nearly identical to a direct plot of the ψ contours in Fig. 3(b). The slight asymmetry about $x = 0$ in the particle orbits is due to the $1/R$ toroidal field effect absent in the ψ plot. For both plots $r_s = 0.6$, $r_o = 0.8$, $w = 0.4$, and $\alpha = 0.4$.

Fig. 4. Orbits of high energy particles in the presence of an $m = 2$ island, showing the distortion and shrinkage of the islands in the drift surfaces as the particle energy increases. Here $M = 0$, $r_s = 0.6$, $r_o = 0.8$, $w = 0.4$, and $\alpha = 0.4$ for all cases ($I_s \approx 200 \text{ kA}$).

It should be noted that the outermost edge of the island in a high energy runaway drift surface can extend slightly beyond the outermost point in the separatrix of the flux surfaces. This agrees with the interpretation of the Pulsator group with respect to runaway loss in the predisruptive phase (see Introduction), but it is clear that the detailed structure of outward-shifted drift surfaces is not the same as that of the magnetic island itself.

One peculiar feature of the highly displaced drift surface is shown in Fig. 5. As the normal island structure shrinks with increased shift, there appears an $m = 2$, $n = 1$ island-like structure 90° out of phase with the island in the flux. This is seen to occur both with and without the $1/R$ dependence of B_z ; we have no explanation for this feature at the present, except to note that the islands in the drift surfaces have never been observed to enclose the minor axis.

Another interesting feature of the drift surfaces for the shifted orbits is the appearance of $m = 3$, $n = 1$ structures in some cases (see Fig. 6). These structures occur in a localized region between $q = 1$ and $q = 2$ in both the $B_z \propto 1/R$ and $B_z = \text{constant}$ models, so they are apparently due to the coupling between the $m = 2$ field perturbation and the $m = 1$ orbit shift itself. (They are seen only for small shifts.) No higher order modes have been observed in our runs, although it is possible that fine-scale structures have been missed in our sampling of orbits.

It should be noted again that these high energy drift surfaces can be mapped out over hundreds of toroidal transits without showing any ergodicity (i.e., wandering of the particle from the initial drift surface). In this case such a wandering might have been expected due to the coupling between the $m = 2$ magnetic structure and the $m = 1$, $n = 0$ outward shift.

5. TRAPPED PARTICLE ORBITS

Although high energy runaways are not expected to have a pitch angle near to that which is necessary for mirroring,³ it is nevertheless of some interest for other applications to determine the effect of islands on trapped particle orbits. To our knowledge, this case has not been treated previously.

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Fig. 5. An island structure in the drift surface of a high energy particle, which is 90° out of phase with the island in the magnetic flux [same parameters as Fig. 4(d)].

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Fig. 6. An $m = 3$, $n = 1$ structure in the particle drift surfaces, apparently due to a coupling between the $m = 2$ island and the $m = 1$ orbit shift. $E = 10$ MeV, $B_z = \text{constant}$, and the island parameters are the same as those for Fig. 4.²

In a brief investigation of these orbits, we have found that the magnetic island does not seem to perturb the trapped particle orbit at all. In Fig. 7 we show a set of orbits with a fixed energy and initial position in which the initial pitch angle was varied. The untrapped orbits show the usual $m = 2$ structure in the shifted drift surface, while the trapped orbits show the usual banana structure without any evidence of an $m = 2$ perturbation. In fact, the trapped orbits look nearly the same with or without the magnetic island perturbation (see Fig. 8), except very near the trapping boundary (see Fig. 9).

It is fairly obvious that for narrow banana widths the particle should retrace its orbit back and forth around the torus, and so should not experience the net resonant perturbation necessary for island formation. The code shows that this unperturbed behavior is obtained for both narrow and fat bananas.

One subtlety of the calculation for $M \neq 0$ should be mentioned; that is, the banana tips for both perturbed and unperturbed fields are observed to have a slow z -drift. (This drift can be seen from the fact that the puncture plots of Figs. 7 and 8 map out the whole banana shape.) Such a drift might tend to "smear out" the island structure in the drift surface (if it existed); nevertheless, we believe that the absence of any $m = 2$ structure in the trapped orbits shows that the magnetic island has no influence even on these z -drifting bananas.

It should be mentioned that the code correctly conserves the particle magnetic moment $M \propto V_{\perp}^2 R$ over the whole trapped orbit, with or without the island perturbation [see Eq. (1)].

6. ACCELERATING PARTICLE ORBITS

The $M = 0$ drift orbits shown in Fig. 4 were calculated for a fixed particle energy; but since runaways in tokamaks can accelerate freely from rest in the applied electric field, it is interesting to determine the evolution in time of the orbit as the energy is gradually increased. This is modelled through the E terms in Eq. (1).

In Fig. 10 we show the evolution of an $M = 0$ orbit in the case in which there is no island perturbation. The orbit displacement is seen to

Fig. 7. Orbits with increasing pitch angle ξ are shown for a low energy particle in the presence of an $m = 2$ island. Untrapped particles (a),(b) show the usual island structure in the drift surfaces; trapped particles (c),(d) show the typical banana orbit without an apparent influence of the island. The orbits shown in (c),(d) are actually symmetric about $y = 0$, but only about 30 punctures have been plotted here.

Fig. 8. A trapped particle orbit with (a) and without (b) $m = 2$ island of Fig. 4. In both cases the particle was started at $x = 0.8$ with $E = 5$ MeV and $\xi = 70^\circ$. The orbits are nearly identical, i.e., the orbit (a) has the same poloidal and toroidal structure as orbit (b).

Fig. 9. Orbit structure near the trapping boundary with an $m = 2$ island. At $\xi = 57^\circ$ (d), the orbit shows some complicated structure due to the interaction between the banana orbit and the $m = 2$ perturbation. All parameters except ξ are the same as for Fig. 8.

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Fig. 10. Evolution of an accelerating particle orbit with no magnetic island. As the particle gains energy in the applied electric field, the orbit gradually shifts outward, retaining its original minor radius.

increase as expected with energy, and the minor radius of the orbit is seen to remain constant over this time.³ In Figs. 11 and 12 we show the behavior of accelerating orbits in the presence of an $m = 2$ island. It can be seen that the orbit which was initially at a minor radius less than the island separatrix tends to remain unislanded even though the orbit displacement brings it into the region of the perturbed magnetic flux surfaces. Similarly, the orbit which was initially islanded generally keeps its island structure as it is displaced outward [an exception to this is shown for the highest energy orbit in Fig. 11(e)].

The observed behavior can be summarized by saying that an accelerating particle shifts outward and roughly retains its initial minor radius. (The instantaneous orbits are of course identical with those plotted in Fig. 4 given this constraint.) Conversely, the orbit of a decelerating particle (i.e., a fast ion injected against the E field) in the presence of an $m = 2$ island should be shifted inward in time as it decelerates, while again roughly retaining the initial minor radius of the orbit.

7. DISCUSSION AND CONCLUSIONS

We conclude the following:

- (1) High energy particle drift surfaces in the presence of an $m = 2$ magnetic island are shifted off the flux surfaces as usual; the island structure in the drift surface can be retained for shifts at least as large as the island width. The islands in the drift surfaces are distorted and shrink for large shifts.
- (2) Trapped collisionless particles are not significantly perturbed by the presence of the $m = 2$ island, apparently because their mirroring prevents them from following the helical field around the torus.
- (3) Accelerated particle orbits shift outward with increasing particle energy, roughly retaining their initial minor radius. Particles initially on an islanded flux surface at zero energy tend to retain an islanded drift orbit as the energy is increased.
- (4) The coupling between the $m = 2$, $n = 1$ island and the $m = 1$, $n = 0$ orbit shift can produce an $m = 3$, $n = 1$ structure in some of the particle drift surfaces, but a large-scale magnetic surface breakup

Fig. 11. Accelerating particle orbit in the presence of an $m = 2$ island. The particle initially inside the island retains the island structure as it gains energy. Here again $r_s = 0.6$, $r_o = 0.8$, $w = 0.4$, and $\alpha = 0.4$ for this island. As in Fig. 7, the drift orbits are actually symmetrical around $y = 0$.

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Fig. 12. Accelerating particle orbit in the same island as in Fig. 11. In this case, the orbit was chosen to start inside the island and is seen to retain the unislanded structure even though it passes through the region of perturbed magnetic flux.

has not been observed, even in the case of some relatively large $m = 2$ islands in the presence of a $1/R$ toroidal field.

These results can have some consequences for the confinement of high energy particles such as runaways, injected fast ions, or fusion-produced alpha particles. Generally speaking, it is reassuring to see that these particles can still be well confined in the presence of a large $m = 2$ island, since in principle the mixing of the $m = 2$ mode with the $m = 1$ toroidal field or orbit shift could result in large-scale ergodicity and thus rapid particle loss. It remains possible, though, that such ergodic particle orbits may play a role in the major disruption, especially if the $m = 1$ internal mode or a modified unperturbed current profile is taken into account.⁷

The implication of these results for high energy runaway confinement remains somewhat obscure, however. It is clearly possible that the islanded runaway drift surfaces displayed in this memo can result in the observed modulation of hard x-ray flux to the limiter (as discussed in Ref. 2), but without a detailed knowledge of the island parameters and of the runaway energy,³ it is not possible at present to attempt a quantitative explanation of the experimental results. Such a detailed study would have to take into account, for example, the spatial bunching of orbits near the island tips, and the time evolution of the magnetic island itself.

Among the many possibilities for further investigation are:

- (1) the inclusion of an $m = 1, n = 1$ island in addition to the $m = 2, n = 1$ island, in order to better simulate the experimental tokamak situation (Is it possible for a shifted orbit to "jump" from the internal $m = 1$ structure to the outer $m = 2$ structure?),
- (2) the study of particle orbits in a growing or fluctuating island structure (Is there an additional particle transport in this case?), and
- (3) the study of the effect of a nonzero toroidal current associated with a group of shifted, islanded particles — for example, due to runaways or to neutral beam injection into an existing $m = 2$ structure (Is it possible that these cross-field currents can stabilize the $m = 2$ mode?).

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