TF Ripple Loss of Alpha Particles from the ITER Interim Design: Simulation and Theory

M. H. Redi[a], R. J. Goldston[a], R. B. White[a], R. V. Budny[a],

D. C. McCune[a], C. O. Miller[b], S. J. Zweben[a]

[a] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543

[b] Richard Stockton College of New Jersey, Pomona, N. J. 08240

1. Introduction

Ripple loss of alphas can result in reduced alpha heating and potentially severe localized wall damage in fusion reactors. In this paper we show guiding center code (GC) calculations of ripple-induced alpha loss in ITER, under a number of different operating conditions for the ITER Interim Design [1]: L-mode, H-mode, post-sawtooth, and reversed-shear configurations. In all cases except for the last, alpha loss is very small [2, 3]. In the case of reversed-shear operation, alpha banana convection loss can be important. We also present a new theoretical calculation of the stochastic threshold [2], which gives excellent agreement with the much more computationally intensive GC calculations.

2. Guiding Center Code Method

Recently, the ORBIT Hamiltonian coordinate guiding center code [4] has been used to quantitatively evaluate TF ripple losses for TFTR alpha particles [5] and to adjust the normalization of a simple model for stochastic ripple losses within the TRANSP code [6]. Collisions were found to be far more important than had been expected, with pitch angle scattering during the alpha particle slowing down time moving particles into the stochastic regions and thus causing losses about twice those without collisional effects. Good agreement was found in comparing appropriately normalized TRANSP simulations to measured confined alpha profiles [6].

3. Application to ITER

ORBIT GC simulations for the 21 MA, 20 TF coil ITER Interim design are based on comprehensive, self-consistent TRANSP simulations of two scenarios: moderately peaked density profiles (L-mode) and flat profiles (H-mode). ITER equilibria were obtained with the PEST code using pressure and q profiles from TRANSP, based on cases in the ITER database. TRANSP simulations of ITER also provided alpha source profiles, before and after sawtooth broadening, and collision rates.

The TF ripple data field was fit to

$$\delta(R,Z) = \delta_o exp[((R - R_{MIN}(Z))^2 + b_r Z^2)^{0.5}/w_r].$$

Here b_r is the ellipticity, w_r is the scale length of the ripples, δ_o is the minimum value of the ripple field, and $R_{MIN} = 6.75 - 0.034Z^2$ is the radius at which this minimum occurs. The magnetic axis is typically at Z = 1.5 m. The ripple field strength increases exponentially with R, and with vertical distance from the midplane, Z. We find $\delta_o = 3.75 \times 10^{-6}$, with w_r and b_r 0.535 m and 0.268, respectively.

Monte Carlo simulations were carried out for 256 alpha particles of birth energy 3.5 MeV, including collisional pitch angle scattering over one alpha slowing down time and with R = 8.14 m, a = 2.8 m, Ip = 21 MA, B = 5.7 T and edge q of 3.3. The alpha particle source profiles were calculated by TRANSP from simulation of DT fusion, with prescribed D and T profiles and a simple Kadomtsev sawtooth model. Two different alpha source profiles occur in the TRANSP L-mode simulations. A peaked, pre-sawtooth profile was fit by $(1 - |r/a|)^3$ and a sawtooth-broadened profile was fit by uniform density out to $r/a = 0.7$, and zero for

$r/a > 0.7$. Constant collision rates used were $\nu^{\alpha}_{perp} = 0.126 sec^{-1}$ and $\nu^{\alpha}_{\epsilon} = 5.0 sec^{-1}$.

GC simulations of ITER with the presawtooth, L-mode alpha profile showed no losses of the 256 particles followed, Monte Carlo errors in the particle loss calculations are approximated by $n^{0.5}/n_T$ where n is the number of particles lost and n_T is the total number of Monte Carlo particles followed. When simulations yield no particles lost, the error should be less than calculated for one lost particle ($\pm 0.4\%$), thus an upper bound to alpha ripple losses is $\sim 0.4\%$ in the new design.

The physics of the sawtooth instability is an active area of present research with the details of the sawtooth magnetic field reconnection and its effect on the fast particle distribution function not yet well known. See for example Ref. 7 where energetic ions were detected very near the plasma edge immediately after sawtooth events in PDX. The sawtooth broadened L-mode alpha profile led to particle (power) losses of 0.8(0.7) $\pm 0.6\%$. Because of the very short duration of sawtooth broadened alpha profiles in experiments and in present models of the sawtooth instability, the pulse averaged energy losses should be virtually unaffected by the existence of sawteeth and so described by the upper bound 0.4%. However pulsed energy loss may be significant, particularly if large sawteeth give rise to MHD activity. Alpha losses from the sawtooth broadened L-mode ITER, with reversed direction of toroidal field, were $1.6(0.8) \pm 0.8\%$ particle (power) losses.

Simulations were also carried out for the H-mode scenario. The source profile was modelled as trapezoidal, flat to r/a = 0.4, decreasing to zero at r/a = 0.7. The slowing down and pitch angle scattering times are similar to those for L-mode, as are the alpha profiles outside r/a = 0.3. No losses were simulated so that alpha particle energy losses are $< 0.4\%$.

Initial simulations of a Reversed Shear ITER plasma [1] led to no first orbit losses, but

16% alpha ripple power loss and 19% alpha particle losses due to strong banana convection (see Sec. 4 below). An alternative ITER/RS equilibrium [8], with reduced elongation to make the plasma more nearly centered within the TF coil set, is found to lose only $2.9 \pm 0.4\%$ of alpha particles. Since it fits the outer wall less snugly, it may present increased problems of vertical control. Figs. 1 and 2 show the ripple trapping regions for the ITER 21 MA case and the Interim Design Reversed Shear plasma.

We estimate the heat load for maximum alpha ripple losses for the 21 MA case of 0.4% gives $\sim 0.01 MW/m^2$, and for the RS cases $0.07 - 0.40 MW/m^2$. The wall heat load may be increased by MHD and TAE enhanced losses, in addition to toroidal peaking factors.

4. Theory

In principle, since the mechanisms of ripple-induced alpha loss are well understood, it should be possible to provide a very fast algorithm for determining alpha loss, without the large computational effort associated with unaccelerated GC orbit calculations. Previous efforts [6] in this direction have been based on using a very simplified version of the stochastic loss criterion, given as Eq. 3 in Ref. 9. To provide a match between GC calculations and the stochastic loss criterion, substantial ad hoc normalization factors were required. This is understandable, since the loss criterion used in that work ignored the poloidal dependence of the stochasticity threshold, as well as the effects of toroidal precession.

As indicated in Ref. 9, the transition to chaos occurs when the radial step size in the banana map reaches a critical value, scaled either by the spacing between precession resonances (where the banana precession distance, $R\phi_p$, changes by $2\pi R/N$) or between banana-length resonances (where the banana length, $R\phi_b$, changes by $2\pi R/N$). For the usual case where the the banana-length resonances are much more closely spaced than the precession resonances, detailed calculations of the transition to chaos give the threshold radial displacement:

Eq (1)

$$\Delta_s = c/[N(|\phi_b'| + d|\phi_p'|)]$$

with c = 1.0 and d = 0.5, as opposed to c=1.0, d=1.0 estimated in Eq. 15 of Ref. 9. (Primes indicate radial derivatives.) Investigation of the underlying map shows that the transition to chaos in this case occurs as the islands centered at precession resonances replicate across the banana-length resonances and begin to fill all of space. In the region where ϕ_b'/ϕ_p' is not large, the phasing between the two kinds of resonant surfaces becomes important, as represented by $w_k = N\phi_b/2 + N\phi_p/2$, evaluated at resonant surface k. In particular, for $w_k = \pi/2$ and $\phi_b'/\phi_p' = \pm 1$, the stochastic threshold goes to infinity! In the region $|\phi_b'/\phi_p'| < 4$, the stochasticity threshold must be evaluated as a function of w_k (Fig. 3) as well as ϕ_b'/ϕ_p', and used instead of Eq. (1), above. Eq. (1) has also been generalized for top-bottom asymmetry, giving

Eq (2)

$$\Delta_s = 1/[N((2 - r^p)|\phi_b'| + 0.5r^q|\phi_p'|)]$$

with r equal to the ratio of the smaller to the larger ripple strength at the banana tips, p = 0.2, and q = 0.55. Δ_s is the threshold value of the larger ripple. The result of comparing this calculation with GC calculations of stochastic loss for a wide range of equilibria in ITER and TFTR is very favorable, with no evidence of error outside of the expected Monte Carlo statistical noise, as shown in Fig. 4.

In order to provide detailed comparison with full GC calculations (and to predict overall losses), other loss mechanisms must be taken into account. When banana tips are located in regions of ripple wells, two very important processes must be included. If the ripple wells are on the gradB drift side of the plasma, then in most magnetic geometries collisionless ripple trapping is likely to be very rapid [10]. On the other hand, if ripple wells are located on the opposite side of the device, and no ripple wells are located on the gradB drift side - due to up-down asymmetry - then a rapid net outward convective drift of alpha particles is induced. A calculation of this drift rate is shown in Fig. 12 of Ref. [10] and discussed in some detail in Ref. [11]. Finally, any of these loss mechanisms must persist along a near vertical trajectory of constant $|B|$, in order for an alpha to be fully lost from the system.

In order to include the collisional effects of pitch-angle scattering and slowing down, all three loss criteria are evaluated 10 to 100 times as the alphas slow down. This permits the GC slowing-down calculation to take place in toroidally symmetric fields, and with greatly accelerated collisions. A factor ~ 200 improvement in computer run time is achieved, while preserving accuracy to within the Monte-Carlo noise of the GC runs, for cases examined to date.

5. Conclusions

Encouraging results are presented for predicted alpha losses in most ITER cases. However, since the losses are so small, more careful evaluation of the alpha birth profiles and sawtooth ejection patterns may be in order to give quantitively accurate results. Potentially serious wall damage issues appear to be avoidable for the 20 TF coil ITER, if the first wall is carefully designed to allow for predicted levels of alpha ripple loss and wall heating and if MHD and TAE enhanced loss is controllable. Attractive reversed shear regimes also appear accessible.

A first principles algorithm with no adjustable normalization factors has been developed which provides an accurate and computationally economical method of evaluating alpha losses. It is well suited for detailed parameter scans in support of ITER flexibility studies.

Acknowledgment

We are grateful to W. Nevins and S. Putvinski, for their interest and help in this work and also to R. J. Hawryluk, K. McGuire and N. Sauthoff for their interest and encouragement. This research was supported by the U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073. C. O. Miller was suppported by a DOE National Undergraduate Research Fellowship.

REFERENCES

1. ITER Interim Design Report, July 12, 1995, ITER JCT, San Diego, CA (private communication, S. Putvinski).
2. R. B. White, *et al.*, Phys. Plas. **3** (1996) 3043.
3. M. H. Redi, *et al.*, Phys. Plas. **3** (1996) 3037.
4. White, R. B. and Chance, M. S., Phys. Fluids **27** (1984) 2455.
5. Redi, M. H., *et al.*, Nucl. Fusion, **35** (1995) 1191.
6. Redi, M. H., *et al.*, Nucl. Fusion, **35** (1995) 1509.
7. Goldston, R. J., *et al.*, Nucl. Fusion **27** (1987) 921.
8. W. M. Nevins, LLNL, private communication 1996).
9. Goldston, R. J., *et al.*, Phys. Rev. Lett. **47** (1981) 647.
10. Goldston, R. J., *et al.*, J. Plasma Phys. **26** (1981) 283.
11. Yushmanov, P. N., *et al.*, Nucl. Fusion **33** (1993) 1293.

FIGURES

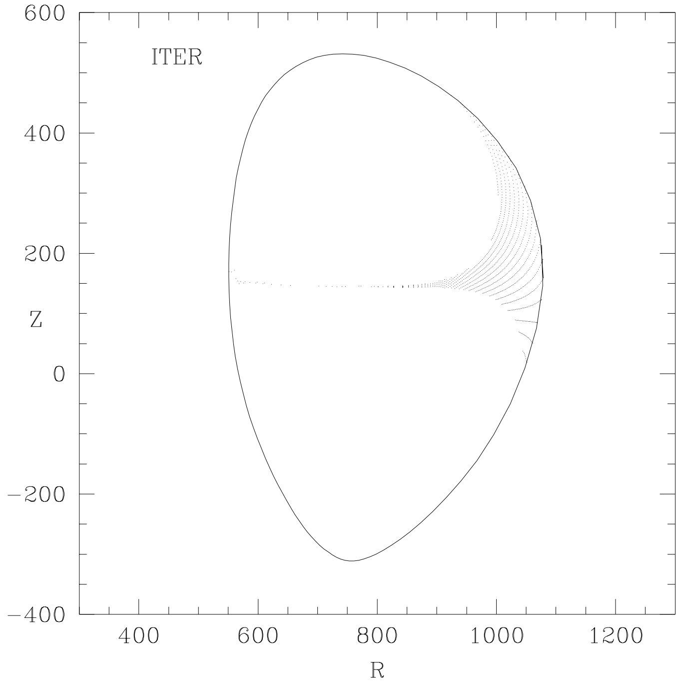

Fig. 1. Ripple well domain in 21 MA ITER equilibrium.

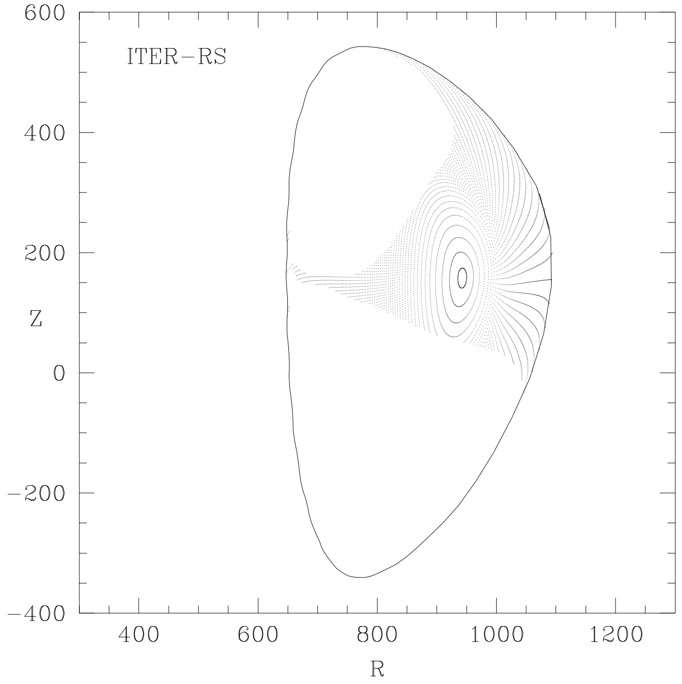

Fig. 2. Ripple well domain in reversed shear ITER equilibrium 01.

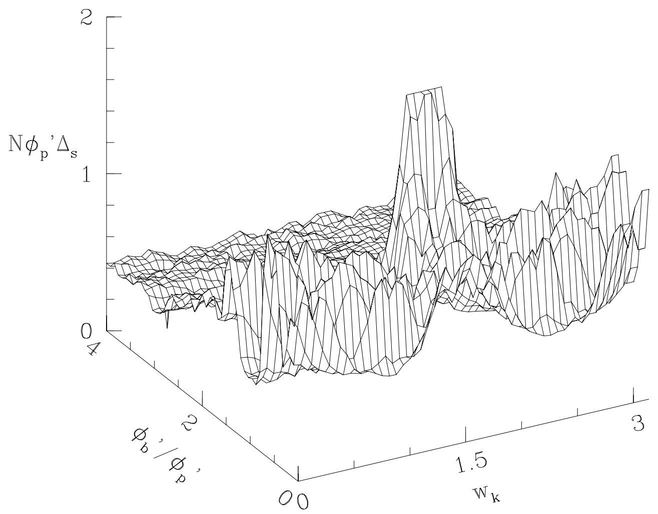

Fig. 3. Transport barrier to stochastic diffusion at large ϕ_p'/ϕ_b'.

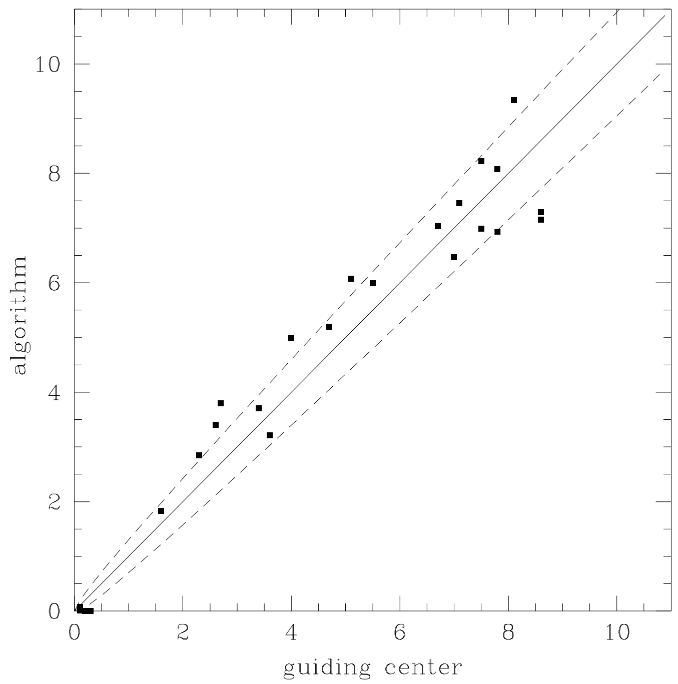

Fig. 4. Good agreement between algorithm and gc simulation of loss (%).