Modelling Fast Particle Loss in Advanced Tokamaks

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OUTLINE

I. Introduction
   Stochastic Diffusion
   Ripple Trapping
   Banana Convection

II. Guiding Center Code Simulations

III. Application to ITER Interim Design

IV. New ITER Reverse Shear Equilibrium
   reduces ripple loss

V. New first principles method
   for rapid ripple loss calculation

VI. Conclusions

Note: For more detail and additional figures see
Redi et al., Phys. Plas. 3 (1996) 3037
White et al., Phys. Plas. 3 (1996) 3043
Goldston et al., J. Plas. Phys. 26 (1981) 283.

I. Introduction

* High energy particles in a Tokamak weakly influenced by fluctuating potentials.

* Orbits are neoclassical.

* Alpha particle orbits closed in the poloidal cross-section (toroidal symmetry).

* Precess toroidally.

* Broken symmetry, from discrete toroidal field coils, causes small orbit perturbations.

* Poloidally trapped particles (banana shaped orbits in the poloidal cross section)

* Strongly influenced by the field perturbations at the banana tips where the parallel velocity vanishes.

* Due to orbital precession, orbit perturbations can be resonant.

* Islands arise in the Poincare section consisting of the map of the poloidal flux and toroidal angle of the banana tip each bounce.

* For toroidal field ripple $\delta B/B \sim 10^{-3}$, stochasticized banana orbits can lead to large, unacceptable fusion alpha particle loss

* Collisions during slowing down substantially increase α losses by causing scattering into loss domains

Three types of ripple losses

* Ripple trapping

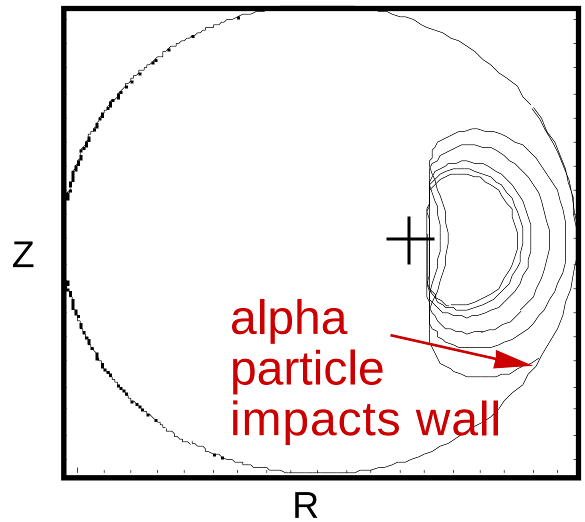
requires $\alpha^* < 1$ $\alpha \equiv (\delta B/\delta\varphi|_{sym})/(N\delta B)$

=> local wells, rapid collisionless trapping in most geometries

TFR-400 beam ions

* Banana drift diffusion

- Stochastic threshold (collisional or collisionless)



* Banana convection

-Requires top/bottom asymmetry

- Requires $\alpha^* < 1$ on non-gradB drift side
(if $\alpha^*<1$ on grad B drift side,
then ripple-trapping dominates)

For $\alpha^*<1$, net average reduced time near banana tip
=>steady banana convection,
if top/bottom asymmetric

1) ALL are handled correctly in guiding center code.
2) Now can also use δ_{WGRB} stochastic threshold model
+ assumption of rapid ripple trapping and/or
banana convection loss, when appropriate

II. Guiding Center Code

* Hamiltonian Coordinates

* Particle guiding center followed in toroidal geometry

* Equilibrium from PEST

* Pitch angle scattering and energy slowing down
  collisional effects

* Simulated on CRAY-YMP/C916 supercomputer,
  ~ 6 hours to follow 256 alphas
  over one slowing down time

III. Application to ITER

III.A. ITER Interim Design
20 TF Coils

* ITER TF Ripple Field

- Tokamak toroidal field (TF) ripple

$$\delta = (B_{MAX} - B_{MIN}) / (B_{MAX} + B_{MIN}),$$

B_{MAX} and B_{MIN} are maximum and minimum field magnitudes along a field line

- Fit to analytic form

$$\delta (R, Z) = \delta_0 \ \exp\{[(R - R_{MIN})^2 + b_r Z^2]^{0.5} / w_r\}$$

b_r is the ellipticity,

w_r is the scale length of the ripples,

δ_0 is the minimum value of the ripple field,

R_{MIN} is the radius at which this minimum occurs

- Unlike TFTR, a Z dependence in R_{MIN} improves fit.

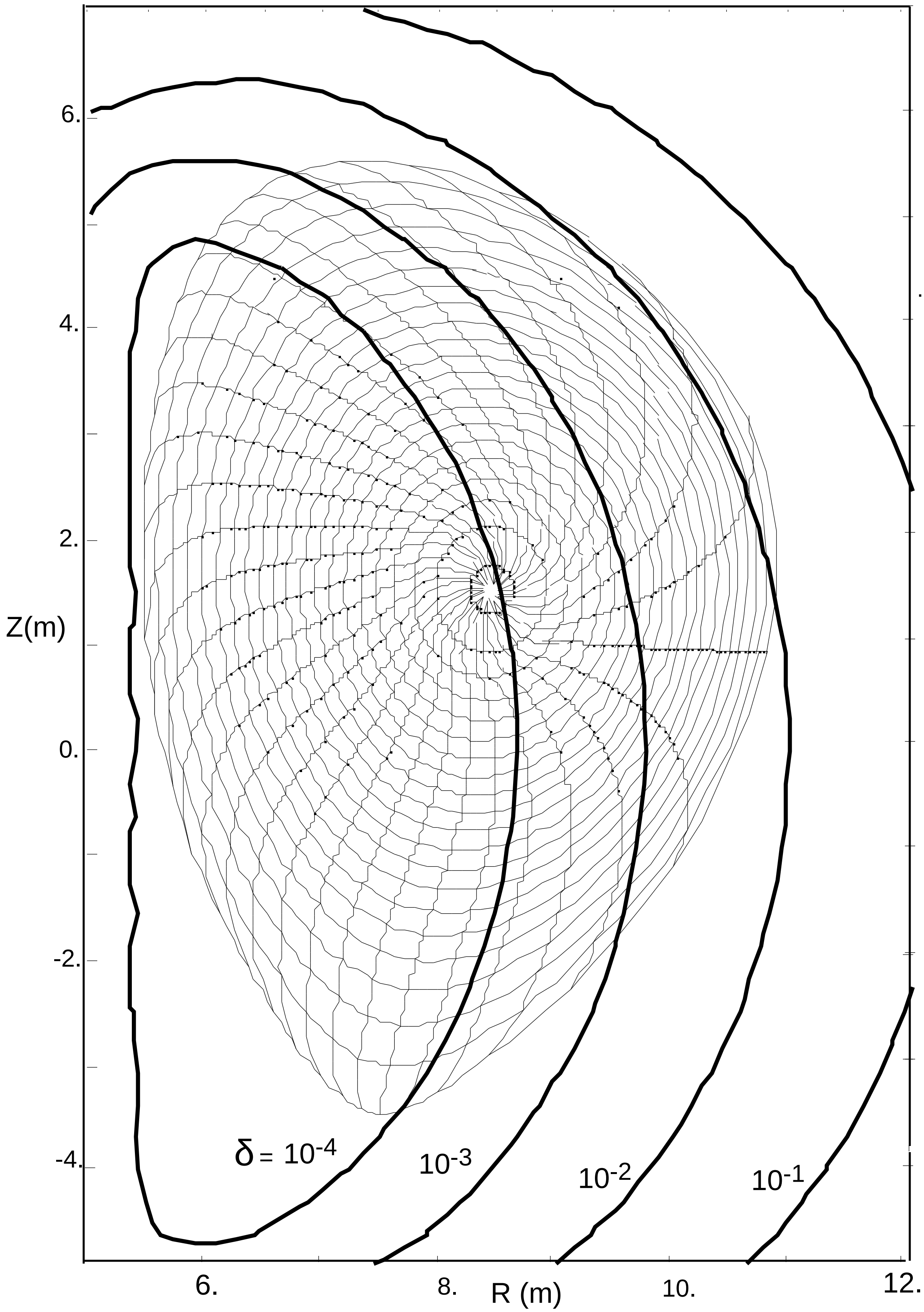
R_{MIN} is symmetric about Z = 0, parabolic,

$$R_{MIN}(m) = 6.75 - 0.034Z^2.$$

- Find $\chi^2 = 0.00334$ for

$\delta_0 = 3.75 \times 10^{-6}$, $w_r = 0.535$ m, $b_r = 0.268$.

ITER Equilibrium and RIpple Contours - L-mode



* Guiding Center Code Simulations of ITER Scenarios

L-mode, peaked density profiles. H-mode, flat profiles.

- For both scenarios

  PEST equilibrium was obtained

  256 alpha particles followed of birth energy 3.5 MeV

  Source profiles taken from TRANSP.

  R = 8.14 m, a = 2.8 m, Ip = 21 MA,

  B = 5.7 T at R_{axis} = 8.57 m, q_a = 3.3.

  - ν_{perp}^{α} = 0.126 sec^{-1}, $\nu_{\varepsilon}^{\alpha}$ = 5.0 sec^{-1}

  - Alpha profiles similar outside r/a = 0.3

- L-mode Scenario

  -- peaked, pre-sawtooth profile

  modelled by the function $(1 - |x|)^3$ with x=r/a,

  -- flat, sawtooth-broadened profile

  modeled with Heaviside functions [H(x) - H(0.7-x)]

  no particles outside r/a = 0.7

- H-mode Scenario

  sawtooth average profile

  trapezoidal profile flat to r/a = 0.4,

  decreasing linearly to zero at r/a = 0.7.

III. B. RESULTS
1. L- and H-mode scenarios

* ORBIT simulations of 256 particles in ITER L-mode scenario I with collisional pitch angle scattering over τ^{α}_{S} showed no losses.

- Monte Carlo errors ~$n^{0.5}/n_T$; n=lost, n_T=total followed

- 1-σ upper bound on alpha ripple losses ~ 0.4%

- Losses < 0.4% simulated with reversed TF direction

* For sawtooth broadened profiles ~ 1.6 +/- 0.8% loss.

- ITER transport simulations show alpha profile sawtooth broadened for small fraction of pulse length.

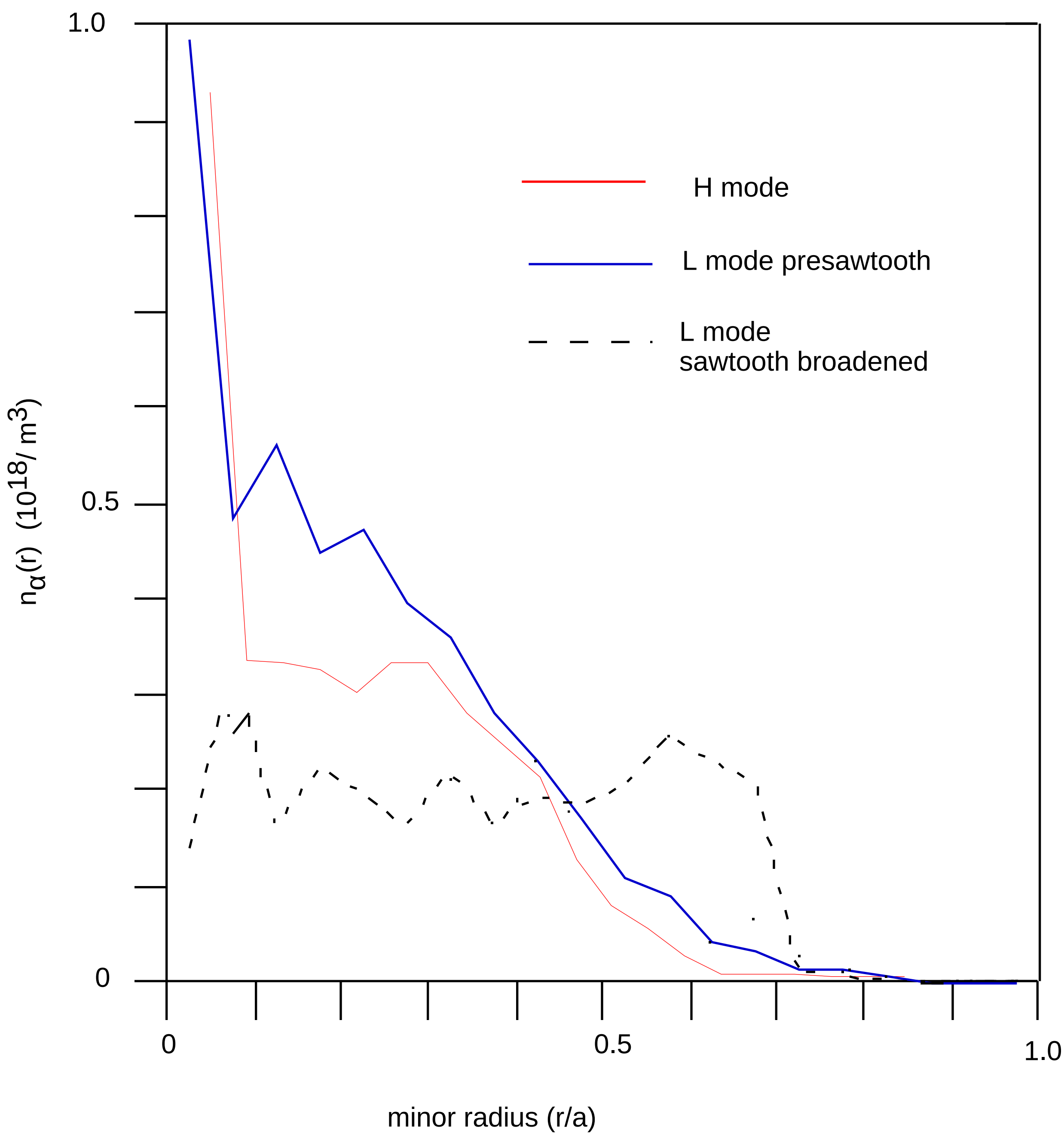
- Pulse averaged losses unaffected by sawteeth.

- Instantaneous energy deposition must be evaluated especially if MHD activity is excited.

- More complete model of sawtooth physics needed.

* H-mode scenario losses < 0.4%.

TRANSP Alpha Profiles
Show H-mode Broadening and
Transient Sawtooth Broadening



Summary of Guiding Center Code Alpha Losses(%)

1. ITER 21MA

	Ripple Loss		First Orbit Loss
	power	particle	
L-mode	0	0	0
L-mode grad B reversed	0	0	0
sawtooth broadened	0.7	0.8+/-0.6	0
sawtooth broadened, grad B reversed	0.8	1.6+/-0.8	0
H-mode	0	0	0

2. ITER/RS (Nevins)

	Ripple Loss power	Ripple Loss particle	First Orbit Loss
L-mode profiles	16	19+/-1.4	0.1+/-0.1

IV. New RS Equilibria Reduce TF Ripple Losses (Nevins)

* Appear to maintain confinement and vertical stability characteristics of Interim Design R/S plasma

	Alpha Ripple Loss	First Orbit Loss
* L-mode profiles		
Reduced elongation κ*	2.9+/-0.4	0.1+/-0.1
Reduced major radius R*	2.5+/-0.5	0
Reduced R and κ*	0.3+/-0.2	0

* Calculation using algorithm described in Sec. V.

* Dominant process is banana convection due to ripple wells and vertical asymmetry.

V. Rapid Calculation

(See Poster 6Q.04, McCune, TRANSP)

A. Goldston, White, Boozer stochastic ripple loss threshold

* Previous analysis code model for ripple loss

$$\delta_{GWB} = (\varepsilon / (N \pi q))^{1.5} \; (1 / \rho q')$$

ε = inverse aspect ratio,

N = number of coils,

q is the plasma safety factor,

q' = dq/dr and ρ is the ion Larmor radius.

- Trapped ions for which δ exceeds the threshold δ_{GWB} at birth bounce point are lost by stochastic ripple diffusion.
- Neglects toroidal precession, θ dependence of threshold, collisions, banana width and up/down asymmetry.
- Very strong q dependence, $q^{5/2}$

* Renormalization factors for TFTR and ITER from comparison with GC simulation,vary from 0.6 to 4.0
  - δ_{GWB} from Eq 3 of Goldston, White, Boozer, PRL'81
  - Build on more complete Eq 15, improved threshold theory

3. Heat load Estimate

* 20 TF coil design heat load first wall 0.5 MW/m^2

- Heavily armored toroidal belt limiter
- For startup and shutdown, 5.0 MW/m^2
- 3 meters below the magnetic axis height Z_m.
- Would not protect against alpha ripple loss near Z_m

* Heat load for maximum alpha ripple losses

- 21 MA Interim Design , ITER/RS(Nevins) ~0.4-19%
- Footprint of alpha ripple loss:
  2π (11m)(~3m) ~ 100m^2.
- Alpha ripple loss heat load ~ 0.01 - 0.4 MW/m^2.
- Wall heat load increased by
  MHD and TAE enhanced losses
  Toroidal wall heat load peaking factor

* Toroidal peaking factor > 1

- Possible misalignment of tiles, 2mm can be significant
- Radial movement of the field line itself due to TF
  ripple, field line will bow out between the TF coils
- Edges of the ports near the midplane, intercept alpha
  loss otherwise distributed over the port area.

* Clever first wall design

- Eliminate or protect against these effects
- Knowing how much, where alpha loss is expected.
- Requires more calculations, for all 3 kinds of loss:
  ripple trapping, banana convection, stochastic diffusion
- Do we need to be able to reverse B_T?

VB. New Stochastic Threshold Loss Algorithm

(Poster 6Q.02 White)

* Toroidal field ripple value for stochastic diffusion:

$$\delta_s = \Delta_s B (\delta_\theta B/B)^{0.5} / (g \rho (\pi N q)^{0.5})$$

* Collisionless diffusion conserves energy and μ

* Field strength at the banana tip is conserved;
  Particle lost if an uninterrupted loss path to the wall.

* Complete Algorithm for collisionless loss includes:
  - Prompt loss (Conservation of E, μ, P_φ, no ripple)
  - Rapid collisionless ripple well trapping
    ($\alpha^* < 1$ grad B drift side in most geometries)
  - Rapid banana convection
    ($\alpha^* < 1$ on reversed grad B drift side)
  - Stochastic collisionless diffusion loss

* Typical alpha particle confinement domain on TFTR.

2. Reversed shear operation in ITER difficult because of asymmetric ripple banana convection

Substantial Ripple Well in Reversed Shear Mode

Ripple Losses of Alpha Particles in Reversed Shear ITER Equilibrium Reduced for Smaller Elongation

(W. M. Nevins, LLNL)

With new algorithm, Sec. V

2.9±0.4% alpha ripple losses

Equilibrium 95015-02

$R = 9.49$ m, $Z = 1.052$ m, $B_{max} = 4.94$ T,

$\kappa = 1.960$, $a = 2.34$ m, $I_p = 12$ MA

Good agreement between theory and guiding center simulations

Loss due to stochastic ripple diffusion

Many different equilibria and particle energies tested

VI. CONCLUSIONS

* ITER Interim Design

- Number of TF coils (24 => 20) and TF ripple (2.1%=> 1.8%)were reduced in change from ITER Outline Design to new Interim Design

- Find ORBIT losses < 0.4% with collisions, sawtooth broadening and reversed grad B drift

- May need to improve birth profiles for more precision

- 21MA ripple loss appears not damaging to first wall First wall design needed for heat load estimate

- Initial results on R/S plasma show 19% loss, Much improved with new lower elongation equilibria

* New Method for Rapid Ripple Loss Calculation

- Theoretical understanding of ripple induced stochastic loss process
  - speeds calculation of alpha loss by x200
  - accelerate collisions and check periodically for fast loss due to ripple

- Algorithm compares well to guiding center code for alpha slowing down loss in various equilibria.

- Rapid algorithm being installed in TRANSP data analysis code for TFTR and other machines