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TF Ripple Loss of Alpha Particles in TFTR DT Experiments

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1. Introduction

Quantitative evaluation of TF ripple loss of DT alpha particles is a central issue for reactor design because of potentially severe first wall heat load problems. DT experiments on TFTR [1] allow experimental measurements to be compared to modelling of the underlying alpha physics, with code validation an important goal. Modelling of TF ripple loss of alphas in TFTR now includes neoclassical calculations of alpha losses arising from first orbit loss, stochastic ripple diffusion, ripple trapping and collisional effects. Recent Hamiltonian coordinate guiding center code (ORBIT) [2] simulations for TFTR have shown that collisions enhance the stochastic TF ripple losses at TFTR [3]. A faster way to simulate experiment has been developed which uses a simple stochastic domain model for TF ripple loss within the TRANSP analysis code [4].

2. ORBIT/TRANSP Renormalization of the Stochastic Domain Model

TRANSP, the primary PPPL time-dependent analysis code, has been upgraded with a simple model of fast ion ripple loss, renormalized by guiding center code simulations [3]. A simple criterion was obtained by Goldston, White and Boozer (GWB) for fast ion particle loss due to the TF ripple of tokamaks, which lack perfect axisymmetry due to a finite number of toroidal field coils [5]. The criterion, derived with a zero banana width, collisionless approximation in simplified geometry, compares the TF ripple $\delta = (B_{MAX} - B_{MIN})/(B_{MAX}+B_{MIN})$ to a stochastic ripple loss threshold $\delta_{GWB} = (\varepsilon/N\pi q)^{3/2}(1/\rho q')$. Here B_{MAX} and B_{MIN} are the maximum and minimum field magnitudes at constant major radius and elevation, 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 whose turning point lies in a region where δ exceeds the threshold, δ_{GWB}, are subject to stochastic ripple diffusion.

The ripple loss model in TRANSP is based on the above criterion. For both neutral beam ions and fusion products such as alpha particles, Monte Carlo ions are followed so that at each bounce point the TF ripple is compared to a threshold δ_S proportional to δ_{GWB}. The ratio δ_S/δ_{GWB} is evaluated by comparing particle and energy loss fractions to those found from ORBIT simulations for the same equilibrium geometry and source profile [4].

The total alpha energy which was ripple lost in each TRANSP and ORBIT simulation was used to renormalize the stochastic threshold for alphas. The $\delta_S = 0.6\ \delta_{GWB}$ threshold for alphas is reduced compared to the GWB model estimate, possibly due to the large banana width of the alpha particles. Eriksson and Helander [6] have examined semi-analytically, the stochastic ripple loss of RF heated ions at JET. They find that finite banana width causes the stochastic threshold to be decreased by as much as an order of magnitude.

For neutral beam ions, evaluating the stochastic threshold is complicated by the effects of charge exchange which are significant for these ions in the plasma. TRANSP follows beam and fusion product ions with an algorithm for artificial acceleration of pitch angle collisions (AAPAC) relative to the banana bounce time, to minimize computational time. The stochastic threshold for neutral beam ions is very sensitive to the AAPAC level. $\delta_S = 2\ \delta_{GWB}$ is practical at the default level used for routine transport analysis at TFTR, but $\delta_S = 4\ \delta_{GWB}$ corresponds to minimal AAPAC. For 100 keV beam ions, this high threshold, compared to δ_{GWB}, may arise from collisional stochastization of the resonant contribution to banana ripple diffusion or from present oversimplifications: the finite ripple diffusion time for neutral beam ions is not modelled, requiring an effectively higher threshold to match ORBIT code losses.

These code comparisons indicate that analysis codes, such as MAPLOS and SNAP, which set $\delta_S = 0.5\ \delta_{GWB}$ for all fast ions and which do not include effects of pitch angle scattering on the loss fractions, will underestimate alpha particle ripple losses by about a factor of 2 and will overestimate neutral beam ion ripple losses by about the same factor. The TRANSP code calculates the selfconsistent evolution of the plasma equilibrium along with ripple loss, collisional effects, beam driven and bootstrap current, *etc.* As a result, a new stochastic loss region develops near the magnetic axis when ripple losses are calculated [4]. The appearance of this region may be an artifact of modelling the diffusion process too simplistically.

3. Comparison with Experimental Measurements

The renormalized stochastic domain ripple model has been used for analysis of current TFTR DT experiments. Ripple loss energy fractions range from 2-15% for alpha particles and from 2-20% for neutral beam ions. The effects of pitch angle scattering accummulate over τ^{α}_S so that losses increase as Ip increases, as was also found in ORBIT simulations [3].

General Atomics, the Princeton Plasma Physics Laboratory and the Ioffe Physical-Technical Institute have developed a pellet charge exchange diagnostic (PCX) [7] to observe the confined alpha particle distribution function. For a sawtooth free experiment (#84550), good agreement with the ORBIT/TRANSP renormalized stochastic domain model [8] is found. This is an important validation of the ripple model, unaffected by unresolved questions about sawtooth modelling.

Limiter heating found with DT experiments agrees within a factor of 2 with estimates from alpha heating based on 6.2 MW maximum fusion power [9].

Lost alpha measurements [10] are difficult to compare quantitatively with the TRANSP modelling, which does not follow the entire ripple lost ion orbit. Figure 1 shows (a) the Ip dependence of alphas measured on TFTR at about 20 degrees below the midplane and 1.7 cm behind the limiter shadow, as well as (b) the TRANSP global loss rates for the alpha particle stochastic ripple and first orbit losses. TRANSP error bars are due to Monte Carlo noise for simulations with 2000 particles. Both measurements and calculations of global stochastic ripple losses show increased loss with increasing Ip at low current. At high Ip, the current dependent behavior of midplane alpha data [11] and its time dependence after neutral beam turnoff are similar to the TRANSP global first orbit loss, with no increase in alpha loss per DT neutron nor decreased average lost alpha energy after beam turnoff, unlike global stochastic ripple loss calculations. The predicted increase in stochastic ripple loss after NBI, strongest at zero degrees, might not be observable with the probe. Differences between the observed and predicted current and time dependence of alpha losses after beam turnoff, may be due to the midplane probe collecting significant first orbit and "fattest banana" orbit losses. Further work is in progress to resolve understanding of the data.

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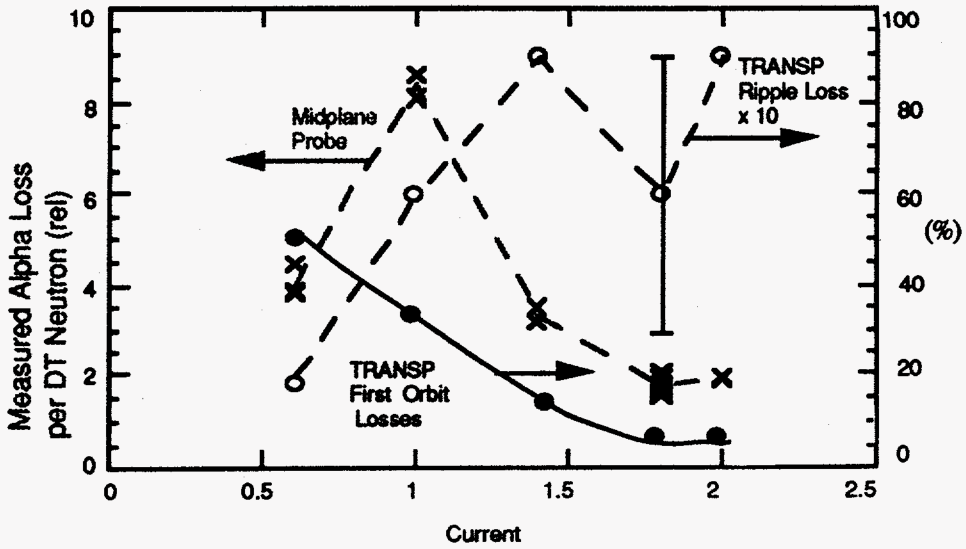

Fig. 1: Ip dependence of alpha ripple losses for R=2.52m plasmas from midplane probe measurements and TRANSP calculations of global loss.