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Alpha Particle Loss in TFTR Deuterium-Tritium Plasmas with Reversed Magnetic Shear

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1. Introduction

The confinement and loss of fusion alpha particles are examined for reversed magnetic shear plasmas in TFTR. Such plasmas, with high central q and non-monotonic q profiles can exhibit remarkably reduced energy and particle transport of the thermal ions. However, these same conditions are theoretically predicted to produce high levels of stochastic ripple loss of suprathermal particles, which may reduce the efficiency of plasma heating by the alpha particles and other heating schemes involving fast ions. This paper presents calculations of guiding-center code alpha particle orbit loss from deuterium-tritium (DT) simulations of TFTR deuterium-only experiments. They are compared to results of measurements made in DT reversed shear plasmas of both the confined alpha particle distribution and the alpha particles lost from the plasma. Large fast particle losses have also been found in reversed shear ITER simulations (up to 20%)[1,2] and from measurements of triton burnup in reversed shear experiments on JT-60U (12%)[3].

2. Guiding-Center Code Method

A new, fast, Hamiltonian-coordinate guiding center code, ORBIT[4], has been used for the simulations which makes use of a rapid accurate algorithm for the stochastic-free, confinement domain. Figure 1 shows the confinement domains for alpha particles in reversed and monotonic shear as a function of energy[5]. In the reversed shear plasma, the entire plasma is above threshold for stochastic ripple loss of trapped alpha particles at the birth energy, 3.5 MeV. All of the 33% trapped alphas are lost rapidly through unconfined orbit losses or stochastic ripple loss, as $q(r) \geq 2$ throughout the plasma. Pitch angle scattering of passing particles refills the trapped distribution and leads to continued alpha loss throughout the slowing down process.

In Table 1 are shown results for reversed shear plasmas with large major radius where toroidal magnetic field ripple is most significant. They are compared to those previously published[6] for similar experiments on TFTR but with a monotonic shear profile, at both high and low current. The predicted losses for reversed shear (~40%) are about twice the total alpha losses predicted for the high current plasma with a monotonic shear profile.

It is found that the simple renormalized Goldston, White, Boozer[7] ripple loss model[8] used in the TRANSP code for TFTR leads to alpha ripple losses in agreement with the guiding center code simulations for both the reversed shear and monotonic shear cases. The simulations show that transport due to TF ripple, for both monotonic and reversed shear q profiles, lies primarily within $r/a = 0.5$. Ripple loss is not greatest at the plasma edge, nor is there enhanced ripple broadening of the alpha profile toward minimum q in the reversed shear region. Including radially-varying collision rates or increased alpha profile peakedness does not significantly change the predicted losses. Strong synergism between collisions and ripple transport, predicted for high current, monotonic shear plasmas, is not found in reversed shear because of high first orbit loss and strong collisionless ripple diffusion.

3. Comparison with Confined Alpha Particle Data

ORBIT was used to model the observations of the pellet charge exchange diagnostic (PCX)[9]. Alpha particles with initial profiles consistent with Abel-inverted neutron profiles measured on TFTR, were followed for τ_s and $2\tau_s$ in monotonic and reversed shear magnetic geometries. Because the PCX diagnostic has an observation window which detects only very deeply trapped alphas with pitch $v_{//}/v = -0.05$ at the midplane ($\theta = 0$), it was necessary to follow a very large initial ensemble of alpha particles to obtain adequate statistics within a window of constrained pitch and poloidal angle to model the diagnostic. For simulations of PCX in monotonic shear plasmas an initial ensemble of 50,000 alphas was sufficient (as compared to 256 alphas for global estimates of alpha loss rates which takes ~4 hours Cray C90 cpu time). In reversed shear on TFTR, however, because only passing, neo-natal alphas pitch-angle scattered into trapped orbits can be seen by PCX, it was necessary to simulate ~2,000,000 alpha particles to obtain adequate statistics of ~400 alphas, within the simulated PCX window having $v_{//}/v = -0.15$ to $+.05$ and $|\theta| \leq 0.1$. Time dependence of the initial distributions was not modelled.

To minimize computational run time, ORBIT used the new stochastic loss algorithm and accelerated collision rates, ν_{PA} and ν_s. This method of speeding up the loss calculations gives good global loss estimates even for reversed shear equilibria. Use of conservation laws for ion energy and magnetic moment were also used to project the final orbits to $\theta = 0$ to further improve statistics. Without the rapid calculation features of the new code the simulations would not have been possible and even so are just at the edge of present computational resources.

In Figure 2 the simulated profiles are compared to PCX analysed data for monotonic and reversed shear plasmas. In monotonic shear, at one slowing down time (1.3 MeV) and at two slowing down times (0.5 MeV) the profiles are similar to those observed with PCX. The simulated profile at 0.5 MeV extends over a larger region in r/a as expected from the larger stochastic free region at lower energy.

In reversed shear two features of the PCX analysed data are distinctly different from the monotonic shear case: 1) a flat or hollow distribution at 1.71 MeV, which appears to be filled as the energy of observed alphas decreases to 1.3 MeV and 0.5 MeV; 2) a very steep profile at 0.5 MeV. The model predicts the general characteristics of alpha loss in reversed shear which clarify how a hollow profile could arise. In reversed shear no trapped alphas would be observed at 3.5 MeV, while at lower energies a peaked, flat or hollow profile can result depending on pitch angle scattering and the passing alpha distribution. The simulated profiles for reversed shear were obtained with a pitch angle scattering rate twice that of the experiment for which data is presented. 50,000 particle simulations with various collision rates indicate that agreement with PCX would be achieved with a reduction in ν_{PA}. At 0.5 MeV, ORBIT results are in good agreement with the data, showing a steep profile obtained after $2\tau_s$.

4. Lost Alpha Particle Data

Measurements of alpha loss 90 degrees below the midplane during I=1.6 MA RS/ERS discharges showed an alpha loss per DT neutron to be about three times larger than during standard 1.6 MA DT supershots, roughly consistent with the expected increase in first orbit loss at the vessel bottom due to the higher q(r) near the center. Measurements of alpha ripple loss to the outer midplane could not be made due to the large minor radius of the RS/ERS plasmas and the shadowing effect of the outer limiters.

5. Neutral Beam Ion Ripple Loss in Reversed Shear

DT reversed shear plasmas exhibit neutron levels a factor of 2-3 lower than expected from extrapolation of the neutron emission from DD plasmas with similar confinement. The effects of ripple diffusion of neutral beam ions and the Maxwellian tail of thermal ions on the neutron rate are being investigated. Preliminary guiding-center code simulations predict losses for tritium beams to be about the same as for deuterium beams at the same energy and pitch angle, although higher triton loss rates are expected from the reduced stochastic threshold (20% lower due to the higher Larmor radius). The TRANSP ripple loss model is being upgraded to make use of the new confinement domain algorithm and may account satisfactorily for low DT reversed shear neutron emission. The present GWB ripple loss model predicts ~20% loss of D or T beams for R=2.6m TFTR supershots[8] and in reversed shear. TRANSP simulations adjusted to match the neutron emission are found to have reduced tritium neutral beam ion heating corresponding to 20-30% additional tritium loss. TRANSP has been used to see if anomalous impurity accumulation to deplete reacting D and T ions would reduce predicted neutron emission while retaining good confinement and agreement with measurements of the perpendicular stored energy. Simulations of RS plasmas into which short tritium beam pulses are injected show that the uncertainties in recycling and Z_{eff} are not sufficient to account for the DD/DT neutron discrepancy[10].

6. Conclusion

Simulations with a Hamiltonian coordinate guiding-center code of a reversed shear plasma in TFTR predict that alpha particle losses are near 40%, about double the total alpha losses from a comparable plasma with a monotonic shear profile[5]. In the reversed shear case, the entire plasma is above threshold for stochastic loss of trapped alpha particles at birth energy. Pitch angle scattering of passing particles refills the trapped distribution and leads to continued alpha loss throughout the slowing down process.

The simulations are in qualitative agreement with PCX confined alpha profile data for monotonic shear. In reversed shear at low energy, the ripple loss modelling and pitch angle scattering rates from DT simulations give profiles roughly consistent with PCX. At high energy agreement is less good. The simulations were based on a TFTR experiment having a pitch angle scattering rate twice that of the plasma in which the PCX data was taken. Predictions for this profile are most sensitive to the pitch angle scattering rate because of the loss of birth energy trapped alphas.

Qualitative agreement of ORBIT simulations with measurements of confined alpha profiles and alpha loss data gives confidence in the simulation method for predicting the global losses of TFTR and ITER (3-19% for some reversed shear configurations). Guiding center code simulations of neutral beam ion ripple loss and TRANSP analysis of the effects on the DT neutron emission in reversed shear are also needed. The discovery of reversed shear plasma configurations with dramatically improved transport holds promise for future applications of controlled fusion. The high losses predicted for TFTR and ITER reversed shear scenarios support new constraints on the allowed TF ripple for such reactors. The exploitation of reversed shear equilibria for reactor design will require minimal magnetic field ripple and impurity levels to reduce collisional ripple loss and to optimize alpha particle confinement and heating.

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Table 1. Guiding Center Code Alpha Losses (%) for R=2.6 m TFTR Cases

	Reversed Shear (1.6 MA)	Monotonic Shear (1.8 MA)	Monotonic Shear (0.9 MA)
First Orbit	18	6	21
Delayed Particle Loss	22	17	13
Total Particle Loss	40	23	34
Total Energy Loss	38	19	32

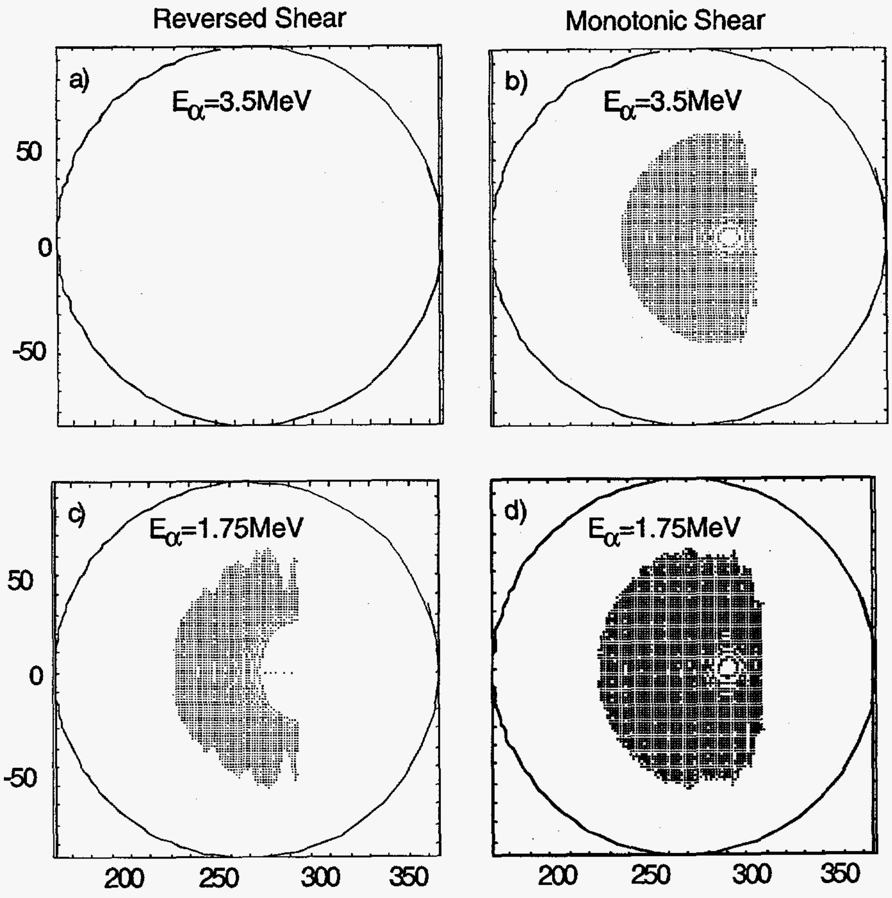

Figure 1. Confinement region for alpha particles in reversed shear (1a,1c) and monotonic shear (1b,1d) as a function of alpha energy.

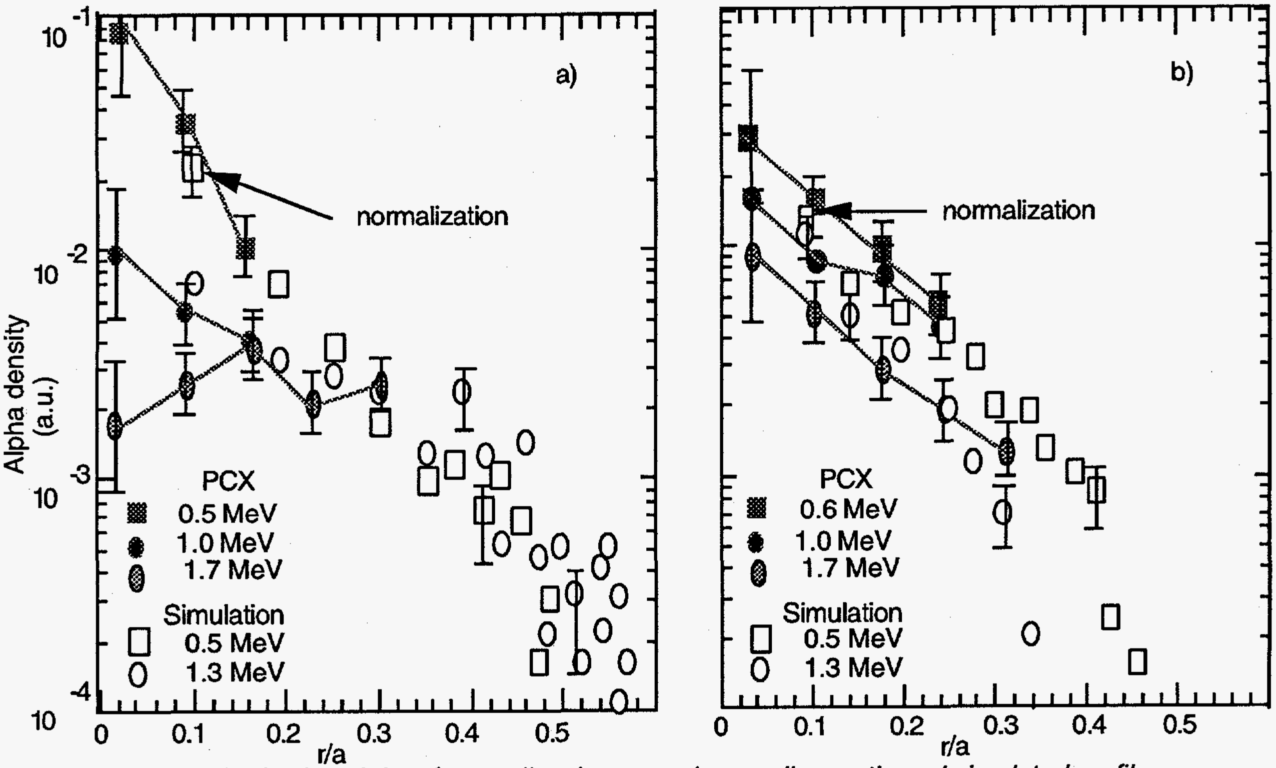

Figure 2. Analysed data from pellet charge exchange diagnostic and simulated profiles for reversed shear (2a) and monotonic (2b) plasmas as a function of alpha energy.