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## **Aspects of Trapped Confined Alpha Physics on TFTR**

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### ***Abstract***

The energy distributions and radial density profiles of the fast-confined trapped alpha particles in DT experiments on TFTR are being measured in the energy range 0.5 to 3.5 MeV using the Pellet Charge Exchange diagnostic developed in a collaboration involving General Atomics, the A.F. Ioffe Physical-Technical Institute, and the Princeton Plasma Physics Laboratory. A brief description of the measurement technique which involves active neutral particle analysis using the ablation cloud surrounding an injected lithium or boron pellet as the neutralizer is presented. In the core of quiescent TFTR discharges, measured alpha spectra are consistent with classical slowing down. Measured Doppler broadening of alphas near the birth energy is consistent with the effective temperature of interacting deuterium and tritium ions. Outside the core alpha energy spectra and density profiles are influenced by the magnetic field ripple and appear to be consistent with stochastic ripple diffusion. Sawtooth oscillations lead to the significant broadening of alpha density profiles. The experimental data are modeled using a Fokker-Planck Post TRANSP (FPTP) code which includes the effects of the classical slowing down, magnetic field ripple losses, and the sawtooth mixing of alpha particles. The comparison of the experimental data with the FPTP calculations shows that broadening of trapped alpha density profiles after the sawtooth crashes can be explained by the influence of poloidal electric field generated during the crashes.

## 1. Introduction

The energy distributions and radial density profiles of the fast confined trapped alpha particles in DT experiments on TFTR are being measured in the energy range 0.5 to 3.5 MeV using the Pellet Charge Exchange (PCX) diagnostic. This technique uses the active neutral particle analysis with the ablation cloud of an injected lithium or boron pellet as the neutralizer [1]. Initial measurements of the fast confined alpha energy distributions and alpha density radial profiles in the presence of stochastic ripple diffusion and sawtooth oscillations were reported previously [2,3]. This paper focuses on more detailed analysis of some aspects of fast confined alpha physics on the basis of modeling of PCX experimental results with and without the presence of stochastic ripple diffusion and sawtooth mixing.

## 2. PCX Technique and Data Analysis

The PCX diagnostic on TFTR uses lithium and boron pellets injected along a midplane major radius. The neutral particle analyzer views the pellet from behind with a sightline at a toroidal angle of 2.75 deg to the pellet trajectory. Consequently, only trapped alphas with velocities close to  $v_{||}/v = -0.048$  are detected in these experiments. The radial position of the pellet as a function of time is measured with a linear photodiode array situated on the top of the vacuum vessel. From the time dependence of the PCX signal, radially resolved fast ion energy spectra and density radial profiles can be derived with a radial resolution  $\sim 5$  cm. Further details of the PCX measurements were presented in Ref. 4.

The experimental data are compared with modeling results obtained with a specially developed Fokker-Planck Post TRANSP (FPPT) processor code [5]. TRANSP [6] follows the orbits of alphas as they slow down and takes into account the spatial and temporal distributions of the background plasma parameters for each particular shot. The FPPT code is based on a numerical solution of the drift-averaged Fokker-Planck equation for the particular PCX pitch angle ( $v_{||}/v = -0.048$ ):

$$\delta f / \delta t = \langle St(f_\alpha) \rangle + \langle S_\alpha \rangle - f_\alpha / \tau_\delta - f_\alpha / \tau_{\text{conf}} \quad (1)$$

where  $f_\alpha$  is the distribution function of alphas including the thermal broadening effect,  $St(f_\alpha)$  is the collisional integral describing the slowing down of alphas,  $S_\alpha$  is the alpha source taken from TRANSP code,  $\tau_\delta$  is the confinement time of alphas determined by the effect of toroidal field ripple, and  $\tau_{\text{conf}}$  is the confinement time of alphas determined by alpha radial transport of any other type excluding ripple effects.

### 3. Alpha Slowing Down in the Core of Quiescent Discharges

In the TFTR DT experiments, pellets for the PCX diagnostic typically are injected 0.2 to 0.5 s after termination of neutral beam heating. This timing delay allows  $T_e$  and  $n_e$  to decrease, resulting in deeper penetration of the pellet as well as enhancement of the signal-to-noise ratio because the neutron background decays significantly faster than the confined alpha population. Here we present studies of the distribution functions of alphas in the plasma core of a quiescent discharge where there is neither significant ripple nor MHD influence on alpha particles. Figure 1 shows the energy spectrum of alphas in the plasma center which was obtained using a Boron pellet injected 0.2 s after the termination of 1.0 s, 15 MW beam pulse (#86291). The alpha slowing down time in this case is equal to  $\tau_{sl} = 0.32$  s. The solid line shows the FPPT calculation assuming that  $\tau_{conf} \gg \tau_{sl}$  ( $\tau_{conf} = 300 \tau_{sl}$ ). The dotted lines present the cases where  $\tau_{conf}/\tau_{sl} = 3.0, 1.5, 0.8$  and  $0.4$ . It is seen from Fig. 1 that the case  $\tau_{conf} \gg \tau_{sl}$  provides the best modeling fit to the data. This supports the statement that the alpha energy spectra is determined only by the classical slowing down without significant transport during the slowing down.

### 4. Studies of the Effect of Toroidal Ripple on Trapped Alphas

Figure 2 presents PCX radial density profiles of alphas with energies of 0.64, 0.8, 1.0, 1.21 and 1.41 MeV measured 0.3 s after termination of 20 MW beam injection, normalized at  $R = 2.65$  m (#84550). Also shown is the Goldston-White-Boozer (GWB) stochastic ripple diffusion radial boundaries [7] for alpha energies of 0.64, 1.41 and 3.5 MeV. These boundaries are defined by the following expression:  $\delta_{TF} \rho q' (\pi N q / \epsilon)^{3/2} > 1$ , where  $\delta_{TF}$  is toroidal field ripple,  $\rho$  is the alpha gyroradius,  $N$  is the number of toroidal field coils,  $q$  is the safety factor,  $q' = dq/dr$ , and  $\epsilon$  is the inverse aspect ratio. Inside the GWB boundaries the alpha behavior is classical while outside there exists a domain where alpha particles are strongly affected by stochastic ripple diffusion. It is seen that alpha density radial profiles are consistent with the GWB boundary for  $E_\alpha = 3.5$  MeV. This demonstrates the absence of significant alpha transport outward during slowing down from the birth energy to at least 0.64 MeV and the strong ripple influence on alphas outside the GWB boundary. Ripple diffusion causes alphas born outside the GWB boundary to be promptly lost while alphas born inside this boundary are confined and slowing down there in the absence of any outward transport. Note that at the time of measurement (0.3 s after the termination of neutral beam heating) the generation of alphas is practically absent. This result is consistent with the data presented in Fig. 1. Figure 3 presents the experimental alpha density profiles and the FPPT code predictions for  $E_\alpha = 0.64$  and 1.21 MeV with and without ripple. Modeling results are normalized to the PCX data separately for both energies. It is seen that experimental data are in good agreement with the ripple modeling. It is seen also that the modeling without ripple predicts much broader radial density profiles than experimentally measured.

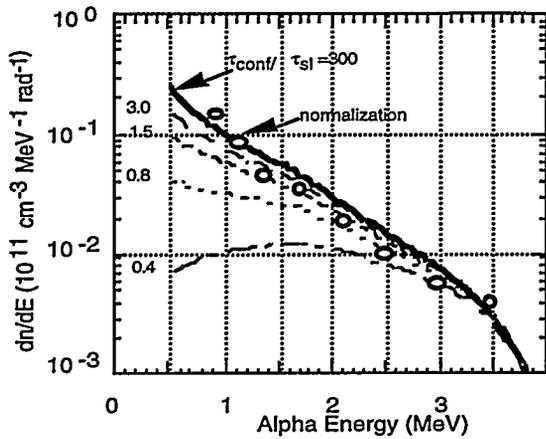


Fig. 1. Alpha energy spectra in the plasma core.

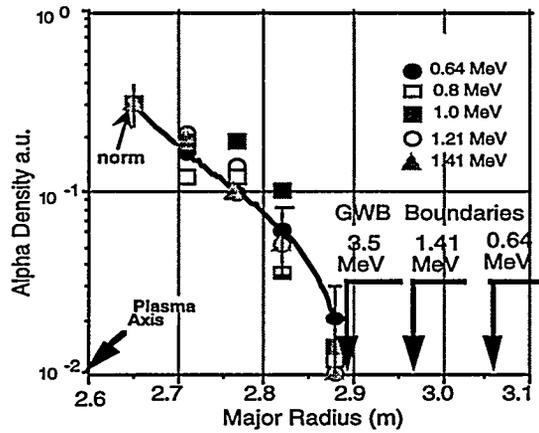


Fig. 2. Alpha radial density profiles.

## 5. Sawtooth Mixing of Alpha Particles

Sawtooth crashes in TFTR usually occur 0.3 to 0.4 s after termination of neutral beam injection. For PCX measurement of the sawtooth mixing of the alphas, a Li pellet was injected immediately before the first sawtooth crash in one discharge and immediately after the sawtooth crash for a similar discharge. Figure 4 presents the alpha radial density profiles ( $E_\alpha = 1.21$  MeV) before and after the crash. A significant outward transport of alphas well beyond the  $q = 1$  surface is clearly seen. The magnitude of this sawtooth mixing is observed to decrease with increasing alpha energy. Sawtooth models [8] based on magnetic reconnection and the conservation of magnetic flux and particle energy and density can not provide the strong outward transport of trapped alphas observed experimentally. Recently, a model of the sawtooth mixing of trapped alphas was implemented in the FPPT code in which a helical electric field produced by the sawtooth crash leads to a change in the alpha energy [5]. In Fig. 4, results from this model before and after the sawtooth crash are shown by the solid lines. Also shown are the GWB boundaries for  $E_\alpha = 1.21$  and 3.5 MeV. The modeling results are in agreement with the PCX experimental data and the alpha density profiles are consistent with the GWB boundaries. It is seen that the sawtooth oscillations transport trapped alphas radially to near the stochastic ripple loss region, which can lead to enhanced ripple losses.

## 6. Summary

In the plasma core of quiescent TFTR DT plasmas, the trapped alpha particles are well confined and slow down classically without any significant losses. In outer regions,

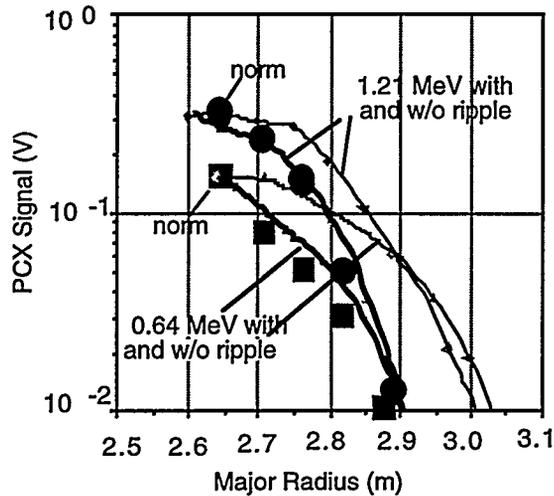


Fig. 3. Alpha density profiles with and without ripple

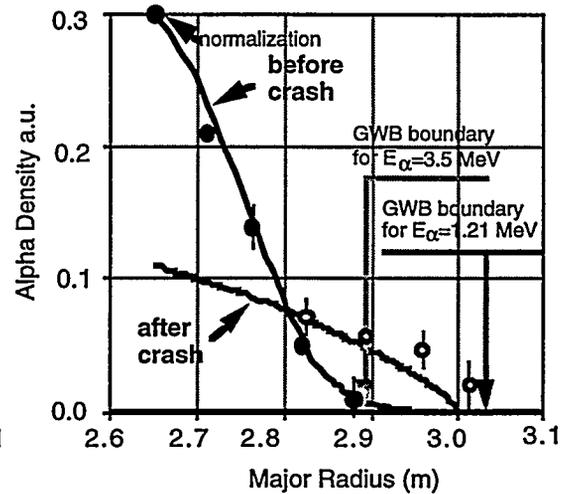


Fig. 4. Sawtooth mixing of alphas

trapped alphas are strongly affected by magnetic field ripple and by sawtooth mixing which can be modeled on the basis of a perturbed helical electric field.

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