LOSS OF ALPHA PARTICLES INDUCED BY SAWTOOTH OSCILLATIONS IN TFTR

Ya.I. Kolesnichenko[1], **V.V. Lutsenko**[1], R.B. White[2], Yu.V. Yakovenko[1], and S.J. Zweben[2]

[1]*Scientific Centre "Institute for Nuclear Research", Kyiv, 252650, Ukraine*
[2]*Princeton Plasma Physics Laboratory, P.O.Box 451, Princeton, NJ, 08543, USA*

1. Introduction

The work presents results of both experimental and theoretical studies of alpha particle flux to the wall induced by crashes of sawtooth oscillations in the Tokamak Fusion Test Reactor (TFTR).

The investigation of escaping fast ions is of importance for better understanding of the physics of fast ion transport in the presence of sawteeth, as well as for reliable modeling of the effect of sawtooth oscillations on the energy deposition of alpha particles and other fast ions in tokamak reactors. Moreover, studying the lost particles, one can make certain conclusions concerning the physics of the sawtooth crash itself.

2. Numerical simulations of the motion of single alpha particles affected by a sawtooth crash

To carry out the numerical simulation, we use the model description of the sawtooth crash proposed in Ref.[1]. We assume that only sawtooth oscillations break the axial symmetry of the magnetic field. In order to describe the magnetic field in the vacuum gap between the plasma and the wall, we use an approximate solution of the Grad-Shafranov equation in this region, which was found in this work assuming that (i) plasma touches the wall at the inner midplane of torus and (ii) the gap is narrow, so that the Shafranov shift can be approximated as $\Delta = \Delta_a + \Delta'(r - a)$, where r is the flux surface radius, a is the plasma radius.

Based on the formulated equations, we studied the behavior of particles located inside the sawtooth mixing region before a crash. The following parameters relevant to the TFTR DT shot #87530 were used: $I = 1.4\,\mathrm{MA}$, the magnetic field at the axis $B_0 = 3.2\,\mathrm{T}$, $a = 87\,\mathrm{cm}$, the minor radius of the wall $r_w = 99\,\mathrm{cm}$, the crash duration $\tau_{cr} = 3.5 \times 10^{-5}$s, the sawteeth mixing radius $r_{mix} = 57\,\mathrm{cm}$, $q_0 \equiv q(0) = 0.8$. The profile of the inverse safety factor (q^{-1}) was taken as two parabolas at $0 \leq r \leq r_{mix}$ and $r_{mix} \leq a$, aligned smoothly at $r = r_{mix}$. In addition, the $q = 1$ radius was assumed to be $r_{mix}/\sqrt{2}$.

Our calculations have shown the following. Only a narrow group of particles, which are marginally circulating and located sufficiently close to the magnetic axis before a crash, can be expelled to the wall. The process of the particle escape can be divided into two stages. First, interaction of the particles with the MHD perturbation, which expels the particle from the plasma core. This process is terminated by transformation of the circulating particle into a marginally trapped one, accompanied by a sharp change of the orbit width. After the transformation occurs, the particle can be lost within one bounce (see Fig. 1).

It has been found that only particles with sufficiently high energy, $\mathcal{E} \geq \mathcal{E}_{min}$ can be lost, and that the lost particles reach the wall at $\theta_{min} \leq |\theta| \leq \theta_{max}$ (either below or above the midplane of the torus, depending on the direction of the toroidal magnetic field). Escaping particles either strike the wall or have the orbits tangent to the wall surface at a certain poloidal angle $\theta_\tau(\mathcal{E})$. The latter angle separates the wall areas where $\Gamma_\mathcal{E} = 0$ and $\Gamma_\mathcal{E} \neq 0$ ($\Gamma_\mathcal{E}$ is the flux of alpha particles with given energy to the wall), and $\theta_{min} \equiv \min \theta_\tau(\mathcal{E})$. The characteristic angles $\theta_\tau(\mathcal{E})$ and θ_{min} exist due to the presence of the vacuum gap which produces the shadowing effect in the region of small $|\theta|$. On the other hand, θ_{max} is associated with the fact that trapped particles can strike the wall only at a point located at $R > R_t$ where R is the distance to the major axis of the torus, and R_t is the point of orbit transformation.

3. Experimental observations and theoretical description of the alpha flux to the wall

Sawtooth oscillations were observed in several TFTR DT shots with $I = 1.4\,$MA and $I = 2\,$MA. They occurred only in discharges at relatively low neutral beam injection power. It was found that the dominant effect of the sawteeth on alpha particles consists in their redistribution inside the plasma. Most of experimental data on the sawtooth-induced loss of alpha particles comes from the 1.4-MA shots.

Observations of the alpha loss during sawtooth crashes were made using the lost alpha scintillation detectors located $90°$, $60°$, $45°$, and $20°$ below the outer midplane (in the ion ∇B-drift direction). It turned out that the alpha flux to the wall is strongly inhomogeneous, being strongly peaked at the $20°$ and $90°$ detectors and on the noise level at the $45°$ detector.

This experimental fact and our analysis in Sec. 2 indicate that different physical mechanisms are responsible for the escape of alphas to the wall at $|\theta| > 45°$ and near the equatorial plane of the torus. Indeed, it follows from results of Sec. 2 that the particles lost because of the orbit transformation cannot reach the wall area at small $|\theta|$. On the other hand, one can expect that the stochastic (collisionless) ripple diffusion may be responsible for the alpha loss at $|\theta| < 45°$. This hypothesis was partly verified by numerical calculations carried out with using the Hamiltonian guiding-center code ORBIT [2]. It was found that if the alpha source vanishes outside the sawtooth mixing radius (which models the crash-induced source) then the dominant fraction of the escaping particles consists of moderately trapped particle with the energy close to 3.5 MeV and $\vartheta_t \lesssim \pi/2$, where ϑ is the poloidal angle on a flux surface (ϑ and θ are different as the centres of the cross sections of a flux surface and the chamber wall do not coincide), the subscript "t" refers to the banana tips. Such particles can reach the wall only at $|\theta| < 30°$. This conclusion follows from Fig. 2, which shows the dependence of θ_τ on λ for particles with various $\mathcal{E}$, where $\lambda = \mu B_0/\mathcal{E}$, μ is the particle magnetic moment. It also follows from Fig. 2 that the particles with $\lambda \sim 0.8$, which is typical for the particles escaping due to the orbit transformation, reach the wall at $|\theta| > 30°$. Note that the dependence of θ_τ on λ shown in Fig. 2 is rather general, being almost independent on the specific mechanism leading to the particle loss. Therefore, Fig. 2 confirms, in particular, the shadowing effect for delayed loss in Ref.[4] and shows that the shadow for orbit transformation loss of particles with the same energy is essentially larger (unlike the statement in Ref.[4] that the shadowing effect is absent in the last case).

In order to describe the poloidal distribution of the alpha flux to the wall for $|\theta| \geq 30°$, an approach based on the assumption that the crash duration essentially exceeds the particle transit time / bounce period was suggested. This approach implies that a crash induces additional alpha prompt loss with the source of alphas localized in the vicinity of the X point of the separatrix between the trapped and circulating orbits $(r_X, \vartheta_X = \pi)$. Two models of the crash were used: first, the Kadomtsev model [3] and, second, the "strong mixing" model with $V(r_X) = \text{const}$, where $V(r_X)$ is the volume of the plasma reaching the transformation point during the crash. Results of the calculations and experimental data are shown in Figs. 3–4. It follows from Fig. 4 that there is a reasonable agreement between the theory and the experiment.

4. Conclusions

Sawtooth crashes in TFTR may result in alpha flux to the wall, which is strongly inhomogeneous. The dominant physical mechanisms responsible for the alpha particle escape are the crash-induced prompt loss, which leads to wall load mainly near the chamber bottom, and stochastic diffusion resulting in wall load near the midplane of the torus. The first mechanism leads to the escape of particles which were circulating before the crash, whereas the second one affects mainly trapped particles.

Note that the physical picture of the prompt escape of fast ions caused by core localized MHD perturbations of different kinds seems to be similar to the considered one, involving two stages (interaction with MHD perturbation followed by orbital loss). This may explain why experimentally measured on TFTR poloidal distributions of alpha flux to the wall at $|\theta| \geq 45°$ are rather similar for the losses induced by sawtooth oscillations, Mirnov oscillations and minor disruptions [5]. The differences at the first stage may explain very different wall load magnitude due to the mentioned processes.

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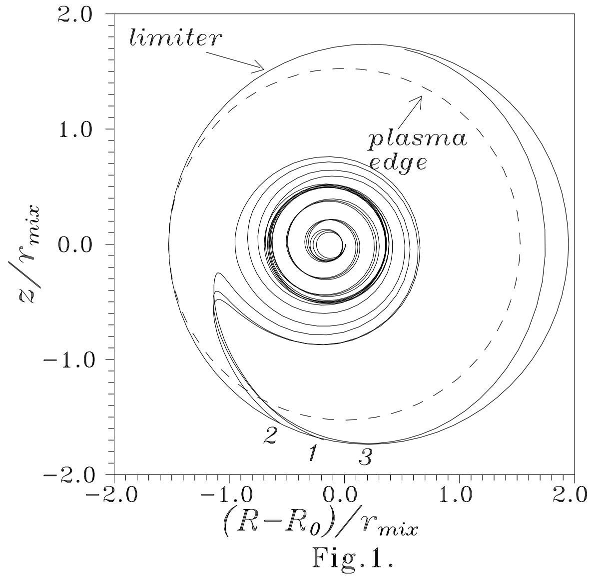
References

[1] Ya.I. Kolesnichenko and Yu.V. Yakovenko: Nucl. Fusion **36**, 159 (1996).
[2] R.B. White and M.S. Chance: Phys. Fluids **27**, 2455 (1984).
[3] B.B. Kadomtsev: Sov. J. Plasma Phys. **1**, 389 (1976).
[4] V.A. Yavorskij et al.: *Proc. 5th IAEA Tech. Comm. Meeting on Alpha Particles in Fusion Research*, Abingdon, 1997, p. 29.
[5] S.J. Zweben et al.: Bull. Am. Phys. Soc. **42**, 1971 (1997).



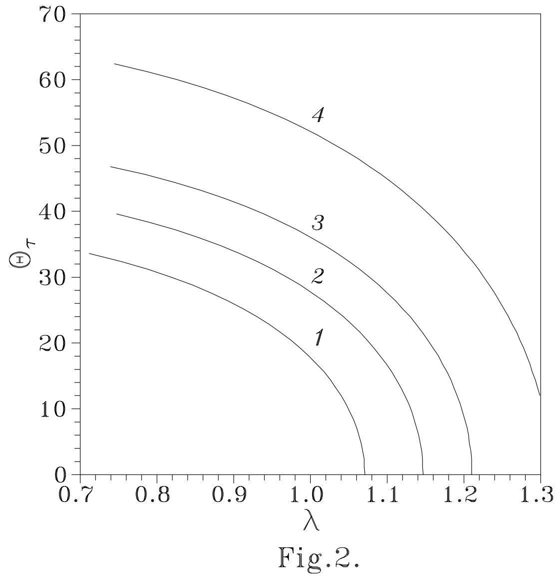
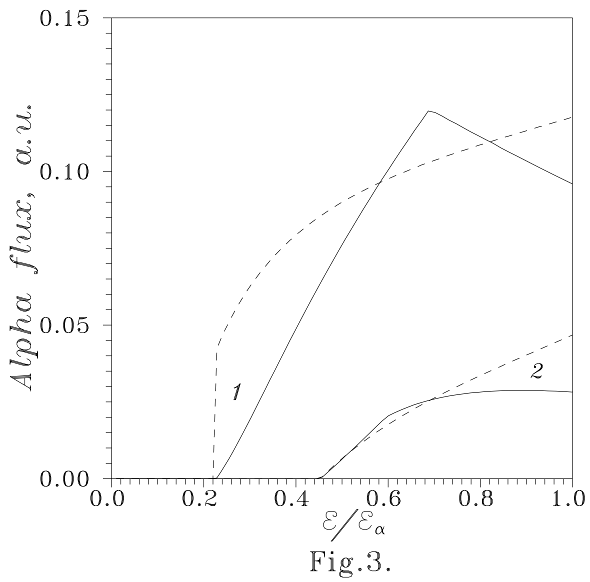


Fig. 1. Crash-induced escape of circulating α-particles with $\lambda = 0.75$ and various energies (1, $\mathcal{E} = 3.5$ MeV; 2, $\mathcal{E} = 3.0$ MeV; 3, $\mathcal{E} = 2.5$ MeV) accompanied by orbit transformation in the TFTR DT shot #87530, $\Delta' = 1.8/A$, A is the plasma aspect ratio. Orbit of the particle with $\mathcal{E} = 2.5$ MeV touches the wall, therefore this energy is minimum for escaping particles with given λ.

Fig. 2. θ_τ versus λ for various $\mathcal{E}$ in the same shot as in Fig. 1. 1, $\mathcal{E} = 3.5$ MeV; 2, $\mathcal{E} = 3.0$ MeV; 3, $\mathcal{E} = 2.5$ MeV; 4, $\mathcal{E} = 1.5$ MeV. Particles with given $\mathcal{E}$ which escape because of the orbit transformation reach the wall at $|\theta| \geq \theta_\tau(\mathcal{E}, \lambda = 0.75 + \delta\lambda)$, where $0 \leq \delta\lambda \leq 0.05$; stochastic diffusion leads to the wall load at $|\theta| \simeq \theta_\tau(\mathcal{E}, \lambda \simeq 1.1)$.



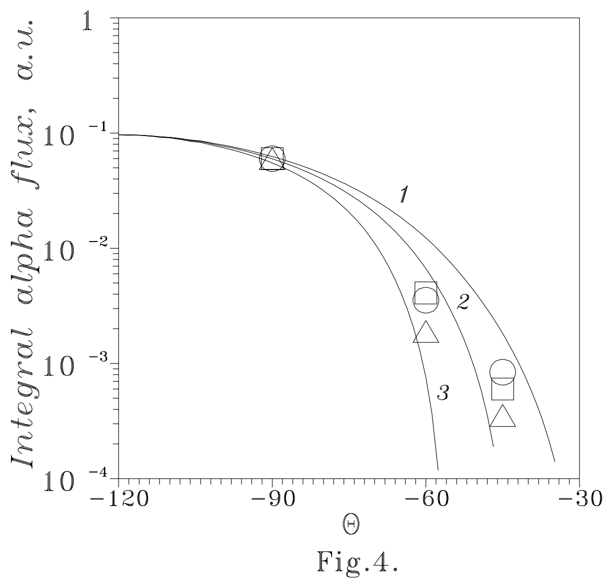


Fig. 3. Energy spectrum of escaping α-particles in the same shot as in Fig. 1. 1, 90° detector; 2, 60° detector; solid line, Kadomtsev crash; broken line, "strong mixing" crash ($V(r_X) = \text{const}$).

Fig. 4. Calculated (lines) and measured (symbols) poloidal dependencies of alpha flux to the wall for three different crashes in the same shot as in Fig. 1. 1, $\Delta' = 1.67/A$; 2, $\Delta' = 1.8/A$; 3, $\Delta' = 2/A$.