BEHAVIOR OF MEV IONS IN THE PRESENCE OF SAWTOOTH OSCILLATIONS IN TFTR AND JET

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Abstract. Flux of alpha particles to the wall induced by sawtooth crashes in TFTR DT shots has been observed to be very inhomogeneous in poloidal direction. A theory is developed, which reveals two main physical mechanisms responsible for the alpha loss in these experiments and describes the observed flux distribution. An interpretation of the ICRF minority heating experiment on JET where the “hot spot” (a strongly localized gamma ray and neutron emitting region) disappeared after a crash is suggested.

1. Introduction

In 1995, it was predicted theoretically that there is a critical energy, $\mathcal{E}_{crit}$, such that when the ion energy, $\mathcal{E}$, exceeds $\mathcal{E}_{crit}$, the bulk of energetic trapped ions with small banana width is weakly sensitive to sawtooth crashes, whereas circulating particles are strongly redistributed [1]. Later, the quantity $\mathcal{E}_{crit}$ was successfully used to interpret the experimentally observed effect of crashes on well trapped alpha particles in TFTR [2,3]. Furthermore, one can see that the quantity $\mathcal{E}_{crit}$ and other results of Ref. [1] can be useful also for explanation of experimental data of Refs. [4,5], as well as results of numerical simulations in Ref. [6].

However, a recent theory [7,8] has shown that certain groups of particles, which are in resonance with the electromagnetic field of the crash (“resonant particles”), are to be sensitive to the crash even when $\mathcal{E} > \mathcal{E}_{crit}$, the response of these particles to the crash being different from that of particles with low energy. On the other hand, experimental data from JET [4] indicate that there is a very narrow group of fast ions with the energy of several megaelectronvolts, i.e., with $\mathcal{E} \gg \mathcal{E}_{crit}$, which is strongly affected by the crash in contrast to the bulk of fast ions having lower energy, $\mathcal{E} \sim 2\,\mathrm{MeV}$. In the mentioned experiment, where fast ions were produced due to ICRF ^{3}He minority heating, a crash resulted in disappearance of the so-called “hot spot” – a strongly localized emitting region near the magnetic axis, which presumably is associated with redistribution of the mentioned narrow group of ^{3}He ions [4]. A question arises whether the exceptional behavior of the hot-spot ions is a result of their resonant interaction with the electromagnetic field of the crash. To answer this question is a purpose of this work.

Another purpose of the work is to present results of both experimental and theoretical investigation of alpha particle loss associated with sawtooth crashes in TFTR. Note that till now only a few experimental works and no theoretical works on the sawteeth-induced fast ion loss were published.

2. Interpretation of the “hot spot” experiment on JET

The condition of resonant interaction of fast ions and the electromagnetic field of the crash, $s\omega_b = n\omega_\phi$, determines the resonance curves on the (λ, J) plane when $\mathcal{E}$ is fixed, where ω_b is the bounce frequency, ω_ϕ is the frequency of the particle motion in the toroidal direction, n is the toroidal mode number, s is an integer, $\lambda = \mu B_0/\mathcal{E}$, μ is the particle magnetic moment, B_0 is the magnetic field at the magnetic axis, and J is the canonical angular momentum. But in fact, due to the finite width of the resonances, there are resonance regions rather than resonance curves. The width of the resonances is determined by the width of superbanana orbits belonging to the particles that are trapped in the electromagnetic field of the crash [7,8]. Note that the width of the superbananas produced by the crash depends on the particle energy (in contrast to that of the superbananas in stellarators), decreasing with $\mathcal{E}$.

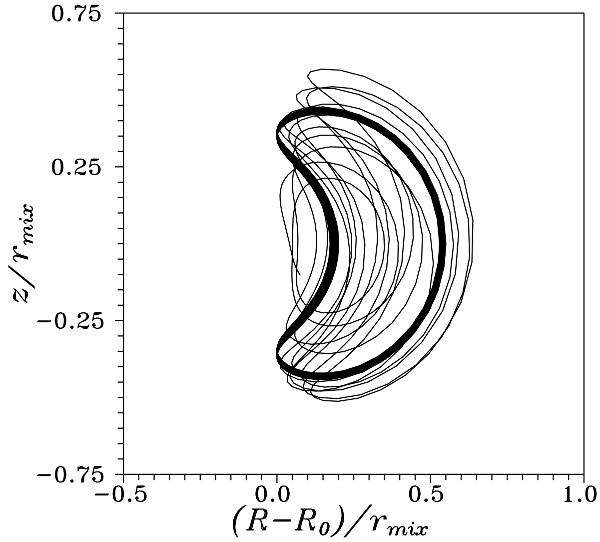

FIG. 1. The effect of a sawtooth crash on a typical fast ion with $\mathcal{E} = 2MeV$ in JET. Bold line, pre-crash ion orbit; thin line, the orbit during the crash. The crash duration is 10^{-4} s; the sawtooth mixing radius, 80 cm.

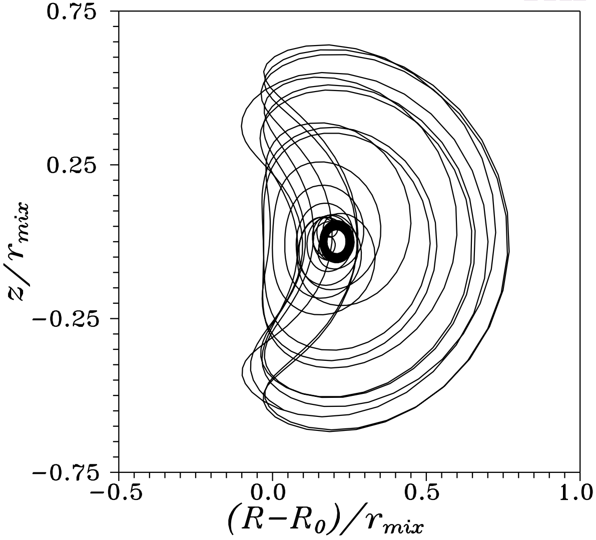

FIG. 2. The effect of a crash on a hot-spot ion with $\mathcal{E} = 5MeV$. The crash parameters and notations are the same as in Fig. 1.

In order to see which particles are resonant, it is convenient to use the variables L, P instead of λ, J, where $L \equiv (1-\lambda)\nu^{-1}$, $P \equiv -2cJq/(keB_0R_0^2\nu^2)$, $\nu \equiv [2q\rho/(kR_0)]^{2/3}$, $\rho = v/\omega_B$ is the Larmor radius, R_0 is the radius of the magnetic axis, k is the ellipticity of the flux-surface cross section, q is the safety factor. The resonance curves on the (L, P) plane depend on the particle energy relatively weakly; in particular, for $\nu = 0.11$ they are presented in Fig. 3 of Ref. [8]. The mentioned figure enables one to estimate the ratio of ω_ϕ/ω_b for a given particle, which is required for subsequent evaluation of the resonance width either analytically or by generating a Poincaré map [8].

Following Ref. [4], we assume that the typical fast ions are trapped particles with the banana tips in the vicinity of the ICRF resonance layer. Concerning the hot spot ions we assume that they have orbits that are well localized in the poloidal and radial directions near the equatorial plane of the torus, where the hot spot is located. Such orbits exist for ions with very small pitch angles and belong to semi-trapped particles that are trapped poloidally but untrapped toroidally.

Allowing for these facts, we take $\mathcal{E} = 2\,\mathrm{MeV}$, $\lambda = 1$, and the banana tip radius $r_t = 28\,\mathrm{cm}$ for a typical fast ion. Then we obtain that $L = 0$, $P = 1.1$, which implies that the typical ion is outside of the region of resonances with $n = 1 \div 3$ important for the crash resulting from the $m = n = 1$ instability. For this reason, one can expect that the crash will weakly affect the bulk of fast ions. A numerical simulation with the guiding-center code OFSEF (Orbit Following in the Sawtooth Electromagnetic Field) used for the first time in Ref. [8], which employs the analytical expression of the electromagnetic field perturbation modeling the Kadomtsev-type crash [1], confirms this, see Fig. 1.

As examples of the hot-spot ions, we take the ions with $\mathcal{E} = 2 \div 5\mathrm{MeV}$, the pitch angle of 100°, and $R - R_0 = 20\,\mathrm{cm}$. We find that they can be resonant, being located between the $s/n = 1/2$ and $s/n = 1$ resonances on the (L, P) plane. Generated Poincaré maps confirm that these particles are indeed resonant and have large width of the superbanana orbits. In addition, direct numerical simulation of the particle behavior during a crash with the code OFSEF shows that the the hot-spot ions are expelled well outside the region where they were located before the crash, which implies disappearance of the hot spot. The examples of the orbits of typical and hot-spot ions are presented in Fig. 2.

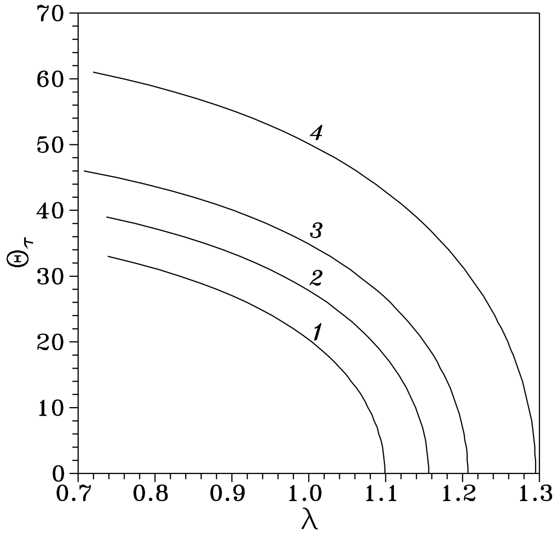

FIG. 3. θ_τ *versus* λ *for various* $\mathcal{E}$ *for a 1.4-MA DT shot #87530 in TFTR. 1,* $\mathcal{E}$ = 3.5 *MeV; 2,* $\mathcal{E}$ = 3.0 *MeV; 3,* $\mathcal{E}$ = 2.5 *MeV; 4,* $\mathcal{E}$ = 1.5 *MeV. Particles with given* $\mathcal{E}$ *which escape because of the orbit transformation reach 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* $|\theta| \simeq \theta_\tau(\mathcal{E}, \lambda \simeq 1.1)$.

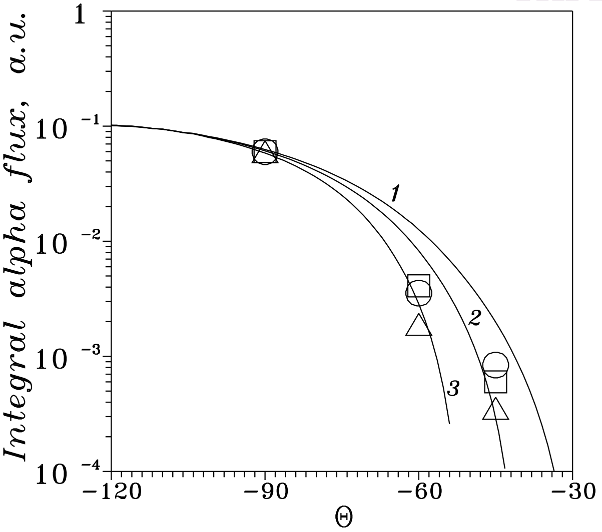

FIG. 4. Calculated (lines) and measured (symbols) poloidal dependencies of alpha flux to the wall for three different crashes in the same shot as in Fig. 3. 1, $\Delta' = 1.67/A$*; 2,* $\Delta' = 1.8/A$*; 3,* $\Delta' = 2/A$. $\Delta' \equiv d\Delta/dr$*;* Δ *is the Shafranov shift; A is the plasma aspect ratio.*

3. Escaping alpha particles in TFTR D-T experiments

Sawtooth oscillations were observed in several TFTR DT shots with $I = 1.4\,\mathrm{MA}$ and $I = 2\,\mathrm{MA}$. 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 alphas 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, having sharp maxima at the 20° and 90° detectors and being on the noise level at the 45° detector.

This experimental fact indicates 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. Our theoretical studies and numerical simulations reveal these mechanisms, which were found to be different for circulating and trapped particles.

In particular, a numerical simulation with the code OFSEF showed that only a narrow group of circulating particles can be expelled to the wall. These particles are marginally circulating and located sufficiently close to the magnetic axis before a crash. 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. Only particles with sufficiently high energy, $\mathcal{E} \geq \mathcal{E}_{min}$ can be lost, and 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).

Trapped particles can escape from the plasma because of the stochastic (collisionless) ripple diffusion. This was found with using the dependence of θ_τ on λ given in Fig. 3 and the Hamiltonian guiding-center code ORBIT [9]. Calculations with ORBIT showed that when the alpha source vanishes outside the sawtooth mixing radius (which models the crash-induced source), the dominant fraction of the escaping particles consists of moderately trapped particle with the energy close to 3.5 MeV and $\lambda \gtrsim 1$. Therefore, according to Fig. 3, the crash-induced stochastic diffusion leads to alpha wall load at $|\theta| < 30°$.

It also follows from Fig. 3 that the particles with $\lambda \sim 0.8$, which is typical for the particles escaping due to the orbit transformation, reach the wall at $|\theta| > 30^\circ$. Note that the dependence of θ_τ on λ shown in Fig. 3 is rather general, being almost independent on the specific mechanism leading to the particle loss. Therefore, Fig. 3 confirms, in particular, the shadowing effect for delayed loss in Ref. [11] and shows that the shadow for the orbit transformation loss of particles with the same energy is essentially larger (unlike the statement in Ref. [11] that the shadowing effect is absent in the latter case).

In order to describe the poloidal distribution of the alpha flux to the wall for $|\theta| \geq 30^\circ$, a theory based on the assumption that the crash duration essentially exceeds the particle transit time / bounce period was suggested. There is reasonable agreement between predictions of this theory and experimental data, see Fig. 4.

Note that the results presented in Figs. 3, 4 take into account the finite Larmor radius of alpha particles. Similar results in Ref. [12] neglect this factor. We observe that, in spite of the fact that the Larmor radius is of order of the width of the vacuum gap, there are only minor differences between Figs. 3, 4 and corresponding figures in Ref. [12].

4. Conclusions

In the experiment on JET [4], the hot-spot ions are in resonance with the electromagnetic field of the sawtooth crash. Therefore, the crash results in superbanana orbits of these ions with large width, which results in disappearance of the hot spot. Unlike the hot-spot ions, most of fast ions are non-resonant trapped particles having the energy $\mathcal{E} \gg \mathcal{E}_{crit}$, which explains why they are weakly sensitive to the crash.

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 leading to wall load mainly near the chamber bottom and the crash-induced 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.

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