Structure of fast-ion flux to tokamak wall during bursts of MHD activity

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The fusion particles lost from the plasma during bursts of MHD modes go to the wall in distinct jets with narrow distributions in energy and pitch angle.

Experiments at the TFTR tokamak,[1,2] in which the loss of DD tritons to the chamber wall was studied, revealed a correlation between the loss of particles and bursts of MHD waves in discharges with a high MHD activity of the plasma. At the peak of this loss, the particle flux is an order of magnitude greater than the average level of the direct loss in a quiet plasma. It was suggested in those papers that the ejection of particles was a consequence of a anomalous loss of passing particles which accumulate in the plasma between bursts of MHD perturbations. In the present letter we analyze the spatial structure of the flux and the energy spectra of the fusion ions with a wide banana trajectory, $\Delta r_b \approx a$, which are lost during the growth of one or several MHD modes in the plasma.

In the phase space of a fast particle there exists a region (a cone) of direct loss from which a particle moving along a drift trajectory goes to the first wall of the tokamak. One boundary of the direct-loss region is that which separates the trapped particles (the banana particles) and the passing particles which are moving opposite the plasma current. As they cross this boundary, which forms a separatrix surface in phase space,[3] the negatively passing particles convert into banana particles with a radial excursion from the magnetic surface which is roughly twice that of the passing particles, so they escape to the wall. If the trajectory is characterized by the values of the total velocity V, the pitch angle $\chi_G = V_\parallel / V$, and the radial coordinate at the time at which the particle reaches the wall, R_G (the distance from the major axis of the torus), then the separatrix boundary is a surface $\chi_G = \chi_G^s(R_G, V)$. Since each point of the boundary is a separatrix trajectory, the position of the boundary must be sensitive to perturbations of the magnetic field which lead to the formation of a stochastic layer near the separatrix.

We consider a plasma with circular magnetic surfaces. We describe the motion of the particles by drift equations, and we assume that the perturbations are in a steady state. The latter assumption is based on the circumstance that the period (τ_b) of the motion of the fusion particles is short in comparison with the period of the perturbations or the plasma rotation period. In this case the equations of motion take the form

$$\dot{\rho} = - V_{dr} \sin\vartheta + V_{\|}\tilde{B}_{\rho}/B_T,$$
$$\dot{\vartheta} = V_{\|}/qR_0 - (V_{dr}/\rho)\cos\vartheta + V_{\|}\tilde{B}_{\vartheta}/B_T,$$
$$\dot{\varphi} = V_{\|}/R_0 .$$

Here V_{dr} is the toroidal drift velocity, $V_{\|}$ is the velocity projection onto the magnetic field, R_0 is the major radius of the torus, and $\tilde{B}$ is the perturbation of the poloidal magnetic field. We are using the toroidal coordinate system $(\rho, \partial, \varphi)$, where ρ is the distance from the magnetic axis. Adopting $\tau = \varphi/q$ as an independent variable, we can write this system of equations for the passing particles in the form of Hamilton's equations with the "radial" coordinate $y = 1 - \rho^2/\rho_s^2 - \Delta^2/2$ and the poloidal angle ϑ as canonical variables. The Hamiltonian H is

$$H = H_0 + \psi_0(y)\cos(m\vartheta - nq_s\tau), \tag{1}$$

$$H_0 = y + \Delta^2 + \frac{s}{2}(y^2 + y\Delta^2) - 2\Delta(2\cos^2(\vartheta/2) - \frac{1}{2}(y + \Delta^2/2)\cos\vartheta)^{1/2},$$

where

$$\Delta = \frac{q_s V}{\epsilon^{1/2}\rho_s\omega_{i0}}; \qquad \epsilon = \rho_s/R_0; \qquad q_s = q(\rho_s).$$

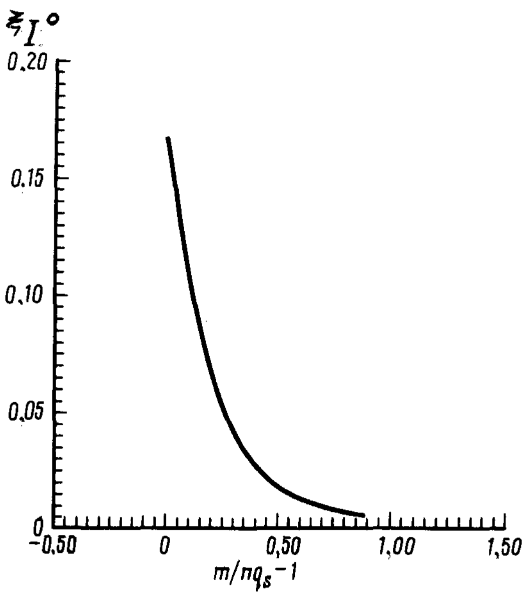

FIG. 1. Maximum width of the stochastic zone, H_0^m, versus $m/nq_s - 1$.

The normalization radius ρ_s is chosen such that $V_{\parallel}\ (\rho_s,\ \vartheta=\pi)=0$, where ψ_0 the amplitude of the perturbations of the magneic flux, is normalized to $\pi\rho_s^2 B_T/q_s$, and $s=q'/q_s$.

Estimating the width of the stochastic layer, which is always present near the separatrix ($H_0=0$), from the Chirikov criterion,[4] we find that the growth of the stochastic zone reaches saturation, $H_0 \approxeq H_0^m$, at large perturbation amplitudes. With a further increase in the perturbation amplitude ψ_0, the width of this zone varies by an exponentially small amount. This width, H_0^m, is determined by the inequality

$$\frac{m}{nq_s} - 1 \leqslant - sH_0^m + \frac{\Delta}{\sqrt{2H_0^m}} .$$

Figure 1 shows H_0^m as a function of $m/nq-1$. The maximum width of the stochastic zone,

$$H_0^m \approx \left(\frac{\Delta}{\sqrt{2}s}\right)^{2/3} ,$$

corresponds to resonant separatrix trajectories for which the x point lies near the resonant magnetic surfaces, with $m/nq_s - 1 < (s\Delta^2/2)^{1/3}$. We would thus expect that during excitation of one or several large-amplitude MHD modes in the plasma the flux of particles would take the form of distinct jets with a narrow pitch-angle distribution near $\chi=\chi_G$.

The energy spectra of the ejected particles can be estimated on the basis of a kinetic equation describing the steady-state particle distribution function which is established between bursts of MHD activity:

$$\frac{1}{\tau_s V^2}\ \frac{\partial}{\partial V}(V^3+V_*^3)f + D(H_0)\ \frac{\partial^2 f}{\partial H_0^2} + Q(H_0)\frac{\delta(V-V_0)}{V^2} = 0, \qquad (2)$$

where $Q(H)$ is the particle source, and $V_* = (3\sqrt{\pi}m_e/4m_i)^{1/3}V_{Te}$. In (2) we have retained the leading terms, which describe the Coulomb slowing by plasma electrons and ions, the stochastic diffusion of particles in the radial direction, and the source of fusion ions (the variable H_0 is used as the radial coordinate). We are interested in the fast part of the particle spectrum, $V_* < V < V_0$, so we will ignore the slight Coulomb scattering by plasma ions in (2). We assume that at the time of a burst the diffusion coefficient in the stochastic zone, $H < H_0^m$, changes abruptly from a small value D_0 to a value D_1, where $D_1 \gg D_0$. Just after this change in the diffusion coefficient, the steady-state particle flux $\Phi_0 = D_0 \partial f/\partial H$ increases by a factor of D_1/D_2, and then it begins to fall off, because of the decrease in the gradient $\partial f/\partial H$, with a time scale $\tau_1 = (H_0^m)^2/D_1$. It follows from (2) that the total number of particles which reach the wall from the stochastic zone over this time is

$$\Delta N_1 = \frac{\partial f}{\partial H}\frac{(H_0^m)^2}{2} \sim \frac{(V/V_0)^{4/3}}{\dfrac{(V^3+V_*^3)}{(V_0^3+V_*^3)}\ln\left\{\dfrac{(V_0^3+V_*^3)}{(V^3+V_*^3)}\right\}} .$$

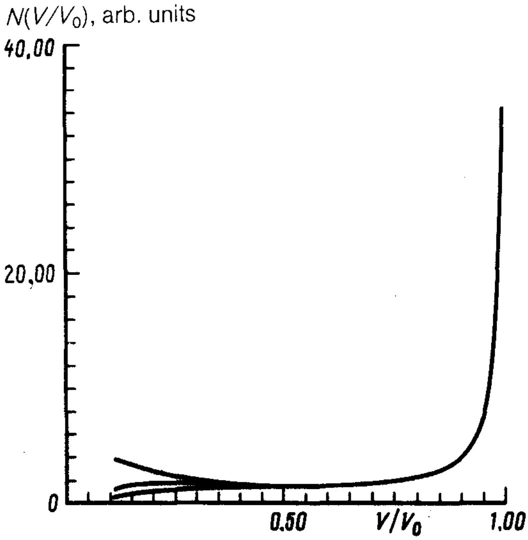

FIG. 2. Velocity spectra of the particles which are lost. *1*—$V_* = 0.1$; *2*—$V_* = 0.2$; *3*—$V_* = 0.3$.

Figure 2 shows a plot of ΔN_l versus the particle velocity. The different curves correspond to different values of V_*. The spectrum of lost particles is seen to be dominated by particles with energies close to the energy at which the particles are produced.

In summary, this loss mechanism, involving bursts of MHD activity in the plasma, should lead to particle fluxes to the wall in the form of distinct jets with a narrow pitch-angle distribution of the particles. The spectrum of particles consists primarily of fast particles with energies close to the energy at which the particles are produced. Actual measurements of the structure of the flux of fusion particles at the wall might provide information about the structure of the MHD modes which are excited in the plasma.

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