REVIEW PAPER

THE ROLE OF ALPHA PARTICLES IN TOKAMAK REACTORS

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ABSTRACT. The author reviews the theoretical work on those properties of a thermonuclear plasma that relate to the charged products of nuclear fusion reactions – α-particles. Three basic lines of research – on classical mechanisms of α-particle loss in tokamaks, collective processes in the plasma initiated by α-particles, and the energy balance stability of a thermonuclear plasma – are considered.

1. INTRODUCTION

In recent years considerable progress has been made in plasma experiments and in our understanding of the physics of a high-temperature plasma. The most striking progress has been made with tokamak-type devices. As a result, thermonuclear research programmes have been set up in a number of countries which aim at conducting demonstration fusion reactor experiments on tokamaks in the period 1980–90 [1–3, 125]. This has made it necessary to solve a new set of physics and engineering problems, which in turn has stimulated

$$\frac{a_{\mathrm{eff}}}{r_{B\alpha}} < \left(\frac{v_\alpha}{v_\alpha - v_1}\right)^{1/2} (\omega_{B\alpha}\tau_f)^{1/4} \frac{v_{Ti}}{v_\alpha} \tag{148}$$

When this inequality holds the confinement time of resonance α-particles in the plasma is short: $\tau_{n\alpha} < \tau_{\parallel}^{\alpha e}$. In the opposite case, $\tau_{n\alpha} > \tau_{\parallel}^{\alpha e}$, and the instability in question is suppressed by Coulomb collisions after a time of the order of $\tau_{\parallel}^{\alpha e}$.

The foregoing evaluations for turbulent particle fluxes, together with condition (148), remain valid to within a factor of the order of $\sqrt{\beta}$ if the non-linear mechanism leading to energy transfer into the damped part of the spectrum consists of three-plasmon processes involving compressional Alfvén waves (under tokamak-reactor conditions, processes involving slow magnetoacoustic waves are impossible).

In conclusion, let us compare the turbulent electron and ion fluxes obtained with the neoclassical fluxes (Γ^N). We find that $\Gamma^T > \Gamma^N$ for the typical parameters of tokamak reactors. As a result, the turbulent state discussed here may be accompanied by ion diffusion towards the axis of the plasma column.

3.4.3. The Sigmar-Chan theory of α-particle diffusion induced by an Alfvén instability due to trapped particles [74]

Let us consider the possibility of anomalous diffusion of α-particles, assuming that these particles excite an instability characterized by the conditions $\xi_p \ll 1, \eta_p \gtrsim 1, k_p^2 \gg k_b^2$ (see Section 3.3.1.2).

To carry out this analysis we shall need to know the threshold density for the instability (n_α^{cr}). Following Sigmar and Chan [74], we shall consider it to be determined by the collisional energy dissipation of waves on trapped electrons, and we shall not take into account quasi-linear distortion of the electron distribution function. Thus, the system of equations describing the development of the instability consists of only two equations: a quasi-linear equation for the α-particle distribution function and an equation for the waves. The system can be written in the following form [74]:

$$\frac{\partial f_\alpha}{\partial t} = \frac{\partial}{\partial \mathscr{E}} D_{\epsilon\epsilon} \frac{\partial f_\alpha}{\partial \mathscr{E}} - \frac{D_{\rho\rho}}{d^2(t)} f_\alpha + \mathrm{St}^{\mathrm{coll}}\{f_\alpha\}$$

$$+ \frac{n\delta(v - v_\alpha)}{\tau_f 4\pi v_\alpha^2} \tag{149}$$

$$\frac{\partial E_{\vec{k}}}{\partial t} = \gamma_{\vec{k}} \vec{E}_{\vec{k}} \tag{150}$$

Here, d(t) is the characteristic radial dimension of the inhomogeneity of the α-particle distribution, $\mathscr{E} = v^2/2$, and the diffusion coefficients $D_{\epsilon\epsilon}$ and $D_{\rho\rho}$ are given by the expressions:

$$D_{\epsilon\epsilon} = \sum_{\vec{k}} |E_{\rho\vec{k}}|^2 \sum_{\rho} \frac{|P|}{k_\rho^2} J_\rho^2(\eta_\rho^v) \frac{2\pi\sqrt{\epsilon}\, e^2}{qR\sqrt{\mathscr{E}} m^2} \tag{151}$$

$$D_{\rho\rho} = \frac{c^2}{B^2} \sum_{\vec{k}} |E_{\theta\vec{k}}|^2 \sum_{\rho} \frac{8\sqrt{2}\pi^2}{|\rho|} Rq J_\rho^2(\eta_\rho^v) \tag{152}$$

in which η_ρ^v is identical with η_ρ as determined by Eq.(88) if we put $v_\alpha = v$ in the latter. The diffusion coefficient $D_{\rho\rho}$ is obtained from the equation

$$D_{\rho\rho} = \int_{-\infty}^{t} dt' \left\langle \frac{dr_{GC}(t)}{dt} \frac{dr_{GC}(t')}{dt'} \right\rangle \tag{153}$$

where $dr_{GC}/dt = c\widetilde{E}_\theta/B$, and $\langle\,\rangle$ indicate averaging overall the phase angles between the waves and particles. The dependence d(t) is determined by the particle conservation equation which follows from Eq.(149):

$$\frac{\partial n_\alpha}{\partial t} - \frac{1}{\rho} \frac{\partial}{\partial \rho} r \overline{D}_{\rho\rho} \frac{\partial n_\alpha}{\partial \rho} = \frac{n}{\tau_f} \tag{154}$$

where

$$\overline{D}_{\rho\rho} = 2\sqrt{2\pi} J_\rho^2(\eta_\rho) \frac{c^2 |E_\theta|^2}{B^2} \frac{\sqrt{\epsilon}}{|\rho|\omega_{b\alpha}} \tag{155}$$

Note that the diffusion coefficient $\overline{D_{\rho\rho}}$ is easy to obtain by means of the expression

$$\Gamma_\alpha = -\frac{2c}{e_\alpha B} \int \frac{d\vec{k}}{(2\pi)^3} k_b (N_{\vec{k}} \delta\gamma_{\vec{k}\alpha} + \gamma_{\vec{k}\alpha} \delta N_{\vec{k}}) \tag{156}$$

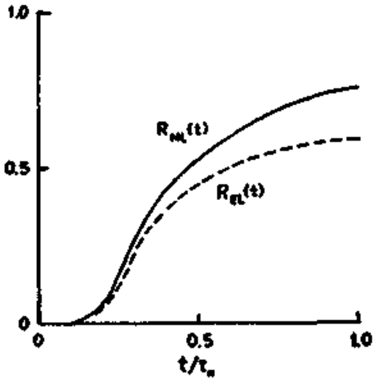

FIG.19. Alpha-particle loss rate coefficient, R_{NL}, and α-particle energy loss rate coefficient, R_{EL}, as a function of time. R_{NL} and R_{EL} are determined by Eq.(158) [74].

if we allow for the fact that

$$\delta\gamma_\alpha = \sum_\rho \pi e \frac{m_\alpha}{m_i} \frac{\omega_{B\alpha}}{\omega} \frac{k_b}{k_\rho^2 qR} |\rho| v_\alpha J_\rho^2(\eta_\rho) \frac{1}{n_i} \frac{\partial n_\alpha}{\partial \rho} \tag{157}$$

$$E_\theta / E_\rho = k_b / k_\rho$$

and put $\delta N_{\vec{k}} = 0$. In fact, as can be seen from expressions (135), the correction $\delta N_{\vec{k}}$ plays an important role. Nevertheless, in a qualitative description of diffusion, it is possible to use the expression for $\overline{D_{\rho\rho}}$ (155), which does not take this correction into account.

This system of equations was solved numerically in Ref.[74]. The following tokamak parameters were used: B = 50 kG, a/R = 120/400, q(a) = 2.5, $n_e = 5 \times 10^{13}$ cm^{-3}, T = 15 keV, and I = 3.6 MA. It was assumed that the instability develops on the second bounce harmonic.

The calculations showed that turbulent loss of α-particles is sufficiently rapid for a distribution $f_\alpha(\epsilon,t)$ with $t \sim \tau_\parallel^{\alpha e}, \mathscr{E} \lesssim \mathscr{E}_\alpha$ to have a maximum. This means that there is a steady turbulent state for $t \gtrsim \tau_\parallel^{\alpha e}$. The amplitudes of the electromagnetic fields in this state reach values of $E^2/(8\pi nT) \sim 10^{-5}$. It should be noted, however, that they correspond to a very high noise energy: $W/(nT) = 1.8 \times 10^{-2} (10^9/v_A)^2$. At this energy a strong interaction between waves is to be expected which is not taken into account by Eq.(150).

To illustrate the dynamics of the development of the instability and its influence on α-particle losses, Fig.19 shows the dependence on time of the α-particle loss rate coefficient, R_{NL}, and the α-particle energy loss rate coefficient, R_{EL}, which were obtained as follows by the authors of Ref.[74]:

$$R_{NL} = 1 - n_\alpha(t)/(nt/\tau_f)$$

$$R_{EL} = \Delta(n_\alpha \mathscr{E}_\alpha)/(\mathscr{E}_\alpha nt/\tau_f) \tag{158}$$

where

$$\Delta(n_\alpha \mathscr{E}_\alpha) = \int_0^t dt\, d^{-2}(t) \int d\vec{v}\, \frac{mv^2}{2} D_{\rho\rho} f_\alpha$$

3.5. Alpha-particle losses in tokamaks as a result of the development of thermonuclear cone instabilities [38]

Turbulent diffusion across the magnetic field is not the only cause of anomalous α-particle losses in tokamaks. A simpler mechanism – diffusion in velocity space – can also lead to such losses if cone-type thermonuclear instabilities are excited in the plasma. Let us take a closer look at the effectiveness of this leakage channel for fast ions.

It is clear that the number of α-particles entering the loss region as a result of quasi-linear diffusion is strongly dependent on the width of the region of resonance interaction between α-particles and waves ($\Delta v_\parallel^r$). When the instability first arises this region is very narrow, $\Delta v_\parallel^r \sim v_{T\Sigma} \chi_s$, but it can become considerably wider as the instability develops. The broadening is accompanied by a reduction in the gradients of the function $f(\vec{v})$ and consequently by a decrease in the growth rate of the instability. It can therefore lead to the establishment of some steady state in which $0 < \gamma_\alpha^{st} < \gamma_\alpha(t = 0)$, the growth rate being non-zero because of the systematic influx into the resonance region of α-particles produced by the thermonuclear reaction.

The quasi-linear evolution of the α-particle distribution begins at the time when $n_\alpha \approx n_\alpha^{cr}$ and in some wave vector range $\gamma_{\vec{k}} \cong 0$. For the instabilities discussed in Section 3.3.3, $\gamma_{\vec{k}} \approx 0$ if $\gamma_{\vec{k},\alpha} \approx \omega_{b\alpha}$, i.e. the vanishing of the growth rate is not due to the background plasma. As a result, the time for establish-

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