

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.

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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

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

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]:

$$\frac{\partial f_\alpha}{\partial t} = \frac{\partial}{\partial \mathcal{E}} D_{\epsilon\epsilon} \frac{\partial f_\alpha}{\partial \mathcal{E}} - \frac{D_{\rho\rho}}{d^2(t)} f_\alpha + \text{St}^{\text{coll}} \{f_\alpha\} + \frac{n\delta(v - v_\alpha)}{\tau_f 4\pi v_\alpha^2} \quad (149)$$

$$\frac{\partial \vec{E}_k}{\partial t} = \gamma_k \vec{E}_k \quad (150)$$

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

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

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

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

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

where $dr_{GC}/dt = c\tilde{E}_\theta/B$, 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):

$$\frac{\partial n_\alpha}{\partial t} - \frac{1}{\rho} \frac{\partial}{\partial \rho} \bar{r} D_{\rho\rho} \frac{\partial n_\alpha}{\partial \rho} = \frac{n}{\tau_f} \quad (154)$$

where

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

Note that the diffusion coefficient $\bar{D}_{\rho\rho}$ is easy to obtain by means of the expression

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

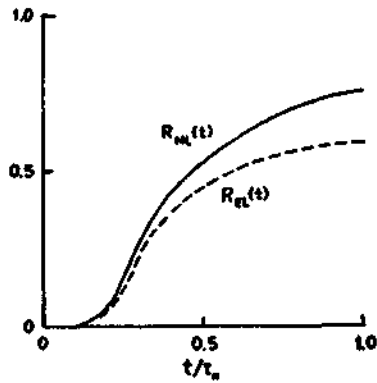


FIG.19. Alpha-particle loss rate coefficient, R_{NL} , and α -particle energy loss rate coefficient, R_{EL} , as a function of time. R_{NL} and R_{EL} are determined by Eq.(158) [74].

if we allow for the fact that

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

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

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 $D_{\rho\rho}$ (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 $f_{\alpha}(e, t)$ with $t \sim \tau_{\parallel}^{\alpha e}$, $\mathcal{E} \lesssim \mathcal{E}_{\alpha}$ 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]:

$$R_{NL} = 1 - n_{\alpha}(t)/(nt/\tau_f) \quad (158)$$

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

where

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

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 ($\Delta v_{\parallel}^{\alpha}$). When the instability first arises this region is very narrow, $\Delta v_{\parallel}^{\alpha} \sim v_{T\Sigma} \chi_{\alpha}$, 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 $\gamma_{\vec{k}} \approx 0$. 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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