Physics Letters A 378 (2014) 2683–2687

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Cooling and transport of energetic ions due to the global geodesic acoustic mode

Ya.I. Kolesnichenko *, V.V. Lutsenko, B.S. Lepiavko

Institute for Nuclear Research, Prospekt Nauky 47, Kyiv 03680, Ukraine

ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form 14 July 2014
Accepted 15 July 2014
Available online 18 July 2014
Communicated by F. Porcelli

Keywords:
Tokamaks
Particle orbits
Energetic ions
Geodesic acoustic mode

ABSTRACT

It is shown that (i) the destabilization of global Geodesic Acoustic modes (GAM or E-GAM) by passing energetic ions in tokamaks can be accompanied with a considerable energy transfer from these ions to the mode; (ii) the mode-induced slowing down of the energetic ions leads to a radial shift outwards/inwards of the ions moving in the direction counter to/of the plasma current, in spite of the fact that the canonical angular momentum of the particles is conserved during GAMs. Some practical consequences of these phenomena are discussed.

1. Introduction

The aims of this work are, first, to study a possible energy transfer from the passing energetic ions to the global Geodesic Acoustic Mode (GAM) or to Energetic-ion-induced GAM mode (E-GAM), and second, to clarify whether GAMs can lead to the motion of these ions across the magnetic field. These questions actually have been arisen after the observation of large (10–15%) drops of the neutron emission during bursts of an E-GAM instability driven by counter-injected energetic ions in the DIII-D tokamak: drops of the neutron emission indicated on the expulsion of the injected ions from the plasma core and, possibly, on their loss (neutrons were produced mainly by the beam-plasma fusion reaction) [1]. More recent DIII-D experiments have given a direct evidence of the influence of the E-GAM instability on the deterioration of the confinement of injected ions [2]. This effect was explained by the change of pitch angles of the injected ions and concomitant transformation of counter-passing particles into trapped ones; it was claimed that the radial diffusion is not expected because the particle canonical angular momentum, P_ϕ, is conserved (the GAM/E-GAM mode does not break the axial symmetry of the magnetic configuration of tokamaks) [1,2]. However, in this work, we will show that although $P_\phi = const$, the orbit transformation is not the only reason for the radial displacement of the energetic ions. In addition, we will show that the injected energetic ions can be considerably cooled during GAMs.

2. Fast ion motion caused by slowing down during GAM instabilities

Our idea is simple: the energetic particles exciting the instability give their energy to the electromagnetic field. This means that the instability cools these ions. Because the particle magnetic moment, μ, is conserved (due to $\omega \ll \omega_B$, with ω the mode frequency and ω_B the particle gyrofrequency), only the longitudinal energy of the energetic ions, $\mathcal{E}_\parallel$, changes because of the instability. Due to the decrease of $\mathcal{E}_\parallel$ and conservation of P_ϕ, counter-passing ions move outwards and co-passing particles move inwards. This is seen from the following [we used $P_\phi = MRv_\parallel - (e/c)\psi_p$, where R is the distance from the major axis of the torus, $v_\parallel$ is the particle velocity along the magnetic field, ψ_p is the poloidal magnetic flux, M is the ion mass, e is the ion electric charge; a right-handed coordinate system (r, θ, ϕ) is used, where r, θ, and ϕ are the radial coordinate, poloidal angle, and toroidal angle, respectively]:

$$e\Delta\psi_p = cMR_0\Delta u, \tag{1}$$

where $\Delta\psi_p = \psi_p^f - \psi_p^i$, $\Delta u = u^f - u^i$, $u \equiv v_\parallel(\theta = \pi/2)$, superscripts "$i$" and "$f$" label initial and final magnitudes, i.e., the magnitudes before and after the slowing down, respectively, R_0 is the major radius of the torus. Note that saying "slowing down" we mean the decrease of the fast ion energy because of the instability,

* Corresponding author.
E-mail address: yk@kinr.kiev.ua (Ya.I. Kolesnichenko).

http://dx.doi.org/10.1016/j.physleta.2014.07.023
0375-9601/

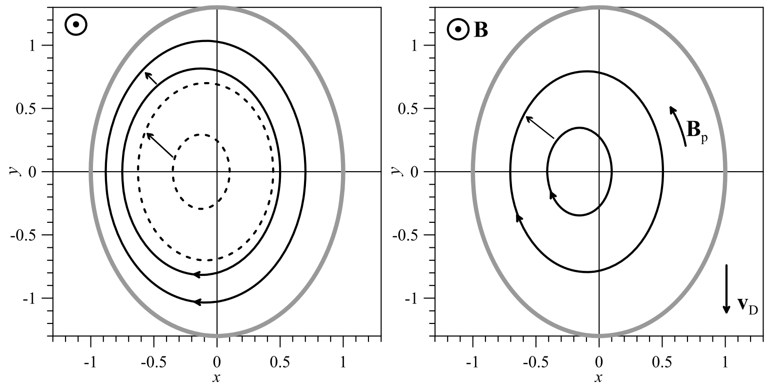

Fig. 1. Orbits of passing 75-keV deuterons moving in the direction counter to the plasma current in a DIII-D like tokamak before and after the slowing down when $\mathcal{E}^f = 0.5\mathcal{E}^i$, $P_\phi^f = P_\phi^i$, and $\mu^f = \mu^i$: left panel, $q(r) = 3.5$, $\lambda^i = 0.2$; right panel, $q(r)$ which took place in the E-GAM DIII-D experiment [1], $\lambda^i = 0.35$. The edge of the plasma is shown by a grey thick line, $x = (r/a)\cos\theta$, $y = \kappa(r/a)\sin\theta$. The arrows on the orbits show the direction of the particle orbital motion. The arrows between the orbits are directed from the initial orbits to final ones (i.e., to the orbits after the slowing down caused by the GAM/E-GAM mode). The following tokamak parameters were used: $B = 2$ T, $a = 60$ cm, $R_0 = 170$ cm, $\kappa = 1.3$. It was assumed that the flux surfaces are concentric ellipses. The major axis of the torus is located to the left from the plasma cross section shown, the plasma current has the same direction as the magnetic field. Notations: $\mathbf{v}_D$ is the velocity of the ion toroidal drift, $\mathbf{B}_p$ is the poloidal magnetic field.

not because of Coulomb collisions with the plasma particles. In addition, we note that Coulomb collisions, in contrast to GAM/E-GAM modes, do not conserve P_ϕ and, therefore, the effect of slowing down caused by Coulomb collisions is not described by Eq. (1). It is clear that $\Delta u > 0$ for counter-passing ions ($v_\parallel < 0$) and, thus, $\Delta\psi_p > 0$, whereas $\Delta u < 0$ and $\Delta\psi_p < 0$ for co-passing ions losing their energy.

We infer from Eq. (1) that the particle radial displacement is given by

$$\Delta r = \alpha \frac{q^i \rho^i}{\kappa \epsilon^i}, \tag{2}$$

where $\rho = v/\omega_B$, $\alpha = \Delta u/v^i$, $\epsilon = r/R_0$, r is the radial coordinate defined by $\Psi_p(r) = B_0 \int_0^r dr_1 r_1 \kappa/q(r_1)$, B_0 is the magnetic field at the magnetic axis, $r \le a$, a is the plasma radius in the equatorial plane of the torus, $\kappa = b/a$ is the plasma elongation, and b is the plasma radius in the vertical plane. Noting that the largest banana width is $\Delta_b = 2\sqrt{2}q\rho/(\kappa\sqrt{\epsilon})$, we conclude that Δr given by Eq. (2) exceeds the displacement caused by the transformation of passing particles into trapped ones ($\Delta_b/2$) when $\alpha > \sqrt{2\epsilon}$. In the limit case of $|u^i| = v^i$ and $|u^f| \ll v^i$ the orbit displacement due to the slowing down exceeds that caused by the orbit transformation by the factor of $(2\epsilon)^{-1/2}$. Eq. (2) indicates that the effect of slowing down on Δr is largest in the case of small ϵ [$\Delta r \propto (1/r^i)$]. However, r in Eq. (2) cannot be arbitrarily small because this equation is valid only for particles with narrow orbits, $\Delta_b \ll r$ [in contrast to Eq. (1), which is applicable also to particles with orbits passing through the near-axis region, i.e., to so-called "potato" orbits].

When $P_\phi = const$ and $\mu = const$, the evolution of the energetic ion distribution function, $F(\mathcal{E}, \mu, P_\phi)$, under the influence of the waves is governed by the operator $\hat{\Pi} \equiv \partial/\partial\mathcal{E}$. Proceeding to the variables ($\mathcal{E}$, λ, ψ_p), where $\lambda = \mu B_0/\mathcal{E}$ is the pitch-angle parameter, we can write:

$$\hat{\Pi} = \frac{\partial}{\partial\mathcal{E}} - \frac{\lambda}{\mathcal{E}}\frac{\partial}{\partial\lambda} + \frac{R_0 c}{eu}\frac{\partial}{\partial\psi_p}, \tag{3}$$

where $u = \sigma v\sqrt{1-\lambda}$, $v = \sqrt{2\mathcal{E}/M}$, and $\sigma = \operatorname{sign} v_\parallel$. It follows from (3) that the particle energy, pitch angle, and radial position change simultaneously. Those energetic ions which are responsible for the instability are cooled, giving their energy to the waves. For GAMs, $F(\mathcal{E}, \lambda, \psi_p)$ flattens in the region around the transit resonance $\omega = v_\parallel/(qR_0) \equiv \omega^{tr}$, the width of this region being about the separatrix width of the wave-particle interaction. The characteristic time of the motion of fast ions trapped into the wave, τ^{isl}, exceeds $(\omega^{tr})^{-1}$. Therefore, we can write the following equation for the radial motion of resonant particles:

$$\bar{\dot{r}} = -v_D \overline{\sin\theta}, \tag{4}$$

where v_D is the toroidal drift velocity, the overline means transit time averaging, $\overline{\sin\theta} \ne 0$ due to the GAM term in the equation

$$\dot{\theta} \approx \omega^{tr} - \frac{c\hat{E}_r}{rB}\cos\omega^{tr}t, \tag{5}$$

$\hat{E}_r$ is the amplitude of the GAM electric field defined by $\tilde{E}_r = \hat{E}_r\cos\omega^{tr}t$, tilde labels perturbed quantities. The GAM term is the θ-component of the $[\tilde{\mathbf{E}} \times \mathbf{B}]$ drift velocity. Because $\overline{\sin\theta} \ne 0$, $\bar{\dot{r}} \ne 0$, which explains why $\Delta\psi_p \ne 0$ in Eq. (1), in spite of the fact that the radial component of the $[\tilde{\mathbf{E}} \times \mathbf{B}]$ drift is negligible [$\tilde{\mathbf{E}} \approx (E_r, 0, 0)$ in GAMs]).

One of the characteristics of Eq. (3) is $P_\phi = const$, which leads to Eq. (1). Another characteristic is

$$\lambda\mathcal{E} = const \tag{6}$$

(which immediately follows from $\mu = const$). It follows from Eq. (6) that the particle slowing down is accompanied by the increase of λ. This eventually can lead to the transformation of passing particles into trapped ones. However, before the transformation, a passing particle can lose a considerable part of its energy and be displaced outwards. Furthermore, the transformation may even not occur at all: a passing particle can be lost to the wall or its pitch angle can remain to be small, less than $(1-\epsilon^f)$ [$\epsilon^f = r^f/R_0$, $r^f = r^i + \Delta r$] when the initial pitch angle parameter satisfies the inequality $\lambda^i < (1-\epsilon^f)\mathcal{E}^f/\mathcal{E}^i$.

In order to demonstrate the influence of the slowing down on the ion location, we calculated numerically several pairs of orbits with $\mathcal{E}^i = 75$ keV and $\mathcal{E}^f = 0.5\mathcal{E}^i$ in a tokamak with parameters close to those in DIII-D, see Fig. 1. The equations $\mathcal{P}_\phi(r, \mathcal{E}, \lambda) = const$, $\lambda\mathcal{E} = const$, and $\kappa = const$ were used. The calculations were carried out for the strongly non-monotonic $q(r)$ shown in Ref. [1] and for $q(r) = const$. The latter case shows that the particle radial displacement is considerable even at a moderately high safety factor, $q \sim 3.5$ (in DIII-D, q was about 5 in the near-axis region, 5–7 in the periphery, and $\sim$3.5 at $r/a \sim 0.5$ [1]). However, we should note the radial displacement (2), being independent on the plasma radius, will be small in comparison with the plasma radius in ITER-size machines.