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Effect of Radial Electric Field on α-Particle Loss in Tokamaks

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Abstract

Effect of the radial electric field near plasma edge on the ripple-trapped loss of fusion α-particles is discussed. The order of magnitude of the potential difference, which substantially affect the localized wall heat load, is also studied. If the potential difference is of the order of the plasma temperature, the peaking of the localized heat deposition on the first wall becomes weaker owing to the energy distribution of the ripple-trapped loss particles.

Keywords: Alpha-particles, tokamaks, reactor, wall heat load, ripple loss, radial electric field, adiabatic invariance

§1 Introduction

The loss of unthermalized α-particles is a critical problem in designing the fusion reactors. In tokamaks, slight violation of the toroidal symmetry is known to have strong effect on the α-particle loss. The intensive study has been performed for the realistic tokamak geometry, including the detailed orbit calculations[1-3]. Even in the absence of the instabilities, the loss casts critical problems. This loss deteriorates the efficiency of the α-particle heating of the central region; the major concern is that the loss of unthermalized α-particles, which are trapped in the ripple of toroidal field coils, causes a localized heat deposition on the first wall[4].

The strong radial electric field can be piled up near the plasma surface. This has been predicted[5] and confirmed[6,7] in the H-mode plasma, which is considered to be a possible target of the burning plasma. Even in the L-mode plasma, the strong radial electric field is predicted near the edge[8]. The effect of this radial electric field on the particle orbit must be studied to evaluate the peaked heat load on the wall.

In this article, we study the effect of the large electric field near edge on the α-particle orbit. The motion of the ripple-trapped banana is discussed based on the J-invariance of the particles. The radial electric field is treated as a given parameter. The influence on the shift and half width of the localized wall heat load is discussed. The location of the peak heat load moves due to the edge electric field. The width is less affected for the fixed particle energy. If the energy distribution of the ripple trapped loss particle is wide, the peak heat flux can be lower.

§2 Model

Figure 1 illustrates the geometry of our model. The major radius is R_0. The cylindrical coordinates (R, ζ, z) is used. The magnetic field strength is modeled as

$$B = B_0 \left[\frac{R_0}{R} + \varepsilon_r(R,z)\cos(N\zeta) \right] , \qquad (1)$$

where ε_r is the ripple due to the discrete toroidal field (TF) coils, and N is the number of TF coils. The ripple trapped particles[1,4] of our concern is trapped in the shallow ripple by the toroidal field coils. The super banana orbit is formed. The banana orbit drifts in the z-direction and crosses the first wall, causing the localized heat deposition. The motion of the banana center, which is trapped by ε_r, is approximately described by the J-invariance. The J-invariance for the trapped particle is defined as

$$J = \frac{1}{2\pi} \oint v_{/\!/} d\ell. \qquad (2)$$

We also assume that the static potential is constant on the magnetic surface and is given as $\Phi(\psi(R,z))$ (ψ is the magnetic flux function).

The J-invariance is given as[9]

$$J = \frac{2}{M} R \sqrt{\frac{\mu B_0}{M}} \sqrt{\varepsilon_r} \, F(\kappa^2) , \qquad (3)$$

where

$$F(\kappa^2) = \frac{4}{\pi} [\, E(\kappa) - (1-\kappa^2) K(\kappa) \,] \qquad (4)$$

and

$$\kappa^2 = \frac{W - \mu B_0 (R_0/R - \varepsilon_r) - q\phi}{2\varepsilon_r \mu B_0} . \qquad (5)$$

Notations are μ: magnetic moment, W: particle energy, M: mass, q: charge. The functions K and E stand for the complete elliptic integrals of the first kind and the second kind, respectively.

The equations (3) and (5) yield two constants of motion, i.e.,

$$\hat{J} = \sqrt{\varepsilon_r} F(\kappa^2) \qquad (6)$$

and

$$\frac{W}{\mu B_0} - 1 = (2\kappa^2 - 1)\varepsilon_r - \frac{R}{R_0} + 1 + \frac{q\phi}{\mu B_0} . \qquad (7)$$

The guiding center motion has two invariances $\hat{J}$ and $W/\mu B_0$. By eliminating κ^2 from Eqs.(6) and (7), we have the integral of motion for the trapped particles. Equations (6) and (7) contain the elliptic integral and require numerical solution. One limit to allow the analytic treatment is $\kappa=0$, i.e., deeply trapped particles. Taking the Taylor expansion of the elliptic integrals, we here derive the approximate formula which is valid for the barely trapped particles. The function F is expanded as

$$F(\kappa^2) = \kappa^2 \{ 1 + \frac{1}{8}\kappa^2 + \frac{3}{64}\kappa^4 + \cdots \}. \tag{8}$$

Taking the first order correction with respect to κ^2, the classification of the trapped particle orbits has been made in helical systems[10,11]. This approximation is useful even for the barely trapped particles[11]. Replacing F by κ^2 in Eqs.(6) and (7), we have the integral of the motion of the banana orbit as[11]

$$\Psi_0(R,z) + \frac{R}{R_0} - 1 = 1 - \frac{W}{\mu B_0} \tag{9}$$

with

$$\Psi_0(R,z) = [\sqrt{\varepsilon_r(R,z)} - \kappa_1^2\sqrt{\varepsilon_r(R_1,z_1)}]^2 - \kappa_1^4\varepsilon_r(R_1,z_1) - \frac{q\phi}{\mu B_0}. \tag{10}$$

The position (R, z) of the particle which starts from (R_1, z_1; κ_1) satisfies the relation Eq.(9).

The integral provides the basis to calculate the effect of the radial electric field. In order to have an analytic insight, we simplify the shape of the ripple as

$$\varepsilon_r(R,z) = \varepsilon_r(R), \tag{11}$$

i.e., the ripple is z independent. This is the case of the race-track toroidal field coils. We consider the case where the large radial electric field exists near edge. The shift of the banana center in R-direction occurs when it crosses the region of strong radial electric field. Equation (9) gives

$$\varepsilon_r(R) - 2\kappa_1^2\sqrt{\varepsilon_r(R)\varepsilon_r(R_1)} + (2\kappa_1^2-1)\varepsilon_r(R_1) + \frac{R-R_1}{R_0} = \frac{q}{\mu B_0}\Delta\phi. \qquad (12)$$

where $\Delta\Phi$ is the potential difference across the layer.

We consider the case where the potential difference is of the order of the bulk plasma temperature. Then the relation $\Delta\Phi/W \ll 1$ holds, because the ripple trapped α-particles reach near surface without being slowed-down completely. Under these circumstances, we expand Eq.(12) with respect to x (which is defined as $x=R-R_1$), and have

$$\frac{x}{R} = \frac{q\Delta\phi}{\mu B_0}\frac{1}{[1+(1-\kappa_1^2)\varepsilon_r'(R_1)R]}\,. \qquad (13)$$

The shift is approximately given by $q\Delta\Phi/W$.

This formula also gives the shift in the R-direction of the ripple trapped banana as a function of the initial pitch parameter κ_1. The dependence of x on κ_1 shows the difference of the shift. Subtracting $x(\kappa_1=0)$ from $x(\kappa_1=1)$, we have the dispersion of the orbit in R-direction as

$$\Delta x_1 = x(\kappa_1=0)-x(\kappa_1=1) \cong \frac{q\Delta\phi}{\mu B_0} R^2\varepsilon_r' \qquad (14)$$

for given energy of α-particles.

The magnitude of the ripple near the outer edge can be approximated as

$$\varepsilon_r(R) \simeq \varepsilon_{ref}(R/R_{ref})^{N-1}, \qquad (15)$$

where the suffix ref indicates the reference major radius of the localized heat load on the wall. This model leads

$$\varepsilon_r' R \simeq (N-1)\varepsilon_r. \qquad (16)$$

In usual situations, ε_{ref} is of the order of 10^{-2} and N is around 12 to 16. We have

$$\Delta x_1/x \simeq (N-1)\varepsilon_{ref} \qquad (17)$$

This result shows that the dependence of the shift on the pitch angle is weak.

The κ_1 dependence of x modifies of the shape of the localized heat load. Other origin of this modification of the peak heat load comes from the energy dependence. Consider two particles with different energy, W_1 and W_2. Equation (13) gives the difference of x, Δx_2, as

$$\Delta x_2 = R\, q\Delta\phi\{\frac{1}{W_1} - \frac{1}{W_2}\}\,. \qquad (18)$$

Equations (17) and (18) indicate that Δx_1 is not large compared to shift itself but Δx_2 can be comparable to x.

§3 Application

The detailed analysis on the distribution of the alpha-particles crossing the plasma surface has been performed. It is found that the energy distribution of the ripple trapped particles have peaks near 3MeV and 0.5MeV.[4] The low energy part (<1MeV) and high energy part (~3MeV) have similar contribution to the energy flux. From Eq.(13), we see that the effect is large for the lower energy part. We have the approximate result as

$$x/R \sim \frac{1}{250}\,\Delta\phi_{keV}\,, \tag{19}$$

where $\Delta\phi_{keV}$ is measured in keV.

Substituting $W_1 \simeq 0.5$MeV and $W_2 \simeq 3$MeV, we have

$$\Delta x_2/R \sim \frac{1}{300}\,\Delta\phi_{keV}\,. \tag{20}$$

For the parameters discussed above, $\varepsilon_{ref} \sim 10^{-2}$, $\Delta x_1/x$ is of the order of 0.1 but x_2/x is about unity. The distribution of the localized heat deposition on the wall becomes wide by the energy distribution of the α-particles, not much by the pitch angle dependence of x. The peak heat load is substantially affected if the Δx reaches the half width of the localized heat deposition, d, i.e.,

$$\Delta x \approx d. \tag{21}$$

Note d is given in the absence of the radial electric field. If we consider the divergence due to the κ_1 dependence, Eqs.(17) and (21) gives the condition that the potential difference reaches the order of

$$\frac{1}{250}\,\Delta\phi_{keV} \simeq \frac{1}{N\varepsilon_{ref}}\,\frac{d}{R}\,. \tag{22}$$

If we take the energy dependence, and assume that the lower energy part and higher energy part in the energy distribution have similar heat flux according to Ref.[4], Eq.(21) turns out to be

$$\frac{1}{300}\,\Delta\phi_{keV} \simeq \frac{d}{R}\,. \tag{23}$$

The potential difference near edge associated with H-mode has been studied recently. JFT-2M tokamak has shown that the radial electric field of 200V/cm exists in the region of a few cm[7]. The potential difference at edge may reach the average ion temperature. The measurement in D-III-D has given the electric field of 500V/cm, indicating the potential difference of the order of keV. Standing on these measurement, we can assume that $\Delta\Phi$ reaches of the order of average ion temperature, i.e., several to 10 keV in the burning plasmas. Taking the peak of the lower energy part of α-particles as 0.5MeV, we see that the value of $\Delta\Phi_{keV}/300$ is of the order of 0.01-0.02. This value would be larger than or comparable to the typical evaluation of d/R. (Reference [4] reported that d/R (d is evaluated by the half width at half maximum) is about 1/50.) Under this condition, we see that the location and the width of the heat deposition by ripple-trapped α-particles is affected substantially by the radial electric field of the H-mode.

§4 Summary and Discussion

In summary, we estimate the effect of the edge radial electric field on the orbit of the ripple trapped α-particles. The analytic estimation based on the J-invariance indicates that the peak of the localized heat of α-particles moves in major radius direction. As a result of this shift, the location of the selective heat deposition can move in the poloidal direction on the wall owing to the change of the electric field. The protection against the localized heat deposition must be wide enough to cover this shift.

The pitch angle dependence of the shift is small so that the peakedness of the deposition is not affected much by this mechanism, so long as the potential difference is of the order of the plasma temperature. However, the spread in the energy distribution of the ripple trapped loss α-particles causes the widening of the heat load. This mechanism may lower the peak heat load.

This analysis is also applicable to the investigation of the loss of the NBI particles caused by the trapping in the TF ripples. In this case, the trapping occurs without the reduction of the energetic ion energy below the injected energy.[12)] In these circumstances, the widening of the local heat deposition is not expected, and more strong protection against the peak heat load is necessary.

It is noted that this model does not include the effect of trapping-detrapping which may arise due to the steep gradient of E_r. Further careful study would be necessary to evaluate the peak heat load.

It is also noted that the calculation is performed under the assumption that the electric field is given as a parameter, i.e., the effect of the α-particle loss on the field itself is not kept. The selfconsistent treatment of the radial electric field is left for the future study.

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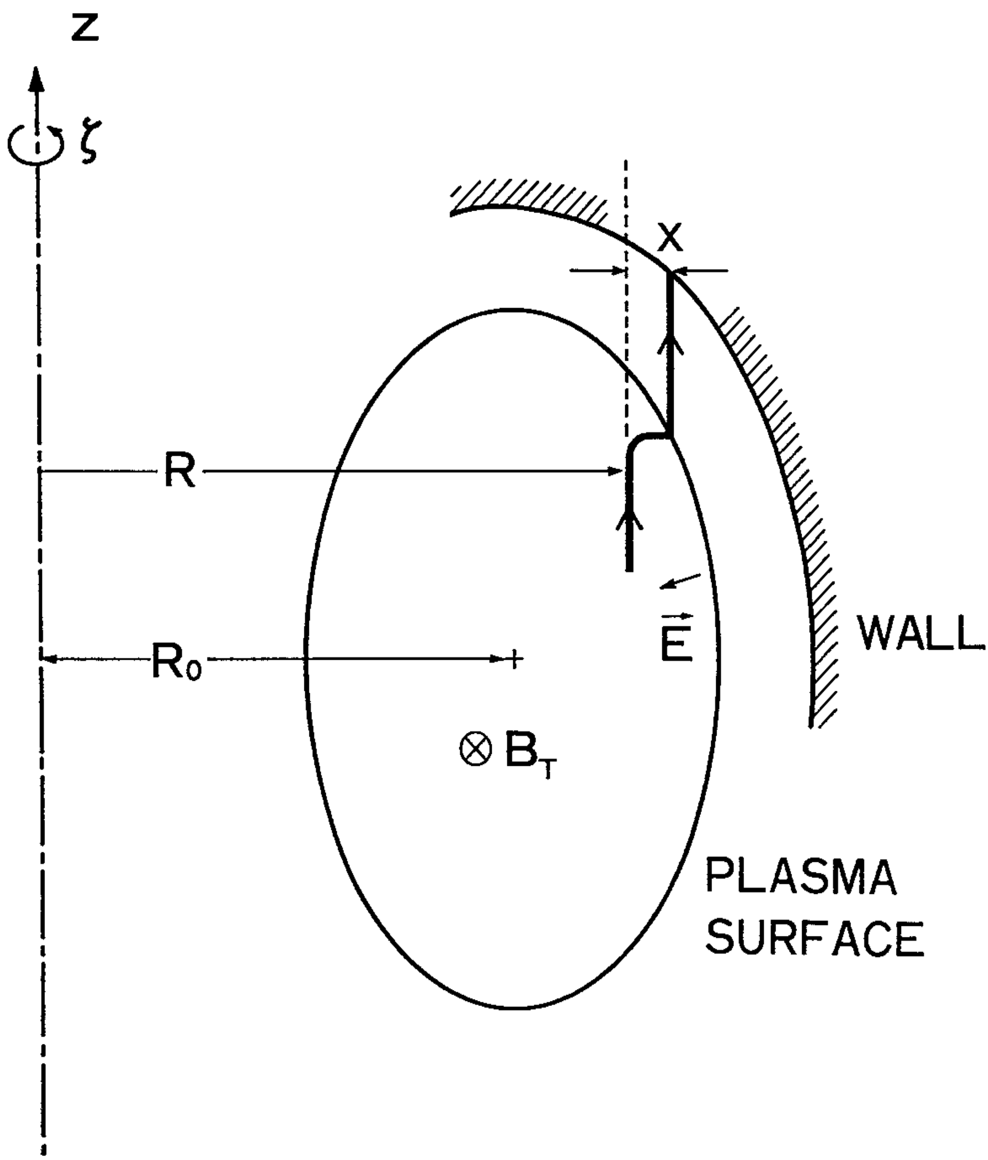
Figure Caption

Fig.1 Poloidal cross section of the tokamak. Negative radial electric field is strong near surface. Thick line indicates the drift orbit of the ripple-trapped banana. x denotes the shift in the major radius direction.

Fig. 1



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