Confinement of Alpha Particles in a Low-Aspect-Ratio Tokamak Reactor

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Studies on the loss of fusion produced alpha particles enhanced by toroidal field (TF) ripple in a low-aspect-ratio tokamak reactor (VECTOR) have been made by using an orbit-following Monte-Carlo code. The ripple loss is strongly reduced as the aspect ratio becomes low. Consequently, alpha particles are well confined in VECTOR. In a low-aspect-ratio system, the dependence of the ripple loss on the number of TF coils is very weak, if the edge field ripple is kept constant. Thanks to the good confinement of alphas in a low-aspect-ratio system, the number of TF coils can be reduced to about 6, one half of the original VECTOR, by installing cooling systems near the outer edge of plasma and making allowances for about 30% increase in the bore diameter of TF coils.

Keywords : low aspect ratio, tokamak, fusion reactor, alpha particle, ripple loss, toroidal field coil

1. Introduction

A low-aspect-ratio tokamak has many attractive features as a fusion reactor⁽¹⁾⁽³⁾. For example, β values are expected to be higher than those of conventional aspect-ratio systems and consequently there is a possibility to downsize the system. Confinement of fusion produced alpha particles is one of the key issues to be investigated first of all to design a tokamak reactor. The loss of alpha particles in a tokamak reactor is mainly caused by an axisymmetric component of toroidal magnetic field (TF ripple) or oscillations in the plasma such as TAE modes. In the present work, we focus our attention only to the ripple losses of alpha particles. The confinement of alpha particles in a tokamak reactor with a conventional aspect ratio has been investigated by using an orbit-following Monte-Carlo (OFMC) code⁽⁴⁾⁽⁵⁾. However, only preliminary studies on the loss of alpha particles in low-aspect ratio tokamaks have been made⁽⁶⁾. As part of the design work for a low-aspect-ratio tokamak reactor, more extensive numerical studies have been made by using the same OFMC code⁽⁷⁾.

Preliminary results indicate that the ripple loss of alpha particles shows a marked reduction in a low-aspect-ratio system⁽⁶⁾⁽⁸⁾. Preliminary results also show that in a tokamak system with a conventional aspect ratio, the reduction of the number of toroidal field (TF) coils results in a considerable increase of alpha particle losses⁽⁹⁾. The number of TF coils is one of the key parameters for the design of tokamak system. The smaller the number is, the easier the design of reactor system becomes. Then the following simple question can be addressed. Is there a possibility to reduce the number of TF coils in a low-aspect-ratio tokamak?

In the present work, qualitative investigations of the ripple loss into the dependence of the aspect-ratio and the dependence of ripple losses on the number of TF coils have been made by using analytical MHD equilibria. Also, quantitative investigations of the ripple loss into the dependence on the edge field ripple, the dependence on the number of TF coils have been made by using realistic MHD equilibria for both hollow and parabolic plasma current profiles in VECTOR⁽⁶⁾⁽⁸⁾ to find the allowable field ripple and the minimum number of TF coils.

2. Qualitative Investigations of the Ripple Loss

Qualitative studies on the ripple loss of alpha particles have been made by adopting the following analytical MHD equilibrium for a non-circular plasma.

$$\psi = \psi(\rho) \quad \dots\dots\dots (1)$$

$$\rho^2 = \left[1 + \frac{\delta}{a} (R - R_t) \right] \frac{Z^2}{\kappa^2} + (R - R_t)^2 \quad \dots\dots\dots (2)$$

where a , R_t , κ and δ are the minor radius, the major radius, the elongation and the triangularity, respectively. Then the vertical coordinate Z can be given by

$$Z = \frac{\kappa}{\sqrt{1 + \delta(R - R_t)/a}} Z^c, \quad \dots\dots\dots (3)$$

where Z^c is the vertical coordinate in a circular plasma. Hereafter, variables with the superscript 'c' denote those in a circular plasma with the same safety factor at plasma surface $q_s(a)$.

By using the above MHD equilibrium, the ripple-well parameter can be given by

$$\alpha_w \cong \sqrt{1 + \delta(R - R_t)/a} \frac{1}{N\gamma} \left| \frac{B_R^c}{B} \right|, \quad \dots\dots\dots (4)$$

where N , γ and B_R^c are the number of TF coils, the local field ripple and the radial component of the magnetic field B in a circular plasmas, respectively. Concerning the ripple loss of fast

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ions, there is another important parameter, the drift of banana orbit enhanced by TF ripple. The averaged displacement of canonical angular momentum enhanced by ripple ΔP_ϕ is given by

$$\Delta P_\phi = \Delta Z \frac{\partial \psi}{\partial Z} \cong \frac{1}{\kappa [1 + \delta(R - R_t)/a]^{1/4}} Z^c \sqrt{N\pi} \left| \frac{B_R^c}{B} \right|^{-3/2} \rho_L \gamma \frac{\partial \psi}{\partial \rho}, \quad (5)$$

where ΔZ and ρ_L are the Z displacement enhanced by ripple averaged over the toroidal angle and the Larmor radius, respectively.

When the above displacement of canonical angular momentum is large enough and

$$\frac{d\varphi_b}{d\psi} \Delta P_\phi \geq \frac{1}{N}$$

where φ_b is the toroidal angle difference between adjacent two banana tips, the banana orbit becomes stochastic. The critical field ripple for the stochastic orbit is given by

$$\gamma_s \approx \kappa \left[1 + \frac{\delta}{a} \left\{ \frac{1}{4} (R - R_t) + \frac{1}{\pi} (\rho + q_s / q'_s) \right\} \right] \gamma_s^c \quad (6)$$

where

$$\gamma_s^c \approx \frac{1}{(N\pi R_t q_s / \rho)^{3/2} \rho_L q'_s} \quad (7)$$

is the critical field ripple derived by Goldston, White and Boozer⁽¹⁰⁾.

It is noted that the number of alpha particles born in the above mentioned stochastic region is usually very small. The major loss process of alpha particles is the ripple-enhanced banana-orbit diffusion given by Eq.(5) and the collisionality⁽⁴⁾. Therefore, collisional processes are very important even for energetic alpha particles. In our OFMC code, Coulomb collisions of alpha particles, Coulomb drag and pitch angle scattering, are described by Monte-Carlo techniques. Initially, test particles are distributed according to the local fusion reaction rate. After they have been launched, we follow them until they all slow down to the local thermal energy of bulk plasma ions.

Calculation parameters are summarized in Table 1 and shapes

Table 1. Calculation parameters

Major radius	$R_t = 3.7 \sim 9.2\text{m}$
Minor radius	$a = 1.9\text{m}$
Toroidal field @ $R=R_t$	$B_t = 3.1\text{ T}$
Plasma temperature	$T_e(\Psi) = T_{e0} (1-\Psi)$ $T_i(\Psi) = T_{i0} (1-\Psi)$ $T_D(\Psi) = T_T(\Psi) = T_i(\Psi)$ $T_{e0} = T_{i0} = 35\text{ keV}$
Plasma density	$n_e(\Psi) = n_{e0} (1-\Psi)^{0.3}$ $n_D(\Psi) = n_T(\Psi) = n_i(\Psi)$ $n_{e0} = 2 \times 10^{20} \text{ m}^{-3}$
Plasma current	$j(\Psi) = j_0 (1-\Psi)^{1.3}$
Safety factor @ $\Psi=1.0$	$q_a = q_s(a) = 2.56$
Elongation	$\kappa = 1.55$
Triangularity	$\delta = +0.5$
Effective Z	$Z_{\text{eff}} = 1.9$ (uniform)
Charge number of impurity	$Z_{\text{imp}} = 6.0$ (carbon)
Number of TF coils	$N = 4 \sim 18$

of plasma, first wall and TF coils are shown in Fig.1(A). The distribution of the safety factor is also shown in Fig.1(B).

2.1 Dependence on the Aspect Ratio Simulations were performed by changing the major radius only and keeping the relative positions of plasma, first wall and TF coils, the field ripple at outer plasma edge γ_o and the safety factor at plasma surface.

The distribution of the field ripple in a system with vertically long TF coils is approximately given by

$$\gamma(R) = \gamma_o \left(\frac{R/a}{A+1} \right)^{N-1} + \gamma_i \left(\frac{A-1}{R/a} \right)^{N-1}, \quad (8)$$

where γ_o and γ_i are the field ripple at the outer and inner edge of plasma. Equation (8) indicates that the distribution of the field ripple strongly depends on the aspect ratio. Distributions of the field ripple for various aspect ratios are shown in Fig.2 where N was set to 12. It is noted that the decay of the field ripple in the plasma becomes stronger as the aspect ratio becomes smaller.

From Eqs.(4)-(6), the aspect-ratio dependence of the ripple-well parameter, the ripple-enhanced banana drift and the critical field ripple for stochastic orbit can be summarized as follows:

$$\left. \begin{aligned} \alpha_w &\propto 1/A, \\ \Delta P_\phi &\propto A^{3/2}, \\ \gamma_s &\propto 1/A^{3/2}. \end{aligned} \right\} \quad (9)$$

These equations show that the area of ripple-well region, the size of the ripple-enhanced banana drift and the area of stochastic orbit region are all become smaller, as the aspect ratio is reduced. As mentioned above, the distribution of the field ripple also strongly depends on A . By the synergy of all of these effects, the ripple loss shows a very strong dependence on A as $A^{4.3}$ for $A > 3$. Consequently, alpha particles are well confined in a

Fig. 1. Plasma shapes, first wall and TF coils (A), and the profile of the safety factor (B)

Fig. 2. Distributions of the field ripple for various aspect ratios; The number of TF coils $N=12$

low-aspect-ratio tokamak.

2.2 Dependence on the Number of TF Coils N From Eqs.(4)-(6), the dependence of α_w , ΔP_ϕ and γ_s on the number of TF coils N and the local field ripple γ can be summarized as follows:

$$\left. \begin{aligned} \alpha_w &\propto 1/(N\gamma), \\ \Delta P_\phi &\propto \sqrt{N}\gamma, \\ \gamma_s &\propto 1/N^{3/2}. \end{aligned} \right\} \dots\dots\dots (10)$$

Above equations indicate that the area of ripple-well region, the size of the ripple-enhanced banana drift and the area of stochastic orbit region are all become smaller, as the number of TF coils is reduced. However, Eq.(8) implies that the field ripple γ strongly depends on N and becomes larger as N is reduced. In order to investigate the complicated problem, simulations were performed by changing only the number of TF coils and keeping the field ripple at outer plasma edge γ_o and the safety factor at plasma surface q_a . Results are shown in Fig.4 for a large and a small aspect ratio, $A=4.32$ and $A=2.21$.

Equation (8) shows that if the edge ripple γ_o is fixed, the field ripple in the plasma increases as the number of TF coils N is reduced. This effect to enhance the ripple losses of alpha particles can not be compensated by those described by Eq.(10) in a conventional aspect ratio system which is shown in Fig.4 by the

Fig. 3. Total power loss fraction against aspect ratio A for $\gamma_o=1\%$, $N=12$ and $q_a=2.56$

Fig. 4. Total power loss fraction of alpha particles against the number of TF coils for a large and a small aspect ratio, $A=4.32$ and 2.21 , and for fixed edge field ripple $\gamma_o=1\%$

curve of $A=4.32$ for $N>6$. In case of a low aspect ratio ($A=2.21$), these effects might compensate each other and consequently the ripple loss shows a very weak dependence on N.

3. Quantitative Investigations of the Ripple Loss

Quantative studies on the ripple loss of alpha particles in VECTOR have also been made by using the same OFMC code. In expectation of a good plasma confinement by a negative shear, a hollow current drive is chosen as one of operational options in VECTOR. Then, two different MHD equilibria with a parabolic and a hollow current profile have been adopted for the numerical studies. Shapes of plasma, first wall and TF coil are shown in Fig.5(A). Profiles of the safety factor are also shown in Fig.5(B). The major radius $R_t=3.7m$. Other parameters besides the major radius, the elongation, the triangularity and the plasma current are the same as those summarized in Table 1.

Numerical investigations on the total power loss of alpha particles for a hollow and a parabolic current profile have been made by changing the edge field ripple γ_o . Results are shown in Fig.6.

Non-negligible amount of alpha particle loss due to axisymmetric loss orbits has been found in the hollow current profile. This is due to large size potato orbits which make long excursions from the plasma central region to the periphery.

Also, numerical studies on the total power loss of alpha particles have been made by changing the number of TF coils N and keeping the edge field ripple $\gamma_o=1\%$. Results are shown in Fig.7. The N dependence of the total power loss of alpha particles

Fig. 5. Plasma shapes, first wall and TF coils (A), and the profile of the safety factor (B) for VECTOR

Fig. 6. Dependence of the total power loss fraction of alpha particles on the edge field ripple γ_o for a parabolic and a hollow current profile in VECTOR; The number of TF coils $N=4$

Fig. 7. Dependence of the total power loss fraction of alpha particles on the number of TF coils for a parabolic and a hollow current profile in VECTOR; The edge field ripple $\gamma_o=1\%$

Fig. 8. Poloidal distribution of heat load due to loss alpha particles for parabolic current profile (a) and hollow current profile (b); The number of TF coils $N=6$ and the edge field ripple $\gamma_o=1\%$

for a parabolic current profile is very weak. On the other hand, the total power loss and N for a hollow current profile show a positive correlation, though it is weak. In case of a hollow current profile, ∇B drift in the current hole effectively pushes alpha particles near plasma periphery where the change in the field ripple with N is rather weak and the effects described by Eqs.(10) might be dominant.

One of the main objectives of the present work is to investigate a possibility to reduce the number of TF coils in a low-aspect-ratio tokamak.

As shown in Figs.6 and 7, alpha particles are well confined in a low-aspect-ratio tokamak. Then, the allowable field ripple is mainly given by the maximum heat load on the first wall due to loss particles. It is known that the allowable heat loads on the first wall are about 2MW/m^2 and 1MW/m^2 with and without cooling systems⁽¹¹⁾, respectively. In the present Monte-Carlo analyses, the total number of test particles were limited only to 4,000 for each run because of limited available CPU time. It is very difficult to investigate 2-D (poloidal and toroidal angles) distribution of the heat load by using such a small number of test particles. Then, only poloidal-angle distributions have been calculated.

Typical poloidal distributions of the heat load due to loss particles are shown in Fig.8 for a parabolic current profile (a) and a hollow current profile (b) in VECTOR. The number of TF coils and the edge field ripple are $N=6$ and $\gamma_o=1\%$, respectively.

Fig. 9. Maximum heat load averaged over toroidal angle against the edge field ripple γ_o for a hollow and a parabolic current profile; The number of TF coils $N=6$

Table 2. Allowable edge field ripple γ_o for $N=6$

	with cooling	without cooling
hollow current	about 1.5 %	below 1 %
parabolic current	about 2.0 %	about 1 %

Fig. 10. Equi-ripple contours for $\gamma_o=1.0$ and 2.0% with respect to the number and the horizontal bore diameter of TF coils

Contributions of loss particles enhanced by ripple and those due to axisymmetric loss orbits to the local heat load are shown by closed and open bars, respectively. Figure 8 shows a large amount of heat load due to axisymmetric loss orbits near poloidal position #35 in the case of hollow current profile. Note that a divertor with a powerful cooling system is installed in the region between poloidal positions #30 and #40. Figure 8 also shows that most of loss alpha particles enhanced by ripple hit the very limited area on the first wall near the plasma outer edge.

Figure 9 shows the maximum heat load averaged over the toroidal angle against the edge field ripple for $N=6$.

Assuming a peaking factor (peak/average over toroidal angle) about 2, the allowable edge field ripple from Fig.9 can be summarized as shown in Table 2.

The number of TF coils and the edge field ripple of the original VECTOR are $N=12$ and $\gamma_o=1\%$, respectively. If some cooling systems are installed in the loss region on the first wall to improve the allowable heat load, the number of TF coils can be reduced to about 6 keeping the outer edge field ripple 1.5-2.0%. It is noted that the size of TF coils may be enlarged to reduce N keeping $\gamma_o=1.5-2.0\%$. Figure 10 shows equi-ripple contours for $\gamma_o=1.0$ and 2.0% with respect to the number and the horizontal bore diameter of TF coils. It is shown in Fig.10 that the size or weight of TF coils of VECTOR becomes larger by about 30% from the original design to keep $\gamma_o=2.0\%$. This is a trade-off between the weight of

TF coils and the space for blankets, poloidal coils and maintenance.

4. Conclusions

Studies on ripple losses of fusion produced alpha particles in a low-aspect-ratio tokamak reactor have been made by using an orbit-following Monte-Carlo code. Conclusions of the present work can be summarized as follows:

(1) The ripple loss is strongly reduced as the aspect ratio becomes low (proportional to $A^{4.3}$ for $A > 3$). Consequently, alpha particles are well confined in VECTOR.

(2) In a low-aspect-ratio system, the dependence of the ripple loss on the number of TF coils is very weak, if the edge field ripple is kept constant.

(3) Thanks to the good confinement of alphas in a low-aspect-ratio system, the number of TF coils can be reduced to about 6, one half of the original VECTOR, by installing cooling systems near the outer edge of plasma and making allowances for about 30% increase in the bore diameter of TF coils..

The third conclusion has been derived on the assumption that the toroidal peaking factor is about 2. For more precise treatment, the peaking factor should be evaluated by a simulation to investigate 2-D heat load using more than a million of test particles. The ripple loss of alpha particles strongly depends on the field ripple near banana tips. This implies that the loss can be reduced by optimizing not only the shape of plasma but also the shape of TF coils. It is expected that these optimizations are effective to alleviate the increase of coil size as well as to remove the cooling systems. A reduction of field ripple by installing ferrite boards under the TF coils might also be effective⁽¹²⁾. These investigations are left for future works.

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