Ripple Loss of Alpha Particles in a Low-Aspect-Ratio Tokamak Reactor

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Abstract

Studies on the loss of 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. In actual TF coil systems, the ripple loss of alpha particles is strongly reduced as the aspect ratio becomes low (the power loss $\propto A^{8.8}$ for $A \geq 2.5$) and the reduction of the number of TF coils results in a large amount of ripple loss even in a low-aspect-ratio tokamak. To reduce the number of TF coils from 12 to 6, about 40% of coil size enlargement is necessary in VECTOR. Ferrite plates are very effective to reduce ripple losses of alpha particles. By using ferrite plates, the coil size enlargement for N=6 can be relaxed to 15% and the number of coils can be reduced from 12 to 8 without enlargement of coil size in VECTOR.

1. Introduction

It has been shown in previous works that the toroidal field ripple shows a very strong decay in the plasma region in a low-aspect-ratio tokamak [1,2]. Moreover, 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. By these synergetic effects, the ripple loss of alpha particles is strongly reduced as the aspect ratio becomes low (the power loss is proportional to $A^{4.3}$ for $A>3$) and consequently, alpha particles are well confined in a low-aspect-ratio tokamak reactor “VECTOR (the Very Compact Tokamak Reactor)” [2,3]. It has also been shown by numerical studies using an orbit-following Monte-Carlo (OFMC) code [4] that thanks to the good confinement of alphas in a low-aspect-ratio system, the number of TF coils can be reduced from 12 to 6 in VECTOR by keeping the maximum heat load due to loss alpha particles on the first wall within an acceptable level (~1MW/m^2).

These results, however, have been obtained by using a model field ripple [5]. In order to reexamine the ripple loss of alpha particles in an actual field ripple, a new code to calculate 3D magnetic field in a realistic TF coil system (Fig.1) has been developed and combined with the OFMC code. In the code, radial shift and radial expansion of coil configuration can be set by input data, radial coil expansion factor F_{exp} and radial shift R_{shft}, as shown in Fig.1. Calculations of the effect of ferrite plates on the field ripple are also available.

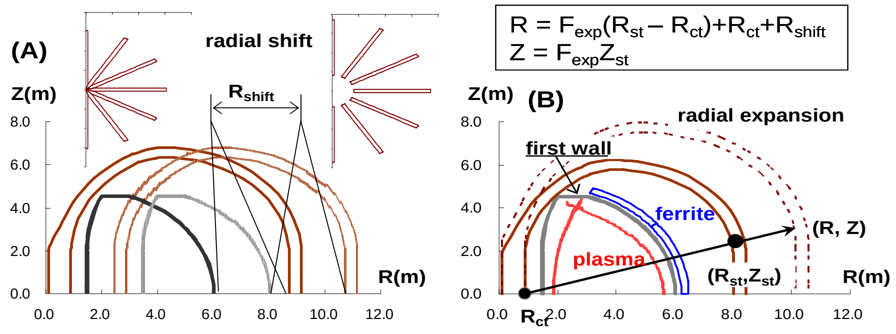


Fig.1 TF-coil system to calculate field ripple, radial shift (A) and expansion (B). Typical shapes of plasma and first wall of VECTOR are also shown in (B).

2. Reexamination of Loss of Alpha Particles in Actual Field Ripple

Qualitative studies on the ripple loss of alpha particles have been made by adopting an MHD equilibrium for a non-circular plasma [6]. Calculation parameters are summarized in Table 1 and shapes of first wall and TF coils are 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 and the safety factor at plasma surface. Results for an actual field ripple are shown in Fig.2 (A) and those for a model field ripple (constant edge ripple γ_o =1%) are also shown in (B) for reference. The aspect-ratio dependence of the ripple loss in an acutual field ripple is much stronger ($\propto A^{8.8}$) than that in a model field ripple ($\propto A^{4.3}$) because the edge field ripple depends on A as shown in (A).

Table 1 Calculation parameters

Major radius	R_t = 3.7 ~9.2m
Minor radius	a = 1.9m
Toroidal field @R=R_t	B_t = 3.1 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 keV
Plasma density	$n_e(\Psi) = n_{e0}\,(1-\Psi)^{0.3}$ $n_D(\Psi) = n_T(\Psi) = n_i(\Psi)$ $n_{e0} = 2\text{x}10^{20}\ \text{m}^{-3}$
Plasma current	$j(\Psi) = j_0\,(1-\Psi^{1.3})$
Safety factor @Ψ=1.0	$q_a = q_s(a)$ = 2.56
Elongation	κ = 1.55
Tiangularity	δ = +0.5
Effective Z	Z_{eff} = 1.9 (uniform)
Charge number of impurity	Z_{imp} = 6.0 (carbon)
Number of TF coils	**N = 4 ~ 18**

Fig.2 Dependence of the ripple loss loss of aplha particles on the aspect ratio in an acutual field ripple (A) and in a model field ripple (B).

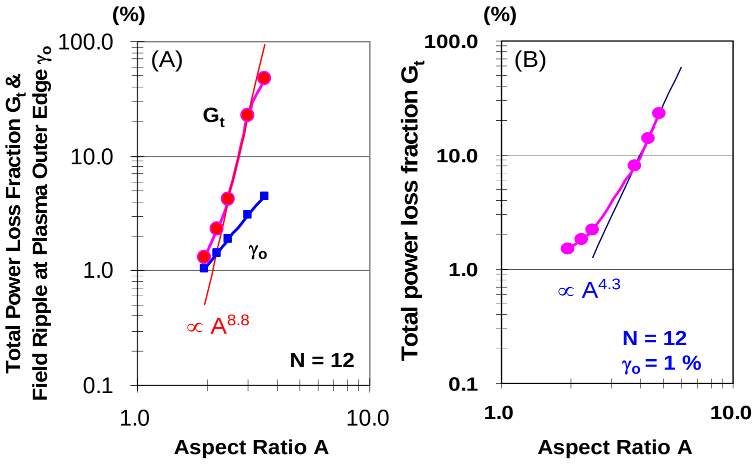
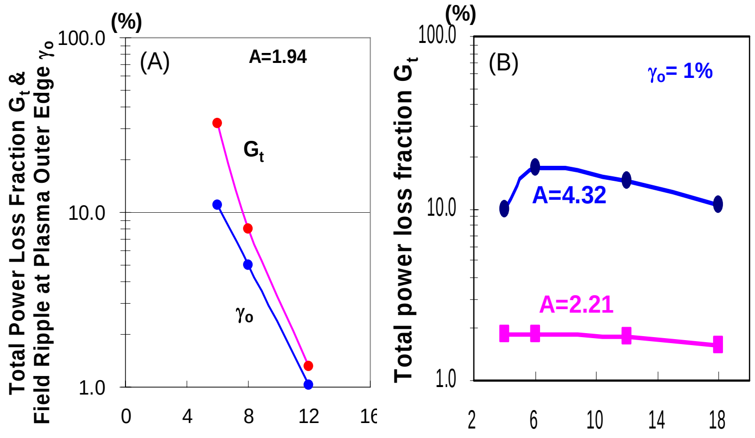


Fig.3 Dependence of the ripple loss of aplha particles on the aspect ratio in an acutual field ripple (A) and in a model field ripple (B).



2-2 Dependence on the number of TF coils

Results in an actual field ripple calculated by changing only the number of coils and keeping the safety factor at plasma surface q_a are shown in Fig.3(A). Results of the previous work for a model field ripple obtained by keeping the field ripple at outer plasma edge γ_o=1% shown in Fig.3 (B) for reference. In a realistic TF coil system, the edge field ripple strongly depends on the number of TF coils, consequently, the ripple loss is substantially increased as the number of coils is reduced.

3. Evaluation of TF Coil Parameters by 2-D Heat Load

Quantative studies on the ripple loss of alpha particles in VECTOR have been made for a realistic MHD equilibrium and an actual field ripple by adopting the same OFMC code. A bird's-eye view of VECTOR is shown in Fig.4. Shapes of the plasma and the first wall are shown in Fig.1(B). The major radius R_t=3.7m. Other parameters besides the major radius, such as the elongation, the triangularity and the plasa current are the same as those summarized in Table 1.

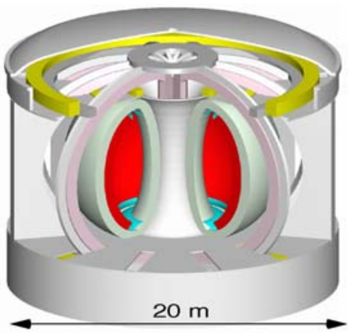


Fig.4 Bird's-eye view of VECTOR

Two dimensional distribution of the heat load due to loss particles have been evaluated by using 30,000 test particles. It took about 6 hours of CPU time by using 128 processors of SGI Altix3900.

Targets of the present work are as follows;

1. To evaluate two dimensional heat load due to loss particle,
2. To evaluate the effect of ferrite plates on the ripple loss of alpha particles, and
3. To find the minimum number and the size of TF coils to meet the allowable peak heat load.

A typical poloidal distribution of the heat load averaged over the toroidal angle is shown in Fig.5. Usually, there are three loss regions, top and bottom divertor regions and near the plsama outer edge. We concentrate our attention only on the peak near the midplane, because powerful cooling systems are ususally installed in the divertor regions.

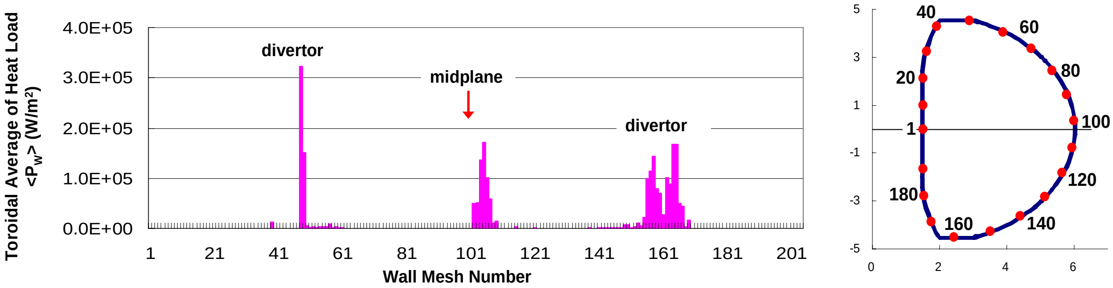


Fig.5 Typical poloidal distribution (toroidal average) of heat load on the first wall

Two dimensional heat load on an axisymmetric first wall for F_{exp}=1.2 and R_{shift}=0 with ferrite plates (0.25m thick at 0.63m from the plasma surface as shown in Fig.1(B)) is shown in Fig.6(A). The heat load is stlongly localized in both poloidal and toroidal directions. If the firs wall surface is corrugated along the magnetic field line, the heat load is substantially flattend in the toroidal direction as shown in Fig.6(B).

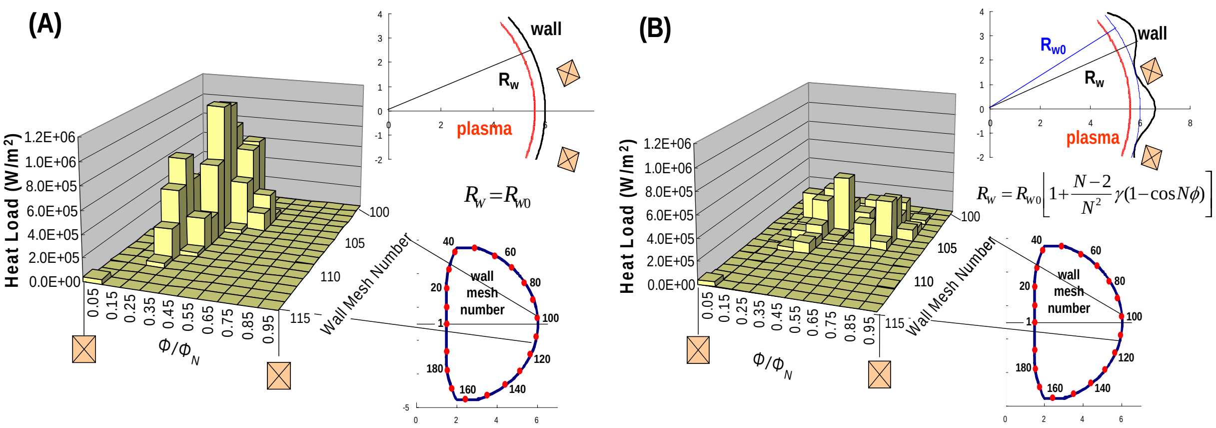


Fig.6 Two dimensional heat loads on an axi-symmetric and axi-asymmetric first wall for F_{exp}=1.2 and R_{sfift}=0 with ferrite plates.

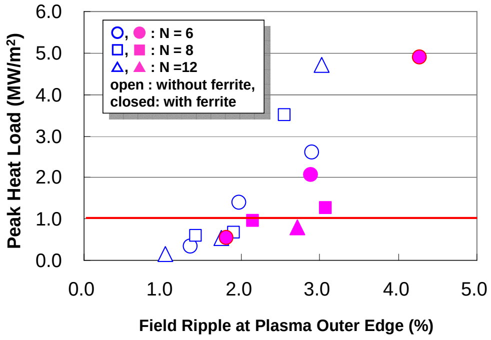


Fig.7 Peak heat load against edge field ripple for various cases.

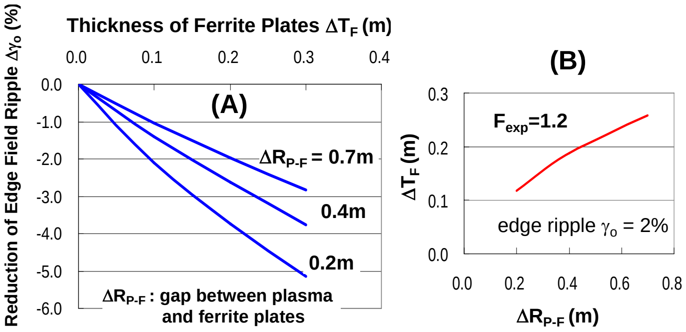


Fig.8 Reduction of field ripple by ferrite plates for various gaps between plqsma and ferrite plates against plate thickness (A) and a contour for edge ripple 2%(B).

The peak heat load against the edge field ripple is shown in Fig.7 for various cases. It is known that the allowable heat loads on the first wall is about 1MW/m^2 without cooling system [7]. Figure 7 shows that generally, allowable field ripple at plasma outer edge γ_o to meet the peak heat load less than 1 MW/m^2 is about 2.0%.

Reduction of field ripple by F82H ferrite plates for various gaps between plqsma and plates ΔR_{P-F} against their thickness ΔT_F and a ΔR_{P-F} - ΔT_F contour line of γ_o= 2% for F_{exp}=1.2 are shown in Fig.8 (A) and (B), respectively. In the calculation of field ripple with ferrite plates, a magnetization surface current $j_m(\phi) = j_m(1 + \cos N\phi)/2$ is assumed to remove higher haromonics of the field. Figure 8 shows that studies to optimize the gap ΔR_{P-F} and the thickness ΔT_F should be made in future. The higher harmonics of the field ripple might have an impact on the 2-D distribution of the heat load. These studies are left for furure works.

Finally, contours of peak heat load of 1MW/m^2 with respect to the number of TF coils N and coil expansion factor F_{exp} with and without ferrite plates (ΔR_{P-F} =0.63m, ΔT_F =0.25m) are shown in Fig.9. Even in a low-aspect-ratio system, if the number of TF coils is reduced, it is necessary to allow some enlargement of the coil size to control the edge field ripple less than 2% and consequently the ripple loss of alpha particles. Figure 9 shows that about 40% of enlarghement of coil size is necessary to meet the requirement for the allowable peak heat load without cooling system to reduce the number of TF coils by one half (from 12 to 6) in VECOR. The enlargement can be relaxed to 15 % by using ferrite plates. It is noted that by using ferrite plates, the number of coils can be reduced to 8 without any enhancement of coil size.

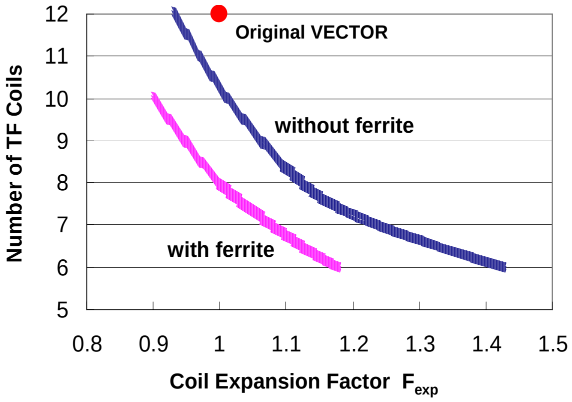


Fig.9 Contours of number of TF coils and coil expansion factor to meet peak heat load of 1MW/m^2 with and without ferrite plates ($\Delta R_{P\text{-}F}$ =0.63m, ΔT_F =0.25m)

4. Conclusions

Conclusions of the present work can be summarized as follows:

1. In actual TF coil systems, the ripple loss of alpha particles is strongly reduced as the aspect ratio becomes low (the power loss $\propto A^{8.8}$ for $A\geq 2.5$) .
2. In actual TF coil systems, the reduction of the number of TF coils results in a large amount of ripple loss even in a low-aspect-ratio tokamak.
3. Corrugation of the first wall surface along the magnetic field line is effective to reduce the peak heat load due to loss particles.
4. To reduce the number of TF coils from 12 to 6, about 40% of coil size enlargement is necessary in VECTOR. Ferrite plates are very effective to reduce ripple losses of alpha particles. By using ferrite plates, the coil size enlargement for N=6 can be relaxed to 15% and the number of coils can be reduced from 12 to 8 without any enlargement of coil size in VECTOR.

Following studies are left for future works;

1. To optimize the configuration of ferrite plates (position, thickness etc.).
2. To evaluate the effect of higher harmonics of TF ripple by ferrite plates on the peak heat load due to loss particles.

References

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