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低环径比托卡马克堆中等离子体特性及α粒子输运

PLASMA FEATURES AND ALPHA PARTICLE TRANSPORT IN LOW-ASPECT RATIO TOKAMAK REACTOR

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低环径比托卡马克装置的等离子特性及α粒子输运*

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摘　　要

低环径比托卡马克装置的实验和理论结果已证实它有利于改善MHD稳定性。基于目前等离子体物理，向减小环径比方向外推，初步讨论了低环径比托卡马克堆的物理特征。在自洽的低环径比托卡马克堆参数下，计算了α粒子约束和损失以及不同环径比对α粒子约束和损失的影响。此结果对紧凑托卡马克堆的可行性研究提供参考。

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Plasma Features and Alpha Particle Transport in Low-Aspect Ratio Tokamak Reactor*

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ABSTRACT

The results of the experiment and theory from low-aspect ratio tokamak devices have proved that the MHD stability will be improved. Based on present plasma physics and extrapolation to reduced aspect ratio, the feature of physics of low-aspect ratio tokamak reactor is discussed primarily. Alpha particle confinement and loss in the self-justified low-aspect ratio tokamak reactor parameters and the effect of alpha particle confinement and loss for different aspect ratio are calculated. The results provide a reference for the feasible research of compact tokamak reactor.

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INTRODUCTION

The conventional tokamak plasma has an aspect ratio $A=R/a \geqslant 2.5$ and the spherical tokamak or low-A tokamak has a very amall aspect ratio $A<2$. Although it had been known for a long time that the MHD stability of axisymmetric confinement configurations will be improved with the decrease of aspect ratio, it is not full to study in theory and experiment for the low-A tokamak. the recent results of the experiment and the theory from low-A tokamak devices, such as START, CDX-U, TS-3, HIT [1~4] and Y-K. M. Peng et al. [5] show that stable configuration can be obtained at large plasma current, modest toroidal field and high beta, which may lead to more economical compact neutron source and compact fusion reactor. These outstanding results have stirred up interest in the low-A tokamak.

In this paper based on present plasma physics and extrapolation to reduced aspect ratio, the feature of physics of low aspect ratio tokamak reactor is discussed primarily. For low aspect ratio self-justified reactor parameters, α-particle loss and the effect of aspect ratio on the confinement of α-particles has been calculated, so that provide reference for the feasible research of compact tokamak reactor.

1 FEATURE OF LOW-*A* TOKAMAK PLASMA

Low-A tokamak plasma is similar to conventional takamak palsma in the physics. Based on present plasma physics and extrapolation to reduced aspect ratio, some features of low-A tokamak plasma can be obtained.

1.1 Large plasma current

The equilibrium toroidal plasma current can be approximated by the formula:

$$I_{\mathrm{p}} = \frac{5aB_{\mathrm{T}}}{2A\,q_{\psi}}[1+K^2(1+2\delta^2-1.2\delta^3)]\left[\frac{(1.17-0.65/A)}{(1-1/A^2)^2}\right] \qquad (1)$$

where B_{T} is the toroidal field, A is the aspect ratio. We find that leads to a potential high current for low-A tokamak. If A is reduced from 2.5 to 1.5, I_{p} increases by a factor of about 4 for a given other parameters. It is evident that I_{p} increases as A is decreased.

1.2 High β limit

The β limit imposed on plasma by magnetohydrodynamic instability, that is

$$\beta_c = gI_p/aB \tag{2}$$

where B is the average field strength. For plasma with double-null poloidal divertor forming D-Shape plasma, I_p/aB can be approximately written as [5]

$$I_p/aB \approx I_p/aB_{T0} \approx 1.9K^2\left(\frac{1}{A}\right)^{0.5}/q_\psi\left(1-\frac{1}{A}\right)^{0.9} \tag{3}$$

where K is the elongation at edge of plasma. For a given K and q_ψ, I_p/aB increases by a factor of about 2 if A is reduced from 2.5 to 1.5. This leads to a similar β limit increase if coefficient g can be maintained.

1.3 Large shaping factor S

Shaping factor S ($\equiv I_p/aB \cdot q_\psi$) is a important value in the tokamak. Because of the product $\beta \cdot \tau_E$ has been used as important figure of merit for the plasma confinement. Based on reference [6] $\beta \cdot \tau_E$ can be expressed as

$$\beta \cdot \tau_E = 0.31\left(\frac{S^2 R^2}{1+K^2}\right)\left(\frac{F}{q}\right)^2 \tag{4}$$

where (F/q) is the confinement factor, K is the elongation. For constant (F/q), $\beta \cdot \tau_E$ increases as S is increased, and S increases strongly as A is reduced. Therfore $\beta \cdot \tau_E$ increases strongly as A is reduced. For a given K, R and (F/q), we plot S vs. A and $\beta \cdot \tau_E$ vs $\cdot$ S in Fig. 1 and Fig. 2.

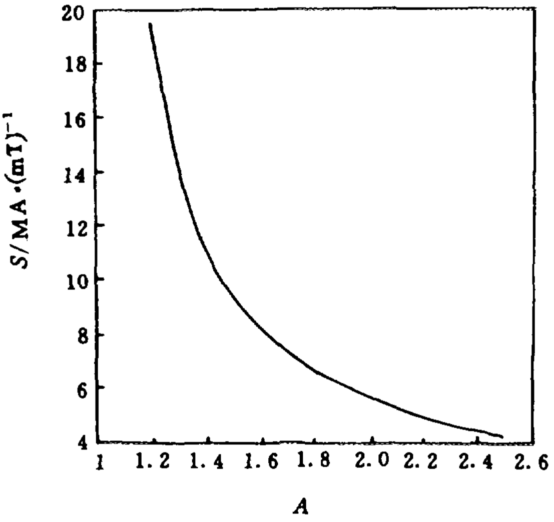

Fig. 1 S vs. A for a given $K=1.5$

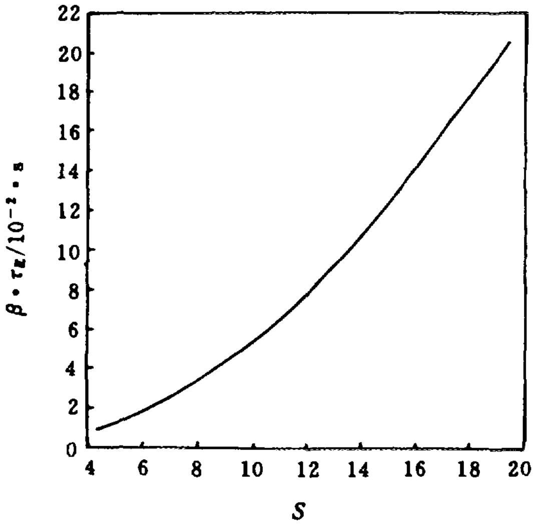

Fig. 2 $\beta \cdot \tau_E$ vs $\cdot$ S for a given $K=1.5$ $R=1.5$ m and $(F/q)=1/2$

1.4 Bootstrap current

Bootstrap current has relation to $\varepsilon\beta_p$, and $\varepsilon\beta_p$ can be written as [5]

$$\varepsilon\beta_p \leqslant 7.6\, g q_\psi \left(\frac{1}{A}\right)^{0.5} \left(1 - \frac{1}{A}\right)^{0.9} \tag{5}$$

where g is the scaling factor, q_ψ is the edge safety factor, and ε is the inverse aspect ratio. For a given g and q_ψ, $\varepsilon\beta_p$ remains roughly unchanged if A is reduced from 2.5 to 1.5.

Based on reference [7], the bootstrap current fraction can be written roughly as

$$\begin{aligned} f_{bs} &= I_{bs}/I_p \approx C_{bs}(\varepsilon^{0.5}\beta_p)^{1.3} \\ C_{bs} &= 1.32 - 0.24(q_\psi/q_0) + 0.019(q_\psi/q_0)^2 \end{aligned} \tag{6}$$

Thus for constant β_p and (q_ψ/q_0), bootstrap current fraction increases about 15% if A is reduced from 2.5 to 1.5. However, the relation between bootstrap current and aspect ratio needs to study in the future.

1.5 Particle confinement

For low-A tokamak, the trapped particle has a very narrow banana orbit and hence particle confinement will be improved with the decrease of aspect ratio. Based on the classical transport theory, the particles have a larmor radius ρ, their banana orbits have a width $\Delta\gamma_b \approx \varepsilon^{-\frac{1}{2}}\rho q$, effective scattering frequency $\upsilon_{eff} = \upsilon_\perp/\varepsilon$, a fraction of the particles trapped are $\varepsilon^{1/2}$ and hence the classical diffusion coefficent is

$$D \approx \varepsilon^{-3/2} q^2 \rho^2 \upsilon_\perp \tag{7}$$

where $\varepsilon = 1/A$ is the inverse aspect ratio. It is evident that D decreases as A is decreased. In order to analyse the particle confinement in low-A tokamak in detail, α-particle transport is calculated in section 2.

2 α-PARTICLE TRANSPORT CALCULATION

2.1 Physical models

The research of α-particle transport problem is important to future fusion reactor. The energetic α-particles produced by fusion transfer their energy to the plasma to sustain power balance. Otherwise α-particle bombardment on the first wall will lead to the damage of the material and result in an increase of impurity. Based on reference [8], in the fusion reactor, since the density of α-particles is far less than the density of plasma, it is suitable to describe the α-particle transport by test-particles approximation. Thus the two dimensional (space and velocity) Fokker-Planck equation reads:

$$\frac{\partial f}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD^{G}\frac{\partial f}{\partial r}\right) + \frac{1}{v^{2}}\frac{\partial}{\partial v}\left[v^{2}\left(Af + D^{v}\frac{\partial f}{\partial v}\right)\right] + S_{\text{eff}} \tag{8}$$

where $f = f\ (r,\ v,\ t)$ is the distribution function of α-particles, D^{G} is the diffusion coefficient in geometry space, A is the dynamic friction coefficient, D^{v} is the dynamic diffusion coefficient, S_{eff} is the effective source. The geometry boundary condition reads:

$$\left.\frac{\partial f}{\partial r}\right|_{r=0} = 0,\ f|_{r=a} = 0 \tag{9}$$

According to the continuity of particles in velocity space, the boundary condition of the velocity space is:

$$\begin{gathered} \left[Af + D^{v}\frac{\partial f}{\partial v}\right] = 0 \\ \left.\frac{\partial f}{\partial v}\right|_{v=0} = 0,\ f|_{v\to\infty} = 0 \end{gathered} \tag{10}$$

2.2 α-particle loss calculation

By using the two-dimensional time-dependent Fokker-Plank numerical code [8], the loss fraction of α-particle, the heating efficiency and the particle confinement time are calculated for low-A tokamak, which the parameters are shown in Table 1. These parameters are self-justified, they satisfy MHD equilibrium, stability and scaling law [9]. The selected parameters in the calculation are $B_{\text{T}} = 2.5$ T, $a = 1$ m. The self-justified parameters from Table 1 show that when aspect ratio A decreases, plasma curent I_{p}, shaping factor S and β_{c} increase as A is decreased.

Table 1 Parameters of reactor core

A	2.5	1.8	1.4	1.3	1.2
q_ψ	2.1	2.5	3.9	5.3	7.7
"Nature" elongation$K$	1.1	1.3	1.6	1.8	2
Density $\langle n \rangle$ / $(10^{20} \cdot m^{-3})$	0.9	1.4	2	2.2	2.7
Temparature $\langle T \rangle$ /keV	4.9	6	8.1	9.7	11.4
Current I_p/MA	3.7	7	13	17.2	25.5
$\beta_t / \%$	5	9.8	18	24	36
τ_E/s	0.4	0.42	0.5	0.55	0.7
$S/$ $(MA \cdot m^{-1}T \cdot {}^{-1})$	3	7	20	36.3	79
Fusion power P_f/MW	6.7	24	98	186	422
$P_w/$ $(MW \cdot m^{-2})$	0.05	0.22	1.05	1.97	4.5

The calculation results of α-particle loss are shown in Table 2, where τ_p is the particle confinement time, H is the heating efficiency, L_p is the prompt loss fraction, $L_p{}^S$ is the slowing particle loss fraction, $L_E{}^S$ is the slowing energy loss fraction.

Tabel 2 Particle confinement and loss fraction

A	τ_p/s	H	L_p	$L_p{}^S$	$L_E{}^S$
2.5	0.403	0.838	0.155	0.843	0.006
1.8	0.833	0.970	0.021	0.976	0.009
1.4	1.469	0.982	0.006	0.988	0.012
1.3	1.899	0.982	0.004	0.989	0.013
1.2	2.308	0.982	0.002	0.984	0.014

If given a set of parameters: $q_\psi = 3.9$, $a = 1$ m, $\langle n \rangle = 2.0 \times 10^{20}$ m^{-3}, $\langle T \rangle = 8.1$ keV, $I_p = 13$ MA, $P_W = 1.05$ MW/m^2, the calculation results of α-particle loss as A is decreased are shown in Table 3.

Table 3 Particle confinement and loss fraction

A	τ_p/s	H	L_p	$L_p{}^S$	$L_E{}^S$
2.5	1.643	0.982	0.007	0.987	0.012
1.8	1.547	0.982	0.006	0.988	0.012
1.4	1.469	0.982	0.006	0.988	0.012
1.3	1.443	0.982	0.006	0.988	0.012
1.2	1.429	0.982	0.006	0.988	0.012

The calculation results from Table 2 show that when aspect ratio A decreases, particle confinement is improved, prompt loss is decrease, heating efficiency is increased. In addition, we give a set of parameters, only aspect ratio A is changed, the effect of aspect ratio on the confinement of α-particle is given in Table 3. It can be seen from Table 3 that particles confinement, heating efficiency, prompt loss and slowing loss are nearly unchanged as A is decreased.

REFERENCES

1 Sykes A, et al. Plasma Phys. and Controlled Fusion, 1993, 35: 1051

2 Hwang Y. S, et al. IAEA-AN-60/A5-Ⅱ-5 (1994)

3 Ono M, et al. IAEA-CN-56/E-2-5 (1992).

4 Jarboe T. R, et al. IAEA-CN-60/A5-Ⅱ-6-1 (R) (1994)

5 Y-K. M. Peng, et al. "Small Tokamaks For Fusion Technology Testing" (to be published).

6 Lazarus E. A, et al. IAEA-CN-60/A-5-I-1 (1994)

7 N. A. Uckan and ITER Physics Group, ITER Documentation Series, No. 10 (1989)

8 Wang Shaojie, Qiu Lijian. α-particles classical transport in tokamaks. Nuclear Fusion (to be published).

9 Xu Qiang, Xiao Bingjia. Reactor Core Parameters Self-justified Calculations (to be published).

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