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从$q>1$至$q<1$位形演变

THE EVOLUTION OF CONFIGURATION FROM $q>1$ TO $q<1$

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从 $q>1$ 至 $q<1$ 位形演变*

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摘　要

给出了沿极小势能轨迹从类托卡马克至反场箍缩(RFP)的演变。在反场箍缩条件下可允许用强等离子体电流充分加热等离子体到点火温度，而不需要辅助的中性束或射频加热系统。

* 国家自然科学基金资助课题。

THE EVOLUTION OF CONFIGURATION FROM $q>1$ TO $q<1$*

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ABSTRACT

The evolution of configuration from an initial state of tokamak-like plasma to RFP along the trajectory of minimum energy state is studied. The high plasma current allowed in a RFP is expected to be sufficient to heat the plasma to ignition without the need of auxiliary neutral-beam or radio-frequency heating.

* Supported by National Natural Science Fundation.

INTRODUCTION

We propose the evolution of configuration[1,2] from tokamak-like plasma initial state to reversed field pinch (RFP). It is a new method of RFP as auxiliary heating to tokamak, furthemore it froms RFP configuration of the skin. The pitch is increased with decreasing radius near axis, moreover, grade of B_z and shear is increased at the boundary. It yields enhanced stability arising from the both as mentioned before[1].

The evolution of configuration from tokamak-like plasma initial state to RFP along the trajectory of the minimum energy state is discussed[2]. Therefore, the reversed field pinch for Ohmic heating of the plasma to ignition has superiority over high field tokamak.

The advantages of a RFP reactor, i. e. high beta combined with low toroidal field, result in high power density plasma without large stresses on the confining coils. The current flowing in external coils con be sufficiently low for normal copper coils to be used while keeping Ohmic losses equal to a small fraction of the fusion power.

The free choice of aspect ratio, in optimizing the overall engineering design, is another advantage.

1 MODEL OF EVOLUTION

A torus of large aspect ratio may be represented by a cylinder of radius a.

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{B} \tag{1}$$

where μ is a constant for a plasma enclosed in a conduting wall and in a minimum energy state. In this case, the solution to eq. (1) with cylindrial symmetry (r, θ, z) and $\nabla \cdot \boldsymbol{B}=0$ is given by

$$\begin{aligned} B_z/B_0 &= J_0\left(\frac{2r}{b}\Theta(t)\right), \\ B_\theta/B_0 &= J_1\left(\frac{2r}{b}\Theta(t)/b\right), \\ B_r/B_0 &= 0, \end{aligned} \tag{2}$$

where J_0 and J_1 are the zeroth-order and first-order Bessel function, B_0 is value of B_z at $r=0$.

From Ampere's law

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} \tag{3}$$

and eq. (1); this readily obtained

$$\begin{aligned} \mu(t) &= \mu_0 I_p(t)/\Phi(t) \\ &= 2\Theta(t)/b, \end{aligned} \tag{4}$$

where b is the radius of vacuum chamber wall. I_p is the plasma current and the toroidal flux is

$$\Phi(t) = \pi b^2 B_0 J_1(2\Theta(t))/\Theta(t). \tag{5}$$

Using the field reversal ration F and the pinch parameter Θ, the safety factor at wall is given by

$$q_w(t) = \epsilon \cdot F(t)/\Theta(t) \tag{6}$$

where $\epsilon = b/R$ and

$$F = \Theta(t)\frac{J_0(2\Theta(t))}{J_1(2\Theta(t))} \tag{7}$$

When $F(t) = 1$, the safety factor at axis is given by

$$q_0(t) \approx \epsilon/\Theta(t) \tag{8}$$

The pitch of magnetic line is

$$P(r,t) = Rq(r,t) \tag{9}$$

where

$$q(r,t) = \frac{r}{R}J_0\left(\frac{2r}{b}\Theta(t)\right)\bigg/J_1\left(\frac{2r}{b}\Theta(t)\right) \tag{10}$$

The magnetic energy of the B_z field is

$$\begin{aligned} W_z &= \int \frac{B_z^2}{2\mu} dV \\ &= \frac{\pi^2 R B_0^2 b^2}{\mu_0}[J_0^2(2\Theta(t)) + J_1^2(2\Theta(t))], \end{aligned} \tag{11}$$

The magnetic energy of the B_θ field is

$$W_\theta = \frac{\pi^2 R b^2 B_0^2}{\mu_0}[J_1^2(2\Theta(t)) - \frac{1}{\Theta(t)}J_0(2\Theta(t))J_1(2\Theta(t)) + J_0^2(2\Theta(t))] \tag{12}$$

Total magetic energy is

$$\begin{aligned} W_B &= W_z + W_\theta \\ &= \frac{2R}{\mu_0 b^2}\Phi^2(t)\Theta^2(t)\left[1 + \frac{J_0^2(2\Theta(t))}{J_1^2(2\Theta(t))} - \frac{J_0(2\Theta(t))}{2\Theta(t)J_1(2\Theta(t))}\right] \end{aligned} \tag{13}$$

The inductance of plasma is

$$\begin{aligned} L_p &= 2W_\theta/I_p^2 \\ &= \frac{\mu_0 R}{2}\left[1 + \frac{J_0^2(2\Theta(t))}{J_1^2(2\Theta(t))} - \frac{J_0(2\Theta(t))}{\Theta(t)J_1(2\Theta(t))}\right] \end{aligned} \tag{14}$$

From eq. (4) we have

$$I_p = \frac{2\Theta(t)}{\mu_0 b}\Phi(t) \tag{15}$$

and from Ampere law. I_θ is given by

$$I_\theta = \frac{2R}{\mu_0 b^2}\Phi(t)F(t) \tag{16}$$

The poloidal magnetic flux in plasma region is

$$\psi_p = R\Phi(t)\left[1-J_0\left(2\Theta(t))\frac{r_p}{b}\right)\right]/bJ_1(2\Theta(t)) \tag{17}$$

In region between plasma and conducting wall the poloidal magnetic flux is

$$\begin{aligned}\Psi_\theta &= 2\pi R\int_{r_p}^{b} B_\theta dr \\ &= R\Phi(t)\left[J_0(2\Theta(t))\frac{r_p}{b})-J_0(2\Theta(t))\right]\Big/ bJ_1(2\Theta(t)).\end{aligned} \tag{18}$$

Total poloidal magnetic flux inside conducting is

$$\begin{aligned}\Psi_0 &= \Psi_p + \Psi_w \\ &= R\Phi(t)[1 - J_0(2\Theta(t))]/b \cdot J_1(2\Theta(t)).\end{aligned} \tag{19}$$

From magnetic energy and eq. (1) it can be given that:

$$\begin{aligned}W &= \int \frac{B \cdot (\nabla \times A)dV}{2\mu_0} \\ &= \frac{R\Phi^2(t) \cdot \Theta(t)}{\mu_0 b^2}\left[\frac{K}{A\Phi^2(t)} + \frac{J_0(2\Theta(t))}{J_1(2\Theta(t))}\right],\end{aligned} \tag{20}$$

where $A = R/b$. The magnetic helicity is

$$K = \int A \cdot B dV. \tag{21}$$

From eqs. (13) and (20) the ratio of poloidal magnetic flux to torodal magnetic feux is

$$K/\Phi^2 = \frac{2R}{b}\left\{\Theta(t)\left[1 + \frac{J_0^2(2\Theta(t))}{J_1^2(2\Theta(t))}\right]-\frac{J_0(2\Theta(t))}{J_1(2\Theta(t))}\right\}. \tag{22}$$

From eq. (15) and used q it can be written:

$$I_p(\text{RFP})/I_p(\text{TOK}) = A.\Theta_{RFP} \cdot q_{tok} \tag{23}$$

From Suydam condition $\Theta < 2.1$ with $\beta = 0.1$. The sufficient stability canditian gives $\Theta < 2.04$ in $\beta = 0.3$ and the helical deformation condition is $\Theta = 2.02$ with $\beta = 0.3$.

For satisfying RFP stability[3], in general we get critical value $\Theta = 2$ and from eq. (15) we can get the plasma current limit in RFP

$$I_p(\text{RFP}) \leqslant \frac{2\pi b}{\mu_0}\Theta_c \cdot < B_z >, \tag{24}$$

where $< B_z >$ is the value of the toroidal magnetic field averaged over the minor cross section, Θ_c can be determined from the stability condition, for the Suydam Condition $\Theta_{cs} = 2.1$, Robinson criterion $\Theta_c = 1.58$, when $\beta = 0$.

2 NUMERICAL RESULTS

Fig. 1~5 show evolutions of configuration along the trajectory of F- Θ from $q > 1$ to $q < 1$.

Fig. 1 is the evolutions of the minimum energy states. The states at t_1, t_2, t_3, t_4 are all located in the curves. The time evolution of the magnetic field and the pitch of the field-line are shown in Fig. 2~5, also it shows the evolution of pitch from large value to small one. The typical q-profiles of tokamak-like configuration, ULQ, spheromak and RFP are shown in Fig. 6. Where q decreases as Θ increases. Fig. 7 shows the profile of toroidal flux and poloidal flux with increasing Θ and Fig. 8 is the profile of $\eta = K/(\frac{R}{2b}\Phi^2))$ and $K = K/(2R\pi^2 B_0^2 b^3)$ with increasing Θ. Fig. 9 shows the profile of toroidal and poloidal energy with increasing Θ. Fig. 10 shows the variation of I_p(RFP)/I_p(TOK) with Θ and q.

In RFP case, $1.2 < \Theta_{RFP} < 2$; In tokamak or tokamak-like case, $1 < q_{tok} < 3$ and, for $A = 5$, $\Theta = 1.5$ and $\Theta = 2$. I_p (RFP)/ I_p (Tok) ratio value are shown in table. 1.

Table 1 shows the variation of I_p(RFP)/I_p(TOK) with Θ and q

Table 1

q_T		1	1.5	2	2.5	3
I_p(RFP)/I_p(TOK)	($\Theta = 1.5$)	7.5	11.25	15.00	18.75	22.50
	($\Theta = 2$)	10.00	15.67	20.00	25.00	30.00

Table 2 shows plasma current in stable operation (I_p) comparing with its critical value (I_{pc}). I_p is less than I_{pc}.

Table 2

Device	ZT−40M	HBTX.1A	TPE-1RM	η-β II
radius b. m	0.2	0.26	0.9	0.125
magnetic field $< B_z >$. T	0.15	0.225	0.11	0.13
pinch ratio Θ	2.1	20	2.0	2.1
theory I_{pc}. kA	300	585	99	184
experiment. I_p. kA	250	500	85	180
References	[4]	[5]	[6]	[7]

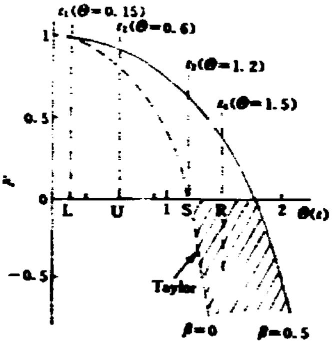

Fig. 1 The states at $t_1(\Theta = 0.15)$, $t_2(\Theta = 0.6)$, $t_3(\Theta = 1.2)$, $t_4(\Theta = 1.5)$ each state of them are located at the F-Θcurves.

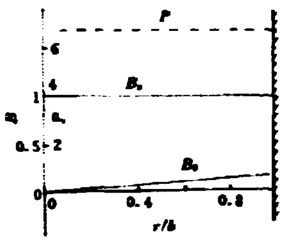

Fig. 2 The tokamak-like ($F \approx 1, \Theta < 0.15$) at t_1

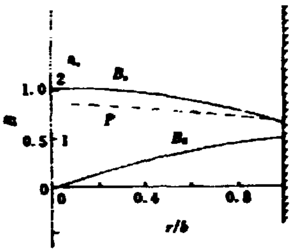

Fig. 3 The ULQ ($F > 0, \Theta < 1.2$) att_2

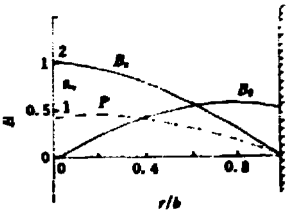

Fig. 4 The spheromak ($F = 0, \Theta = 1.2$) at t_3

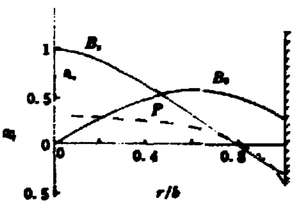

Fig. 5 The RFP ($F < 0, \Theta > 1.2$) at t_4

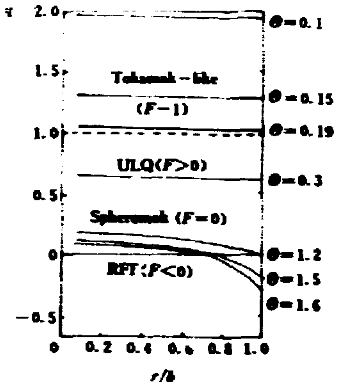

Fig. 6 The typical q-profiles of the tokamak-like, ULQ, spheromak and RFP

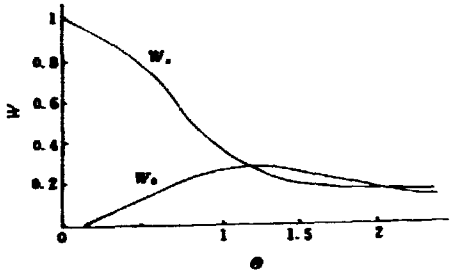

Fig. 9 The variation of toroidal and poloidal energy with Θ

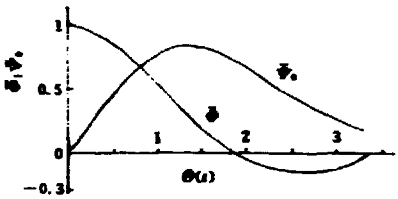

Fig. 7 The profile of toroidal flux and poloidal flux with Θ

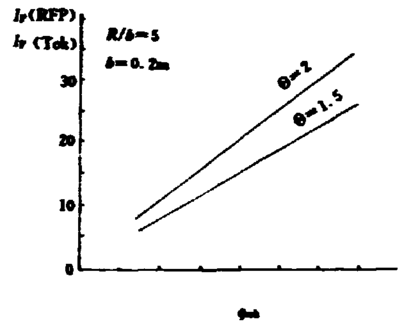

Fig. 10 The variation of I_p(RFP)/I_p(TOK) with Θ and q

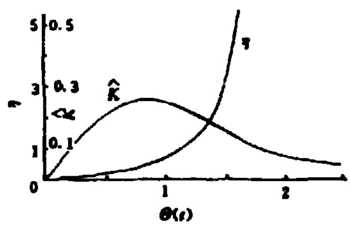

Fig. 8 The profile of η and K with increasing Θ

3 DISCUSSION

(1) The evolution of configuration from $q>1$ to $q<1$ along the trajectory of F-Θ cure, it is satisfied for suydam condition[8].

(2) If the skin time [9] to, is less than diffusion time of magnetic field through plasma t_d, it is results in skin effet. For example . $r_p = 0.2$m, $T_{e0} =$

100eV, t_e =12ms; r_p =0. 1m T_{e0} =20eV, t_e =0. 268ms, r_p =0. 2m, T_{e0} =50eV, t_e =4. 24 ms.

(3) Plasma current rising time is greater than the skin time, there is no skin effect in verso the skin effect will be taken place. the reversal toroidal field rising time t_r must be less than diffusion time of magnetic field t_d, and t_r must be greater then permeating time of stainless steel bellows vacuum vessel, t_L i. e. $t_L < t_r < t_d$.

for example, HBTX1A: t_r =0. 4~4 ms.

RFX: t_r =7~50 ms.

(4) RFP configuration stability exists[10], in the skin current condition. Then

$$\left(\frac{2}{r} - \mu_0 \frac{J \cdot B}{B_z B_\theta}\right)^2 > - \frac{8\mu_0}{rB_z^2}(J \times B)_r \tag{25}$$

It is noted that Suydam inequality shows that the presence of a paralled component of the surface current is essential to satisfy Suydam condition in the skin time.

(5) In the evolution of configuration from $q>1$ to $q<1$, I_p (RFP)/I_p (TOK) ratio value can increase by a factor of 10. The high plasma currents allowed for RFP are expected to be sufficient for heating the plasma to temperature of ignition.

(6) The plasma current limit for RFP is given as eq. (26). We can choose $\Theta<2.1$ from the Suydam stability condition [3] It satisfies that I_p (exm) is less than I_p (theory) of the critical value in table 2.

(7) For example

After setting an initial state of tokamak-like (or tokamak) and using programme of the aids of reversal field or matched reversal field, the RFP configuration can be established, as in table 3 and 4.

Table 3 when a =0. 2m

initial state of tokamak-like(or tokamak) q = 2, a/R = 1/5						
B_t, T		0. 3	0. 9	1. 8	2. 7	3. 3
I_p, kA		30	90	180	270	330
RFP a/R =1/5						
$<B_t>$, T		0. 3	0. 9	1. 8	2. 7	3. 3
I_p, kA	(Θ =1. 6)	480	1440	2880	4320	5280
	(Θ =2)	600	1800	3600	5400	6600

R. A. Krakowski[8] has given plasma current $I_p = 7.533$MA of ignition, and T. Tamanohas designed Ohmic heating RFP reactor[9], with $R = 2.42$m, $a = 0.27$ m, $I_p = 6.6$M. A, where a is plasma radius.

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Table 4 when $a = 0.6$m

initial state of tokmak-like(or tokamak)						
B_t, T		0.3	0.9	1.8	2.7	3.3
I_p, kA		90	270	540	810	990
RFP $a/R = 1/5$						
$<B_t>$, T		0.3	0.9	1.8	2.7	3.3
I_p, kA	($\Theta = 1.6$)	1440	4320	8640	12960	15840
	($\Theta = 2$)	1800	5400	10800	16200	19800

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