Magnetic Surface Compression Heating in the Heliotron Device

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Abstract

The slow adiabatic compression of the plasma in the heliotron device is examined. It has a prominent characteristic that the plasma equilibrium always exists at each stage of the compression. The heating efficiency is calculated. We show the possible access to fusion. A large amount of the initial investment for the heating system (NBI or RF) is reduced by using the magnetic surface compression heating.

1. INTRODUCTION

The slow adiabatic compression to heat the plasma was first demonstrated its utility in ATC device (1). The theoretical analyses have been also practiced and developed (2). However, those studies were mainly concentrated on the tokamak discharges, and they are concerned with the two important points, i.e., the plasma heating and the isolation of the plasma from the first wall in order to reduce the impurity influx. In this paper, an application of this slow adiabatic compression to the heliotron device is discussed. Since the heliotron has a characteristic that the size of the last closed magnetic surface can be changed freely by changing the ratio of the toroidal coil field B_{t_0} to the helical coil field $B_{h\phi_0}$ (3), the plasma is compressed adiabatically when the size of the magnetic surface is reduced keeping the magnetic flux constant. This method is called a magnetic surface compression. It was first proposed in the reference (4). Since the aspect ratio of the heliotron is large ($R/a \simeq 10$), the magnetic surface compression is performed as the two dimensional compression. The heating efficiency is less than that of ATC. However, the most advantageous point is that the equilibrium exists in each phase of the compression owing to the external helical field. A magnetic limiter configuration effectively reduces the plasma wall interaction. Since the time scale of the compression should be slower than the Alfven time and faster than the diffusion time, the compression time should be several tens of msec.

The calculated efficiency of the compression strongly depends on the scaling of the confinement. In this paper, Trapped Ion Mode and ALCATOR scalings (5) (6) are refered to, considering the present status of confinement studies.

Trapped Ion Scaling $$n\tau = 1.3 \times 10^{-9} \frac{B^2 n^2 a^4}{T^{\frac{7}{2}}} A^{\frac{5}{2}} \ \mathrm{m}^{-3}\mathrm{sec} \qquad (1)$$

ALCATOR Scaling $$n\tau = 5 \times 10^{-24} n^2 a^2 \ \ \mathrm{m}^{-3}\mathrm{sec} \qquad (2)$$

B	: magnetic field	Tesla
n	: plasma density	m^{-3}
a	: plasma minor radius	m
T	: plasma temperature	eV
A	: aspect ratio	

2. HELIOTRON DEVICE

The helical heliotron field is produced by the current of the helical coil ($\kappa=2\pi R/$(pitch length)$=m/\ell, \ell=2$) of which pitch number is much larger than that of the conventional stellarators (7). The values of the rotational transform and the shear of the helical heliotron magnetic field are almost one order larger than those of conventional stellarators. The examples of the magnetic surfaces are shown in Fig. 1(a), in which the aspect ratio of the helical conductor is 8.34. The parameter α^* in the figure is the ratio of B_{t_0} to $B_{h\phi_0}$, where B_{t_0} is the longitudinal component of the magnetic flux density on the axis produced by the toroidal coils and $B_{h\phi_0}$ is that produced by the helical coil. α^* is called a magnetic surface parameter. The helical coils are shown with shaded circles.

The magnetic surface is elliptic and its elongation factor is about 2. In Fig. 1(b), the mean minor radius of the last closed magnetic surface is shown with a solid curve for the range of α^* from 0 to -0.5. To compress the plasma, the minor radius is reduced satisfying the flux conservation.

3. EFFICIENCY OF THE MAGNETIC SURFACE COMPRESSION

We define the four plasma states as follows to discuss the efficiency.

Plasma I	:	before compression, maximum minor radius (a_1) and minimum magnetic field (B_1),
Plasma II	:	after compression, minimum minor radius (a_2) and maximum magnetic field (B_2),
Plasma III	:	after expansion, maximum minor radius (a_1) and maximum magnetic field (B_2),
Plasma IV	:	without compression, maximum minor radius (a_1) and maximum magnetic field (B_2),

The processes of the magnetic surface compression are shown in Fig. 2. Plasma I is the initial plasma before compression. It turns into Plasma II after the magnetic surface compression. The parameters of Plasma II are chosen to satisfy the self-sustaining condition of D-T burning. Plasma III is the final full scale burning plasma. It is produced by the slow expansion of Plasma II keeping the magnetic field constant and supplying a new fuel. No additional heating is necessary in this process. On the other hand, it is possible to produce a plasma at the maximum minor radius a_1 and the maximum magnetic field B_2 without compression. This is defined as Plasma IV. If the parameters of Plasma IV are better than those of Plasma II or III, there is no advantage to perform the magnetic surface compression. The parameters are calculated using fomulas of the thermodynamics. Here, the maximum density without compression is supposed n_1. (Table 1)

4. Process Analysis of the Magnetic Surface Compression

Reactor studies on the tokamak have been done in detail, for example, by Wisconsin, PPPL, Culham and JAERI groups (10). To calculate the practical path to the fusion, we considered the parameters presented by them. We also considered the results of the preliminary design works of the heliotron reactor (11). The values of the third column in Table 2 are the examples of the burning plasma of the reactor, which corresponds to Plasma III in Table 1 and Fig. 2. The values of the compressed plasma parameters (Plasma II) and the initial plasma parameters (Plasma I) are determined using the relations in Table 1. The dynamic processes of the compression and the expansion are the same as that of Fig. 3. α^* is reduced from 0 to -0.4, which corresponds to the 50 % reduction of the minor radius. In the expansion process, the plasma density and $n\tau$ value are kept constant. At the bottom of Table 2, the necessary heating powers are shown to heat the plasma directly to the temperatures of Plasma I and Plasma III. The heating efficiency is supposed 50 %. Without compression, the necessary heating power to obtain the state of Plasma III which has the largest volume of the machine specification is 3~4 times as large as that of Plasma I. This fact makes clear another advantage of the magnetic surface compression. Utilizing magnetic surface compression, a large additional heating system (NBI or RF) turns out to be unnecessary. Since the additional heating system is used only in the initial phase to heat a plasma to the igniting temperature, it is not good to spend a lot of investment to such an enormous system. Above all, it is very difficult to design the 1000MW class heating system. In the magnetic surface compression, the heating power is supplied by the electric power supply of the magnetic field coils. The initial investment certainly becomes small. Detail engineering aspect will be reported in a near future (12).

5. CONCLUSION

We discussed the feasibility of the magnetic surface compression in the heliotron device. It is the compression in the poloidal plane and the efficiency is less than that of ATC type three dimensional compression. However it has two advantages. The first is that owing to the external helical coil field, the plasma equilibrium always exists in the each state of the compression. This makes it possible to sustain the stable and high temperature plasma. The second is that the magnetic limiter configuration is always satisfied. It is effective to reduce the wall-plasma interaction and a large impurity influx which cools down the plasma. The magnetic surface compression should be used as the final additional heating method to raise the plasma temperature to the ignition condition. When the compression ratio of the minor radius a_2/a_1 is one half, the additional heating power is 330MW which is necessary to obtain Plasma I. It is one third of the necessary additional heating power to obtain Plasma III without compression. After the initial plasma is compressed and once D-T reaction is ignited, the radius of the plasma is slowly expanded keeping the magnetic field constant and supplying a new fuel. Then we get the full size burning plasma of the machine specification, which is the final stage of the heliotron reactor.

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FIGURE CAPTION

Fig. 1 (a) Cross Section of the Magnetic Surface, The shaded circle means the position of the helical coil.

(b) Dependence of the Minor Radius of the Magnetic Surface to α^* (Solid Curve), α^* is the ratio of the toroidal coil field B_{t_0} to the helical coil field $B_{n\varphi_0}$. The dotted curves mean the following approximating curves. $a = a_1(1 - |\alpha^*|^{\xi})$.

Fig. 2 Process of the Magnetic Surface Compression

Fig. 3 Dynamic Process of the Magnetic Surface Compression Heating, The solid curves mean the compression process. The dotted curves mean the expansion process.

Table 1

		Plasma I (initial)	Plasma II (compressed)		Plasma III (expanded)		Plasma IV (without compression)
a		a_1	a_2		a_1		a_1
B		B_1	$B_1(\frac{a_1}{a_2})^2$		$B_1(\frac{a_1}{a_2})^2$		$B_1(\frac{a_1}{a_2})^2$
n	(trapped ion)	n_1	$n_1(\frac{a_1}{a_2})^2$	>	$n_1(\frac{a_1}{a_2})^{\frac{6}{5}}$	>	n_1
	(ALCATOR)	n_1	$n_1(\frac{a_1}{a_2})^2$	>	$n_1(\frac{a_1}{a_2})$	>	n_1
T	(trapped ion)	T_1	$T_1(\frac{a_1}{a_2})^{\frac{4}{3}}$	=	$T_1(\frac{a_1}{a_2})^{\frac{4}{3}}$	>	$T_1(\frac{a_1}{a_2})^{\frac{8}{3}}$
	(ALCATOR)	T_1	$T_1(\frac{a_1}{a_2})^{\frac{4}{3}}$	=	$T_1(\frac{a_1}{a_2})^{\frac{4}{3}}$	>	T_1
$n\tau$	(trapped ion)	$n_1\tau_1$	$n_1\tau_1(\frac{a_1}{a_2})^{\frac{22}{6}}$	=	$n_1\tau_1(\frac{a_1}{a_2})^{\frac{11}{3}}$	>	$n_1\tau_1(\frac{a_1}{a_2})^{\frac{8}{3}}$
	(ALCATOR)	$n_1\tau_1$	$n_1\tau_1(\frac{a_1}{a_2})^2$	=	$n_1\tau_1(\frac{a_1}{a_2})^2$	>	$n_1\tau_1$

Table 2

	I (Plasma I)	II (Plasma II)	III (Plasma III)	
B(Tesla)	1.5	6	6	
a(m)	1.8	0.9	1.8	
R(m)	12.5	12.5	12.5	
$n\tau$(m^{-3}sec)	5.6×10^{19}	2.0×10^{20}	2.0×10^{20}	
T(keV)	6.0	15	15	
n(m^{-3})	6.6×10^{19}	2.6×10^{20}	1.6×10^{20}	1.31×10^{20}
β(%)	13.9	8.8	5.2	4.4
W_T(GW)*	0	2.45	8.7	6.1
P(MW)**	350	0	1400 (Trapped Ion)	1130 (ALCATOR)

W_T* : thermal output

P** : Additional heating powers (efficiency 50 %) to produce Plasma I and Plasma III without Compression

I : initial plasma parameters for the magnetic surface compression

II : plasma parameters after compression

III : plasma parameters after expansion and standard design parameters of a fusion reactor

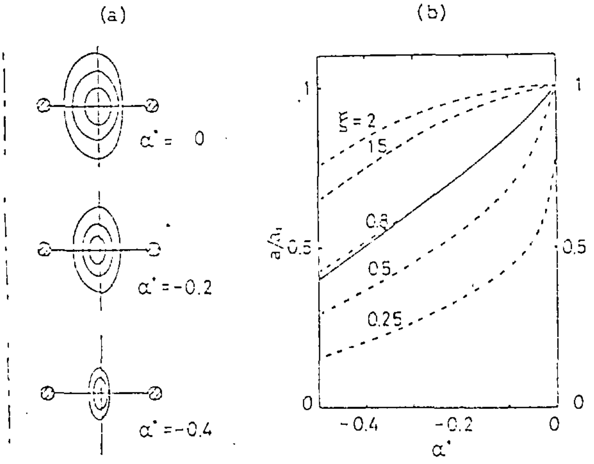


Fig. 1 K. Uo and O. Motojima

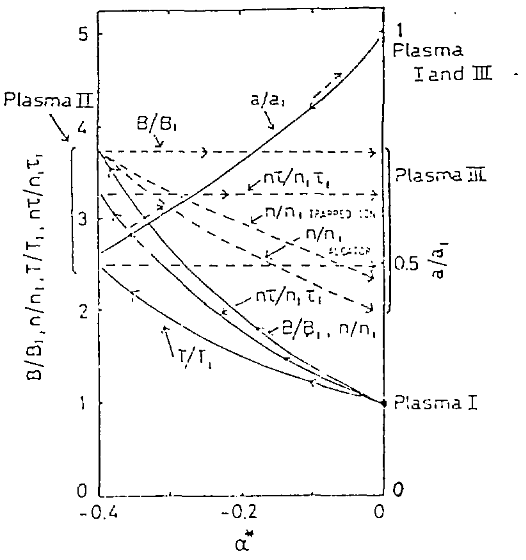
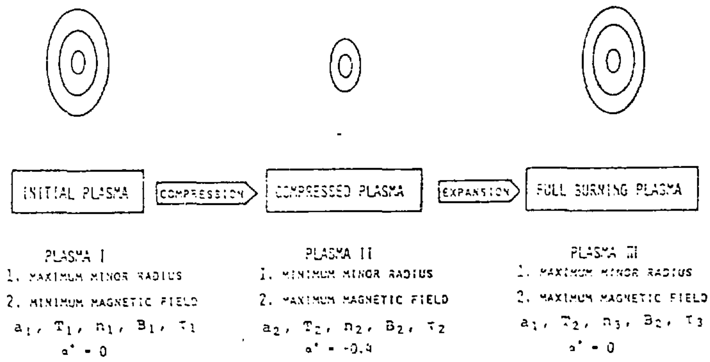


Fig. 3 K. Uo and O. Motojima



note : $a_1 = 2a_2$, $B_2 = (a_1/a_2)^2 B_1$, $n_2 > n_3 > n_1$, $\tau_3 > \tau_1 \geq \tau_2$

Fig. 2 K. Uo and O. Motojima