be shown to reduce to Eqs. (1) and (2), respectively.

In conclusion, we have shown that convective cells can be excited when β exceeds the square of the inverse aspect ratio even in the presence of a magnetic shear. In this regime of β, the particle confinement is expected to deteriorate drastically.

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Study of Current-Driven Magnetohydrodynamic Instability in the Heliotron-D Device

O. Motojima, A. Iiyoshi, and K. Uo
Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Japan
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Ohmic-current-driven magnetohydrodynamic instabilities in the Heliotron-D device, which has large external rotational transform ($\iota_F > 1$) and strong shear ($\theta > 0.5$), have been studied experimentally. Since those instabilities satisfy the regular relations between the external and the ohmic-current transforms ($\iota_{\rm OH}$), kink and resistive tearing-mode instabilities are supposed to exist. The strong shear plays a major role to suppress the magnetohydrodynamic instabilities, and the Ohmic current exceeds the $\iota_{\rm OH} = 1$ limit stably.

In many stellarators such as Wendelstein VII A (W VII A),[1] CLEO,[2] L-2,[3] and TORSO,[4] Ohmic current is used to produce and heat the plasma. In these devices, studies have been carried out to analyze the effect of the stellarator field on current-driven magnetohydrodynamic (MHD) instabilities. The observed MHD activity is considered to be due to the kink and resistive tearing modes.[5,6] In addition, the current disruption, which is familiar in tokamaks, is observed in these devices. In W VII A which has an external rotational transform with low shear, the internal disruption has been observed when the resonant surface of $\iota = 1$ is present in the plasma column, where ι is the sum of the rotational transforms due to the Ohmic current ($\iota_{\rm OH}$) and the external field (ι_F). This experiment also shows that the $m = 2$ (poloidal mode number) oscillation seems to play the dominant role in major disruptions. In the case of L-2 and CLEO, which have fairly large shear, the rather peaked plasma current has a tendency to make the ι profile flat. Once the $\iota = 1$ condition is satisfied within the plasma, the major disruption occurs. Thus, in these stellarators, the value of ι cannot stably exceed unity, just as in tokamaks.

On the other hand, the external rotational transform of the Heliotron D is larger than unity at the boundary of the plasma column as shown in Fig. 1(a). The magnetic surface with $\iota = 1$ exists in the middle of the plasma; or it can be removed with a small Ohmic current, corresponding to $\iota_{\rm OH}(a)$ from 0.2 to 0.4, where the argument a refers to the value at the boundary. In this Letter

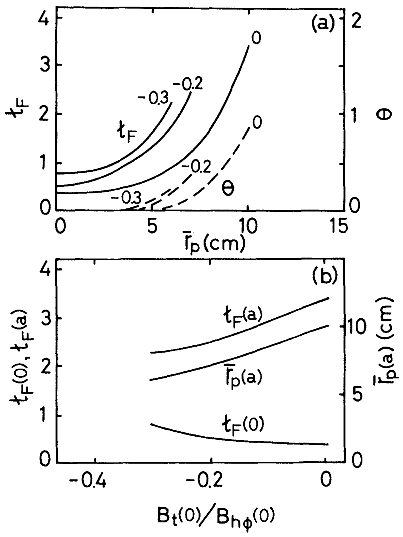

FIG. 1. (a) Radial dependence of external rotational transform (ι_F: solid curves) and shear (θ: broken curves). The parameter is $B_t(0)/B_{h\varphi}(0)$, where $B_t(0)$ and $B_{h\varphi}(0)$ are the toroidal fields on the axis by the toroidal coils and helical conductors, respectively. (b) Mean minor radius $[\bar{r}_p(a)]$ and external rotational transforms at the center $[\iota_F(0)]$ and the boundary $[\iota_F(a)]$ vs $B_t(0)/B_{h\varphi}(0)$.

we discuss the stability of the Ohmically heated plasma in the Heliotron D. In Table I, we present the dimensions and typical plasma parameters of W VII A, CLEO, L-2, TORSO, and Heliotron-D to show the similarities and differences between devices.[7]

We have already reported that under the condition of $\iota_{OH}(a) \lesssim 2[\iota(a) \lesssim 4.5]$ Ohmic current is sustained without any drastic MHD instabilities.[8] While MHD fluctuations have been observed on the magnetic probe signal, we could not detect any sign which suggested that this MHD activity played the primary role in the diffusion process, i.e., confinement times did not show a drastic (resonant) decrease even in the regimes where the MHD activity was observed. The most typical frequency of the fluctuations is about 10 kHz and the fluctuation level $\tilde{B}_p/B_p$ is less than 5%, where B_p is the poloidal field. In this paper, we describe in detail this minor MHD activity in order to understand the features of the heliotron magnetic field.

We show the radial dependence of the external rotational transform (ι_F) and shear (θ) of the Heliotron D in Fig. 1(a). The parameter is $B_t(0)/B_{h\varphi}(0)$, where $B_t(0)$ and $B_{h\varphi}(0)$ are the toroidal fields on the axis due to the toroidal coils and the helical conductors, respectively. Both ι_F and θ are larger than those of stellarators. In Fig. 1(b), we show the mean minor radius $[\bar{r}_p(a)]$ and the external rotational transforms at the boundary $[\iota_F(a)]$ and center $[\iota_F(0)]$ for the regime of $-0.3 \leq B_t(0)/B_{h\varphi}(0) \leq 0$. The vacuum magnetic surfaces are elliptic and their ellipticities are about 0.85. Thus, by changing the ratio $B_t(0)/B_{h\varphi}(0)$, we are able to obtain a wide range of ι_F profiles.

Plasma parameters are in the Pfirsh-Shlüter regime, i.e., the electron temperature T_e is from 20 to 50 eV and the mean electron density N_e is from 5×10^{12} to 1×10^{14} cm^{-3}. Ohmic current is changed widely from $\iota_{OH}(a) = 0.5$ to 2 and is directed to increase the rotational transform (additive direction). The working gas is helium.

MHD activity was analyzed by an array of magnetic probes outside the plasma. Four probes were distributed at intervals of 90 deg in both the poloidal and equatorial planes. In Fig. 2(a), we show an example of the poloidal field fluctuations (traces 1 and 2) detected by the magnetic probes located at the top and bottom of the plasma. The traces 3, 4, and 5 are the signals of the loop voltage (10 V/div), the Ohmic current (1.1 kA/div), and the interferometer (raw fringes, 70 GHz and 2.8×10^{12} cm^{-3}/fringe), respectively.

TABLE I. Parameters of stellarators. $r_p(a)$ and r_h are the radii of plasma and helical conductor, respectively.

Devices	R (cm)	$r_p(a)$ (cm)	r_h (cm)	B (kG)	l	m	ι_F	T_e (eV)	N_e ($\times 10^{13}$ cm^{-3})	τ_E (msec)	I_{OH} (kA)
W VII A	200	13.5	23	25	2	5	0.23	200–900	0.5–8	1–2	37
CLEO	90	10	18.7	20	3	7	0.5	350	2	1–2	5–25
L-2	100	11.5	23	20	2	14	0.7	300	1.5	5–8	20
TORSO	40	6.5	10	20	3	12	0.8	200	0.1–10	0.5–1	1–10
Heliotron-D	108.5	10	13	3	2	25	3	150	1–10	0.5–1	15

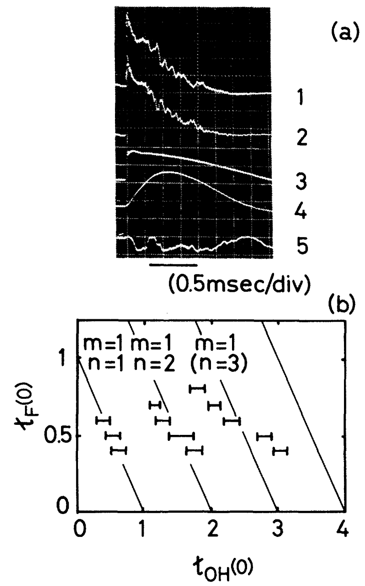

FIG. 2. (a) Oscillogram of poloidal field fluctuations (trace 1 and 2) detected by the magnetic probes located at the top and bottom of the plasma. The fluctuation is indicated by the underline. The traces 3, 4, and 5 are the signals of the loop voltage (10 V/div), the Ohmic current (1.1 kA/div), and the interferometer (raw fringes, 70 GHz, and 2.8×10^{12} cm^{-3}/fringe), respectively. $B = 1.7$ kG, $T_{e_{max}} = 40$ eV, and $B_t(0)/B_{h\varphi}(0) = 0$. (b) Instability diagram between $\iota_F(0)$ and $\iota_{OH}(0)$. Observed instability regimes are indicated with horizontal bars. The current profiles are supposed parabolic $[\iota_{OH}(a) = \iota_{OH}(0)/2]$. Mode numbers which were indentified experimentally are shown without parenthesis.

The experimental conditions are $B = 1.7$ kG, $T_{e_{max}} = 40$ eV, and $B_t(0)/B_{h\varphi}(0) = 0$. In this case the identified poloidal and toroidal mode numbers (m, n) and the total rotational transform at the center $[\iota(0)]$ are all unity. Here the profile of ι_{OH} is taken to be parabolic, since the T_e profile measured by the laser scattering method resulted in parabolic current profile for this experimental condition. To obtain the profile of ι_{OH}, we assumed constant Z_{eff} and Spitzer's classical conductivity. In the case of parabolic current profile, we have the following relations:

$$\iota_{OH} = \iota_{OH}(a)\times \{2 - [\bar{r}_p/\bar{r}_p(a)]^2\}$$

and

$$\iota_{OH}(0) = 2\times \iota_{OH}(a).$$

We have analyzed these instabilities for many kinds of magnetic surfaces which have different values of $\bar{r}_p(a)$, $\iota_F(0)$, and $\iota_F(a)$, as shown in Fig. 1(b). Figure 2(b) is the result of our analysis which identifies the region where the instabilities are observed in the diagram of $\iota_F(0)$ and $\iota_{OH}(0)$ (assuming parabolic profiles). Observed instability regimes are indicated with horizontal bars. Instability seems to occur discretely along the lines for which the sum of $\iota_F(0)$ and $\iota_{OH}(0)$ is an integer. The identified mode numbers (m, n) are shown in the figure without the parentheses, and they satisfy the following relation,

$$\iota_F(0) + \iota_{OH}(0) = n/m.$$

The value in parentheses is estimated according to this relation.

Thus we find that the Ohmic current can exceed the unstable regimes and that stable discharges can be obtained for $\iota_{OH} > 1$. Cannici *et al.*[1] also made a survey of their MHD modes, and they have made a chart similar to Fig. 2(b). They have observed disruption depending on density at high current ($\iota_{OH} < 1$) and low external transform ($\iota_F \lesssim 0.1$). We did not observe disruption in the regime of $\iota_{OH} \sim 1$ even at high density. This is thought to be due to the difference in ι_F and shear parameter (especially at the boundary). As shown in Table I and Fig. 1(a), the external transform and shear of the Heliotron-D are a few times larger than those in W VII A.

Theoretical studies of stellarator stability have been done mainly for the conditions that ι_F and ι_{OH} are both less than unity, and the shear and the deformation of the magnetic surface from a circle are both small.[5,6] They showed that the kink and resistive tearing modes occurred along the line $\iota_F + \iota_{OH} = n/m$. Our experimental result indicates that this relation is applicable even in the large ι cases and that kink and resistive tearing modes are supposed to exist. There are some deviations of the experimental data from the line $\iota_F + \iota_{OH} = n/m$ which might depend on the profile effect of the rotational transform (shear). To analyze and understand more detail, it is necessary to calculate the energy integral and identify the stable and unstable regime.[9]

Since the experiments are performed with the heliotron magnetic limiter,[10] it is necessary to confirm that the Ohmic current does not seriously deform the closed magnetic surfaces and that no current exists outside the last closed surface. In order to determine whether any current flowed outside the last surface, the following studies were made. First, we used a small Rogowsky coil and measured the current outside the plasma column. Within the error of measurement we could detect no such external current. Second, we located a Mo limiter just outside the plasma column and compared the peak Ohmic current with and without the limiter. This limiter is similar in shape to, but a bit larger than, the last closed magnetic surface. While the maximum current obtained with the limiter is less than the current without the limiter, due to the plasma-limiter interaction, we still obtained $\iota_{\rm OH}(a)$ greater than unity. Third, there is a pair of limiters outside the helical conductors which interrupt the toroidal circulation of the particles. Considering these facts, there is no possibility that Ohmic current flows outside the plasma. With regard to deformation of the vacuum magnetic surfaces by the Ohmic current, we have confirmed that this deformation is small by computations of flux surfaces including a filamentary current on the magnetic axis.

To clarify the stabilizing effect of strong shear, we have performed an experiment to study the mechanism of limitation of the Ohmic current We observed that the limit lay around $\iota_{\rm OH}(a)=2$ in the vicinity of $B_t(0)/B_{h\varphi}(0)=0$ and at this limit the fluctuation level increased drastically (by a factor of 10) and the plasma became disruptive. Then we compared the profiles of ι_F, $\iota_{\rm OH}$, and $\iota=\iota_F+\iota_{\rm OH}$ for the case of $B_t(0)/B_{h\varphi}(0)=-0.2$ in the meridian plane. Here we again measured the T_e profiles and calculated the current profiles (parabolic) assuming constant $Z_{\rm eff}$ and Spitzer's classical conductivity. The results are shown in Fig. 3, for the cases of $\iota_{\rm OH}(a)=1$ (broken curve) and 2. As suggested in the L-2 and CLEO stellarators, the profile of ι becomes almost flat at the limit of $\iota_{\rm OH}(a)=2$. While the critical values of ι are different (they are unity for L-2 and CLEO and 4.5 for Heliotron-D), these results suggest the importance of shear, i.e., its stabilizing effect on the MHD instability is great and a stable plasma can be obtained as long as the magnetic field maintains the strong shear. In the Heliotron-D, the Ohmic current can increase until the ι profile becomes flat by passing through the unstable regimes without disruption because of the presence of strong shear, and thus a stable plasma can be obtained beyond the $\iota_{\rm OH}=1$ critical condition.

Finally we present another fact which suggests that the strong shear is effective in suppressing the MHD instability. We have discussed the current-driven MHD instabilities for the case in which ι_F and $\iota_{\rm OH}$ have the same sign (additive case). But in the subtractive case, we have obtained stable plasmas even when a zero point of the total rotational transform (ι) is supposed to exist within the plasma. It is reported that in the CLEO experiment the plasma becomes disruptive in this configuration.[11] These observations can be explained by the difference in the value of shear parameter at the point where $\iota=0$, since the shear parameter of the Heliotron-D is about ten times larger than that of CLEO.

We thank M. Wakatani (Kyoto University) and P. A. Politzer (Massachusetts Institute of Technology) for valuable discussions and support.

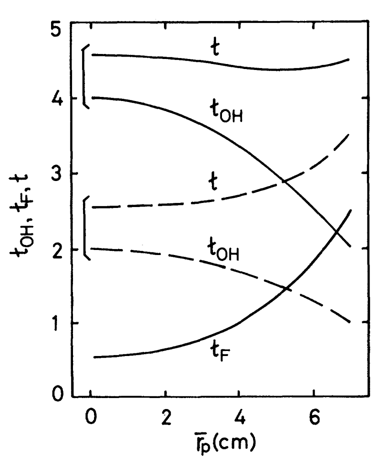

FIG. 3. Radial dependences of ι_F, $\iota_{\rm OH}$, and $\iota=\iota_F+\iota_{\rm OH}$ for the cases of $\iota_{\rm OH}(a)=1$ (broken curve) and 2. The current profiles are supposed parabolic. $B_t(0)/B_{h\varphi}(0)=-0.2$, $B=1.5$ kG, $T_{e\,\max}=30$ eV, and $N_e=5\times10^{13}$ cm^{-3}.

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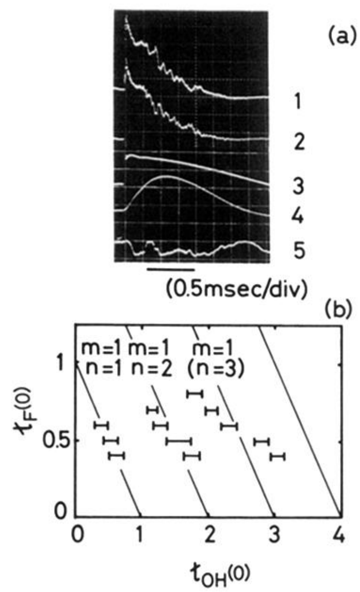

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