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An H-mode-Like Bifurcation in Core Plasma of Stellarators

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Abstract

The radial electric field, reduction of anomalous transport, and ion temperature profile are simultaneously analysed in the Wendelstein-VIIA (W VII-A) stellarators. Neoclassical formula is used to determine the radial electric field. Bifurcation of the anomalous transport is found at a critical injection power, above which improved confinement is possible. Experimental results of W VII-A, which have shown the sharp reduction of the H_α signal after the injection of the neutral beam, are revisited.

Keywords: Improved Confinement, H-Mode, Wendelstein VII-A, Stellarator, Radial Electric Field, Anomalous Transport

The finding of the H-mode in tokamaks[1] has initiated the following achievement of the various kinds of the improved confinement. These varieties in the confinement properties have activated the investigation on the understanding of the anomalous transport, which has the nature of the threshold and bifurcation, as well as have relaxed many obstacles in planning the future burning plasma experiment. The modelling on the H-mode has been developed focusing at the role of radial electric field structure, which either gives rise to the bifurcation in the confinement states[1-3] or suppresses micro-instabilities thus reducing the anomalous transport[2-5]. The important role of radial electric field has been widely recognized for stellarators. The influences on the absolute trapping and on the neoclassical loss have been intensively studied[6,7]. It is worthwhile to see the effect on the anomalous transport in stellarators, which has been known to be the dominant loss mechanism in experiments[8-10].

The sudden reduction of H_α brightness and the improved confinement was found in the NBI (neutral beam injection) heating experiments of the Wendelstein-VIIA (W-VIIA)[8]. The reduction of the plasma current and the increment of the external rotational transform, thus keeping the total rotational transform constant, causes the sudden reduction of the H_α signal and the increased energy confinement time as well. Figure 1 is quoted from ref.[8]. Clear decrease of the H_α signal can bee seen. The radial electric field was also observed in this discharge[11].

The comparison of the radial electric field, E_r, in W-VIIA and the theoretical estimation was made in Refs.[11,12]. A weak but finite toroidal ripple in the magnetic field gives rise to the bipolar particle fluxes for the bulk plasma component[13]. The motion of the energetic particles that are generated by the NBI has large influence on the electric field structure, because W-VIIA has large aspect ratio ($R/a \simeq 20$) and moderate rotational factor (the safety factor of q is around 2 to 3), and the poloidal gyroradius is comparable to the minor radius.

The inhomogeneous radial electric field affects the microinstabilities and associated anomalous transport. Since the poloidal gyroradius can be of the order of the gradient length of E_r, the suppression can be considerable. We find and discuss in this article that this coupling between the temperature gradient, electric field and anomalous transport has the property to cause the bifurcation. This allows a multiple solution of the gradient for the given heat flux in the whole plasma column. This is in contrast to tokamaks, in which theories predict that the bifurcation is such that multiple flux solution is allowed for given gradient and that the transition of E_r takes place near plasma edge[1-5] and particular rational surface, say q=1 surface[14]. The change of the transport coefficient in stellarators after the bifurcation is slower than tokamaks.

We consider the NBI heated plasma in W VII-A stellarator (minor radius is 20cm, major radius is 2m, toroidal magnetic field is 2.5-3.5T). The radial electric field near the half radius, $r \propto a/2$, is determined by the bipolar fluxes of bulk particles. For the range of experimental parameters, (ions and electrons are in the plateau regime, $T_e \simeq T_i$), the neoclassical theory on the ripple diffusion gives the estimation

$$eE_r/T_i = \alpha T_i'/T_i + n'/n. \tag{1}$$

where $\alpha \simeq 3.4$ for the present parameter[12]. In this form, we see that the gradients of the ion temperature and density are important. On the contrary, the fast ion loss plays an important role for the radial electric field near the edge region, $r/a > 0.75$. The steep temperature gradient is sustained near the half radius. We study the influence of the radial electric field on the appearance of the steep gradient. The temperature gradient near edge is reported to be very small[11]. The enhanced gradient near the half radius is, if there exists the improved confinement, the origin of the enhancement of the global confinement time.

The electric field gradient

$$u_g = \rho_p E_r'/v_{Ti} B_p \tag{2}$$

gives the measure for the stabilization for the drift-like instabilities. (Prime ' indicates the radial derivative.) The analysis on the trapped particle instability has shown that[2,5,15]

$$u_g \simeq 1 \tag{3}$$

is the condition for stabilizing the linear mode. Substituting Eq.(1) into Eq.(2), we have the simplified relation for the case of $|T_i'/T_i| \gg |n'/n|$ as

$$u_g \simeq \rho_p{}^2/\ell^2 \qquad (4)$$

where ℓ indicates the gradient length of the ion temperature, and we estimate $T_i' \simeq T_i/\ell$ and $T_i'' \simeq T_i/\ell^2$. Note that the suppression by the radial electric field depends on the sign of E_r'.[5,15] However, suppression of the microinstabilities occurs in both the cases of large positive and negative E_r'. We therefore neglect the sign dependence for the simplicity, and discuss in terms of the absolute value of E_r'. Using the parameters, a/R=1/20, q=2, B_T=3T, and the ion mass of 2, we have

$$u_g = T_{100}\ [4\alpha a^2/75\ell^2], \qquad (5)$$

where T_{100} is ion temperature divided by 100eV. The value of u_g is unity for the condition of T_i=100eV and ℓ/a = 2/5, which is satisfied in experiments.

The gradient ℓ itself is dependent on the change of the transport coefficient. Let us write the effective ion thermal diffusivity χ_i (χ_i is defined as the ratio of the ion heat flux to the ion temperature gradient) as[5]

$$\chi_i = \chi_{i0} \cdot F(u_g) \qquad (6)$$

where F indicates the u_g dependence, i.e., F=1 as $u_g \to 0$, and F becomes small as u_g approaches 1. The energy balance equation of ions is written as

$$\chi_i \; T_i/\ell = P/4\pi^2 rR \qquad (7)$$

where P is the injected power. From this relation, we have

$$a/\ell = Pa/[4\pi^2 rR \; T_i \; \chi_i]. \qquad (8)$$

Using Eqs.(5) and (6), we have a closed set of equation for u_g as

$$u_g \; F(u_g)^2 = H \qquad (9)$$

$$H = [\alpha T_{100}(Pa/17\pi^2 rR \; T_i \; \chi_{i0})^2] \qquad (10)$$

An approximate form was discussed[5] as $F(X)=\sqrt{1-u_g/u_c}$ ($u_c \simeq 3$). Even if the mode of our interest is stabilized, χ need not to vanish and is governed by the residual process, which has the secondary importance in the absence of the electric field gradient. We therefore take a form

$$F(u_g) = \begin{cases} \sqrt{1-u_g/u_c} & (u_g < u_c) \\ F_\infty & (u_g > u_c) \end{cases} \qquad (11)$$

where F_∞ is treated as a small constant in this article, indicating the residual contributions to the heat transport. Equations (9) and (11) gives a bifurcation in the solution as the parameter H changes. Figure 2 illustrates equation (9), demonstrating that multiple solution of the gradient is possible. Figure 3 shows the suppression factor F as a function of H. At certain critical values of H, $H_{1,2}$, the bifurcation takes place. For $H>H_1$ and $H<H_2$, Eq.(9) has one solution. For the parameters of $H_1>H>H_2$, three solutions exist. The branch of the small u_g (i.e., large F and χ_i) is attributed to the state of the poorer confinement. The branch with larger u_g (i.e., smaller F and χ_i) is considered to be a state with better confinement. The transition between them takes place when H reaches the critical value, H_1.

The approximate form of the critical point is given as

$$H_1 \simeq u_c{}^2/4 \tag{12-1}$$

$$H_2 \simeq u_c F_\infty{}^2. \tag{12-2}$$

If H is small, the solution is found in the region of small u_g. Approximating $F\simeq 1$ ($u_g \to 0$) and $F \simeq F_\infty$ ($1/u_g \to 0$), we have the two limiting forms of the solution

$$u_g = \begin{cases} H & (H \ll H_1) \\ H\ F_\infty{}^{-2} & (H \gg H_1) \end{cases} \tag{13}$$

indicating the asymptotic forms for the two branches.

The critical value in H can be interpreted in the form of the threshold power through the relation of Eq.(10). Assume that the effective thermal conductivity has a dependence $\chi_{i0} \propto T^{\hat{\alpha}}$. When the temperature gradient is a weak function of the input power as is in the case of low confinement, T has a dependence of $P^{1/(1+\hat{\alpha})}$. Substituting this form in Eq.(10), we have

$$H \propto P^{1/(1+\hat{\alpha})} \tag{14}$$

showing the critical power in order to achieve the critical condition for the transition.

The character of the bifurcation which is found here is different from the models predicted for H-mode in tokamaks. Firstly, the shape of the heat flux, as a function of the gradient, is N-shaped, while that in H-mode is S-shaped. Hence the transition, if it happens, takes longer time compared to tokamaks. Second, the transition is possible at any magnetic surface in stellarators due to the neoclassical ripple loss. Third, this bifurcation occurs in the energy balance equation, while that in H-mode modelling appears in the charge neutrality equation (or, in other words, in the momentum balance equation). The process which is modelled in tokamak H-mode may be possible, in addition to this mechanism, and requires further analysis.

In summary, we have find the bifurcations in the plasma transport and radial electric field in the stellarators. In a configuration like W-VIIA, the transition from the state with high transport coefficient and small electric field inhomogeneity (and as a consequence with small temperature gradient) to that with small transport coefficient, large electric field gradient and large ion temperature gradient can occur. This transition can take place when the injection power reaches a threshold value.

The experimental observations on the radial electric field indicated[11] that the parameter u_g reaches of the order of 10, which can lead substantial reduction of the anomalous transport. The reduction of the fluctuations in the range of drift wave frequency has been reported associated with the decrease of H_α signal for this kind of discharge[16]. This transition, contrary to tokamaks, can occur not only near the edge, but also in the core plasma. When the transition takes place, say at the half radius, the reduction of the transport propagates with the time scale of the energy transport. This would be the reason that the observed reduction of H_α was not so sharp in comparison with tokamak experiments. It is also noted that this transition is easy for the system with high aspect ratio and high q value. The parameter region of plateau regime is helpful with large α coefficient. The parameter dependence for other devices will be discussed in a separate article.

The expression for the suppression of anomalous transport, $F(u_g)$, is valid for the process of drift reversal by electric field inhomogeneity. The magnetic shear will also have a strong influence for the stability. The reduction of the toroidal current, which was effective in reducing the H_α signals in W-VIIA, was also found in the tokamak[17] and requires further quantitative analysis.

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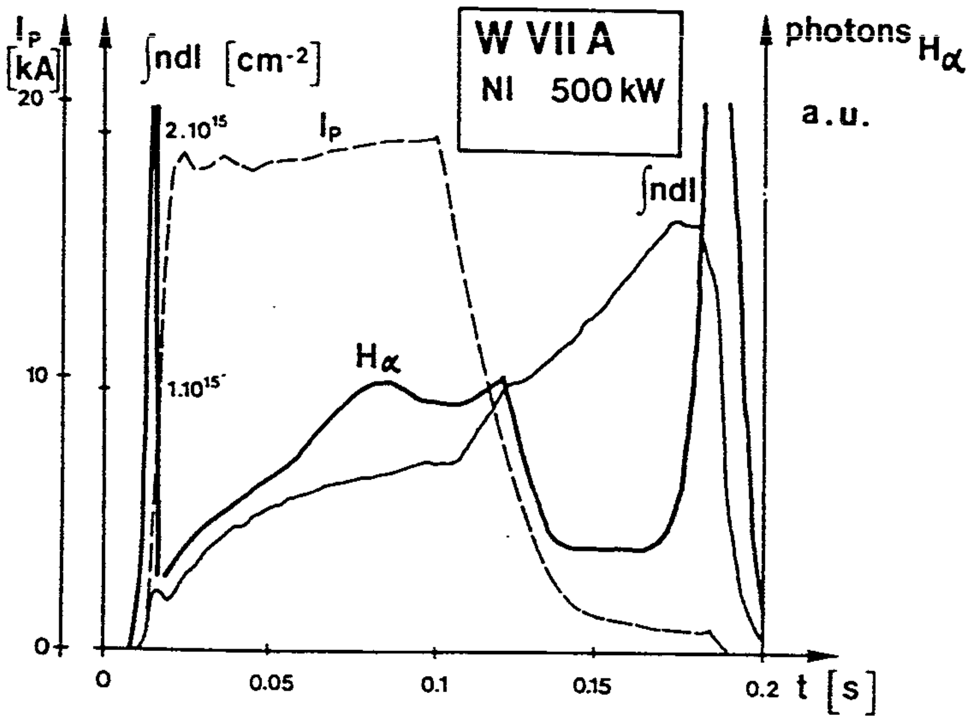
Figure Captions

Fig. 1 Trace of a discharge in W VII-A. After the injection of the neutral beam, current is reduced and external rotational transform is increased. The H_α signal then shows a rapid reduction followed by the further increment of the density. (Quoted from Ref. [8].)

Fig. 2 Function $u_g F(u_g)^2$ (solid line). Multiple solution exists for the parameter $H_2 < H < H_2$. Transition to the better confinement occurs at $H=H_1$, and that to the poor confinement takes place at $H=H_2$. We choose $u_c= 3$ and $F_\infty=0.4$ for example.

Fig. 3 Suppression parameter F as a function of H. Parameters are same as in Fig. 2.

Fig. 1



W VII A
NI 500 kW
I_p [kA]
∫ndl [cm⁻²]
photons H_α a.u.
2.10¹⁵
1.10¹⁵
I_p
H_α
∫ndl
20
10
0
0
0.05
0.1
0.15
0.2
t [s]

Fig. 2

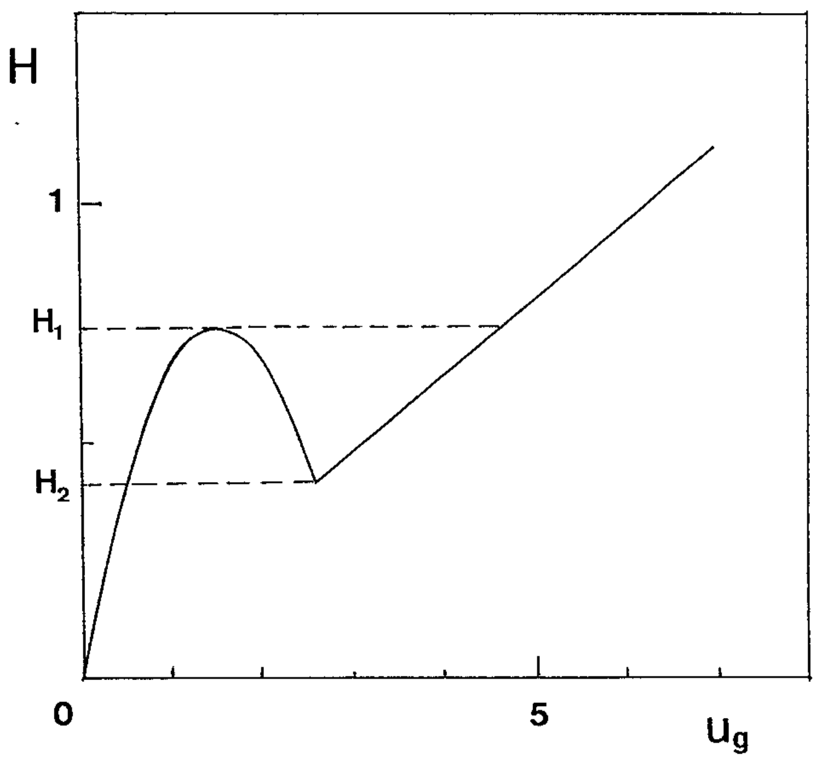
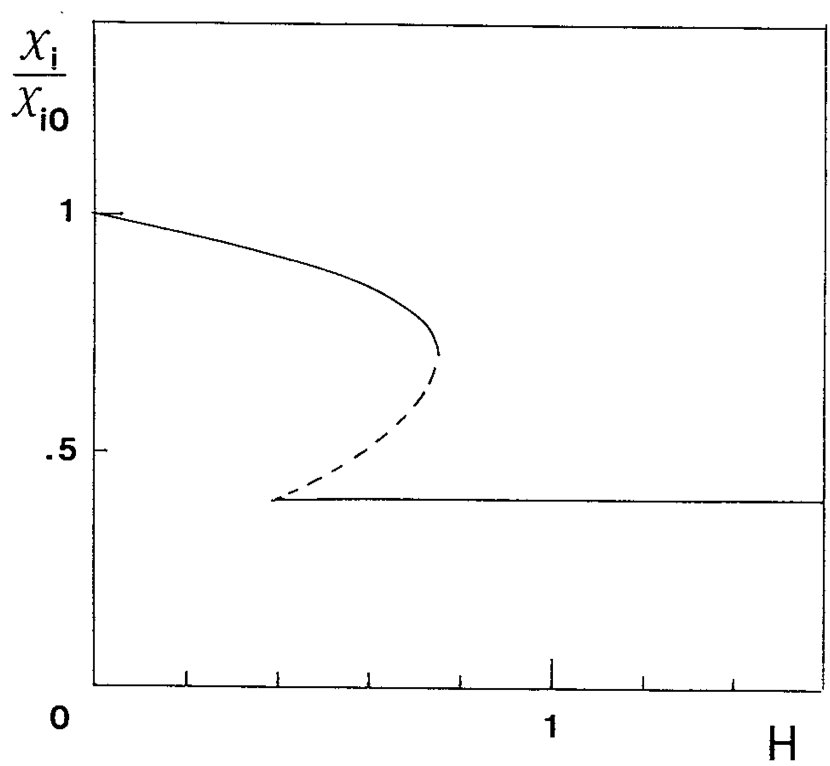


Fig. 3



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