24P030-P

Thermal Stability Analysis of Detached Divertor Plasma
非接触ダイバータプラズマの熱的不安定性に関する解析

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One-dimensional transport equations for plasma fluid are used to investigate the thermal stability in the region of divertor. Equilibrium equations and perturbation equations are combined into the linear differential equations for each perturbation. We consider effects of radiation from impurities, charged particle-neutral interactions, recombination and ionization. Neutral density and the rate parameters of charged particle-neutral interactions and recombination are related to the stability of divertor plasma.

1. Introduction

Divertor heat loads should be reduced for fusion reactors with a large amount of heating power. One of the solutions is the plasma detachment. The feature of the detachment is a sharp reduction of the temperature in the divertor region. It has been observed in some experiments. [1] The Plasma detachment is triggered by effects of radiation from impurities, charged particle-neutral interactions, recombination and ionization. Recent study has simulated the divertor plasma with the 1-D fluid equation, and shown the attached and detached states in the divertor region. [2] The interactions with Neutral particles can cause instability of the detached divertor plasma. Figure 1 shows the position of the detachment front as a function of the neutral particle density at the divertor plate. When neutral density is high($n_n \geq 3.98\times10^{19}$ m^{-3}), plasma detachment occurs.

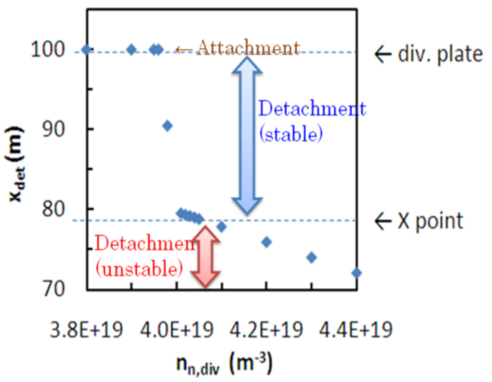

Fig.1.movement of detachment front

In this study, we will propose a stability model based on the 1-D fluid equations. It describes instability for the plasma detachment in the divertor region.

2. Formulation

In past studies [3], the analysis was based on the heat balance equation. Perturbation of temperature was introduced to investigate the MARFE instability.

We use the fluid equations for plasma and the neutral particle diffusion equation as follows.

$$\frac{\partial n_n}{\partial t}+\frac{\partial}{\partial x}\left(-D_n(n,T)\frac{\partial n_n}{x}\right)=n^2\langle\sigma v\rangle_{rec}-nn_n\langle\sigma v\rangle_{ion} \tag{1}$$

$$\frac{\partial n}{\partial t}+\frac{\partial(nv)}{\partial x}=-n^2\langle\sigma v\rangle_{rec}+nn_n\langle\sigma v\rangle_{ion} \tag{2}$$

$$\frac{\partial(mnv)}{\partial t}+\frac{\partial\left(mnv^2+2nT\right)}{\partial x}=-mnv\left(n_n\langle\sigma v\rangle_{CX}+n\langle\sigma v\rangle_{rec}\right) \tag{3}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(3nT+\frac{1}{2}mnv^2\right)+\frac{\partial}{\partial x}\left\{\left(5nT+\frac{1}{2}mnv^2\right)v-\kappa_{\parallel e}\frac{\partial T}{\partial x}\right\}=\\&-\left(\frac{1}{2}mv^2+\frac{3}{2}T\right)nn_n\langle\sigma v\rangle_{CX}-\left(\frac{1}{2}mv^2+3T\right)n^2\langle\sigma v\rangle_{rec}-I_{ion}nn_n\langle\sigma v\rangle_{ion}-nn_nL(T)\end{aligned} \tag{4}$$

From these equations, a set of equations of the 1st order perturbations of neutral density, plasma density, momentum, and temperature are derived. Equilibrium equations (5) and perturbation equations (6) are combined into the linear differential equations (8) for each perturbation.

$$f\left(n_n,n,v,T\right)=0 \tag{5}$$

$$f\left(n_n+\tilde{n}_n,n+\tilde{n},v+\tilde{v},T+\tilde{T}\right)=0 \tag{6}$$

$$\frac{\partial\mathbf{X}}{\partial t}=\mathbf{AX}\quad\text{Where }\mathbf{X}=\begin{pmatrix}\tilde{n}_n\\\tilde{n}\\\tilde{v}\\\tilde{T}\end{pmatrix},\quad\mathbf{A}=\begin{pmatrix}a_{11}&a_{12}&a_{13}&a_{14}\\a_{21}&a_{22}&a_{23}&a_{24}\\a_{31}&a_{32}&a_{33}&a_{34}\\a_{41}&a_{42}&a_{43}&a_{44}\end{pmatrix} \tag{7}$$

Spatial perturbations are assumed as follows.

$$\tilde{n}_n=e^{ik_{nn}x},\ \tilde{n}=e^{ik_nx},\ \tilde{v}=e^{ik_vx},\ \tilde{T}=e^{ik_Tx} \tag{8}$$

Here, wavenumber k is assumed as follows.

$$k_{nn}=\frac{1}{\alpha L_{nn}},\ k_{n}=\frac{1}{\alpha L_{n}},\ k_{v}=\frac{1}{\alpha L_{v}},\ k_{T}=\frac{1}{\alpha L_{T}} \quad (9)$$

L_b is the decay length of the variable b on the detachment front. α is a free parameter and here assumed to be 1/10 when maximum eigenvalue become zero in the case of steady detachment front as shown in fig.2.

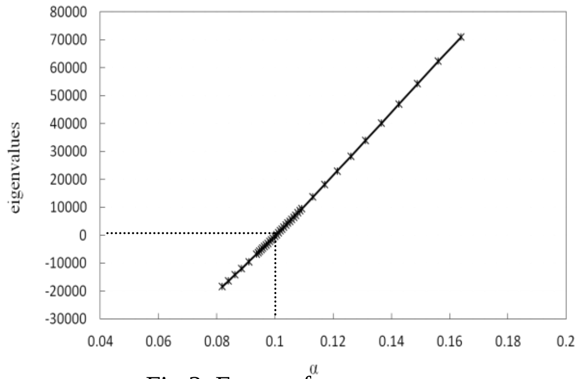

Fig.2. Factor of wavenumver

We investigate the instability of plasma detachment by evaluating the eigenvalue of equations (7). In this study, ITER-like plasma parameters are assumed.

3. Result

3-1 Neutral particle density

Figure 3 shows the maximum eigenvalues near the divertor plate. In the case of small neutral particle density ($n_n \leq 3.98\times10^{19}$ m^{-3}), these are negative values. These indicate the attached or steady detachment plasma in the condition. When the neutral density is higher than 3.98×10^{19} m^{-3}, eigenvalues become positive. In this condition, plasma detachment becomes unstable.

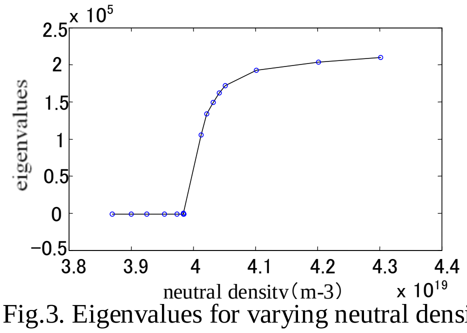

Fig.3. Eigenvalues for varying neutral density

3-2 Charge exchange and recombination

In order to investigate the effects of rate parameters, each rate parameter was changed as free parameter. Figures 4 and 5 shows the eigenvalues as functions of the rate parameters of charge exchange and recombination. Ionization and impurity radiation loss were also taken into account, but these were found not affect the eigenvalues. In the case of varying charge exchange, smaller rates reduce instability. Larger rates of recombination reduce the eigenvalues, but there is a limit to the small instability. The effect of varying charge exchange rates is larger than recombination rates.

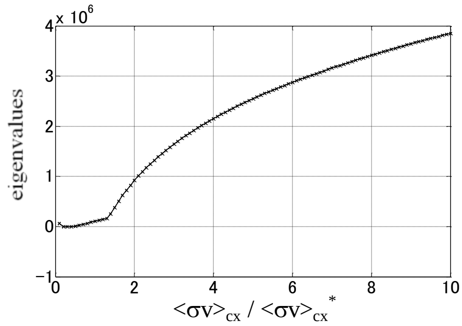

Fig.4. Eigenvalue for varying charge-exchange rate

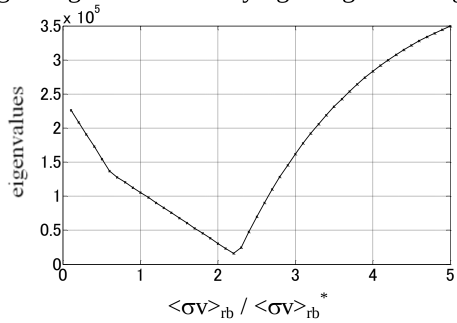

Fig.5. Eigenvalue for varying recombination rate

4. Discussion & Conclusion

We proposed the analytical model of the thermal stability of the detachment fronts in which perturbations of neutral density, plasma density, momentum, and temperature were taken into account. This model enables to evaluate Instability in the divertor region. In the state of the attach plasma or steady detached plasma, the system equation represent the negative eigenvalues; The states are stable. In the state of the unsteady detached plasma, eigenvalue of the system equation is positive; the state is instable. The Neutral density and the rate parameters of charged particle-neutral interactions and recombination are related to the stability of divertor plasma.

The stability analysis in this paper takes into account the time perturbation and assumed wavenumber. On the other hand, Wesson et al. proposed another analysis. The stability problem is time-independent and omits the space variable. We apply Wesson's theory to the plasma fluid equations and neutral transport equation.

References

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