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### **A Review on Application of MHD Theory to Plasma Boundary Problems in Tokamaks**  10 Plasma Boundary Problems in Tokamaks

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# **A Review on Application of MHD Theory** to Plasma Boundary Problems in Tokamaks

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This review is prepared for presentation This review is prepared for presentation at 3rd International Workshop on Plasma Edge Theory

Keywords: Edge plasna, UHD equation, tokamak, transport, scrape - Keywords: Edge plaslla, UHD equation. tokamak. transport. scrapt: off layer, H-mode. edge-localized nodes, ELMs, radial off layer. H-mode. edge-localized odes. ELWs. radial electric field, plasma rotation, viscosity, beta linit, electric field. plasma rotation. viscosity. beta limit. ballooning mode, magnetic well, MARFE, detachment, impurity

 $1 - 1$ 

#### **Abstract**  Abslracl

A survey is made on the problems of the edge plasmas, to A survey is made 00 the problems of the edge plasmas, to which the analyses based on the **UHD** theory have been successfully which the analyses based on the WHD theory have been successfully applied. Also discussed are the efforts to extend the model equation to more general (and important as well) problems such as H-node physics. H-mode physics.

An overview is first nade on the advantages of the UHD An overview is first made 00 the advantages of the WHD picture, and the necessary supplementary physics are examined. picture. and the necessary supplementary physics are examined.

Next, one- and two-dimensional models of the spatial struc-Next. one- and two-dimensional models of the spatial struc ture of the edge plasma is discussed. The results on the ture of the edge plasma is discussed. The results 00 the stationary structure, both analytical and numerical, are stationary structure. both analytical and numerical. are reviewed: Typical example as well as the scaling law are shown. reviewed: Typical example as well as the scaling law are sbown

The instabilities associated with edge plasma is next The instabilities associated with edge plasma is next reviewed. The surface kink node, ballooning mode, interchange reviewed. The surface kink mode. ballooning mode. interchange mode, resistive interchange mode and thermal instability are discussed. Role of the geometry such as the location of the X-discussed. Role of the geometry such as the location of the X point is studied. Influences of the atomic processes, and those point is studied. Influences of the atomic processes. and those of the radial electric field are also discussed. of the radial electric field are a150 discussed

The analysis of the H-mode transition physics is finally The analysis of the H-mode transition physics is finally discussed. The boundary plasma is a nonlinear media which possesses the possibility for bifurcation in which the radial possesses the possibility for bifurcation in which the radial electric field plays a key role. The model of the ion viscosity electric field plays a key role. The model of the ion viscosity is also studied. Transition physics is developed. Analysis on is also studied. Transition physics is developed. Analysis on the self-generating oscillation is shown and the relation with the self-generating oscillation is shown and the relation with ELUs is discussed. ELWs is discussed

After reviewing these problems, several comments are made to what directions the study can be deepened. what directions the study can be deepened

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#### *Part A* A REVIRI QH APPLICATION OF HUD THEORY TO PLASMA BOUNDARY PROBLEMS IN TOUMAI S TO PLASU BOURDARY PROBLEMS IN TOUKUS Part A A REVIEW ON APPLICATION OF MHD THEORY

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#### [ I] Introduction

The important roles of the edge plasna have been widely recognized both on the plasna confinenent research and the design study of fusion reactors. The basic physics approach was conpiled in Ref. [1]. Recent experimental findings, such as the  $h$ -mode $^{2}$ ), had a large impact in the progress in this field, as is reviewed in [3]. One of the keys is the sensitivity of the plasna response to the change of the plasna position, such as the plasna-wall distance or the directions of the ion VB drift and X point location<sup>2,3)</sup>. It is necessary to find out the key parameter which characterizes the spatial structure in modelling the edge plasna phenonena. The iipact of the plasna properties on the design of future large devices is also well known. For instance, the estination of the heat localization width and its dynamic change (such as in the large ELMs (edge localized modes)) are critical issues. nai<br>hi<br>me Poffusio:<br>CPBO F2210eE in the<br>Pact in the<br>M 11et--Ereras is the<br>Sama position<br>Parameter<br>Insmaller laemnaatrik<br>Insmaller laemnaatrik entersutge eftsva<br>Exhension lesether allegether the plane<br>difference in the plane of the plane<br>of the plane edge p<br>edge p<br>gn of f<br>ation of desi<br>dalone<br>one of<br>estings the<br>desi<br>esting hthe sconpicture<br>e<sup>2)</sup>, had<br>not different contained in the contact of individual<br>of the other contained in the same of the sam pch<br>chwadi<br>Ideby<br>Itherschilder<br>Institutions<br>Institutions នៃ<br>៖<br>1 s eer<br>eerhviseus die verhouwende van die verhouwen<br>eerdsoeken each die verhouwen en die verhouwen van die verhouwen van die verhouwen van die verhouwen van die v<br>eerhviseus die verhouwen van die verhouwen van die verhouwen v nent<br>csahas<br>haspnassara<br>stahaspnassara ine<br>ysi<br>as as<br>na di<br>Ital<br>pla rccgepwoos--aahn lnp-daltekd efh-slin S1ysaIapoa ptla-nS3SI nEadhE2eotuaslfeareh umport<br>he pla<br>tal fi<br>tal finithity of<br>he pla<br>pocatio<br>izes t<br>impact The<br>11actors.<br>11actors.<br>11actors.<br>11actors.<br>11actors.<br>11actors.<br>11actors.<br>11actors. Ibrepseu<br>Ibrepseu<br>Isreuk<br>Ibna

In the study of these problems. the analysis based on the magneto– hydroc<sub>i</sub>-ramic (MHD) equation has been performed. This equation has the advantage that phenomena of various time scales, from the Alfven transit **time to transport time, can be treated and that the plasma configuration** is easily taken into account. In this article, we present a brief survey 15 ea5ily laken into account. In this article, we present a brief survey on the problems in edge plasmas, for which the analysis based on the fluid equations are successfully applied. We also discuss the efforts to extend the model equation to investigate more general and important problems such as H mode physics. We finally discuss the future possible investigations,

#### [II] Structure of Edge Plasmas

The plasma and geometry of our analysis are shown in Fig.1. The thick dotted line indicates the separatrix. The definition of the 'edge plasma' has not been made uniquely. le here consider that the edge plasnas are ie here considcr that the edge plas as are consist of the plasma (1) outside of the outermost magnetic surface (i.e., scrape off layer) and some inside of the separatrix. i.e., in the region (2) where the inhomogeneity along the field line is appreciable or (3) in which the radial gradient length depends weakly on the minor radius. (Po'oidal nesh is for 2-D calculation.) layer) and some inside of the separatrix.<br>
i.e., in the region (2) where the inhomoger<br>
meity along the field line is appreciable or<br>
(3) in which the radial gradient length<br>
(Poloidal nesh is for 2-D calculation.)



.1 .

**The basic equations, i.e.. the continuity equations of the**  The basic equations. i.e.. the continuity equations of the density, the momentum and the energy, are given in literatures as<sup>5)</sup>

$$
\partial \rho / \partial t + \nabla \cdot (\rho \nabla) = S_n \tag{1-1}
$$

**pdV/dt - - 7-D t R + F + S <sup>n</sup> Cl-2)**   $\rho dV/dt$  -  $\nabla \cdot \mathbf{I} + \mathbf{R} + \mathbf{F} + \mathbf{S}_m$  (1-2)

$$
a(\rho E_{\rm S})/at + \nabla \cdot (E_{\rm S} \Psi) = -\Pi; \nabla \Psi + (R + P) \cdot \Psi - \nabla \cdot q + S_{\rm E}
$$
 (1-3)

**p is the mass density, E . is the internal energy per unit lass,** *t* **is the**  P is the lIass density, Es is the inlernal energy per unit ass , is the external force, and other notations are standard. The **WHD equations are not closed by thenselves . and we need to specify the closure such as the**  oot closed by the selves. and we need to specify the closure such as the equation of state, the stress tensor **II**, and the transport coefficient, and the model of the sources (S<sub>p</sub>, S<sub>m</sub>, S<sub>E</sub>).

The common choice of the closure is that the parallel transport is **classical, and only the diagonal part of the stress tensor, eleient of**  classical. and ooly the diagonal part of the stress tensor. ele.ent of **which is p\*nT, is kept. The frictional force K is calculated by Spitzer**  which is p"'nT. is kept. The frictional force H is C'alculated by Spitzer **col lis ion frequency. The classical values are used for the plasaa resis-**collision frequency, The classical values are used for the plaslla resis**tivity**  $\eta$  **and parallel thermal conductivity. The electron energy flux**  $q_a$  **is** tivity n and parallel thermal conductivity. The electron energy flux q<sub>e</sub> is<br>given by q<sub>u</sub><sup>e</sup> + q<sub>T</sub><sup>e</sup>, and that for ion is given by q<sub>T</sub><sup>i</sup>, where

$$
q_{\mu} = -0.71T_ej/e + (3T_e\nu_e/2eQ_e)bxj.
$$
  
\n $q_{\tilde{T}} = -\kappa_g\nabla_g T - \kappa_g\nabla_i T + (5nT/2eB)b \times \nabla T.$ 

 $\nu_{\mu}$  is the electron collision frequency,  $\Omega_{\mu}$  is the electron cyclotron frequency. **b**≈B/B and **k**=n%. The perpendicular transport coefficients are **considered to be anomalous, and the prescribed form is employed.**  considered to be anomalous. and the prescribed forll is ellployed

**The particle source can be calculated once the neutral density is**  Thc particlc source can be calculated once the neutral deosity is given. This term depends on the geometry strongly. The connection with the computation on **neutral dynamics is discussed in [6]**.

**T he boundary condition s at the p 1 assa - raterial interface are**  The boundary condilions al Lhe plasma'uterial inlerface are given'<sup>J</sup> in the form of the Bohm sheath criterion and energy transmission coefficient  $\tau_{e,\;i}$ . The current across the plasma-wall interface is often assumed to be zero. The extension to the case where the current flows across the wall (e.g., the divertor biasing) is also possible.

**The plasma distributio n along the field line in the scrape-**Thc plasma distribution along the field line in the scrape**off layer is first studied. Bhen the plasma thickness is paraneterized by**  off layer is firsL studied, Ihen the plas a thickness is parueterized by **i. the parallel energy conduction equation along the field line gives <sup>8</sup> '**  d.. the pural1el energy conduction equaLion along the field lioe gives 8)

$$
T(1)^{3.5} - T_{div}^{3.5} + 7q_{y} 1/2\kappa_{0}, q_{y}^{*} - B_{t}P_{out}/B_{p}2\pi\Delta R.
$$
 (2)

where **I** is the distance along the field line from the divertor plate.  $\kappa_{ii}$  =  $\kappa_{0}$ T<sup>2, 5</sup>,  $P_{out}$  is the total energy outflux to SoL, a and R are the minor and **major radius, and the energy deposition in the SoL plasma is neglected for**  major radius. and the encrgy deposition in the SoL plaslla is neglected for the simplicity. Though very simplified, this equation reveals essential

characters of the SoL plasma.

The Bohm sheath criterion gives the plasma parameter in front of the **divertor as**  di vertor as

$$
T_d - P_{out}/Gr_t r_{out}
$$
 and  $n_d - \sqrt{n_i r_t} (B_t/B_p 2\pi \Delta R) (Gr_{out})^{3/2} / \sqrt{P_{out}}$ 

 $\mathbf{u} = \mathbf{u}_t - \mathbf{u}_t + \mathbf{v}_t$  . G is the enhancement factor of the particle flux in Sol plasma and  $\Gamma_{\rm out}$  is the particle flux out of the main plasma.  $\Gamma_{\rm d}$  and  $\rm n_{d}$ **are essential in evaluating the performance of the divertor.**  are essentia! in evaluating the perfcr.ance of the divertor

The parameter **A** is determined by the cross field energy transport. Solving the equation  $\kappa^{}_{\rm I} \, \pmb{\mathrm{v}}^{}_{\rm I}$  -  $\cdot\,$   $\cdot\,$   $\qquad\rm q}$ <sub>.</sub> ( $\scriptstyle\sim$   $\rm P_{\rm out}$   $\prime$   $\scriptstyle\rm 4\pi^2$ aR). the estimation of A is obtained in [9]. If the cross field transport is given by the Bohm<sup>.</sup><br>like diffusion. <sub>'1.\*</sub> T/eB. we have<sup>lOJ</sup> **like diffusion, i <sup>x</sup> « T/eB, ve have 1 0 <sup>5</sup>**

$$
\Delta/a = 5\kappa_a (\text{LB}_t/\kappa_0 a_{p}^2)^{4/11} (\text{R/P}_{\text{out}})^{3/11}
$$
 (3)

**•here L is the distance between midplane and divertor along the field**  ..bere L is tbe distance between idplane and divertor along the field line and  $\kappa_{\text{L}}$  **+** $\kappa_{\text{a}}$ **T.** The heat flux channel becomes narrower as the power **1 increases. It is also shown that***<sup>t</sup>* **does not scale to a <sup>1</sup> . (For instance.**  increases. It is also sho n that A does noL scale to a1. CFor instance. **if**  $P_{\text{out}} \sim a^3$ , then  $A \sim a^{5/11}$ .)

ut ~ a<sup>s</sup>, then A ~ a<sup>9/11</sup>.)<br>The drift heat ilux (VTxb term in q<sub>T</sub>) can also affect the heat chan<sup>.</sup> ne1<sup>11)</sup>. This term depands on the direction of **B**, and can be taken into account in Eq.(3) by modifying  $\kappa_{\mathbf{g}}$ .

The numerical analysis has been performed in crder to obtain the two dimensional structure of the Sol. plasma<sup>6,12–16)</sup>. These calculations can also determine the neutral particle profile, and hence the parameter **G**. **Example is shown in Fig.2. It is shown that the dense and cold divertor** plasma is established, and the neutral particles are localized nea; by.



rig. 2 Examples of the 2:D simulation in the SoL region. Profiles of<br>T. n., n are given. (Nodel of IFI 2M plassma, the ion VB drift is<br>in the direction of the X point, the total fluxes from core are P<sub>out</sub><br>-0.5MW and P<sub>out</sub> -ra l<br>1 --- `e, n<sub>is</sub> no are given, (Nodel of 1972M p<br>hithe direction of the X point, the tota<br>0.5MW and f<sub>out "</sub>5×10<sup>21</sup>/sec, respectively ード  $\frac{1}{1}$ eo -温 F E g 2

**Though the 2-D conputations can now be fluently done, scaling study**  is desirable to have a fast grasp of the phenomena. The scaling study has<br>been performed by using the 2-dimensional numerical code (assuming the<br>Bohm diffusion coefficient) to give<sup>15</sup> **been perfone d by using the 2-dinensional numerical code (assuning the**  is desirable to have a fast grasp of th<br>been performed by using the 2-dimension<br>Bohm diffusion coefficient) to give<sup>15</sup>) 。e-z eh

$$
n_d \sim \Gamma_{\text{out}}^{1.1} P_{\text{out}}^{0.35}, \quad T_{\text{e},d} \sim P_{\text{out}} \Gamma_{\text{out}}^{-1}.
$$
 (4-1)

$$
n_d \sim \Gamma_{out}^{1/1} P_{out}^{0.37}
$$
,  $T_{e,d} \sim P_{out} \Gamma_{out}^{1/4}$ .  
\n $n_b \sim \Gamma_{out} P_{out}^{-0.3}$ ,  $T_{e,b} \sim P_{out}^{0.5} \Gamma_{out}^{-0.25}$ . (4-2)

$$
\begin{array}{l}\n\text{I}_{\text{D}} \sim \text{Sott out} \\
\text{I}_{\text{T}} \sim \text{F}_{\text{out}}^{\text{0.4}} \text{P}_{\text{out}}^{\text{0.4}} \text{P}_{\text{out}}^{\text{0.23}} \text{I}_{\text{m}} \sim \text{F}_{\text{out}}^{\text{0.24}} \text{P}_{\text{out}}^{\text{0.15}}\n\end{array} \tag{4-3}
$$

**\*T**  $\sim$  <sup>1</sup> out<sup>\*\*\*\*</sup>Fout \*\*\*\*\*, **\***n  $\sim$  <sup>1</sup> out \*\*\*\*\*\*\*\*out \*\*\*\*\*<br> **\*** there **i**<sub>T</sub> and **i**<sub>n</sub> are the scale lengths of the radial gradients, T/T' and **n/n' C'ad/dr), at the aidplane, respectively This result confirns that**  the analytic result is a good estimate. If we eliminate  $\Gamma_{\text{out}}$  from Eq. (4where  $L_T$  and  $L_n$  are the scale lengths of the radial gradients. I/T and  $n/n'$  ( $'ed/dr$ ), at the minimum scheen the and the and the and the and the and the scale straine is a good estimate. If we eliminate  $\Gamma_{01}$  from E **2/11 The see that the plasma structure is well understood, and what is eally necessary is the understanding of the cross field transport.**  ive<br>I<br>ons<br>is<br>ist<br>ft ect<br>te<br>atiure<br>go r),<br>; r<br>ae<br>ssa<br>ion .<br>.<br>.  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$ 

**Extension to the impure plasmas has also been performed<sup>14,16)</sup>** 

#### **[III] Stability of Edge PUsia s**  [III] Stability oC Bdle Plas.as

**HHD equation is lost successfully applied to the study on'**  KHD equation 18 ost successfullY applied to the study on the plasma stability. The strong shear associated with the separatrix and the poloidal location of the X-point are critical for the study on the stability beta **limit**.

The average magnetic curvature at edge of the tokamak plasma is **favourable (except the case where the X-point is outside of the tcrus).**  favourable (except the case where the X-point i5 outside of the tcrus) The unstable **node may be** localized in the outside of the torus (where the local bad curvature exists). The wave length along the filed line is long, i.e., k<sub>#</sub>• b·V = 1/a but the one across the filed line is short. **a/aB>>1/a.** For the perturbation  $\phi(r, \theta, \zeta)$ , the ballooning transformation **was introduced as <sup>17</sup>) φ(r, θ, ζ) = Eexp( in Θ+πζ)**  $\int$  **dxφ(x)exp{i(n -nq(r))x}. where q(r) is the safety factor and m and n are the poloidal and toroidal**  where q(r) i8 the safety factor and 11 and n are the poloidal and toroidal **node numbers, respectively. (Note x is the coordinate, not thermal conductivity. le here follow the notation of Ref.[18].) The Euler equation**  ductivity. Ie here follo tbe notation of Ref. [18J.) The Eulet equation for high-n mode is given in a form of the ordinary differential equation.

**Analytic foriula for ideal IIHD node was obtained in the high aspect**  Analytic for ula for ideal WHD lIode was obtained in the bigh aspect ratio limit of the circular plasma. The Euler equation is characterized by the three parameters, i.e., 5 rq'/q (local shear), a- -2Rq<sup>2</sup>B <sup>2</sup>y' (local **pressure gradient) and 6-(l-q"<sup>2</sup> )r/R (average well). The Euler equation is**  pressure gradient) and  $6-(1-q^{-2})r/R$  (average well). The Euler equation is simplified as  $(3/3x)(1+t^2)3\Phi/3x+(a(\cos x - 1\sin x)-6-r^2(1+t^2))\Phi = 0$ , I = sx. **αsin1**, and T is the growth rate. The instability condition for 'nw s case is given as  $3/4(\alpha^2 \cdot \sqrt{\alpha^4/2 \cdot 32 \alpha 6/9})$   $\lt$  s  $\lt$   $3/4(\alpha^2 \cdot \sqrt{\alpha^4/2 \cdot 32 \alpha 6/9})$ , showing that the ballooning mode is stable for **¤<0.8/s** and **¤>2.2/s** (the s*econd stabili*– ty). Figure 3 illustrates the stability limit for the pressur<mark>e gradient</mark><br>(α) as a function of the shear. **(a) as a function of the shear.** 





**In the edge plasnas , the plasna resistivit y** *n* **is snail but finite. T he dissipatio n proces s can destabiliz e the node for the regiiie wher e ideal WHD** pode is predicted to be stable. The effect of the resistivity **h as been studie d in detail 1 8 ' 1 9 - ' . For the f ini te - resist ivi ty plasna. Eu 1 er equatio n is reforeed, and is characterize d by the four parameters ,**  has been studied in detail<sup>18,19)</sup>. For the finite–resistivily plasma,<br>Euler equation is reformed, and is characterized by the four parameters,<br>s. α, δ and S. where S is the magnetic Raynolds number, S=ν<sub>Α</sub>μ<sub>Ο</sub>α<sup>2</sup>/η?. Fo the case of the strong ballooning limit ( $|x| \ll 1$ ), the growth rate r is determined by (growth rate **T** is normalized to v<sub>\*</sub>/R) The dissipation process can destabilize the node for the regime where<br>ideal WHD node is predicted to be stable. The effect of the resisti<br>has been studied in detail<sup>18.19</sup>). For the finite-resistivity plasma<br>Euler equatio or<br>ec<br>y<br>stb

$$
\tau^3 + (k_\theta^2 / 2S) \tau^2 - \tau_1^2 \tau - (k_\theta^2 / 2S) (\alpha \cdot \delta) = 0.
$$
 (5)

**where**  $\mathbf{r}_1$  **is the growth rate in the ideal UHD limit.**  $\mathbf{r}_1^2 = \alpha \cdot \sqrt{\alpha/2} - 6$ **. It is** shown that, in the absence of well (6-0). the node is unstable for all **value of a, i.e.. the stabilit y beta limit is zero (see Fig.3) . The node growth rate is given as** 

> *T* $\sim$  **(αk<sub>0</sub><sup>2</sup>/2S)<sup>110</sup> for τ<sub>I</sub>n r**

In the presence of the magnetic well, the critical beta for stability appear below the ideal WHD stability limit. An estimate for stability **fron Eq.(5 ) is given by a<6.** 

**T he conpariso n study of the occurrenc e of the 'Type-I ' ELMs^ ) cor**responds to the stability boundary for the ideal WHD instability, suggesting the importance of this kind of instability. However, the catastrophic **nature, such that the sudden growth of the node with n-vlO acts as the precursor of Giant ELMs<sup>21</sup>, is not understood.** cor<br>ugge<br>trop<br>he WHD stability limit. An estimate for stabili<br>  $\alpha$ (5.<br>
dy of the occurrence of the 'Type-I' ELWs<sup>20)</sup><br>
ty boundary for the ideal WDD instability, substitution<br>
his kind of instability. However, the catast<br>
udden growth of mate f<br>Type-I<br>insta<br>ever,<br>muld<br>espons<br>aspons esti<br>|e||<br>|KHD<br>|th<br>| th y lim<br>curre<br>for t<br>instanteracte<br>racters<br>sly.<br>such<br>nen[ iatnngsheek<br>inngsheek<br>eks Semble<br>Semble diameter<br>Semble diameter<br>Strate-Strate--strate--strate--strate--strate--strate--strate--strate--strate--strate--strate--strate--strate-<br>Strate--strate--strate--strate--strate--strate--strate--strate--strate-idea<br>vens<br>tabi<br>e-of-he-ELI-ssi<br>tabi<br>bili ole also and an act is seed as a second term of the state of the s re(Eq.(5) is<br>Eq.(5) is<br>The compa<br>mds to the<br>ne import<br>e. such the<br>formal social interpolation nips<br>Global interpolation ppea<br>tom<br>espo<br>ng t<br>atur<br>ffec<br>adia Iafrina<br>Fina

**Atonic proces s is also the characteristi c to the edge plasna, and affect ihe edge stabilit y trenendously .** 

**Global instabilities are known such as WARFE<sup>22</sup> and detachment. The** radiation loss is nodelled as S<sub>E</sub> -  $n_{e}n_{L}(T_{e})$ , where  $n_{L}$  is the **inpurity density . Model s on L(T f i ) and the dynani c respons e of n. with**  L

respect to the pecturbation are necessary to quantify the growth rate. The latter is usually denoted by the parameter  $\bar{\epsilon} = (\bar{h}_e / n_e + \bar{h}_I / n_I)(1/\bar{f})$ .<br>Asympetric thermal instability (p-1/n=0, i.e., MARFE) can grow if 22) Asymmetric thermal instability (o-!/n=0. i.e., HARFE) can grow if <sup>2</sup>**<sup>f</sup> 2 2 <sup>&</sup>gt;**

$$
n_1[al/at+el/T] > (\kappa_1/(a \cdot r_h)^2 + \kappa_2/q^2R^2), \text{ and } \epsilon_{n_1}L/T > \kappa_4/q^2R^2. \tag{6}
$$

where  $(r_{\rm b},a)$  is the region of the analysis, where 3L/3T is negative and in the region of the analysis, where  $b$ L/3T is negative and large. If the latter condition of (6) does not hold, the poloidally sym-<br>metric mode (i.e., datachment) starts to grow. This picture is often<br>referred to as an origin of the density limit. The lighter impurities **metric mode (i.e., detachment) starts to grow.** This picture is often referred to as an origin of the density limit. The lighter impurities large. If the latter condition of (5) does not hold, the poloidally sy<br>metric node (i.e., detachment) starts to grow. This picture is often<br>referred to as an origin of the density limit. The lighter inpurities<br>(for which while the heavier one to the detachment (and then disruption): These predictions are consistent with experiments. th<br>pic<br>ead<br>upt d.<br>Ii<br>er nd<br>hm<br>of<br>e<br>th a<br>aT<br>ie th<br>is<br>al/<br>al/<br>aav

The microscopic mode is also affected by atomic process. For ins<sup>.</sup> lance, if the neutral density  $\bm{{\mathsf n}}_{\bm{{\mathsf f}}}$  is constant, then the density fluctuation ff gives the source of fluctuation S<sub>n</sub>~γ<sub>n</sub>?r≤n<sub>0</sub>?(<dv>. This positive feed back enhances the growth rate of drift–like waves by the amount of T  $^{\rm 23)}$ . The<br>neutral density itself contains the fluctuating component, and a relation neutral density itself contains the fluctuating component, and a relation  ${\tt S}_n$   $\cdot$   ${\tt r}_n$ h is not always valid. Further analysis is required.

The sharp gradient of the radial electric field (flow velocity shear) can also affect the stability of the edge plasma. The electric field gradient influences the stability through modifying the ion orbit $^{24)}$ . The effect was studied by WHD equations $^{25)}$ . Stabilization is expected if

$$
|\mathbf{E}_{\mathbf{r}}^{\top} \mathbf{k}_{\theta}/\mathbf{B}\mathbf{k}_{\mathbf{r}}| \sim \tau_{\mathbf{L}} \tag{7}
$$

where  $\bm{r}_{||}$  is the linear growth rate in the absence of E<sub>r</sub>'. Recent progress has shown that the mode amplitude is not necessarily reduced by the velocity shear, a.d the intensive study is under way  $^{26}$ . The study in this direction was mclivatcd by the prediction of the radial electric field at has shown that the mode asplitude is not necessarily reduced by the velocity shear, and the intensive study is under way<sup>26</sup>. The study in this direction was metivated by the preduction of the radial electric field at the  $t_{\rm eff}$  and II  $\tau$  is confirmation by experiments  $\tau_{\rm eff}$  and its confirmation by experiments.  $|E_r^* k_B/Bk_r| \sim r_L$  (7)<br>  $r_L$  is the linear growth rate in the absence of  $E_r^*$ . Recent progres<br>
nown that the mode applitude is not necessarily reduced by the velo-<br>
shear, and the intensive study is under way<sup>26</sup>). The s e、吋mo

#### [IV] Bifurcation Phenomena

One of the most dramatic finding in recent plasma confinement experiments was the H node<sup>2)</sup>. It has shown the generic nature of the edge<br>piasma that the multiple states are allowed for given external condit<br>that it bas a rapid tine scale for the trensition. Efforts have also<br>that it bas a plasm. that the multiple states are allowed for given external conditions, that the typical gradient length can be free from the minor radius, and that it has a rapid time scale for the transition. Efforts have also been made to model these phenomena in the framework of the fluid picture of the plasma, and are illustrated in the following. -ne dge<br>ndition<br>s. and<br>also be<br>re of t ne<br>fo<br>itkk e<br>S<br>D n t<br>all<br>he<br>fr One of the most draments was the H mode<sup>2)</sup>.<br>
plasma that the multiple<br>
that the typical gradient<br>
that it has a rapid time<br>
made to model these phenoments

A possible mechanism of the bifurcation was proposed by taking into  $\arctan$  the effect of the loss cone<sup>27)</sup>. The basic physics picture was<br>that the gradient flux relation should have the form, which is that the gradient-flux relation should have the form, which is

schematically drawn in Fig.4. to ex<sup>.</sup> **plain the sequence of the transition and**  plaln thc sequence of lhe lransition and **that this is possible at edge (not**  lhat this is possible at edge (oot **character ized by the separatrix) .**  characterized by the separatrix)

To quantify the model, it is neces<sup>.</sup> **sary to study the nature of the visco-**sary to sludy the nature of the viscosity term in the basic equation. **We** *write the Poisson* equation *combining*  write the Poisson equation co bjnjns **with the equation of motion as** 



(8)

$$
\epsilon_0 \epsilon_1 \partial \epsilon_r / \partial t = e(\Gamma_{re} - \Gamma_{ri} - \Gamma_{lc})
$$
 (8)

**where** *£±* **is the perpendicular dielectric constant. r <sup>r</sup> <sup>e</sup> is the bipolar**  component of electron flux,  $\Gamma_{n}$ ; is that of ion flux, and  $\Gamma_{1n}$  is the loss**cone current of ions. [These terns are neglected in assuning DVp by the unit tensor.)** The stationary solution is obtained by solving  $\Gamma_{r,0}$  **+** $\Gamma_{1,0}$ . The term Γ<sub>1c</sub> has the dependence on E<sub>r</sub> as Γ<sub>1c</sub> ~ ρ<sub>ρ</sub>π<sub>i</sub>μ<sub>i</sub>ε <sup>ν. J</sup>exp(·ΞΧ°) where<br>ν, is the ion collision frequency, εma/R, Ξ indicates the effect of orbil **squeezing due to the inhonogeneity of E <sup>r</sup> 3 0 \ and X-eE <sup>f</sup> p"/T . (X is equal to**  the poloidal Mach number V<sub>P</sub>B/v<sub>Ti</sub>B<sub>p</sub> if V<sub>p</sub>=E<sub>r</sub>/B<sub>t</sub>.) This shows that the loss<br>flux can reduce if E\_ is large enough. Figure 5(a) illustrates the case **flux can reduce if E <sup>f</sup> is large enough. Figure 5(a) illustrates the case**  study that  $\Gamma_{\text{re}}$  is proportional to ( $\cdot$ n'/n+eE<sub>r</sub>/ $\Gamma_{\text{e}}$ ), and  $\Gamma_{\text{re}}$  is neglected. lectron flux,  $\Gamma_{r,i}$  is that of ion flux, and  $\Gamma_{1c}$  is the loss<br>fions. (These terms are neglected in assuming  $I\!U\rho$  by the<br>The stationary solution is obtained by solving  $\Gamma_{r}e^{-\Gamma_{r,i}+\Gamma_{i}}$ <br>as the dependence on the line<br>e<sup>=1</sup><br>x<sup>2</sup>] ois<br>is<br>the is<br>BIV<br>BIT<br>p(-Hect<br>fect<br>(X that<br>eshere ryis<br>in<br>d by<br>ni<sup>p</sup>ies<br>s-eE<br>Thi<br>a) i pn fl<br>ected<br>caine<br>^ Pp<br>indic<br>and<br>it.)<br>e 5('T<sub>e</sub>). that<br>are<br>ion<br>Erf Evf<br>erf<br>if V<br>Eh. of e<br>nt o<br>r.)<br>ion<br>due<br>al Meduc leor<br>11dae<br>11dae onen<br>curten<br>term<br>sthezin<br>polocan<br>yth comp<br>unit<br>The<br>pineus<br>the<br>flux<br>stud







**Fig.5** Balance of loss cone loss  $\Gamma_{1c}$ **Fig. 5** Balance of loss cone loss  $\Gamma_{1c}$ <br>and electron loss  $\Gamma_{1c}$  determines<br>the radial electric field X= **ep E** *n <sup>i</sup>* **(a) . For the r.. e of** *i*  **(snail A= P n'/n) , one la.ge-flu) solution is allowed. Multiple solutions are possible for the**  solulions are possible for the **nediun** *X* **case (B and C) . and the one small-flux solution is allowed**<br>for large value of  $\lambda$  (D). The *for large value of*  $\lambda$  (D). **resultant flux as a function of**  weddus  $\lambda$  case (B and C), and the<br>one small-flux solution is allowed<br>for large value of  $\lambda$  (D). The<br>resultant flux as a function of  $\lambda$ <br>is shown in (b). The characteristic<br>response in Fig. 4 is recovered.<br>Then the el **Then the electron loss term**  $\Gamma_{\text{re}}$ **driven flux –rright and riscosity'<sup>6</sup><br>driven flux –r<sub>ri</sub> and r<sub>ic</sub> (solid and<br>dashed lines, respectively) determine** the radial electric field (c). The<br>function  $\Gamma(\lambda)$  shows the similar<br>response as in (b). **function T(A) shows the sinilar response as in (b) .**  eρ<sub>p</sub>E<sub>r</sub>/T<sub>i</sub> (a). For the c.e of A<br>(small λ=ρ<sub>p</sub>n'/n), one la.ge-flux<br>solution is allowed. Multiple Then the electron loss term  $\Gamma$ re is negligible, the ion viscosi.y<sup>re</sup> driven flux  $-\Gamma_{r,i}$  and  $\Gamma_{\rm lc}$  (solid and<br>dashed lines, respectively) determine

**The jump of r is predicted at the critical**  The jUIIP of f is predicted at the critical gradient

$$
\lambda = \rho_n n'/n = \lambda_n, \quad \text{and } \lambda_n \sim 0(1)
$$
 (9)

**as is shown in Fig.5(b). This example shows that the singularity of the**  as is shown in Fig 5(b), This exa ple sho 5 that the singularity of the transport property **T[Vn]** can be explained by using a <u>continuous</u> function **of r[E\_] ,**  of r[ E.l

q 1 1 **The extension of the model is possible by considering r <sup>r</sup> i • The**  The extension of lhe lodal is possible by considerins: fri31). Tbe **bulk viscosity generates the force on ions in the poloidal direction as**  bulk viscosity generates the force on ions in the poloidal direction as **F -v -• <sup>i</sup> n <sup>i</sup> U:q <sup>2</sup> V <sup>p</sup> f(X) . The function f(X) is unity for |x"|<<1 and behaves**  F<sub>p</sub> ~ -m<sub>i</sub>n<sub>i</sub>ν<sub>i</sub>q<sup>2</sup>V<sub>p</sub>f(X). The function f(X) is unity for |X|<<1 and behaves<br>like exp(-X<sup>2</sup>) (plateau regime) or X<sup>-2</sup> (Pfirsch-Schluter regime)<sup>31,32)</sup>. **Figure 5(c) illustrates the balance of**  $\Gamma_{\textrm{lc}}$  **.**  $\cdot$  $\Gamma_{\textrm{ri}}$  **confirming that the bifurcation can occur at the particular value of the edge gradient, λ<sub>ε</sub>ν 0(1) . Variety of the bifurcation is predicted. fhen the electron term**  0(1). Variety of the bifurcation is predicted, fhen tbe electron terl **r is negligible, the transition occurs to the tore negative E <sup>f</sup> . and that**  fre is negligible. the transition occurs to the Ilore negative Er' and that to the more positive E<sub>r</sub> takes place if  $\Gamma_{\text{re}}$  is important. Other candidates such as the VVV term or the turbulence driven flux are also studied<sup>33)</sup>.

**The proposal of the electric bifurcation 2 7 ' was tested by experi-**The proposal of the electric bifurcation27) was tested by experi **ments. D-III D 2 8 <sup>3</sup> and JFT-2M 2 9 ) confine d the radial electric field. The**  lIents, D-IIl D28) and JFT-2M29) confir ed the radial electric field. The transition can be excited by the radial current driven by the probe and external circuit<sup>y o</sup>f. The layer width is of the order of e<sub>p</sub><sup>893</sup>. The layer is the property of the section of the section of  $95^{\circ}$ . external circuit<sup>34)</sup>. The layer width is of the order of e<sub>p</sub><sup>29)</sup>. The<br>nonlinear response of F<sub>n</sub> to X is confirmed by the biasing experiment<sup>35)</sup>.

**Various types of ELMs are known in experiments<sup>22)</sup>. Some is corre**lated with the critical gradient of edge pressure against the ballooning **mode, and some is** *not.* **The bifurcation theory predicts a aodel of small**  Dode. and soe is not, The bifurcation theory predicts a .odel of s all and continuous ELMs<sup>36)</sup>. The hysteresis between **Vn and F can generates the oscillation ('limit cycle solution'). The dynamical equation (8) is solved with continuity equation and the model equation**  $\Gamma[X, p]$ **. Model** equation can be formulated in the form of the Gintzburg-Landau equation as

**a**n/at - (a/ax)D(X)an/ax, (10-1)

**wax/at - -NU.A.n) + ii3<sup>z</sup>X/ax<sup>2</sup> (10-2)**  E

waX/at = -N(X,x,n) + µa<sup>2</sup>X/ax<sup>2</sup><br>• here D is the effective diffusivity, x=a-r, o is the smallness parameter *of* **tbe order of (pj/p <sup>p</sup> ) <sup>2</sup> , M is tbe shear viscosity, and H represents the current e[r^ <sup>c</sup> + r <sup>r</sup> ^-r r e ] which has the nonlinearity and depends on both E <sup>p</sup> and Vn. Introduction of the shear viscosity allows us to study the radial structure of the barrier.** (Note that normalization is used as  $\mathbf{x}/\rho_n \rightarrow \mathbf{x}$ , **D/D<sup>Q</sup> -»D, II/D<sup>0</sup> -\*M, t/(p <sup>2</sup> /D<sup>0</sup> )-»t, and B Q being the diffusivity** *in* **L-phase. )**  be order of  $(\rho_i/\rho_p)^2$ ,  $\mu$  is the shear viscosity, and N represents then the  $[\Gamma_{1c} + \Gamma_{ri} - \Gamma_{re}]$  which has the nonlinearity and depends on both  $E_i$ <br>Th. Introduction of the shear viscosity allows us to study the radio<br> esen<br>priminsh rto<br>x/d rp)<br>2. ascinoss<br>poss<br>high  $P_i/P_p$ <sup>2</sup>.  $\mu$  is the shear viscosity, and R repr<br> $P_i/P_p$ <sup>2</sup>.  $\mu$  is the shear viscosity and depends<br>tion of the shear viscosity allows us to stude<br>barrier. (Note that normalization is used as<br> $\sqrt{(P_p^2/P_0)}$ -t, and  $P_0$  ty,<br>ows<br>ion<br>iffu<br>if-s<br>lf-s<br>scil scosi<br>y all<br>lizat<br>lizat<br>the se<br>quati<br>he se<br>niso-<br>erwise ef {<br>+Γri<br>oduc<br>the<br>μ, t<br>fied<br>suie<br>alue<br>alue of the curre<br>and strue<br>D/D<sub>C</sub><br>A/P<sub>i</sub>show<br>for

**A simplified model was studied where H(X,x,n) is given N(X,g) (g» A/VJ ) and N(X,g) is modelled by the cubic equation as in Fig.6(a). It is shown that the set equation (10) predicts the self-sustaining oscillation for a fixed value of the flux from core. This oscillation is possible in a 1imited area in the parameter space. Otherwise, either the high-con-**'oo

finenent state (H) or low confinement state (L) is allowed. Figure 6(b) and (c) illustrate the oscillatory solution of the out flux, and the radial profile of the effective diffusivity in H and L phases. In the tin phase of good confinement, the reduction of D extends from the surface to the layer, the characteristic width of which is given  $\sqrt{\mu/\rho_P}$ .



Fig.6 **Model of the effective diffusivity D** (D–  $\Gamma/\Psi$ n) as a function of rig. Conservation of the gradient parameter A/u- (a). Transilum occurs at points A and B'.<br>Two branches H and L are shown. The predicted oscillation, for given<br>constant Cluy from core, is shown in (b). The profile of D at Two branches H and L are shown. The proditted oscillation, for given<br>constant flux from core, is shown in (b). The profile of D at the two The predicted oscillation. for given time slices (arrows in  $(b)$ ) are shown  $(c)$ and x<-2 to the core plasma. *w*n (c) = x 0 corresponds to the surface. The gradient parameter  $\lambda/\mu_1(\alpha)$ . Transition occurs at points A and B are shown in Two branches il and L are shown in (b). The profile of D at the two constant flux from core, is shown in (b). The profile of D at the tw r--r

These results also illustrates the importance of the viscosity in the These results al50 illuslrates the lllportance of the viscosity in the dynamics and structure of the edge plasmas.

#### [V] **Summary** and Future **Problems**

In this article, we briefly surveyed the applications of the **MHD**  theory for the understanding of the edge plasma physics. The edge phenomena is geometry-dependent, a^d contains various time scales. The HDD equation is a suitable tool for modelling the phenomena in the edge plasmas. It was successfully applied to study the two-dimensional profile of the plasma, the behaviour of impurities, and the stability analysis. In this article, we briefly surveyed the applications of the MHD<br>theory for the understanding of the edge plasma physics. The edge<br>phenomena is geometry-dependent, and contains various time scales. The<br>WHD equation is a su role of the radial electric field and the viscosity. role of the radial electric field and the viscosity Th<br>es<br>na<br>men<br>lit<br>inv Fuches<br>Fuche unders<br>In the unders<br>In the second standard<br>Sunda-was standard<br>Sundard baradial<br>Corts has be radial el -th<br>thph<br>pl<br>of

•e here stressed that the UHD equations are not closed by themselves, and need some closure model. The study on the stress tensor II can and need some closure model. The study on the stress tensor II can<br>largely extend the area of the application. Many results are dependent on<br>the choice of the anomalous transport coefficient. re nere stressed that the mini-equations are no<br>and need some closure model. The study on the stre<br>largely extend the area of the application. Many<br>the choice of the anomalous transport coefficient.

Combining the theory that the radial inhomogeneity of E<sub>r</sub> (or V<sub>p</sub>) can stabilize the microscopic instabilities, the structure of the established electric field (flow velocity) are considered to suppress the microinstabilities and associated anomalous transport. The reduction of the anomalous transport further improves the confinement inside of the transport barrier. Figure 7 illustrates the present 'standard model' for the tran-

sition phenomena at edge, though many part of the elements are still qualitative vet

There are couple of probless which require future studies The influence of the atomic processes has been examined in the MHD analysis Further analysis to refine sodels for the impurity response is required The determination of the stability limit is now a well-defined problem for the realistic geometry and profile. There are. however, several oroblens:



Fig 7 Schematic diagram between the radial electric field/ rotation. the radial current, anomalous transport, and plasma fluxes.

e e, bursis of magnetic perturbation are observed and wait explanations. Taknig into account of the change of the current diffusivity due to the instability itself, the magnetic trigger phenomena has been analysed<sup>37)</sup>. The quantitative improvement of the modelling of the viscosity and the radial currents is also necessary. The model must be extended so that the quantitative prediction of E, is possible. Wany further inprovement of confinesent have been proposed based on the electric bifurcation model. The verification of the model is surely an important issue.

We here have few room to show how the *understanding* of the edge plasma confinement is used to *control* it. Examples are seen<sup>38)</sup> in the analysis of the divertor bias, or possibilities to excite the H-mode transition by the ion beam and to sustain grassy ELMs by external oscillations. The control of the edge plasma, e.g., for the good energy confinement, efficient pumping, suppression of impurities, or tolerating the heat load, is an urgent task. The understanding and podelling of edge plasma are inevitable for it, and the MHD analysis will be very useful.

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**References** 



*Part B*  Part B

# **Lecture Note on Application of HHD Theory**  Lecture lote 00 pplication of MHD Theory **to Plasia Boundary Problens in Tokaaaks**  to Plasla Boundary Problems in Tokamaks

 $\cdot$ 

#### [I] **Introduction**  [11 IDtroductioD

Recently the important roles of the edge plasma have been Recently the important roles of the edge plasma have been widely recognized both on the plasma confinement research and the widely recognized both on the plasma confinement research and the design study of fusion reactors. The basic *physics* approach has design study of fusion reactors. The basic physics approacb has been compiled in Ref.[i] Recent experimental findings, such as the H–mode<sup>2)</sup>, had a large impact in the progress in this field, as is reviewed in [3]. The core plasma confinement should be as is reviewed in [3], The core plasma confinement should be more tightly coupled to the edge plasma condition than has been more tightly coupled to the edge plasma condition than has been thought, if we judge from the phenomena like Improved Ohmic thought. if we judge from the phenomena like Impro.ed Ohmic Confinement<sup>4)</sup> (IOC), in which the reduction of the gas puffing rate leads to the peaked density profile at the core. One of the rate leads to the peaked density profile at the core. One of the key features is the sensitivity of the plasma response to the key features is the sensitivity of the plasDa response to the change of the locations of the plasma, such as the plasma-wall change of the locations of the plasma. such as the plasma-wall distance or the directions of the ion VB drift and X-point loca-distance or the directions of the ion VB drift and X-point loca tion<sup>2), 3)</sup>. These observations indicate the importance to take the realistic geometry (or alternatively, to find out the key parameter to characterize the spatial structure) in the modelling parameter to characterize the spatial slructure) in the mOdel1ing of the edge plasma phenomena. At the same time, various atomic of the edge plasma phenomena. At the sa e time. various atomic processes introduce variety of the plasma dynamics in the edge processes introduce variety of the plasma dynamics in the edge region. The short mean free paths of atomic processes enhances the influence of the geometry *on* the global plasma *structure.*  the influence of the geometry on the global plasma s!ruc!ure.

Other progress of the research has been seen in evaluation Other pragress of the research has been seen in evaluation of the impact of the plasma properties on the design of the rlasma facing component in the future large devices. For rlasma facing component in the future large devices. For instance, it is well known that the estimation of the heat locali– zation width is a crucial issue. Also necessary is the evalu- zation width is a crucial issue. Also necessary is the evalu

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ation of the dynamic change of the heat load such as that in the ation of the dynamic change of the heat load such as that in the large ELMs (edge localized modes). These issues also illustrate the importance of the study on the structure and dynamics of the edge plasma in a realistic plasma configurations. edge plasma in a realistic plasma configurations

In the study of these problems, the analysis based on the magnetohydrodynamic (MHD) equation has been performed. This equation has the advantage that phenomena of various tine scales, equation has the advantage that phenomena of various time scales. from the Alfven transit time to transport time, can be treated and the realistic configuration is more easily taken into account and the realistic configuration is more easily taken into account in comparison with other approaches (such as Vlasov equation), assuming that the physics coefficient (such as transport coefficient) and boundary conditions are given. coefficient) and boundary conditions are given

In this article, we present a brief survey on the problems 1n this article. we present a brief survey on the problems for which the analysis based on the fluid equations are success-for which the analysis based on the fluid equations are success fully applied to the edge plasmas. We also discuss the efforts to extend the model equation to apply more general and important to extend the model equation to apply more general and important problems such as H-mode physics. We finally discuss the future problems such as H-mode physics. We flnally dlscuss the future possible investigations. [It is noted that the terminology of possible iovestigations. [lt is noted that the ter inology of 'MHD equation' in this article is not the one for the one fluid ideal MHD equation. Various extensions to the physics processes are included in terms of the transport coefficient.] are included in terms of the transport coefficient. 1

#### [II] Structure of Edge Plasmas

#### (2.1) Fluid Equation and Boundary Condition

The plasma and geometry of our analysis are shown in Fig. 1. The plasma and geametry of our analysis are shown io Fig.l. The definition of the 'edge plasma' has not been made uniquely. The definition of the 'edge plas has oot been made uniquelY. We here consider that the edge plasmas are consist of the plasma (1) outside of the outermost magnetic surface (i.e., scrape-off (1) outside of the outermost magnetic surface (i e" scrape-off layer) and *soae* in the inside of the outeroost magnetic surface. layer) and 80me in the inside of the Qutermost magnetic surface The latter is the plasma (2) in the region where the inhomoge-The latter is the plasma (2) in the region where the inhomoge neity along the field line is appreciable or (3) in the region in neity along the field line is appreciable or (3) in the region in which the radial gradient does not scale linearly with minor which the radial gradient does not scale linearly with minor radius but is determined by the distance from the surface.

The basic equations consist of the continuity equations of the density, the momentum and energy  $as<sup>5</sup>$ 

$$
\mathbf{a}\rho/\mathbf{a}\mathbf{t} + \nabla \cdot (\rho \mathbf{V}) = \mathbf{S}_{\mathbf{n}} \tag{1}
$$

$$
\rho dV/dt = -\nabla \cdot \mathbf{I} + \mathbf{R} + \mathbf{F} + \mathbf{S}_{\mathbf{g}}
$$
 (2)

$$
a(\rho E_S)/at + \nabla \cdot (E_S V) = -\mathbf{I} \cdot \nabla V + (\mathbf{R} + \mathbf{F}) \cdot \nabla - \nabla \cdot \mathbf{q} + S_g \tag{3}
$$

for each plasma species (suffix to identify the species is sup-for each plasma species Csuffix to identify the species i5 Suppressed for the simplicity), where  $\scriptstyle\rm I\!I$  is the stress tensor,  $\scriptstyle\rm I\!R$  is the frictional force,  $\mathbf{F} = \mathbf{q}(\mathbf{E} + \mathbf{V} \mathbf{x} \mathbf{B})$ ,  $\mathbf{E_S} = \mathbf{V}^2 + \mathbf{w}$ , w is the internal energy per unit mass.  $S_n$ ,  $S_n$ ,  $S_g$  are the sources of particle, momentum and energy, and other notations are conventional. One momentum and energy, and other ootatioos are conventional' One fluid MHD equations use the variables total mass density, *p.*  fluid UHD equations use the variables total mass density.ρ,

 $+18.$ 

solve the plasma response and the field. velocity of the plasma. V. charge density  $\rho_q$ , and current density j. instead of  $\rho_{e,i}$  and  $\nabla_{e,i}$ . And the Maxwell equation is used to

The MHD equations are not closed by themselves, and we need The WHD 8Quations are not closed by themselves, and we need to specify the closure such as the equation of state, the stress to specify the closure such as the equation of state, the stress tensor **II**, and the transport coefficient, and the model of the sources. sources

The common choice of the closure is that the paraIlel trans– port is classical, only the diagonal part of the stress tensor, port is classicaI, only the diagonal part of he stress tensor. element of which is p=nT, is kept, and E<sub>s</sub> is approximated by 3p/2. The frictional force R is calculated by Spitzer collision 3p/2. The frictional force R is calculated by Spitzer collision frequency, and interaction between neutral particles are included frequency, and interaciion between neutral particles are included in S<sub>p</sub>. The classical values are used for the plasma resistivity *f\* and parallel thermal transport coefficient x . The perpendicu-and parallel thermal transport coefficient x. The perpendicu lar transport coefficient are considered to be anomalous, and the lar trassport coefficient are considered to be anomalous. and the prescribed form is substituted in the HHD equation. prescribed form is substituted in the WHD equation

The electron energy flux  ${\tt q}_{\rm e}$  is given by  ${\tt q_{\rm u}}^{\rm e}$  +  ${\tt q_{\rm T}}^{\rm e}$ , and that for ion is given by  $\mathbf{q_{T}}^{1}$ , where

$$
\mathbf{q}_{\mu} = -0.71T_{e}\mathbf{j}/e + (3T_{e}\nu_{e}/2e\Omega_{e})\mathbf{b}\times\mathbf{j}
$$
 (4)

$$
\mathbf{q}_{\mathrm{T}} = -\kappa_{y} \nabla_{y} \mathbf{T} - \kappa_{1} \nabla_{1} \mathbf{T} + (\mathbf{5nT}/2eB) \mathbf{b} \times \nabla \mathbf{T}
$$
 (5)

 $\boldsymbol{\nu}_{\mathbf{e}}$  is the electron collision frequency,  $\boldsymbol{\Omega}_{\boldsymbol{e}}$  is the electron cyclotron frequency, b=B/B and  $\kappa$ =nx.

The *particle* source can be calculate' once the neutral The particle source can be calculate" once the neutral density is given. (This term depends on the geometry strongly. density is given. CThis term depends On the geometry strongly.

$$
19 -
$$

The connection with the computation on neutral dynamics is di scussed in [6,7].) discussed in [6.7J.)

The boundary conditions at the plasma-material interface are The boundary conditions at the plasma-material interface are wall interface is often assumed to be zero. The extension to the oall interface is often assumed to be zero. The extension to the case where the current flows across the wall, e.g. in the study of the divertor biasing, is also possible.  $x$ iven $8.9$ ) in the form of the Bohm sheath criterion and energy transmission coefficient  $\tau_{_{\mathbf{\theta},\;\mathbf{i}}}.$  The current across the plasma-

In this section, we study the static (equilibrium) structure in the edge plasmas. Stability and dynamic responses are in the edge plasmas. Stability and dynamic responses are discussed in the next sections.

#### (2.2) Structure Along the Field Line

In studying the structure of the plasna distribution in the ln studying the structure of the plas a distribution in the scrape-off layer, the competition between the parallel and scrape-off layer. the competition between the parallel and perpendicular heat transports is examined. For the plasma paraneter of present experiments, the energy transport along the parameter of present experiments. the energy transport along the field line is the fast process. When the plasma thickness is parameterized by  $\Delta$ , the averaged temperature in the flux tube with thicknes  $\Delta$  is given by integrating the parallel energy conduction equation along the field line as<sup>10)</sup>

$$
T(\pm)^{3.5} = T_{\text{div}}^{3.5} + T_{\text{div}}^{2/2} \kappa_0 \tag{6}
$$

where 1 is the distance along the field line from the divertor plate, the parallel heat flux  $\mathbf{q}_y$  is given as

 $q_t = B_t P_{\text{out}} / B_p 2 \pi \Delta R$ 

$$
\kappa_{jj} = \kappa_0 T^{2.5}.
$$

Pout is the total energy outflux to SoL, and the energy deposition in the Sol plasma is neglected for the simplicity. Though very simplified, this equation reveals essential characters of the Sol plasma.

The Bohm sheath criterion gives the plasma parameter in front of the divertor plasma as

$$
T_d = P_{out}/6\tau_t F_{out} \tag{7-1}
$$

$$
n_d = \sqrt{n_i \tau_t} (B_t/B_p 2 \pi \Delta R) (6 \Gamma_{out})^{3/2} / \sqrt{P_{out}}
$$
 (7-2)

where

$$
\mathbf{r_t}^{\mathbf{-1}} \mathbf{e^{+T_i}.}
$$

G is the enhancement factor of the particle flux in SoL plasma and  $\Gamma_{out}$  is the particle flux out of the main plasma. These parameters T<sub>d</sub> and n<sub>d</sub> are essential in evaluating the performance of the divertor.

#### (2.3) Structure Across the Field Line

The parameter  $\Delta$  is determined by the cross field energy transport. The cross field transport is stronger for higher

temperature plasma, the width  $\Delta$  is determined by the perpendicular diffusion near the midplane. From Eq.(6), one sees perpendicular diffusion near the midplane. From Eq. (自), one sees that T∝1<sup>2/1</sup> so that T(1) is approximated to be constant T<sub>b</sub> near the mid plane. Solving

$$
\mathbf{F}_{\perp} \mathbf{V}_{\perp}^{\mathrm{T}} = -\mathbf{q}_{\perp} (\approx \mathbf{P}_{\mathrm{out}} / 4\pi^2 \mathbf{a} \mathbf{R}).
$$

the estimation of A is obtained in [11]. If the cross field the esti ation of A is obtained in [11]. If the cross field transport is given by the Bohm-like diffusion transport is given by the Bohm-like diffusion

 $\tau_1 \propto T/eB$ .

we have  $|2\rangle$ 

$$
\Delta/a = 5\kappa_a (LB_t/\kappa_0 aB_p)^{4/11} (R/P_{\text{out}})^{3/11}
$$
 (8)

where a and R are the ninor and major radius, L is the distance where a and R are the minor and major radius, L is the distance between midplane and divertor along the field line and  $\kappa_1 = \kappa_a T$ . The heat flux channel becomes narrower as the power increases. The heat flux channel becomes narrower as the power increases It is also shown that A does not scale to a<sup>1</sup>. (For instance, if  $P_{\text{out}} \sim a^3$ , then A  $\sim a^{5/11}$ ,)

The drift heat flux CVTxb term in Eq.(5)) can also affect The drift heat flux ('Txb term in Eq. (5)) can also affect the heat channel $^{13)}$ . This term depends on the direction of **B**. In the configuration like Fig.l with B<sub>t</sub> directed into the paper, (i.e.,VB-drift of ions directs to the X-point), this heat flux is (i.e. .'B-drift of ions directs to the X-point). this heat flux is inward of the major radius. The heat flux across the magnetic inward of the maJor radius. The heat flux across the magnetic surface reduces (outside of torus) or increased (inside of surface reduces (outside of lorus) or increased (inside of

 $22 \,$ 

torus) When the power is deposited mainly at the outside *of* the torus) When thc power is deposited ID3ln!y at the outsldc of the torus, this term reduces the average radial transport, reducing A torus, this term reduces the average radlal transport, reducing t and enhancing T<sub>b</sub>.

### (2.4) Comparison with Numerical Simulation

The numerical analysis has been performed in order to obtain The numerical analysis has been performed in order to obtain the two dimensional structure of the SoL plasma<sup>7, 14-17)</sup>. These calculations can also determine the neutral particle profile, and calculations can a1so determine the neutral particle profile, and hence the parameter G. Example is shown in Fig.2. It is shown hence the parameter G. Example i8 shown in Fig.2. It is shown that the dense and cold divertor plasma is established, and the that the dense and cold divertor plasma is established, and the neutral particles are localized nearby. neutral particles are localized nearby

The 2-D computations can now be fluently done, scaling study The 2-D computations can now be fluently done, scaling study is desirable to have a fast grasp of the phenomena. The scaling is desirable to have a fast grasp of the phenomena. The scaling study has been performed by using the 2 -dimensiona] numerical study has been perfor ed by using the 2-dimensional numerical code (assuming the Bohm diffusion coefficient) to give<sup>16)</sup>

$$
n_{\rm d} \sim \Gamma_{\rm out}^{1.1} P_{\rm out}^{0.35}, \quad \Gamma_{\rm e, d} \sim P_{\rm out} \Gamma_{\rm out}^{-1}.
$$
 (9-1)

$$
n_b \sim \Gamma_{out} P_{out}^{-0.3}
$$
,  $T_{e, b} \sim P_{out}^{-0.5} \Gamma_{out}^{-0.25}$ , (9-2)  
 $I_{-a, \Gamma} = 0.4b$ , (9-2)  
 $I_{-a, \Gamma} = 0.4b$ , (9-3)  
 $I_{-a, \Gamma} = 0.4b$ 

$$
\mu_{\text{T}} \sim \Gamma_{\text{out}}^{0.4} P_{\text{out}}^{-0.23}
$$
,  $\mu_{\text{n}} \sim \Gamma_{\text{out}}^{-0.24} P_{\text{out}}^{0.15}$  (9-3)  
where  $\mu_{\text{T}}$  and  $\mu_{\text{n}}$  are the scale lengths of the radial gradients.

T/T' and n/n', at the midplane respectively. This result confirms that the analytic result is a good estimate. If we eliminate  $\Gamma_{\alpha\mu\tau}$  from Eq.(9–2), we have

 $T_{e, b} \sim P_{out}^{0.4} n_b^{-.25}.$ e,b \* out th<br>Analytic theory *[Eqs. (6) and (8)] gives*  $\frac{1}{2}$  ,  $\frac{1}{2}$  and  $\frac{1}{2}$ ・<br>! a n n a

$$
T_b \sim P_{out}^{4/11} n_b^{-2/11}
$$

showing that the analytical estimate is confirmed by the a a / l l o u t ~ sho.ing that the analytical esti.ate is confirmed by the simulation. Figure 2 also show that the electron temperature is almost constant at the plasma boundary, which is assumed in almost constant at the plasma boundary, which i5 assumed in deriving Eq.C8). We see that the plasma structure is well deriving Eq. (8) e see that the plasma structure is well understood, and what is really necessary is the understanding of understood, and what is really necessary is the understanding of the cross field transport. the cross field transport.

Extension to the impure plasmas has also been performed. Extension to the ipure plasmas nas also been performed. The screening of impurities which are generated from the divertor The screening of impurities which are generated from the divertor wall is also been analyzed quantitatively. Analytic estimates are also discussed in Refs.[18.19]. are also discussed in Refs. [18 191

#### [Ill] **Stability of Bdse Plasaas**  [111] Stability of Kdge Plas.as

MHD equation is most successfully applied to the study on UHD equation is most successfully applied to tbe study on the plasma stability. The edge plasma can have a large pressure gradient (though the pressure itself is low), the study on the gradient (thougb tbe pressure itself is 10.). the study on the stability beta limit is important. Another characteristic feature of the edge plasma from the view point of the MHD stability is the strong shear associated with the separatrix, and stability is the strong shear associated with the separatrix. and the location of the X–point. We here briefly survey the findings of the stability analysis.

#### (3.1) Ballooning Mode (Ideal MHD Mode)

The average magnetic curvature at edge of the tokamak plasma is favourable, i.e., in the 'well' configuration (except the case where the X–point is outside of the torus). In such a case, the unstable mode may be localized in the outside of the torus (where the local bad curvature exists). The wave length along the filed line is long, i.e.,  $\mathbf{k}_x$ = **b**·V  $\sim$  1/a but the one across the filed line is short,  $a/a\theta$ )>l/a. For the perturbation  $\phi(r, \theta, \zeta)$ , the ballooning transformation was introduced as  $^{\rm 20)}$ 

$$
\phi(r, \theta, \zeta) = \Sigma \exp(-i\pi\theta + n\zeta) \int_{\alpha}^{\infty} d\phi(\kappa) \exp(i(m \cdot nq(r))\kappa)
$$
 (10)

where  $q(r)$  is the safety factor and m and n are the poloidal and toroidal mode numbers, respectively. (Note x is the coordinate, toroidal mode numbers. respectively. (Note x is the coordinate. not thermal conductivity: Behaviour of  $\phi(x)$  at  $x\rightarrow\infty$  corresponds to that of φ(r) at the rational surface.) We here follow the

$$
-25-
$$

notation of Ref.[21]. The Euler equation for the ideal UHD mode notation of Ref. :21 J. The Euler equation ror the ldeal WHD ode is written for an ordinary differential equations for high– toroidal-iode-number modes, which has the large growth rate. toroidal-mode-number modes. which has the large growth rate

Analytic formula was obtained in the high aspect ratio limit Analytic formula was obtained in the high aspect ratio limit of the circular plasma. The Euler equation is characterized by of the circular plasma. The Euler equation i8 characterized by the three parameters, i.e., the three parameters, i.e.,<br>s = rq'/q (local shear),

*α* = –2Rq<sup>4</sup>B <sup>2</sup> p' (local pressure gradient)  $\alpha = E_0$ 

and

 $6 = (1 - q^{-2})r/R$  (average well)  $\ddot{\phantom{0}}$  $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$   $\frac{1}{21}$ 

where '=d/dr. The ballooning equation is simplified as where • :d/dr. The ballooning equation is simplified as

$$
(a/a\mathbf{x})[1+\mathbf{I}^2]a\Phi/a\mathbf{x} + \{\alpha(\cos\mathbf{x}\cdot\text{Isin}\mathbf{x})\cdot\mathbf{6}\cdot\mathbf{r}^2(1+\mathbf{I}^2)\}\Phi = 0,
$$
 (11)  
I =  $\mathbf{x}\cdot\mathbf{a}\sin\mathbf{x}$ , and **r** is the growth rate which is normalized to  $\mathbf{v}_A/R$ 

( $v_A$ : Alfven velocity). The instability condition for low s case is given as 18 glven as

$$
3/4[\alpha^{2} \cdot \sqrt{\alpha^{4}/2 \cdot 32 \alpha 6/9}] \leq s \leq 3/4[\alpha^{2} \cdot \sqrt{\alpha^{4}/2 \cdot 32 \alpha 6/9}]
$$
 (12)

showing that the ballooning mode is stable for α<0.81s and  $\alpha$ >2.2 $\sqrt{s}$  (the second stability). Figure 3 illustrates the

stability limit for the pressure gradient (a) as a function of stability limit for the pressure gradient (α) as a function of the shear. the shear

#### <u>(3.2) Effect of Plasma Dissipation on the Ballooning Mode</u>

In the edge plasmas, the plasma resistivity η is small but finite. The dissipation process can destabilize the mode for the regime where ideal WHD mode is predicted to be stable. This process is important in estimating the beta value at the stability boundary. (The problem, whether the stability limit for beta is the experimental 'beta limit' or not, deserve further study, and discussed later. ) study, and discussed later, 1

The effect of the resistivity has been studied in detail $^{22)}$ . For the finite-resistivity plasma Eq.(ll) is reformed' as For the finite-resistivity plasma Eq, (11) is refor ed'as

 $(a/\partial x)[z/(\sqrt{1+z}k\theta^2/\tau S)]\partial \Phi/\partial x + (\alpha(\cos z-\sin z)-\delta-z\tau^2)\Phi = 0,$  (13)

where  $z = 1 + I(z)^2$  and  $k_B = ma/r$ . The eigenvalue equation is now characterized by the four parameters,  $\mathbf{s}, \mathbf{a}, \mathbf{a}$  and S, where S is the magnetic Raynolds number,<br>S=v<sub>A</sub>µ<sub>0</sub>a<sup>2</sup>/ηR.

$$
S = v_A \mu_0 a^2 / \eta R.
$$

and  $v_A$  is the Alfven velocity. For the case of the strong balooning limit (  $|s\mathbf{x}|<$ ( ), Eq.(13) is approximated by the Weber Equation, and the growth rate T is determined by Equation, and the growth rate r is determined by

$$
\tau^3 + (k_\theta^2 / 2S) \tau^2 - \tau_I^2 \tau - (k_\theta^2 / 2S) (\alpha \cdot \delta) = 0.
$$
 (14)

where  $\pmb{\tau}_\text{I}$  is the growth rate in the ideal MHD limit,  $\pmb{\tau}_\text{I}$  =  $\propto$ - $\sqrt{\pmb{\alpha}/2}$ -**6.** It is shown that, in the absence of well (6+0), the mode is unstable for all value of *a,* i.e., the stability beta limit is unstable for all value ofαi.e.. the stability beta limit is zero. (See Fig.4.) The mode growth rate is given as zero. (See Fig.4.) The mode growth rate is given as

$$
\tau \sim (\alpha k_{\theta}^2 / 2S)^{1/3} \tag{15}
$$

for the narginal stability for the ideal mode (r^O). In the for the marginal stability for the ideal mode (T~O). In the presence of the magnetic well, the critical beta for stability presence of the magnetic well. the critica1 beta for stability appear below the ideal MHD stability limit as shown in Fig.4(b). appear below the ideal UHD stabi1ity 1imit as shown in Fig.4(b) Simple estinate for stability from Eq.(14) is given by Simple estimate for stability from Eq. (14) is given by

$$
\alpha \leftarrow \delta. \tag{16}
$$

The importance of the magnetic well was investigated for the JT–60 plasma (with outer X–point) $^{23)}$ . Parameter D<sub>R</sub> (Dp"a(a-6)/s) is calculated for outer-X-point configuration and (DR"α(α-6)/s2) is calculated for outer-X-point configuration and limiter configuration. (The condition D<sub>R</sub><O is the stability criterion from the above simple estimate, Eq.(16). ) Compared to criterIon from the above simple 8sti ate. Eq. (16).) Compared to the limiter case, in which D<sub>R</sub> is negative, the outer–X–point configuration has large and positive D<sub>R</sub> for given pressure gradient, indicating stronger instability. Experiments has also gradient. indicating stronger instability. Experiments has alsa shown that the high frequency oscillations appear in the outer - X - shown that the high frequency oscillations appear in the outer~Xpoint configuration but not in the limiter case. In this experi-point configuration but not in the limiter case. In this experiment, the appearance of this fluctuations coincides with the ment. the appearance of this fluctuations coincides with the change of the sign of  $D_R$ . The influence of these oscillations on

the global confinement, however, was not analysed yet.

It is believed that the microscopic (high-n) instabilities lt is believed that the microscopic (high-n1 instabilities may lead to anomalous transport with 'soft beta limit', and that the real hard 'beta limit' comes from the development of the modes with low-to-medium mode numbers. The anomalous transport modes with low-to medium lIode nu bers. The anoma10us transport based on the resistive turbulence has been developed<sup>24)</sup>, but is<br>not enough to explain present observations*.* not enough to explain present observations.

The comparison study of the occurrence of the 'Type- $I^{\,\prime}$ ELMs $^{25)}$  corresponds to the stability boundary for the ideal MHD instability, suggesting the importance of this kind of instability, suggesting the importance of this kind of instability. Nonlinear simulation of the high-m pressure driven instability, Nonlinear simulation of the high-m pressure driven instability has recovered a rapid grow of the mode near the instabi1ity has recovered a rapid grow of the mode near tbe edge<sup>2)</sup>. However, the catastrophic nature, such that the sudden growth of the mode with m~10 acts as the precursor of Giant ELWs<sup>26)</sup>, is not understood.

#### (3.3) Instabilities Driven by Atomic Processes

Atomic process is also the characteristic to the edge plasma, and affect the edge stability tremendously.

Global instabilities are known such as MARFE<sup>19)</sup> and<br>detachment, The radiation loss is modeled such that detachment. The radiation loss is modeled such that

$$
S_E = -n_e n_l L(T_e). \tag{17}
$$

where  $n<sub>I</sub>$  is the impurity density. Since  $\partial L/\partial T_{\rho}$ <0 holds for a range of temperature and the enhanced radiation reduces the range of temperature and the enhanced radiation reduces the electron temperature, this loss term in principle leads to the electron te perature. this 1058 term in principle 1eads to the

instability of the electron temperature. Models on L(T<sub>e</sub>) and the dynamic response of  $\mathtt{n_{I}}$  with respect to the perturbation are necessary to quantify the growth rate. The latter is usually necessary to quantify the grooth rate. The latter is usually denoted by the parameter denoted by the parameter

$$
\xi = -(\pi_e / n_e + \pi_I / n_I) / (\tilde{T} / T).
$$

Asymmetric thermal instability (m/n=1/0, i.e., MARFE) can grow  $if<sup>19</sup>$ 

$$
n_{\text{I}}[aL/aT + \xi L/T] > x_{\text{I}}/(a - r_{\text{b}})^2 + x_{\text{II}}/q^2R^2
$$
 (18-1)

([r<sub>b'</sub>a] is the region of the analysis, where aL/aT is negative and large) and

$$
\epsilon n_{\mathsf{T}} L / \mathsf{T} \rightarrow \mathbf{x}_{\mathsf{N}} / q^2 R^2. \tag{18-2}
$$

If Eq.(18) does not hold, the poloidally symmetric mode (m=0/n=0 If Eq. (181 does not hold. the poloidallY symmetric mode (m=O/n= mode. i.e.. detachment) starts to grow. mode. i.e.. detachment) starts to grow,

This picture is often referred to as an origin of the This picture is often referred to as an origin of the density limit. If one assumes that  $n_I/n_e$  is constant. Eq.(18–1) set an upper bound for the electron edge density against the thermal instability. This theory of m=1 and m=0 modes also explains the difference of the condition for MARFE and detachment to appear. Equation (18–2) is more easily satisfied for (1) lower T<sub>e</sub>, (2) larger device and (3) higher heating power; In other words, the lighter impurities (for which the condition other oords. the lighter impurities (for which the condition

aL/aT<O holds for the lower plasma temperature and Eq.(18–2) is more easily satisfied) lead to the MARFE while heavier one to the detachment (and then disruption): These prediction is consistent detachment (and then disruption): These prediction is cansistent with experiments. The dynamics of impurities needs further with experiments. The dynamics of impurilies needs further analyses for quantitative comparisons. analyses for quantitative comparisons.

The atonic process can also destabilize the microscopic mode such as drift wave $^{27)}$ . For instance, the radiation loss increases the growth rate by the amount of –n<sub>I</sub>aL/aT. If there is the constant neutral density, t<mark>h</mark>en the density fluctuation **ff** gives the source of fluctuation S<sub>n</sub>=γ<sub>n</sub>∏≡n<sub>O</sub>∏<dv). (n<sub>O</sub> is the neutral particle density.) This positive feed back enhances the growth rate of drift like waves by the amount of  $\bm{\tau}_{\bm{\text{n}}}$ . Estimation was made that the ionization can affect the fluctuation level at edge considerably if  $\tau_\mathrm{n}$ >5x10<sup>3</sup> (s<sup>-1</sup>) for small devices. It should be noted that in this kind of computations, the density of the be noted that in this kind of computations, the density of the neutral particle is assumed to be constant (the parameter  $\bm{\tau}_{\text{n}}$  is taken as a constant parameter). This assumption in reality is not always a good model. The neutral density itself contains the fluctuating component in the case that the plasma density is flucluating component in the case that the plasma density is fluctuating: In such a circumstance, simple relation of  $S_n$  =  $\tau_n$  T ( $\tau_n$ >0) is no longer valid. Further analysis is required.

#### (3.4) Effect of Radial Electric Field

The sharp gradient of the radial electric field is also The sharp gradient of the radial electric field is also characteristic to the boundary plasmas. It can also characteristic to the boundary plasmas. It can also affect the stability *of* the edge plasma and gives rise to the affect the stability of the edge plasma and gives rise to the variety of the transport properties. variety of the transport properties.

The study on the stabilizing effect of E<sup>r</sup> ' was studied *much*  The study 00 the stabilizing effect of Er' was studied much in kinetic theories. The electric field gradient car. influence the stability through modifying the ion orbit<sup>28-30</sup>'. The ion Landau damping stabilizes the kinetic mode if  $|E_{\bm r}\rangle/B|> |v_{\bm T\hat{\textbf{\textit{i}}}}\nabla n/n|$ is satisfied. Also it can change the direction of the toroidal is satisfied. Also it can change the direction of the toroidal drift of trapped particle to favourable direction. drift of trapped particle to favourable direction

The effect was also studied by WHD equations $31,32)$ , in terms of the shear flow. The shear flow first tends to localize the radial extent of the mode. Stabilization is expected if

$$
E_r^{\dagger}k_B/Bk_r \sim \tau_L \tag{19}
$$

where  $\bm{\tau}_{\parallel}$  is the linear growth rate in the absence of E<sub>r</sub>'. (If the inhomogeneity of the velocity shear (d $^2$ V/dr $^2$ ) is too large. then the Kelvin-Helmholtz instability is destabilized.) This then the Kelvin-Helmholtz instability is destabilioed.) This stabilization reduces the anomalous transport which is caused by stabilization reduces the anomalous transport which is caused by the microscopic instabilities at the edge. Recent progress has the microscopic instabilities at the edge. Recent progress has shown that the mode amplitude is not always reduced by the velocity shear $^{33)}$  and the necessity to treat the electric field in a self consistent manner was pointed out. The intensive study in a self consistent maoner was pointed out. The intensive study is under way. is under way.

The study in this direction was motivated by the prediction The study in this direction was otivated by the prediction of the radial electric field at the L– and H–mode transition $^{\mathfrak{g}4)}$ and its confirmation by experiments $^{35,\,36}$  . Also revived is the careful study of the dynamics of the radial electric field and careful study of the dynamics of the radial electric field and plasma rotation. The important role of the viscosity was plasma rotation. The lmportant role of the viscosity was recognized, which is discussed in next section.

 $-32-$ 

#### [17] Bifurcation *Phenomena*  [1'] &ifurcatioD PheDoeDa

#### (4.1) Finding of the H-mode

One of the most dramatic finding in recent plasma confinement experiments was the H-mode<sup>2)</sup>. This was the break through against the degradation of the energy confinement time with power. And it enlarged the possibility in achieving the ignition plasma in future devices. At the same time it has cast the physics picture that the plasma surface has the generic nature that the multiple states are allowed for given external conditions, that the spatial structure (typical gradient length) can be free from the minor radius and that it has a rapid time scale for the transition. It thus enriched the physics of the confined plasmas. Efforts have also been made to model these phenomena in the frame work of the fluid picture of the plasma, and are illustrated in the following. illustrated in the following

#### (4.2) Bifurcation of the Radial Electric Field and Rotation

After the finding of the H - mode, a model was first proposed After the finding af the H-mode. a model was first propased that the transport barrier would be made in the SoL $^{\rm 37)}$  due to the electric field along the field line. The experimental study electric field along the field line. The experimental study clarified that the barrier exists inside of the plasna surface. c1arified that the barrier exists inside of the plasma surface. This model turns out incomplete, but pointed out the possible This model turns out incomplete, but pointed out the possible important role of the electric field on the transport in the edge plasma.

A possible mechanism of the bifurcation of the perpendicular A possible mechanism of the bifurcation of the perpendicular transport was proposed by taking into account the effect of the transport was proposed by taking into account the effect of the

 $-33-$ 

loss cone $^{34}$  . The basic physics picture was that the gradient– flux relation should have the form in Fig. 5 to explain the flux relation should have the form in Fig 5 to explain the sequence of the transition (i.e., very rapid reduction of the outflux at transition followed by the establishment of the outflux at transition followed by the eslablishmenl of the pedestal in the profile) and that this is possible at edge (not pedestal in the profile) and that this is possible at edge (not characterized by the separatrix). This model in Fig.5 can be characterized by the separatrix). This model in Fig.5 can be constructed by introducing a 'hidden variable' E<sub>r</sub>. The 'edge phenomena" indicates that (1) the gradient a/ar is no longer phenomena indicates that (1) the gradient a/ar is no longer limited to the order of 1/a but can be order of l/(a-r) [i.e., limiled 10 the order of I/a but can be order of I/(a-r) [i.e., 0(l/ρ<sub>p</sub>) for (a–r) v ρ<sub>p</sub>, ρ<sub>p</sub> being the ion poloidal gyroradius], and that the process such as loss cone can affect the global t ransport. transport

To quantify the lodel, it is necessary to study the nature To quantify the model, it is necessary to study the nature of the viscosity tern in the basic equation, ffe write the of the viscosity term in the basic equation fe write the Poisson Equation combining with the equation of motion as Poisson Equation combining with the equation of motion as

$$
\epsilon_0 \epsilon_{\perp} \delta E_r / \delta t = -e(\Gamma_{re} - \Gamma_{ri} - \Gamma_{1c})
$$
 (20)

where  $\bm{\epsilon}_{\perp}$  is the perpendicular dielectric constant,  $\bm{\Gamma_{re}}$  is the bipolar component of electron flux,  $\Gamma_{r\, \mathrm{i}}$  is that of ion flux, and  $\Gamma_{1{\rm\text{c}}}$  is the loss cone current of ions. These terms are neglected in assuming n/p by the unit tensor. The stationary solution is in assuming D/p by the unit tensor. The stationary solutioo is obtained by solving  $\Gamma_{\texttt{re}}\texttt{=}\Gamma_{\texttt{ri}}\texttt{+}\Gamma_{\texttt{lc}}$ . The term  $\Gamma_{\texttt{lc}}$  has the dependence on E <sup>r</sup> as 00 Er as

$$
\Gamma_{1c} \sim \rho_p n_i \nu_i \epsilon^{-0.5} exp(-\Xi \chi^2)
$$
 (21)

where  $u_i$  is the ion collision frequency, ε=a/R, Ξ indicates the effect of orbit squeezing due to the inhomogeneity of  $\epsilon_r^{-38}$ ), and

$$
\chi = e E_{\Gamma} \rho_{\rho} / T.
$$

(X is equal to the so called poloidal Mach number  $\mathbb{V}_n$ B/v $_{\mathrm{T}}$ ;B<sub>n</sub> if  $\mathtt{V_p\text{-}E_p/B}_t$ .) This shows that the loss flux can reduce if  $\tt\tt{E}_r$  is 1arge enough. large enough

Figure 6(a) illustrates the case study that T<sub>re</sub> is proportional to (–n'/n+eE<sub>r</sub>/T<sub>e</sub>) such as the ripple diffusion, as

$$
\Gamma_{\Gamma e} = -D_{e} n [n'/n + e E_{\Gamma}/T_{e}],
$$

and  $\Gamma_{r,i}$  is neglected. The jump of  $\Gamma$  is predicted at the critical gradient gradient

$$
\lambda = \rho_p n'/n \lambda_c \tag{22}
$$

and  $\lambda_c$  is O(1) as is shown in Fig.6(b). This example shows that the singularity of the transport property  $\Gamma[\nabla n]$  can be explained by using a <u>continuous</u> function of  $\Gamma (E_{_{\rm I}})$ .

The extension of the model is possible by considering The extension of the model is possible by considering  $\mathsf{r}_{\mathsf{r}\,\mathsf{i}}^{39}$ ). The bulk viscosity generates the force on ions in the poloidal direction as poloidal direction as

$$
\mathbf{F}_{\mathbf{p}} \sim -\mathbf{n}_{i} \mathbf{n}_{i} \nu_{i} \mathbf{q}^{2} \mathbf{f}(\mathbf{X}) \mathbf{Y}_{\mathbf{p}}.
$$

where the function  $f(\chi)$  is  $33.4$ 

 $f(X) = 1$  (for  $|X| \ll 1$ )

and behaves in the large *\J \* limit like and behaves in the large Ix I limit like

 $f(X) \propto exp(-X^2)$  (plateau regime)

 $f(X) \propto X^{-2}$  (Pfirsch–Schluter regime),

Taking this form of  $F_p$ ,  $\Gamma_{\text{ir}}$  was calculated. Figure 6(c) illustrates the balance of  $\Gamma_{1{\rm c}}$  =  $\Gamma_{\rm r1}$ , confirming that the bifurcation can occur at the particular value of the edge bifurcation can occur at the particular value of the edge gradient.  $\lambda_0 \sim D(1)$  and that the edge plasma can have bistable states for a given condition<sup>39)</sup>. Variety of the bifurcation is also predicted. When the electron term  $\rm r_{re}$  is negligible, the transition occurs to the more negative E<sub>r'</sub> and that to the mode positive E<sub>r</sub> takes place if T<sub>re</sub> is important. Other candidates such as the VVV term or the turbulence driven flux are also studied<sup>41,42)</sup>.

Combining the theory that the radial inhomogeneity of E<sub>r</sub> (or the established electric field (flow velocity) are considered to the established electric field (flow velocity) are considered to suppress the microinstabilities and associated anomalous suppress the microinstabilities and associated anomalous transport. The reduction of the anomalous transport further transport. The reduction of tne anomalous transport further improves the confinement inside of the transport barrier. Figure 7 illustrates the present 'standard model' for the transition 7 illustrates the present 'standard model' for the transition  $V_p$ ) can stabilize the microscopic instabilities, the structure of

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phenomena at edge, though many part of the elements are still phenomena at edge, though any part of the elements are stil1 qualitative yet. qualitative yet

# (4.3) Observation of the Structure of  $R_{\texttt{f}}$  and  $\mathcal{Y}_{\texttt{p}}$

The proposal of the electric bifurcation  $\sim$  was tested by The proposal of the electric bifurcation<sup>34)</sup> was tested by<br>experiments. D–III D<sup>35)</sup> and JFT-2M<sup>36)</sup> confirmed the establishment of the radial electric field. Also observed is that the ment of the radial electric field Also observed is that the transition can be excited by the radial current driven by the transition can be excited by the radial current driven by the probe and external circuit $^{\{4\}}$ . The layer width is of the order of  $\rho_{\rm p}^{\rm \,36}$ ). Experiments by the electrode have confirmed the nonlinear response of the radial current to  $E_r^{-44}$ ).

These observations seem to confirm the basic physics model These observations seem to confirm the basic physics model of the electric bifurcation. However, there still remain the of the electric bifurcation However, there still remain the mystery. Figure 8 shows the gradients near edge of the JFT-2M mystery Figure 8 shows the gradients near edge of the JFT-2M plasma. Peaks of V|E<sub>r</sub>|, VT and Vn seem to exist at different positions. It looks that future progress of the theory is positions It looks that future progress of the theory is necessary to understand the internal structure of the transport necessary to understand the internal structure of the transport barrier. barrier

#### (4.4) Self-Sustaining Oscillation and ELMs

Various types of ELMs are known in experiments $\texttt{2.25}$  . Some is correlated with the critical gradient of edge pressure against correlated with the critical gradient of edge pressure against the ballooning node, and soue is not. In former case, the good the ballooning mode, and some is not, 1n former case, the good confinement is considered to allow the edge gradient to achieve confinement is cansidered to allow the edge gradient to achieve the limit imposed from the UHD stability. Small and continuous the limit imposed from the MHO stability Small and continuous ELMs ('grassy ELMs') needs different modelling. ELWs (' grassy ELWs') needs differcnt modelling

The bifurcation model predicts a self-sustaining oscillation The bifurcation model predicts a self-sustaining osciIlation

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under the constant flux from the  $\texttt{core}^{\textbf{45}}$  . The hysteresis between Vn and r can generates the oscillation C' limit cycle solution'). Vn and r can generates lhe oscillation C' limit cycle solution') The dynamical equation (20) is solved with Eq.(1) and the model equation  $\Gamma[X,\nabla n]$ . Simplified model equation can be formulated in the form of the Gintzburg–Landau Equation as

$$
an/\partial t = (d/\partial x)D(X)dn/\partial x, \qquad (23-1)
$$

$$
u \partial X / \partial t = -N(X, \lambda, n) + \mu \partial^2 X / x^2
$$
 (23-2)

where D is the effective diffusivity, x=a-r, o is the smallness where D is the effective diffusivity. x=a-r. v is the smallness parameter of the order of ( ${\color{black} \rho}_\text{j}/ {\color{black} \rho}_\text{p} )^{\color{black} Z}$ ,  $\mu$  is the shear viscosity, and N represents the current e[ $\Gamma_{\rm 1c}$ + $\Gamma_{\rm r\,i}$  – $\Gamma_{\rm re\,}$ ] which has the nonlinearity and depends on both E<sub>r</sub> and Vn. Introduction of the shear viscosity allows us to study the radial structure of the shear viscosity allows us to study the radial structure of the barrier. The transition may occur on one magnetic surface. The barrier. The transition may occur on one magnetic surface. The velocity V<sub>p</sub> and field E<sub>r</sub> cannot be discontinuous, and the transition on a magnetic surface propagates to different magnetic transition on a magnetic surface propagates to different magnetic surface by the ion viscosity. [Note that normalization is used as surface by the ion viscosity. [Note that normalizatiun is used as

$$
x/\rho_p \rightarrow x, \quad D/D_0 \rightarrow D, \quad \mu/D_0 \rightarrow \mu, \quad t/(\rho_p^2/D_0) \rightarrow t
$$

( DQ being the typical diffusivity in the L-phase. )] (00 being the typical diffusivity in the L-phase.)J

A simplified model was studied where N(X,A,n) is given A simplified model was studied where N(X n) is given  $N(X, g)$  (g= $\lambda/\nu_{\text{i}}$ ) and  $N(X, g)$  is modeled by the cubic equation as in Fig.9(a). It is shown that the set equation (22) predicts the self–sustaining oscillation for a fixed value of the flux from

core. This oscillation (limit cycle solution) is possible in a core. This oscillation (limit cycle solution) is possible in a<br>limited area in the parameter space. Otherwise, either the highconfinement state (H) or low confinement state (L) is allowed. Figure 9(b) and (c) illustrate the oscillatory solution of the Figure 9(b) and (c) i11ustrate the oscillatory solution of the out flux, and the radial profile of the effective diffusivity in out flux. and the radial profile of the effective diffusivity in H and L phases. H and L phases.

In the time-phase of good confinement, the spatial structure In the time-phase of good confinement, the spatial structure shows that 'he reduction of D extends from the surface to the diffusion Prandtl nuiber has an important role in determining the diffusion Prandtl number has an important role in determining the thickness of the transport barrier. Since the value of D(x) thickness of the transport barrier. Since the va1ue of O(x) takes the intermediate values of D in *I-* and H- branches of takes the intermediate values of D in L- and H- branches of Fig.9(a). this layer is also called as the mesophase of the two states. s t a t es. layer, the characteristic width of which is given  $\sqrt{\mu/D} \rho_{\rm n}$ . The

These results also illustrates the importance of the These results also illustrates the importance of the viscosity in the dynamics and structure of the edge plasmas. viscosity in the dynamics and structure of the edge p1asmas.

# **[V] Summary and Future Problems**

In this article, we briefly survey the applications of the MHD theory for the understanding of the edge plasma physics. It UHD tbeory for the understanding of the edge plasma physics. 1t is known that the edge phenomena is strongly geometry-dependent, is known that the edge phenomena is strongly geometry-dependent, and contains various tine scales. From this point of view, the and contains various time scales. From this point of view. the **MHD** equation is a suitable tool for modelling the phenomena in the edge plasmas. It was successfully applied to study the two– dinensional profile of the plasma, the behaviour of impurities, dimensional profile of the plasma. the behaviour of impurities, and the stability analysis. Recent efforts are to extend the and the stability analysis. Recent efforts are to extend the applicable area by investigating the role of the radial electric applicable afea by investigating the role of the radial electric field and the ion viscosity. field and the ion viscosity

We here also stressed that the MHD equations are not closed by themselves, and need some closure model. It is illustrated in by themselves, and need 50me closure model. It is illustrated in §1V that the study on the viscosity tensor can largely extend the ~IV that the study 00 the viscasity tensor can largely extend the area of the application. Hany results are shown here to be dependent on the choice of the anomalous transport coefficient. Experimental studies on x in the SoL are in progress as is Experimental studies 00 1 in the SoL are in progress as is reviewed in Ref. [3 ], and the improvement of our knowledge can be reviewed in Ref. [3], and the impfovement of our knowledge can be expected. At the same time, the research in this direction must be enforced. be enforced.

The influence of the atomic processes are also examined in The influence of the atomic processes are a150 examined in the UHD analysis by proper choice of the models on the radiation the YHD analysis by proper choice of the models on the radiation loss, particle source, CX loss and so on. A successful example is seen in the model of ELMs and detachment, and hence gave an i8 seen in the model of ELMs and detachment. and hence gave an insight for the density limit disruption. The analysis has also shown that not only the static radiation structure (MARFE) but also the oscillation nature of the radiation<sup>16)</sup>. Further

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analysis would be required for research in this direction with analysis would be required for research in this direction with refined models for the impurity response. refined models for the impurity response

One particular example is the problems in the braided magnetic field. The separatrix configuration is vulnerable to masnetic field. The separatrix configuration is vulnerable to the braiding due to the error field or to the instability. The the braiding due to the error field or to the instability. The destruction of the flux surface is sometimes introduced artificially in order to control edge plasmas. The braiding at artificially in order to control edge plasmas. The braiding at one hand causes homogeneity, but at the same time gives rise to one hand causes homogeneity. but at the same time gives rise to the new structure. the new structure

The UHD stability analysis has made progress, and the The YHD stability analysis has made progress. and the determination for the stability limit is now a well-defined problem in a realistic geometry and plasma profiles. There are, problem in a realistic geometry and plasma profiles. There are, however, several problems associated with the MHD instability however. several problems associated with the WHD instability near edge. Largest one is the problem of the trigger. Bursts of near edge. Largest one is the problem of the trigger. Bursts of magnetic perturbation are observed, suggesting that the dramatic magnetic perturbation are ohserved. suggesting that the dramatic change of the growth rate. Figure 10 is an example form PBX-M, where a sudden growth of the fluctuations within the time of the order of 10µsec<sup>46)</sup>. The rate of the change of T, ar/at, can be estimated by C*ar/dp'*)(aa'/at). The typical time for the change estimated by (aT/aβ. )(as'/atl. The typical time for the change of  $\beta$  is required to get a large value of  $\tau$  after the parameter  $\beta'$ reaches the critical value for instability. This time period seems too slow compared to the rise time of bursts. A method to model the trigger problem was proposed in [471. Another problem model the trigger problem was proposed in (47]. Another problem is the prediction of the stability boundary in the presence of is the prediction of the stability boundary in the presence of the plasma dissipation, which dramatically reduce the critical the plasma dissipation, which dramaticallY reduce the critical value. Usual argument is that the dissipative mode only enhance value. Usual argument is that the dissipative mode only enhance the anomalous transport but the ideal mode really limits the

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beta. This kind of hypothesis must be examined more carefully. beta. This kind of hypothesis must bc cxa ined ore carefully

The quantitative improvement of the modelling of the The quantitative improvement of the odelling of the viscosity and the radial currents is also necessary. It is worth viscosity and the radial currents is also necessary. 1t is worth to extend to the level that the quantitative prediction of E<sub>r</sub> is possible. Some of the elements  $\Gamma_{\alpha}$  ; has been confirmed by experiments. Figure 11 is the data from TEXTOR on the radial current due to the bulk viscosity $^{44)}$ . Many further improvement of confinement have been proposed based on the electric of confinement have been proposed based on the electric bifurcation uodel. The verification of the model is surely an bifurcation model. The verification of the model is surely an important issue. The study on the time-dependent problems has important issue. The study on the time ωdependent problems has shown that the fruitful results are expected from the MHD shown that the fruitful results are expected from the WHD approach. approach

The research on the electric field and viscosity is also The research on the electric field and viscosity is also inevitable in promoting the research of the impurity–related problems. For instance, the thermal instability critically problems. For instance. the thermal instability critically depends on the parameter  $(\pi_I/n_I)/(\bar{T}_e/T_e)$ . Recently, careful experimental study on the impurity transport was made on experimental study 00 the impurity transport was made on <code>ASDEX $^{4\,8}$ </code>), and it was found that the anomalous transport affects considerably the impurity flux. It is also known that the considerably the impurity flux. 1t is also known that the difference of wall material can lead the dramatic difference of difference of wall material can lead the dramatic difference of the plasma response. Examples are found in the super H-rode for the plasma response. Examples are found in the super H-mode for Boronized wall (D-III D), change of the current quench time at disruption between carbonized wall and Beryllium wall, so on. disruption between carhonized wall and Beryllium wall, 80 on Intensive research is required in future. Intensive research is required in future

It is also noted that the study on the edge barrier is the It is also noted that the study on the edge barrier is the problem of the self-generating structure across the field. It is problem of the self-generating structure across the field. It is well Vnown that there is a self-generating structure along the well known that there is a self-generating slructure along the

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field Jine, such as the double layer. the width of which is independent of the system size. The barrier of the H-node would independent of the system size. The barrier of the H-mode would be the first example that the cross-field gradient is free from be the first example that the cross-field gradient is free from the system size and reaches its new characteristic length. (The the system size and reaches its new characteristic length. (The bifurcation model predicts the length scale with  $\sqrt{\mu/D}P_{\rm n}$ .) It may reveal the generic nature of the confined plasma and have a particulary and have a structure in the sensul of the summary and the sensul barrow and the sensul barrow and the sensul barrow and the sensul barrow and the sens future impact to wider area of the physics.

These studies may lead to the understanding of the more These studies may lead to the understanding of the more mysterious nature of the plasma. For instance, the core plasma mysterious nature of the plasma. For instance, the core plasma profile can be peaked when the edge neutral density changes profile can be peaked when the edge neutral density changes through affecting the radial electric field profile $^{\text{49}}$  (model of  $\mathtt{IC^{4}}$ ). The interaction between the core and edge plasma has not been clarified enough. been clarified enough.

We here have few room to show how the <u>understanding</u> of the edge plasma confinement is used to <u>control</u> it. One example is seen in the analysis of the divertor bias<sup>50,51)</sup>. The other is the excitation of the H–mode transition by the ion beam $^{52)}$ , or the sustenance of grassy ELMs by external oscillations<sup>53)</sup>. The control of the edge plasma, e.g., for the good energy contro1 of the edge plasma. e. g., for the good energy confinement, efficient pumping, suppression of impurities, or confinement, efficient pumping, suppression of impurities. or tolerating the heat load, are urgent tasks. The proper tolerating the heat load. are urgent tasks. The proper modelling of edge plasma is inevitable for it, and the MHD modelling of edge plasma is inevitable for it. and the YHD analysis will still be very useful in the research in this analysis will still be very useful in the research in this direction. directios.

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- Fig.1 **Example of the edge plasma region (model of JFT-2M** plasma). Thick dashed line denotes the separatrix magnetic plasma). Thick dashed line denoles the separatrix magnetic surface, in which the magnetic surfaces (shown by thin dotted lines) are nested and closed. Out of the separatrix, dollcd lincs) are nested and closed. Out of the separatrix. field lines are connected to the divertor region or the \*all. Meshes in the poloidal direction are given for the two dimensional computations. Flux surfaces of the core plasma are net drawn. .
- Fig 2 **Examples of the plasma and neutral profiles in the SoL** region. Frofiles of T<sub>e</sub>. n<sub>1</sub>, n<sub>0</sub>, and D<sub>α</sub> are given. (Model )  $\epsilon$ : .)FT 2M plasma, the ion VB direction is into the X–point, .<br>The total fluxes from core are P<sub>out</sub> -0.5MW and  $\Gamma_{\rm out}$  =  $\stackrel{>}{\varepsilon}$ xlO $^{21}$ /sec. respectively.) (Quoted from Ref.[16].).  $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 &$
- Fig.: Stability instability boundary for the ideal MHD mode in the s  $\alpha$  plane. (Quoted from Ref. [21].)
- 4 Stability instability boundary in the s-a plane for the fig.4 Stability instability boundary in the s-αplane for the resistive plasma (a). The effect of the Shafranov shift  $(B_n)$ resistive plasma (a). The effect of the Shafranov shift (B<sub>p</sub><br>=B<sub>nn</sub>/(I–Acosθ)) is taken into account. which stabilizes the resistive mode in the second stability region. The finite resistive mode in the second stability region. The finite resistivity extends the unstable region to low beta region. resistivity extends the unstable region to low beta region. [There is a narrow stable region near a=0 in case 6 is [There is a narrow stable region nearα=0 in case 6 is not zero.] (Quoted from Sykes et al., [22].) not zero.] (Quoted from Sykes et al., [22].)

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Example of the growth rate is shown in (b) in the Example of the growth rate is shown in (b) in the presence of magnetic well. The critical beta-limit for presence of magnetic wel1. The crilical beta-limit for the resistive instability is smaller than the prediction of the resistive instability i5 smaller than the prediction of ideal MHD theory. The case of S=10<sup>4</sup> is shown. (Quoted from Strauss, [22]. ) Strauss, [22].)

- Fig.5 Schematic model relation of the gradient (Vn, VT) and flux (r, q) for the edge plasma, in order to explain the flux (r, q) for the edge plasma, in order to explain :he rapid change of the energy loss at the onset of H-mode transition (a). Singularities appear at particular values transition (a). Singu1arities appear at particu1ar va1ues of the gradient. The gradient - flux relation for the case of of the gradient. Thc gradient-flux relation for the case of the *slow* transition is shown in (b) for the reference. the slow transition is shown in (b) for the reference
- Fig.6 Balance of the loss cone lcss  $\Gamma_{1c}$  and electron loss  $\Gamma_{re}$ allowed. Multiple solutions are possible for the medium λ case (B and C), and the one small-flux solution is allowed case (B and C), and the one small-flux solution is allowed for large value of A (D). The resultant flux, as a function for large value ofλ(D). The resultant flux, as a function of λ, is shown in (b). 'he characteristic response in Fig.5 is recovered. When the electron loss term  $\Gamma_{\texttt{re}}$  is negligible, the ion viscosity–driven flux  $\Gamma_{\rm r \, i}$  and  $\Gamma_{\rm 1c}$ determine the radial electric field (c). The function r( A ) determine the radial electric fleld (c). The function r(λ) shows the similar response as in (b). determines the radial electric field  $X = e \rho_p E_r/T_i$  (a). For the case of A (small  $\lambda = \rho_n n'/n$ ), one large-flux solution is
- Fig.7 Schematic diagram between the radial electric field/ Fig.7 Schematic diagram betwees the radial electric field/ rotation, the radial current, anomalous transport, and

50 50

plasma fluxes piasma fluxes

- Fig.8 Profile of the gradients of the radial electric field Fig.8 Profile of the gradients of the radial electric field (a), temperature (b), and density (c) for the H- and L-mode (a), temperature (b), and density (c) for the H- and L-mode in the JFT-2U plasma. Solid lines indicate the result in in the JFT-2M plasoa. Solid lines indicate the result in the H–mode, and dashed lines are for the L–mode.
- Fig.9 Model of the effective diffusivity  $D (D = -\Gamma/\nabla n)$  as a Fig.9 Model of the effective diffusivity D (D=–Γ/Vn) as a<br>function of the gradient parameter g≡λ/ν<sub>i</sub> (a). Transition occurs at points A and B'. Two branches, H and L, are shown. occurs at points A and B'. Two branches, H and L. are shown. The intermediate branch (between A and B' ) are the The intermediate branch (bet.een A and B') are the thermodynanically unstable branch. The predicted thermodyna ically unstable branch. The predicted oscillation, for given constant flux from core, is shown in oscillation. for given constant flux from core is shown in (b). The radial shape of D at the two time slices (high-(b). The radial shape of D at the 1.0 lime slices (high and low-confinement states) are shown in (c). and low-confinement states) are shown in (c)
- Fig. 10 Burst of the magnetic fluctuation was observed prior to Fig.l0 Burst of the magnetic fluctuation was observed prior to the giant ELM in the PBX–M. This burst of fluctuation precedes to the occurrence of the ELM. The rise time of the precedes to the occurrence of the ELM. The rise time of the fluctuation is of the order of lOjisec. (Quoted from [46].) fluctuation is of Ihe order of 10μsec. (Quoted from [46].)
- Fig. 11 Radial current driven by the bulk viscosity was studied Fig 11 Radial current driven by the bulk viscosity was studied in TEXTOR. (Quoted from [44]. ) in TEXTOR. (Quoted froo [44].)

 $51$ 

Fig.1



Fig. 2















Fig. 6









 $-60-$ 

Fig. 9

 $Fig. 10$ 



 $Fig. 11$ 



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