On the Source of Turbulence by Fuelling*)

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In order to understand observations that the wall conditioning, wall material and the way of fuelling of neutral particles influence the core confinement in magnetic confinement devices, possible roles of particle fuelling to enhance edge turbulence are discussed. Bootstrapping of edge turbulence by the coupling with the particle source and turbulence in SoL is shown to enhance of edge turbulence (i.e. *fuelling fuels turbulence*). Inference of this enhanced edge turbulence is discussed, including an additional role that makes the H-mode state more robust.

Keywords: effect of fueling on confinement, edge tubulence, SoL turbulence, neutral particle dynamics

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1. Introduction

In the research of magnetically confined plasmas, empirical knowledge tells that the wall conditioning, wall material and the way of fuelling of neutral particles influence the core confinement. Under the condition of wall degassing, the centrally peaked profile of core plasma (such as supershot [1]) has been observed. The reduction of gas puffing can induce variety of improved confinement. Examples include the change from saturated Ohmic confinement (SOC) to improved Ohmic confinement (IOC) [2], and the improved L-mode (IL mode) [3], etc. (See a review, e.g., [4].) In addition, the confinement improvement factor of the H-mode has been known influenced by the wall material [5]. Such a dependence of core confinement on the wall material is still observed in present day experiments [6]. Nevertheless, not much understanding has been made on these observations (the coupling between core plasma confinement and the way of fuelling, wall conditioning, wall material, etc.) These problems may possibly be a source of uncertainty in predicting the property of future experimental devices such as ITER.

One hypothesis for the carrier of the physical information of the way of fuelling, wall conditioning, wall material, etc., to the core plasma is the neutral particles. It was applied to understand the influence of wall material on the performance of the H-mode [7]. Extending this way of thinking, it was pointed out theoretically that the turbulent fluctuation in the SoL (scrape-off-layer) plasma is imprinted in neutral particles; thus the turbulence in the SoL plasma, which is usually much stronger than the one in the core plasma, can penetrate into the confined plasma via the fuelling of neutral particles (i.e. 'fuelling fuels turbulence') [8]. The new source of turbulence in the edge plasma was pointed out in the model. This process can enhance the fluctuations in plasmas substantially. In this article, we discuss this Bootstrapping of edge turbulence by the coupling with neutral particles and turbulence in SoL. A possibility of enhancement of edge turbulence is discussed. Inference of this enhanced edge turbulence is discussed, including an additional role that makes the H-mode state more robust.

2. Model and Fluctuations that are Fuelled by Fuelling

We here shortly revisit the analysis in the previous work [8]. The model of neutral particle dynamics is summarized in Fig. 1, and the mean plasma parameters (in the core as well as in SoL) are prescribed and assumed to be

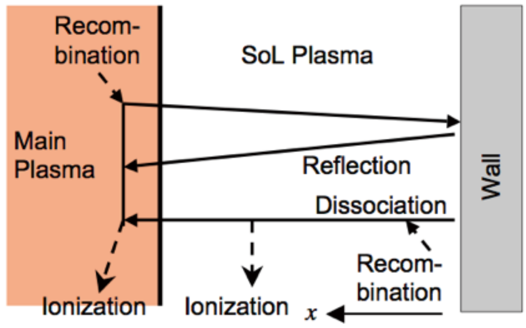

Fig. 1 Schematic diagram of the circulation of neutral particles in the vicinity of the wall. (Reproduced from [8].)

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stationary. The reflection coefficient of neutrals at the wall, R, and the energy spectrum of dissociated neutrals from the wall are treated as parameters.

On the way from the wall to the confined plasma, the neutral particles are subject to ionization and charge exchange (CX) with SoL plasmas (profiles of which are prescribed). Because there are strong fluctuations in SoL plasma (such as Blob [9] and others), the ionization of neutrals in SoL is fluctuating in time. The number of neutral particles, which penetrate into the confined region of plasma, is not constant in time. The fluctuations in SoL are imprinted in the penetrating neutrals, so that the source of electrons in the ionization region near edge fluctuates in time. This is a new source of edge turbulence. Response of fluctuations in electron number density against this fluctuating particle source was calculated.

Leaving the derivation to [8], the coupling between the edge turbulence, neutrals and SOL turbulence was derived. The particle source in the edge plasma is fluctuating owing to the turbulence in edge plasma and SoL plasma,

$$\tilde{S} = \langle S \rangle \left[\frac{\tilde{n}_e(a)}{\langle n_e(a) \rangle} + C \left\{ \frac{\tilde{n}_e}{\langle n_e \rangle} \right\}_{SoL} \right], \tag{1}$$

which drives the further fluctuations in the edge as

$$\frac{d\tilde{n}_e}{dt} = -\frac{\tilde{n}_e}{\tau_{NL}} + \tilde{S}. \tag{2}$$

Here, $\tilde{n}_e$ and $\tilde{S}$ are the fluctuations of electron density and particle source in the edge plasma, respectively, $\left\{ \frac{\tilde{n}_e}{\langle n_e \rangle} \right\}_{SoL}$ is the normalized level of fluctuations in SoL, C is a numerical coefficient of the order of unity, and τ_{NL} is the nonlinear de-correlation time of edge turbulence. In Eq. (1), the first term in the parenthesis of the right hand side shows the coupling between mean neutral density and edge fluctuations. The second term in the RHS parenthesis indicates that the turbulence in SoL is imprinted in the edge plasma.

3. Impact of Fluctuations that are Fuelled by Fuelling

The impacts of the new terms (the RHS of Eq. (1)) can have a substantial contribution for the edge turbulence. The contribution of the second term in the parenthesis of he RHS of Eq. (1), i.e., the imprinting of the SoL turbulence on the edge turbulence was discussed in [8]. The magnitude of the edge turbulence, which is driven by the SoL turbulence via neutral fuelling, was compared with the mixing length estimate, and one has

$$\frac{|\tilde{n}_e|}{\langle n_e \rangle} \sim \frac{1}{\rho_i \Delta_n k^2} C \sqrt{\overline{\left\{ \frac{\tilde{n}_e}{\langle n_e \rangle} \right\}_{SoL}}} \sqrt{\left[\frac{|\tilde{n}_e|}{\langle n_e \rangle} \right]_{\text{mixing length estimte}}}, \tag{3}$$

where Δ_n is the penetration length of neutral particles, a is the minor radius, and all parameters are evaluated at the edge. The relative fluctuation amplitude in SoL, $\overline{\left\{ \frac{\tilde{n}_e}{\langle n_e \rangle} \right\}_{SoL}}$, can be $O(1)$, so that the imprinting of SoL turbulence in the source can occupy a substantial part of the edge turbulence [8].

The new mechanism (i.e., fluctuations are generated via coupling between neutral particles and edge turbulence) generates other source of edge turbulence. Keeping the first term in the RHS of Eq. (1), and combining it with Eq. (2) (with neglecting nonlinear damping term, the condition for which is discussed later), one has a linear growth rate of the instability

$$\gamma_f \sim \frac{a \langle n_e \rangle_{vol}}{\Delta_n \langle n_e(a) \rangle \tau_p}, \tag{4}$$

where $\langle n_e \rangle_{vol}$ is the mean plasma density of core plasma, τ_p is the global particle confinement time, and the condition for the mean particle source $\langle S \rangle = \frac{a}{\Delta_n} \frac{\langle n_e \rangle_{vol}}{\tau_p}$ is used. The instability is driven by the coupling between density fluctuation and particle fuelling at edge. This result Eq. (4) shows that, when the parameters satisfy the condition that γ_f approaches $K \rho_i c_s / L_n$ (which is a characteristic growth rate and a nonlinear damping rate of the gradient-driven drift instability, where K is the typical wave number of gradient-driven turbulence, L_n is gradient scale length, ρ_i is the ion gyroradius, and these parameters are introduced as local values),

$$\frac{a \langle n_e \rangle_{vol}}{\Delta_n \langle n_e(a) \rangle \tau_p} \sim K \rho_i c_s / L_n, \tag{5}$$

this fuelling-driven instability can be as strong as gradient-driven instability.

This result shows that, if the parameter

$$\frac{1}{K \rho_i} \frac{\langle n_e \rangle_{vol} a}{\langle n_e(a) \rangle \Delta_n \tau_p} \frac{L_n}{c_s}, \tag{6}$$

approaches unity, the intensity of fluctuation at plasma edge can be enhanced strongly. This shows a possibility of the bifurcation of the edge turbulence from pressure-gradient-driven turbulence to the neutral-fuelling-driven turbulence. One may also interpret this result that the core plasma density is limited as,

$$\frac{\langle n_e \rangle_{vol}}{\langle n_e(a) \rangle} < K \rho_i \frac{\Delta_n \tau_p}{a} \frac{c_s}{L_n}, \tag{7}$$

where $K \rho_i$ is usually a few tenth for drift wave turbulence. A message of this equation is that the global plasma profile of plasma density could be limited by the edge turbulence, which is driven by fuelling of neutral particles. If other parameters are fixed, the ratio $\langle n \rangle_{vol} / n_{edge}$ is limited. At this moment, the meaning of this criticality is not completely clarified, because all plasma parameters are treated as prescribed (input) parameters, and self-consistent and dynamical analysis of fluctuation and plasma parameters is not performed. Therefore, it is better not to discuss conclusively the outcome of Eq. (5), but present it here as a key for the future studies. Only a few conjectures (based on Eq. (5)) is noted here. The result might be related with the change from Linear Ohmic Confinement (LOC) regime to the Saturated Ohmic Confinement (SOC) regime. This conjecture is driven by the empirical knowledge that, when the particle fuelling is increased to enhance the plasma density, the peaking of density profile is no longer retained, and enters into the SOC regime. If one terminates the gas puff onto the SOC plasma, the confinement time is improved, i.e., SOC-IOC (Improved Ohmic Confinement) transition takes place. These empirical observation motivates further study of 'fuelling-induced' turbulence near the condition of Eq. (5). For the understanding of this influence of fuelling-induced turbulence on the core confinement, the core-edge coupling of turbulence must be studied further. One possibility is the long-range transportation of turbulence clump, via turbulence spreading and or ballistic propagation [e.g., [10–12]]. Another implication is the role of this process in the L-H transition. The L-H transition occurs in conjunction with the change of strong mean radial electric field near edge [13]. Once the L-H transition happens and the particle outflux jumps down, the reflected as well as dissociated neutral particles into the core plasma are dramatically reduced: As a result of this, the damping of radial electric field by neutral particles is reduced, and the source of turbulence (1) is quenched as well. This link can make the H-mode state (which appears after the transition) more robust. Multiple steps in the change of mean electric field was implied in the experimental observation [14], motivating the analysis of the coupling between plasma and neutral particles.

4. Summary

The source of edge turbulence, which is carried by neutral particles for plasma fuelling, is studied. Under the condition that the plasma parameters in the confined region and in SoL are prescribed, the influence of fuelling-driven fluctuation in the plasma edge is analyzed. A new bifurcation of edge turbulence is predicted. Implication of the new criticality of edge turbulence is discussed. The result stimulates future work, which follows the self-consistent dynamics.

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