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Effect of gas puff on edge transport

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1. Introduction

Gas puff is a standard method for density control in fusion devices. However, a too intensive puffing applied in order to achieve high densities leads often to a degradation of the energy confinement and transitions from the regimes with good performance (linear ohmic confinement, H-mode in divertor machines, radiative improved (RI) mode under impurity seeding) to the L-mode [1]. A recent modelling [2] has allowed to interpret this behavior as a self-organization of transport processes in the plasma core triggered by the events at the plasma edge initiated through the gas puff. In particular, it was recognized that a significant intensification of the edge particle transport is a necessary precondition for the observed confinement deterioration in the plasma core.

In Ref. [3] the influence of puffed neutrals on drift instabilities through their friction with plasma ions in charge-exchange processes was considered as a possible cause for the enhancement of the edge turbulence with gas puffing. In the present contribution an indirect effect, which takes place due to changes in plasma parameters in the vicinity of the puffing location [4], is discussed. This results in a local increase of the electron collision frequency which leads in toroidal magnetic geometry to drift resistive ballooning (DRB) instability [5]. Present computations predict that also globally on magnetic surfaces the linear growth rate of perturbations and resulting anomalous transport increase by a factor of 2-3.

2. Effect of gas puff on edge plasma

By puffing of the working gas a large amount of neutral particles is brought very locally into the plasma edge. The heat flow transferred from the plasma core perpendicular to the magnetic surfaces is not enough to compensate energy losses on ionization and heating of these particles. Indeed, the penetration depth of neutrals is normally of several cm and a direct heat flux to the cloud of neutrals is of 10^{-4} of the total power transported to the edge from the plasma core in a device like TEXTOR. This is much less than the power, which should be supplied to the puffed particles, whose influx is normally of several percents of the total plasma flow through the last closed magnetic surface. The rest of required energy is provided by the parallel heat conductivity from distant locations on the same magnetic surface. That requires a temperature gradient parallel to the magnetic field. If the gas puff is too intensive the temperature in the cloud of puffed neutrals becomes very low, the density increases dramatically due to pressure equilibration and a MARFE-like formation with a cold dense plasma arises [4]. Figures 1a and 1b shows the variation of the plasma temperature and density near the puffing position as a function of the gas influx and the variation of these parameters along the magnetic field with the distance from the cold plasma cloud computed for a gas influx of 5×10^{21} s^{-1}. These dependencies were calculated for a typical additionally heated discharge in TEXTOR using the model presented in Ref.[4]. Recent measurements on TEXTOR confirms indirectly a significant increase of the plasma density and reduction of the temperature near the position of a strong gas puff.

3. Effect of a cold dense plasma cloud on DRB instability

The formation of a cold dense plasma region should influence characteristics of unstable drift modes, in particular, due to DRB instability [6]. Indeed, the growth rate of DRB instability, which is proportional to the collision frequency of electrons, ν_e, increases significantly in this region. Due to the interconnection of different locations on a magnetic surface along field lines the averaged effect is less pronounced, however, remains noticeable. In the case of DRB modes perturbations of the plasma density, $\tilde{n}$, radial and parallel components of electric current, $\tilde{j}_r$ and $\tilde{j}_\parallel$, and potential, $\tilde{\varphi}$, are related by the following set of linearized transport equations:

Particle continuity: $\partial\tilde{n}/\partial t + \tilde{V}_r\, \partial n/\partial r = 0$

Momentum balance in the perpendicular direction y: $2T\,\partial\tilde{n}/\partial y = -\tilde{j}_r\, B/c$

Charge conservation: $\partial\,\tilde{j}_\parallel/\partial l + \partial\tilde{j}_r/\partial r = 0$

Parallel Ohm's law: $T\,\partial\tilde{n}/\partial l = en\,\partial\tilde{\varphi}/\partial l + m_e\nu_e\,\tilde{j}_\parallel/e$

Here *T* is the plasma temperature assumed the same for electrons and ions, *c* – the speed of light, *e* – the electron charge, *l* - the distance along the magnetic field *B* related to the poloidal angle as $l = \vartheta qR$, *q, r* and *R* - the safety factor, minor and major radius. The radial motion is due to drift in the perturbed poloidal electric field: $\tilde{V}_r = c\,\tilde{E}_y/B = -c/B\,\partial\tilde{\varphi}/\partial y$.

The time derivative of parallel Ohm's law provides an equation for the potential:

$$\frac{\partial}{\partial l}\left\{\frac{1}{\nu_e}\left[\frac{\partial}{\partial l}\left(\frac{cT}{eB}\frac{\partial\tilde{\varphi}}{\partial y}\frac{\partial n}{\partial r}-n\frac{\partial^2\tilde{\varphi}}{\partial t\partial l}\right)\right]\right\}=\frac{\partial}{\partial r}\left(\frac{2c^2Tm_e}{e^2B^2}\frac{\partial^2\tilde{\varphi}}{\partial^2 y}\frac{\partial n}{\partial r}\right) \qquad (1)$$

We consider modes with a certain poloidal wave vector k_y, $\tilde{\varphi}\propto\exp(ik_y y-i\omega t)\times F(l)$, where the function F describes a slow variation of the mode amplitude along the magnetic field. In the tokamak case $B={B_0}\big/{(1+r/R\cos\vartheta)}$ and ${\partial B^{-2}}\big/{\partial r}\approx{2}\big/{R_0B^2}\times\cos\vartheta$. By using the condition of pressure constancy on magnetic surfaces, $n(\vartheta)T(\vartheta)=n_0T_0$, where n_0 and T_0 are the plasma parameters far from the puff position, we get an equation for the function F:

$$\frac{d}{d\vartheta}\left[\Theta^{5/2}\left(\frac{\omega}{\Theta}-\omega_*\right)\frac{dF}{d\vartheta}\right]=-i\left(2qk_y\rho_e{}^0\right)^2\nu_e{}^0\frac{R_0}{L_n}\cos\vartheta\times F \qquad (2)$$

with $\omega_*=\frac{cT_0}{eB}\frac{k_y}{L_n}$, $L_n=-\frac{1}{n_0}\frac{\partial n_0}{\partial r}$, $\rho_e^0=\frac{c\sqrt{T_0m_e}}{eB_0}$ are the drift frequency, density *e*-folding length and electron Larmor radius computed far from the neutral source.

An approximate solution of Eq.(2) is determined by the Ritz method. We adopt $F=C_0F_0+C_1F_1$, where F_0 describes the case of drift waves without trigger, i.e., with the right hand side equals zero, and F_1 matches the situation of strong instability. One can find that $F_0=$ *const* and F_1 satisfies the following equation with $\Theta(\vartheta)=T(\vartheta)/T_0$:

$$\frac{d}{d\vartheta}\left(\Theta^{3/2}\frac{dF_1}{d\vartheta}\right)=-\left(2qk_y\rho_e{}^0\right)^2\frac{\nu_e{}^0}{\gamma}\frac{R_0}{L_n}\cos\vartheta\times F_1 \qquad (3)$$

The Sturm-Liouville problem for Eq. (3) was solved numerically for the case with the position of puffing at the outer board, ϑ=0. The coefficients $C_{0,1}$ are determined by the condition that the total solution F provides an optimum to the functional:

$$\Phi(F)\equiv\int_0^{2\pi}\left[\Theta^{5/2}\left(\frac{\omega}{\Theta}-\omega_*\right)\times\left(\frac{dF}{d\vartheta}\right)^2-i\left(2qk_y\rho_e{}^0\right)^2\nu_e{}^0\frac{R_0}{L_n}\cos\vartheta\times F^2\right]d\vartheta$$

The real and imaginary, i.e. the growth rate, part s of the frequency ω are determined by equating of the real and imaginary parts in $\Phi(F)$:

$$\omega_r=\omega_*\frac{\int_0^{2\pi}\Theta^{5/2}\times\left(\frac{dF_1}{d\vartheta}\right)^2d\vartheta}{\int_0^{2\pi}\Theta^{3/2}\times\left(\frac{dF_1}{d\vartheta}\right)^2d\vartheta},\quad \gamma=\left(2qk_y\rho_e{}^0\right)^2\nu_e{}^0\frac{R_0}{L_n}\frac{\int_0^{2\pi}\cos\vartheta\times F_1{}^2d\vartheta}{\int_0^{2\pi}\Theta^{3/2}\times\left(\frac{dF_1}{d\vartheta}\right)^2d\vartheta}, \qquad (4)$$

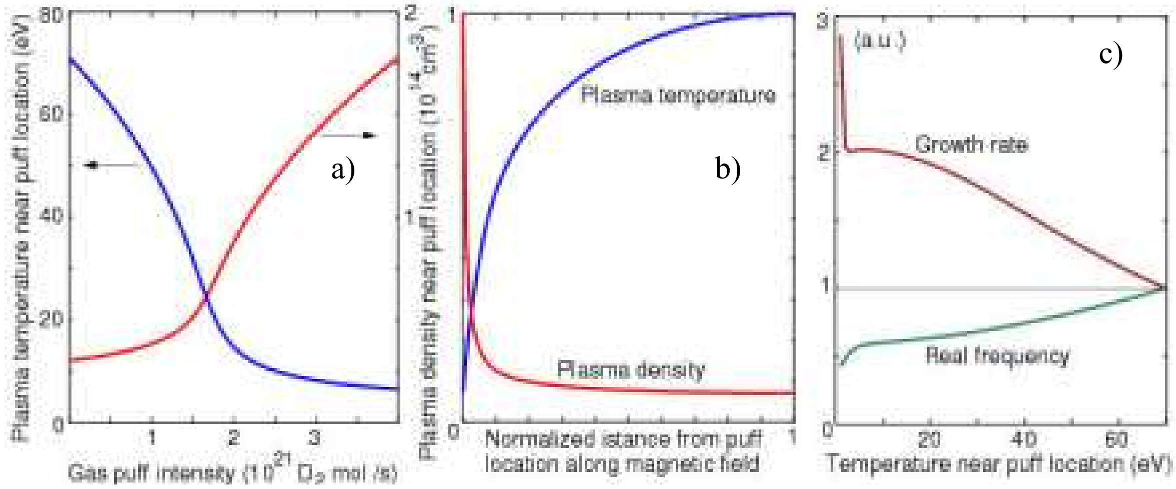

Fig.1. Changes of the plasma parameters near the puff location with the puffing intensity computed for TEXTOR parameters (a), variation of the plasma density and temperature along the magnetic field with the distance from the gas source (b) and the real frequency and growth rate of DRB instability versus the plasma temperature at the gas injection position.

4. Conclusion

One can see from Eqs.(4) that the formation of a temperature minimum near the puff location, with $\Theta(\vartheta=0)<<1$, results in a decrease of the real frequency of perturbations and increase of their growth rate. This is explained by the fact that $\omega_r \propto \omega_* \propto T$ and $\gamma \propto \nu_e \propto n/T^{3/2}$. Such a behaviour of the instability characteristics is in a qualitative agreement with the results of reflectometer measurements of fluctuations in the confined volume near the last closed magnetic surface of TEXTOR (see Ref.[2]). The computed dependence of ω_r and γ on the temperature in the cloud of puffed neutrals is presented in Fig.1c. The growth rate of DRB instability is proportional to the square of k_y and the particle diffusivity estimated in mixing length approximation, $D_\perp \approx \gamma/k_y^2$ increases proportionally to γ. Thus, the effect on DRB turbulence caused by the formation of a region with cold dense plasma can explain, at least partly, the increase in the edge anomalous transport which trigger the transition back to the L-mode by intensive gas puffing into the RI-mode in TEXTOR.

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