Modeling of the Edge Plasma of MAST in the Presence of Resonant Magnetic Perturbations

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Abstract The transport code B2SOLPS5.2 was used to simulate L and H-mode discharges on MAST with and without resonant magnetic perturbations (RMP). The simulated variation of the radial electric field (less negative for RMP) and toroidal rotation (spin-up in the co-current direction for RMP) is in agreement with experiment. The pump-out effect in the L-modes with high and medium plasma density and in the H-mode is caused by the additional neoclassical radial plasma flow in the electric field modified due to the electron loss along the stochastic field lines. The pump-out in the low density L-mode can be reproduced only by a significant rise of the turbulent transport coefficients. The modeling suggests strong RMP screening. An analytical model for RMP screening is proposed.

1. Introduction

It has been demonstrated on DIII-D [1] and later on JET [2] that edge localized modes (ELMs) can be suppressed or mitigated by applying resonant magnetic perturbations (RMP) to the high confinement mode (H-mode) of a tokamak. Resonant coils for RMP are installed or planned on almost all large tokamaks: DIII-D, JET, MAST, ASDEX-Upgrade (AUG) and ITER. The widely accepted mechanism for ELM suppression during RMP is the reduction of the pressure gradient in the pedestal region below the stability limit for type I ELMs. The main contribution to the pressure gradient decrease is the pedestal density drop – the so-called ‘pump-out effect’, while the pedestal temperature does not drop and might even increase. Up to now this effect was not completely understood. On the other hand, as was known from several earlier [3] and recent [4, 5, 6] observations, inside the stochastic layer the radial electric field becomes less negative or even positive and co-current toroidal rotation is generated.

An analytical model which can describe these effects has been suggested in [7]-[9] and the first simulations made by the B2SOLPS5.2 transport code [9] demonstrated that the results are consistent with the analytical predictions. The key element of the model is the account of the radial current of electrons in a stochastic magnetic field. The parallel current is driven by the radial electric field, density and electron temperature gradients in the presence of the radial magnetic field perturbations. The radial projection of the parallel current, averaged over the flux surface, provides a radial current of electrons which is proportional to the square of the radial magnetic field perturbations. Since the net radial current should be zero due to the ambipolar constraint, a radial current of ions is generated. This current flows when the radial electric field is different from the neoclassical electric field. Its value has been calculated in [10]-[11] and see also the review in [12]. The value of the ion radial current is controlled by so-called neoclassical radial conductivity and roughly speaking is proportional to the difference between the radial electric field and its neoclassical value. The ambipolar condition determines the ambipolar radial electric field which is less positive than the neoclassical electric field. In addition the radial ion current generates a toroidal rotation in the co-current direction due to a $\vec{j} \times \vec{B}$ force.

The impact of the RMP on the pedestal profiles according to the analytical model and simulations [9] is described in the following. An additional particle flux which is proportional to the ion radial current is generated during RMP. This flux reduces the density in the pedestal region causing pump-out effect. The effect is more pronounced for the H-mode where the additional particle flux is large in the presence of strong gradients and strong radial electric field while the turbulent diffusivity is reduced inside the edge transport barrier. In the L-mode the effect should be more modest. The change in the temperatures is controlled by two factors acting in the opposite directions. On one hand the pedestal temperature should rise to keep the same heating power coming from the core when the density is reduced. On the other hand, additional electron heat conductivity in a stochastic magnetic field reduces the pedestal temperature. As shown in the simulations [9] the result of the interplay of these two factors is the modest rise of the pedestal temperature which is consistent with observations.

One of the most important issues is the level of the magnetic field perturbations in the plasma. There is some evidence that the vacuum magnetic field perturbations are strongly screened by the plasma so that the resulting RMPs are significantly lower than the vacuum ones. An amplification of the perturbation is also possible. Up to now RMP screening models were based on the screening of a separate magnetic island; see, for example, [13]. However, screening models for the separate island are not directly applicable to the case of RMP due to overlapping of the magnetic islands and stochastization of the magnetic field. In this situation the radial pressure gradient, radial electric field, poloidal and toroidal flows remain finite inside a region of stochastization in contrast with the case of a separate island. Therefore for the case of RMP a new approach to the problem of screening is required. This was done in [14] analytically; while in [15] a similar simplified approach has been incorporated into a MHD code.

In the present paper the impact of RMP on the structure of the edge plasma of MAST has been studied using the B2SOLPS5.2 transport code. Results are compared with experimental data obtained on MAST in the shots with and without RMP. The radial electron current and electron heat flux produced by RMP are taken into account in the equations solved in the code. Simulations were performed for several L-mode shots with different densities with and without RMP. It was found that the electric field at the core side of the separatrix becomes less negative and the plasma is accelerated in the co-current direction in all the cases. The variations in the electric field and in the toroidal rotation are consistent with those measured in these shots.

H-mode shots with and without RMP have been simulated as well. For H-mode discharge as well as for the medium-density L-mode it was demonstrated that the additional particle flux in the barrier region due to the stochastic field might explain the pump-out effect and the rise of the pedestal electron temperature observed. However, for the low density L-mode case the additional particle flux due to the stochastic field is not sufficient to cause the significant pump-out which is observed. The simulations show that in order to match the observed pump out, the transport coefficients in the low density L-mode shot with RMP have to be significantly increased compared to the shots without RMP. This increase in the transport coefficients correlates with the observed increase in the amplitude of the ion saturation current fluctuations.

It is shown that the level of the magnetic field perturbations required to match the pump-out effect in the H-mode and the variation of the radial electric field and toroidal rotation in the L-mode is significantly smaller than that calculated using the vacuum magnetic field, i.e. significant screening of the perturbed magnetic field is required. The mechanism and level of the screening are discussed.

2. Model

The simulations were performed with the B2SOLPS5.2 code [16]. In this code the system of fluid transport equations is solved including all perpendicular currents, ∇B drift, $\vec{E}\times\vec{B}$ drift, and drifts associated with viscosity. The formalism provides a transition to the neoclassical equations when the anomalous transport coefficients are replaced by the classical values. In order to account for the stochastization an additional radial electron current and additional electron heat flow were introduced. The radial current density of electrons in a stochastic magnetic field is given by a simple expression [17] (y is a dimensionless radial coordinate, h_y is the metric coefficient)

$$j_e = \sigma_{St}\left(E_y + \frac{T_e}{e}\frac{d\ln n}{h_y dy} + 0.5\frac{T_e}{e}\frac{d\ln T_e}{h_y dy}\right). \tag{1}$$

The coefficient 0.5 here corresponds to the collisionless limit. The stochastic conductivity is $\sigma_{St} = k(ne^2/T_e)\chi_e^{RR}$ with χ_e^{RR} being the Rechester-Rosenbluth expression for the electron heat conductivity [18] coefficient in a stochastic magnetic field

$$\chi_e^{RR} = \sqrt{\frac{T_e}{m_e}}D_{St}, \tag{2}$$

while $k<1$ is a numerical coefficient (in the simulations $k=0.3$ was chosen). Here D_{St} is a stochastic diffusion coefficient for the magnetic field lines. For MAST the value of D_{St} was calculated for vacuum magnetic field perturbations with the ERGOS code [19], which can trace magnetic field lines.

The heat flow of electrons has a contribution from the convective electron flow associated with radial electron current and from the additional heat conductivity caused by stochastization:

$$q_y^{stoch} = -\frac{5}{2}T_e\frac{j_e}{e} - \chi_e^{RR}\frac{nT_e}{e}\frac{\partial\ln T_e}{h_y\partial y}. \tag{3}$$

The standard source term $-\dfrac{j_e}{en}\dfrac{\partial nT_e}{h_y\partial y}$ was also added to the r.h.s. of the electron heat balance equation. We did not consider the direct ion flux caused by the stochastisity since the corresponding diffusivity is the order of $\chi_e^{RR}\sqrt{m_e/m_i}$ which is small with respect to the neoclassical effects.

The current continuity equation $\nabla\cdot\vec{j}=0$ which is solved in the code with account of electron radial current (1) determines the self-consistent radial electric field. A stochastic diffusion coefficient D_{St} was taken as a free parameter and its value was chosen to match the observed variations in the radial electric field and toroidal rotation. An independent analytical estimate of screening effect has been performed [14] which justifies the choice of the RMP level the in plasma.

3. Simulation results

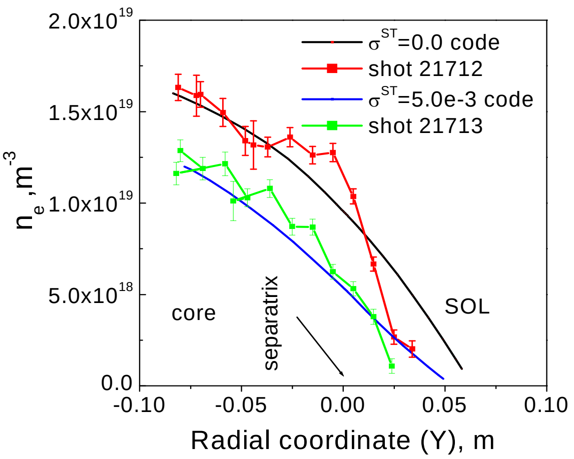

FIG.1. Electron density profile at the outer midplane for L-mode shot №21712 (without RMP) and shot №21713 (with RMP) .

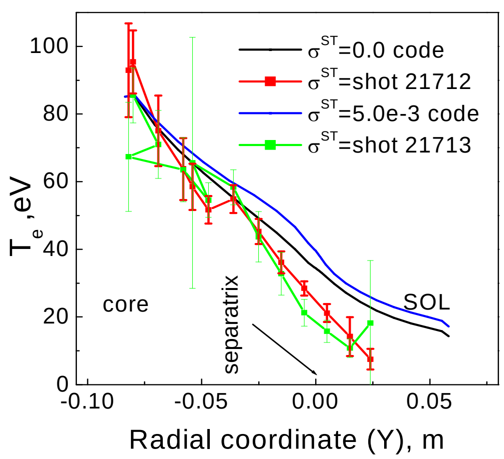

FIG.2. Electron temperature profile at the outer midplane for L-mode shot №21712 (without RMP) and shot №21713 (with RMP).

Several MAST L-mode shots with different densities were chosen for simulations. To match the experimental profiles the following transport coefficients were chosen for the medium density shots 21712 (without RMP) and 21713 (with RMP): particle diffusivity $D = 2.5m^2/s$, electron and ion heat conductivities $\chi_e = \chi_i = 1.5m^2/s$. Density and temperatures profiles for these shots are shown in Figs. 1-2. The radial electric field and parallel rotation profiles are shown in Figs. 3-4. Simulation results are compared with experimental profiles obtained in [20]. Measurements of the radial electric field and parallel flows have been made using a reciprocating probe equipped with a Gundestrup head. The value of D_{St} was taken to be $D_{St} = 2\cdot10^{-7}m$ which is twice smaller than the value $D_{St} = 4\cdot10^{-7}m$ calculated from the vacuum magnetic field. The pump out effect observed

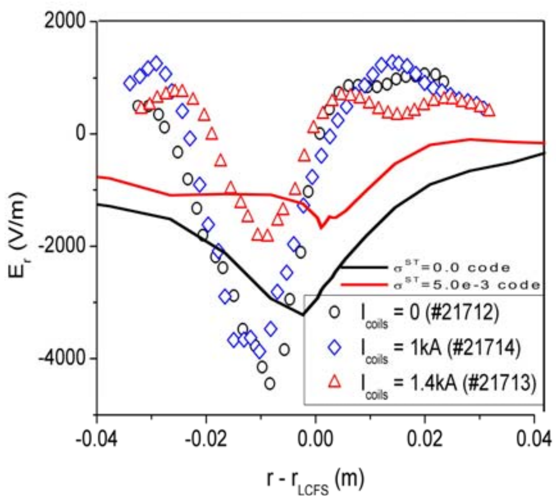

FIG.3. Comparison of experimental and simulated radial electric field profiles at the outer midplane for L-mode shots with and without RMP.

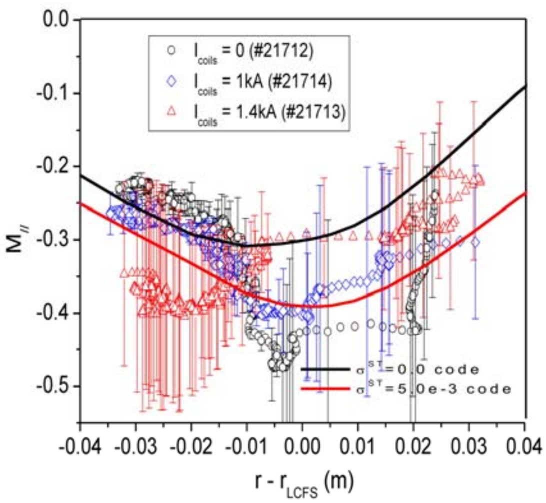

FIG. 4. Comparison of experimental and simulated parallel Mach numbers at the outer midplane for L-mode shots with and without RMP.

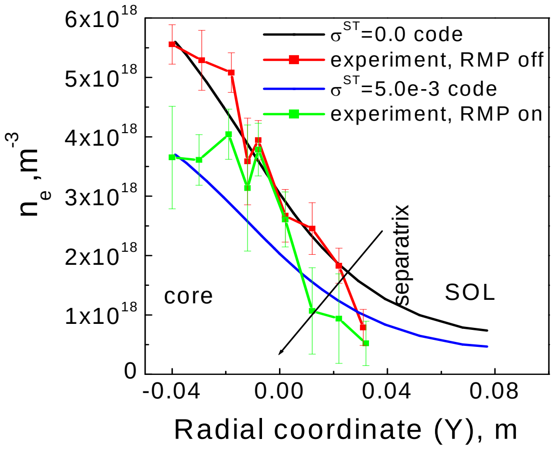

FIG. 5. Electron density profile at the outer mid-plane with and without RMP for low density L-mode shots №20449 and №20451.

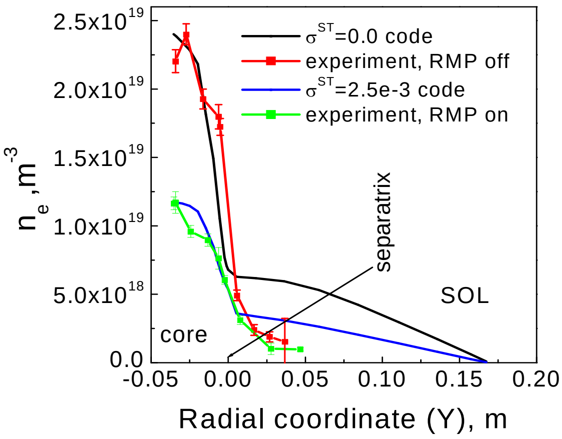

FIG. 6. Electron density profile at the outer mid-plane with and without RMP for H-mode shots №20387 and №20381.

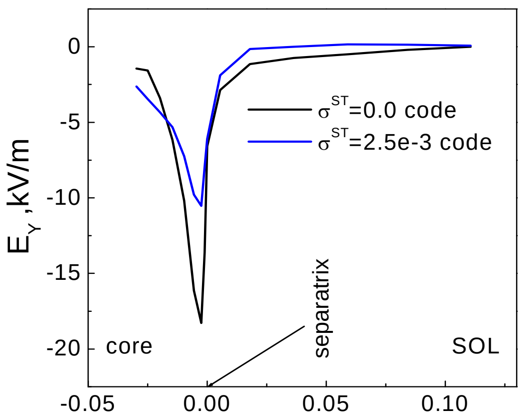

FIG. 7. Simulated radial electric fields at the outer mid-plane with and without RMP for H-mode shots №20387 and №20381.

in the experiment could be attributed to the additional particle flux caused by the neoclassical ion current. The simulated change in the radial electric field and in the toroidal rotation velocity is of the same order as in the experiment. Note that for the vacuum magnetic field these changes would be bigger than in the experiment. Results for the other L-mode shots with exception of the low density case are similar. For the higher density case the pump out effect was more modest both in the simulations and in the experiment.

In contrast, in the low density case, Fig. 5, the observed pump-out effect can not be reproduced for the same transport coefficients as in the absence of RMP. In this case additional particle flux is not sufficient to cause such a strong density drop. To match the experiment in the RMP case the particle diffusivity was increased from a value $D = 4.0 m^2/s$ without RMP to $D = 7.7 m^2/s$ with RMP. This increase in turbulent transport is consistent with the increase in the density fluctuations measured by the reciprocating Langmuir probe. The physical reason for the increase of the turbulent transport in the L-mode with edge stochastization is unclear at present. The electron temperature profiles with and without RMP are very similar to those in the experiment.

The results from a simulation of a H-mode shot [16] are presented in Figs. 6-7. The following transport coefficients were chosen outside the barrier: $D = 2.0 m^2/s$, $\chi_e = \chi_i = 0.5 m^2/s$. In the barrier region with a width $2cm$ inside the separatrix at the equatorial midplane the diffusion coefficient was reduced by factor 10, and heat conductivities by factor 2. Here the strong pump out effect is caused by the additional neoclassical ion current. The value of D_{St} in the modeling is 7 times smaller than the value calculated from the vacuum magnetic field. For the vacuum magnetic field the pump-out effect would be significantly bigger than in the experiment.

4. Screening of RMP

The screening RMP was analyzed in [14]. The stochastic magnetic field generates a radial current of electrons given by Eq. (1). Since the stochastic layer is thin we consider a slab geometry where x is the poloidal, y - radial and z - toroidal coordinates. The radial current is the radial projection of the parallel current

$$j_{\|} = \sum j_{\|\vec{k}} = j_y \frac{\sum B_{y\vec{k}} / B}{\sum \left|B_{y\vec{k}}\right|^2 / B^2} \quad . \tag{4}$$

Here B_y is the full perturbation of magnetic field in the plasma, while B_y^0 is the vacuum magnetic field and $\tilde{B}_y$ is the magnetic field caused by the plasma current. Both the parallel current and the magnetic field perturbation are sums of the contributions with different toroidal and poloidal mode numbers which correspond to a discrete set of wave vectors $\vec{k}$. One harmonic of the current is related to the magnetic field according to Maxwell equation:

$$j_{\|\vec{k}} \approx j_{z\vec{k}} = \frac{1}{\mu_0}\left(ik_x \tilde{B}_{y\vec{k}} - \frac{\partial \tilde{B}_{x\vec{k}}}{\partial y}\right) \quad . \tag{5}$$

Combining Eq.(5) with $\nabla \cdot \vec{B} = 0$, and taking into account that the poloidal scale of the magnetic field perturbation k_x^{-1} is much bigger than the radial scale of the RMP, we have

$$j_{\|\vec{k}} = \frac{1}{\mu_0}\left(ik_x \tilde{B}_{y\vec{k}} - \frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2}\right) \approx -\frac{1}{\mu_0}\frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2} \quad . \tag{6}$$

Note that the generated magnetic field $\tilde{B}_{y\vec{k}}$ is shifted by $\pi/2$ with respect to the parallel current and therefore with respect to the full magnetic field $B_{y\vec{k}}$. The vacuum field is the difference of the full and the generated magnetic fields which are shifted by $\pi/2$ with respect to each other. Therefore the amplitude of each of these two contributions should be smaller than that of the vacuum field. Combining Eq. (4) with Eq. (6) one obtains

$$\frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2} = \frac{i\tilde{B}_{y\vec{k}}}{k_x L^2} = -\mu_0 j_y \frac{B_{y\vec{k}} / B}{\sum \left|B_{y\vec{k}}\right|^2 / B^2} \quad , \tag{7}$$

where L is the radial scale of the RMP. Let us introduce the screening parameter

$$\alpha = \frac{k_x L^2}{B} \frac{j_y}{\sum \left|B_{y\vec{k}}\right|^2 / B^2} \mu_0 \quad , \tag{8}$$

so that $i\tilde{B}_{y\vec{k}} / B = -\alpha B_{y\vec{k}} / B$. Keeping in mind that $B_{y\vec{k}} = \tilde{B}_{y\vec{k}} + B^0_{y\vec{k}}$, we have

$$\frac{B_{y\vec{k}}}{B} = \frac{1+i\alpha}{1+\alpha^2}\frac{B^0_{y\vec{k}}}{B} \quad \text{and} \quad \left|\frac{B_{y\vec{k}}}{B}\right|^2 = \frac{1}{1+\alpha^2}\left|\frac{B^0_{y\vec{k}}}{B}\right|^2 \quad . \tag{9}$$

If the parameter $\alpha > 1$ the screening is large and the stochastic diffusion coefficient D_{st} and the radial current of electrons are reduced by $(1+\alpha^2)$ with respect to the vacuum values.

To estimate the screening factor for MAST it is necessary to know the parameter $j_y / \left(\sum |B_{yk}|^2 / B^2 \right)$. It can be found from Eq.(1) assuming that $E_y + \frac{T_e}{e} \frac{d \ln n}{h_y dy} + 0.5 \frac{T_e}{e} \frac{d \ln T_e}{h_y dy} \sim \frac{T_e}{e} \frac{d \ln n}{h_y dy}$.

For the MAST H-mode shot with RMP coils switched on the estimate is $\alpha \approx 3 \div 5$. So the stochastic diffusion coefficient should be an order of magnitude smaller than the vacuum one, which is consistent with B2SOLPS5.2 simulations. In the L-mode the radial electric field and plasma density are smaller. Therefore the electron current caused by stochasticity and screening effect are also smaller than in the H-mode. The estimate for the medium-density L-mode is $\alpha \approx 0.5 \div 1$. This value is in agreement with modeling, where D_{St} is twice smaller than that calculated for the vacuum magnetic field.

5. Conclusions

Simulations of the impact of RMP on MAST discharges were performed using the B2SOLPS5.2 transport code. The predicted changes of radial electric field (less negative for RMP) and toroidal rotation velocity (spin-up in the co-current direction with RMP) are consistent with observations. The observed density pump-out effect on MAST can be attributed to a self consistent redistribution of the radial plasma flows in the ambipolar electric field modified due to the electron loss along the stochastic field lines (an additional neoclassical flux) for H-mode and several L-mode shots. For the low-density L-mode shot a significant rise of the turbulent transport coefficients were required to match the experimental profiles. A strong RMP screening is predicted analytically and is consistent with the performed simulations.

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