Self-consistent Simulation of Kinetic Pedestal Transport and RMP Penetration

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Penetration of RMP (Resonant Magnetic Perturbation) into a tokamak plasma in a realistic magnetic separatrix geometry has been simulated self-consistently with kinetic response of the edge pedestal. The axisymmetric XGC0 kinetic particle-in-cell code, with electrons and ions orbiting under externally applied RMPs, is coupled to a magnetic field solver routine. Self-consistent radial electric field E_r, plasma rotation, particle-momentum-energy conserving Coulomb collisions, and neutral kinetic transport phenomena are included. The simulation shows that the plasma density is pumped out without loss of heat and that the E_r-well structure survives to some degree, in a manner qualitatively consistent with DIII-D experiments. The simulation also shows that there is a significant local shielding of externally applied RMPs just inside the magnetic separatrix and that the locally non-shielded components of RMPs penetrate deep into the core plasma resulting in particle pumping.

I. Introduction

A successful ITER experiment is expected to demand a high edge pressure in the form of edge plasma pedestal (see Fig. 1) in the so-called H-mode operation. However, a higher edge pressure pedestal produces a steeper gradient ∇p, which can destabilize large scale edge localized modes (ELMs). Theoretically, ELMs can be avoided if the average ∇p is reduced by increasing the radial extent of the edge pedestal. One such technique is to create stochastic magnetic field in the edge region by applying small RMPs using external coil arrays.

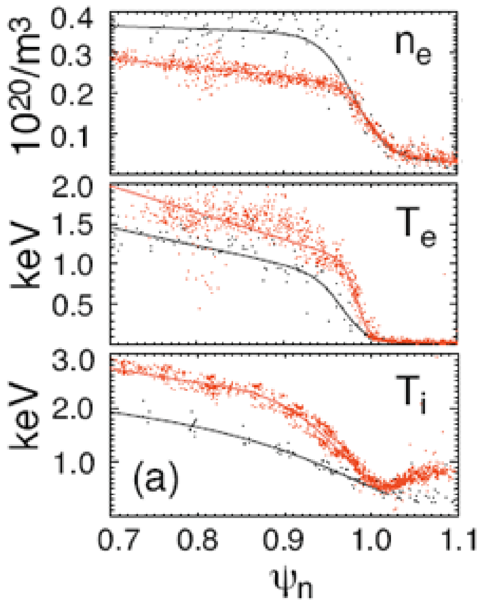

Fig. 1. Experimentally observed changes in n_e, T_e, T_i after the RMP application (from black to red) on experimental DIII-D discharge 126006.

Experiments on the DIII-D tokamak [1] (and later on JET [2]), have indeed demonstrated ELM control using RMPs, but ∇p changes are achieved in a rather unexpected manner. After applying RMPs, experiments observe a strong reduction of the pedestal electron density n_e without reduction in the electron temperature, which is opposite to the physical picture of the completely collapsed electron temperature predicted by the well-known plasma transport theory in a stochastic magnetic field by Rechester and Rosenbluth (R-R theory) [3]. Figure 1 displays the experimentally observed plasma profiles for DIII-D discharge 126006 versus the normalized poloidal magnetic flux ψ_N, a radial coordinate normalized to 0 at the magnetic axis and

1 at the separatrix. Narrowing of the electron transport barrier to the closer vicinity of the magnetic separatrix can be noticed. Figure 2 shows the change in the radial electric field E_r profile before (black) and after (red) the RMP turn-on. It can be seen that the negative E_r well is preserved to some degree, with a narrowing of the width. Ad-hoc analytic modeling and fluid modeling have used the same essential ingredients of R-R theory without much success in explaining simultaneously the non-reduction in the electron temperature, the strong reduction in the electron density, the narrowing of the edge transport barrier, and the preservation of E_r well and its width narrowing. Lack of understanding of the dominant RMP penetration and the edge transport mechanisms makes the extrapolation of the ELM control by RMP coils to future reactors uncertain.

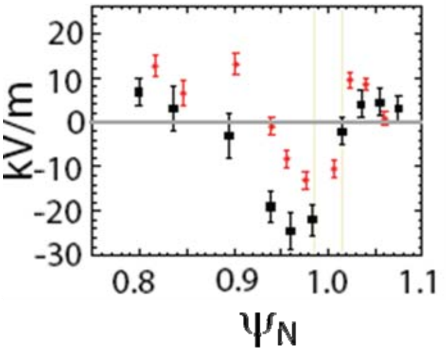

Fig. 2. Experimentally observed change in E_r profile before (black) and after (red) from DIII-D discharge 126006

For the axisymmetric edge plasma response to RMPs, we use the full distribution function (full-f) guiding-center PIC code XGC0 [4], which includes kinetic ions, electrons, and neutrals. Simulation includes magnetic perturbation by external RMP coils, particle source from neutral recycling/ionization and charge exchange, heat and momentum fluxes from the core plasma, impurity radiation in the scrape-off layer, and plasma losses to the material wall with neutral recycling. The present study includes most of the relevant physics self-consistently, but assumes that the electrostatic potential variation within a flux surface is negligible, that the edge localized modes are stabilized, and that the turbulent transport effect is small compared to the RMP-driven transport.

II. Coupled Simulation

Perturbed plasma current $\delta j_{||}$, together with other self-consistent plasma quantities, in the presence of perturbed non-axisymmetric magnetic field is evaluated in XGC0. The perturbed magnetic field has to be consistent with the perturbed plasma current through Ampere's law in toroidal geometry. We thus have two coupled systems to solve:

$$\delta j_{||} /B = F(\delta\psi) \qquad (1)$$

$$\Delta^{*}\delta\psi = \mu_0 \, I \, \delta j_{||}/B \qquad (2)$$

where B is the magnetic field magnitude, I=RB with R being the major radius, and the operator F denotes the Vlasov-Poisson system of XGC0 with particle-momentum-energy conserving Coulomb collisions, $\delta\psi$ is the perturbed poloidal magnetic flux, and Δ^{*} is the two-dimensional Laplacian operator in a torus (conventionally called the Grad-Shafranov operator) for each toroidal mode number

$$\Delta^{*}\psi = R\, \partial/\partial R\, [(1/R)\, \partial\psi /\partial R] + \partial^2\psi /\partial Z^2.$$

Here, R and Z are the cylindrical coordinates (major radius and vertical distance, respectively). For the field equation (2), we use the spectral solver routines in the M3D code. Other MHD equations in M3D are not used here. In other words, M3D in this coupling plays its role as a perturbed magnetic field solver only, and shall be simply called as a "solver code" in this report in order to point out to the readers that we do not use the MHD equations of M3D. The solver routine uses the vacuum RMP distribution for the boundary condition outside the separatrix where plasma pressure is low.

Equation (1), denoting the full-f particle code XGC0, is a nonlinear equation. The perturbed current $\delta j_{||}$ should be solved from the total $\delta\psi$. On the other hand, the Ampere's law, Eq. (2), is linear. Fourier decomposed (m,n) components are solved in the solver code.

When $\delta\psi$ is imported back to XGC0, the total $\delta\psi$ is used. This scheme reduces particle noise since $\delta j_{||}$ does not have to be calculated at each local position.

We use the damped Newton iteration scheme [5] to solve the coupled Eqns. (1) and (2)

$$\delta\psi_{k+1,(m,n)} = \delta\psi_{k,(m,n)} + s_{(m,n)}\, \Delta\psi_{k,(m,n)}$$

$$s_{(m,n)} = \mathrm{Min}\ [1, \alpha\ \mathrm{Min}\ (|\delta\psi_{k,(m,n)} / \Delta\psi_{k,(m,n)}\ |)]$$

where $\Delta\psi_{k,(m,n)}$ is the correction amount in $\psi_{k,(m,n)}$ at the k-th iteration step. An ordinary un-damped Newton iteration may not produce a robust stable solution because of the particle noise and the slow evolution of the background profile in XGC0 during the iteration (even though its amount is small). The iteration needs to converge before a significant background evolution has taken place. The particle number then needs to be large enough for robust convergence in such iterations (normally < 20 iterations). When the overall relative correction $\Delta\psi_{k,(m,n)}$ to the vacuum value $\psi_{vacuum,(m,n)}$ is less than 2%, we finish the iteration. In the case presented here, the target accuracy is obtained in seven iterations.

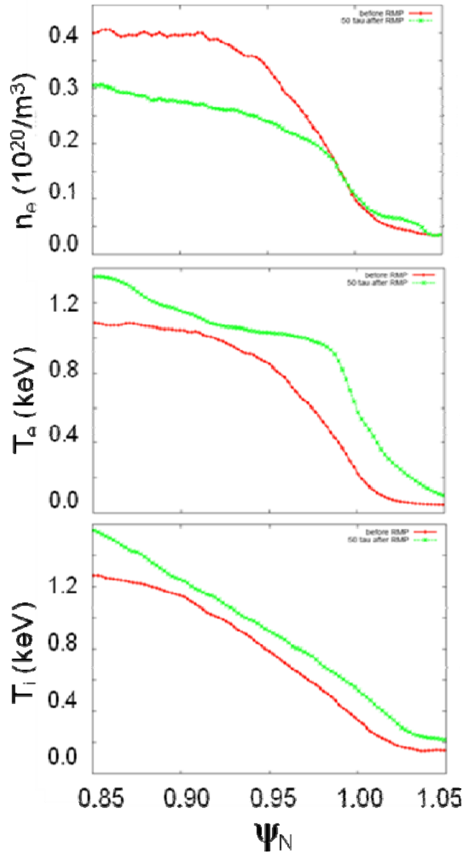

Fig. 3. Numerically obtained change in plasma density and temperature profiles before (red) and 4ms after (green) the RMP turn-on.

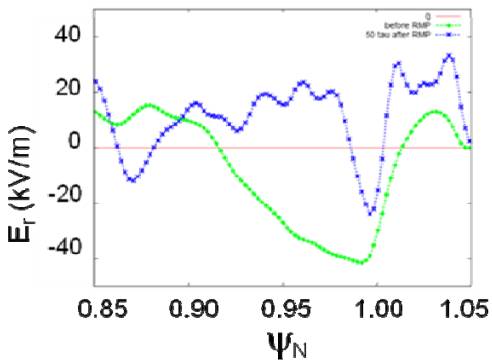

Fig. 4. Numerically simulated change of E_r profile from XGC0 before (green) and 40ms after (blue) the RMP turn-on

III. Results

In the case shown here, 6 MW of heat flux from the core plasma, as suggested by experiment, is evenly divided into ions and electrons at the core-edge boundary (ψ_N=0.8) and the neutral recycling coefficient of 0.9 is used. 4 N-m of toroidal torque is also added at the core-edge boundary, again suggested by experiment. Figure 3 shows the time evolution of the radial pedestal electron density n_e, electron temperature T_e, and the ion temperature T_i. just before and about 4 ms after the RMP turn-on. An ambipolar anomalous transport, on top of the Lagrangian neoclassical particle motions, is included in the form of a radial random walk of the guiding center particles. Radial anomalous transport at the level of $D=\chi_e=\chi_i=0.2\ m^2/s$ is found to be necessary to reproduce the experimental plasma profile before the RMP turn-on. After the RMP turn-on, the anomalous transport is left at the same level, which is much smaller than the RMP-driven transport level hence will not mask the RMP transport study.

Pump out of the plasma density, increase in the electron temperature, and the narrowing of the transport barrier can be seen from Fig. 3, qualitatively consistently with experimental observations as shown in Fig. 1. Figure 4 shows the radial profile change in E_r by RMPs. It can be seen that the negative E_r well structure is preserved to some degree, with the width being reduced. This is again qualitatively consistent with the experimental observation as shown in Fig. 2.

We note here that the simulation time scale of 4 ms after the RMP turn-on is much shorter than the real experimental time scale. In the simulation, the plasma density and temperature profiles are still evolving, while the E_r profile shows saturation. When the heat and particle sources balance the losses at a later time, the plasma density and temperature profiles are expected to saturate. We will attempt such a longer simulation in the future.

We also note here that the radial profile of the perturbed magnetic field lines and Poincare puncture plot (Fig. 5) show a significant localized reduction of the radial resonant RMP components (thus, the local stochasticity of the field lines) in the close vicinity of the magnetic separatrix where the transport barrier still survives. It can be observed that a significant level of magnetic stochasticity still remains deep into the core plasma. These observations explain the reduction in the transport barrier width, the survival of the negative E_r well at reduced width, and the particle loss from deep in the core plasma. Disappearance or significant reduction of the magnetic island structures in the edge pedestal, when compared with vacuum RMPs, can also be noticed from the Poincare puncture plot.

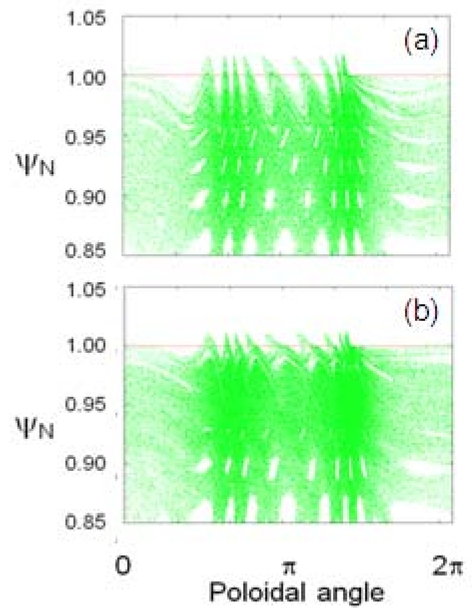

Fig. 5. Poincare puncture plot of the magnetic field in poloidal angle – radius plane for (a) vacuum RMPs and (b) with plasma response.

Detailed new study of the plasma transport in stochastic magnetic field has been reported in Ref. [6], using vacuum RMPs in a realistic diverted tokamak plasma. Reference [6] shows the inapplicability of the Rechester-Rosenbluth theory to a tokamak plasma due to the important role played by trapped particles in toroidal geometry. The same basic mechanisms hold in the plasma-distorted RMPs: The particle transport is significantly enhanced by the modified E_r in the non-axisymmetric magnetic perturbation, which creates a toroidal friction between the trapped and passing ions leading to enhanced radial particle transport. The electron heat flux is significantly reduced from the Rechester-Rosenbluth value dominantly because of the trapped particle effect. Trapped particles reverse their parallel streaming directions before they reach the stochastic decorrelation distance. Self-consistent ambipolar E_r and the trapped particle dynamics are important factors in getting the correct transport processes in non-axisymmetric magnetic field.

IV. Conclusion and discussion

A self-consistent kinetic simulation of the RMP penetration into plasma and the edge pedestal transport has been obtained. The results are qualitatively consistent with the modeled DIII-D discharge, in the density, the temperatures, and the radial electric field behaviors. Plasma rotation also shows qualitatively correct behavior, with increase in the co-current direction.

Detailed experimental validation will not be limited to DIII-D in the future, but to be extended to other conventional tokamaks, such as JET, as well as to the low aspect-ratio devices, MAST and NSTX, which have much stronger trapped particle kinetic effects than

DIII-D or JET and which are expected to show different kinetic behavior upon RMPs. After a satisfactory validation in the present devices, the code framework will be used to predict the RMP effect on ITER plasma.

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