GYROKINETIC-MHD COUPLED SIMULATION OF RMP PENETRATION AND PLASMA TRANSPORT IN TOKAMAK EDGE PLASMA REPRODUCES DENSITY PUMP-OUT

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Abstract

The gyrokinetic neoclassical particle-in-cell code XGCa coupled to the MHD code M3D-C1 is applied to study particle and energy flux in the presence of resonant magnetic perturbations (RMP) in a model DIII-D H-mode plasma. The simulation produces density pump-out and steepening electron temperature pedestal around $\psi_N \sim 0.99$. The basic physics is explained as a neoclassical 3D effect. Effects from plasma turbulence are left for future work.

1 INTRODUCTION

Externally applied small amplitude 3D perturbations of the equilibrium magnetic field in tokamak fusion reactors, called resonant magnetic perturbations (RMP), have become an important tool for suppressing or at least mitigating edge localized mode (ELM) activity [1] in high-confinement mode (H-mode) operation. Since the predicted violent ELM bursts in ITER operation scenarios could produce transient heat loads on the reactor wall that are large enough to result in unacceptably short lifetime of divertor components [2], RMP coils for ELM control have been included in the ITER design [3]. However, a common side-effect of RMP fields in H-mode operation is increased particle flux that decreases the height of the density pedestal [4], an effect that is generally called density pump-out. Pump-out occurs with or without ELM suppression [5], and understanding its physics basis is important for developing predictive understanding because it can degrade fusion efficiency [6].

Penetration of the external RMP field into the plasma, together with its effects on (neoclassical and turbulent) plasma transport and ELMs, constitute a multi-scale, multi-physics problem that has not been well understood yet. There have been too many papers on the issues related to the 3D perturbation physics to introduce them in the present paper. We restrict ourselves to providing a few examples. Plasma response to an externally applied magnetic perturbation (mode penetration) is often studied with fluid or MHD models such as in Refs. [7, 8, 9]. Heyn et al. employ a linear kinetic model to compute the plasma response [10]. Past studies of RMP mode penetration, however, do not include neoclassical and turbulent transport consistently. Plasma transport in kinetic codes, on the other hand, has been studied under a given 3D perturbed magnetic field [11, 12, 13, 14, 15].

In this work, we study neoclassical plasma transport using coupled simulations with the edge gyrokinetic-neoclassical code XGCa [16, 17] and the extended MHD code M3D-C1 [18]. The advantages of this approach are the use of the screened RMP field computed by M3D-C1 (instead of a manually modified vacuum field as in Ref. [11]), and the use of a total-$f$ (instead of $\delta f$ as in Ref. [19]) gyrokinetic code that retains the full neoclassical driving force, evaluates radial and poloidal electric fields self-consistently, uses a fully-nonlinear collision operator, covers the whole plasma volume including the SOL, and takes into account neutral particle recycling. Our approach can easily be extended to include either a phenomenological turbulent transport model in XGCa or self-consistent neoclassical and turbulent transport by using the gyrokinetic turbulence code XGC1 [17] instead of XGCa. Kinetic calculation of the screened 3D magnetic field perturbation consistently with the kinetic plasma transport, using an Ampère’s equation solver in XGCa (such as in Ref. [20]), or iterative solution of the RMP penetration and the kinetic plasma transport between M3D-C1 and XGCa can also be considered.

One issue in understanding the plasma pump-out at the top of the pedestal without involving the full kinetic particle dynamics has been the lack of enhanced ion particle transport across the nested KAM surfaces formed in an MHD-screened RMP field. Magnetic flutter effect has been used to explain
the enhanced electron transport, but its effect on the ions is negligible [21]. Due to the ambipolarity requirement, the radial plasma pump-out cannot occur unless the ions can follow the enhanced electron transport. Our simulations exhibit a significantly enhanced ambipolar particle flux throughout the pedestal in the presence of an RMP field, despite the existence of intact nested toroidal flux-surfaces at the pedestal top. We investigate the kinetic mechanisms that are the cause for the enhanced particle flux and demonstrate that, in the case studied for this work, collisionless 3D transport is not sufficient to explain the density pump-out observed in experiments. Moreover, we observe substantial changes in the \( \mathbf{E} \times \mathbf{B} \) shearing rate that may influence turbulent transport.

The remainder of this article is organized as follows. The numerical approach to the density pump-out problem is explained in Sec. 2. In Sec. 3 we describe the time evolution of the plasma density and temperature in the presence of an RMP field. A detailed study of the radial particle and energy flux is given in Sec. 4. The RMP effect on the radial electric field is discussed in Sec. 5, and conclusions are given in Sec. 6.

2 NUMERICAL APPROACH

The simple workflow used for this work consists of a one-way coupling in which, as the first step, both the axisymmetric equilibrium magnetic field and the 3D perturbations generated by the RMP coils are computed in M3D-C1. The (two-fluid) plasma response currents are included in these calculations. Descriptions of this process can be found in Refs. [7, 22, 23].

In the second step, the axisymmetric equilibrium magnetic field and the 3D perturbation obtained from M3D-D1 are read in XGCa for gyrokinetic calculation of plasma ion and electron transport. XGCa is a total-f, electrostatic, gyrokinetic particle-in-cell code specialized in neoclassical simulation of boundary-plasma. A comprehensive summary of the edge specific features of XGCa, most of which are shared with the gyrokinetic turbulence code XGC1, can be found in Ref. [17]. Here, we list only those physics capabilities that are most relevant for the discussion in the remainder of this article. Because of the smallness of the 3D magnetic perturbation \( |\delta B/B| = \mathcal{O}(10^{-3}) \), we assume the toroidal variation of the electrostatic potential to be small so that an axisymmetric Poisson solver can be used for lowest order accuracy. Possible error from this assumption will be investigated in the future by using a 3D solver in XGC1. In order to model radiative cooling in the edge and SOL, cooling is applied with the total cooling power adjusted such as to hold the electron temperature on the separatrix at a value close to experimental measurements, between 70 and 100 eV. The XGCa simulations are initialized without RMP field and run for four edge toroidal ion transit times \( \tau_i \sim 0.1 \) ms (computed for deuterium ions at 200 eV) to establish a quasi-steady neoclassical transport state that sets the baseline for the comparison of the transport levels with and without the RMP field. To save computing time while minimizing the transient oscillatory behavior triggered by changes of the magnetic field, the RMP field is ramped up linearly over \( 2\tau_i \), which is significantly shorter than the experimental ramp-up time of about 100 ms [6]. Because of the fast radial dynamics of marker particles, the quick saturation of the radial electric field with RMP field, and the significant computational cost of the simulations, the time interval studied is restricted to the first approximately 0.5 ms after the RMP field is switched on. Core heat and torque sources as well as an anomalous transport module available in XGCa are not used because the focus of this study is neoclassical 3D transport and because of the short time scale allowed for the simulations.

We investigate a case based on the DIII-D H-mode discharge 157308 which has been studied recently by Lyons et al. with an integrated workflow (comprised of M3D-C1 and other codes) aimed at predicting the plasma response to external RMP fields [24]. The axisymmetric equilibrium magnetic field and the RMP perturbation are calculated in M3D-C1 based on an EFIT [25] reconstruction at 4.2 ms into the discharge when the \( n = 3 \) RMP field is already at full strength. Figure 1 a) shows a Poincaré plot of the total magnetic field, which exhibits a narrow edge layer at \( \psi_N \gtrsim 0.98 \) in which the magnetic field becomes increasingly stochastic and field lines are connected to the material wall. From this observation, it is straightforward to understand why increased radial particle flux can be expected due to the RMP field at the pedestal foot. In the region around the pedestal top \( \psi_N \approx 0.95 \), however, closed flux-surfaces exist between mode rational surfaces that separate the stochastic or island regions into many bounded layers.

For the purpose of studying the density pump-out, the initial density, temperature, and rotation profiles are chosen to correspond to the plasma state before the application of the RMP field. The initial toroidal rotation profile corresponds to the toroidal rotation of carbon impurities. The initial density profile in the edge pedestal is shown in Fig. 1 b) together with the location of the primary \( n = 3 \) resonant surfaces (dotted lines) and the banana orbit width \( \Delta_b \) of a thermal deuterium ion at the location of the
maximum of the plasma pressure gradient (dashed lines). The fact that the density pedestal width is comparable to $\Delta_B$ while the structure of the 3D perturbed field is on a much smaller scale ($\sim$ ion gyroradius) is another hint at the importance of kinetic treatment.

3 EVOLUTION OF DENSITY AND TEMPERATURE PROFILES WITH RMP FIELD

In the first part of our analysis of RMP induced transport, we provide a qualitative view of how the plasma density evolves with an RMP field. A more detailed analysis of the transport mechanisms for ions and electrons is given in Sec. 4.

There are two mechanisms that could increase transport over the axisymmetric neoclassical level in 3D perturbed fields: collisionless transport along perturbed field lines, and changes in collisional transport caused by the 3D perturbation. It is important to understand if one of the two is dominant. Therefore, we first compare the time evolution of the flux-surface averaged density between collisionless and collisional XGCa simulations.

The time evolution of the flux-surface averaged plasma density from the collisionless simulation is shown in Fig. 2 a). While the density at $t = 0.322$ ms, the time when the RMP field has just been turned on, hardly differs from the initial density inside the separatrix (it is slightly lower in the SOL due to the low recycling factor of 90%), an increased outward density flux can be seen just inside the separatrix ($\psi_N \gtrsim 0.98$) during and after the RMP ramp-up phase. The increased radial particle transport just inside the separatrix is caused by prompt particle losses from field lines connected to the material wall. At the pedestal top, however, the density changes very little on the time scale of the simulation. The results demonstrate that collisionless transport in the case studied here cannot be responsible for the density pump-out observed in experiments.

Figure 2 b) shows the flux-surface averaged plasma density from the collisional XGCa simulation. The density inside the separatrix changes very little in the first 0.3 ms of the simulation reflecting the smallness of neoclassical density flux. When the ramp-up of the RMP field starts at $t = 0.319$ ms (the ramp-up ends at $t = 0.479$ ms), the density profile changes noticeably even on the short timescale covered by the simulation. There is a clear reduction of the density from the pedestal top to the pedestal center ($0.93 \lesssim \psi_N \lesssim 0.97$), and an increase in the SOL.

The time evolution of the flux-surface averaged ion and electron temperatures in the collisional case is shown in Figs. 2 c) and d). The ion temperature $T_i$ in the SOL drops quickly in the beginning of the simulation due to initial transient orbit loss and neutral particle recycling. Since there is no anomalous heat flux and core heat source, there is not enough heat flux to let $T_i$ recover. From the pedestal top to the pedestal center, $0.92 \lesssim \psi_N \lesssim 0.97$, $T_i$ changes little after the initial transient until the RMP field is turned on. [Therefore, $T_i$ after the initial transient is not shown in Fig. 2 c).] Then, $T_i$ decreases faster than without RMP field in this region indicated by the temperature drop between $t = 0.32$ ms and 0.62 ms. In a narrow layer around the separatrix, $0.995 \lesssim \psi_N \lesssim 1.01$, $T_i$ actually starts to increase. The electron temperature $T_e$ hardly changes without RMP field because axisymmetric neoclassical electron heat transport is very small. With RMP field ($t \gtrsim 0.32$ ms), $T_e$ drops at $0.93 \lesssim \psi_N \lesssim 0.97$, but increases at $0.97 \lesssim \psi_N \lesssim 0.99$. The separatrix electron temperature does not change much due to the applied
cooling in the SOL. On a longer time scale, this suggests that the electron temperature profile will become steeper just inside the separatrix \(0.97 \lesssim \psi_N \lesssim 0.99\), similar to experimental observation [4, 11].

## 4 Analysis of Ion and Electron Transport Channels

We extend the qualitative description of the time evolution of the plasma density and temperature in Sec. 3 by a more quantitative analysis of the particle and heat fluxes. In the following the flux-surface average of a radial flux is computed along the unperturbed flux-surfaces given by the axisymmetric background magnetic field. For more accurate calculation of radial fluxes, we numerically separate adiabatic Maxwell-Boltzmann \(f_M\) and non-adiabatic \(\delta f\) components of the distribution function because (due to the cancellation properties of the adiabatic fluxes) the only relevant fluxes are the ones from the non-adiabatic distribution function. In the kinetic formulation of XGCa, fluxes across the unperturbed flux-surfaces result from three transport channels: the \(E \times B\) drift \(v_E \cdot \nabla \psi\), the magnetic inhomogeneity drift \(v_D \cdot \nabla \psi\), and the parallel flow along the perturbed field lines \(v_\parallel (\delta B/B) \cdot \nabla \psi\). In the following, we call the sum of the \(E \times B\) and magnetic drift fluxes “3D neoclassical fluxes”, and the fluxes along the perturbed magnetic field simply “3D \(\delta B\)-fluxes”. Particle flux \(\Gamma\) is defined as the moment of \(\delta f\) with respect to \(v \cdot \nabla \psi/\langle \nabla \psi \rangle\), kinetic energy flux \(Q\) as the moment with respect to \((m/2)(v_\perp^2 + v_\parallel^2)v \cdot \nabla \psi/\langle \nabla \psi \rangle\), and heat flux as \(q\) as \(Q - (5/2)eT\Gamma\). Note that ion moments are evaluated with the gyrocenter distribution function, not with the particle distribution function. Since particle fluxes in a gyrokinetic simulation are ambipolar and electrons in XGCa are driftkinetic, the particle flux \(\Gamma\) is equal to the electron flux \(\Gamma_e\). Effective transport coefficients \(D\) and \(\chi\) are evaluated with the simple transport model

\[
\begin{align*}
\frac{\partial \langle n \rangle}{\partial t} &= -\nabla \cdot \Gamma = \nabla \cdot \langle D \nabla \langle n \rangle \rangle, \\
\frac{3}{2} \frac{\partial \langle n T \rangle}{\partial t} &= -\nabla \cdot \left[ q + \frac{5e\langle T \rangle}{2}\Gamma \right] = \nabla \cdot \left[ \langle n \rangle \chi \nabla \langle T \rangle + \frac{5e\langle T \rangle}{2} D \nabla \langle n \rangle \right],
\end{align*}
\]

where the particle flux \(\Gamma\) and the kinetic energy flux \(Q = q + 5/2e\langle T \rangle\Gamma\) are computed in XGCa.
Time traces of the effective particle diffusivity $D$ and the heat conductivities $\chi_e$ and $\chi_i$ corresponding to Figs. 2 b), c), and d) are plotted on four flux-surfaces in the edge pedestal in Fig. 3. In the first approximately 0.3 ms of the simulations before the RMP field is switched on, the neoclassical particle diffusivity in the pedestal region $0.94 \lesssim \psi_N \lesssim 1$ is of the order of $10^{-3} \text{m}^2\text{s}^{-2}$, and can barely be registered on the scale of the diffusivity with RMP field at $t > 0.32$ ms. During the ramp-up phase of the RMP field, the particle diffusivity increases close to linearly until the end of the ramp-up phase at $t \approx 0.48$ ms. Afterwards, the transient diffusivity settles down to an almost steady state, with $D \approx 0.2 \text{m} \text{s}^{-2}$ in the stochastic layer $\psi_N \gtrsim 0.98$ and $D \approx 0.05 \text{m} \text{s}^{-2}$ at $0.94 \lesssim \psi_N \lesssim 0.98$. These values are comparable to experimental results [4]. Compared to the transport level without RMP field, the diffusivity is elevated by a factor between 10-30 at $0.95 \lesssim \psi_N \lesssim 0.98$. While the ion heat conductivity $\chi_i$ does not differ much between the pre-RMP phase ($t \lesssim 0.32$ ms) and the later RMP phase ($t \geq 0.5$ ms), the electron heat conductivity $\chi_e$ changes significantly under the influence of the RMP field. At $t \lesssim 0.32$ ms, $\chi_e \approx O(10^{-3}) \text{m} \text{s}^{-2}$. With RMP field, $\chi_e \approx 0.12 \text{m} \text{s}^{-2}$ at $\psi_N \approx 0.99$. But at $0.95 \lesssim \psi_N \lesssim 0.98$, $\chi_e$ is slightly negative with a minimum of approximately $-0.02 \text{m} \text{s}^{-2}$. There is a cancellation between the radially inward thermal pinch and the convective energy transport in the electron temperature equation (1). This heat pinch together with the very small electron temperature right around the separatrix and in the SOL, is responsible for the heating of the pedestal center region around $\psi_N \sim 0.98$.

A comparison of the transport channels introduced at the beginning of Sec. 4 provides a useful insight into differences between ion and electron transport. Radial profiles of the ion gyrocenter and electron particle fluxes at the end of the collisional XGCa simulation are shown in Fig. 4 a). For electrons, the $\delta B$-flux is clearly the dominant transport mechanism. The 3D neoclassical flux is almost negligible in comparison. Due to the high thermal velocity of electrons, this is easy to understand. Collisions enable electrons to drift across (the perturbed) flux-surfaces. Then, the rapid parallel electron dynamic is picked up as net radial flux across the unperturbed surface as 3D $\delta B$-flux. In case of the ions, which flow much slower along magnetic field lines, $\delta B$-flux and 3D neoclassical flux are comparable in the
pedestal top region with the neoclassical flux being somewhat smaller. However, closer to the separatrix at $\psi_N \gtrsim 0.97$, as the ion temperature decreases, the 3D neoclassical flux increases and becomes the dominant transport mechanism. Note that a difference between the total ion gyrocenter and electron fluxes implies time-varying electric field. Because of the their low mass, the electron $\delta B$-flux is effectively regulated by the radial electric field (Sec. 5) [26, 14], which adjusts itself such that ion particle (not gyrocenter) and electron flux are ambipolar. In agreement with the different parallel dynamics of ions and electrons, we find that the onset of the ion gyrocenter flux during the RMP ramp-up phase lags the onset of the electron particle flux by approximately 0.07 ms, implying a rapid change of the radial electric field. This time lag corresponds to the toroidal ion transit time of a 500 eV deuterium ion, which corroborates the kinetic nature of increased particle flux in tokamaks with RMP field.

5 3D EFFECT ON EXB SHEAR

The radial electric field acts as an important regulator of 3D electron particle flux (and turbulent transport). Our transport analysis in Sec. 4 implies that the electric field must change due to the RMP field. Figure 4 b) shows the $E \times B$ shearing rate along the outer midplane at the beginning and end of the RMP ramp-up, as well as at 1$\tau_i$ and 2$\tau_i$ after the end of the RMP ramp-up. Since the initial shearing rate is zero, it is not shown in Fig. 4 b). The shearing rate profile shown in Fig. 4 b) implies the existence of a strong radial electric field ($E_r$) well with two dipolar $E \times B$ shearing layers. During the ramp-up of the RMP field, the shearing changes very rapidly in agreement with the greater difference between ion gyrocenter and electron particle flux mentioned in Sec. 4. The outer shearing layer moves inward from $\psi_N \approx 1$ to $\psi_N \approx 0.99$ during the RMP ramp-up phase and the maximal shearing rate drops from $\approx 30$ MHz to $\approx 10$ MHz. The inner shearing layer also weakens as it moves slightly inward. These observations imply that edge $E_r$ well becomes shallower. The fast time evolution at $\psi_N \gtrsim 0.98$ is caused by the prompt losses of electrons along field lines connected to the wall. Because of their high thermal velocity, electron flux on those field lines is much faster than ion gyrocenter flux, especially at the beginning of the RMP ramp-up phase. Consequently, radial electric field and shearing rate change most where field lines are connected to the material wall to counter the electron loss and increase ion orbit loss to ensure quasi-neutrality. After the RMP ramp-up, $E_r$ and $\gamma_{E \times B}$ evolve much slower along with the relaxation of the density pedestal indicating that ion gyrocenter flux and electron particle flux have become comparable. The observed changes of the shearing rate imply a possible change of the turbulent transport that is not included in the current study. We plan to use the XGC1 code [17] to assess how turbulence is affected by the RMP field.

6 CONCLUSIONS

Coupled gyrokinetic-MHD simulations of a model DIII-D H-mode discharge with the codes XGCa and M3D-C1 exhibit increased particle flux in the entire edge pedestal consistent with the transport level required for density pump-out [see Figs. 2 b) and 3 a)]. The simulations also produce a steepening of the electron temperature pedestal around $\psi_N \sim 0.99$. The basic physics is explained as a neoclassical (collisional) 3D effect. Plasma turbulence has not been considered here and is left for future work. The density pump-out occurs in spite of the presence of intact nested toroidal flux-surfaces (KAM surfaces) in the pedestal top region. Compared to neoclassical transport in the absence of 3D magnetic perturbations [$D \sim O(10^{-3})$ m$^2$s$^{-1}$], the effective particle diffusivity is elevated by a factor of approximately 10-30 in the pedestal region [$D \sim O(0.1)$ m$^2$s$^{-1}$], which results in sizable particle flux due to the steep pedestal gradient. A comparison of particle fluxes in collisionless and collisional simulations demonstrates that collisionless 3D transport is too small to cause density pump-out, and that the RMP induced enhancement of the neoclassical particle flux is a collisional effect. The kinetic transport mechanisms for ions and electrons have been identified. Ion particle flux is still dominated by the usual collisional balance of $E \times B$ and magnetic inhomogeneity drift fluxes, which is equivalent to diamagnetic fluxes caused by a parallel pressure gradient in the fluid picture. Due to the high thermal velocity of electrons, however, radial electron particle flux is dominated by parallel streaming along the perturbed magnetic field lines with collisions refilling this loss channel by enabling electrons to drift across the perturbed flux-surfaces.

Inward electron thermal pinch effect is observed in the pedestal just inside the separatrix surface, which cancels the outward convective energy transport to some degree and produces the RMP-steepening of the electron temperature profile around $\psi_N \sim 0.99$. This is similar to the phenomenon observed in many experiments.
Both the ion and electron transport channels are regulated by the radial electric field, which adjusts such that ion and electron fluxes are ambipolar. The changes of the $E \times B$ shearing rate are large enough that changes of turbulent transport can be expected. This will be studied by importing the perturbed magnetic field in the gyrokinetic turbulence code XGC1 [17]. While our simulations show that neoclassical transport in the H-mode pedestal in the presence of an RMP field is large enough to cause relaxation of the density pedestal on the experimental density pump-out time scale, the simulated time interval is not long enough to study the density pump-out from the core into the pedestal, which is necessary to obtain density pump-out as observed in experiments. This core-to-edge transport may also require core turbulence, which dominates over neoclassical transport, to be added to our numerical approach, e.g. by switching on a turbulent transport model available in XGCa.

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REFERENCES