Gyrokinetic PIC Study on RMP Affected Neoclassical Transport in Toroidal Plasmas

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In magnetically confined fusion plasmas, the breaking of 'magnetic flux-surfaces' due to resonant magnetic perturbations (RMPs) can generate magnetic islands and alter field topology to significantly impact plasma confinement and transport. This work investigates the effect of magnetic islands on neoclassical radial energy transport within the core plasma of an analytic circular tokamak using the XGC-S global gyrokinetic particle-in-cell code. Findings from our simulations revealed substantial enhancements in electron neoclassical radial energy diffusivity in and around the islands, in addition to a newly observed two-peak structure at the O/X-points and outer island boundary in the electron diffusivity profile.

Keywords: particle-in-cell, XGC-S, neoclassical transport, RMP, magnetic islands

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Toroidal nuclear fusion devices employ magnetic fields to confine hot plasmas, but the presence of resonant magnetic perturbations (RMPs), which may be used for the mitigation of edge-localised-modes (ELMs), can lead to the formation of magnetic islands, which can alter flux surface topology and affect energy transport. In this study, we use the X-point Gyrokinetic Code for Stellarators [1, 2] (XGC-S) to investigate the effects of magnetic islands on neoclassical radial energy transport in the core plasma of a circular tokamak. XGC-S is a global gyrokinetic Particle-in-Cell (PIC) code which does not assume axisymmetry and thus can model the non-axisymmetric topology of magnetic islands which follow the helical winding of flux surface field lines.

We have utilised an analytic magnetic field given by $\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$ with $\mathbf{B}_0 = \hat{R}(-B_{\rm ax}Z/qR) + \hat{\varphi}(-B_{\rm ax}R_{\rm ax}/R) + \hat{Z}(B_{\rm ax}(R - R_{\rm ax})/qR)$, and $\delta\mathbf{B} = \nabla \times (\alpha\mathbf{B})$ where $\hat{R}$, $\hat{\varphi}$, $\hat{Z}$ are the unit vectors in cylindrical coordinates, B_{ax} = 2 T, and $R_{\rm ax}$ = 1.2 m. Here, we have defined $\alpha \equiv \alpha_0 \cos\,(m\theta - n\phi)\, \exp\left[-\left(r_{\rm mn}^2 - r^2\right)^2 \Delta r^{-4}\right]$ in the present simulations. The RMP amplitude is fixed as $\alpha_0 = 2.0 \times 10^{-5}$ m for all cases in this paper. Here, m and n are the poloidal and toroidal mode numbers respectively, r is the minor radial position, $r_{\rm mn}$ = 0.242 m is the minor radial position of the rational surface with mode numbers (m, n) = (5, 2), a = 0.38 m is the minor radius, and Δr = 0.1 m is the RMP width. A Poincaré plot of the perturbed analytic field is given in Fig. 1. We assume a linearly decreasing background temperature profile with respect to the normalized minor radius r/a with $T = T_0 - T_1(r/a)$, where T_0 = 1.137 keV is the temperature at the magnetic axis and T_1 = 0.227 keV is the proportionality coefficient, neglecting the effects of the thin magnetic islands on the background temperature. The initial radial density profile is uniform, and all ions are hydrogen. Under these conditions the electron and ion thermal gyroradii at the magnetic axis are ρ_e = 56.9 μm and ρ_i = 2.44 mm respectively. The affected

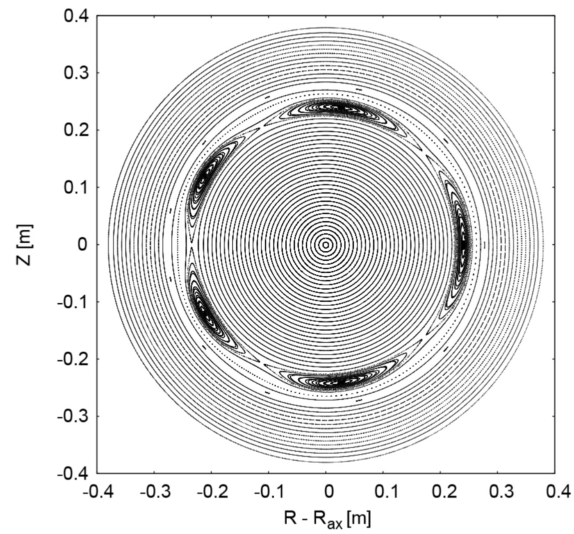

Fig. 1. Poincaré plot of the perturbed analytic magnetic field.

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rational surface has mode numbers ($m = 5, n = 2$), with the safety factor $q^{-1} = 0.48 - 0.2669(r/a)^4$. To account for the toroidal asymmetry of magnetic islands, XGC-S employs particle-mesh interpolation on fine unstructured meshes, whereby the weighted contribution of charge of each marker particle is calculated and distributed to adjacent poloidal cross sections. This particle-mesh interpolation is involved in the estimation of the radial energy diffusivity. The mesh interpolation scheme is described in Moritaka *et al.* [1].

In our simulation setup XGC-S solves the complete gyrokinetic equation including the relaxation of background plasma due to all magnetic drifts using the complete δf methods described by Trivedi *et al.* [3]. Collisions are handled by the Monte-Carlo methods of Boozer *et al.* [4], which have been benchmarked in XGC-S against FORTEC-3D via cross-comparison with GT5D as overviewed by Matsuoka *et al.* [5] which uses more sophisticated collision models in the LHD configuration. The simulation reached a steady state and flattening of the electron pressure profile in the island regions was observed as shown in Fig. 2, where we see the 2-D profile of time averaged normalised pressure perturbation. Similar ion pressure flattening was also observed but was very small in comparison.

Neoclassical diffusivity results from XGC-S were benchmarked against neoclassical theory for ions [6] and against the drift kinetic code KEATS (Kanno *et al.* [7]) for electrons; good agreement was seen in cases without RMPs.

The results of our simulations revealed enhancements in electron radial energy diffusivity near the magnetic islands, where multiple peaks in the diffusivity profile indicated localized radial energy flux (Fig. 3(b)). The ion response was substantially smaller due to their significantly greater inertia (Fig. 3(b)). The largest diffusivity peak was observed at the point of maximum RMP amplitude $r/a = 0.636$, which is close to the island O/X-points, and a prominent second peak is observed close to the outer magnetic island boundary. The deviation of the main diffusivity peak from $r/a = 0.636$ could be due to the difference in position of the island O/X-points and the position of peak RMP amplitude. We interpret the electron energy diffusivity profile as that the contribution from X-points constitutes much of the most prominent diffusivity peak located at $r/a = 0.636$ in Fig. 3(a) which is the poloidally averaged profile. This aligns with the fact that closed magnetic flux surfaces are constructed around the O-point.

In conclusion, a simulation study was conducted on RMP affected neoclassical transport using the global gyrokinetic code XGC-S in a circular tokamak configuration. Results newly revealed distinct regions of diffusivity enhancement in the vicinity of magnetic islands. The ion response was almost negligible in comparison. We observed multiple diffusivity peaks in radial profiles, suggesting locality of the underlying mechanism of diffusivity enhancement along the magnetic island boundaries.

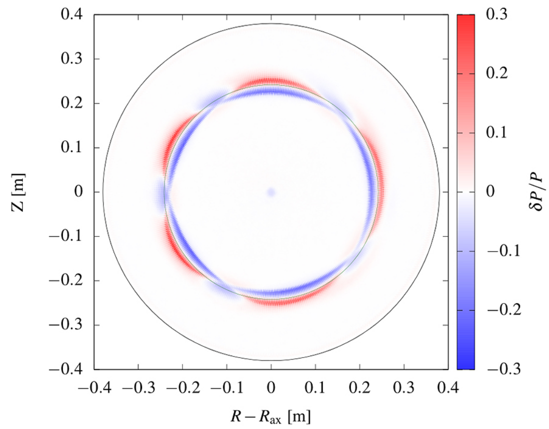

Fig. 2. Time averaged 2D profile of total normalised pressure perturbation with initial density of $n = 4 \times 10^{19}$ m^{-3}.

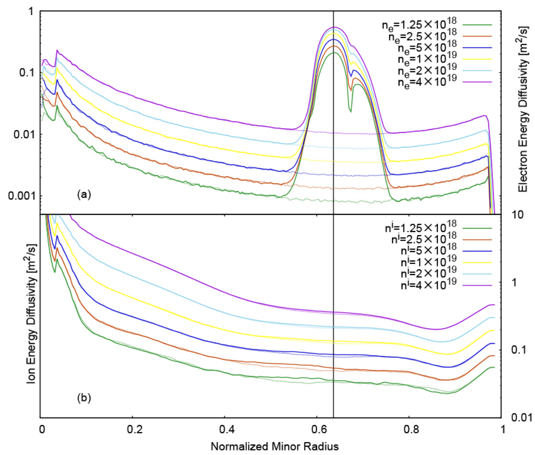

Fig. 3. (a) Radial ion energy diffusivity as calculated by XGC-S with (solid) and without (dashed) the presence of magnetic islands at the vertical line. (b) Radial electron energy diffusivity as calculated by XGC-S with (solid) and without (dashed) the presence of magnetic islands at the vertical line.

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