BOUT++ SIMULATION STUDY OF THE EFFECT OF RESONANT MAGNETIC PERTURBATION ON THE TURBULENCE TRANSPORT

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The resonant magnetic perturbation (RMP) has been demonstrated as an effective way for controlling edge-localized modes (ELMs). Accompanied with the RMP-induced ELM suppression, the density pump-out phenomenon [1-3] has been also observed. Several mechanisms have been proposed to explain this phenomenon. One possible mechanism is the forming of magnetic islands in the pedestal region or the stochastic magnetic fields at the edge, both of which enhance radial particle transport [4, 5]. The neoclassical toroidal viscosity (NTV) effects [6] due to the break of the toroidal symmetry of the equilibrium magnetic field is also considered as a possible mechanism. Enhanced turbulent transport also contribute to the density pump-out. After the suppression of ELM using resonant magnetic perturbations (RMPs) in devices such as EAST, ASDEX Upgrade, HL-2A, and DIII-D, an enhancement in density fluctuations has been observed.

In this work, the effect of magnetic perturbations on turbulent transport is focused. To investigate the underlying mechanism, a BOUT++ six-field two-fluid numerical simulation scheme is developed to introduce the perturbed magnetic field induced by RMP $\vec{B}_{\mathrm{rmp}}$. The unit equilibrium magnetic field vector $\vec{b}_0$ is defined as the sum of the equilibrium and perturbed magnetic fields, i.e. $\vec{b}_0 = \vec{b}_0^{'} + \vec{B}_{\mathrm{rmp}} / \left|\vec{B}_0^{'}\right|$, and for the physical quantity F $\nabla_{\parallel}^0 F = \vec{b}_0^{'} \cdot \nabla F + \vec{B}_{\mathrm{rmp}} \cdot \nabla F / \left|\vec{B}_0^{'}\right|$.

The simulation is based on the discharge profiles of EAST #94048 during n = 4 RMP-induced ELM suppression. The plasma response field is calculated using CLTx (Ci-Liu-Ti, meaning MHD in Chinese) [7]. As shown in Fig. 1, compared to the vacuum field, the resonant components of the response field are significantly shielded, reaching only 40% of the vacuum field, while some of the non-resonant components are amplified.

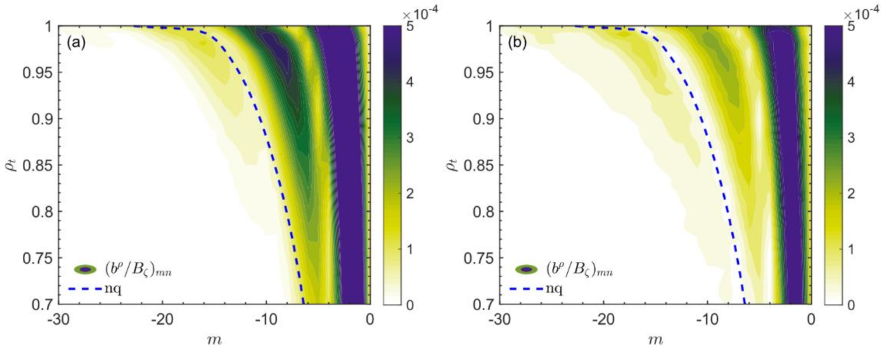

Figure 1. The calculated (a) vacuum field, (b) plasma response field using CLTx code.

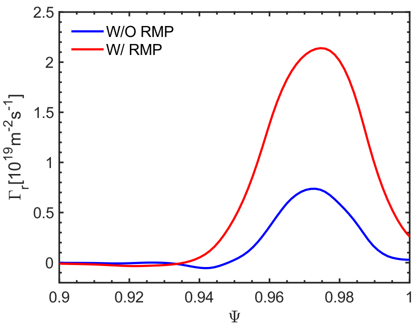

Figure 2. Simulated radial particle fluxes averaged over magnetic surfaces for the cases with (red) and without (blue) perturbed fields induced by RMP.

The numerical simulation results show that, after considering the RMP, the radial particle flux in the pedestal region is significantly increased, reaching approximately four times that of the case without RMP, as shown in Fig. 2. As the radial particle flux can be expressed by the product of the amplitudes of density and electric potential perturbations and sine of the phase difference between them, it is found that the increase in the radial particle flux is due to both factors: (1) The amplitudes of density fluctuations and electric potential perturbations are enhanced as shown in Fig. 3, especially for the modes of n = 8, 12, 16 and 20, which are found to have about 70% contribution to the total particle flux. (2) When including RMP induced perturbed fields, as shown in Fig. 4 for n = 16 mode as an example, the phase difference remains ~ $\pi/2$ for most of the time, which facilitates the outward particle transport.

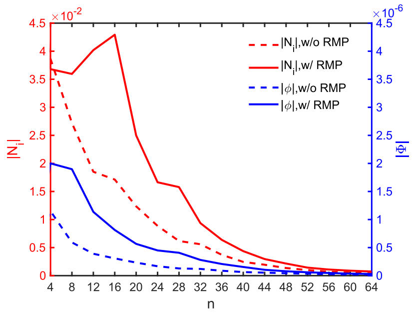

Figure 3. The amplitudes of density and potential fluctuations for different toroidal mode numbers. The red line represents the density perturbation amplitude, the blue line represents the electric potential perturbation amplitude. Solid lines indicating results with RMP and dashed lines indicating results without RMP.

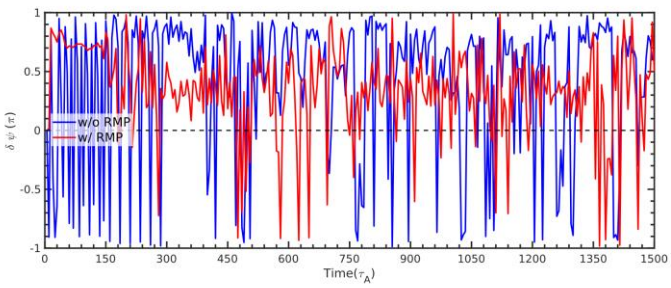

Figure 4. Time evolution of the phase difference between the density and electric potential fluctuations for the n=16 mode. The blue lines represent results without RMP, while the red lines represent results with RMP.

In summary, based on the BOUT++ simulations, it is found that the RMP induced three-dimensional field leads to a significant enhancement of turbulent transport. The increase in the radial particle flux is not only due to the increase in fluctuation amplitude, but also the change in phase difference between the density and electric potential fluctuations. Further simulations are ongoing for different perturbed field strengths to investigate the relation between the radial particle flux and the strengths of RMP field. The interaction between the perturbed field and the peeling-ballooning modes will be further analyzed.

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