Effects of dynamic magnetic islands on bootstrap current in toroidal plasmas

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Abstract

Effects of dynamic magnetic island on bootstrap current in toroidal plasmas are investigated based on the first principles of drift-kinetic particle simulation. The perturbed magnetic and electric fields associated with the dynamic magnetic island are calculated self-consistently from a three-dimensional toroidal MHD code (CLT), instead of artificial imposed magnetic island perturbation. Kinetic simulation results indicate that the bootstrap current has an asymmetry in the poloidal direction. The poloidal asymmetry becomes more evident with increasing of the effective collision frequency v^*. Inside the static magnetic island, the bootstrap current is decreased as expected with the effective collision frequency $v^*=0.1$ (in the banana regime). In case of a tearing mode instability, the bootstrap current distribution changes significantly with inclusion of the induced electric field. The bootstrap current is mainly affected by the radial electric field $\boldsymbol{E}_r$ rather than the parallel electric field $\boldsymbol{E}_{//}$, because the perturbed $\boldsymbol{E}_r$ is much larger than the perturbed $\boldsymbol{E}_{//}$. If the bootstrap current turns on when the tearing mode saturates, the width of magnetic islands ascend rapidly and saturate again for both static and dynamic cases. But the saturated island width of the dynamic case is smaller than that of the static case because the magnetic islands in the dynamic case is rotated due to strong asymmetric distribution of the bootstrap current in the vicinity of the X-points.

Keywords: bootstrap current, drift kinetic simulation, magnetic island, Tokamak

Introduction

Tearing mode instability causes a topologic change of the magnetic field in a rational surface to form magnetic island structures in a tokamak. The fast parallel diffusion along magnetic field lines causes a flattening of the radial temperature, density, or pressure profiles in magnetic islands. The reduction of the bootstrap current inside the magnetic island resulted from the flattening of the plasma pressure will boost development of the tearing mode, which is so called the neoclassical tearing mode (NTM)[1]. NTM not only limits the maximum achievable plasma beta, but also leads to disruption in Tokamak. NTM instability typically occurs at high-performance plasma discharges with a high pressure inside the plasma. Therefore, it is a significant issue for ITER operating in an H-mode scenario[4].

The NTM dynamics involve many physics processes in different spatial and temporal scales, such as neoclassical effects, magnetic island dynamics, drift wave turbulence [6], and energetic particles [7]. Many kinetic and fluid simulations have recently been carried out to investigate NTM physics, including thresholds of the seed island size and linear and nonlinear island dynamics. In MHD numerical investigations on NTM[8] or DNTM[9], the bootstrap current in the Ohm's law is obtained from the fluid model with an average of the flux surface $j_{bs} = \langle \mathbf{B} \cdot \mathbf{J} \rangle_{bs} = -f\left(\varepsilon/B_\theta\right)\partial p / \partial r$. It is supposed that the island width W is much larger than the particle banana width w_b. Therefore, the bootstrap current completely vanishes inside the magnetic island. However, in the early phase of an NTM, the seed island size W is often nearly equal to particle banana width ($W \approx w_b$). In this limit, the kinetic simulation showed that the orbits of charged particles, especially ions, in the region around the island could overlap the island and provide the source of the pressure gradient inside the island. Therefore, a significant fraction of the bootstrap current survives inside the island[10]. Furthermore, our kinetic simulation shows that bootstrap current distribution is a poloidal asymmetry, which is not reported in the previous literatures.

It is helpful to recall the physical mechanism of the bootstrap current briefly. In an inhomogeneous magnetic field, such as tokamak, trapped particles with negative (or positive) parallel velocities will drift inwards (or outwards) and form the banana orbits. In the presence of a density gradient, it leads to an asymmetry in the velocity-space distribution. Consequently, it produces a parallel current, and we refer to it as the banana current. The diamagnetic current is caused by gyromotions of particles. Similarly, the physical origin of the banana current is the banana orbits of the trapped particle without collision. The banana current is only a small part of the bootstrap current and is carried by trapped particles. However, the main part of the bootstrap current is carried by passing particles and is generated through the collisional coupling of trapped and passing particles. To be more specific, the distribution has a discontinuity at the trapped-passing boundary. Collisions between the trapped and passing particles lead to the distribution to be continuous. The collisions result in trapped particles giving their momentum to passing particles that carry most of the bootstrap current. These two kinds of the bootstrap current can be ordered as follows: banana current: bootstrap current = ε: 1[10].

δf Monte Carlo calculation scheme was used to study a neoclassical transport and the bootstrap current[14]. In the presence of a magnetic island, Poli et al.[10, 18] found that a significant fraction of the ion bootstrap current can survive inside the island when banana-orbit widths of trapped ions w_b approach the island width $W \approx w_b$. The bootstrap current is no loss for the ratio $w_b/W \geq 1$. Wang et al. discussed the physics of the recovery of the ion density gradient inside the islands in various collision regimes. It suggested that the recovery of the pressure gradient, instead of finite banana-orbit effects, may play a more critical role in reducing the driving force of the ion bootstrap current in the evolution of the NTM[11]. However, because the banana-orbit widths of electrons is much smaller than that of ions, the effect of magnetic islands on the density gradient and the bootstrap current of electrons is more sensitive than that of ions. In the presence of a magnetic island, the electron bootstrap current level changes little in banana regime. But the bootstrap current is completely suppressed at the island centers in the plateau regime, and a small but finite bootstrap current can exist inside the islands in the collisional regime. Besides that, at the island separatrix, a steeper electron density gradient causes a high electron bootstraps current level [19].

However, the previous bootstrap current simulation based on the δf Monto Carlo method only considers the imposed static magnetic island perturbation in the form of $\delta\mathbf{B} = \nabla \times \alpha \cos\xi \mathbf{B}_0$, where $\mathbf{B}_0$ is the equilibrium magnetic field, α represents the strength of the perturbation, and ξ is the helical angle. However, during the evolution of the (neoclassical) tearing mode, an electric field $\boldsymbol{E}$ is induced by magnetic reconnection. The parallel component of the electric field $\boldsymbol{E}_{//} = (\boldsymbol{E} \cdot \boldsymbol{b})\boldsymbol{b}$ responds to acceleration or deceleration of the plasma along the flux surfaces. Furthermore, when magnetic field lines become stochastic, electrons are lost along these field lines while ions are trapped. Therefore, a strong radial electric field $\boldsymbol{E}_r$ appears [20]. The radial electric field $\boldsymbol{E}_r$ may affect the drift displacements and the orbits of charged particles and modify the parallel flow, which can noticeably enhance the bootstrap current [21].

We refer to the time revolution of magnetic island perturbation with the self-consistently induced electric field $\boldsymbol{E}$ as a dynamic magnetic island. The motivation of this work is to develop the kinetic NTM simulation. To be more specific, we will use high accuracy nonlinear MHD code (CLT)[23][24] in combination with the newly developed drift-kinetic bootstrap current model to study crucial NTM dynamics. The drift-kinetic bootstrap current $\boldsymbol{J}_{\mathrm{bs}}$ has been included in Ohm's law $\boldsymbol{E} = -\mathbf{v} \times \boldsymbol{B} + \eta(\boldsymbol{J} - \boldsymbol{J}_0 - \boldsymbol{J}_{bs})$ instead of an average of the flux surface $j_{bs} = -f(\varepsilon/B_\theta)\partial p / \partial r$.

This paper considers the effect of dynamic magnetic island perturbation on the bootstrap current. The perturbed magnetic and electric fields associated with the dynamic magnetic island are calculated self-consistently from a three-dimensional toroidal MHD code (CLT), instead of artificial imposed magnetic island perturbation. Surprisingly, our preliminary kinetic simulation results indicate that the bootstrap current distribution has a strong asymmetry in the poloidal direction. Moreover, the dynamics of magnetic islands induce an electric field which includes the parallel electric field $\boldsymbol{E}_{//}$ and the radial electric field $\boldsymbol{E}_{\mathrm{r}}$. The bootstrap current is mainly affected by the radial electric field $\boldsymbol{E}_{\mathrm{r}}$ rather than the parallel electric field $\boldsymbol{E}_{//}$ because $\boldsymbol{E}_{\mathrm{r}}$ is far larger than E//. Consequently, redistributed dynamic bootstrap current changes and rotates the topology of the magnetic island again.

The paper is organized as follows: in Section II, the formulation and verification of the neoclassical simulation scheme are present. Section III discusses the asymmetry bootstrap current for the equilibrium magnetic field, the flattened density inside the magnetic island, the bootstrap current in the static and dynamic magnetic islands, and magnetic islands respond to bootstrap current. The conclusion and discussion are given in Section V.

II. Formulation and verification of neoclassical simulation

In fusion plasma, kinetic simulations of toroidal plasmas have been applied to study instabilities, turbulences, and transports. Our focus is to study the neoclassical bootstrap current in dynamic magnetic islands in this work. We use a cylindrical coordinate system (R, ϕ, Z). The perturbed magnetic and electric fields associated with the dynamic magnetic island are calculated self-consistently from the CLT code[23][24]. In this case, we use an equilibrium with q=2 to calculate the tearing mode instability with m/n=2/1 islands, which is most catastrophic in tokamak experiment.

A. δf Mente Carlo method for neoclassical transport with dynamic magnetic Islands

In the guiding-center phase space ($\mathbf{X}$, $v_{//}$), $\mathbf{X}$ and $v_{//} = \boldsymbol{b} \cdot \dot{\mathbf{X}}$ denote the guiding-center position and the guiding-center parallel velocity, respectively. Then the kinetic equations for the guiding-center distribution function f with a dynamic magnetic island are given in the following form[25]:

$$\frac{df}{dt}=\frac{\partial f}{\partial t}+\dot{\mathbf{X}}\cdot\nabla f+\dot{v}_{//}\frac{\partial f}{\partial v_{//}}-C(f)=0$$
$$\frac{d\mathbf{X}}{dt}=\frac{1}{B_{//}^*}\left(v_{//}\mathbf{B}^*+\mathbf{E}^*\times\mathbf{b}\right) \tag{1}$$
$$\frac{dv_{//}}{dt}=\frac{Ze}{mB_{//}^*}\mathbf{B}^*\cdot\mathbf{E}^*$$

where $B_{//}^*=\mathbf{b}\cdot\mathbf{B}^*$ is the effective magnetic field $\mathbf{B}^*$ in the parallel direction, where the effective electromagnetic fields $\mathbf{B}^*=\nabla\times\mathbf{A}^*$ and $\mathbf{E}^*=-\nabla\Phi^*-\partial\mathbf{A}^*/\partial t$ are defined in terms of the effective electromagnetic potentials

$$\Phi^*=\Phi+\frac{1}{Ze}\mu B+\frac{m}{Ze}\left|\frac{\mathbf{E}\times\mathbf{B}}{B^2}\right|^2$$
$$\mathbf{A}^*=\mathbf{A}+\frac{mv_{//}}{Ze}\mathbf{b}+\frac{m}{Ze}\frac{\mathbf{E}\times\mathbf{B}}{B^2} \tag{2}$$

$\mathbf{E}$ is the perturbed electric field due to the dynamics of magnetic island or tearing mode. The distribution f is decomposed into a time-independent equilibrium part f_0 and a perturbed part δf. Local Maxwellian distribution is considered for this equilibrium $f_0=n_0(\mathbf{X})f_M$. The weighting scheme for the δf method of the kinetic particle simulation is adopted[14]. The particle weight $w=\delta f/f$ is expressed as:

$$\frac{dw}{dt}=-(1-w)\left(\frac{v_{//}^2\nabla\times\mathbf{b}_0}{\Omega}+\frac{\mu\mathbf{b}_0\times\nabla B_0}{m\Omega}+v_{//}\frac{\delta\mathbf{B}}{B_0}+\frac{\mathbf{E}\times\mathbf{b}}{B}\right)\cdot\boldsymbol{\kappa} \tag{3}$$

where $\boldsymbol{\kappa}=\nabla n_0/n_0+(E/T_0-3/2)\nabla T_0/T_0$ is associated with an equilibrium gradient scale parameter and $\Omega=ZeB/m$ is the gyrofrequency. The first and second terms of the bracket in RHS of Eq. (3) are the guiding center neoclassical drift velocity, including the magnetic curvature and gradient drift. The third term is the guiding center velocity in the direction of the magnetic field due to the magnetic flutter drive, and the fourth term is the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocity. This perturbed electric field $\boldsymbol{E}$ is induced by magnetic reconnection associated with the tearing mode instability.

As we know, the neoclassical transport is caused primarily by the varying depth of particle trapping in the magnetic well along the magnetic field with collision. The Monte Carlo pitch angle scattering model of the Lorentz collision operator is implemented to update the particle pitch angle $\lambda = v_{//}/v$ [14][26]

$$\lambda_{new} = \lambda_{old}\left(1-v_c\Delta t\right)+\left(R-0.5\right)\left[12\left(1-\lambda_{old}^2\right)v_c\Delta t\right]^{1/2} \quad (4)$$

where Δt is the size of the time step, v_c is the collisional frequency. The effects of the Lorentz scattering operator will be reproduced if $\nu_c\Delta t<<1$. R is a uniform random number between 0 and 1, and λ_{old} and λ_{new} are the pitch angles after and before collision.

B. Verification of bootstrap current calculation

To benchmark our simulation results with the analytic prediction in the absence of magnetic islands[12], the plasma parameters with the major radius R_0=3, the minor radius a=1, and B_0=1 are adopted. The safety factor q and density profiles are shown in Figure 1(a). With the specified marker weight $w=\delta f/f$, the bootstrap current within a selected magnetic surface can be calculated as follows[14][16]

$$J_b = \left\langle \frac{J_\parallel}{B} \right\rangle B_T = \left\langle \frac{1}{B}\sum_{i=1}^{N} q v_{//} w_i \delta\left(\mathbf{X}-\mathbf{X}_i\right)\right\rangle B_T \quad (5)$$

where $J_\parallel = \int q v_{//}\delta f dv^3$ and the brackets < > denotes the flux surface average. The effective collision frequency ($v^*=\varepsilon^{-3/2}vqR_0/v_{th}$) is defined as the physical collision frequency normalized by the bounce frequency, where $\varepsilon=r/R0$ is the inverse aspect ratio, v_{th} is the particle thermal velocity. A series of cases for different effective collision frequencies v^* is conducted. The bootstrap current is normalized by the collisionless limit value j_{b0}. The expression of the normalized analytic bootstrap current (j_b/j_{b0}) with dependence of the effective collision frequency v^* is [12]

$$J_b/J_{b0} \propto \frac{1}{1+\sqrt{v^*}+av^*} \quad (6)$$

Figure 2(a) shows the scaling of the bootstrap current with the fitting parameter a=0.74 instead of an analytic value a=0.54. J_{b0} is calculated at a low collisional frequency $v^*\sim10^{-3}$. The results from other codes indicate a similar scaling with a different fitting parameter a=1.44[16]. The simulation results agree with the analytic theory, and this numerical scheme is sufficiently accurate to measure bootstrap current.

Figure 2(b) shows that the bootstrap current reaches the steady-state in several collision times.

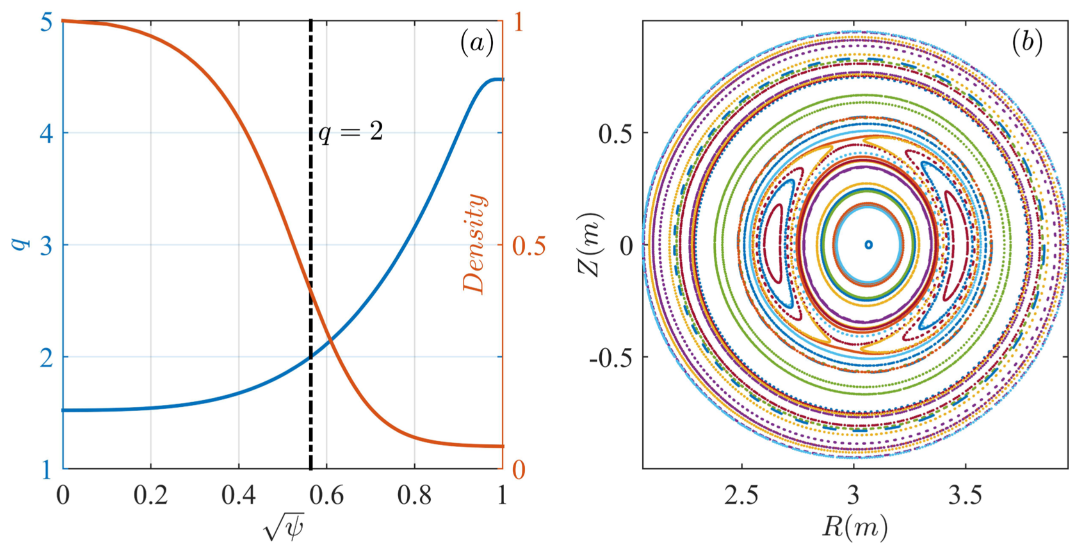


Figure 1. (a) Initial safety factor and density profile, (b)Poincare plots of the (2, 1) magnetic islands on the poloidal cross-section of toroidal angle ϕ=0°.

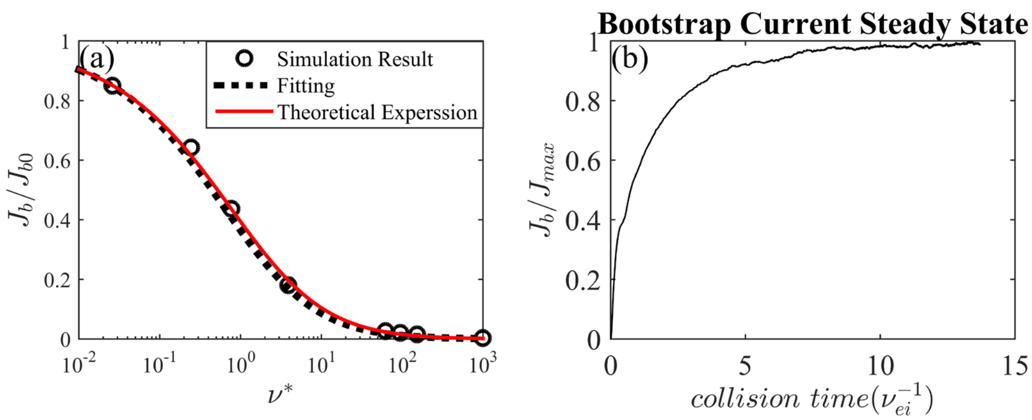


Figure 2. (a)Scaling of the bootstrap current J_b (normalized by J_{b0}) as a function of the effective collisional frequency v^*. j_{bo} is calculated at a low collisional frequency $v^* \sim 10^{-3}$. (b)The time evolution of the bootstrap current that reaches an asymptotic value in several collision time.

III. Simulation Results

a. Asymmetry bootstrap current at an equilibrium magnetic field

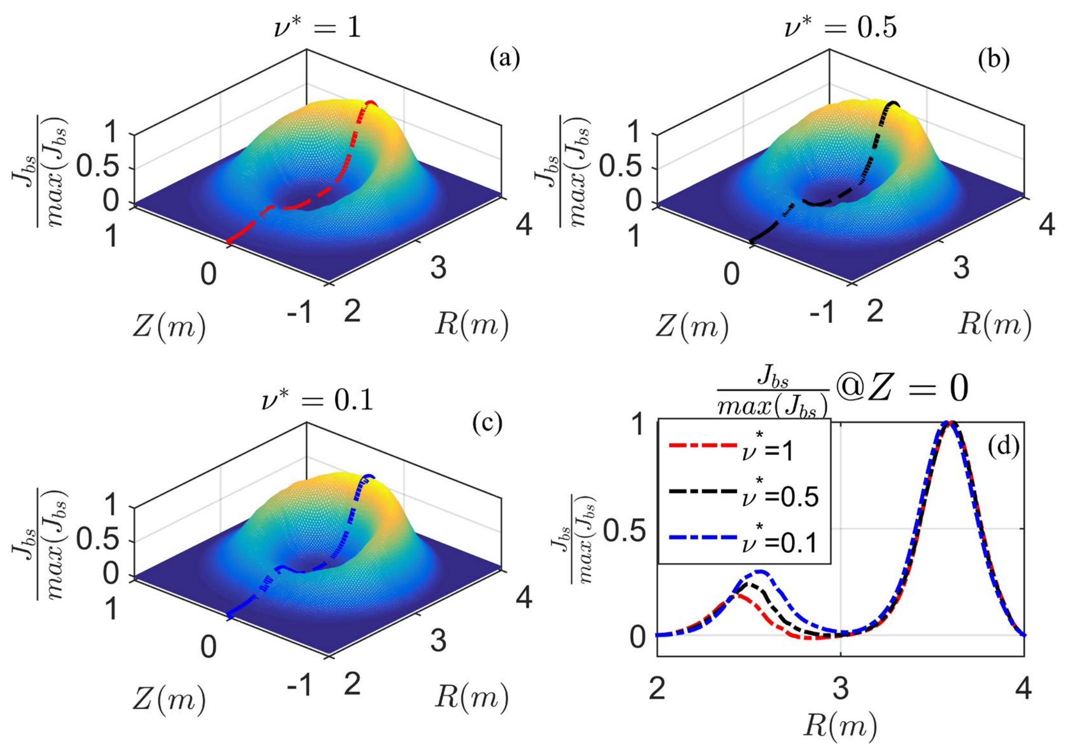


Figure 3. Bootstrap current distribution at difference effective collision frequencies v^* without a magnetic island.(a) v^*=1, (b) v^*=0.5 and (c) v^*=0.1. (d) the bootstrap current profile at the middle plane Z=0 with difference v^*=0.1, 0.5 and 1.

The bootstrap current distribution with difference effective collision frequencies v^* is studied without a magnetic island. The preliminary kinetic simulation result indicates that bootstrap current distribution has an strong asymmetry in the poloidal direction as shown in Figure 3 (a, b, and c). In order to clearly compare the poloidal asymmetry with difference v^*, we draw the bootstrap current profile at the middle plane Z=0 together in Figure 3(d). The poloidal asymmetry becomes more evident with the increase of the effective collision frequency v*. No matter how high the temperature (low v^*) is, the asymmetric distribution in the poloidal direction always exists. This asymmetric distribution of the bootstrap current is quite different from the conventional

HMD model. In previous HMD numerical investigations on NTM, the bootstrap current is obtained from the fluid model with flux surface average $j_{bs} = \langle \mathbf{B} \cdot \mathbf{J} \rangle_{bs} = -f\left(\varepsilon / B_\theta\right) \partial p / \partial r$. Therefore, the poloidal asymmetry in the bootstrap current distribution is ignorable.

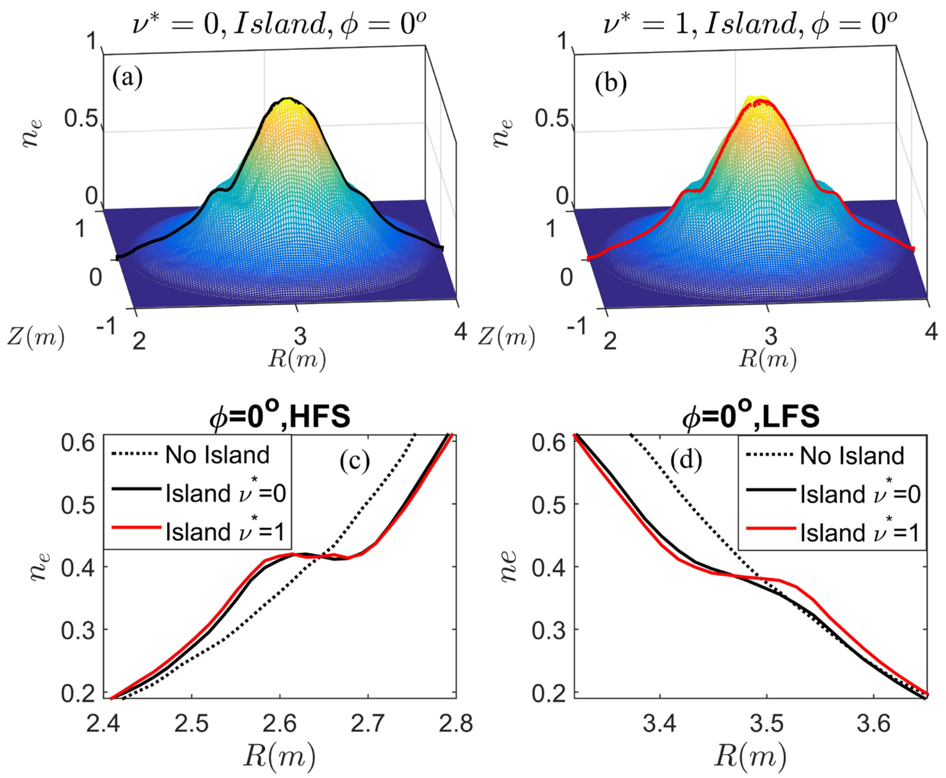
The physical mechanism of the poloidal asymmetric distribution of the bootstrap current can be explained by particle dynamics. The bootstrap current is generated through the collisional coupling of trapped and passing particles. Specifically, the number of trapped particles in the low field side (LFS) is much larger than in the high field side (HFS). Collisions between trapped and passing particles transfer momentum from trapped particles to passing particles in LFS. The momentum gained by passing particles contributes the bootstrap current. In other words, the bootstrap current is carried by passing particles, which also means that the source of the bootstrap current is in LFS instead of HFS. These passing particles will move along magnetic field lines from LFS to HFS. Then the bootstrap current generated in LFS is transported into HFS. However, collisions have a diffusive character. The passing particles lose their momentum when they move toward the HFS. Consequently, the distribution of the bootstrap current has a poloidal asymmetry. Another important reason is the mirror effect associated with inhomogeneous magnetic field. The particle energy $E = \mu B + m v_{//}^2 / 2$ is conserved, where μ is the magnetic moment and invariant. Particles will normally experience the increasing magnitude of the magnetic field and their parallel velocities are reduced as they move around magnetic field lines towards HFS. Thus, the parallel velocity $v_{//}$ of a passing particle in HFS is lower than in LFS. Consequently, the bootstrap current carried by passing particles becomes poloidal asymmetric $j_{bs} \sim \left(q v_{//}\right) @ HFS < \left(q v_{//}\right) @ LFS$.

b. Verification of density flattening by magnetic island

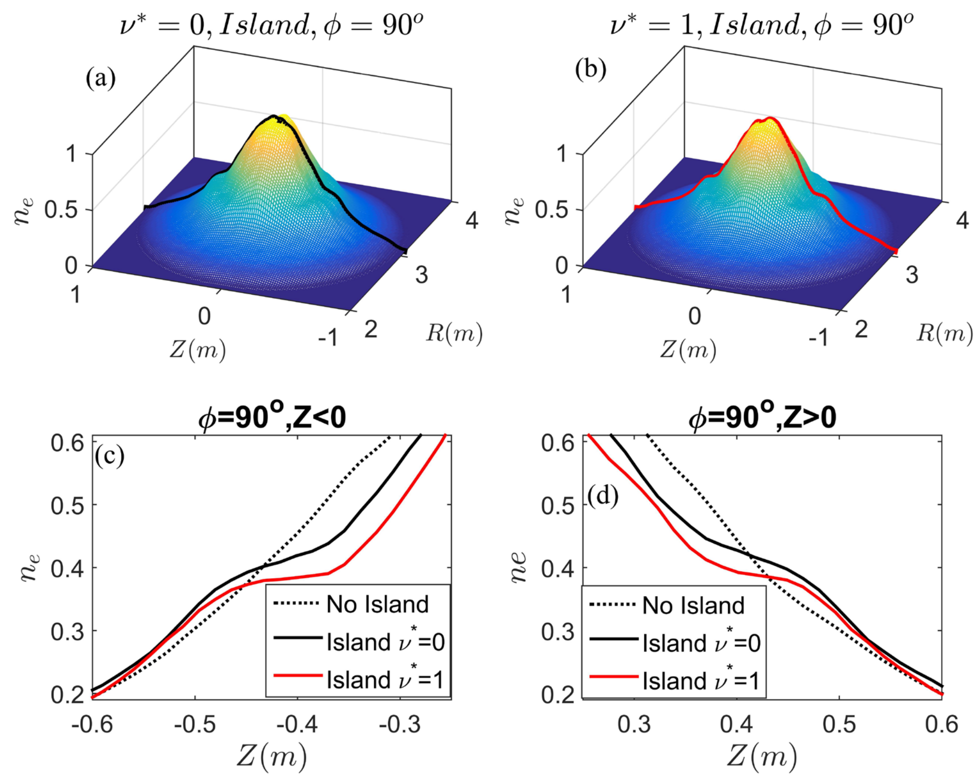
The m/n=2/1 islands are calculated self-consistently from the CLT code. Due to the fast parallel transport, the electron density distribution flattens inside the island.

Figures 4 and 5 show the surface plots of the plasma density at the poloidal cross-sections with the toroidal angles ϕ=0° and ϕ=90°, respectively. As we can see, formation of magnetic islands makes the plasma density flattened because of fast parallel transport along magnetic field lines. Trapped particles may encounter a mirror point and do not go through entire field lines around the islands. Therefore, trapped particles are mainly located at LFS, which results in a less flattened density profile in LFS than in HFS as shown in Figure 4(c,d).

Moreover, particle collisions make the density profiles more flattened inside the islands (ϕ=0°) in LFS as shown in Figure 4. The same phenomenon occurs at the poloidal cross-section of the toroidal angle ϕ=90° where the O-point of the island are located at the $R=R_{axis}$ plane as shown in Figure 5. Particle collisions could remove the discontinuity in the velocity distribution at the trapped–passing boundary and generate the poloidal asymmetry associated with particles. The influence of scattering from trapped to passing further flattens the density profile.



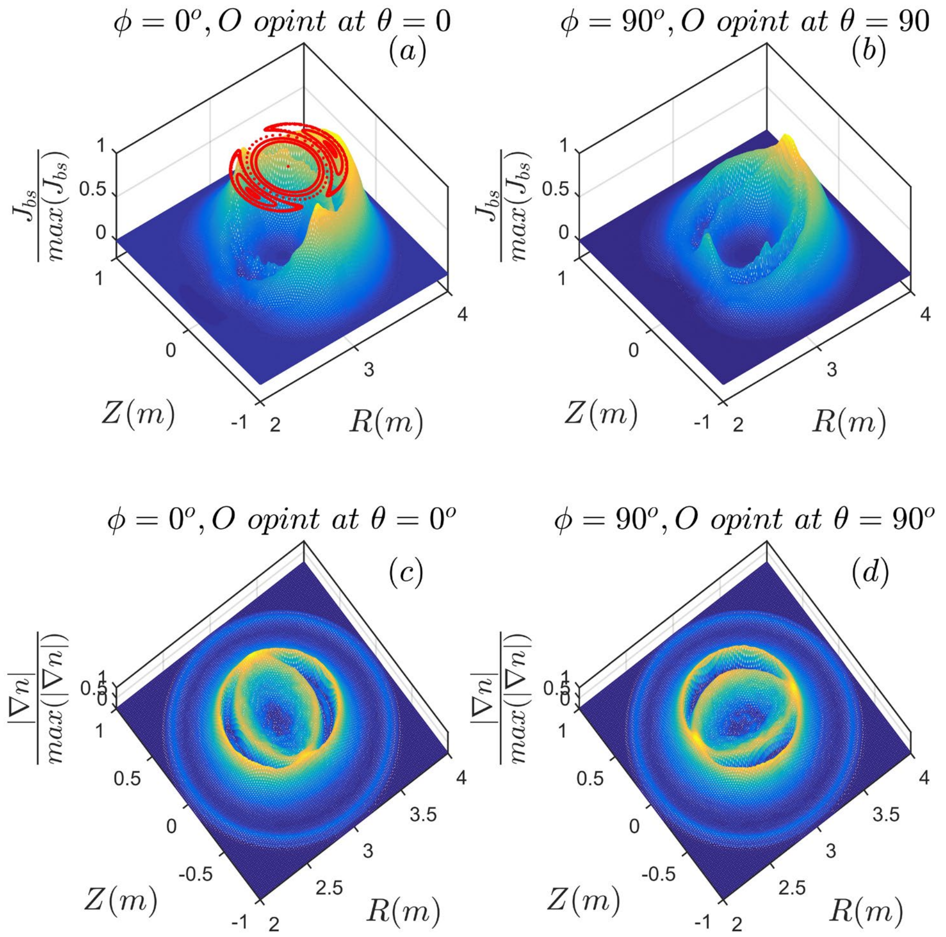
Figures 4. Surface plots of the plasma density at the poloidal cross-section of toroidal angle ϕ=0° for a static magnetic island with (a) v^*=0 and (b) v^*=1. To exhibit the effect of v^* on the density distribution, we draw the density profile at the middle plane Z=0 together in (c) HFS and (d) LFS.



Figures 5. Surface plot of the plasma density at the poloidal cross-section of the toroidal angle ϕ=90° with a static magnetic island for (a) v^*=0 and(b) v^*=1. To show the effect of v^* on the density distribution, we draw the density profile at the R=R_axis plane together in Z<0(c) and Z>0 (d).

c. Bootstrap current on static and dynamic magnetic islands

The bootstrap current inside the static islands with different values of the ratio w_b/W in the banana regime has been investigated in Refs. [10]. Dong et al. [19] has studied the effect of the collisional frequency v^* on the bootstrap current inside the static magnetic islands in detail. Our simulation study focuses on the two-dimension bootstrap current distribution in both static and dynamic magnetic islands with effective collisional frequency v^*=0.1 (banana regime). In this study, the initial equilibrium with q=2 is adopted to calculate the tearing mode insatiability with m/n=2/1 islands. The static and dynamic magnetic islands are self-consistently obtained from the CLT code.



Figures 6. Surface plots of the two-dimension bootstrap current at the poloidal cross-section of the toroidal angle (a) ϕ=0° and (b) ϕ=90°. The ralative density gradient at the poloidal cross-section of the toroidal angle (c) ϕ=0° and (d) ϕ=90° are also presented.

Inside magnetic islands, the bootstrap current is dropped as expected while the current converges to the unperturbed level far away from the island as shown in Figures 6 (a) and (b). The bootstrap current behaviors in Figures 6 (a, b) are consistent with the gradient distribution of the plasma density as shown in Figures 6 (c, d). Because the local density gradient is large around the magnetic separatrix and at the X-point, the bootstrap current becomes very strong.

The conventional knowledge is that a static magnetic island can reduce the plasma pressure gradient through parallel transports and consequentially reduce the bootstrap current inside the island. However, a dynamic magnetic island will induce an electric field during the evolution of the tearing mode instability as shown in Figures 7 (a) and (b). Some charged particles gain or loss energy because of accelerating or decelerating by the parallel electric field $\boldsymbol{E}_{//}=(\boldsymbol{E}\cdot\boldsymbol{b})\boldsymbol{b}$ in Figure 7 (c). The radial electric field $\boldsymbol{E}_{\mathrm{r}}$ could affect the drift displacement and the trajectory of a charged particle. Therefore, the induced electric field $\boldsymbol{E}$ by a dynamic magnetic island makes some charged particles cross the trapped-passing boundary and changes their orbits, which can noticeably modify the parallel flow and alter the bootstrap current as shown in Figure 8. To be more specific, the initial equilibrium with q=2 is employed to calculate the tearing mode instability with m/n=2/1 islands. Firstly, the induced electric field $\boldsymbol{E}$ is removed, and only the magnetic field **B** remains, which is a "static magnetic island". Figure 8 (a) shows the steady-state bootstrap current distribution in the static magnetic island. Then the induced perturbed electric field $\boldsymbol{E}$ is retained, which is a "dynamic magnetic island". Figures 8 (b) and (c) show that the distribution of the bootstrap current is significantly changed for 100 and 250 Alfvèn time in case of retaining of the perturbed $\boldsymbol{E}$. As we can be seen from the contour plot of the bootstrap current distribution in Figure 8(d), the bootstrap current is mainly affected by the radial electric field $\boldsymbol{E}_{\mathrm{r}}$ rather than the parallel electric field $\boldsymbol{E}_{//}$ because the perturbed $\boldsymbol{E}_{\mathrm{r}}$ is far large than the perturbed $\boldsymbol{E}_{//}$ in tearing mode instability shown in figure 7 (a) and (b).

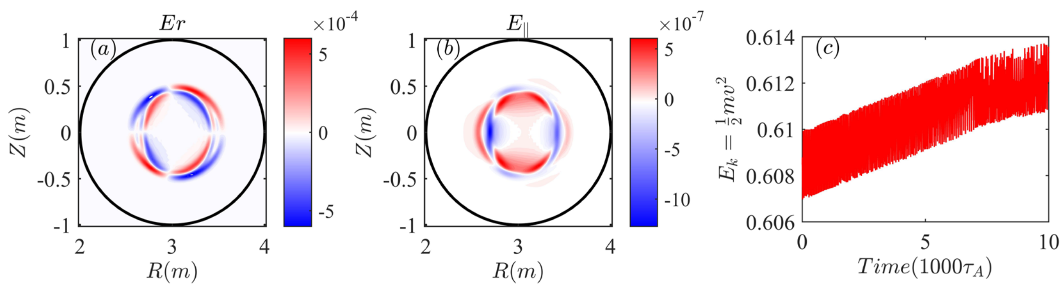


Figure 7. Contour plots of (a) the radial electric field $\boldsymbol{E}_{\mathrm{r}}$ and (b) the parallel electric field $\boldsymbol{E}_{//}$ on the poloidal cross-section of the toroidal angle ϕ=0° for the m/n=2/1 tearing mode. (c) Charged particles gain or loss energy because of accelerating or decelerating by the parallel electric field.

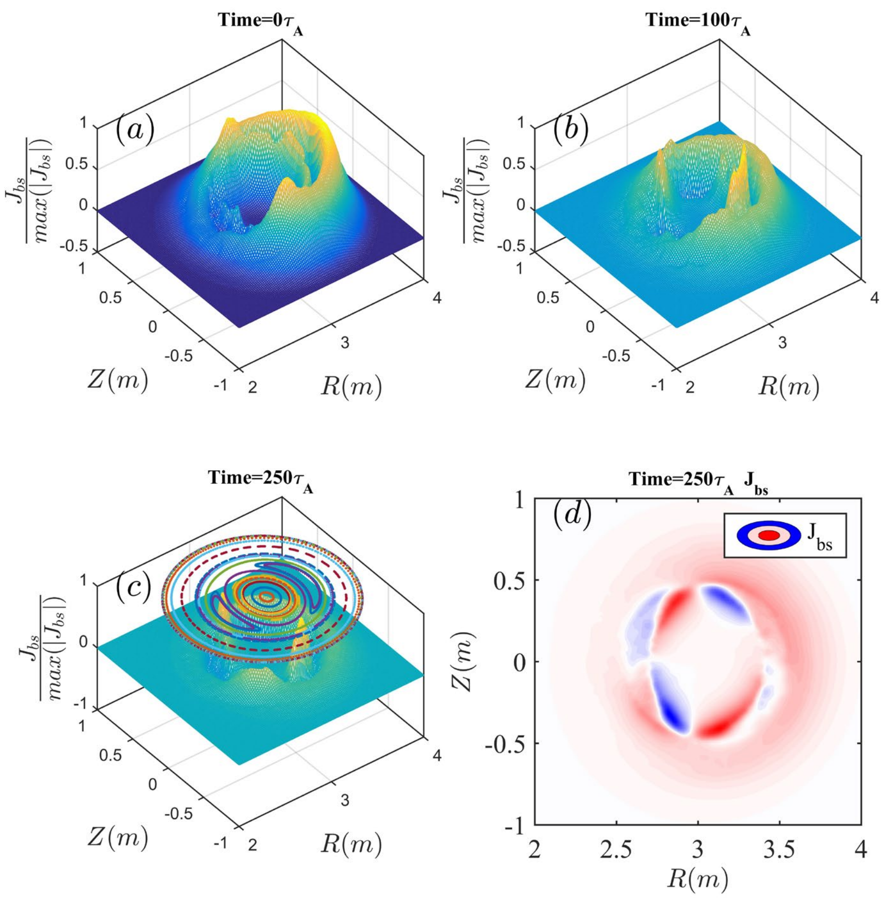


Figure 8. (a) Surface plat of the steady state bootstrap current for a static magnetic island. Surface plots of the dynamic bootstrap current for (b) time=100 τ_A and (c) time=250 τ_A after imposing the perturbed **E**. (d) Contour plot of the dynamic bootstrap current at time=250 τ_A.

D Magnetic Islands respond to static and dynamic bootstrap current

The perturbation of the bootstrap current due to the pressure flattening inside the magnetic island can also play an important role in the growth of a tearing mode. Kinetic NTM simulations consider the static or dynamic perturbed bootstrap current to investigate the nonlinear evolution of magnetic islands.

In the general tearing mode case, the island dynamics driven by magnetic free energy without bootstrap current is shown by the solid black line in Figure 9(a). The equilibrium bootstrap current is nearly 10.0 percent of the total plasma current at the q=2 surface. The bootstrap current turns on at time=21000τ_A when the tearing mode saturates. It should be noted that in the simulation, bootstrap currents are assumed to be unchanged during the subsequent reconnection process. Figure 9 (a) shows the time evolution of the width of m/n=2/1 magnetic island driven by the static (blue line) and dynamic (red line) bootstrap currents. The width of magnetic islands ascend rapidly and saturate again for both cases. The saturate island width is 0.133a for general tearing without bootstrap current, 0.159a with static bootstrap current and 0.140a with dynamic bootstrap current. As an analytical theory, the perturbed bootstrap currents play a destabilizing role in the nonlinear island. The resulting reduction of the bootstrap current inside magnetic islands will boost the development of the tearing mode. We also find that the saturated island width of the dynamic case is smaller than that of the static case. Moreover, during the reconnection process, the opposite current sheet near the X-point results in the loss or gain of magnetic flux. Consequently, the saturated magnetic island is rotated due to asymmetric perturbation bootstrap current in dynamic island shown in Figure 10 and Figure 11.

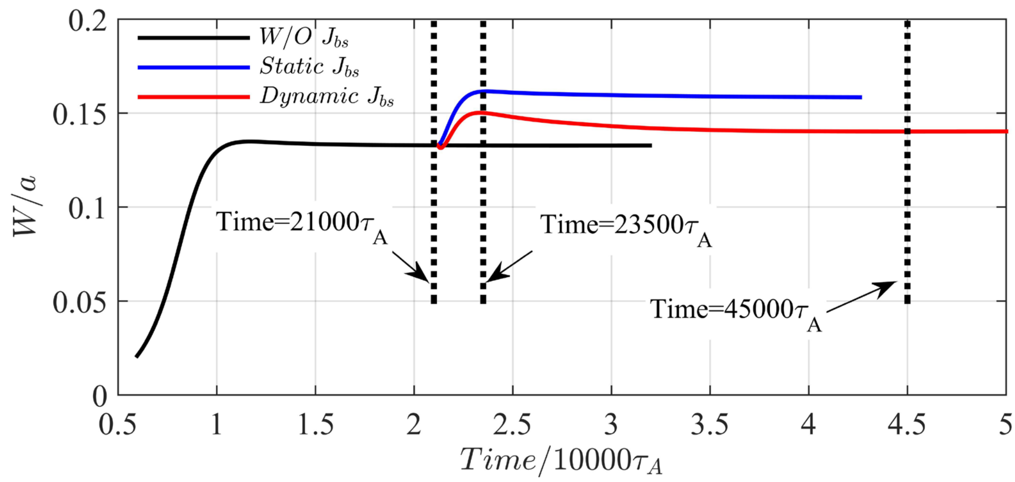


Figure 9. (a)Time evolution of the width of the m/n = 2/1 magnetic island driven without the bootstrap current (black line)/with the bootstrap current for static island (blue line)/ in dynamic island (red line).

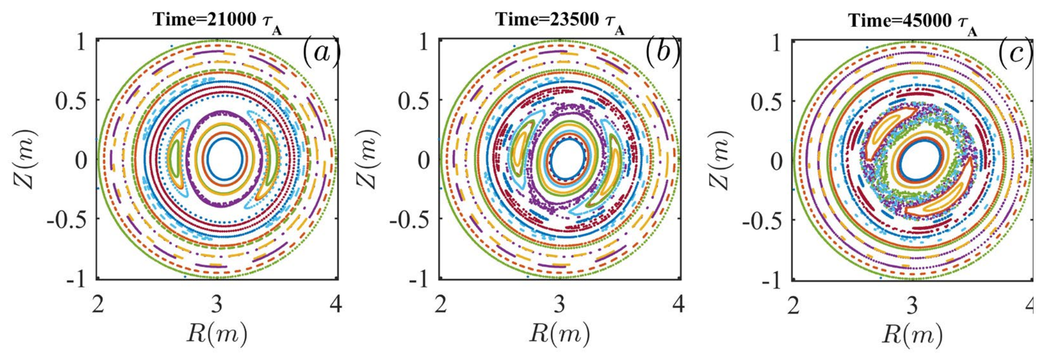


Figure 10. Time evolution of the topology of magnetic island for dynamic case in the toroidal cross sections ϕ=0°, (a) time at 2100τ_A, (b) time at 23500τ_A and (c) time at 4500τ_A .

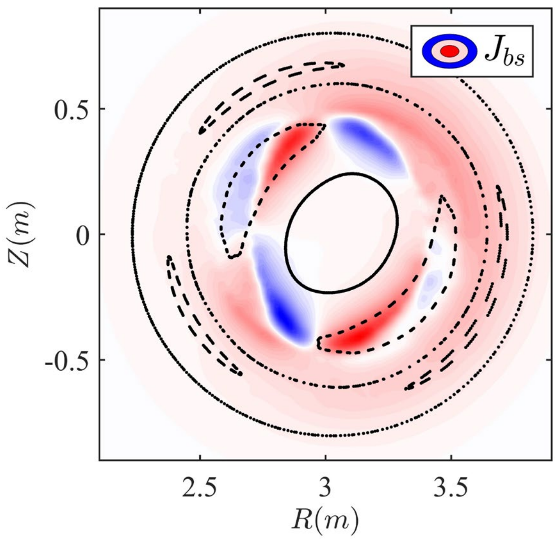


Figure 11. Contour plot of bootstrap current in dynamic magnetic island and Poincare plots of magnetic islands for toroidal cross sections ϕ=0° at island's saturation.

V. Conclusion and Discussion

In the present work, we have investigated the distributions of the bootstrap current with/without magnetic islands based on the first principles of the drift-kinetic particle simulations. The perturbed magnetic and electric fields associated with the dynamic magnetic island are calculated self-consistently from a three-dimensional toroidal

MHD code (CLT), instead of artificial imposed magnetic island perturbation. In this case, we use the initial equilibrium with q=2 to calculate the tearing mode instability with m/n=2/1 islands, which are most catastrophic in tokamak experiment. If the induced perturbed electric field $\boldsymbol{E}$ is removed and only the magnetic field $\boldsymbol{B}$ remains, we call it as a "static magnetic island". If the induced perturbed electric field $\boldsymbol{E}$ is retained, we call it as a "dynamic magnetic island". The main achieved results are summarized as follows:

(1) The distribution of the bootstrap current has an asymmetry in the poloidal direction. The poloidal asymmetry becomes more evident with increasing of the effective collision frequency ν*. Particle collisions can transfer the momentum from trapped particles to passing particles by which the bootstrap current is carried. These passing particles will move along magnetic field lines from LFS to HFS. Then the bootstrap current generated in LFS is transported into HFS. However, particle collisions have a diffusive character. The passing particles lose their momentum when they move toward to the HFS. Consequently, the distribution of the bootstrap current has a poloidal asymmetry. The mirror effect between LFS and HFS could also contribute to the poloidal asymmetry.

(2) Magnetic island makes the plasma density flattened because of fast parallel transports along magnetic field lines. Nevertheless, trapped particles are mainly in the LFS, resulting in a less flattened density profile in LFS than in HFS. Moreover, particle collisions make the density profiles more flattened inside the islands.

(3) Inside the static magnetic island, the bootstrap current is dropped as expected with the effective collision frequency ν^*=0.1 (in the banana regime). However, in the case of the tearing mode instability, the induced electric field significantly changes the bootstrap current distribution. The bootstrap current is mainly affected by the radial electric field $\boldsymbol{E}_r$ rather than the parallel electric field $\boldsymbol{E}_{//}$, because the perturbed $\boldsymbol{E}_r$ is far large than the perturbed $\boldsymbol{E}_{//}$. If the bootstrap current turns on when the tearing mode saturates, the width of magnetic islands ascend rapidly and saturate again for both static and dynamic cases. In the dynamic case, the distribution of the bootstrap current in the vicinity of the X-points is strong asymmetric, which causes the rotation of the magnetic

island. Consequently, the saturated island width of the dynamic case is smaller than that of the static case.

In fact, during the time revolution of the (neoclassical) tearing mode instability, the bootstrap current distribution is related to many parameters, such as magnetic island topology, stochastic magnetic, island rotation, induced electric field, effective collision frequency, banana-orbit width, and so on. This paper only considers the effect of an induced perturbed electric field associated with a dynamic magnetic island on the bootstrap current with $\nu^*=0.1$ (in the banana regime). To accurately evaluate the NTM dynamics, more of these parameters may need to be reconsidered. These are beyond the scope of this paper and left for future investigation.

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