Numerical simulation of driven plasma rotation shear and fast magnetic reconnection caused by double tearing modes

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1. Introduction

Advanced scenarios, generally found in tokamak experiments with non-monotonic profiles of the safety factor q and reversed magnetic shear in the central region, allow for the possible steady operation of a fusion reactor due to their high bootstrap current fraction. Experimental results indicate that the internal transport barriers (ITBs) in these scenarios start preferentially when the minimum q reaches an integer value [1-3]. On the other hand, weak or strong MHD instabilities are also found when the low order rational q surfaces are inside the plasma [1-4]. Two types of fast electron temperature crashes, the *annular crash* and the *core crash*, were observed in experiments for non-monotonic q-profiles with q>1, and both occurred in a time scale of tens of microseconds [4]. The electron temperature was flattened only in a local region away from the magnetic axis during an *annular crash* but over a much larger region up to the magnetic axis during a *core crash* [4].

To understand the experimental results, simulations basing on two-fluid equations with large aspect-ratio approximation have been carried out, taking into account the electron inertia, diamagnetic drift and ion polarization current [5]. The following input parameters are utilized: the toroidal field $B_t = 2T$, the electron temperature (density) $T_e = 2keV$ ($n_e = 3 \times 10^{19} m^{-3}$) and the plasma minor (major) radius $a = 0.5m$ ($R = 1.7m$). A parabolic profile for the original equilibrium electron temperature and density, the plasma viscosity $0.2m^2/s$, the perpendicular particle diffusivity $0.04m^2/s$, and the parallel and perpendicular electron heat conductivities $2 \times 10^8 m^2/s$ and $0.2m^2/s$ are assumed. Considering of the neoclassical damping of poloidal plasma rotation, a larger plasma viscosity for the $m/n = 0/0$ component (m/n is the poloidal/toroidal mode number), $20m^2/s$, is used.

2. Annular crash and driven plasma rotation shear

Figure 1 (a) show the radial q-profiles of the original equilibrium utilized for our studies. The black curve shows a case where the inner and outer $q = 3$ surfaces are at $r_{s1} = 0.244a$ and $r_{s2} = 0.598a$, respectively, with the normalized distance between two resonant surfaces $\Delta\rho \equiv |r_{s2} - r_{s1}|/a = 0.354$. Keeping the radial profile of plasma current density unchanged while decreasing its amplitude, the q-profiles are upwards shifted, as shown by the red, green, blue, and magenta curves.

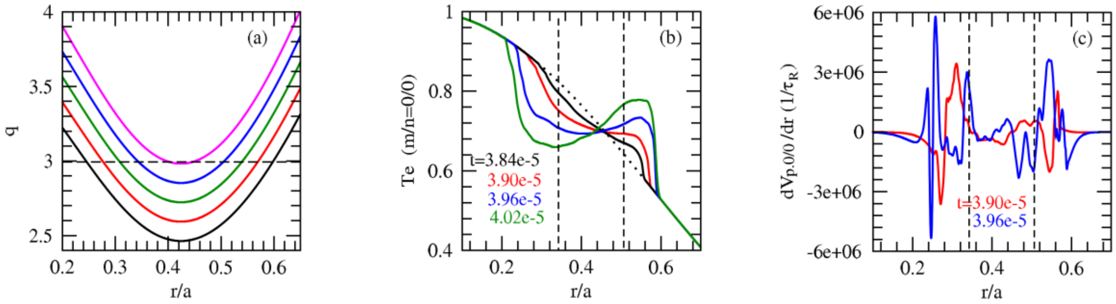

Figure 1 (a) Radial equilibrium q-profiles with $\Delta\rho \equiv |r_{s2} - r_{s1}|/a = 0.354$ *(black curve),* 0.295 *(red),* 0.233 *(green),* 0.164 *(blue), and* 0.055 *(magenta). The* $q = 3$ *value is marked by the horizontal dashed line; (b) Radial profiles of the averaged* T_e *at* $t = 0$ *(dotted black curve),* $3.84\times$ *(solid black),* $3.90\times$ *(red),* $3.96\times$ *(blue), and* $4.02\times10^{-5}\tau_R$ *(green), where* $\tau_R = 23s$ *. The equilibrium electron diamagnetic drift frequencies at the inner and outer resonant surfaces are* $f_{*e1} = 2.35kHz$ *and* $f_{*e2} = 1.97kHz$*; (c) Corresponding to (b), radial shear of poloidal plasma rotation velocity at two times.*

With a small distance between two equilibrium q=3 surfaces, $\Delta\rho = 0.164$, radial profiles of the averaged ($m/n = 0/0$ component) electron temperature during the nonlinear growth of the $m/n = 3/1$ double tearing mode (DTM) are shown in figure 1 (b), obtained for zero equilibrium plasma rotation velocity and bootstrap current. The time interval between the solid black and green curves is 41 μs. Within this short time scale the local electron temperature between two $q = 3$ surfaces, marked by vertical dashed lines, are flattened, in agreement with the time scale of the *annular crash* observed in experiments [4]. The profiles are hollow after the fast magnetic reconnection process because the inner (outer) magnetic island reconnects to the magnetic surfaces on the outer (inner) side of another island [5]. The local electron density is flattened in the same time scale, and the averaged safety factor, calculated from the averaged poloidal field, are flattened to a value of $q = m/n$ by the DTM between two resonant surfaces, as found in experiments [1,3].

Meanwhile, plasma rotation is driven by the DTM. Corresponding to figure 1 (b), profiles of the radial shear of the averaged poloidal plasma rotation velocity ($m/n = 0/0$ component) at two times are shown in figure 1 (c). The rotation shear is about $5\times10^6/\tau_R$ ($2.2\times10^5/s$) around the inner edge of the temperature flattening region. The measured poloidal rotational shear is in the order of $10^5/s$ in JET experiments with ITBs, being larger than the growth rate of the ion temperature gradient mode [6]. In addition to the $m/n = 3/1$ DTM, the $2/1, 4/1, 5/1$, and $6/1$ DTMs are also found to cause *annular crash* and drive strong poloidal plasma rotation shear, when the two resonant surfaces are close.

3. Core crash and nonlinear regimes

Increasing the distance between two resonant surfaces to a medium range, the $m/n = 2/1, 3/1$ and $4/1$ DTMs are found to cause the *core cra*sh. As an example, radial profiles of the averaged electron temperature during the $2/1$ DTM growth for $\Delta\rho = 0.233$ are shown in figure 2 (a) at by the solid black, red, blue, and green curves, obtained for zero equilibrium plasma rotation velocity, $f_{*e1} = 1.61\mathrm{kHz}$, and $f_{*e2} = 1.32\mathrm{kHz}$. The equilibrium bootstrap current density fractions at the inner and outer resonant surfaces are $f_{b1} = 0.15$ and $f_{b2} = 0.22$. The time interval between two neighboring curves from the solid black to the green curves is 13.8 μs. The electron temperature profile is flattened up to the magnetic axis in tens of microseconds. This time scale agrees with the experimental observation [4].

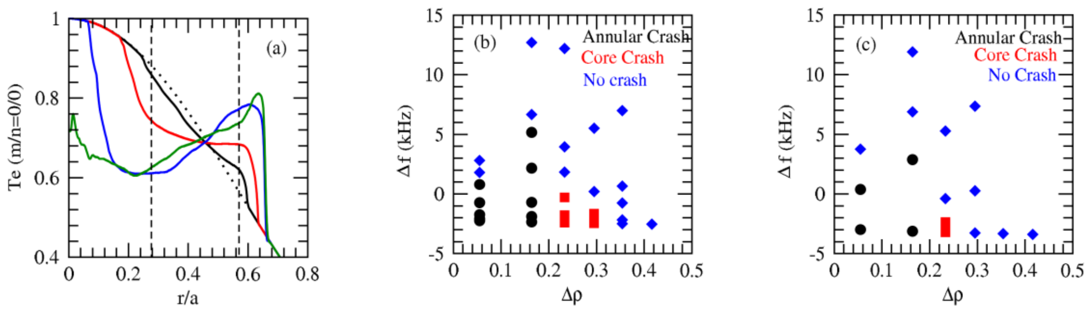

Figure 2 (a) Radial profiles of the averaged electron temperature during the $2/1$ DTM growth at $t = 0$ (dotted black curve), $6.35\times$ (solid black), $6.41\times$ (red), $6.47\times$ (blue), and $6.53\times10^{-5}\,\tau_R$ (green). The equilibrium q=2 surfaces are marked by vertical dashed lines; (b) The stability diagram for the $3/1$ DTM in the $(\Delta\rho - \Delta f)$ plane. The black circles (red squares) mark the cases that the annular (core) crash are found. The blue diamonds mark the cases without fast crash of the plasma pressure. With $\Delta\rho = 0.055 - 0.416$, $f_{*e1} = 2.24 - 2.54kHz$ and $f_{*e2} = 2.12 - 1.61kHz$ for $m = 3$, $f_{b1} = 0.35 -\ 0.33$ and $f_{b2} = 0.39 - 0.53$; (c) Similar to (b) but for the $4/1$ DTM.

To learn which plasma parameters lead to the *annular* or *core crashes*, many simulations have been carried out. The results are summarized in figure 2 (b) for the $3/1$ DTM in the $(\Delta\rho - \Delta f)$ plane, where $\Delta f = f_{e\perp,1} - f_{E2}$, $f_{e\perp,1}$ (f_{E2}) is the equilibrium electron fluid (plasma rotation) frequency at the inner (outer) resonant surface. The equilibrium plasma rotation at the inner resonant surface is in the ion drift direction with respect to that at the outer one. The black circles mark the cases that the *annular crashes* are found, located in the region with a relatively small distance between two resonant surfaces and a not too large value of Δf. The smallest values of Δf in the figure correspond to the cases without equilibrium plasma rotation, being negative due to the electron diamagnetic drift frequency at the inner resonant surface. The red squares mark the cases that the *core crashes* are found, located in the region with a medium distance between two resonant surfaces and a low relative frequency. The blue diamonds mark the cases in which no fast crashes of the plasma pressure are found, existing for a sufficiently large relative frequency or distance between the two resonant surfaces. In this regime the DTM saturates at a finite amplitude, causing a local flattening of the plasma pressure at the outer resonant surface.

Using downwards shifted equilibrium q-profiles such that the radial locations of two $q = 2$ surfaces are the same as those of the $q = 3$ surfaces, the *core crash* region for the $2/1$ DTM is found to be much larger than that for the $3/1$ DTM, indicating that the *core crash* will be more easily encountered in experiments when the minimum q value is below 2.

Using upwards shifted equilibrium q-profile such that the radial locations of two $q = 4$ surfaces are the same as those of the $q = 3$ surfaces, three regimes are shown in figure 2 (c) for the $m/n = 4/1$ DTM in the $(\Delta\rho - \Delta f)$ plane. The local equilibrium bootstrap current density fraction, $f_{b1} = 0.47 - 0.44$ and $f_{b2} = 0.52 - 0.71$ for $\Delta\rho = 0.055 - 0.416$, is larger than that for the $m/n = 3/1$ DTM, while the *core crash* region is smaller, indicating that the non-monotonic q-profile becomes more stable with increasing the minimum q value to be above 3. To avoid *core crashes*, a medium distance of two resonant surfaces together with a low differential rotation frequency should be avoided.

4. Summary

With non-monotonic q-profiles, the DTM is found to lead to fast magnetic reconnection. The fast reconnection plays double roles: generating plasma rotation shear in the order of $10^5/s$ (around the edge of the local pressure flattening region) for a small distance of two resonant surfaces, which might reduce the plasma turbulence level or correlation to trigger the ITB formation, but causing a large degradation in the core plasma confinement in tens of microseconds for a medium distance, as seen in experiments [4]. Increasing the minimum q value to be above 3, the *core crash* region exists only for a low differential plasma rotation frequency between two resonant surfaces.

References

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