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.

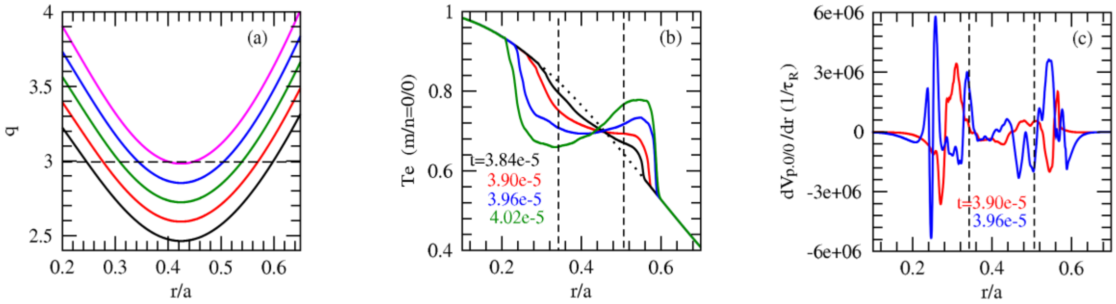

Figure 1 (a) Radial equilibrium q-profiles with $\Delta\rho \equiv |r_{s2} - r_{s1}|/a = 0.354$ (black curve), 0.295 (red), 0.233 (green), 0.164 (blue), and 0.055 (magenta). The $q = 3$ value is marked by the horizontal dashed line; (b) Radial profiles of the averaged T_e at $t = 0$ (dotted black curve), $3.84 \times$ (solid black), $3.90 \times$ (red), $3.96 \times$ (blue), and $4.02 \times 10^{-5}\tau_R$ (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 $5 \times 10^6/\tau_R$ ($2.2 \times 10^5/s$) 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.