Influence of Zonal Component on Core-crash Sawtooth in Tokamaks

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Abstract: The core-crash sawtooth caused by *m/n*=2/1 double tearing mode in Tokamaks is investigated using a three-dimensional toroidal MHD code (CLT). It is found that mode-mode coupling effect plays a crucial role during the core-crash sawtooth. The zonal component and all other high n harmonics generated by mode-mode coupling of the *n*=1 mode gain more than 40% of the total kinetic energy and become unneglectable at the nonlinear phase. The zonal component has significant influence on the dynamic evolution of magnetic islands during core-crash sawtooth in Tokamaks. Without the zonal component, the change of position of the *m/n*=2/1 magnetic islands on two resonant surfaces will not occur.

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I. INTRODUCTION

Locally reversed magnetic shear can help to stabilize short-wavelength ballooning instabilities[1], suppress trapped electron modes [2, 3], and then improve energy confinement in Tokamaks [4-8]. Reversed magnetic shear profile can be obtained by many methods, such as neutral beam injection and radio frequency wave injection. [9-12] However, double tearing mode instability [13-16] (DTM), which grows much faster than a single tearing mode, often takes place in the system with multiple resonant surfaces. During the nonlinear evolution of DTM, an off-axis sawtooth or a core-crash sawtooth may occur and the energy confinement can be greatly reduced.[17] Therefore, it is very important to understand the physical mechanism of DTM to achieve high performances and steady state operations of advanced Tokamaks.[18-22]

The linear growth rate of DTM is $\gamma \sim S^{-1/3}$ [14], which is different from tearing modes with m>1($\gamma \sim S^{-3/5}$) in Tokamak [23-25], if the two resonant surfaces are close enough. The faster linear growth is resulted from that the tearing modes on neighboring resonant surfaces can be strongly coupled with each other. If the separation of the two resonant surfaces is large, two tearing modes will develop independently and become two ordinary tearing modes. The most effective way to suppress the strongly coupled DTM is to destroy the strong coupling mechanism by shear flow[15, 26-29] and electron diamagnetic drift[18, 30] or to change current profile by driven current [31].

It is widely accepted that the off-axis sawtooth and core-crash sawtooth observed in the Tokamak Fusion Test Reactor (TFTR) are closely related to the nonlinear evolution of *m/n*=2/1 DTM.[17] However, it is still questionable that what causes fast reconnection during the off-axis sawtooth and why sometimes an off-axis sawtooth converts into a core-crash sawtooth [32-35]. Since most of previous studies have been carried out in the cylindrical geometry, [26, 28, 33, 34, 36] the toroidal effect is missing and the mode-mode coupling is somewhat artificial[37]. Thus, it is necessary to further study DTM dynamics in the nonlinear phase with a toroidal geometry. In the present paper, we present the nonlinear dynamics of the *m/n*=2/1 DTM through a three-dimensional, toroidal and non-reduced MHD code CLT[38-40].

II. MODEL DESCRIPTIONS

The code CLT is developed based on resistive-MHD equations with dissipations given as follows:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot [D\nabla(\rho - \rho_0)] , \quad (1)$$

$$\frac{\partial p}{\partial t} = -\mathbf{v} \cdot \nabla p - \Gamma p \nabla \cdot \mathbf{v} + \nabla \cdot [\boldsymbol{\kappa}_{\perp} \nabla (p - p_0)] + \nabla \cdot [\boldsymbol{\kappa}_{\parallel} \nabla_{\parallel} p] , \quad (2)$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla \mathbf{v} + (\mathbf{J} \times \mathbf{B} - \nabla p) / \rho + \nabla \cdot [\upsilon \nabla (\mathbf{v} - \mathbf{v}_0)] , \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} , \quad (4)$$

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta (\mathbf{J} - \mathbf{J}_0) , \quad (5)$$

$$\mathbf{J} = \nabla \times \mathbf{B} , \quad (6)$$

where ρ, *p*, **v**, **B**, **E**, and **J** are the plasma density, the plasma pressure, the velocity, magnetic field, the electric field, and the current density, respectively. The subscript "0" denotes the initial quantities. $\Gamma (= 5/3)$ is the ratio of specific heat of plasma. All variables in CLT are normalized as follows: $\mathbf{x}/a \rightarrow \mathbf{x}$, $\rho / \rho_0 \rightarrow \rho$, $p/(B_0^2/\mu_0) \rightarrow p$, $t/t_A \rightarrow t$, $\mathbf{v}/v_A \rightarrow \mathbf{v}$, $\mathbf{B}/B_0 \rightarrow \mathbf{B}$, $\mathbf{E}/(v_A B_0) \rightarrow \mathbf{E}$, $\eta / (\mu_0 a^2 / t_A) \rightarrow \eta$, and $\mathbf{J}/(B_0/\mu_0 a) \rightarrow \mathbf{J}$ where a is the minor radius, $v_A = B/\sqrt{\mu_0 \rho}$ is the Alfvén speed, and $t_A = a/v_A$ is the Alfvén time. B_0 and ρ_0 are the magnetic field and the plasma density at the magnetic axis, respectively. D, $\kappa_{\perp}$, $\kappa_{\parallel}$, and υ are the diffusion coefficient, perpendicular and parallel thermal conductivity, and viscosity, respectively.

III. SIMULATION RESULTS

In the present paper, a toroidal Tokamak configuration with the inverse aspect ratio $\varepsilon = a / R_0 = 1/4$ is chosen. The initial safety factor (q) profile and pressure profiles are shown in Figure 1. $q_0 = 2.9$ (where q_0 is the safety factor value at the magnetic axis) , the minimum value of q is $q_{\min} = 1.6$, and the distance between two $q = 2$ surfaces is $\delta r_s = 0.35a$. This is a typical equilibrium configuration for m/n=2/1 DTM. The equilibrium magnetic field $\mathbf{B_0}$ and $\mathbf{J_0}$ are obtained from NOVA code.[41] The grids used in the simulations are $256 \times 32 \times 256$ (R, ϕ, Z). The parameters are chosen to be $\eta = 1 \times 10^{-5}$, $D = 2.5 \times 10^{-5}$, $\kappa_\perp = 5 \times 10^{-6}$, $\kappa_\parallel = 5 \times 10^{-2}$, and $\upsilon = 2.5 \times 10^{-5}$.

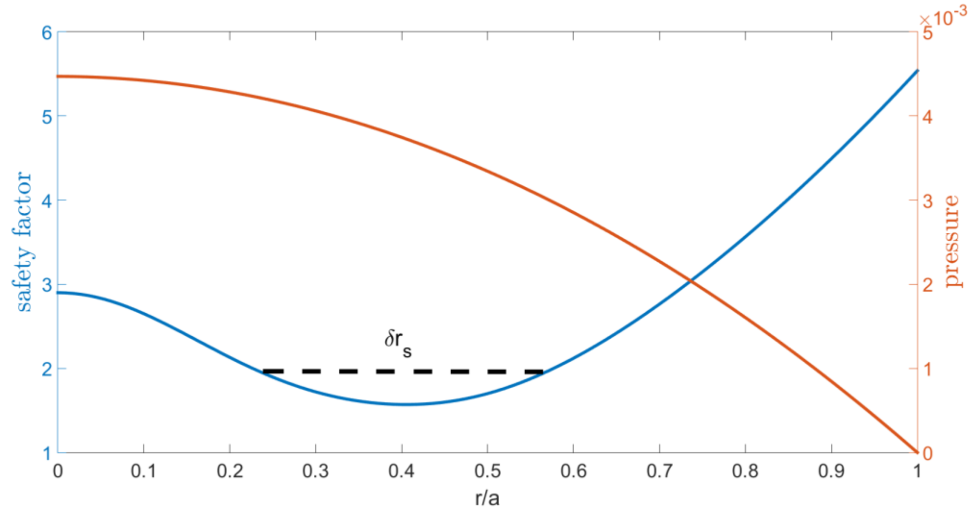

Figure 1 initial safety factor profile and pressure profile.

Figure 2 shows Poincare plots of the magnetic field, the pressure profile in the R and Z direction at four different times of the core-crash sawtooth ($t = 1328 t_A$, $t = 1593 t_A$, $t = 1947 t_A$, and $t = 2658 t_A$). It is evident that there is a clear boundary between the magnetic islands from two m/n=2/1 resonant surfaces at $t = 1328 t_A$, which means that they do not overlap with each other although the size of islands are quite large. As $\kappa_\parallel >> \kappa_\perp$, the pressure profile becomes flattened inside the magnetic islands and becomes sharp at the edge outside the islands. Magnetic islands on the inner/outer resonant surface move out/in through the X points on the outer/inner resonant surface, which results in changes of the X-point positions as shown in Figure 2(d), (g), and (j). It should be noted that the temperature in the outer islands are lower than that in the inner islands before core-crash occurs as shown in Figure 2(b) and (c). Thereafter, the hot and cold plasmas from inner and outer islands are mixed after the core crash as seen in Figure 2(h) and (i).

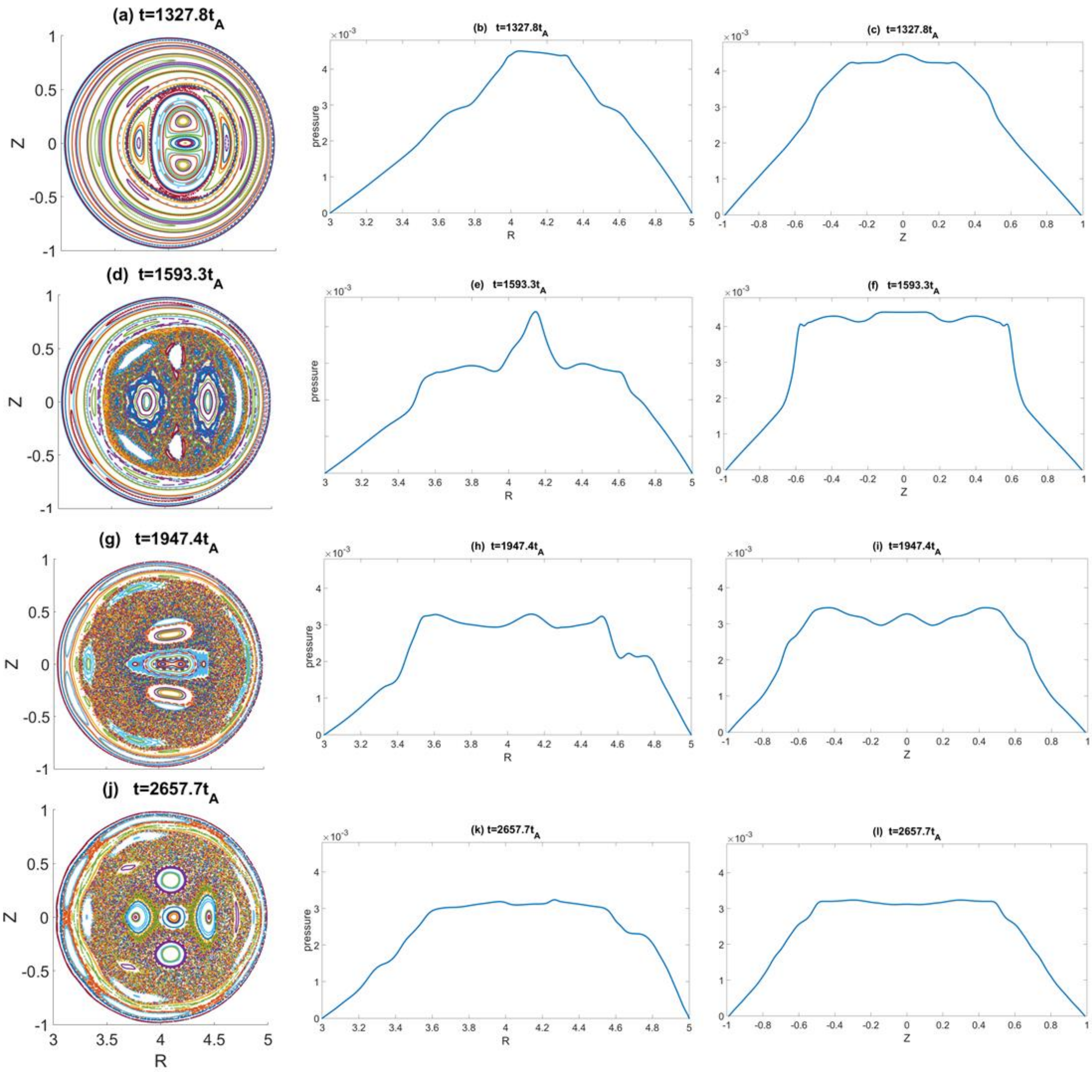

Figure 2 the Poincare plots of the magnetic field, the pressure profiles in the R and Z direction at four different times of the core-crash sawtooth ($t = 1328 t_A$, $t = 1593 t_A$, $t = 1947 t_A$, and $t = 2658 t_A$).

During this process, the magnetic axis is unable to be determined and the high temperature plasma at the magnetic axis quickly collapses due to the stochasticity of the magnetic field lines around the axis as shown in Figure 2(e), (f), (h), and (i). The evolution of the plasma pressure at the magnetic axis is presented in Figure 3. It is clearly shown that the plasma pressure at the magnetic axis keeps almost unchanged during the long precursor of *m/n*=2/1 DTM, then exhibits a sudden reduction from $t = 1593t_A$ to $t = 1682t_A$, which is consistent with experimental observations.[17] As a result, all magnetic field inside the q=3 resonant surface becomes stochasticity and the temperature becomes flattened in this region, which degrades the energy confinement severely.

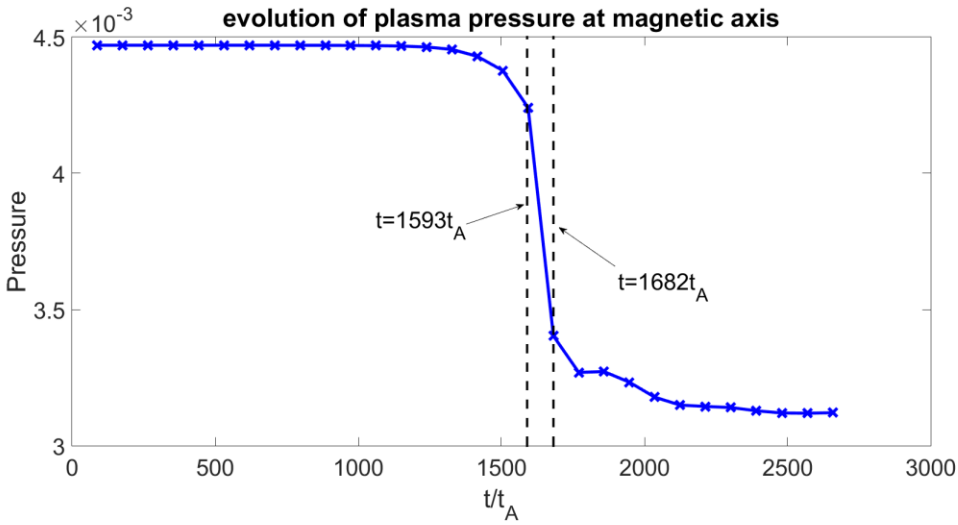

Figure 3. Time evolution of the plasma pressure at the magnetic axis. The plasma pressure at the magnetic axis exhibits a sudden reduction from $t = 1593t_A$ to $t = 1682t_A$.

The *q* profiles (derived from a trace-field-line code) at four different times are also presented in Figure 4. It is evident that the safety factor value at the magnetic axis remains unchanged ($q_0 = 2.9$) before the core-crash sawtooth ($t = 1328t_A$) as shown in Figure 4(a). During the core-crash, the outer and inner magnetic islands move towards each other and finally merge into a large island as given in Figure 2(a) and (j). Meantime, q_0 is gradually reduced to 2.0 in Figure 4(b) and 4(c). After the core-crash, q_0 starts to recover its initial value due to external heating and another two islands form on the outer q=2 surface.

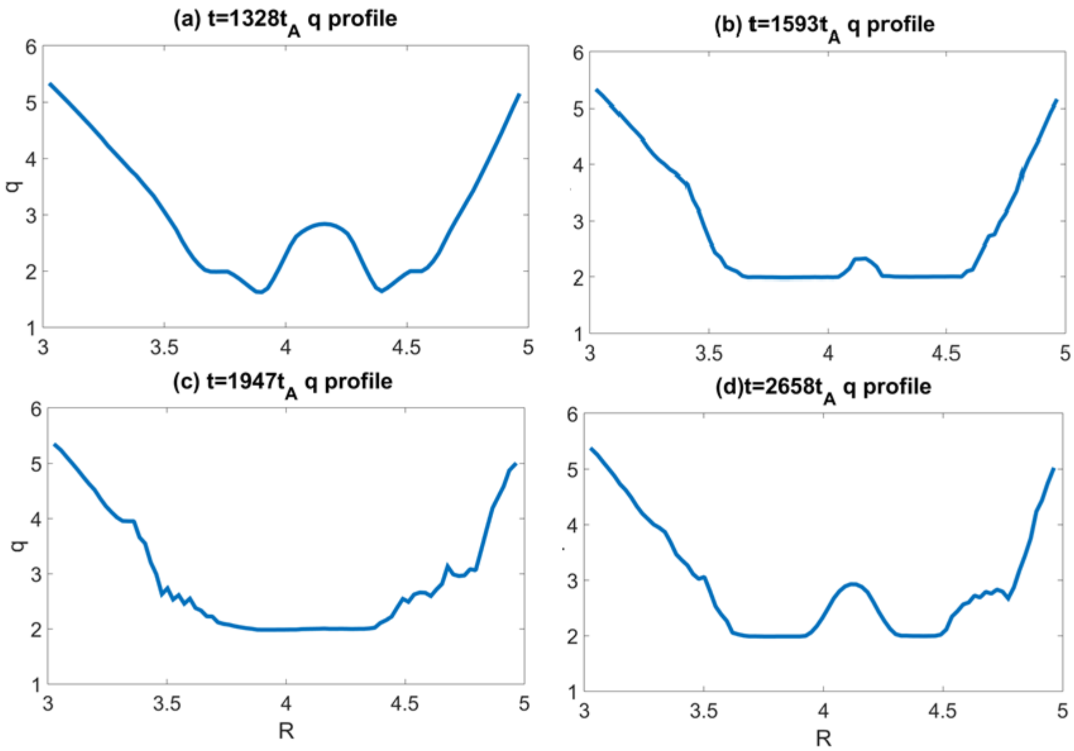

Figure 4 Snapshots of the q profile at four different time ($t = 1328t_A$, $t = 1593t_A$, $t = 1947t_A$, and $t = 2658t_A$).

Although previous simulations based on a cylindrical geometry [17] can produce core-crash sawtooth, but they are unable to address why the magnetic islands change their positions during the core-crash sawtooth. From our simulation result, it is clear indicated that the change of positions of the magnetic islands is due to development of the zonal (or n=0) component of magnetic perturbations that is resulted from the mode-mode coupling of the $n = \pm 1$ modes. The zonal component of the magnetic field perturbation will modify the equilibrium magnetic field and the q profile. To examine the importance of the zone component on the change of positions of magnetic island, we filter out the zonal component of the magnetic field perturbation. It is found that magnetic islands on two resonant surfaces roughly keep their initial position as shown in Figure 5.

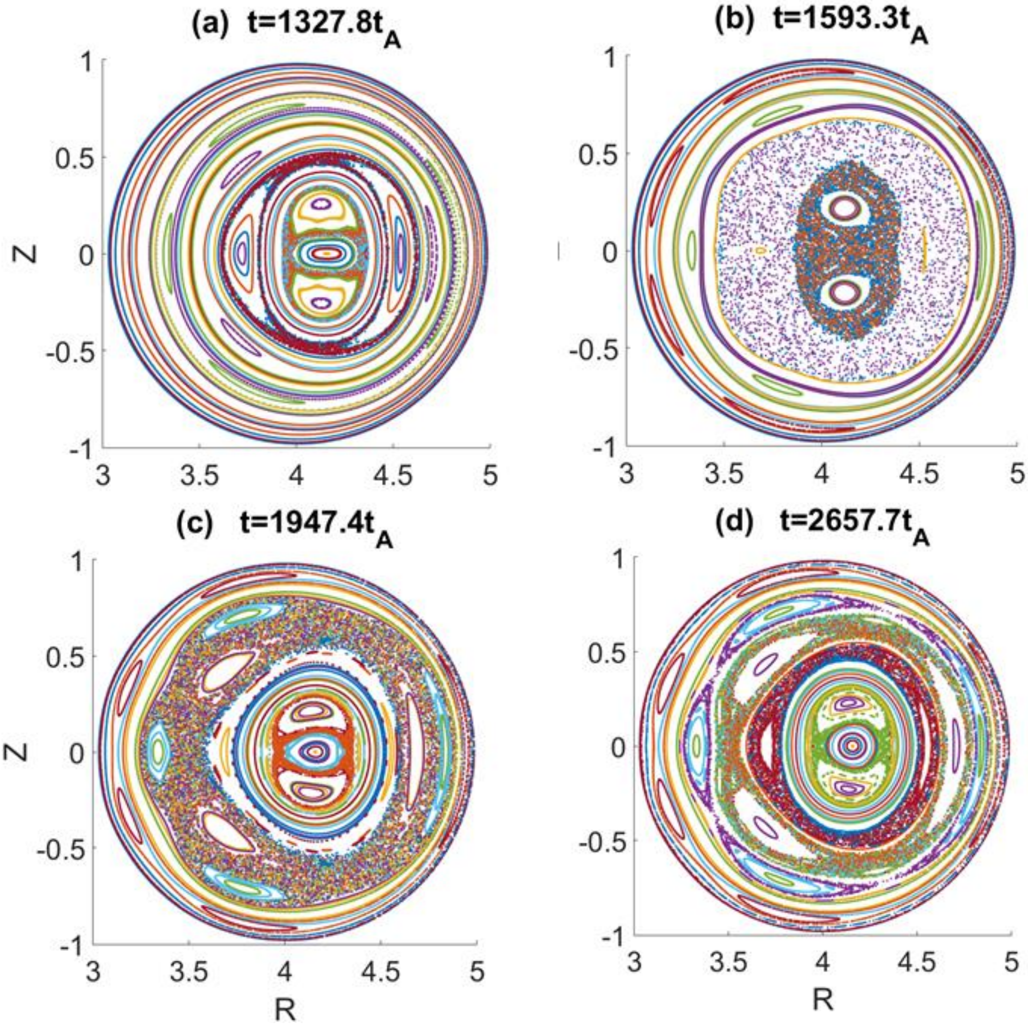

Figure 5 Snapshots of the Poincare plots of the magnetic field without zonal component of magnetic field perturbation at the different times as the same with Figure 2. It is clear that magnetic islands on two resonant surfaces keep unmoved all the time.

The time evolutions of the kinetic energy for different toroidal mode numbers *n* are shown in Figure 6. In the linear phase, the most unstable mode is the *m/n*=2/1 DTM and its linear growth rate is about 0.01. The zonal component is generated by mode-mode coupling of the $n = \pm 1$ component. Thus, its growth rate must be twice of the n=1 component.[42] Indeed, it is clearly shown in Figure 4 that the growth rate of the zonal part is about 0.02, which is exactly predicted from the theory. Similarly, the n=2 harmonic is generated by the mode-mode coupling of the n=1 component and the n=3 harmonic is generated by the n=1 and n=2 components. Their growth rates are 0.02 and 0.03, respectively. Although all other components in the linear have larger growth rates, but their amplitudes are still much smaller to compare with the amplitude of the n=1 component. Therefore, the m/n=2/1 DTM plays a dominant role, In the nonlinear phase, the zonal component and the high n harmonics become important because their amplitudes increase to about 1×10^{-5} which is almost in the same order as the n=1 component (about 4×10^{-5}). It is obvious that the mode-mode coupling is crucial to the dynamic evolution of the DTM, especially in the nonlinear phase.

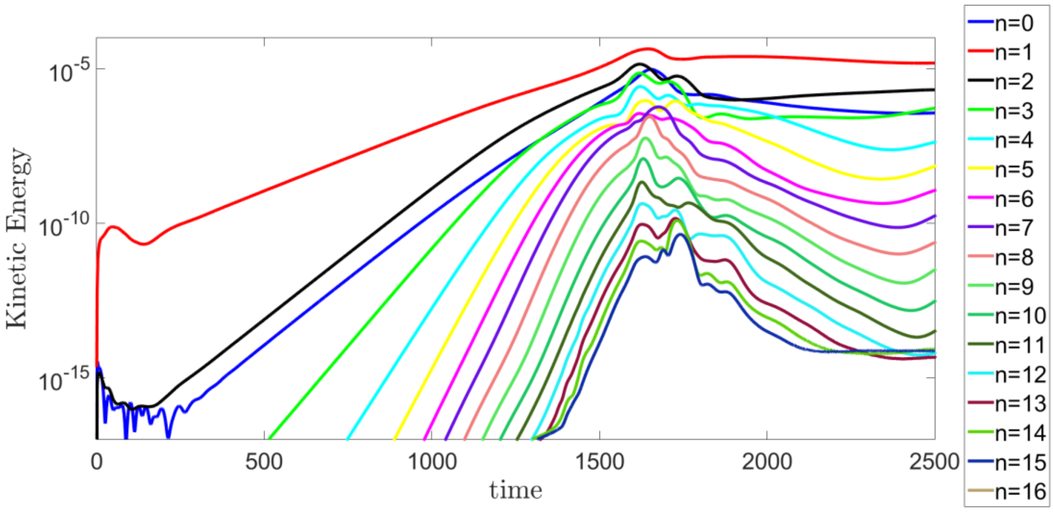

Figure 6 evolution of the kinetic energy of modes with different toroidal numbers.

IV. DISSCUSION AND SUMMARY

Locally reversed magnetic shear configuration has been widely used in advanced Tokamaks as it can significantly improve the energy confinement in Tokamaks. This reversed magnetic shear profile will also be adopted in future fusion reactors, such as ITER[43, 44] and CFETR[45]. One of the most crucial problems is how to prevent the off-axis sawtooth and the more dangerous core-crash sawtooth.

In the present paper, we have investigated the core-crash sawtooth caused by the *m/n*=2/1 DTM through the toroidal geometry MHD code CLT. It is found that during the core-crash sawtooth, the magnetic field becomes stochastic and the pressure profile becomes flattened in a broad region ($r < 0.8a$). The energy confinement in Tokamaks is largely degraded in case of core-crash sawtooth.

At the nonlinear stage, the mode-mode coupling becomes very important. The amplitudes of the zonal component and the high n harmonics are comparable to that of the *m/n*=2/1 DTM and become unneglectable. It is also found that the change of positions of the *m/n*=2/1 magnetic islands on two resonant surfaces is resulted from the nonlinear development of the zonal component. Without the zonal component, the outer and inner magnetic islands will keep unmoved.

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