Influence of helical external driven current on resistive tearing mode in tokamak

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Abstract. The influences of helical driven currents on tearing mode instabilities are studied by using a three-dimensional toroidal resistive magnetohydrodynamic code (CLT). We carried out two types of helical driven currents: stationary and time-dependent. It is found that the helical driven current is much more efficient than the Gaussian driven current used in our previous study[1]. The stationary helical driven current cannot be able to persistently control the tearing mode instability. When the magnetic island reduces to a small size, the stationary helical driven current begins to plays a negative role on controlling the tearing mode. For the time-dependent helical driven current with persistently locking on the O-point, the magnetic island not only quickly decreases but also continuously maintains at a low level, which indicates that the classical tearing mode instability is fully controlled although the small magnetic island remains.

I. INTRODUCETION

It is widely accepted that tearing mode instabilities[2] play an important role in both space[3~4] and laboratory[5~6] plasmas. Tearing mode instabilities lead to the topological change of magnetic fields. During this process, magnetic energy is converted into kinetic energy and thermal energy[7~8]. Tearing mode instability is considered to be the primary cause for the degradation of the plasma confinement in the magnetic confined fusion device such as tokamak[9~10].The dynamics of resistive tearing mode instabilities were firstly studied analytically by Furth et al[11] in the framework of resistive magnetohydrodynamics (MHD), and the growth rate of resistive tearing mode instabilities is $\gamma \sim S^{-3/5}$ where S is the magnetic Lundquist number.

Tearing mode instabilities[12~14] can degrade the plasma performance or even cause plasma disruptions when magnetic islands overlap[15] with each other. Therefore, the suppression or control of tearing mode instabilities is critical to plasma confinement. In order to control tearing mode instabilities, various methods have been studied such as feedback control by external fields[16], localized heating[17~18], current driven[19~24], and so on. The current driven has been used in many tokamak experiments. It is a very successful method to control the tearing mode instabilities. To suppress the tearing mode instabilities, one of the most appropriate methods is the electron cyclotron current drive (ECCD). ECCD has showed good property to control tearing mode instabilities in Tokamaks such as ASDEX upgrade tokamak[25], D-IIID[26] and JT60U[27].

In 1983, Reiman[19] considered the influence of a driven current on tearing mode instabilities and obtained the evolution equation of magnetic islands with the driven current:

$$\frac{\mu_0}{\eta}\frac{dw}{dt} \approx \Delta' + \frac{4}{\psi''(r_s)w}(J_{cdO} - J_{cdX}) \qquad (1)$$

where w is the width of magnetic island. Δ' is the discontinuity of the radial derivative of the perturbed magnetic flux across the rational surface. Note that, ψ is the equilibrium helical magnetic flux and $\psi'' = -\frac{B_{z0}r_s}{R}\frac{q'}{q_s^2}$. In general, $\psi'' < 0$ so that the driven current on the O-point will suppress the growth of the magnetic island and the driven current on the X-point will stimulate the growth of magnetic island. Besides, a lot of theoretical works on driven current have been done based on generalized Rutherford equation which describes the evolution of magnetic islands.[28]

In our previous simulation study[1], a stationary Gaussian distribution driven current is applied. The simulation results indicate that the driven current can successfully suppress the tearing mode instabilities. The suppression of the tearing mode instability by the driven current is mainly resulted from the Δ' reduction due to the modification of the equilibrium q profile. But with a stationary Gaussian distribution, the tearing mode instability cannot completely suppressed and the magnetic island will grow up again in the late stage because the driven current on the X-point has a negative effect on controlling tearing mode instabilities according to the reference[19].

In the present paper, we investigate the influence of helical driven current on tearing mode instabilities. It is found that the helical driven current is more efficient and can persistently suppress the tearing mode instability. The strength of the helical driven current is about a quarter of the stationary Gaussian distribution driven current. The results are very similar to the results of D-IIID[26], which indicated that the neoclassical tearing mode (NTM) is completely suppressed by co-ECCD because the driven current locks on the O-point.

CLT[1] is used to investigate the dynamics of the classical tearing mode instability with external driven current. CLT[29] is an initial-value resistive-MHD code and can be used to investigate MHD instabilities in toroidal tokamak configurations.

The paper is arranged as follows. In Section II, the basic equations used in CLT are presented including driven current. In Section III, we present our simulation results to show the influence of time-dependent helical driven current on m/n=2/1 tearing mode instability. Finally, we summarize our work in Section VI.

II. BASIC EQUATIONS IN CLT

The full set of the resistive-MHD equations including dissipations are given as follows:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot [D\nabla(\rho - \rho_0)] \tag{2}$$

$$\frac{\partial p}{\partial t} = -\mathbf{v} \cdot \nabla p - \Gamma p \nabla \cdot \mathbf{v} \tag{3}$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v} + (\mathbf{J}\times\mathbf{B} - \nabla p)/\rho + \nabla\cdot[\upsilon\nabla(\mathbf{v}-\mathbf{v}_0)] \tag{4}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \tag{5}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta(\mathbf{J} - \mathbf{J}_0 - \mathbf{J}_{cd}) \tag{6}$$

$$\mathbf{J} = \nabla\times\mathbf{B} \tag{7}$$

where ρ , p, v, B, E, and J denote the plasma density, the thermal pressure, the plasma velocity, the magnetic field, the electric field, and the current density, respectively. The subscript “0” denotes the equilibrium quantities. The driven current density $\mathbf{J}_{cd}$ has been included in the ohm’s law. $\Gamma(=5/3)$ is the ratio of specific heat of plasma. The variables are normalized as follows: $\mathbf{B}/B_0 \to \mathbf{B}$, $\mathbf{x}/a \to \mathbf{x}$, $\rho/\rho_0 \to \rho$, $\mathbf{v}/v_A \to \mathbf{v}$, $t/t_A \to t$, $p/(B_0^2/\mu_0) \to p$, $\mathbf{J}/(B_0/\mu_0 a) \to \mathbf{J}$, $\mathbf{E}/(v_A B_0) \to \mathbf{E}$, $d_i/a \to d_i$ and $\eta/(\mu_0 a^2/t_A) \to \eta$ where *a* is the minor radius, $v_A = B/\sqrt{\mu_0\rho}$ is the Alfven speed, and $t_A = a/v_A$ is the Alfven time. B_0 and ρ_0 are the initial magnetic field and the plasma density at magnetic axis, respectively.

CLT is a resistive-MHD code and unable to handle full particle kinetic dynamics. It is beyond our ability to consider self-consistent driven current. Therefore, we assume the driven current only appears in the Ohm’s law as an extra source.

In general, the driven current is parallel to magnetic field. Then, we assume,

$$\mathbf{J}_{cd} = J_{cd0} G_{cd}\mathbf{b} = I_{cd} g_{cd}\mathbf{b} = f_{cd} I_0 g_{cd}\mathbf{B}/B \tag{8}$$

where J_{cd0} and G_{cd} are the amplitude and the distribution of the driven current density, respectively. $\mathbf{b} = \mathbf{B}/B$ is the unit vector along the magnetic field line. $I_{cd} = \oint \mathbf{J}_{cd} \bullet d\mathbf{S}$ is the total driven current. $g_{cd} = G_{cd}/\oint G_{cd}\mathbf{b}\bullet d\mathbf{S}$ is the normalized distribution function. I_0 is the total initial plasma current. $f_{cd} = I_{cd}/I_0$ is the ratio of driven current to initial plasma current.

In our previous study, the driven current density is assumed to be a Gaussian distribution i.e.

$$J_{cd} = J_{cd}(\psi) = J_{cd0}\exp[-(\psi-\psi_0)^2/\delta_{cd}^2] \tag{9}$$

and

$$f_{cd} = J_{cd0}[\oint \exp(-(\psi-\psi_0)^2/\delta^2)dS]/I_0 . \tag{10}$$

With the steady Gaussian driven current, tearing mode instabilities cannot persistently be suppressed and the magnetic island will grow up again in the late stage because the driven current at the X-point exhibits a destabilized effect on the tearing mode.

In the present paper, we use a new type of the driven current i.e. the time-dependent helical driven current. The simulation results show that the helical driven current is effective and complete to control the tearing mode. The strength of time-dependent helical driven current $f_{cd} = 0.01$ is about a quarter of a stationary Gaussian driven current.

III. SIMULATION RESULTS

The geometry of EAST is chosen for our simulation. The major radius $R_0 = 1.85m$, the minor radius $a = 0.45m$, the elongation E=1.9 and the triangle $\sigma = 0.5$. The initial q profile is showed in Figure 1. The dominant unstable mode is the m/n=2/1 tearing mode. The initial magnetic field B_0 and current density J_0 are obtained from the code NOVA[30]. Other parameters in the present paper are normalized resistivity $\eta = 1.0\times10^{-5}$, viscosity $\nu = 1.0\times10^{-5}$ and diffusion coefficient $D = 1.0\times10^{-4}$. Since the pressure is not crucial during tearing mode instabilities, $\beta_0 \sim 0$ is assumed in the present paper.

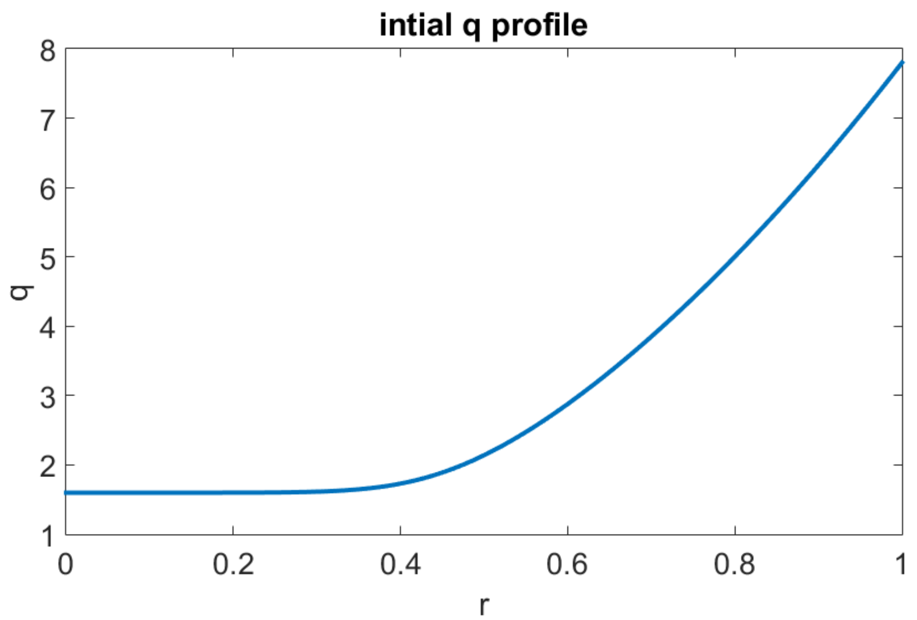

Figure 1. Initial q profile

A. Stationary helical driven current

As we know, the driven current on the O-point can suppress the tearing mode while on the X-point it leads to destabilize the tearing mode. A stationary helical driven current is used to study its influence on the tearing mode instability. The driven current density is given as follows:

$$J_{cd} = J_{cd}(\psi) = J_{cd0}\exp[-(\psi-\psi_0)^2/\delta_{cd}^2][1+\alpha\cos(m\theta+n\phi)] \tag{11}$$

where α represents the strength of the helical driven current, m and n are the poloidal and toroidal mode numbers. We choose $\alpha = 1$ for simplicity. In this paper, we focus on the m/n=2/1 tearing mode instability. ψ_0 determines the location of driven current, so ψ_0 equals to the magnetic flux on the q=2 rational surface. δ_{cd} is the width of the driven current. I_{cd} is the strength of the total driven current and I_p is the total plasma current density. $f_{cd} = I_{cd}/I_p = \int J_{cd}dS/I_p$ is the ratio of the driven and the total plasma current density. The same procedure is employed as in our previous paper[1]. The helical driven current turns on after t=5137 when the tearing mode saturates. The driven current and the magnetic island for the toroidal cross sections $\phi = 0$ and $\phi = \pi$ are showed in Figures 2. Figure 3 shows the perturbed radial magnetic field for the driven currents ($f_{cd} = 0$, $f_{cd} = 0.01$, $f_{cd} = 0.02$, and $f_{cd} = 0.04$). At the first, the perturbed radial magnetic field declines rapidly and its decreasing rate increases with increase of the driven current strength. But it is clear that the minimum value of the perturbed radial magnetic field does not become smaller as the driven current increases. In addition, after it reaches its minimum value, the tearing mode grows up again even though the driven current still exists.

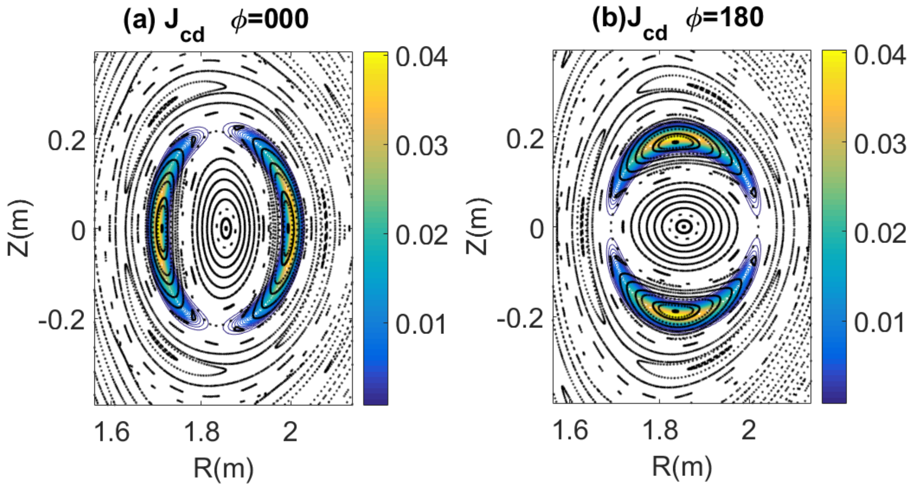

Figure. 2 Helical driven current and magnetic islands for toroidal cross sections (a) $\phi=0$ and (b) $\phi=\pi$

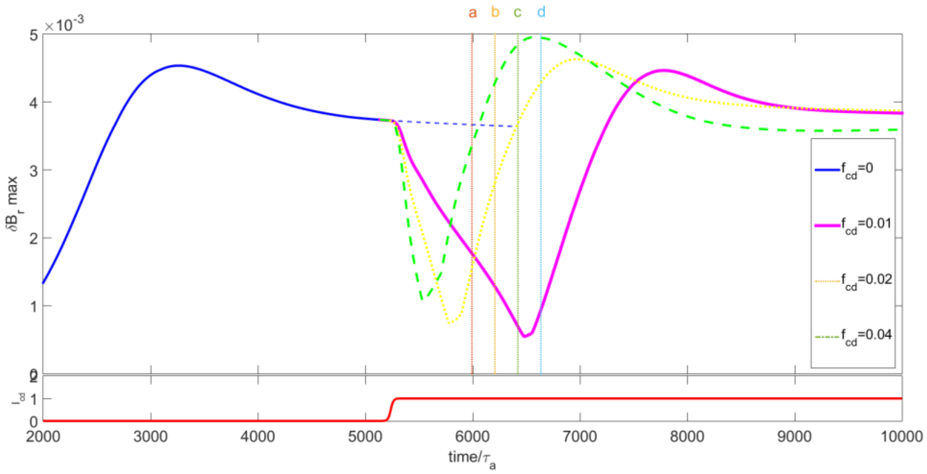

Figure 3. The perturbed radial magnetic field

To further examine the tearing mode dynamics with the helical driven current ($f_{cd}=0.01$), the mode structures (δE_{ϕ}), the total toroidal current density J_{ϕ}, and the magnetic islands at the four different stages (as indicated with vertical lines in Figure 3) are showed in Figure 4. It is obvious that the helical driven current has significant effects on evolution of the mode structure (δE_{ϕ}) and the magnetic islands. The magnetic island quickly reduces to a small size. The toroidal electric field at the O-point exhibits gradual decrease and becomes negative from positive after the helical driven current switches on. At the meantime, the electric field at the X-point increases to a positive value from a negative value. Apparently, the change of the electric field at the O-point is because the external helical driven current has the strongest value at the O-point. The sign reversal of the total electric field indicates that the tearing mode instability becomes unstable and the O-point finally changes to the X-point due to steady external helical driven current.

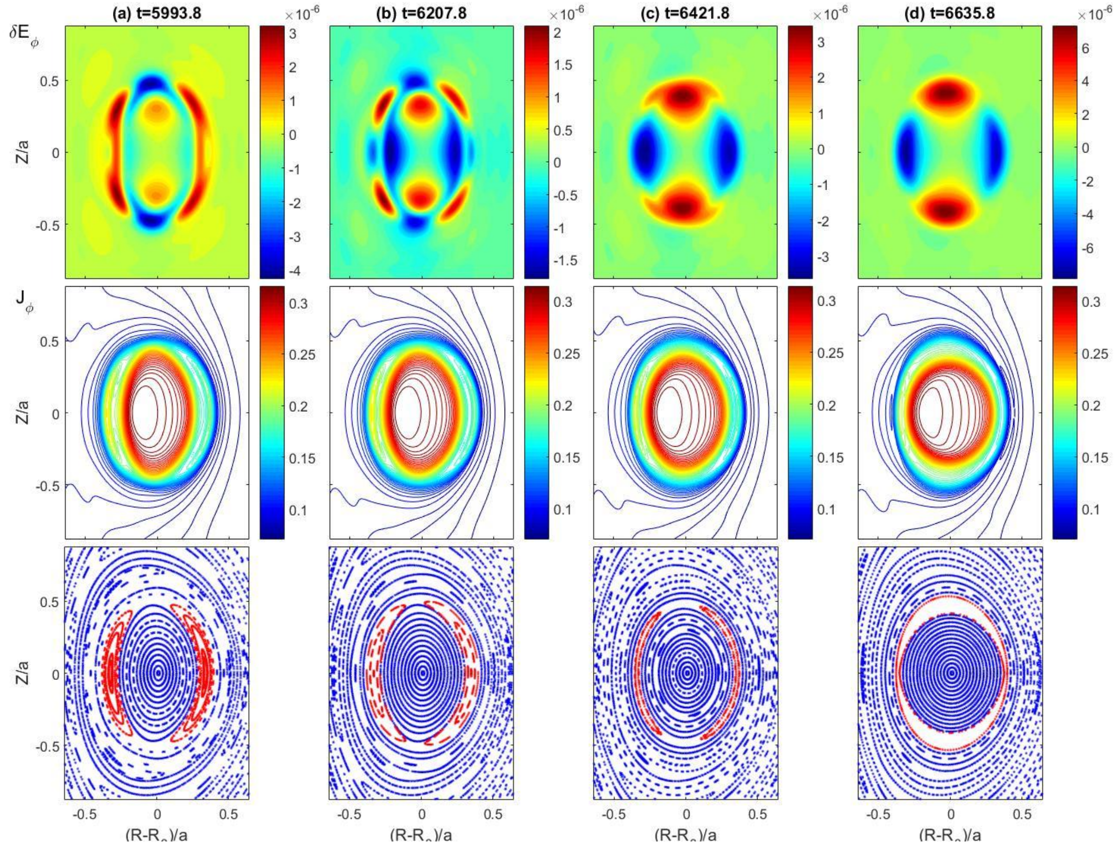

Figure 4 The mode structures (δE_{ϕ}), the total toroidal current density J_{ϕ}, and the magnetic islands at (a) t=5993.8, (b) t=6207.8, (c) t=6421.8, and (d) t=6635.8.

B. Time dependent helical driven current

In the above subsection, it is indicated that with stationary helical driven current, the tearing mode instability is suppressed first, then destabilized again.

In this subsection, we choose a time dependent helical driven current which helical component changes with the size of the magnetic island. The maximum point of the driven current locks on the O-point. The helical current density is as follows

$$J_{cd} = J_{cd0} \exp[-(\psi - \psi_{cd})^2 / \delta_{cd}^2]\{1 + \alpha(t)\cos[m(\theta - \theta_O(t)) + n\phi]\} \qquad (12)$$

where $\psi_{cd} = \psi_{q=2}$ is the magnetic flux on the m/n=2/1 rational surface. θ_O is the poloidal angular of the O-point. Since we are not able to determine the O-point during the simulation, we treat the position of the maximum δE_{φ} as the location of the O-point. Thus, the phase term $\cos[m(\theta-\theta_O(t))+n\phi]$ included in the driven current guarantees that the driven current locks on the O-point all the time. As the width of the magnetic island reduces due to the driven current, we assume that the helical component $\alpha(t)$ of the driven current makes a corresponding change as follows

$$\alpha(t)=w(t)/w_{sat}=\sqrt{\delta B_r/\delta B_{sat}} \tag{13}$$

where w_{sat} and δB_{sat} are the saturation values of the magnetic island width and the radial perturbation of the magnetic field, respectively. When $\alpha(t)$ decreases to zero, the driven current becomes uniform in the toroidal and poloidal direction which has been studied in our previous paper[1].

At t=5137, we turn on the time-dependent helical driven current ($f_{cd}=0.01, \delta_{cd}=0.03$). The m/n=2/1 tearing mode instability is persistently suppressed and the magnetic island is reduced to a very small size by the time-dependent helical driven current as shown in Figure 5. The destabilization phenomenon of the tearing mode instability has not been observed even the driven current is continuously present, which is different from that the tearing mode becomes unstable again in our previous paper.[1] With the time-dependent helical current, the position of the maximum current density always automatically locks on the O-point of the magnetic island when the tearing mode destabilizes again, which leads to persistently suppressing tearing mode instability. The mode structure (δE_{φ}), the magnetic islands with the driven current, and the total toroidal current density at (a) t=5351.6, (b) t=6849.8, (c) t=8560.9 and (d)t=9950.8 are shown in Figure 6, respectively. δE_{φ} becomes smaller, the width of magnetic island becomes narrower and the peak value of driven current becomes lower, meanwhile, the total toroidal current density restores gradually. At t=9950.8, δE_{φ} further reduces, the magnetic island becomes very small eventually. But it should be noted that the island never goes zero, and the toroidal current profile is not fully recovered.

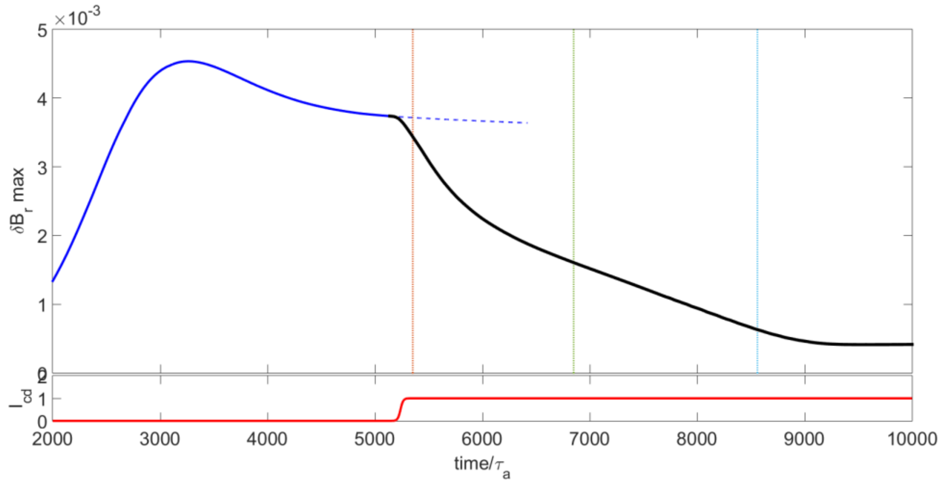

Figure 5. Time evolution of the perturbed radial magnetic field (solid black line) after time-dependent helical driven current turns on.

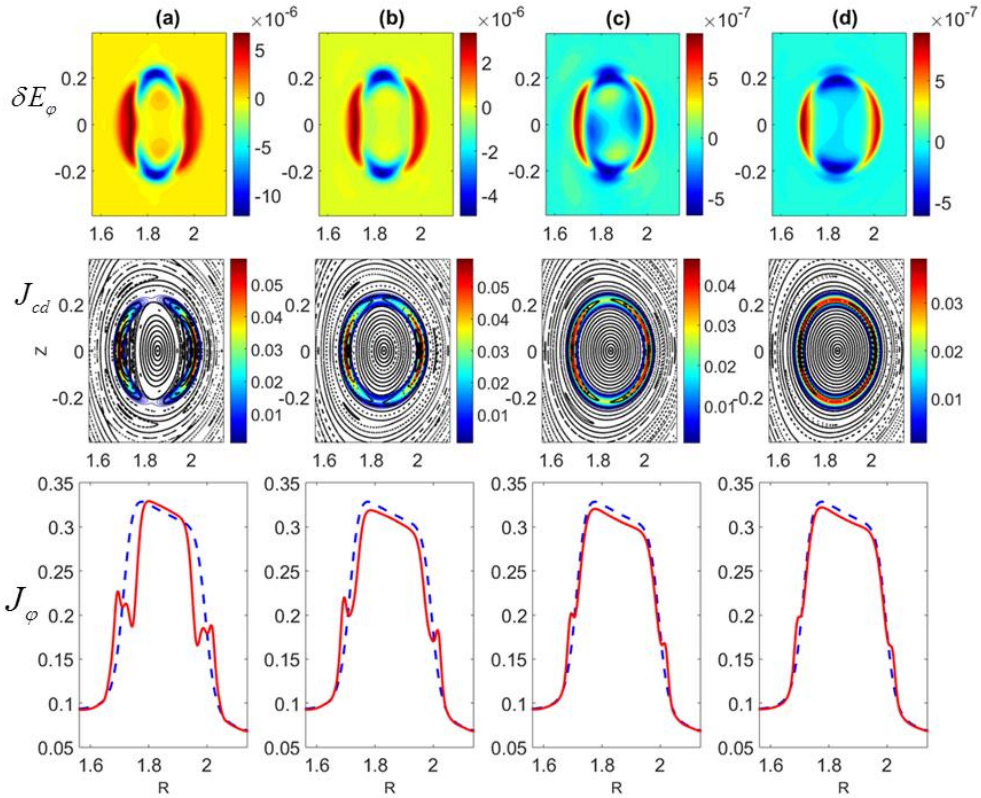

Figure 6 The mode structure (δE_{φ}), the magnetic islands with the driven current, and the total toroidal current density (The equilibrium toroidal current profile is also given with the blue dash line.) at (a) t=5351.6, (b) t=6849.8, (c) t=8560.9 and (d) t=9950.8

IV. Summary

In our previous work,[1] the stationary Gaussian driven current, whose magnitude only has radial dependent, is used to suppress the tearing mode instability. It is found that the tearing mode instability cannot be completely suppressed and the magnetic island grows up again in the late stage because the driven current at X-point plays a negative effect on controlling tearing mode instabilities. In the present paper, the stationary and time-dependent helical driven currents are employed. It is indicated that the helical driven current is much more efficient than the Gaussian driven current. With a small helical current $f_{cd} = 0.01$ which is one percent of the total toroidal plasma current or about one quarter of the Gaussian driven current, the tearing mode instability is successfully suppressed to a sufficient small level. But for the stationary helical driven current cannot be able to persistently control the tearing mode instability. When the magnetic island reduces to a small size, the stationary helical driven current begins to play a negative role on controlling the tearing mode. With the time-dependent helical driven current, the magnetic island not only quickly decreases but also continuously remains at a low level. The tearing mode never comes back again, which suggests that the classical tearing mode instability is able to be controlled by time-dependent helical driven current. It should be noted that the magnetic island does not completely disappear although its size is substantially reduced. It is well known that NTM is linearly stable while classical tearing mode is linearly unstable. For controlling NTM, we only need to reduce the magnetic island to be below the threshold, thus NTM becomes stable. Our results may explain the D-IIID experimental results[26] that use co-ECCD to control neo-classical tearing mode instabilities. It is a little hard to control classical tearing mode because it will grow again due to its linear instability. It could be the only way to suppress the classical tearing mode by time dependent helical driven current with persistently locking on the O-point.

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