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Abstract. Some negative currents should be driven in the central region of the tokamak by bootstrap current and off-axis current drive when the amplitude of driven current is large enough. Once a surface with a zero poloidal magnetic field appears, however, a toroidal equilibrium is lost and any static state cannot exist. Plasma motion along the horizontal direction occurs by the force unbalance between the inside and outside of the torus. A pair of vortices with counter rotation grows in this case. Once the vortex rotation grows enough, the plasma current profile is kept flat by this convective motion. We investigate the growth of this convective motion and find the appearance of the flat current profile, the formation of a current hole, by resistive MHD simulations. After the current hole is formed, additional current drive to the central becomes difficult by the plasma flow.

1. Introduction

In early of 1970's, the theory of bootstrap current is proposed [1-3]. From that time it has been believed that a certain amount of current drive at the center, so called seed current, is needed to keep a tokamak equilibrium and the efficiency of tokamak power plants is limited by the necessary power of the current drive for the seed current. Many theoretical efforts have been done to develop an effective way to drive the seed current. However, detailed study to understand what phenomena will happen actually when total bootstrap current exceed original plasma current.

Recently in several tokamak experiments, the measured toroidal currents in the central region are consistent with the value of almost zero [4-5]. These "current hole" phenomena are sustained for longer time than the transient time scale of resistive skin effect. One explanation for the "current hole" formation is that it is produced by MHD activity, where an m=1/n=0 internal kink mode grows and flattens the plasma current in the central region [6]. In the case of JT-60 experiment, however, no MHD activity is observed. Moreover, additional current drive by electron cyclotron wave ECW or neural beam injection NBI is impossible in both directions inside of it [7]. In this paper, we propose a new mechanism to sustain the "current hole", where a pair vortex is formed in a central region of a plasma column. When an eddy turnover time ($\tau_h = r_h / v_h$; r_h, v_h are the size of a current hole and flow velocity on the horizontal plane respectively) of them becomes shorter than the resistive skin time, the plasma current profile is kept flat by this convective motion.

2. Model and Simulation Results

2.1 Model and Pair Vortex Formation

The plasma parameter is almost flat within the internal transport barrier ITB in the JT-60 experiment and we neglect the time evolution of plasma pressure and resistivity. We employ a simulation code with a reduced set of resistive MHD equations in a cylindrical and also in a toroidal geometry [8]. Time evolution of the stream function Φ and the he flux function Ψ are obtained numerically in a cylindrical coordinate (R,φ,Z) with,

$$\frac{\partial \Psi}{\partial t} + \mathbf{v}\cdot\nabla_\perp \Psi = B_0 \frac{\partial \Phi}{\partial \zeta} + \eta\left(J - J_{CD}\right) + E_w,$$

$$\frac{\partial U}{\partial t} + \mathbf{v}\cdot\nabla_\perp U = \left(\frac{R}{R_0}\right)^2 \nabla\zeta\cdot\nabla_\perp\Psi\times\nabla_\perp J + B_0\frac{\partial J}{\partial \zeta},$$

and

$$\mathbf{B} = B_0\nabla\zeta + \nabla\zeta\times\nabla_\perp\Psi, \quad \mathbf{v} = \left(\frac{R}{R_0}\right)^2 \nabla\zeta\times\nabla_\perp\Phi,$$

$$J = \left(R^2\nabla_\perp\frac{\nabla_\perp\Psi}{R^2}\right)\nabla\zeta, \quad U = \left(\frac{R}{R_0}\right)^2 \nabla_\perp^2\Phi,$$

where

$$\zeta = R_0\varphi \quad \text{and} \quad \nabla_\perp \equiv \frac{\partial}{\partial R}\nabla R + \frac{\partial}{\partial Z}\nabla Z.$$

Here, U, J, $\mathbf{v}$ and $\mathbf{B}$ are vortex, current density, plasma velocity and the magnetic field respectively and η and ν is plasma resistivity and viscosity respectively. The time is normalized Alfvén transit time ($\tau_A=R_0/V_A$, R_0 is a major radius and V_A is Alfvén velocity). Usual simulation runs are performed in cylindrical geometry and we set $R/R_0=1$.

To drive the negative current in the central region, a strong positive current I_{cd}, which is larger than the total plasma current I_p, is driven at r~0.6a with Gaussian profile width 0.2a with keeping I_p constant. For $I_{cd} > I_p$, a negative one-turn voltage is applied externally to keep the I_p value. The negative one-turn voltage in the central region causes sawtooth-like oscillation in usual cylindrical computation as shown by Stratton et al [9]. However, a tokamak has toroidicity and this toroidal effect acts as a large perturbation for m/n=1/0 mode, where m and n are a poloidal and toroidal mode number respectively. Effective m=1 components plays a role of a large initial perturbation when system cross the marginal point and changes the behavior in later stage completely. To simulate the toroidal effect, a small shift of a plasma column is applied in horizontal direction by an external vertical field which is applied by a certain value of m=1 component of flux function at r=a. We use the value of Ψ_1~ $0.002\Psi_0$ for typical value for this modification, which correspond to shift the plasma column to right ~0.04a.

The time evolution of a plasma current profile on the equatorial plane is shown for I_{cd} = $1.28I_p$, $\eta=5\times10^{-5}$ and $\nu=5\times10^{-3}$ in Fig.1. The current drive is performed from $t=200\tau_A$ and a resonant surface for n=0 modes appears for $t>1900\ \tau_A$. In the cylindrical case without external m=1 error fields (a), a negative one-turn voltage in the central region causes sawtooth-like oscillation as Stratton et al. [9]. The thick (blue) lines show the contour lines for the zero value of current density. In the case with external m=1 field components, a plasma column is shifted to right (~0.04a), as soon as a negative current appear in the central region, a force balance in the horizontal direction is lost and a convective motion grows as. The current profile is flattened after the formation of the convective motion as shown in Fig. 1 (b),.

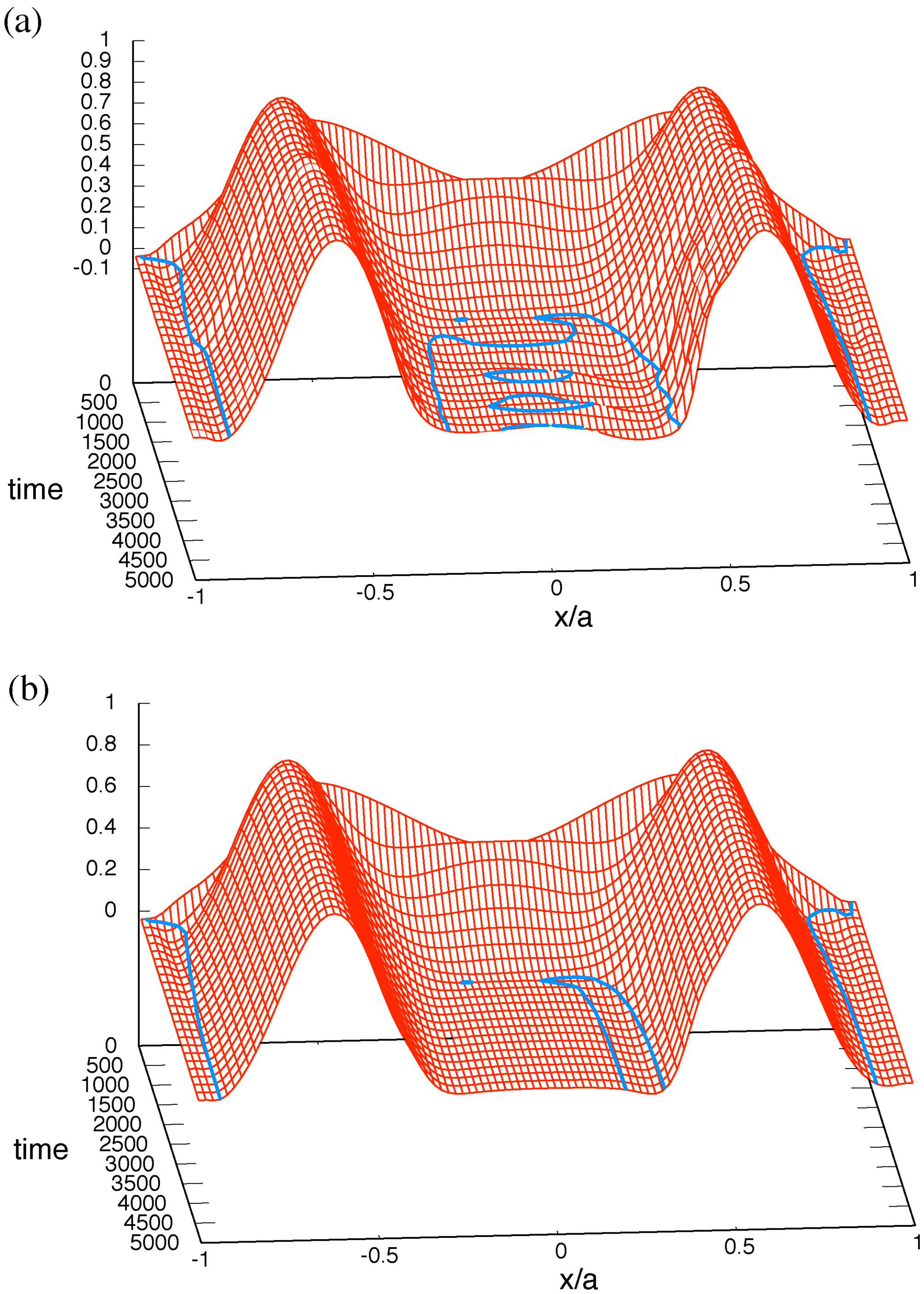


Fig. 1. Time evolution of a current profile on the equatorial plane is shown for I_{cd}=1.28I_p and, $\eta=5\times10^{-5}$ and $\nu=5\times10^{-3}$, case (a); a usual cylindrical simulation without an external perturbation and case (b); a simulation with m/n=1/0 external perturbation. Repeated reconnection events occur for case (a). On the contrary steady current flattening in the central region occurs for t>2000 Alfvén time for case (b). The thick (blue) lines show the contour lines for the value of zero.

External m=1 components plays an essential role for the behavior of this system. The dependence of the flow velocity on the strength of external m=1 field is shown in Fig. 2. We give the m/n=1/0 component of flux function at plasma surface. For small or none external field, system becomes oscillatory, clash events occur repeatedly. For large external field, a steady state is established. The existence of a steady state of this kind was also shown in a toroidal simulation by Huysmans [10] for almost marginally unstable case. For larger external field, current hole is pressed against an external wall and the flow velocity is reduced. Simulation runs in toroidal geometry also performed and the results is qualitatively same in cylindrical cases and the flow velocity weakly depend on aspect ratio A. The dependence of the flow velocity on the strength of current drive is shown in Fig. 3 and The flow velocity is proportional to $(I_{cd}/I_p\text{-}1)^{0.38}$. As we increase I_{cd}, flow velocity increase and finally the solution becomes oscillatory for $I_{cd} > 3.5I_p$. Even with an appropriate external m=1 field, the behavior of this system become oscillatory as the case without an external one for larger resistivity, smaller viscosity. For a large tokamak such as JT-60 and JET, plasma resistivity is smaller than the value used in our simulation by factor $\sim 10^{-3}$ and we can conclude from scaling study that a steady state will be realized for large tokamaks.

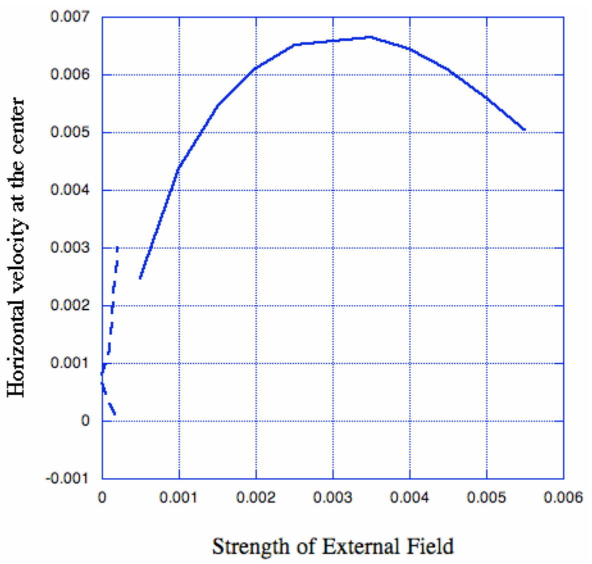


Fig. 2 The dependence of the flow velocity on the strength of external m=1 field, $\Psi_{1/0}$ at r=a for $\eta=5\times10^{-5}$ and $\nu=5\times10^{-4}$.

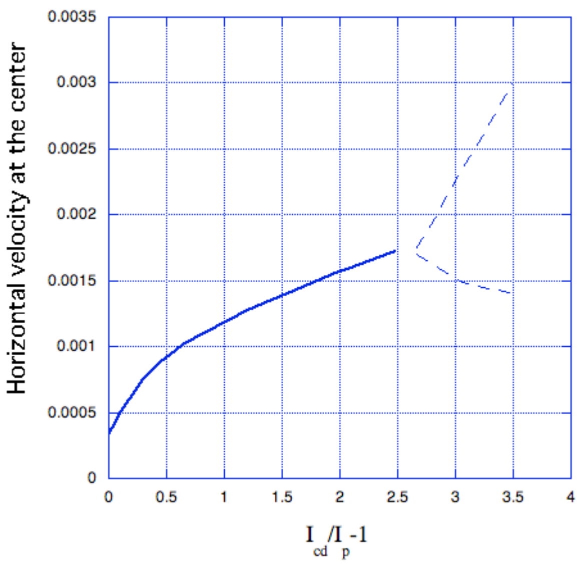


Fig.3 The dependence of the flow velocity on the strength of current drive for $\eta=5\times10^{-5}$ and $\nu=5\times10^{-3}$. The parameter Icd/Ip-1 is proportional to the value of negative one-turn voltage.

Contour plots of (a) stream function **Φ**, (b) current density **J** and (c) flux function **Ψ** plots at t=9600τ_A with the external m=1 field are shown in Fig.4. The plasma parameter is same as Fig.1 case. The value of current density is not completely zero inside of the "current hole" and small positive and negative current flow as shown in Fig.4b, the green line reveal the value of zero, and j×B torque drives the vortex motion continuously. As shown in Fig.4 (a), the vortex motion extend a little to outer region, large positive current flows there and the vortex motion extracts the positive current from there to the inside of the current hole and positive current extend to interior of the current hole region as in Fig.4 (b).

2.2 Direction of Flow

The direction of rotation and flow depends on the parity of external m=1 fields. If the position of plasma column (a magnetic axis) is shifted to right by the external vertical field, the plasma flows to right on the equatorial plane, the vortex rotates in counterclockwise in upper half plane and rotates clockwise in lower half plane. In the case of toroidal geometry, during the current decay at the plasma center, a plasma column shift to inside by toroidal effect and plasma flow on the equatorial plane direct to inside of torus after the vortex formation.

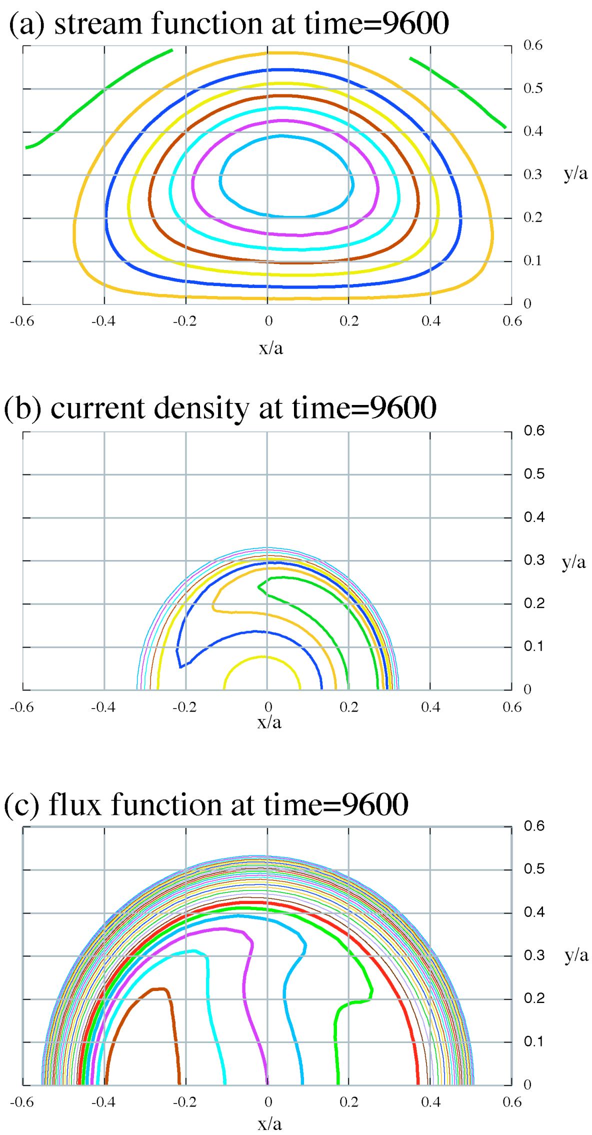
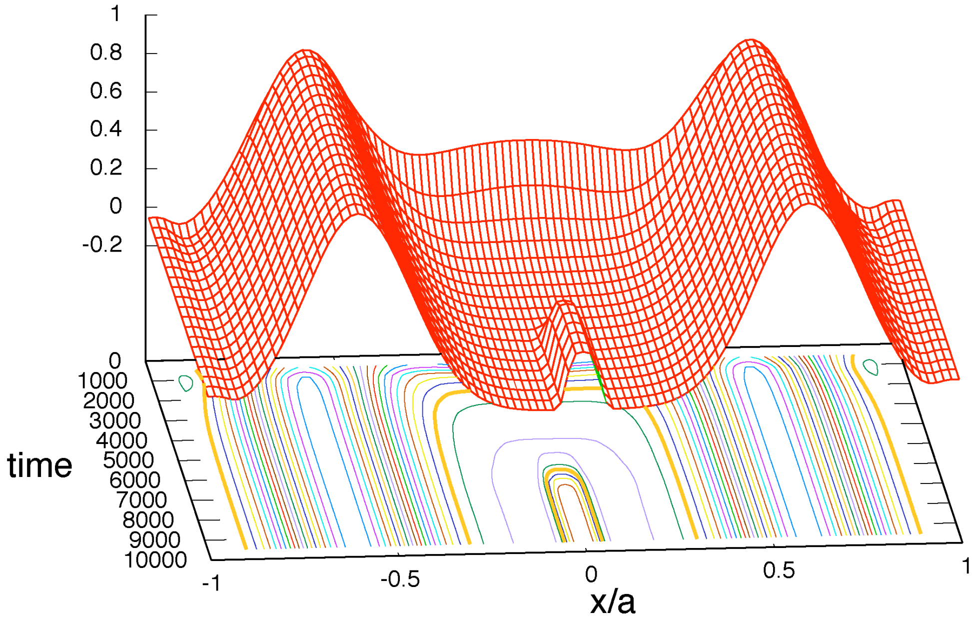


Fig.4. Contour plots at t=9600τ_A of (a) stream function **Φ**, (b) current density **J** and flux function **Ψ**. The contour lines for large **J** and **Ψ** are too clouded to show and only lines for small radial region, inside the current hole, are plotted for **J** and **Ψ** in (b) and (c). Current density in the outer region is much larger than within the current hole. Plasma flow on the equatorial plane is directed to right and is extended a little from "current hole" region.

(a) time evolution of current profile without vortex motion



(b) time evolution of current profile with vortex motion

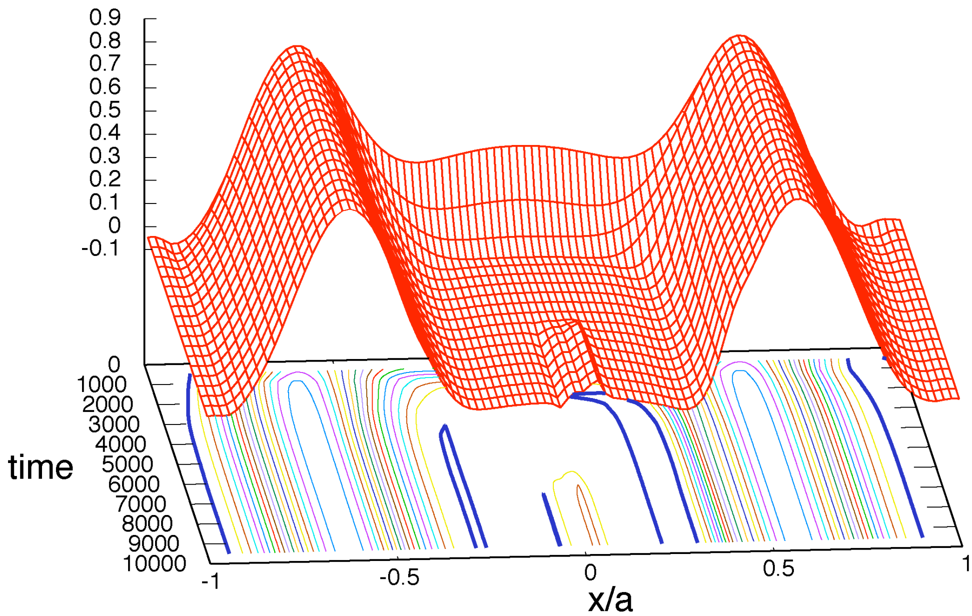


Fig.5. Time evolution of a current profile on the equatorial plane is shown for $\eta=5\times10^{-5}$ and $I_{cd}=1.28I_p$, the thick (blue) lines show the contour lines for the value of zero. Additional current drive~$0.001I_p$ applied from t=5000 Alfvén time. Case (a); a vortex motion is suppressed, we solve only m=0 components and case (b); a simulation with vortex motion by m/n=1/0 external perturbation. Steady current flattening in the central region occurs for t>2000 Alfvén time for case (b) and the vortex motion dose not change after secondary current drive. The vortex motion reduces driven current by additional current drive.

2.3 Additional Current Drive

We also simulate a case with an additional current drive to examine the profile stiffness observed in JT-60 experiments [7]. In the experiment, we couldn't observe the any current change during a additional current drive to the central region. We apply a current drive with small amplitude (I_{cd}~$0.001I_p$) at the center to see the response of the plasma with a vortex motion. If we set all the m>0 modes to zero initially, any m=1 perturbation dose not grows and the effects of vortex motion on current drive can be omitted. The result without the vortex effect is shown in Fig. 5 (a). Additional current drive starts form $t=5000\tau_A$ and plasma current increase after a skin time delay, estimated by the width of current drive source. In the case without the vortex motion, safety factor at the center changes from –18 to +11. On the other hand, in the case with vortex motion, after a pair of vortices sufficiently grows, advective term in 2nd term of RHS of 1st equation in our basic equation system becomes dominant and the current drive within the current hole becomes ineffective as shown in Fig. 5 (b). Safety factor at the center, changes from –100 to +120 by the additional current drive. Of course, in this case, the topology of magnetic field lines change and safety factor at the center means only a measure of the current density. The reduction of driven current is also observed for current drive in a negative direction.

If we introduce this additional current drive to a oscillatory plasma, without an external m/n=1/0 field case, the reduction of current drive efficiency do not occur and the same order of central current is driven during quiet phases and the formed current peak is flatten by clash events repeatedly. If the current hole phenomena is produced by repeated MHD activity, m/n=1/0 internal kink mode, the repeated driven current should be observed

3. Discussion

In the plasma parameter of JT-60, the current diffusion time in the "current hole" region is ~1second and the size of the current hole is ~0.4 m. So if we have a flow velocity of the vortex motion of ~ 1m/s, the current profile is easily modified by such a small velocity. The current density within the current hole is estimated as q~100, q is the safety factor in the central region in the JT-60 experiment [5] and the maximum velocity within current hole should be limited as v_{max} ~ ploidal Alfvén velocity ~ 10^4m/sec. Usually simulation run is performed with a parameter $\eta \sim 10^{-5}$. If we extrapolate the simulation results to $\eta \sim 4\times10^{-8}$ and other parameters for JT-60 plasma, we can estimate the value of flow velocity of 2000m/s. Unfortunately, such a small velocity may not be measured by any existence diagnostic method.

Because we want to examine a steady state solution, we don't use a current ramp up phase in our simulations to produce a negative one-turn voltage in the central region. In the experiment in JT-60 and JET, the plasma current is ramped up during the formation of the current hole to help the negative one turn voltage in the central region and create the current hole. If we introduce the current ramp up phase in our simulation, the current profile at the appearance of zero current region and the linear stability for m/n=1/0 mode is changed transiently. However, after many skin time has passed, the character of the steady state will not changed.

4. Conclusion

Pair vortices formation phenomena are often observed as “Modon” in geophysics and drift turbulence. Similar vortices with counter rotation grow in the central region of tokamak plasma and flat the current profile and keep the value of almost zero. This mechanism can keep “current hole” steadily for a long duration enough to explain the experiments. In conclusion, tokamak with zero or negative central current density has no equilibrium state, which has larger bootstrap current (non-inductive current) than total plasma current, but it has a steady state with plasma vortex motion.

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