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# Stability of Double Tearing Mode in Current Hole Configuration

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A current profile with a strong current peak on the outside of a region with almost zero current density was observed in *current hole* experiments. Such a profile offers the possibility of having a good stability for double tearing modes, even where two resonant surfaces exist, because no magnetohydrodynamic activity identified for a double tearing mode was observed. We examine the stability of a double tearing mode for a current profile with a strong peak around an inner resonant surface and show that the profile is stable for a double tearing mode if the peak exists inside of the surface. This fact shows the possibility of stabilizing a double tearing mode by a localized co-drive current.

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## I. INTRODUCTION

The current density is expected to be negative in a central region of a tokamak when the amplitude of bootstrap current or off-axis current drive is large enough. A flat current profile with almost zero value, however, has been observed in experiments, even in a situation where negative one-turn voltage exists in the central region of the plasma [1, 2]. Once a surface with a zero poloidal magnetic field appears, a conventional toroidal equilibrium is lost and a static state disappears. A pair of vortices with counter rotation grows in this case. Once the vortex grows strong enough, the plasma current profile is kept flat by this convective motion [3].

Observed current profiles have a strong peak on the outside of the *current hole* and broad profile around $q_{min}$, as shown in Fig. 1 [2].

Double tearing mode (DTM) is unstable for a reversed magnetic shear configuration in a tokamak [4] and it sometimes destroys a reversed shear configuration, even in a low-beta region. DTM also has the possibility of being unstable for a current profile with a *current hole*, and some MHD activities seeming to be DTM are observed in JET before the formation of the current hole [1]. In the contrast, no MHD activity is observed in the JT-60 experiment [2]. Hence, a current profile with *current hole* has the possibility of being stable for DTM, even with double resonant surfaces. Therefore, we investigate the stability of DTM and study the condition of appearance of DTM with resistive RMHD simulations.

## II. CALCULATION PROCEDURE

### 1. Model

We employ a simulation code with a reduced set of resistive MHD equations in single helicity approximation and in a toroidal geometry [5]. Time evolutions of the

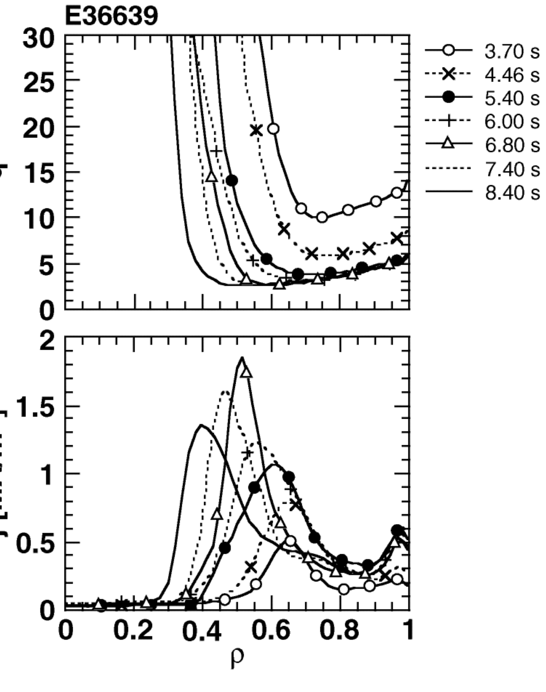

Fig. 1. Radial profile of safety factor $q$ and current density $j$ at several times in JT-60 experiment [2].

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stream function $\Phi$ and the flux function $\Psi$ are obtained numerically in cylindrical coordinates $(R,\ \varphi,\ Z)$ as

$$\frac{\partial \Psi}{\partial t} + \mathbf{v} \cdot \nabla_\perp \Psi = B_0 \frac{\partial \Phi}{\partial \zeta} + \eta \left( J - J_{CD} \right) + E_w, \qquad (1)$$

and

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

where

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

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

Here, $U$, $J$, $\mathbf{v}$ and $\mathbf{B}$ are vortex, current density, plasma velocity and magnetic field, respectively and $\eta$ and $\nu$ are plasma resistivity and viscosity respectively.

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

The time is normalized by Alfvén transit time ($\tau_A = R_0/\mathrm{V}_A$; $R_0$ is a major radius, and $\mathrm{V}_A$ is Alfvénvelocity) and the length is normalized by plasma radius $a$. Resistivity $\eta$ is chosen to be flat profile and set to $5 \times 10^{-5}$, and viscosity $\nu$ is $1 \times 10^{-5}$ in normalized unit. Simulation runs are performed mainly in a cylindrical geometry with single helicity constraint. Toroidal simulation is also performed in some cases to check the stability of other helicity modes with higher toroidal mode number, $n = 2$ or 3, simultaneously.

### 2. Current profile control

We use current drive (CD) to control a current profile to a similar current profile in *current hole* experiments.

We use

$$J_{CD} = A_1 \left( 1 - \frac{r}{a} \right) \exp \left[ - \frac{(r - p_1)^4}{d_1^4} \right]$$
$$+ A_2 \exp \left[ - \frac{(r - p_2)^2}{d_2^2} \right] \qquad (3)$$

for the profile of CD. The first term is used to produce a broad profile around the $q_{min}$ surface. The second term is used to simulate the inner current peak in the experiments. Here, we chose parameters as $d_1 = 0.3a, p_1 = 0.5a$ and $d_2 = 0.05a$. The coefficients of CD amplitude, $A_1$ and $A_2$ are given as a function of time and set to be zero at an initial stage. The total plasma current is kept constant during simulations.

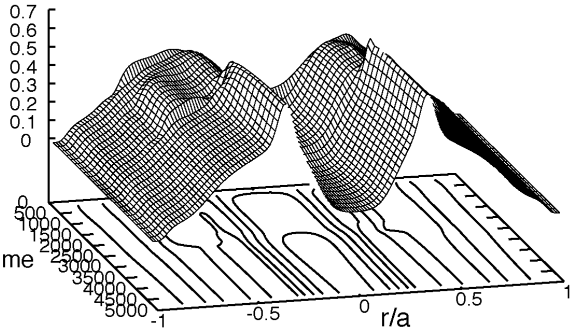

Fig. 2. Time evolution of current density on an equatorial plane. $I_{cd2}/I_p = 0.055$ and $p_2 = 0.35$. For $1000\tau_A < t < 2000\tau_A$, the DTM activity flattens the current profile $0.45 < r/a < 0.6$, around $\mathrm{q}_{min}$. For $t > 2000\tau_A$, a localized co-driven CD around $0.35a$ stabilizes the DTM and a peaked current profile is realized.

## III. RESULTS

### 1. Stabilized case

In Figs. 2-4, we show a case where DTM is stabilized by localized CD, $p_2 = 0.35a$. The first CD with broad profile starts from t $\sim 200\tau_A$ with 63 % of the plasma current and DTM ($m/n = 5/1$, $m$ is a poloidal mode number) is destabilized and the minimum value of a safety factor $q$ is limited to 5 by DTM activity from $t \sim 1000\tau_A$ to $t \sim 2000\tau_A$.

After a second CD with localized profile of 5.5 % of the plasma current has been applied, DTM is stabilized and the current is flattened as shown in Fig. 2.

In Fig. 3, the time evolution of Fourier components of magnetic energy and kinetic energy,

$$ME_{m/n} = \frac{\pi}{2} \int_0^a \left[ \left( \frac{\partial \psi_{m/n}}{\partial r} \right)^2 + \left( \frac{m}{r} \psi_{m/n} \right)^2 \right] r dr$$

and

$$KE_{m/n} = \frac{\pi}{2} \int_0^a \left[ \left( \frac{\partial \phi_{m/n}}{\partial r} \right)^2 + \left( \frac{m}{r} \phi_{m/n} \right)^2 \right] r dr,$$

are shown. At $t \sim 2200\tau_A$, DTM is weakly destabilized once by the second CD. Then, a magnetic reconnection event occurs and all the perturbations are slowly damped.

Current and $q$ profile during saturated DTM ($t = 160\tau_A$ in the thick line and + symbol) and in the final stage ($t = 4800\tau_A$ in the thin line and $x$ symbol) are shown in Fig. 4. The thin line shows a $q$ profile when DTM is saturated under only a first CD with a broad profile. After a second CD was been applied, an inner resonant surface moves to inside. The minimum value of $q$ goes down to 4.5.

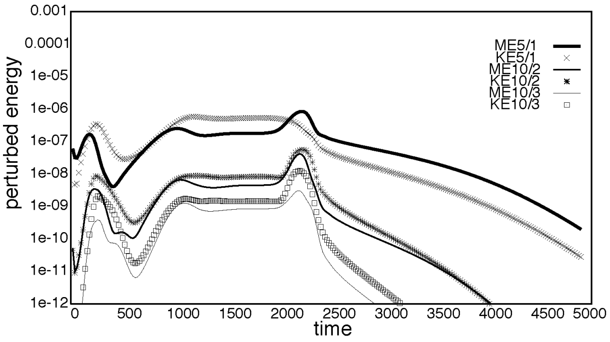

Fig. 3. Time evolution of Fourier components of perturbed energy. Parameters are the same as in Fig. 2. After a second CD is applied from t = $2000\tau_A$, DTM is stabilized and perturbed energies are damped.

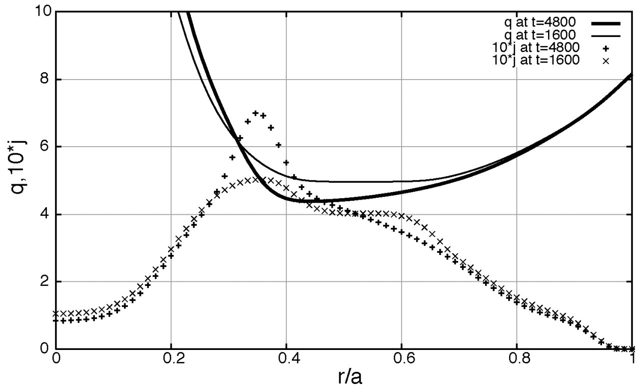

Fig. 4. Profiles of $m = 0$ and $n = 0$ component of current density and$q$at $t = 1600\tau_A$, $4800\tau_A$. Parameters are the same as in Fig. 2. Thin line shows a $q$ profile at $t = 1600\tau_A$. DTM is saturated and current density is flattened by DTM activity. Thick line shows a q profile at $t = 4800\tau_A$. At that time, DTM is stabilized by the second co-driven current and $q_{min}$ goes down to 4.5.

If both CDs start simultaneously at $t \sim 200\tau_A$, DTM is stabilized from an initial stage. All components of energy are damped down, except $m = 0$ and $n = 0$. Other helicity modes, $m/n = 11/2$, $6/1$ *etc.*, are linearly stable in this case. When the amplitude of a second CD is enhanced to $I_{cd2}/I_p = 0.1$, we can decrease the minimum $q$ value below 4 in a simulation with $m/n = 5/1$ helicity. However, in this case, $m/n = 4/1$ DTM becomes unstable in a single helicity simulation with $m/n = 4/1$ or in a toroidal simulation. To stabilize 4/1 mode, the position of the second CD should be moved to more inner side, for example $p_2 = 0.25$.

Whether the 2nd CD works as stabilizes or destabilizes is very sensitive to its position, as shown in the next section. However, it depends weakly on its amplitude. In the present case, one fourth of the additional CD amount is enough to stabilize DTM.

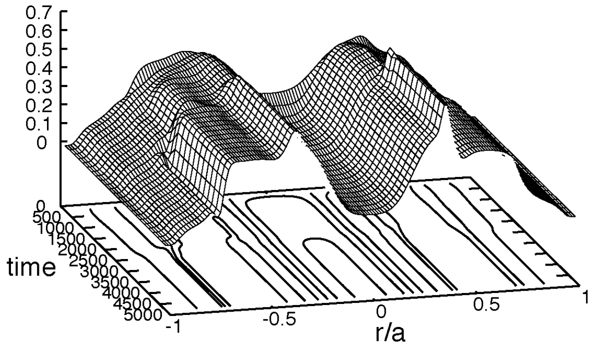

Fig. 5. Time evolution of current density on an equatorial plane. Drive position of the 2nd CD is changed to $p_2 = 0.40a$ and other parameter are the same as in Figs. 2-4 case. For $t > 2000\tau_A$, a localized co-driven CD enhances the DTM activity and the minimum $q$ value is not changed from 5.

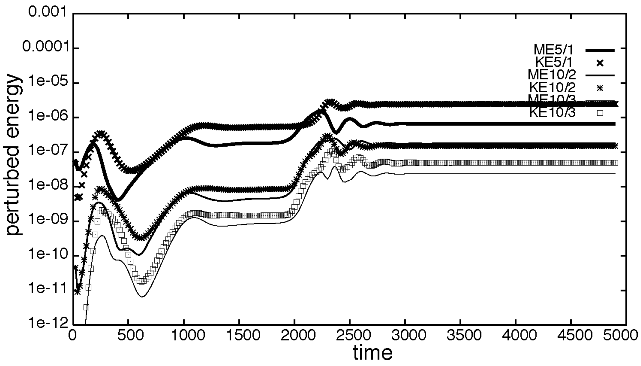

Fig. 6. Time evolution of Fourier components of perturbed energy. Drive position of the 2nd CD is changed to $p_2 = 0.40a$ and other parameters are the same as in the Figs. 2-4 case. Unstable DTM is enhanced by the second co-driven current for $t > 2000\tau_A$.

### 2. Destabilized case

In Figs. 5-7, we show a case where a localized CD destabilizes DTM. The position of the peaked CD moved slightly to the outside, $p_1 = 0.40a$. Other parameters are same as in Section III.1. Only a small shift of drive position, $0.05a$, changes the effect of additional CD from stabilization to de-stabilization. The current profile is modified by DTM activity, $0.4 < r/a < 0.7$ and a current peak due to the second CD can be seen even with DTM activity, as shown in Fig. 5. The perturbed energy is also enhanced by the additional CD as shown in Fig. 6.

If the position of the second CD is moved more to the outer region, for instance $p_2 = 0.5a$, the effect is also destabilizing and a current peak due to additional drive is not observed due to DTM activity.

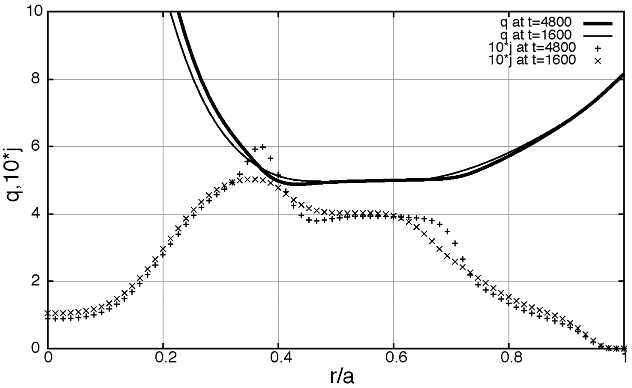

Fig. 7. The profiles of $m = 0$ and $n = 0$ component of current density and $q$ at $t = 1600\tau_A$ and $4800\tau_A$. Drive position of the 2nd CD is changed to $p_2 = 0.40a$ and other parameters are the same as in Figs. 2-4 case. Thin line shows a $q$ profile at $t = 1600\tau_A$. Thick line shows a $q$ profile at $t = 4800\tau_A$. At this time, DTM is destabilized by the second co-driven current and $q_{min}$ is limited to 5.

## IV. DISCUSSION

Perturbation theory shows that a normal tearing mode in a positive magnetic shear configuration is stabilized by a localized co-driven current on a resonant surface and a small shift of its position changes the sign of the effect [6]. Here, "perturbation" means that the $q$ profile is not modified by a small additional current drive. If we apply this theory to the DTM cases, co-driven current on the inner resonant surface, $q'$ is negative there, and works for destabilization. However, even with small amplitude of localized current drive, a few percent of the plasma current, the position of a resonant surface is moved in the order of the localization of the current drive. So, we should be careful to apply the theory.

## V. CONCLUSIONS

Current density profile in *current hole* configurations, which has a strong current peak outside of the zero current region, has a good stability nature for a double tearing mode. The fact shows that a double tearing mode has a possibility to be controlled by co-driven current with peaked profile inside the inner mode rational surface.

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