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Recent simulation studies of sawteeth from CLT

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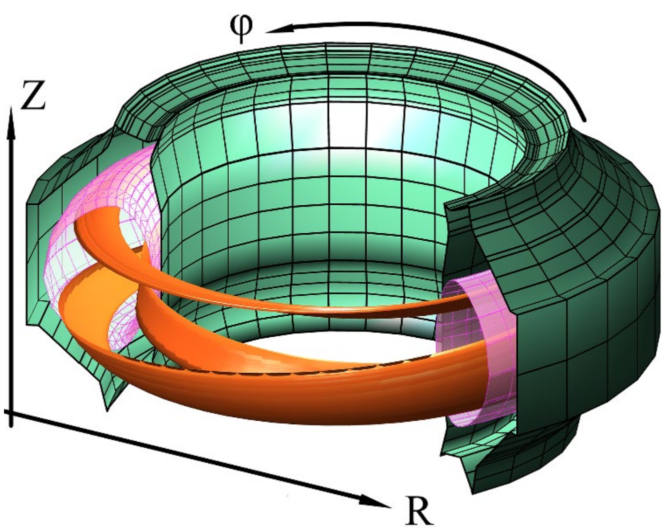
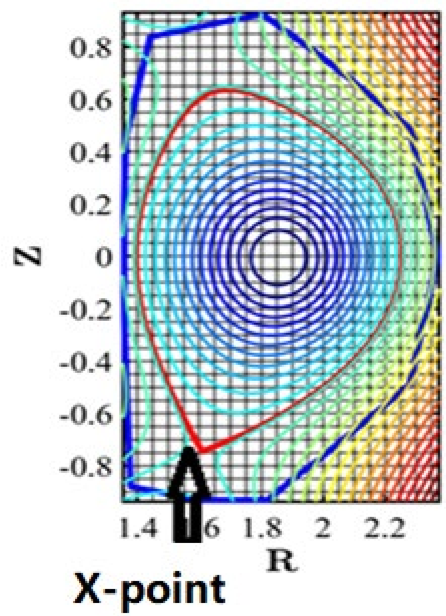
1. Introduction to the CLT code

- **CLT(Ci Liu Ti): 3D toroidal nonlinear Hall-MHD code, developed in Zhejiang University, China.**
  - **The toroidal geometry under the cylindrical coordinate system（R, φ, Z）is adopted.**
  - **The Cut-cell method is applied to handle the boundary conditions.**





The cylindrical coordinate system（R, φ, Z）

1. Introduction to the CLT code

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

$$\frac{\partial p}{\partial t} = -\mathbf{v} \cdot \nabla p - \Gamma p \nabla \cdot \mathbf{v} + \nabla \cdot [\boldsymbol{\kappa} \nabla (p - p_0)]$$

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

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

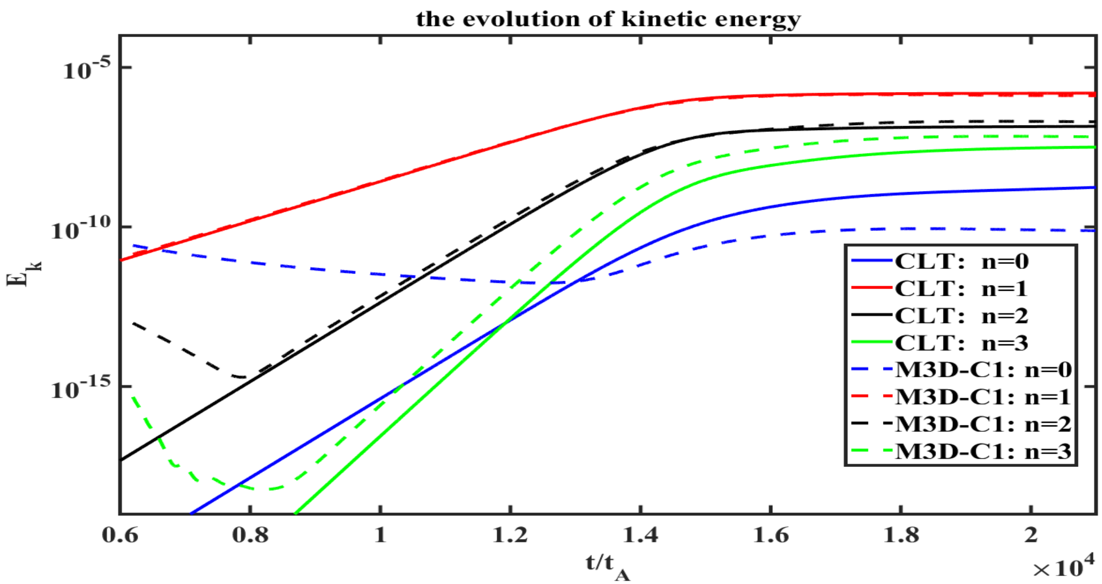
$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta(\mathbf{J} - \mathbf{J}_0) + \frac{d_i}{\rho}(J \times B - \nabla P_e)$$

$$\mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

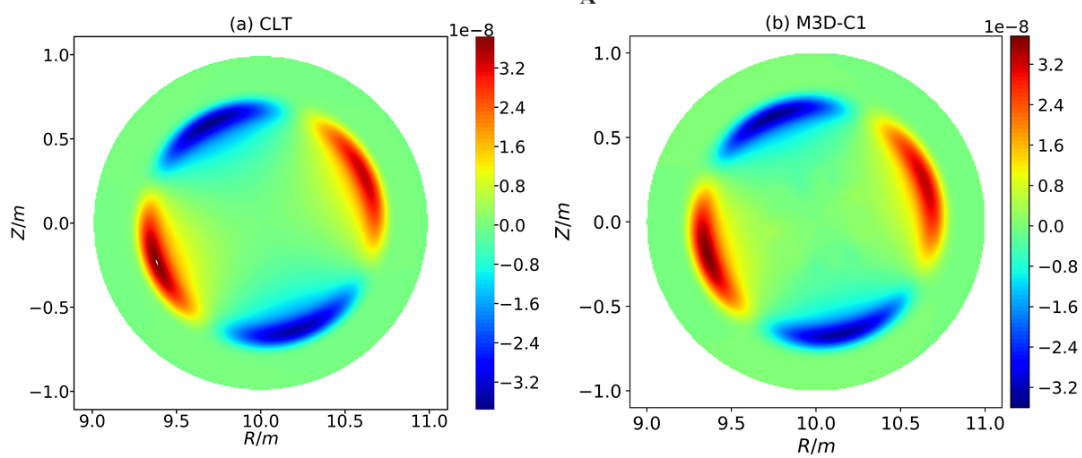
The nonlinear Hall-MHD equations are used in CLT. The electric field **E** is used as an intermediate variable, which can guarantee $\nabla \cdot \mathbf{B} = \mathbf{0}$, throughout the simulation. The fourth-order finite difference method is used to derive the spatial derivatives, and the fourth-order Runge–Kutta scheme is applied to calculate the time integration.

1. Introduction to the CLT code

Nonlinear benchmark with the M3D-C1 code (PPPL).



- The linear and nonlinear simulation results are quantitively the same.
- The benchmark between CLT and M3D-C1 confirms that the simulation results are both reliable.



The mode structures of m/n=2/1 tearing mode in (a) CLT and (b) M3D-C1

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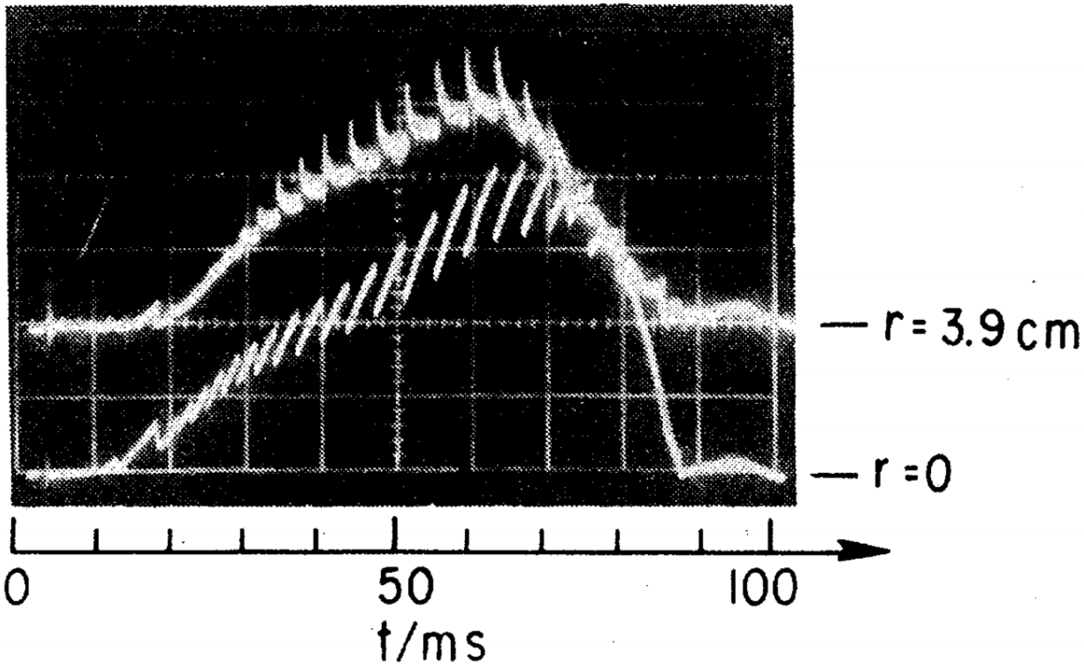
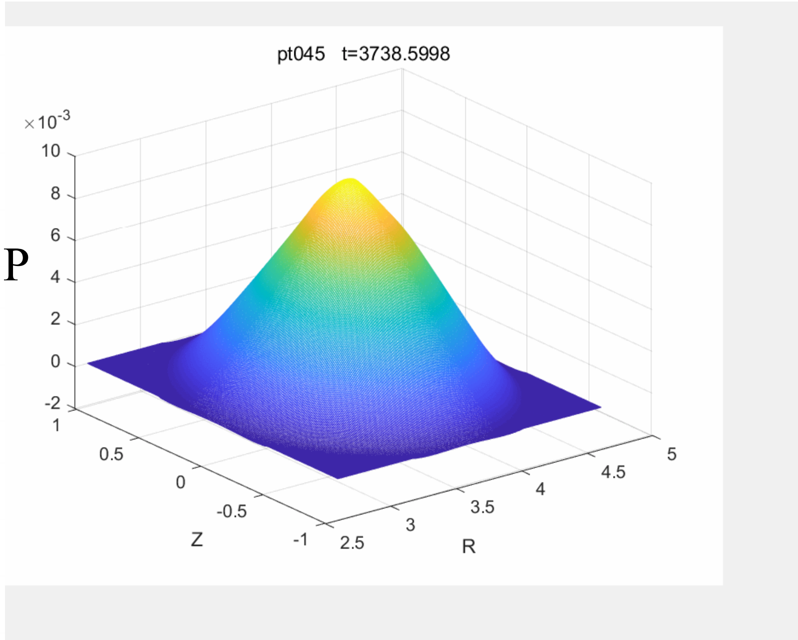
2. Research background



First observation of sawtooth (Goeler et al. PRL 1974)



Pressure evolution from CLT's simulation

A sawtooth consists of a slow ramp, during which the plasma temperature, density, and current density profiles peak in the core region, and a rapid relaxation, also called the sawtooth crash, during which the temperature, density, and current density profiles are rapidly flattened.

2. Research background

- Normal sawtooth always develops into a large-amplitude crash and significantly destroys the energy confinement of Tokamaks.
  - It has been shown that plasmas with large-amplitude sawtooth are more susceptible to edge localized modes (ELMs) and neoclassical tearing modes (NTMs).
- Small sawtooth evolves with a small amplitude and only slightly reduce the energy confinement.
  - It is less likely to trigger neo-classical tearing modes.
  - Moreover, it can help to expel the Helium ash in fusion reactors.
- Quasi-steady state with a n/m=1/1 remnant magnetic island associated by the sawtooth dynamics.
  - It could be another advanced operational scenario for ITER.

2. Research background

- Snake phenomenon observed in tokamak plasmas is likely associated with quasi-steady state sawtooth oscillation with a m/n =1/1 magnetic island.
- Quasi-steady state sawtooth was obtained in the previous simulation studies by adopting the flux pumping [Jardin et al 2015] or assuming a very high viscosity to damp dynamic oscillation [Shen and Porcelli, 2018] .
- In view of the importance of sawtooth control in tokamak fusion experiments, the following issues we investigated:
- Can a stationary m/n =1/1 magnetic island associated with sawtooth be achieved with a low viscosity.
- What is the mechanism that causes the fast pressure crash?
- Is “incomplete reconnection” or partial crash of the sawtooth really resulted from formation of the secondary plasmoid suggested by Yu et al. [NF 2014]?

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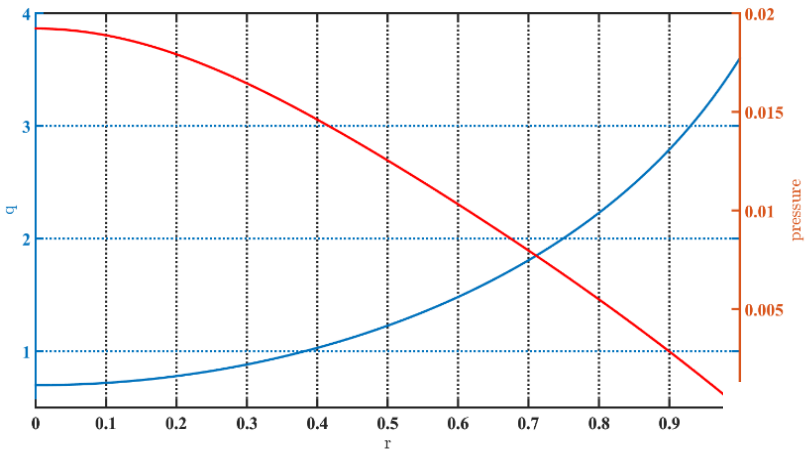
3. Simulation results

a. The mechanism for the quasi-steady state with m/n=1/1 magnetic island.



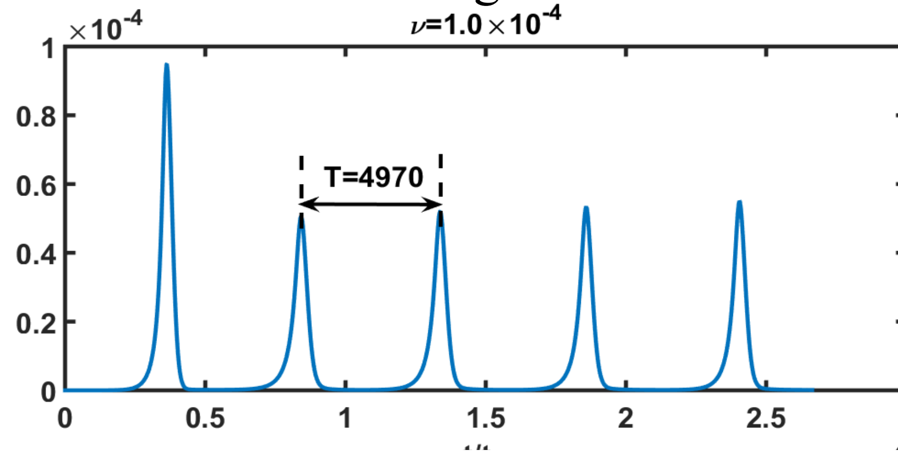
Initial safety factor and pressure profiles used in the simulations.

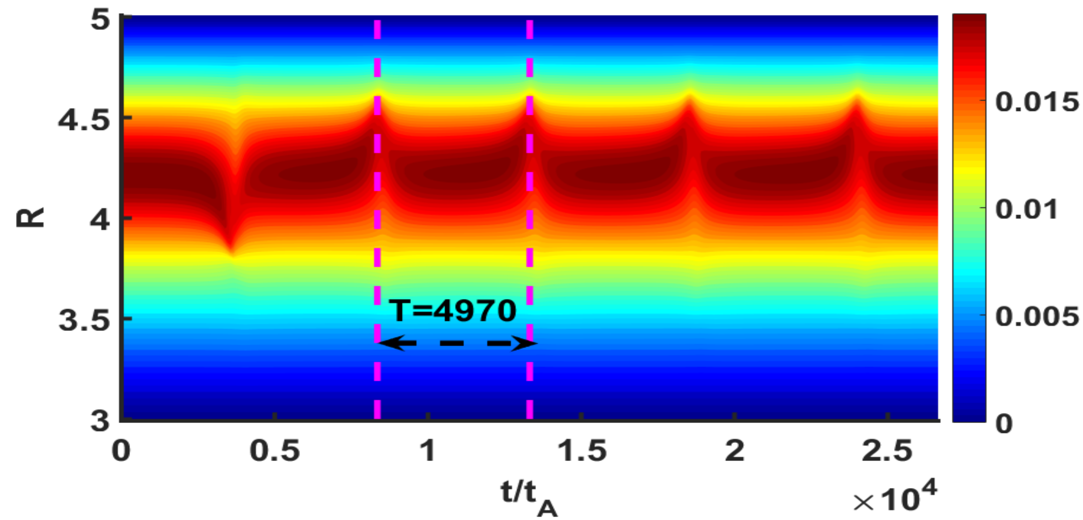
$\eta = 3\times10^{-6}$ $\kappa_{\parallel} = 5\times10^{-2}$ $\kappa_{\perp} = 3.0\times10^{-6}$

$\upsilon = 3\times10^{-5}$ $D = 1.0\times10^{-4}$

$R_0 = 4$ $a = 1$

$400\times64\times400\,(R,\phi,Z)$





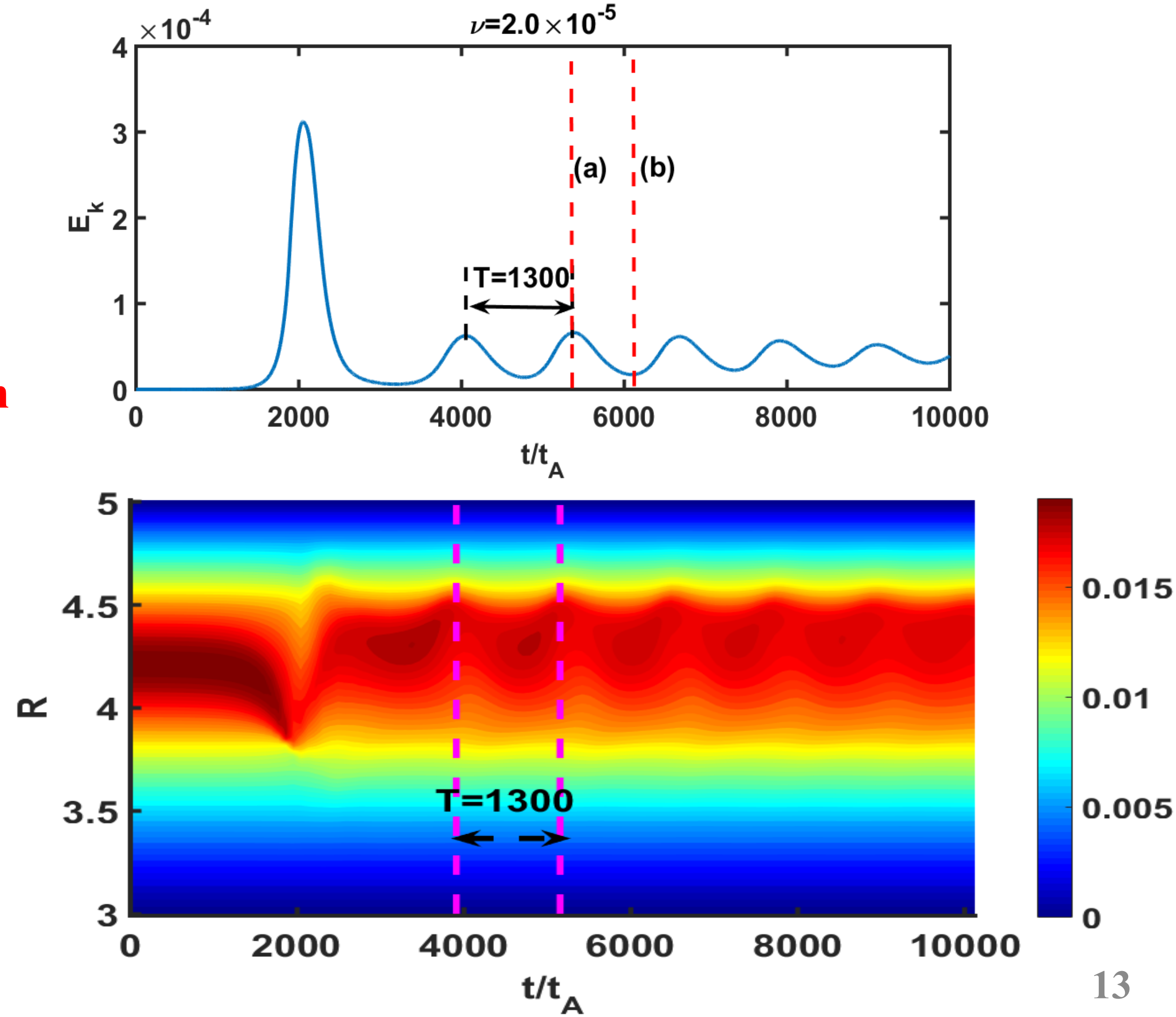
Normal sawtooth oscillation with the viscosity $\nu = 1.0\times10^{-4}$

3. Simulation results

a. The mechanism for the quasi-steady state with m/n=1/1 magnetic island.

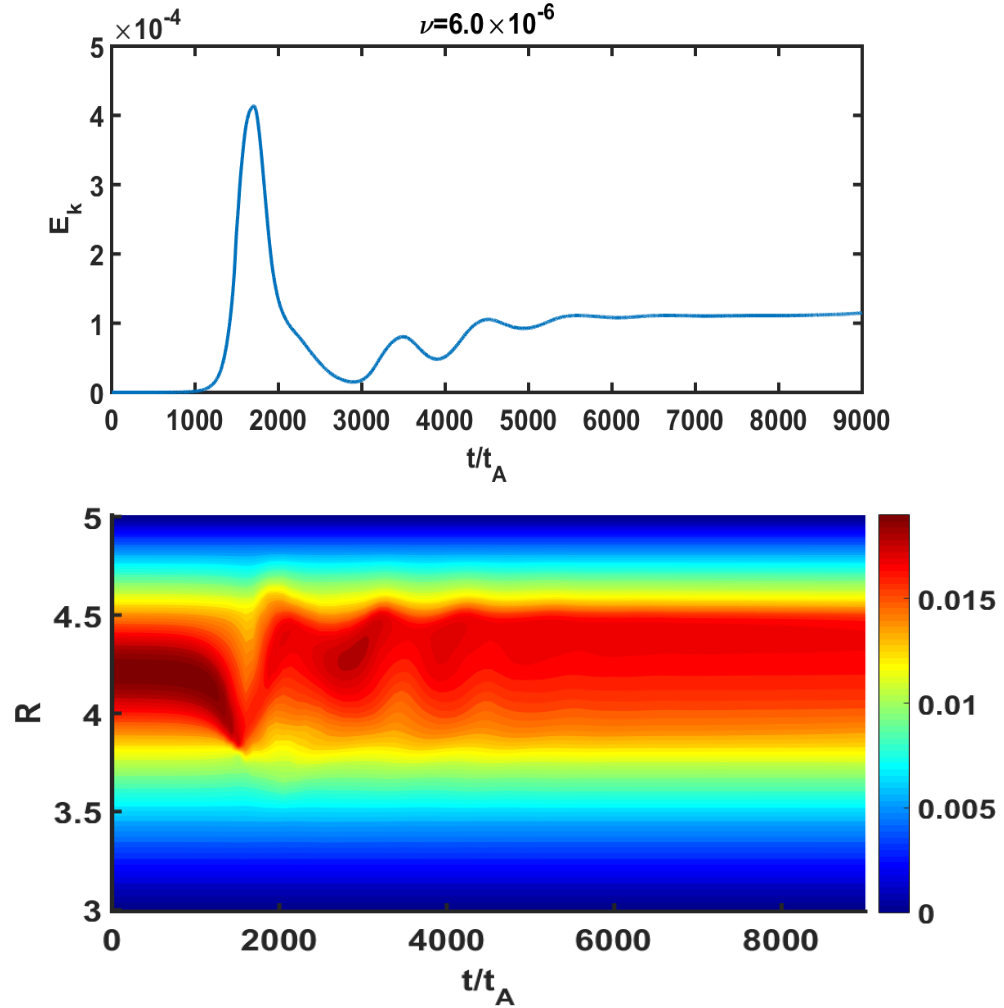
Small sawtooth oscillation with the viscosity

ν=2.0×10^{-5}



3. Simulation results

a. The mechanism for the quasi-steady state with m/n=1/1 magnetic island.



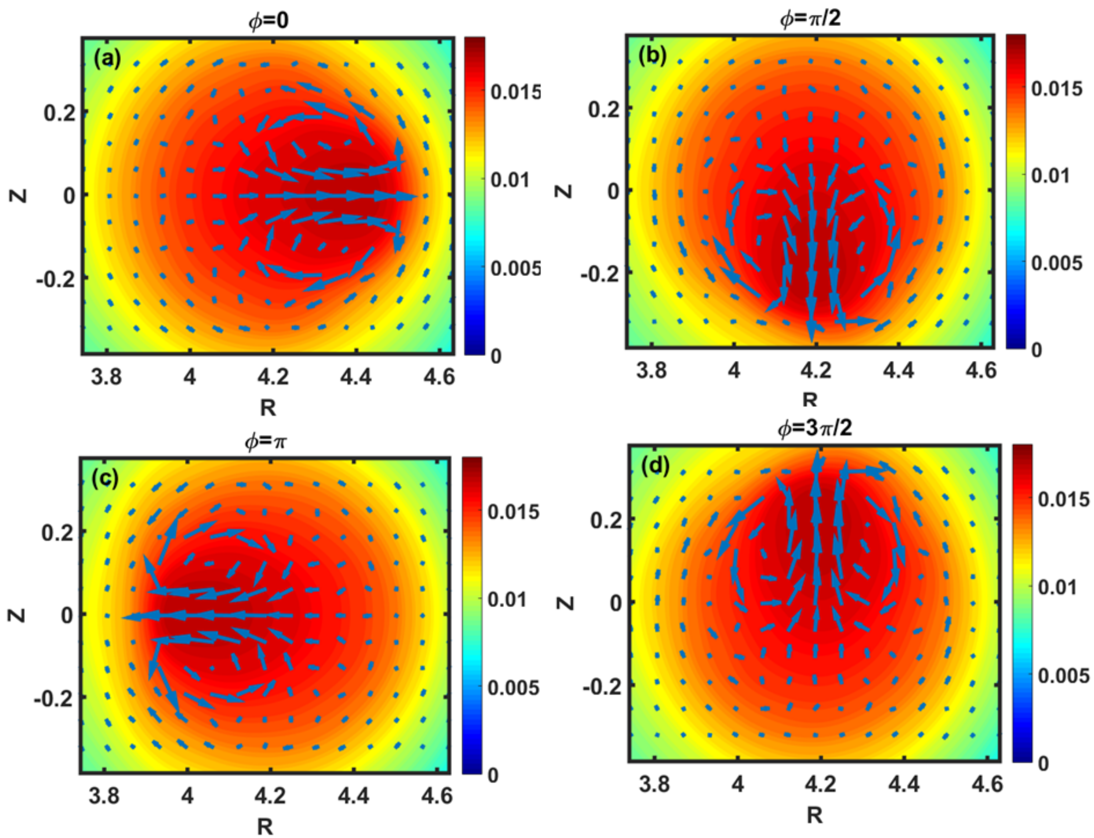
Quasi-steady state with low viscosity

$\nu=6.0\times10^{-6}$

3. Simulation results

a. The mechanism for the quasi-steady state with (1,1) magnetic island.

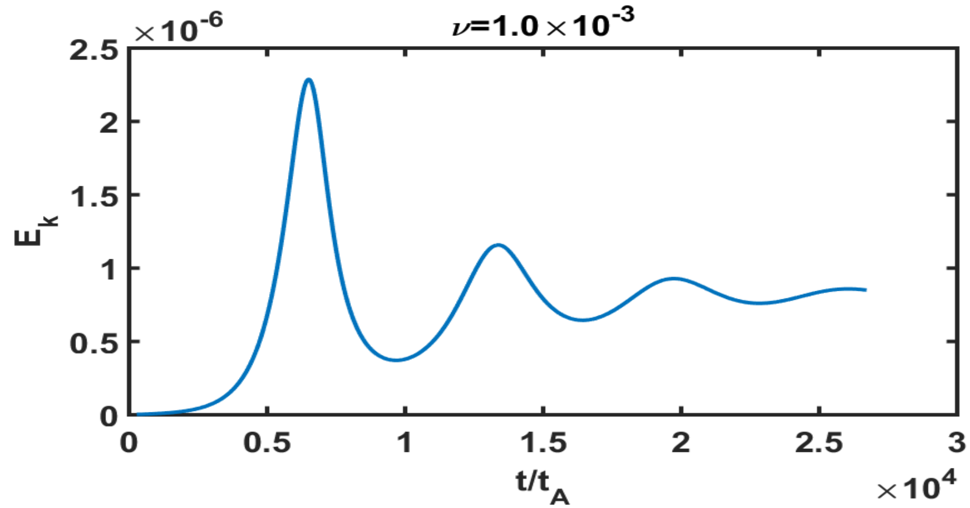
The flow patterns at the steady state (a)$\varphi = 0$, (b)$\varphi = \pi/2$, (c)$\varphi = \pi$, and (d)$\varphi = 3\pi/2$

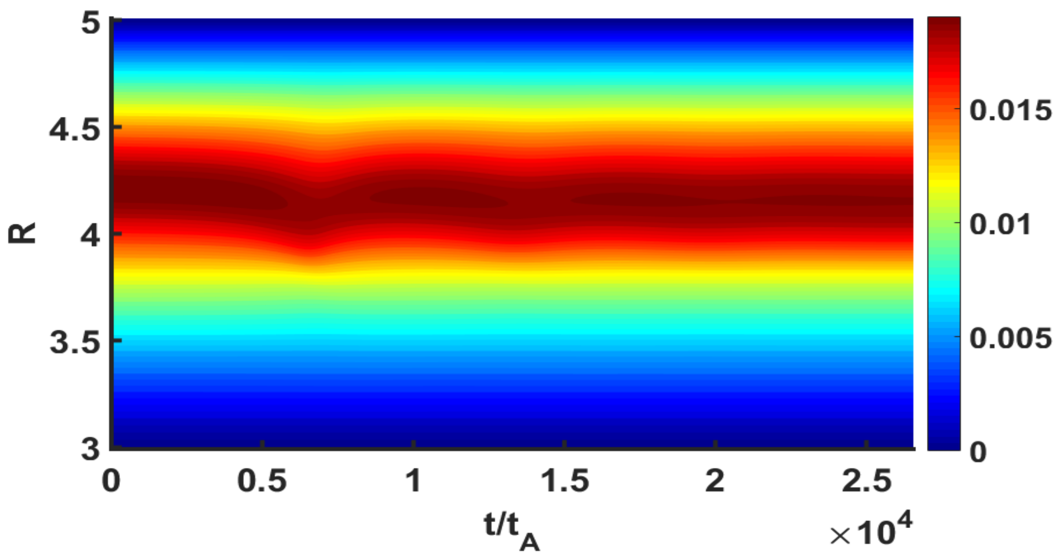


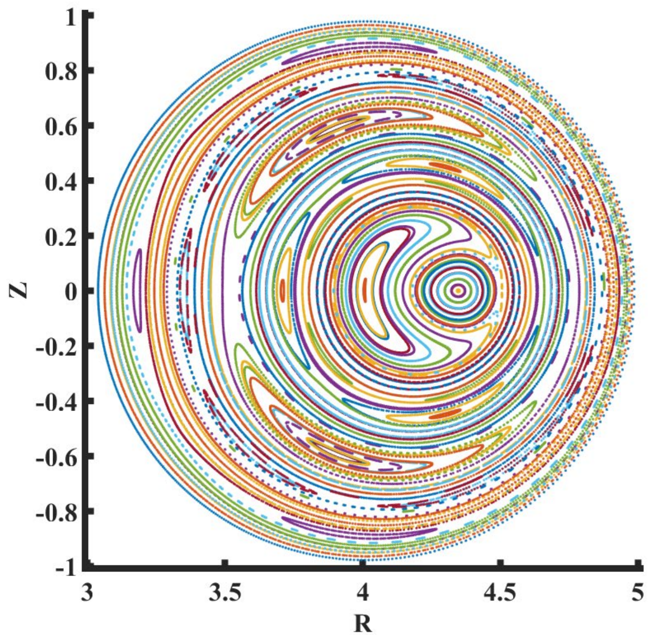
Strong plasma flows with (1,1) helicity exist at the quasi-steady state.

3. Simulation results

a. The mechanism for the quasi-steady state with m/n=1/1 magnetic island.







Quasi-steady state with large viscosity

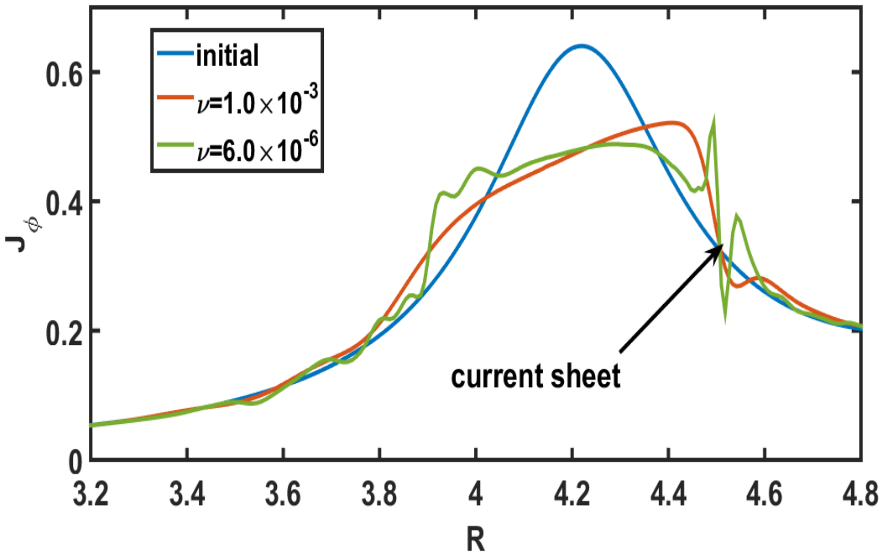
$\nu=1.0\times10^{-3}$

[Shen and Porcelli, 2018]

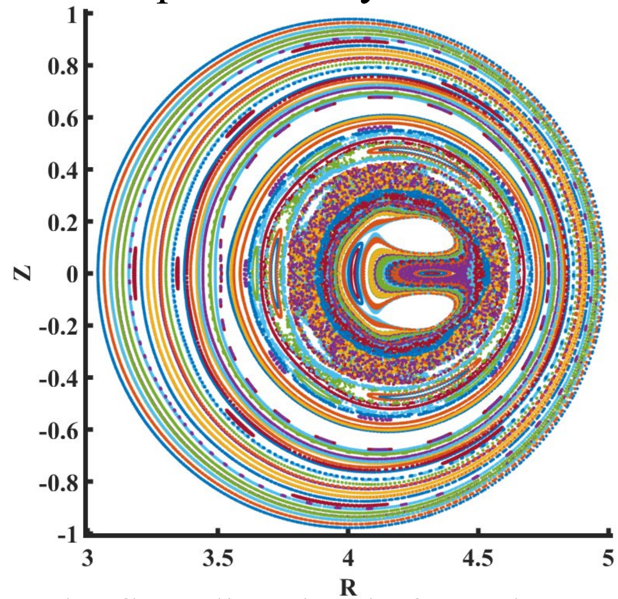
3. Simulation results

a. The mechanism for the quasi-steady state with (1,1) magnetic island.

The profiles of the toroidal current at the quasi-steady state.



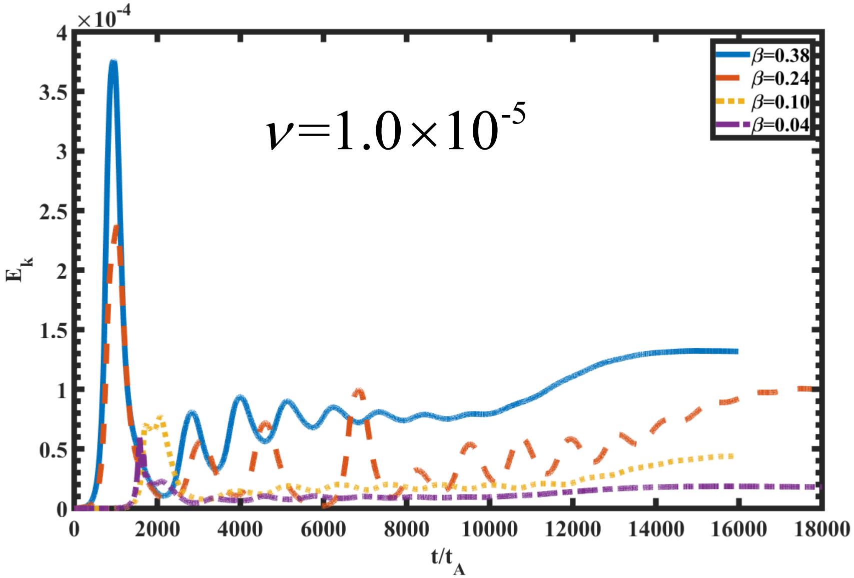
The Poincare plots of the magnetic field at the quasi-steady state.



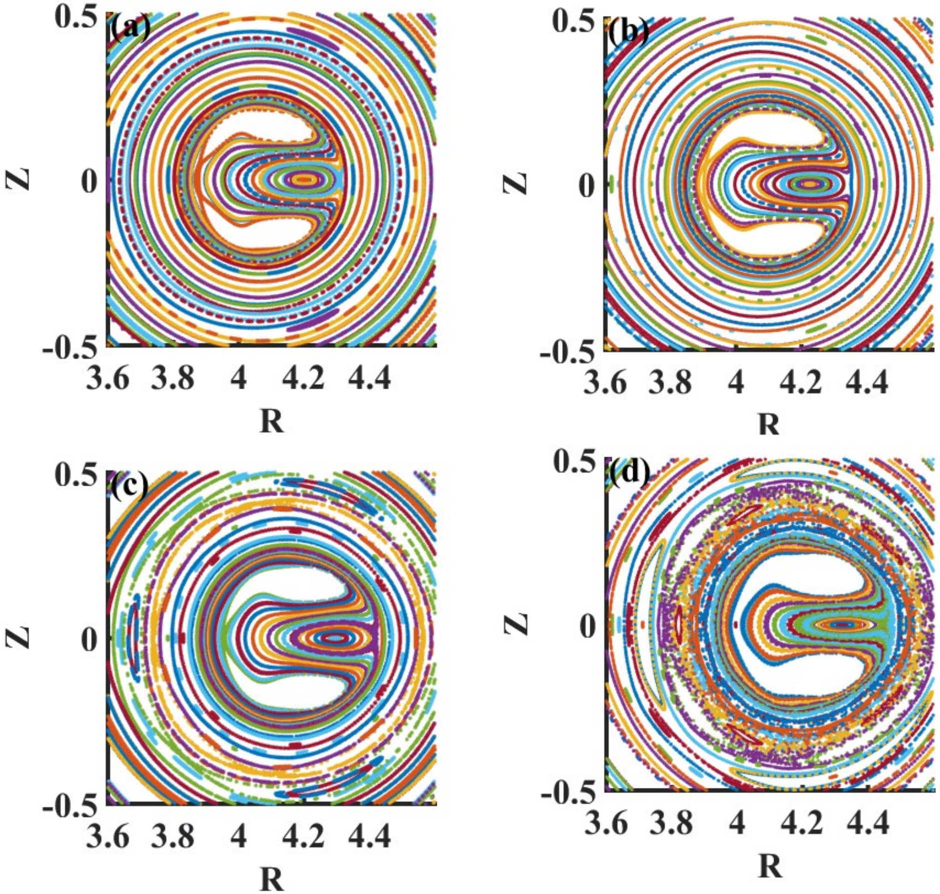
The new poloidal flux is pumped into the core region. The flow direction is from the core to the reconnection region. The flux is almost frozen in the plasma, except for the reconnection region. It means that the plasma flow continues to transfer the new formed flux into the reconnection region. The quasi-steady state is owing to the balance between the pumped magnetic flux and the flux loss inside the reconnection region.

3. Simulation results

a.The mechanism for the quasi-steady state with (1,1) magnetic island.



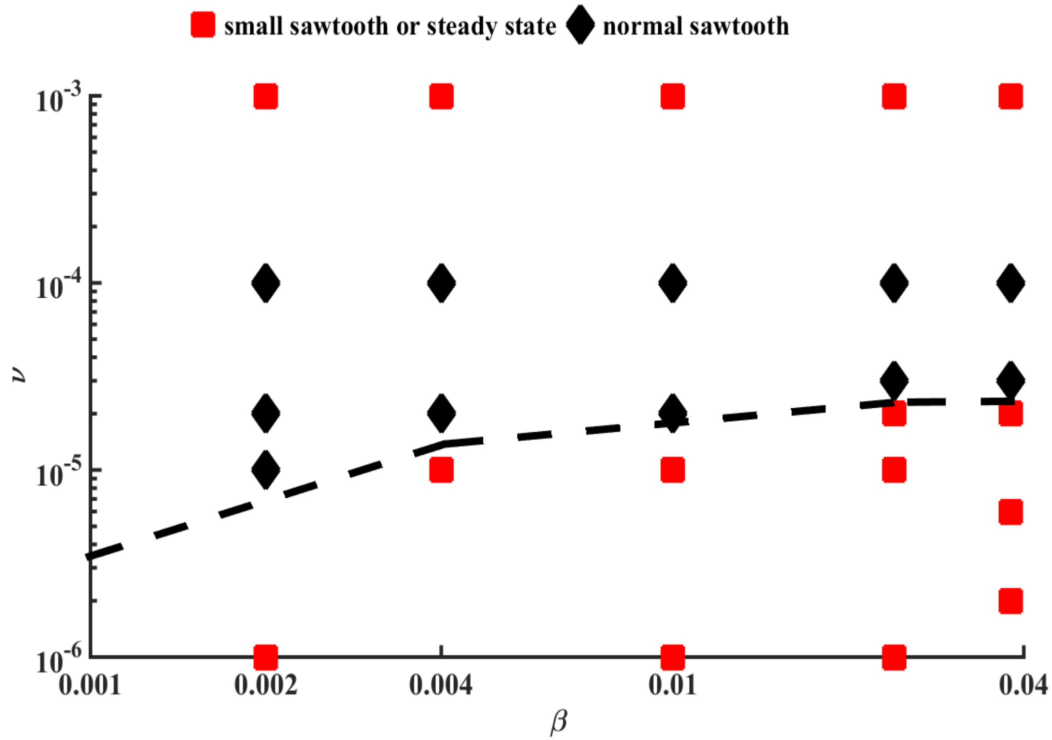
The final kinetic energy increases with increasing β .



The final displacement of the magnetic axis increases with increasing β.

3. Simulation results

a. The mechanism for the quasi-steady state with (1,1) magnetic island.



The threshold of normal sawtooth increase with increasing β. The growth rate of the kink mode increases with increasing β, and the plasma flow generated by the kink mode is stronger with higher β. As a result, the higher viscosity is needed to get the normal sawtooth.

3. Simulation results

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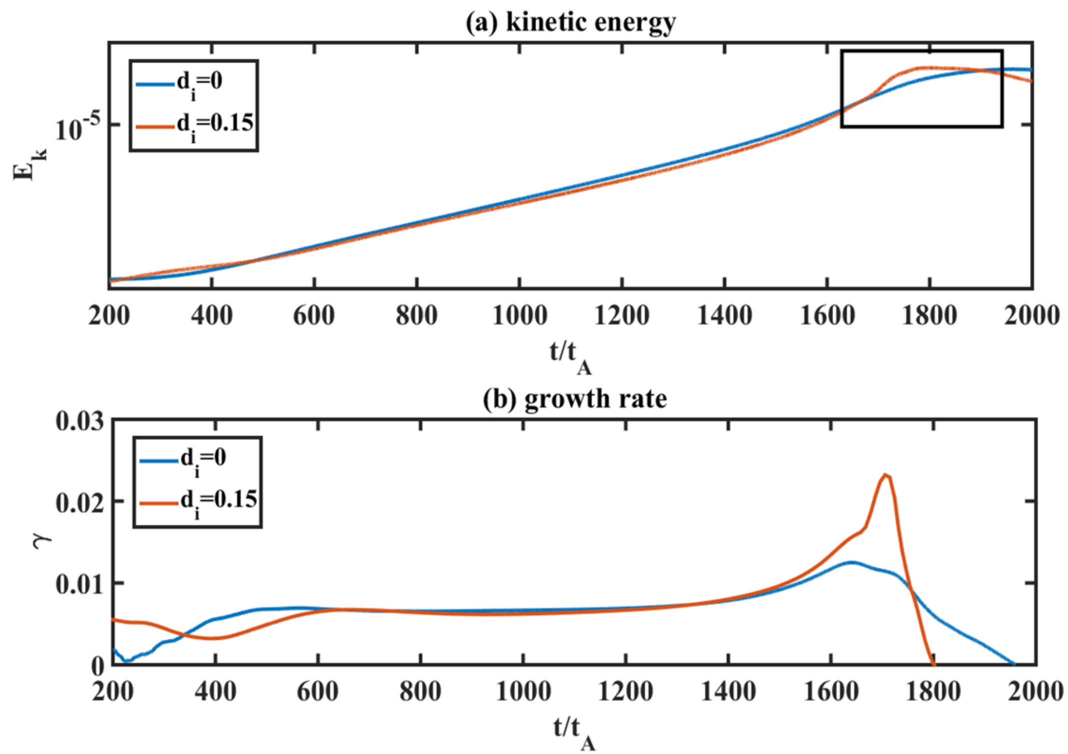
b. The mechanism for the fast pressure crash.



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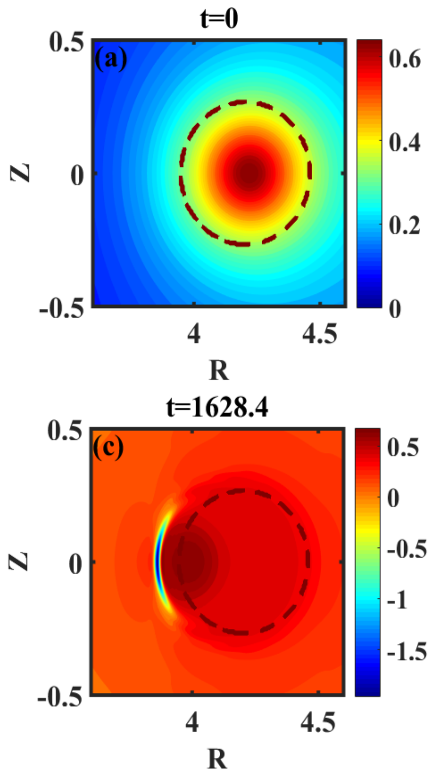
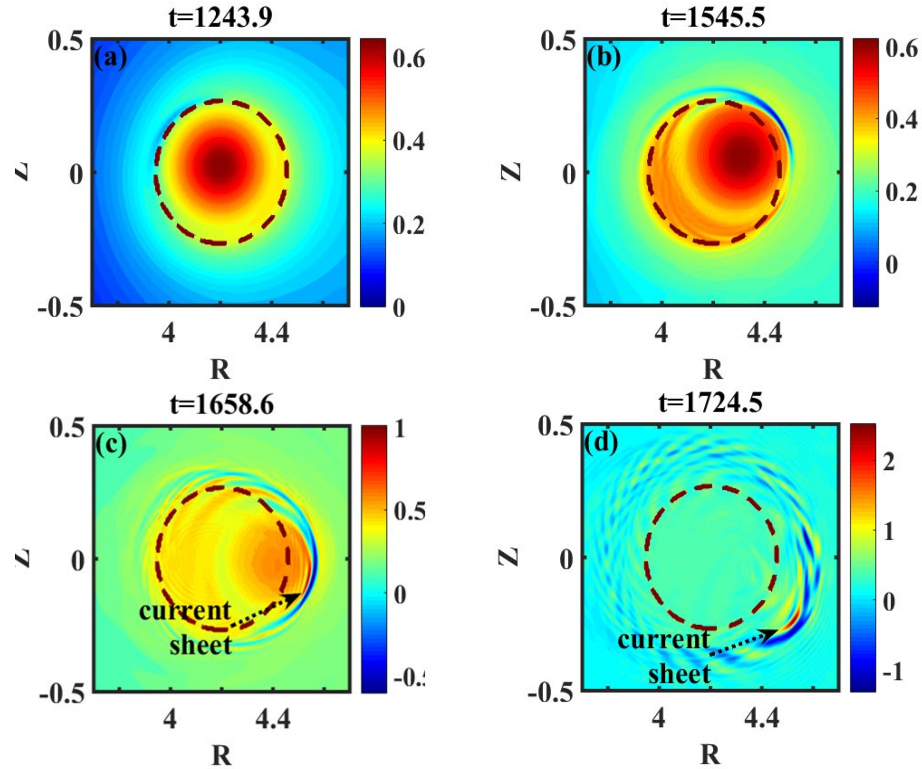
The evolutions of the kinetic energy and the growth rate for the resistive-MHD simulation and the Hall-MHD simulation.

3. Simulation results

b. The mechanism for the fast pressure crash.



The toroidal current distributions at four typical moments in Resistive-MHD simulation.

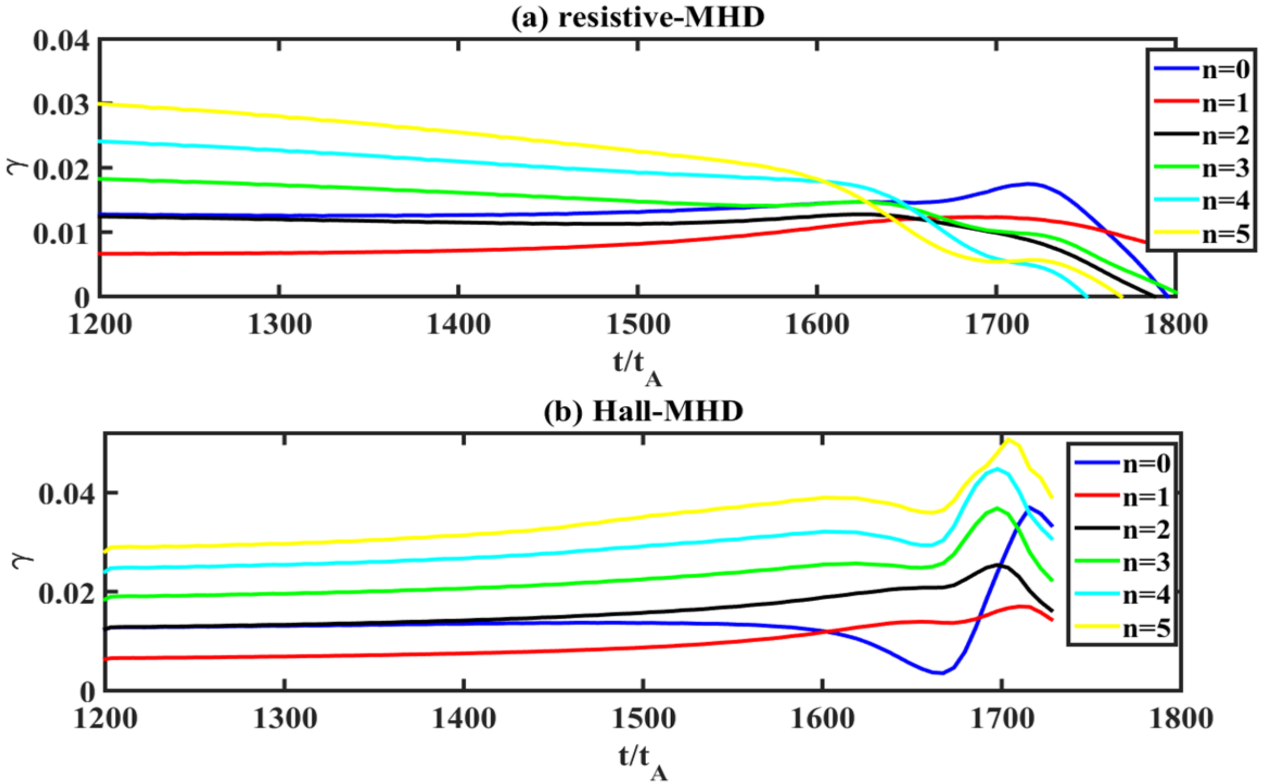


The toroidal current distributions at four typical moments in Hall-MHD simulation.

At the nonlinear stage, the current sheet transforms from Y-type to X-type. (Aydemir Phys. Fluids B 1992; X. G. Wang et al. PRL 1993.)

3. Simulation results

b. The mechanism for the fast pressure crash.



The growth rates of the high-n modes are reduced at the nonlinear stage of the resistive-MHD simulation. However, they significantly increase in Hall-MHD simulations.

3. Simulation results

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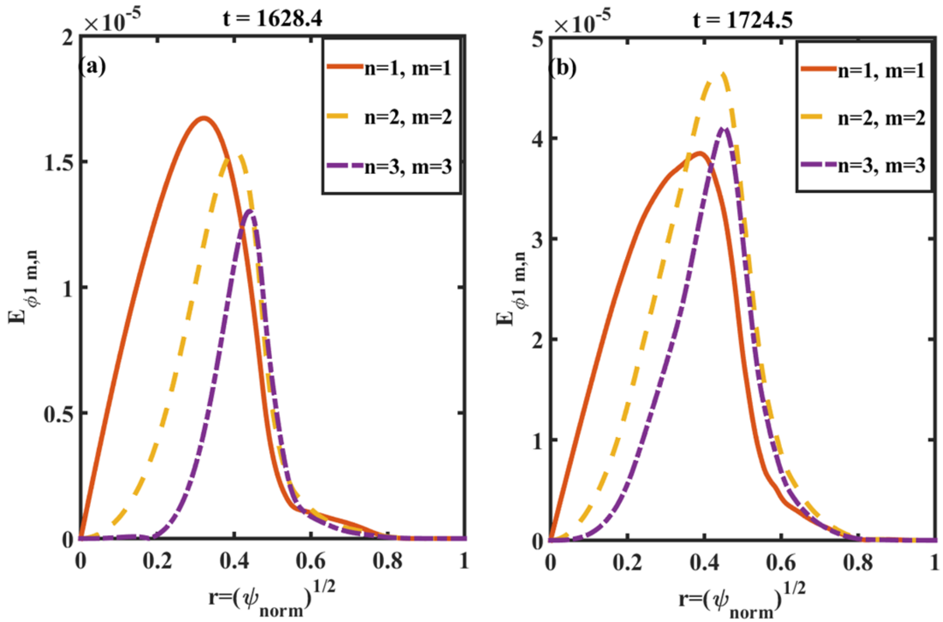
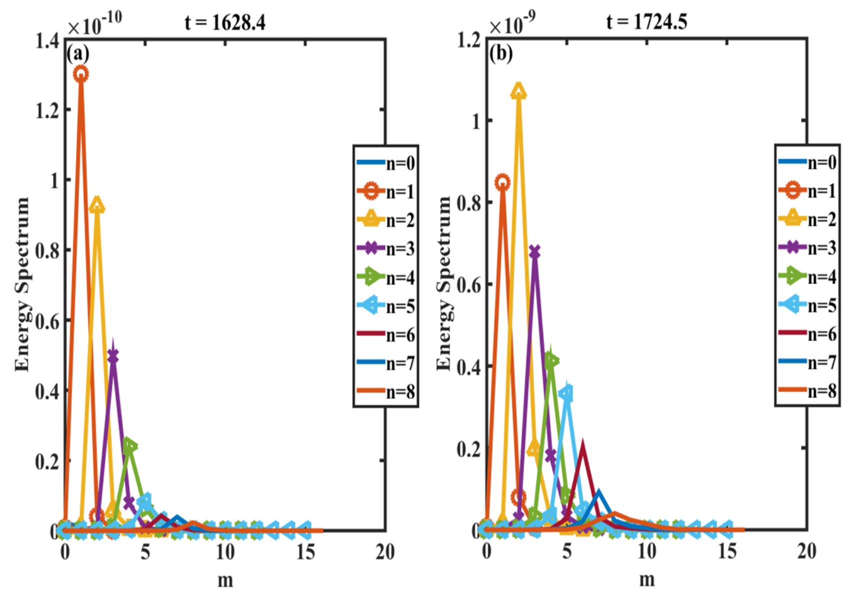
b. The mechanism for the fast pressure crash.

The mode structure distributions for (a) resistive-MHD (b) Hall-MHD.



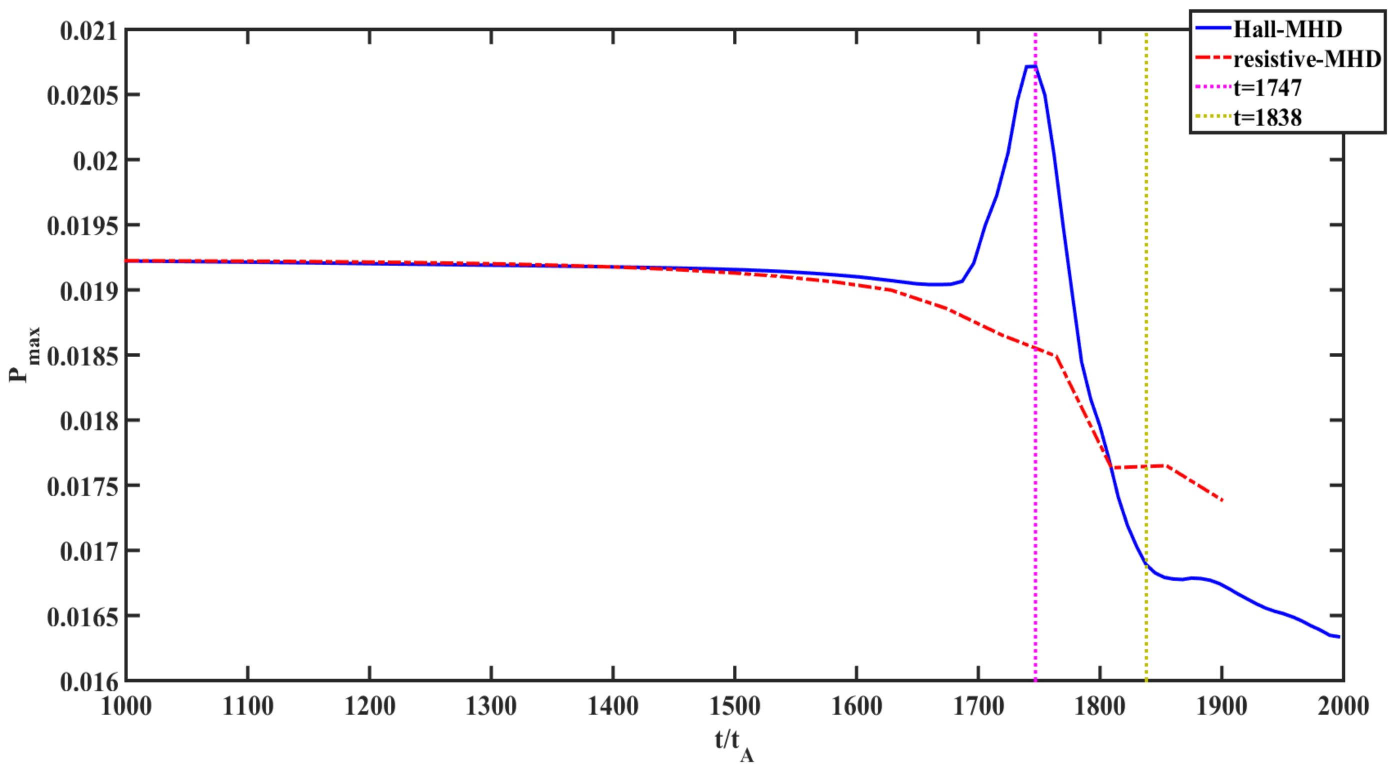
The kinetic energy spectrum for (a) resistive-MHD (b) Hall-MHD。



The n=1 mode is always with the largest amplitude throughout the Resistive-MHD simulation. However, the n=2 mode will be dominant at the nonlinear stage of the Hall-MHD simulation.

3. Simulation results

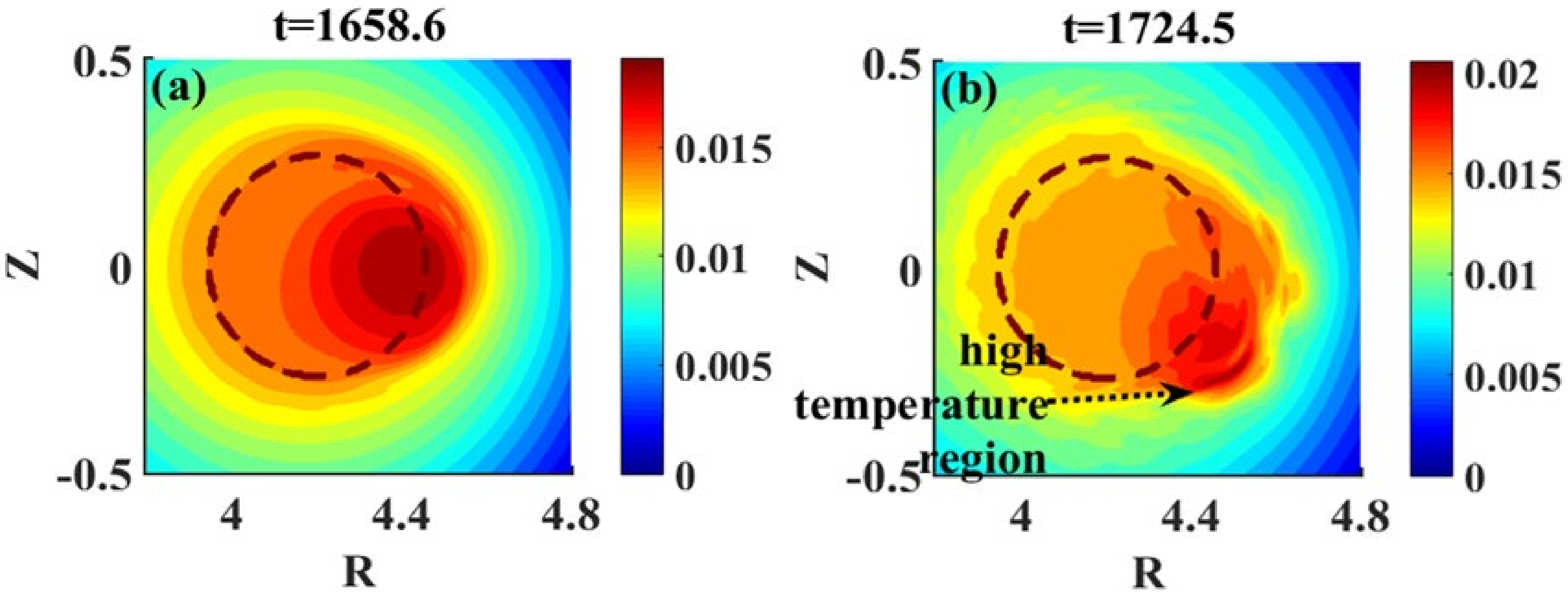
b. The mechanism for the fast pressure crash.



The pressure crash in the Hall-MHD simulation is much faster than that in the resistive-MHD simulation. For typical Tokamak parameters, the crash time in Hall-MHD simulation is about 20μs, consistent with experimental observations.

3. Simulation results

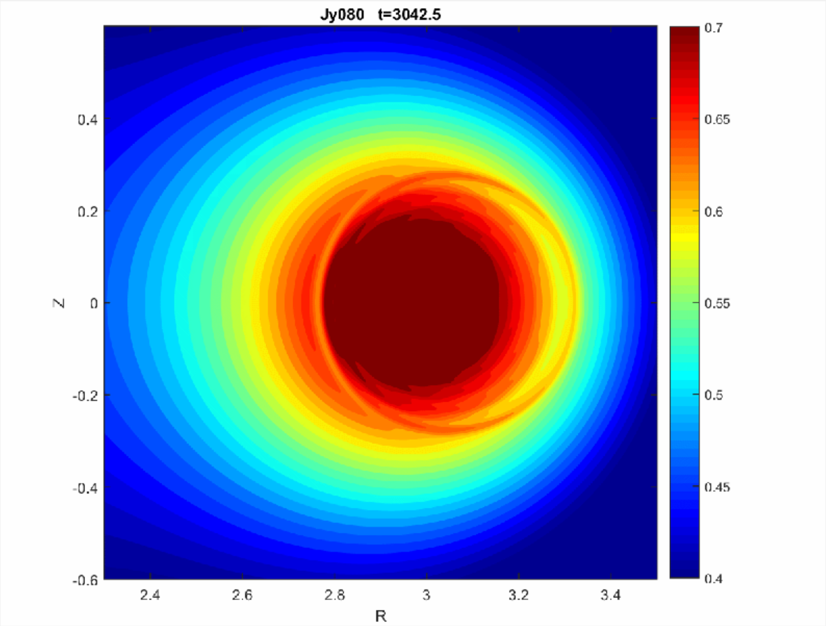
b. The mechanism for the fast pressure crash.

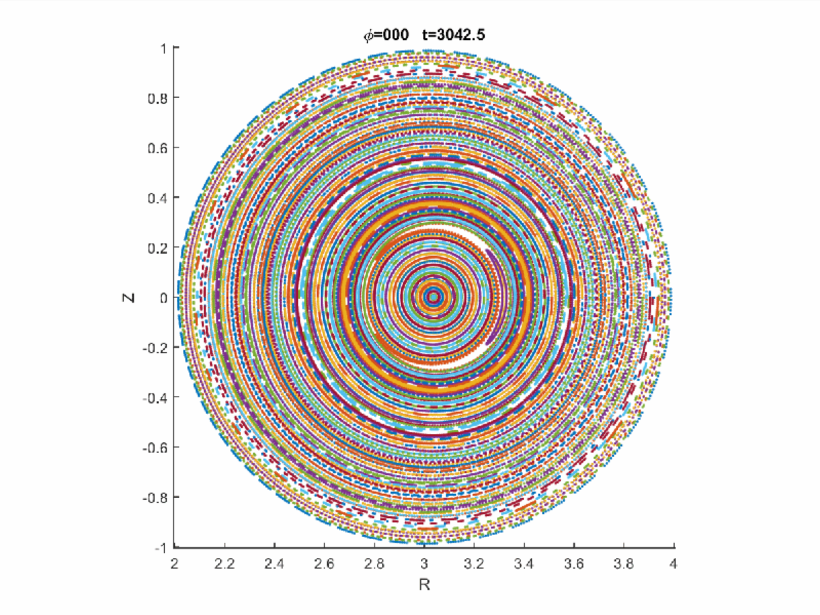


The pressure distributions (a)before the crash and (b) during the crash in the Hall-MHD simulation. The hot core plasma is compressed into a narrow region with high pressure before the final crash. This is the reason why the pressure increases instead of decreasing before the final crash.

3. Simulation results

c. Incomplete reconnection with plasmoid.

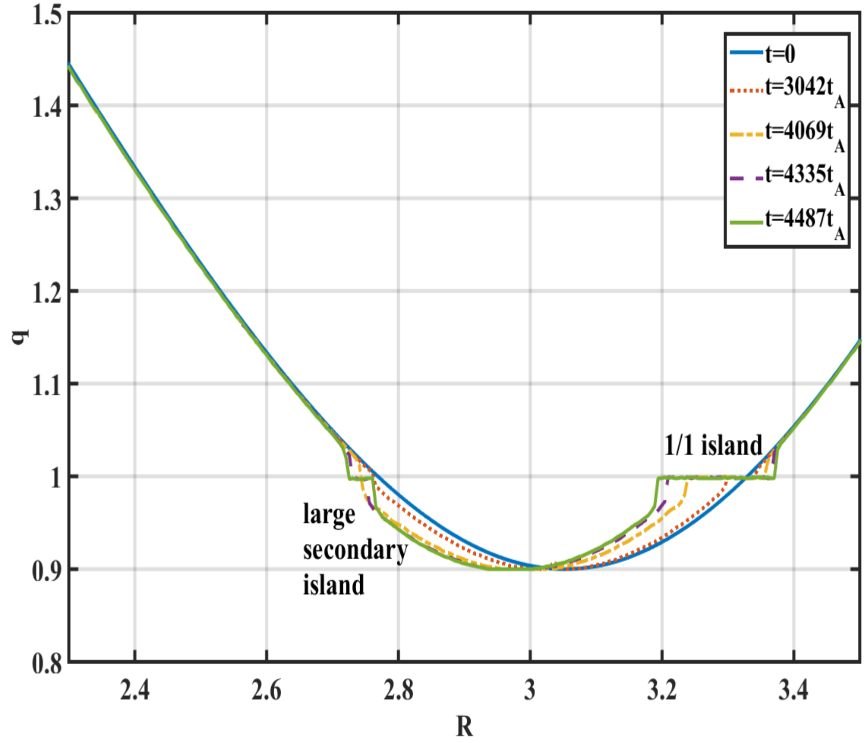


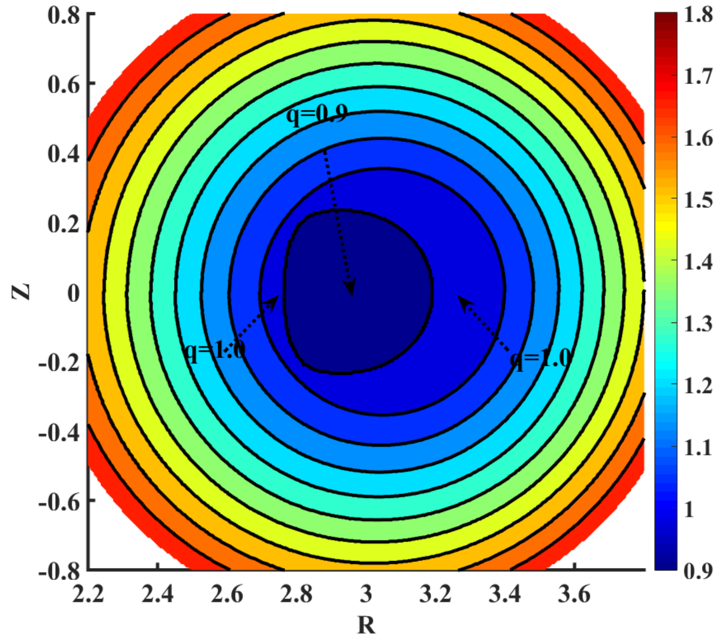


With low resistivity, the nonlinear evolution of the resistive-kink mode can lead to a thin current sheet. If the current sheet is thinner than a critical value, it becomes unstable for the secondary tearing instability. The thin current sheet is then broken up with development of the secondary tearing instability. Formation of the secondary island indeed stops further reconnection as suggested by Yu et al..[NF, 2014]

3. Simulation results

c. Incomplete reconnection with plasmoid.

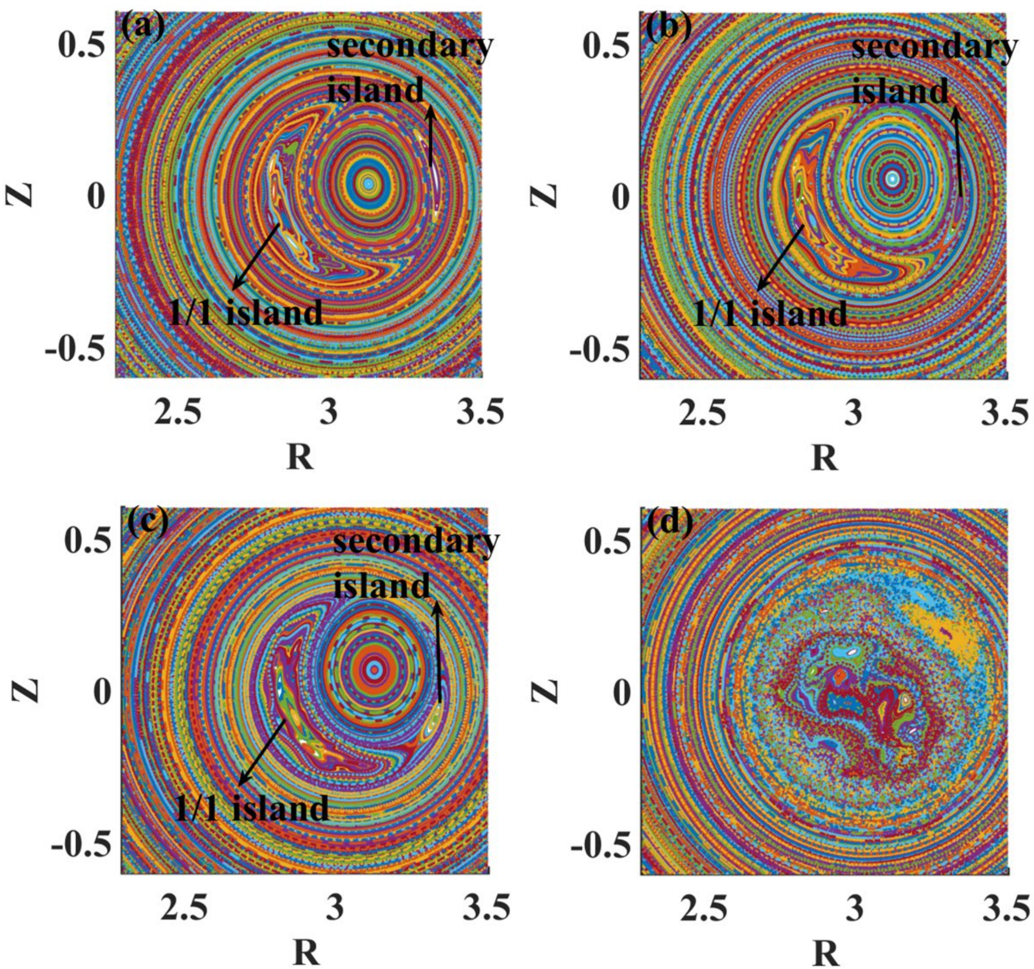




The contour plot of the safety factor values at the saturated stage.

3. Simulation results

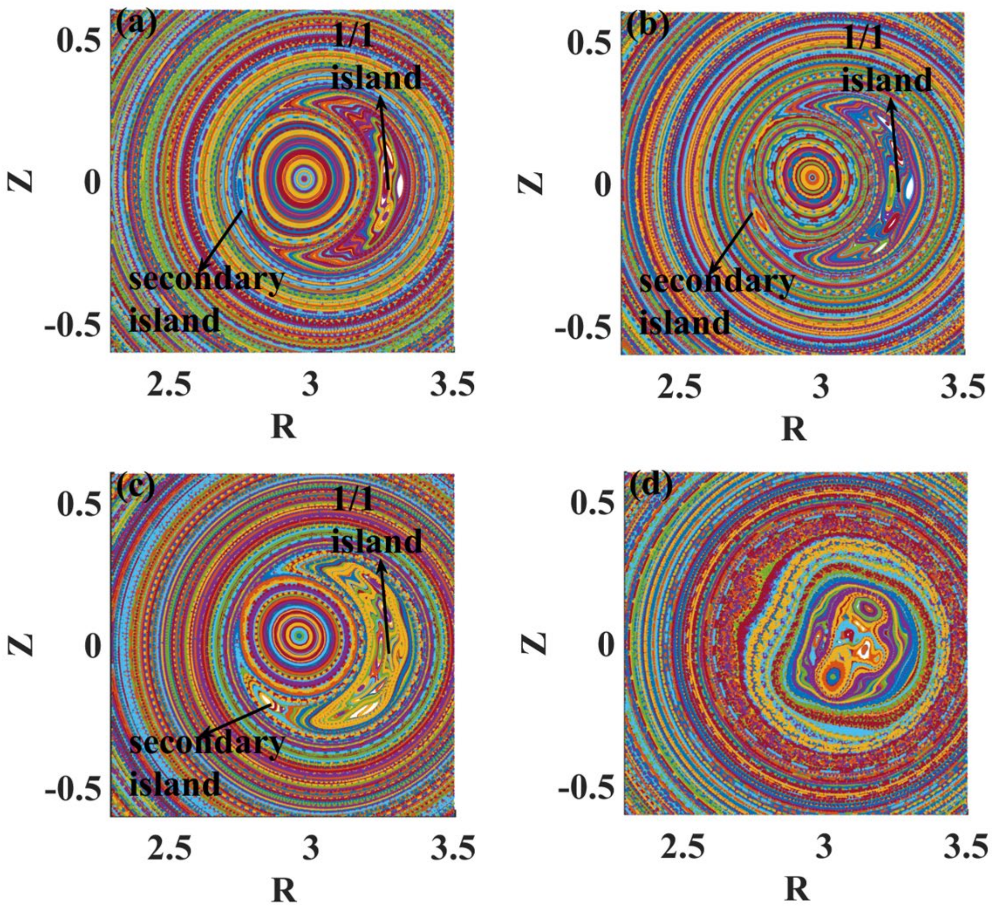
c. Incomplete reconnection with plasmoid.



The toroidal flow breaks the symmetry, the formation of the large secondary island cannot prevent the further development as it does without toroidal flow. With the growth of the prime island, the secondary island is finally forced to merge into the prime island.

3. Simulation results

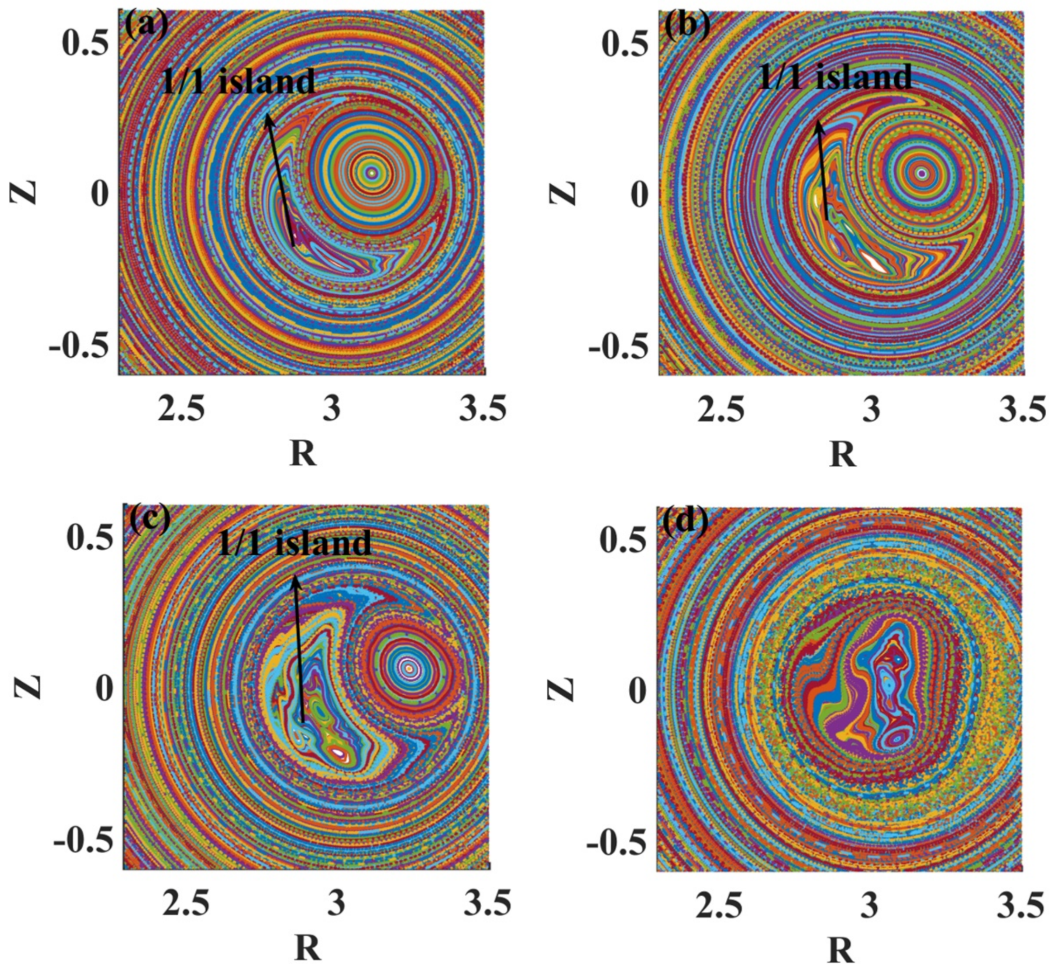
c. Incomplete reconnection with plasmoid.



The two-fluids effect (di=0.001) breaks the symmetry, the formation of the large secondary island cannot prevent the further development as it does in the resistive MHD. The secondary island is finally forced to merge into the prime island.

3. Simulation results

c. Incomplete reconnection with plasmoid.



For the case with the ion inertial length di=0.03, no large secondary island forms throughout the simulation.

Contents

4. Brief Summary

- Low viscosity and extremely high viscosity both can lead to steady states.
  - The steady state with low viscosity is more relevant to experimental observations.
  - The steady state is mainly owing to the balance between the magnetic pump and the flux reconnection.
- The fast pressure crashes during sawtooth oscillations mainly result from fast magnetic reconnection dominated by the Hall effect.
  - The current sheet transforms from Y-type to X-type at the nonlinear stage.
  - The hot core is compressed and forms a thin hot plasma layer before the crash.
- Formation of the secondary plasmoid cannot prevent further crash of the sawtooth or lead to incomplete reconnection.
  - Either toroidal flow or two fluid effects can breaks the symmetry, which prevent the large secondary island from further developing.
  - The secondary island is finally forced to merge into the prime island.

Thank you!