UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA

Simulation of Resistive Instabilities in the presence of Runaway Current

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Outline

- Motivation
- Physical Model
- Simulation Results
  - Linear results
  - Nonlinear results
- Conclusion and discussion

Motivation

- During the disruption:
  - Damage of runaway electrons to the first wall
  - During the thermal quench, temperature drops quickly, resistivity increases correspondingly, plasma current starts to decay.
  - During the current quench, the current is contributed partly or completely by runaway current.
  - Runaway current profile is usually more peaked than the pre-disruption current, may induce resistive instabilities.
  - Resistive instabilities may influence the confinement of runaway electrons.

Motivation

- The generation of runaway current (H. Smith, *et.al.,PoP,2006*)
  - Two of the generation mechanisms: Dreicer and Avalanche

$$\frac{\partial n_{re}}{\partial t} = \frac{\partial n_{re}^{I}}{\partial t} + \frac{\partial n_{re}^{II}}{\partial t}, \qquad (1)$$

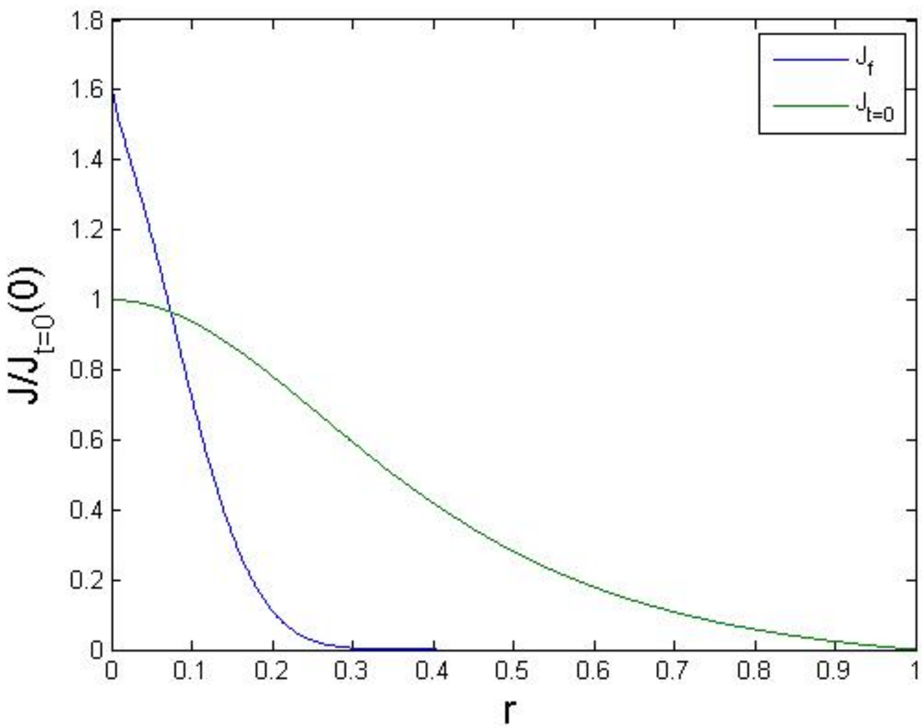
- Ohm's Law and Faraday's Law

$$J_{//} = \sigma_{//} E_{//} + e n_{re} c, \qquad (2)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial E_{//}}{\partial r} \right) = \mu_0 \frac{\partial J_{//}}{\partial t}, \qquad (3)$$

Motivation

- The initial and final current profile



calculated from the above model

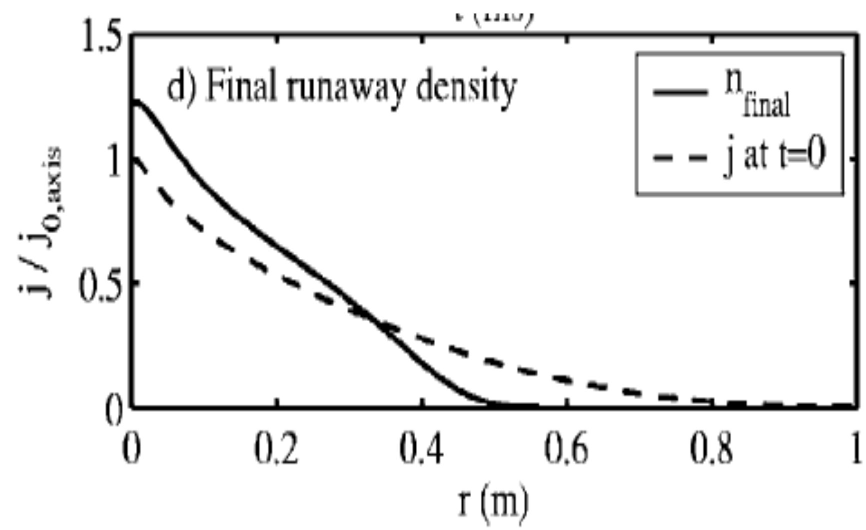


FIG. 2. A simulation of the runaway dynamics in JET discharge 63 133.

H. Smith, *et.al.,PoP,2006*

Physical Model

- Parallel Ohm's Law

$$E_{//} = \eta(J_{//} - J_{re}) \qquad (4)$$

- Momentum equation

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p_c - \nabla \cdot \mathbf{P}_{re} + \mathbf{J} \times \mathbf{B} \qquad (5)$$

- Runaway density equation

$$\frac{\partial n_{re}}{\partial t} + \nabla \cdot \left(n_{re} v_{//} \mathbf{b} - n_{re} \frac{m_e v_{//}^2}{eB} \mathbf{b} \times \boldsymbol{\kappa} - n_{re} \frac{\mathbf{b} \times \mathbf{E}}{B} \right) = 0 \qquad (6)$$

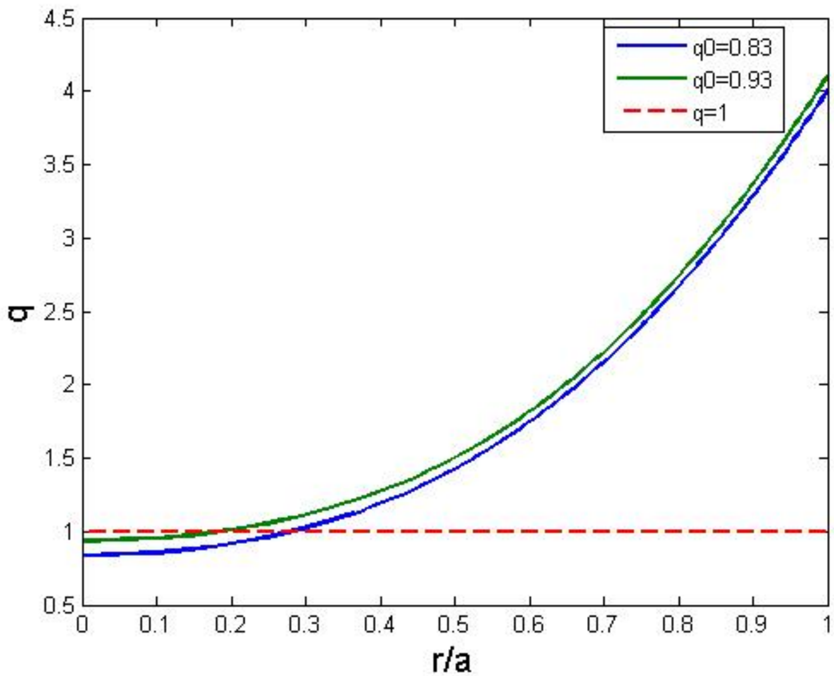
$J_{re} = -en_{re} v_{//}, P_{re} = n_{re} m_e v_{//}^2, |v_{//}| \sim c$ is assumed. Due to this assumption,

Eq.(6) is derived from the drift kinetic equation, similar to that of Helander,et. al., PoP, 2007

- Implement the above extended-MHD model in the M3D-k code.

Simulation results

- As a first step, we consider only the effects of runaway current. The effects of runaway pressure tensor are neglected.
- For simplicity, the current is assumed to be completely carried by runaway electrons.
- Given the profile of safety factor as

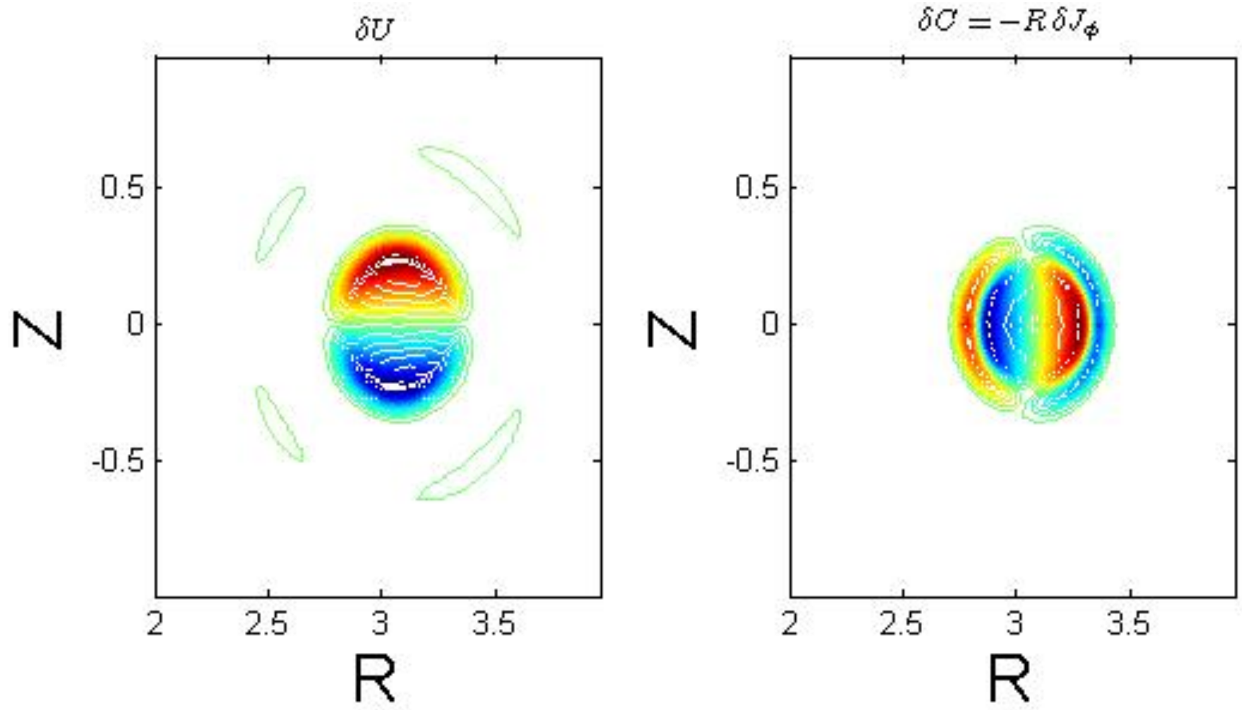


- Two cases: $q_0 = 0.83, 0.93$

Linear results

◆ Case1: q0=0.83

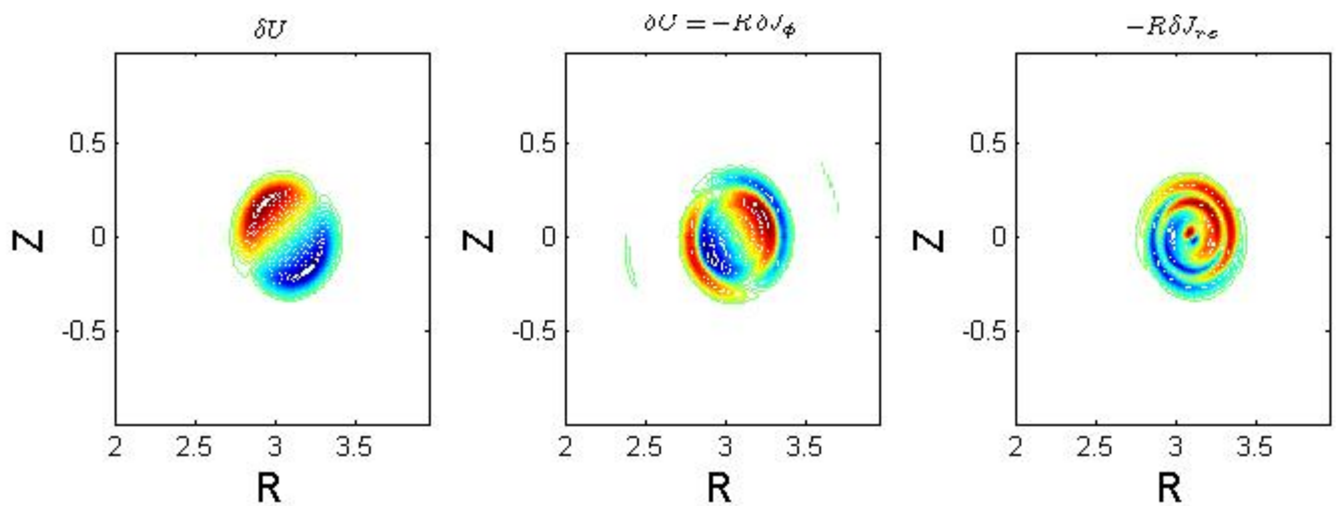
➢ Without runaway current, the growth rate of 1/1 mode is about 2.14e-2, the mode structures are shown below



- It is the resistive kink mode.

Linear results

- ◆ Case 1:q0=0.83
- ➢ With runaway current, the growth rate of 1/1 mode is about 2.56e-2, the mode structures are shown below



- The growth rate is enhanced slightly, and the mode structures keep almost the same.

Linear results

◆ The physics: the linearized equations in cylindrical geometry are

$$-(im/q-in)\delta\hat{\phi}+\gamma\delta\psi=\hat{\eta}\left(\nabla_\perp^2\delta\psi-R\delta\hat{J}_R\right), \qquad (7)$$

$$\gamma\nabla^2{}_\perp\delta\hat{\phi}=-\frac{imR}{r}\frac{d\hat{J}_{//0}}{dr}\delta\psi+\frac{in}{q}\left(\frac{m}{n}-q\right)\nabla_\perp^2\delta\psi, \qquad (8)$$

$$(m/q-n)\delta J_R-\frac{m}{r}\frac{d\hat{J}_R}{dr}\delta\psi=0, \qquad (9)$$

where runaway current is a flux function approximately, due to $|v_{//}|\sim c$.

Order analysis: $\delta J_{//}\sim O(\delta\psi/w_l^2),\delta J_R\sim O(\delta\psi/w_l)\rightarrow\delta J_{//}>\delta J_R$

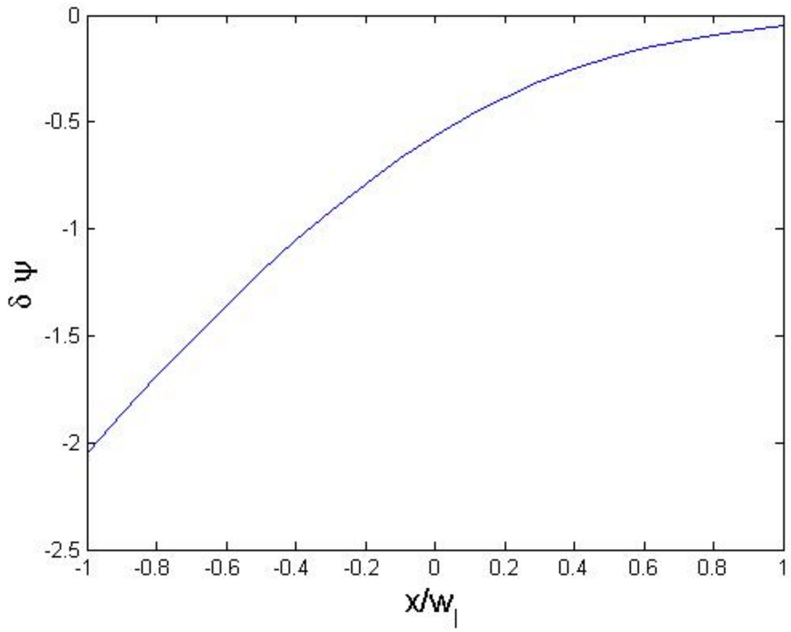
The perturbation of runaway current is of higher order.

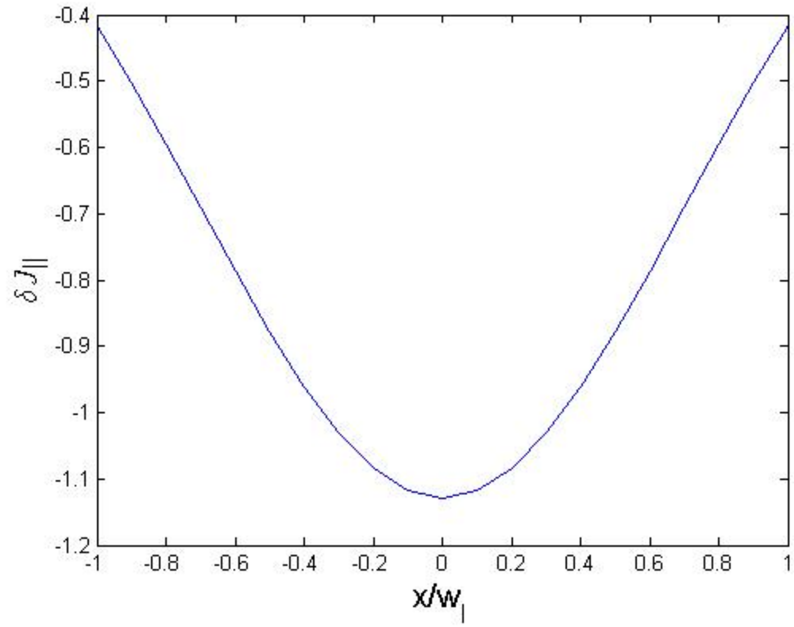
The characteristic functions in the resistive layer without runaway are

$$\delta\psi=b/2\left[x\,erfc(x/w_l)-\left(w_l/\sqrt{\pi}\right)\exp\left(-(x/w_l)^2\right)\right]$$

$$\delta\phi=i(b/2)\left(w_l/\sqrt{2}\right)erfc(x/w_l)$$

Linear results



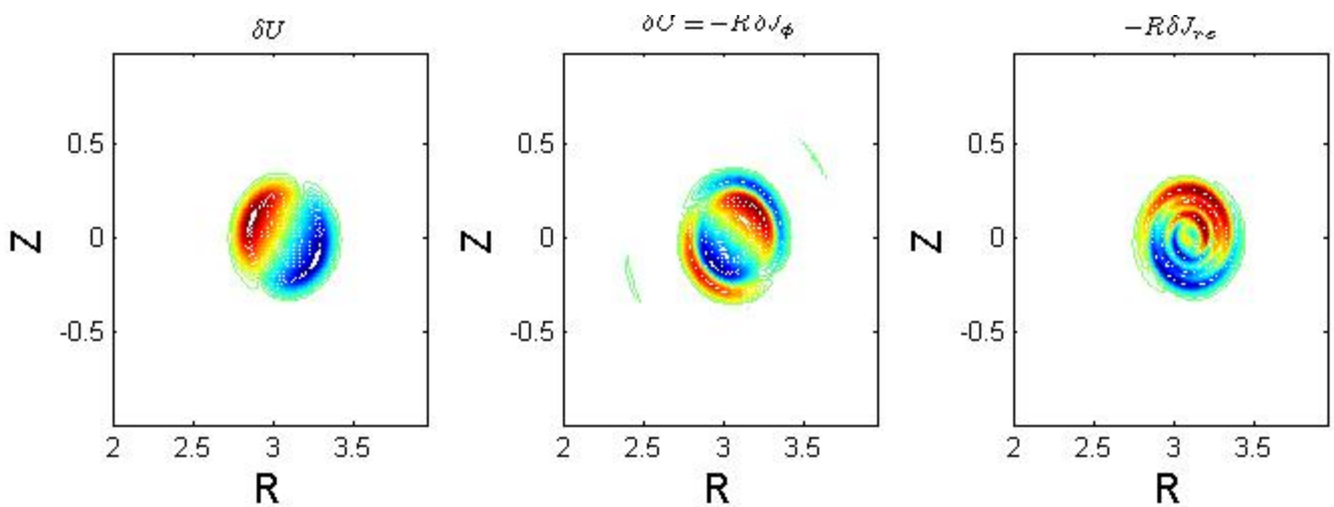


$$\delta J_R = -\frac{q_s}{s}\frac{d\hat{J}_R}{dr}\frac{\delta\psi}{x}, \quad \frac{d\hat{J}_R}{dr} < 0, \implies \langle \delta J_{ohm} \rangle = \langle \delta J_{//} - \delta J_R \rangle > \delta J_{//}$$

The perturbation of runaway current tends to enhance the perturbation of Ohm' current, so that it will increase the growth rate of the resistive kink mode.

Linear results

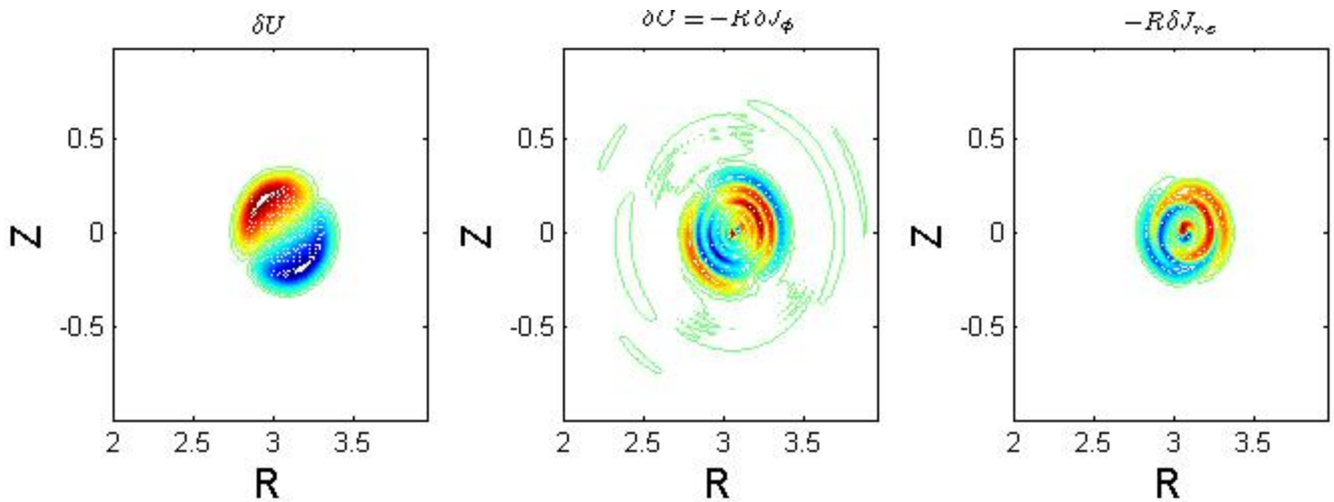
➢ With runaway current, without electric drift contribution in runaway equation, the growth rate is 2.45e-2, mode structures are



- The contribution of electric drift in runaway equation is small, due to $c / v_A >> 1$.

Linear results

➤ With runaway current, without magnetic drift contribution in runaway equation, the growth rate is 2.6e-2, mode structures are

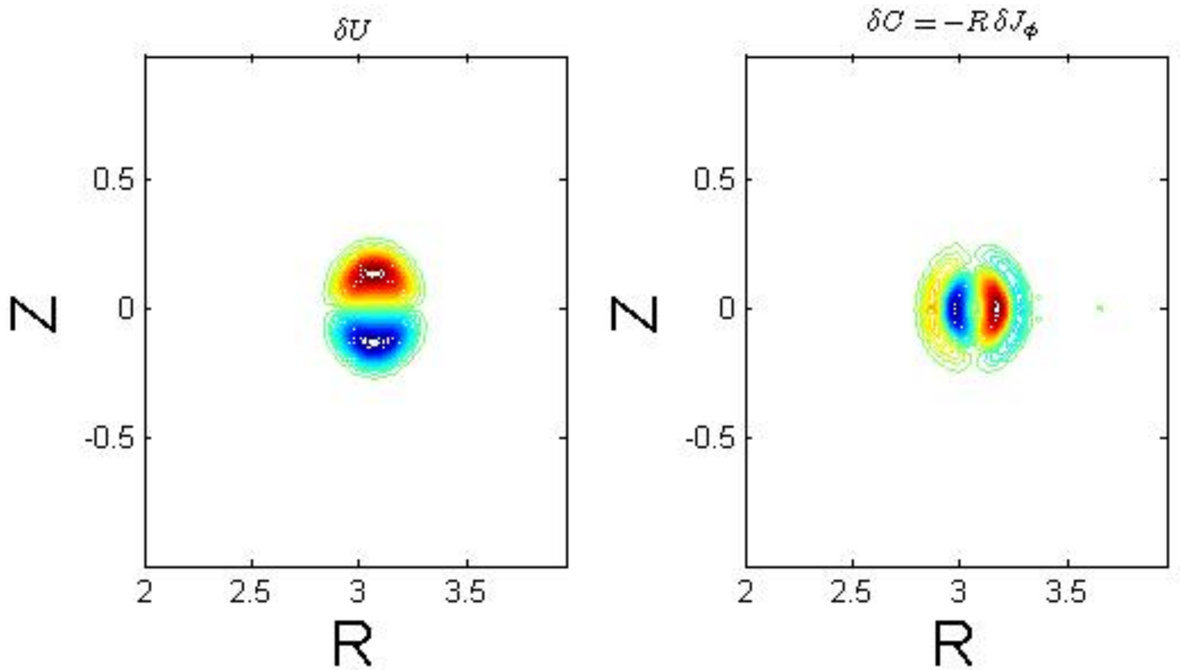


- The effect of magnetic drift velocity is small due to $\Delta_b / \Delta_{layer} >> 1$.

Linear results

◆ Case2: q0=0.93

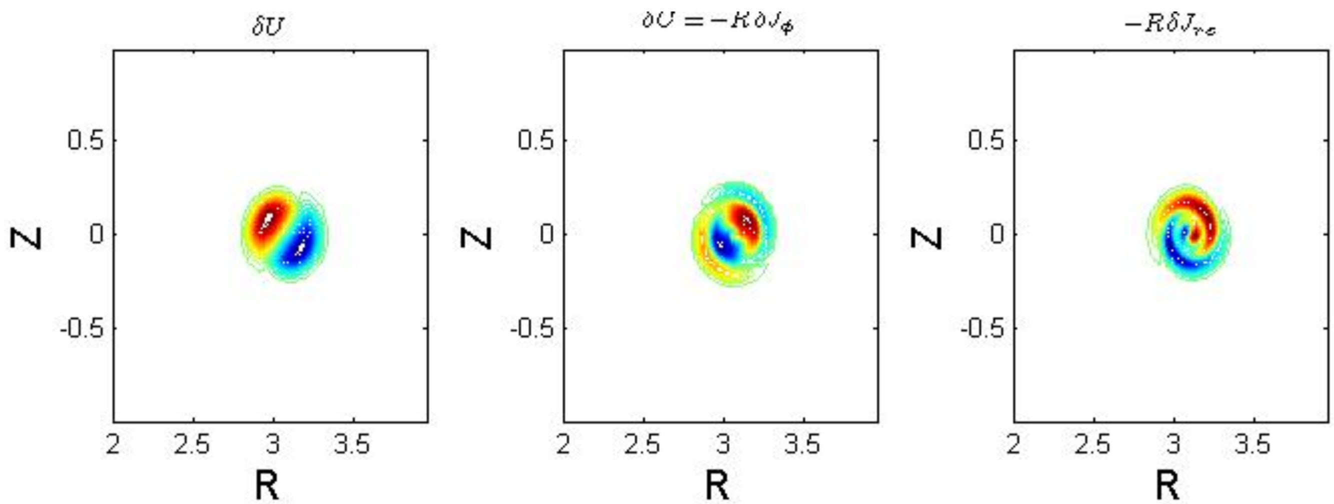
➢ Without runaway current, the growth rate of 1/1 mode is about 9.3e-3, the mode structures are



Linear results

◆ Case 2:q0=0.93

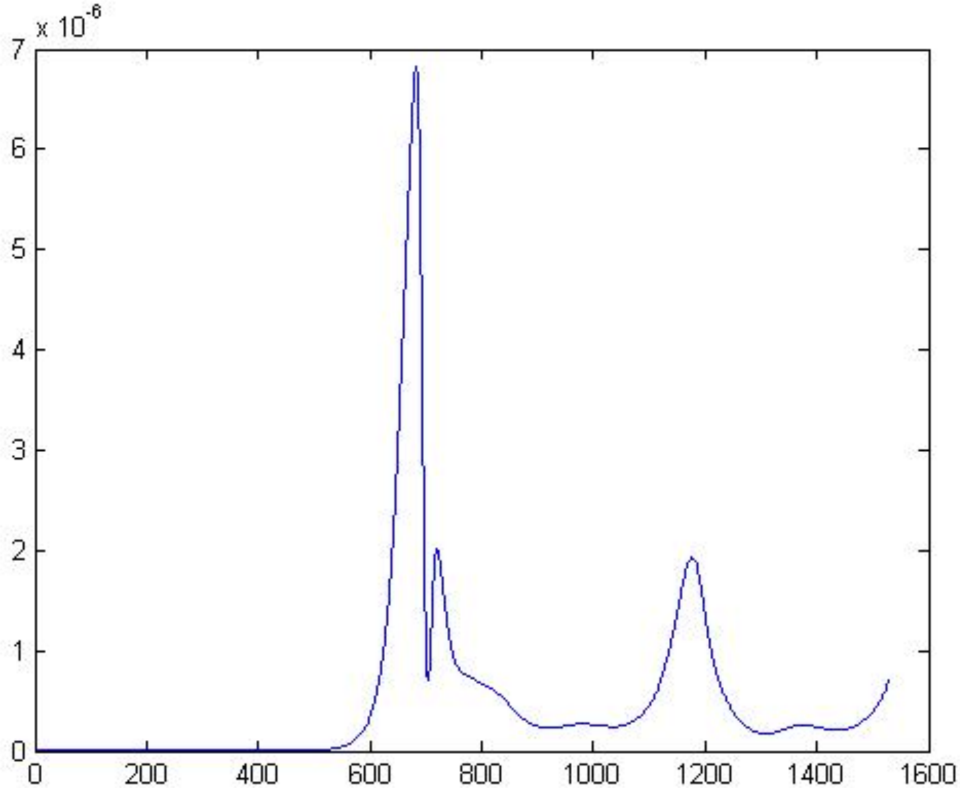
➢ With runaway current, the growth rate of 1/1 mode is about 1.72e-2, the mode structures are



- The growth rate is enhanced, and the mode structures keep almost the same.

Nonlinear results

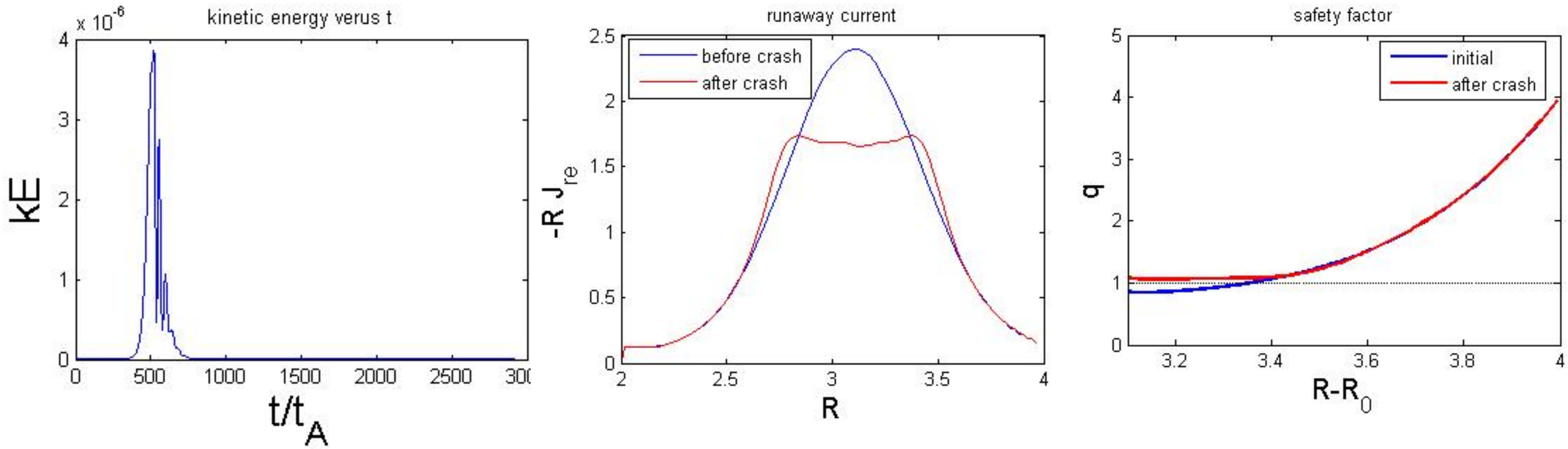
◆Case1:q0=0.83, without runaway current



◆The usual sawteeth are observed in the simulation.

Nonlinear results

◆Case1:q0=0.83, with runaway current



◆Resistive kink mode results a single sawtooth crash only.

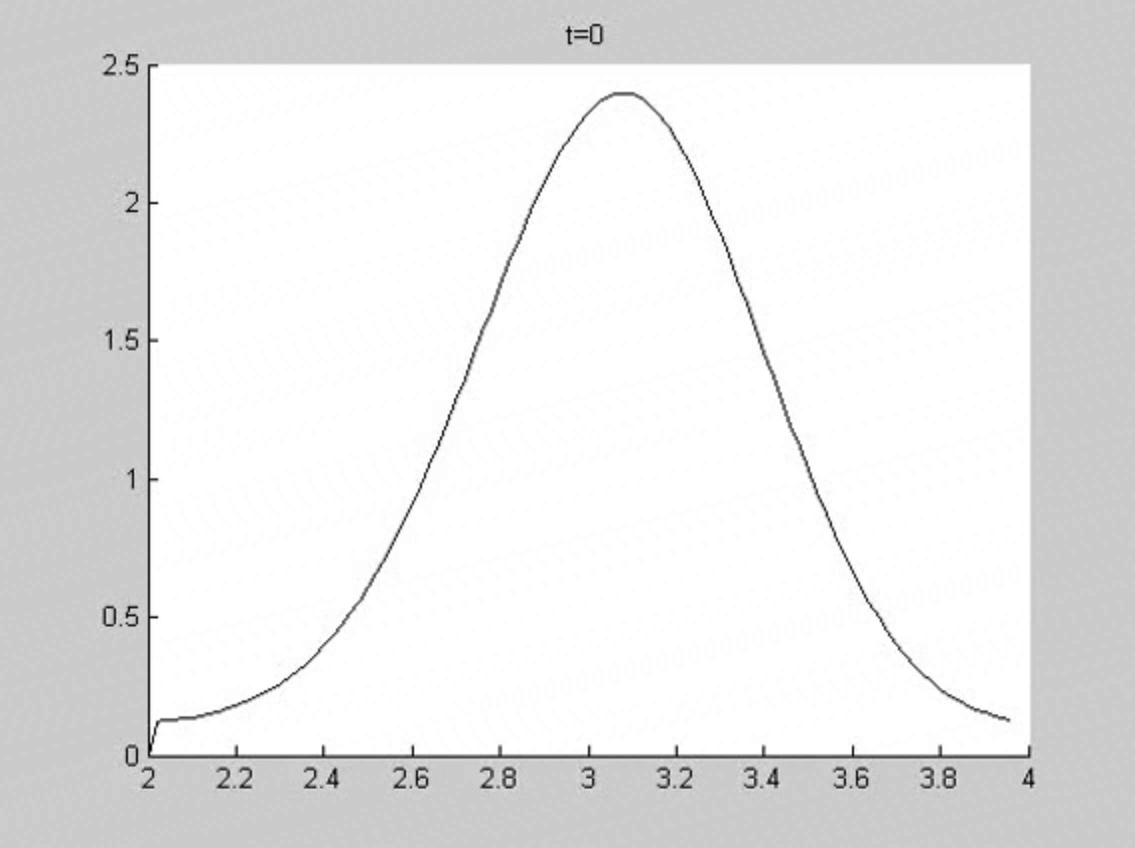
◆A steady state with axi-symmetric equilibrium is reached after the crash.

◆The plasma current and runaway current become flatten within q=1 surface, q0 greater than 1.

Physics: sawtooth crash tends to flatten current within q=1 surface. After the crash, the runaway current, acting as a current source, stays flatten.

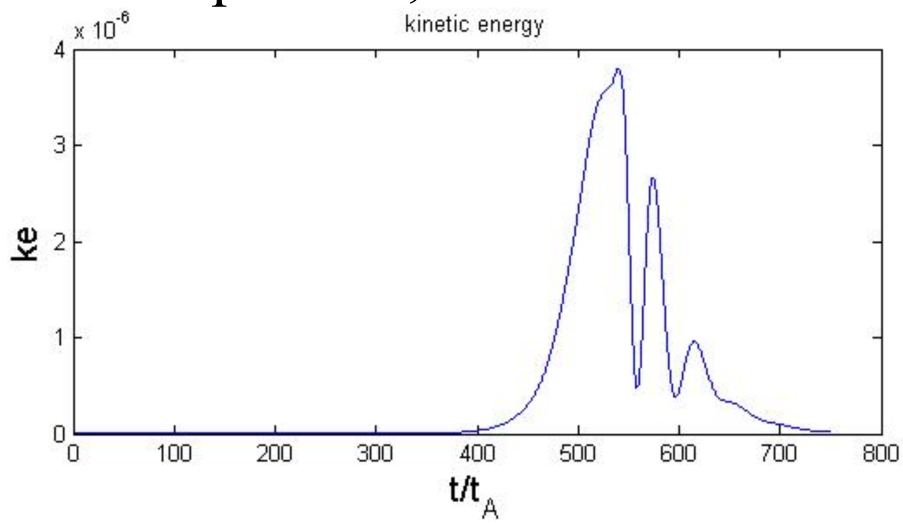
Simulation results

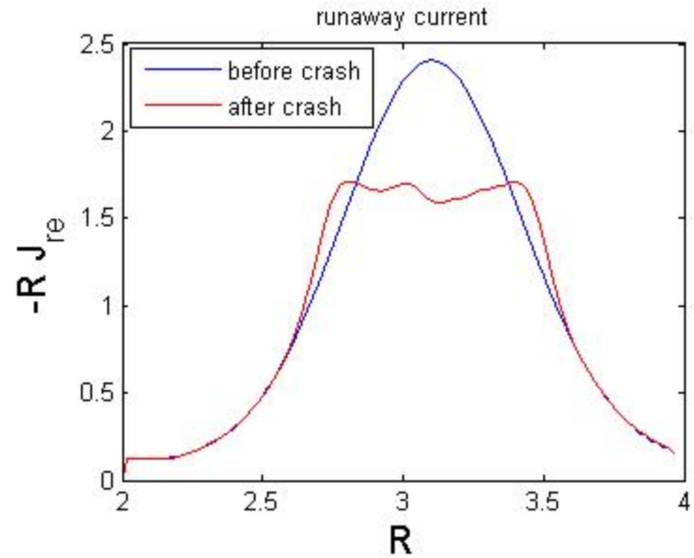
- The evolution of current

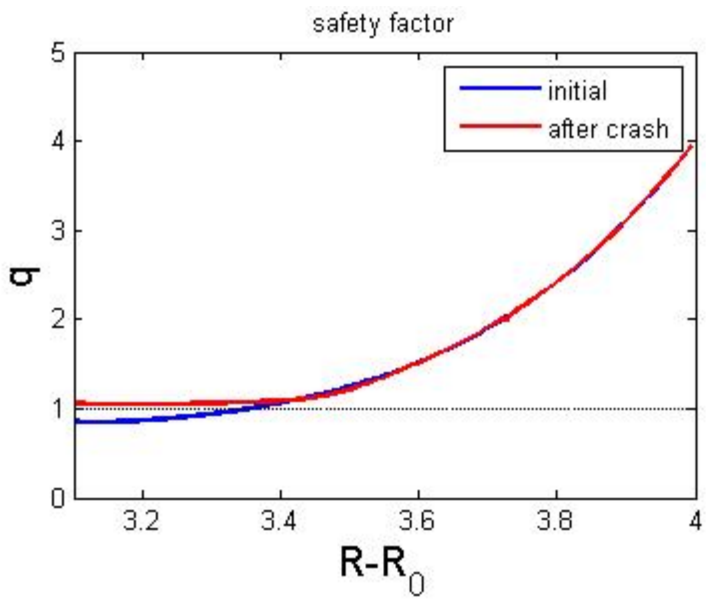


Nonlinear results

◆Case1:q0=0.83,without electric drift,

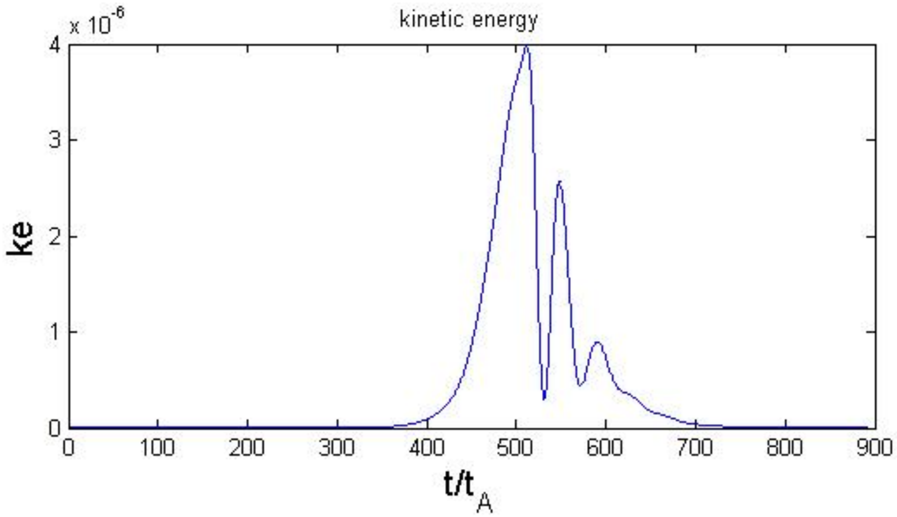


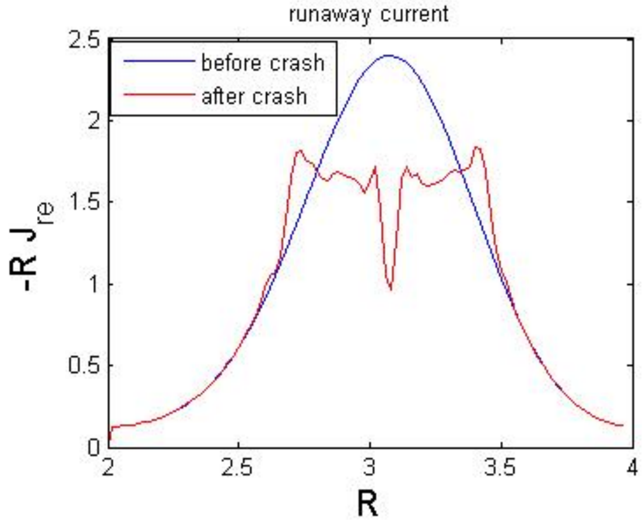


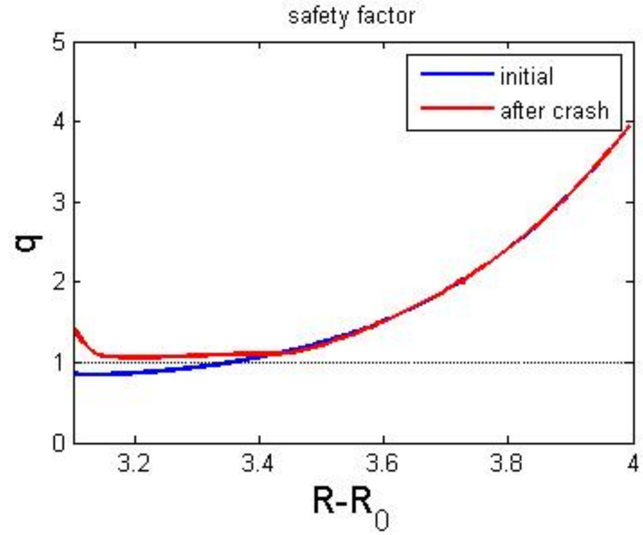


Nonlinear results

◆Case1:q0=0.83, without magnetic drift

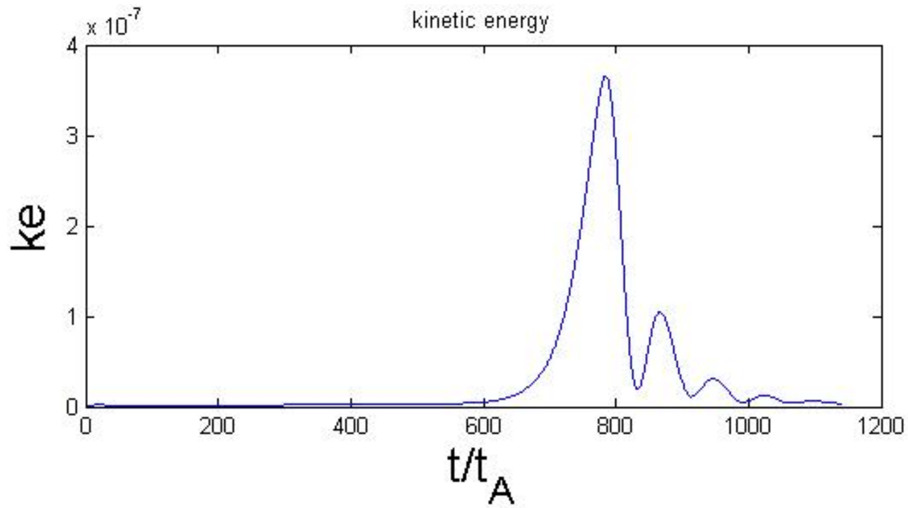


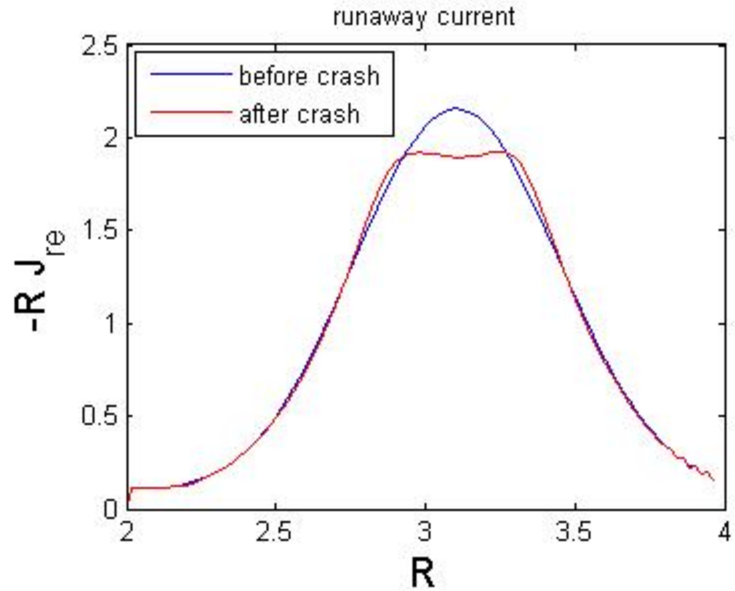


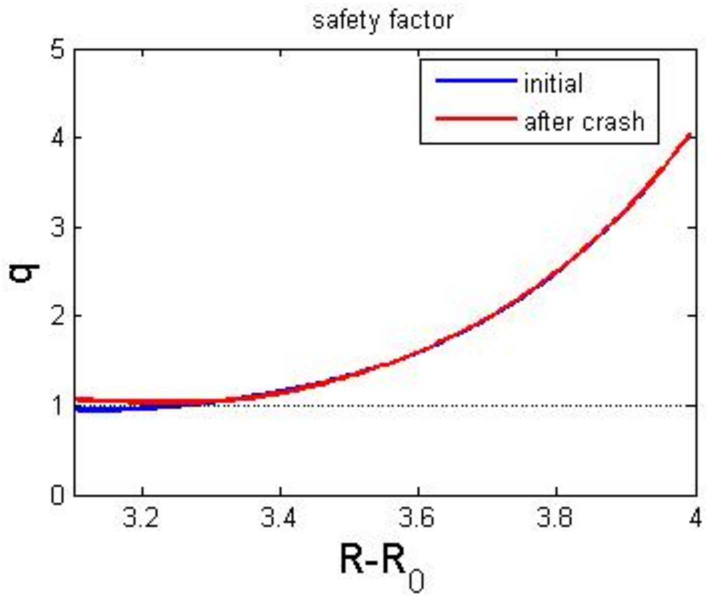


Nonlinear results

◆Case2:q0=0.93.







➢The same trend with q0=0.83.

Conclusion and discussion

- The linear growth rate of 1/1 resistive kink mode is enhanced by the effects of runaway current.

- After a single sawtooth crash, plasma reaches a new steady state with axi-symmetric equilibrium.

- The profiles of plasma current and runaway current are flatten within q=1 surface.

Thank you for your attention!