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A Triggering Mechanism of Fast Crash in Sawtooth Oscillation

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A TRIGGERING MECHANISM OF FAST CRASH IN SAWTOOTH OSCILLATION

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Keywords

tokamak, sawtooth oscillation, computer simulation, magnetohydrodynamics, magnetic reconnection

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A TRIGGERING MECHANISM OF FAST CRASH IN SAWTOOTH OSCILLATION

Abstract

Full-torus, compressible, resistive MHD simulations have been performed to study the mechanism of fast crash in the sawtooth oscillation. The simulation results reveal that the q value, which at first decreases in accordance with current peaking subject to ohmic heating, starts increasing in the $q < 1$ region due to strong excitation of nonlinear modes and becomes flattened. When the q profile is flattened in the $q < 1$ region, the plasma flow pushes the magnetic surface radially outwards and the poloidal magnetic field lines are driven to reconnect rapidly with each other across the $q=1$ surface. Consequently, the central hot plasma is pushed out towards the wall to crash its confinement. It turns out that the $m=1$ plasma flow induced by the kink instability, rather than the pressure gradient, plays a decisive role in the crash process.

1. Introduction

The mechanism of fast crash in the sawtooth oscillation phenomenon yet remains unclarified while there have been many theoretical researches reported [1-3]. The temperature distribution after the crash in recent large tokamak experiment data [4] seems to support Kadomtsev's resistive model [5] rather than Wesson's interchange mode model [6] as far as the geometrical change of the plasma is concerned, but it remains difficult to account for the rapid time scale of the fast crash.

Here, we propose a triggering mechanism of the fast crash by means of a self-consistent three-dimensional compressible resistive MHD simulation for a torus geometry. For this purpose, we have elaborated the previous model [7] and reconstructed a more feasible simulation model representing an ohmically heated tokamak plasma.

2. Simulation Model

The basic equations are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \tag{1}$$

$$\rho \frac{d \boldsymbol{v}}{d t} = \boldsymbol{j} \times \boldsymbol{B} - \nabla p, \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times (\boldsymbol{j}/S), \tag{3}$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p\, \boldsymbol{v}) = (\gamma - 1)(-p \nabla \cdot \boldsymbol{v} + \boldsymbol{j}^2/S\,) + \kappa \Delta T, \tag{4}$$

where the magnetic Reynolds number S is classical and proportional to 3/2 powers of the temperature and the thermal conductivity coefficient κ is constant. The thermal conduction effect, $\kappa \Delta T$, is switched on only when the shift of the temperature axis from the initial plasma center becomes more than 20 percent of the minor radius due to the temperature crash. This effect is introduced merely for recovering the initial plasma pressure profile after the crash, assuming that a certain anomalous heat transport mechanism would operate, which is beyond the scope of the present MHD model.

The tokamak device is modeled by a torus surrounded by a conducting wall with a square cross section, where cylindrical coordinates (R, θ, Z) are adopted ; R is the major radius, θ the toroidal angle, and Z the vertical axis. The initial equilibrium configuration without resistivity is obtained by solving the Grad-Shafranov equation under the above geometry. The initial on-axis S value is set to be 40000 and its distribution is calculated from the temperature.

3. Simulation Results

The simulation results show that the ramp-up phase and the ensuing crash are formed in the following way. The evolutions of the magnetic field line mapping on a poloidal plane and the q profile are shown in Fig. 1.

The q value at the plasma center which was initially set to be 1.03 ($t = 0$; Fig. 1-(a)) gradually decreases in accordance with current peaking caused by ohmic heating. As the on-axis q value falls below 1, an m=1/n=1 ideal kink mode appears near the axis. After the magnetic field of n=1 mode develops to a certain amplitude, q stops reducing the on-axis value and turns to increase in the q < 1 region to become flattened ($t = 374\tau_{pA}$; $\tau_{pA} = R_0/V_{tA}$ denotes the poloidal Alfven transit time for the aspect ratio $R_0/a = 3.$; Fig. 1-(b)). As time elapses, the q-profile gets more and more flattened toward q = 1 in the whole region of q < 1. When the q-profile becomes almost flattened ($t = 480\tau_{pA}$; Fig. 1-(c)), the plasma flow pushes the magnetic surface radially outwards so that the poloidal magnetic field lines are driven to reconnect rapidly with each other across the original q=1 surface [8] and the energy deposited in the region $q \leq 1$ is swiftly released to the outside region. Consequently, the central hot plasma is pushed out towards the wall and the temperature distribution crashes ($t = 488\tau_{pA}$; Fig. 1-(d)).

In Fig. 2 the time evolutions of the magnetic field energy of the n=1 mode and the nonlinear modes are shown by the solid lines (a) and (b), respectively. When the system reaches to a turning point (T.P.) where the on-axis q value changes from decrease to increase in the ramp-up phase, nonlinearly excited modes grow drastically. In order to examine what causes the turning of the q profile change, two artificial simulations are executed where both the magnetic field and the plasma flow of the n=1 mode are artificially suppressed at a time before the system reaches to the turning point and at a time before the q profile is flattened. The time evolutions of the magnetic field energy of the n=1 mode for these cases are shown by the dashed lines (c) and (d) in Fig. 2, respectively. The results show that while the on-axis q value continues to decrease, nonlinear modes start growing drastically after a while and the system reaches to the turning point. In Fig. 2, one can see an interesting fact that the magnitude of the energy at the turning point in each case (line (a), (c) and (d)) is almost the same, which suggests that the magnitude of the n=1 magnetic field determines the turning point.

Another artificial simulation is carried out where both the magnetic field energy and the kinetic energy of nonlinear modes are fixed to those values at $t = 309\tau_{pA}$ (before the turning point). Then, the simulation results show that the q value keeps decreasing instead of being flattened, thus, no crash appears.

These facts certainly indicate that the turning point is the time when the system goes into a strongly nonlinear phase, and that both the n=1 magnetic mode and the nonlinearly excited modes play the leading role in the flattening of the q-profile and the ensuing crash process.

Magnetic reconnection driven by the kink flow plays a decisive role in the destruction of the magnetic surface, while no apparent magnetic reconnection occurs through the ramp-up phase in contrast to the previous study [7] where a periphery vacuum region was modeled by an artificial high resistivity medium. When we have executed a simulation in which the term $-\nabla \times (\boldsymbol{j}/S)$ is removed from Eq. (3) at a time before the q profile is flattened, thus magnetic reconnection being inhibited, the q profile flattening has continued but no crash has occurred.

In order to clarify the role of the plasma pressure in triggering the crash, we made a simulation where the pressure gradient force was removed from the equation of motion, Eq. (2). The result is that crash did occur in the same way as in the case with the pressure gradient force. This simulation indicates that the crash is not due to a pressure-driven instability, but really due to the plasma flow-driven reconnection.

Driven magnetic reconnection occurs at the head point of the kink flow on the q=1 surface. Thus, the geometrical feature of the destruction of the magnetic surface is similar to that of Kadomtsev's model rather than that of Wesson's. An important and essential difference from Kadomtsev's, however, is that the destruction takes place in the MHD time-scale rather than the resistive time-scale.

In Fig. 3, the equi-contours of the temperature at the times corresponding to Fig. 1 and at (e) t=521 τ_{pA} are shown. The temperature axis stays at its initial position until the time of the turning point (Fig. 3-(a) and (b)). At the time just before the magnetic surface disruption (Fig. 3-(c)), the temperature axis shifts a little bit subject to the strong kink flow, while the magnetic axis does not. When the crash occurs, the high temperature spot in the central region slides towards the wall, leaving a temperature plateau region in the central region (Fig. 3-(e)). These features are in good agreement with experimental results such as those of TFTR. [4]

The on-axis temperature is plotted against time in Fig. 4, where the thermal conduction effect is switched on at t=537 τ_{pA} for the first sawtooth oscillation. Returning to the initial state of the pressure profile is completed at t=602 τ_{pA} and the thermal conduction is then switched off. The system then returns to the ramp-up phase and a similar sawtooth feature is repeated. In the present work, the heat release mechanism is not specified, but it certainly plays an essential role in retrieving a normal state form a crash phase.

As can be seen in Figures 1 and 4, the time-scale of the disruption of the magnetic surface due to magnetic reconnection is 20 $\sim$ 30 τ_{pA} and the temperature on the plasma axis drops in the time-scale of 50 $\sim$ 100 τ_{pA}. In a compressible plasma the time-scale of the driven magnetic reconnection is almost independent of the resistivity, but dependent greatly on the magnitude of the plasma flow. [9] Therefore, when a higher magnetic Reynolds number is chosen as the initial on-axis value, the time-scale of the crash does not differ much as long as the kink flow velocity develops into the same order of magnitude, while the time-scale of the ramp-up phase becomes longer because the q profile change is strongly depending on the S number and the crash depth becomes smaller.

Suppose that the simulation be executed in which the density continuity equation is not solved, i.e., incompressible plasma. Then, the magnetic Reynolds number will affect seriously on the reconnection rate and, hence, on the time scale of the crash. This can explain why the time-scale of the crash in our simulation is of the order of 100 τ_{pA} and different from that in the other simulations such as Aydemir's. [1–2]

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Figure Captions

Fig. 1. The evolutions of magnetic field line mapping on a poloidal plane and the q profile at (a) t=0, (b) t=374 τ_{pA}, (c) t=480 τ_{pA}, (d) t=488 τ_{pA}.

Fig. 2. The time evolutions of the magnetic field energy of ; (a) the n=1 mode ; (b) the nonlinear modes ; (c) the n=1 mode for the case where the n=1 mode is artificially suppressed at a time before the turning point ; (d) the n=1 mode for the case where the n=1 mode is suppressed before the flattening.

Fig. 3. The equi-contours of the temperature at (a) t=0, (b) t=374 τ_{pA}, (c) t=480 τ_{pA}, (d) t=488 τ_{pA}, corresponding to Fig. 1, and at (e) t=521 τ_{pA}.

Fig. 4. The on-axis temperature plot against time.

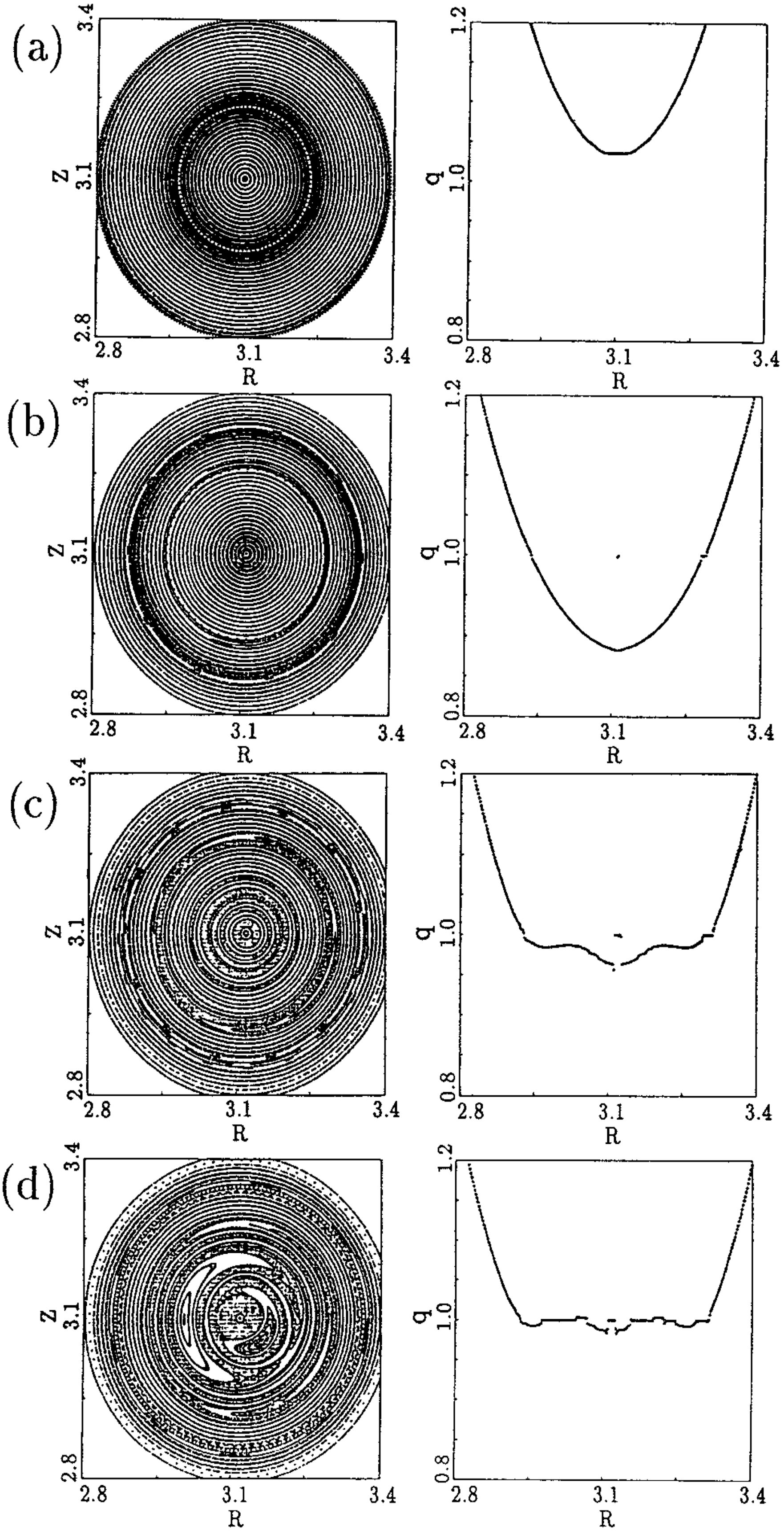
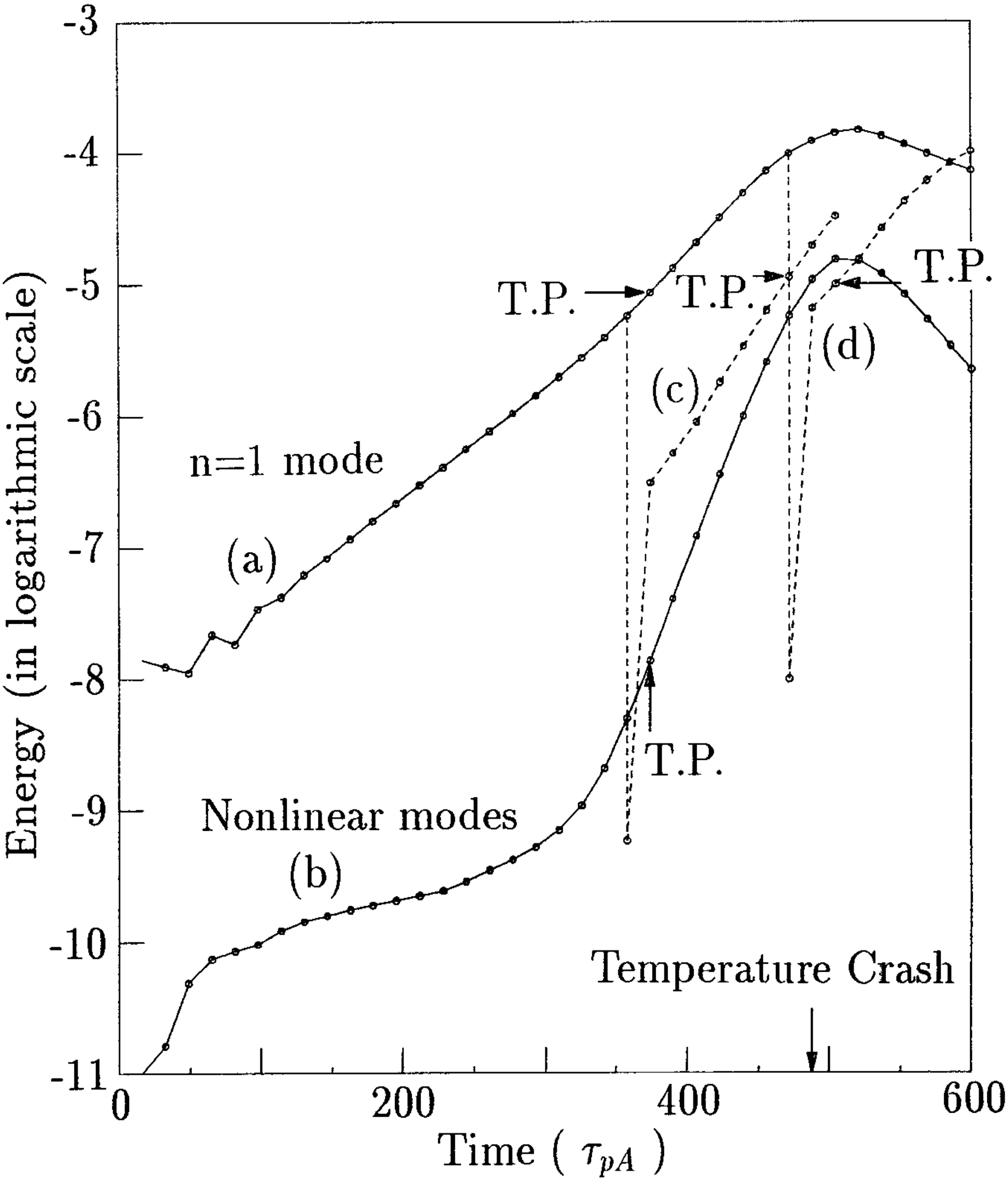


Fig. 1



-3
-4
-5
-6
-7
-8
-9
-10
-11
0
200
400
600
Energy (in logarithmic scale)
Time (τ_{pA})
n=1 mode
(a)
Nonlinear modes
(b)
(c)
(d)
T.P.
T.P.
T.P.
T.P.
Temperature Crash

Fig. 2

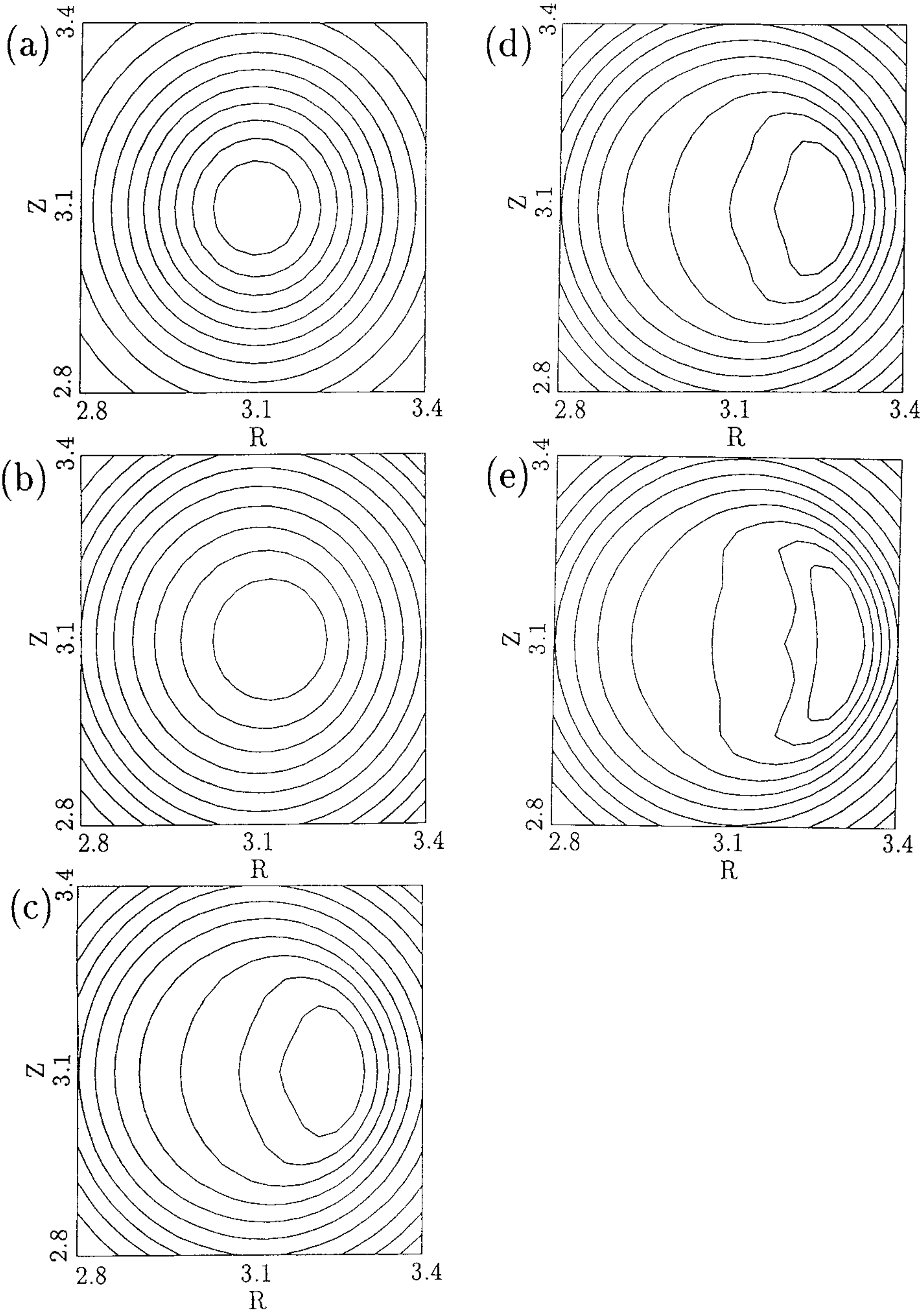


Fig. 3

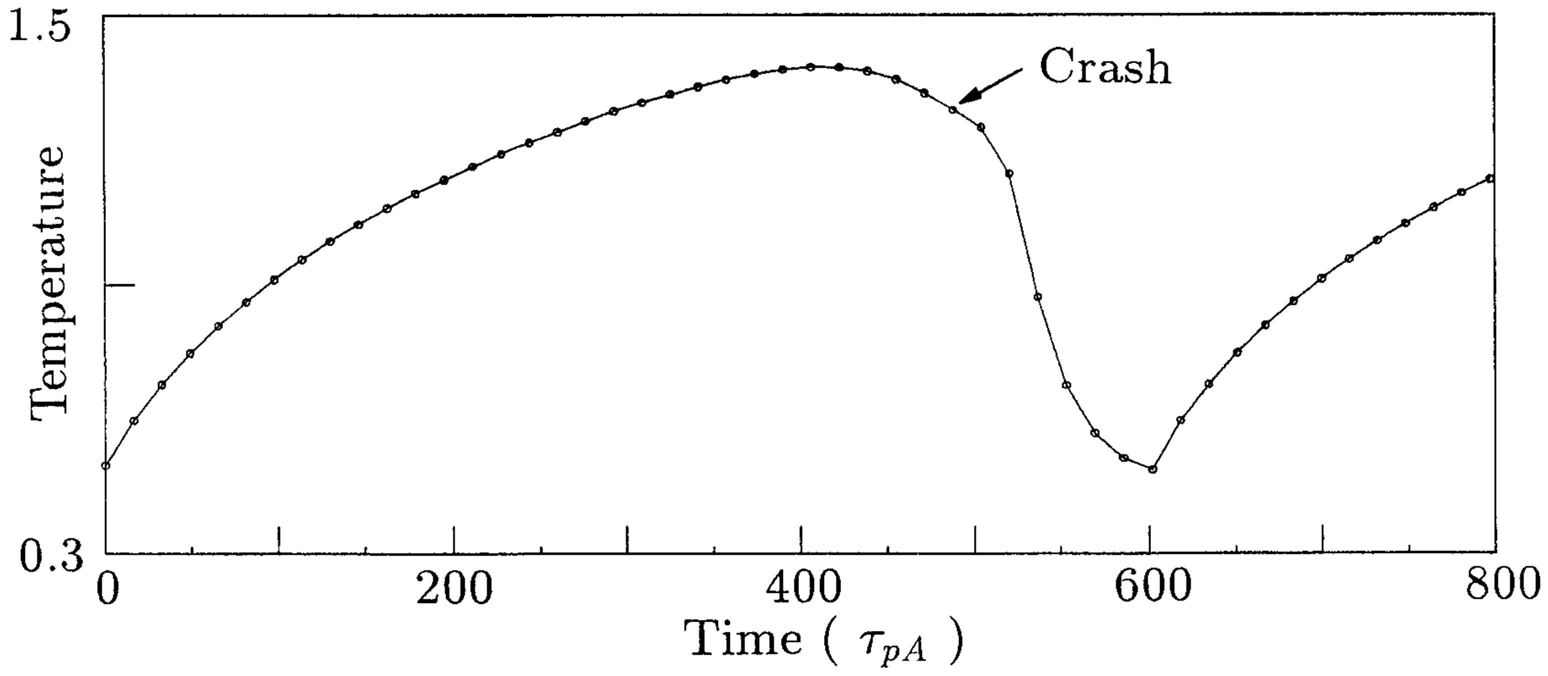


Fig. 4

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