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Axisymmetric MHD Simulation of ITB Crash and Following Disruption Dynamics of Tokamak Plasmas with High Bootstrap Current

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Abstract

Axisymmetric MHD simulation using the Tokamak Simulation Code demonstrated detailed disruption dynamics triggered by a crash of internal transport barrier in high bootstrap current, high β, reversed shear plasmas. Self-consistent time-evolutions of ohmic current, bootstrap current and induced loop voltage profiles inside the disrupting plasma were shown from a view point of disruption characterization and mitigation. In contrast with positive shear plasmas, a particular feature of high bootstrap current reversed shear plasma disruption was computed to be a significant change of plasma current profile, which is normally caused due to resistive diffusion of the electric field induced by the crash of internal transport barrier in a region wider than the internal transport barrier. Discussion based on the simulation results was made on the fastest record of the plasma current quench observed in JT-60U reversed shear plasma disruptions.

Keywords:

disruption, internal transport barrier, reversed shear plasma, current quench

1. Introduction

Steady-state operation of advanced tokamak reactors requires development of disruption mitigation by reducing the speed of plasma current quench and by avoiding vertical displacement event (VDE) [1,2] to attain high-β, high-performance fusion plasmas. The fastest current quench of the major disruption, however, was recently observed in JT-60U Reversed Shear (RS) plasmas with strong Internal Transport Barrier (ITB) [3], and impacted on design study of vacuum vessel and plasma facing components of ITER. Hence, it is particularly important to clarify the mechanism governing such a fast current quench and to understand not well-known disruption characteristics of RS plasmas, where the ITB-generated, high BootStrap (BS) current might play a different role on advanced tokamak operation from Positive Shear (PS) plasmas.

Axisymmetric simulation using the Tokamak Simulation Code (TSC) [4] demonstrated a detailed process of the ITB crash and following disruption dynamics of RS plasmas which interact with a conducting wall and sets of axisymmetric conductors. Self-consistent time-evolutions of the inductive and non-inductive current profiles and the relevant electric field profile were studied through out the major disruption triggered by the ITB crash. A particular feature of the disruption dynamics of RS plasmas was also discussed in contrast with the PS plasmas.

2. TSC simulation

We utilized TSC, which solves modified magneto-hydrodynamic equations inside a computational domain that includes a plasma region, a vacuum region, a specified number of solid conductors and a wall of JT-60U. A simple ITB model, which reproduced a current ramp-up of RS plasmas and a current hole formation in JT-60U well [5], was also used in our computational studies. The ITB and relevant BS current profiles were prescribed by assuming the pressure profile which is consistent with the magnetic shear profile of RS plasmas. Then, the ITB crash was modeled by introducing an abrupt decrease in the core plasma pressure within 4 ms as illustrated in Fig. 1. Central plasma density $n_e(0)$ was assumed to be unchanged during the simulation, while the profile was assumed as $n_e(\rho) \sim n_e(0) \cdot \sqrt[3]{p(\rho)/p(0)}$.

Figure 2 shows TSC time-evolutions of poloidal beta β_p,

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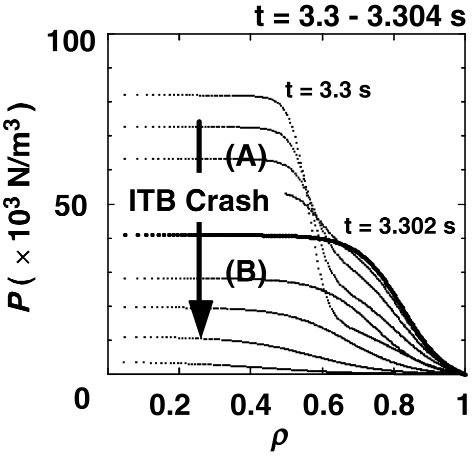

Fig. 1 Assumed time evolution of plasma pressure profile plotted with intervals of 4 ms for ITB crash modeling. Time phases of (A) and (B) are defined in Fig. 2.

plasma current I_p and BS current I_{bs} during the ITB crash and following disruption. Typical plasma parameters prior to the ITB crash are $\beta_p \sim 1.3$, $I_p \sim 1.4$ MA and $I_{bs} \sim 0.44$ MA. The vertical equilibrium position of plasma magnetic axis is $z_p \sim 0.16$ m, which is the neutral point for avoiding VDE in JT-60U [2,6].

The disruption dynamics of Fig. 2 are characterized into four phases as (A), (B), (C), (D) by its specific features of the RS plasma. Here, each phase was defined by the following typical events, i.e., end of (A): the largest BS current growth near the plasma surface of Fig. 3, end of (B): the largest loop voltage growth plotted in Fig. 4, end of (C): the largest ohmic current growth at plasma center displayed in Fig. 5, and (D): later than phase (C). Figure 3 shows the time-evolutions of plasma current, BS current, induced loop voltage and q profiles in the first phase of Fig. 2 (A: t = 3.3 – 3.302 s). The ITB-generated BS current disappears quickly due to the ITB crash, and loop voltage of a few volts is induced around the ITB region. As a consequence, the current and q profiles are left almost unchanged, conserving the poloidal magnetic flux. Subsequently, the BS current appears in accordance with an increase in the pressure gradient near the plasma surface. Thus, the BS current exceeds the ohmic current near the plasma surface, causing an over-driven state of local current density accompanied by a negative E-field around there. Figure 4 also shows the time-evolutions of the plasma current, BS current, loop voltage and q profiles in the second phase (B: t = 3.302 – 3.306 s). As the electron temperature drops, E-field grows rapidly, and then diffuses into the core region. Consequently, the plasma current in the ITB region begins to decrease, while the current grows in the core region. The q profile also starts to flatten in the core region.

In phase (C) (t = 3.306 – 3.31 s), we observed a specific feature of RS plasma disruptions, i.e., a significant change of plasma current profile from hollow to centrally peaked as shown in Fig. 5. At the final stage of phase (C), the E-field was relaxed by the resistive diffusion, leading to a centrally peaked current profile. As a consequence, a rapid increase in

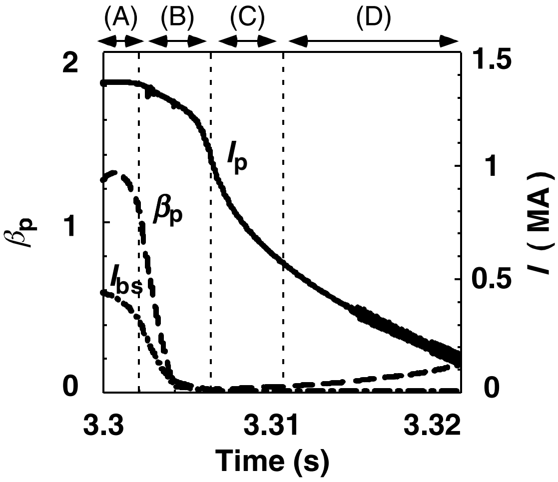

Fig. 2 Computed time-evolutions of poloidal beta β_p, plasma current I_p and BS current I_{bs} during ITB crash and following disruption phases (A), (B), (C), (D) with TSC.

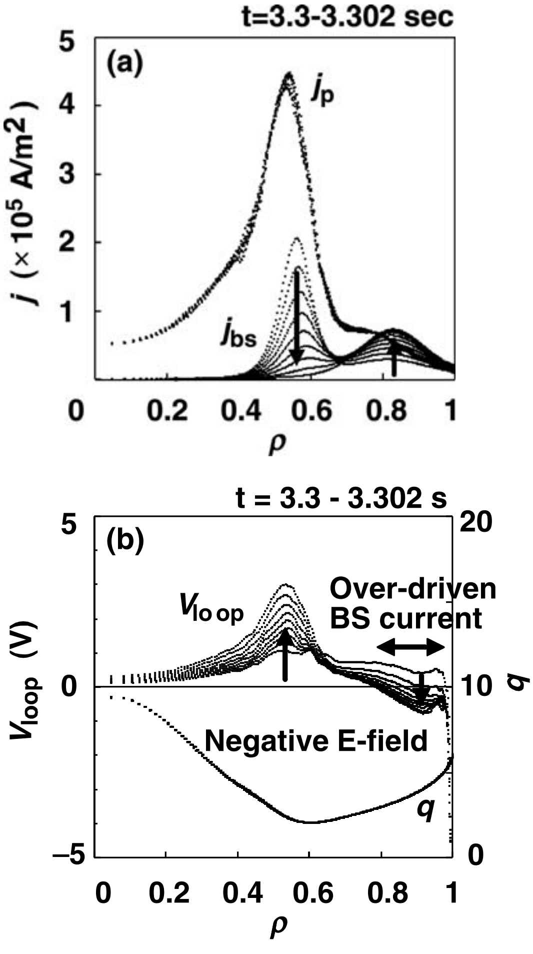

Fig. 3 TSC time-evolutions of plasma current, BS current, induced loop voltage and q profiles in phase (A) of Fig. 2 (t = 3.3 – 3.302 s). BS current disappears quickly due to ITB crash, and loop voltage of a few volts is induced around the ITB region. Near the plasma surface, BS current appears in accordance with an increase in the pressure gradient. Nevertheless, the plasma current and q profiles are left nearly unchanged. The end of phase (A) is defined by the largest BS current growth near the plasma surface.

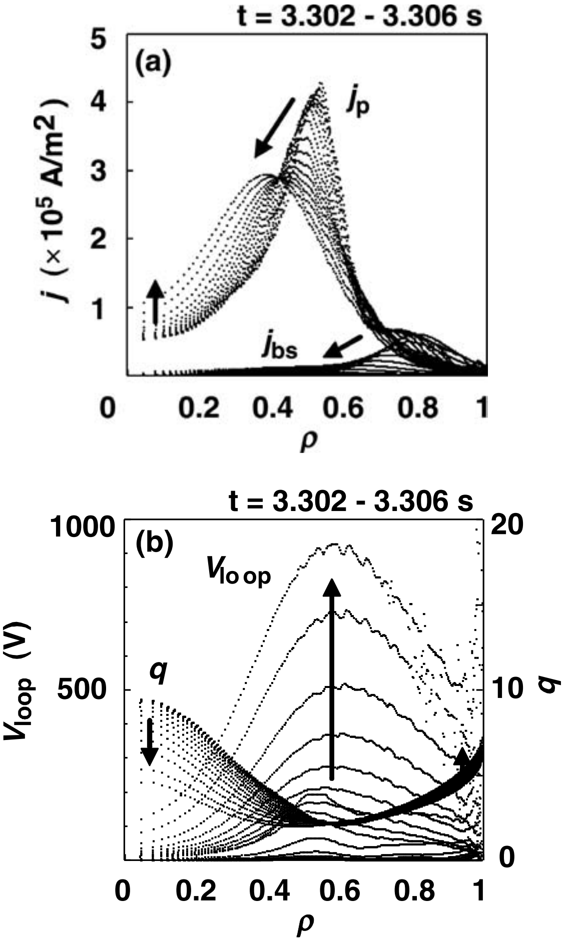

Fig. 4 TSC time-evolutions of plasma current, BS current, loop voltage and q profiles in phase (B) (t = 3.302 – 3.306 s). Toroidal electric field substantially grows because of T_e drop, and then diffuses into the plasma core region. The plasma current in the core region increases, and the q profile also begins to flatten. The end of phase (B) is defined by the largest loop voltage growth.

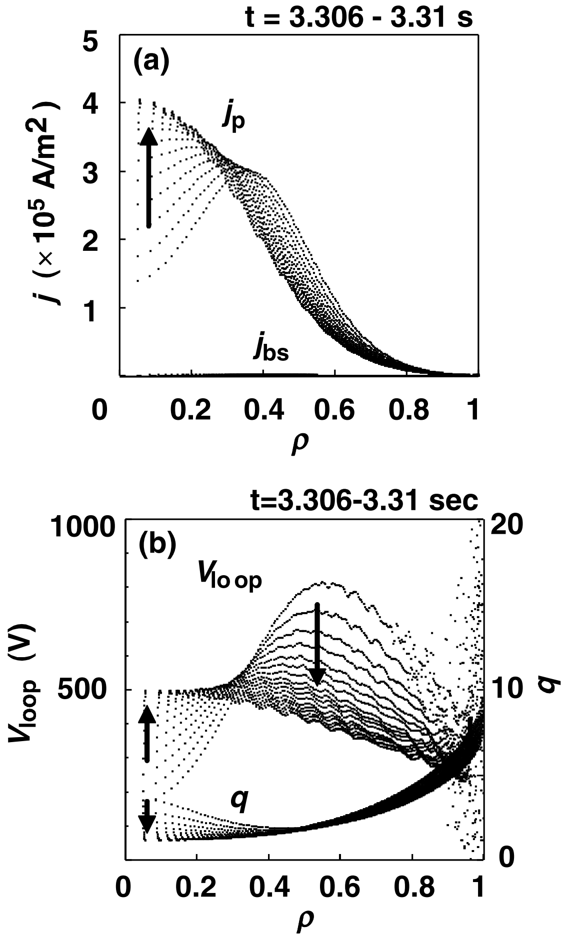

Fig. 5 TSC time-evolutions of plasma current, BS current, loop voltage and q profiles in phase (C) (t = 3.306 – 3.31 s). Notice that the plasma current profile changes significantly from hollow to centrally peaked in accordance with a flattening of E field, resulting in the faster current decay than the other phases. The end of phase (C) is defined by the largest ohmic current growth at plasma center.

the internal inductance appeared, resulting in a current decay faster than the other phases.

After 3.31 s of phase (D) (t > 3.31 s), the disruption dynamics of the RS plasma was similar to PS plasmas with peaked current profile with current quenches in accordance with a shrinkage of plasma cross section, while all the profiles of the plasma current, loop voltage and safety factor were slightly changed.

3. Conclusions

Simulation studies of the ITB crash and following disruption dynamics of RS plasmas have clarified the detailed evolutions of the induced loop voltage, BS current and ohmic current profiles. In addition, the significant change of the plasma current profile from hollow to centrally peaked was demonstrated, and the relevant dynamics of E-field flattening was also revealed in detail. As a consequence, one of physics reasons, which can explain the fastest record of the current quench observed in the RS plasmas, was found to be a rapid increase in the internal inductance due to the current profile change. It was also pointed out that the disruption dynamics of the RS plasma is similar to the PS plasmas in the final shrinking phase of plasma cross section. Future studies on the disruption triggered by the abrupt degradation of energy confinement are planned using a transport modeling self-consistent with the ITB-generated BS current, involving energy balance between much intensified joule heating and radiation loss during the disruption. The generation of runaway electrons due to the strong toroidal E-field is also left as a future work, and now under study.

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References

[1] ITER Physics Basis Editors, Nucl. Fusion **39**, 2251

(1999).
[2] Y. Nakamura *et al.*, Nucl. Fusion **36**, 643 (1996).
[3] Y. Kawano, M. Sugihara, T. Ozeki and M. Shimada, *30th EPS Conference on Controlled Fusion and Plasma Physics*, P-2.129, St Petersburg, Russia, July 7-11, 2003.
[4] S.C. Jardin, N. Pomphery and J. Delucia, J. Comput. Phys. **66**, 481 (1986).
[5] Y. Nakamura, H. Tsutsui, N. Takei *et al.*, *30th EPS Conference on Controlled Fusion and Plasma Physics*, P-2.128, St Petersburg, Russia, July 7-11, 2003.
[6] R. Yoshino *et al.*, Nucl. Fusion **36**, 295 (1996).