*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.141 (2004)*

TSC Simulation of ITB Crash and Following Disruption Dynamics on JT-60U High-β Reversed Shear Plasmas

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1. Introduction

Although Reversed Shear (RS) plasma, whose current profile essentially allows large BootStrap (BS) current, is one of the leading candidates for advanced scenarios, frequent disruptions limit the performance and feasibility of tokamak reactors. Recently, a fastest disruptive current quench was observed in JT-60U RS plasmas with strong Internal Transport Barrier (ITB) [1], and has impacted design study of ITER. Hence, it is particularly important to understand such disruption characteristics of fast current quench in RS plasmas and further to clarify the underlying mechanism accounting for the role of ITB-generated, high BS current, which might play a different role from Positive Shear (PS) plasmas.

Axisymmetric MHD simulation using Tokamak Simulation Code (TSC) [2] has demonstrated detailed process of the ITB crash and following disruption dynamics of high-β plasmas, and direct comparison with the JT-60U experiments were made. Disruption dynamics specific to the RS plasmas, such as plasma current spikes at thermal quench and following current decay, were also described in contrast to the PS plasmas.

2. Simulation Modeling

In the TSC, a simple ITB model was additionally installed such that location of the ITB with a prescribed pressure gradient is always adjusted to the magnetic shear profile, *i.e.,* the ITB foot was placed on the magnetic shear reversal. We utilized the model of BS current given by Hirshman [3]. In addition, we made use of a model of destruction of magnetic surfaces or “magnetic braiding” [4], which describes fundamentally nonlinear three-dimensional effects on a two-dimensional axisymmetric field representation as follows:

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j} - \frac{\boldsymbol{B}}{B^2} \nabla \left(\lambda \frac{\nabla j_{//}}{B} \right),$$

where λ is an arbitrary positive function of position. The second term of RHS leads to anomalous current viscosity, dissipating energy, but conserving global helicity. Thus, the model of “magnetic braiding” enables us to reproduce the experimentally observed abrupt change of the current profile during thermal quench [5].

Consequently, one can model an abrupt disappearance of high-β region inside the ITB and a simultaneous destruction of magnetic surfaces, both of which are prime events of thermal quench. Therefore, we can always ensure profile consistency of the ITB-generated BS current during both disruptions of high-β PS and RS plasmas.

3. Disruption of High-β Positive Shear Plasma

Figure 1 shows T_i, T_e profiles in the JT-60U high-β PS discharge (E26446). A steep gradient was observed in T_i profile at $\rho \sim 0.7$, indicating existence of the ITB. Major parameters of the initial plasma are poloidal beta $\beta_p \sim 1.1$, plasma current $I_p \sim 2.2$ MA and effective safety factor $q_{\mathrm{eff}} \sim 4.3$ before the disruption. Notice that the plasma is positioned much inner ($R_{\mathrm{J}} \sim 3.2$ m) than the geometric center of the vacuum vessel ($R_{\mathrm{vv}} \sim 3.4$ m). TSC estimated the BS current of $I_{\mathrm{bs}} \sim 0.7$ MA.

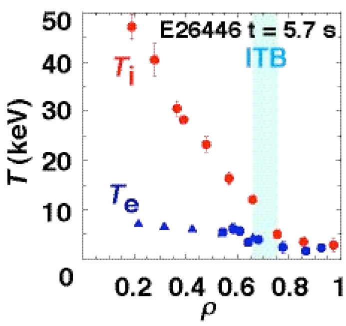

Fig. 1: Temperature profiles in JT-60U high-β PS discharge (E26446). ITB exists at $\rho \sim 0.7$.

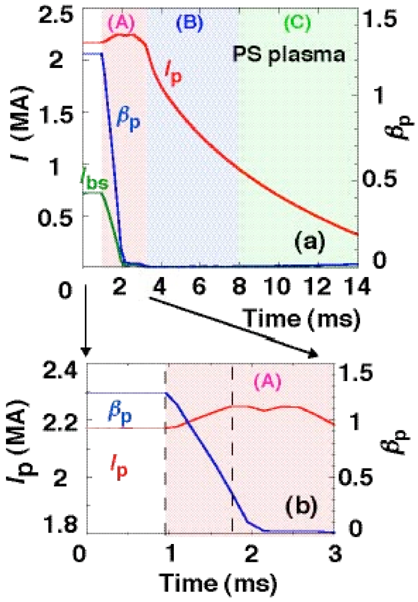

Fig. 2: TSC time-evolutions of PS discharge (E26446). (a): β_{p}, I_{p} and BS current I_{bs} during the ITB crash and following disruption phases (A), (B), (C). (b): details of β_{p} and I_{p} at t = 0 – 3 ms. The ITB crash was modeled by abrupt β_{p} drop (t = 1 - 2 ms) and subsequent "magnetic braiding" (t = 2 - 3 ms). Notice that the β_{p} drop and subsequent "magnetic braiding" lead to a positive current spike.

Figure 2 shows TSC time-evolutions of β_{p}, I_{p} and I_{bs} during the ITB crash and following disruption of the PS discharge (E26446). The ITB crash was modeled by introducing first an abrupt drop of the core plasma pressure within 1 ms and subsequent "magnetic braiding" within 1 ms in the first phase (A) (t = 1 - 3 ms). The disruption dynamics are characterized into three phases as (A), (B), (C) by the following typical events:

(A) ITB crash due to β_{p} drop and "magnetic braiding" (t = 1 - 3 ms)

Figure 3 shows the time-evolutions of plasma current, BS current and q profiles. While the ITB-generated BS current disappears quickly, the plasma current and q profiles were left almost unchanged besides near plasma boundary. This implies that the poloidal magnetic flux was conserved during the β_{p} drop. As shown in Fig. 2, the β_{p} drop leads to a positive current spike. One can see the corresponding current increase of $j_{\mathrm{p}}(\rho)$ near the plasma boundary of Fig. 3. It was newly found that this current increase is arising from the eddy current effect of the surrounding vacuum vessel. The eddy current during the β_{p} drop affects conversely the plasma current change in accordance with the radial plasma position. When the plasma is positioned closer to inner side of the vacuum vessel, the inward shift increases the plasma current, while it decreases the current in case of positioning closer to further outside of the vessel [6].

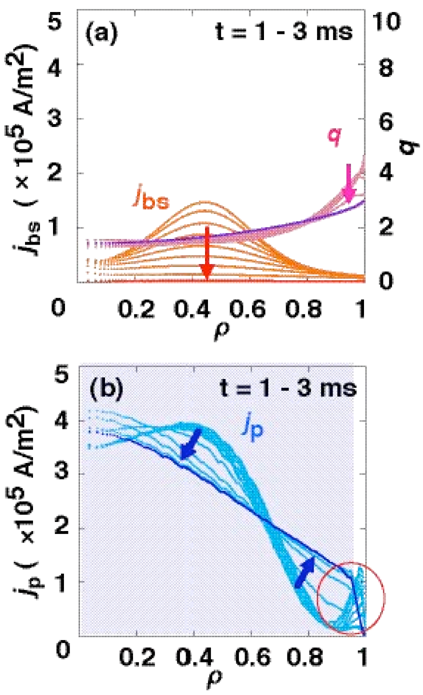

Fig. 3: TSC time-evolutions of BS current, q and plasma current profiles during ITB crash (t = 1 - 3 ms). While the ITB-generated BS current disappears quickly, plasma current and q profiles were left almost unchanged besides near plasma boundary. Notice that the current increases near plasma boundary, arising from eddy current effect of vacuum vessel.

Subsequent to the β_{p} drop, "magnetic braiding" was introduced into almost whole area of the plasma region (t = 2 - 3 ms), leading to a consequent flattening of the current and q profiles. The associated current spike was positive as shown in Fig. 2.

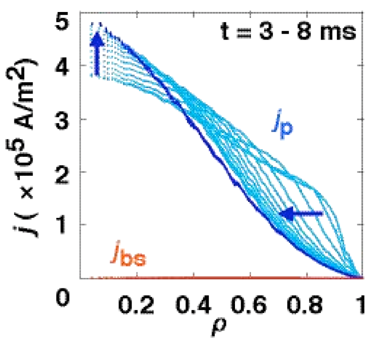

Fig. 4: TSC time-evolutions of plasma current and BS current profiles in the second phase (B) (t = 3 - 8 ms). Always keeping the similar positive shear profile, the current, once flattened due to ITB crash, grows in core region, while decreases near plasma boundary.

(B) Current profile relaxation and current decay (t = 3 - 8 ms)

Figure 4 shows the time-evolutions of the plasma current and BS current profiles. Always keeping the similar positive shear profile, the current, once flattened due to the ITB crash, grows in the core region, while decreases near the plasma boundary. An increase in the internal inductance, however, is smaller than that of RS plasmas as shown later.

(C) Current decay and shrinkage of plasma (t > 8 ms)

After the relaxation process of current profile settled down, the dominant process was a monotonic current decay and a shrinkage of plasma cross-section without any of profile changes.

4. Disruption of High-β Reversed Shear Plasma

Figure 5 shows T_i, T_e profiles in the JT-60U high-β RS discharge (E27302). A steep gradient of ITB was observed in T_i and T_e profiles at ρ ~ 0.6. Major parameters of the initial plasma prior to the ITB crash are β_p ~ 1.2, I_p ~ 2.5 MA and q_{eff} ~ 4.8. The plasma is positioned much inner (R_J ~ 3.2 m) than the geometric center of the vacuum vessel (R_{vv} ~ 3.4 m) as well as the PS plasma (E26446). TSC estimated the BS current of I_{bs} ~ 0.85 MA.

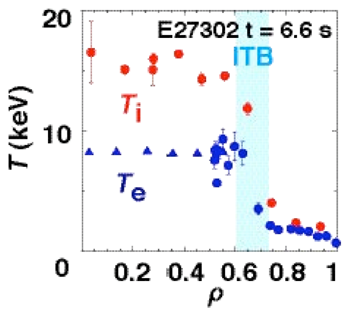

Fig. 5: Temperature profiles in the JT-60U high-β RS discharge (E27302). ITB exists at ρ ~ 0.6.

Figure 6 shows TSC time-evolutions of β_p, I_p and I_{bs} during the ITB crash and following disruption of the RS discharge (E27302). The similar ITB crash was modeled by introducing β_p drop within 1 ms and almost simultaneous “magnetic braiding” in the first phase (A) (t = 1 - 2 ms). The disruption dynamics are characterized into three phases as (A), (B), (C) by the following typical events:

(A) ITB crash due to β_p drop and “magnetic braiding” (t = 1 - 2 ms)

Figure 7 shows the time-evolutions of plasma current and BS current profiles. Although the ITB-generated BS current disappears quickly, the plasma current profile was left almost unchanged besides near plasma boundary. As shown in Fig. 6, the β_p drop leads to a similar positive spike to the PS plasma (E26446). Underlying mechanism of the current spike due to the β_p drop in the RS plasma is quite same as the PS plasma.

Simultaneously with the β_p drop, a “magnetic braiding” was introduced into almost whole area of the plasma region (t = 1 - 2 ms), leading to a consequent flattening of the current and q profiles. The associated positive

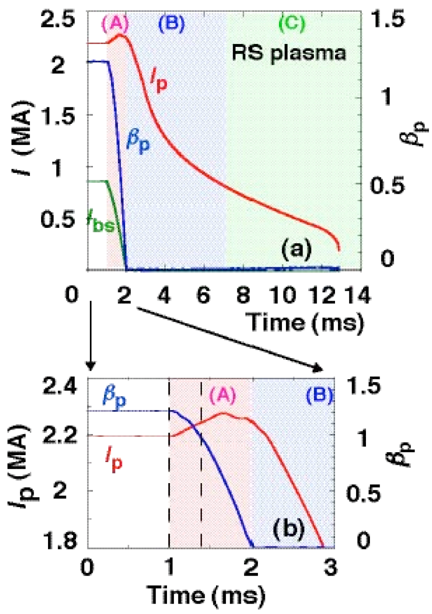

Fig. 6: TSC time-evolutions of RS discharge (E27302). (a): β_p, I_p and BS current I_{bs} during the ITB crash and following disruption phases (A), (B), (C). (b): details of β_p and I_p at t = 0 – 3 ms. Similar ITB crash was modeled by β_p drop (t = 1 - 2 ms) and “magnetic braiding” (t = 1.4 - 2 ms). Notice that the β_p drop leads to a similar positive spike to the PS plasma (E26446), but much smaller.

spike was much smaller than that of PS plasmas as shown in Fig. 6.

(B) Current profile relaxation and current decay (t = 2 - 7 ms)

Figure 8 shows the time-evolutions of the plasma current and BS current profiles. As the electron temperature drops, the current grows in the core region. Thus, the relaxation in the RS plasma leads to a significant change of current profile from hollow to centrally peaked in contrast to the PS plasma. Hence, it follows that a rapid increase in the internal inductance appeared, resulting in a current decay much faster than the other phases. At the phase of current decay and shrinkage of plasma (t > 7 ms), the disruption dynamics of the RS plasma is very similar to the PS plasmas.

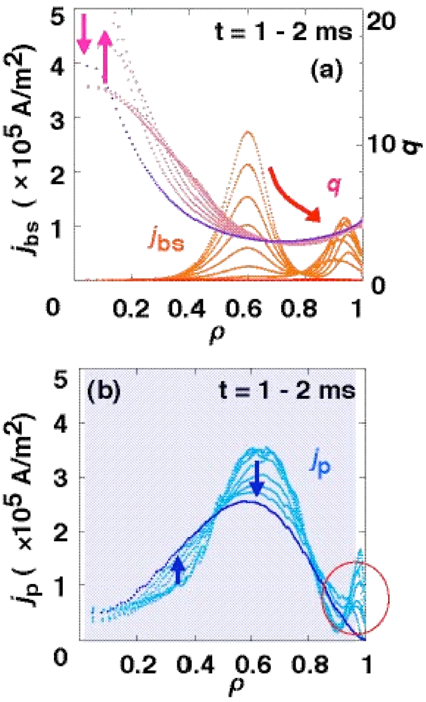

Fig. 7: TSC time-evolutions of BS current, q and plasma current profiles during ITB crash (t = 1 - 2 ms). Although the ITB-generated BS current disappears quickly, the plasma current and q profiles were left almost unchanged besides near plasma boundary. Notice that the current increases near the plasma boundary, arising from eddy current effect of vacuum vessel.

5. Conclusions

A self-consistent TSC study on high BS current plasmas has clarified the detailed evolutions of the induced loop voltage, BS current and ohmic current profiles during the ITB crash and following disruption of high-β plasmas. Newly developed simulation models nicely reproduce experimentally observed JT-60U disruption dynamics both of PS and RS high-β plasmas. During the thermal quench due to the ITB crash, it was first pointed out that the shell effects, which become significant especially at a strong pressure of the high-β plasmas, plays an important role in the current spike, *i.e.,* positive or negative ones in accordance with the relative radial location of the initial plasma and the vacuum vessel. Secondly, it was also clarified that the flattening of current profile due to destruction of magnetic surface leads to a significant increase in plasma current, particularly in PS plasmas. In addition, one of physics reasons, which is enough to explain the fastest record of current quench observed in the JT-60U RS plasmas, was found to be a rapid increase in internal inductance due to the current profile change, which should be much larger than the PS plasmas.

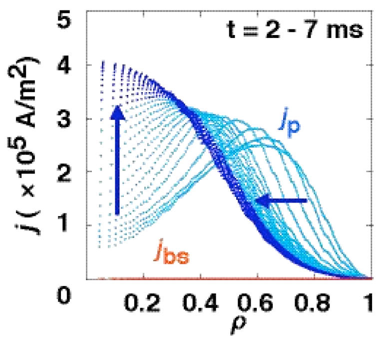

Fig. 8: TSC time-evolutions of plasma current and BS current profiles in the second phase (B) (t = 2 - 7 ms). The relaxation in the RS plasma leads to a significant change of current profile from hollow to centrally peaked in contrast to the PS plasma (cf. Fig. 4), resulting in a current decay much faster.

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