33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.133 (2006)

# A Simulation Study on Stable Current Shutdown in Non-Inductive Reversed Shear Tokamak Discharges

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## 1. Introduction

Reversed Shear (RS) plasma with high BootStrap (BS) current is a promising candidate for steady state tokamak operation in ITER. As for the steady state operation, self-generated BS current sustains a substantial portion of the non-inductive plasma current together with auxiliary current drive sources such as neutral beam (NB) and electron cyclotron wave. Therefore, when the auxiliary current drive sources are removed due to intentional shutdown of the plasma current, internal transport barrier (ITB) may be destroyed, and then, the plasma energy confinement degrades drastically. Recently, intermittent minor collapse was observed after a forced NBCD switch-off in JT-60U non-inductive RS plasmas. Hence, in order to develop stable ramp-down methods in tokamak reactors, we need to understand the non-inductive and inductive current dynamics after removal of the auxiliary current drive sources as well as the BS current effect on the ITB-formation.

We study experimentally and computationally a shutdown scenario of fully non-inductive RS plasma with ITB-generated high BS current. We performed self-consistent transport simulations using Tokamak Simulation Code (TSC) [1], which calculates the evolution of the current, density, and temperature profiles and 2D free-boundary equilibrium consistent with external poloidal field coil currents. TSC has reproduced details on the redistribution process of the BS current and "Return" current profiles associated with loop voltage after a NBCD switch-off, and a direct comparison with the JT-60U experiment was made. We also describe dynamics of intermittent minor collapse of non-inductive RS plasma.

## 2. Simulation Modeling

In the TSC, the transport coefficients are given as a sum of the turbulent term $\chi_{\mathrm{CDBM}}$, which was derived from the self-sustained turbulence theory of the current diffusive ballooning mode (CDBM) [2], and the neoclassical term $\chi_{\mathrm{NC}}$ [3]. The CDBM model predicts the reduction of thermal diffusivity when the magnetic shear is weak or negative and when the plasma pressure gradient becomes large. It has successfully described the ITB formation in high $\beta_{\mathrm{p}}$ and reversed shear plasmas [2]. The particle transport coefficient is taken as 0.1 ($\chi_{\mathrm{CDBM}} + \chi_{\mathrm{NC}}$). To model an edge transport barrier, neoclassical transport alone was assumed in the outer region ($\rho > 0.85$).

In order to model minor collapse, we introduce "transport enhancement" and "hyper-resistivity" [4] into TSC. "Transport enhancement", which means strong enhancement of thermal and particle diffusivities, leads to a reduction of the plasma pressure as well as the ITB. "Hyper-resistivity" 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 $\lambda$ 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 "hyper-resistivity" enables us to reproduce the experimentally observed abrupt change of the current profile during minor collapse.

Consequently, one can model an abrupt pressure drop and a simultaneous change of the plasma current profile, both of which are prime events of the minor collapse. Therefore, we can always ensure profile consistency during the minor collapse of the non-inductive RS plasmas.

## 3. Characteristics of intermittent minor collapse in JT-60U

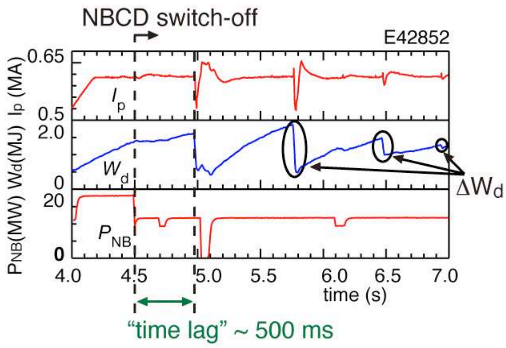


Fig.1: Waveforms of JT-60U non-inductive RS discharge (E42852): (a) plasma current $I_p$, (b) stored energy $W_d$, (c) total NB power $P_{NB}$. Notice that intermittent collapse occurred at 5.0, 5.8, 6.5 and 6.9 s after NBCD switch-off ($t$ = 4.5 s). There was time lag (~ 500 ms) between NBCD switch-off and onset of the first collapse.

Figure 1 shows time traces of the plasma current $I_p$, stored energy $W_d$, and total NB power $P_{NB}$ in the JT-60U non-inductive RS discharge (E42852). Major parameters before NBCD switch-off are the normalized beta $\beta_N$ ~ 1.6, plasma current $I_p$ ~ 0.6 MA and NB power $P_{NB}$~18 MW. Here, the plasma current was kept constant by feedback control. All the co-tangential beams and one of two counter-tangential beams were switched off to ensure no co-NBCD at $t$ = 4.5 s. As shown in Fig. 2, a steep gradient was formed in $n_e$ profile at 4.85 s, indicating existence of the ITB. Notice that the intermittent collapse occurred at 5.0, 5.8, 6.5 and 6.9 s after the NBCD switch-off as shown in Fig. 1. There was a time lag (~ 500 ms) between the NBCD switch-off and the onset of the first collapse. It follows that the loss of NB driven current has some effect on the onset of the first collapse. In addition, the loss of stored energy $\Delta W_d$ was decreasing after every collapse. And then, the profile of safety factor, $q$, was observed to vary from a very reversed to a monotonic during the intermittent collapse.

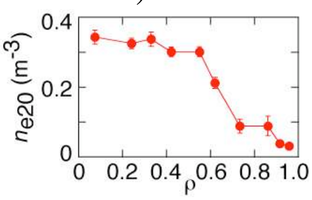


Fig.2: Plasma density profile at 4.85 s in Fig. 1. ITB exists at $\rho$ ~ 0.6.

## 4. TSC simulation

Figure 3 shows TSC time-evolutions of the normalized beta $\beta_N$, plasma current $I_p$, BS current $I_{BS}$ and NB driven current $I_{NBCD}$ after NBCD switch-off and following minor collapse of non-inductive RS plasma (E42852). A fully non-inductive equilibrium was prepared, with total plasma current of 0.6 MA, BS current fraction of 1/2 and NB driven current fraction of 1/2. The plasma current was kept constant by feedback control, as in JT-60U experiment. In order to introduce a NBCD switch-off, a reduction in NB driven current was prescribed from about 0.3 to 0 MA on the slowing-down time (~ 100 ms). The NB power was decreasing from 18 to 12 MW simultaneously as in JT-60U experiment. Here, the peaked off-axis deposition profile of the NB heating is assumed fixed throughout the simulation. And then, the peak position of NB driven current profile is located outside high-$T_e$ ITB region. In addition, the minor collapse was modeled by introducing first "transport enhancement" within 0.5 ms and subsequent "hyper-resistivity" within 0.5 ms at the start of the second phase (B) ($t$ = 0.7 – 1.4 s).

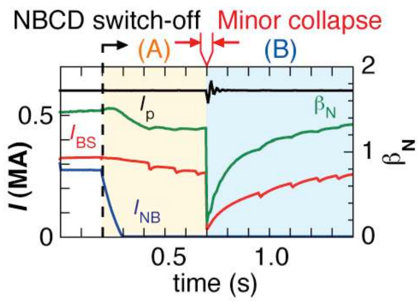


Fig. 3: TSC time-evolutions of normalized beta $\beta_N$, plasma current $I_p$ and BS current $I_{BS}$ after NBCD switch-off and following minor collapse phases (A), (B) in RS discharge (E42852).

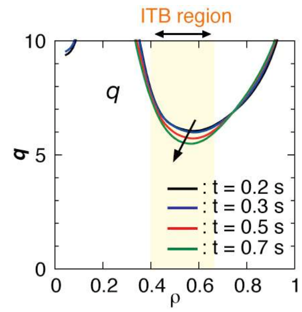


Fig. 4: TSC time-evolution of $q$ profile in the first phase (A) ($t$ = 0.2 – 0.7 s). "Return" current penetration into ITB region leads to further lowering of $q_{\min}$ together with inward drift of $\rho_{q\min}$ on $\tau_{\rm relax}$ (~ 600 ms).

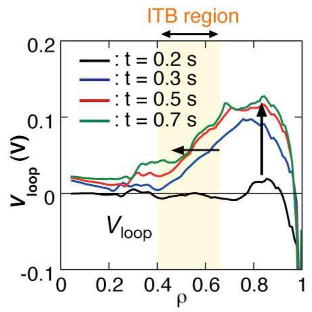


Fig. 5: TSC time-evolution of loop voltage $V_{\rm loop}$ profile in the first phase (A) ($t$ = 0.2 – 0.7 s). Induced loop voltage penetrates into ITB region on $\tau_{\rm relax}$ (~ 600 ms).

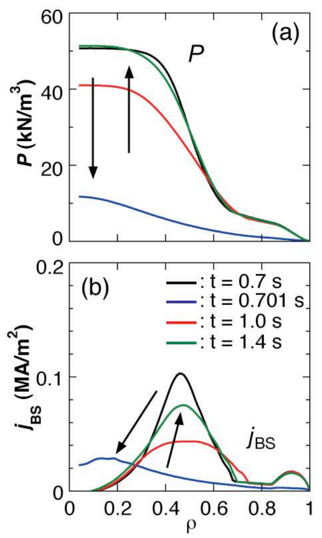


Fig. 6: TSC time-evolutions of (a) plasma pressure $P$ and (b) BS current $j_{\rm BS}$ profiles in the second phase (B) ($t$ = 0.7 – 1.4 s). "Transport enhancement" leads to reduction of BS current as well as plasma pressure within 0.5 ms, as observed in JT-60U experiment. Under continuous NB heating, BS current increases in accordance with recovery of the plasma pressure on $\tau_E$ (~ 100 ms).

The profile dynamics of BS current, "Return" current associated with loop voltage after NBCD switch-off are characterized into two phases as (A), (B) by the following typical events:

(A) Further lowering of $q_{\min}$ after NBCD switch-off ($t$ = 0 – 0.7 s)

Figure 4 shows the time-evolution of $q$ profile. While the NB driven current with the peaked off-axis profile was reduced (~ 100 ms), the $q$ profile was left almost unchanged. To conserve the poloidal magnetic flux, the NB driven current was fully replaced by transiently induced current $j_\Omega$ ("Return" current) associated with loop voltage $V_{\rm loop}$ just after the NBCD switch-off. The induced loop voltage subsequently penetrates into the high-$T_e$ ITB region on relaxation time $\tau_{\rm relax}$ (= $\mu_0\delta^2/\eta$ ~ 600 ms) as shown in Fig. 5. Here, $\eta$ is the Spitzer resistivity, $\delta$ is the width of the steep pressure gradient region (~ 15 cm). Consequently, the "Return" current, which is proportional to $T_e^{3/2}\cdot V_{\rm loop}$, increases notably at the high-$T_e$ ITB region ($\rho$ ~ 0.5) on $\tau_{\rm relax}$.

The "Return" current penetration into the high-$T_e$ ITB region leads to further lowering of $q_{\min}$ together with an inward drift of $\rho_{q\min}$ on $\tau_{\rm relax}$. The relaxation time is consistent with the time lag (~ 500 ms) between the NBCD switch-off and the onset of the first collapse in JT-60U experiment. It follows that the decrease of $q_{\min}$ would lead to onset of the first minor collapse in JT-60U experiment.

(B) Minor collapse after NBCD switch-off ($t$ = 0.7 – 1.4 s)

Figure 6 shows the time-evolutions of the plasma pressure $P$ and BS current $j_{\rm BS}$ profiles. "Transport enhancement" leads to a reduction of the plasma pressure within 0.5 ms ($t$ = 0.7 – 0.7005 s), as observed in JT-60U experiment. The pressure loss causes a drastic reduction of the BS current. Subsequent to the "transport enhancement", "hyper-resistivity" was introduced into area in the vicinity of the minimum $q$ surface ($t$ = 0.7005 – 0.701 s), leading to a consequent relaxation of the current and $q$ profiles as shown in Fig. 7.

Under continuous NB heating, the plasma pressure is recovered on the energy confinement time $\tau_E$ (~ 100 ms), as observed in JT-60U experiment. BS current increases in accordance with recovery of the plasma pressure on $\tau_E$ as shown in Fig. 6. As the BS current increases under continuous NB heating, the plasma current profile becomes deeply hollow on $\tau_E$, leading to the ITB-formation. And then, $q_{\min}$ is decreasing and $\rho_{q\min}$ drifts towards the edge on $\tau_E$ as shown in Fig. 7. Thus, some MHD mode would become unstable. It follows that a change of $q$ profile due to an increase of BS current would lead onset of minor collapse for the second and subsequent times.

Figure 8 shows TSC time-evolutions of the normalized beta $\beta_N$, plasma current $I_p$, BS current $I_{BS}$ and NB driven current $I_{NBCD}$ after NBCD switch-off and following intermittent minor collapse of E42852. $\beta_N$ is almost recovered to that before collapse as observed in JT-60U experiment. RS $q$ profile is varying to a normal shear in accordance with penetration of the induced loop voltage into core region by repeating the intermittent minor collapse.

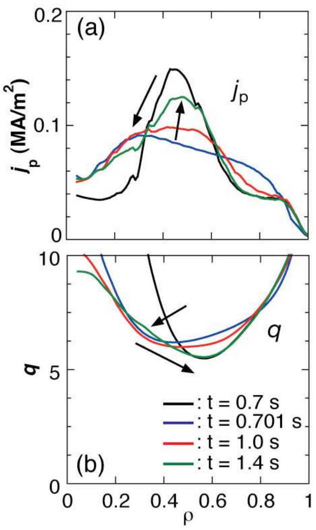


Fig. 7: TSC time-evolutions of (a) plasma current $j_p$ and (b) $q$ profiles in the second phase (B) ($t$ = 0.7 – 1.4 s). "Hyper resistivity" flattens plasma current and $q$ profiles ($t$ = 0.7005 – 0.701 s). As BS current increases under continuous NB heating, plasma current profile becomes deeply hollow on $\tau_E$. And then, $q_{\min}$ is decreasing and $\rho_{q\min}$ drifts towards the edge on $\tau_E$.

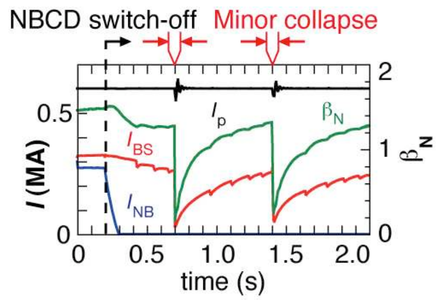


Fig. 8: TSC time-evolutions of normalized beta $\beta_N$, plasma current $I_p$, BS current $I_{BS}$ and NB driven current $I_{NBCD}$ after NBCD switch-off and following intermittent minor collapse of non-inductive RS plasma (E42852). $\beta_N$ is almost recovered to that before collapse as observed in JT-60U experiment.

## 5. Conclusions

A shutdown scenario of fully non-inductive RS plasma with ITB-generated, high BS current has been studied experimentally and computationally. A self-consistent TSC simulation has clarified profile dynamics of BS current and "Return" current associated with loop voltage after NBCD switch-off. Newly developed simulation model nicely describes the experimentally observed intermittent collapse of JT-60U non-inductive RS plasmas. We first found that the penetration of induced "Return" current into high-$T_e$ ITB region causes a lowering of $q_{\min}$, leading to onset of the first minor collapse. Secondly, it is pointed out that the increase of BS current under continuous NB heating would be a leading cause of second and subsequent minor collapses. In addition, we exhibited that $q$ profile changes from very reversed to monotonic during intermittent minor collapse as observed in JT-60U experiment. The new interpretation of induced "Return" current penetration into high-$T_e$ ITB region reasons out a highly self-organized non-inductive plasma behavior with reducing auxiliary current drive sources.

## References

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