J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 196–198

Current Profile Behavior during Ramping-up Phase in High Bootstrap Current Tokamak Plasmas

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(Received: 9 December 2003 / Accepted: 31 March 2004)

Abstract

Slow and quiet current ramp-up, which is necessary scenario to meet the requirements of advanced superconducting (SC) tokamak reactor like ITER, was investigated via axisymmetric magnetohydrodynamic (MHD) simulations. Despite the intention controlling a monotonic transition from positive shear (PS) to weak negative shear (WNS) of steady state target plasmas, cooperative link between non-inductive driven and ITB-generated bootstrap (BS) currents exhibited a self-organized recurrent appearance of PS and NS profiles. Underlying physics and operation conditions of the newly found recurrent plasma disturbance were described in detail as well as the current profile behaviors. Impact of the induced voltage and current on SC coils during the oscillating ramp-up and favorable scenario to avoid and control a current hole formation are also discussed from both reactor engineering and plasma control aspects.

Keywords:

axisymmetric MHD simulation, ramp-up scenario, bootstrap current, ITB, magnetic shear, tokamak plasma, self-organized recurrence

1. Introduction

Current profile control is one of the key issue in high performance, long pulse tokamak operations, where negative shear (NS) plasmas tend to substantially evolve according to the penetration of inductive currents into a core region and to the distribution of non-inductive bootstrap (BS) currents and off-axis LHCD [1,2]. A stable starting-up particularly requires careful discharge controls to obtain steady state target plasmas with weak negative shear (WNS) under certain restrictions imposed by MHD and control aspects. For example, superconducting (SC) tokamak reactor normally dislikes both running in rapid operation and suffering plasma disturbance, any such MHD activities as edge localized modes (ELMs). Hence it follows that the optimization of current ramping-up scenarios is required to attain advanced and high performance tokamak operations.

The profile effect of the internal transport barrier (ITB)-generated BS currents on the ramping-up dynamics was studied using Tokamak Simulation Code (TSC) [3]. This paper reports the simulation results on the optimization of current ramp scenarios, that is, how to establish the stable starting-up and sustaining scenarios in the WNS long pulse operation, how to find the stable path to a low q regime without collapses at a low ramping-up rate and how to avoid and control current hole (CH) formation.

2. TSC modeling

To investigate details of the current profile behavior during ramping-up phase, we newly installed a simple ITB model into the TSC [4]. The ITB strength and width were prescribed providing a functional form of the plasma pressure profile, sharing the total pressure between the ITB and the edge transport barrier (ETB) [5]. Radial location of the ITB foot, however, was continually adapted in accordance with the movement of the radius of a magnetic shear reversal that was monitored throughout TSC simulations. Therefore, if the magnetic shear reversal lies on the magnetic axis, i.e. the PS plasma, then the ETB bears the whole plasma pressure. On the contrary, if the magnetic shear reversal lies on the plasma edge, i.e. the fictitious NS plasma, then the ITB bears the whole plasma pressure. The model of the ITB-generated BS current was given by the expression for arbitrary values of the aspect ratio and effective charge [6].

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As a reference scenario in our study, ITER-FEAT operation scenario #4 was used, i.e., 9 MA steady state scenario with the WNS profile of fusion power > 300 MW, $Q > 5$ and the ramping-up time of ~ 24 s for 0.4–7.0 MA [7]. As for this scenario, a lot of self-consistent ASTRA [8], DINA [9] simulations have been done using feedback and feedforward controls of plasma current and shape under poloidal field power supply restrictions. Particular features are a low current ramp rate of ~ 0.3 MA/s for reducing AC loss of SC coils, and a low Te target plasma till "start of heating (SOH)" for reducing heat load to outside limiter [7].

In addition to the ITER scenario #4, a non-inductive current drive of ~ 20% of the plasma current was adopted in order to attain the WNS profile. A substantial plasma pressure which generates the BS current of ~ 20% of the plasma current was also introduced. Thus, the fraction of ohmic current was assumed to be low around 60%.

3. Current profile behaviors during ramp-up

3.1 Recurrent appearance of NS region during PS to WNS transition

Figure 1 shows time-evolutions of radial location of magnetic shear reversal ρ_{s0}, plasma current I_p of 0.4–7 MA, non-inductive driven current I_{LH} and BS current I_{bs} (both ~ 20% of the plasma current) during a hybrid ramp-up of t = 0.0–22 s. Although the ramp-up control from the PS to WNS profiles is monotonic, a recurrent transition of NS regions appears, being not monotonic but intermittent. The non-inductive current gives rise to the NS region around the deposition area (ρ ~ 0.6). The ITB once formed, however, disappears soon after 1–2 s. Appearing and disappearing of NS regions, once the WNS profile is accomplished, the recurrent appearance of the NS profile has never come back any more (later than ~ 11 s).

Figure 2 shows behaviors of the current profiles of I_p, I_{LH}, I_{bs} and the q-profile during the time period of t = 0.0–5.5 s, that is, the first one of the recurrences. One can see a cooperative link between non-inductive driven and BS currents, which gives rise to one cycle of forward and backward transitions between the PS and NS profiles. The mechanism can be described as following sequence: (a) External driving of substantial non-inductive current (> 20% of plasma current), (b) Formation of the NS profile, (c) ITB formation near the NS region, (d) Growth of the ITB-generated BS current (~ 20% of plasma current), (e) Profile-mismatch of the BS and non-inductive driven currents, (f) Inward drift of the NS region, (g) Disappearance of the NS region, (h) Disappearance of the ITB and the relevant BS current, and finally (x) Recurrence to the PS profile.

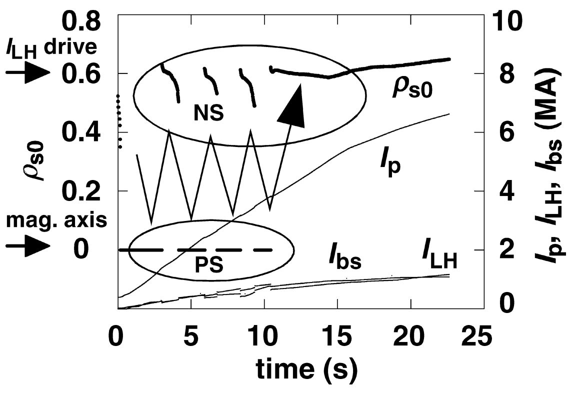

Fig. 1 Time-evolutions of magnetic shear reversal ρ_{s0}, plasma current I_p, non-inductive driven current I_{LH} at ρ ~ 0.6 and BS current I_{bs} during ramp-up. Although the ramp-up control from the PS to WNS profiles is monotonic, a recurrent transition of NS regions appears.

3.2 Evolution of magnetic shear profile during PS to WNS transition

Figure 3 shows two examples of the recurrent evolutions of magnetic shear profiles during the PS to WNS transition, i.e., the first one of Fig. 2 and the final one after the WNS accomplishment of t > 10 s. As shown in Fig. 3(A), the non-inductive driven current deforms local shape of the magnetic shear to the NS around ρ ~ 0.6. Subsequently, the ITB was

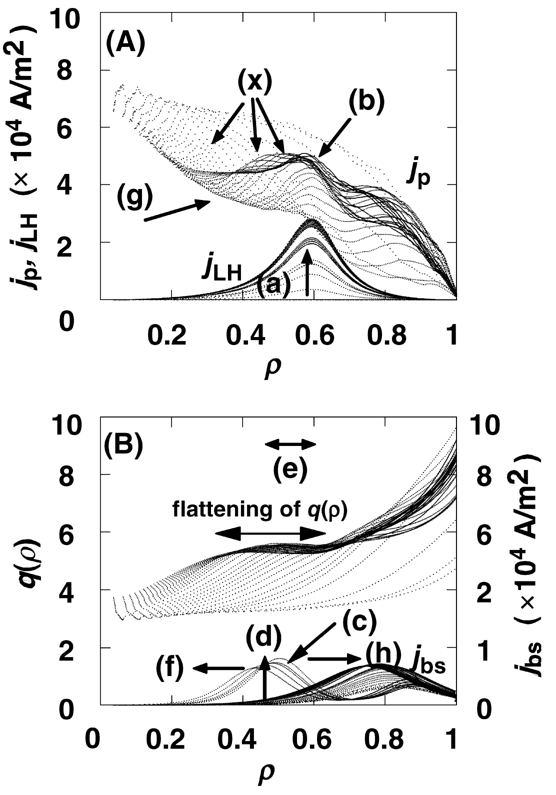

Fig. 2 Current profile behaviors of the first one of the recurrences of Fig. 1. (A) : j_p, j_{LH}; (B) j_{bs}, safety factor q during t = 0.0–5.5 s. Sequential mechanism of cooperative link between non-inductive driven and BS currents can be described as: (a) External driving of substantial non-inductive current, (b) Formation of the NS profile, (c) ITB formation near the NS region, (d) Growth of the ITB-generated BS current, (e) Profile-mismatch of the BS and non-inductive driven currents, (f) Inward drift of the NS region, (g) Disappearance of the NS region, (h) Disappearance of the ITB and the relevant BS current, (x) Recurrence to the PS profile.

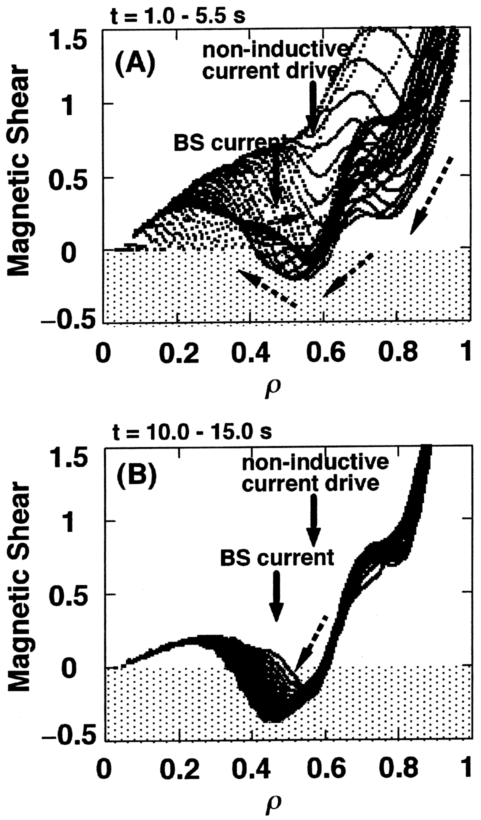

Fig. 3 Evolutions of magnetic shear profiles. (A) t = 1.0–5.5 s. (B) t = 10.0–15.0 s. Non-inductive current driven around $\rho \sim 0.6$, while BS current distributed around $\rho < 0.6$ just inside the ITB.

formed to generate the BS current distributed around $\rho < 0.6$ just inside the ITB. Therefore, the BS current, whose distribution is mismatched with the non-inductive current, drags the NS region inwards, and eventually erases it, i.e., loss of the ITB. Thus, after retuning to the PS profile, the NS region appears again, and then backward going to the PS. While approaching the WNS profile in such the way, the extent of the PS inside the ITB region tends to decrease. Consequently, after the latest formation of the NS, the PS profile never come back anymore, that is, accomplishment of the WNS profile, as is shown in Fig. 3(B).

3.3 Discussions

3.3.1 On an impact of Recurrent NS Appearance upon SC coils

The newly found recurrent plasma disturbances between the PS and NS profiles may cause an additional AC loss of SC coils of reactors in accordance with the feedback control of the oscillating plasma position. At the every moment of the PS and NS transitions, the induced surface voltage was evaluated to be ~ 10 V via TSC, while the normal loop voltage of the quiet ramping-up is < 2 V. Particularly, the radial control was shown to cause jumps of the feedback current of ~ 50 kA. Hence, it follows that from a viewpoint of the reactor engineering we have to give careful consideration to the additional impact of the induced voltage and current on SC coils during the oscillating ramp-up.

3.3.2 On a possibility of CH Formation

A strong heating after SOH (~ 22.6 s) is to be imposed on the WNS plasmas in the ITER scenario #4. Therefore, possibility of the CH formation is one of our chief concerns relevant to the aspect of the plasma control. In order to see whether a CH can be formed and how easily, the TSC simulations were carried out. By changing radial locations of the ITBs, a strong heating was imposed on the WNS plasmas. It was shown that it seems difficult to form a large CH of $\rho > 0.6$, even when a very high BS current fraction of ~ 70%. As the ITB region becomes smaller ($\rho_{s0} < 0.6$), the CH becomes easy to appear. Hence, a favorable scenario to avoid and control the CH formation can be proposed as follows: When a sign of the CH formation is detected, 1) Quit heating, 2) Expand the ITB region by controlling the deposition position of the external non-inductive current drive.

4. Summary

A slow and quiet current ramp-up scenario was investigated via TSC simulation for advanced SC tokamak operational purpose. It was first shown that despite the intention controlling a monotonic transition from the PS to WNS profiles, a cooperative link between the non-inductive driven current and BS currents exhibited a self-organized recurrence of the PS and NS profiles. The recurrence process can be repeated as a sort of limit cycle, however this is not always the case for a lower external non-inductive current drive. Once the WNS profile is accomplished, the repeating process does not appear any more.

An impact of the induced voltage and current on SC coils was discussed from a viewpoint of the plasma disturbance control. Furthermore, possibility of the CH formation, which might arise at a strong heating after SOH, was briefly examined. Following issues are listed for future study, i.e., model improvement of the ITB-relevant transport instead the prescribed pressure, external control to expand the ITB region for control of the CH formation, and a similar cooperative link between the heating profile and the ITB formation in burning plasmas.

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