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Bootstrap Current Effects on Stable Non-Inductive Current Buildup in Low Aspect Ratio Tokamaks

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1. Introduction

The fundamental geometry of a low aspect ratio tokamak precludes the presence of a large center solenoid normally equipped for inductive current buildup. Therefore, non-inductive techniques [1] to establish, maintain, control and modify the current distribution have been expected for promising low aspect ratio reactor concepts [2]. One important consequence clarified by way of theoretical and experimental studies might be that the natural timescale for the non-inductive current buildup with MHD stability could be even longer than one for the totally inductive buildup [3, 4].

This paper presents first a TSC (Tokamak Simulation Code [5]) simulation of profile behaviors during hybrid ramp-up using off-axis non-inductive drive, and next a newly found non-linear link between ITB-generated BS current and BS current-modulated magnetic shear, which plays a substantial role in reduction of the current buildup time to attain negative shear (NS) target plasmas, avoiding formation of current hole.

2. TSC modeling

To investigate details of the current profile behavior during ramping-up, we newly installed a simple ITB model into the TSC [5]. The ITB strength and width were prescribed providing a functional form of the plasma pressure profile, sharing the whole pressure between the ITB and the edge transport barrier (ETB) [6]. Radial location of the ITB foot, however, was continually adapted in accordance with the movement of the radius of magnetic shear reversal that was monitored throughout TSC simulations [7]. 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

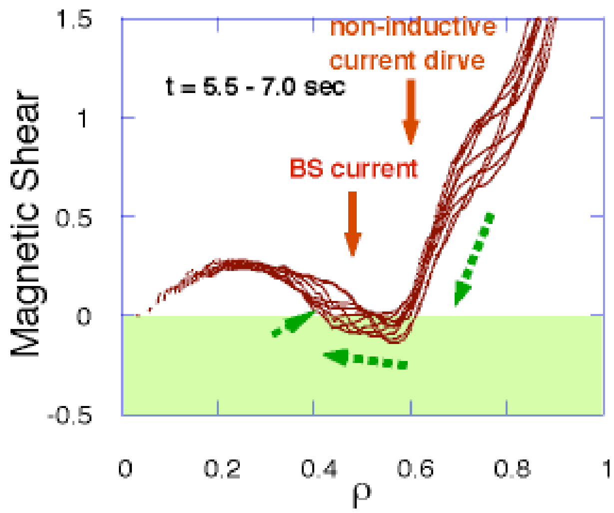

Fig. 1 Evolutions of magnetic shear profiles. Non-inductive current driven around $\rho \sim 0.6$, while BS current distributed around $\rho < 0.6$ just inside the ITB. Cooperative link between non-inductive driven and BS currents first forms ITB near the NS region, next ITB-generated BS current drifts the NS region Inward, and eventually the ITB and relevant BS current disappers.

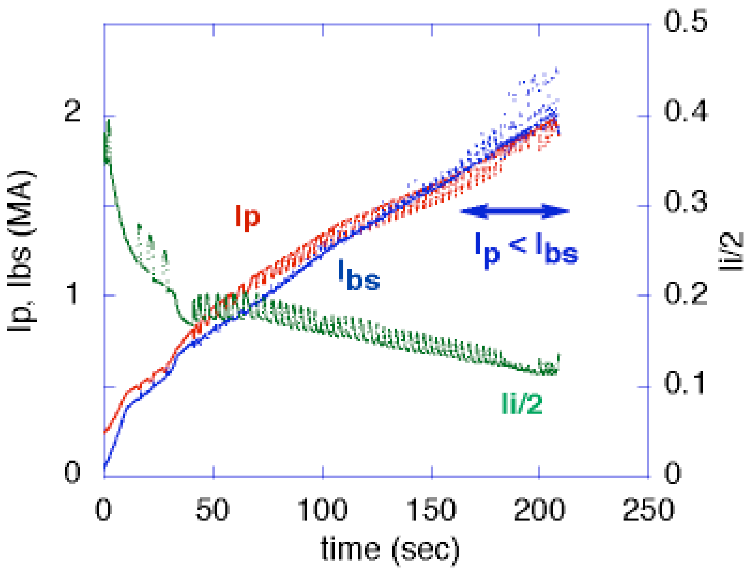

Fig. 2 Slow current buildup of high BS current, high β_p plasma on VECTOR tokamak without center solenoid. Notice oscillatory behaviors of I_p, I_{bs} as well as internal inductance l_i.

plasma pressure. ITB-generated BS current in low collision frequency regime was estimated by the expression for arbitrary values of the aspect ratio and effective charge [8].

3. Current profile behaviors during hybrid ramp-up

As a reference scenario in our study, ITER-FEAT operation scenario #4 was used, *i.e.*, 9 MA steady state scenario with NS profile and a very slow ramping-up time of ~ 24 sec for 0.4 - 7.0 MA [9]. In addition to a substantial plasma pressure which generates the BS current of ~ 20 % of the plasma current, a non-inductive current drive of I_{LH} ~ 20 % of the plasma current was adopted at ρ ~ 0.6. Although a ramp-up control from the positive shear (PS) to NS profiles is monotonic, a recurrent transition of NS regions appears [10].

Figure 1 shows the recurrent evolution of magnetic shear profile during the PS to NS transition. The non-inductive driven current deforms local shape of the magnetic shear to the NS around ρ ~ 0.6. Subsequently, the ITB was formed to generate the BS current distributed around ρ < 0.6 just inside the ITB. Therefore, the BS

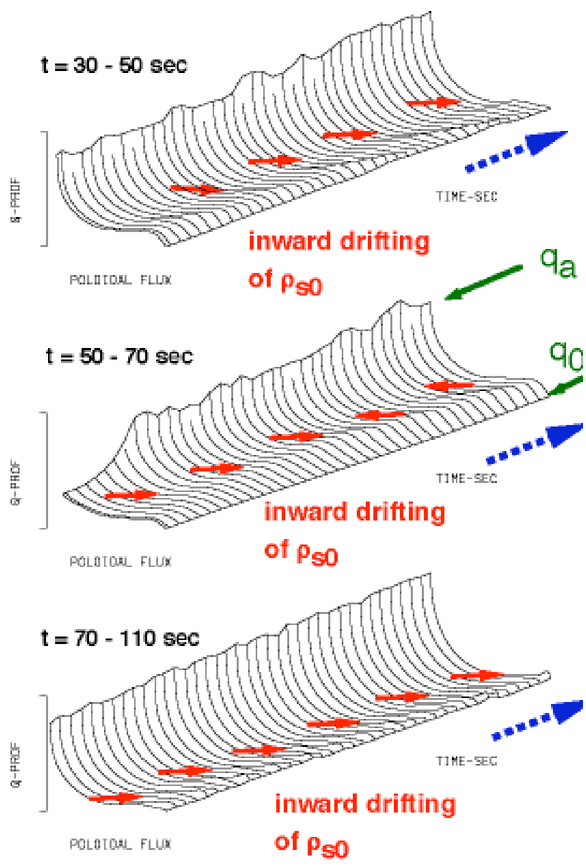

Fig. 3 Time-evolution of q-profile. time-evolutions of q-profile. Magnetic shear reversal appears first around a dent of q-profile, and then drifts inward to magnetic axis.

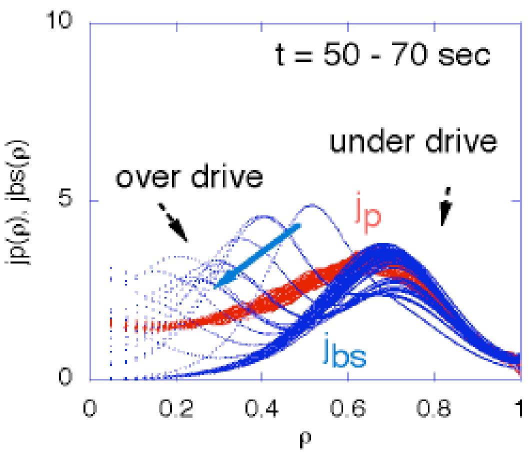

Fig. 4 Inward drifts of ITB-generated BS current. Over current-driven region lies around the drifting ITB region, while under drive region lies in other region. Inward drift lifts up the current profile around core region, otherwise being kept much lower.

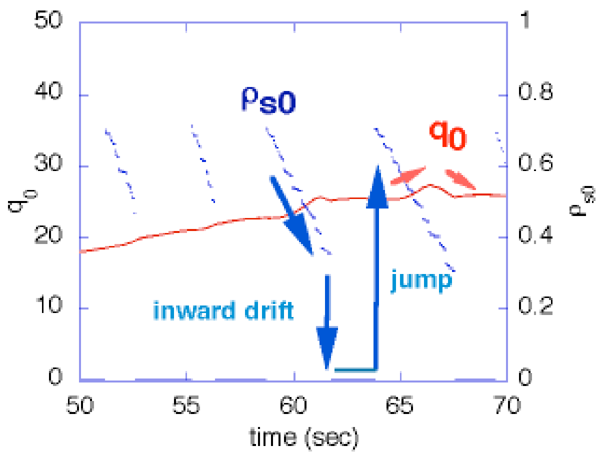

Fig. 5 Inward drift of magnetic shear reversal ρ_{s0}, sudden jump to magnetic axis and re-appearance of magnetic shear reversal around $\rho \sim 0.7$. Cycle period time is ~ 5 sec (<< 1000 sec).

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.

4. Full BS current ramp-up in CS-less low aspect ratio tokamak "VECTOR"

"VECTOR" is a low aspect ratio JAERI tokamak without Center Solenoid [2]. It offers new challenge of very slow current build-up (~ 0.01 MA/sec!) of full non-inductive current drive scenarios, cf. ~ 0.3 MA/sec in ITER scenario #4. Almost non-inductive current ramp-up till 2 MA out of full current of 14 MA was followed up to 210 sec by the TSC simulation, which holds a self-consistency of ITB-generated, high BS current with magnetic shear profile. To realize high BS fraction (> 95%), a high β_p (~ 3.5) was assumed throughout the TSC simulation.

As illustrated in **Fig. 2**, both of plasma and BS currents show oscillatory behaviors, which is synchronizing with changes of the current profile. **Figure 3** shows time-evolutions of q-profile. One can see such repeating process that the magnetic shear reversal appears first around a dent of q-profile, and then drifts inward to magnetic axis. Thus, appearance and disappearance of ITBs repeats throughout the slow ramp-up of fully BS current-driven plasmas. **Figure 4** shows inward drifts of ITB-generated BS current. Strong locality of high BS current makes the plasma current over current-driven around the drifting ITB region, while making an under drive state in other region. Such profile structure strongly modulates the magnetic shear profile, causing the inward drift of the ITB. As shown in

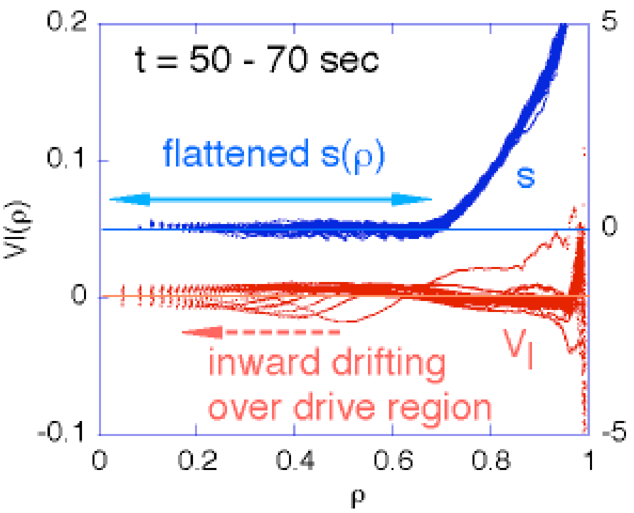

Fig. 6 Flattened shear profile over wide region of $0 < \rho < 0.6$ and inward drifting negative loop voltage, arising from cooperative link between BS current and BS current-modulated shear profile. Shear profile is widely supressed to nearly "ZERO", avoiding Current Hole formation.

Fig. 5, the magnetic shear reversal ρ_{s0} drifts inwards, and then suddenly jumps to magnetic axis. After staying there for a while, ρ_{s0} appears again around $\rho \sim 0.7$. In Fig. 5, these cycles reccurrently appears 4 times / 20 sec, *i.e.* the period time is ~ 5 sec (<< 1000 sec). As a consequence, the inward drift of ITB-generated BS current lifts up the current around core region, otherwise being kept much lower. Hence, it follows that the cooperative link between the BS current and BS current-modulated shear profile makes the magnetic shear more flat over wide region of $0 < \rho < 0.6$. **Figure 6** shows the shear profile is widely supressed to nearly "ZERO", avoiding Current Hole formation.

5. Summary

A slow and quiet current ramp-up, which is necessary scenario to meet the requirements of advanced superconducting, CS-less tokamak "VECTOR", was investigated via TSC simulation. It was first shown that despite the intention controlling a monotonic transition from the PS to NS profiles, a cooperative link between the non-inductive driven current and ITB-generated BS currents exhibited a recurrence of the PS and NS profiles. In addition, cooperative link between BS current and BS current-modulated magnetic shear was demonstrated to exhibit an oscillatory current ramp in BS current-fully driven high β plasmas. Underlying physics and operation conditions of the newly found recurrence were discussed in detail as well as the current profile behaviors. Profile mismatch between the BS current and the magnetic shear was clarified to give rise to these oscillatory behaviors. Favorable scenario to avoid and control a current hole formation are also discussed from both reactor engineering and plasma control aspects.

Following issues are listed for future study, *i.e.*, (a) ITB model improvement using transport instead of the prescribed pressure model, (b) Model validation via comparative study with JT-60U CS-less ramp-up experiment, (c) external control scenario to expand the ITB region for controlling the CH formation, and (d) a similar cooperative link between the heating profile and the ITB formation in burning plasma state.

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