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Simulation Modeling of Fully Non-Inductive Buildup Scenario in High Bootstrap Current Tokamaks without Center Solenoids

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1. Introduction

Challenging non-inductive techniques to establish, maintain, control and modify the plasma current distribution have been required for promising consept of a low aspect ratio, compact tokamak operation without center solenoids (CS) [1]. For example, realistic current buildup scenarios stand in need of the effective use of high bootstrap (BS) current generated by strong internal transport barrier (ITB) [2]. Therefore, the stable ITB control technique is important in order to save current-driving power externally applied. A reliable external control of the ITB profile might be also the key technique to high sustainability of steady state fusion-burn in advanced tokamak.

This paper describes a consistent numerical simulation using Tokamak Simulation Code (TSC) [3] implemented with an anomalous transport model, *i.e.* CDBM [4]. The fully non-inductive current buildup from 0.5 to 10 MA in 1000 seconds in a CS-less reactor was studied, taking the transport improvement and the consequent ITB formation into consideration. In the case of high power NB-heating, a self-organized, spatio-temporal oscillation of the plasma pressure and current was predicted to occur. A new operation was examined using a downsized, compact "Slim CS", which was additionally installed in the CS-less tokamak to recover the external controllability of the ITB profile.

2. Simulation modeling

Primary issues of the non-inductive buildup technique are: (a) feasibility of such slow buildup as $\tau \sim 100$ sec, cf. ~ 1 sec by inductive CD at present, (b) stable ITB-formation with external CD control, (c) feasibility of high BS fraction to save driving power, *e.g.* $f_{bs} > 50$ %.

From a practical standpoint of non-inductive techniques, we set the operational requirements as NB-heating and CD power limit of P_{NB} and $P_{CD} < 100$ MW. The external CD limit was assumed to $I_{CD} = \eta_{CD} P_{CD}/n_e R < 4$ MA, providing that the current drive efficiency $\eta_{CD} \sim 0.2$. From confinement and MHD physics points of view, we set the requirements as Greenwald density limit of $n < n_{GW}$, energy confinement of HH = $\tau_E/\tau_{E,y2} < 1.3$ and equilibrium limit of $\beta_p < 1.5$. During the buildup, the normarized beta is normally small as β_N ~1. Axisymmetric MHD fluid dynamics was obtained by solving the momentum equation with Faraday's law and Ohm's law. The transport coefficients are given by as a sum of the turbulent term χ_{CDBM} based on the self-sustained turbulence theory [4] and the neoclassical term χ_{NC}. The CDBM is the L-mode based, turbulent transport model, involving the effect of the improved core confinement in accordance with the local magnetic shear. In weak or negative magnetic shear region, the anomalous transport is significantly reduced to enhance the local pressure gradient, resulting in the ITB-formation. The theoretically derived expression of the transport coefficient is a function of the magnetic shear, the normalized pressure gradient and the magnetic curvature [4]. To model an ETB structure near the plasma edge, the neoclassical transport was assumed in a prescribed region (ρ > 0.95). An off-axis deposition profiles of the NB-heating and the external CD are also given as fixed ones for the sake of simplicity.

Two scenarios of very slow, fully non-inductive buildup which attains the target plasma current of 10 MA from 0.5 MA with the buildup time of 1000 sec were studied: (1) enhanced NB-heating of 100 MW with lower CD of 2 MA and (2) lower NB-heating of 75 MW with enhanced CD of 3.5 MA. The plasma density was controled by feedback.

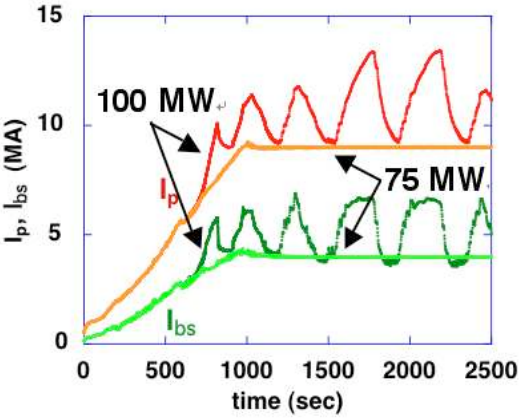

Fig. 1 Stable non-inductive current buildup lasting till ~ 700 sec and a large amplitude oscillation in high power NB-heating of 100 MW, while any oscillation did not appear in lower NB-heating of 75 MW.

3. Self-sustained, spatio-temporal oscillation

Figure 1 shows the stable non-inductive buildup lasting till ~ 700 sec. The limiter plasma takes off to a diverter configuration at *t* ~ 200 sec. The transition from PS to NS profiles occurs at 260 sec. In the case of the high power NB-heating of 100 MW, a large amplitude oscillation appeared from ~ 700 sec, while any oscillation did not appear in the case of the lower NB-heating of 75 MW. The oscillation period is quite long, ~ 400 sec, a few times of the electric field diffusion time.

As shown in Fig. 2, the high BS current modifies the magnetic shear, causing an inward drift of the shear reversal ρ_{s0}, resuling in a reduction of the BS current fraction. The safety factor $q(\rho)$, that is, equivalently the magnetic shear, widely oscillates between strongly NS (negative shear) and nearly PS (positive shear) profiles. This self-sustained, spatio-temporal oscillation indicates an interplay of the ITB- and ETB-formations, as displayed in Fig. 3. As the ETB temperature rises along with the expansion of the ETB region, the ITB drifts outwards and the ITB steepens. Subsequent to the formation of the strong NS profile, the ETB temperature has turned to decrease. Consequently, the ITB drifts inwards and becomes flattened afterward.

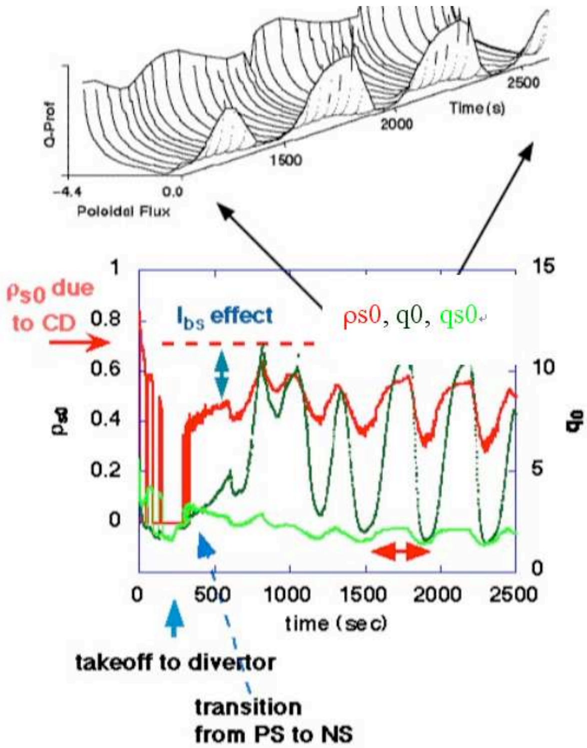

Fig. 2 Self-sustained, spatio-temporal oscillation, indicating interplay of the ITB- and ETB-formations. Safety factor $q(\rho)$ widely oscillates between strongly NS and nearly PS profiles.

Figure 4 indicates two different phases of the CD dynamics. During the transition phase from the nearly PS to the strong NS, the total amount of the non-inductive CD exceeds the

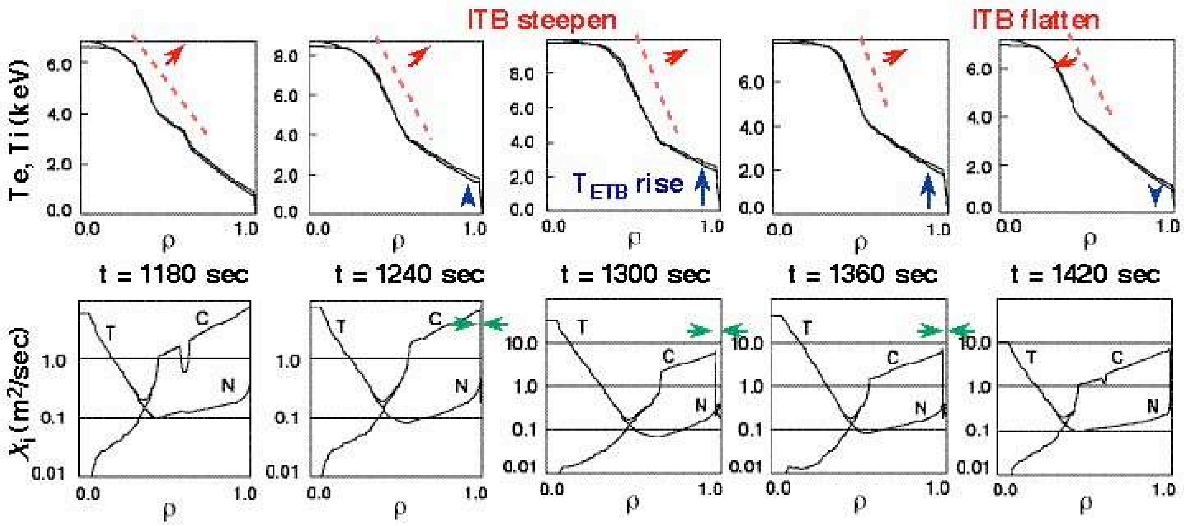

Fig. 3 T_e, T_i profiles and profile of ion thermal conductivity χ_i during one-cycle of large amplitude oscillation of Fig. 3. The symbols of χ, *i.e.* N, C and T, denote Neoclassical, CDBM and Total, respectively.

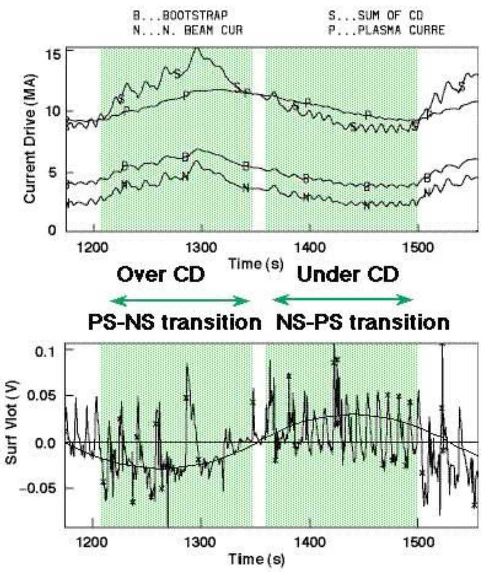

Fig. 4 Time-evolution of plasma and non-inductive currents and surface voltage during one-cycle of large amplitude oscillation of Fig. 2.

plasma current, *i.e.* an over CD state. In the subsequent transition phase from the strong NS to the nearly PS, the total amount of the non-inductive CD falls below the plasma current, *i.e.* an under CD state. The surface voltage V_{loop} was clarified to negative in the PS-NS transition phase, while positive in the NS-PS transition phase. It follows that the high power NB-heating causes the H-mode-like, strong ETB-formation accompanied by the high BS current. It follows that the enhancement of the BS current is the key to trigger the self-sustained, large oscillation.

The mechanism of the spatio-temporal oscillation at the high NB-heating is schematically shown in Fig. 5. First, the high NB-heating increase the heat-flux to the plasma edge, leading to the formation of the H-mode-like, strong ETB along with the increasing BS current. Therefore, the reverse "Return Current" is induced in the plasma edge, and then the associated negative electric field propagates into the core region. The induced negative current drags the ITB outward to steepen the ITB, resulting into a confinement improvement. Consequently, the heat-flux to the edge decreases, leading to loss of the H-mode-like ETB. Now, the process sequence follows the reverse of the generation

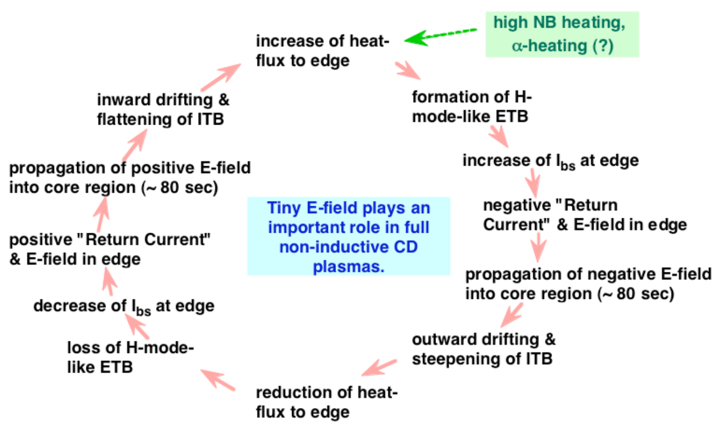

Fig. 5 Mechanism of spatio-temporal oscillation at high NB-heating

of the negative electric field.

4. External ITB control via "Slim CS"

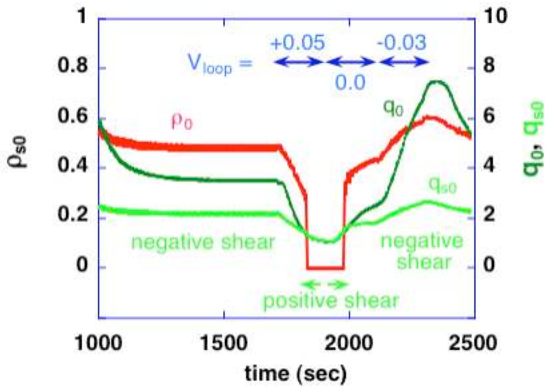

Fig. 6 External ITB control via "Slim CS"

By supplying the tiny electric field for a longer time than the electric field diffusion time, the *q*-profile was shown to undergo a drastic change. Here, we propose a new practical scenario of the external ITB control via "Slim CS". Figure 6 shows the simulation of the *q*-profile. During the period of 1700-1900 sec, a small positive, toroidal electric field of +0.05 volt was applied to drag the ITB inwards. After the electric field diffusion time (~ 80 sec), the magnetic shear reversal ρ_{s0} arrives at the magnetic axis ρ = 0, *i.e.* the totally PS profile. The ITB was completely disappeared by the external control. Then, the positive electric field was removed during the period of 1900-2100 sec. After a time lag of ~ 80 sec, the *q*-profile almost returns to the previous one, *i.e.* the transition from the PS to NS profiles. During the subsequent period of 2100-2300 sec, a small negative electric field of –0.03 volt was applied to drag the ITB outwards. Consequently, the magnetic shear reversal ρ_{s0} moved much closer to $\rho \sim 0.7$.

5. Summary

Using the TSC with L-mode based, improved core confinement model, *i.e.* CDBM [4], consistent simulations of fully non-inductive buildup were carried out from the practical control aspects of the compact, CS-less tokamak. The integrated scenario was shown to meet the control and physics requirements set by plasma shaping, available NB-heating power, reasonable HH factor and allowable Greenwald density limit.

In a high power NB-heating, a self-organized, spatio-temporal oscillation of the plasma pressure and current was predicted to occur, while no oscillation at lower power NB-heating. The oscillation mechanism was clarified that in the full non-inductive CD plasmas, tiny, toroidal electric field plays the key role in the ITB-formation. Furthermore, a new challenging technique of the external ITB-control via tiny, toroidal electric field was proposed for non-inductive driven, advanced operation.

The strong ITB-structure may affect the NB and CD deposition profiles, which are assumed fixed in the present study. The further modeling of the interplay between the ITB-structure and the deposition profile is left for future study. Property of the spatio-temporal oscillation should should depend on the ELM activity that limits the pedestal pressure, and this is left for future study.

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