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A Simulation Modelling of Inductive/Non-inductive Current Ramp-up at Slow Rate for Low l_i, High Vertical Stability

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1. Introduction

In tokamak fusion reactors with superconducting PF coil system, ramping-up of the plasma current for startup of discharges is essentially restrained at a rate much slower than the current tokamak with normal PF conductors. Therefore, the induced plasma current can penetrate deeply into the core region with higher electron temperature, *i.e.* low Ohmic resistivity, leading to a centrally peaked current profile. Consequently, such the high l_i, highly elongated configuration imperative to divertor formation has a dangerous property of causing vertical instability. Meanwhile, the centrally peaked current profile lower q_0 on magnetic axis, leading to sawtooth activity that could reduce the current ramp-efficiency. Additional heating at early phase of the ramp-up has been addressed as one of startup procedures that retard the penetration of plasma current. A potential drawback, however, is the substantial increase of direct heat load to limiter.

The paper presents a comprehensive simulation modelling of the stable plasma current ramp-up at a slow rate, based on the ITER 15 MA inductive Scenario 2 [1,]. Using TSC [2], a self-consistent simulation, including a model for improved core energy confinement, non-inductive current sources, has been performed in consideration of sawtooth-free condition, $q_{\min} \geq 2$ to avoid internal MHD activity in reversed shear plasmas and flux consumption that could seriously compromise the available duration of the burn phase. Phasing of the earliest possible formation of a diverted plasma, formation of internal transport barrier (ITB), transition from L to H-mode, timing of the heating and non-inductive current driving using off-axis EC current drive (CD) source are discussed.

2. Simulation modelling

Using TSC, operation scenarios which attain the target plasma current of 15 MA from 0.4 MA with buildup time of 100 sec, *e.g.* ITER 15MA inductive scenario 2, were examined. Our prime interest is attached to see how the external control means: *(a) self-generated bootstrap (BS) current after L to H-mode transition; (b) additional heating to retard current penetration; (c) off-axis ECCD* meet the operation and physics requirements for slow 15 MA ramp-up: $q_0 > 1$ for sawtooth stability, engineering limit of $I_{PF6} < 17.5$ MA, lower l_i-operation for vertical stability ($l_i << 1.2$), high ramp-efficiency for saving OH flux ($C_{Ejima} \sim 0.4$), Plasma shaping control ($\kappa_{95} < 1.8$), and early X-point formation for reducing heat load to limiter structure.

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 [3] 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 an ITB-formation. To model an edge transport barrier (ETB) of H-mode, the neoclassical transport was assumed in a prescribed edge-region ($\rho > 0.9$). An off-axis deposition profiles of the NB-heating and the external CD using 170 GHz EC source are also given as fixed ones for the sake of simplicity. BS current was provided by the model of Hirshman and Sigmar. The plasma density was controled by feedback.

3. TSC simulation of inductive/non-inductive current ramp-up

3.1. (a) Plain inductive ramp and L to H-mode transition by high power NB heating

Figure 1 shows the current ramp-up, starting from an outboard-limited plasma of I_p = 0.4 MA, positioned on midplane: Z_p = 0 m. An early X-point was formed at I_p ~ 4.5 MA, t ~ 22 s. Subsequently, the plasma with bottom divertor was vertically moved back to Z_p ~ 0.5 m of the nominal equilibrium position. As long as the plain inductive ramp lasts, the internal inductance l_i continued to increase till t ~ 78 s. When l_i reached unity, high power NB heating of P_{NB} ~ 27 MW started in order to intentionally cause an L to H-mode transition. Ohmic power was P_{OH} ~ 10 MW, and hence, total power for plasma heating was ~ 37 MW. Here, the threshold power needed for the L/H transition was estimated at $P_{L/H}$ ~ 30 MW, using the transiton threshold of $P_{L/H} = 2.84\ M^{-1}\ B_T^{0.82}\ n_e^{0.58}\ R^{1.00}\ a^{0.81}$. As denoted by the oval sign in Fig. 1, a remarkable change of l_i, *i.e.* δl_i ~ -0.3, was observed after the L/H transition. In the case without the L/H transition, l_i still further continued to increase up to ~ 1.2 at t ~ 100 s. Figure 2 shows time-evolutions of toroidal current density j_ϕ and toroidal loop voltage V_{loop}. A strong edge structure of H-mode appears in the j_ϕ profile after the L/H transition, generating a large BS current around the pedestal ($\rho > 0.9$). According to the remarkable l_i-change shown

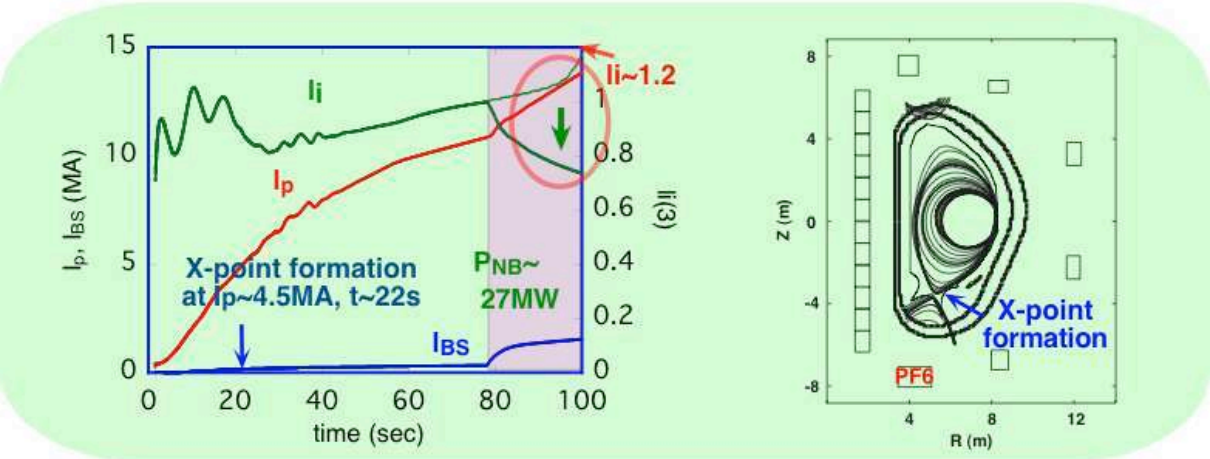

Fig. 1. Current ramp-up from I_p = 0.4 MA, Z_p = 0 m. Early X-point formation at I_p ~ 4.5 MA, t ~ 22 s. During inductive ramp, l_i continued to increase till t ~ 78 s. NB heating of P_{NB} ~ 27 MW with Ohmic power of P_{OH} ~ 10 MW started to cause L to H-mode transition, while the L/H transition threshhold was $P_{L/H}$ ~ 30MW. As denoted by the oval sign, a remarkable change of l_i, *i.e.* δl_i ~ -0.3, was observed after L/H transition. In the case of inductive ramp without L/H transition, l_i increased up to ~ 1.2 at t ~ 100 s.

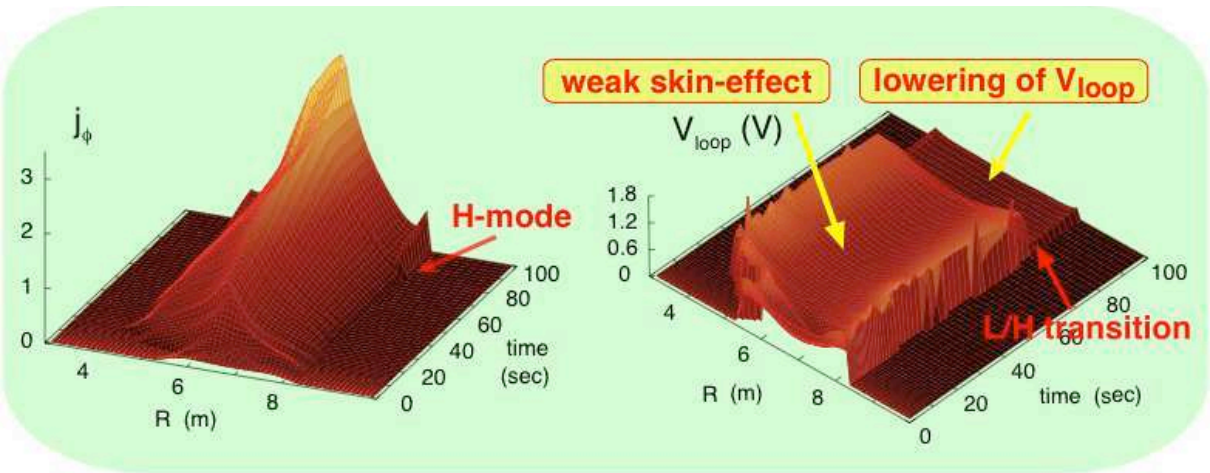

Fig. 2. Time-evolutions of toroidal current density j_ϕ and toroidal loop voltage V_{loop}. A strong edge j_ϕ structure of H-mode appears after L/H transition, generating a large BS current around $\rho > 0.9$. Emergence of edge BS current greatly lowers V_{loop}, leading to the remarkable l_i-lowering. Consequently, peaking of j_ϕ profile eventually ceased after L/H transition.

in Fig. 1, the peaking of the j_ϕ profile eventually ceased after the L/H transition. It follows that once the L to H-mode transition occurs, an emergence of the non-inductive, edge BS current greatly lowers V_{loop}, leading to the remarkable l_i-lowering, hence vertical stability. Additionally, the edge BS current improves ramp-efficiency: $C_{Ejima} \sim 0.65$, while $C_{Ejima} \sim 0.8$ without the L/H transition. Unfortunately, plasma shape control after the L/H transition, however, becomes extremely difficult, because the drastic l_i-change to ~ 0.7 alters the plasma elongation κ up to ~ 1.9. In the present TSC simulation, PF6 coil current was beyond the engineering limit of $I_{PF6} < 17.5$ MA.

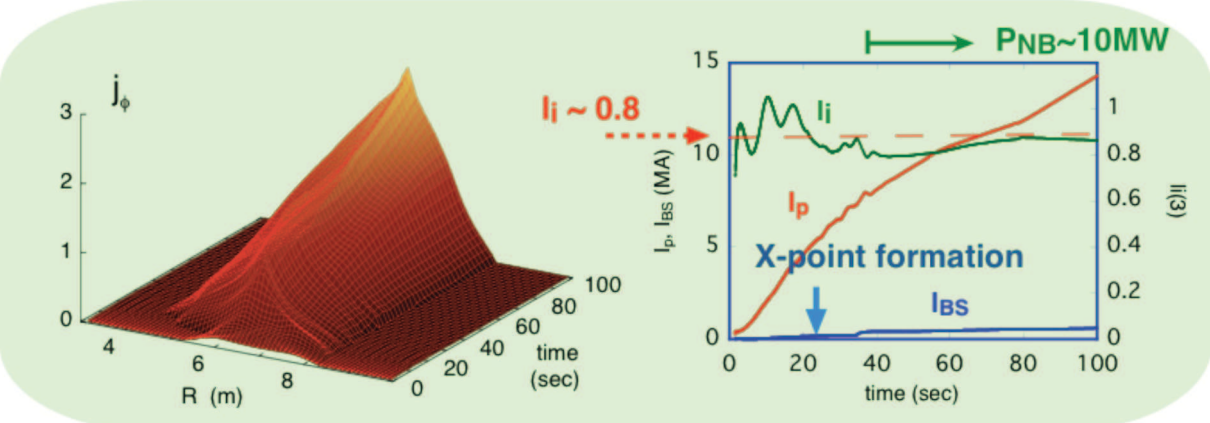

Fig. 3. Time-evolution of toroidal current density j_ϕ and waveforms of plasma current I_p, BS current I_{BS} and internal inductance l_i. j_ϕ profile becomes more flat than the plain inductive ramp, *i.e.* l_i remains ~ 0.8.

3.2. Inductive ramp with low power NB heating

An inductive current ramp scenario without L to H-mode transition was investigated. NB power of P_{NB} ~10 MW less than the L/H transition threshold was applied 10 s after the X-point formation. Figure 3 shows time-evolution of toroidal current density j_ϕ, together with waveforms of plasma current I_p, BS current I_{BS} and internal inductance l_i. Compared with the plain inductive ramp, the j_ϕ profile becomes more flat, and hence l_i remains ~ 0.8. The NB heating retards penetration of the inductive current into the plasma core region. Figure 4 shows that the NB heating enhances a skin-effect on V_{loop} profile in a great deal, lowering V_{loop} by half. Furthermore, the shape control was fairly good, and the ramp-efficiency was allowable: $C_{Ejima} \sim 0.55$. Therefore, additional heating with lower power than $P_{L/H}$ (~ 37 MW) can provide one of possible operation modes for low l_i (~ 0.8), *i.e.* vertical stability, while avoiding L to H-mode formation. However, controllability of q_0 was not acceptable, because $q_0 < 1$ has been yet observed at the later phase of current ramp: $t > 80$ s.

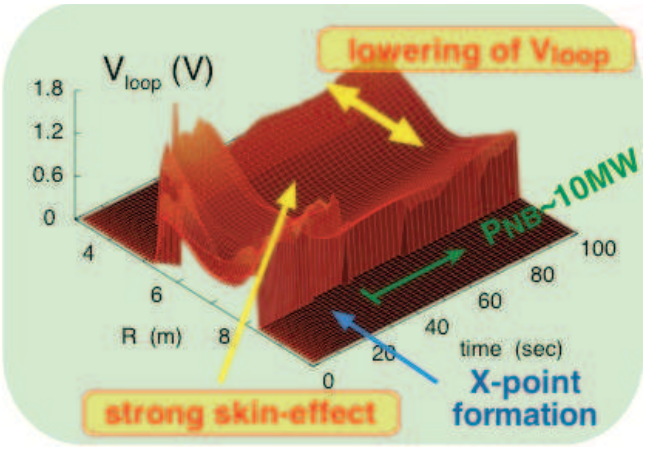

Fig. 4. V_{loop} profile of inductive ramp with low power NB heating, enhancing skin-effect while lowering V_{loop} in a great deal. lowering V_{loop} by half.

3.3. Inductive ramp with off-axis EC current drive

While avoiding the L/H transition, additional heating of $P_{NB} \sim 5$ MW and $P_{EC} \sim 5$ MW to raise electron temperature T_e and to drive off-axis EC current by $I_{EC} \sim 1.5$ MA were applied 10 s after the X-point formation. Figure 5 shows time-evolution of j_ϕ, together with waveforms of I_p, EC-driven current I_{EC}, I_{BS} and l_i. Although the off-axis EC current increases,

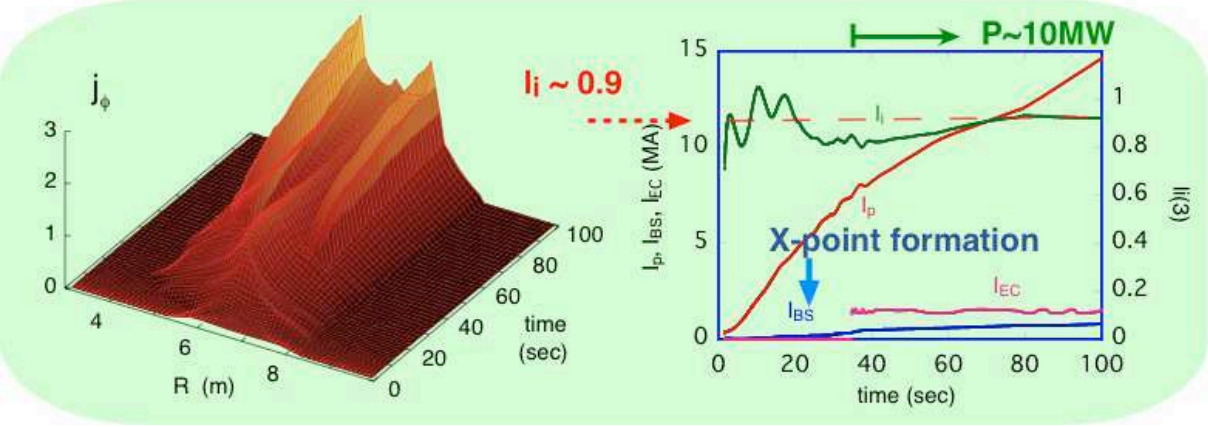

Fig. 5. Time-evolution of j_ϕ; waveforms of I_p, EC-driven current I_{EC}, I_{BS} and l_i for the scenario without L/H transition and with P_{NB} ~ 5 MW; P_{EC} ~ 5 MW and off-axis I_{EC} of ~ 1.5 MA. Although off-axis EC current increases, inductive current at mag. axis remained modest. l_i was low as ~ 0.9, and $q_0 > 1$.

the inductive current around magnetic axis remained modest. During the current ramp, l_i was kept low as ~ 0.9, and $q_0 > 1$ remains over the ramp. As in the case of Fig. 4, time-evolution of V_{loop} profile, shown in Fig. 6, implies the heating with P_{NB} and P_{EC} enhances a skin-effect on V_{loop} profile in a great deal. retarding inductive current penetration. Note that the off-axis ECCD of ~ 1.5 MA gives rise to a local dent strucutre of V_{loop}, hindering the inductive current from penetrating into the plasma core region. The shape control was fairly good as κ ~ 1.83, as well as the ramp-efficiency was kept as C_{Ejima} ~ 0.45.

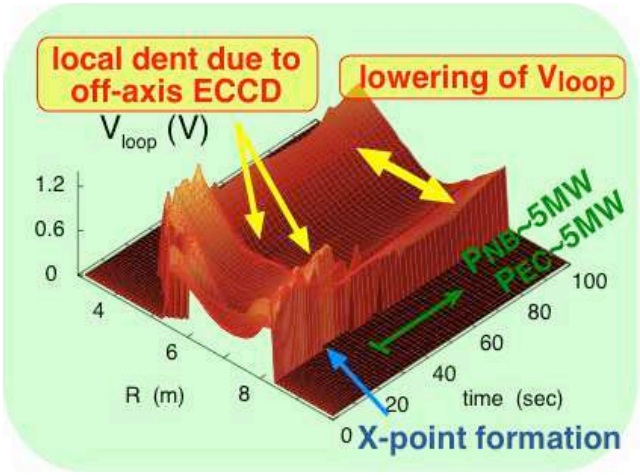

Fig. 6. Time-evolution of V_{loop}, implyin P_{NB} and P_{EC} enhance skin-effect great deal, which retards inductive current penetration. Note that off-axis ECCD of 1.5 MA gives rise to local dent of V_{loop}, hindering penetration.

4. Summary

Using TSC, inductive/non-inductive current ramp-up from I_p ~ 0.4 to 15 MA were examined, demonstrating an early X-point formation at I_p ~ 4.5 MA, t ~ 22 s. Plain inductive ramp at a slow rate like ITER 15 MA inductive scenario 2 was shown to cause high-l_i state (~1.2), leading to vertical instability. q_0 was lowered (< 1), leading to sawtooth activity, and hence the ramp-efficiency was reduced (C_{Ejima} ~ 0.8).

From the point of view of establishing high vertical stability (low-l_i), sawtooth-free ($q_0 >$ 1), high efficiency (low-C_{Ejima}), external control means to tailor current profile: *(a) L/H transition control, (b) additional heating, (c) off-axis ECCD* were investigated. It was shown that *(a) If L/H transition happens, the edge BS current reduces l_i too much, leading to failure of plasma shape control (I_{PF6} > 17.5 MA). (b) Additional heating with lower power than $P_{L/H}$ provides a lower l_i-operation for vertical stability (l_i ~ 0.8) without H-mode. The ramp-efficiency was allowable: C_{Ejima} ~ 0.55. However, q_0 remains less than unity. (c) Cooperating with additional heating, off-axis ECCD provides best scenario for high ramp-efficiency (C_{Ejima} ~ 0.45), vertical stability (l_i ~ 0.9) and sawtooth stability ($q_0 > 1$).*

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[2] S.C. Jardin, N. Pomphery and J. Delucia, J. Comput. Phys. **66** (1986) 481.
[3] A. Fukuyama, et. al., Plasma Phys. Control. Fusion **37** (1995) 6611.