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Development of real-time controls in dynamically self-regulating plasmas in JT-60U

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1. Introduction

Real-time controls have been developed in self-regulating plasmas in JT-60U where the current, rotation, and pressure profiles (j(r), v(r), p(r)) are closely linked with each other, emphasizing understanding of the complex response of the plasmas to the actuators and raising issues in establishment of control scheme for the steady-state advanced tokamak. Especially utilizing the development of real-time multi-channel motional Stark effect (MSE) diagnostic for real-time evaluation of safety factor profile q(r), cross-linkage of the current or safety factor profile to v(r) and p(r) through not only the plasma but external controllers has become an interesting target of study. Such examples are explained in this paper. In addition, toward the control of burning plasma, like ITER, where the plasma self-regulates the heating through α-heating, experimental simulation of control of the self-heating is presented. Although it has been thought that controlling the rotation in such burning plasma becomes difficult, momentum transport is investigated in order to examine possibility of controlling the rotation profile.

2. Real-time Control of NB-injected Momentum at MHD-unstable Condition (integer q_{min})

One of parameters that relates to extent of the self-regulation is the bootstrap current fraction (f_{BS}). Linkage between the current and pressure profiles become stronger at higher f_{BS}. In JT-60U, the high f_{BS} condition usually appears in reversed-shear (R/S) plasmas, where strong internal-transport-barrier (ITB) is formed. In long-time sustainment of the R/S plasmas, frequent collapses/disruptions appear when the minimum of the safety factor (q_{min}) becomes an integer, especially 4, even if we apply real-time control of total pressure. One of possible cause of the collapses/disruptions is large pressure gradient at the integer q_{min} location. Experimental knowledge to reduction of pressure gradient at ITB location is to control plasma rotation shear through the change in momentum input by tangentially injected neutral beam (NB); stop of ctr-NB reduces the pressure gradient at ITB. Thus, in order to avoid the collapses/disruptions, a real-time control of momentum-input at integer q_{min} has been developed. In order to keep current drive fraction high aiming at steady operation, co-tangential beams are always injected so that the toroidal rotation is controlled by injection of ctr-tangential beam. Since the MSE system in JT-60U observes the ctr-NB, real-time q profile is not available when ctr-NB is off for reduction of pressure gradient at integer q_{min} pass. Thus, the control system must restart ctr-NB injection after a period of the ctr-NB stop (Δt_{stop}) to

current through control of LH power (P_{LH}) aiming at under no momentum-input change. Increase in the P_{LH} increases the off-axis LHCD current so that the on-axis OH current decreases and q_{min} near the plasma center increases. Thus, the q_{min} is controlled through the system. In a high-β_p ELMy H-mode plasma (f_{BS} = 0.46, β_N = 1.6), the real-time control of q_{min} is demonstrated at an external current drive fraction of 0.41 including the real-time-controlled LHCD [2] (see Fig. 3). Before application of the control, q_{min} is about 1.2, and lower than its reference $q_{min,ref}$=1.3. Then, the system increased P_{LH}. Although the current profile is changing just after the LH injection and the start of control, change in q_{min} is a little delayed. The q_{min} reaches to its reference at t ~ 10 s, and the q_{min} follows its reference increasing in time. Due to the increase in the central q, reversed-shear region is formed near the axis at t ~ 12.5 s. Then, a sudden increase in electron density observed due to the change in q profile. Also increases in electron temperature, ion temperature and ion toroidal rotation are observed in the core region at this timing. The formation of electron and ion ITBs leads to decrease in q_{min} through increases in not only the bootstrap current, but also the electric conductivity near the axis, as indicated by q_{min} decrease after t = 13.5 s in Fig. 3. The control system recovers the decrease in q_{min} through the increase in P_{LH}.

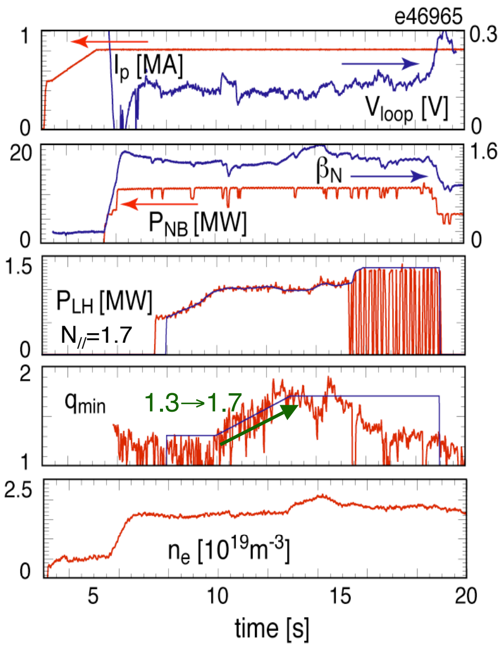

Fig. 3: Temporal evolution of plasma current, loop voltage V_l, NB injection power P_{NB}, β_N, LH injection power P_{LH}, q_{min} and its reference, electron density, in real-time q_{min} control discharge.

4. Experimental Simulation of Real-time Control of α-heating by External Heating in "Burning Plasma"

The self-regulation also becomes apparent in the burning plasma where the intrinsic alpha-heating power P_α exceeding the external heating power P^{Ex}. Control of the burn status is experimentally simulated using two groups of NBs $P_{NB}{}^{\alpha}$ and $P_{NB}{}^{Ex}$ corresponding to P^α and P^{Ex}, where $P_{NB}{}^{\alpha}$ is proportional to the neutron yield rate S_n [3]. Without control of total pressure by $P_{NB}{}^{Ex}$, the simulated α-heating $P_{NB}{}^{\alpha}$ continuously increases until it

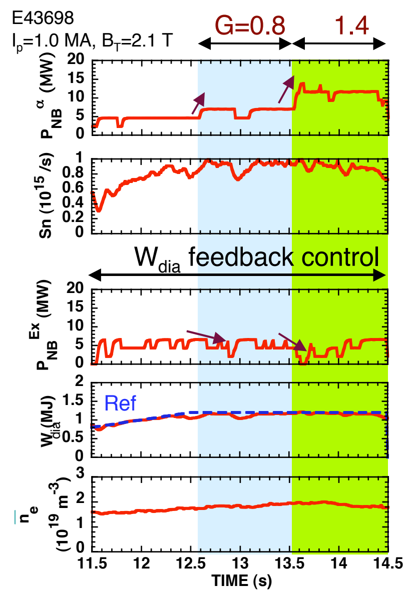

Fig. 4: Temporal evolution of NB power allocated for α heating $P_{NB}{}^{\alpha}$, neutron yield rate S_n, NB power allocated for external heating $P_{NB}{}^{Ex}$, total pressure W_{dia} and its reference, line-averaged electron density.

reaches to the NB power limit. Thus, the self-heating mechanism is appropriately simulated. With the real-time control of total pressure by the P_{NB}^{Ex}, the “burning” plasma having positive-shear is successfully controlled (Fig. 4), where the equivalent fusion gain reached $Q \equiv 5P_{NB}^{\alpha}/P_{NB}^{Ex}=30$.

5. Momentum Transport Study

Toward such burning plasma control, in order to examine possibility of controlling the rotation profile, the momentum transport is investigated using the transient analysis by using the momentum source modulation [4]. The momentum source here is ripple-loss of fast ions produced by NB injected perpendicular to toroidal direction, which is spatially localized at the plasma edge (Fig. 5). The transport of toroidal momentum is investigated in terms of radial diffusion coefficient χ_ϕ and convection velocity V_{conv}. Evaluated χ_ϕ and V_{conv} profiles are shown in Fig. 5. Using the transport coefficients by transient response analysis, the steady-state toroidal rotation profile $V_t(r)$ in the experiment is well reproduced, showing good predictability of toroidal rotation.

Acknowledgment

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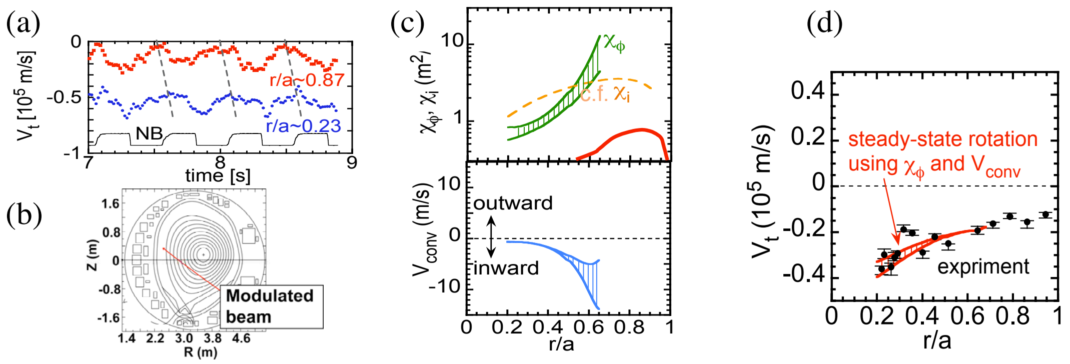

Fig. 5: (a) Temporal evolution of toroidal rotation V_t with modulated NB injection pattern (total injected power). (b) Plasma configuration and trajectory of NB producing ripple-loss ions. (c) Diffusion coefficient χ_ϕ profile in comparison with ion-thermal-diffusion coefficient χ_i profile and convection velocity V_{conv} profile. (d) Steady-state V_t profile in comparison with reconstructed V_t from χ_ϕ and V_{conv}.