

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

obtain q profile. Tuneable parameters are $q_{\min}$ to stop ctr-tangential NB ($q_{\min, \text{stop}}$), and the Δt_{stop} . When $q_{\min, \text{stop}}$ is set too close to 4, reduction of pressure gradient is not enough to pass $q_{\min} = 4$, so that collapse occurs. When Δt_{stop} is too long, the reduction of pressure gradient at ITB is not recovered by restart of the ctr-NB after $q_{\min} = 4$ pass.

Selecting appropriate parameters ($q_{\min, \text{stop}}$ and Δt_{stop}), a self-regulating reversed-shear plasma with a high bootstrap current fraction ($f_{\text{BS}} = 0.7$) is successfully sustained for about 8 s (Fig. 1) [1]. In the plasma, a collapse is avoided through the reduction of pressure gradient by the real-time control of rotation using momentum-input of NBs, when $q_{\min}$ experiences integer ($q_{\min} = 4$).

With the control, an interesting cross-linkage of rotation, pressure and current profiles has become apparent (Fig. 2) In the blue-hatched region in Fig. 2, when $q_{\min}$ approaches to $q_{\min, \text{stop}}$ of about 4, ctr-NB stops, and the ion temperature gradient is reduced through the change in rotation. Thus, collapse at $q_{\min} = 4$ is avoided. After Δt_{stop} period after the stop of ctr-NB, ctr-NB injection restarts as indicated by the purple-hatched region in Fig. 2. Then, rotation profile changes, and the ion temperature gradient increases showing recovery of ITB. Then, the bootstrap current at the ITB increases and $q_{\min}$ starts increasing. Again, the $q_{\min}$ approaches to 4 so that the control system stops the ctr-NB to avoid collapse. Under the real-time control, such cross-linkage between $q_{\min}$, pressure and rotation repetitively observed.

3. Real-time Control of $q_{\min}$ Using Off-axis LHCD in High- β Plasma

For positive-shear plasma, attainable b for a long-time is usually limited by MHD instabilities, especially neo-classical tearing mode (NTM) appearing low $q=m/n$ (e.g. 3/2, 2/1) or the sawtooth ($m/n=1/1$). These instabilities will not appear if the mode-resonant rational surfaces do not exist. Thus, to avoid / suppress the MHD instabilities, another real-time control system has been developed utilizing the real-time MSE. The system controls $q_{\min}$ by off-axis LHCD

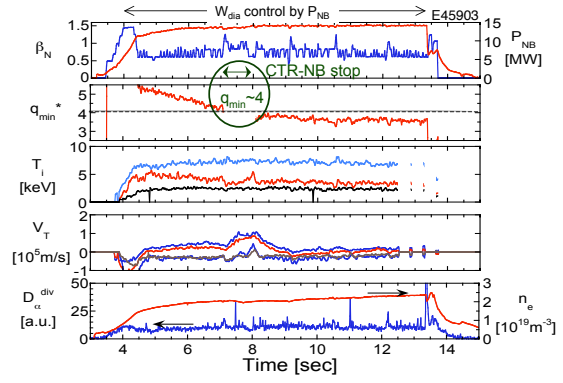


Fig. 1: Sustainment of high $f_{\text{BS}}=0.7$ for about 8s. Collapse at $q_{\min}=4$ was avoided by application of the real-time control of momentum-input. Changes in toroidal rotation V_t to co-direction and degradation of ion temperature is observed due to the controlled stop of ctr-tangential NB.

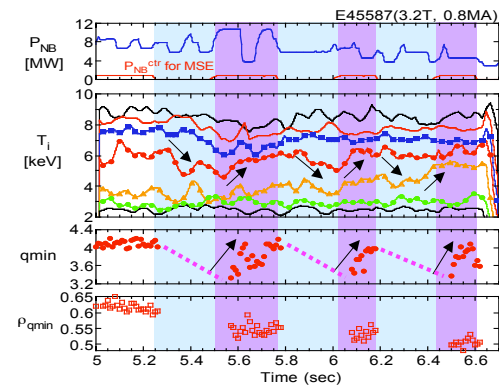


Fig. 2: Temporal evolution of NB power (total and ctr-NB), ion temperatures at various r/a locations, $q_{\min}$ and location of $q_{\min}$ ($\rho_{q_{\min}}$) in R/S plasma having $f_{\text{BS}}=0.7$.

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 ($f_{BS} = 0.46$, $\beta_N = 1.6$), 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 $t \sim 10$ 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 $t \sim 12.5$ 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} .

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}^α and P_{NB}^{Ex} corresponding to P^α and P^{Ex} , where P_{NB}^α 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}^α continuously increases until it

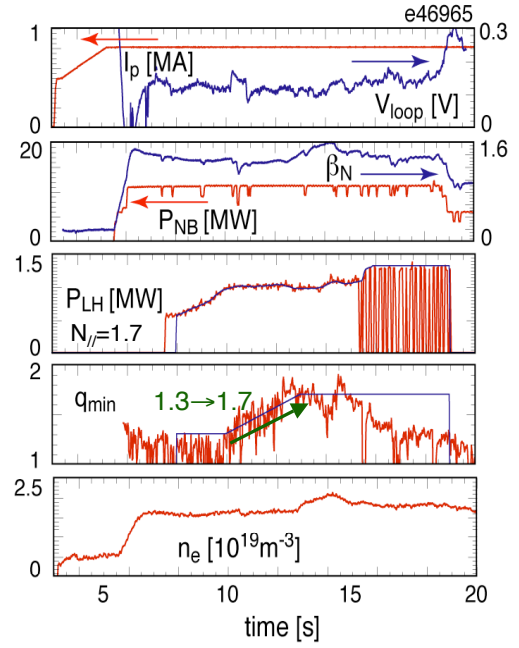


Fig. 3: Temporal evolution of plasma current, loop voltage V_i , NB injection power P_{NB} , β_N , LH injection power P_{LH} , q_{min} and its reference, electron density, in real-time q_{min} control discharge.

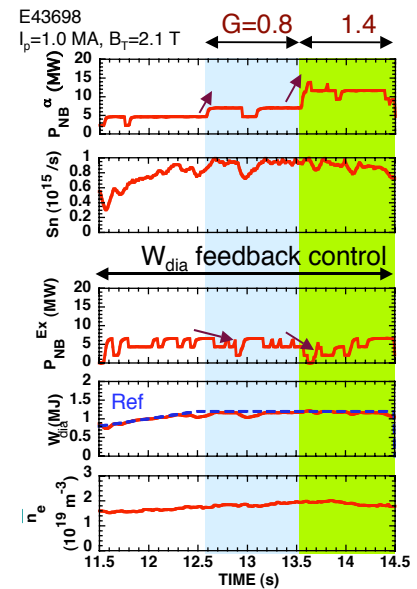


Fig. 4: Temporal evolution of NB power allocated for α heating P_{NB}^α , neutron yield rate S_n , NB power allocated for external heating P_{NB}^{Ex} , total pressure W_{dia} and its reference, line-averaged electron density.

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 $Q=5P_{NB}^{\alpha}/P_{NB}^{Ex}=30$.

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.

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References

- [1] T. Suzuki et al., in Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) (Vienna: IAEA) CD-ROM file EX/6-4 and <http://www-naweb.iaea.org/napc/physics/FEC/FEC2006/html/index.htm>.
- [2] Y. Sakamoto et al., in Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) (Vienna: IAEA) CD-ROM file EX/P1-10 and <http://www-naweb.iaea.org/napc/physics/FEC/FEC2006/html/index.htm>.
- [3] H. Takenaga et al., Fusion Sci. Tech. **50**, 76 (2006).
- [4] M. Yoshida et al., Nuclear Fusion, in press.

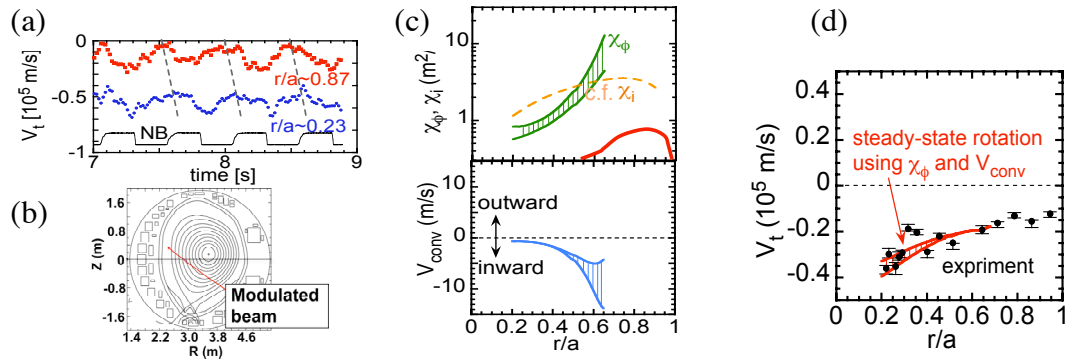


Fig. 5: (a) Temporal evolution of toroidal rotation V_t with modulated NB injection pattern (total injected power). (b) Plasma configuration and trajectory of NB producing ripple-loss ions. (c) Diffusion coefficient χ_{ϕ} profile in comparison with ion-thermal-diffusion coefficient χ_i profile and convection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