

Burn control study using burning plasma simulation experiments in JT-60U

Y. Miura¹, H. Takenaga¹, H. Kubo¹, Y. Sakamoto¹, H. Hiratsuka¹, H. Ichige¹, I. Yonekawa¹,
Y. Kawamata¹, S. Tsuji-Iio², R. Sakamoto³, S. Kobayashi⁴

¹ Japan Atomic Energy Research Institute, Naka, Ibaraki 311-0193, Japan

² Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo 152-8550, Japan

³ National Institute for Fusion Science, Oroshi-cho, Toki, Gifu 509-5292, Japan

⁴ Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

1. Introduction

The mission of ITER is to achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power of at least 10. In a burning plasma, plasma pressure and heating power are strongly linked through α particle heating. This strong linkage could easily cause a change of the fusion output without burn control. It is a self-heating state. Moreover, a collective behavior of high energy α particles may affect the confinement properties. These are the main differences from the present non-burning plasma. The real D-T fueled fusion plasma research has been performed in JET [1] and TFTR [2] to confirm the heating by α particles near break-even condition and 16.1 MW of fusion power has been produced in a D-T JET discharge [1]. In those studies, the heating by α particles has been confirmed and the understanding of fusion plasma physics and technologies have been progressed. In these experiments, however, plasmas are not in a self-heating state. In JT-60U, in order to study the linkage between the pressure and heating power, a burning plasma simulation scheme has been developed and the preliminary experiment has been performed. Through this experiment, we would like to investigate the response and controllability of a burning plasma.

2. Preliminary Burning Plasma Simulation Experiments

Figure 1 shows a scenario for the burning plasma simulation experiment. In this scenario, two NB groups are used, where one simulates α particle heating (P_{NB}^{α}) and the other simulates external heating (P_{NB}^{Ex}). For α heating simulation, the heating power proportional to the D-D neutron flux (S_n) is

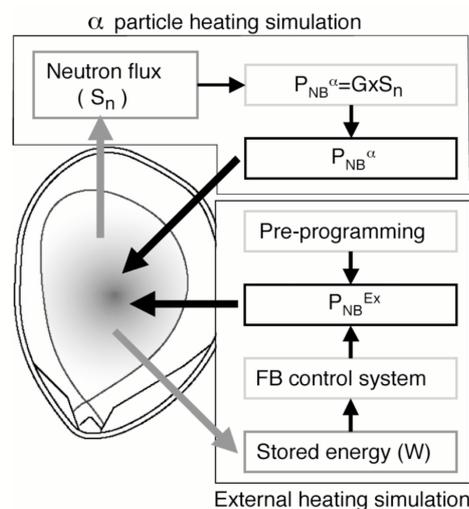


Fig. 1 Schematic drawing for a burning plasma simulation.

injected using a real time control system ($P_{NB}^{\alpha} = G \times S_n$, where G is the proportional gain). Since the NB power is changed by changing the number of injected NB unit (~ 2.2 MW/unit), P_{NB}^{α} is changed stepwise against S_n . The P_{NB}^{Ex} is determined by the preprogramming or by the feedback control system for diamagnetic measured stored energy (W). In this experiment, we can define Q value as $Q = 5 \times P_{NB}^{\alpha} / P_{NB}^{Ex}$ with assuming D-T fusion reaction. In this scenario, the dependence of D-T fusion reaction rate on ion temperature and D-T density ratio is not considered. Since beam-thermal neutron flux gives a large contribution to the total D-D neutron flux, then the P_{NB}^{α} has strong dependence on ion density and the slowing down time of injected beam. The simulation scheme is applied to an ELMy H-mode plasma ($I_p=1.0$ MA and $B_T=1.9$ T) without an internal transport barrier (ITB) and a reversed shear (RS) plasma ($I_p=1.0$ MA and $B_T=3.7$ T) with an ITB. Figure 2 shows typical wave-forms for the preliminary burning plasma simulation experiments. The simulation of α particle heating (P_{NB}^{α}) is applied from $t=10.5$ s for the ELMy H-mode plasma and $t=5$ s for the RS plasma by changing the P_{NB}^{α} control from preprogramming to feedback by S_n . In these plasmas, the constant P_{NB}^{Ex} is applied, which means no burn control. In both plasmas, the neutron flux and the P_{NB}^{α} increase, leading increase in the stored energy. In the ELMy H-mode plasma, P_{NB}^{α} is increased from 2.4 MW to 14 MW in about 0.2 s and reaches to the upper limit of the applicable NB power. It corresponds to increase in Q from 3.8 to 22. In the RS plasma, P_{NB}^{α} is increased from 5.1 MW to 10.7 MW, which is also limited by the applicable NB power. The value of Q is increased from 6.67 to 14. Due to high confinement in the RS plasma, once heating power is increased, the beam ion and thermal ion density are enhanced and the neutron flux increased. Then, P_{NB}^{α} is increased until the limitation even with smaller G compared with the ELMy H-mode case. The strong ITB is produced, and the stored energy and neutron flux go on increasing even with the constant heating power by the applicable limit of NB power and finally the plasma is disrupted due to low β limit. In the case of small G case ($G=0.35 \times 10^{-14}$), where P_{NB}^{α} is not increased during the simulation, the constant NB power ($P_{NB}^{\alpha}=5.1$ MW and $P_{NB}^{Ex}=3.8$ MW :

$Q=6.67$) is injected. In this case, the store energy is kept constant and the plasma is sustained without disruption. The plasma with such a strong ITB, in which the pressure and current profile has strong linkage through bootstrap current, is a self-organized state even without burning. The feedback control of the heating power using the measurement of diamagnetic

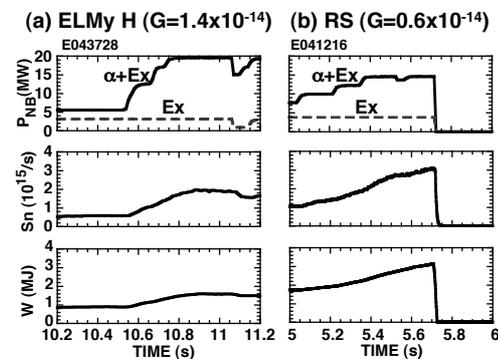


Fig 2 Typical wave-forms in the burning plasma simulation experiments for (a) ELMy H-mode plasma and (b) reversed shear plasma.

stored energy plays a key role to operate the plasma with strong ITB. In the case with burning, the control of this plasma will have much more difficulty. One of the most important issues of this simulation study is to establish the controllability of the plasma with strong ITB in RS plasmas.

Figure 3 shows that the stored energy feed back (FB) control by P_{NB}^{Ex} is applied together with P_{NB}^{α} in the similar discharge shown in Fig. 2 (a). The value of P_{NB}^{α} is increased by increasing G to 0.8×10^{-14} during $t=12.5-13.5$ s and to 1.4×10^{-14} during $t=13.5-14.5$. The stored energy is well controlled at a constant value after $t=12.5$ s by reducing P_{NB}^{Ex} against the increase in P_{NB}^{α} . Although the controllability is not lost at $t=13.6$ s with $P_{NB}^{Ex} \sim 0$ due to the degradation of the confinement. The reduction of P_{NB}^{Ex} to zero indicates that the control margin is not so large in this discharge ($Q \sim 30$). A zero dimensional model by energy confinement time, slowing down time for fast ions, particle confinement time both edge and core [3], it is found that the increase of G simulates the increase of energy confinement time and the time history of S_n and the heating power in the experiment is roughly explained. Also found is that the coupling between P_{NB}^{α} and S_n is strong. The reason is coming from the result that the source of S_n is mainly beam-thermal reaction and it is set as $P_{NB}^{\alpha} = G \times S_n$.

3. Discussions and Future Plan

In the previous section, preliminary burning plasma simulation experiments are discussed. In that simple scheme by the present non-burning plasma, there are many limitations to simulate burning plasma. The followings are the list of those limitations.

- (1) The difference of the temperature dependence between $\langle \sigma v \rangle_{DD}$ and $\langle \sigma v \rangle_{DT}$. It means that the dominant reaction between D-D (beam-thermal and thermal-thermal) and D-T (thermal-thermal) is different.
- (2) No consideration of density ratio of T to D.
- (3) No consideration of mass dependence of transport.
- (4) The difference of the change of the heating power between NB (stepwise) and α

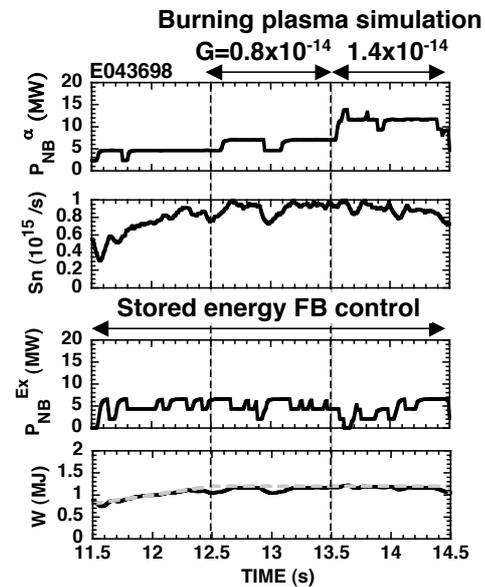


Fig. 3 Simultaneous use of α particle heating simulation and stored energy FB control. In the bottom figure, solid line indicates measurement and dashed line indicates reference for FB control.

particles (continuous).

- (5) The difference of the heating profile and velocity distribution between NB heating and α heating.
- (6) α particles principally heat electrons as a result of their high energy, the electron and ion temperature equilibration time should be shorter than the energy confinement time. In JT-60U, NB heating except negative ion based NB heats both ion and electron.
- (7) No consideration of effects on instability triggered by the collective α particles.

Figure 4 shows a more precise control scheme by using pellet injection with improving its long time applicability and the fast measurement of ion temperature, T_i . It is considered that the deuterium pellets, gas puffing (hydrogen or deuterium) and hydrogen beams are used to this scenario. It will improve the above limitations of (2) and (3). And the fast velocity of hydrogen beam will partly improve the limitation of (6). The density ratio will be evaluated by the measurement of D_α/H_α ($\gamma=n_D/n_i=(D_\alpha/H_\alpha)/(1+D_\alpha/H_\alpha)$), or the measurement of S_n , T_i and density ($\gamma=S_n/V/f_{DD}(\langle T_i \rangle)^{0.5}/n_i$), where V is the plasma volume, f_{DD} is a function of ion temperature to determine the D-D reaction rate. In this case, the temperature would be a volume averaged one, $\langle T_i \rangle$. The P_{NB}^α will be determined by the calculated power of $P_{demo} = E_\alpha(1-\gamma)\gamma n_i^2 V f_{demo}(\langle T_i \rangle)$, where E_α is the energy of α particle and f_{demo} is a function of ion temperature for D-T reaction rate. The time response of both D_α/H_α and ion temperature is less than about 10 msec, then we will be able to control the hydrogen P_{NB}^α within the delay time of less than 20 msec. In this scenario, we will be able to improve the burning plasma simulation method, and we can study the response of the simulated burning plasma and develop how to control a burning plasma.

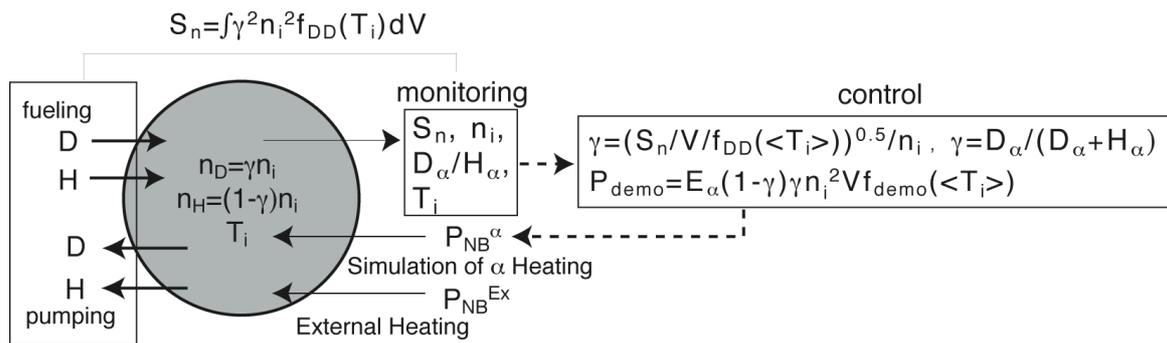


Fig. 4 Improved scenario for a burning plasma simulation

Acknowledgements

This work was partly supported by JSPS, Grant-in-Aid for Scientific Research (A) No. 16206093.

References

- [1] JET Team, Nucl. Fusion **39** (1999) 1227.
- [2] K.M. McGuire, et al., in Fusion Energy 1996 (Proc. 16th Int. Conf. Montreal, 1996) **Vol. 1** IAEA, Vienna (1997) 19.
- [3] H. Takenaga et al., Nucl. Fusion **39** (1999) 1917.