Research on Burn Control of Core Plasma with the Transport Code*)

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For the fusion reactors or experimental devices, one will be required to control several plasma parameters, like the fusion power, the heat flux, the neutron flux, the beta-value and so on. To control these parameters, many diagnostics and actuators are needed, but the diagnostics and actuators available in DEMO/commercial reactors are limited because of the high heat or neutron flux. For these reasons, to realize the fusion reactors, the construction of the reactor control logic is required. We are developing the burn control logic in the core plasma with a 1.5D transport code, and discussing on the relationship between control parameters and actuators. To demonstrate the feasibility of the core plasma control, we have demonstrated the simultaneous control of the fusion power and the safety factor profile with the gas-puff and NBI.

Keywords: burn control, NBI, gas-puff, q-profile, multiple control

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1. Introduction

In operating fusion experimental and DEMO reactors, control of many various parameters would be indispensable from the viewpoints not only of plasma performance but also of engineering requirements. For example, one is required to keep the plasma density, temperature, fusion power and so on to the target values, by taking many physical and/or engineering constraints such as the limitation of the heat flux to the divertor into account. For satisfying these requirements, the consideration on the diagnostics and the actuators is very important, because almost all of diagnostic tools might be unavailable under the environment of high radiation and methods of active control would be quite limited. Taking these limitations and constraints, it is, therefore, required to identify the combination of diagnostics and actuators and to construct the control logic [1–3].

For this purpose, at first, we have started the simulation of core plasma control by using core plasma transport code. Similar analyses are done in some researchers; e.g., the current drive simulation with the measurement of current profile peaking factor [4], the current drive and control simulation in ITER [5, 6], the density profile control analysis in ASDEX [7]. The plasma burn control simulation is done in JT-60U [8–10] and in Ref [11]. In most of these researches, they control one parameter with one actuator for moderate performance plasma. For the future reactors, however, controlling multiplex parameters with multiplex actuators in higher performance plasma is needed. It is also needed to clarify the tolerance of controlling the high performance plasma.

To do this, one must take the interaction between the actuators into account. Based on this perspective, one can write the relationship between the control values and the

$$\overleftrightarrow{G} \times \vec{A} = \overleftrightarrow{C}, \tag{1}$$

actuators which is need for future reactor as follows for convenience.

Here, we call the tensor G in left hand of eq. (1) 'governing tensor', the vector A in left hand of eq. (1) 'actuator vector' and the vector C in right hand of eq. (1) 'control volume vector'. The elements of actuator vector are gas-puff, NBI, DT fuel pellet, impurity injection and so on, while those of the control volume vector are fusion power, plasma density, q-profile, divertor heat load and so on. In general, for example, fusion power mainly depends on the amount of gas-puff. The influence, however, of NBI, pellet injection and impurity injection for the fusion power also must be taken into account. This means that off-diagonal terms in the governing tensor might become quite important, and the control might become very complex. In addition, sometimes we may consider the situation that the number of the actuator would be less than that of the control volume; i.e., the governing tensor is not a square matrix.

In this article, we will show the simulation of simultaneously control of the fusion power and the safety factor profile with gas-puffing and NBI for the ITER steady-state operation plasma. In this case, the control logic can be

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written as follows:

In an alpha-heating dominated plasma, the amount of

$$\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} P_{\mathrm{fus}} - P_{\mathrm{fus}}^{\mathrm{ref}} \\ q_{\mathrm{min}} - q_{\mathrm{min}}^{\mathrm{ref}} \end{pmatrix} = \begin{pmatrix} P_{\mathrm{puf}} \\ P_{\mathrm{nbi}} \end{pmatrix}, \tag{2}$$

gas-puff, which governs the plasma density, strongly affects on the fusion power and the NBI, which is expected to control the current profile, contributes to the minimum q-value. In section 2, the simulation model of the core plasma control is shown. In section 3, we show the several simulation results such as the fusion power control by use of the PID control of the gas puff, the minimum-q value control by use of the NBI, and the simultaneous control of fusion power and the minimum value of the safety factor by uses of gas-puff and NBI. Consideration on the actuators and control parameters in fusion reactor is quite important. In section 4, the discussion and summary are presented.

2. Simulation Model of the Core Plasma Control

The simulation is done with 1.5D transport code. Here we adopt the ITER steady-state operation mode. The main input parameters are as follows:

$$R_{\mathrm{p}} = 6.3\,\mathrm{m},\ a_{\mathrm{p}} = 1.75\,\mathrm{m},\ \kappa = 1.8,\ \delta = 0.4,$$
$$I_{\mathrm{p}} = 9\,\mathrm{MA},\ B_{\mathrm{t}} = 4.76\,\mathrm{T},$$
$$P_{\mathrm{nbi}} = 70\,\mathrm{MW},\ E_{\mathrm{nbi}} = 1\,\mathrm{MeV},$$

where R_{p}, a_{p}, κ, δ are the plasma major radius, minor radius, elongation, triangularity, respectively, and I_{p}, B_{t}, P_{nbi}, E_{nbi} are the plasma current, the toroidal magnetic field, the power of NBI, the energy of NBI, respectively. The transport coefficients are below.

$$D_j = 0.02/n_{\mathrm{e}}(10^{20}\,\mathrm{m}^{-3}),$$
$$\chi_j = 0.08\,T_{\mathrm{e}}(\mathrm{keV})/n_{\mathrm{e}}(10^{20}\,\mathrm{m}^{-3}).$$

The amount of gas-puff is determined based on proportion, integration and differential of fusion power. The PID gain is decided with Ziegler-Nichols ultimate sensitivity method. The plasma transport equation are from

$$\frac{\partial n_j(r,t)}{\partial t} = \frac{1}{V}\frac{\partial}{\partial r}\Gamma_{\mathrm{ion}}^{j}(r,t) + S^{i}(r,t), \tag{3}$$

$$\Gamma_{\mathrm{ion}}^{i}(r,t) = V\langle|\nabla r|^2\rangle \times \left(D_j\frac{\partial n_j(r,t)}{\partial r} = \frac{1}{V} + V_j n_j(r,t)\right), \tag{4}$$

$$S^{j}(r,t) = S_{\mathrm{NBI}}^{j}(r,t) + S_{\mathrm{ntr}}^{j}(r,t), \tag{5}$$

$$\frac{3}{2}\frac{\partial p_i}{\partial t} = \frac{1}{V}\frac{\partial}{\partial r}\left(Q_j + \frac{5}{2}T_j\Gamma_{\mathrm{ion}}^{j}\right) + \frac{1}{V}\frac{\Gamma_{\mathrm{ion}}^{j}}{n_j}\frac{\partial p_j}{\partial r} + S_{pj}, \tag{6}$$

$$Q_j = V\langle|\nabla r|^2\rangle\left(\chi_j\frac{\partial p_j}{\partial r} + p_j v_j\right), \tag{7}$$

$$\frac{\partial \Theta}{\partial t} = -\frac{1}{\Phi}\frac{\partial}{\partial r}\left(\frac{\langle \eta R^{-1}(J_{\varphi} - J_{\varphi}^{\mathrm{ex}})\rangle}{\langle R^{-2}\rangle}\right), \tag{8}$$

$$\Theta \equiv \frac{\partial \Psi}{\partial \Phi} \equiv \frac{1}{(2\pi)^2 q},\ \Phi = \int_r \frac{I(\Psi)}{R^2}\mathrm{d}^3x, \tag{9}$$

eq. (3) to (9).

Where index j, S_{NBI}^{j}, S_{ntr}^{j} and S_{pj} are particle species, source from NBI injection, source from gas-puff and heat source respectively. S_{ntr}^{j} is calculated from Boltzman equation with Monte-Carlo method. S_{NBI}^{j} is calculated from 1-D Fokker-Plank equation and NBI current profile is calculated at the same time.The NBI and bootstrap currents are self-consisitently determined from the tranpsort simulation results, and since the total plasma current is kept to the fixed value, the remainder of the current is presumed to be ohmic current.

3. Transport Simulation Result

3.1 Fusion power control

At first, we have carried out the fusion power control by using the modulation of the gas puffing. The simulation result is shown in Figs. 1 and 2. Figure 1 shows the control of burning plasma with the fusion power of about 350 MW.

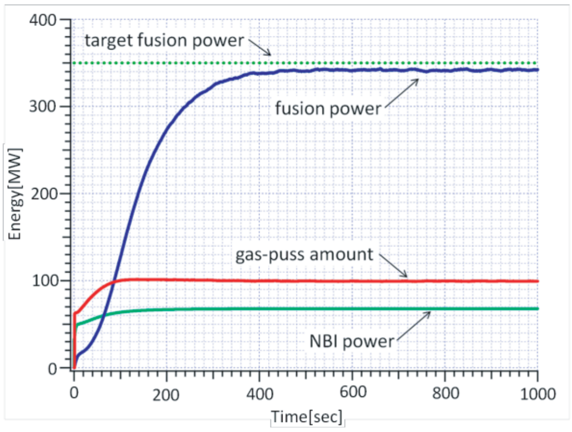

Fig. 1 The blue, red and green solid lines are fusion power, gas-puff amount and NBI power respectively, and green dashed line is target fusion power.

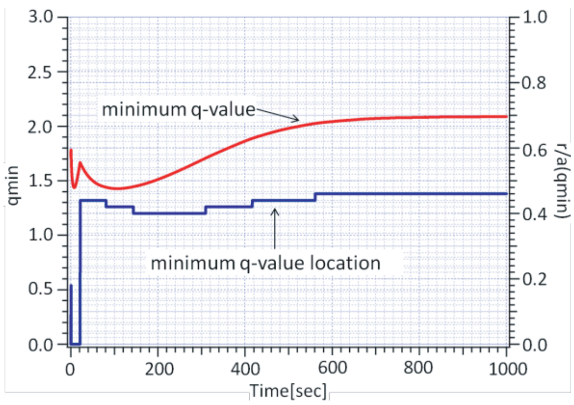

Fig. 2 The red line and blue line are minimum q-value and r/a where q-value is minimum.

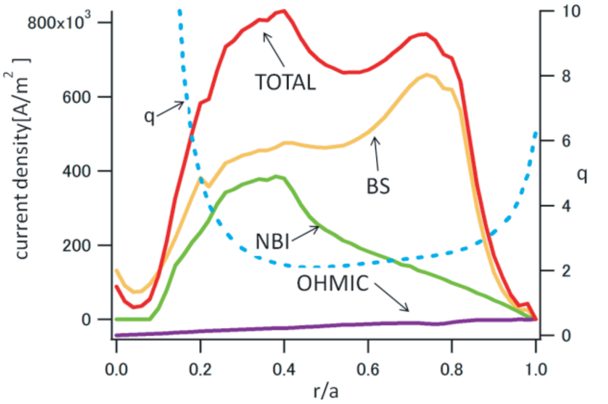

Fig. 3 The red, yellow, green and blue lines are total, boot strap, NBI and ohmic current profile, and light blue dashed line is q profile.

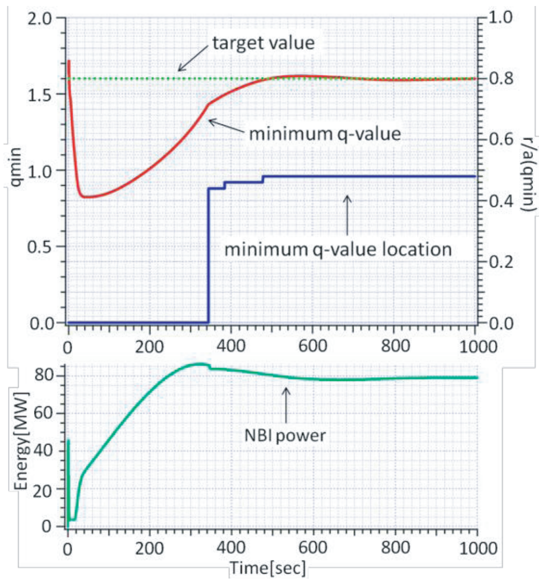

Fig. 4 The red blue and green solid line are minimum q-value, r/a where q-value is minimum and NBI power respectively. The green dashed line is target minimum q-value.

Since the NBI power is 70 MW, the achievement of $Q > 5$ plasma is demonstrated. Figure 2 shows the minimum q-value and its location. Since the location of the minimum q-value is in the region of $r/a = 0.45$, the reversed shear profile is observed. The current profile at 1000 sec is shown in Fig. 3. Since the ohmic current is nearly zero, the steady-state operation is realized in this simulation. This might be a typical target plasma for the steady-state operation in ITER, while the plasma parameters with the normalized beta value of 2.71, the H factor of 2.82 and the plasma density normalized by the Greenwald density limit of $\langle n \rangle / n_{\mathrm{GW}} = 0.90$ are presumed for this plasma.

3.2 Minimum *q*-value control

In this section, we show the minimum q-value control with NBI. Most of input parameters are same with those in the previous section. The amount of gas-puff is fixed to be 8.0×10^{21} particle/sec and NBI power is determined so as to achieve the reference value of the minimum q-value by using the PID control technique. The simulation results are shown in Fig. 4. In this case, the PID gain is determined with the ultimate sensitivity method too. Figure 4 demonstrates the control of the minimum q-value to be 1.6. However, we should remark that the minimum q-value is less than 1 between 20 sec and 200 sec. At this time, the fusion power becomes about 210 MW and Q is less than 5, so it seems to be necessary to control the fusion power. In this simulation, the NBI power is about 80 MW, gas-puff amount is 8.0×10^{21} particle/sec and minimum q-value is 1.6 at 1000 sec, in the while, in the fusion power control simulation of the previous section the NBI power is 70 MW, gas-puff amount is about 10.0×10^{21} particle/sec and minimum q-value is about 2.1 at 1000 sec. This shows the minimum q-value is depend heavily on not only NBI power but also gas-puff amount. Figure 5 shows the current profile at 1000 sec in minimum q-value control case. As shown in Fig. 5, bootstrap current is less than that in Fig. 3 and NBI current in Fig. 5 is larger than that in Fig. 3.

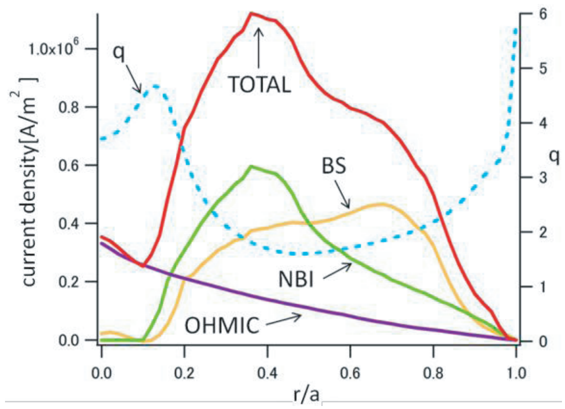

Fig. 5 The red, yellow, green and blue solid lines are total, boot strap, NBI and ohmic current profile, and light blue dashed line is q profile.

It seems that gas-puff amount has large influence on bootstrap current.

3.3 Simultaneous control

In the previous sections, we show that it is difficult to control the plasma at the target state with only one actuator. In this section, we show the simultaneous control of fusion power and minimum q-value. Both the fusion power and minimum q-value depend heavily on the amount of gas-puff and NBI power. The neutral gas injected by the gas puff is ionized near the plasma surface, and introduced as a particle source in the density transport equation. The density profile directly affects not only on the fusion power but also on the bootstrap current, resulting in the change of the safety factor profile. On the other hands, the NBI might be expected for the current profile control. The NBI could,

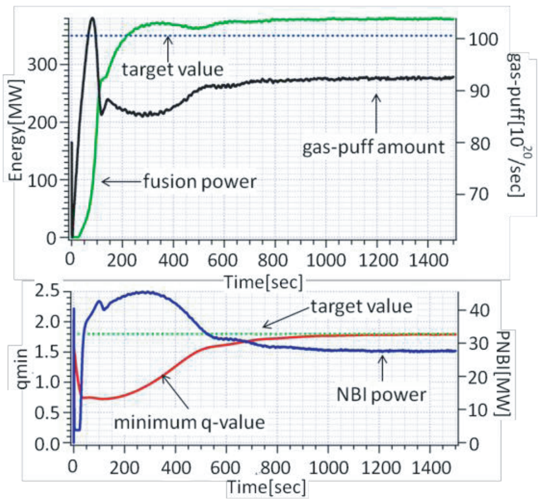

Fig. 6 The green, black, blue and red solid lines are fusion power, gas-puff amount, NBI power and minimum q-value respectively, and blue and green dashed lines are target fusion power and target minimum q-value respectively.

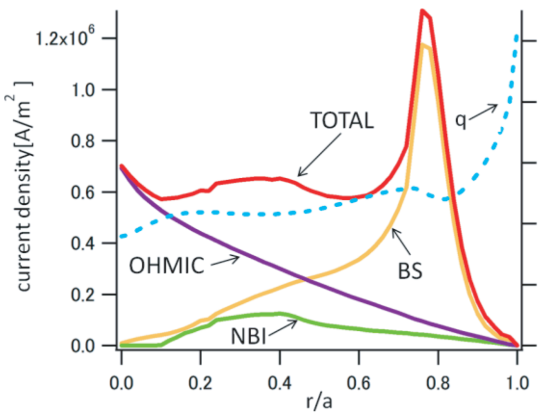

Fig. 7 The red, yellow, green and blue solid lines are total, boot strap, NBI and ohmic current profile, and light blue dashed line is q profile.

of course, contribute to the density/temperature equations as particle/heat sources, yielding in the change of the fusion power. This results in simultaneous control of fusion power and q-min with a combination of the gas puff and NBI power. To simulate the simultaneous control, we add the off-diagonal term in eq. (2), i.e., the effect of the NBI power to the fusion power is taken into account, by introducing the PD control technique. The simulation results are shown in Fig. 6, where the fusion power goes to constant value smoothly, keeping a slightly higher fusion power of the target value (350 MW). In this case, the energy gain Q seems to achieve over 10. At the same time, q-value goes to the target value ($q_{\min}$ = 1.8) smoothly. The reversed shear current profile, however, is not observed in this calculation and it is not full steady state operation, yet. The current profile is shown in Fig. 7. To produce the full steady state operation like Fig. 3, reversed share profile will be needed. To do this, more appropriate control logic of current profile is needed.

4. Discussion on Control Parameters and Summary

For the future reactors, the control of many plasma parameters is indispensable. To satisfy this requirement, the construction of the ideal control logic with the combination of the multiplex diagnostics and the multiplex actuators is needed. To find out what parameters are most important, what actuators are most efficient and what diagnostics can be extrapolated in the future reactors is the ultimate goal. The most of previous researches analyze the control of one actuator and one parameter, and the analysis of multiple controls hasn't been done much. Here, we show the example of the combination control simulation. We control the fusion power and the safety factor with gas-puff and NBI. The fusion power and the safety factor are controlled by gas-puff and NBI respectively with the PID logic. The PID gain is determined with Ziegler-Nichols ultimate sensitivity method. To control them individually is easy, but simultaneous control is difficult because of their interaction. In this article, we adjust the PID gain of safety factor and add the PD gain of fusion power to the NBI power at the simultaneous simulation, so as to control these parameters to the target value. In this case, however, reversed shear profile is not observed and it is not full steady state operation. More detailed analysis of minimum q-value control is needed. The current profile control simulation in the advanced tokamak is shown in Ref [12], where the current profile is controlled with LHCD and FWCD assuming that plasma parameters are measureable in real time. In our simulation, we control the current profile with NBI assuming the ITER steady-state operation mode as the first step to the analysis of the Demo reactors or the commercial reactors.

By the way, the time constant of current profile is several tens of seconds, so the time required for the feedback will be a few seconds. Even though we have no direct measurement of the safety factor profile in a fusion reactor, it might be possible to evaluate the current profile (i.e., q-min value and position) by using transport simulation. Therefore, we could control the safety factor profile with the help of the transport simulation in parallel with the plasma operation. The fusion reactor control with a help of simultaneous plasma simulation might be feasible in the future, and this kind of "smart control" seems to be very attractive and helpful in the case that measurable parameters are quite limited such as a fusion reactor.

More detailed discussion of the diagnostics is also needed. There is deep relationship between the parameters which we can control and measureable parameters. The measurable parameters in fusion reactors should be considered and reasonably determined. For example, the diagnostics of the neutron will be available in demo or com-

Table 1 Parameter categorization.

Ulitimate goal	Direct parameter	mid parameter
Electrical output	P_{fus}	n_{e}, Z_{eff}, f_{D}, f_{T}, T_{i}, T_{e}
Maintenance	q_{div}, W_{load}	q_{rad}, q_{elm}, n_{edg}, τ, Z_{eff}, f_{imp}
stability	β_{N}, n_{GW}, q_{min}, *rotation*	*Ip, ap, j(r),Bt*
shape,position	$Rp, ap, \kappa, \delta, d_{\mathrm{gap}}$	*Ip, j(r)*

mercial reactor, but plasma current or current profile measurement will be difficult. The diagnostics in the DEMO are discussed in Ref [13] and [14]. The discussion of diagnostics systems through the simulation of burn control is shown in Ref [15]. To discuss the measureable parameters and the parameters which we want to measure, we categorize the goal of the fusion reactor into four items, and list up the parameters associated with them in Table 1. Most of the parameters which we can measure are mid parameters in Table 1. This categorization might be helpful for discussing the control of the fusion reactors. More detailed analysis of the control logic and discussion of diagnostics are future work.

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