§4. Study on Standardization of Fusion Reactor System Based on an Integrated Design Code

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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 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. For this purpose, at first, we have started the simulation of core plasma control by using core plasma transport code. For the future reactors, 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.

Here, let us introduce the following equation;

$$G \cdot A = C ,$$

where the tensor G is called ‘governing tensor’, and the vectors A and C are ‘actuator vector’ and ‘control volume vector’, respectively. 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.

Here 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. 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:

$R_p = 6.3\text{m}$, $a_p = 1.75\text{m}$, $\kappa = 1.8$, $\delta = 0.4$,
$I_p = 9\text{MA}$, $B_t = 4.76\text{T}$,
$P_{nbi} = 70\text{MW}$, $E_{nbi} = 1\text{MeV}$,

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.

$D_j = 0.02/\mathrm{n_e}\ (10^{20}\mathrm{m}^{-3})$ $\chi_j = 0.08T_e\ (\mathrm{kev})\ /\mathrm{n_e}\ (10^{20}\mathrm{m}^{-3})$

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 NBI is calculated with 1-D Fokker-Plank equation.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.

We show the simultaneous control of fusion power and minimum q -value. Both the fusion power and minimum q-value strongly depend 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. In addition, the NBI could 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.

The simulation results are shown in Fig. 1, where the fusion power goes to constant value smoothly, keeping a slightly higher fusion power of the target value (350MW). 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 share current profile, however, is not observed in this calculation and it is not full steady state operation, yet. To produce the full steady state operation, reversed share profile will be needed. To do this, more appropriate control logic of current profile is needed.

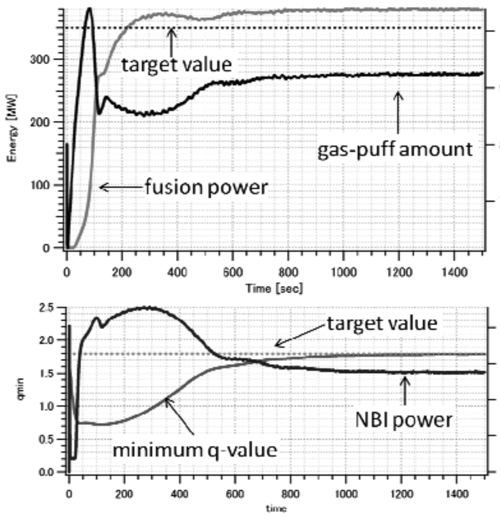

Fig 1. The green, black, blue and red solid lines are fusion power, gas-puff amount, NBI power and minimum q- value respectively, and blue and green dashed lines are target fusion power and minimum q- value respectively.