Simulation of burning ITER plasma
in multi-variable kinetic control system

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<u>Abstract.</u> For successful reactor operation, the development of kinetic control system is required along with magnetic control system creation. The paper is devoted to investigating capabilities and quality of kinetic control of plasma integral characteristics of tokamak-reactor by means of multivariable astatic feedback control system with adaptation as well as studying plasma behavior in the open system at various disturbances. Numerical simulations were carried out on plasma-physics code ASTRA for ITER parameters [1]. For analysis we selected the steady-state ITER scenario with plasma current I_p=9 MA, average plasma density $n_e \sim 7 \times 10^{19}$ m^{-3}, with the reversed shear region in the plasma core and completely non-inductive current drive.

<u>Testing MIMO plasma model.</u> Plasma in tokamak is a complicated multi-linked (Multi-Inputs Multi-Outputs [MIMO]) plant: each input action influences on the main output signals. Modeling showed that often this creates contradictory conditions for operation of various control channels in attempting to act on several plasma parameters simultaneously. More over, contradictions are enhanced because of nonlinear interactions via plasma between separate feedback circuits. The situation is improved owing to considerable difference in characteristic times of some processes and possibility to use different system loops to control the same parameter. The detailed analysis of influence of each input of the controlled ITER plasma to the set of outputs showed that some channels exist which do not interact so much via internal links of the plasma column.
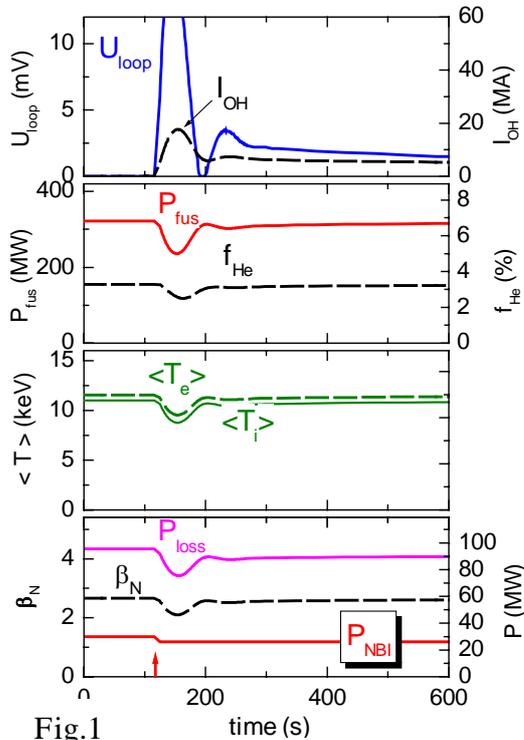

Fig.1

Thus, the condition of the existence of plasma internal decoupling channels was revealed and the corresponding favorable input-output pairs had been found. Just that condition provided the real possibility of developing multi-variable system to control basic integral kinetic plasma parameters of the reactor independently. It gave a chance to design a diagonal multi-variable controller at the lower level of an adaptive system. At the upper level of the system the principle of relative priorities was realized and actuators actions of the lower level were redistributed when one of actuators saturated.

Investigation of system internal links was carried out by means of estimation of plasma responses on testing actions. The most important variations of plasma column characteristics and their radial distributions were analyzed namely: thermonuclear power P_{fus} that is proportional to the neutron flux, average plasma density n_e, average loop voltage U_{loop} (in this case the equality U_{loop}=0

corresponds to the completely non-inductive current drive), radial distribution of a plasma current $J(r)$, plasma temperatures $T_e(r)$, $T_i(r)$ and density $n_e(r)$, relative plasma pressure β, and power losses P_{loss} from plasma to the divertor which is proportional to the power crossing the separatrix. Input actions were step-testing functions of following: neutral beam injection power P_{NBI}, lower-hybrid current drive power P_{RF}, plasma fuelling n_{os} (density of D-T neutrals at the separatrix), argon density n_{Ar} seeding for partial power re-radiation for unloading divertor plates, pumping speed of He, plasma transport and so on. Magnetic parameters that are plasma current, position and shape were assumed to be controlled by independent feedback system. One of the examples corresponding to 30% increase of P_{NBI} is shown in Fig. 1. The most important testing results are as follows. First, significant initial perturbations of parameters decreased and after some change of radial profiles of plasma parameters the output values came back to the vicinity of unperturbed values. This phenomenon demonstrated the existence of internal self-organization processes in plasma column leading to the plasma behavior as a stable attractor. Second, two specific times were observed. One of them corresponds to the plasma transport time (about several seconds), the second one is connected with the reconstruction of current profile and exceeds the first one essentially (~3000 sec).

Modeling the adaptive multi-variable control system. After investigation of the influence of inputs on outputs of open-loop system the modeling 4-loops adaptive astatic feedback system was carried out. The block diagram of the system is shown in Fig. 2.
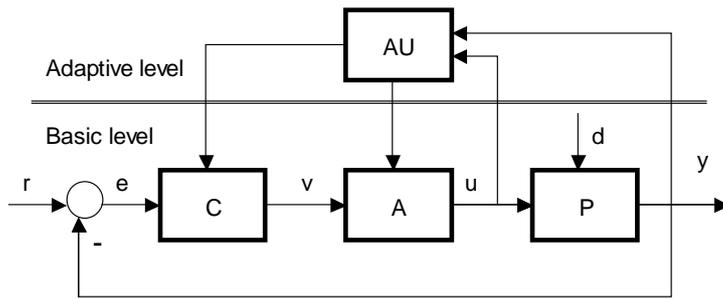

Fig. 2

The system consists of two control levels. The lower (basic) level contains control loop which involves controlled plant P (plasma in tokamak), actuator A, and controller C, closed by negative feedback at measuring output vector y. The reference signal r comes to the input of the lower system level, and the system is subjected to disturbance d. The upper level contains the adaptive unit AU, which accepts the signals of the basic level and acts on the controller and actuator improving the lower level performance in accordance with the goal of the adaptive level. The vectors of control actions u and outputs y were chosen as follows: $u = \begin{bmatrix} P_{NBI} & n_{os} & n_{Ar} & P_{RF} \end{bmatrix}^T$, $y = \begin{bmatrix} P_{fus} & n_e & P_{loss} & U_{loop} \end{bmatrix}^T$. The actuator A was modeled for the simplest case without taking into account its dynamics and was described by a unit matrix $A = I_4$. The transfer matrix of the controller had diagonal structure $C = diag\begin{bmatrix} k_i / s \end{bmatrix}$, $i = 1, \ldots, 4$ where s is a differential operator (or Laplace complex variable), k_i is a proportionality coefficient. The disposition of system inputs and outputs in vectors u and y were chosen accordingly testing results and the usage of the diagonal controller provided the most influence of corresponding input to its output in each signals pair namely: $P_{NBI} \rightarrow P_{fus}$, $n_{os} \rightarrow n_e$ $n_{Ar} \rightarrow P_{loss}$, $P_{RF} \rightarrow U_{loop}$. The astatic control means the presence of integrators in the feedback loop. Principle of operation of the astatic controller chosen is as follows. Corresponding component of an error signal $e_i = r_i - y_i$ is fed to input of the controller where r_i and y_i are components of reference and plant output

respectively (Fig. 2). Controller output component v_i has a link with e_i as an integral transformation $v_i(t) = v_i(0) + k_i \int_0^t e_i(\theta)\,d\theta$ or as an equivalent differential representation $dv_i(t)/dt = k_i e_i(t)$. For a numerical simulation the finite approximation of the former equation was used $v_i(\tau + \Delta\tau) = v_i(\tau) + \Delta\tau k_i e_i(\tau)$ where τ and $\Delta\tau$ are discrete and sampling times respectively. For instance, the control of the main output $P_{fus} = y_1$ at $P_{NBI} = v_1$, $P_{fus}^{ref} = r_1$ was realized by the following difference scheme $P_{NBI}(\tau + \Delta\tau) = P_{NBI}(\tau) + K\left[1 - P_{fus}(\tau)/P_{fus}^{ref}\right]$ where $K = \Delta\tau k_1 P_{fus}^{ref}$ is a proportional coefficient, P_{fus}^{ref} is the reference level of thermonuclear power. If there is an integrator inside feedback loop a zero signal has to be fed to integrator input in the steady-state mode. So if $r_i = const$ then $e_i = 0$ at $y_i = r_i$, and there is an accurate stabilization of the output about its setting action r_i after a transient response caused by a disturbance action.
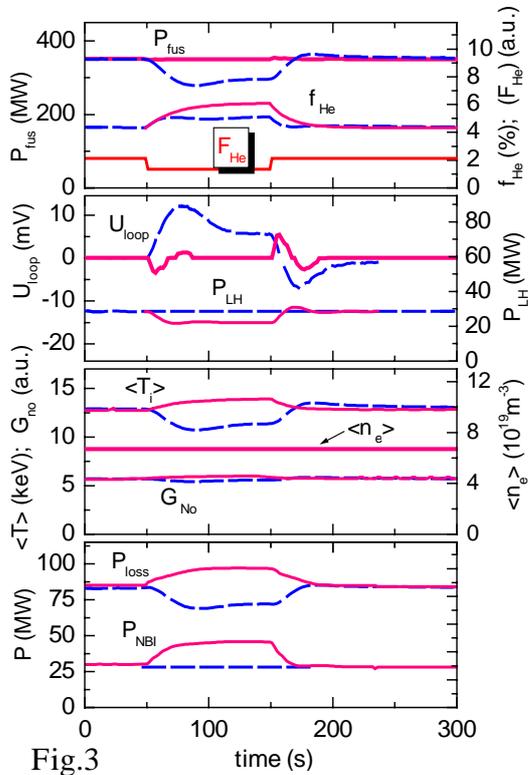

Fig.3

Figs. 3,4 demonstrate such performance for some control channels due to the usage of astatic control law in each of them.

Modelling of the discharge parameters control has been conducted at plasma various disturbances. The examples of transient responses at Helium pumping speed change and getting small Carbon grain onto plasma boundary are shown in Fig. 3,4. In Fig. 3 blue lines correspond to open-loop scheme and red lines agree with the case when the system is closed by feedback. The open-loop scheme case is depicted on the left column of Fig. 4 and feedback case is presented on the right column. Modeling revealed that the plant outputs are stabilized relative to their references with rather high accuracy at impulse disturbances of various natures. Large plasma parameters perturbations were observed when feedback was disconnected. In so doing, rather strong actions on plasma parameters were chosen which required using limit powers of some actuators for perturbation compensation. In a number of cases an introduction of such perturbations at open loop feedback led to plasma column full cooling. The system possibility to use additional relative priorities on the adaptive system level was checked to enlarge feedback dynamical range (Fig. 2). For instance, the condition was introduced that the main discharge characteristic was P_{fus}. When P_{NBI} saturated and P_{fus} change continued, another actuator (for example actuator of P_{RF} generation) was switched from controlling non-inductive current to controlling P_{fus} at the command of AU. This made possible to improve the compensation of P_{fus} changes although U_{loop} perturbations slightly increased. By virtue of the fact that the controlled plant allows stabilization of a set of outputs without decoupling control channels in the
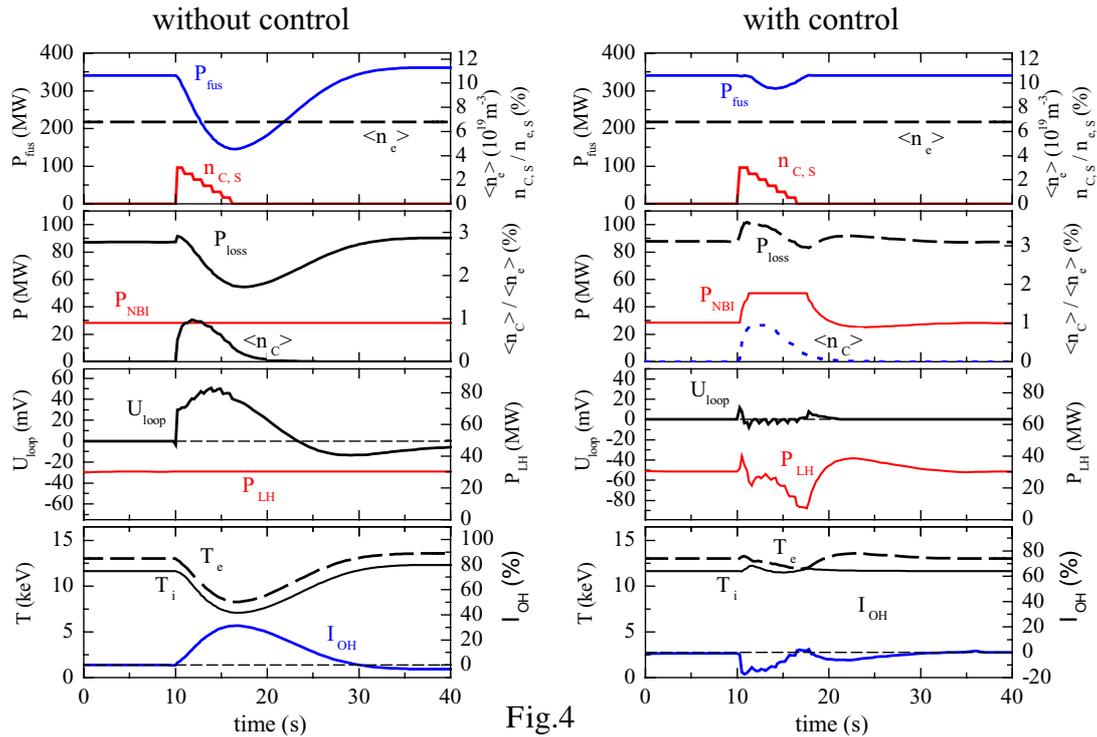
Fig.4

controller of the lower level, this says about not so strong plant internal interconnections, which permits to apply multivariable diagonal controller without additional external decoupling cross-connections.

Conclusions. ♦ Modeling plasma kinetic control processes on plasma-physics code ASTRA for ITER discovered the existence of *internal self-organization processes* of burning plasma leading to plasma behavior as a *stable attractor* in open loop and feedback system with adaptive controller. This makes easier the development of reliable plasma kinetic control systems. ♦ The principle of decoupling control channels on the base of internal interconnections knowledge of the plant was realized at modeling multivariable adaptive astatic feedback system of controlling basic integral kinetic characteristics of plasma column in ITER. ♦ The principle of relative priorities was used on the adaptive control level at saturation of actuator generating P_{NBI}. Nevertheless additional work is required on development of a model identifying internal dynamical plant links. This should give a chance to complete the control system increasing stability margins and improving quality of disturbances suppression. ♦ Plasma accumulates a number of features (distribution of parameters in space, description of differential equations of diffusion type, multi-links, non-linearity, non-stationary characteristics, input-output constraints, high level of model uncertainties), which make difficult to synthesize classical linear control systems significantly and sometimes make it impossible in practice. Therefore, a need to develop *nonlinear robust-adaptive controllers* is required to control integral kinetic plasma parameters and radial profiles $J(r)$, $T_e(r)$, $T_i(r)$ in tokamak-reactor providing the most economic and reliable modes of tokamak-reactor operation [2].

References
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