New Control Method of the Unstable Operating Point in the FFHR Helical Reactor

Osamu MITARAI, Akio SAGARA[1)], Nobuyoshi OHYABU[1)], Ryuichi SAKAMOTO[1)], Akio KOMORI[1)] and Osamu MOTOJIMA[1)]

Institute of Industrial Science and Technical Research, Kyushu Tokai University, Kumamoto 862-8652, Japan
[1)]*National Institute for Fusion Science, Toki, 509-5292, Japan*

(Received 6 March 2007 / Accepted 27 April 2007)

A new and simple control method of the unstable operating point in the Force Free Helical Reactor (FFHR) is proposed for the ignited operation with high-density plasma. Proportional-integration-derivative (PID) control of the fueling has been used to obtain the desired fusion power with the fusion power error of $e(P_{\mathrm{f}}) = (P_{\mathrm{fo}} - P_{\mathrm{f}})$ in the stable operating point. We have discovered that in the unstable regime the error of the fusion power with an opposite sign of $e(P_{\mathrm{f}}) = -(P_{\mathrm{fo}} - P_{\mathrm{f}})$ can stabilize the unstable operating point. Around the unstable operating point, excess fusion power supplies fueling and then increases the density and decreases the temperature. Less fusion power in the sub-ignited regime reduces the fueling, decreases the density, and increases the temperature. The operating point approaches the final unstable operating point as oscillation is damped away.

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Keywords: helical reactor, high-density, unstable ignition boundary, stabilization, PID control

DOI: 10.1585/pfr.2.021

Recently a high-density plasma regime has been observed in Large Helical Device (LHD) experiments [1]. From these experimental results, the high-density and low-temperature operation may be a promising scenario to realize a helical reactor. However, in such a situation the ignited operation usually faces thermal instability, where the operating point moves to the higher-temperature and lower-density regime.

Many stabilizing methods of the thermally unstable ignition point have been proposed, by processes such as fueling [2], impurity injection [3], and heating power modulations [4], and combinations of these. In these controls, zero-dimensional equations of the particle and power balance equations have been linearized around the unstable operating point, and then stabilizing techniques such as H-infinity control [5], non-linear control [6], and neural network control [7] have been applied. In these methods, linearization is necessary in many equations, and hence it may be difficult to apply it to the actual situation. In the previous studies, only stabilization around the unstable operating point has been shown, but access to the unstable operating point from the zero temperature and density has not been demonstrated.

In this study, we propose a new control method to stabilize the thermally unstable operating point without any linearization and with the PID control of the fueling based on the total fusion power. In this paper, we also demonstrate the ignition access to the thermally unstable ignition boundary from the zero temperature and density. In this proposed method no linearization is needed, and fueling is controlled by the PID controller, so the method can be applied to an actual situation in a reactor.

In this analysis, we have employed zero-dimensional equations to demonstrate the controllability of this new method. The detailed formulas of each term were presented in the reference [8]. We used Sudo density limit scaling on the line density of the core plasma with the density limit factor of $\gamma_{\mathrm{SUDO}} = 4.5$ as a measure of density in this study. The external heating power was preprogrammed during the whole discharge, because it is difficult to use this density limit scaling for feedback control of the external heating power. This is different from operations on a stable ignition boundary [8]. In the power balance equation the equal ion and electron temperatures were assumed. In the D-T particle balance equation, the PID control of D-T fueling is used for feedback control of the fusion power as

$$S_{\mathrm{DT}}(t) = S_{\mathrm{DT0}}\left\{e_{\mathrm{DT}}(P_{\mathrm{f}}) + \frac{1}{T_{\mathrm{int}}}\int_0^t e_{\mathrm{DT}}(P_{\mathrm{f}})\mathrm{d}t + T_{\mathrm{d}}\frac{\mathrm{d}e_{\mathrm{DT}}(P_{\mathrm{f}})}{\mathrm{d}t}\right\} G_{\mathrm{fo}}(t) \quad (1)$$

where T_{int} is the integration time, T_{d} is the derivative time, and the error of the fusion power is $e_{\mathrm{DT}}(P_{\mathrm{f}}) = c(1 - P_{\mathrm{f}}/P_{\mathrm{fo}})$ with $c = +1$ for the stable boundary, $c = -1$ for the unstable boundary. $P_{\mathrm{fo}}(t)$ the fusion power set value and $P_{\mathrm{f}}(t)$ the calculated fusion power. $S_{\mathrm{DT}}(t) = 0$ is set in the program when $S_{\mathrm{DT}}(t) < 0$ is required in Eq. (1). The helium ash confinement time ratio of $\tau_\alpha{}^*/\tau_{\mathrm{E}} = 3$ and the ISS95 confinement scaling are used, where $\gamma_{\mathrm{ISS}} = 1.92$ and

author's e-mail: omitarai@ktmail.ktokai-u.ac.jp

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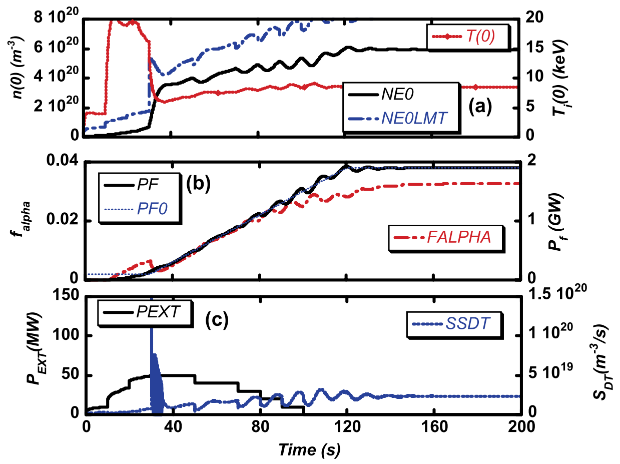

Fig. 1 Temporal evolution of plasma parameters in FFHR at the unstable boundary. (a) The peak ion temperature $T(0)$, the peak density $NE0$, the density limit $NE0LMT$, (b) the alpha ash fraction $FALPHA$, the fusion power PF, its set value $PF0$, (c) the external heating power $PEXT$ and the fueling $SSDT$. The fusion power rise-up time is $\tau_{\text{rise}} = 120$ s. $T_{\text{d}} = 1$ s, $T_{\text{int}} = 10$ s and $\gamma_{\text{SUDO}} = 4.5$ after 30 s.

$\gamma_{\text{LHD}} = 1.2$ represent the confinement enhancement factors over the ISS95 and present LHD scalings, respectively. We have used the parameters of the FFHR ($R = 14$ m, $a = 1.73$ m, $B_{\text{o}} = 6$ T, $P_{\text{f}} = 1.9$ GW, and the parabolic density and temperature profiles) used at the thermally stable boundary [8].

The thermally stable operating point can be transferred to the thermally unstable point on Plasma Operating Contour map (POPCON) by changing the sign of the error of the fusion power and having a slightly smaller value of P_{fo} than P_{f} after reaching the stable operation point. Of course, the operating point can proceed to the thermally unstable point from the early phase. As shown in Fig. 1, the transition was set at 30 s by changing $c = +1$ to $c = -1$ and using a slightly smaller set value of P_{fo} than P_{f}. The density abruptly increases, and the temperature drops after 30 s, but the fusion power P_{f} is increased as desired. During the ignition access oscillations take place, but eventually are damped away, and the final operating point is reached. Fueling to stabilize the operating point, $S_{\text{DT}}(t)$, is oscillating corresponding to $e_{\text{DT}}(P_{\text{f}}) = -(1 - P_{\text{f}}/P_{\text{fo}})$, and it is always positive as seen in Fig. 1 (c). The PID control parameters are $T_{\text{d}} = 1$ s and $T_{\text{int}} = 10$ s after 30 s. The derivative time in the fueling is an important parameter and should be $T_{\text{d}} > 0$ for stabilizing the operating point. This is quite different from the stable operating point where $T_{\text{d}} = 0$ can be used [8]. Final operating parameters are the temperature of $T(0) = 8.5$ keV (15.3 keV), the density of $n(0) = 6 \times 10^{20}\,\text{m}^{-3}$ ($2.8 \times 10^{20}\,\text{m}^{-3}$), the beta value of $\langle\beta\rangle = 3.5\%$ (3.0), and the confinement time of $\tau_{\text{E}} = 3.9$ s (1.9 s). The steady state values at the stable operating point for the same fusion power are described in parentheses.

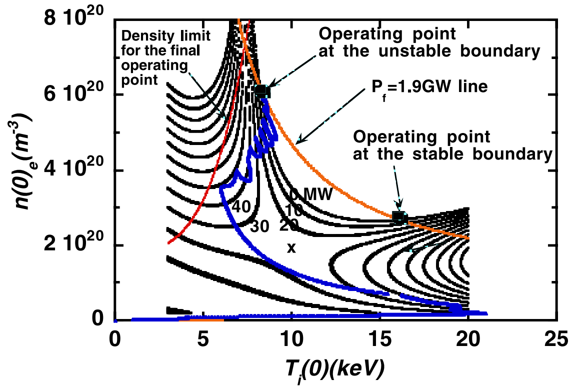

Fig. 2 Operation path (blue) to the unstable ignition point on POPCON. Transition to the unstable point is set at 30 s.

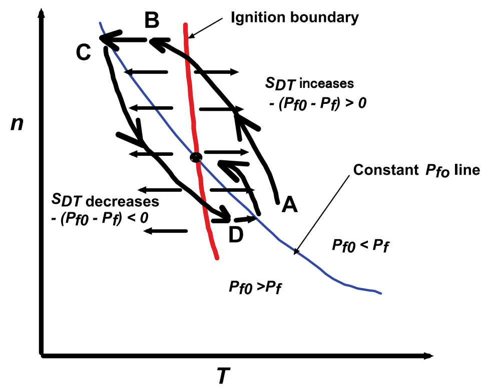

Fig. 3 Schematic movement of the operating point around the unstable ignition point on POPCON.

The operating path corresponding to Fig. 1 is plotted on POPCON in Fig. 2. It can be clearly seen that the operating point proceeds to the thermally unstable operating point from the early phase.

This behavior is understood as shown in POPCON in Fig. 3. When P_{f} is larger than P_{f0}, the operating point (A) moves toward the higher density and shifts to the higher temperature side due to ignition nature. When it enters in the sub-ignition regime (B), it goes to the lower temperature side due to sub-ignition nature and crosses the constant P_{fo} line (C). The fueling is now decreased, and the operating point proceeds to the lower-density and higher-temperature side, and goes into the ignition regime (D), and crosses the constant P_{fo} line. Oscillation takes place, but is damped away.

This control method is robust for parameter changes. If the alpha ash confinement time ratio $\tau_\alpha{}^*/\tau_{\text{E}}$ is increased from 3 to 5, it can be controlled. Even if the fuel particle confinement time ratio $\tau_{\text{p}}{}^*/\tau_{\text{E}} = 3$ (at present) is increased to 15, for example, it can be controlled when the derivative time $T_{\text{d}} = 5$ s is chosen. We have thus demonstrated that a new and simple control method of the unstable operating point for the high-density helical reactor. The error of the fusion power with an opposite sign as $e(P_{\mathrm{f}}) = -(P_{\mathrm{fo}} - P_{\mathrm{f}})$ with PID control can stabilize the unstable operating point. At the same time the fusion power is regulated. These results ensure the possibility of a high-density operation in a helical reactor.

This work is performed with the support and under the auspices of the NIFS Collaborative Research Program NIFS04KFDF001 and NIFS05ULAA116.

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