§28. Simulation Study for DT Fusion Ignition of LHD-type Helical Reactor by Joule Heating Associated with Magnetic Axis Shift

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LHD-type magnetic configuration (Heliotron configuration) is produced by continuous helical and vertical coil systems. A new concept to achieve current drive with magnetic axis shift, which is caused by vertical magnetic field coil current change is proposed$^{1)}$. It is confirmed numerically that an LHD-type helical fusion reactor can be ignited by high-current Joule heating.

LHD experiments have succeeded in the generation of the ultra high density core plasma ($n_0 \gtrsim 10^{21}/\mathrm{m}^3$) and have achieved an average beta value of 5 % without beta collapse. Steady state burning of high density plasma is relatively easy, because the DT alpha particle heating ratio is proportional to n^2. On the on the other hand, fusion ignition of high density plasma is difficult due to the necessity of effective high power heating procedure.

In addition to the Joule heating, the plasma current also improves the plasma confinement performance as shown in the IPB98y2 scaling. This leads to a possibility of "current-driven and current-less" hybrid operational scenario for an LHD-type helical reactor. Fusion ignition of a low-density current carrying plasma is relatively easy because of a high confinement performance. Strong alpha heating after the ignition enables the transfer to a steady-state burning of high-density plasma in current-less mode.

To confirm the "current-driven and current-less" hybrid operational scenario for an LHD-type helical reactor, we have analyzed the plasma Joule heating method by examining the coupling systems for the IV coil (a set of vertical field coils placed at the inboard side of the torus) current equation (1), the plasma loop current equation (2), and the plasma power balance equation (3):

$$\begin{aligned} V_c &= R_c\, i_c + L_c \frac{\mathrm{d}i_c}{\mathrm{d}t} + \alpha\sqrt{L_p L_c}\frac{\mathrm{d}i_p}{\mathrm{d}t}, && (1) \\ 0 &= R_p\, i_p + L_p \frac{\mathrm{d}i_p}{\mathrm{d}t} + \alpha\sqrt{L_p L_c}\frac{\mathrm{d}i_c}{\mathrm{d}t}, && (2) \\ \frac{\mathrm{d}}{\mathrm{d}t}\left(3nTV_{\mathrm{lcfs}}\right) &= -\frac{3nTV_{\mathrm{lcfs}}}{\tau_E} - P_{\mathrm{BRM}} \\ &\quad + R_p\, I_p^2 + P_{\mathrm{ECH}} + P_{\mathrm{F}}, && (3) \end{aligned}$$

where, i_c, i_p, and T are the IV coil current, plasma current, and plasma temperature, respectively. The plasma density is assumed to be sustained constant.

Resistance R_c inserted in the IV coil circuit was set so that the time constant of the IV coil current was 100 s. L_c is self inductance of the IV coil group. The self-inductance and loop resistance of the plasma torus were calculated assuming a circular cross section with minor radius a_p and major radius R_{ax} ;

$$L_p = \mu_0 R_{\mathrm{ax}}\left[\ln\left(\frac{8R_{\mathrm{ax}}}{a_p}\right) - \frac{7}{4}\right],\ 2\pi^2 a_p^2\, R_{\mathrm{ax}} = V_{\mathrm{lcfs}}, \quad (4)$$

$$R_p = \frac{2\pi R_{\mathrm{ax}}}{\pi a_p^2} 1.65 \times 10^{-9} Z_{\mathrm{eff}} T([keV])^{-3/2} \ln\Lambda. \quad (5)$$

α is the coupling constant between the plasma loop and the IV coil set.

$$\ln\Lambda = 15.5 + \ln\frac{T([keV])}{n/10^{20}}, \quad (6)$$

$$P_{\mathrm{BRM}} = 5.4 \times 10^3 Z_{\mathrm{eff}}\left(n/10^{20}\right)^2 \sqrt{T([keV])} V_{\mathrm{lcfs}}. \quad (7)$$

P_{BRM}, P_{F}, and P_{ECH} are the Bremsstrahlung loss, alpha heating ratio, and ECH heating power, respectively.

We assume energy confinement time τ_E for the current-carrying helical systems as a hybrid combination of τ^{ISS95} and $\tau^{IPB98y2}$ given by

$$\frac{1}{\tau_E} = \frac{1}{\gamma_{\mathrm{iss}}\tau^{ISS95}} \cdot \frac{I_0^2}{I_0^2 + I_p^2} + \frac{1}{\tau^{IPB98y2}} \cdot \frac{I_p^2}{I_0^2 + I_p^2}, \quad (8)$$

where γ_{iss} represents the confinement enhancement factor over the ISS95 scaling; it is assumed to be $\gamma_{\mathrm{iss}} = 2.3$ in the following computations. I_0 is a constant parameter of the fitting. When $I_p << (>>)\, I_0$, the energy confinement is essentially governed by the ISS95 (IPB98y2) scaling.

Applied voltage for the IV coil, V_c, was set to obtain the optimized magnetic surface in the steady state starting from magnetic surface with outer shifted magnetic axis. To obtain sufficient magnetic flux change for the current drive, voltage slightly in excess was applied for a short time ($t \leq 140$ s). The parameters just before Joule heating starts (initial) and for the stationary state are summarized in Table I. The parameters at the time of maximum Joule heating ($t = 64.39$s) and maximum plasma current ($t = 140$s) are also included. Parameters used for the computation are summarized in Table II.

Table I: Parameters for the initial and stationary states.

t(s)	0	64.39	140	∞
$N\,(\mathrm{m}^{-3})/10^{20}$	0.40	0.40	0.48	1.56
I_p (MA)	0.01	6.25	9.54	0.00
T (keV)	0.80	4.99	10.59	18.88
β (%)	0.10	0.64	1.64	9.49
P_{BRM} (MW)	2.52	6.31	13.22	186.54
P_{ECH} (MW)	11.42	11.42	0.00	0.00
P_{J} (MW)	$\cdots$	1.27	0.99	0.00
P_{F} (MW)	$\cdots$	4.99	63.33	2071.50

Table II: Parameters used for the computation.

B_{ax}(T)	R_{ax}(M)	V_{lcfs} (M^3)	Z_{eff}	α	γ_{iss}
5	16.1	1633.3	2	0.3	2.3

1) Tsuguhiro WATANABE, Plasma Fusion Res. 6, 2405130 (2011).