(5) Steady-State Operation and Plasma Wall Interaction

§1. Improving Steady-State Discharge by RF Heating in the LHD

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Steady-state discharge without ohmic heating current has been studied in the Large Helical Device (LHD), and the long-pulse operation for one hour was demonstrated in 2006 with the line averaged electron density n_e of $0.4\text{x}10^{19}$ m^{-3}, central electron temperature T_{e0} of 1.3 keV and the averaged heating power P_{rf} of 0.5 MW (ICH:0.4MW+ECH:0.1MW) for hydrogen minority heating scenario of the helium plasma. The plasma termination time-scale was 0.2 sec, and it was caused by impurity penetration at the plasma edge.

In 2012, in order to foresee the large particle and heat fluxes to divertor and wall at the steady-state fusion reactor, we have challenged to realize higher-performance steady-state discharge. The steady state plasma of discharge length of 18 min. 55 sec. with n_{e0} of $1 \text{ x } 10^{19}$ m^{-3} and T_{e0} of 2.5 keV was achieved by P_{rf} of ~1MW (ICH:0.7MW+ECH:0.24MW). Figure 1 shows the achievement and target region for steady-state discharge in 2012 (16th LHD experimental campaign), and the LHD achieved the high performance plasma with n_{e0} of 10^{19} m^{-3}, T_{e0} of a few keV and the discharge length of longer than 1000 sec. in the magnetic fusion plasma experiment for the first time.

Figure 2 shows the high performance steady-state discharge waveforms on the magnetic configurations of R_{ax} = 3.65m/ B_t = 2,712T. The magnetic axis was swept with the sweeping distance of ± 1cm, and it was effective to disperse the local heat load on the carbon divertor plates. Consequently, the divertor temperature (Div82) in Fig. 2 synchronizes with magnetic axis sweeping with the period of 140 sec., and the divertor plate temperature is almost saturated after 400 second. By estimating averaged divertor heat removal by the water-cooling, the power to divertor is approximately 0.6MW (60% for injection power). Average radiation power measured by bolometer is approximately less than 0.2 MW (20% for injection power).

The electron density gradually increased after 600 second, and gas-fueling ratio was manually controlled. In order to keep electron density after 800 sec, precise gas-fueling control is needed with small fueling ratio, because gas-fueling ratio after 600 sec is much smaller than that before 300 second. These experimental results suggest that integrated gas-fueling system taking account of time dependence of gas-fueling ratio is necessary for long pulse operations.

This discharge was terminated by unintended heating power reduction of ICRF, and the plasma termination time-scale of 4 sec. is much longer than the previous one of 0.2 second. The sustainable plasma density is decreased just after the unintended power reduction, and the electron density gradually exceeds the sustainable density in a few second. Due to the increase of the heating injection power in this campaign, electron temperature is higher than that of previous experiment. It seems that higher electron temperature avoids quick plasma collapse, which is caused by the edge cooling due to impurity penetration such as previous plasma terminations.

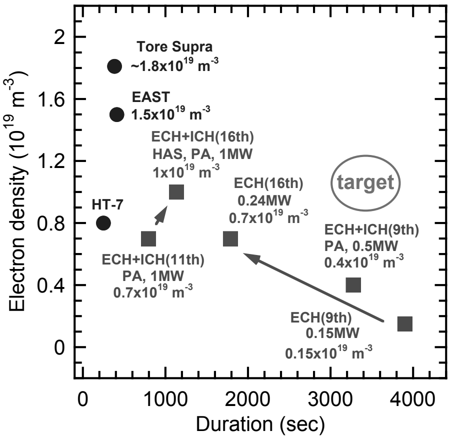

Fig. 1. Achieved higher performance steady-state discharge and the target scope.

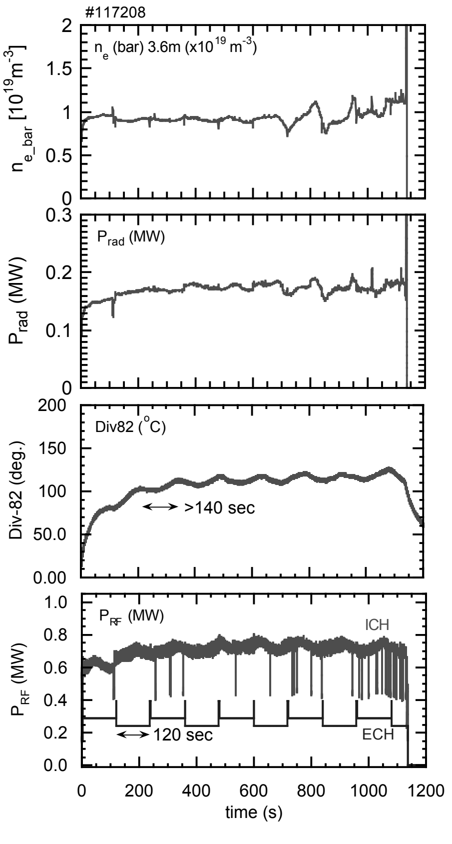

Fig. 2. Longest discharge waveform with the central electron density n_{e0} of $1\text{x}10^{19}$ m^{-3}, T_{e0} of 2.5 keV in 2012.