## §2. Improving Plasma Performances on Steady-state Operation

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The Large Helical Device (LHD) has a pair helical coils with the strong magnetic field (< 3T) used a superconductor, and it is no needs externally to drive plasma current, which is important fully to make magnetic field to confine the plasma. This is one of the great advantages in plasma heating system, because the realization of current drive needs larger heating power than only plasma heating without toroidal torque. Ultra-long-pulse plasma with the plasma duration time ($\tau_d$) of 54 min is already demonstrated in a relatively lower density plasma with the electron density ($n_e$) < $0.4\text{x}10^{19}$ $m^{-3}$ and radio frequency (RF) heating power ($P_{RF}$) of 0.5 MW in the LHD. In order to design a fusion reactor, we have to understand the plasma physics with high-performance steady-state condition.

In order to produce the high performance steady-state plasmas with $n_e > 1\text{x}10^{19}$ $m^{-3}$, $T_e \sim T_i >$ keV, it is necessary to develop the high power continuous heating system for ion cyclotron heating (ICH), electron cyclotron heating (ECH) and neutral beam injection (NBI). For RF heating system (ICH), three kinds of ion cyclotron range of frequencies (ICRF) antennas, a handshake (HAS) antenna, a field-aligned impedance transform (FAIT) antenna [1] and a poloidal array (PA) antenna, are installed on different toroidal sections with the same frequency of 38.5 MHz for hydrogen minority heating regime. For ECH, steady-state gyrations with several kinds of frequencies, 77GHz, 82.4GHz, 84GHz and 154GHz, are operated as on- and off-axis heating focused on the electron cyclotron resonances.

Figure 1 shows the results of steady-state experiment with $\tau_d$ > 40 sec. Before the last campaign (~ FY 2012), a target of RF heating power in steady-state operation (SSO) was approximately 1 MW, and in FY 2013 available RF heating power for SSO is up to ~ 3 MW, which is the design value for the continuous heating power in the LHD. In particular, the steady-state high power RF heating system has been well developed, and the local heat load for the energetic particle accelerated in front of ICRF antennas were effectively mitigated. In the novel long-pulse discharge for the last campaign, the plasma duration time of 48 min was achieved, and the typical plasma and heating parameters were as follows: $n_e \sim 1.2\text{x}10^{19}$ $m^{-3}$, $T_e \sim T_i \sim 2$ keV and $P_{RF} \sim 1.2$ MW (ICH ~ 0.93MW, ECH ~ 0.24MW) [2]. The total injection energy for plasma heating arrived at 3.4 GJ, and it is a new world record in toroidal plasmas.

By increasing RF heating power, higher density plasmas (> $1\text{x}10^{19}$ $m^{-3}$) were easily maintained with $T_e$ > keV in Fig.1, and the plasma performance and the heating condition are similar level to the high power steady-state operation such as Tore Supra [3], in which lower hybrid heating is used to drive plasma current. Figure 2 shows the experimental results for plasma duration vs electron density in the LHD and major steady-state devices of tokamaks. Plasma duration time was extended in various electron density with $P_{RF}$ > 1MW, and in higher density region with $n_e > 1\text{x}10^{19}$ $m^{-3}$ with $P_{RF}$ > 2 MW, relatively long-pulse discharge with $\tau_d$ > 100 sec could be easily repeated in these experiments. The high-power SSO was carried out at the end of experimental campaign and just after ultra-long operation with $\tau_d$ > 40 min, and a mixed-material layer seemed to be largely and thickly accumulated inside of vacuum vessel. The mixed-material layer was easily removed from the surface of dome plates and first wall, and the large amount of the penetration at the plasma edge was one of causing radiation collapse in SSO.

1) K. Saito et al., this annual report
2) H. Kasahara et al., this annual report
3) B. Sautic et al., *Fusion Eng. Des.* **56** (2009) 1079.

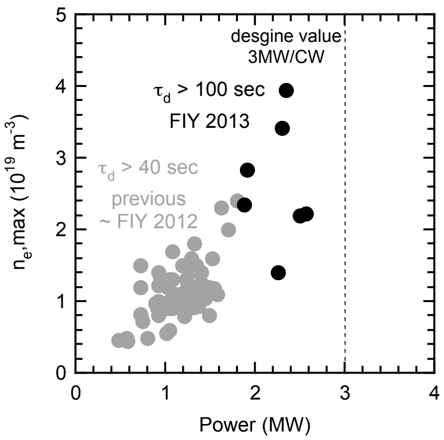


Fig.1. Extending the high power RF heating regime on the steady-state operation

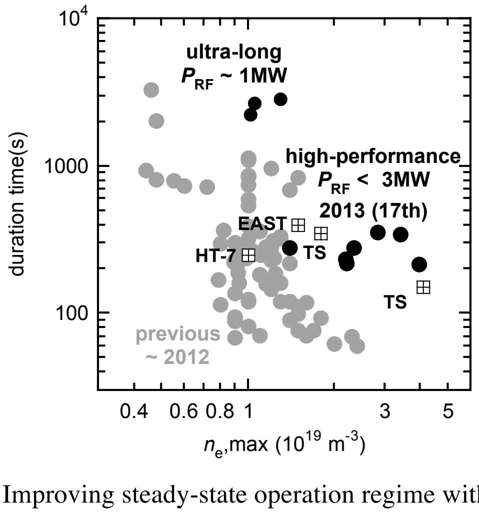


Fig.2. Improving steady-state operation regime with the RF heating power over 1 MW