§ 51. Progress towards Steady State Operation

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Our efforts towards steady-state operation mainly have been devoted to the extension of the discharge duration using both NBI and ICRF heating systems [1, 2]. The progress in long pulse discharges is shown in Fig. 1, where the time traces of averaged electron density are indicated for both NBI and ICH discharges. Before the 1999 campaign, all the strike points at the divertor legs were covered with graphite tiles, and it enabled us to enlarge the operational range of density and duration to a great extent. In the last 2002 campaign, a 150 s discharge has been achieved with the ICH power of 0.5 MW. However, this discharge was terminated by radiation collapse due to the density increase. The density limit of ICRF heated plasma depends on the ICH power ($n_{cr}\,(10^{19}m^{-3}) = 1.8\ P_{ICH}\,(MW)$). The available power of the heating system was restricted up to 0.7 MW for long pulse operation as shown in Fig. 2, where the injected energy (E_{inj}) is plotted in terms of the injection power. The maximum injected energy into the plasma chamber is about 75 MJ. In order to extend the discharge duration, the available heating power should be upgraded to increase the plasma density.

Plasma performance of long pulse discharges is almost the same as that of short pulse discharges. Both NBI and ICRF heated long-duration plasmas in the inward shifted configuration (R=3.6 m) indicated an enhancement factor of around 1.5 relative to the ISS95 scaling as well as in short pulse discharges. In this case, a scaling of fusion triple product is derived from ISS95 in the following equation: $n_0\tau_E T_{i0}\ (10^{20}keVm^{-3}s) = C\ n_e(10^{19}m^{-3})^{1.02}\ P_{ICH}(MW)^{-0.18}$. To determine the numerical factor, experimental data are plotted in Fig.3, whose abscissa and ordinate are $n_e(x10^{19}m^{-3})^{1.02}\ P_{ICH}(MW)^{-0.18}$ and $n_0\tau_E T_{i0}\ (10^{20}keVm^{-3}s)$, respectively. The numerical factor can be determined to be C = 0.03 from this figure [3]. In this empirical scaling, we can find that $n_0\tau_E T_{i0}$ strongly depends on the plasma density and is not so much influenced by the heating power.

Demonstration of long-duration discharges with high performance is illustrated in Fig. 4, which shows plasma performance (through the usual criterion $n_0\tau_E T_{i0}$) versus pulse duration. In LHD, when the available ICRF heating power is 3 MW, the plasma density is increased up to 5.4 x $10^{19}m^{-3}$ and the fusion triple product can be assessed over $10^{19}keVm^{-3}s$ and a high performance plasma will be sustained for long time.

References
[1] Noda, N., et al., Nuclear Fusion **41** (2001) 779
[2] Nakamura, Y., et al., Nuclear Fusion **43** (2003) 219
[3] Kumazawa, R., et al., Phys. of Plasmas **8** (2001) 2139

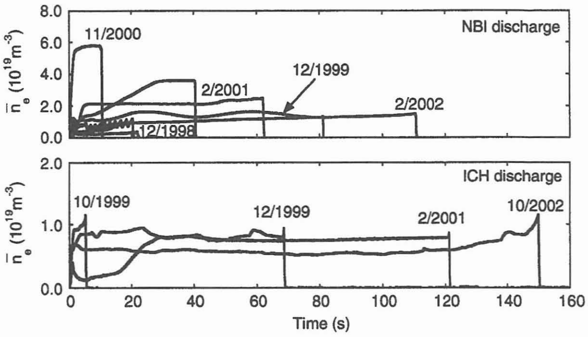

Fig. 1 Progress in NBI and ICH long-pulse discharges.

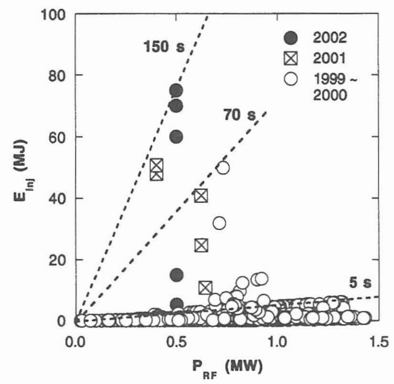

Fig. 2 History of injected RF energy in ICH experiments.

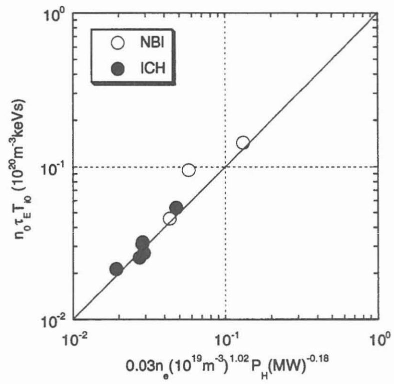

Fig. 3 Empirical scaling of fusion triple product of $n_0\tau_E T_{i0}$.

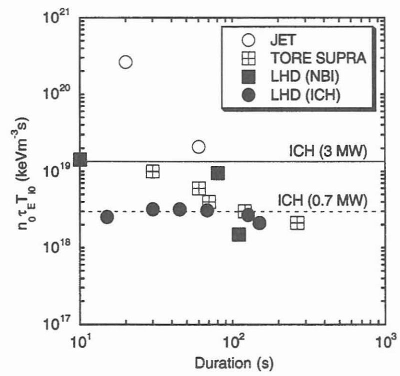

Fig. 4 Plasma performance versus pulse duration.