§9. Fueling Requirements of Super-high-density Plasmas towards Innovative Ignition Regime

Sakamoto, R., Yamada, H.

Super-high-density plasma with an internal diffusion barrier (IDB) which is observed in the Large Helical Device has been extrapolated to a fusion reactor grade plasma to explore an innovative ignition regime and to clarify essential requirements for pellet fueling. The peaked density profiles due to the internal diffusion barrier formation allow reduction in the required minimum temperature to sustain a self-burning plasma down to 10 keV. Direct core fueling beyond the internal diffusion barrier is essential to sustain the peaked density profile. In order to sustain a self-burning plasma with an internal diffusion barrier, therefore, extremely high velocity pellet injection beyond 10 km/s is inevitable unless another solution to the core fueling is found.

In order to estimate the self-burning property of the IDB plasma taking the time evolution of plasma profiles into consideration, the plasma profile evolution was calculated by the combination of the simple particle diffusion equation and the direct profile extrapolation (DPE) method in which the normalized plasma pressure profile obtained from the LHD experiment is directly extrapolated into a burning plasma by assuming gyro-Bohm type parameter dependence. The main justifications for the direct extrapolation from the LHD experiments to the self-burning reactor are based on the fact that (i) the LHD plasma shows gyro-Bohm type parameter dependence under wide experimental conditions, (ii) the collisionality of the self-burning plasma in a helical reactor ($\nu_{\mathrm{b}}^{*} \sim 0.1$) is within the range of collisionality under the LHD experimental conditions, and (iii) the heating power density in the self-burning plasma is nearly the same as that in the LHD experiments. The assumed pellet size is within a range between 0.5×10^{22} and 6.4×10^{22} atoms per pellet and it correspond to the ratio within a range between 2.5 % and 32 % to the number of the particles contained in the target plasma. It is assumed that the IDB foot position is at $\rho = 0.5$ as is the case with a typical IDB profile in the LHD experiments at the magnetic axis of $R_{\mathrm{ax}} = 3.75$ m. The stable operational point of the self-burning plasma near the minimum fusion output is searched by scanning the pellet injection interval under the direct core fueling condition ($\lambda/a = 0.9$) at various pellet sizes. It is found that the averaged fueling rate, which is defined by the product of the pellet size and injection frequency, is a key to control the fusion output, and it is possible to obtain similar fusion output by keeping an averaged fueling rate even if the pellet size differs by more than 10 times. Figure (a) shows pellet size dependence of the density profile just before and after pellet injection, and Figure (b) shows the time evolution of the fusion α output, temperatures and densities, under the same averaged fueling rate condition at 1.43×10^{23} /s. Although the impact of the pellet fueling on the fluctuation of the plasma properties becomes significant as the pellet size increases, the averaged values of the fusion α output, temperature and density remain at almost the same level at $P_{\alpha} \sim 900$ MW, $T_{\mathrm{e}}(0) \sim 12$ keV and $n_{\mathrm{e}}(0) \sim 3.5\times10^{20}$ /m^3, respectively. Figure (c) shows the pellet size dependence of the fusion α output fluctuation due to the direct core fueling. The fusion output fluctuation level varies in proportion to the pellet size. In the case of a 0.5×10^{22} pellet size, the fluctuation level is as small as 0.3 %. However, the fluctuation level is beyond 16 % at a 6.4×10^{22} pellet size and such a large fluctuation should be unacceptable in terms of heat load onto the plasma facing components. The pellet size dependence of the required pellet velocity which is estimated by the neutral gas shielding pellet ablation model is shown in Figure (d). The required velocity is reduced as the pellet size is increased. The velocity reducing curve can be fitted by the inverse five-ninth power of the pellet size as shown by a broken line, and it is consistent with the parameter dependence of the NGS pellet penetration depth scaling. What is important is that the required velocity is beyond 10 km/s even though a relatively large pellet that may induce a large fluctuation is employed, and it becomes 60 km/s at a 0.5×10^{22} pellet size. The required pellet speed is widely different from the present-day injection technology, the establishment of an entirely new technological innovation is indispensable.