§6. Super Dense Core Ignition Scenario

Ohyabu, N., Yokoyama, M., Sakamoto, R., Motojima, O.

In recent experiments on the Large Helical Device, repetitive pellet fueling raised the plasma density to record values. In these plasma discharges, a Super Dense Core plasma with density as high as $4.6\times10^{20}\mathrm{m}^{-3}$ and temperature of 0.85 keV is maintained by an Internal Diffusion Barrier with very high density gradient. The fusion triple product ($n_o\tau_E T_o$) is an order of magnitude higher compared with those fueled by gas puffing. These results may extrapolate to a novel scenario for fusion ignition at very high density and relatively low temperature in helical devices. Raising the plasma temperature to thermonuclear temperature in a toroidal device is a very difficult task especially in high density regime. This may be accomplished more easily by dividing plasma confining region into two regions, very high density core and relatively low density mantle, as illustrated in Figs. 1a and 1b. In the mantle region with relatively low density, a high value of temperature gradient can be expected, leading to core temperature above the minimum value required for ignition. In the core region, an SDC plasma is maintained by the IDB as in LHD. With such a division, high density region does not overlap with high ∇T region. Thus a significant enhancement of the energy confinement can be expected.

First we attempt to find the lowest possible temperature for ignition. Self heating power density (alpha power density minus bremsstrahlung power density) is given as

$$C\cdot(\,n_o\;T_o)^2\cdot F(T_o,Z_{eff}\,)$$

where n_o,T_o are core density and core temperature, respectively (see Fig. 1b). C is 0.14 MWm^{-3} with f (T=10keV) = 1. F (T_o, Z_{eff}) = $f(T_o)[1-g(T_o,Z_{eff})]$ takes into account a deviation from $(nT)^2$ dependence of self heating power (g: the ratio of the bremsstrahlung to that of the alpha power density). The units of n_o, T_o, χ_m, Δ_m are 10^{20} m^{-3}, 10keV, $\mathrm{m}^2\mathrm{s}^{-1}$, m, respectively. For Z_{eff} =2, the minimum temperature required for ignition is 7-8 keV, namely below this temperature, the self heating power density decreases rapidly with decreasing temperature. The operational temperature (or density) can be varied without losing the fusion power substantially as long as the core pressure (2 n_oT_o) is kept unchanged and T_o is higher than 7-8 keV. For our proposal, we choose the minimum core temperature (7-8 keV) as an operational temperature and the maximum core density, determined by the beta limit, as an operational density.

For ignition, the self heating power flux (q_{self}(MWm^{-2})) must be greater than the sum of the conductive and convective heat fluxes at the barrier-mantle boundary, i.e., at $r = r_c$

$$q_{cond}(r_c)+q_{conv}(r_c)\;<\;\;q_{self}(r_c)\quad\text{where}$$

$$q_{self}\;=\;\;C\cdot n_o^{\,2}\cdot T_o^{\,2}\cdot F(T_o,Z_{eff})(r_c/2)\,,$$

$$q_{cond}(r_c)=C^*(C_m\;n_m\chi_m/n_o\Delta_m)\cdot n_oT_o\quad\text{and}$$

$$q_{conv}(r_c)=C^*\left(5C_bD_b\;\;/\Delta_b\right)n_oT_o$$

Definitions of quantities such as χ_m, Δ_m are given in Fig.1b. The thermal diffusivity, χ (T, ∇T) is a function of T and ∇T. C_m is defined as $q = -\,n\chi\nabla\,T)_{r=rc+0} = C^*C_m\,n_m\,\chi_m\,(T_o,\,T_o\,/\,\Delta_m).T_o\,/\,\Delta_m$. The constant C^* is 0.16 MJm^{-3}. D_b (n, ∇n) is diffusion coefficient at $r = r_c-\Delta_b+0$ and is defined similarly as χ_m (χ at $r = r_c+0$). For constant D and χ, C_b and C_m are unity.

In the IDB discharge, the convective heat flux is small in the mantle

$$\text{i.e.,}\;\;(\Delta_b/5\Delta_m)\cdot(n_m/n_o)\cdot C_m\chi_m\;>>\;C_b\,D_b\,.$$

In such a case, the ignition condition is expressed by

$$n_mT_o\tau_E^*>\cdot(n_m/n_o)^2/F$$

where τ_E^* is almost the energy confinement for the case without SDC.

$$\tau_E^*=0.43\;r_c\cdot\Delta_m/C_m\cdot\chi_m$$

The fusion triple product ($n_mT_o\tau_E^*$) for ignition is $(n_m/n_o)^2$ times less than the conventional Lawson value for the case with flat density profile (n_o = n_m). Thus attainment of ignition becomes much easier with SDC core. In other words, the alpha power is $(n_o/n_m)^2$ times higher compared with the flat case and thus the ignition becomes easier.

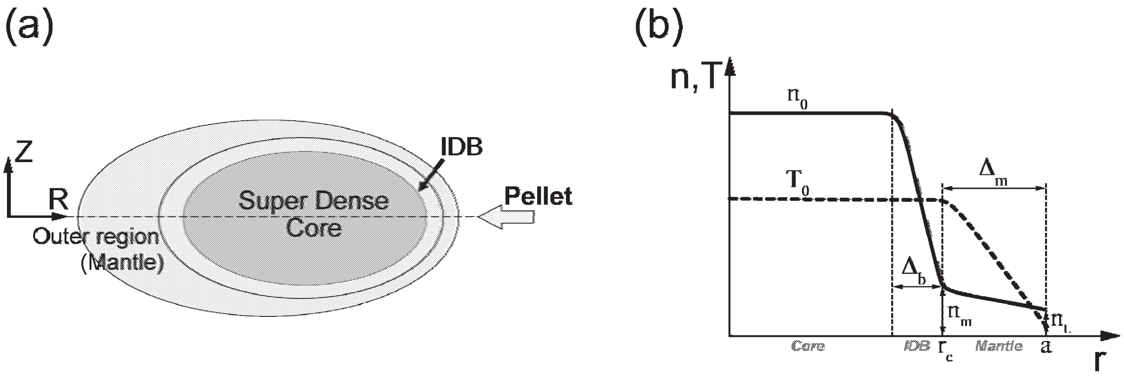

Fig. 1 Illustration of an SDC plasma (a): Super dense core plasma is surrounded by IDB (internal transport barrier). Outside the IDB, low density mantle region exists. (b): Simplified density and temperature profiles for SDC plasma.