# §14. Analysis of Density Limit with Radial Profile of Electric Field in Helical Plasmas

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The study of the plasma confinement physics is the urgent task of nuclear fusion research. The phenomena of the density limit control how the plasma performance is achievable. In tokamaks, the properties of the confinement and the density limit are dictated. In helical plasmas, attention has been paid to the phenomena of the density limit. The helical plasmas have an additional freedom in magnetic geometry, which is utilized to investigate the transport mechanisms. The density limit phenomena in toroidal helical plasmas were examined with the analytic point model. In tokamak plasmas, the importance of the plasma dynamics and the critical density in the vicinity of the strong sources of impurities was discussed. Since the radial electric field determined by the ambipolar condition in a non-axisymmetric system is known to affect the confinement property significantly, theoretical analysis of the density limit including the radiation loss in helical plasmas is necessary with the effect of the ambipolar radial electric field in a set of transport equations. To examine the density limit for the thermal stability in helical plasmas, we add the term of the radiation loss rate of the energy to the temporal equation of the electron temperature in a set of one-dimensional transport equations. The combined mechanism of the transport and the radiation loss of the energy is discussed. The dependence of the electron temperature profile on the electron heating is studied when the radiative cooling rate is included in a set of the transport equations to examine the density limit in helical plasmas. The parameter dependence of the critical density is derived, when the effect of the radial electric field is included. The dynamics of the $E_r$ transition point can be shown when the competition between the transport loss and the radiative loss is studied.

As an example, we take an oxygen plasma with $n_{oxygen} = 0.01n$, where $n_{oxygen}$ is the density of the oxygen. For simplicity, the density profile is used for the Internal Diffusion Barrier (IDB) plasma as the temporally fixed density profile in the calculation here. We examine the temporal evolutions of the electron and ion temperatures, and the profile of the radial electric field from the ambipolar condition. The radial profiles of the radiative cooling rate $P_Z$ are examined in the region $0.8 < \rho < 1.0$. The profiles of the electron temperature are also examined with two cases of the electron heating. In the case that the electron heating is 3.7MW, the sharp decrease of the electron temperature is shown near the edge. This is because the radiative loss rate rapidly increases at the low temperature ($T_e < 50$eV). The effect of the ambipolar radial electric field is included in this calculation. The radial profiles of the ambipolar radial electric field in two cases of the electron heating are studied in the cases of 3.7MW and 3.71MW. Even if there is a little difference between two values of the electron heating power, the phenomena like the transition near the edge in the $E_r$ profile is obtained only in the case that the electron heating power is 3.7MW. The value of $E_r$ radially changes from the negative one to the value which is close to zero near the edge. Therefore, the value of the turbulent heat diffusivity is significantly reduced due to the steep gradient of the radial electric field near the edge, when the electron heating power is 3.7MW. Next, we determine the necessary (minimum) heating power in order to realize the stationary solution in the presence of the radiative loss and the transport loss. We use temporally fixed density profiles for IDB plasmas in this calculation. The necessary value $P_{min}$ of the electron heating power to obtain the stationary state of plasmas is the function of the line-averaged density $n_c$. The condition $P_e > P_{min}$, can be shown as $n < n_c$, where $P_e$ is the electron heating power. The minimum value $P_{min}$ is also the function of the temperature $T_e$ and the condition $P_e > P_{min}$, can be shown as $T_e > T_{ec}$. The dependence of the critical density $n_c$ on the minimum electron heating power $P_{min}$ is also given in Fig. 1. The critical density $n_c$ shows the relation as the function of the minimum electron heating power $P_{min}$, with the solid line in Fig. 1. The Sudo scaling of the density limit was shown from the experimental results in helical plasmas as $n^S \propto P^{0.5}$, where $P$ is the absorbed power. The dependence of the critical density $\bar{n}_c \propto P_{min}^{0.614}$ on the minimum electron heating power derived in the case of the IDB here is slightly stronger than the case of the Sudo scaling of the density limit.

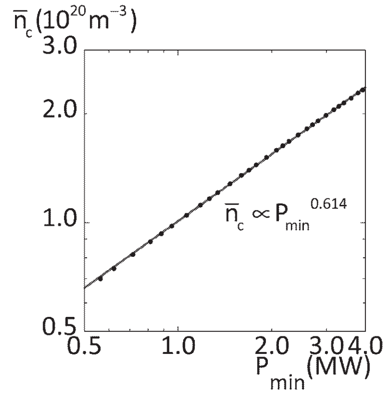


Fig. 1: The dependence of the critical density on the heating power.