Density dependence of tokamak equilibria with consistent bootstrap current and steady-state temperature profile including burning and radiation loss effects

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ITER[1] construction has progressed and JT-60SA[2] device is now under integrated commissioning. Design studies of DEMO have been conducted in Japan and overseas. In Japan, JA DEMO concept was proposed in 2014[3]. Its major radius is 8.5 m, the toroidal magnetic field is 5.94 T, the aspect ratio is 3.5, ellipticity is 1.65, triangularity is 0.33, and the plasma current is 12.3 MA. The target normalized beta $\beta_{\rm N} = 3.4$, the bootstrap current fraction $f_{\rm BS}$ is around 60%, and the fusion power $P_{\rm fus}$ is 1.5 GW level in steady-state operation.

In such design studies, the pressure profile should be consistent with steady-state density and temperature profiles of their transport equations, and the current density should include bootstrap current consistent with the density and temperature profiles. Therefore we must comfirm, if such self-consistent equilibria with the parameters proposed in JA DEMO 2014 exist. However, transport properties of such burning plasmas is not fully understood. Therefore, our motivation in this paper is to find trends in the heat transport properties of burning plasmas.

Based on this motivation, we have utilized the integrated model GOTRESS+ code[4] that calculates an MHD equilibrium of which the bootstrap current density profile consistent with temperature and density profiles, where the temperature profile satisfies steady-state transport equations of which transport coefficients consistent with the MHD equilibrium profiles. Therefore, we can obtain equilibria as consistent as possible for given density profile, heating and current drive.

We plan to find dependency and sensitivity of the consistent equilibria and their figure of merits on limited number of controllable parameters by using the GOTRESS+ code. In the present study, the density dependence of the consistent temperature and safety-factor profiles, $P_{\rm fus}$, $\beta_{\rm N}$, and $f_{\rm BS}$ is investigated. The electron density $n_{\rm e}$ was varied by $1.5\times10^{19}\ {\rm m}^{-3}$ at the center for a fixed pedestal density profile as shown in Fig. 1 (left). The total current was given and fixed to be $I_{\rm p} = 11.9$ MA. The toroidal field strength 5.95 T as well as the cross-sectional shape were fixed. The heating input was the neutral beam. If the sum of the beam driven and the bootstrap currents were less than the given total value, an additional current with a given radial profile was included. Note that the pedestal profile was obtained by the EPED1 model[5]. The Bohm/gyroBohm model was used for the heat transport. The calculations were performed assuming dueterium, tritium, helium, and iron as ion species. Consistently obtained electron temperature $T_{\rm e}$ and safety factor q profiles are shown in Fig. 1 (right). The $T_{\rm e}$ decreased as the $n_{\rm e}$ was increased. The q profile remained almost same, since the fractions of beam driven and bootstrap currents to the total current were small. Figure 2 shows dependency of $P_{\rm fus}$, $\beta_{\rm N}$ and $f_{\rm BS}$ the central $n_{\rm e}$. Although $T_{\rm e}$ decreased, $P_{\rm fus}$, $\beta_{\rm N}$ and $f_{\rm BS}$ increased as the central $n_{\rm e}$ is increased almost linearly in this density range.

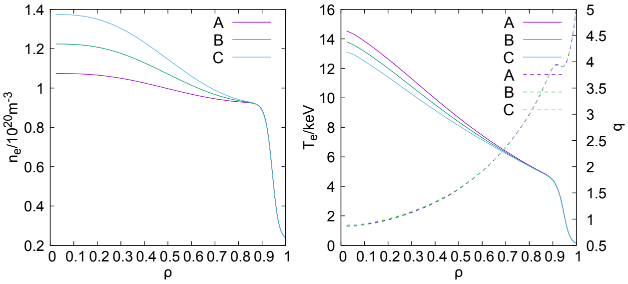

Figure 1: Electoron dencity (left), electron temperature and safety factor (right) profiles.

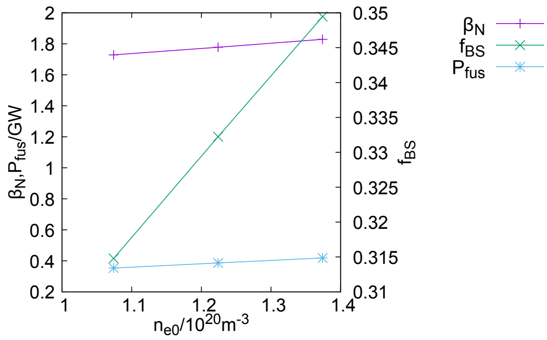

Figure 2: Density dependence of fusion power, normalized beta and bootstrap current fraction.

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