Current ramp-up scenario with reduced central solenoid magnetic flux consumption in JT-60SA

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1. Introduction

The amount of magnetic flux swing capability of central solenoid (CS) is a fundamental parameter of a tokamak reactor, since it affects the overall size and the output power of the reactor. If it is required that the plasma current should be ramped-up solely by the CS induction, the minimum size of the CS imposes a strong constraint on the reactor designs. In this study, we have investigated reduction of the CS flux required in the current ramp-up phase in JT-60SA using an integrated modeling code suite (TOPICS). In the previous study on current ramp-up with reduced CS flux consumption in JT-60SA, we developed a scenario in which the plasma current is ramped-up from 0.6 MA to 2.1 MA without additional CS flux consumption by overdriving the plasma current using neutral beams (NB) and electron cyclotron (EC) waves[1]. The investigation of the ramp-up scenarios with several prescribed density profiles revealed that a pressure profile with an H-mode pedestal and a wide internal transport barrier (ITB) whose foot location is at a large minor radius is required in order to obtain a large bootstrap current within the MHD stability limit. However, the pressure profiles were strongly dependent on the prescribed density profiles in the previous study. If the particle transport is solved, the width and the location of the density ITB might be different from the prescribed density profiles. Therefore, in this study we investigate the possibility of modification of the pressure profiles using the heating and current drive (H&CD) actuators in JT-60SA by solving both the particle transport and the thermal transport.

2. Modeling tools and assumed experimental conditions

TOPICS is an integrated modeling code suite and its main part solves the 1-D transport equations in accordance with the 2-D free boundary equilibrium. Several turbulent models can be used for the integration of the anomalous heat transport in TOPICS. Among them, we use CDBM model which demonstrated its ability to reproduce plasma profiles with ITB in JT-60U[2,3]. As for the particle transport calculation, we assume that the anomalous particle diffusivity is proportional to the thermal diffusivity according to experimental results of JT-60U. In the reversed shear plasmas on JT-60U, the effective particle diffusivity in the ITB region was estimated to be 0.04-0.2 times the ion thermal diffusivity when only the diffusion term was considered[4]. Thus, we assume an effective anomalous particle diffusivity $D_{\mathrm{ano}} = 0.2 \times \chi_{\mathrm{CDBM,i}}$ and calculate the particle transport assuming that the particle diffusivity is a sum of neoclassical and anomalous diffusivities with zero particle pinch velocity. The neoclassical diffusivity is needed for including a strong neoclassical diffusion inside the reversed shear region. Particle sources are NBI and the edge gas puff. The volume averaged density is feedback controlled by the edge gas puff.

JT-60SA will be equipped with two tangential negative ion based neutral beams (NNB), 24 positive ion based neutral beams (PNB) and a steerable EC wave launcher. The beam energy of the NNB will be 500 keV while that of the PNB will be 85 keV. One of the NNB will be injected on-axis and the other will be off-axis to the plasma magnetic axis, which can be used to modify the current profile, and each beam power will be 5 MW. There will be three groups in the PNB, which will be co-tangential beams, counter-tangential beams and perpendicular beams to the plasma current. Co- and counter-tangential beams consist of four beams with 1 MW power each, respectively, and perpendicular beams consist 16 beams with 1 MW power each. The maximum power of the EC wave will be 7 MW.

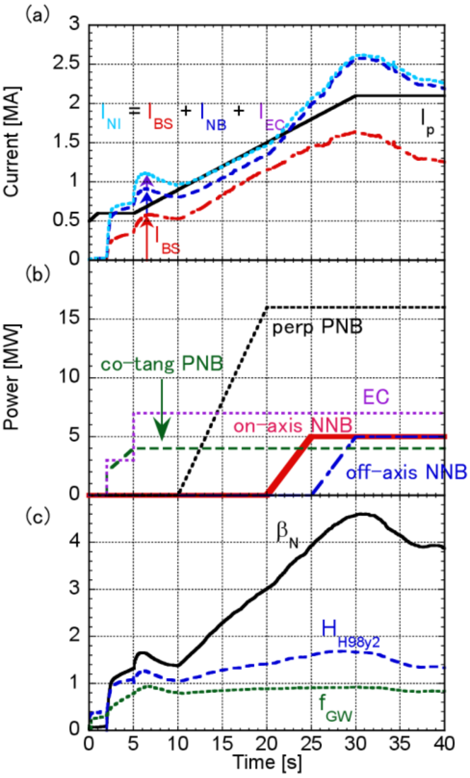

Figure 1. The TOPICS simulation of the current ramp-up scenario from 0.6 MA to 2.1 MA without resistive flux consumption. Time evolutions of (a) the plasma current, the bootstrap current and non-inductively driven current, (b) input powers used for the auxiliary heating and current drive and (c) the confinement enhancement factor (H_{H98y2}), the ratio of the electron density to the Greenwald density limit (f_{GW}), the normalized beta (β_{N}) .

3. Controllability of density and temperature profile during current ramp-up

Figure 1 is one of the results of the ramp-up scenario simulation. At the low current (0.6 MA) phase, only co-tangential PNB and EC can be used because shine through losses of on- and off-axis NNB and perpendicular PNB are large. Then, the plasma current is overdriven using co-tangential PNB and EC from 2 s. The toroidal injection angle of EC wave is 10 degrees in the co-direction and the EC is locally absorbed at $\rho = 0.45$. On the other hand, once the plasma current exceeds 1 MA and the electron density becomes higher than 2 x 10^{19} m^{-3}, shine through losses of on- and off-axis NNB and perpendicular PNB become less than 5%. The electron density in the scenario is relatively high and the fraction of the electron density to the Greenwald density limit (f_{GW}) is kept approximately 0.8 throughout the current ramp-up in order to obtain a high bootstrap current fraction. The confinement enhancement factor from ITER-98(y,2) scaling (H_{H98y2}) is less than 1.7 and the normalized beta (β_{N}) is less than 4.6.

The response of the density and the temperature profiles to the change in H & CD input is investigated at the low current phase (0.6 MA at 5 s) by changing a fraction of the input power of co-tangential PNB and EC while the total power is kept 7 MW. As shown in Fig. 2, a broader ITB in the density and the temperature profiles are formed when 4MW co-tangential PNB and 3MW EC are injected. With only EC, the width of ITB becomes narrower and the ITB foot moves slightly inwards. As a result, the bootstrap current reduces. If the location of EC is moved from ρ = 0.45 to ρ = 0.55 by changing the injection angle of the EC wave, the modification of the q-profile becomes small because the current drive efficiency decreases. As a result, the ITB becomes weak and the bootstrap current reduces more than 25 % although the ITB foot is moved outward. The current drive efficiency of co-tangential PNB is greater than EC. Therefore it is better to use co-tangential PNB with assist of EC for obtaining not only a large NB driven current but also a large bootstrap current by forming a broader pressure profile.

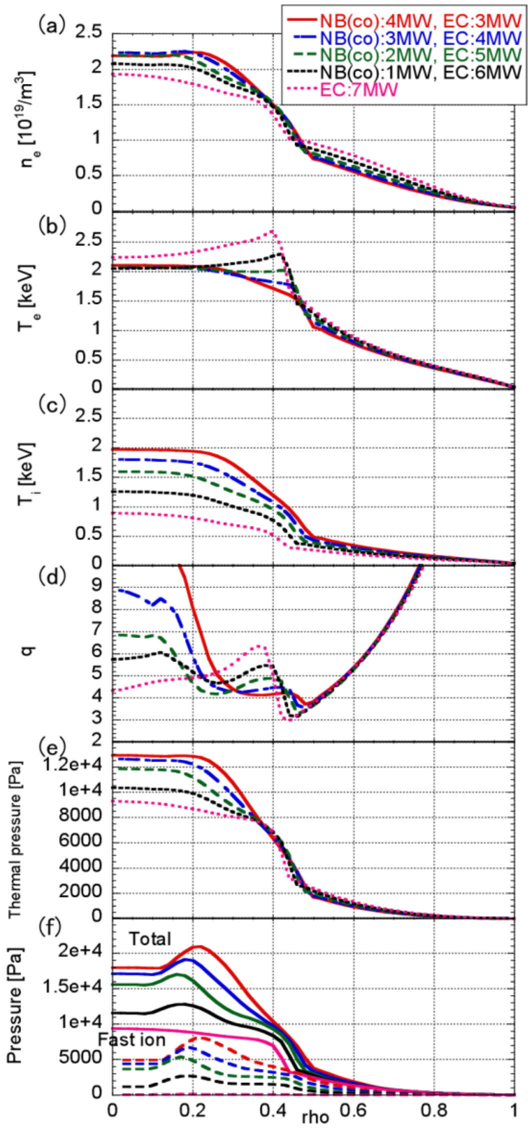

Figure 2. The change of (a) the density profile, (b) the electron temperature profile, (c) the ion temperature profile, (d) the safety factor profile, (e) the thermal pressure profile and (f) the total pressure profiles and the fast ion pressure profiles at the low current phase (0.6 MA at 5 s) in the scenario shown in figure 1 when input power fraction of co-tangential PNB and EC is changed.

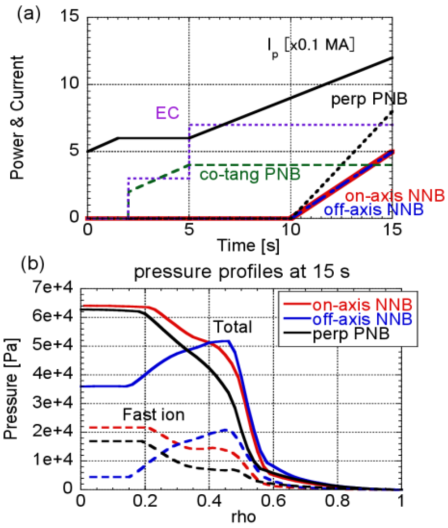

Figure 3. (a) Time evolutions of the plasma current and input powers. Note that on-axis NNB, off-axis NNB and perpendicular PNB are not injected simultaneously but alternatively. (b) The difference of the pressure profile at 15 s in the cases when the additional input power is on-axis NNB, off-axis NNB or perpendicular PNB.

As for the investigation of the response of the density and the temperature profiles to the change in H & CD input at the middle current phase (1.2 MA at 15 s), three scenarios are calculated. As shown in Fig. 3(a), on- and off-axis NNBs or perpendicular PNB are started to be injected in addition to 4 MW co-tangential PNB and 7 MW EC from 10 s and ramped-up to 5 MW or 8 MW at 15 s, respectively. ITB foots can be moved outward from the position at 10 s ($\rho = 0.52$) in all the three cases, as shown in Fig. 3(b). Among them, the largest ITB foot radius can be obtained by off-axis NNB. Therefore, this case might be suitable for further H & CD. However, the bootstrap current in the off-axis NNB case is 0.74 MA and slightly smaller than that in the on-axis NNB case (0.82 MA) and the perpendicular PNB case (0.84 MA) because the ITB width becomes narrower due to a strong neoclassical diffusion inside ITB which is caused by a sharp rise of the safety factor. The currents driven by on-axis NNB and off-axis NNB are large and the overdriven currents are more than 0.4 MA. Therefore, the total input power required for overdriving the plasma current can be reduced and a gentler pressure gradient which is preferable for the MHD stability could be obtained in the on-axis case and the off-axis NNB case by reducing the input power of EC, for example.

4. Summary

The possibility of control of the density and the temperature profiles in the reduced CS flux current ramp-up scenario is investigated using TOPICS. Both in the low current (0.6 MA) phase and the middle current phase (1.2 MA) the pressure profiles can be modified by changing the H & CD method. The optimization of the pressure profile considering the ideal MHD stability is remained as a future work.

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