Simulations of ITER and DEMO plasmas during pellet operation using BALDUR code with a theory-based toroidal velocity model

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Introduction

The injection of small solid deuterium-tritium pellets has been demonstrated in various tokamak experiments that the pellet injection can give rise to the enhancement of the central plasma density and yield fusion performance to be in a more desirable range [1]. Moreover the transition from L-mode to H-mode can be accessed through pellet operation [2]. The pellet injection, as it entered into a hot plasma, also perturbs surrounding environment. In this work we investigate the modification of the toroidal rotation and the radial electric field after the pellet injection in ITER and EU-DEMO using 1.5D BALDUR integrated predictive modeling code [3].

Neutral Gas Shielding Model

The neutral gas shielding model for ablation of frozen hydrogenic pellets was developed by Milora and colleagues and has been integrated into BALDUR code [4]. The model accounts for the effects of 1) an initial Maxwellian distribution of incident electron energies; 2) a cold plasma shield outside the neutral shield; 3) energetic neutral beam ions and alpha particles; and 4) self-limiting electron ablation in the collisionless plasma limit. The pellets in this study were launched into a tokamak from low field side (LFS). As it traveled into the targeted plasma, the pellet particles near the surface are subsequently ionized due to collision with background ion and electron plasma and neutral particles from neutral beam injection heating. This leads the formation of neutral cloud around the pellet material. The rate of the ablation process is approximately given by [4]

$$\dot{r}_p = -1.25 \frac{\int_{r_p}^{r_0} n^0 dl}{2 r_p n_s^m} \left(q^0 r_p \frac{\gamma - 1}{2} \right)^{1/3} \tag{1}$$

where q^0 is the net energy flux, $\gamma = 7/5$ the ratio of specific heats for hydrogen gas, m_p the mass of a proton, A_p the atomic mass number of the pellet species, n^0 the atomic density in the neutral cloud, r_0 the radius of the neutral cloud. The detailed calculation was presented in [4].

Toroidal Rotation Model

The toroidal rotation of the plasma is mainly contributed by two parts: neoclassical toroidal viscosity (NTV) and ion cyclotron resonance frequency (ICRF) heating, in which the auxiliary heating includes the effects of neutral beam injection (NBI), ion cyclotron resonance frequency (ICRF) heating, and lower hybrid (LH) heating. The toroidal rotation due to the auxiliary heating, in general, is much smaller than the other component from NTV; therefore, it was excluded in this study. The toroidal velocity component from NTV is caused by symmetry breaking of a non-axissymmetric field and has the form [5]:

$$v_{\phi,NTV} = \frac{1}{eZB_\theta}\left(3.54 - \left(\frac{r}{R}\right)K_l\right)\frac{dT_i}{dr} \tag{2}$$

Results and Discussion

The BALDUR integrated predictive transport modeling code with is used to carry out the simulations for two designs: ITER with the designed parameter ($R = 6.2$ m, $a = 2.0$ m, $I_p = 15$ MA, $B_T = 5.3$ T, $\kappa_{95} = 1.70$, $\delta_{95} = 0.33$ and $n_l = 1.0 \times 10^{20}$ m^{-3}) [6], and EU-DEMO with the designed parameters ($R = 9.0$ m, $a = 2.25$ m, $I_p = 30.5$ MA, $B_T = 7.36$ T, $\kappa_{95} = 1.70$, $\delta_{95} = 0.33$ and $n_l = 1.03 \times 10^{20}$ m^{-3}) [7]. The pellet ablation is described by NGS model, while an anomalous transport is calculated using the MMM95 transport model. The boundary condition are computed through the pedestal model based on magnetic flow shear stabilization.

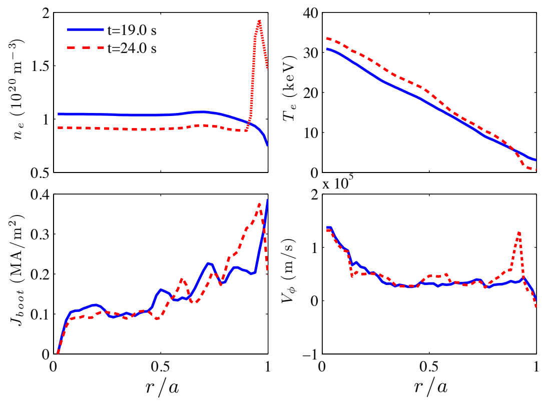

Figure 1: Comparison of the plasma profiles when pellets enter the target plasma in ITER.

Figure 1 illustrates the simulation results of the electron density n_e, the electron temperature T_e, the bootstrap current J_{boot}, and the toroidal velocity V_ϕ as predicted for ITER. The blue solid lines and the red dashed lines respectively represent the profiles before and after the pellet operation. The deuterium pellets of radius 3 mm and speed of 300 m/s were launched from LFS during time of $t = 20 - 70$ s. The launching frequency is 8 Hz. We will refer this injection scheme as Scenario I. After the pellets were released, one can see an overshoot in the density profile due to mass deposition of the pellets. The electron temperature also drops significantly near the edge, while it slightly increases in the central core area. The increased particle density also leads to an increase of the bootstrap current density near the edge of the plasma. The toroidal current is slightly suppressed near the edge of the plasma because of the increasing particle density in the local region. We also observed a peak of the toroidal current where the gradient of the electron temperature has the largest value.

While injection of small pellets at low speed is feasible for our current technology, launching the pellets of very large size and high speed into dense plasma is still scientifically interesting. In this part, we simulate the plasma profiles after the pellet injection as obtained by using EU-DEMO design. The pellets of radius 9 mm and speed of 8 km/s are injected from LFS plasma. The frequency of the pellet injection is 1 Hz. The time period of the inject is $t = 20 - 70$ s. This injection procedure will be called as Scenario II. The toroidal speed also shows larger value than the other case.

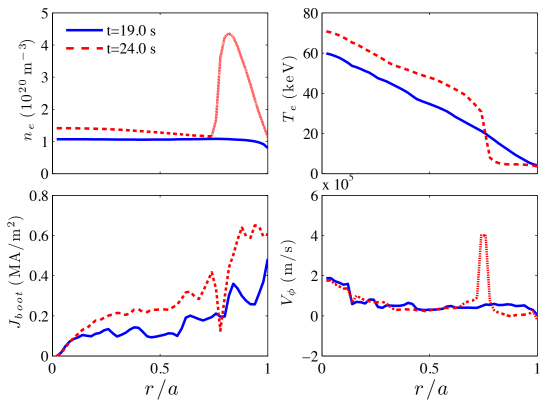

Figure 2: Plasma profiles in EU-DEMO before ($t = 19.0$ s) and 4 seconds after ($t = 24.0$ s) pellet injection. Note that the pellet size and speed are 9 mm and 8 km/s. The injection frequency is 1 Hz.

Figure 2 shows the plasma profiles before and after the pellet injection. Under this circumstance, the pellet operation results in an increase of the electron density and the electron temperature at the central core region. The size of the pellet used in Scenario II is substantially larger than that in Scenario I. Thus pellets are able to penetrate the plasma deeper and deposit larger amount of pellet material. This also leads to enhancement of the bootstrap current throughout the plasma region.

It is known that the toroidal rotation plays a crucial role in the mechanism of flow shear suppression for ITB formation. One quantity that plays crucial role such formation is the radial electric field which can be computed from the radial force balance equation:

$$E_r = v_{\phi i} B_\theta - v_{\theta i} B_\phi + \frac{Z_i}{n_i} \frac{dp_i}{dr}. \quad (3)$$

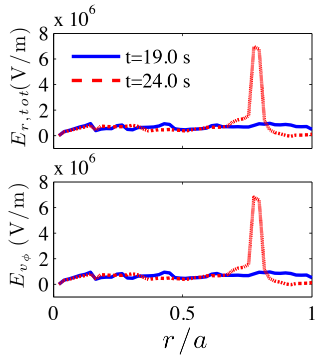

Figure 3: The radial electric field as simulated from EU-DEMO.

The contribution from each term fo the radial electric field as a function of a minor radius is presented in Figure 3 for EU-DEMO and Figure 4 for ITER plasma. As can be seen in Figure 4, the radial electric field E_r is dominated by the toroidal velocity component. The poloidal velocity and the neoclassical temrs are comparable. Consequently they tend to cancel each other. The radial electric field from the toroidal velocity exhibits similar behavior as the toroidal velocity. Both of them show significant reduction near the plasma edge, and a peak at the same location of the density profile.

Conclusion

The impacts of pellets injected from the LFS on the plasma core and edge in ITER, and EU-DEMO are carried out using the 1.5D BALDUR integrated predictive modeling code combined with the NTV model and the NGS pellet ablation model. It is found that injection of pellets from LFS can enhance an increase in the plasma average density in the tokamak devices. As the particle density deposited in the plasma, the bootstrap current fraction increases. The toroidal rotation is suppressed near the plasma edge, but shows an increasing value at the same location of density peak due to the pellet injection. The change in the toroidal velocity leads to a local perturbation in the radial electric field through the radial force balance equation which is dominated by the toroidal velocity term.

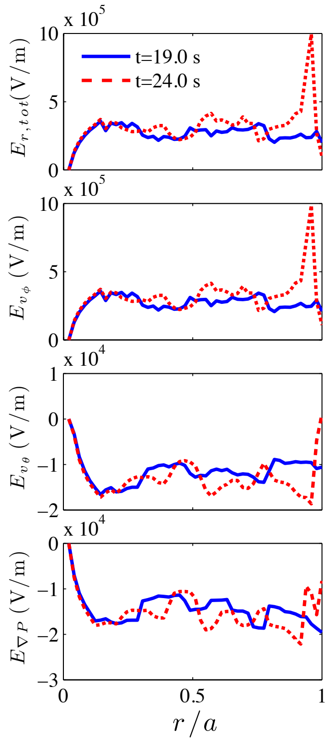

Figure 4: The radial electric field and its contribution from each term as determined from the radial force balanced equation. Data are simulated for ITER plasma after the pellet operation.

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