

Pellet Injection in ITER with ∇B -induced Drift Effect using TASK/TR and HPI2 Codes

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Abstract. the impact of pellet injection in International Thermonuclear Experimental Reactor(ITER) are investigated using integrated predictive modeling codes TASK/TR and HPI2 . In the core, the plasma profiles are predicted by the TASK/TR code in which the core transport models consist of a combination of the MMM95 anomalous transport model and NCLASS neoclassical transport. The pellet ablation in the plasma is described using neutral gas shielding (NGS) model with inclusion of the ∇B -induced $\vec{E} \times \vec{B}$ drift of the ionized ablated pellet particles. It is found that the high-field-side injection can deposit the pellet mass deeper than the injection from the low-field-side due to the advantage of the ∇B -induced drift. when pellets with deuterium-tritium mixing ratio of unity are launched with speed of 200 m/s, radius of 3 mm and injected at frequency of 2 Hz, the line average density and the plasma stored energy are increased by 80%and 25%respectively. The pellet material is mostly deposited at the normalized minor radius of 0.5 from the edge.

1. Introduction

The injection of small frozen hydrogenic pellets in fusion devices has become an important technique for providing efficient fueling and density profile controlling [1]. Much effort in the past in terms of both experimental and theoretical work has been intensively devoted to understand subsequent plasma behaviors due to pellets in order to sustain nuclear fusion performance to achieve a regime for commercial nuclear fusion power plants [2, 3]. Several experiments and simulations also demonstrated that the pellet injection can penetrate deeply into plasma core depending on size, speed, injection frequency, and launching position [4, 2]. It has been shown that the pellet injection is an effective method to produce the peaked density profile in large tokamaks [4]. However, the interaction of pellet material and background plasma is complex. In this work, we explore the condition of pellet injection to achieve the highest performance.

Since the early experiments performed on ASDEX Upgrade, it has been reported that the high field side (HFS) injection of pellets could improve fueling efficient and yields deeper penetration depth compared to the low field side (LFS) injection [5]. This result was subsequently confirmed by various tokamak experiments [6, 7, 8]. Thus, the high speed pellet injections from HFS is considered as a promising tool for efficient fueling in future tokamak devices [2]. For ITER and

its successor devices, i.e. Demonstration Fusion Power Plants (DEMOs) [9], pellet injection will be also one of the main plasma density control tools. However, to extrapolate the result from the present-day tokamak to a larger one is not straightforward and well elucidated yet. Using an integrated transport analysis code TASK/TR [10], this work aims to investigate impacts of high-speed high-field-side (HFS) deuterium pellet injected to the ITER plasma.

This paper is organized as followed. In section 2, the computational model for core plasma transport, a theory-based toroidal velocity calculation, and pellet injection applied in this study are the subjects of discussion. In section 3, the predicted plasma profiles before and during pellet injection from the three tokamak devices are presented. we also show in this section results of analysis of the toroidal velocity, the radial electric field, and the bootstrap current in response of the pellet injection. Summary of the present work is given in section 4.

2. Methodology

2.1. TASK/TR Code

The TASK/TR code is a one-dimensional tokamak transport code that has been developed to analyze the time evolution of a burning plasma accompanied with fusion reaction. Four constituent particles of a core plasma considered in this work include electron, deuterium, tritium, and α -particle produced by the nuclear fusion reactions and impurity ions. The plasma transport in the core region is described by using the multimode core transport model (MMM95) which consists of the Weiland model for the ion-temperature-gradient (ITG) and trapped electron modes (TEM), the Guzdar-Drake model for drift-resistive ballooning modes, as well as a smaller contribution from kinetic ballooning modes [11].

2.2. Pellet Ablation and ∇B -Induced Drift Models

As the frozen pellet entered into the hot and dense plasma, energetic particles, such as background ion and electron plasma, neutral particles from neutral beam injection (NBI) heating, impinge the pellet particles in the surface, where they are subsequently ionized. This causes the formation of a symmetric and spherically expanding neutral cloud of the pellet material. According to the neutral gas shielding (NGS) model [12] The rate of the ablation process (\dot{N}) is approximately expressed by

$$\frac{dN}{dt} = 1.12 \times 10^{16} n_e^{0.3333} T_e^{1.64} r_p^{1.33} M_i^{-0.333}, \quad (1)$$

where T_e and n_e are the electron temperature in eV and the electron density in cm^{-3} , respectively, r_p the pellet radius in cm, and M_i the atomic mass of the pellet material.

As a pellet travels along its trajectory toward the plasma core, the pellet ablatant also experiences the apparent drift in the major radius direction which is caused by an $\vec{E} \times \vec{B}$ drift that arises from a vertical polarization of the ionized part of the ablation cloud due to ∇B and curvature-induced charged particle drift [13]. To account for this drift effect, Pegourie et al. determined the cross-field drift velocity (V_D) can be written as

$$\dot{V}_D = \frac{2(p_0 - p_\infty)}{n_0 m_i R} - V_D \frac{2B_\phi^2}{\mu_0 C_A n_0 m_i Z_0}, \quad (2)$$

where p_0 and p_∞ respectively are the initial pressure inside the plasmoid (refers to the high density blob plasma) and the pressure of the background plasma, n_0 the initial density of the plasmoid, Z_0 is the initial thickness of the ablatant cloud, m_i is the ion mass, and C_A is the speed of the Alfvén wave [14].

In this work to account for the ablation of the pellet material and ∇B -induced drift effect, we employ the predictive simulation code HPI2 developed by Pégourié and co-workers [14] and it is integrated with the TASK/TR code.

3. Results of Numerical Analysis and Discussion

In the present work, we analyze the evolution plasma profile for ITER reactor with consideration the pellet injection. The transports of the core plasma are computed within the integrated predictive modeling code TASK/TR and the mass deposition profiles due to the pellet injection are predicted by the HPI2 code. An anomalous transport is calculated using the MMM95 transport model, while the neoclassical transport is computed using the NCLASS module. At the steady state, we adopt the parameters employed in the design of the ITER as follows: plasma major radius $R = 6.2$ m, minor radius $a = 2.0$ m, ellipticity $\kappa = 1.7$, triangularity $\delta = 0.33$, toroidal magnetic field $B_\phi = 5.3$ T, plasma current $I_p = 15$ MA, auxiliary heating power $P_{aux} = 53$ MW. The density at the core and the edge are 7×10^{19} and $2 \times 10^{19} \text{ m}^{-3}$, respectively. The temperature at the core and the edge are 20 and 2 keV, respectively.

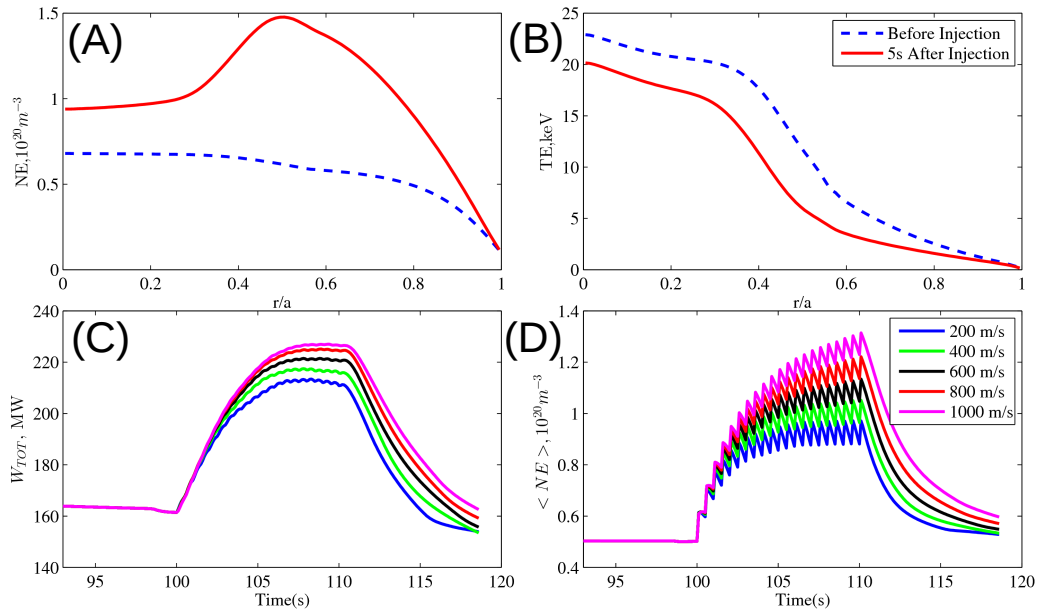


Figure 1. (A) The electron density profiles before the injection and 5 seconds after the first injection. The mass deposition profile of a pellet is shown in a dashed line. (B) The electron temperature profiles before the injection and 5 seconds after the first injection. (C) The plasma stored energy (W_{TOT}) at different injection speeds. Note that the pellets with the injection frequency of 2 Hz and the radius of 3 mm are launched during time between 100 and 110 seconds. (D) The line average of the electron density

For ITER, the pellet injectors is planned for both the low-field side (LHS) and high-field side (HFS) injections. Each injector is capable of launching pellet up to 20 Hz injection frequency with cylindrical pellets with a diameter of 5 mm. Like other simulations [2, 15], we found that the HFS injection shows more promising fueling method over the LFS injection. However, owing to the limited space of the tokamak core region, the curvature of the guiding pellet tube allows the HFS injection with a maximum speed of 300 m/s [16].

Figure 1A and 1B shows the electron density and electron temperature profiles before the pellet injection and five seconds after pellet injections. Note that pellets with unity ratio between deuterium and tritium are launched with the injection frequency of 2 Hz, radius of 3 mm, and speed of 500 m/s. After pellets are released, it results in a sharp increase in the density profile

near the edge and also lead to a peaked density near the normalized minor radius $r/a = 0.5$. On the other hand, we can see the degradation of temperature profile on both edge and core regions due to energy absorption in pellet ablation process.

Figure 1C and 1D shows the predicted temporal evolution of the total plasma stored energy and the line average of electron density when pellets are injected with frequency of 2 Hz, radius of 3 mm, and the injection speeds vary between 200 - 1000 m/s. These graphs show that pellets can increase the plasma stored energy up to 210-230 MW or 25-35% improvement compared with the plasma stored energy of 165 MW before the pellet operation. We found that there is only 10% difference in the energy stored in the plasma when the pellets were injected with 200 m/s and those injected with 1000 m/s. Thus, launching speed of 200-300 m/s is enough to improve the fusion performance by amount of 25%. In further research, pellet parameters (i.e. injection frequency, mixing ratios, injection angles) and plasma stability should be investigated to find more proper ways for fueling and control ITER plasma.

4. Summary

The effects of pellet injection on the ITER plasma are studied using the HPI2 code and the TASK/TR code. The simulation also takes into account of the ∇B -induced drift effect. The result confirms that pellet launched from HFS yields deeper penetration depth than those launched from LFS. When pellets with deuterium-tritium mixing ratio of unity are launched with speed of 200 m/s, radius of 3 mm and injected at frequency of 2 Hz, the line average density and the plasma stored energy are increased up to 80% and 25% respectively. The pellet material is mostly deposited at the normalized minor radius of 0.5 from the edge.

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