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Impact of fast ions on hydrogen pellet penetrations in the LHD experiment
LHD実験における水素ペレットの侵入長に対する高速イオンの影響

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The pellet penetration during neutral beam injection (NBI) heating is studied in the Large Helical Device (LHD). The ablation profiles and pellet trajectories are compared between simulations and the experiments. The present analysis has pointed out that quantitative importance of the fast-ion flux for evaluating the pellet ablation, in the case where fast ions induced by the NBI heating dominate the shielding effects of the ablation cloud.

1. Introduction

Pellet injection is the most promising technique for efficient fueling of high temperature relevant to fusion reactors. In evaluation of the performance of pellet fueling, the penetration depth inside the last-closed flux surface is one of key parameters. In the case where the injection power is moderate, the ambient thermal electron population carries the dominant heat flux ablating the pellet. The penetration depth thus strongly depends on the electron temperature profile, as described by early NGS models [1]. On the other hand, in the case where the injection power is high, the enhancement of the local ablation rates can occur owing to the interaction of the pellet with high-energy ions and electrons. To present, a number of models for this *over-ablation* were developed but have not yet been tested at the same level with models for thermal electron ablation.

In this paper, we apply the ablation routine of the pellet simulation code, HPI2 [2], to study the interaction between the pellet and fast ions. The simulation results are compared with the Large Helical Device (LHD) experiments for the neutral beam injection (NBI) plasmas. To explain the experimental features for the LHD, we have extended the code to include (1) fast-ion fluxes induced by the tangential NBI heating and (2) an unbalance of ablation rates on two sides of the pellet during the one-side NBI. The parametric dependence of the experimental penetrations is considered. The scaling law for the balanced NBI condition is derived and tested for 300 pellets included in the LHD database.

2. Comparison with experiments

The simulation was applied to the first pellet injected into NBI-heated discharge, where the pellet particle content $N_p = 6\times10^{20}$ atoms, the injection velocity $V_p = 1.1$ km/s, and the heating power $P_{\mathrm{NBI}} = 6$ MW. In Fig. 1, the code prediction for ablation profiles is shown to be in good agreement with the H_α emission profiles. The shallower experimental penetration compared to the Parks scaling is a clear demonstration of the over-ablation due to fast ions. In the simulation, the stopping lengths of the incident fast ions and thermal electrons are evaluated for the ionized and neutral ablation cloud, showing that the fast-ion fluxes penetrate deeply into the ablation cloud, reach the pellet surface, and yields significant enhancement of the local ablation rate. In this circumstance, the ambient thermal electrons stop in the outer part of the neutral gas cloud. The thick ablation cloud expands in the direction opposite to the beam injection, because of the *self-shielding* effect, which is efficient enough for the thermal electron flux to vanish in the ablation cloud before reaching the pellet surface.

Experimentally, the interaction of the pellet with fast ions has also been indicated for the one-side NBI case, by the measurement of the pellet trajectories deflecting in the direction of the beam injection [3]. During the one-side NBI, the ablation rates on two sides of the pellet are unbalanced because the ablation rate is enhanced only on the side exposed to the fast-ion fluxes. The unbalance ablation yields the net mass flow in the direction opposite to the beam injection, which results in the rocket acceleration of the pellet in the beam direction. We apply the HPI2 code to simulate the pellet trajectories observed in the LHD. The simulation including the rocket acceleration has reasonably reproduced the measured pellet location. The simulations have shown that the deflection distance depends mainly on the injection velocity, which is in qualitative agreement with the fact that the toroidal deflection has been observed typically for low-speed inject pellets in the LHD experiments.

3. Penetration scaling for NBI plasmas

To derive a scaling law for the experimental penetration is practical for much faster estimation than the full simulation. For ohmically-heated tokamaks, the NGS scaling law [4] has been derived for the case where the electron ablation is dominant. We derive a theoretical scaling to describe the parametric dependence of the pellet penetration for the balanced NBI condition [5]:

$$\lambda_p^{\rm NBI} = C_p^{\rm NBI} m_{\rm pel}^{0.333} V_{\rm eff}^{0.6} \langle n_{f\infty} \rangle^{-0.2} E_b^{-0.954} a^{-0.6}, \qquad (1)$$

where $C_p^{\rm NBI} = 0.3565$, a is plasma minor radius, $m_{\rm pel}$ (10^{20} atoms) is the pellet content, $V_{\rm eff}$ (m/s) is the effective pellet velocity, $<n_{f\infty}>$ (10^{18}m^{-3}) is the volume-averaged fast-ion density, and E_b (keV) is the beam energy. In deriving Eq. (1), the local ablation model was developed analytically and tested by comparison with the HPI2 code. Figure 2 displays, for the 300 pellet data included in the LHD database, the comparison of the experimental penetration with Eq. (1), showing a reasonable agreement. Here, the deviation of the experimental data from the scaling is significantly smaller than those obtained with the NGS scaling law. To explain this result, we consider the operational regime for the LHD and identify the relative contribution of thermal electrons and of fast ions to the local ablation rate. For typical experimental parameters, the fast-ion fluxes dominate the ablation along the whole pellet penetration. Therefore, the electron temperature is considered not to be an intrinsic parameter in evaluating the pellet penetration in the LHD because direct ablation due to thermal electrons is negligible owing to the self-shielding effect of the ablation cloud against fast ions induced by the tangential NBI at 150-180 keV beam energy.

4. Conclusion

The present analysis has reasonably reproduces the local and global behaviors of the pellet ablation observed in the experiments, and has pointed out the quantitative importance of the fast-ion fluxes in the evaluation of the pellet penetration. For the case where its contribution dominates the direct ablation, as in the LHD, the electron temperature is not an intrinsic parameter describing the pellet penetration.

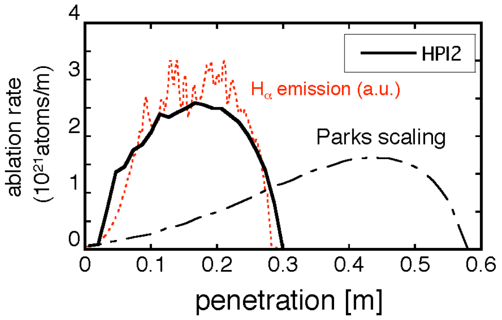

Fig.1. Simulated ablation and measured H_α emission profiles for the balance NBI discharge. A dash-dotted curve is obtained from the Parks model, neglecting effects of fast ions on the pellet ablation.

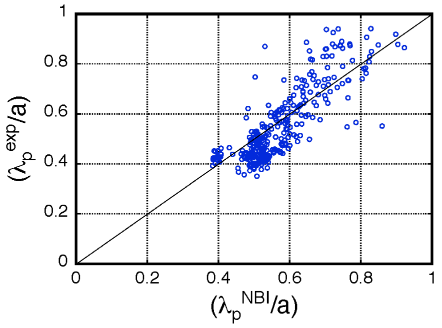

Fig.2. Comparison of the experimental penetrations included in the LHD database with the NBI scaling of Eq. (1).

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