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Steady-state sustainment of divertor detachment with multi-species impurity seeding in LHD

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Divertor detachment was successfully sustained using higher-Z (krypton, Kr) and lower-Z (neon, Ne) superimposed seeding. Plasma radiation could be enhanced at the upstream region in the edge plasma with suppression of impurity accumulation toward the core plasma. Here, the pre-seeded Kr emission was drastically enhanced after the subsequent Ne seeding. Formation of negative radial electric field, E_r, in the edge plasma due to the Ne seeding and inward diffusion due to a hollow electron density, n_e, profile should be a key for the enhancement of the Kr emission and the sustainment of the detachment.

Divertor detachment using impurity seeding is one of the effective operation scenarios to reduce divertor heat loads to lower than 10 MW/m^2 in ITER and fusion reactors. Steady-state sustainment is required for the detachment. Furthermore, to manage the power exhaust, radiation enhancement is required not only in the divertor region but also in the upstream region with suppression of dilution. Therefore, multi species impurity seeding is proposed in JT-60SA [A]. Moreover, it is predicted by the COREDIV code that additional Kr seeding is effective for divertor detachment [B]. In LHD, we have investigated detachment using Ne or Kr seeding individually [C]. Thus, in this study, we attempted to superimposed seeding using Kr and Ne in anticipation of experiments on tokamak devices. Since the cooling rate of Ne reaches a maximum at the electron temperature, T_e, ~ 30 eV while the rate of Kr has a local minimum at T_e ~ 30 eV, it is expected that these impurities could enhance plasma radiation complementarily.

Fig. 1-3 show the plasma behavior using Kr+Ne, Ne, and Kr seeding, respectively. Using Kr+Ne superimposed seeding, the detachment could be sustained for ~ 1 s. On the other hand, using only Ne seeding, the detachment was short-lived. In the case of only Kr seeding, reduction of divertor heat flux, q_{div}, and enhancement of total plasma radiation, P_{rad}, was not significant.

As shown in Fig. 1, Kr was seeded 0.4 s before Ne seeding since the response of Kr is slower than Ne. After the Ne seeding, the plasma was detached and the detachment was successfully sustained ~ 1 s. This detachment was terminated by the limitation of the pulse length of the NBI. The q_{div} decreased by ~ 85% of q_{div} before Kr seeding. The radiation fraction ($f_{rad} = P_{rad}/P_{NBI,abs}$) was ~ 40% which is 10% higher than the case with only Kr seeding and previous sustainment using multi-pulse Ne seeding [C]. Here, P_{rad} and $P_{NBI,abs}$ are total radiation power and absorbed NBI power, respectively. Line-averaged electron density, $n_{e,bar}$, increased due to the ionization of impurities and change of wall recycling. Although NBI port-through power is constant, $P_{NBI,abs}$ increased with increasing $n_{e,bar}$ due to the increase of heating efficiency. $\tau_{E,exp}/\tau_{E,ISS04}$ is ~ 0.8 which is 10% higher than the case with only Ne seeding. Here, $\tau_{E,exp}$ and $\tau_{E,ISS04}$ are energy confinement time evaluated by the experiment and ISS04 scaling, respectively. Kr emission remains very low until Ne seeding, which then triggers KrXIX to increase together with NeVIII.

The direction of E_r plays an important role in this detachment. Using only Ne seeding, positive E_r was formed in the edge plasma after Ne injection as shown in Fig. 2. The positive E_r can exhaust the seeded Ne. Radiation profile and T_e profile indicate that NeVIII, which has the ionization energy of 239 eV, or lower charge states are the dominant radiator. After the Ne seeding, edge T_e decreased due to the ionization of the seeded Ne. Then, P_{rad} in the edge region was enhanced and the plasma was detached. Since the decreased edge T_e recovered with increasing the heating efficiency of NBI, the edge T_e increased. Due to the minor-radially outward shift of the radiation region, the radiative cooling was weakened. Finally, the plasma using only Ne seeding was reattached. Owing to the positive E_r and increase of the edge T_e, the detachment using only Ne seeding was short-lived. In the case of Kr seeding, E_r gradually increased after the Kr seeding and positive E_r was formed as shown in Fig. 3. Moreover, since higher-Z impurities have a lower first ionization energy, Kr is ionized in the more downstream region in the ergodic layer where the friction force is dominant compared with Ne. Therefore, Kr could not penetrate deeply and P_{rad} enhancement was quite small. The moderate q_{div} decrease clearly indicated that Kr only seeding was not effective. On the other hand, in the case of Kr+Ne seeding, negative E_r was formed at the edge region after 4.9 s and a clear decrease in T_e at the plasma edge region was observed due to Ne seeding as shown in Fig. 1. Therefore, Kr could penetrate deeper than the case with only Kr seeding. Finally, radiation was successfully enhanced in the upstream region in the edge plasma compared with the same f_{rad} using only Ne seeding with suppression of impurity accumulation toward the central plasma. Here, E_r increased after 5.4 s. The reason for the increase of E_r can be considered that the measurement position with a Doppler backscattering system was affected by a termination of deuterium gaspuff at 5.3 s.

The direction of diffusion due to a hollow n_e profile can contribute the sustainment of the detachment using Kr+Ne seeding. The T_e at the local maximum of $n_e(r_{eff}/a_{99}\ 0.94)$ was 400 eV after the Ne seeding as shown in Fig. 1. The ionization energies of NeVIII and KrXIX are 239 eV and 785 eV, respectively. Therefore, NeVIII emits outside the position of the n_e local maximum and KrXIX emits inside the position of the n_e local maximum. Here, the direction of the diffusion due to ∇n_e is outward for NeVIII and inward for KrXIX. The inward diffusion can sustain the detachment by holding the Kr slightly inside the LCFS in the case of Kr+Ne seeding while the direction should be outward in the case of only Kr seeding due to inefficient reduction of the edge T_e. The outward diffusion for Ne can exhaust the Ne. It can support the termination of the detachment in Ne only seeded plasmas. Multi-pulse seeding of Ne is a candidate to sustain the detachment, but it is not easy since the reattached plasma shown in Fig. 2 is different from the background plasma, e.g., in $n_{e,bar}$. Density control using further pumping may be helpful. Multiple pulses using moderate Ne seeding could sustain the detachment with f_{rad} ~ 30% 3.

[A] K. Gałązka *et al.*, Contrib. Plasma Phys. **58** (2018) 751.
[B] R. Zagórski *et al.*, Nucl. Fusion **57** (2017) 066035.
[C] K. Mukai *et al.*, Nucl. Fusion **55** (2015) 083016.

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