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Improved screening effect of seeded high-Z impurity through SOL plasma flow enhanced by additional low-Z impurity injection

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Numerical simulations by the integrated divertor code SONIC show that the screening effect on the seeded high-Z impurity in the SOL plasma is improved through the enhancement of plasma flow induced by additional low-Z impurity injection. A single impurity injection of Ar into a steady-state high-beta plasma of JT-60SA results in a high Ar density at the top of SOL plasma, leading to an increase of core Ar density. This issue can be solved with even a small Ne seeding, which reduces Ar density in the SOL and the core plasmas. This is mainly caused by the enhanced friction force due to the higher D^+ parallel flow towards the inner divertor, which is originated from the strong Ne radiation around X-point. We show that the line emission of Ne^{7+} has a key role for the generation of higher D^+ parallel flow.

SONIC: SOL and divertor transport code with kinetic treatment of multiple impurities

The divertor power handling is one of the critical issues for future magnetic fusion devices, such as JT-60SA and ITER. Seeding of impurities such as Ne and Ar into the plasma is regarded as one of the promising methods to mitigate divertor heat load. Impurities dissipate plasma energy by converting kinetic energy into radiation. The impurity radiation in SOL and divertor plasmas contributes to mitigate the heat flux towards divetor plates. Contrarily, the impurity radiation in a core plasma causes a deterioration of plasma performance especially for high-Z impurities. To establish a method for obtaining high impurity radiation power in SOL and divertor plasmas together with low core impurity radiation power by controlling the impurity transport is indispensable for the future fusion devices.

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In order to obtain understanding of impurity transport processes and interactions between plasma and impurity, we have developed the integrated divertor code, SONIC [1]. One of the unique features of SONIC is to compute the impurity transport processes kinetically, while most of other codes treats them fluidly. SONIC provides more precise impurity transport processes, e.g. ionization and recombination of impurities, a kinetic modelling of Coulomb collisions.

In this study, numerical simulations with SONIC on the JT-60SA steady-state high-beta plasma are discussed for the following two cases; Case A: Ar-only seeding (Ar seeding rate of 0.2 Pa m^3/s), and Case B: additional Ne injection (Ne seeding rate of 0.02 Pa m^3/s) to the Ar-only seeding plasma obtained in Case A. In both cases, intrinsic C sputtered from the first wall and the divetors is considered. The seeding locations of Ar and Ne (see Fig. 1), and the input power and particle flux from the core boundary are kept the same throughout the two cases. The simulations show that both Cases A and B result in partial detachment with a similar total impurity radiation power of ~13 MW.

Mechanism of high-Z impurity screening by adding low-Z impurity seeding

A schematic view of the main results for Cases A and B is shown in Fig. 1. As shown in Fig. 2(a), a high Ar density (defined as the sum of all charge states n_{Ar}) is seen around the top of the SOL plasma (TOP) in Case A. In contrast, even a small Ne injection at the seeding rate of 0.02 Pa m^3/s results in lower n_{Ar} in TOP in Case B. The low n_{Ar} in TOP in Case B is mainly due to the higher parallel D^+ flow velocity $\mathbf{u}_{\parallel,\mathrm{D}^+}$ towards the inner divertor (ID) region as shown in Fig. 2 (b). The sum of the friction and thermal forces parallel to the field line $F_{\parallel,\mathrm{fr}} + F_{\parallel,\mathrm{th}}$ of Ar^{10+} is approximately balanced in the high field side in Case B as shown in Fig.2 (c) due to the enhancement of $F_{\parallel,\mathrm{fr}}$ by the higher $\mathbf{u}_{\parallel,\mathrm{D}^+}$ and thus the Ar ions can reach the ID region. On the other hand, in Case A, there exists $F_{\parallel,\mathrm{fr}} + F_{\parallel,\mathrm{th}} < 0$ region between the inner midplane (IM) and the X-point (XP) due to $F_{\parallel,\mathrm{th}}$, which is exerted by the parallel temperature gradient in the detached plasma, i.e. the Ar ions moving towards the ID region are decelerated, or even reflected back towards TOP. Therefore, the additional Ne seeding reduces Ar ions at TOP, which is one of biggest sources for the core Ar ions. This result suggests that the radiation of the core plasma by Ar can be reduced by the small injection of Ne.

The higher $\mathbf{u}_{\parallel,\mathrm{D}^+}$ in Case B is originated from the Ne radiation with the following possible mechanism; First, Ne radiation dissipates the electron energy around XP. Then, the local electron temperature around the XP decreases, and therefore the local electron pressure also decreases. As a result, the electron pressure gradient towards TOP appears in Case B and thus the plasma can have higher $\mathbf{u}_{\parallel,\mathrm{D}^+}$ towards the ID region. We find that the line emission of Ne^{7+}, which is recombined from Ne^{8+}, is the major contributor for Ne radiation power around XP and plays a key role in the above process, resulting in the higher $\mathbf{u}_{\parallel,\mathrm{D}^+}$. The additional calculation without the Ne^{7+} line emission (Case C) is carried out in order to evaluate its contribution to the higher $\mathbf{u}_{\parallel,\mathrm{D}^+}$. As seen from Fig. 2 (b), the high $\mathbf{u}_{\parallel,\mathrm{D}^+}$ cannot be seen in Case C and the Ar impurities are trapped at TOP.

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This result suggests that the line emission of Nen_{Ar} can be used as a knob to control the Ar impurity transport. Both the essential role of Ne**u** and the smaller radiation power in the SOL due to low $_{\parallel,\mathrm{D}^+}$ found in Case B are consistent with the bolometric and the spectroscopic observations in Ar+Ne seeding experiment in JT-60U $F_{\parallel,\mathrm{fr}} + F_{\parallel,\mathrm{th}}$. To our knowledge, this study with SONIC is the first to have shown the improved screening of the seeded high-Z impurity in the SOL plasma with additional low-Z impurity injection by the high SOL D^{10+} flow and resultant strong friction force by numerical simulations. This work provides a solution to avoid the Ar accumulation at the top of the SOL plasma, which is one of the biggest sources into the core Ar ions. This screening effect will be examined in the future JT-60SA experiment.

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