The plasma physics of particle and energy exhaust in a fusion device

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Tokamak has extreme particle and energy exhaust requirements, especially at the divertor plates, which are estimated to be $10^{23\text{-}24}$ $m^{-2}s^{-1}$ of 1-10^3 eV deuteron and triton, $10^{22\text{-}23}$ $m^{-2}s^{-1}$ of 1-10^4 eV Helium, and heat flux of 10-20 MW/m^2 normal to the divertor surface. Here we give an overview of the plasma physics issues underling the plasma-materials interaction (PMI) and plasma exhaust. Two specific issues are examined in details: the first is the so-called sheath energy transmission coefficients, and the second is the plasma sheath potential. Together these two, when coupled to the wall recycling of particle and energy, bring the effect of PMI on the tokamak boundary plasma through a plasma boundary condition. With this theoretical framework, one can characterize the different operating regimes enabled by carbon tiles, liquid lithium, and tungsten.

The key physics subtlety for the sheath energy transmission coefficients hinges on the fact that the plasma mean free path is typically long compared with the Debye length, so the Knudsen number is large on the side of the sheath when examining the plasma heat flux at the sheath entrance, even though the Knudsen number on the side of the presheath is small. This gives rise to a Knudsen layer problem, for which a kinetic treatment is required. We have performed kinetic simulations taking into account a collisional presheath and collisionless Debye sheath, and obtained electron and ion sheath energy transmission coefficients that are significantly different from what were adopted in the literature. The plasma energy recycling at the wall is significantly affected by sheath potential drop, as the sheath electric field can divert energy flow between the electron and ion channels. Conventionally the sheath potential drop is given by the Bohm sheath theory, which predicts a potential drop about 3 Te for a hydrogenic plasma. Here we show, via direct kinetic simulations, that the ion sound speed at the sheath entrance is significantly different, and produces a sheath potential drop that is about 2 Te instead of 3 Te.

Finally we address the strong energy recycling of He plasma by a tungsten wall, a phase of operation proposed for ITER, and use a simplified boundary plasma model including the wall feedback to illustrate how a high-Z reflective wall can lead to a high-T and high-n boundary plasma, which is previously inaccessible by either carbon tile and liquid lithium.