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Mechanisms of XPR formation from SOLPS-ITER modeling

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The X-point radiator (XPR) regime is now routinely obtained at ASDEX-Upgrade [1] and other all-metal machines. This regime is very promising from the point of view of power dissipation in the periphery plasma and protection of divertor from big energy flow. The conditions for transition to this regime were recently theoretically formulated in work [2]. Developed XPR regime is accompanied by the strong radiation of seeded impurity, N, Ar, or Ne from the small toroidally symmetric region located near the X-point. This region is cooled to the low temperature at which the impurity radiation efficiency, calculated in the coronal approximation is big. At the start of the XPR formation the separatrix temperature is typically about 100eV and the impurity radiation efficiency is low in the ASDEX-Upgrade like devices. Therefore, the start of the separatrix cooling should have other causes than the impurity radiation. In Ref. [2] the heat losses due to the heating of the electrons born in the process of ionization were indicated as the main cooling factor at the initial stage of the XPR formation. In the ASDEX-Upgrade modeling study [3] a qualitative agreement was obtained between the atomic density at the separatrix corresponding to the start of XPR formation and the analytical prediction [2]. Still this analysis based on SOLPS-ITER modeling was done without account of drift effects. The modeling with drifts in [3] was done only for the developed XPR.

In the present study the detailed modeling of the start of XPR formation is performed with drifts for the ASDEX-Upgrade, JET and planned full-burning plasma ITER conditions. It is shown that for ASDEX-Upgrade with nitrogen seeding the electrons cooling by radial transport processes and drift effects are as important for initial temperature decrease in the XPR region as the ionization process. The XPR formation starts from the ions cooling by ionization, by radial heat flow towards SOL and by diffusion of cold ions from high field side high density (HFSHD) region. The effects of these factors are comparable. Then, the Boltzmann like electrostatic potential variation along the separatrix appears due to the pressure perturbation and density perturbation associated with ions temperature variation, and potential increases at the X-point. The ExB drift vortex around the X-point leads to the mixing of hot plasma inside the separatrix and cold HFSHD plasma. The effect of the vortex is at least comparable to that of other factors. Electron cooling starts later than that of ions. The mixing of cold and hot plasma plays as important role in it as the ionization processes. When the electron temperature decreases to 60 eV the radiation losses already start to be comparable to the others. At lower temperatures 10-60 eV they play comparable role with drift effect while the ionization losses are smaller. For smaller X-point temperatures the radiation is the dominant factor of the heat loss in the XPR.

For ITER with the neon seeding (planned as the main radiating impurity in it) the situation is different. The electron temperature initial variation at the separatrix can be attained in the modeling only when the impurity seeding is big enough for significant energy loss due to the radiation. Typical temperature at the separatrix in ITER is high $T_e > 150$ eV. The radiative losses have non-coronal character. they are associated with the low ionization states neon ions transported to separatrix by drift and diffusion from cold region below the X-point.

In JET with Ne seeding (the radiator chosen typically in experiments at this machine [4]) the situation is an intermediate one. The impurity radiation is more non-coronal and plays more important role at early stage of XPR region electrons cooling. Contrary to ASDEX-Upgrade, the radiation of impurity above the X-point is visible at 2D distributions even before the cooling of the electrons.

The code SOLPS-ITER was recently modified to correctly reproduce the plasma dynamics. The first dynamic simulations, revealing the time-dependent features of the X-point formation with the seeding increase are discussed in the present study.

References

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[2] U. Stroth et al., Nucl. Fusion 62 (2022) 076008
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