SOLPS-ITER simulations of the initiation of an X-point radiator in the ASDEX Upgrade tokamak

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The X-point radiator (XPR) [1, 2] is an attractive scenario that may contribute to solving the power exhaust problem in future fusion devices, e.g. DEMO [3]. Recently, a series of experiments was carried out on the ASDEX Upgrade tokamak (AUG) to study the operational window and access condition of the XPR. A reduced model [4] was derived to explain the physical mechanisms for initiating a stable XPR. However, 2D numerical simulations are required to interpret the experimental observations not caught by the reduced model, including the spatial distribution of particle and power sources, cross-field transport and the high-field-side/low-field-side asymmetry of an XPR. In this work, the SOLPS-ITER transport code [5, 6, 7] was applied. The simulation [8] was able to present an XPR phenomenon and reproduce the density and temperature profiles measured by the newly installed divertor Thomson scattering [9]. Figure 1 shows the simulation results of the line radiation density with an XPR with nitrogen impurity seeding in AUG. In the confined region near the X-point, a cold XPR core with a temperature lower than 5 eV was achieved, surrounded by a highly radiative band. Substantial volume processes, e.g. ionization and volumetric recombination, were found in the cold XPR core.

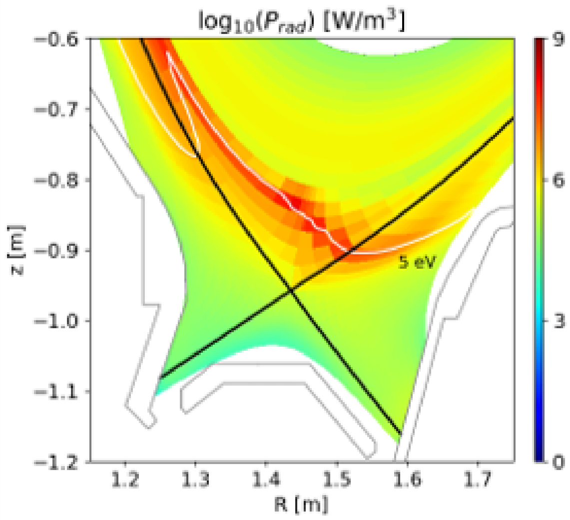

Figure 1: *Cross section of the line radiation density in the SOLPS-ITER simulation with an X-point radiator in AUG.*

A simple sketch of an XPR in the SOLPS-ITER simulation

By analyzing the power, particle and momentum balances in the simulations, a simple sketch of an XPR can be depicted, as shown in Fig. 2. When the temperature in the divertor is low, impurity particles penetrate the confined region near the X-point and reduce the temperature there via line radiation. The parallel temperature gradient leads to a parallel conductive heat flux from the upstream position to the X-point in a narrow layer inside the separatrix. The scrape-off layer and divertor receive less power and become colder, which decreases the opacity for neutrals. In addition to that, the large connection length and large magnetic flux expansion in the vicinity of the X-point can facilitate the volume processes. As a result, more neutrals are able to penetrate the confined region near the X-point and be ionized there. Plasma density and pressure increase in the highly ionizing zone, leading to a radial diffusive transport towards the inner confined region and a parallel convective particle flux from the ionizing zone to the upstream position. The temperature at the X-point is reduced further by the deuterium ionization losses, and the cold XPR core region of the XPR expands further into the confined region. When the temperature at the X-point reaches around 1 eV, the volumetric recombination rate increases substantially. Plasma pressure drops in the cold XPR core region due to volumetric processes, momentum diffusion and radial transport, resulting in a parallel convective particle flux from the ionizing zone to the recombining zone. The particle recycling from the divertor and main chamber wall decreases, while the total ionization rate keeps almost constant, mainly supplied by neutrals generated by volumetric recombination.

With drifts, the cold and dense region of the XPR expands towards the upstream position on the high-field side. In the highly ionizing region, a low plasma potential is found. Radial electric fields are generated by the potential gradients, pointing from the inner confined region to the highly ionizing region, resulting in $E_r \times B$ drifts from the X-point region to the high-field-side upstream position. A potential hill is generated at the X-point, which corresponds to the poloidal current leaving the X-point to the divertor targets and to the upstream position [10]. Given the

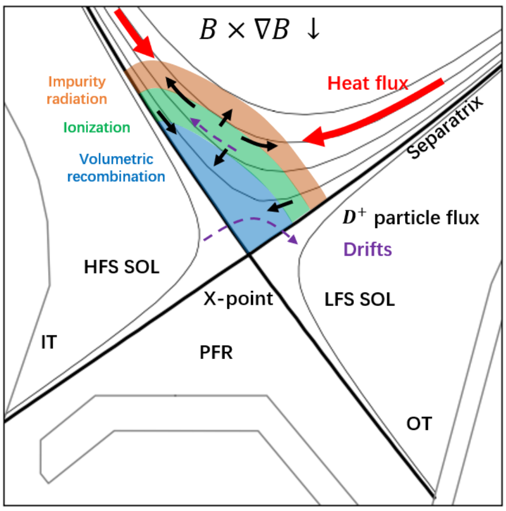

Figure 2: *A simple sketch of an X-point radiator.*

temperature and its gradient as well as the electric conductivity near the X-point are already low, the currents are mainly driven by the poloidal electric field. The poloidal electric field pointing away from the X-point leads to an $E_\theta \times B$ drift transporting particles clockwise from the high-field-side SOL to the low-field-side SOL above the X-point.

Effect of neutrals and the magnetic connection length on the initiation of an XPR

Neutrals penetrating from the adjoining cold divertor region and the large connection length near the X-point play an important role in initiating an XPR. In the simulations, it was not possible to achieve an XPR when an absorbing baffle was added artificially to hinder neutrals penetrating the confined region near the X-point, highlighting the role of neutrals.

In Ref. [4], a reduced model indicates that an XPR is generated when the access parameter,

$$X_A \sim n_{0,X} n_{e,u} f_{exp} B_{t,u}^2 / (T_{e,u}^{2.5} B_{\theta,u}^2), \quad (1)$$

exceeds a certain value. In Eq. 1, $n_{0,X}$ is the neutral density at the X-point, $n_{e,u}$ and $T_{e,u}$ the electron density and temperature at the outboard mid-plane (OMP), respectively, f_{exp} the flux expansion between the OMP and the X-point, $B_{t,u}$ and $B_{\theta,u}$ the toroidal and poloidal magnetic fields at the OMP, respectively.

The access parameter of the reduced model was checked in the SOLPS-ITER simulations. It was found that an XPR with a temperature below 5 eV only occurred when the value of X_A exceed a certain threshold. In addition to this, the threshold values were similar for the flux tubes at different radii. In order to check the effect of the magnetic pitch angle ($\sin a \approx B_{\theta,u}/B_{t,u}$), similar scans of nitrogen seeding rate were carried out in simulations with a toroidal magnetic field of 1.8 T and 2.5 T. The results showed that the threshold of X_A was robust with different toroidal field strengths. This indicates that the XPR access condition derived in the reduced model conclusively contains the main features related to the magnetic field.

According to Eq. 1, an XPR can be achieved with a smaller magnetic pitch angle (i.e. larger connection length) and a larger flux expansion at the X-point. Comparing the simulations with the same input parameters but different toroidal magnetic fields, the case with a toroidal field of 2.5 T (i.e. larger connection length) showed an XPR deeper inside the confined region compared to the case with 1.8 T. In Ref. [11], it was also found that an XPR was achieved in the snowflake divertor configuration with a much lower nitrogen seeding rate than that in the conventional single-null configuration, benefiting from the dramatically larger connection length and flux expansion near the X-point in the snowflake configuration.

Summary

The SOLPS-ITER code package has been applied to study the X-point radiator phenomenon in the ASDEX Upgrade tokamak. The simulations showed qualitative agreement with the experimental measurements and a reduced model for an XPR, filling in the gaps between the experiments and theoretical analysis. The particle, power and momentum balances in the region with an XPR were analysed. In the flux tube close to the separatrix, a cold XPR core was found with recombining region at an electron temperature of ~ 1 eV. The cold XPR core is surrounded by bands of ionizing and radiating regions with an electron temperature of ~ 10 eV.

The simulation results highlight the important role of neutrals and the magnetic connection length in the initiation of an XPR. By checking the dependence between the X-point temperature and the access parameter derived in the reduced model, a threshold of the access parameter was found in the simulations for the initiation of an XPR with a temperature below 5 eV. The threshold is robust for different flux tubes at various radii and for different toroidal magnetic field strengths, indicating that the reduced model already contains the most important physics for initiating an XPR.

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