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Physics basis and design of tungsten divertor for Chinese Fusion Engineering Testing Reactor

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Since 2018, the Chinese fusion community has been working on the physics and engineering design of Chinese Fusion Engineering Testing Reactor (CFETR), which is proposed to bridge the gap between ITER and DEMO [1]. One of the key challenges is that the divertor solution for CFETR must meet requirements beyond that of ITER. With the great efforts on the divertor edge modeling, significant advances have been made on the optimization of divertor geometry and impurity seeding, which can meet the requirements on divertor target lifetime and the core compatibility.

For the standard CFETR operation with the fusion power up to 1 GW, the power across separatrix per unit major radius can reach 30 or 25 MW/m with respect to either fully non-inductive or hybrid mode operation, which are much higher than 17 MW/m for ITER. The high duty cycle of CFETR (0.3-0.5) requires negligible divertor target erosion rate and low enough heat loads that plasma-facing components (PFCs) are capable of withstanding. The divertor solution also needs to be compatible with high core fusion performance, which means low impurity contamination and efficient helium exhaust. The design of divertor geometry has a strong correlation with the plasma configuration and also needs to meet the requirements of the first-wall and blanket. For the plasma current of 13.78 MA, the snowflake configuration could not be obtained since the current of divertor superconducting coil exceeds the engineering limits. Therefore, a lower single-null equilibrium based on the steady state scenario has been used for the divertor design. Taking into account the engineering requirements, a conventional full tungsten (W) divertor with long divertor leg length and V-shape corner structure at the two target corners has been proposed [2].

Extrinsic impurities need to be introduced as the main radiators to reduce the divertor heat loads. The SOLPS-ITER code package with full drifts and currents are employed to evaluate the divertor performance of two candidate radiation impurity species, argon (Ar) and neon (Ne), with two divertor geometries (baseline and long leg divertor) [3]. The self-consistent core-edge integrated code COREDIV coupling with the iteratively calculations of core plasma within the OMFIT framework are used for core-edge integration simulations, which helps to set requirements for SOLPS edge modelling [4], such as the separatrix plasma density, impurity concentration etc. The modeling results show clearly that increasing the seeding rate of Ar or Ne can reduce the target electron temperature and heat flux, which can be reduced further by higher D_2 injection rate. Similar core plasma and divertor conditions, as well as radiated power fraction, can be achieved with 2-3 times less Ar seeding rate than the Ne seeding. In spite of better argon radiation efficiency, no significant increase of core radiation with argon seeding is observed compared to neon seeding, which is due to better argon compression near the divertors caused by its smaller first ionization potential. Longer divertor leg length has a distinct advantage on radiation losses, which has been adopted for the current engineering design. Based on the background plasma from the SOLPS modeling, W erosion and edge transport has been estimated by using the DIVIMP code. The W sputtering is mainly contributed by impurity ions at the far SOL region due to high electron and ion temperature there, but the W net erosion rates at both divertor targets are below the target lifetime requirements for CFETR operation. Shaping of W plasma-facing components (PFCs) is designed to avoid leading edges due to misalignment, which can increase the stationary heat flux by ~49%. Transient heat flux has been calculated using the BOUT++ simulations, which shows a grassy ELMy characteristic for hybrid scenario. The possible divertor solution was obtained for CFETR which can meet the physics requirements on target heat flux, target lifetime and core compatibility.

References

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