9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Development of a static tokamak equilibrium solver and design of cloverleaf configuration

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The XPR (X-point radiator) has been widely observed in existing tokamaks. It is characterized by intense radiation, low electron temperature, and high density inside the confined region near or above the X-point. It, typically accompanied by nearly complete detachment, suppression of edge localized modes, and good core confinement, is considered a potential solution to the power dissipation problem.

A reduced model for XPR regime which is based on power and particle balance, as well as snowflake experiments in the TCV, DIII-D and NSTX indicate that high flux expansion inside the separatrix and long connection length from the outer midplane to the X-point region facilitate XPR stability.[1-3] A potential alternative divertor configuration, known as the cloverleaf, features a third-order poloidal field null. The third-order null is the point where the magnetic field and its first and second spatial derivatives vanish, generating a large low poloidal magnetic field region.[4]

A new free-boundary static equilibrium solver has been developed for magnetic configuration design. The solver is based on Matlab and uses fourth-order finite differences to discretize the space. Picard iteration and Jacobian-Free Newton–Krylov iteration are employed to solve the static inverse and static forward problems.[5] By employing high-order derivatives of the Green's function, the treatment of third-order X-point has been extended.

A cloverleaf configuration and a variant that may bring the XPR deeper into the plasma were designed using the solver, as shown in Fig. 1. The separated X-points result in a region of longer connection length and higher flux expansion compared to the exact cloverleaf, as well as a broader interface between the XPR region and the private flux region. However, the presence of additional X-points increases the sensitivity of the magnetic topology to current variations. The applicability of cloverleaf configuration depends on a balance between enhanced magnetic topology and increased control complexity.

This work was supported by National MCF Energy R&D Program (2022YFE03040002).

References

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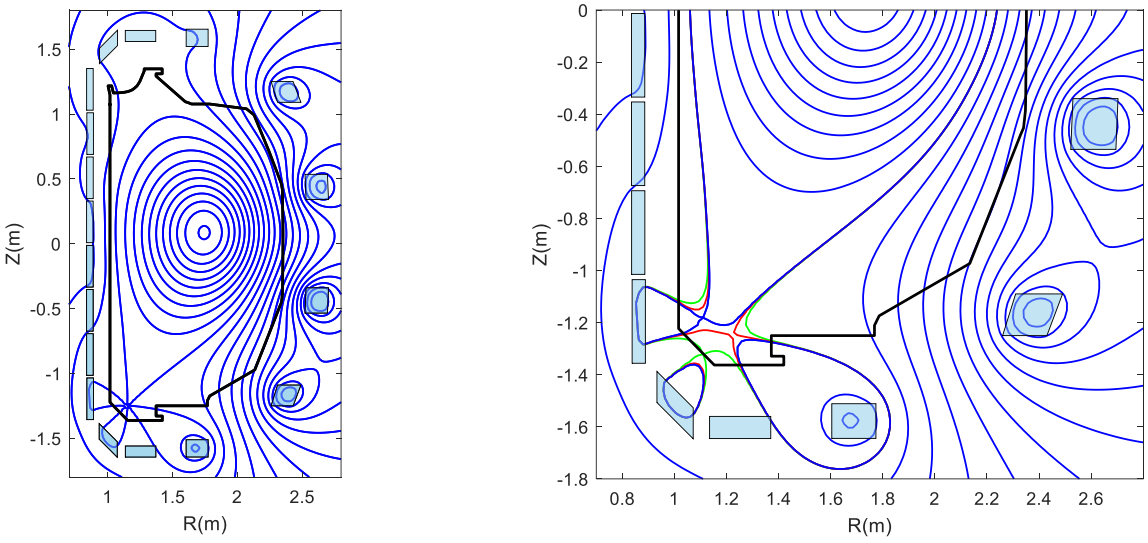

Figure 1. The exact cloverleaf configuration (left) designed using DIII-D geometric parameters, and its X-point separated variant (right), with secondary separatrices denoted in red and green respectively.