Design and Optimization of Advanced Divertor Configurations for Heat Flux Management in the EHL-2 Spherical Torus Project

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The EHL-2 (ENN He-Long 2) spherical torus (ST) project aims to advance spherical torus technology to address the unique challenges of p-11b fusion [1,2]. Achieving proton-boron (p-11b) fusion in a spherical torus (ST) presents significant challenges due to the extreme plasma conditions required. The ion temperature must reach ~200 keV, more than an order of magnitude higher than deuterium-tritium (D-T) fusion, leading to severe heat flux to plasma-facing components (PFCs). The compact size of STs (R_0 = 1.05 m for EHL-2) results in limited major radius of strike point, making heat dissipation and impurity control particularly difficult. Additionally, to sustain high thermal ion modes, a low upstream separatrix density is required, further complicating the feasibility of detachment. To minimize high-Z impurity contamination, carbon-fiber composite (CFC) target plates are selected over tungsten, but their heat load tolerance is limited to ~5 MW/m², necessitating an advanced divertor strategy to mitigate localized overheating and material erosion.

To address these challenges, this study designs an advanced divertor configuration and an optimized poloidal field (PF) coil system for the EHL-2 ST. The equilibrium features an up-down double-null (DN) configuration with a conventional inner divertor and an X-point target (XPT) outer divertor, aimed at enhancing magnetic flux expansion and improving heat load distribution. The outer divertor leg is extended, leading to a substantial increase in flux expansion ($f_{xo} \approx 23$, $f_{xi} \approx 9$) and connection length, which aids in achieving and maintaining detachment. The PF coil system, consisting of 12 coils, is carefully optimized to maintain plasma shape and support flexible equilibrium control. The PF system supports flexible equilibrium control, and accommodate multiple equilibrium configurations, allowing for adjustments in divertor geometry and strike point positioning to optimize heat flux handling.

The divertor is designed with enhanced closure, utilizing baffles and an optimized private flux region (PFR) to improve neutral trapping and radiation dissipation. The inner divertor features a compact structure, while the outer divertor combines vertical and horizontal target plates, ensuring compatibility with the extended-leg XPT configuration. The divertor structure facilitates efficient particle exhaust and power dissipation, reducing the risk of excessive erosion at the strike points.

Simulations using SOLPS-ITER validate the effectiveness of this design. The results show that the proposed divertor configuration enables fully detached divertor operation at lower outer upstream separatrix densities ($1.2 \times 10^{19} m^{-3}$), significantly reducing the peak heat flux on divertor targets. The peak parallel heat flux to the inner and outer divertor plates is estimated at $q_{peak,i} \approx 0.25$ MW/m² and $q_{peak,o} \approx 0.7$ MW/m², respectively, demonstrating the efficacy of the extended-leg XPT divertor in redistributing power exhaust. Furthermore, drift effects and cross-field transport play a significant role in heat flux asymmetry and detachment dynamics. SOLPS-ITER simulations show that E × B and diamagnetic drifts strongly influence radial and poloidal transport in the scrape-off layer (SOL) and divertor regions, leading to asymmetric heat flux distributions. With drifts included, the peak heat flux at the lower inner (LI), upper inner (UI), and upper outer (UO) target plates decreases, while it increases at the lower outer (LO) plate, making detachment in the LO divertor more difficult. However, as the divertor plasma transitions into the detached regime, drift effects become less significant, suggesting a potential pathway for mitigating drift-induced asymmetries.

The results confirm that the EHL-2 divertor and equilibrium design provide a viable solution for heat flux mitigation in ST-based p-11b fusion, offering insights into plasma confinement optimization, advanced divertor configurations, and engineering solutions critical for future high-performance fusion reactors.

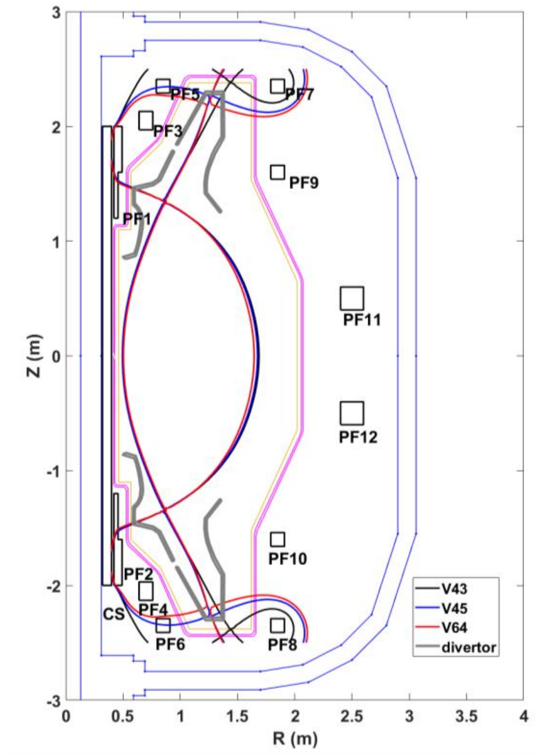

Fig.1 PF system with 12 coils; XPT equilibrium configurations with positive current PF5&PF6 (V43 black line), without PF5&PF6 (V45 blue line) and with negative current of PF5&PF6 (V64 red line);; divertor baffle and target plate(grey line)

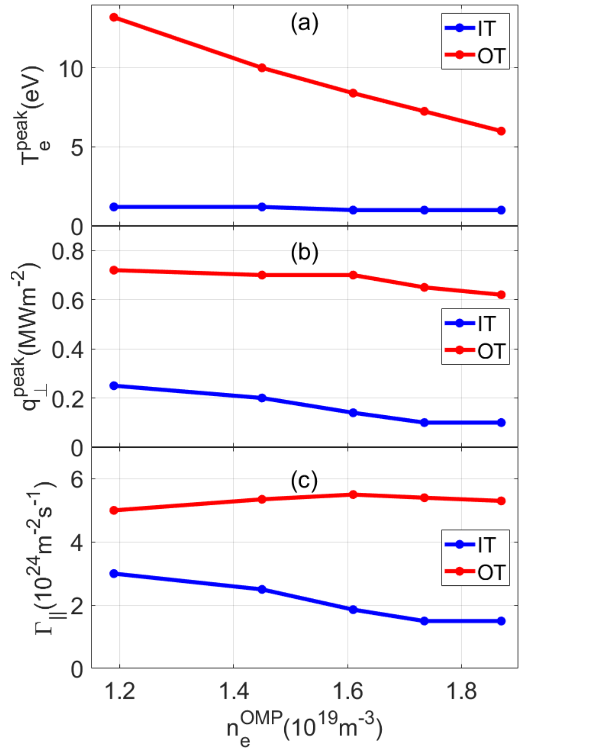

Fig.2 Peak values of the electron temperature (a), perpendicular heat flux (b), and parallel particle flux density (c) at the inner and outer targets, as a function of the separatrix plasma density at the outboard mid-plane.

Reference

[1] M. S. Liu, H. S. Xie, Y. M. Wang, Phys. Plasmas 31, 062507 (2024).
[2] Y. F. Liang, H. S. Xie, Y. J. Shi et al, Plasma Science and Technology, 27, 2, 024001 (2025).