Optimization design of Poloidal field system, Equilibrium and Divertor of the EHL-2 Spherical Torus

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Abstract
The EHL-2 (ENN He-Long 2) project is a spherical torus (ST) facility designed to investigate proton–boron (p-11b) fusion plasmas under extreme conditions, aiming for ion temperatures above 30 keV and densities near $10^{20}m^{-3}$. This study presents an integrated optimization of the poloidal field (PF) system, plasma equilibrium, and discharge scenarios to ensure stable X-point target (XPT) divertor equilibrium operation. Using iterative equilibrium and waveform design, a robust 3 MA discharge was developed, demonstrating stable multi-X point configurations throughout the flat-top phase. Current density profile analysis highlights the role of edge bootstrap currents in reducing PF current requirements. The redesigned PF system, accounting for engineering constraints, enables stable XPT divertor operation in the compact ST configuration. These results establish a solid basis for future experimental exploration of advanced operating regimes in EHL-2 and provide guidance for the development of aneutronic fusion concepts.

1. INTRODUCTION

The EHL-2 project aims to construct a spherical tours (ST) experimental facility with the following key parameters: major radius R_0 = 1.05 m, plasma current Ip = 3 MA, and toroidal magnetic field B_T = 3 T. This device will investigate fundamental physics challenges associated with proton-boron (p-B11) fusion plasmas under extreme conditions, targeting ion temperatures exceeding 30 keV while maintaining densities on the order of 10^{20} m^{-3} within the compact ST configuration [1,2]. Among the critical engineering challenges, heat exhaust management emerges as a primary design consideration, requiring innovative solutions to mitigate power loading and particle recycling effects at the plasma boundary.

Our previous work established a preliminary design for the EHL-2 device, including the PF coil system, equilibrium configuration[3], and divertor physics design[4]. The present study focuses on optimizing these designs based on our prior results. The equilibrium configuration was developed using current profiles derived from high-ion-temperature operational regime. Through discharge waveform design iterations, we performed fine-tuning of both the plasma equilibrium and PF coil system. Following modifications to the equilibrium configuration, we redesigned the closed divertor target geometry and established detachment conditions through systematic analysis.

The following sections will present the design results considering physical requirements and engineering constraints. Section II presents optimized parameters of the PF coil system. Section IV describes the current profile, the equilibrium configuration, and stable discharge waveforms. Section V discusses divertor physics design and establishes detachment conditions. The paper concludes with a comprehensive summary of findings.

2. PF system

The parameters of the PF system have been optimized through an integrated process that takes into account equilibrium configuration requirements, discharge waveform compatibility, coil manufacturing constraints, and power supply specifications. Further optimization of the fast control coils and passive stabilizers is needed to enhance plasma stability control.

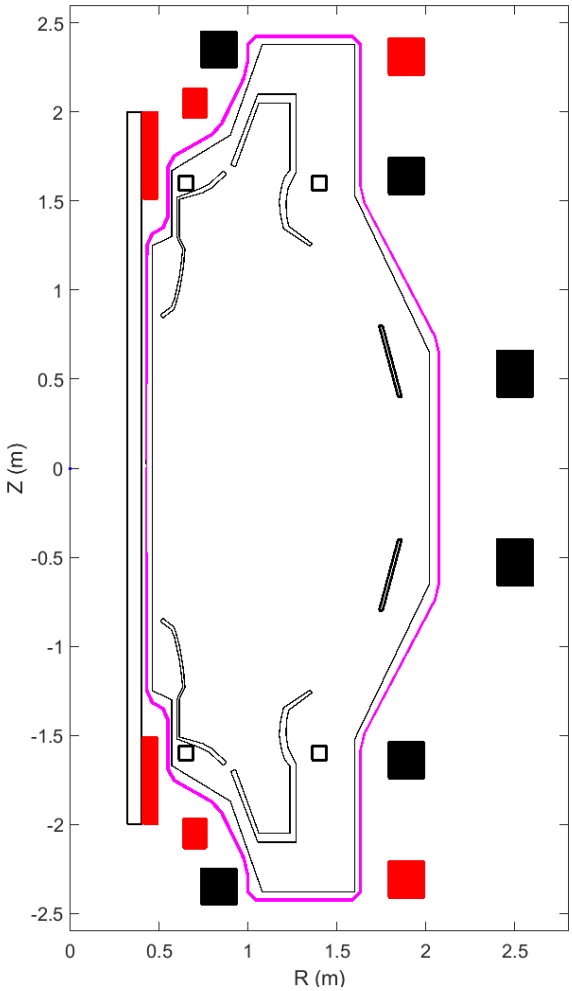

Figure 1 The cross-sectional view of EHL-2 illustrates the integration of key magnetic and plasma-facing components, including: Toroidal Field (TF) Coils, PF System, Vacuum Vessel (VV), Passive Stabilizer Plate (PSP), Fast Control coil, limiter and Divertor

This optimized configuration features: (1) reduced vertical dimensions of PF1-PF2 coils, (2) enlarged PF5-PF12 coil cross-sections, while (3) maintaining prescribed clearance between coils and vacuum vessel.

Table 1 outlines the parameters of the PF system, including the positions of coil center position(R&Z), sizes (W&H) , turns(Nr in R direction, Nz in Z direction and Turn for all) and maximum current of single-turn. The maximum current for single-turn coils and other specifications are based on the coil materials provided by engineering. Minor adjustments will be made as needed for manufacturing.

table 1 Key parameter of poloidal coil system

lables	Xcenter	Ycenter	W	H	NX	NY	N	Angle	IexMax	J
CS	**0.360**	**0.000**	**0.080**	**4.000**	**4**	**75**	**300**	**90**	**70**	**65.63**
PF1	**0.450**	**1.756**	**0.080**	**0.488**	**4**	**18**	**72**	**90**	**17**	**31.35**
PF2	**0.450**	**-1.756**	**0.080**	**0.488**	**4**	**18**	**72**	**90**	**17**	**31.35**
PF3	**0.700**	**2.050**	**0.126**	**0.166**	**6**	**8**	**46**	**90**	**12**	**26.39**
PF4	**0.700**	**-2.050**	**0.126**	**0.166**	**6**	**8**	**46**	**90**	**12**	**26.39**
PF5	**0.835**	**2.350**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF6	**0.835**	**-2.350**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF7	**1.890**	**2.310**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF8	**1.890**	**-2.310**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF9	**1.890**	**1.640**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF10	**1.890**	**-1.640**	**0.200**	**0.200**	**6**	**6**	**34**	**90**	**35**	**29.75**
PF11	**2.500**	**0.530**	**0.200**	**0.260**	**6**	**8**	**46**	**90**	**35**	**30.96**

PF12	**2.500**	**-0.530**	**0.200**	**0.260**	**6**	**8**	**46**	**90**	**35**	**30.96**
PF13	**1.400**	**1.600**	**0.080**	**0.080**	**2**	**2**	**4**	**90**	**16**	**10.00**
PF14	**1.400**	**-1.600**	**0.080**	**0.080**	**2**	**2**	**4**	**90**	**16**	**10.00**
PF15	**0.650**	**1.600**	**0.080**	**0.080**	**2**	**2**	**4**	**90**	**16**	**10.00**
PF16	**0.650**	**-1.600**	**0.080**	**0.080**	**2**	**2**	**4**	**90**	**16**	**10.00**
PF17	**1.800**	**0.600**	**0.020**	**0.400**	**1**	**1**	**1**	**105**	**4**	**0.50**
PF18	**1.800**	**-0.600**	**0.020**	**0.400**	**1**	**1**	**1**	**75**	**4**	**0.50**

3. Equilibrium and discharge

The design of the PFsystem, plasma equilibrium, and discharge waveform is an iterative process, as the latter two directly dictate the PF requirements. Ensuring safe device operation requires that the resulting thermal loads stay within allowable limits; therefore, the conductor cross-section for each PF coil is optimized based on the discharge waveform's evolution to meet all magnetic and thermal constraints.

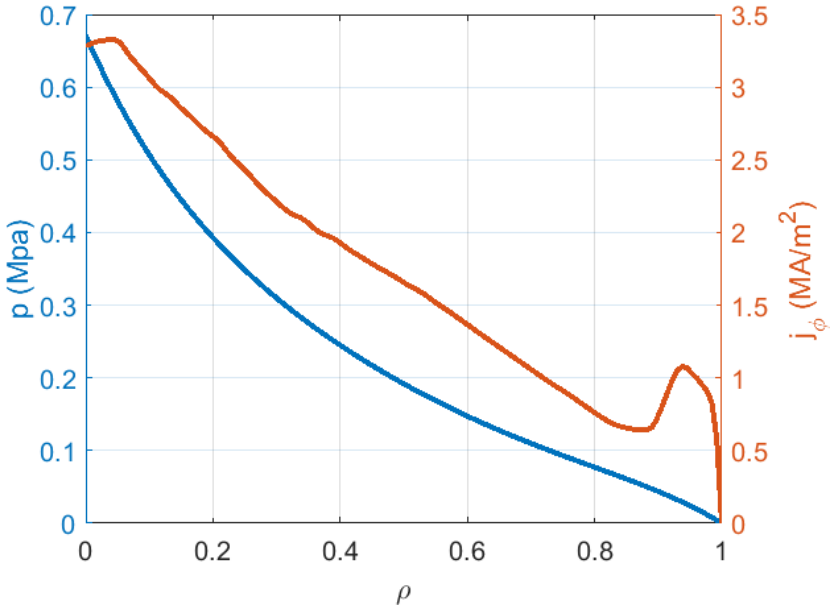

Figure 2 plasma pressure profile (blue line) and current density profile(red line)

In the EHL-2 tokamak, the current density (J) and pressure (p) profiles are derived from a high-ion-temperature operational regime. These profiles resemble those of high-performance scenarios, notably through the development of bootstrap currents at the plasma edge. A key benefit of this edge bootstrap current is a significant reduction in the current demand on the PF coils. This effect is further amplified by the edge-peaked current profile, which positions the plasma current closer to the PF coils, thereby enhancing coupling and reducing the current required to maintain equilibrium. Furthermore, a PF system originally designed using the core-peaked GAQ current model is also capable of supporting equilibria with edge-peaked current profiles.

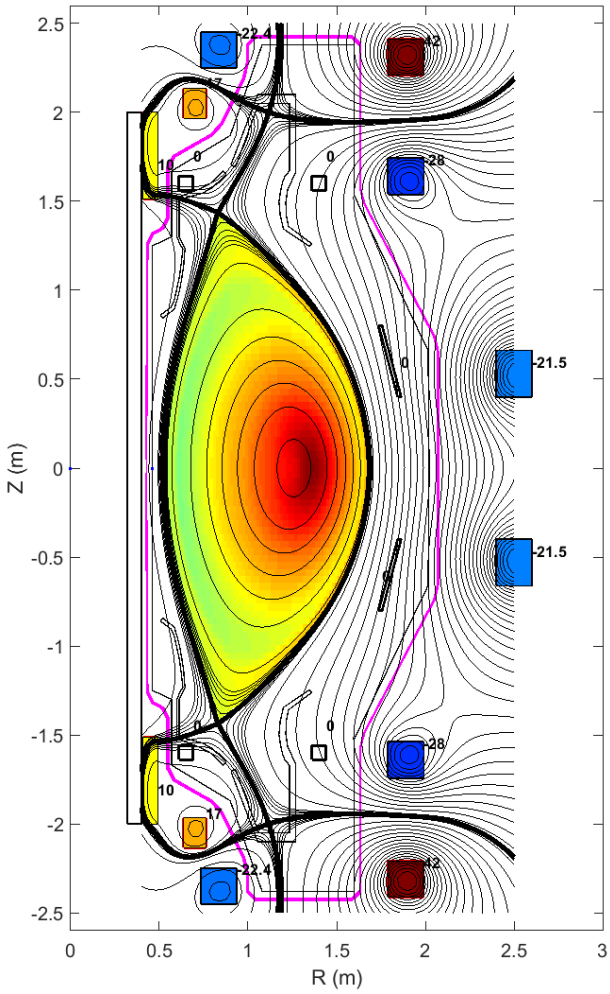

Figure 3 reference equilibrium configuration

Figure 3 illustrates the equilibrium configuration obtained using the current profile model shown in Figure 2. The configuration was calculated with a free-boundary equilibrium solver in SE (Shape Editor) [5], which enables the import of predefined current distributions from external equilibrium files. By actively adjusting the PF coil currents, a stable equilibrium satisfying all target plasma parameters was achieved.

A primary adjustment in the new equilibrium is the vertical placement of the secondary X-point. The original design was limited by the central solenoid (CS) height and field profile, which hindered sustained stability of the XPT through the flat-top phase. To overcome this limitation, the optimized equilibrium positions the secondary X-point at or below the CS elevation, a change that enhances overall stability and controllability.

This positional adjustment results in two major operational consequences: (1) a substantial increase in the required PF coil currents, and (2) the need for enhanced divertor coil capabilities to maintain plasma control. These elevated current demands were the driving force behind the divertor coil system upgrade, which was essential to provide sufficient magnetic control authority for a stable equilibrium in the new configuration. Collectively, these modifications constitute a significant refinement of the magnetic topology, effectively balancing engineering constraints with plasma performance requirements.

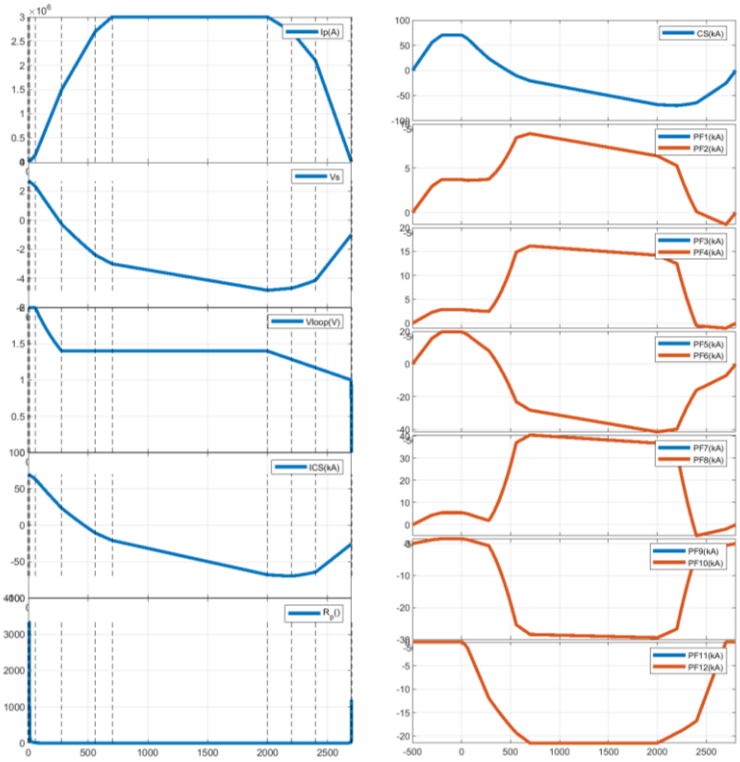

Figure 5 Discharge wave of 3MA for XPT divertor discharge

Based on the discharge waveform design from SE [5], a 3 MA discharge scenario was developed. The scenario begins with the breakdown phase, where ECRH is used to initiate plasma breakdown and generate a small plasma current. Following this, during the current ramp-up phase, the CS drives the plasma current upward as the plasma configuration transitions from a limiter to an XPT divertor. This XPT configuration is then stably maintained throughout the flat-top phase. Finally, in the current ramp-down phase, the plasma is transitioned back from the divertor to a limiter configuration.

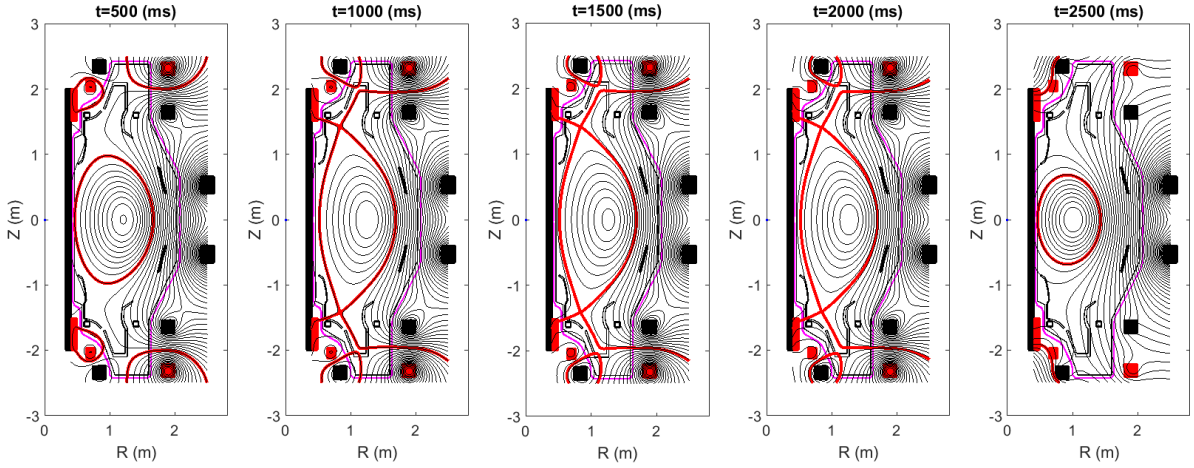

Figure 6 equilibrium evolution with time

Through free-boundary equilibrium calculations, we systematically analyzed the evolution of the equilibrium configurations throughout the discharge. The equilibria at the flattop phase (t = 1000 ms, 1500 ms, and 2000 ms) demonstrate remarkable stability in the positions of the secondary X-points. These results confirm the robustness of multi-null configurations during 3 MA long-pulse operation and provide critical validation for implementing advanced divertor configurations in future fusion devices.

4. Divertor physics design

In order to meet the challenges for increasing heating power for EHL-2, the advanced V-shaped divertor geometry are used, as shown in figure 7. The advanced geometry of the divertor target is determined by the physical goal requirements and engineering constraints. So one good closed divertor geometry has to be

compatible with the possible magnetic equilibrium configurations. Following adjustments to the secondary X-point in the equilibrium configuration, the divertor geometry was modified. In particular, the outer horizontal target plate was elevated, bringing it closer to the secondary X-point, which improves divertor closure and overall plasma confinement.

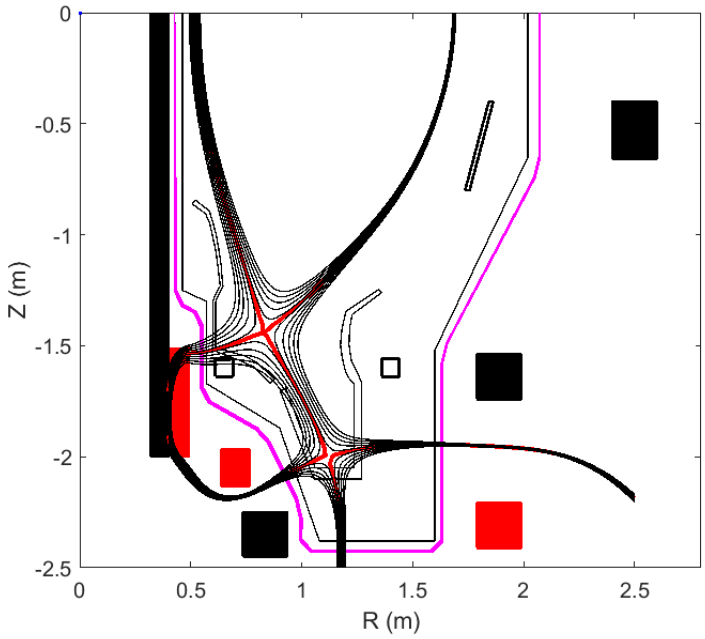

Figure 7 new divertor target with equilibrium

The SOLPS-ITER code [6, 7], is employed to evaluate the steady-state heat load on the divertor targets in EHL-2. The calculations considered hydrogen plasma species (H0, H+), boron plasma species (B0, B+, B2+, B3+, B4+, B5+), and carbon impurities (C0, C+, C2+, C3+, C4+, C5+, C6+). The total input power from the core to the boundary plasma, PSOL=20.0 MW, was equally distributed between ions and electrons, following the standard assumption in two-dimensional fluid boundary plasma modeling. The parallel plasma transport is assumed to be classical and the constant cross-field radial transport coefficients are as follows: the anomalous particle diffusivity, $D\perp = 0.3 m^2 s^{-1}$ and the anomalous ion and electron thermal diffusivity, $\chi\perp,e = \chi\perp,i = 1.0 m^2 s^{-1}$ for all species in the whole mesh. The gas puffing locations for hydrogen and boron were placed at the outer midplane. Carbon impurities were included in the simulations due to the use of carbon-based materials for the divertor target plates, with a carbon sputtering rate set at 4%. A pump is located at the bottom of the vacuum chamber, below a dome (see figure 1), with a recycling coefficient of 0.9. The divertor target heat flux and electron temperature were analyzed across a range of upstream midplane densities (Additional data will be presented during the meeting). At an upstream density of 1.8×10^{19} m^{-3}, both the inner and outer divertor targets experience heat fluxes and electron temperatures that remain within the material limits, ensuring safe operation. This density condition also facilitates favorable plasma detachment characteristics, reducing peak heat loads on the targets while maintaining sufficient particle and energy exhaust. These results provide a critical guideline for optimizing divertor performance under high-power operation. SOLPS-ITER modeling results show that this divertor configuration with a good divertor closure can achieve detachment at a relatively lower outer midplane density. Simulation results indicate that adopting a V-shaped divertor geometry can effectively enhance the geometric closure of the divertor. Under lower plasma density conditions, this geometry facilitates detachment state, thereby alleviating the heat load on the divertor plates and suppressing impurity sputtering from the plates.

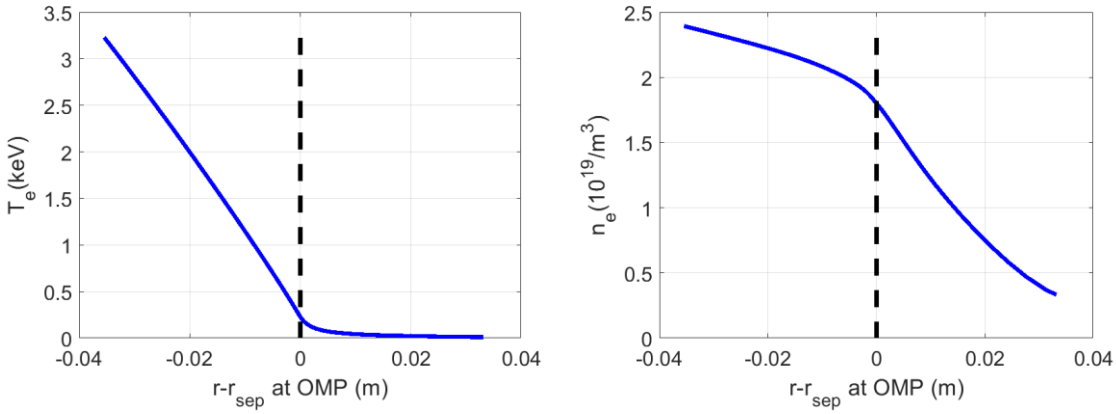

Figure ne and te profile at outer middle plane

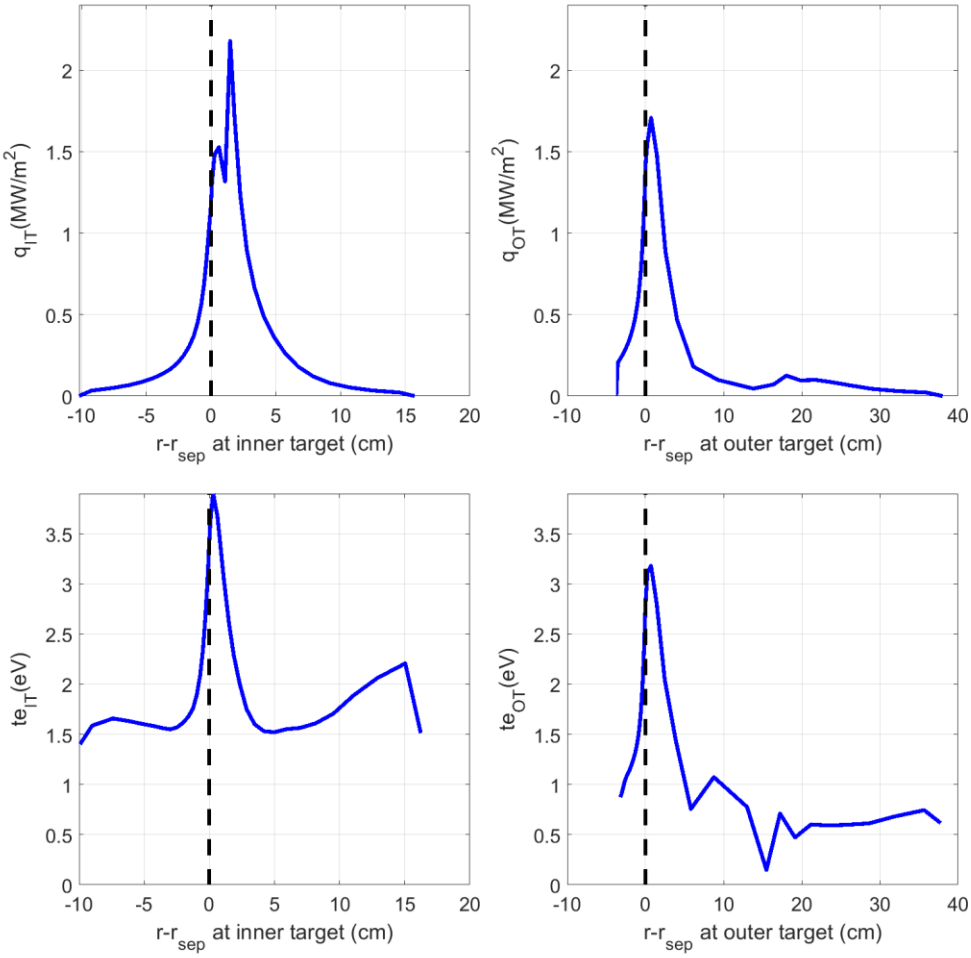

Figure profile of heat flux and electron temperature at inner and outer divertor target plate

5. Conclusion

An integrated optimization of the PFsystem, plasma equilibrium, divertor physics and discharge scenarios has been carried out for the EHL-2 spherical torus. Through iterative equilibrium and waveform design, a stable 3 MA XPT divertor configuration established, demonstrating robust control of multi-x point configurations. The refined PF system accommodates increased current demands while satisfying engineering and thermal constraints, thereby ensuring reliable operation under high-performance conditions. Current density profile analysis confirmed that edge bootstrap currents can reduce PF coil requirements, enhancing the overall feasibility of advanced equilibria in compact spherical torus geometries.

The coordinated improvements in PF system design and equilibrium control provide a solid foundation for EHL-2 to achieve its mission of exploring p–11b fusion plasmas at high temperature and density. These results not only strengthen the technical readiness of EHL-2 but also offer valuable insights into the design of future spherical torus devices aimed at advancing aneutronic fusion research.

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