Non-Inductive Current Start-up and Optimized Ramp-up in EXL-50U for Next-Generation Spherical Torus Devices

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Spherical Torus (ST), known for their high β (the ratio of plasma pressure to magnetic field pressure) properties and compact structure, hold significant potential in fusion research[1,2]. ENN Science and Technology Development Co., Ltd. (ENN) has been working on ST research for many years and has built the ENN XuanLong-50/50 Upgrade (EXL-50/50U) [3–5]. Based on 50GHz electron cyclotron (EC) heating & current drive (H&CD), 1.1 voltage-second (Vs) central solenoid (CS) and 30keV @ 0.5MW neutral beam injection (NBI), the successful experimental results of the EXL-50U include: ion temperature $T_i \sim$ 1keV , plasma current $I_p \sim$ 500kA and center electron density $n_{e0} \sim 2 \times 10^{19} \mathrm{m}^{-3}$[6]. EXL-50U played a crucial role in supporting the construction of ENN He Long-2 (EHL-2) ST, which is an essential device on the path to p-^{11}B fusion[6]. The preliminary design parameters for EHL-2 can be found in Table 1 [7].

Table.1 The preliminary target parameters for ENN EHL-2 ST

Parameters	EHL-2
Plasma current I_p (MA)	~3.0
Magnetic field B_0(T)	~3.0
Beta β	0.11
Confinement time τ_E(s)	0.5
Major radius R_0(m)	1.05
Aspect ratio A	1.85
Avg./Peak density n_e(m^{-3})	-/1.3e20
Heating power P_{heat}(MW)	31
Avg./Peak ion temperature T_i(keV)	-/30
Hot ion mode T_i/T_e	3

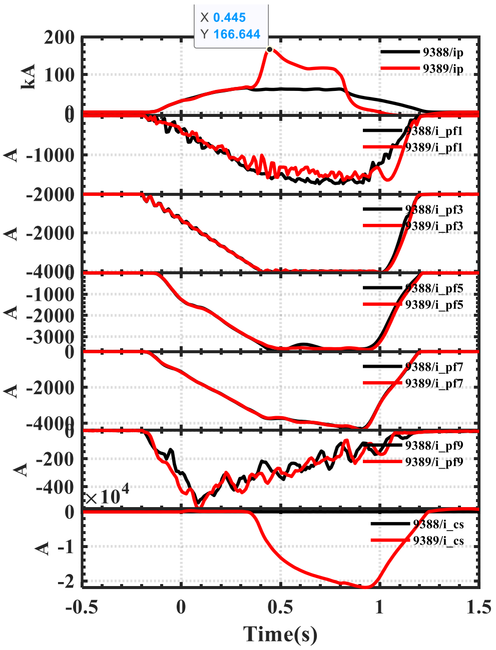


Fig.1 #9388&#9389 EXL-50U experiment comparing with and without CS

Since the EXL-50 was built, the ENN group has completed more than 26,000 discharges on the ST, of which the EXL-50U has accumulated more than 9,000 discharges, covering the current range I_p = 20 kA to 580 kA. The optimization of the discharge process is essential not only for all physics experiments but also for ensuring that the ST hydrogen-boron fusion route can advance to higher current parameters ($I_p \sim$ 3 MA). This study investigates the free movement characteristics of electrons in a trapped particle configuration (TPC) after EC breakdown and their impact on the formation of the initial plasma current. The findings indicate that under the constraints of precise poloidal field (PF) control, the free movement of electrons directly influences the plasma current ramp-up process. To optimize the ramp-up rate, a data-driven approach is proposed, integrating experimental data analysis and numerical simulations to establish an optimal control model for current ramp-up. Shot #9388 in Figure 1 achieved a 64 kA. By applying CS during the flat-top phase of the ECCD, the plasma current was increased to 160 kA, demonstrating that the breakdown pre-ionization + CS ramp-up configuration can be further optimized. In Figure 2, shot #9390 showed that reducing PF 7-10 led to a decrease in plasma current. Figure 3 illustrates a schematic diagram of PF values and Ip current. As PF 7-10 increases, the plasma current exhibits an increasing trend. The pre-ionization equilibrium configuration and the vertical field are crucial for the initial plasma current ramp-up and achieving the maximum value at the flat-top phase.

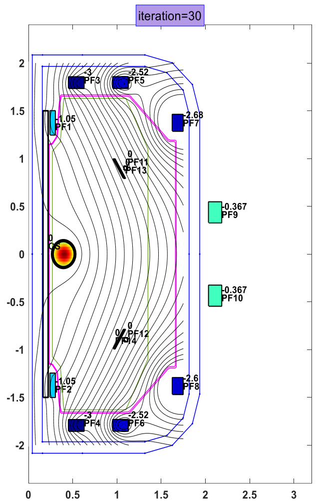
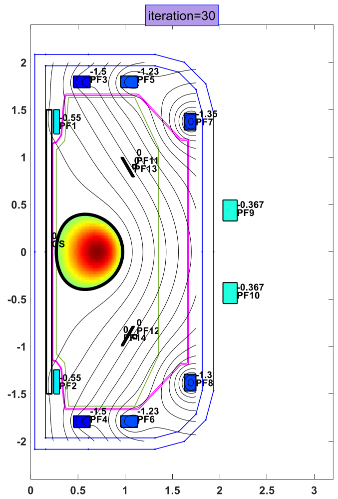


Fig.2 Left: The #9388 configuration under preset PF



Right: #9390 lowering PF 7-10 resulted in a decrease in plasma current to 40 kA

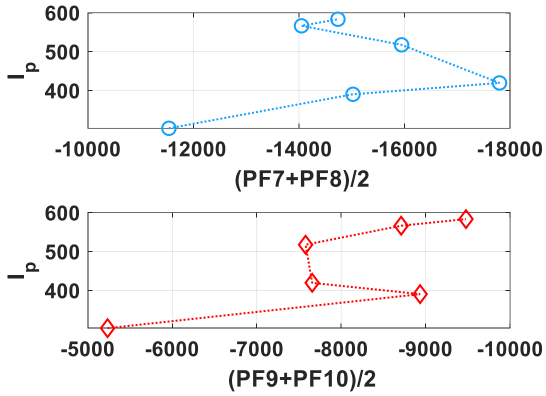


Fig.3 As PF 7-10 increases, the plasma current exhibits an increasing trend.

EHL-2 needs to achieve a 3 MA current while ensuring engineering feasibility[8]. Previous research progress on EXL-50/50U can be found in the review by Shi Yuejiang et al., as well as in the report submitted by the ENN team at the FEC 2025 conference. This study integrate experimental observations and simulation analyses, providing fundamental data and methodological guidance for optimizing current ramp-up. They offer strong support for formulating the optimization strategy for the pre-ionization to ramp-up phase in EXL-50U.This research provides theoretical support for EHL-2 and future hydrogen-boron fusion spherical tokamak (SPH) devices, contributing to the development of digital spherical tokamaks, reducing experimental iteration cycles, and accelerating the realization of hydrogen-boron fusion.

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