

Overview of EXL-50U Experiments: Addressing Key Physics Issues for Future Spherical Torus Reactors

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Abstract (Yuejiang Shi)

ENN's Xuanlong-50U (EXL-50U) is the world's first fully privately funded and operated MA-level magnetic confinement fusion experimental facility. EXL-50U is also the world's first spherical torus device (ST) to achieve

a magnetic field exceeding 1 Tesla and a pulse width reaching the seconds level in actual operation. The major radius of EXL-50U ranges from 0.6 m to 0.8 m, with an aspect ratio of 1.4–1.8. The key physics issues of EXL-50U's experiments related to the future ST reactors are: non-inductive current start-up and drive, development of scenarios for stable high density hot ion mode for ST ($T_{i0} = 3 \text{ keV} \sim 10 \text{ keV}$), and investigation of energy confinement scaling through wide range scans of aspect ratio (1.4 ~ 1.8) and B_T (0.5 T ~ 1.2 T). Another key research focus of EXL-50U is the physical properties of Hydrogen-Boron (p-B) plasmas and hydrogen-boron fusion, which is closely aligned with ENN's p-B fusion roadmap. In the 2025 experiment, EXL-50U achieved a p-B plasma discharge at 1 MA (with boron ions exceeding 10% in the ion fraction), marking the world's first MA-level discharge of high-concentration p-B plasma. A recording 270 kA fully non-inductive current by 380kW electron cyclotron resonance heating (ECRH) is also achieved. The initial real-time Boron-power injection experiments with metal wall in EXL-50U demonstrates the positive effective of Boron on plasma performance. A significant increase in ion temperature was achieved even at lower neutral beam injection (NBI) power injection. When injecting 400 kW NBI power, the core ion temperature reached 1.6 keV. On the other hand, experimental results also indicate that simultaneous injection of ECRH and NBI is detrimental to ion temperature enhancement. AI technology was also applied in EXL-50U experiments, achieving stable 500 kA plasma current and displacement control for over 500 milliseconds. SMBI was applied for density feedback control for the first time in ST device. ENN researchers plan to achieve all of EXL-50U's milestone objectives within a three-year timeframe, contributing their efforts toward the rapid commercialization of magnetic confinement fusion.

1. INTRODUCTION

ENN Science and Technology Development Co., Ltd. founded in 2006, also known as the Energy Research Institute (ENN-ERI), is a subsidiary of ENN Group—the largest private energy enterprise in China. ENN-ERI is committed to developing sustainable, reliable, and economically viable solutions to humanity's energy challenges. Mr. WANG Yusuo, founder and helmsman of ENN Group, believes that fusion is the hope for future energy. ENN-ERI comprehensively initiated scientific research on magnetic confinement fusion starting in 2017, making it the first private company in China to venture into fusion research.

As a company aiming at commercializing fusion, the fast iteration and upgrade of device are key measures to verify the commercial feasibility as early as possible. ENN-ERI built its first-generation spherical torus XuanLong-50 (EXL-50) in 8 months. As China's first medium-sized spherical tokamak device, EXL-50 conducted four years of physics experimental operations from July 2019 to June 2023. It focused on research into non-inductive current drive via ECRH without the central solenoid (CS) and achieved remarkable research results [1-12].

The physics and engineering design of XuanLong-50U (EXL-50U) which is the second generation ST of ENN was completed in the end of 2023. The main device assembly of EXL-50U has been finished in the end of 2023. On the other hand, the third-generation ST device Helong-2 (EHL-2) of ENN has completed all physical design and is planned to finish the main machine construction in 2027 [13]. The goals of EHL-2 are to verify the thermal reaction rates of p-B fusion, establish spherical torus/tokamak experimental scaling laws at 10's keV ion temperature, and provide a design basis for subsequent experiments to test and realize the p-11B fusion burning plasma. At the same time, ENN is committed to the research and development of high-temperature superconducting (HTS) magnets for future ST reactors and has successfully developed a prototype D-shape HTS coil with a magnetic field strength of 12 teslas [14]. Figure 1 illustrates the development timeline of the ST devices of ENN.

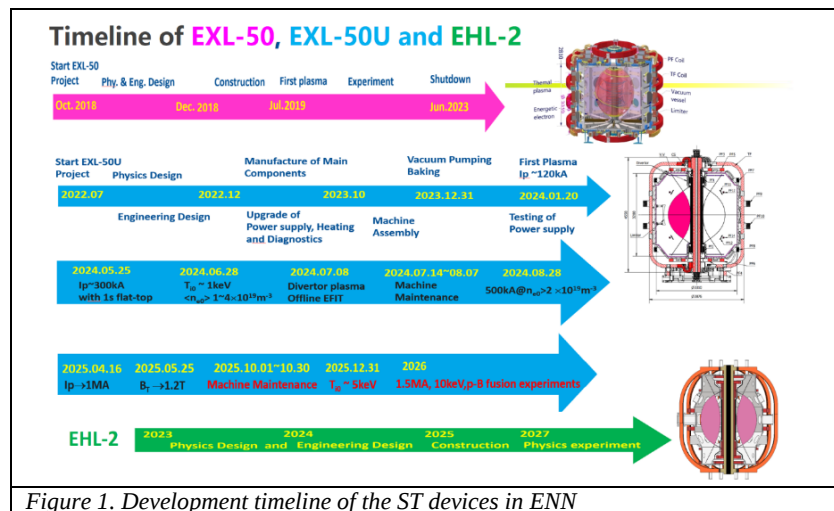


Figure 1. Development timeline of the ST devices in ENN

As a crucial component of ENN's fusion roadmap, EXL-50U is designed with the following key physical issues targeting future ST reactors and p-B fusion:

- non-inductive current drive
- scenarios development for stable high density hot ion mode for ST ($T_{i0} = 3 \text{ keV} \sim 10 \text{ keV}$)
- investigation of energy confinement scaling for wide range scan of aspect ratio (1.4~1.8) and B_t (0.5T~

1.2T)

➤ proton-boron plasma physics and preliminary proton-boron fusion reaction with energetic ions [5,6].

The paper summarized the experimental progress on EXL-50U from 2024 to 2025 [15-16]. The unique discharge scenario (EC start-up + Ohmic assisted ramp-up) in EXL-50U can reduce the loop voltage and consumption of CS flux. Stable and repeatable plasma current were also obtained under 500kA in limiter or divertor configuration with 2.5MA/s ramp-up rate. Artificial intelligence (AI) technology was also implemented in the EXL-50U experiments, enabling stable plasma current and displacement control at 500 kA for over 500 milliseconds. SMBI technology has been verified to be applicable for density feedback control on EXL-50U. Moreover, EXL-50U achieved a 1 MA hydrogen-boron plasma discharge with a boron ion fraction exceeding 10%. Additionally, a fully non-inductive current of 270 kA was sustained using 380 kW electron cyclotron resonance heating (ECRH). Real-time boronization experiments on the EXL-50U showed a significant increase in both plasma density and pressure after boron powder injection. A significant increase in ion temperature was observed even at relatively low neutral beam injection (NBI) power. With 400 kW of NBI power, the core ion temperature reached 1.6 keV. However, experimental results indicated that simultaneous injection of ECRH and NBI had a detrimental effect on ion temperature enhancement.

This paper is organized as follows. The experiment setup in EXL-50U is given in section 2. The main experimental progress and analysis results on EXL-50U are presented in section 3. The summary and outlook is described in section 4.

2. EXL-50U SPHERICAL TOURS

2.1 Device Status

EXL-50U is a typical low aspect ratio tokamak device, or spherical torus (ST) device, and is an upgrade machine of the EXL-50 proposed by Y.K.Martin Peng. In his seminal article from the 1980s [17-18], Dr. Peng pointed out that, compared to conventional large-aspect-ratio tokamak devices, ST exhibits outstanding advantages such as high toroidal beta and high plasma current. These advantages mean that ST devices can achieve higher plasma parameters than conventional large-aspect-ratio tokamaks under the same size and magnetic field strength. In other words, to achieve the same plasma parameters, the required size and magnetic field for a ST can be significantly lower than those for large-aspect-ratio tokamak devices. After the first ST device, START[19], demonstrated that spherical torus could achieve a beta value one order of magnitude higher than the aspect ratio tokamaks, both the United Kingdom and the United States promptly approved the development plans for the megampere-class ST devices MAST [20] and NSTX [21], and rapidly completed their construction. Over the past two decades, spherical torus (ST) devices worldwide, both large and small, have made significant progress in many areas [22-39]. Notably, two small ST devices, Globus-M2 [33] and ST40 [34], have achieved ion temperatures of 50 million and 100 million degrees Celsius, respectively. Compared to other ST devices, both Globus-M2 and ST40 possess relatively high magnetic fields, reaching 1 Tesla and 2 Tesla respectively. The engineered magnetic field of EXL-50U also exceeds 1 Tesla. In recent engineering commissioning tests, EXL-50U maintained a 1.6-second flat-top at a magnetic field of 1.2 T (as shown in figure2), making it the first operating ST device to actually achieve second-long duration at the 1-Tesla level. Like other ST devices, a demountable integrated center stack (which includes the central solenoid and part of the toroidal field magnets) is employed on the EXL-50U. On the other hand, the demountable magnet structure indeed poses a significant challenge for the future application of high-temperature superconductivity (HTS) in spherical torus (ST) devices, and to date, no viable engineering solution has been established. More details on the EXL-50U's vacuum vessel and magnetic coils can be found in Ref. [15]. Boronization in glow discharges with a mixed gas of

Table.1 The main parameters of EXL-50U

Parameter	Value
Plasma current	0.5 – 1.5 MA
Major radius	60- 80 cm
Toroidal magnetic field (R = 60 cm)	1.2 T
Magnetic flux of CS	1.2 Web
Aspect ration	1.4 – 1.85
Elongation	2
Discharge TF flattop duration	2 s @ 1.2 T 8 s @ 0.6 T

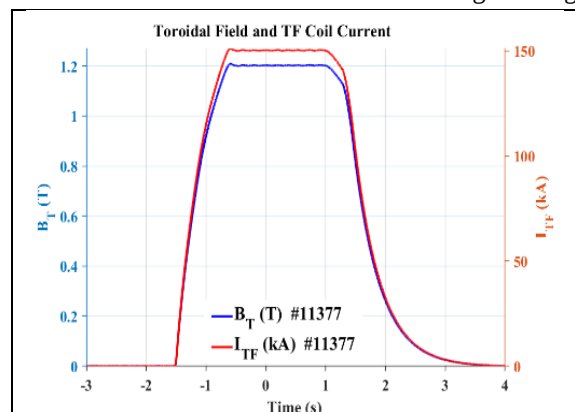


Figure 2 The time evolution of TF current and magnetic field in EXL-50U.

30% Diborane (B_2H_6) and 70% Hydrogen is the regular wall conditioning and cleaning method for EXL-50U. The investigation of the physical properties of magnetic

confined hydrogen-boron plasmas is also one key issue for ENN's fusion research project. Several kinds of boron injection systems have been developed and installed in EXL-50U: the gas-puffing system in central column and SMBI system in low field side with a mixed gas of Diborane and Hydrogen, the boron powder injector installed on a top port of EXL-50U, the boron pellet injector installed on a central horizontal port. The main parameters of EXL-50U is shown in table.1. Figure 1 shows the overall layout of the EXL-50U device hall.

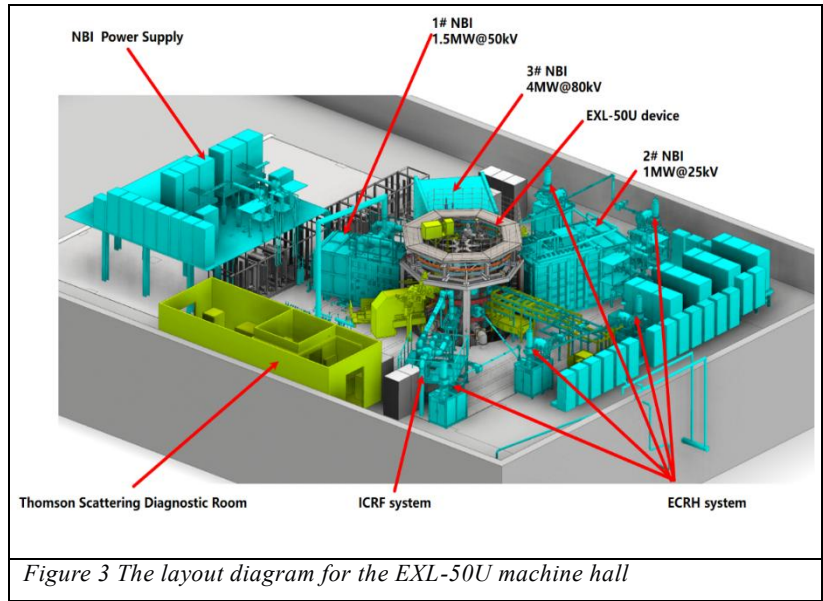


Figure 3 The layout diagram for the EXL-50U machine hall

2.2 Current Drive and Heating systems

The heating and current drive (H&CD) system for the EXL-50U 2025 experimental campaign consists of a 1.5MW/50kV/1s NBI system, three 28GHz/0.4MW/5s ECRH systems, two 50GHz/0.5MW/1s ECRH systems, and a 3-26MHz/0.1MW/3s Ion Cyclotron Range of Frequency (ICRF) system. To achieve the goals of the EXL-50U experiments, the H&CD system will be upgraded to higher power, including a 1MW/25kV/2s NBI system, a 22-50MHz/1MW/1s ICRF system.

The rated parameters of the three NBI systems are shown in Table 2. The ion beam power of the first NBI (1#NBI in figure 2) has reached 46kV/ 40kW ion beam extraction in testbed and 25~30 keV/0.8~1MW kW/0.2~0.3 s in EXL-50U experiment. The second NBI system (2#NBI in figure 2) with high power at lower energy (1 MW @25 kV) is under construction and will be put into use by the end of 2025. It has four ion sources arranged in a two-by-two stack, of which the first one has reached a record of 35kV/32A/0.3s ion beam extraction in testbed. The third NBI system (3#NBI in figure 2) with high power at higher energy (4MW@80keV) is under design and will be put into use before summer of 2026.

Table 2 Designed values of the three NBI systems

Parameter	PNBI 01	PNBI 02	PNBI 03
Ion source number	2	4	4
Beam energy	50keV/20-30keV	25keV	80keV
Injection power	1.5MW	1MW	4MW
Beam current	40A/17A	17A	45A
Pulse duration	1s	1s	1s
Cross section at source	106mm×428mm	106×431mm	106mm×431mm
Injection angle	48.5 °/33.5 °	20.8 °/34.7 °	32.8 °/43 °
Tangential radius	442mm/599mm	284mm/456mm	433mm/546mm
Divergence angle	1.3 °/1.3 °	1.3 °/1.3 °	1.3 °/1.3 °

The ECRH system is used for plasma start-up, electron heating and current drive. All the 28GHz and 50GHz sub-systems have independent launchers, which can change injection angle in both poloidal and toroidal directions. An 1MW ICRF system is currently under construction for EXL-50U, which will be ready by the end of 2025, aiming at producing energetic proton tail by synergy effect with NBI. The 3-26MHz/100kW ICRF system is the prototype one to demonstrate effective coupling of ion cyclotron wave into plasma, reasonable ion heating and detectable energetic proton tail generation. A two current-strap antenna in dipole configuration with a single vacuum feedthrough is used, with a parallel wave number of $\sim 5 \text{ m}^{-1}$.

2.3 Diagnostics

The diagnostics on EXL-50U developed for machine protection, plasma feedback control and physics studies. These main diagnostic tools include magnetic measurements, visible/infrared cameras, HCN far infrared (FIR) interferometers, Thomson scattering diagnostics, $H\alpha$ and impurity spectroscopy, stray electron cyclotron wave (ECW) power monitors, reflectometry and ECE measurement systems, AXUV arrays, soft x-ray and hard x-ray arrays, and Langmuir probes. Spectroscopy include EUV, VUV monitors are also developed. X-ray Crystal

spectrometer has been installed for ion temperature measurements. The layout the diagnostic systems on EXL-50U are shown in figure 4.

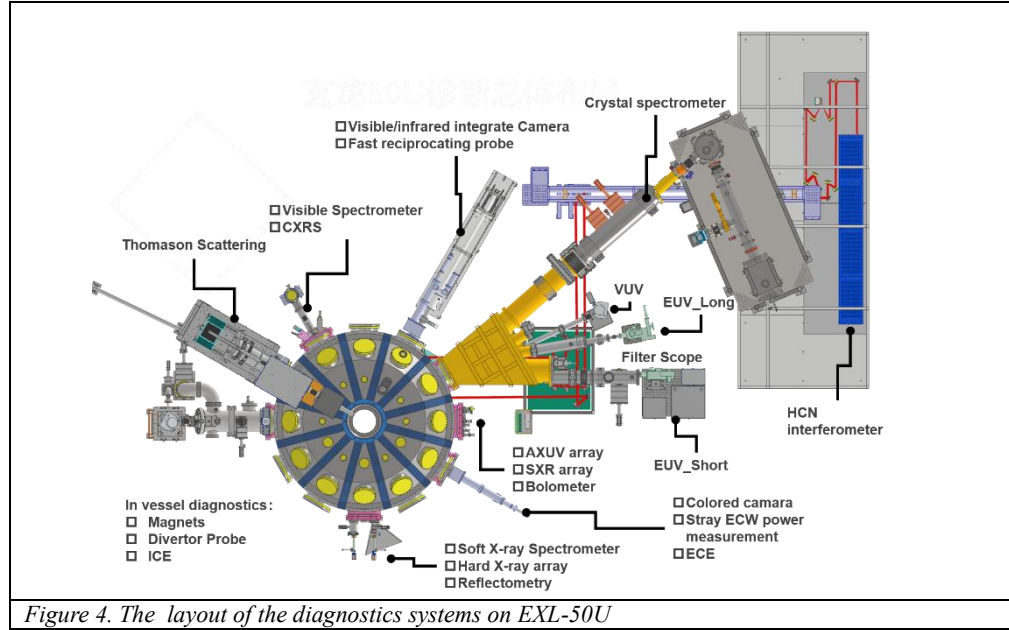


Figure 4. The layout of the diagnostics systems on EXL-50U

3. RESEARCH PROGRESS on EXL-50U

3.1 Non-inductive current start-up and drive

In conventional tokamaks, the start-up and ramp-up of plasma current are typically driven by a toroidal electric field induced by a central solenoid (CS) coil. However, this approach presents significant engineering challenges for spherical tokamaks (STs) due to the limited space available within their narrow central columns. Although some existing STs can be initiated and ramped up entirely using CS drive, this inductive current drive strategy is considered unfeasible for EHL-2 and future ST-based fusion reactors. In inductive current drive operation, the volt-second (VS) consumption rate is highest during the start-up phase, while the total VS consumption is greatest during the ramp-up phase. Therefore, non-inductive current drive must play a central role in EHL-2. To address this, we have developed a new current drive strategy aimed at minimizing VS consumption during start-up and flat-top phases. A small portion of VS is reserved during flat-top for current feedback control—since the CS remains the simplest and most reliable means for real-time regulation.

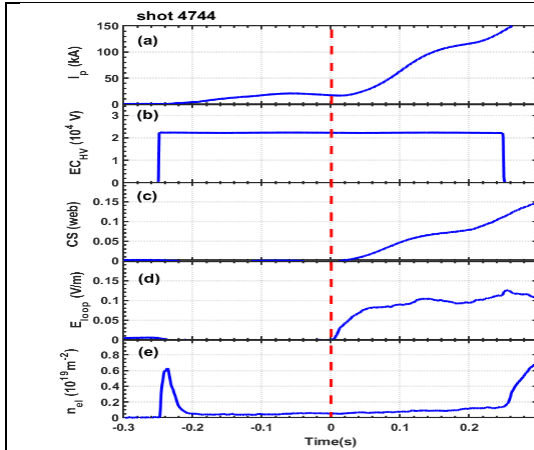


Fig.5 Typical start-up waveforms with 28 GHz ECRH in EXL-50U [1]. The vertical red dashed line indicates the start of CS current. Waveforms from top to bottom are: (a) plasma current; (b) gyrotron anode high voltage; (c) flux consumption of CS coils; (d) toroidal electric field which is below 0.15V/m in whole ramp-up phase (e) line integrated density. Reproduced from [15]. The Author(s). CC BY 4.0.

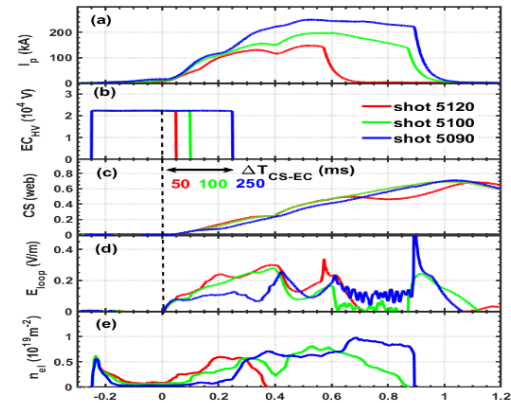


Figure 6 Dedicated shots for the verification of synergetic effects between ECRH and CS. The vertical black dashed line indicates the start of CS current. Waveforms from top to bottom are: (a) plasma current; (b) gyrotron anode high voltage; (c) flux consumption of CS coils; (d) toroidal electric field; (e) line integrated density. Reproduced from [15]. The Author(s). CC BY 4.0.

Recent experiments on EXL-50 [1-2] and EXL-50U [15-16] have successfully demonstrated non-inductive plasma start-up using electron cyclotron resonance heating (ECRH). Moreover, synergistic effects between ECRH and CS have proven effective in reducing VS consumption during ramp-up. The typical start-up waveforms are shown in fig 5. 190 kW ECRH is injected at 250 ms. When the plasma current reaches around several tens kA and the closed magnetic surface has fully formed, the Ohmic heating of CS is then engaged.

During the ramp-up phase, ECRH is continually applied for a period of time, and under the combined action of ECRH and the CS, the plasma current can smoothly ramp up to the preset plateau (fig 6). Moreover, a recording 270kA fully non-inductive current flat-top by 380kW ECRH is also achieved (as shown in Fig.7). On the other hand, one mega ampere (MA) plasma discharges were also achieved in EXL-50U (as shown in Fig.8). A key innovation in MA experiments was the use of a boron-rich fueling strategy incorporating a high-concentration boron-containing gas mixture and real-time boron powder injection during the discharges. The boron content in the fuel reached 10%, representing the first publicly reported MA-class p-B plasma with such a high boron concentration. The non-inductive current ratio is about 50% in MA discharges. More detail about current drive can be seen in Ref. [15, 16, 40].

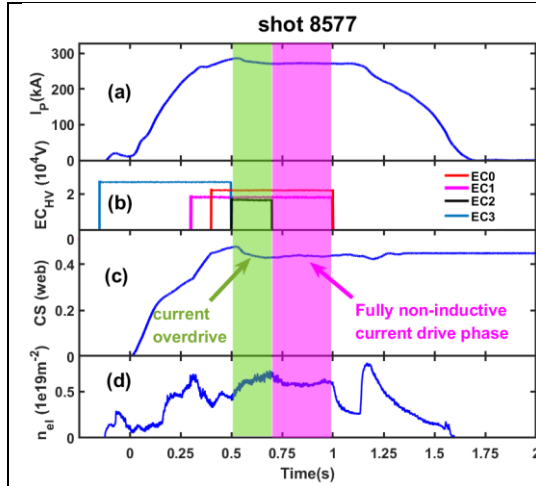


Fig.7 The waveforms of fully non-inductive current by ECRH (magenta shade area in the figure) has been achieved. During the period of higher power ECRH injection phase (green shade area in the figure), current overdrive is achieved.

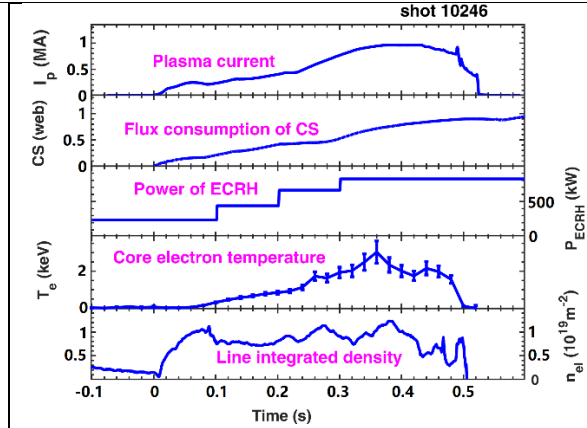


Fig.8 The waveforms of 1 MA discharge in EXL-50U. From top to bottom: plasma current, flux consumption of CS, power of ECRH, core electron temperature measured by Thomson scattering, line integrated density measured by HCN interferometers. A 50 GHz gyrotron operates continuously during the full discharge cycle, with three gyrotrons of 28 GHz operate in the stage from 0.1 s. Reproduced from [16]. The Author(s). CC BY 4.0.

3.2 Plasma control with AI, SMBI, equilibrium and diverter experiment

The EXL-50U device achieves a plasma current flat-top duration on the order of seconds, making a reliable feedback control for plasma current, position, shaping, and density essential to attain and sustain performance plasma during the flat-top phases.

Stable divertor configuration discharge at 500 kA has been regularly achieved in EXL-50U with traditional Proportional-integral-Derivative (PID) method. The discharge waveform (as shown in fig. 9) was designed with dynamic configuration transitions to enhance operational stability and mitigate disruption risks. The plasma initiates in an inboard limiter configuration during the ramp-up phase. Once a critical plasma current threshold is exceeded, it transitions smoothly to a divertor configuration, which is maintained throughout the flat-top phase at the target current. During the ramp-down phase, the plasma reverts to a low-elongation limiter configuration. This controlled switching between limiter and divertor configurations significantly reduces the risk of plasma disruptions caused by loss of vertical displacement control (VDE) during both ramp-up and ramp-down phases.

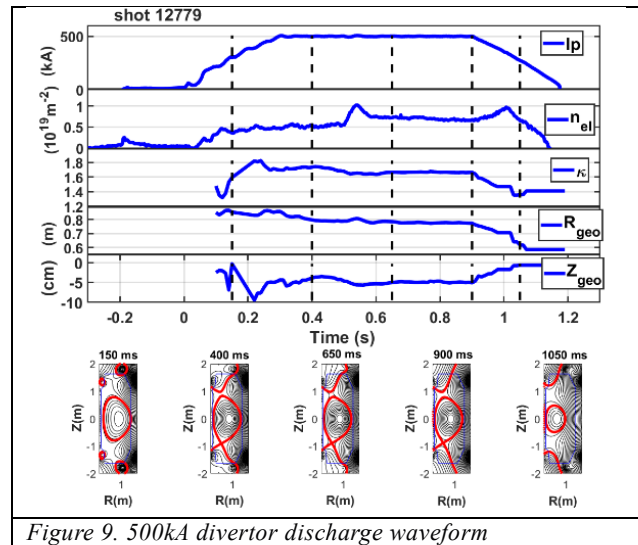
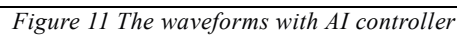
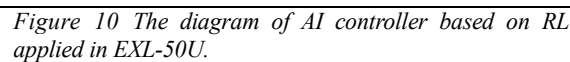


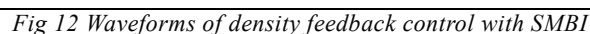
Figure 9. 500kA divertor discharge waveform

On the other hand, Artificial Intelligence (AI) technology is also applied for the control of radial and vertical position and plasma current (RZ- I_p) in EXL-50U. The control framework operates in two stages:

Meanwhile, the real-time equilibrium reconstruction surrogate, EFIT-mini, enabled PID position control with $\pm 1\text{cm}$ accuracy (δR_{mag} , δZ_{mag}). These results show that RL can reliably regulate coupled plasma parameters and integrate seamlessly with conventional PID controllers, marking a step toward autonomous, adaptive control in fusion devices.



Supersonic molecular beam injection (SMBI) was employed to its significantly fast response time. The gas transmission pipeline of gas-puffing installed in the middle of central column of EXL-50U device is several meters long, resulting in a responding delay on the order of 100 ms. This makes it difficult to use for real-time density feedback control. SMBI reduces this delay to less than 3ms. This substantial difference makes SMBI the optimal method for real-time density feedback control in EXL-50U. Both limiter and divertor configurations were tested under various target density levels and waveforms to evaluate the performance of the feedback control



3.3 Proton-boron experiment

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representative discharge #9473, with key time traces shown in Figure 13. In this discharge, boron powder was injected at a rate of approximately 5 mg/s from $t = 580$ ms to 780 ms. Following the injection, a substantial increase in the line-integrated electron density was observed, reaching a value approximately four times higher than the pre-injection level. Concurrently, the H_α emission signal, a key indicator of particle recycling, decreased significantly. This suggests that the injected boron effectively coated the plasma-facing components, acting as a getter to reduce the recycling of hydrogenic species from the wall. This improved wall conditioning is crucial for achieving stable, high-density operation, and the resulting substantial density rise is the primary driver for the notable enhancement in the plasma stored energy (W_{dia}).

The boron deposition was primarily localized to the plasma periphery. This is evidenced by the measurements from the Absolute Extreme Ultraviolet (AXUV) photodiode arrays, where the edge-viewing channel signal shows a much larger increase in radiation compared to the core-viewing channel. This peripheral radiation is beneficial as it helps to cool the plasma edge without significantly degrading core performance. This conclusion is further supported by the Thomson Scattering (TS) measurements presented in Figure 14. A comparison of the electron density profiles before injection ($t = 0.57$ s) and during injection ($t = 0.66$ s and 0.76 s) confirms that the density increase is most pronounced in the outer region of the plasma (for normalized radius $\rho > 0.5$).

Furthermore, the improved plasma performance induced a change in the magnetic configuration. Starting from approximately 680 ms, observations from ion saturation current of the divertor Langmuir probes (Fig. 13c) indicate that the divertor strike points moved radially outward and became more localized. This signifies a transition from a limiter-dominated configuration to a more distinct divertor configuration. The increase in poloidal beta, resulting from the enhanced stored energy and density, is believed to facilitate this equilibrium shift.

BPI on EXL-50U has proven to be an effective technique for improving wall conditions, controlling recycling, and significantly expanding the achievable density and temperature operating region. While these results demonstrate clear improvements in plasma parameters, a detailed analysis of the impact on energy confinement time and transport is ongoing to fully quantify the confinement enhancement.

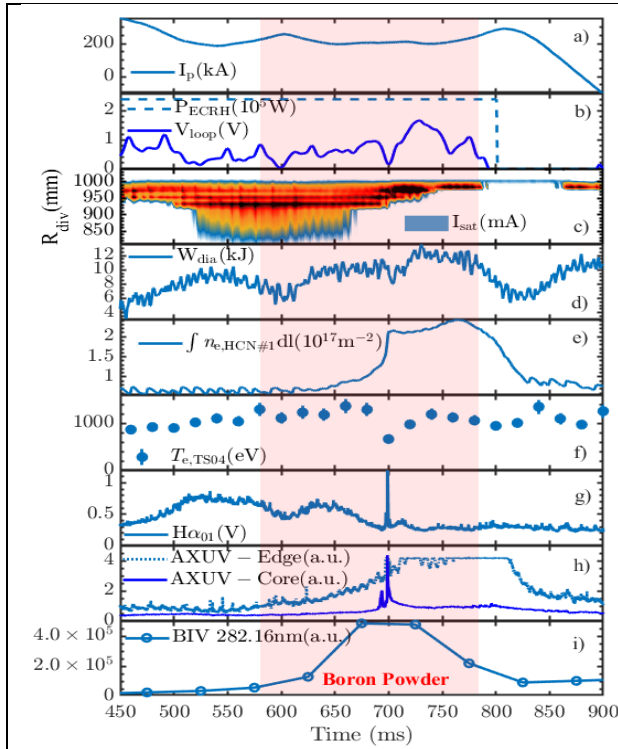


Fig.13 Waveforms of a representative EXL-50U discharge (#9473) with boron powder injection. From top to bottom: a) plasma current, b) ECRH power, loop voltage (V_{loop}); c) 2D distribution of the ion saturation current of the divertor probe; d) diamagnetic stored energy, e) line-integrated electron density; f) core electron temperature from Thomson Scattering, g) H_α emission, h) core and edge AXUV signals, and i) B IV (282.16nm) line emission. The pink shaded area highlights the period of boron powder injection.

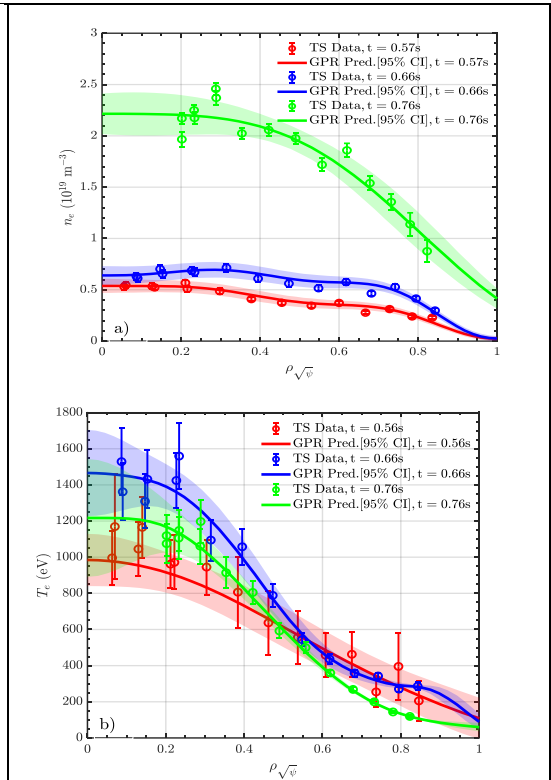


Fig.14 Electron density (n_e) and temperature (T_e) profiles from Thomson Scattering before ($t=0.57$ s) and during ($t=0.66$ s, 0.76 s) boron injection. Solid lines are GPR fits with 95% confidence intervals shown as shaded bands.

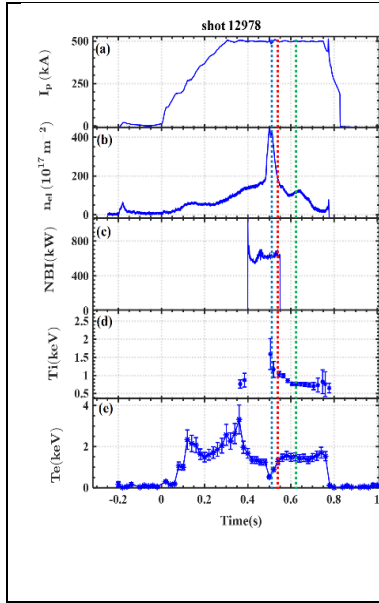


Fig.15 Ion temperature increase during NBI injection in EXL-50U. (a) plasma current; (b) line integrated density; (c) extraction beam power of NBI; (d) The ion temperature of 1.6 keV was achieved during NBI injection; (e) electron temperature.

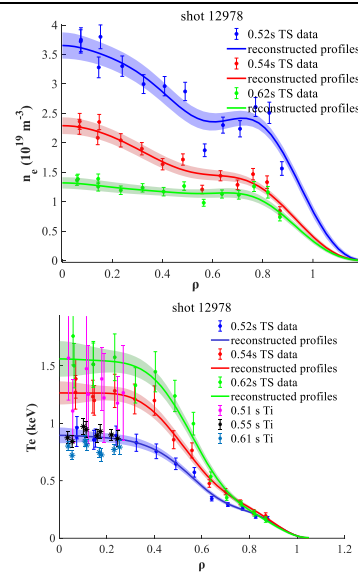


Fig.16 Density (top figure) and (bottom figure) temperature profiles in three time slices for shot 12978.

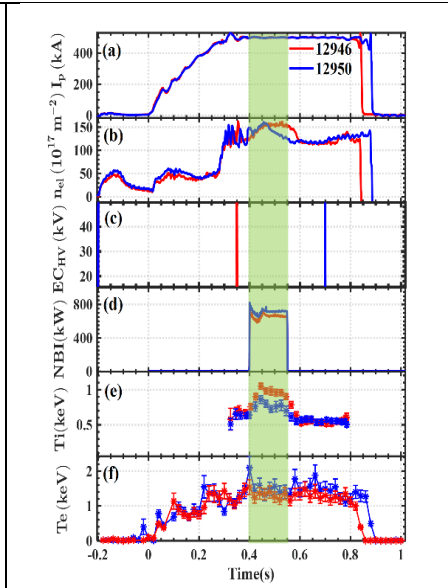


Fig. 17 Experimental results indicate that simultaneous injection of ECRH and NBI is detrimental to ion temperature enhancement. (a) plasma current; (b) line integrated density; (c) gyrotron cathode high voltage; (d) extraction beam power of NBI; (e) ion temperature; (f) electron temperature.

3.4 Ion heating with NBI

Ion temperature is one of the key physical parameters in EXL-50U, and the most important approach for ion temperature enhancement is NBI heating. At present, the extraction beam power of the NBI was 630 kW. Considering the losses due to neutralization and transmission efficiency, a correction factor of 0.65 was applied, corresponding to an injection power of 400 kW. The relative fractions of different energy components measured by beam emission spectroscopy, with the beam power ratio of $E/E/2/E/3/E/18 = 60\%:25\%:11\%:4\%$. In the shot 12798 in fig. 15, boron powder was injected at from 200 ms to 700 ms. The maximum core ion temperature increased to about 1.6 keV during NBI injection in the flat-top phase of the 500 kA plasma current, as shown in Fig. 15 and 16. It can be observed that during NBI injection, the density exhibits a rapid rise and fall, forming a 50 ms bump. The ion temperature reaches its peak, coinciding with the maximum value of the electron density. Subsequently, both the ion temperature and density decrease rapidly.

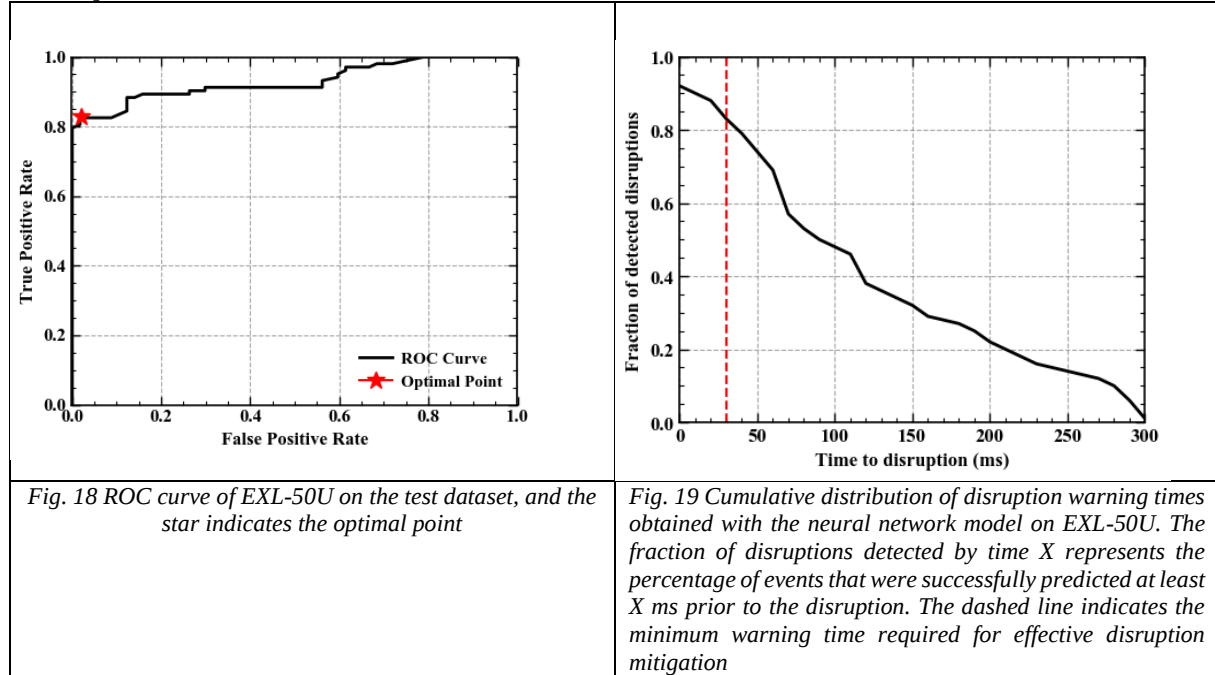
On the other hand, the simultaneous injection of NBI and ECRH was found to be unfavorable for ion temperature enhancement. Fig. 17 shows the waveforms of the two dedicated shots. The main parameters, including B_T , I_p , density, and NBI power were identical between the two shots. The primary difference is that during NBI injection in shot 12950, ECRH was also applied. As shown in Fig. 17, the ion temperature in shot 12946 is clear higher than that in shot 12950. This phenomenon is conjectured to be related to the turbulence instability of ion temperature gradient mode (ITG) and trapped electron mode (TEM) which has been reported in conventional large aspect tokamak [41-42]. The transport analysis and micro-instability simulations will be conducted for NBI heating experiments in future work to elucidate the underlying physical mechanisms.

3.5 Disruption prediction and mitigation

To mitigate disruption-induced damage, techniques such as massive gas injection (MGI) and shattered pellet injection (SPI) have been implemented across various fusion devices. A MGI valve has been developed and installed on EXL-50U, characterized by a fast response time of 0.25 ms. The valve provides an adjustable throughput of up to 5×10^{21} particles, thereby fulfilling the requirements for effective disruption mitigation. To trigger the MGI system, a neural network model has been integrated into the plasma control system. This model, executed via the Open Neural Network Exchange (ONNX) Runtime, enables real-time inference and delivers reliable disruption warnings prior to the onset of the thermal quench (TQ).

The neural network model was trained using the disruption database from EXL-50U, with the corresponding receiver operating characteristic (ROC) curve shown in Figure 1X. The model achieved an area under the curve (AUC) of 0.93. Notably, the optimal point on the ROC curve, characterized by a true positive rate (TPR) of 83.3%

and a false positive rate (FPR) of 2.5%, has been identified. The advance warning time distributions given by the model are shown in figure 2. It is noteworthy that the majority of disruptions (above 83%) predicted by the model are warned more than 30 ms in advance. However, the optimal TPR achieved by the model remains well below the required threshold of 90% for EXL-50U. The result suggests that additional datasets, further model fine-tuning, and the incorporation of advanced feature engineering are necessary to improve predictive accuracy and meet the desired performance standards.



4. Summary and outlook

EXL-50U is advancing the physics and technological basis for the spherical torus as a pathway to commercial fusion energy, and has achieved significant progress in this domain over the past two years. The unique discharge scenario (ECRH non-inductive start-up, ECRH+CS synergy during ramp-up phase) in EXL-50U can reduce the loop voltage and consumption of CS flux, which provide a possible solution for the plasma current start-up and drive for future ST reactors or superconducting tokamak devices. Based on this scenario, record plasma current of 1MA and full non-inductive 280kA have been achieved. Especially, MA-level currents were achieved in p-B plasmas for the first time, demonstrating the scientific feasibility of generating high-performance proton-boron fusion plasmas in a magnetic confinement device. On the other hand, the dedicated Boron powder injection experiments on EXL-50U has proven to be an effective technique for improving wall conditions, controlling recycling, and significantly expanding the achievable density and temperature operating region. These p-B experiments in the EXL-50U shed light on real-time boronization operations in future metal-wall magnetic confinement fusion reactors. The SMBI in EXL-50U has also validated an effective tool for the density feedback control in ST device. AI technology has also been successfully applied in EXL-50U for RZ- I_p control. The real-time feedback control for plasma shaping and advanced divertor configuration in EXL-50U will be implemented as soon as possible with the assistance of AI.

In the upcoming experiments of 2026, the EXL-50U will successively install a second set of 25 kV 1 MW NBI beamlines, a third set of 80 kV 4 MW NBI beamlines, and a 1 MW ICRF heating system. With the commissioning of three sets of high-power NBI systems, it is anticipated that EXL-50U will achieve long-duration quasi-stationary hot-ion modes with an ion temperature of 100 million degrees. The proton-boron fusion reaction will also be investigated with the energetic ions generated through synergetic effects between positive NBI and ICRF in EXL-50U plasmas. The optimization of the divertor configuration is also a key aspect of the upcoming experimental plan. Especially, XPT which is the main reference divertor configuration in EHL-2 [28] will be explored on EXL-50U. The physics and engineering design of closure V-shape divertor in EXL-50U has been finalized and is slated for installation in 2026, replacing the flat divertor. We intend to implement a variety of divertor geometries on the EXL-50U platform, with the dual objectives of ensuring efficient impurity removal and thermal load management under high-power heating conditions, as well as investigating the H-mode detachment and high-triple-product operational regimes.

ENN plans to take three years to fully achieve or verify the key physical goals of EXL-50U to explore the solution for the key physics issues for future ST reactors. The current and future experiments of EXL-50U will strongly support the physical design and operational scenarios of EHL-2 in the areas of current drive, high ion

temperature exploration, energy transport and confinement, and hydrogen-boron physical characteristics. At the same time, the experience in the design, construction, and commissioning of the engineering, heating, and diagnostics systems on EXL-50U is also very beneficial for enhancing the feasibility of the engineering design for next-generation large STs [44-45].

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