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

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The EXL-50U [1] is China's first large spherical torus (ST) device with a toroidal field reaching 1 T. 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. The physics and engineering design of EXL-50U was completed in the end of 2023. The main device assembly of EXL-50U has been finished in the end of 2023. The key physics issues of EXL-50U's experiments which are directly related to EHL-2's physics [2,3] and future ST reactors are as follows:

- non-inductive current drive [4]
- scenarios development for stable high density hot ion mode for ST (T_{i0} = 3keV ~ 10keV)
- investigation of energy confinement scaling for wide range scan of aspect ratio (1.4~1.8) and Bt (0.5T~ 1.2T)
- proton-boron plasma physics and preliminary proton-boron fusion reaction with energetic ions [5,6].

Table 1. The main parameters of EXL-50U

Parameters	Value
Plasma current	0.5MA (already achieved in first phase) 1MA (second phase)
Major radius	0.6-0.8m
Toroidal magnetic field (R=0.6m)	1.0T(first phase) 1.2 (second phase)
Aspect ratio	1.4-1.85
Elongation	1.4~2
Discharge TF flattop duration	2.5s @1.2 T 1.5MW/50kV/5s
NBI	1MW/25kV/2s (second phase) 1MW/200kV/2s (third phase)
ECRH	3×0.4MW/28GHz/5s 2×0.5MW/50GHz/1s 0.5MW/80GHz/2s (second phase)
ICRF	3-26MHz/100kW/CW 13.56MHz/80kW/CW 2MW/25MHz~40MHz/1s (second phase)
LHCD	2×0.2MW/2.45GHz/CW

The first plasma of EXL-50U has been obtained in Jan, 2024. The goal of plasma current in the first experimental phase is 500 kA, and in the future second phase, the goal of plasma current is 1 MA. In the latest experiments, the EXL-50U achieved a plasma current of 580 kA using ECRH (Electron Cyclotron Resonance Heating) for non-inductive current start-up and a current ramp-up with the synergetic effect of ECRH and central solenoid (CS). Stable and repeatable plasma current were also obtained under 500kA in limiter configuration with 2.5MA/s ramp-up rate and 400 kA in divertor configuration. The unique discharge scenario (EC start-up + Ohmic assisted ramp-up) in EXL-50U can reduce the loop voltage and consumption of CS flux (as shown in Fig.1), which is very important for future ST reactors or superconducting tokamak devices. Moreover, a recording 270kA fully non-inductive current by 380kW ECRH is also achieved (as shown in Fig.2). The initial Boron-power injection results in show the positive effective of Boron on plasma performance (as shown in Fig.3). It is worth mentioning that the boron powder injection in the EXL-50U is the first experiment of its kind conducted on a full-metal-wall spherical torus device. This holds significant reference value for real-time boronization using boron powder in future full-metal-wall ST reactors. The core ion temperature of 1 keV was achieved with 270kW low-power NBI heating, and the energy confinement time of 30 ms was reached with Ohmic heating in the flat-top phase. 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 [7-9].

ENN plans to take three years (from 2024 to 2026) 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.

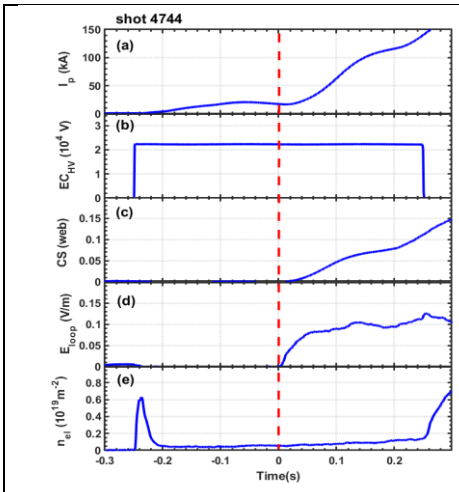

Fig.1 Typical start-up waveforms with 28 GHz ECRH in EXL-50U [1]. The vertical red dashed line indicates the start of CS current. Waveforms from top to bottom are: (a) plasma current; (b)gyrotron anode high voltage; (c) flux consumption of CS coils; (d) toroidal electric field which is below 0.15V/m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

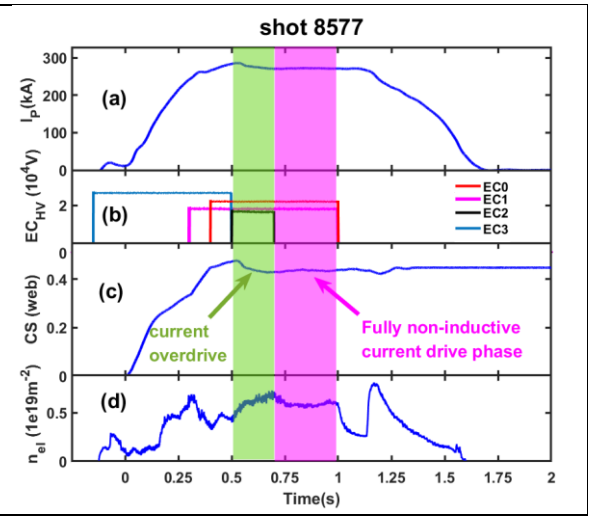

Fig.2 A record-breaking fully non-inductive current of 270kA by 380kW ECRH (magenta shade area in the figure) has been achieved. During the period of higher power ECRH injection phase (green shade are in the figure), current overdrive is achieved.

Reference

[1] SHI Y.J., SONG X.M., GUO D., et al., Strategy and experimental progress of the EXL-50U spherical torus in support of the EHL-2 project, Plasma Sci. Technol. **27** (2025) 024003

[2] LIANG Y.F., XIE H. S., SHI Y.J., et al., Overview of the physics design of the EHL-2 spherical torus, Plasma Sci. Technol. **27** (2025) 024001

[3] XIE H. S., LIANG Y.F., SHI Y.J., et al., Overview of the physics design of the EHL-2 spherical torus for proton-Boron fusion, this conference

[4] JIANG X. C., SHI Y.J., GU X., et al., Non-Inductive Current Start-up and Optimized Ramp-up in EXL-50U for Next-Generation Spherical Torus Devices, this conference

[5] PENG Y.K.M, SHI Y.J., LIU B., et al., Strongly Rotation ST p-11B Fusion Plasmas, this conference

[6] LIU B., LI Z., LUO D., Progress of Proton-Boron Research for Fusion Energy in China, this conference

[7] GU X., F.Q.Wang, J.K.Hua, et al., Design and Optimization of Advanced Divertor Configurations for Heat Load Management in the EHL-2 Spherical Torus Project, this conference

[8] YANG Y.M, WANG Y., CHEN B., et al., Progress of the EHL-2 Spherical Torus Engineering Design, this conference

[9] Chapman I. T., Cowley S. C. and Wilson H. R., The Spherical Tokamak for Energy Production: theme issue introduction, Phil. Trans. R. Soc. A.**382** (2024) 20230416

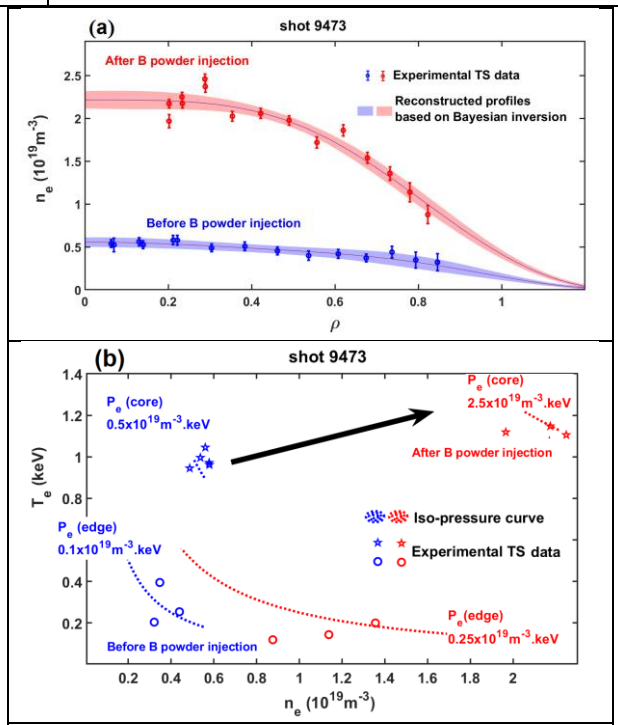

Fig.3 Boron-powder injection results: dramatically global density (as shown in fig.3a) and pressure (as shown in fig.3b) increase with constant heating power. The core density and electron pressure has increased by a factor of 4.