ID: OV-2999

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

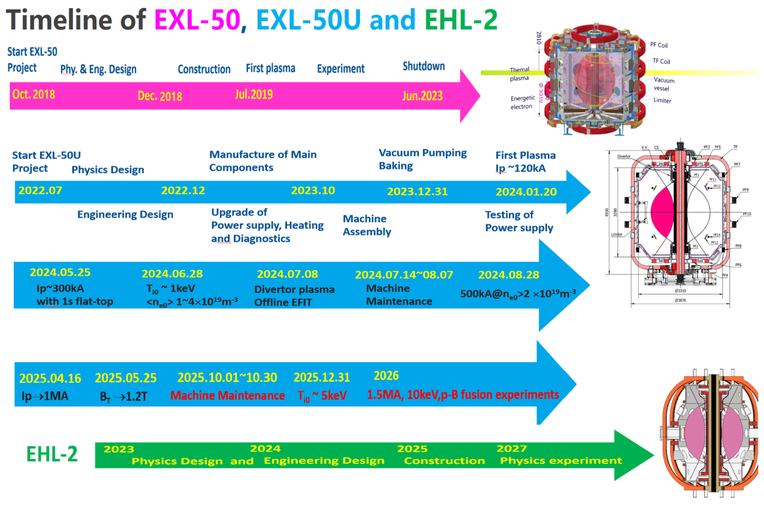
Yuejiang SHI on behalf of the EXL-50U Team

ENN Science and Technology Development Co., Ltd., Langfang 065001, P. R. China

Abstract

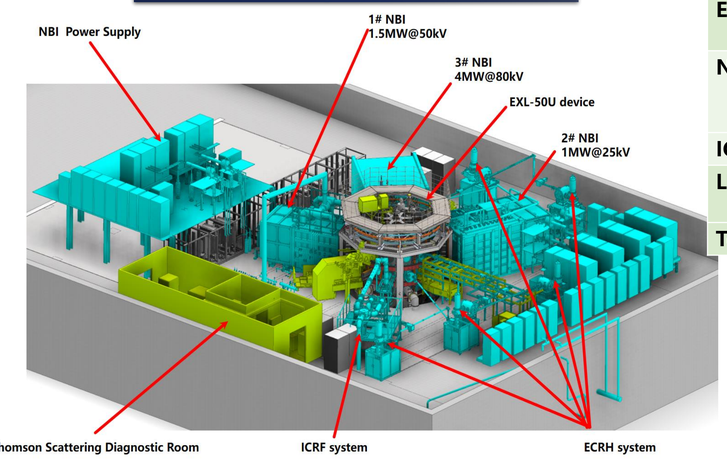
- ECRH non-inductive start-up plus CS induction significantly reduces the loop voltage and consumption of CS flux during ramp-up.
- Record 270kA non-inductive current flattop; record 1 MA proton-boron plasma discharge fueled solely at 10% boron atomic fraction.
- 500kA stable divertor plasmas with PID control; AI-assisted RZ-I_p control; SMBI fueling for density feedback control.
- Real-time boron-power injection with a metal wall in EXL-50U demonstrates the positive effect on plasma performance

Timeline of EXL-50, EXL-50U and EHL-2



- ENN, the first private company in China to enter into fusion energy research.
- Rapid iteration of R&D platforms to accelerate commercial fusion power.
- EXL-50, the first ENN ST, built in 8 months ⇒ highest CS-free ECRH CD currents [1,2].
- EXL-50U achieved 1MA plasmas current and 1.2T@1.6s in April 2025 [3,4].
- EHL-2, a large ST, to complete design in 2025 and construction in 2027 [5-7].

EXL-50U Spherical Torus



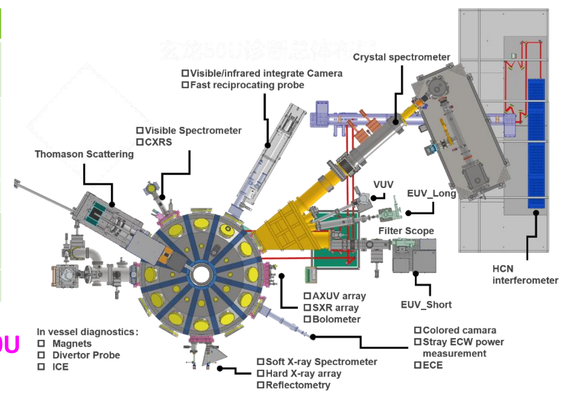
Main parameters of EXL-50U

Diameter	3.87 m
Height	4.55 m
Major Radius	0.6-0.8 m
Minor Radius	0.32-0.5 m
B_T @ R=0.6m	1.2 T
CS Flux	1.2 web
TF flattop duration	2 s @ 1.2 T 8s @ 0.6 T
Plasma current	0.5 – 1.5 MA

H&CD	Parameters
ECRH	3×400kW@28GHz 2×500kW@50GHz
NBI	1.5MW@50keV 1MW@25keV (Nov.2026) 3MW@80keV (2027)
ICRF	1MW@3-26MHz (2027)
LHCD	2×0.2MW@2.45GHz (2028)
Total power	~8MW

Boron injection systems on EXL-50U

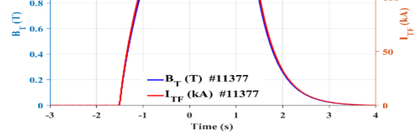
- B_2H_6 gas-puffing
- Boron powder
- Boron pellet
- ☐ Real-time Boronization
- ☐ Boron fueling for concentration and Boron profile control



Layout of diagnostics on EXL-50U

ST reactor physics issues addressed

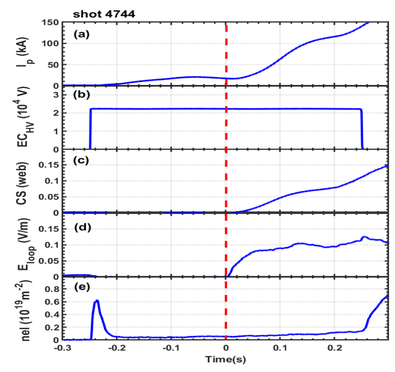
- Non-inductive current drive
- Scenarios for high-density hot-ion-mode (Ti0 = 3 - 10keV)
- Confinement scaling for A = 1.4 - 1.8, Bt = 0.5T - 1.2T
- Proton-boron plasma physics and fusion reaction via suprathermal ions



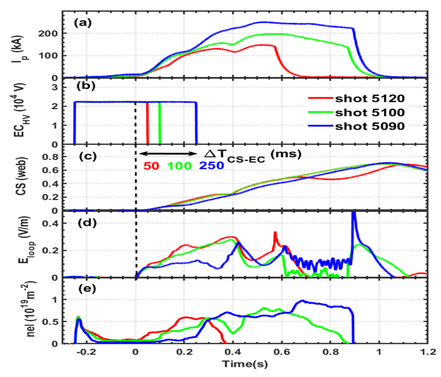
EXL-50U is the world's first ST that can achieve 1.2T with seconds flattop

Unique non-inductive current start-up and current drive

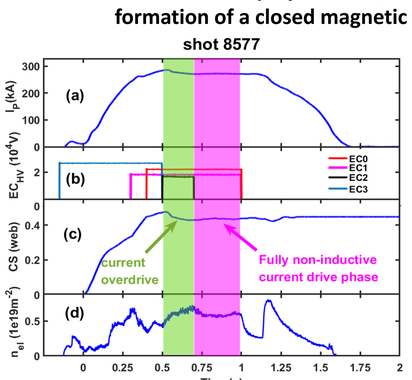
- Start-up by EC
- Ramp-up by EC+CS
- Low V_{loop}
- Low consumption of CS flux
- EC+CS scenario to get a flat-top



Breakdown and startup by EC alone, CS injected after formation of a closed magnetic surface

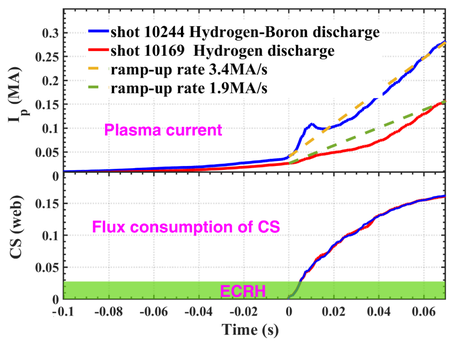


Ip at flattop phase is proportional to ΔT_{CS-EC}

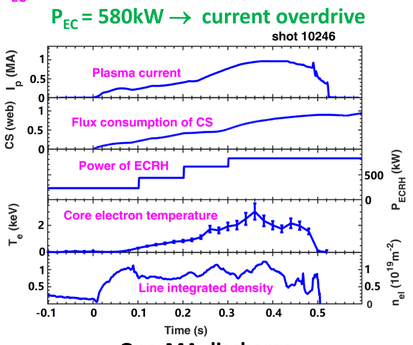


P_{EC} = 380kW → 270kA fully non-inductive CD

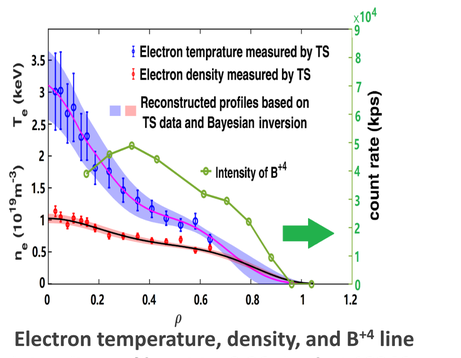
P_{EC} = 580kW → current overdrive



Higher current ramp-up rate for p-B plasmas



One-MA discharge



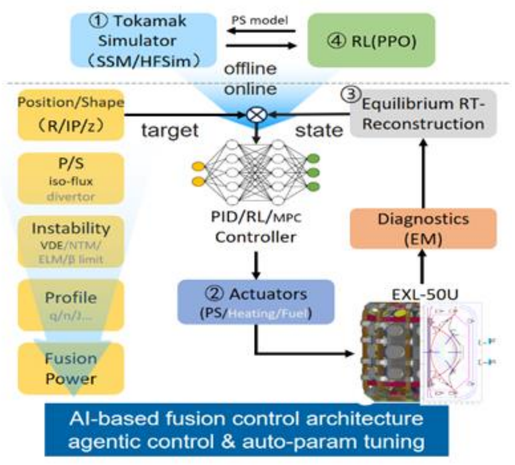
Electron temperature, density, and B^{+4} line intensity profiles at t = 0.36s in shot 10246. Non-inductive fraction > 50%.

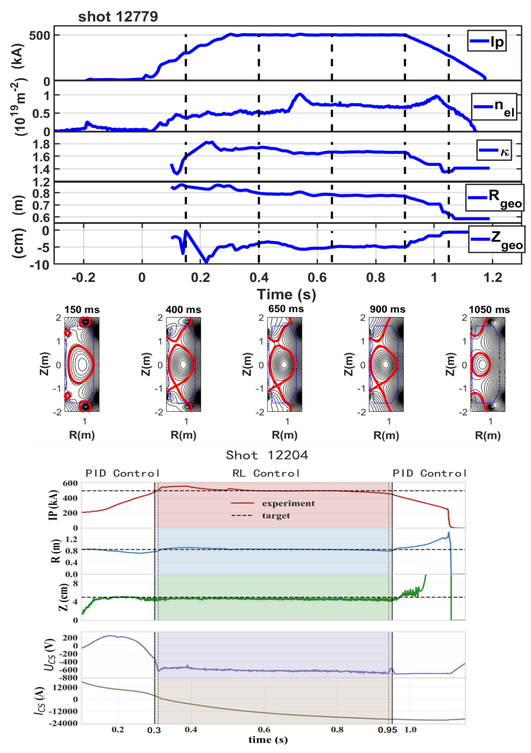
- Pre-fill: diborane-hydrogen mixture (30% B_2H_6: 70%H_2).
- Boron powder injection during ramp-up and flat-top

Plasma control with PID, AI, and SMBI

Stable divertor configuration at 500 kA has been regularly achieved using the Proportional-Integral-Derivative (PID) method.

- Inboard limiter configuration during initiation and ramp-up.
- Divertor configuration produced after exceeding a plasma current threshold.
- Limiter configuration during ramp-down.
- Limiter configurations avoid VDE during ramp-up and ramp-down.

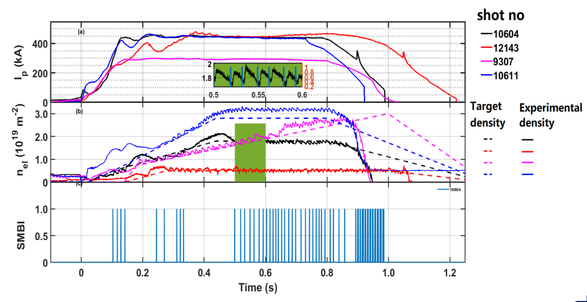




AI controller-maintained plasma current with ±1cm accuracy in (δRmag, δZmag) for 650 ms.

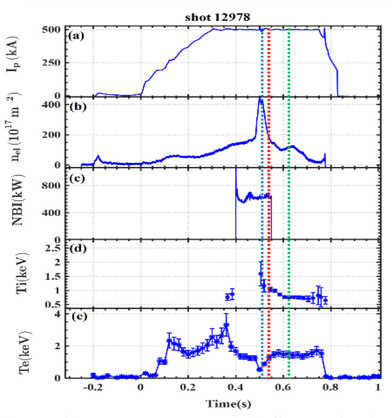
Density feedback control via SMBI

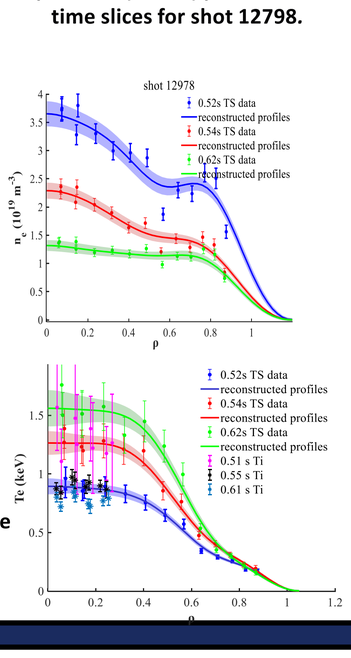
- Gas-puffing at the central column delays response by the order of 100 ms.
- Outboard SMBI response delayed less than 3 ms.
- SMBI enables reliable density ramp-up and flat-top for densities from 0.5×10^{19}m^{-2} to 1.5×10^{19}m^{-2}.



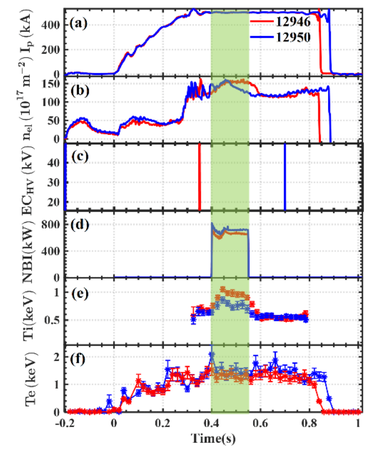
Ion heating with NBI

Electron density (above) and temperature (below) profiles in three time slices for shot 12798.



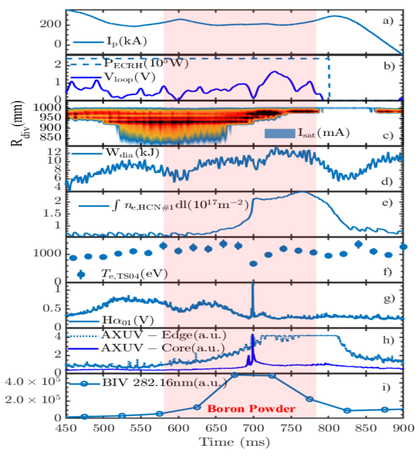


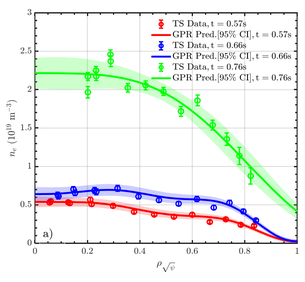
- Central ion temperature briefly reached ~1.6 keV with 400kW NBI injection.
- Boron powder injected from 0.2s to 0.7s.
- Maximum ion temperature coincided with the maximum electron density.
- Improved NBI and plasma control are being implemented.



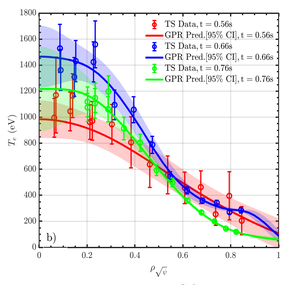
Adding NBI to ECRH (shot 12950 in blue line) lowered the ion temperature. Underlying mechanisms being investigated: Micro-instabilities and/or interference between these heating methods?

Boron powder injection experiment





TS density profiles



TS T_e profiles

- Boron powder injected at a rate of 5 mg/s.
- Line-integrated density increased to 4 times.
- Hα dropped significantly during boron powder injection, indicating a simultaneous reduction in hydrogen recycling.
- Divertor Langmuir probes indicated a transition from limiter to divertor configuration
- Improved wall conditioning is required for reaching high densities.
- Simultaneous rise in plasma stored energy.

Summary & Outlook

- Current drive scenarios in EXL-50U: EC ⇒ Start-up, EC+CS ⇒ Ramp-up.
  Low loop voltage and consumption of CS flux, relevant to S/C designs such as ST reactor and ITER.
- Scientific feasibility of producing and maintaining high-performance hydrogen-boron ST plasmas established.
- AI techniques and SMBI successfully applied for (R,Z,Ip) and density feedback control.
- During the upcoming 3-4 years, ENN plans to reach EXL-50U's R&D goals of addressing key plasma issues for future ST reactors and help establish the physics basis of the EHL-2 physics projections.

ENN's contributions to the 30th FEC

- 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, IAC-2989
- 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, EX-H-3047
- LIU B., LI Z., LUO D., Progress of Proton-Boron Research for Fusion Energy in China, OV-3111
- GU X., SONG X.M., LIU W.J. et al., Design and Optimization of Advanced Divertor Configurations for Heat Load Management in the EHL-2 Spherical Torus Project, TH-D-3179
- YANG Y.M, WANG Y., CHEN B., et al., Progress of the EHL-2 Spherical Torus Engineering Design, TEC-FNT-3012

REF

[1] Y.J.SHI, B.LIU, Y.K.M.Peng et al, Solenoid-free current drive via ECRH in EXL-50 spherical torus plasmas, Nucl. Fusion 62(2022) 086047
[2] Y.J.SHI, Y.M.WANG, B.LIU et al, Overview of EXL-50 research progress, Nucl. Fusion 65(2025) 092004
[3] Y.J.SHI, S.M.SONG, D.GUO 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
[4] Y.J.SHI, D.GUO, X.M.SONG et al, Achievement of 1 MA discharges in hydrogen-boron plasmas on EXL-50U, Plasma Sci. Technol. 27 (2025) 092002
[5] 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

ENN 新奥 用我所能 善待明天