5th International Workshop on Proton-Boron Fusion
8th – 11th Sept. 2025
Belgrade, Serbia

ENN EXL-50 and EXL-50U Experiments, Addressing Physics Basis for p-^{11}B Spherical Torus Power Demonstration

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Outline

I. ENN XuanLong-50U (EXL-50U)

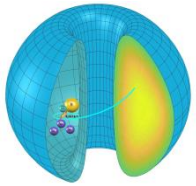
- Mission and research plan
- Boron fueling effects on EXL-50
- Device status

II. EXL-50U Research Progress

- Non-inductive start-up and current drive
- Plasma control and divertor experiment
- Proton-boron experiment
- Energy confinement and transport, Ion heating

III. Summary and Discussion

ENN roadmap for p-B fusion power based on spherical torus



2035
Commercial Demo

Phase I Goal: Achieve scientific and technological breakthroughs and lay the foundation for p-B fusion commercialization

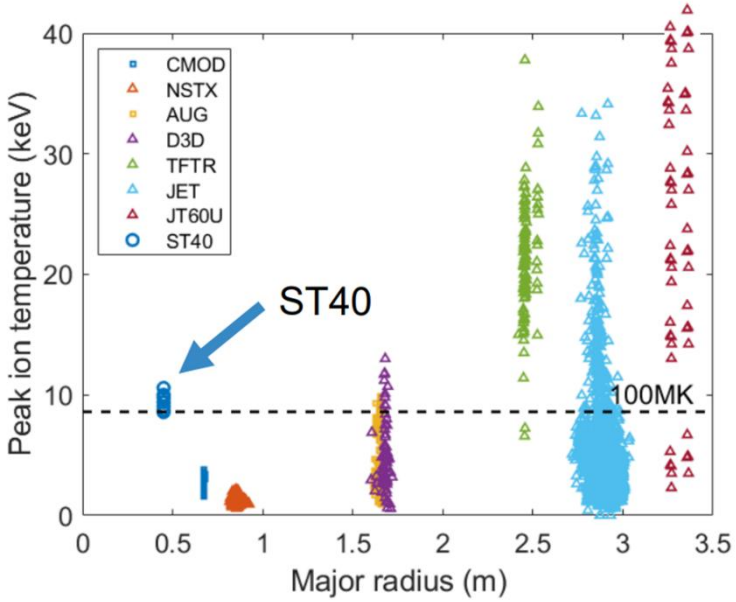
Phase III (commercial demo)
2035-
- Establish cost basis

Phase II (EHL-3)
2027-
- Establish physics basis for scale-up to Demo

Phase I (EHL-2)
2023-
- Develop S&T basis for EHL-3

EXL-50U, the second ST in ENN)
Construction: 2022-2023 Experiment:2024--
- Develop S&T basis for EHL-2

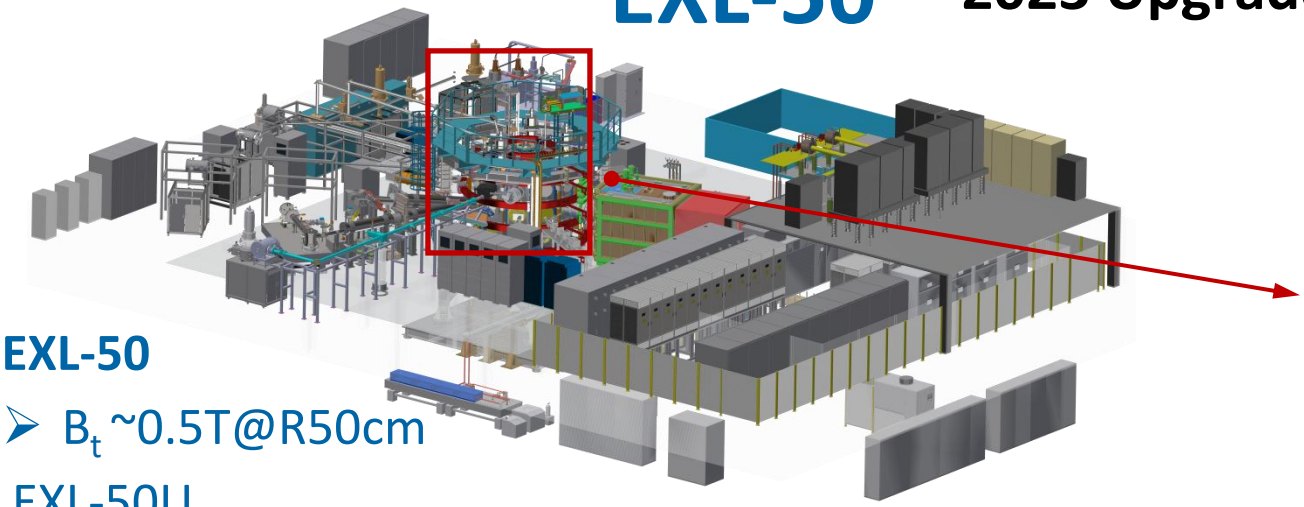
EXL-50, the first ST in ENN
Construction: 2018-2019 Experiment:2019--2023
- Established the basis of ST p-B fusion project

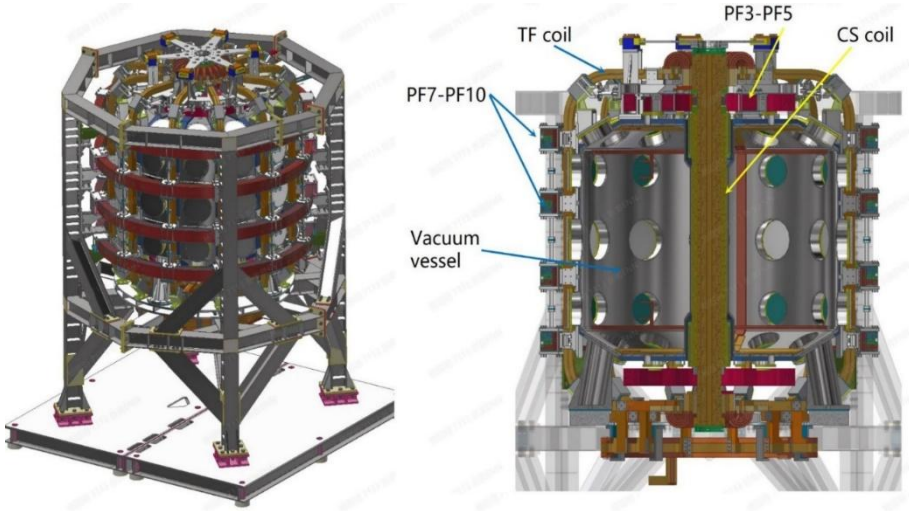


Small ST40 has reached 10 keV ion temperature

Key Physics tasks of EXL-50U for Proton-Boron Fusion Spherical Torus Reactors

EXL-50 → 2023 Upgrade → EXL-50U





Cross sectional view of the EXL-50U

EXL-50

- B_t ~0.5T@R50cm

EXL-50U

- New vacuum vessel and TF&PF magnetic coils
- B_t ~1.2T @R60cm

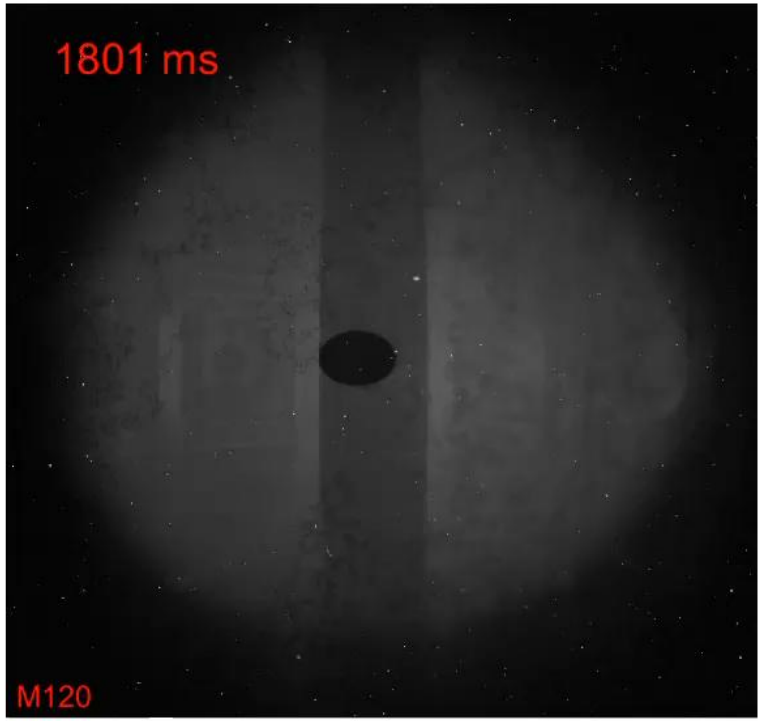
Key physics issues of EXL-50U

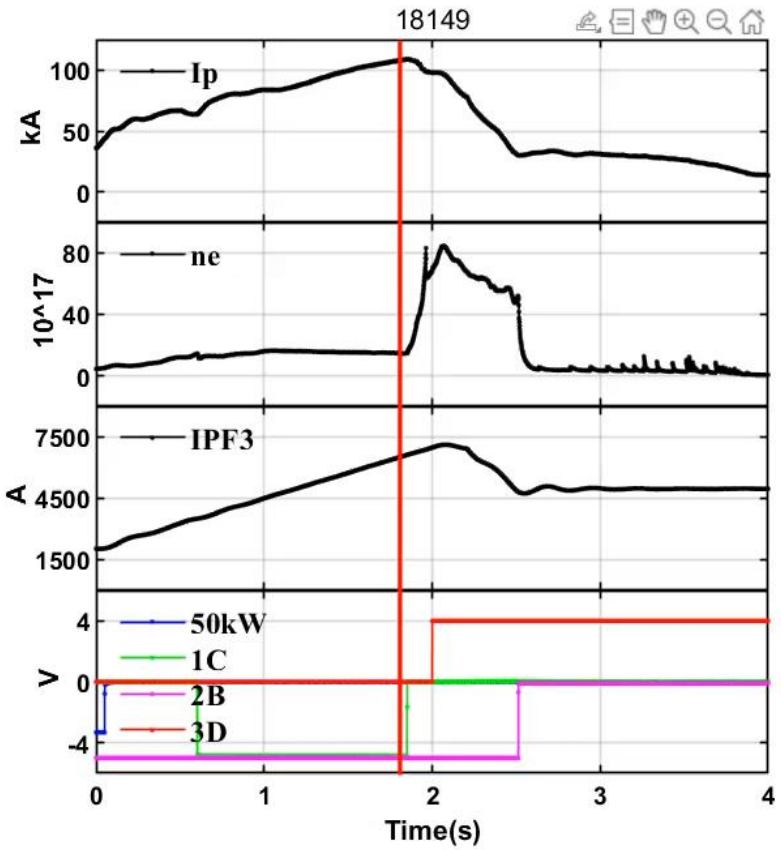
- **Non-inductive current drive**
- **Hot ion mode for ST (T_i/T_e>1.5, T_i = 5~10keV)**
- **ST Energy confinement scaling**
- **p-B plasma physics and preliminary p-B fusion study**

Physics goals of EHL-2*

- **High-performance steady-state scenario**
  Ip 2~3MA, non-inductive faction70%~100%;
- **High ion temperature scenario**
  $T_{i,0}$ ≥ 25keV, T_i/T_e≥2
- **High triple product scenario**
  Confirm ST high confinement scaling (HST≥ 0.5 , τE ≥ 0.5s)
- **Measure fusion reaction rate of p-11B fusion**

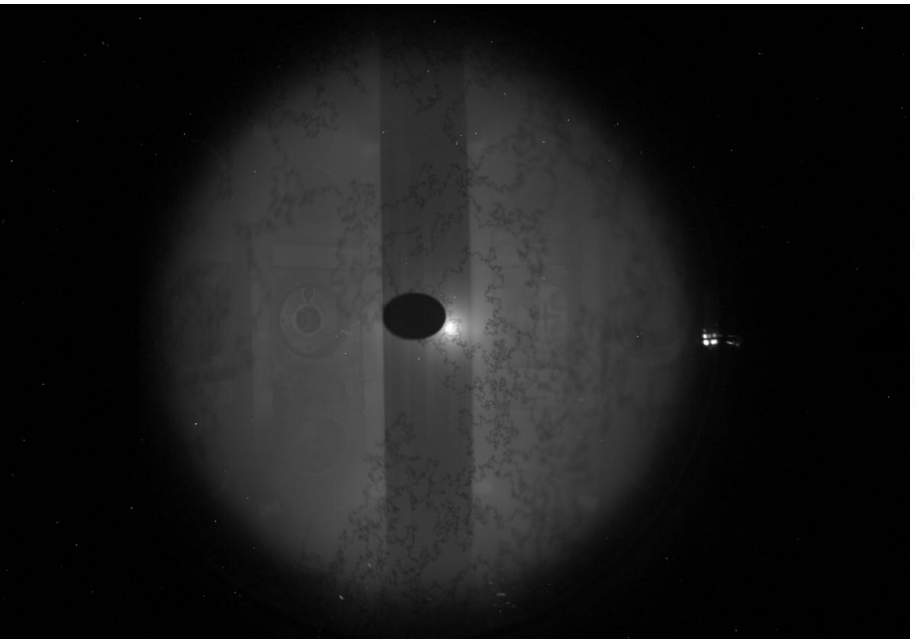
ECRH-only boron power injection results on EXL-50

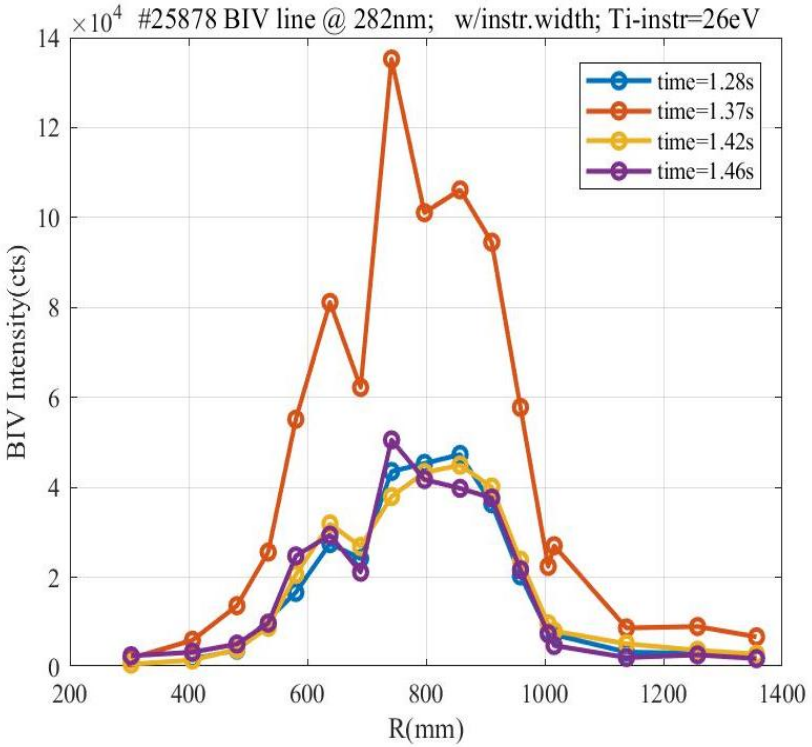


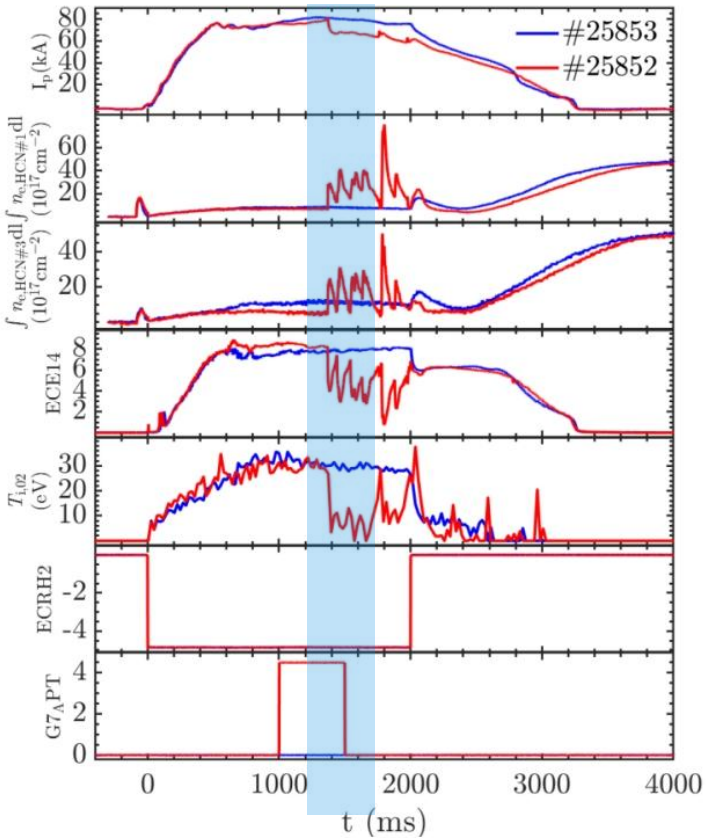


Edge turbulence was suppressed following power injection, while density decreased.

ECRH-only boron pellet injection results on EXL-50

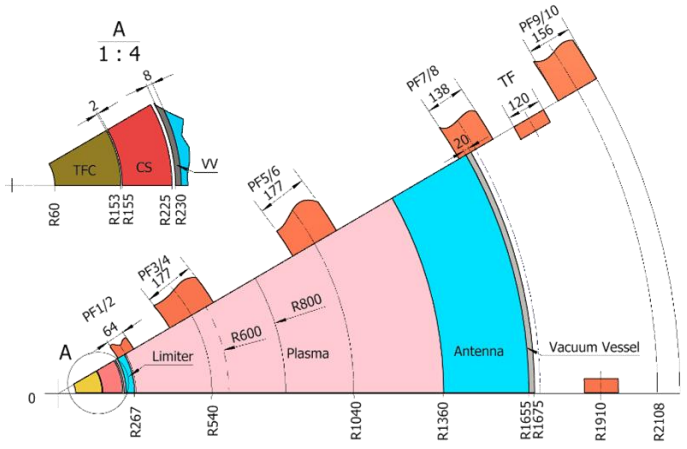






- Pellet injection at **t = 1.0s;** the pellet entered the plasma at **t = 1.37s**. .
- Six pellets were injected in sequence, with significant density increase, a sharp ECE signal drop, a **10-kA** plasma current decrease, and edge turbulence suppressed.

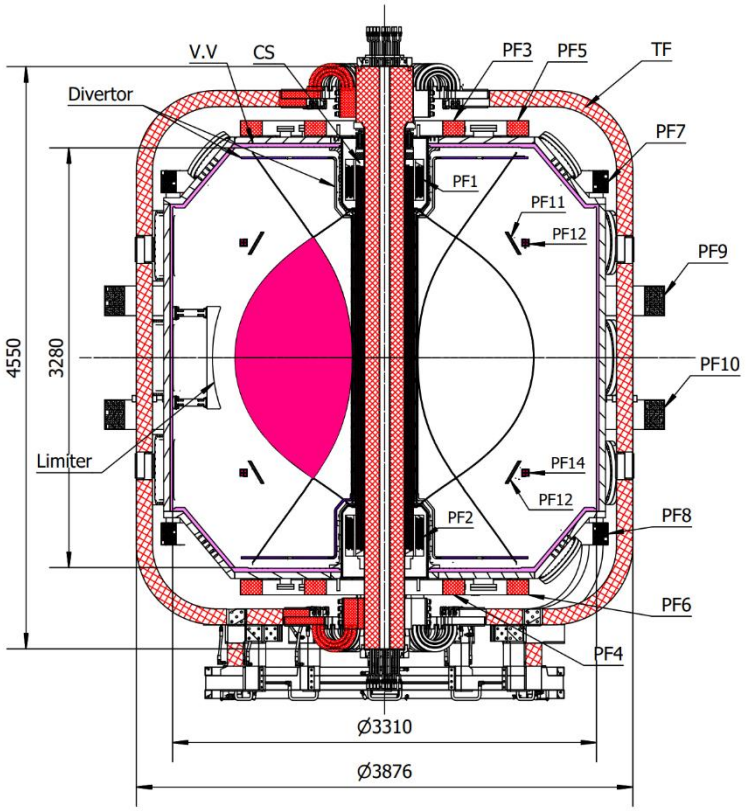
EXL-50U Device (玄龙-50U)



EXL-50U dimension chain

Parameters	EXL-50U
R (m)	0.6~0.8
a(m)	0.32~0.5
R/a	1.4~1.85
k	2.0
Ip (MA)	0.5 (1st phase) 1(2nd phase)
B_T (T)	1.2@R=0.6m
Discharge time *td* (s)	1.5s@1.2T

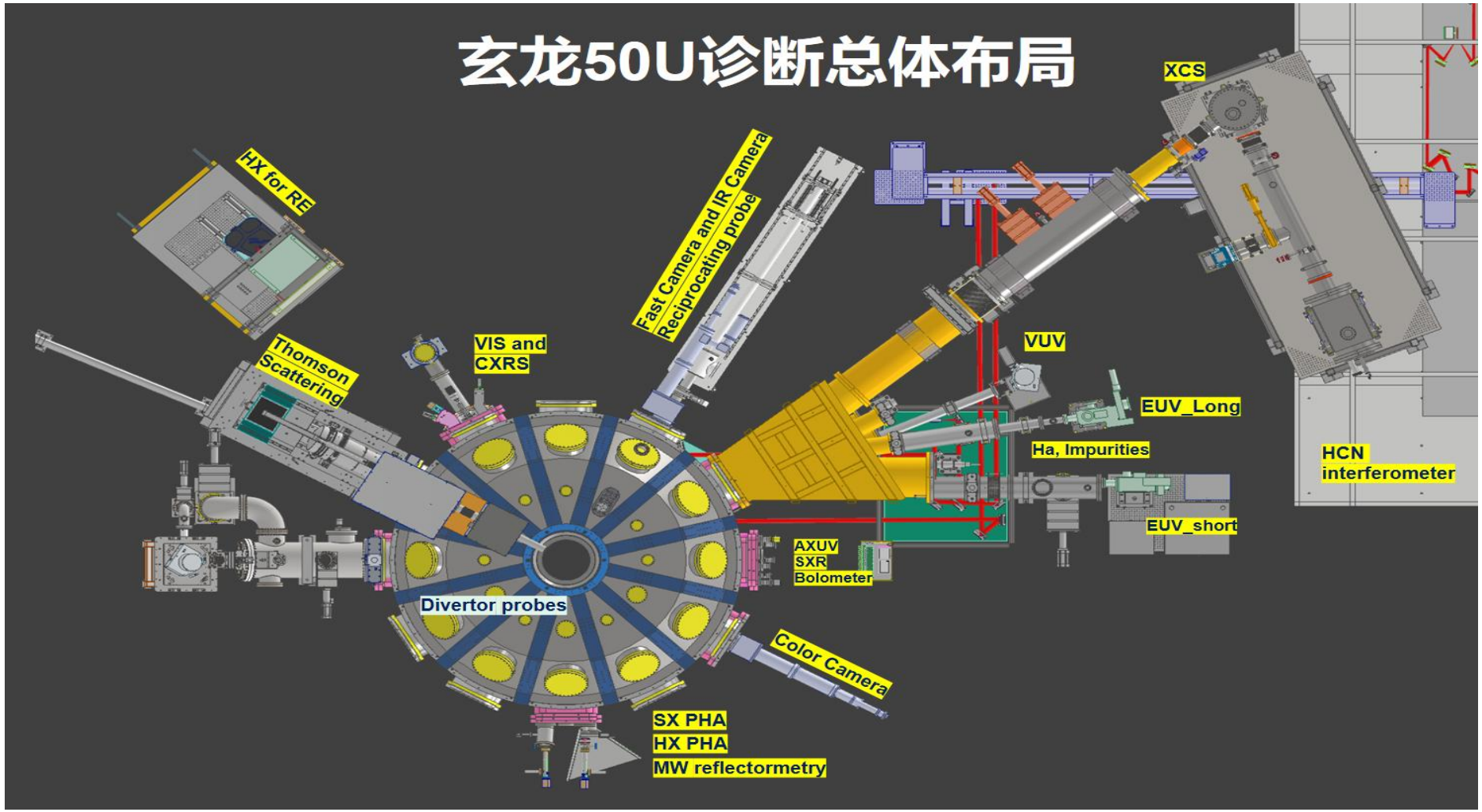
Scan the QR code to start the visual tour of EXL-50U



Poloidal cross-section of EXL-50U

Phase 1: W limiter & Open Diverter +SS first wall
Phase 2: CFC outer-board limiter after Mar. 2025
CFC in-board limiter after Oct.2025
Closure V-shape divertor in 2026

Diagnostics on EXL-50U



- Diagnostics related to device safety and operation are fully equipped
- Diagnostics of key parameter profiles are also in place
- Diagnostics related to fast ions and α particle are under development

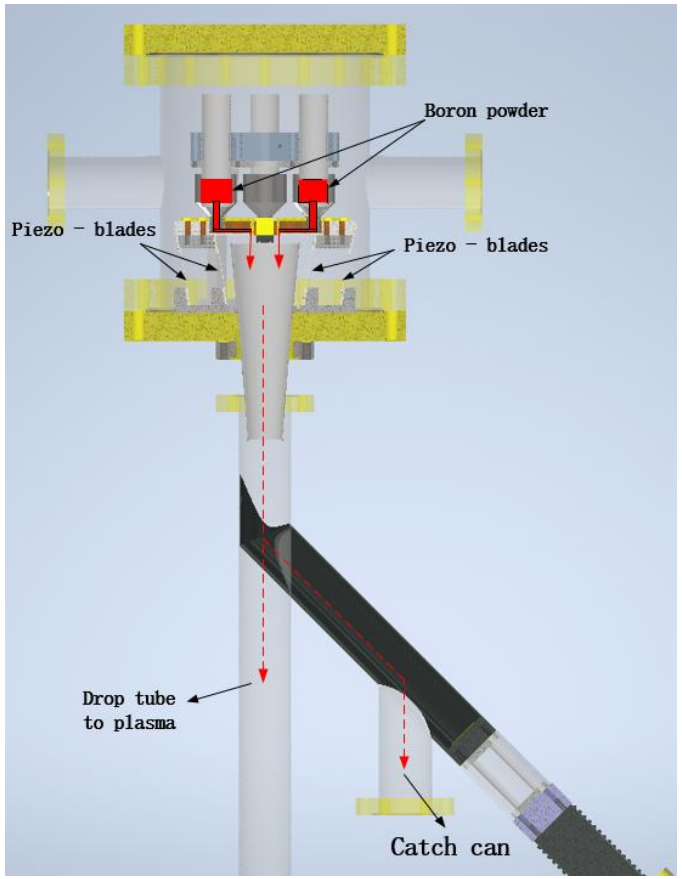
Boron injecting systems on EXL-50U

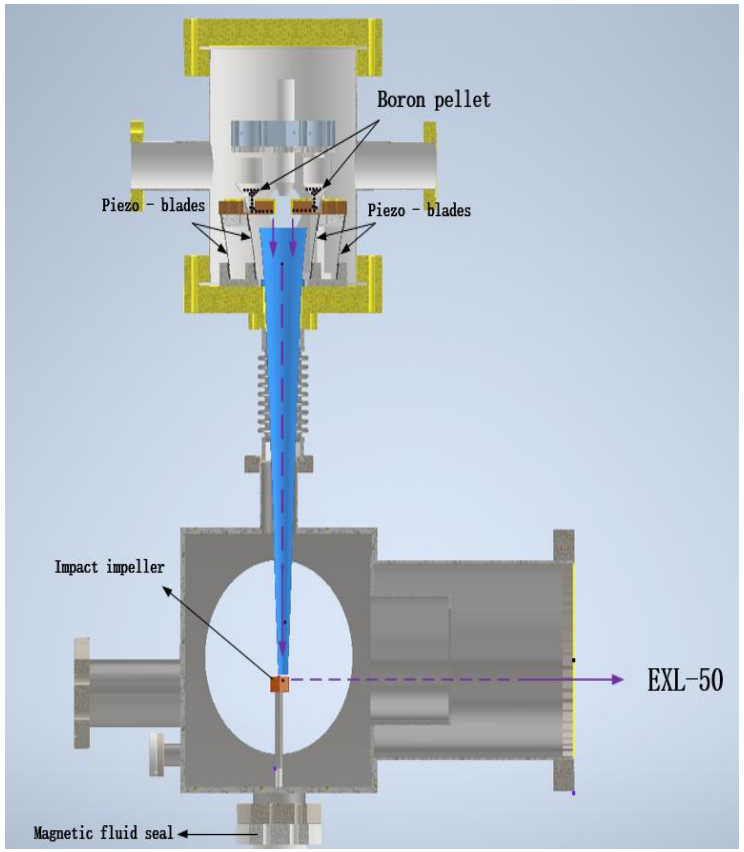
Boron injection on EXL-50 & 50U

1. B_2H_6 gas-puffing
2. Boron powder
3. Boron pellet

P-boron research：

- GDC Boronization
- Real-time Boronization
- Boron fueling and Boron profile control





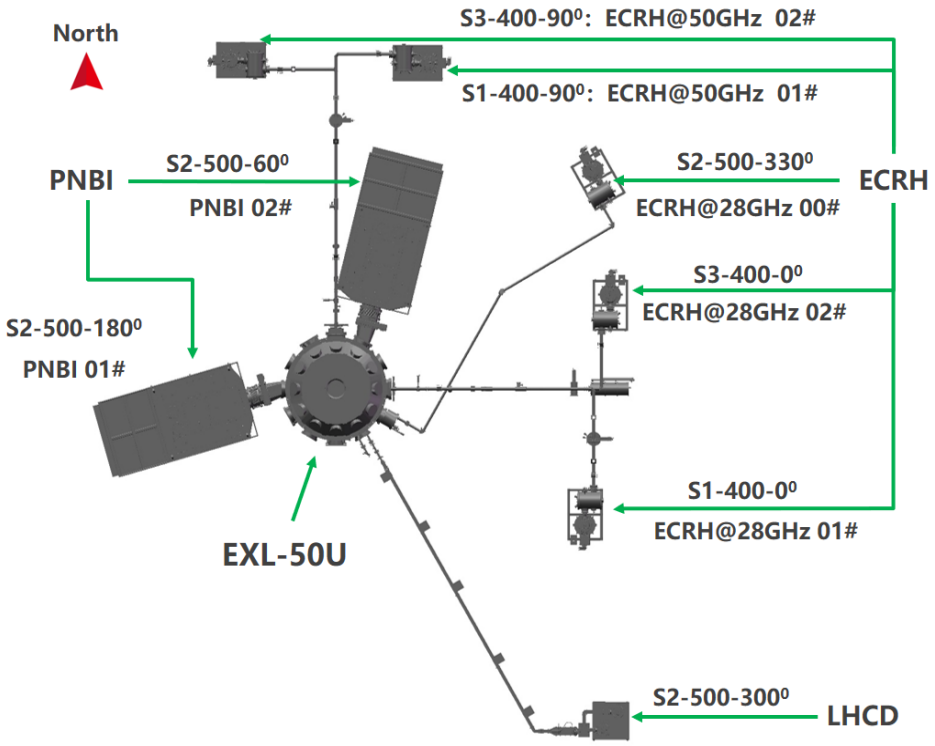
Boron powder injector

- Two cartridges
- Injection rate: 1mg/s~10mg/s
- Injection duration: 50ms to seceonds

Boron pellet injector

- Pellet size: ϕ0.5 mm ~ ϕ 1.0 mm
- Injection speed: 50 ~ 100 m/s

Heating systems on EXL-50U

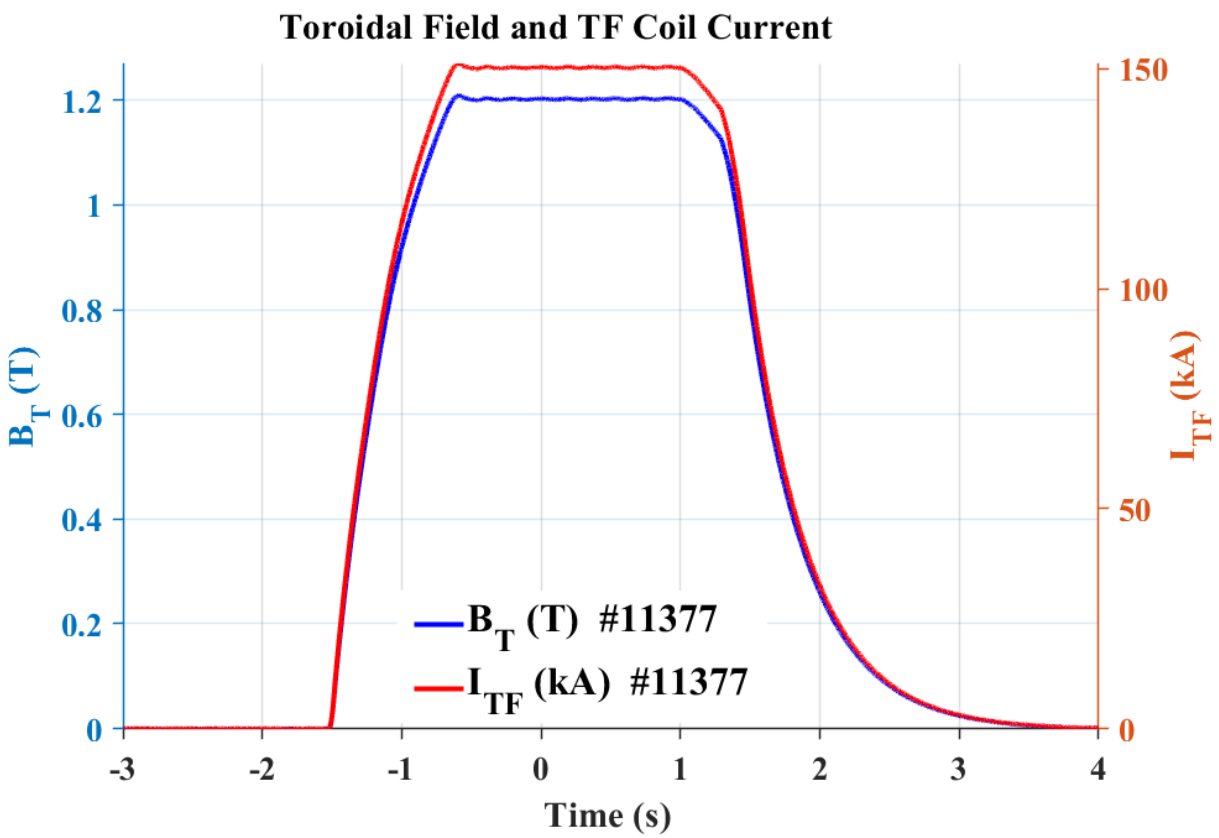


Arrangement of heating systems on EXL-50U

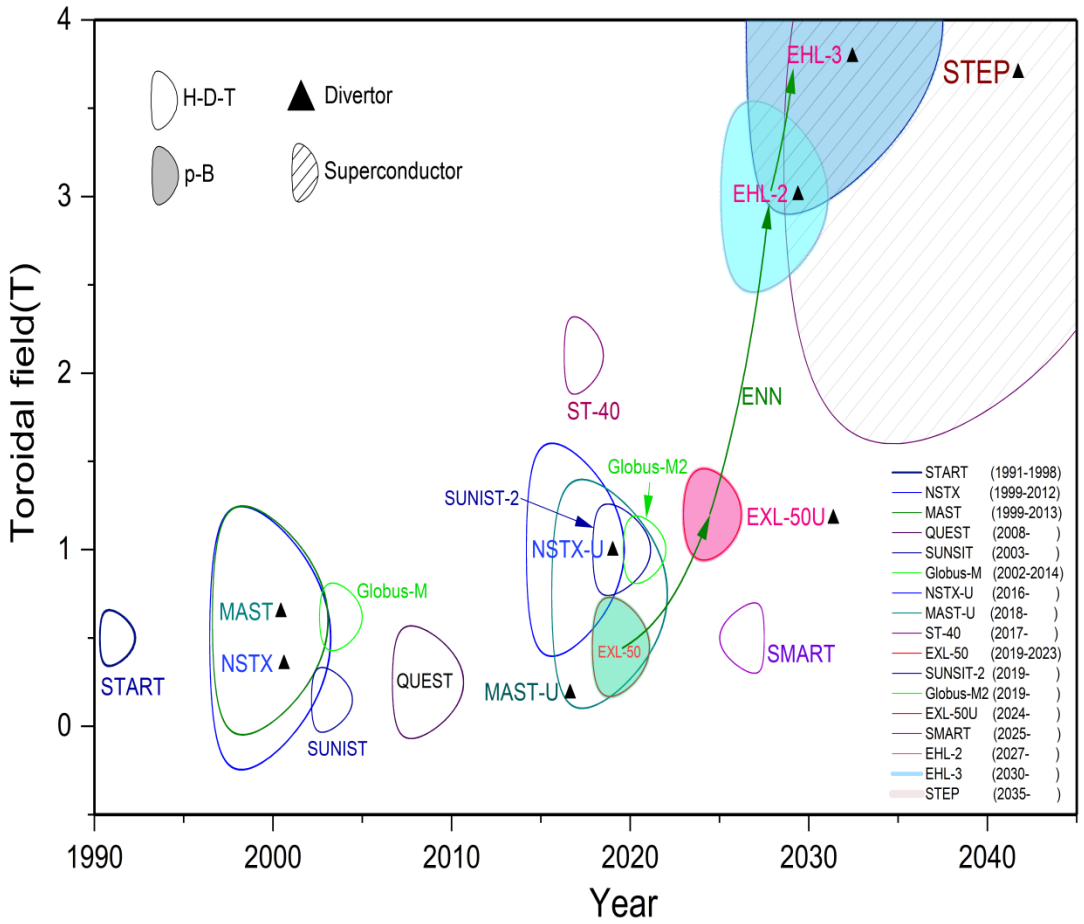
Year		2024	2025	2026
Experimental Target		Current Drive I_p : 300 - 500kA n_{e0} > $2\times10^{19}m^{-3}$ High T_i plasma T_{i0}~1keV Energy confinement Investigation of for OH heating	Current Drive I_p: 500-1000kA n_{e0} >$5\times10^{19}m^{-3}$ High T_i plasma T_{i0} : 3~5keV Energy confinement Verification of ST scaling law of p-B Advanced divertor configuration ● XPT	Current Drive I_p: 1-1.5MA n_{e0} >$8\times10^{19}m^{-3}$ High T_i plasma T_{i0} : 8~10keV p-B reaction rate with energetic ions ● NBI+ICRF synergetic experiment
Heating requirement	NBI	0.3MW@25kV	1MW@25kV 1.5MW@50kV	1MW@25kV 1.5MW@50kV 3MW@80kV
	EC	0.6MW@28GHz 0.3MW@50GHz	1.2MW@28GHz 1MW@50GHz	1.2MW@28GHz 1MW@50GHz
	IC	80kW@3-26MHz	1MW@25-40MHz	2MW@25-40MHz
	LHCD			0.4MW@2.45Ghz

Research Plan for EXL-50U from 2024 to 2026

Key engineering parameters of the EXL-50U device have reached the design target



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

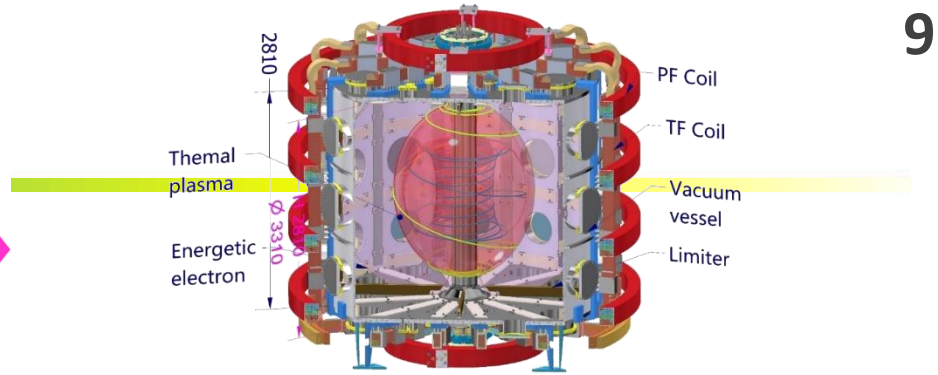


Spherical torus fusion power DEMO by 2035-2040

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

EXL-50

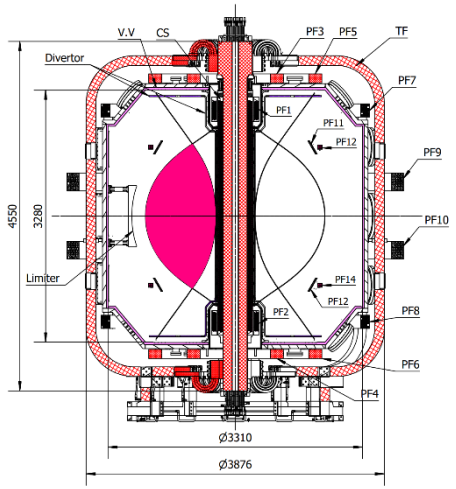
- Start EXL-50 Project — Oct. 2018
- Phy. & Eng. Design — Dec. 2018
- Construction — Jul.2019
- First plasma
- Experiment
- Shutdown — Jun.2023



EXL-50U

- Start EXL-50U Project — 2022.07
- Physics Design — 2022.12
- Engineering Design
- Manufacture of Main Components — 2023.10
- Upgrade of Power supply, Heating and Diagnostics
- Vacuum Pumping Baking — 2023.12.31
- Machine Assembly
- First Plasma Ip ~120kA — 2024.01.20
- Testing of Power supply

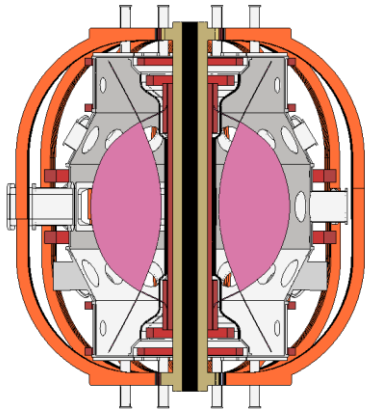
- 2024.05.25 — Ip~300kA with 1s flat-top
- 2024.06.28 — Ti ~ 1keV, <ne> 1~4×10^{19}m^{-3}
- 2024.07.08 — Divertor plasma Offline EFIT
- 2024.07.14~08.07 — Machine Maintenance
- 2024.08.28 — 500kA@n_{e0}>2 ×10^{19}m^{-3}



- 2025.04.16 — Ip 1MA
- 2025.05.25 — B_T 1.2T
- 2025.10.01~10.30 — Machine Maintenance
- 2025.12.31 — Ti ~ 5keV
- 2026 — 1.5MA, 10keV,p-B fusion experiments

EHL-2

- 2023 — Physics Design and
- 2024 — Engineering Design
- 2025 — Construction
- 2027 — Physics experiment



Outline

I. ENN XuanLong-50U (EXL-50U)

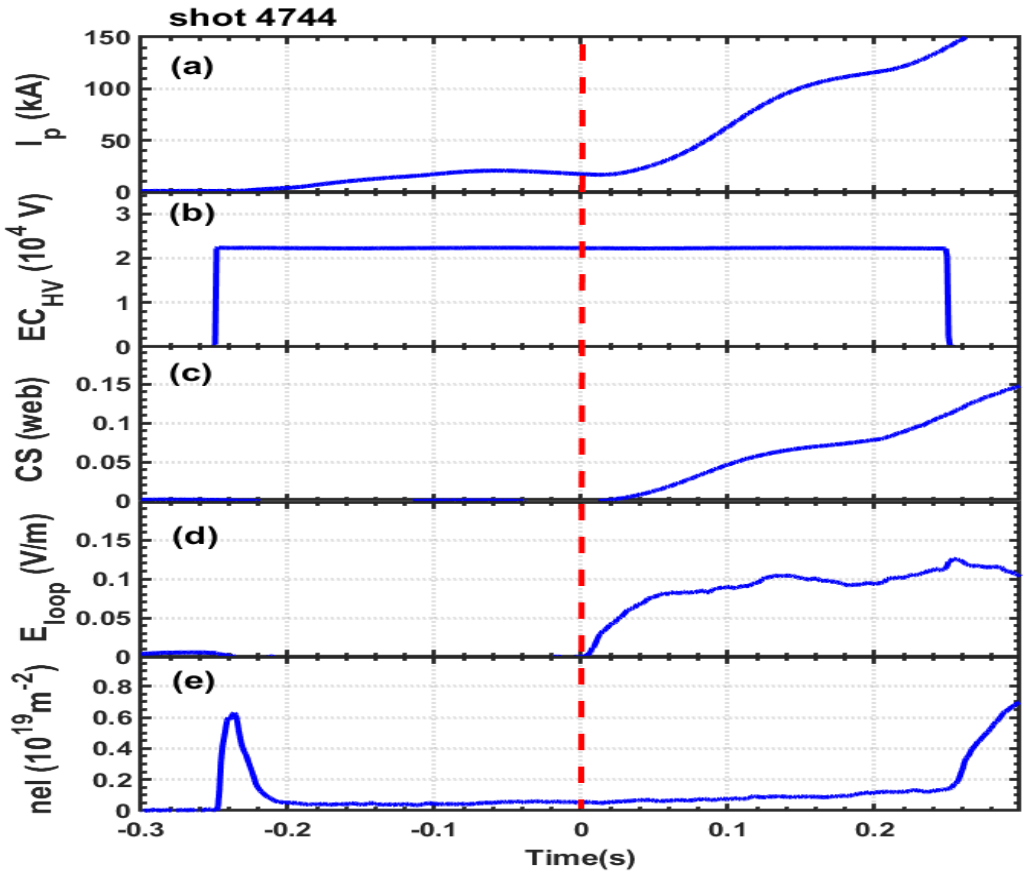
- Mission and research plan
- Boron fueling effects on EXL-50
- Device status

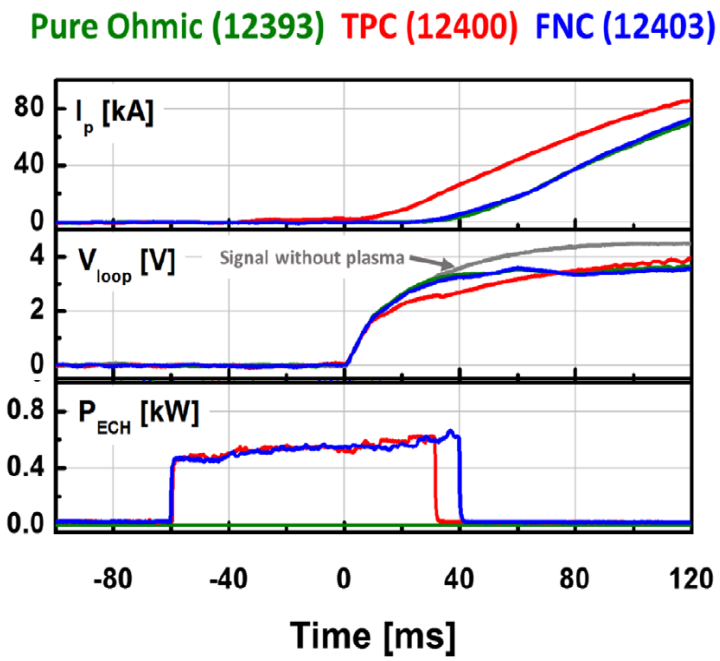
II. EXL-50U Research Progress

- Non-inductive start-up and current drive
- Plasma control and divertor experiment
- Proton-boron experiment
- Energy confinement and transport, Ion heating

III. Summary and Discussion

Unique startup method with EC in EXL-50U





EXL-50U

- Both breakdown and startup by 190kW 28GHz EC alone
- CS is switched on after formation of close magnetic surface with Ip: 20~50kA

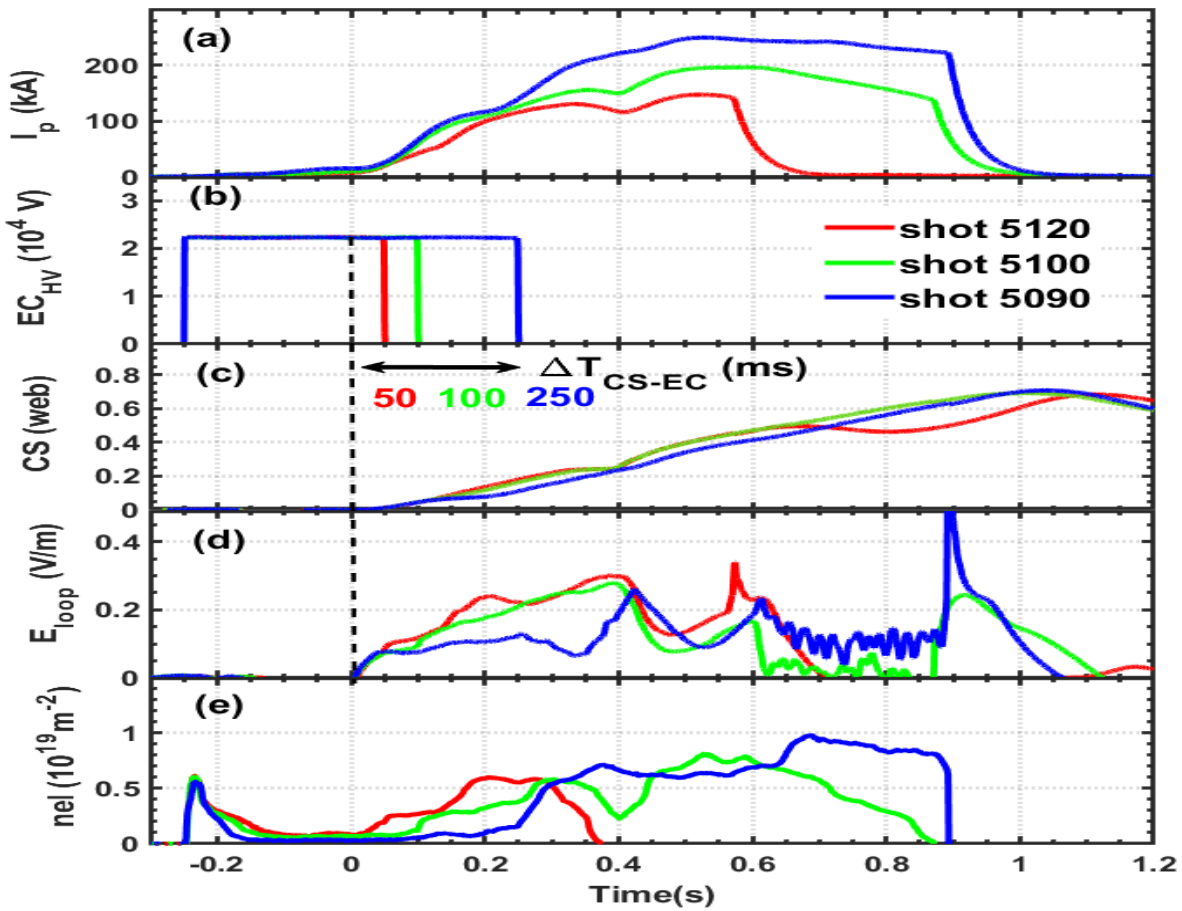
In other machines (KSATR, EAST, J-TEXT, AUG, ITER…)

- EC is for breakdown
- Startup by CS or EC+CS

Current Ramp-up Scenario in EXL-50U

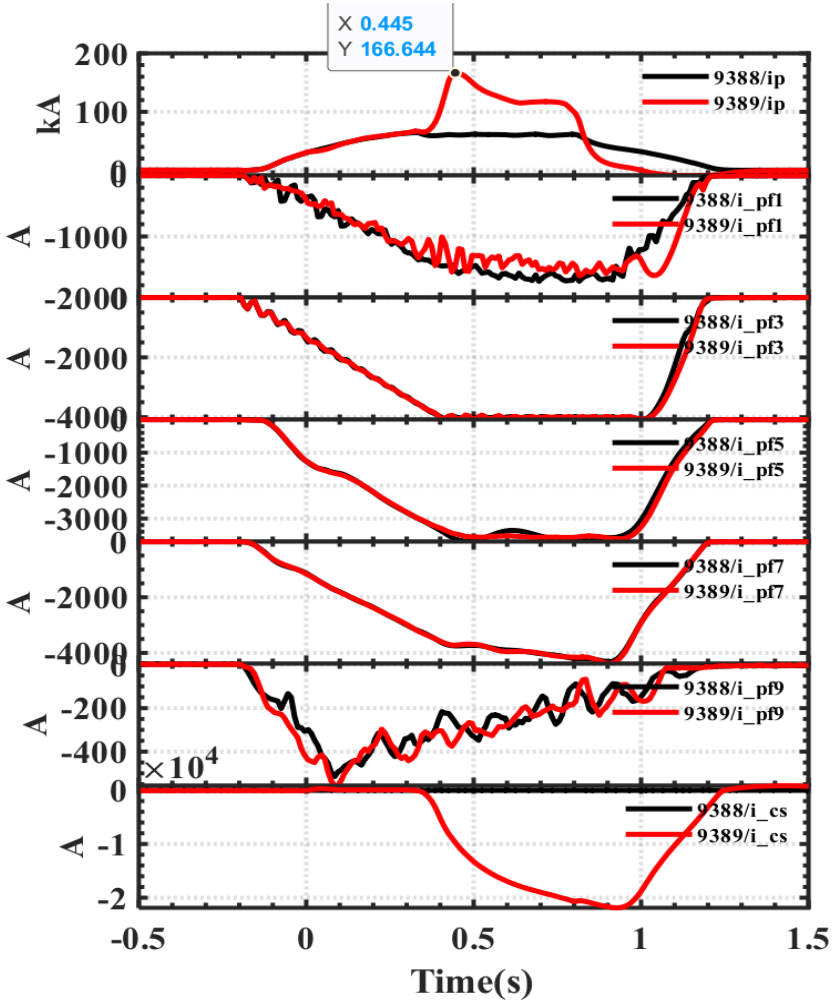
- Start-up by EC
- Ramp-up by EC+CS
- Synergy between EC+CS is key to get flat-top

- Low loop voltage
- Low consumption of CS flux
- potential application to an ST reactor and a superconducting machine, such as ITER

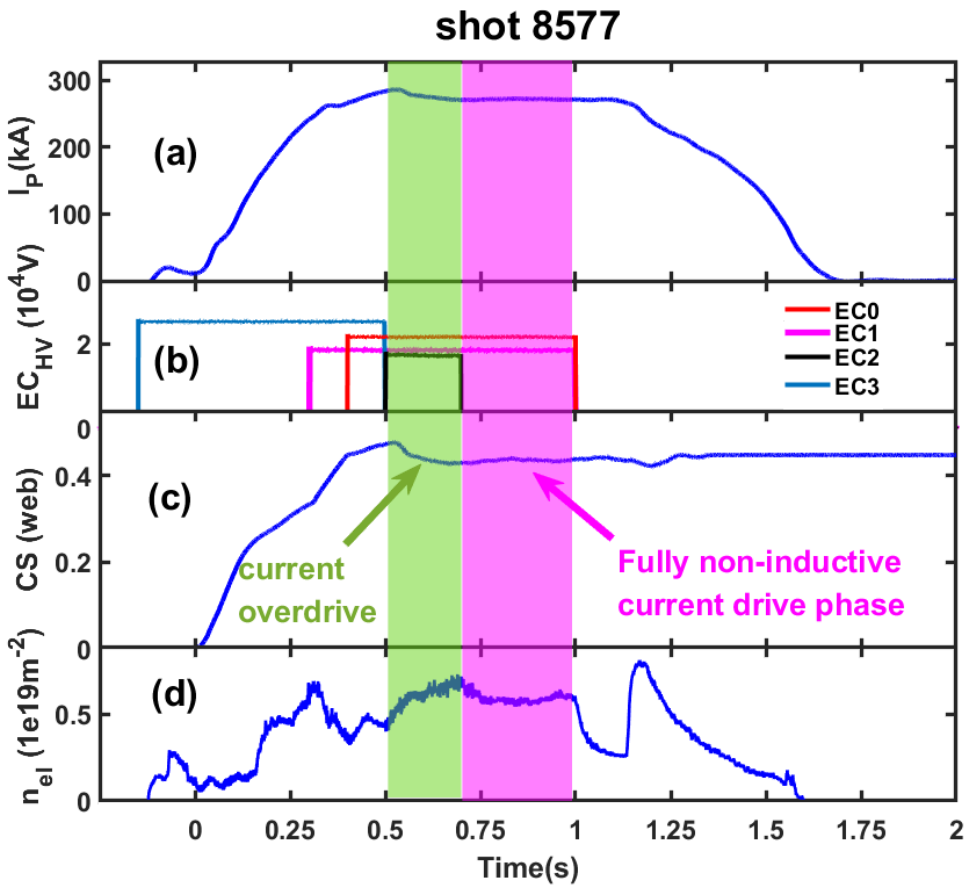


Ip at flattop phase is proportional to ΔT_{CS-EC}

Non-inductive current start-up and current drive



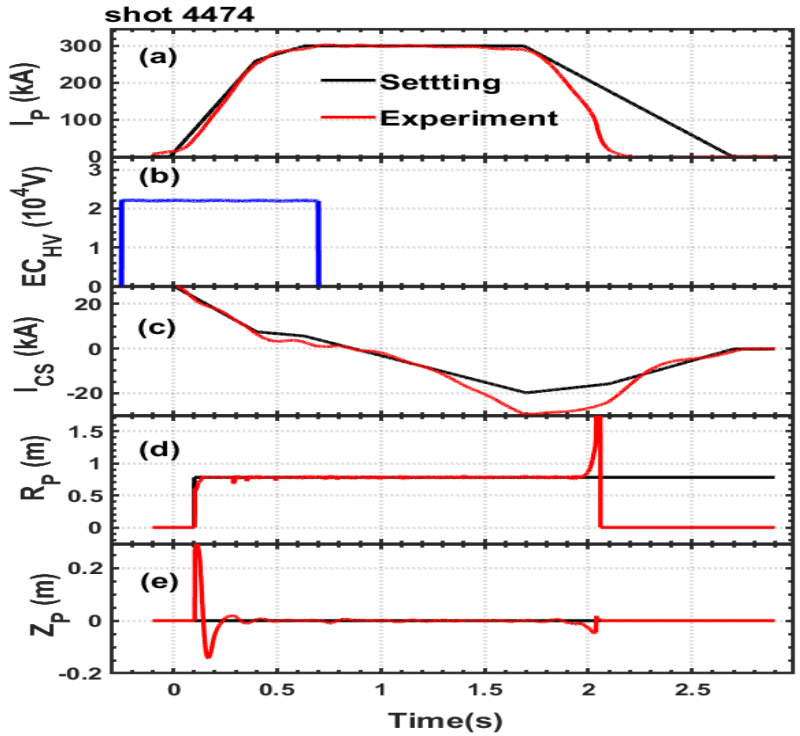
Optimized startup: higher Ip before CS switch on

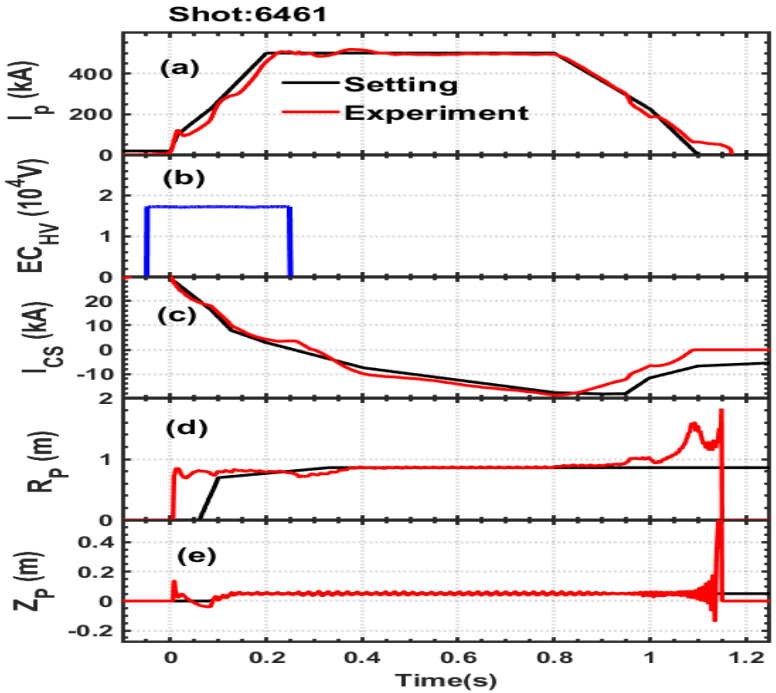


P_{EC} = 380kW → 270kA fully non-inductive CD

P_{EC} = 580kW → current overdrive

RZ-IP feedback control for limiter plasmas



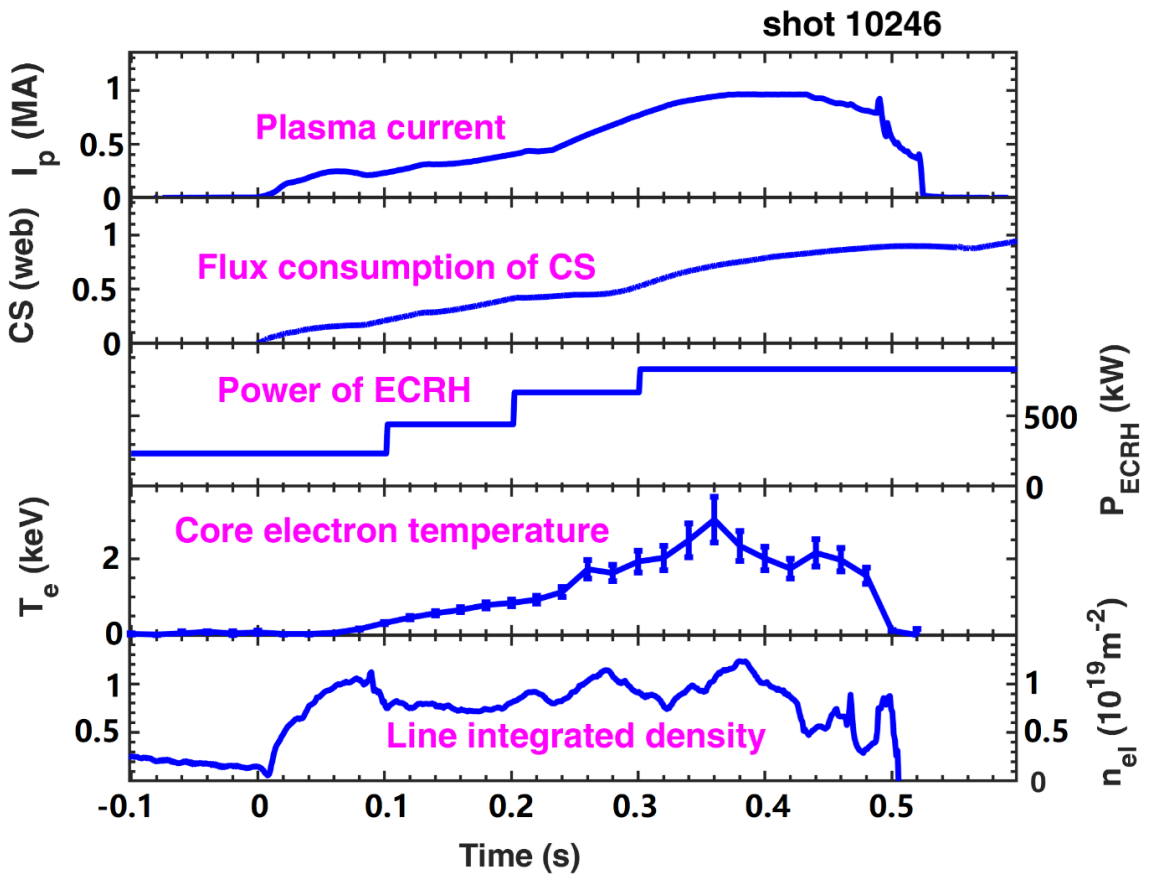


- 300kA discharge with 1200ms flat-top
- Startup by 28GHz EC (P_{EC}~190kW)
- B_T = 0.6T@0.6m

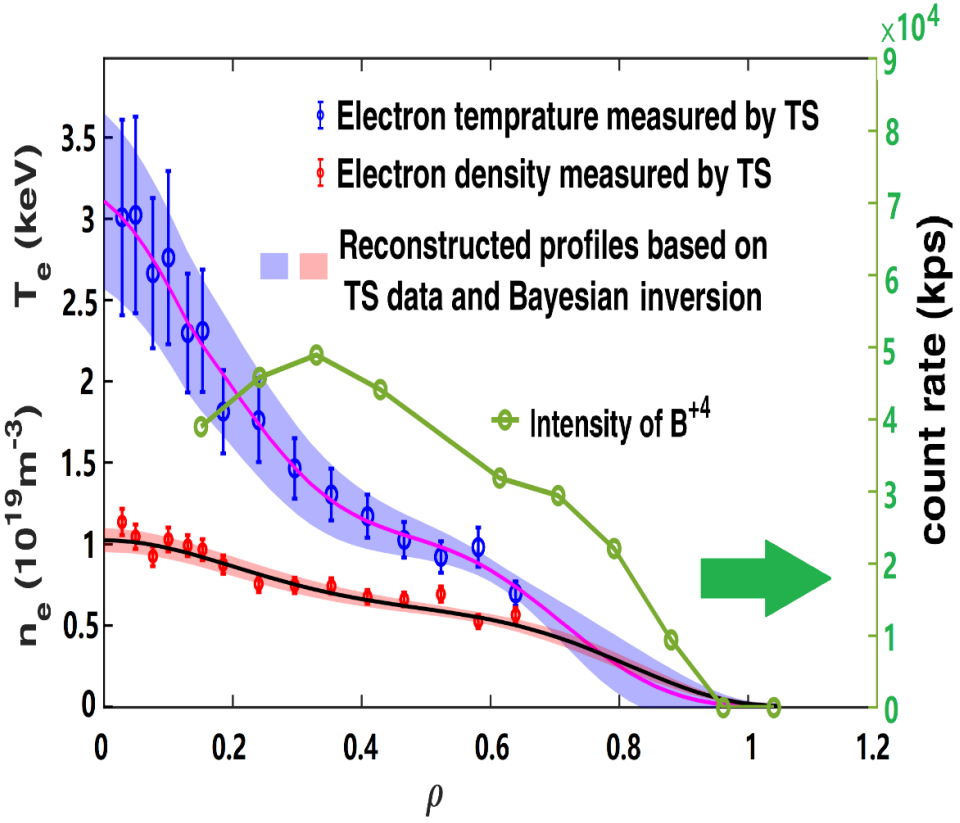
- 500kA discharge with 600ms flat-top.
- Startup by 50 GHz EC (P_{EC}~230kW)
- B_T = 1T@0.6m

RZ-I_P is feedback control is a prerequisite for obtaining (quasi) steady-state high-parameter plasmas.

1 MA discharges in hydrogen-boron plasmas



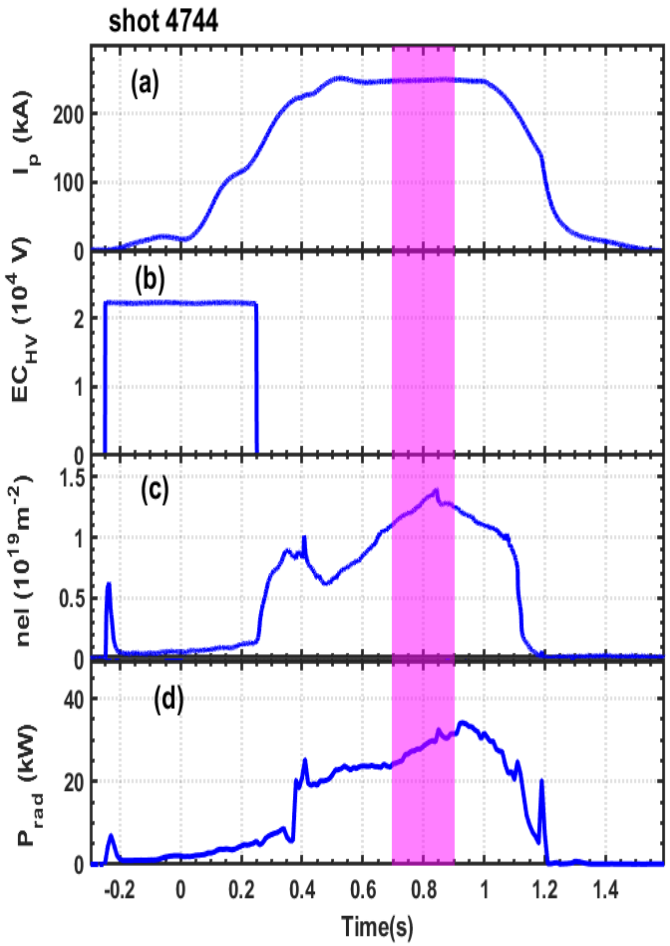
The waveforms of 1MA discharge in EXL-50U.



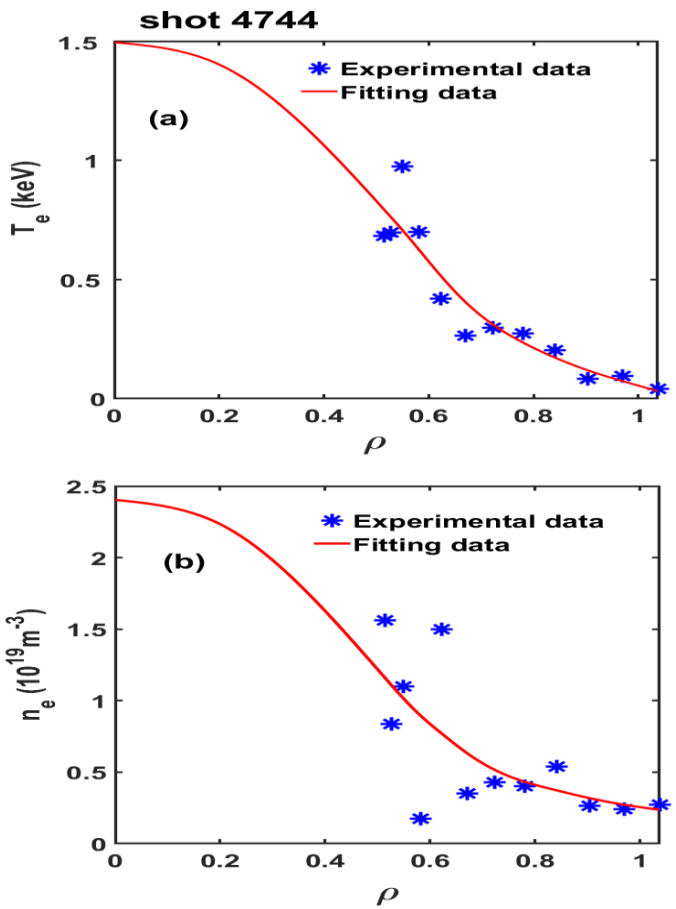
The electron temperature, density, and B^{+4} line intensity profiles at t = 0.36s in shot 10246.

- Filling gas for the entire discharge duration was diborane-hydrogen mixture (30% B_2H_6: 70%H_2).
- Boron powder was injected during ramp-up and flat-top phase
- Boron content (ion ratio) in working fuel is greater than 15%

Initial results of energy confinement time for OH plasmas



Flat-top phase is used for τ_E analysis



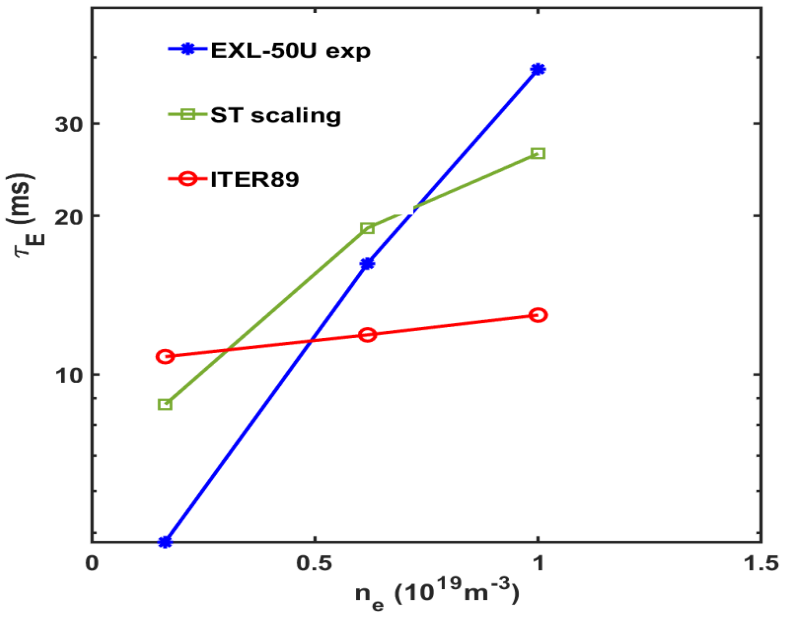
Experiment data is from TS. Bayesian inversion is used to reconstruct the profiles.

τ_E is estimated with power balance method.

$$W_{th} = \frac{3}{2}n(T_e + T_i)V, \quad T_i \sim 0.5T_e$$

$$P_{heat} = P_{Ohm} = I_p * V_{loop}$$

$$\tau_E = \frac{W_{th}}{P_{heat} - P_{rad}}$$



τ_E v.s. density n_e

The experimental τ_E increases with density, which aligns with the scaling laws of both ST and ITER89.

Confinement time scaling

How about τ_E in high-parameter plasmas?

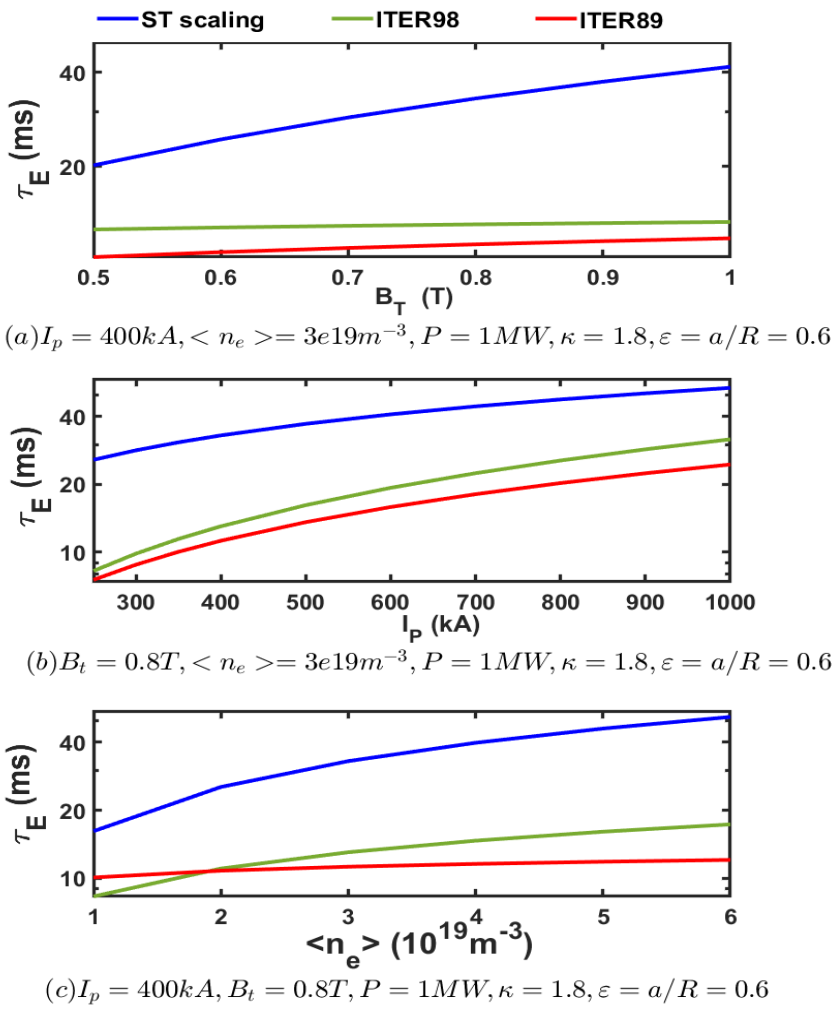
$$\tau_{ST} = 0.066 I_p^{0.53} B_t^{1.05} P^{-0.58} n_e^{0.65} R^{2.66} \kappa^{0.78}$$

$$\tau_{ITER_{89}} = 0.048 I_p^{0.85} B_t^{0.2} P^{-0.5} \left(\frac{n_e}{10}\right)^{0.1} M^{0.5} R^{1.5} \epsilon^{0.3} \kappa^{0.5}$$

$$\tau_{ITER_{98}} = 0.0365 I_p^{0.97} B_t^{0.08} P^{-0.63} n_e^{0.41} M^{0.2} R^{1.93} \epsilon^{0.23} \kappa^{0.67}$$

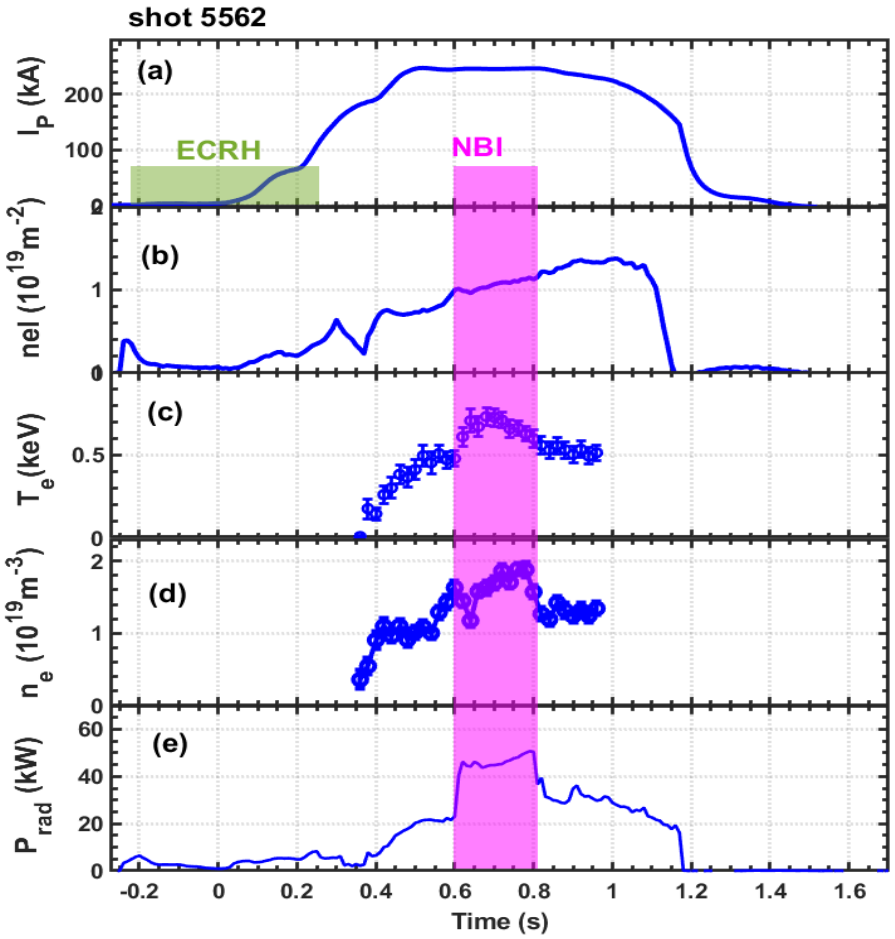
And more?

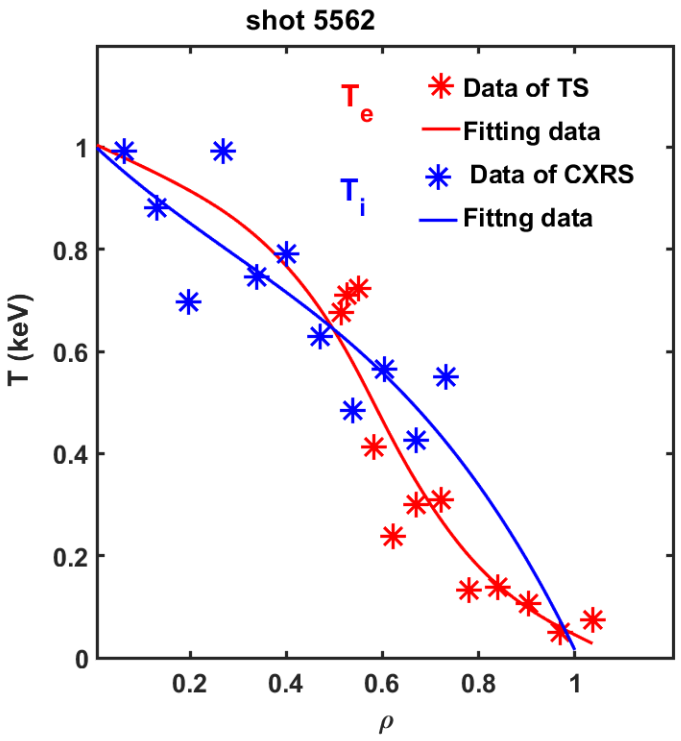
The experiment of EXL-50U will make an important contribution for the ST scaling law and related physics.

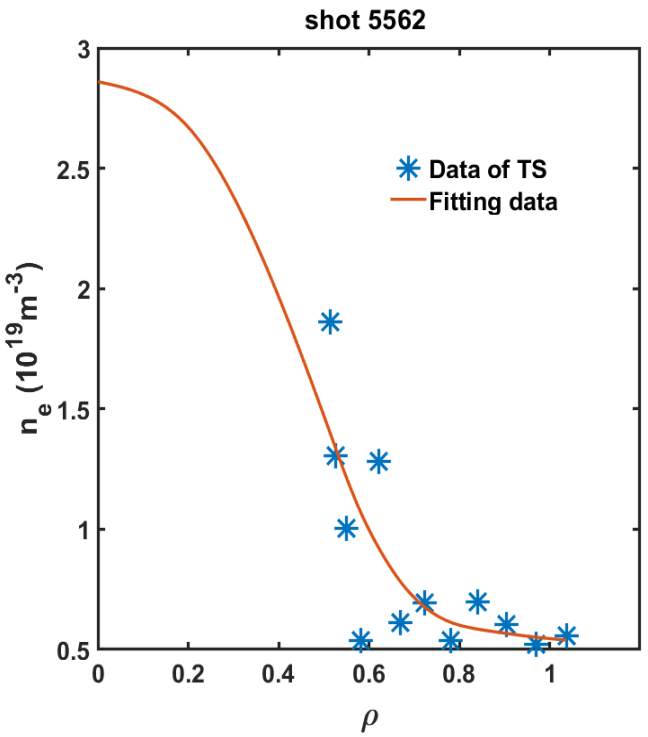


Prediction of energy confinement time with different scaling laws for EXL-50U's plasma.

Preliminary indications of ion heating by NBI





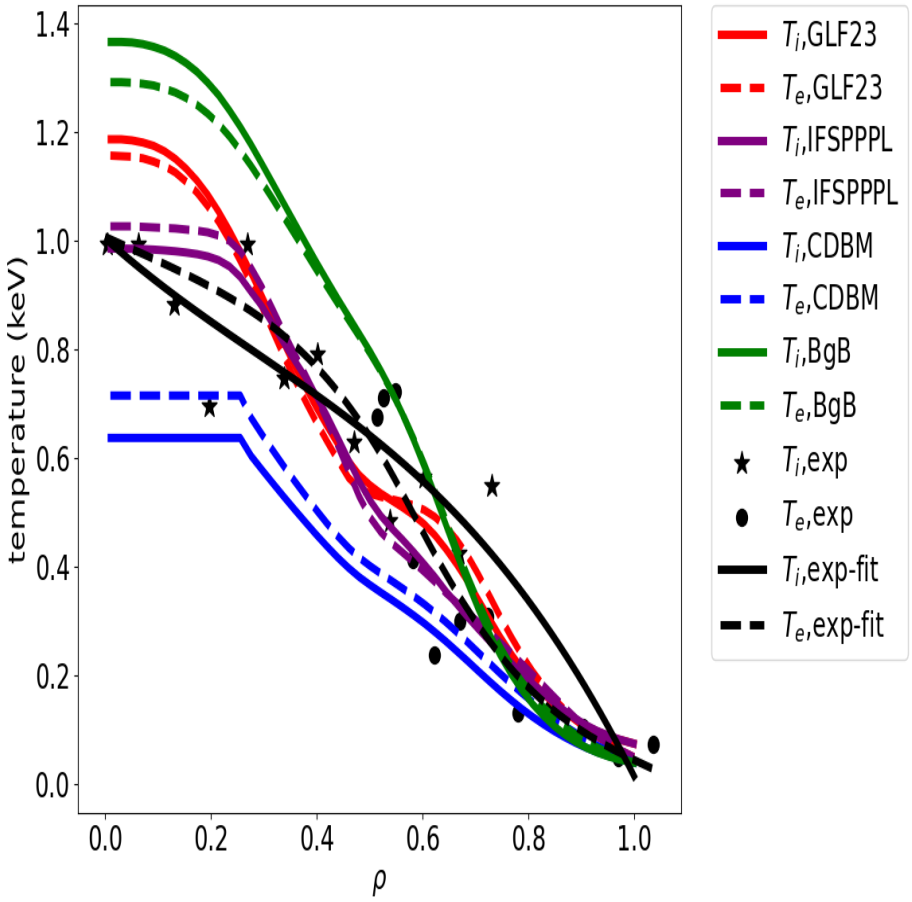


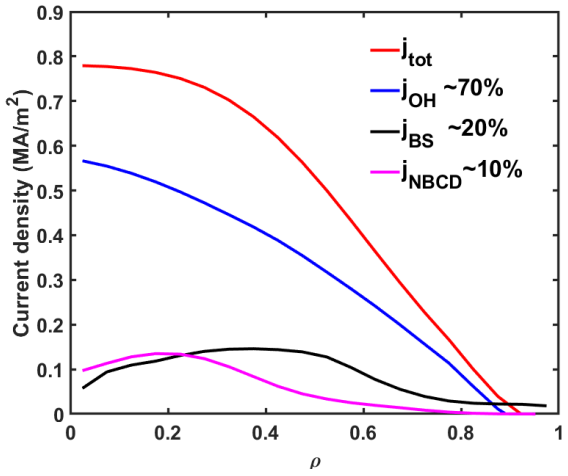
Temperature and density profiles during NBI heating phase

P_{NBI}~270kW @ 25kV

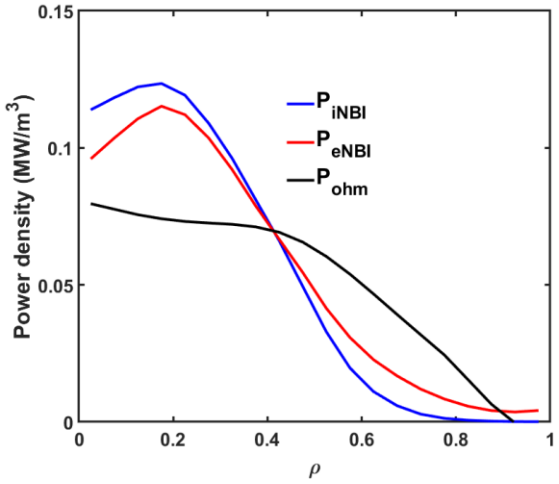
Both T_e and n_e measured by TS increase during NBI phase

Transport analysis for NBI heating plasmas





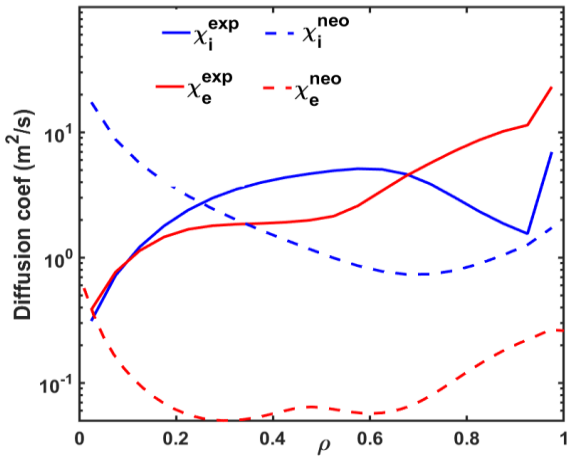
Current density profiles



Power density profiles

For the region 0.2<ρ<0.8

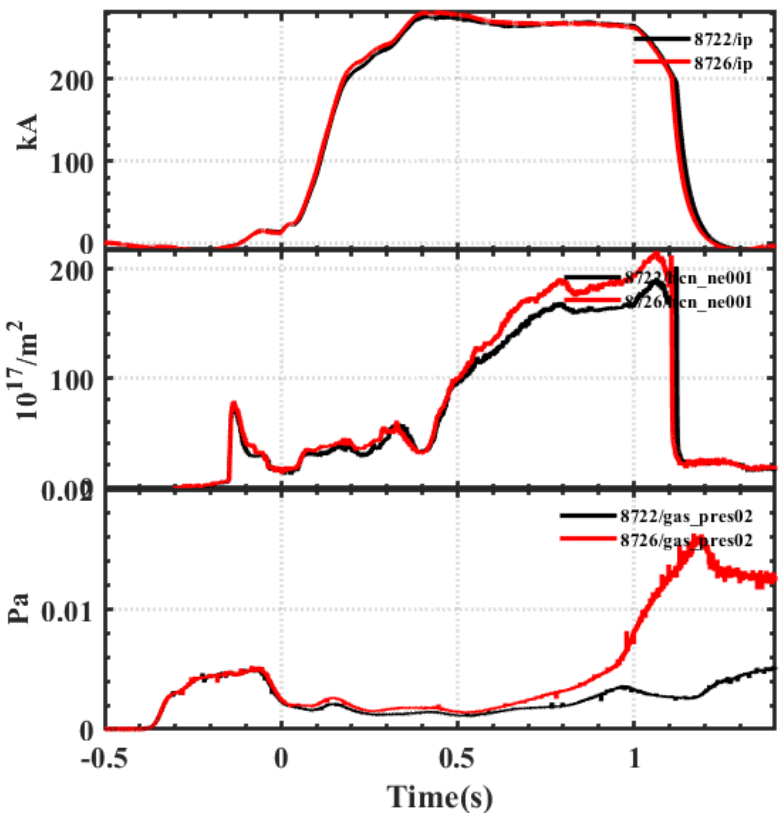
- χ_i^{exp} ~ χ_e^{exp}
- χ_i^{exp} 1~3 χ_i^{neo}
- χ_e^{exp} 30~50χ_e^{neo}

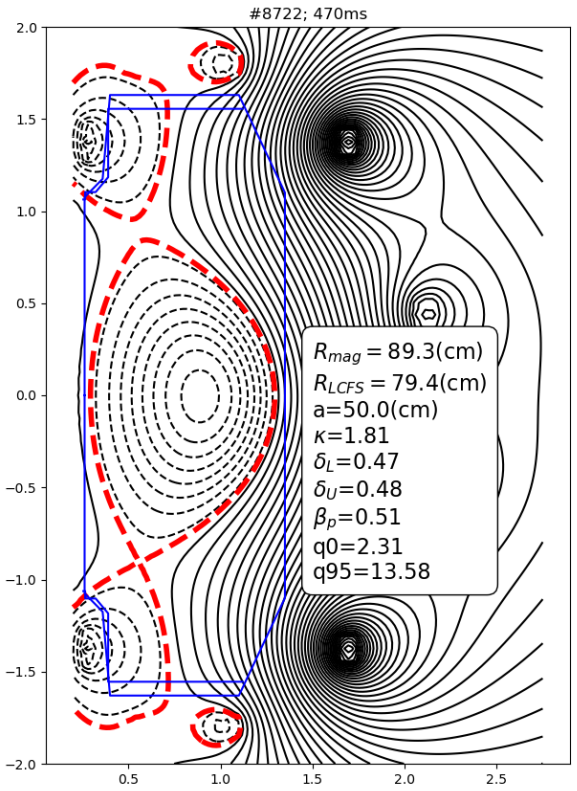


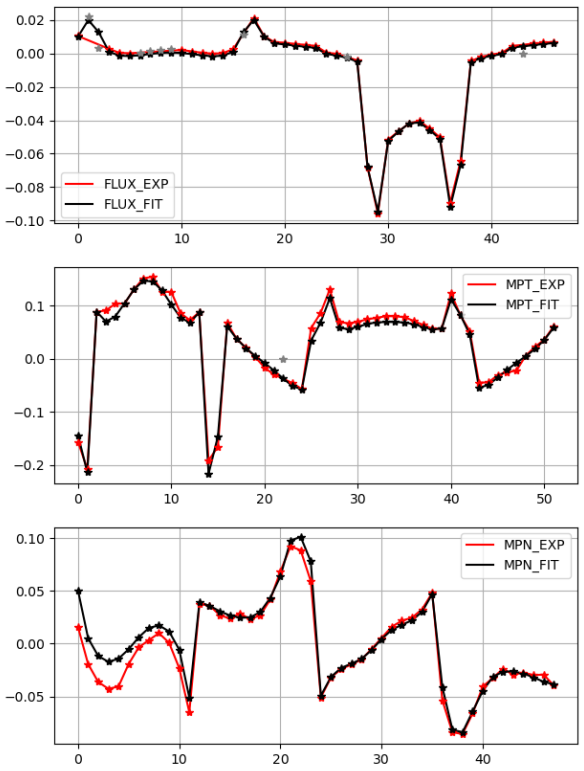
Diffusion coefficient profiles

- Predicted temperature by ASTRA with different transport models
- GLF23 and IFSPPPL are closer to experimental data.

Divertor plasma and offline EFIT reconstruction





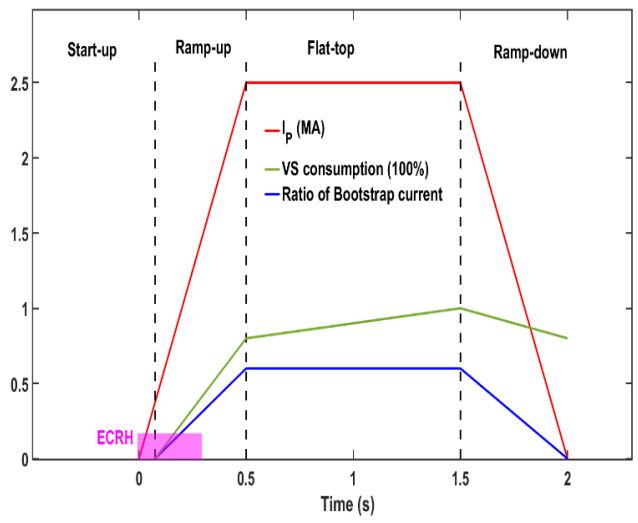


300~400kA Divertor plasmas, $\overline{n_e}$ ~$2\times10^{19}m^{-2}$, k~1.8

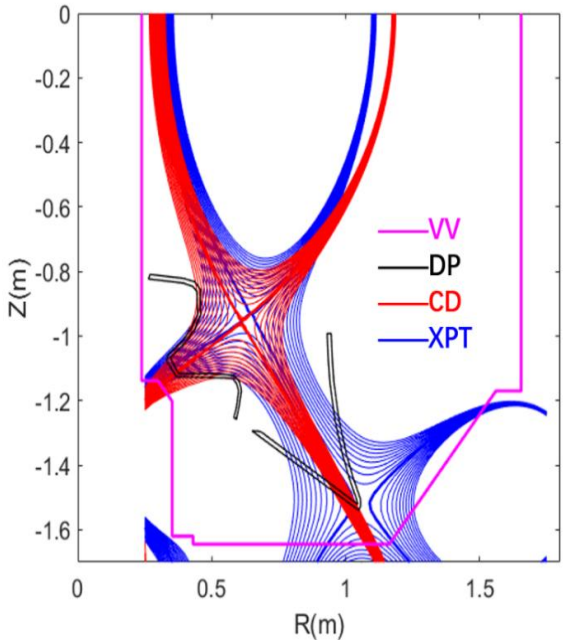
500kA Diertor plasmas, $\overline{n_e}$ ~$1\times10^{19}m^{-2}$

EXL-50U divertor physics design and implications for EHL-2 strategy

- **Current drive scenarios in EXL-50U**
  EC ⇒ Start-up, EC+CS ⇒ Ramp-up
  - **Low loop voltage**
  - **Low consumption of CS flux**
  - **potential applicability in ST reactor or superconducting machine such as ITER**



CD Strategy for EHL-2



- **MA-level discharges achieved on the EXL-50U, demonstrating the scientific feasibility of generating high-performance hydrogen-boron plasmas.**

Design drawing of closure V-shape divertor in EXL-50U. Both XPT and convertional divertor (CD) configuations will be explored in EXL-50U.

- **ENN plans to fully achieve or verify the key physical goals of EXL-50U in three years (from 2024 to 2026) , exploring the solution for the key physics issues for future ST P-B fusion reactors.**

ENN’s commercial fusion power collaboration is expanding

新奥聚变欧洲研发中心（筹建中）

东欧

俄罗斯科学院
- 约飞研究所（Ioffe Institute）：建造了球形托卡马克Globus-M、Globus-M2，正在进行下一代装置Globus-3的概念设计，并为ITER开发诊断系统。
- 西伯利亚分院布德科尔核物理研究所（BINP）：磁约束聚变领域中性束研发的知名机构

西欧

法国原子能和替代能源委员会（CEA）
- 法国最大的原子能和替代能源研发综合性科研机构
- 建有WEST托卡马克装置，重点研究材料科学、超导磁体技术、等离子体控制和诊断技术

英国原子能管理局（UKAEA）
- 英国负责核能研究和开发的官方机构
- 管理运营JET、MAST-U装置，设计STEP球形环聚变装置

西班牙能源、环境与技术研究中心（CIEMAT）
- 欧洲聚变能研究的中心之一，研究集中在磁约束聚变和惯性约束聚变方面

中欧

Marvel Fusion公司
- 研发激光氢硼聚变技术

德国于利希研究中心
- 欧洲最大的科学研究机构之一，重点研究聚变物理与材料

德国马克斯•普朗克等离子物理研究所（IPP）
- 建有实验性仿星器受控核聚变装置Wendelstein 7-X

大洋洲

HB11能源公司
-氢硼激光聚变研发公司

亚洲

韩国核聚变能源研究院（KFE）
- KSTAR超导装置，参与ITER项目

首尔国立大学先进聚变反应堆工程研究中心
-主要研究聚变模拟计算、人工智能技术

日本国立聚变科学研究所(NIFS)
- LHD装置，与TAE合作在磁约束聚变等离子体中进行氢硼聚变实验

新加坡科技研究局（A*STAR）
- 开展聚变物理、诊断研究以及AI在材料科学模拟和新材料发现中的应用等。

新加坡南洋理工大学(NTU)
- AI驱动的湍流输运代理模型开发

北美

普林斯顿等离子体物理实验室（PPPL）
加利福尼亚大学(UC)
威斯康星大学麦迪逊分校(UW–Madison)
ExoFusion公司

Join Hands with ENN to Realize Commercial Fusion Science and Technology!

EXL-50U: an open research platform for the fusion community

Summary and discussion on ST p-B plasma

I. Summary

- 10-year Roadmap to establish S&T basis for commercial power demonstration.
- Edge turbulence suppressed in boron-fueled plasma on EXL-50 with ECRH only.
- Combinations of ECRH + CS voltage reached high parameters.
- Ip ~ 1 MA, ne ~ 10^{19} /m^3, Te ~ 3.5 keV, Ti ~ 2 keV p-B plasma obtained on EXL-50U.
- Limited data on energy confinement time appear favorable vs. tokamaks.

II. Discussion

- Tokamak-based turbulence-transport models' relationship to ST p-B plasma?
- MHD equilibrium model reproduces magnetic signals, but not yet the kinetic data?
- Divertor designs are being explored, but much work remains.
- ST plasmas with ~ 100 x T and ~ 10 x n to test energy confinement?
- ST fusion plasma scenarios to take advantage of the special cross section (a lower sharp peak near 160 keV + a higher broad peak near 600 keV)?

Thank you, and Comments Welcome!