OV-3258

核工业西南物理研究院 Southwestern Institute of Physics
中核集团 CNNC

HL-3 Research towards High-performance Plasma and Power Exhaust Solution

Wulyu Zhong **Southwestern Institute of Physics (SWIP), CNNC**

on behalf of HL-3 team and collaborators

Acknowledgment:

iter — china eu india japan korea russia usa
cea
Huazhong University of Science and Technology
UK Atomic Energy Authority
UC San Diego
Peking University
National Institute for Fusion Science
Kyoto University
HIT
Sun Yat-sen University

Outline

- Introduction of HL-3 tokamak
- Improvement of heating, diagnostic & control
- High-performance plasma
- Power exhaust solution
- Summary and future plan

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- **Introduction of HL-3 tokamak**
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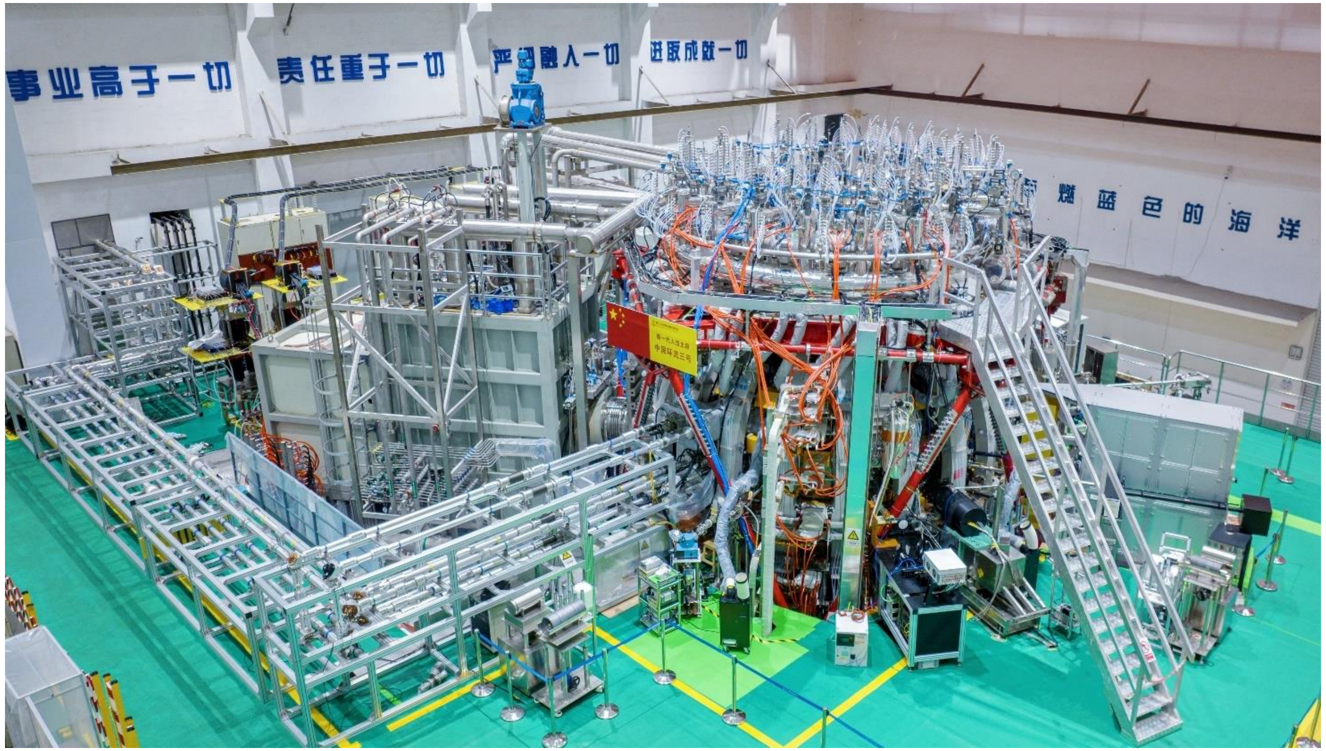
Mission of HL-3 tokamak

- **Critical physics and technology challenges for ITER and next-step fusion devices**
  - High-performance scenarios compatible with low heat load
  - Deep understanding of high-performance plasma physics
  - Tests and validation of high heat flux plasma-facing components



HL-3 Main Parameters	
Major radius	R = 1.78 m
Minor radius	a = 0.65 m
Aspect ratio	R/a = 2.8
Plasma current	Ip = 2.5 (3) MA
Toroidal field	Bt = 2.2 (3) T
Elongation	κ = 1.8-2
Triangularity	$\delta > 0.5$
Heating power	NBI (20) + ECRH (11) + LHCD (4) + ICRH (6) MW

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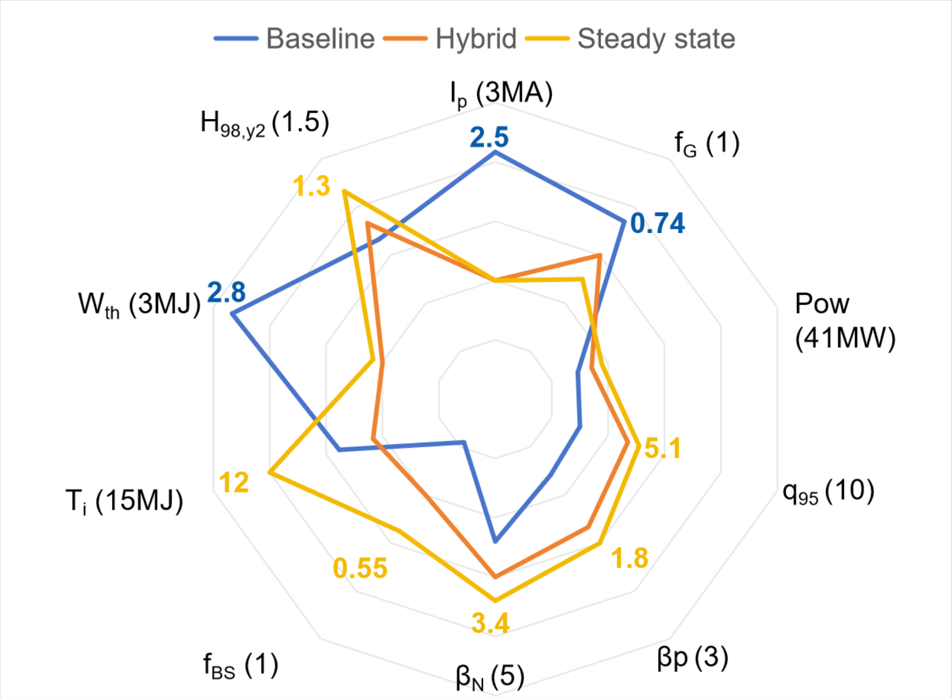
■ Comprehensive operation scenarios



❑ **Baseline** Operation

I_p = 2.5 MA, q_{95}=3, $H_{98,y2}$ = 1.0

❑ **Hybrid** Operation

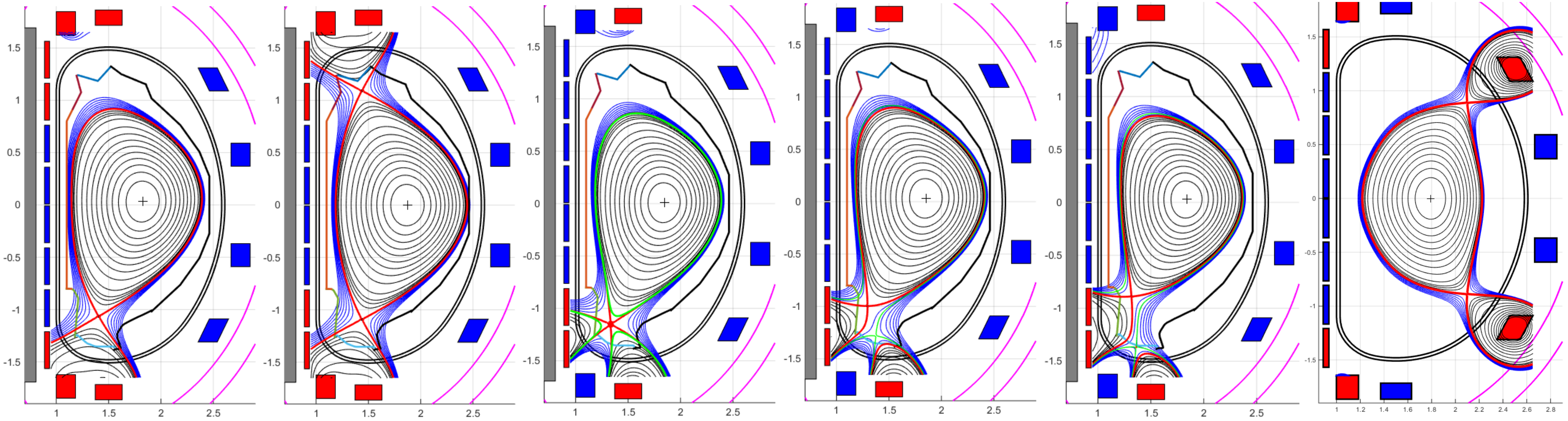
I_p = 1.0~1.4 MA, f_{BS} ~40%, f_{ni} ~70%, β_N > 2.5

❑ **Steady-State** Operation

I_p = 1.0-1.2 MA, fully non-inductive current drive, β_N > 3.0

Key features

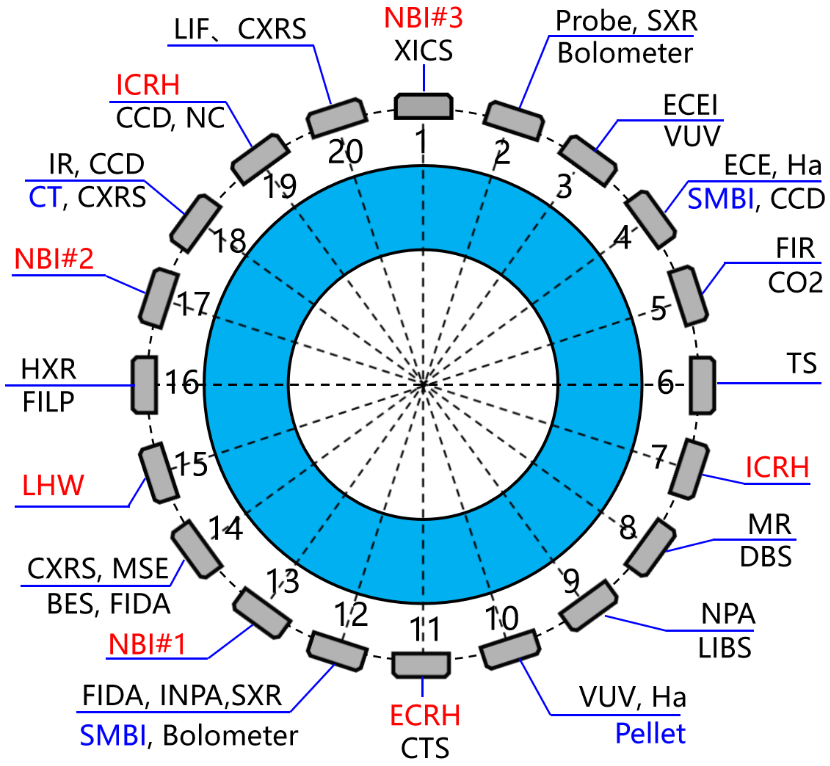
- **Comprehensive operation scenarios**
- **Flexible magnetic configurations**



Single-null | Double-null | Snow flakes(SF) | SF- | Tripod | Negtive triangularity

Key features

- **Comprehensive operation scenarios**
- **Flexible magnetic configurations**
- **High accessibility for experiments**



- 128 ports: diagnostics, fueling, heating and current drive systems
- Flexible capacity on heat and particle exhaust: actively cooling divertor and strong pumping speed cryopump (38 m^3/s)

Staged research plan of HL-3

I. First plasma

- ✓ Ip = 100 kA
- ✓ Limiter/divertor configuration

II. Initial research

- ✓ Ip ≥ 1 MA
- ✓ H mode discharge
- ✓ Advanced divertor control

III. Integrated research

- **Ip ≥ 2 MA**
- **T_i ~ 10 keV**
- Advanced scenarios
- Heat/particle control
- Configuration control
- AI for fusion

IV. Extended research

- **Triple product ＞$10^{20}$$m^{-3}$·keV·s**
- Fusion reactor grade plasma operation and physics research
- Fusion reactor related integration scheme verification
- Fusion reactor related critical components/diagnostic tests

Now, we are here

2020 · · · 2025 · · · 2030

Achievements of HL-3 in 2020-2025

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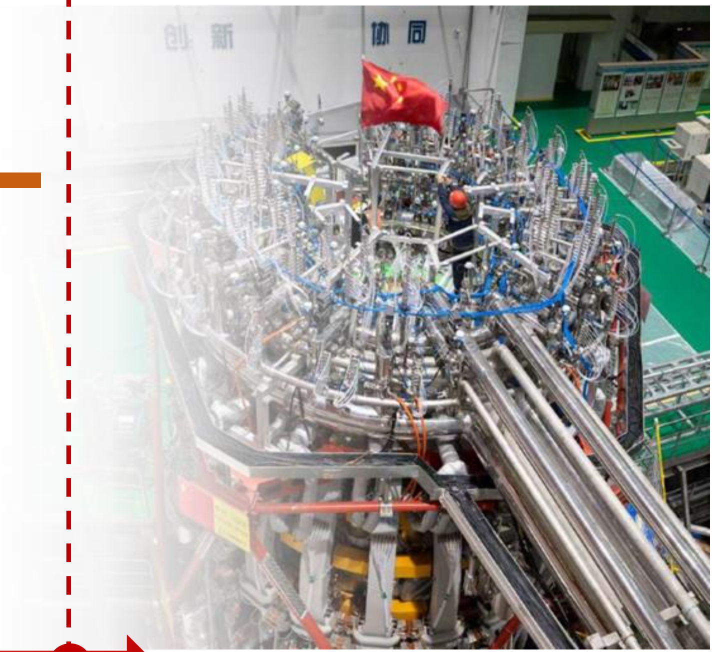
- ✓ T_i = 117 million degrees(>10keV)
- ✓ T_e = 160 million degrees(>13keV)
- ✓ Triple product > $0.67\times10^{20} m^{-3}\cdot keV\cdot s$

- ✓ 1.5 MA H-mode Operation
- ✓ H-mode in Tripod Divertor Configuration
- ✓ High Density Operation (~$1.2\times n_{GW}$)

- ✓ 1MA H-mode Operation
- ✓ Advanced Divertor (Snowflake & Tripod) Operation

First Plasma

1.15MA plasma



2020

2022

2023

2024

2025

Achievements of HL-3 in 2020-2025

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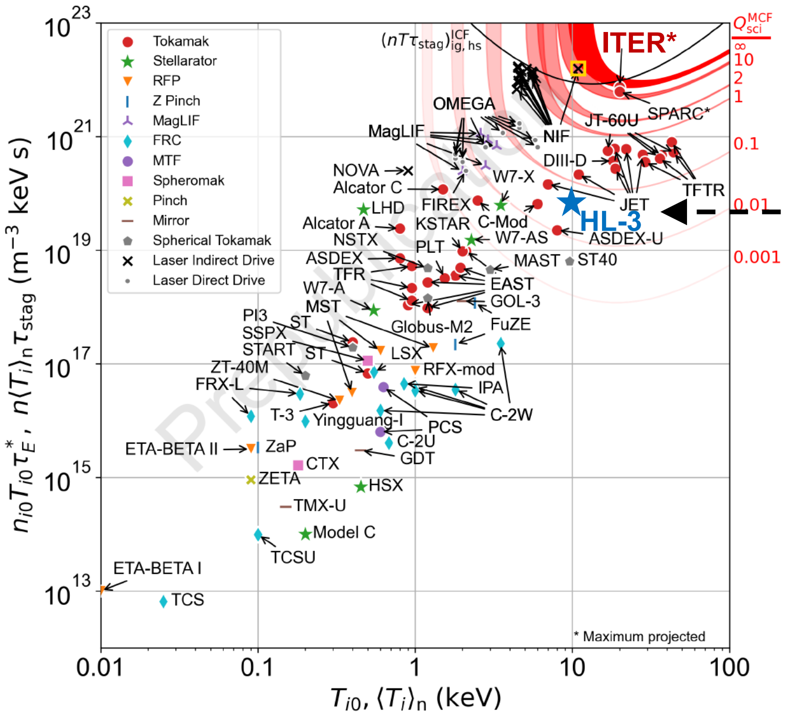

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First Plasma

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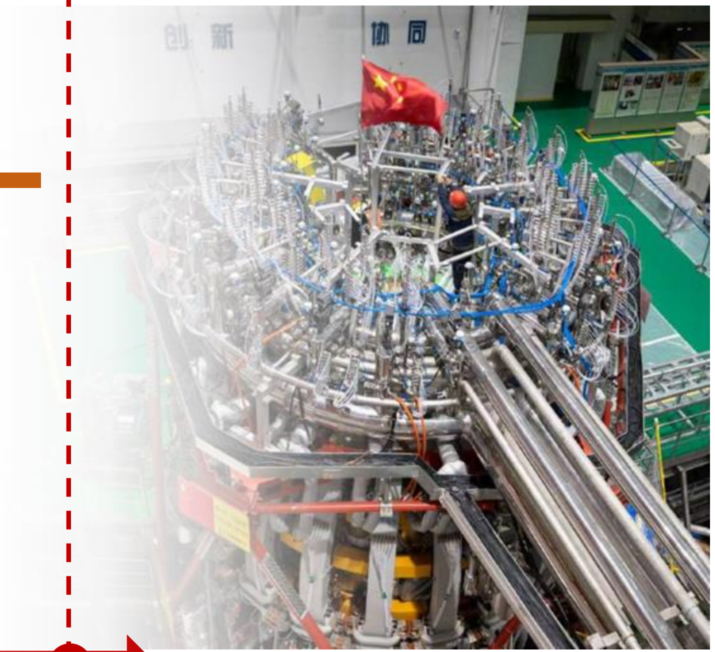

2020 | 2022 | 2023 | 2024 | 2025

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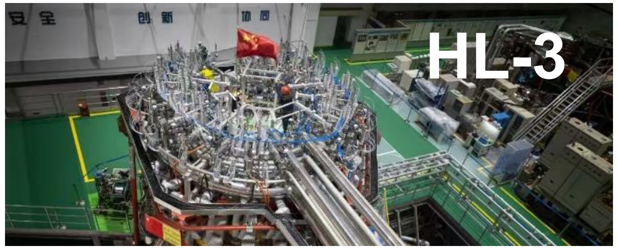


Core

High-performance plasma

- ➢ High T_i
- ➢ High β
- ➢ MHD control
- ➢ Super H-mode

III. Integrated research

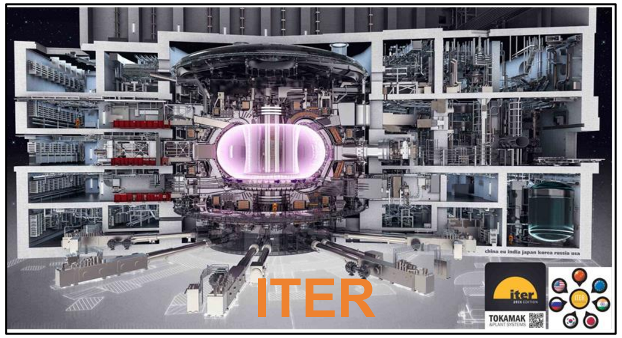
- Improved heating, diagnostic and control
- **Advanced scenarios**
- **Heat/particle control**

Edge

Power exhaust solution

- ➢ Small/no ELM
- ➢ ELM control
- ➢ Advanced divertor
- ➢ Detached divertor

To support ITER and fusion reactors



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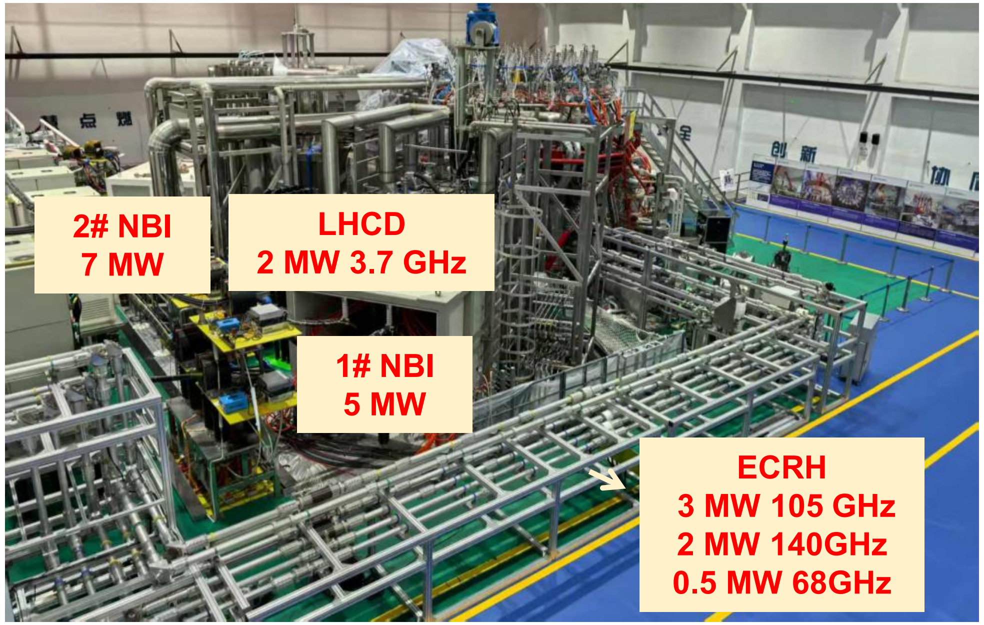
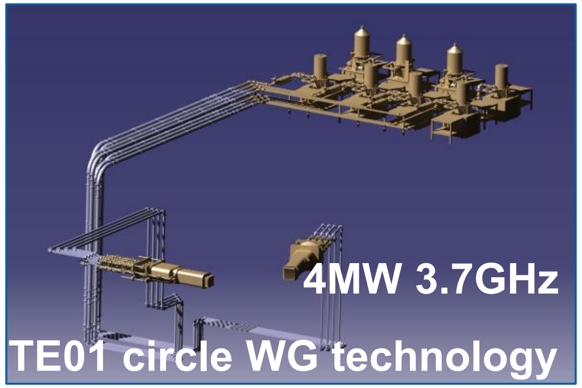
Improvement of heating and current drive systems

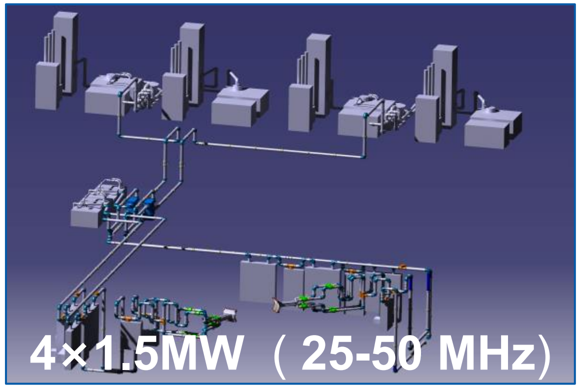
Heating	2025	2027
LHCD	2 MW	4 MW
ICRF	/	6 MW
ECRH	5.5 MW	11 MW
NBI	12 MW	20 MW
TOTAL	**19.5 MW**	**41 MW**





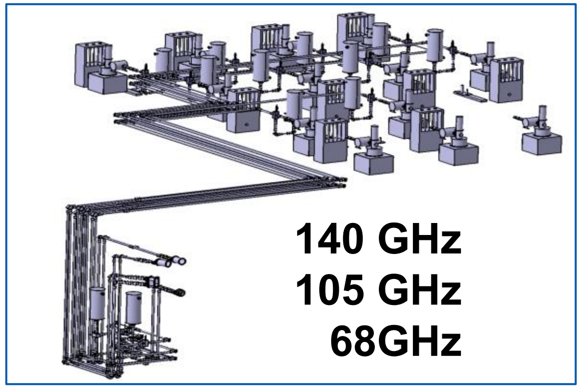
LHCD

This conference,Posters 4 B-70, X.Y. Bai



ICRH

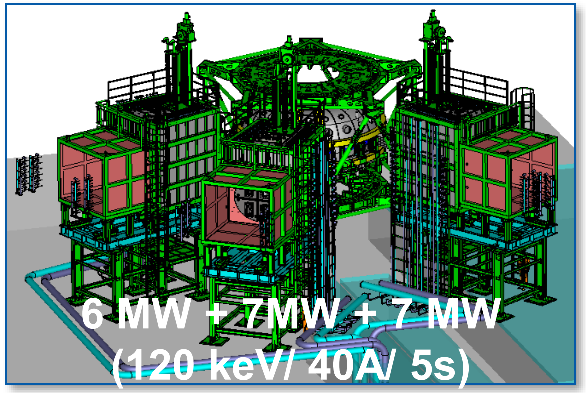
This conference,Posters 4 B-64, L.F. Lu



ECRH

EL：-20~15° NTM control

UL: for CTS



NBI

3 systems

1 # (2023), 2#(2025), 3#(2026)

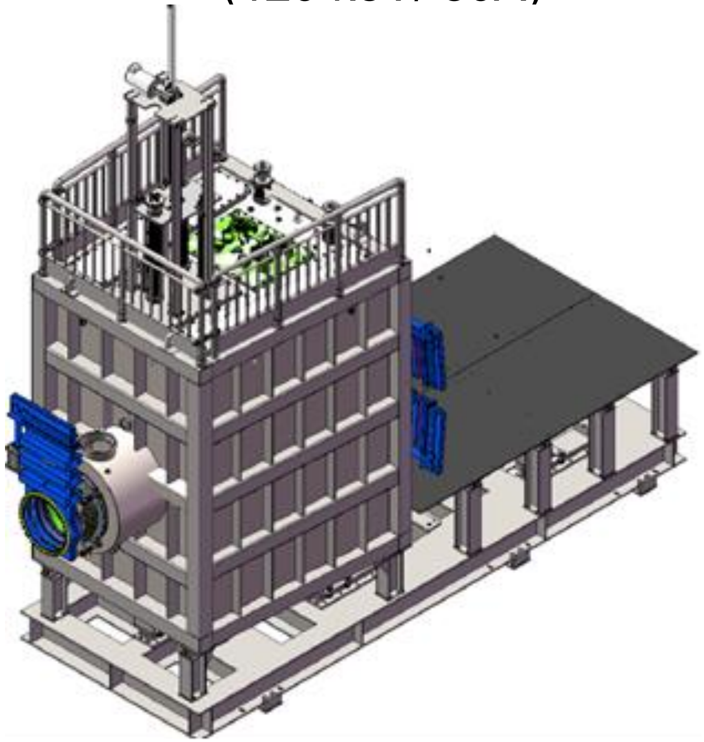
This conference, Poster 2, B-72, B.L. Hao

NBI Platforms for R&D

- **Full-sized ion source commissioning platform and RF negative ion source platform have been constructed in Tianfu fusion R&D site**

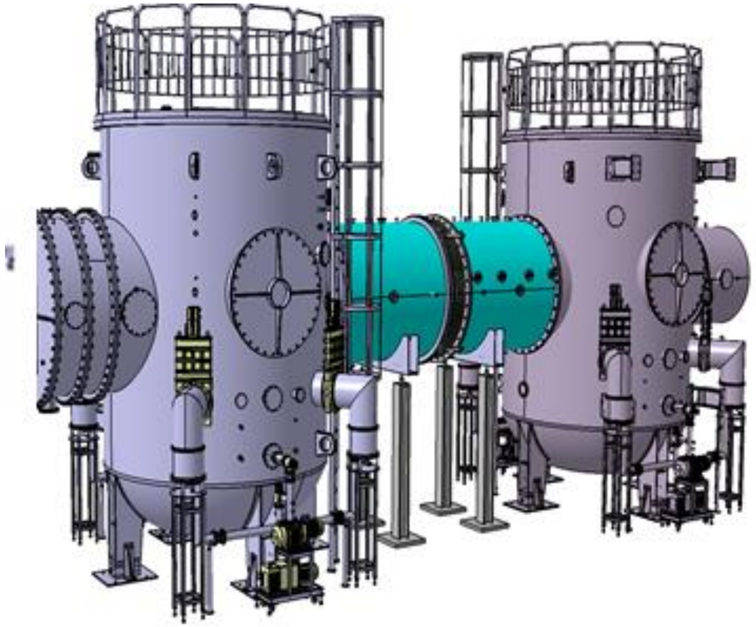
Full-sized commissioning platform

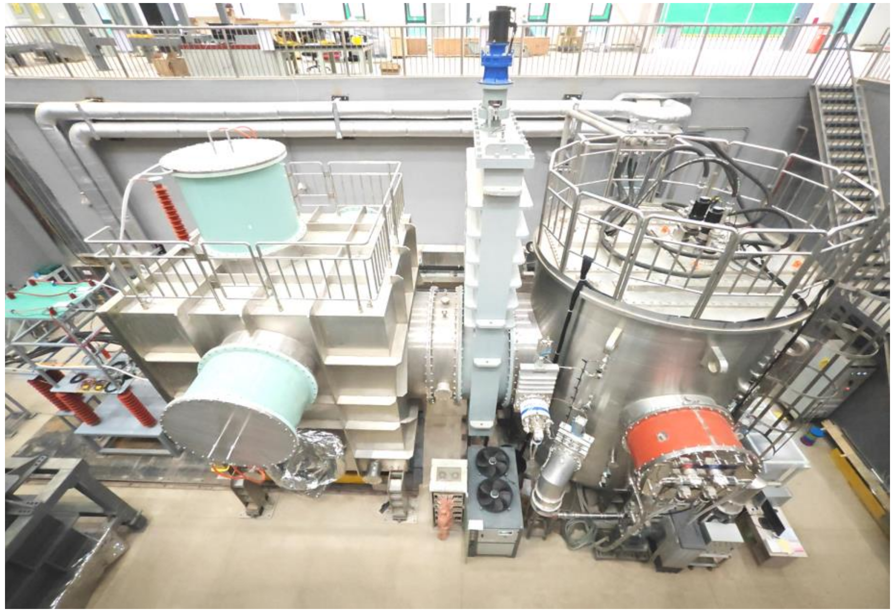
(120 keV/ 80A)



RF Negative Ion Source platform

(3 RF source 400 keV/ 20A)





R&D of VS control for high plasma current operation

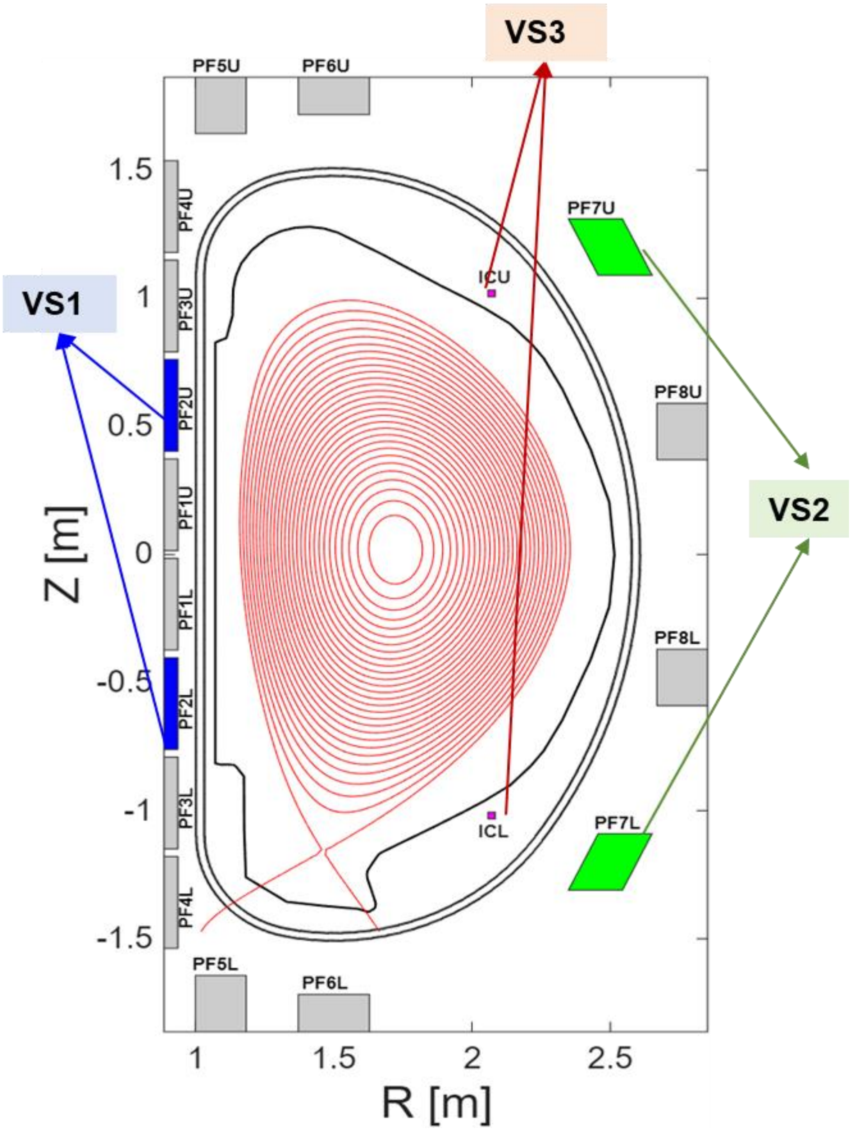
- **First Vertical Stabilization (VS) control system commissioned**
  - ✓ Repeatable divertor plasma: $I_p = 1.5MA,\ k \geq 1.7$ with $\Delta Z \leq 1cm$

This conference, Posters 5 B-44, X. Song

	2023	**2025 (VS1)**
VS power supply	/	**±1kV/±4kA**
elongation ratio κ	1.5	**1.75**
plasma current I_p	1.0 MA	**1.5 MA**
control cycle	/	**200 μs**
control accuracy (ΔZ)	> 2 cm	**< 1 cm**

- **Upgrade: VS2 + in-vessel VS3, control cycle 50~200 μs**
  - ✓ A testbed for ITER control to avoid downward VDEs

	VS1	VS2	VS3
Actuators	PF2	PF7	IC
PS Voltage	±2kV	±4kV	±1kV
PS Current	±10kA	±10kA	±4kA

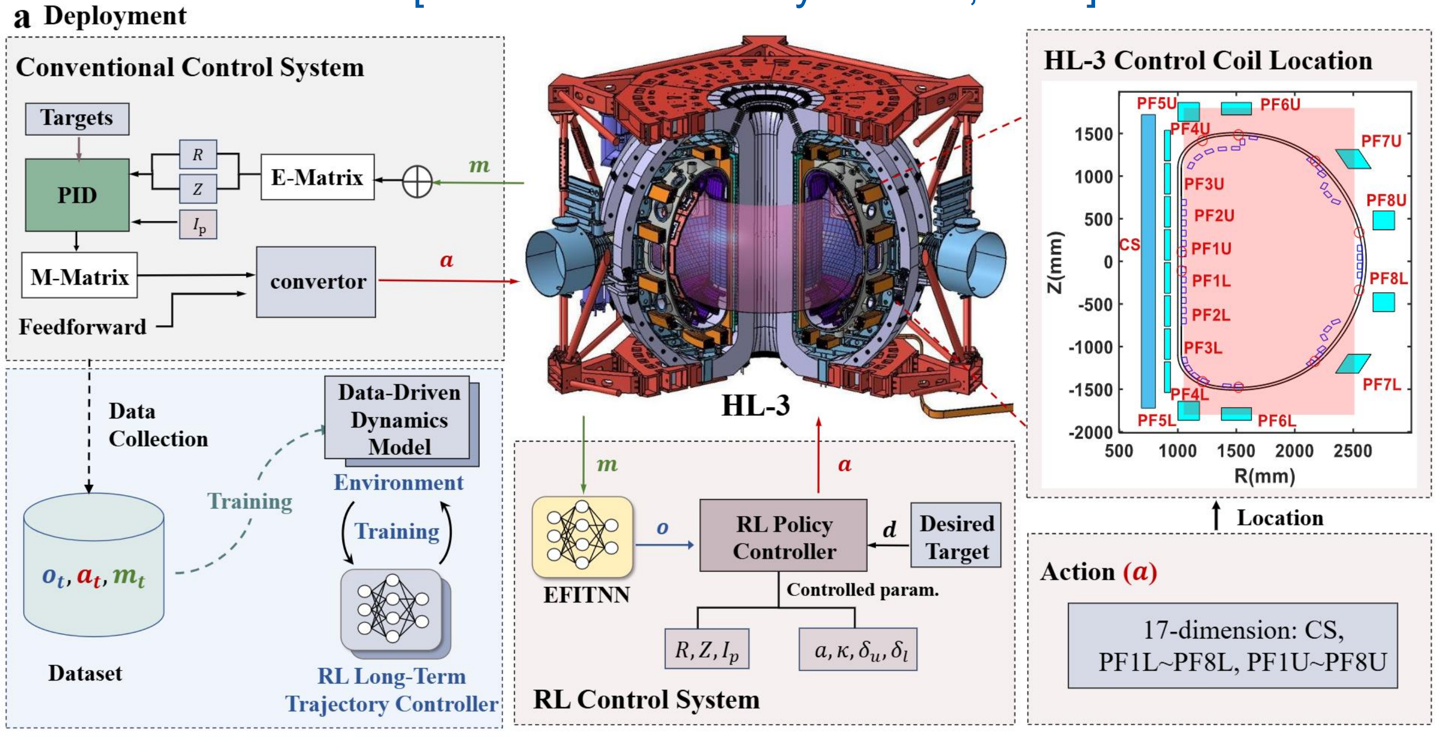


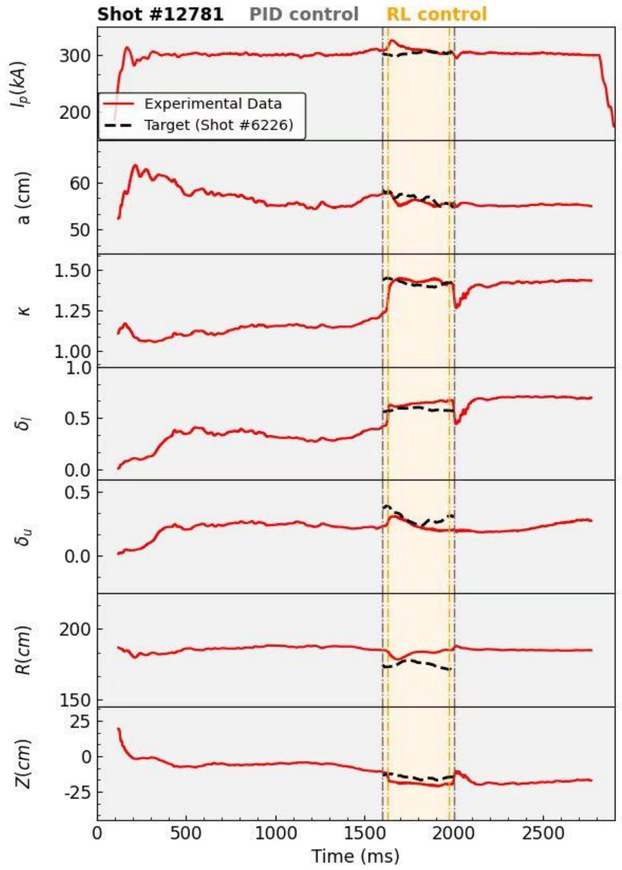
RL-control for exploration of high parameter discharge

- A **high-fidelity data-driven simulator** is developed to train an AI-controller, which successfully control plasma shape in real-time on the HL-3 tokamak
  - ➢ Full handover process: RZIP control → **RL control (400 ms)** → RZIP control
  - ➢ RL control to handle plasma ramp-down and MHD avoidance in high performance discharges

The Framework of RL Magnetic Control on HL-3

[Wu et al Comm. Phys. 8:393, 2025]

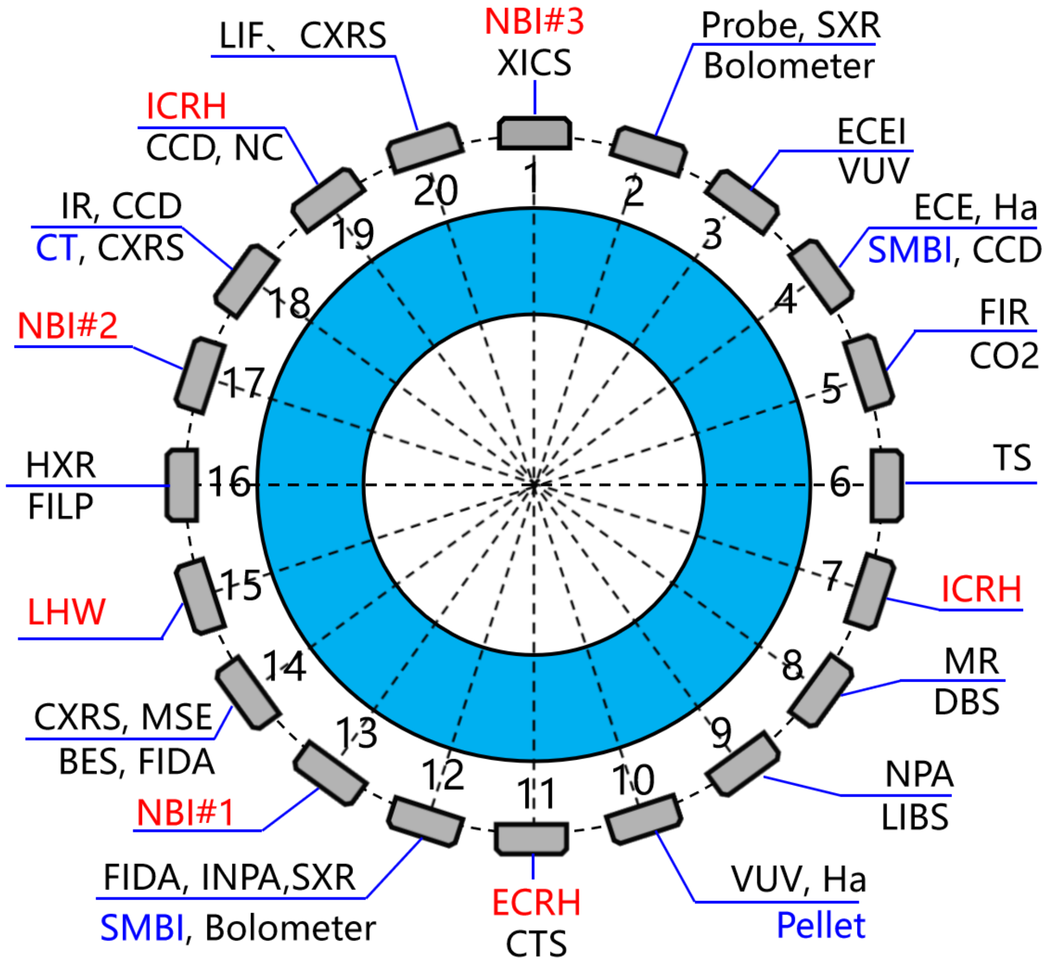




Development of diagnostic systems

■ **More than 50 sets of diagnostic systems deployed on HL-3**

Parameter	Diagnostic techniques	Channels, Resolution
T $T_e(r)$, $n_e(r)$	Thomson scattering	**60** chs, 30 ms, > 1cm
	ECE	**60** chs, 5 μs, 1.5 cm
$T_i(r)$	CXRS	**32-64**chs, ~1cm, 10-50ms
	XICS	**32-64**chs, ~1cm, 10-50ms
$\langle n_e \rangle$, $n_e(r)$	FIR interferometer	**13** chs, 1 μs, 10 cm
	CO2 dispersion Int.	**1** chs, 0.1 ms, line-avg.
Fusion product	Scintillation fiber	**1** chs， DT n， 10 ms
	Fission chamber	**5** chs, fusion power, 1 ms
	ToF	**45** chs, 3%@DT n， 100ms



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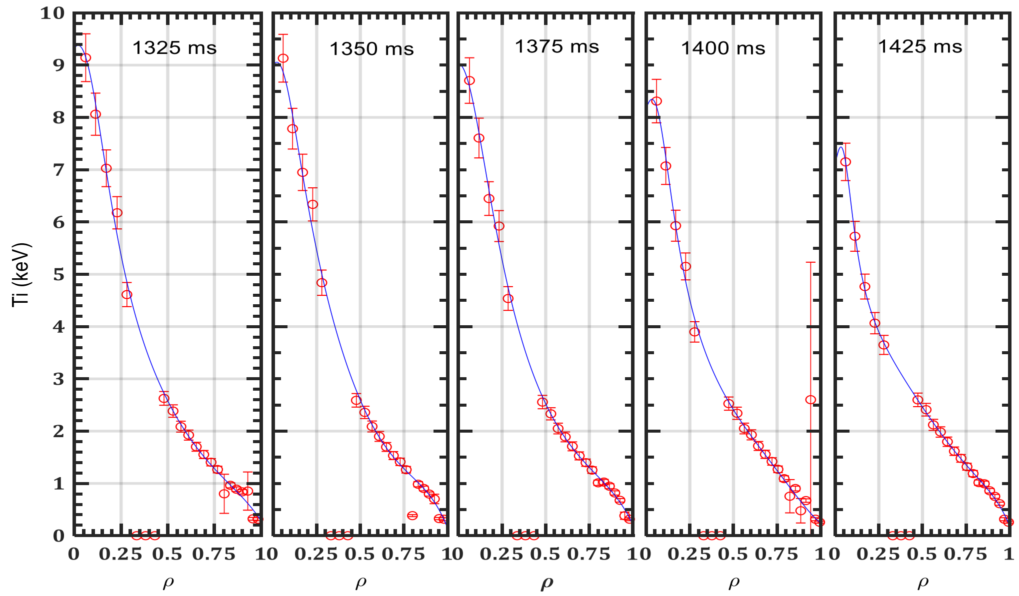
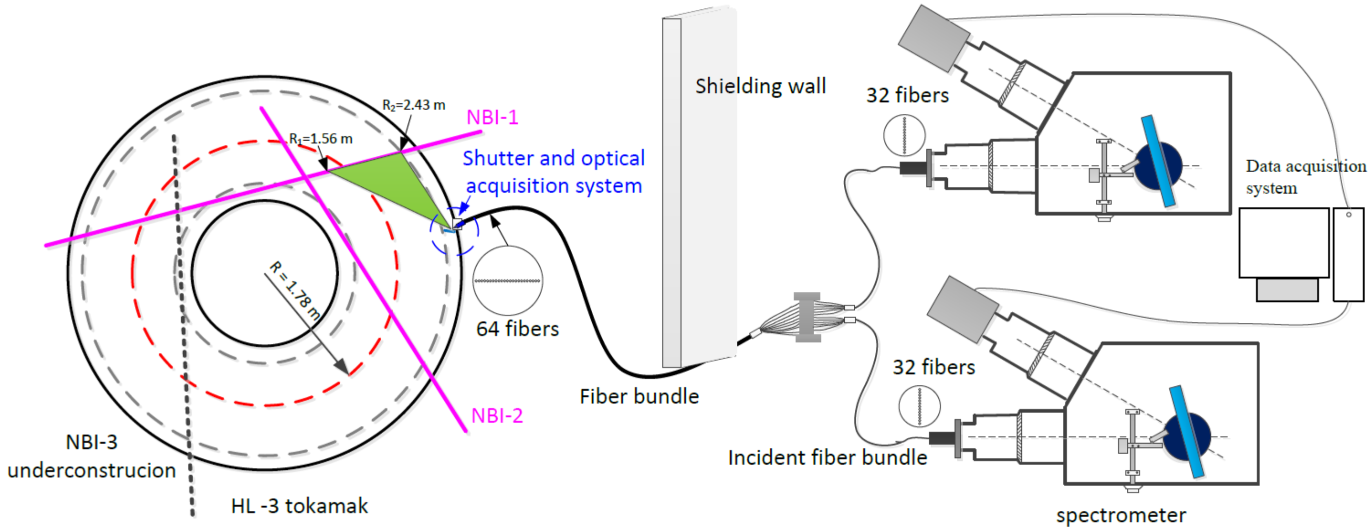
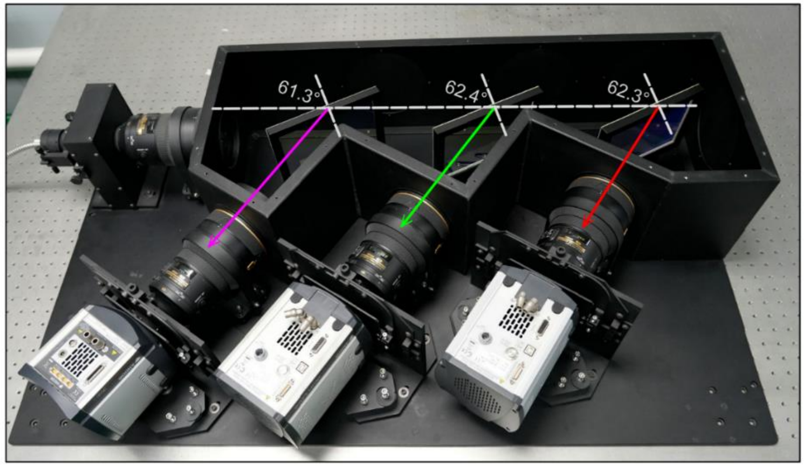
- **Ion temperature and impurity concentration measurement for core transport research**
  - **64-channel CXRS**
    - ✓ T_i/v_t profiles
    - ✓ Spatial resolution: 1~2 cm
    - ✓ Temporal resolution: 20~50 ms
  - **ITER Prototype Contract: Tri-band Spectrometer**
    - ✓ Cascaded gratings
    - ✓ simultaneously measure He II, CVI and Dα lines





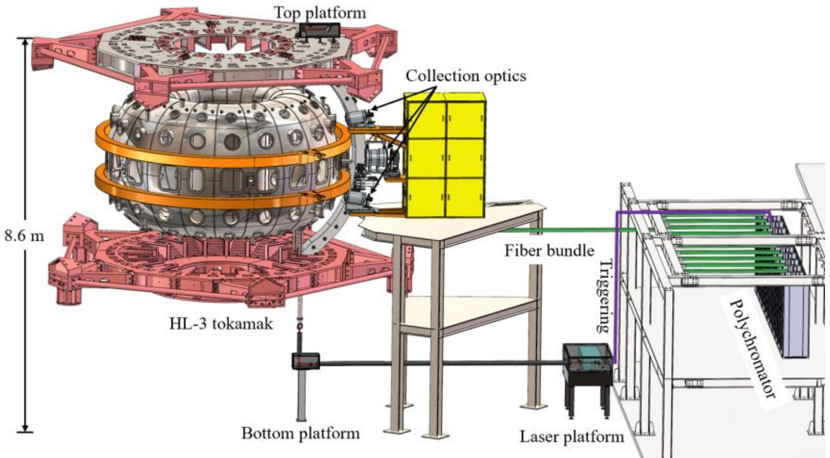


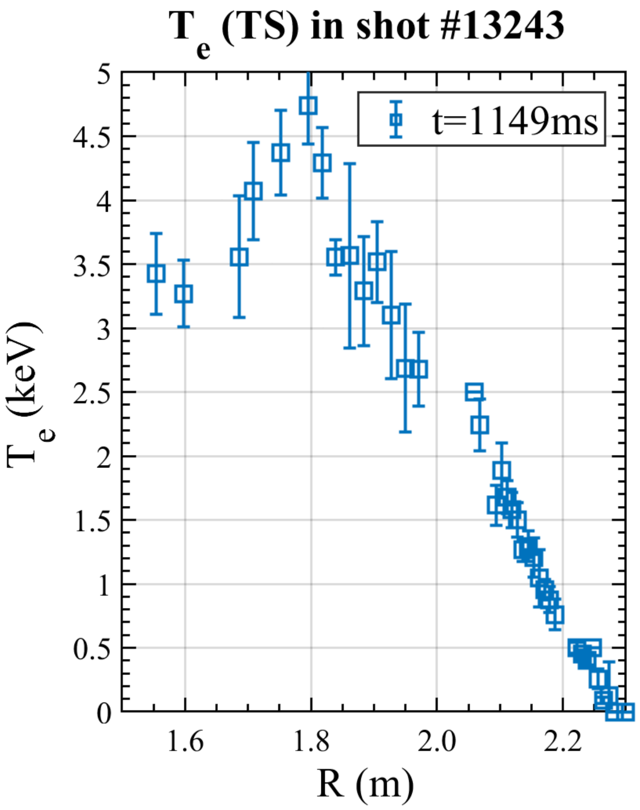
Thomson scattering system

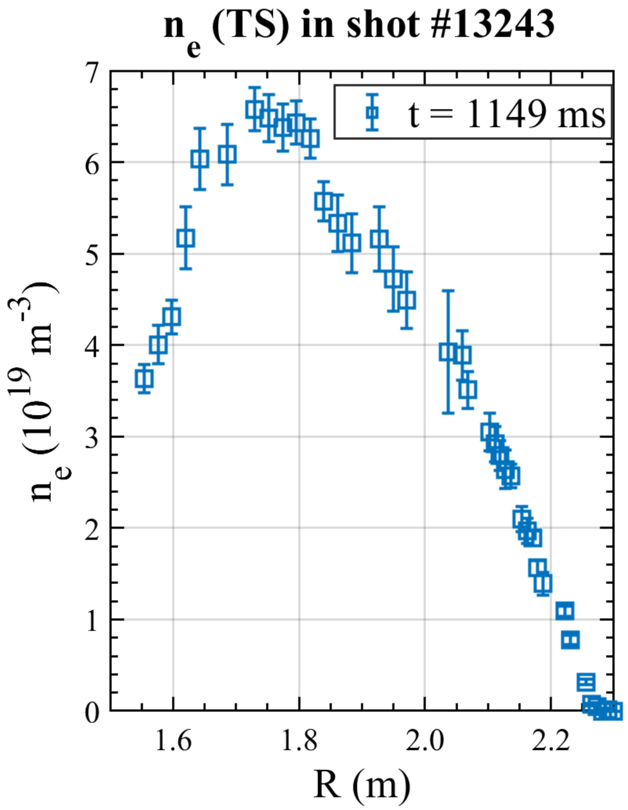
■ **High spatial-resolution TS system for core/pedestal distribution in high-performance plasma.**

✓ Core and Edge Thomson scattering for ne and Te profile measurement

✓ High spatial resolution of 1 mm, 60 channels @25 ms, high-efficiency polychromator based on filters





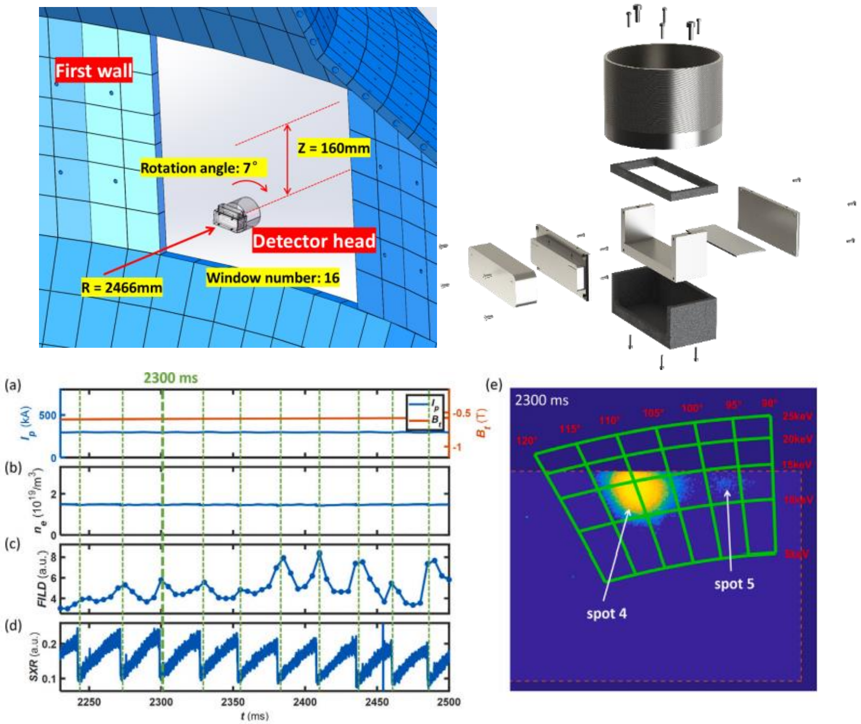


Fusion product and EP diagnostics

- Neutron diagnostics such as **fission chamber and ToF are upgraded;** Other fusion product and energtic particle diagnostics are also developed including: fast ion loss detector **(FILD)**, imaging neutral particle analyzer **(INPA)**, proton detector **(PD)** and collective thomson scattering **(CTS).**

FILD

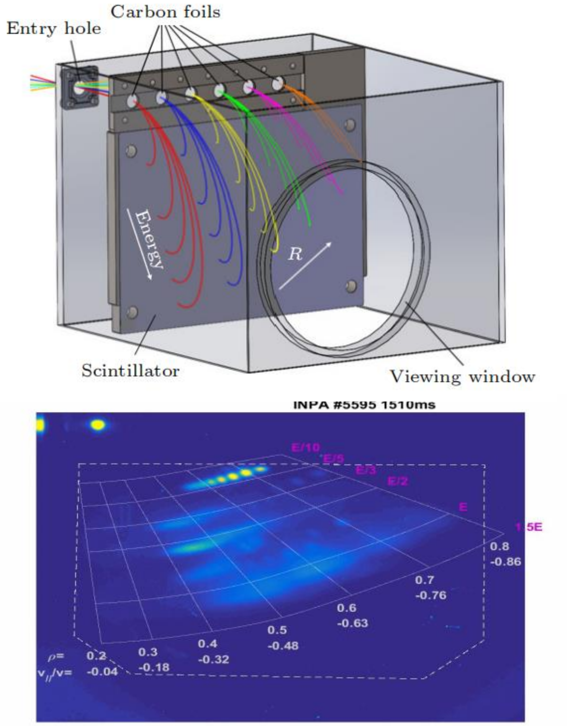
(90-135°, 10-40keV, 5ms)



X.Y. Han, et al Fusion Engineering and Design 221(2025), 115361

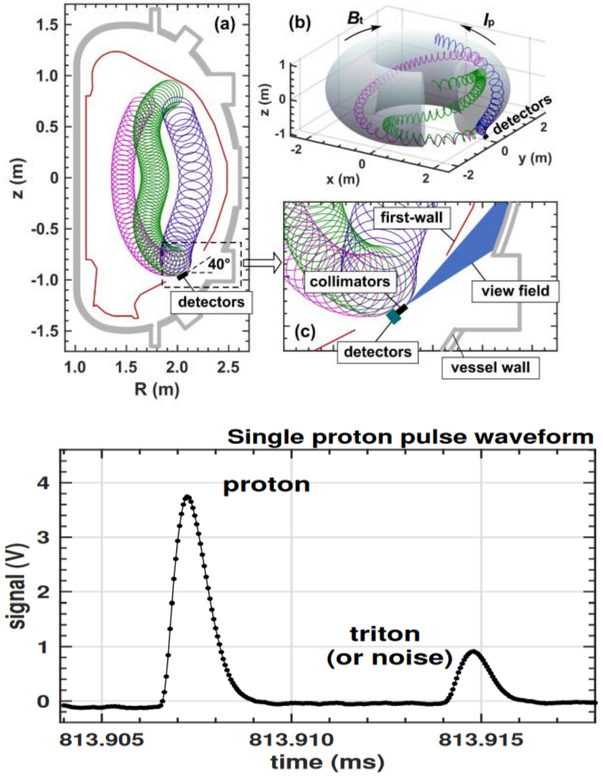
INPA

(0-0.8 a, 4-80keV, Δt=5-20 ms)



PD

(5 chan, 0.5-9MeV, 2 ms,)



X.F. He submitted, 2025, NST-2025-0671

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Approaches to high temperature plasmas

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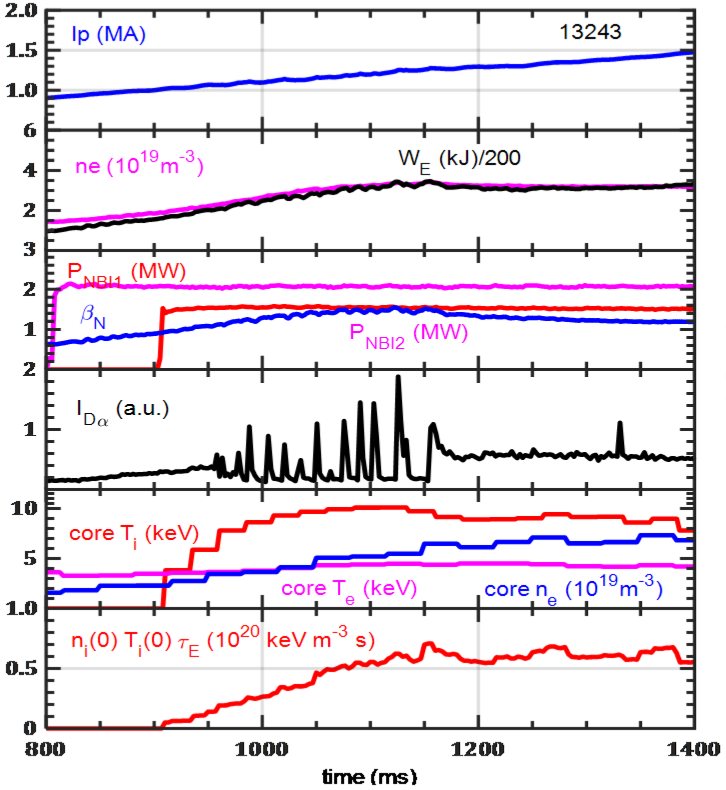
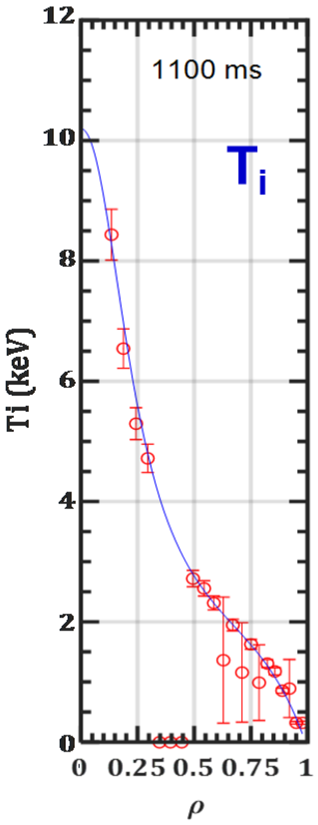
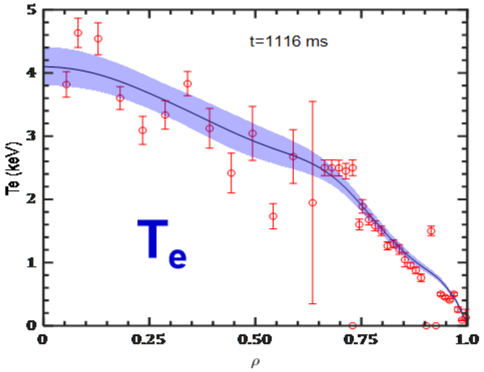
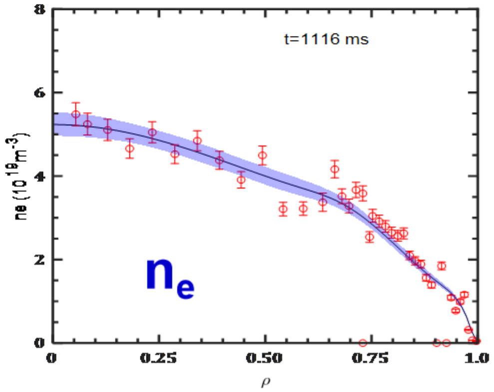
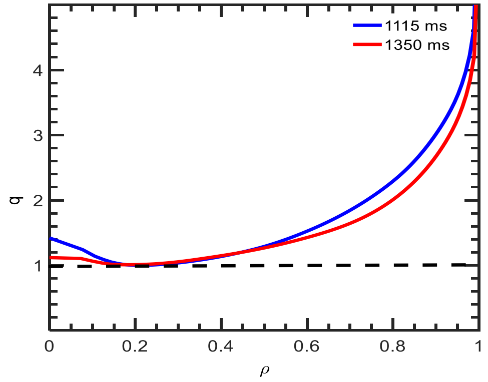
- Stepwise co-NBI heating during current ramp-up produced core reversed magnetic shear
- Flow shear induced by NBI-momentum, suppressed turbulence and MHD instabilities
- Hot ion H-mode achieved with strong ion ITB (T_i =10 keV) and ETB, fusion triple product 0.67×10^{20} m^{-3} ·keV·s

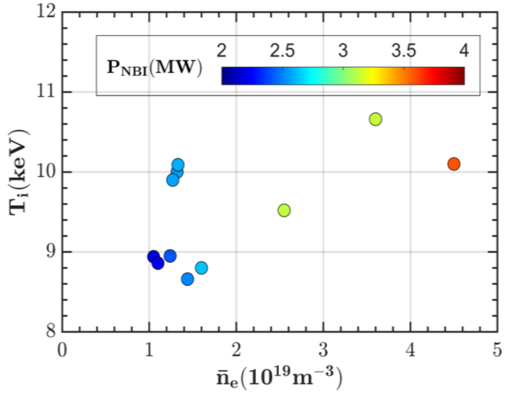












Ion-ITB formation with magnetic islands

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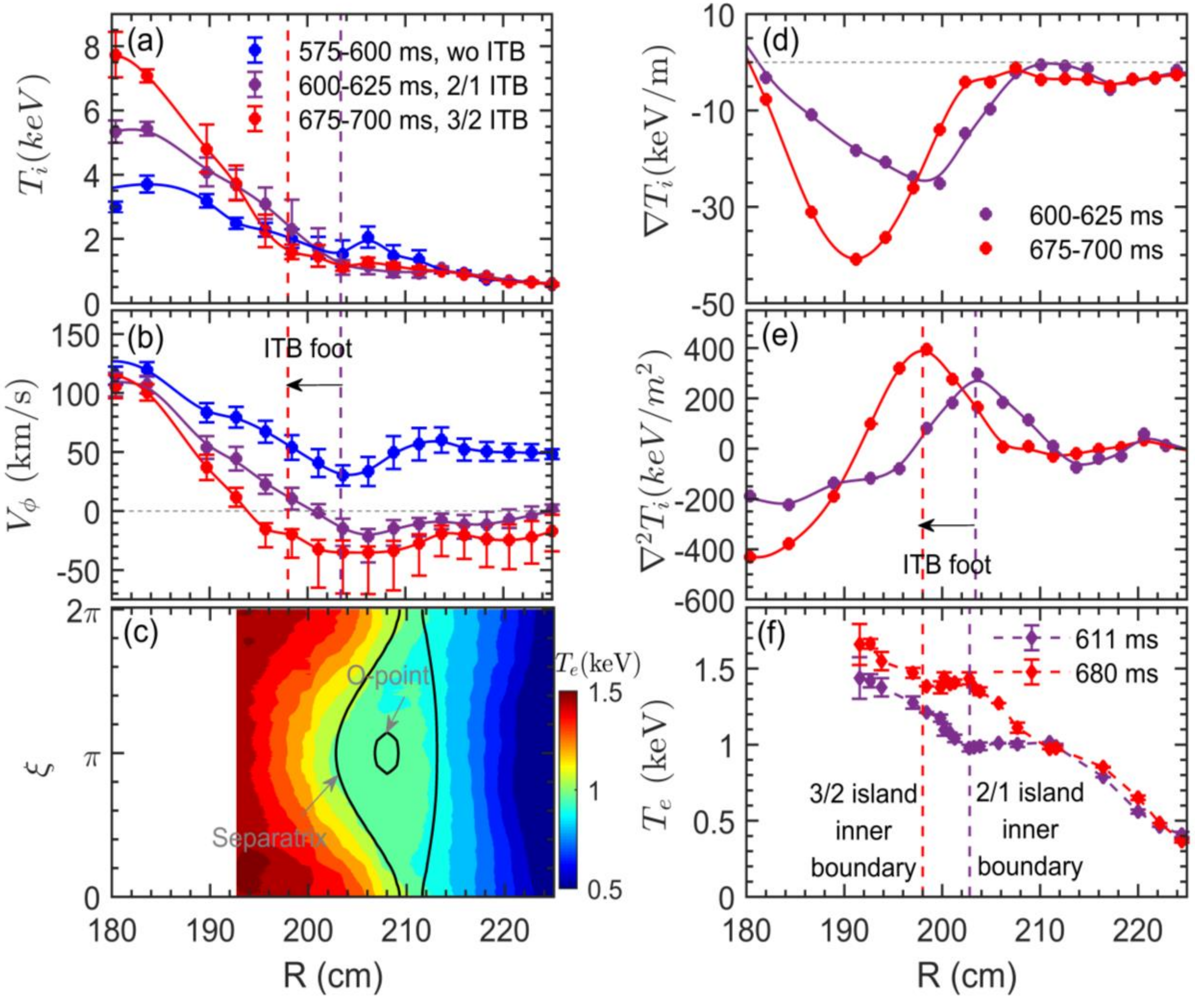
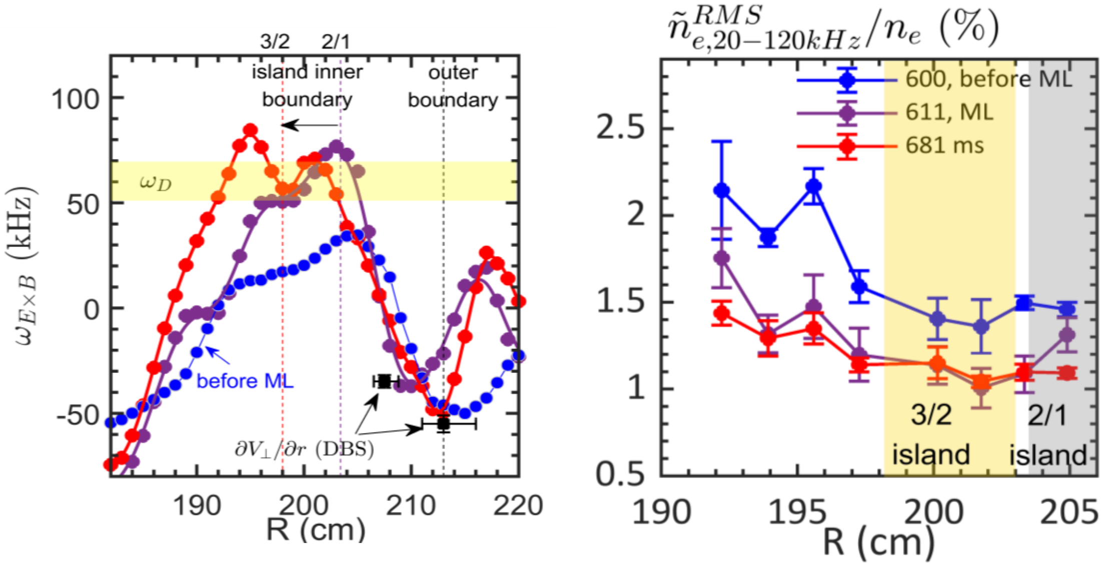
■ **Islands ⟶ strong E×B shear near island boundary ⟶ ion turbulence ↓ ⟶ T_i ↑**





- **ITB Formation:** Ion-ITB formed @ 2/1 island boundary
- **ITB Enhancement:**
  - ⇒ 3/2 island developed
  - ⇒ $\omega_{E\times B}$ @ island boundary ↑ (> ω_D)
  - ⇒ turbulence inside boundary ↓↓
  - ⇒ core Ti ↑↑

ITB foot moved inward

High-beta plasma operation

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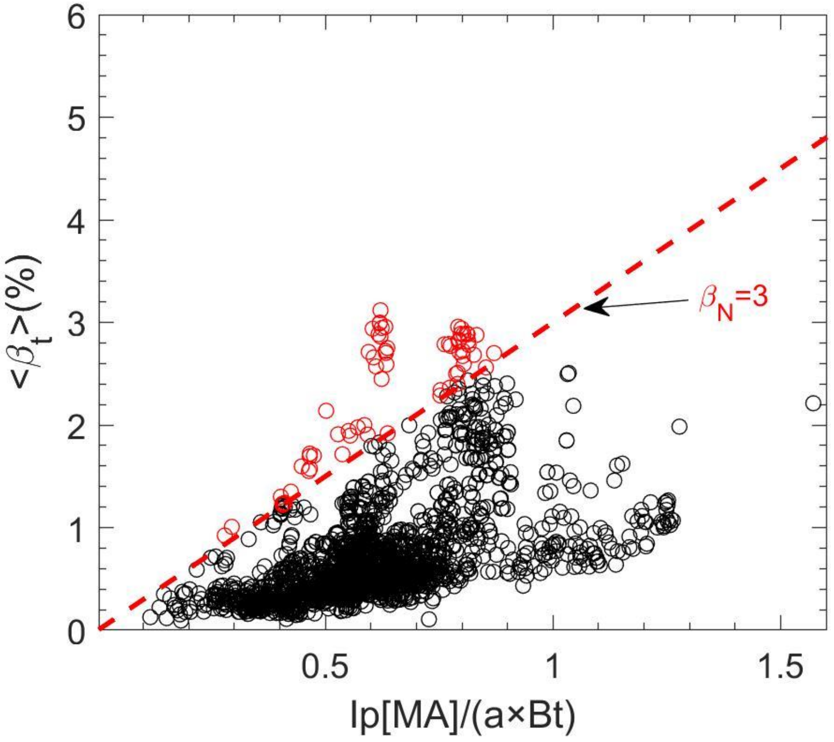
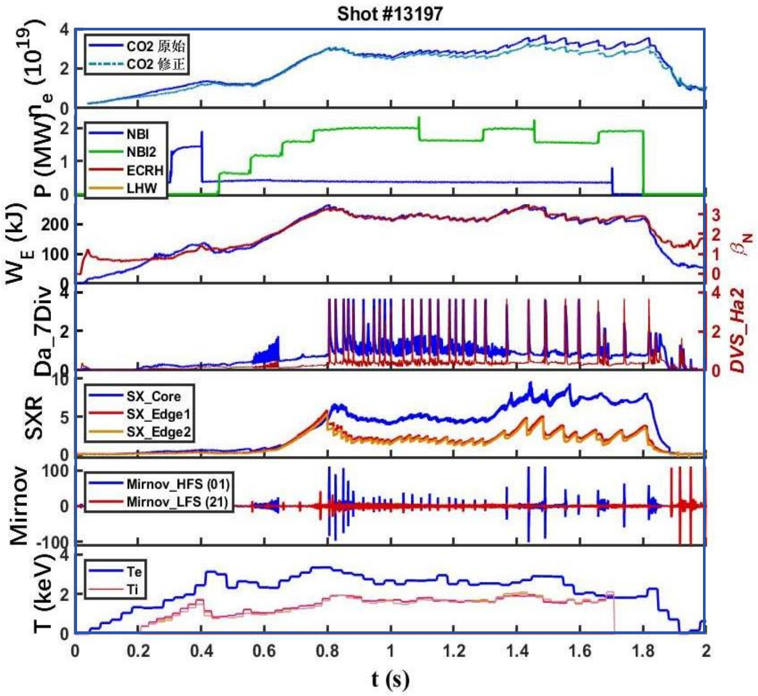
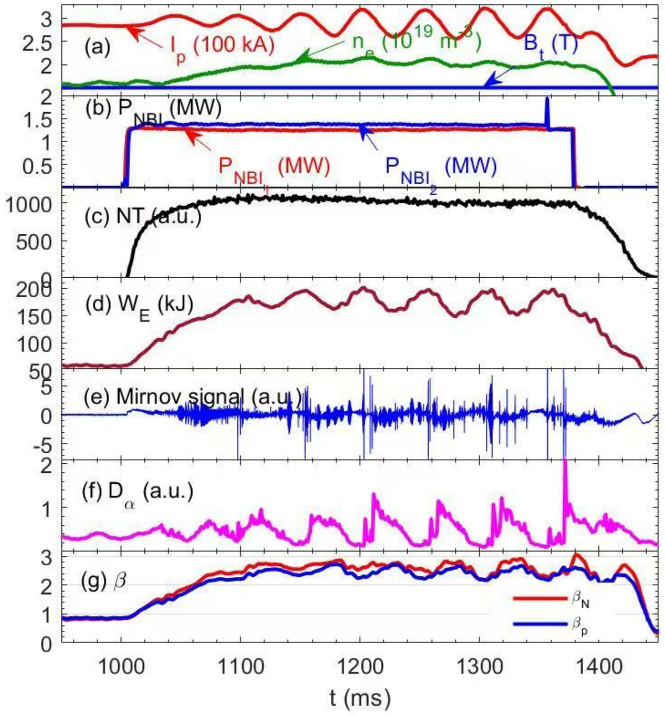
- **Develop high-β scenarios to benchmark MHD and disruption control technologies.**

- **Simulation (MARS-F):** High triangularity (especially positive) and elongation of plasma shape
- **Hybrid operation:** β_N > 2.5 sustained for more than 10 times the energy confinement time
- **High q_{95} operation:** Achieved double transport barrier operation with $\beta_{N,max}$ ≈ 3.0 / $\beta_{p,max}$ ≈ 2.7 with q_{95} = 8 ~10



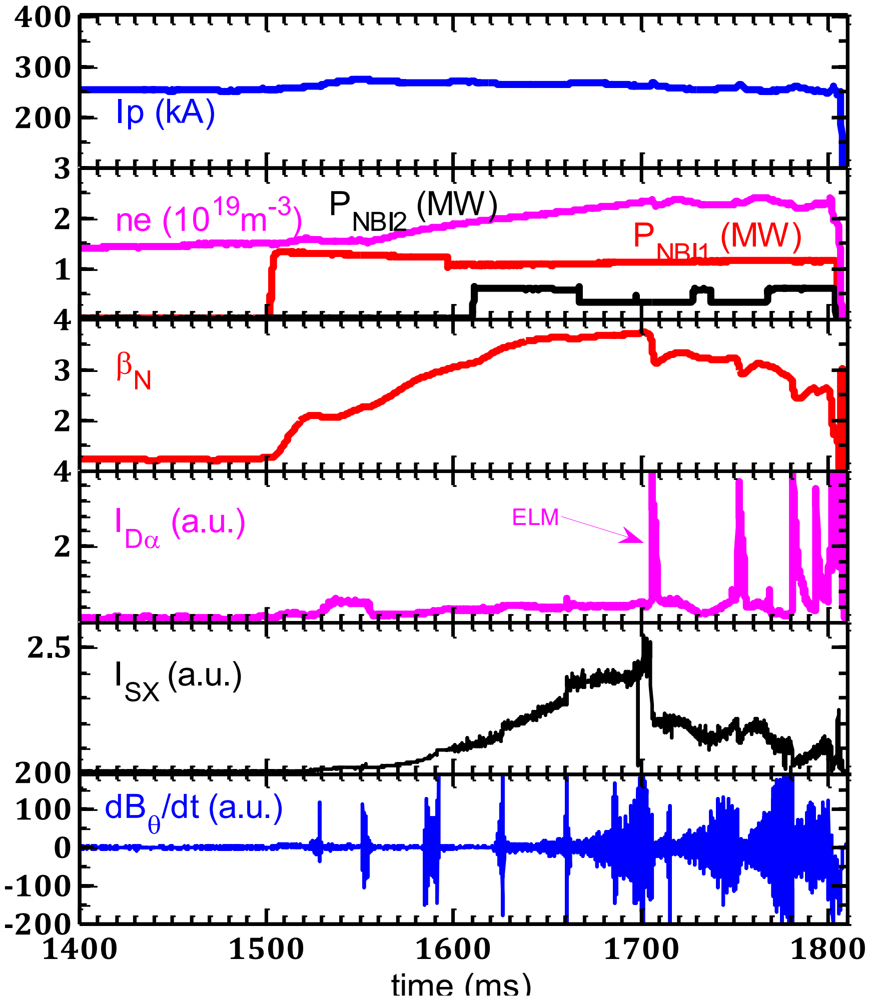


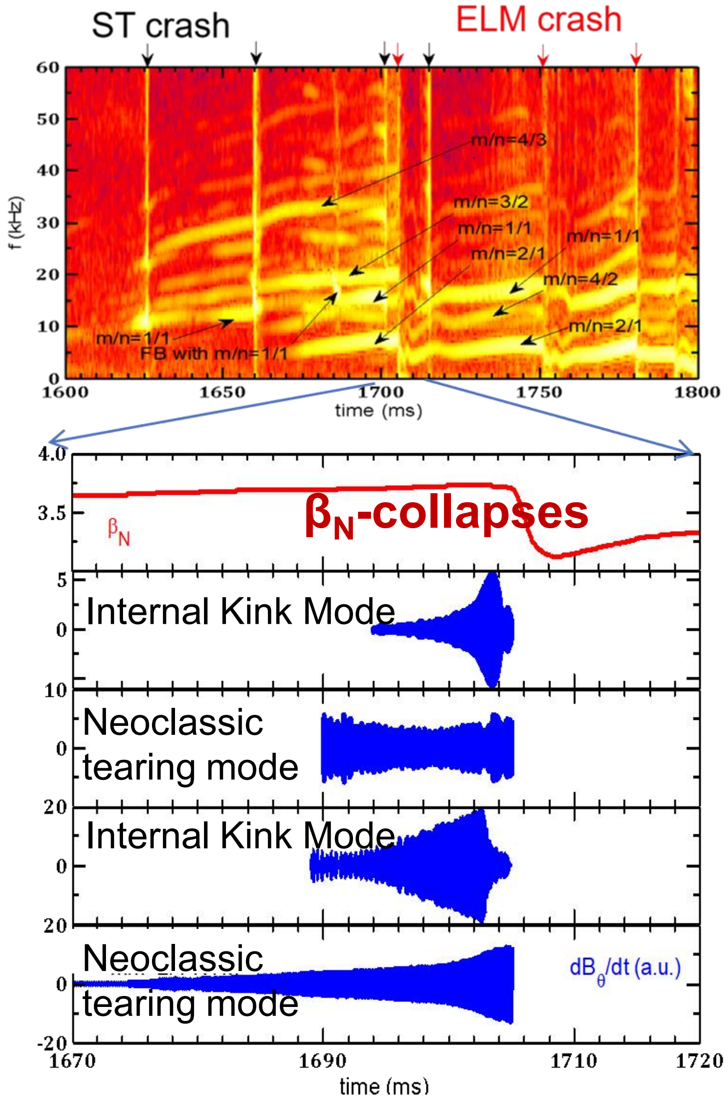


β_N-collapses induced by IKs and NTMs

- **MHDs in high beta plasma induces β_N-collapses**

This conference, Poster 4 B-60, L.M.Yu





- **Plasma parameters:**
  - ✓ n_e/n_G ~ 0.6-0.8,
  - ✓ κ ~ 1.45,
  - ✓ δ ~ 0.5,
  - ✓ q_{95} ~ 3.7,
  - ✓ β_{Nmax} ~ 3.7, H_{98} ~ 1.4

f = 30.5-32.5 kHz
m/n = 2/2 IK

f = 17.5-21.5 kHz
m/n = 3/2 NTM

f = 14.1-18 kHz
m/n = 1/1 IKM

f = 3.9-9.2 kHz
m/n = 2/1 IKM

Fast ion losses induced by 2/1 NTM

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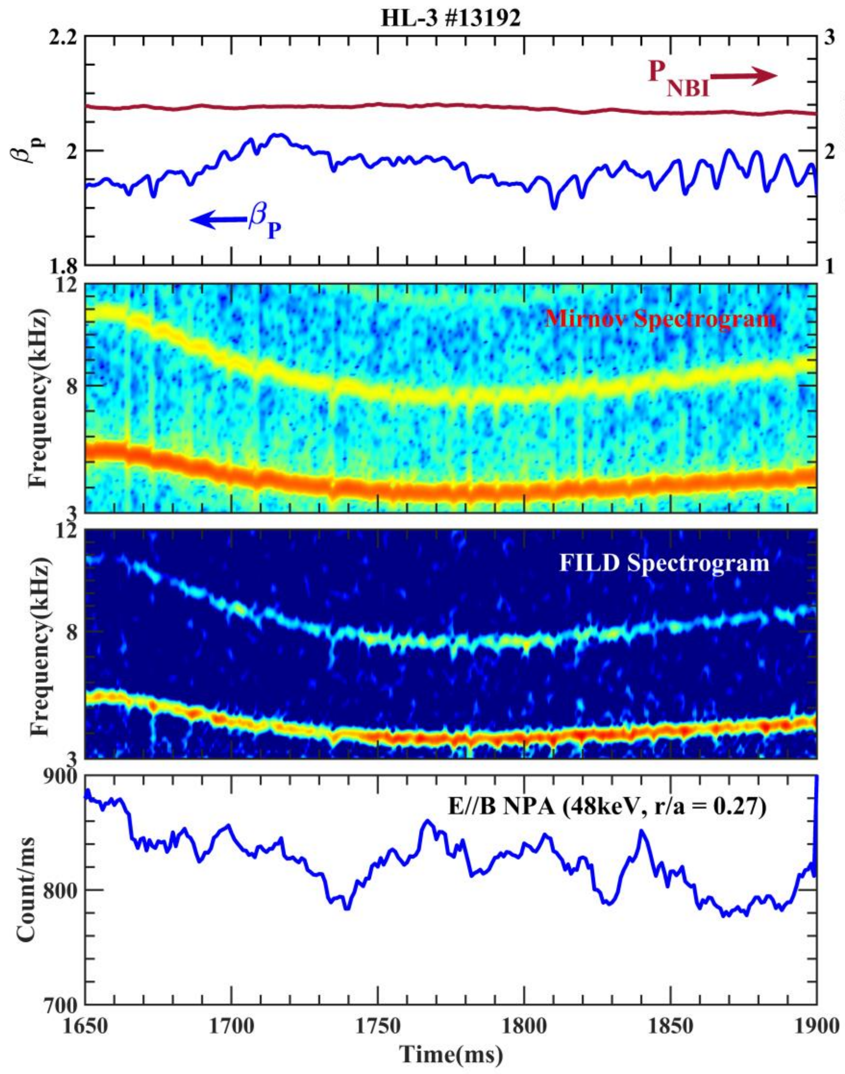
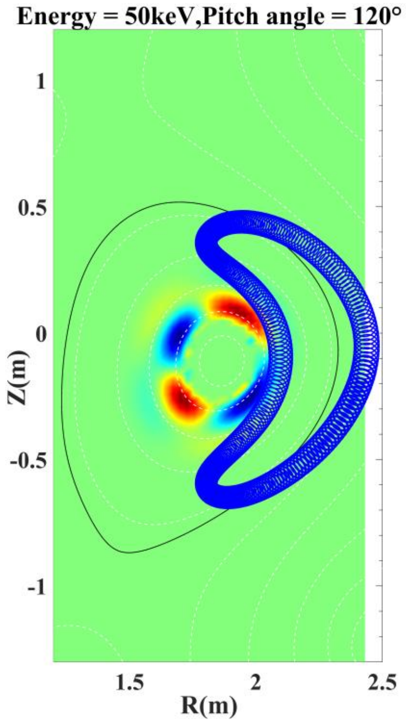
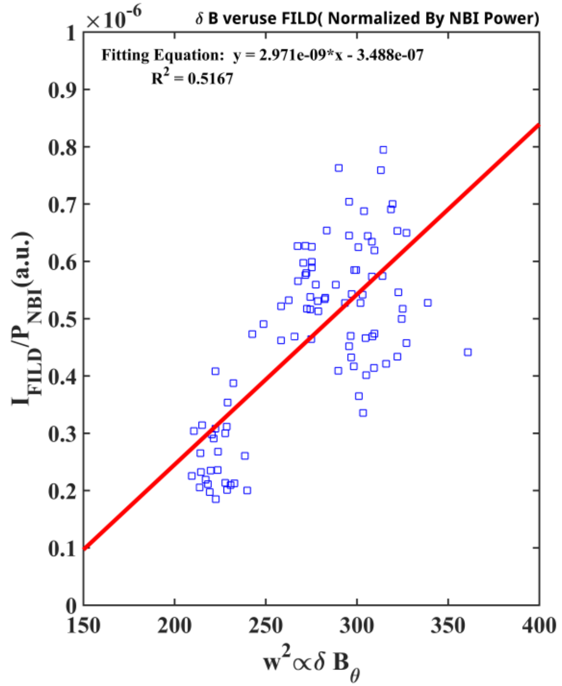
■ Fast ion losses induced by 2/1 NTMs with a convective loss mechanism

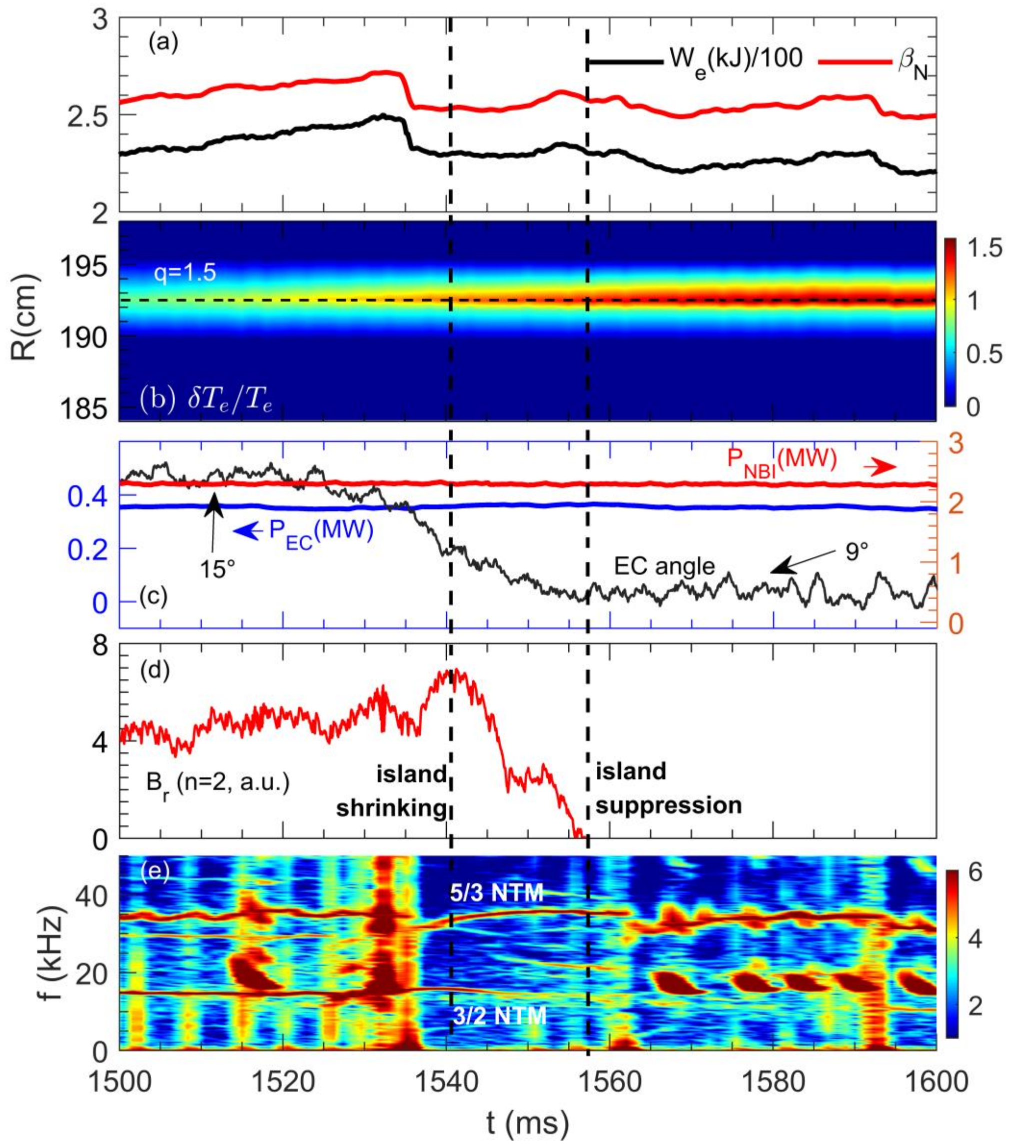






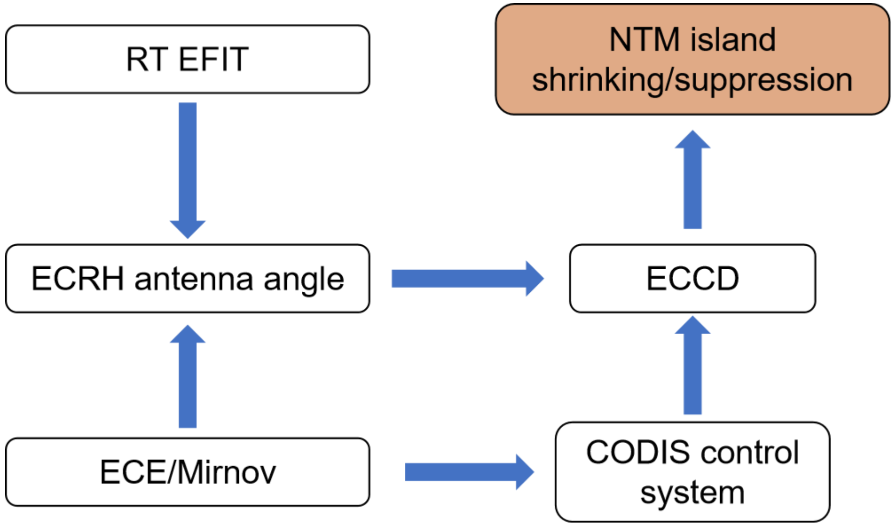
- ☐ Strong correlation between frequencies of 2/1 NTM rotation and FI loss by FILD, suggesting NTM modulates FI losses;
- ☐ Loss orbit of trapped particle intersects with island structure, indicating fast ions interact with NTM island;
- ☐ The linear correlation between FI loss strength and w^2 indicates a convective loss mechanism.

■ Real-time neoclassical tearing mode (NTM) feedback control by ECCD prelimilary realized



NTM identified by ECE → **ECCD injected with particular angle** → **NTM suppressed**

This conference, Poster 5 B-58, X. Yu



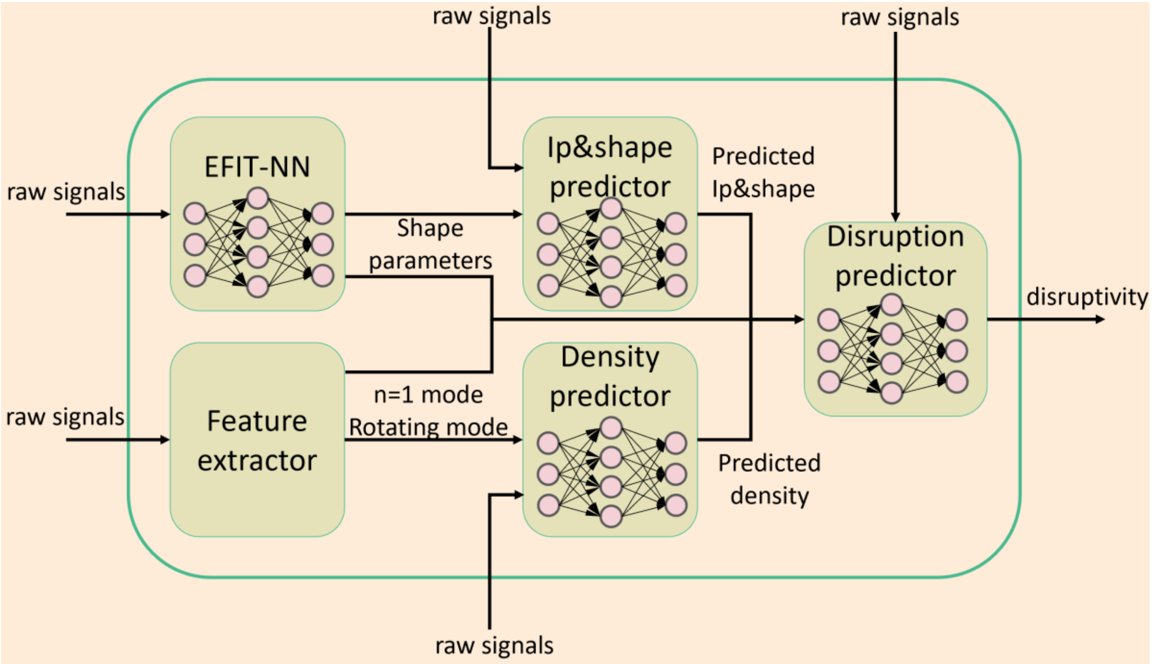
- Optimal EC antenna angle scanned;
- Real-time NTM identification and EC injection achieved, 3/2 NTM island shrank and finally suppressed when EC deposited near q=1.5 surface
- Next step: Real-time angle control to suppress multi-modes.

AI control of high beta disruption

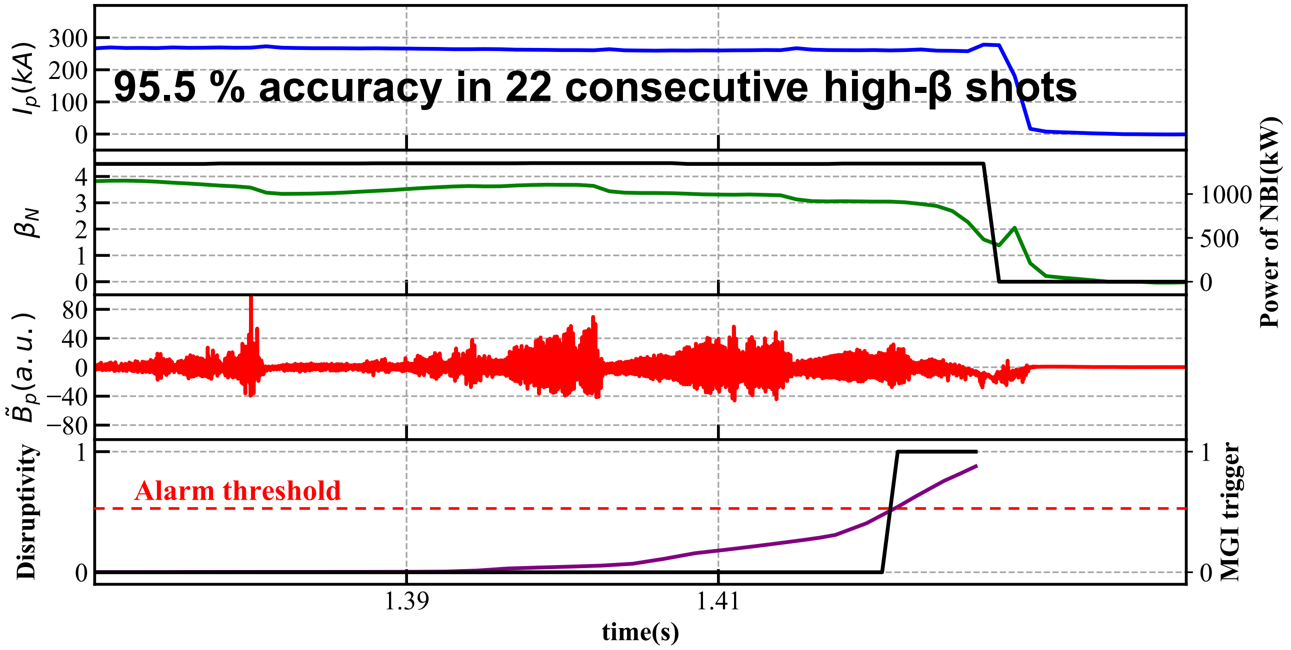
■ **Disruption control in high beta operation (β_N > 2.5): Novel disruption prediction strategy**

(Predict-First Neural Network, PFNN) Z.Y. Yang et al Nuclear Fusion 65 (2025) 026030

- Novel strategy: predicts parameters evolution first, then to predict plasma disruption
- Significantly enhances the extrapolation capability from low to high parameter spaces (I_p, B_t, q_{95}, W_E, β_N)



Framework of HL-3 disruption prediction



Closed loop disruption prediction and mitigation in Shot 12478

Outline

- Introduction of HL-3 tokamak
- Improvement of heating, diagnostic & control
- High-performance plasma
- **Power exhaust solution**
- Summary and future plan

Small / no ELM regimes

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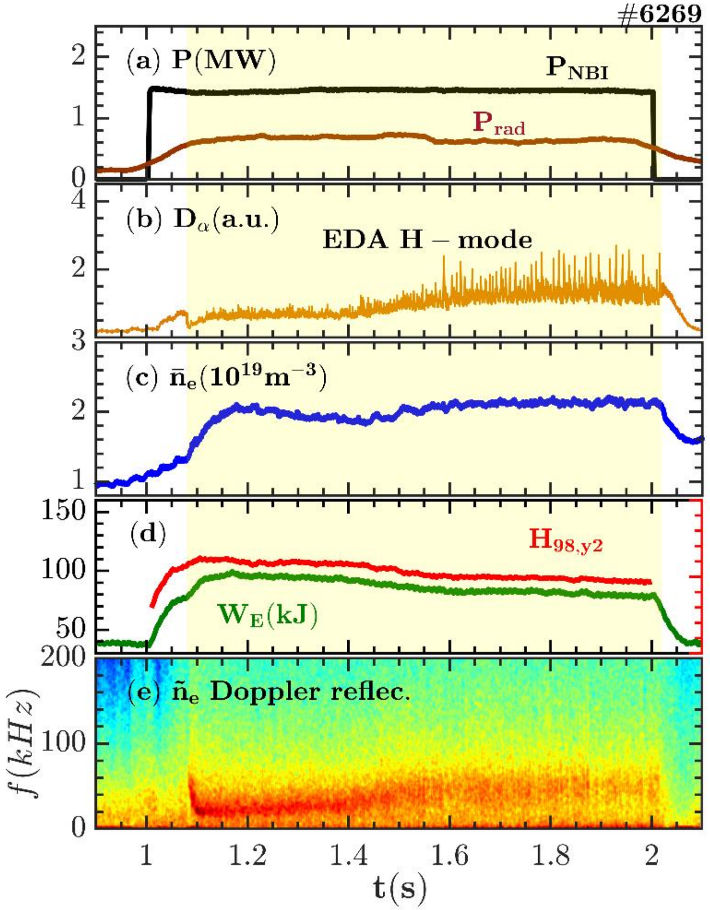
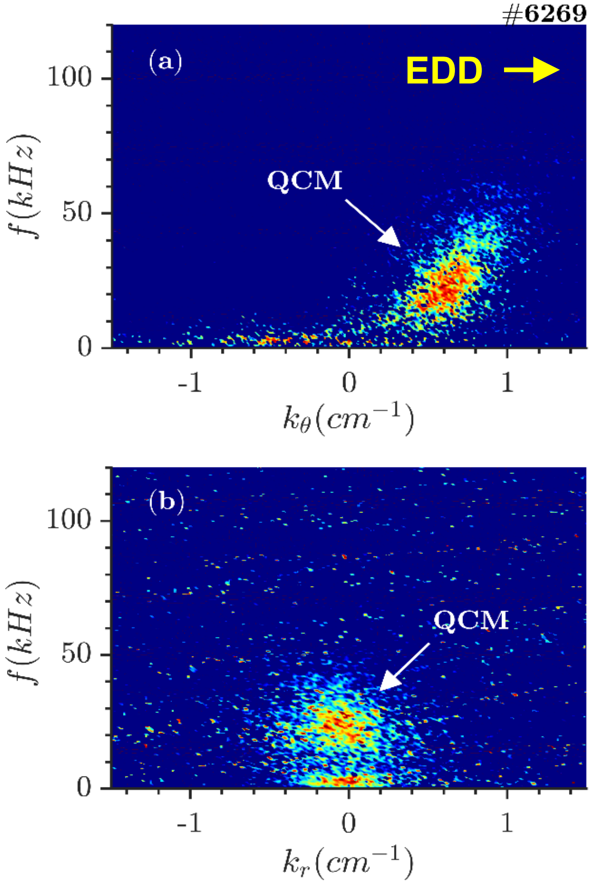
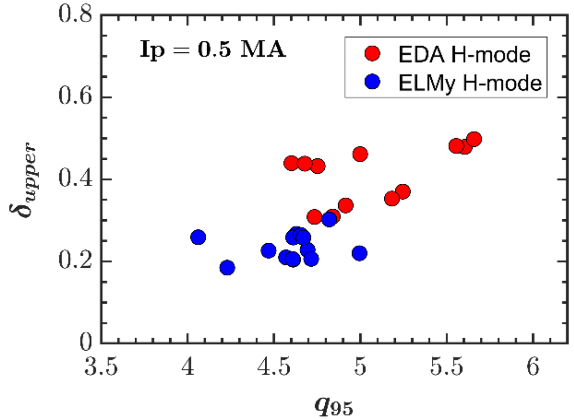
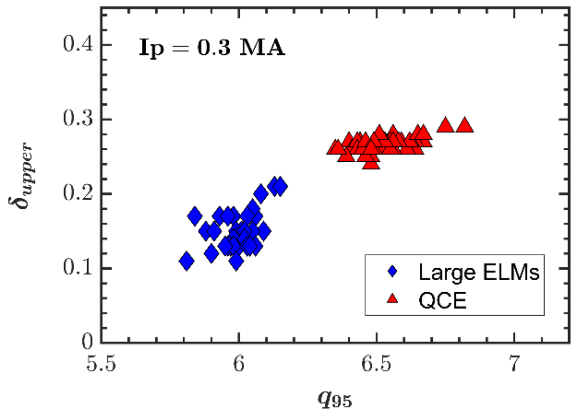
- **Small or no ELM regimes achieved on HL-3, including EDA H-mode, QCE, and QH-mode**
- Typically accompanied by quasi-coherent modes (for EDA & QCE)
- Favorable conditions: High q_{95}, high plasma triangularity (δ)

A. Liang et al 2025 submitted NF-108324









Small / no ELM regimes

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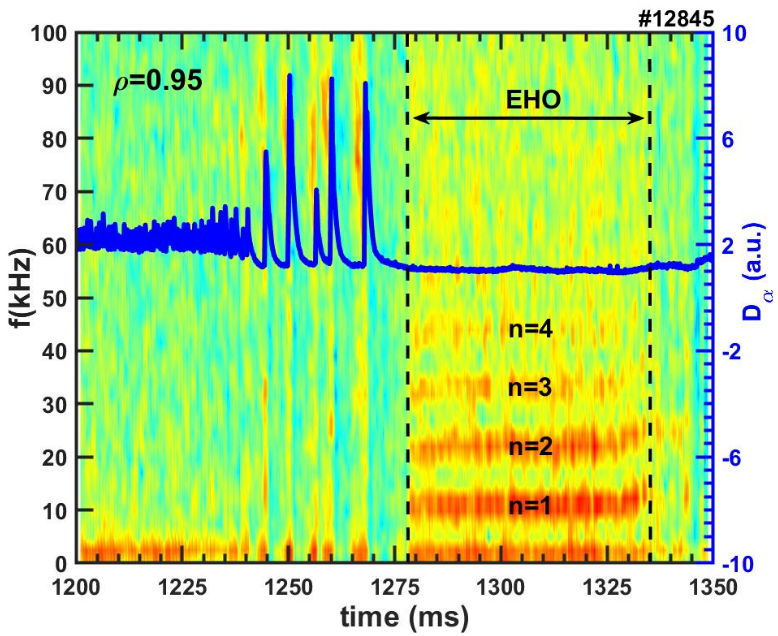
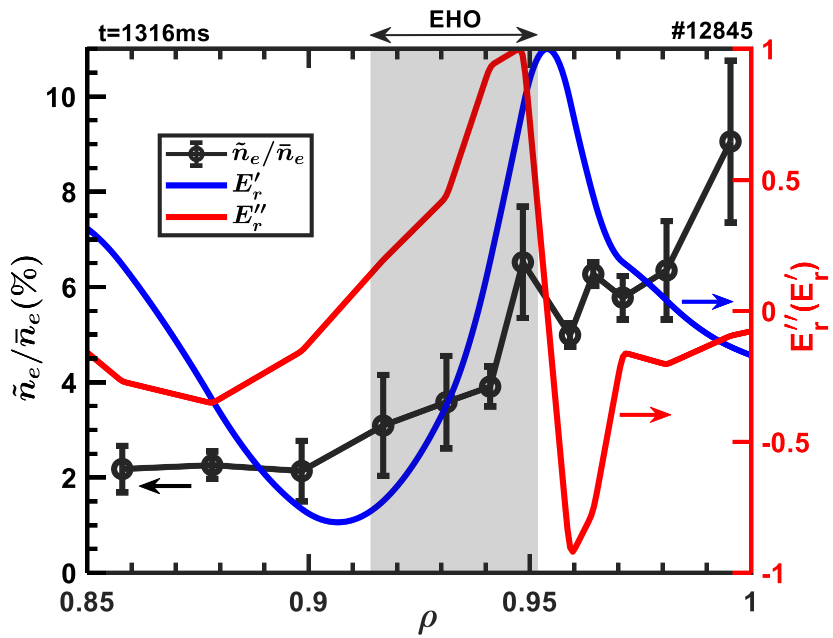
- **Small or no ELM regimes achieved on HL-3, including EDA H-mode, QCE, and QH-mode**
- QH-mode with EHO was observed in an early stage of H-mode ($1.1 < \beta_N < 1.3, 1.2 < H_{98,y2} < 1.3$)
- The driving role of E_r-curvature (E_r'') on EHO, with a critical threshold ($E''_{r,crit}$) is now experimentally confirmed, supporting the earlier theoretical and numerical predictions.

Y. Zhang et al 2020 Phy. Rev. Lett. 125, 255003

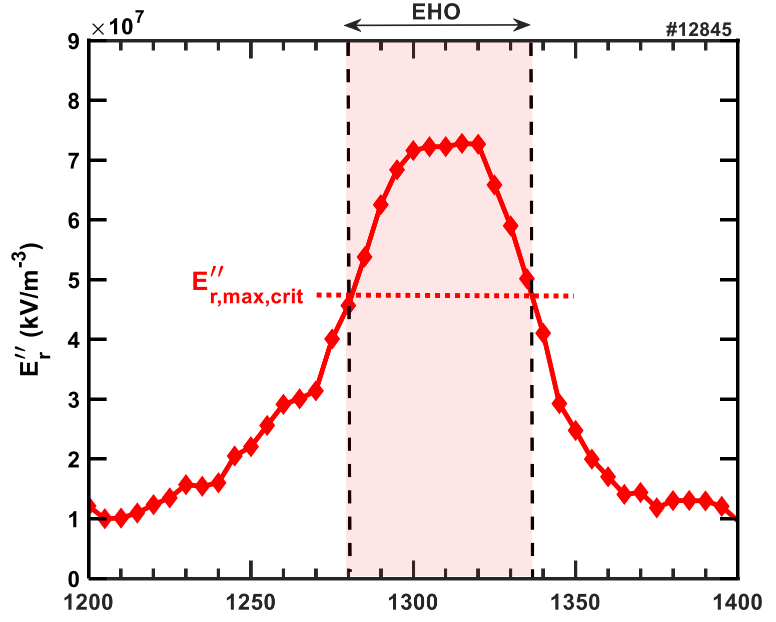
Y. Zhang et al 2022 Phys. Plasmas 29, 112101



Appearance of EHO



EHO's $\tilde{n}_e/\bar{n}_e$ VS E_r-curvature (E_r'')



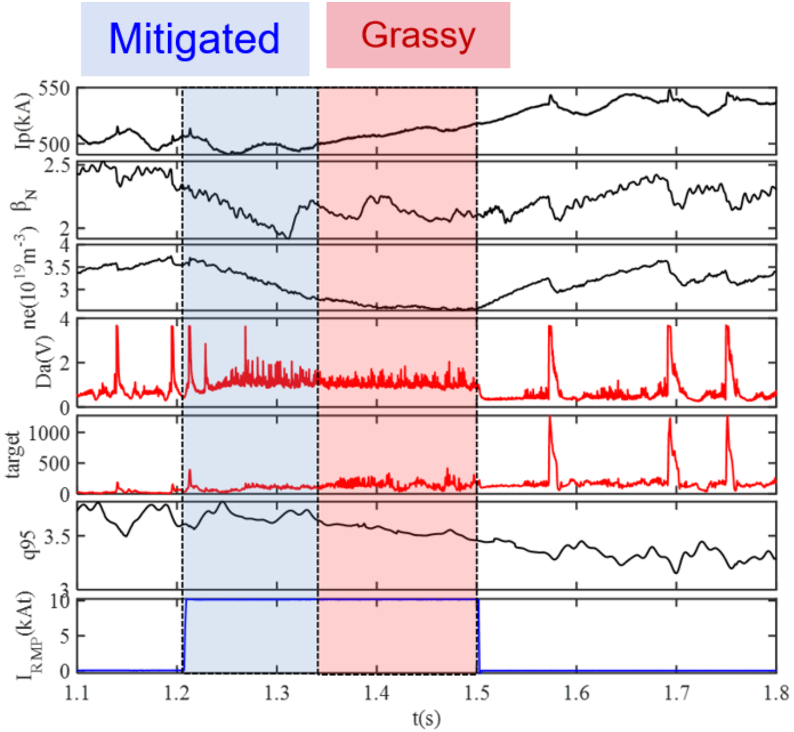
Critical $E''_{r,\max,crit}$ for EHO

Y. Zhang et al 2025 submitted NF-108406

ELM control by RMP

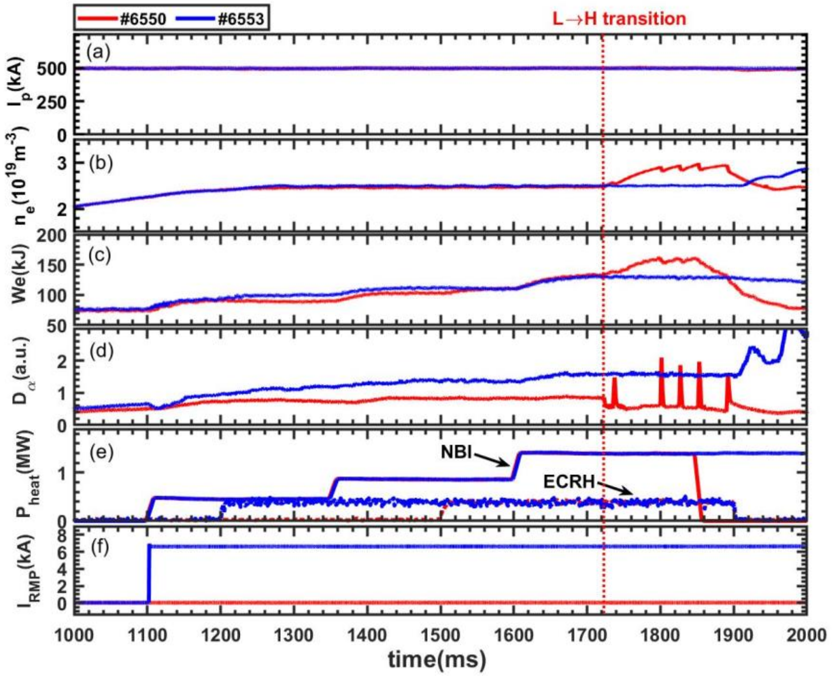
- **RMP coils and power supply were newly installed in HL-3 for ELM control**
- MARS-F simulation suggests odd parity is optimal
- ELM controlled by n = 1 and n = 2 RMPs (odd parity) achieved by scanning I_p (q_{95}).
- Incompatible with L-H transition: lower shear rate $\omega_{E\times B}/\omega_D$ prevents L-H transition

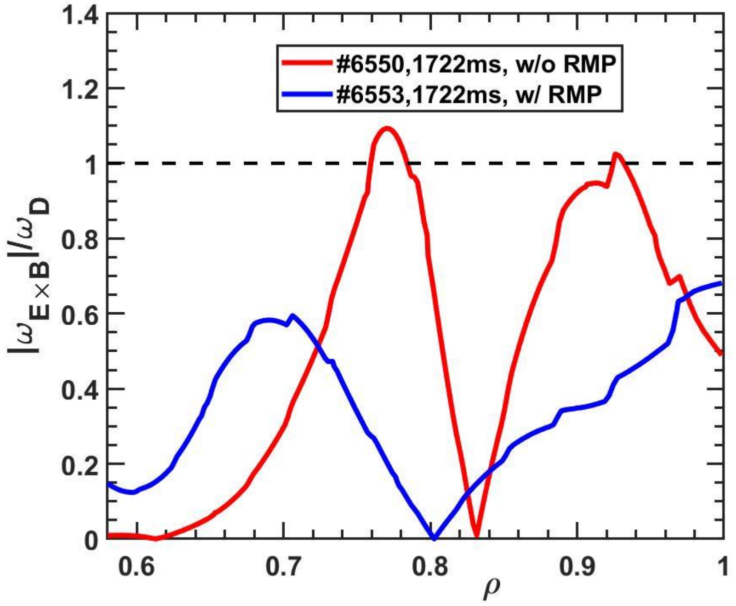
Y. Zhang et al 2025 Nucl. Fusion 65 066016



This conference , Poster 1 B-51 G.Z. Hao

This conference, Poster 1 B-26, N. Zhang

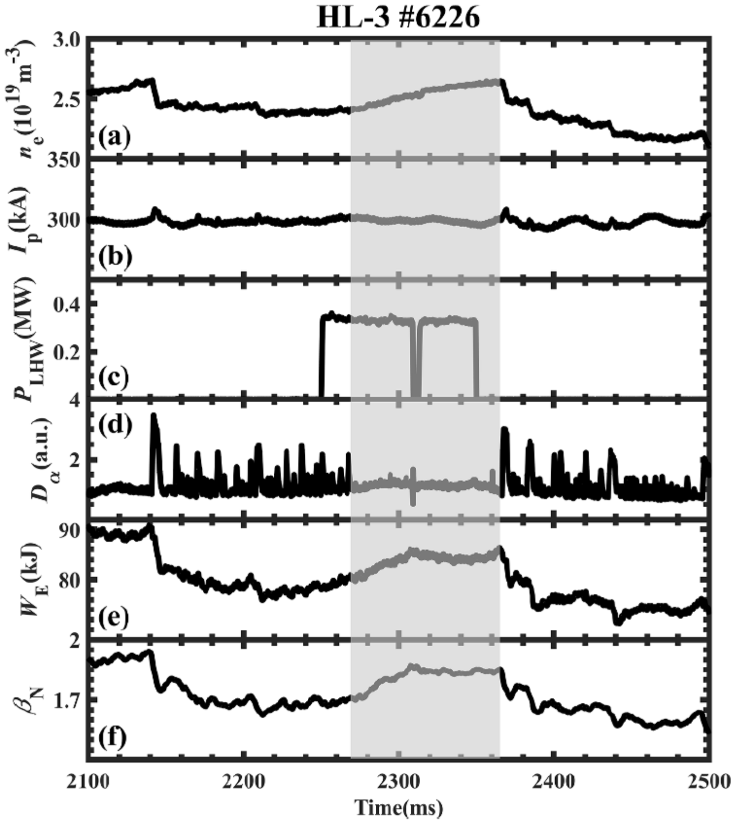


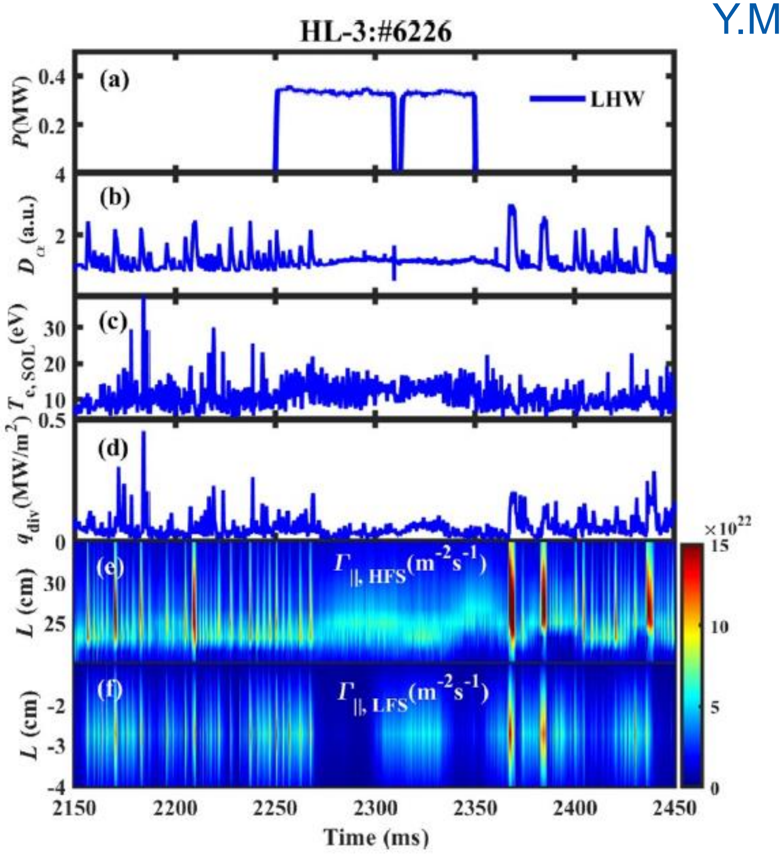


This conference, Poster 3 B-70, M. Jiang

ELM suppression by LHW

■ **ELM suppression by LHW, reducing heat load and improving confinement on HL-3**





Y.M. Zhang et al 2025 Nucl. Fusion 65 096019

Possible physical process:

LHW heating electrons

→ edge electrostatic turbulences ↥

→ soften the pedestal gradient

→ wider and flatter pedestal

→ ELM suppression

■ **Other actuators such as mixture SMBI also suppressed ELMs**

This conference, Poster 6 B-57, G.Q. Xue

Detachment and feedback control techniques

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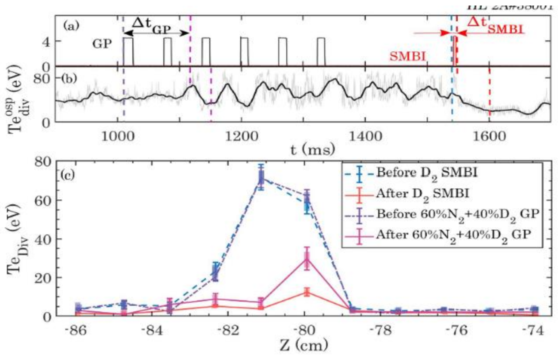
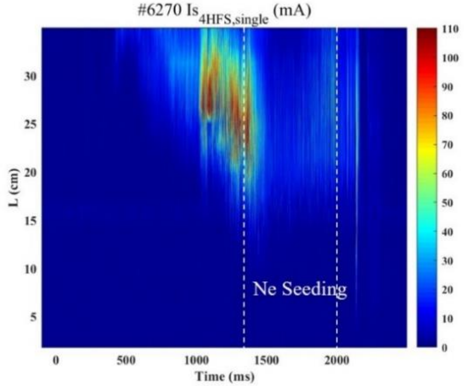
- Divertor SMBI and SD1D modeling code were developed for fast control and simulation
- Detachment feedback control prelimilary realized by real-time measurement of J_{sat}

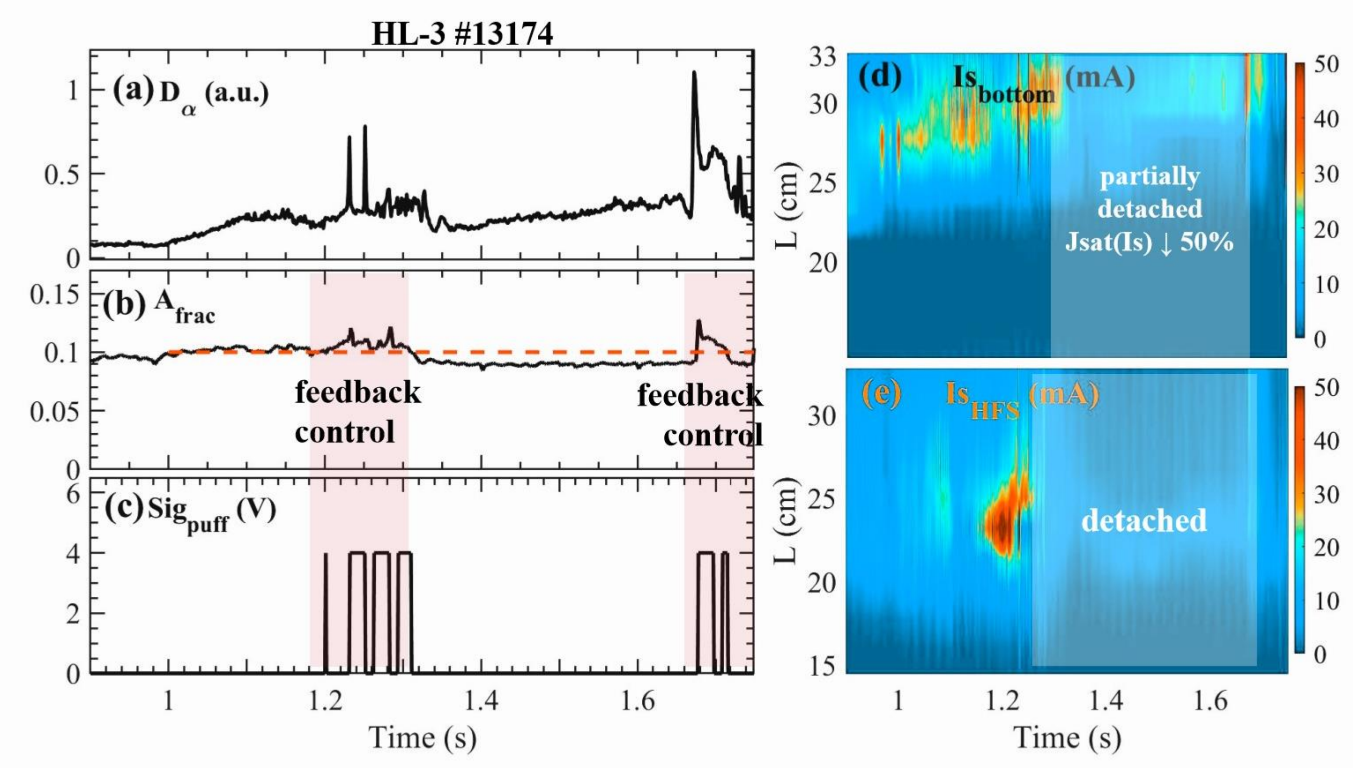
Fast (partially) detachment with divertor SMBI (v>1000m/s)

EX-3117, Regular Oral , 17 Oct. 12:00 G.L. Xiao

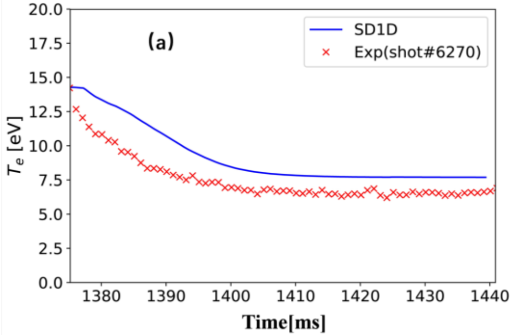


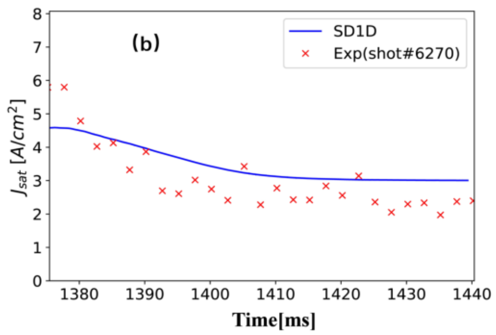


[G.L. Xiao et al Nucl. Fusion 63(2023) 086017]



SD1D: Fast simulation of divertor parameters





Y.L. Zhou et al Plasma Phys. Control. Fusion 67(2025) 055043

Advanced divertor configuration

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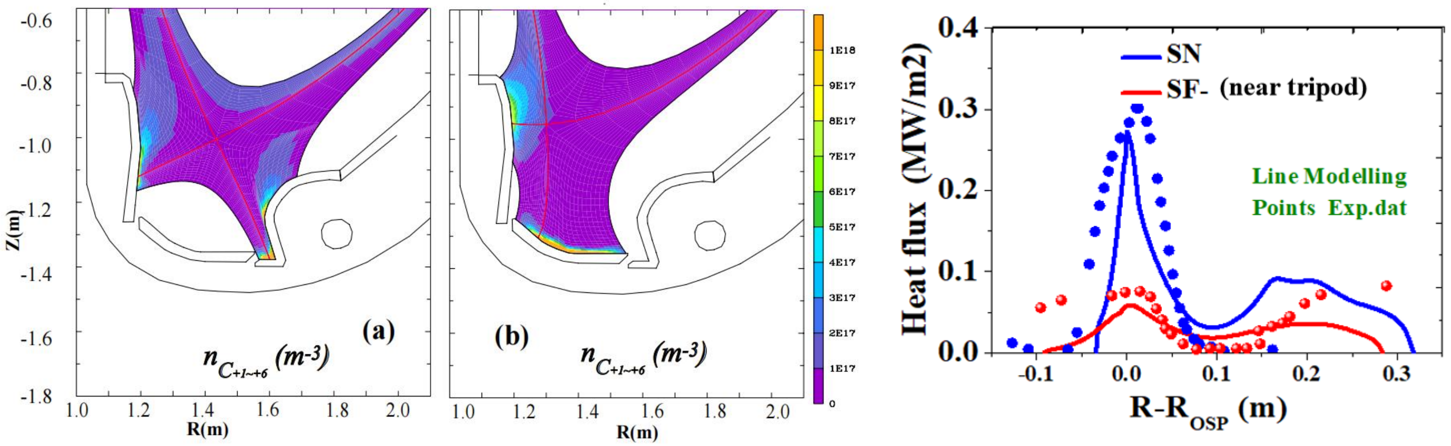
■ **Achieved snowflake divertor configuration significantly reduces target heat flux**

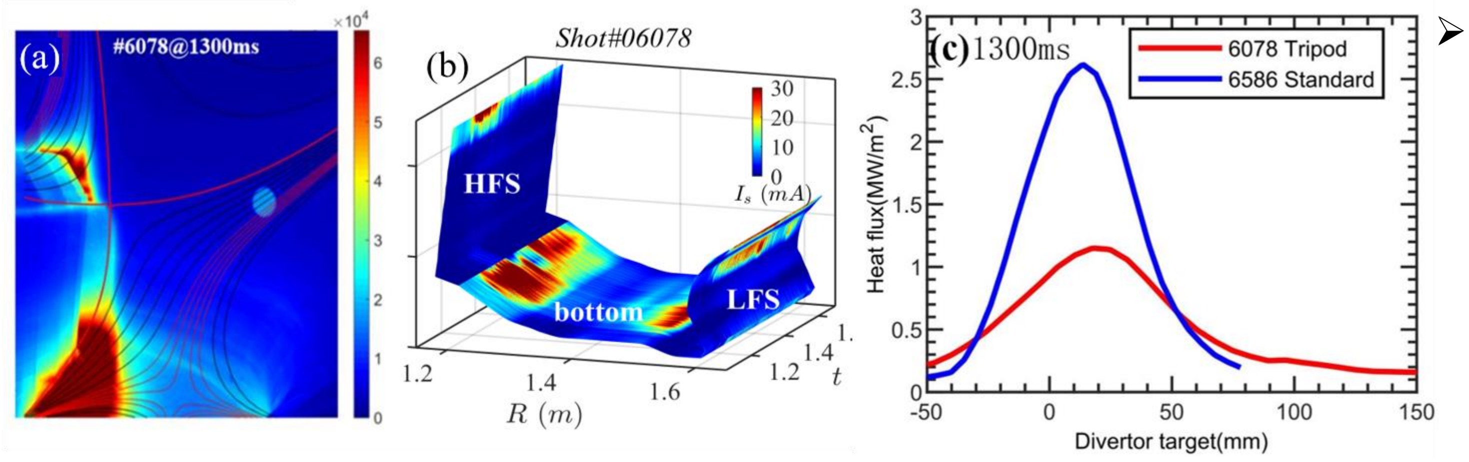


➢ **SOLPS-ITER for SF-(near tripod) simulation:**

✓ Enhanced impurity screening

✓ Small magnetic field-line incidence angle

✓ Large flux-surface expansion



➢ **Experimentally achieved:**

✓ Tripod (longer legs with larger distance between two X points

✓ > 4MW heating power

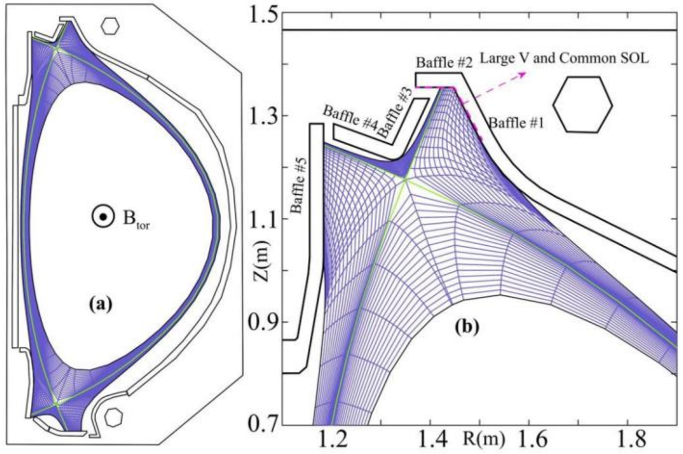
✓ H-mode operation

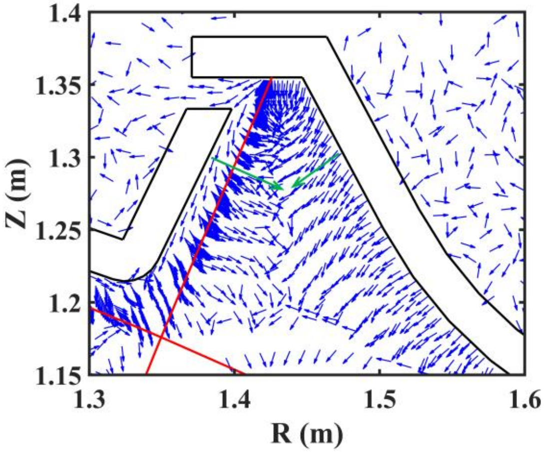
✓ < 40% of the heat flux peak

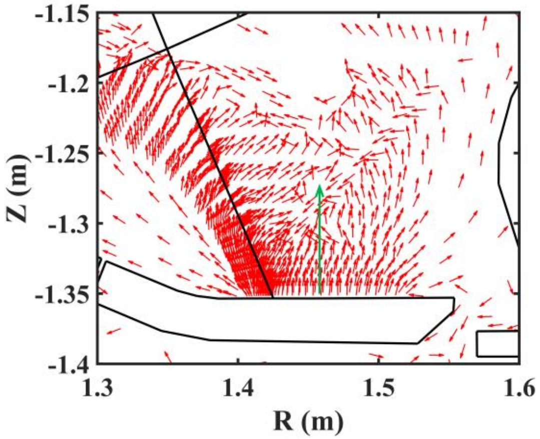
This conference, Poster 2 B-19, D.M. Fan

Design of an X-point Slot Closed (XSC) divertor

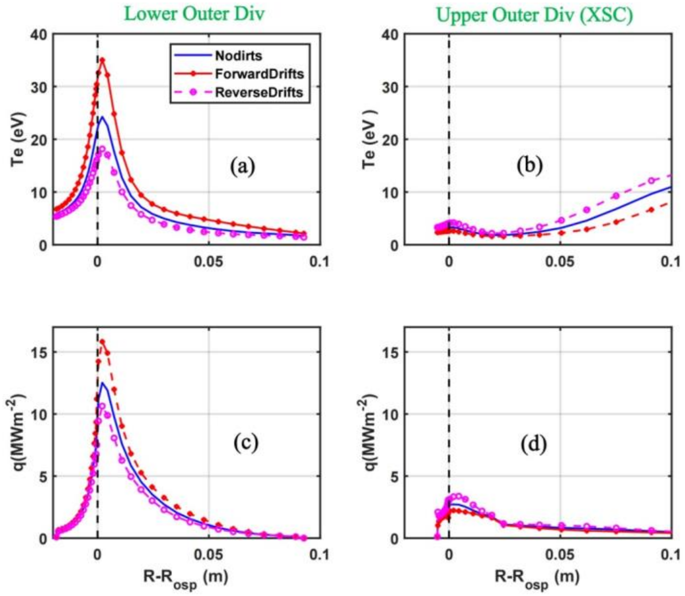
■ **The upper divertor of HL-3 has been designed and optimized based on the lower divertor results**







H.L. Du et al Nuclear Fusion 65(2025) 036023



- **Key features of XSC:**
  - ✓ Increase energy dissipation space
  - ✓ V-shaped + a slot : enhance closure
  - ✓ Suppress impurities entering the core
- XSC compatible with configurations like SF and negative triangular

Outline

- Introduction of HL-3 tokamak
- Improvement of heating, diagnostic & control
- High-performance plasma
- Power exhaust solution
- **Summary and future plan**

Summary and future plan

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- **Significant improvement on heating especially NBI, plasma control (VS, AI magnetic control) and diagnostics**
- **Significant progress on scenario development towards high-performance plasmas**
  - ✓ T_e > 12 keV; T_i > 10 keV; $n\tau T_i \sim 0.7\times10^{20}\ m^{-3}\cdot s\cdot keV$ achieved
  - ✓ High beta operation for MHD and disruption control
- **Effective effort for power exhaust solution**
  - ✓ Small/no ELM operation regime obtained (EDA, QCE, QH) and active control of ELMs
  - ✓ Fast prediction and control method developed as well as RT divertor feedback control
  - ✓ Advanced divertor (snowflake and tripod) configuration achieved
- **Upgrade to support key physics and technologies towards ITER and beyond**
  - ✓ Improve operation capacities to support next step research plan
  - ✓ Enhance understanding of frontier fusion plasma physics
  - ✓ Develop robust technologies for high-performance plasma control

SWIP Research Contributions to IAEA FEC 2025

中核集团 CNNC 核工业西南物理研究院 Southwestern Institute of Physics

ID	Presenter	Type	Time
3403	Wulyu Zhong	Overview Poster	2025/10/14 14:00
3258	Wulyu Zhong	Overview Oral	2025/10/14 17:25
2831	Wei Chen	Regular Poster	2025/10/15 10:35
3206	Neng Zhang	Regular Poster	2025/10/15 10:35
3131	Jie Huang	Regular Poster	2025/10/15 10:35
3291	Baolong Hao	Regular Poster	2025/10/15 14:00
3239	Lin Nie	Regular Poster	2025/10/15 14:00
3204	Ruyan Li	Regular Poster	2025/10/15 14:00
3160	Guangzhou Hao	Regular Poster	2025/10/15 14:00
2960	Ting Wu	Regular Poster	2025/10/15 14:00
3118	Dongmei Fan	Regular Poster	2025/10/15 14:00
3156	Qijie Wang	Regular Poster	2025/10/15 14:00
3231	Bo Hu	Regular Poster	2025/10/15 14:00
3032	Zhongbing Shi	Regular Poster	2025/10/16 8:30
3110	Shiqin Wang	Regular Poster	2025/10/16 8:30
3114	Min Jiang	Regular Poster	2025/10/16 8:30
3125	Liang Liu	Regular Poster	2025/10/16 8:30
3150	Miao Zhao	Regular Poster	2025/10/16 8:30
3109	Ruirui Ma	Regular Poster	2025/10/16 14:00
3139	Haotian Chen	Regular Poster	2025/10/16 14:00
3060	Liming Yu	Regular Poster	2025/10/16 14:00

ID	Presenter	Type	Time
3213	Guoliang Yuan	Regular Poster	2025/10/16 14:00
3119	Peiwan Shi	Regular Poster	2025/10/16 14:00
3098	Lingfeng Lu	Regular Poster	2025/10/16 14:00
3152	Xingyu Bai	Regular Poster	2025/10/16 14:00
3364	Juan Du	Regular Oral	2025/10/16 17:30
3058	Xiao Song	Regular Poster	2025/10/17 8:30
3105	Wenjin Chen	Regular Poster	2025/10/17 8:30
3201	Guoping Yang	Regular Poster	2025/10/17 8:30
3452	Juan Du	Regular Poster	2025/10/17 8:30
3366	Yaxia Wei	Regular Poster	2025/10/17 8:30
3117	Guoliang Xiao	Regular Oral	2025/10/17 12:20
2969	Qinghao Yan	Regular Poster	2025/10/17 14:00
3221	Jiquan Li	Regular Poster	2025/10/17 14:00
3473	Guoliang Xiao	Regular Poster	2025/10/17 14:00
3138	Guanqun Xue	Regular Poster	2025/10/17 14:00
3199	Ting Long	Regular Poster	2025/10/17 14:00
3286	Tengfei Sun	Regular Poster	2025/10/17 14:00
3212	Yiming Wang	Regular Poster	2025/10/18 8:30
3194	Jiming Chen	Regular Poster	2025/10/18 8:30
3203	Jun Wang	Regular Poster	2025/10/18 8:30

Thank you for your attention！

Joint experiments and other collaborations are welcome!