Development of Steady-state Operation Scenarios with Full Tungsten Limiter/Divertor in ITER-Relevant Configuration on EAST

EX/3-4

by

J. Huang[1*]

with **X. Gong[1], A. Loarte[2] , R.A. Pitts[2] , T. Wauters[2], J. Qian[1], R. Ding[1], G. Zuo[1], Y. Sun[1], L. Zeng[3], Z. Wang[3], A. Ekedahl[4], M. Jia[1], X. Zhang[1], B. Zhang[1], W. Liu[1], L. Xu[1], M. Li[1], C. Pan[1], Z. Zhang[1], T. Jia[1], X. Jian[1], Y. Hu[1], P. Li[1], Y. Wang[1], L. Zhang[1], Y. Guan[1], B. Wan[1] and EAST team[1]**

[1]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*
[2]*ITER Organization, CS 90 046, 13067, St. Paul Lez Durance Cedex, France*
[3]*Department of Engineering Physics, Tsinghua University, Beijing, China*
[4]*CEA, IRFM, F-13108 Saint Paul-lez-Durance, France*

Presented at the
30th IAEA Fusion Energy Conference

Chengdu, China Oct 13-18 2024

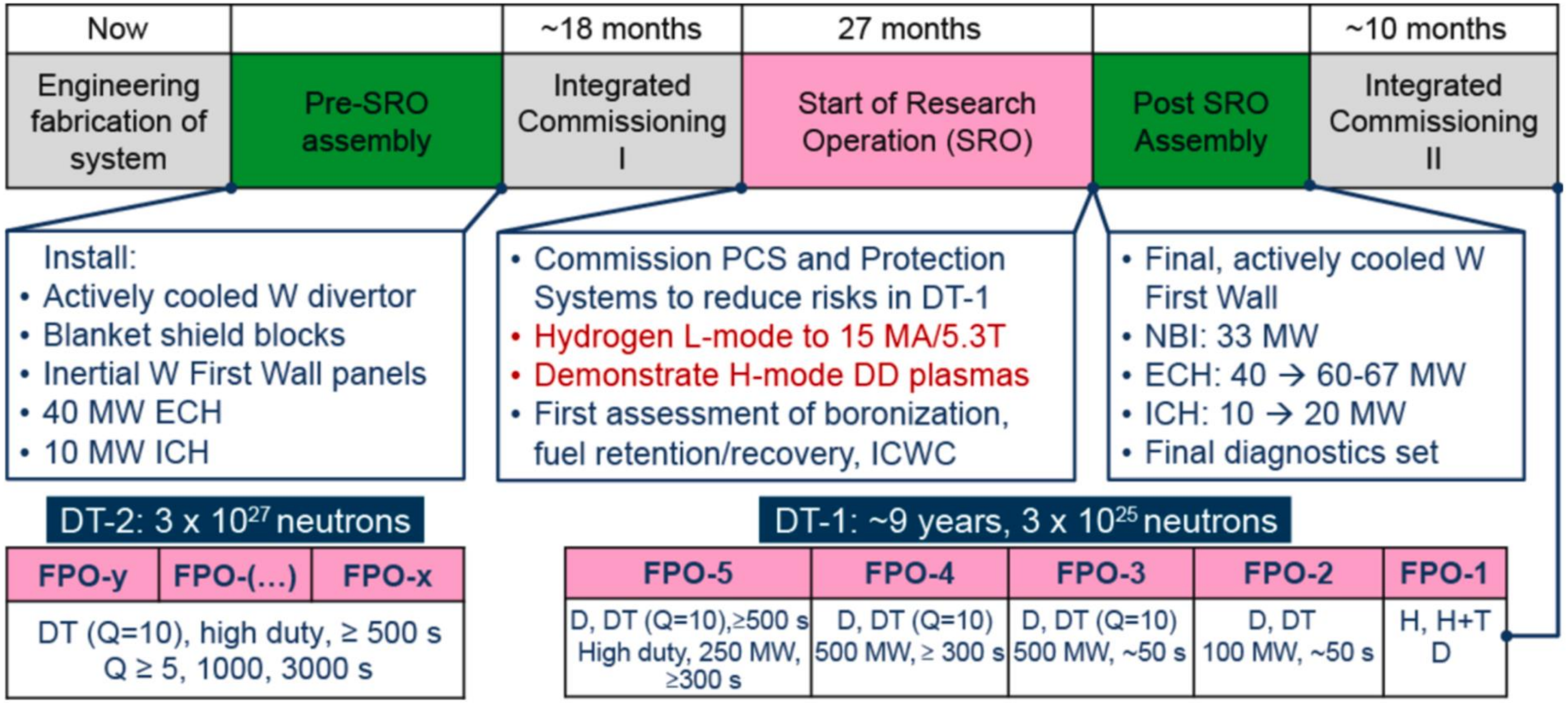
*E-mail: juan.huang@ipp.ac.cn

Outline

- Introduction
- ITER-EAST joint experiments
- High-β_P scenario development on full metal wall
- Summary

New ITER Baseline Brings New Challenges Requiring More R&D and Support from Current Experiments

"ITER New Baseline Phases and Research Plan"



A. Loarte, PPCF 2025
R. Pitts, NME 2025

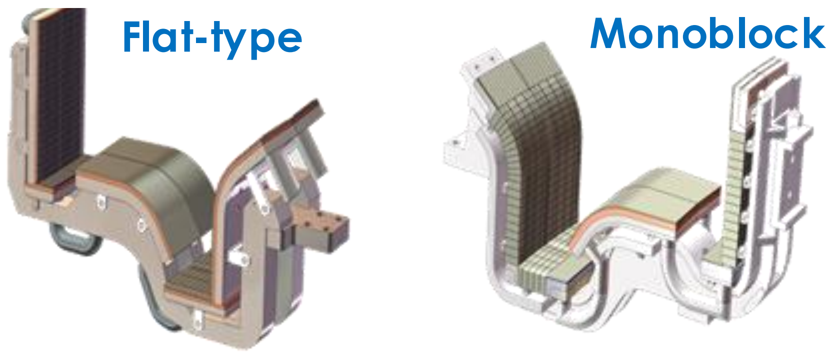
- **Key element of the new baseline: First Wall Material Beryllium → Tungsten**
- **Open issues with impact of W wall on ITER Q ≥ 10 operation and Q ≥ 5 long-pulse SSO**
- **Experimental basis for W wall operation in ITER: Boronization, W-limiter operation, Impact of W wall on H-mode**

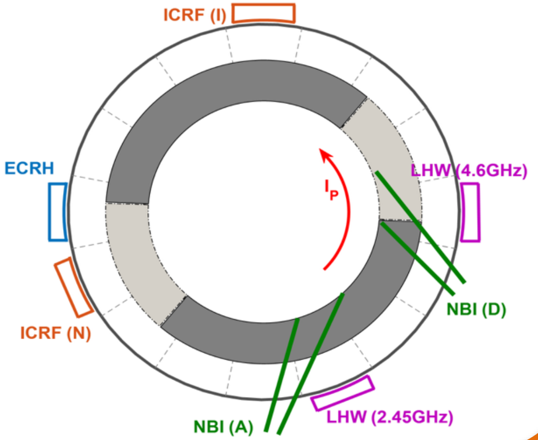
Dedicated EAST/ITER Joint Experiments in Support of ITER NRP

- **EAST experiments with full W-limiter and W-divertors**
  - Boronization studies **(T. Wauters)**
  - W Limiter start-up experiments **(R.A. Pitts)**
  - H-mode operation with W wall **(A. Loarte)**

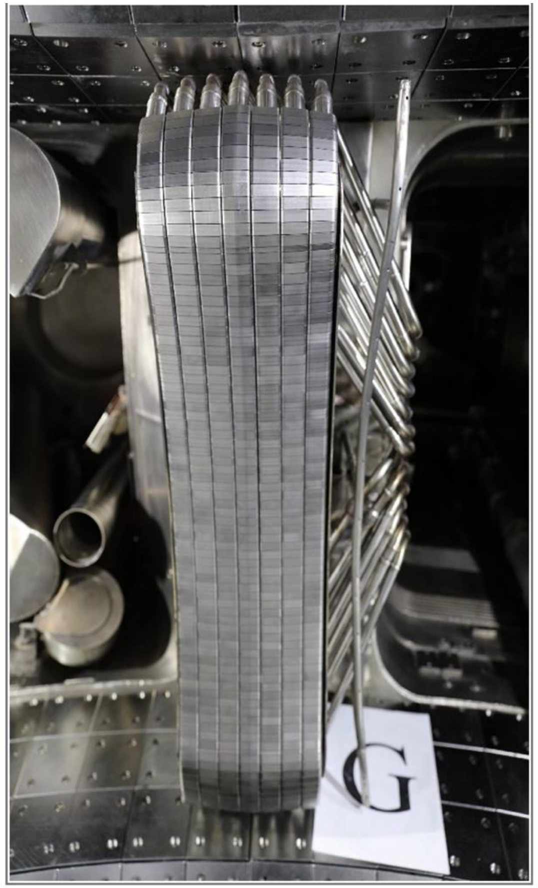
New Tungsten Lower Divertor

After 2021



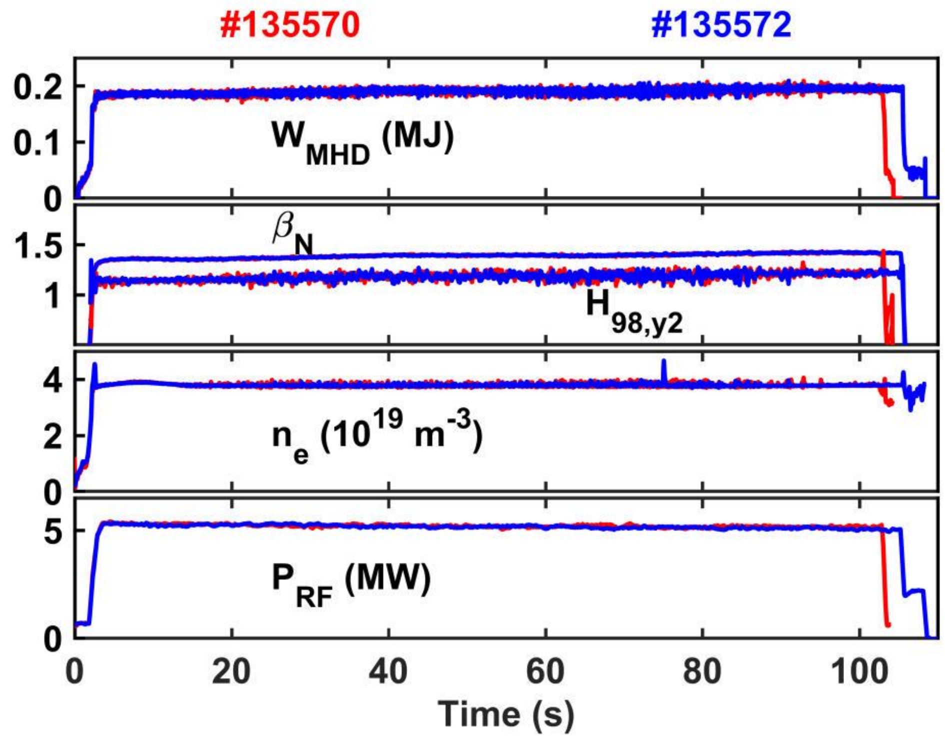


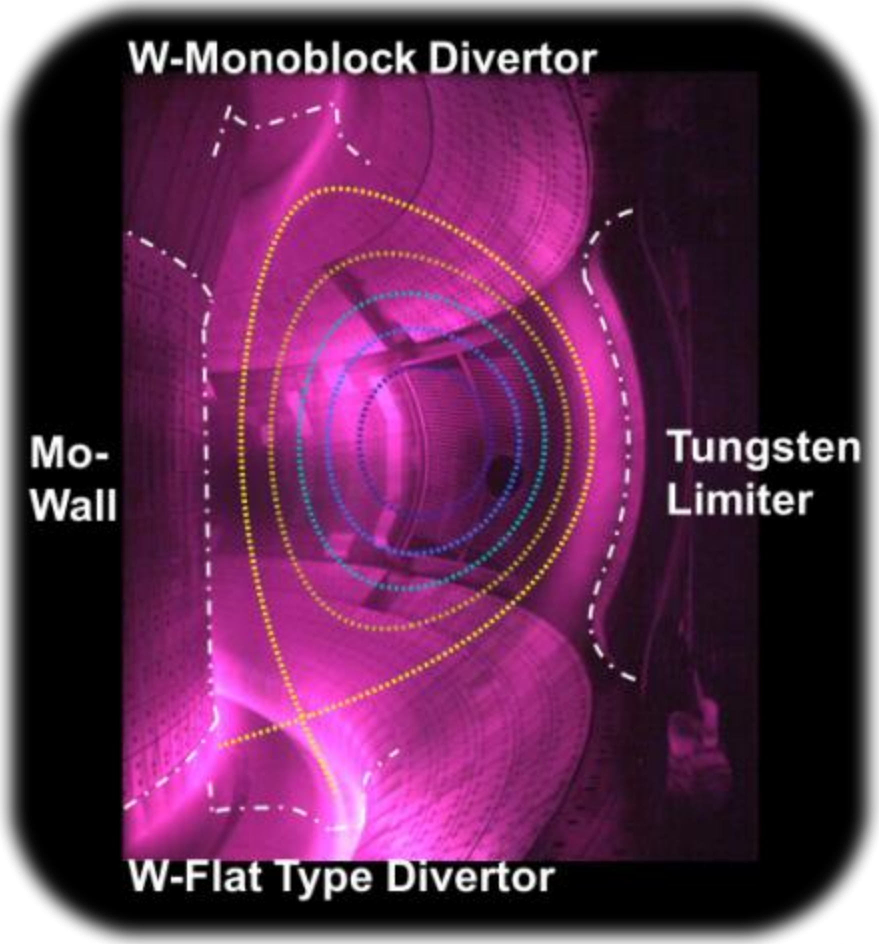
W-Limiter on EAST



Demonstrate Long Pulse H-mode Plasmas on Full Metal Wall

- **Stationary ~100s H-mode plasmas achieved with Boronization**
  - **q_{95}~6.0, n_e/n_{Gr}~0.6, H_{98y2}~1.1**, P_{EC}~ 3.0MW, P_{LH}~2.2MW
- **Optimization of the H&CD coupling**
  - Separatrix W-limiter gap~6cm and using gas puffing
- **Well controlled high Z impurity**
  - Type II ELMs and high density reduced W-sputtering
  - Avoid impurity accumulation by on-axis ECH





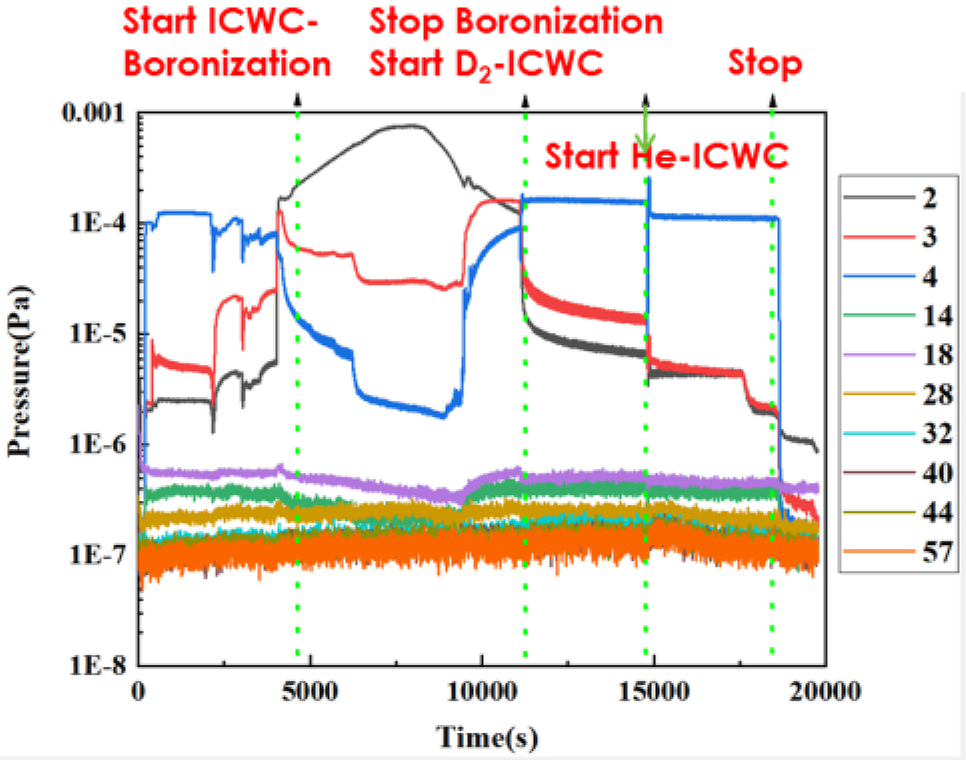
ASIPP

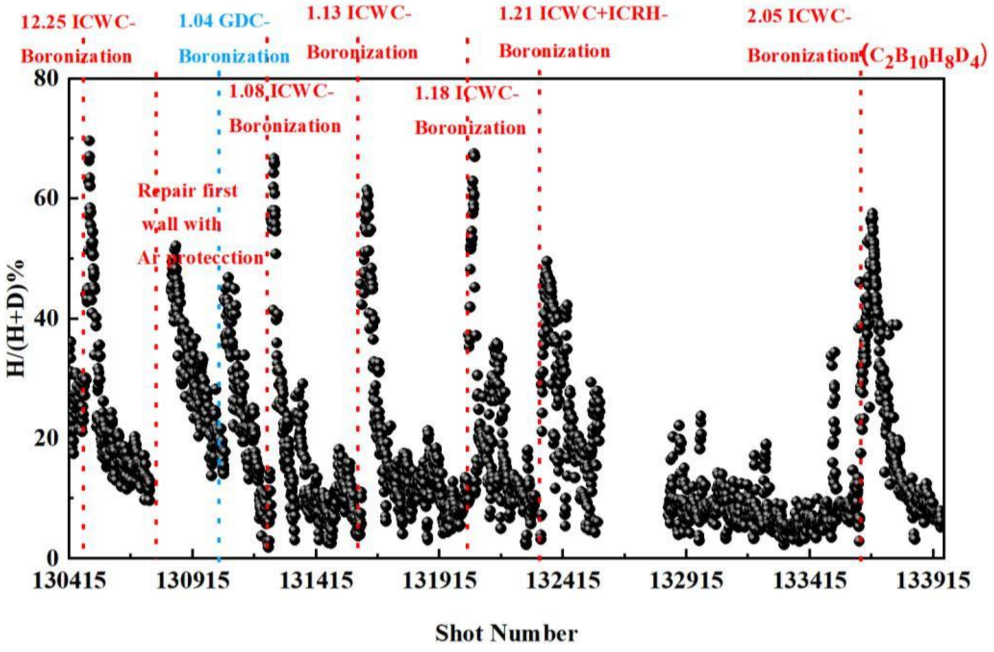
Outline

- Introduction
- ITER-EAST joint experiments
  - Boronization studies
  - Start-up experiments with ECH and W limiter
  - H-mode operation with W wall
- High-β_P scenario development on full metal wall
- Summary

Boronization Technology Developed with Full Metal Wall

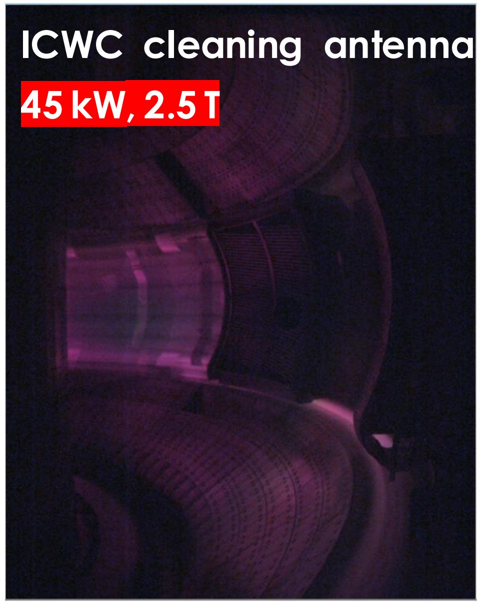
- **$C_2B_{10}H_{12}$ was used for boronization**
  - $C_2B_{10}H_{12}$ evaporated at 80~100°C, coating assisted with D/He ICWC/GDC
- **D/He cleaning was continued for 30-120 min to remove co-deposited H in boron film**

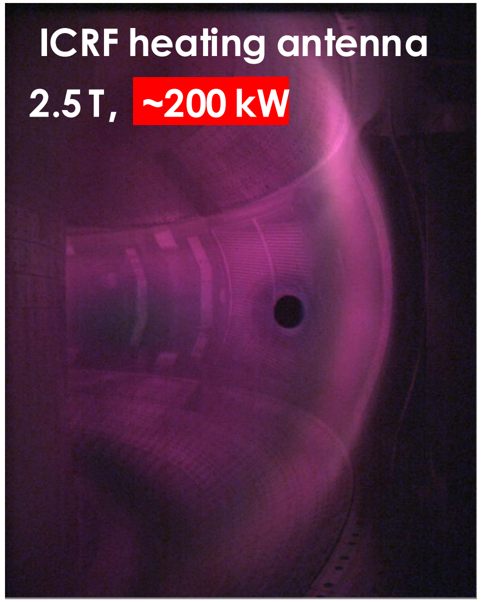


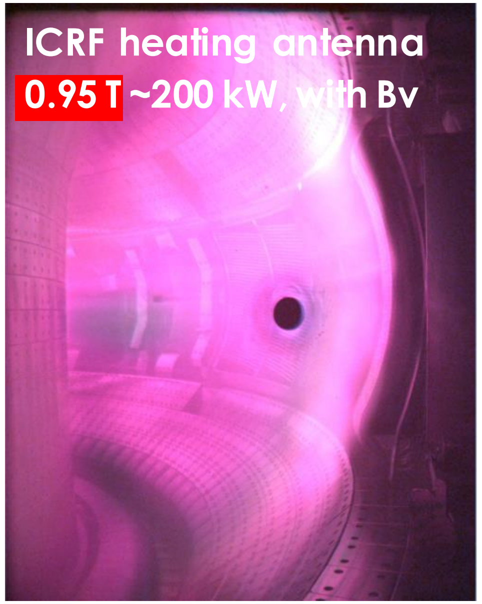


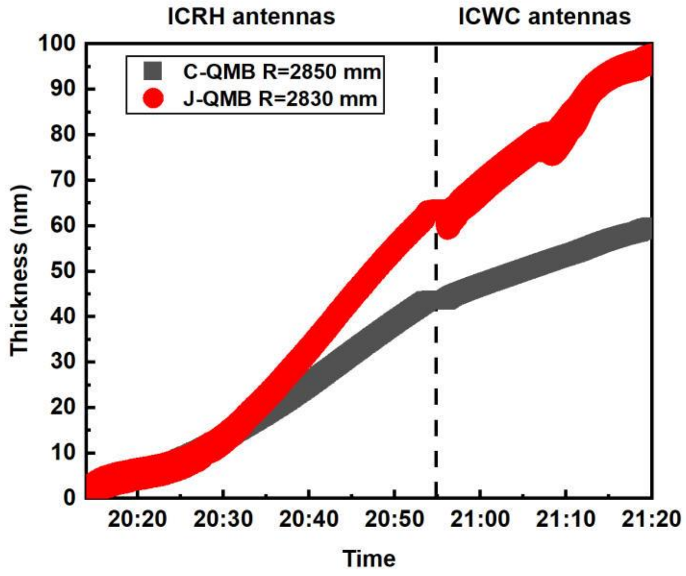
G. Zuo, 2nd IAEA TM LPO, 2024
Y. Guan, NF 2025

Improved Plasma Uniformity and Boron Deposition Rate Obtained by ICRF Heating Antenna









- **ICRF heating antenna for He/D_2 wall-conditioning was performed for the first time**
  - Discharge became brighter and uniform with ICRF heating antenna than ICWC antenna, especially with vertical filed B_V
  - Boronization with ICRF heating antenna had higher boron deposited rate

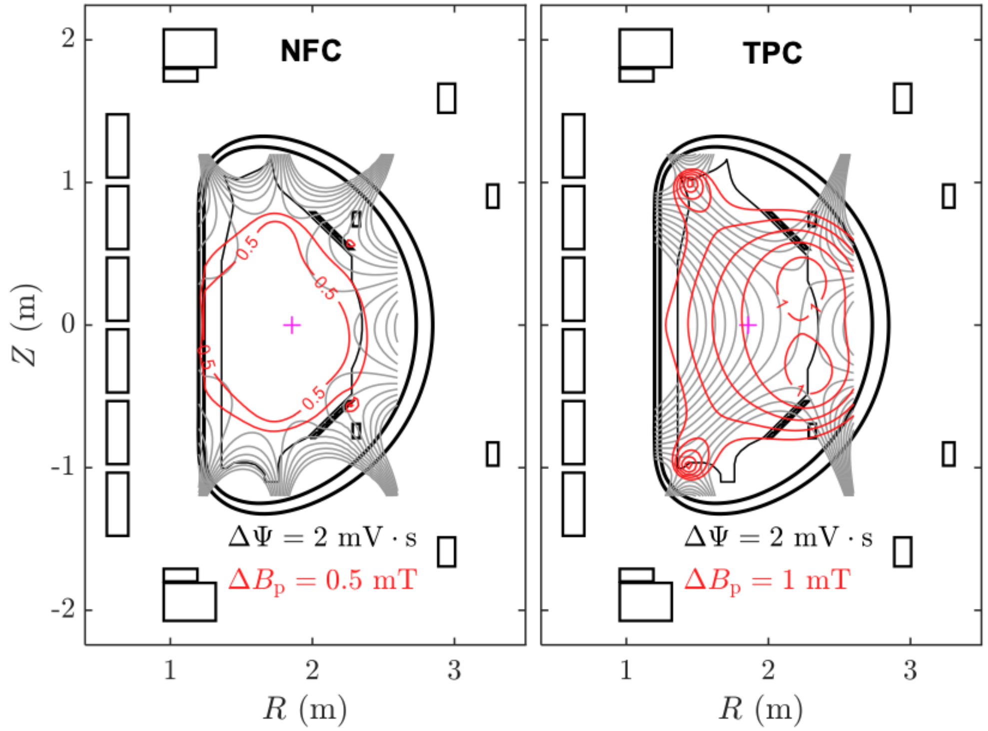
Outline

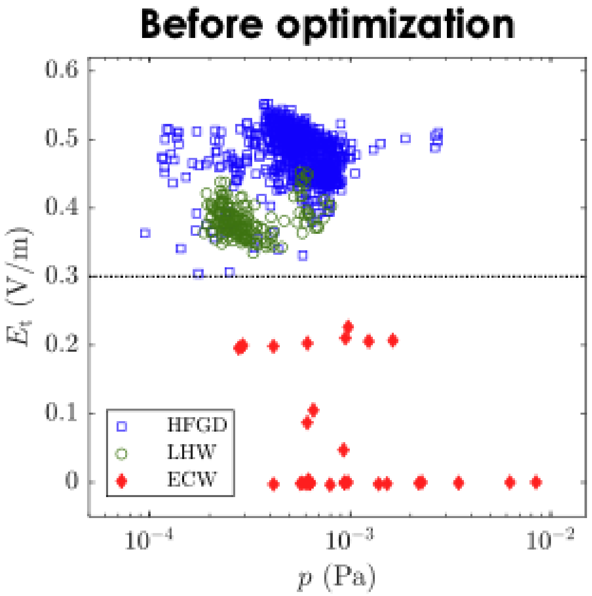
- **Introduction**
- **ITER-EAST joint experiments**
  - Boronization studies
  - Start-up experiments with ECH and W limiter
  - H-mode operation with W wall
- **High-β_P scenario development on full metal wall**
- **Summary**

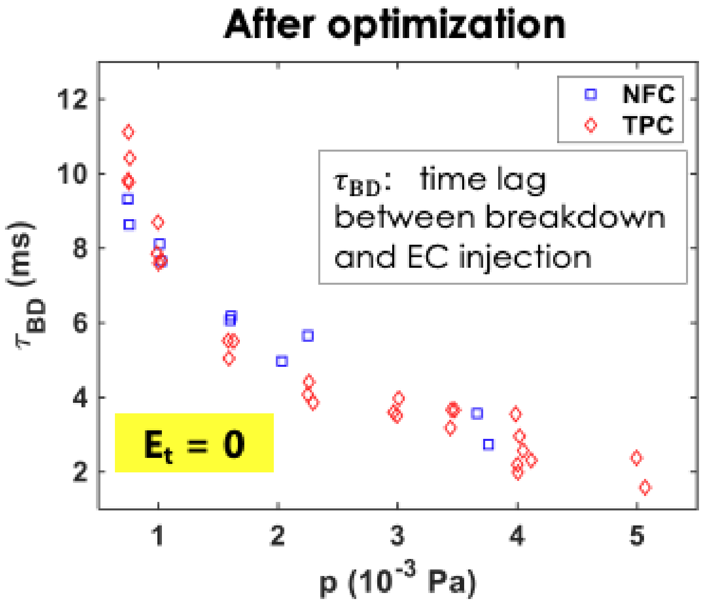
ASIPP

Robust Breakdown and Current Build-up with ECW Assistance

- **Non-inductive breakdown ($E_t = 0$) with optimized NFC and TPC**
  - Wide null field configuration (NFC): stray field < 5 Gs
  - Trapped particle configuration (TPC): mirror-like vertical field (10 – 50 Gs)



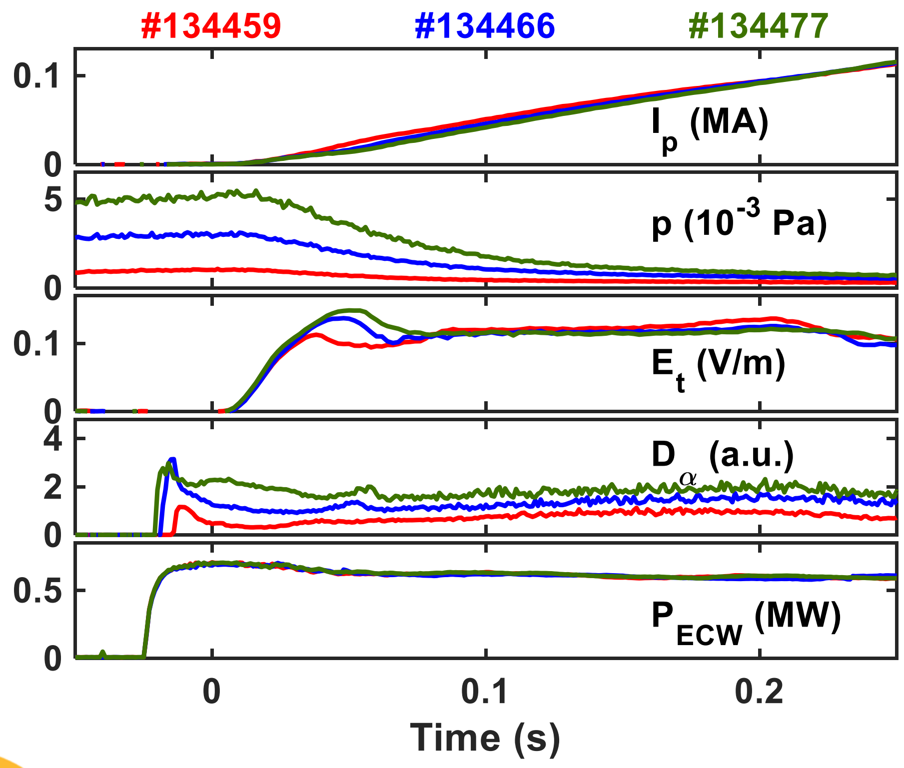


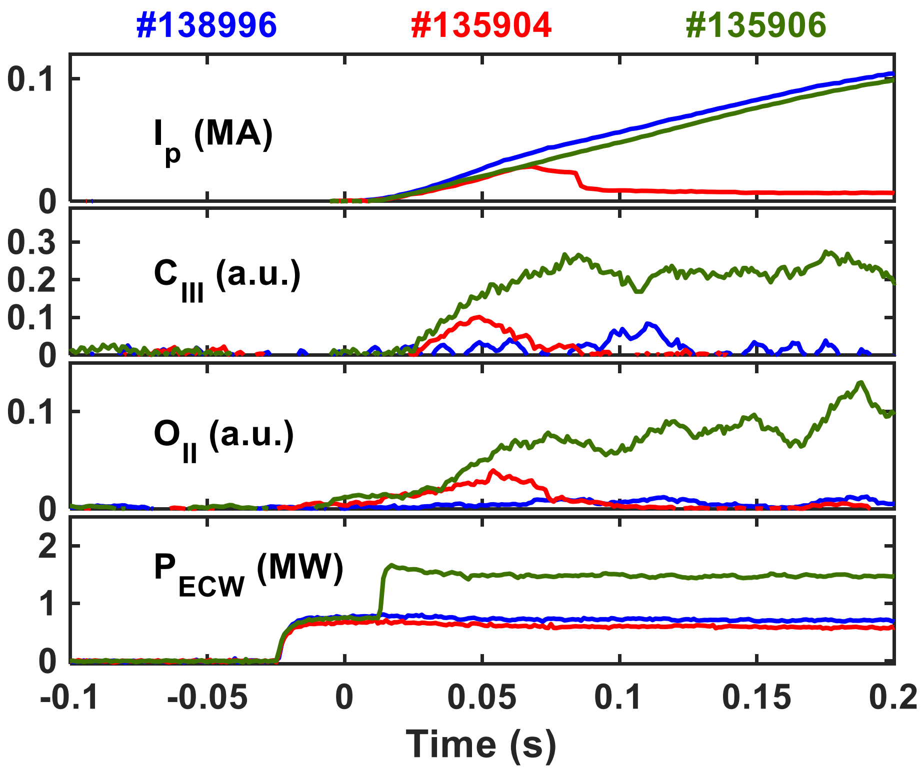


R. Chen, NF 2024

Robust Breakdown and Current Build-up with ECW Assistance

- **Non-inductive breakdown ($E_t = 0$) with optimized NFC and TPC**
- **Significantly reduced E_t (< 0.15 V/m) for initial current build-up with ECW assistance**
  - Robust current ramp-up in a large range of prefill gas pressure (P_{VV}~7.5e-4 Pa-5.1e-3 Pa)
  - Not obstructed by burn-through, tolerance to high impurity level

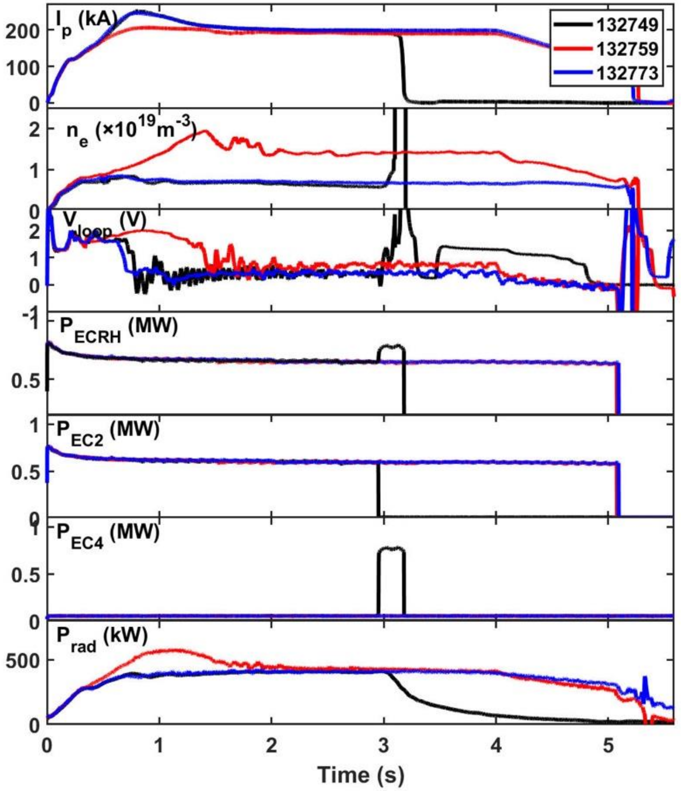


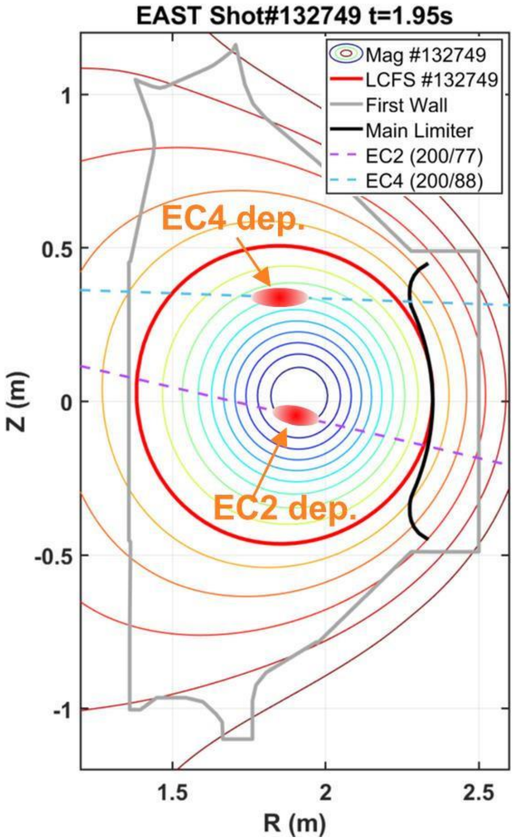


W. Liu, NF 2024

Central ECH Required for Successful Startup on W-Limiter

132773, low f_{GW} ~0.15
132759, high f_{GW} ~0.35
132749, off-axis ECH





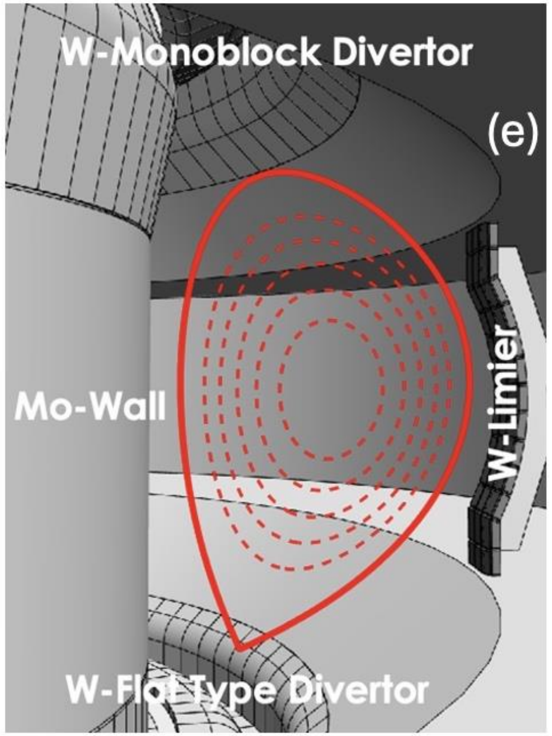
R. Pitts, NME 2025

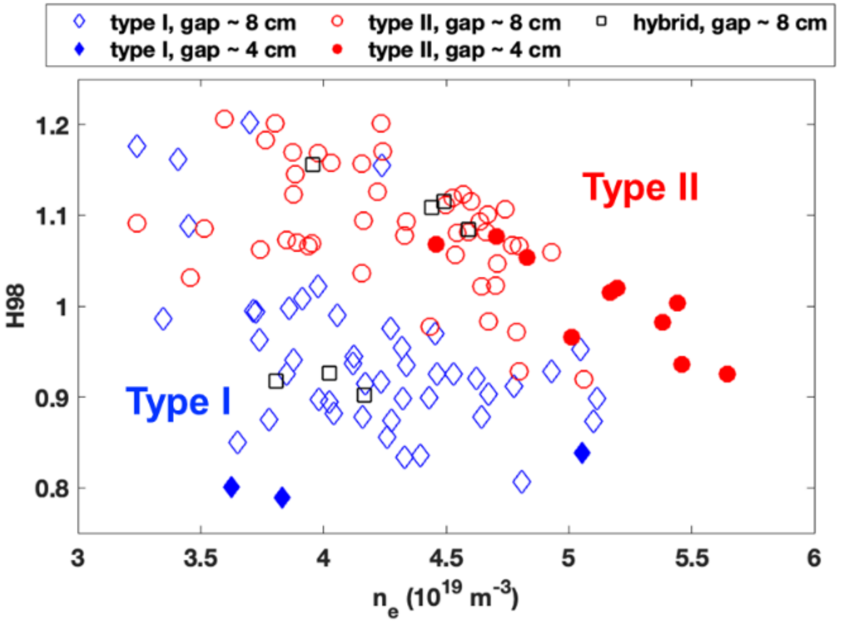
- **On-axis ECH required to avoid radiative collapse by W**
- **Reliable I_p flattop using two EC sources with a range of plasma density**
- **W-limiter start-up experiments required for code validation aiming at ITER limiter phase**

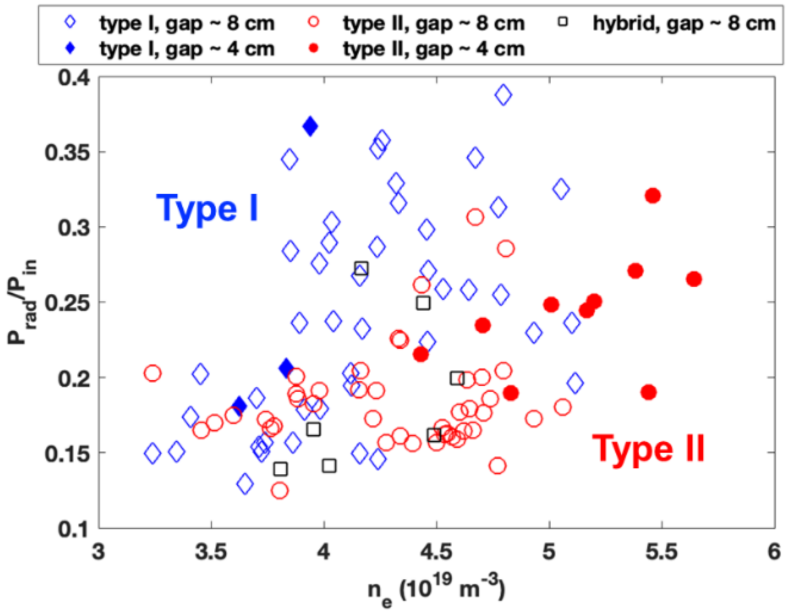
Outline

- **Introduction**
- **ITER-EAST joint experiments**
  - Boronization studies
  - Start-up experiments with ECH and W limiter
  - H-mode operation with W wall
- **High-β_P scenario development on full metal wall**
- **Summary**

Impact of W as First Wall Material on H-mode Performance



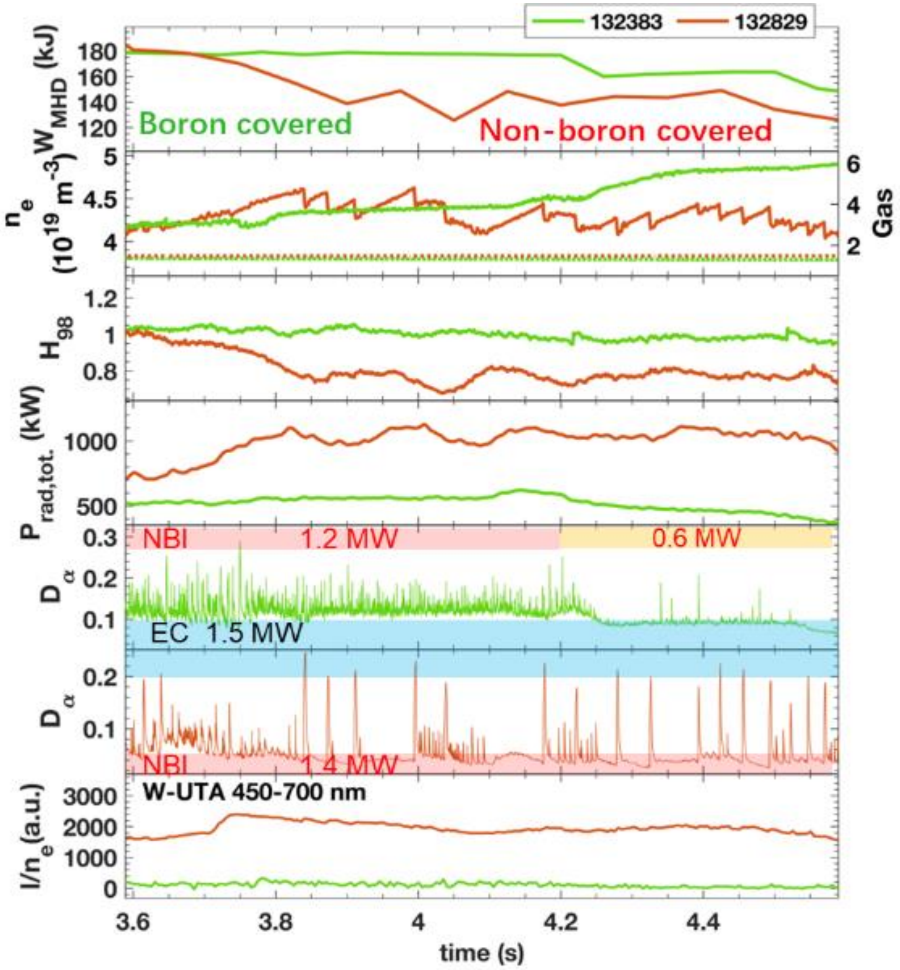




- Assessed for low/no B-film coverage at q_{95} ~ 6 DN plasmas with B_t ~ 2.45 T (central ECH)
- Type II ELMs attribute lower PWI and provide higher confinement, less sensitive to the separatrix-limiter gap and lower radiation fraction than Type I ELMs

A. Loarte, PPCF 2025

Impact of B-film Wall Coverage on H-mode Performance

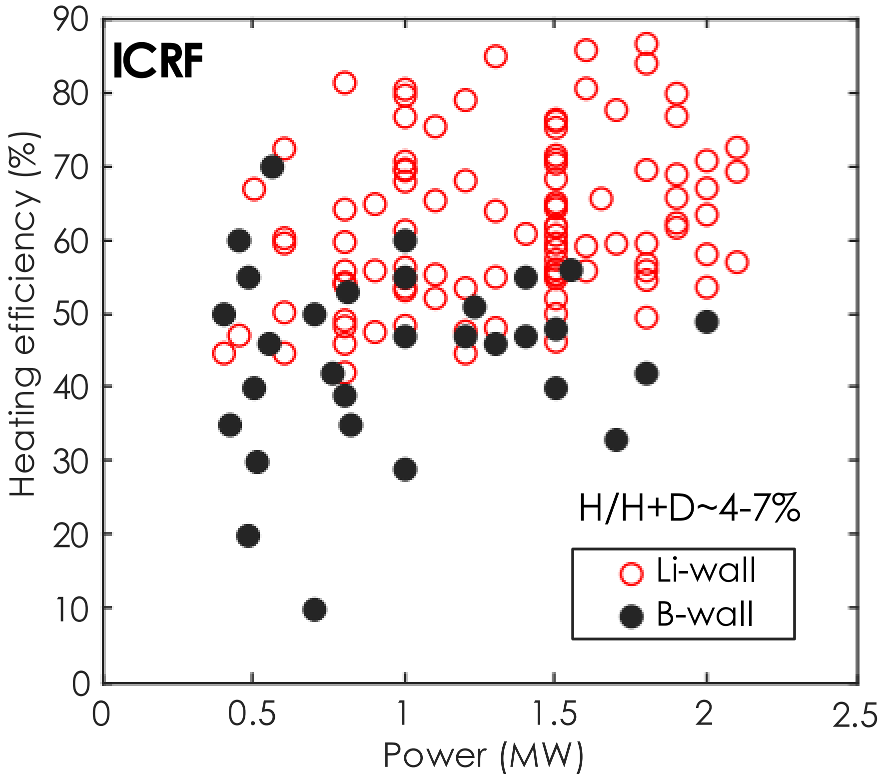


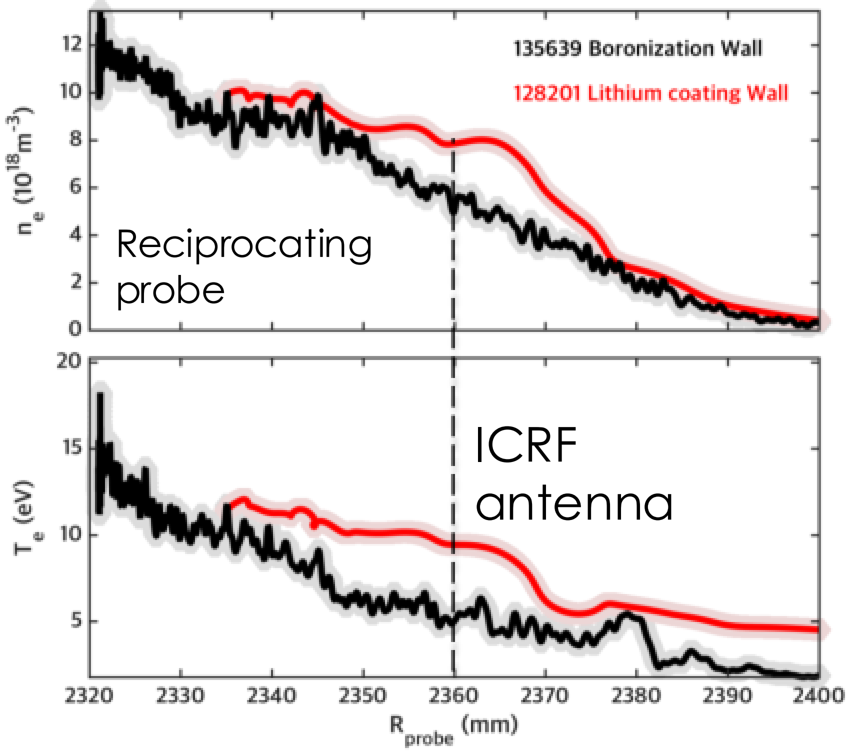
- **B coverage significantly reduced the W density in core**
- **Achieve good confinement type II ELMs with lower P_{EC}~1.5MW, instead of low confinement type I ELMs with non-boron**

A. Loarte, PPCF 2025

ASIPP

Impact of Wall Conditioning on H&CD Efficiency



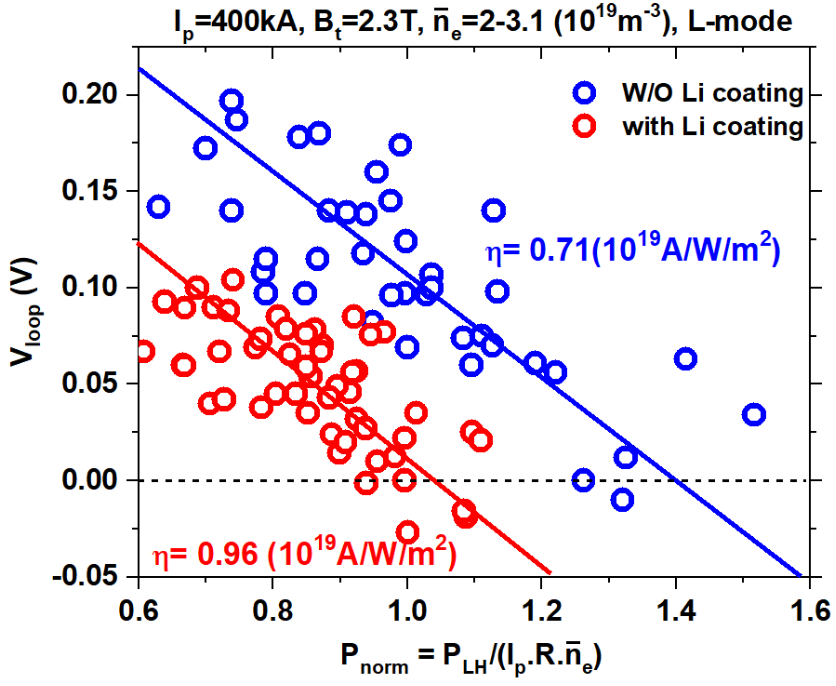


- **The reduced ICRF heating efficiency with Boron-coating compared with Li-coating**
- **Edge profiles changed with different wall conditionings affect RF power coupling**

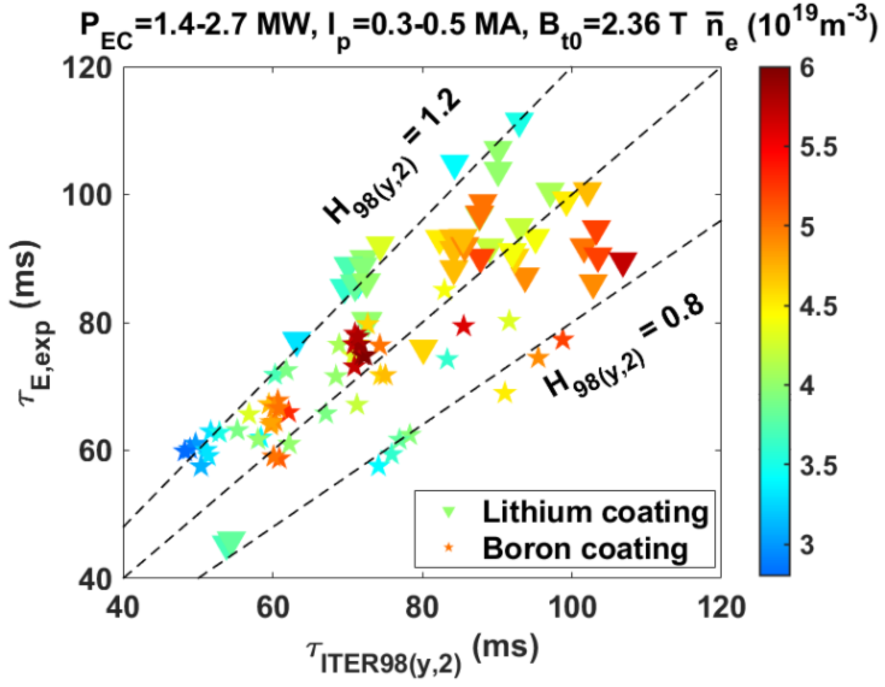
ASIPP

Impact of Wall Conditioning on H&CD Efficiency

LHCD efficiency



Confinement with ECRH



- **LHCD efficiency increased by a factor of 1.35 with li-coating than non-coating**
  – Higher T_e in SOL with li-coating can reduce PDI behavior and collisional power loss
- **ECRH plasma shows similar normalized confinement quality**

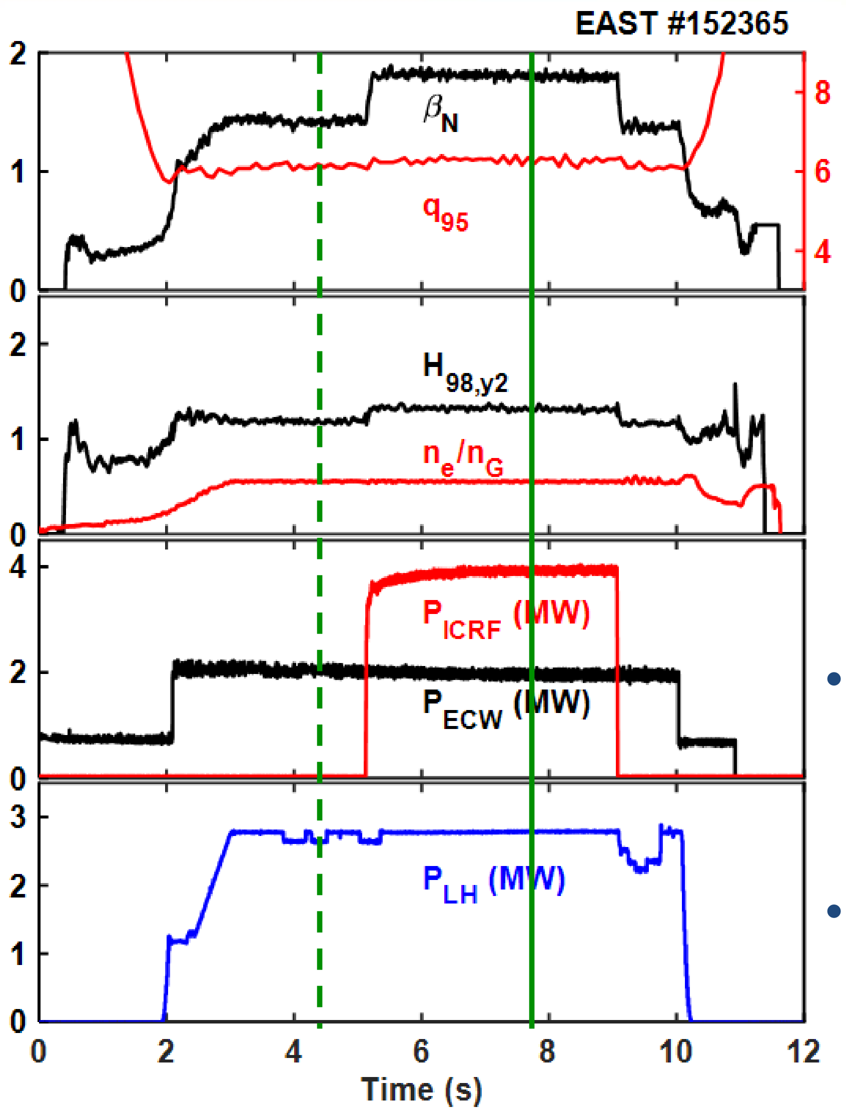
M. Li, NF 2025

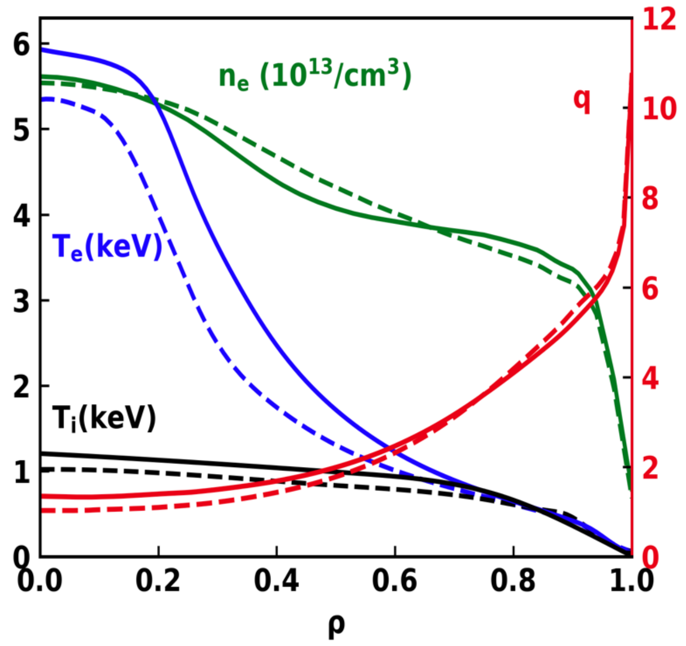
ASIPP

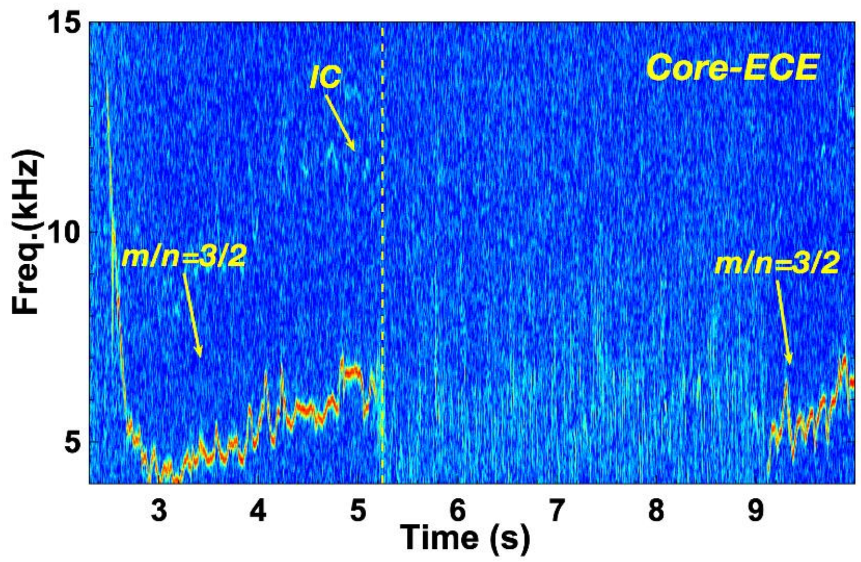
Outline

- ❑ Introduction
- ❑ ITER-EAST joint experiments
- ❑ High-β_P scenario development on full metal wall
- ❑ Summary

Development of Fully Non-inductive High-β_P Scenario by RF H&CD with Boronization



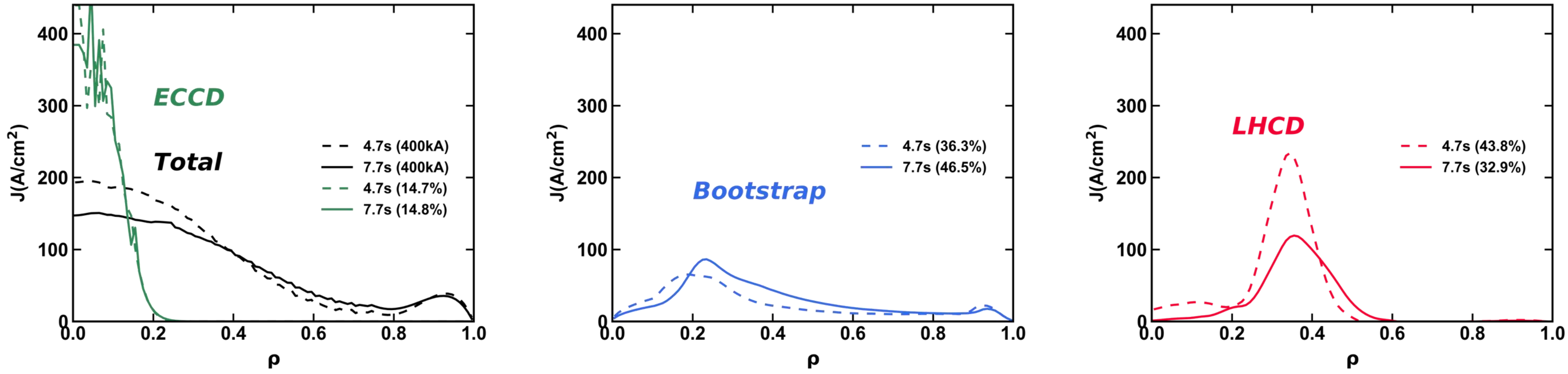




- **Improved performance during IC heating at high B_t~2.5T**
  - V_{loop}~0, P_{LHW}~2.7MW, P_{EC}~2.0MW, **P_{IC}~4.0MW**
  - **n_{Gr}~0.65, β_P~2.1, β_N~1.85, H_{98y2} ~1.35, q_{95}~6.0**
- **Core current density profile kept flat with on-axis q above unity**
  - Improved confinement with broader current density profile with ICRF , accompanied with outer moved T_e-ITB
  - 3/2 tearing mode at rho~0.3 suppressed with ICRF

ASIPP

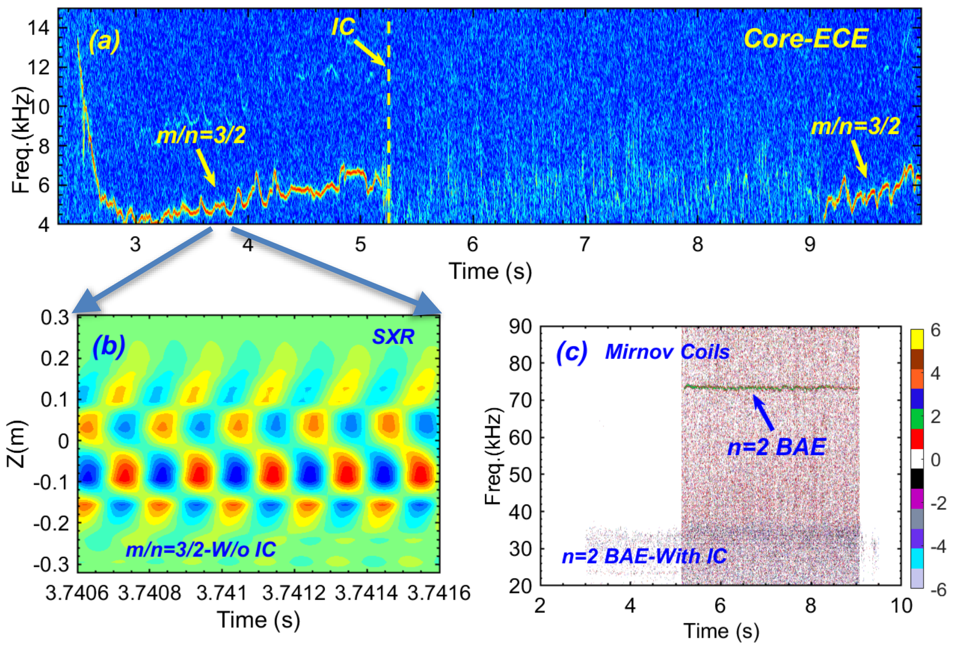
Improved Performance Attributed to Flat and Broader Current Profile

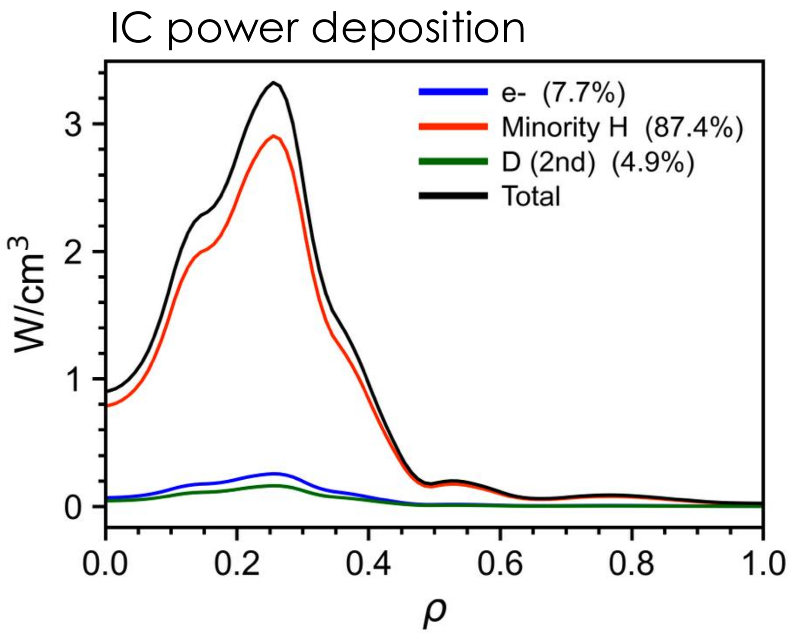


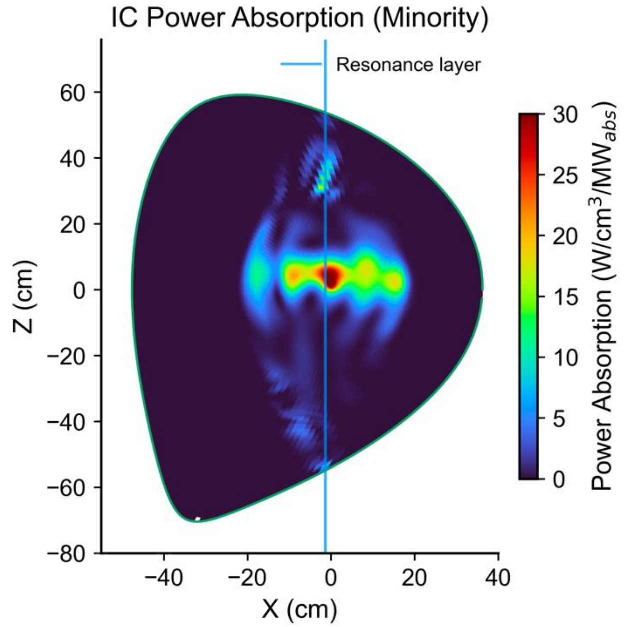
- **Fully non-inductive plasma with core flat current density profile with on-axis q above unity**
  - Strong on-axis ECCD applied
  - Possible current re-distribution occurring inside m/n=3/2 surface at rho~0.3
  - Weaken the magnetic shear in the core, help to improve core performance
- **Broadening of current density profile with ICRF**
  - Bootstrap current density increased due to effective ICRF heating
  - EC current driven profile kept almost unchanged
  - Reduction of LHCD possibly due to increased Z_{eff} and radial transport of fast electrons during ICRF

ASIPP

Features of Core MHD Instabilities



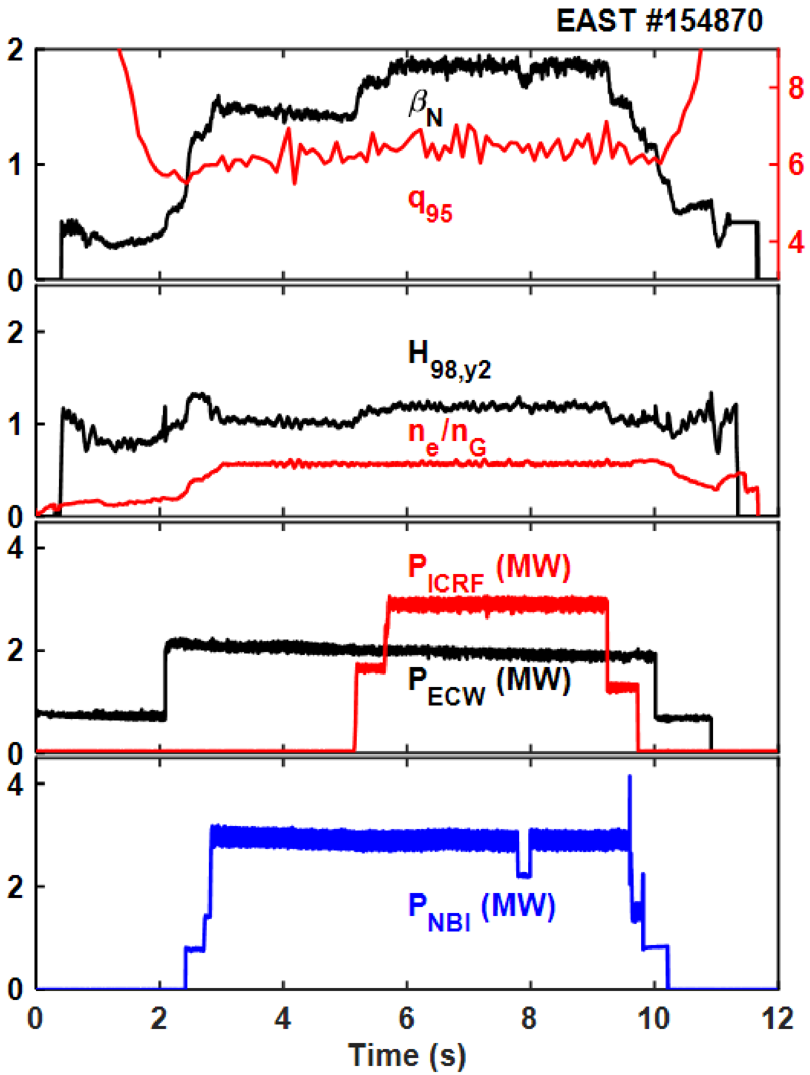


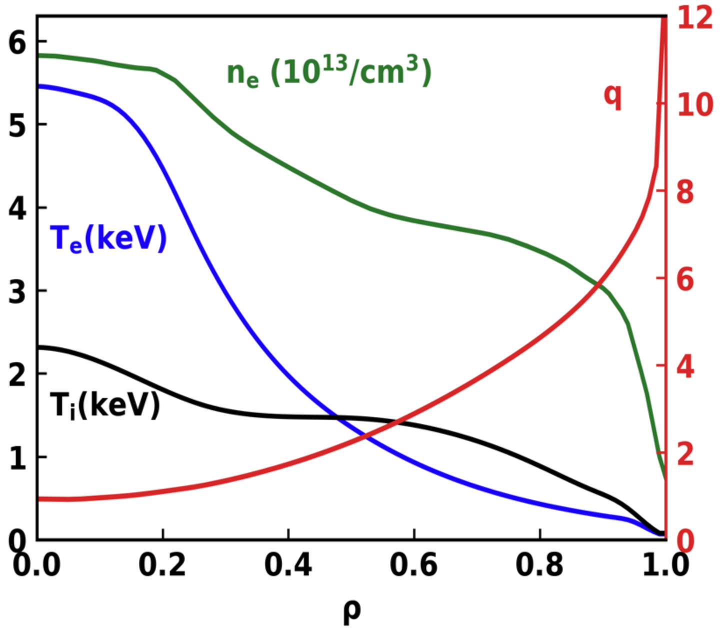


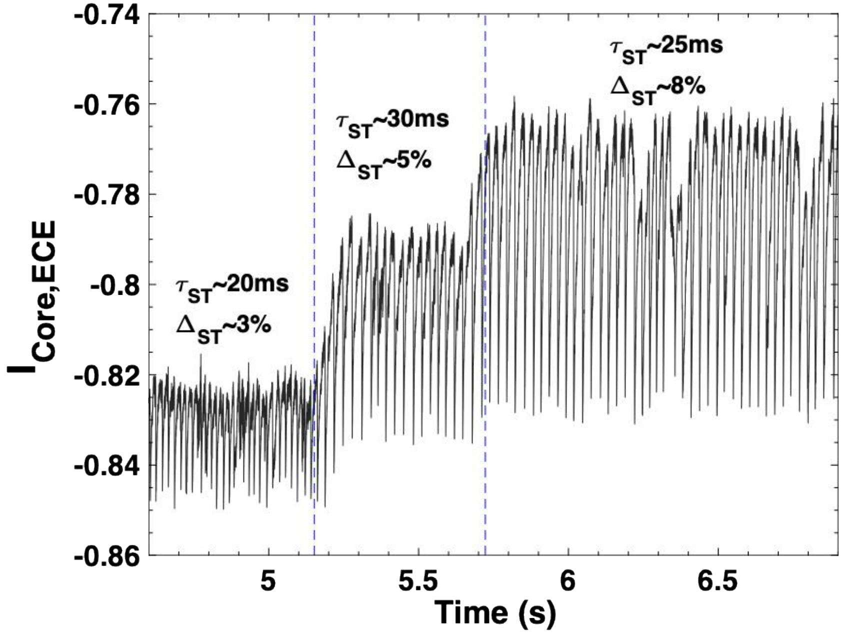
- **m/n=3/2 tearing mode stabilized with ICRF**
  - Central ICRF minority heating scheme
  - Improved core MHD stability due to current density redistribution by effective electron heating

- **n=2 BAE triggered during ICRF**
  - Localized at rho~0.2
  - Enhanced fast-ion pressure in minority heating scheme

Development of High-β_P Scenario with ITER-like Heating Scheme





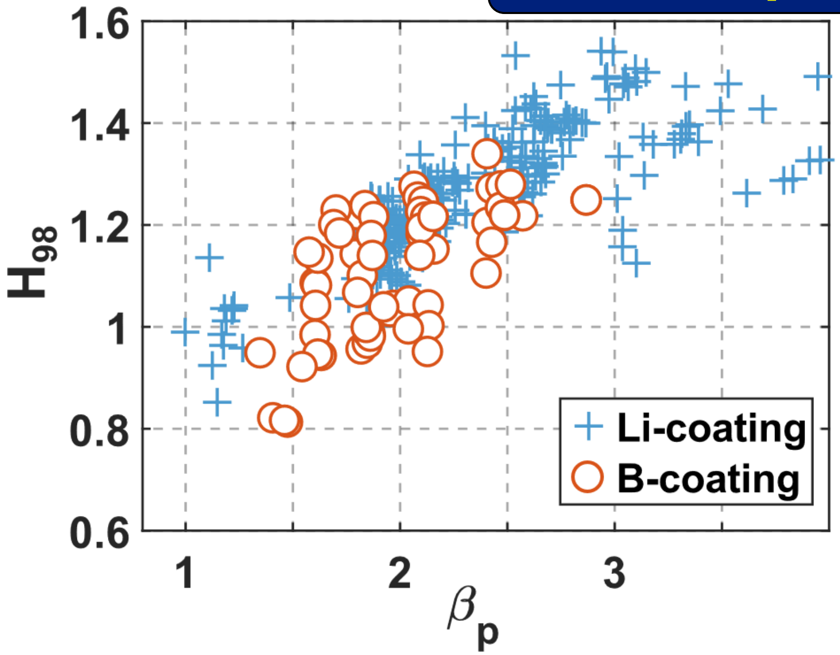


- **High-β_P plasmas with ITER-like heating scheme w/o LHCD at high B_t~2.5T**
  - **P_{NBI}~3.0MW, P_{EC}~2.0MW, P_{IC}~3.0MW**
  - n_{Gr}~0.65, β_P~2.1, β_N~1.85, H_{98y2} ~1.21, q_{95}~6
  - Higher T_i increased by 2, f_{NI}~65% with f_{bs}~38%, f_{EC}~13%, f_{NB}~14%
- **Sawtooth instability with peaked current profile and on-axis q below 1**
  - The ST period increased during ICRF
  - The ST crash amplitude enhanced with ICRF on-axis heating

ASIPP

Challenges for Development of High-β_P Plasma with Boronization

Joint Experiments & Actives for ITPA IOS-3.2



- **Impact of wall conditions on energy confinement**
  - Energy confinement with B-coating is reduced by ~10-15%, compared with Li-coating

- **Next step with enhanced capabilities on EAST towards more ITER-relevant configuration**

→ Explore high-β_P scenario at moderate q_{95} towards high-Q SSO

- Optimize Boronization with ICRF and new B-materials B_2D_6
- Broaden j(r) and active control to improve confinement
- Adjust T_i/T_e by effective ion heating to extend fusion performance
- Account for ITER heating and current mix, etc.

ASIPP

Outline

- Introduction
- ITER-EAST joint experiments
- High-β_P scenario development on full metal wall
- Summary

Summary

- **Dedicated joint ITER-EAST experiments have been performed in support of the ITER NRP.**
  - Long pulse **100s H-mode** were achieved **with Boronization on full metal wall**.
  - The impact of W limiter, heating schemes, boronizaiton on H-mode performance have been evaluated in EAST.
  - High β_P scenario has been developed in boron wall at **q_{95} ~ 6.0**, a range attractive for ITER steady-state operation, with high energy confinement quality **H_{98y2} ~ 1.35, β_N ~ 1.85 at B_t~2.5T**, by dominant electron heating.

- **Future plan with upgrade of inner components and augmented H&CD capabilities**
  - Develop SSO scenario with ITER shaping (LSN) at moderate q_{95} ~5-6 in low aspect ratio
  - Develop SSO scenario in ITER-like heating scheme by enhancing H&CD capabilities
  - Extend plasma performance and improve confinement by broaden j(r) with q_{min}>2 aiming at NCS or weak shear to form ITB in all channels

  → **Demonstrate SSO with extended fusion performance at P_{in} ~ 15-20 MW**

Thank You For Your Attention
Your Suggestions and Comments Will Be Appreciated

ASIPP