Recent Experimental Results on EAST in Support of ITER and CFETR

by

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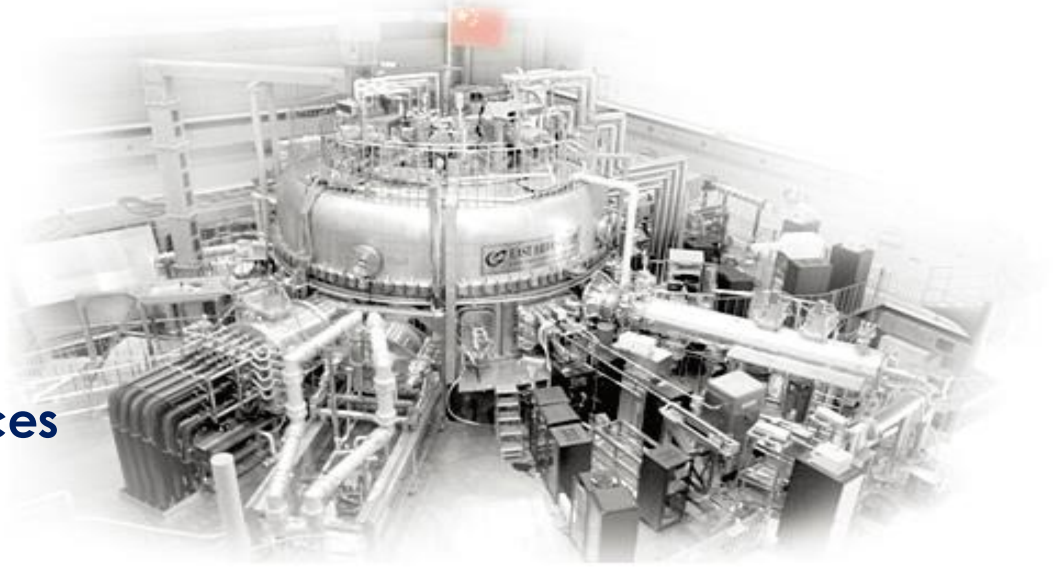

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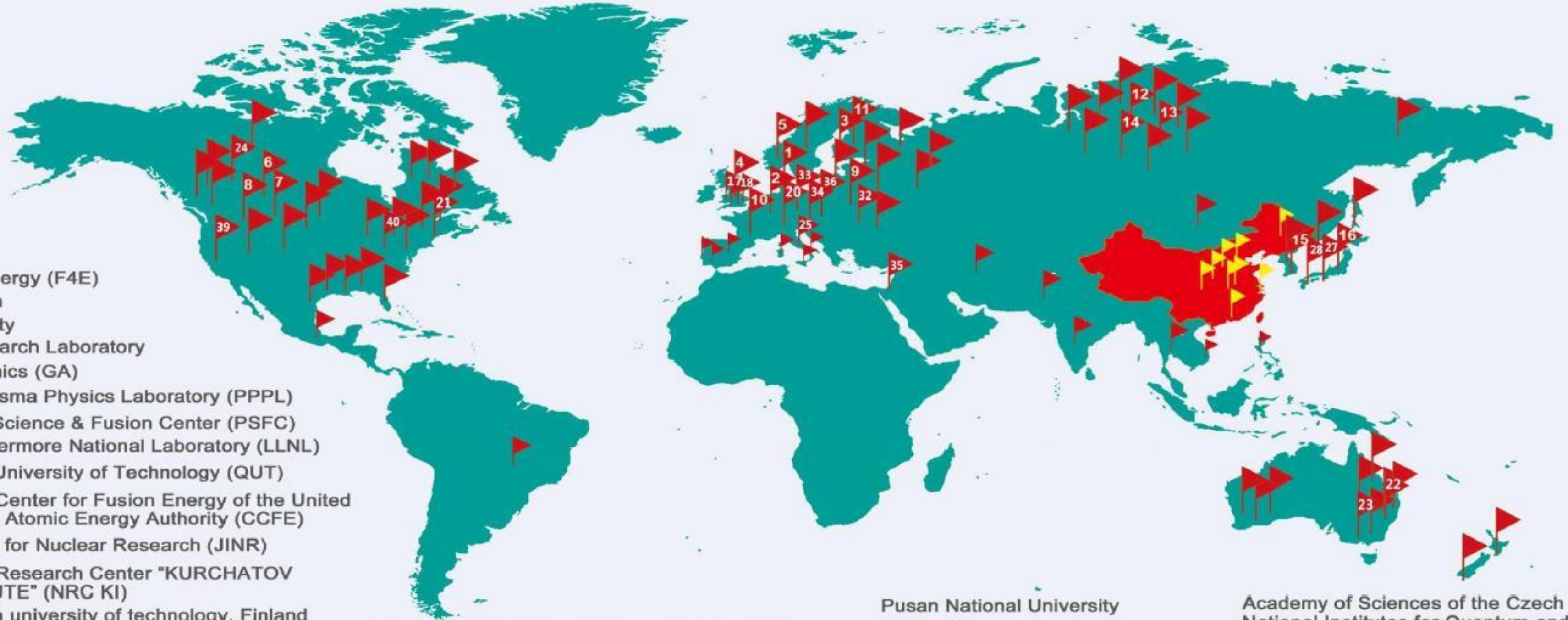
Acknowledgement

Open Test Bench



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Great Progresses on EAST Benefit from Broad Domestic and Wide International Collaborations!

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Outline

- Progress of EAST in support of ITER and CFETR
- Key issues in high-performance and long-pulse regime
- Recent results contributed to ITER new research plan
- Summary

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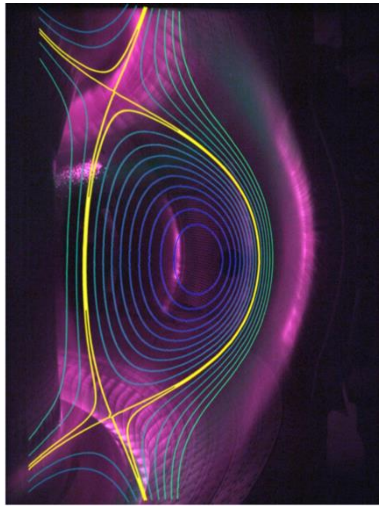
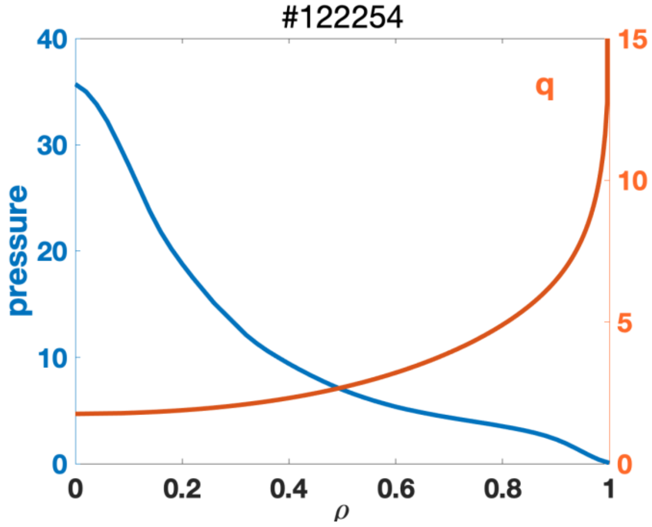
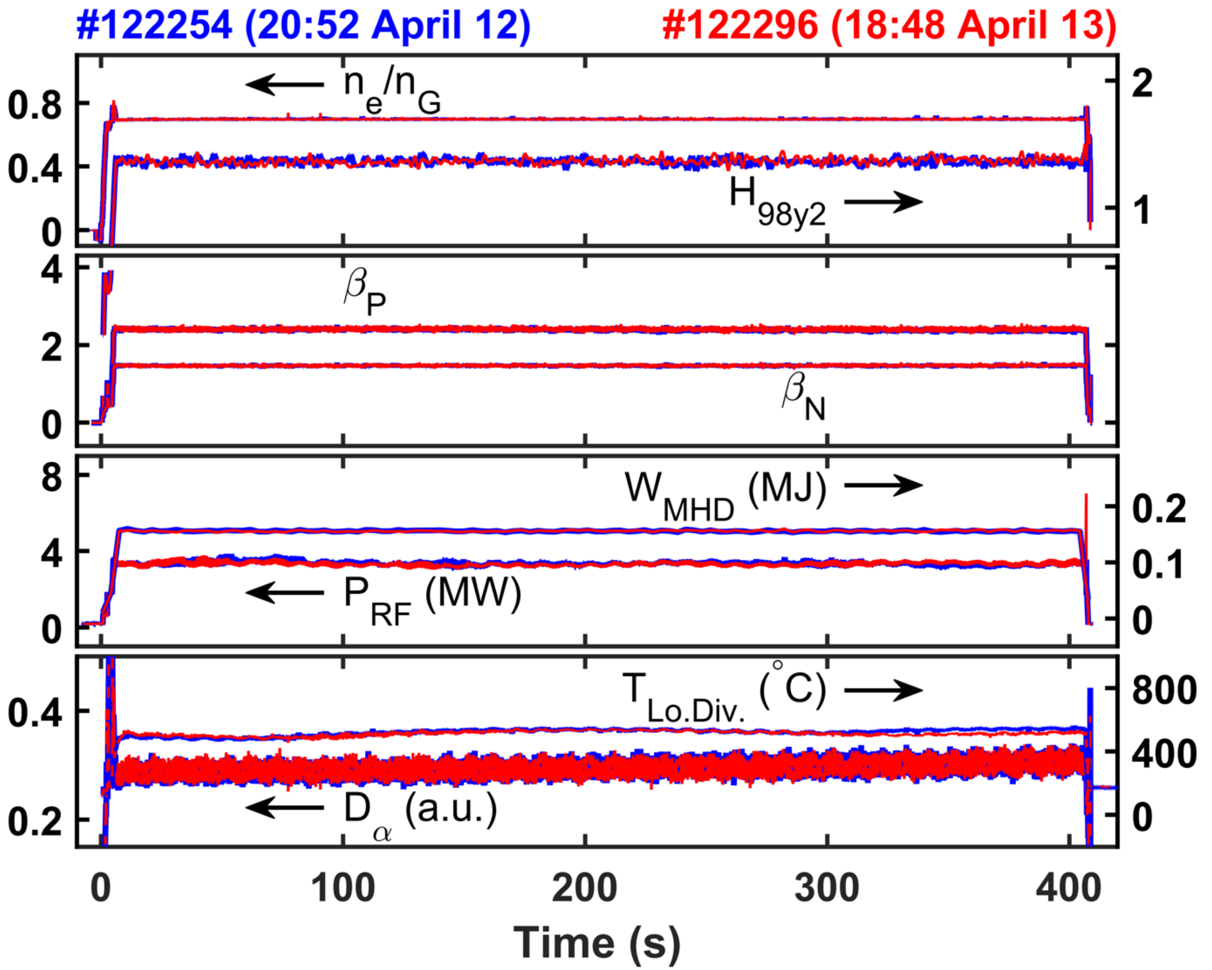
New Record of Reproducible 403 Seconds H-mode Plasmas Demonstrated on EAST with Tungsten Divertor







- A fully non-inductive plasma at f_{GW}~0.7 with f_{BS}>50% by RF heating with zero torque injection
- $H_{98,y2}$ ~1.35 with ITB by electron dominant heating
- Stationary control on particle exhaust and heat load with actively cooling W-divertor
- Small ELMs throughout discharges with high core performance

New Milestone and Tremendous Step Forward

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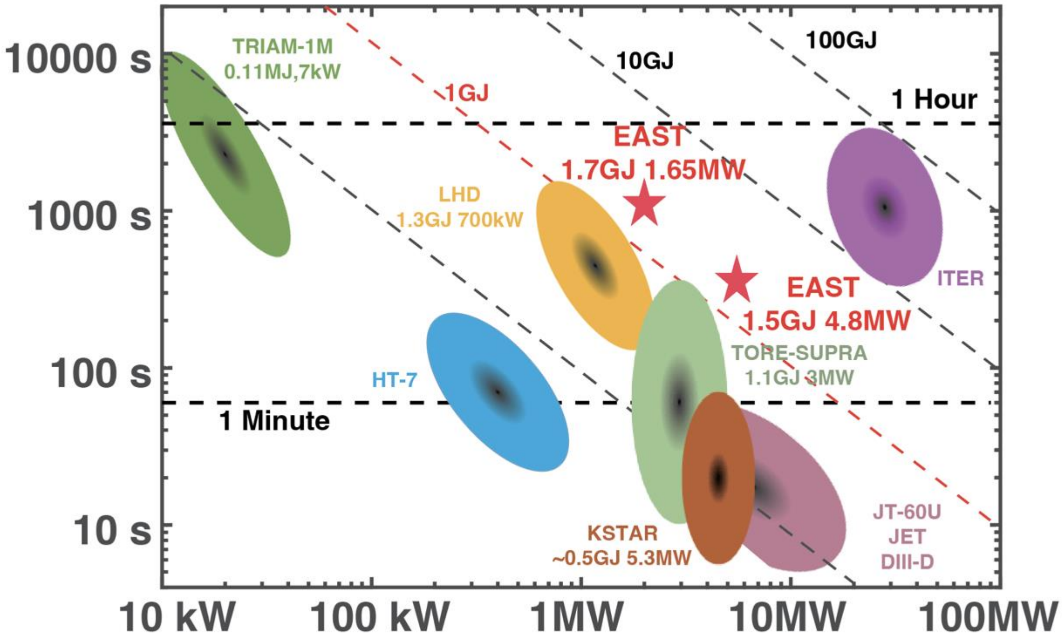
Strategies to Establish Scientific Basis Integrated Solutions for Long-pulse SSO in Support of Future Fusion Devices

S1: Enhance H/CD efficiency & relevant fundamental physics understanding and key diagnostics

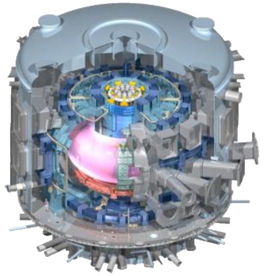
S2: Demonstrate long-pulse (≥400s) H-mode plasmas and develop fully non-inductive high-β scenarios

S3: Extend EAST operation regime to demonstrate steady-state high performance plasmas and deliver relevant physics for ITER and CFETR

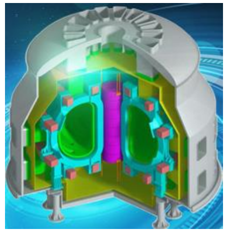
Total injected energy up to 1.73GJ



ITER



BEST



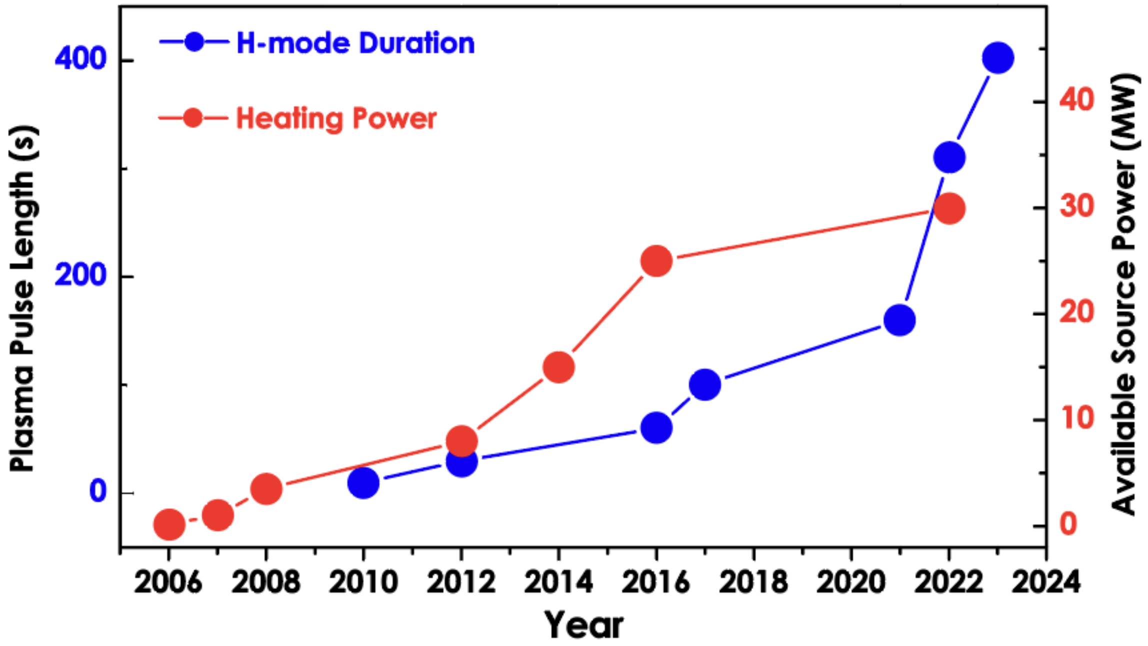
CFETR

Progress of Long-pulse H-mode Plasma on EAST

- **Integrated solutions of high-performance LPO**
  - High confinement and bootstrap current fraction
  - High RF current drive at high density
  - Core-edge integration

- **On time scale of particle and heat balance**
  - Particle recycling
  - ELM mitigation and active control
  - Divertor heat exhaust

- **Increasing pulse length of H-mode**
  - **32s** (FY12) **-101s** (FY17) **- 310s** (FY22) **- 403s** (FY23)



Demonstrate capabilities of engineering and physics issues for LPO on EAST

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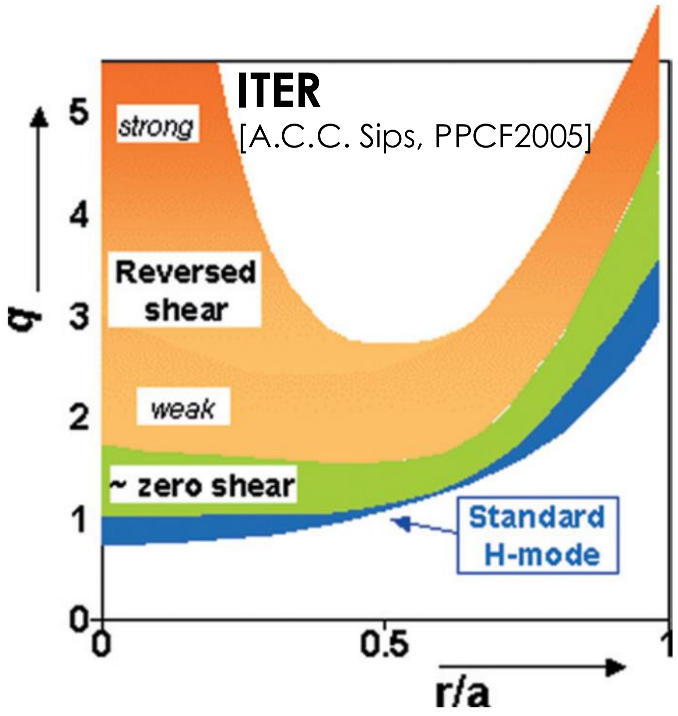
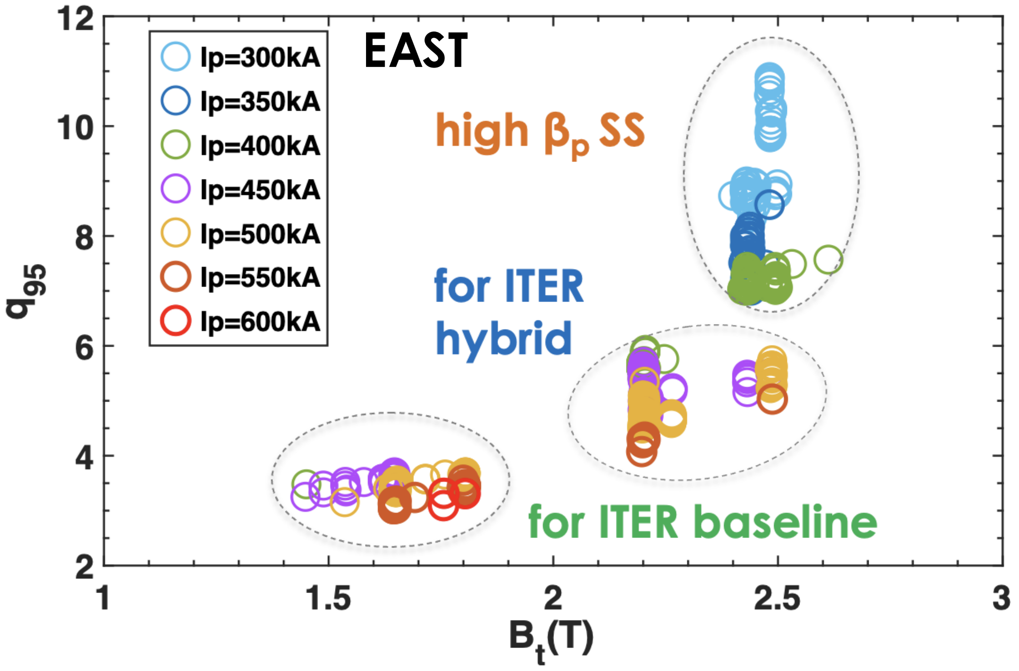
Scenario Development on EAST towards ITER and CFETR

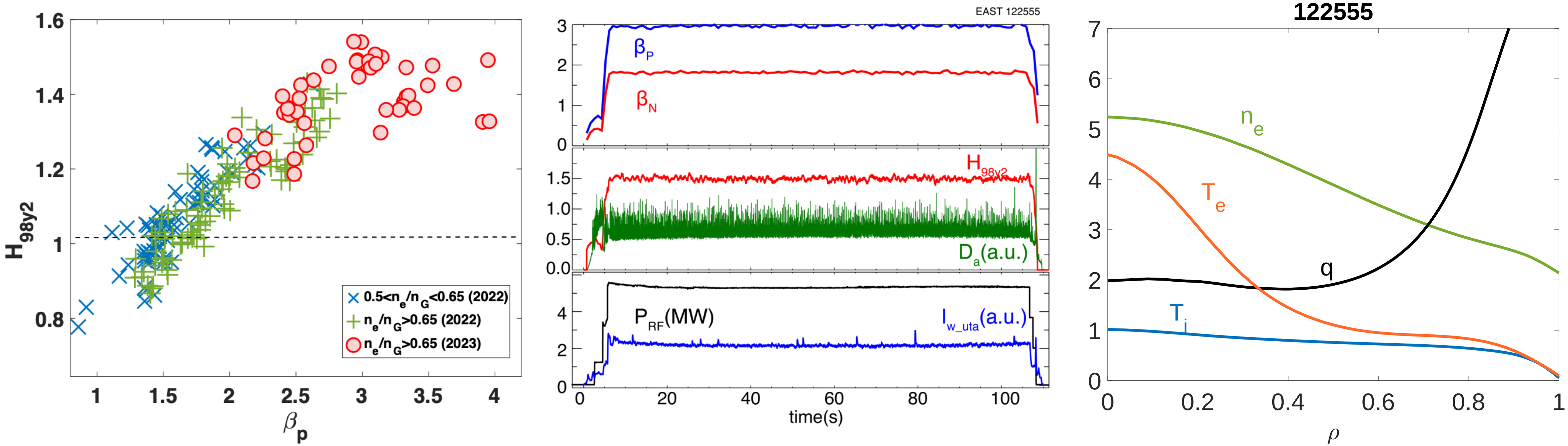




- **Challenges for EAST**
  - Electron heating dominated by RF (LHW)
  - High q_{95} and collisionality

Regime on EAST	q_{95}	B_T(T)	I_p(MA)	H&CD	H_{98y2}	β_N	β_P	f_{GW}
high-β_p SS	6-9	2.4-2.5	0.3-0.4	LHW/ECH/ICRF/NBI	1.2-1.5	1.8-2.5	2.0-4.0	0.65-1
baseline	3-3.5	1.6-1.8	0.45-0.6	LHW/NBI	~1.0	1.8-2.0	1.0-1.2	0.3-0.5
hybrid	4-6	2.3-2.5	0.4-0.6	LHW/ECH/ICRF/NBI	~1.0	1.3-1.9	1.2-1.7	0.5-0.7

Duration of ~100s Steady-state High-performance Plasma Achieved with Zero Torque Injection by RF-heating



- **Improved confinement when extending high β_P regime to higher n_e**
- **Fully non-inductive plasma with dominant e-heating**
  - RF-only: P_{EC}~1.75MW, P_{LH}~2.0MW, P_{IC}~1.6MW
  - H_{98y2} ~1.5, β_P~3.0/β_N ~1.8, f_{GW}~0.82, f_{BS}~56%
  - e-ITB, flat q-profile with weak shear and q(0)>2.0
  - Small ELM (f_{ELM} >2.5kHz) and C_w<<10^{-5}

See **X. Gong's** talk in this meeting

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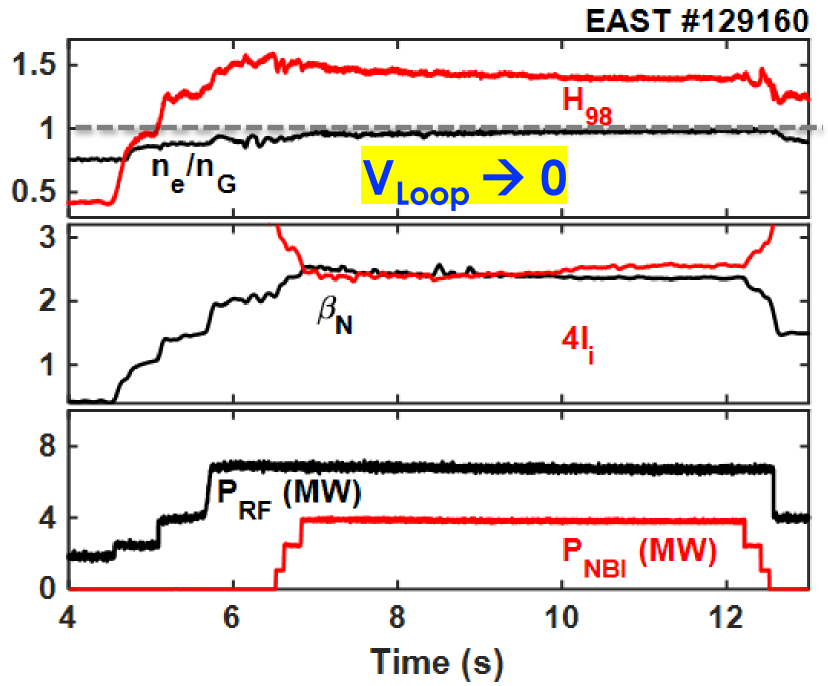
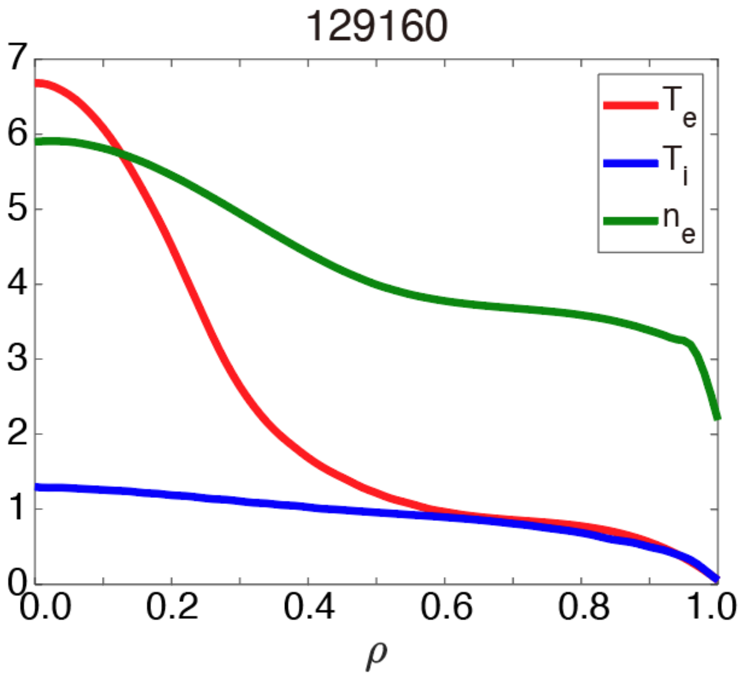
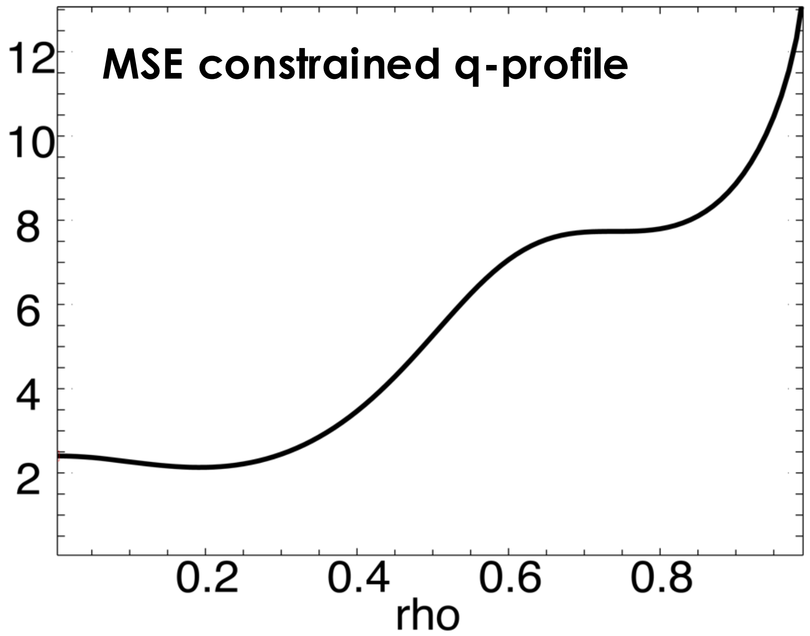
Extension of Fusion Performance in Support of ITER SSO







- Excellent confinement (H_{98y2}~1.5) at high density (n_e/n_G~1) with P_{IN} >10 MW
- High β_N ~2.5 is up to 4*li with broader q-profile (weak shear/NCS) at q_{min}>2
- Future efforts for T_i~T_e at q_{95}~5-7
  - 37MHz ICRF +120keV NBI

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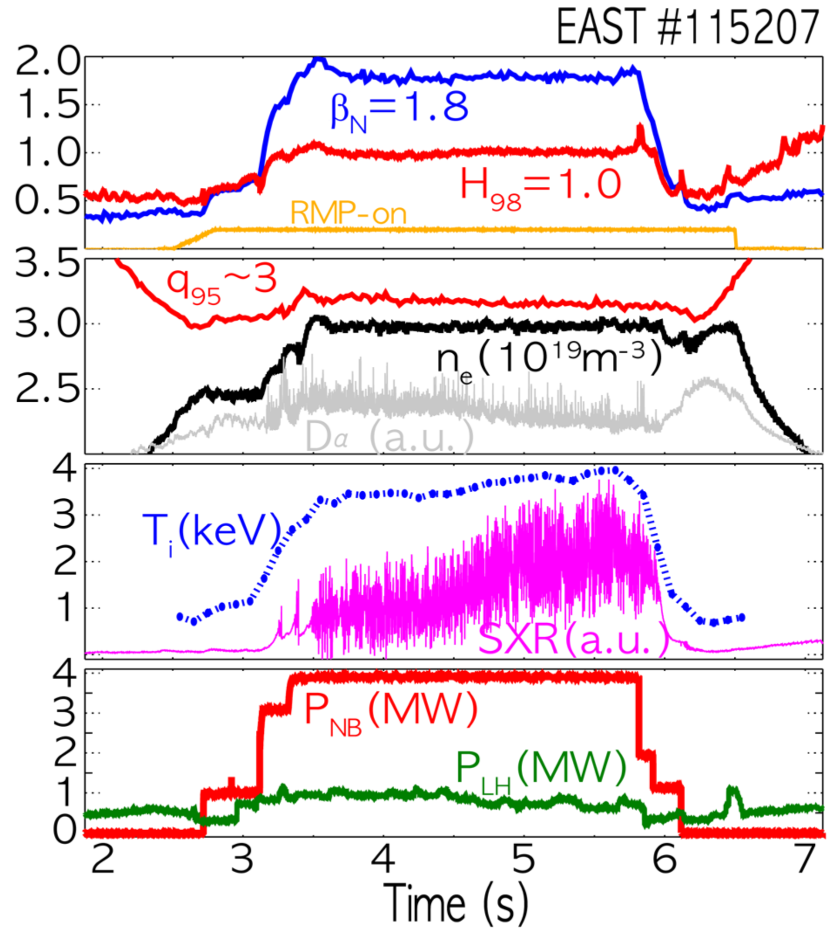
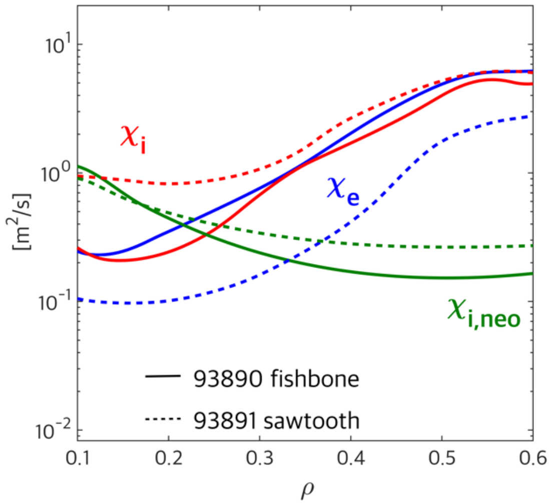
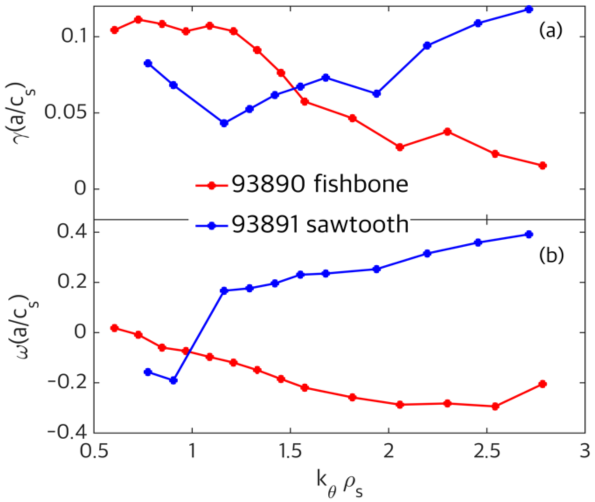
Inductive Scenario Development towards ITER Baseline on EAST



Bin Zhang, NF 2022

- **Dimensionless parameters meet the requirement**
  - β_N = 1.8, H_{98} = 1.0, T_i /T_e ~ 2.0 at q_{95} ~ 3
- **Fishbone, excited by NB fast-ions, acts as a sign of internal transport barrier formation**
  - Stabilization of TEM turbulence
- **Future efforts on electron heating/low torque**
  - 27MHz ICRH + 105GHz ECRH





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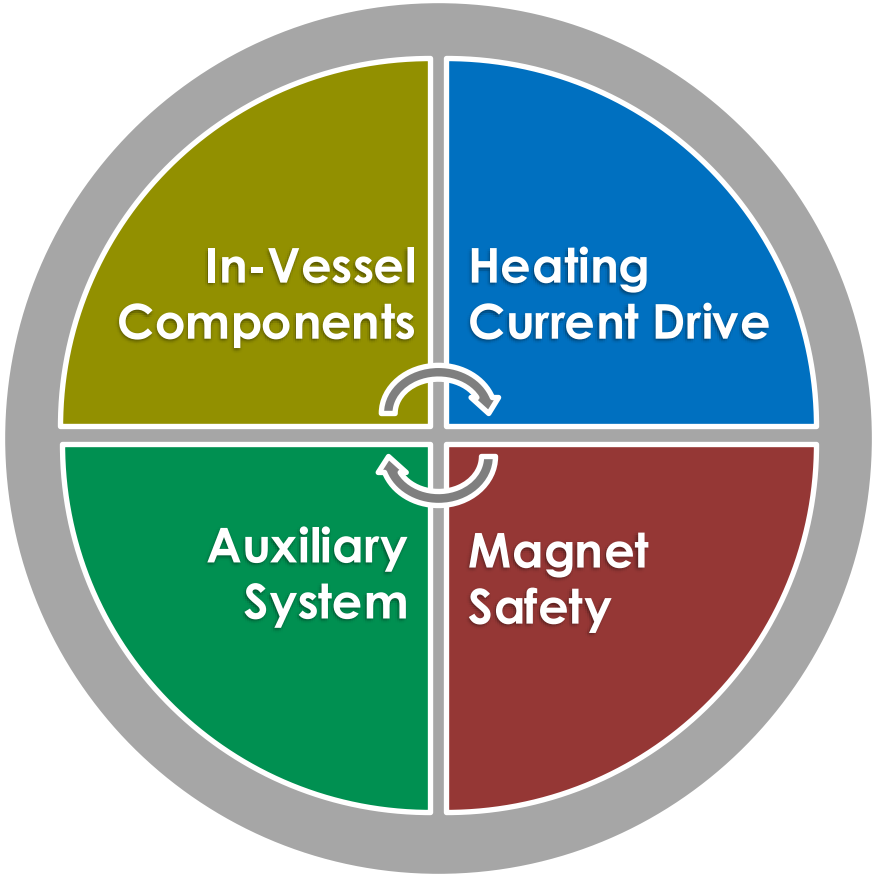
Outline

- **Progress of EAST in support of ITER and CFETR**
- **Key issues in high-performance and long-pulse regime**
  - Current status of EAST
  - Enhanced heating and current driven capabilities
  - Pedestal physics and ELM control
  - Particle and power exhaust handling
- **Recent results contributed to ITER new research plan**
- **Summary**

Hardware Upgrades Support Long Pulse SSO Research

- Improved heat flux and particle exhaust capability for lower divertor
- Higher spatial and temporal resolution for diagnostics

- Capability of cooling water system
- Upgrading cryogenic system for lower temperature operation
- Enhanced particle control technologies



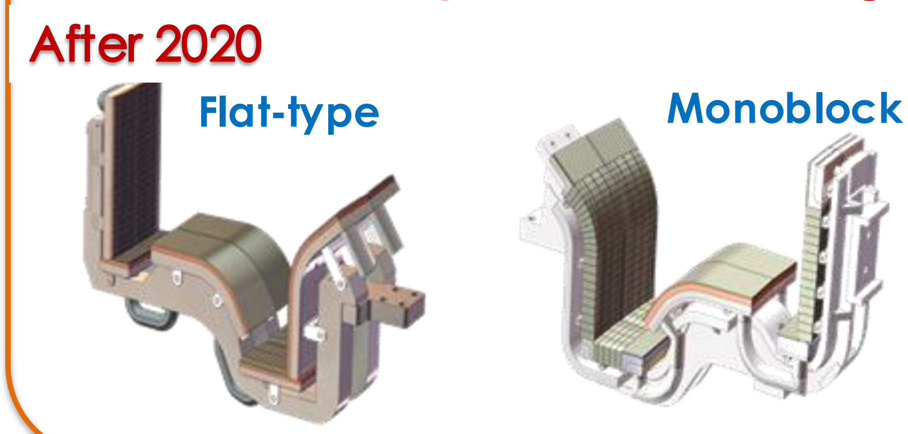
- Rearrangement of ports
- Improved coupling efficiency and injected power
- Guard limiter heat flux capability improvement

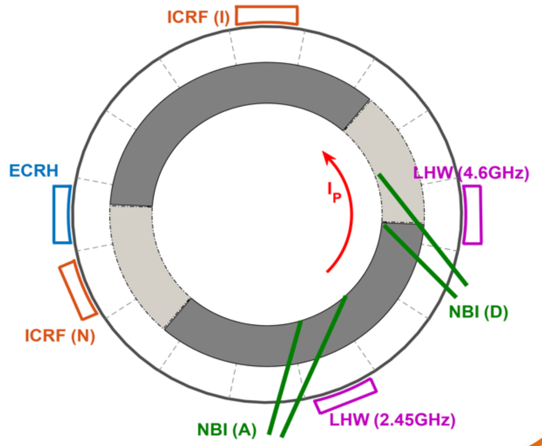
- Capability and reliability of the current leads
- Availability and reliability of coil power supply

Full Metal Wall with Lower Divertor using W/Cu

Old graphite divertor

Updated lower tungsten divertor





- **A new lower water-cooled tungsten divertor installed**
  - ¾ with the monoblock structure
  - ¼ with the flat-type structure
- **Enhanced particle/heat flux load and removal capability**
  - More closed geometry with larger slot to increase flow conductance ~36%
  - Increase steady-state heat exhaust to 10MW/m^2

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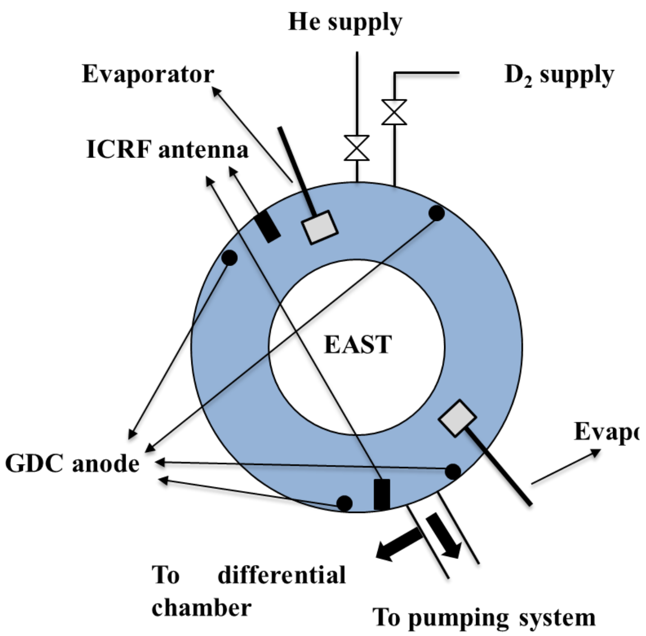
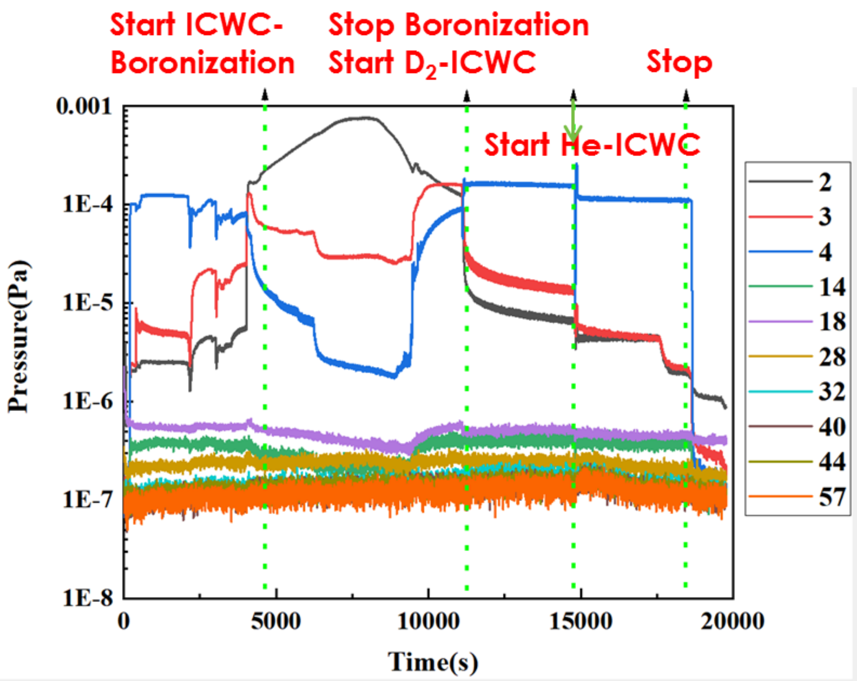
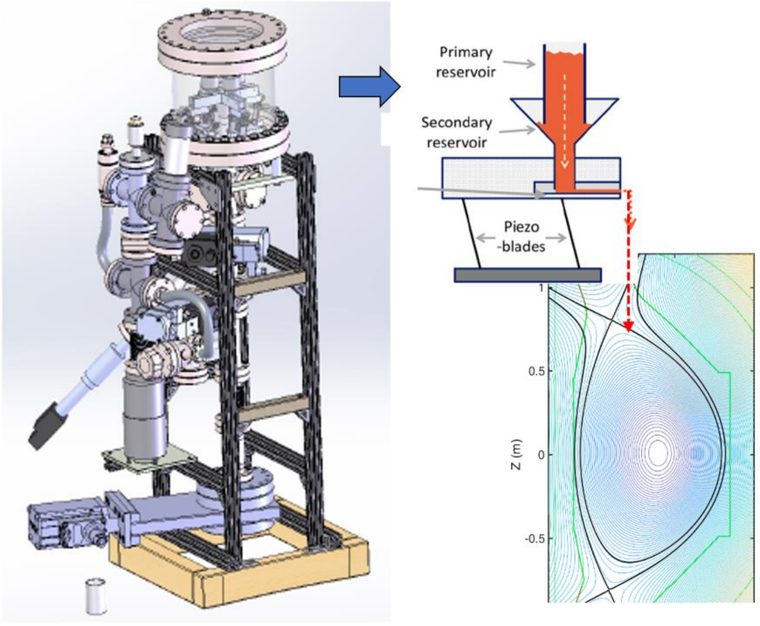
Boron Coating and Real-time Powder Injection

B coating assisted by ICWC/GDC





Realtime Impurity Injection



See **G. Zuo**'s talk this meeting

- **Boronization ($C_2B_{10}H_{12}$) are applied with D/He ICWC/GDC**
  - Support ITER/EAST joint exp. (Dec 2023-Jan 2024)
- **Continuous solid B/Li powder injection**
  - Keep good recycling control during LPO

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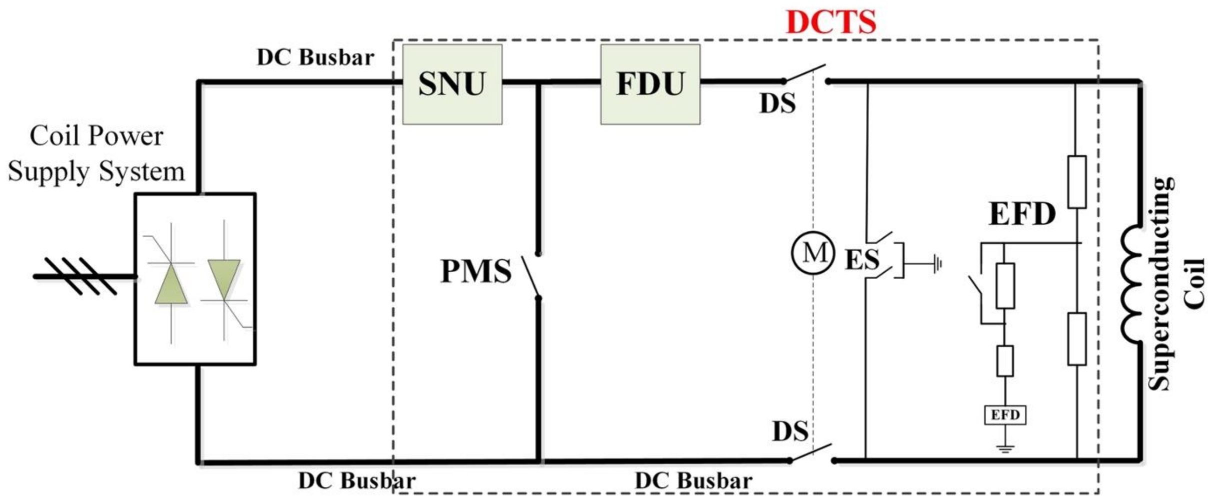
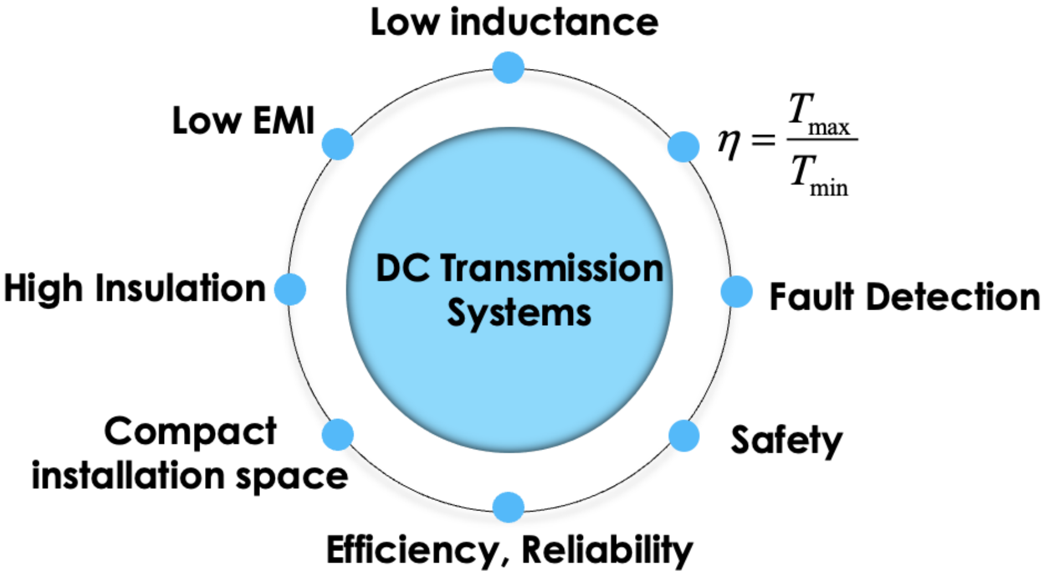
Enhanced Efficiency and Reliability of DC Transmission Systems Adapted to Superconducting Coils for LPO





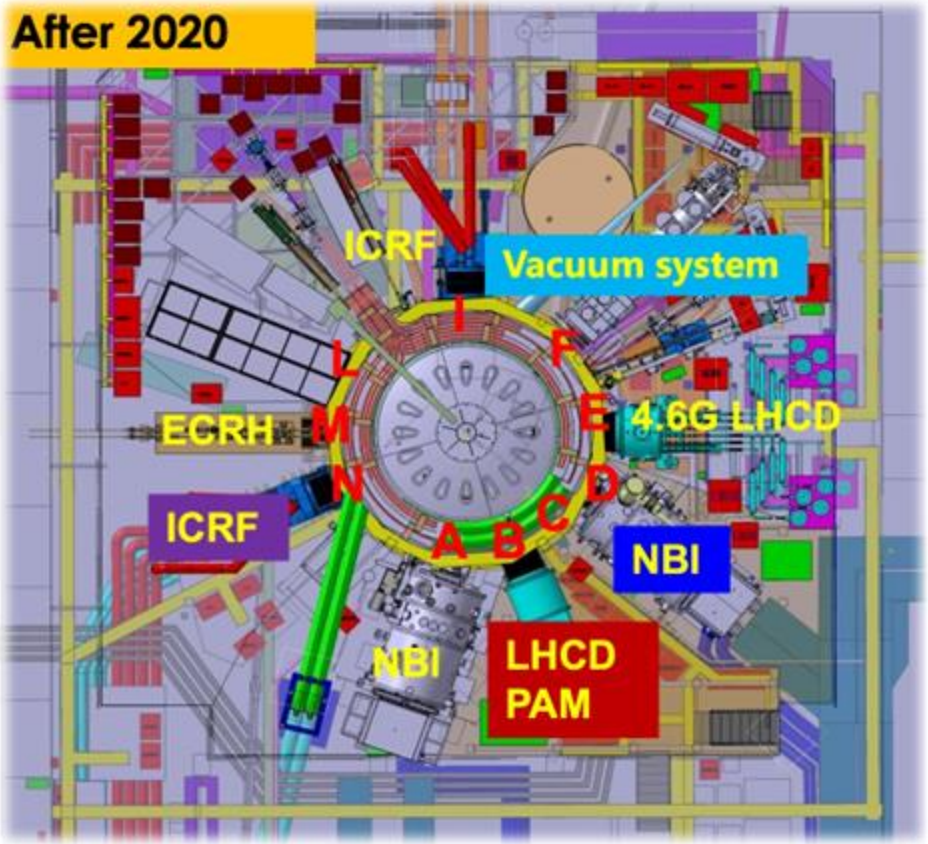
See **Z. Huang**'s talk this meeting

- **Low electromagnetic field intensity (EMI) to improve efficiency of DCTS**
  - $B_{0.7m(y)} < 3mT$, $B_{1.0m(x)} < 3mT$
- **Improved insulation performance by optimizing electric field distribution**
  - $E < 1.2kV/mm$
- **High reliability online protection system for DCTS**

Outline

- ❑ **Progress of EAST in support of ITER and CFETR**
- ❑ **Key issues in high-performance and long-pulse regime**
  - – Current status of EAST
  - – Enhanced heating and current driven capabilities
  - – Pedestal physics and ELM control
  - – Particle and power exhaust handling
- ❑ **Recent results contributed to ITER new research plan**
- ❑ **Summary**

Current Status and Upgrade of Heating and Current Driven Capabilities



- **H&CD capabilities**
  - LHW: 6MW@4.6GHz, 4MW@4.6GHz(PAM)
  - ICRF: 6MW@37MHz, 6MW@27MHz
  - ECW: 6MW@140GHz, 2MW@105GHz
  - NBI: 4MW@80keV, 2MW@120keV
- **Aiming to next step**
  - High-I_p regime at higher/lower B_t
  - More effective heating for ion temperature
  - Current profile control at core and edge

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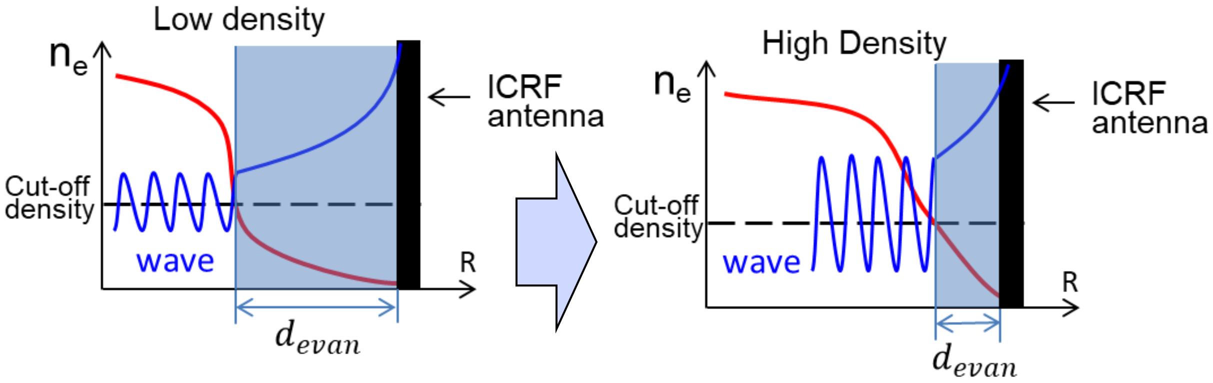
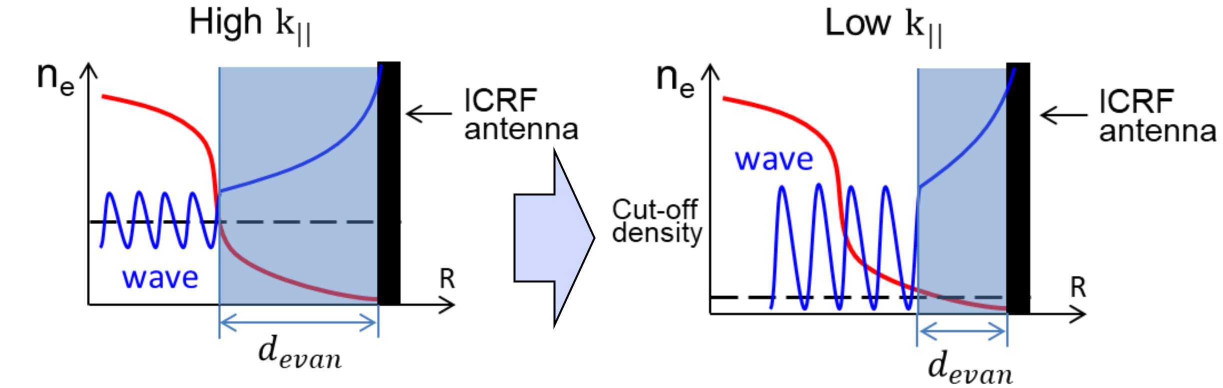
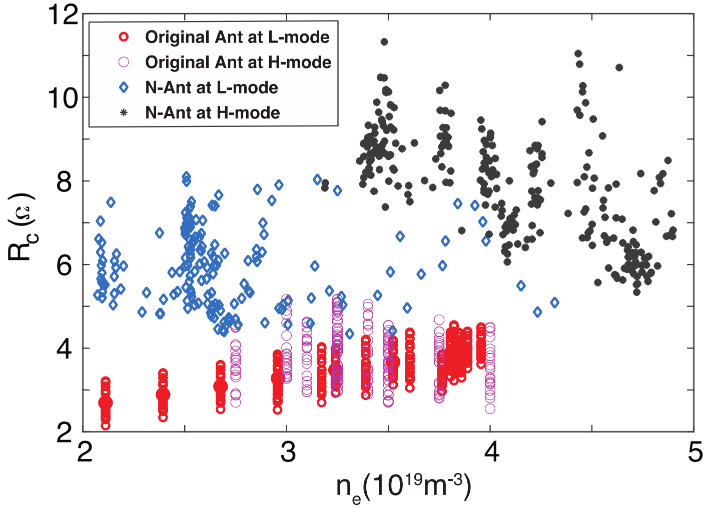
New Antenna with Decreased $k_{||}$ Improves ICRF Coupling and Heating Efficiency

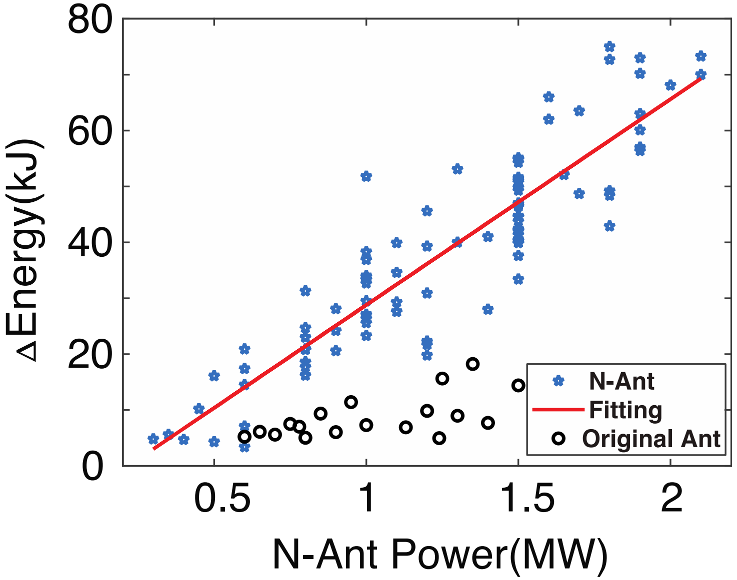


- $n_e \uparrow \rightarrow d_{evan} \downarrow \rightarrow R_c \uparrow$



- $k_{||} \downarrow \rightarrow d_{evan} \downarrow \rightarrow R_c \uparrow$





- **Enhanced coupled ICRF power**

$$P_{IC} \propto R_c \propto e^{-A \cdot k_{||} d_{evan}}$$

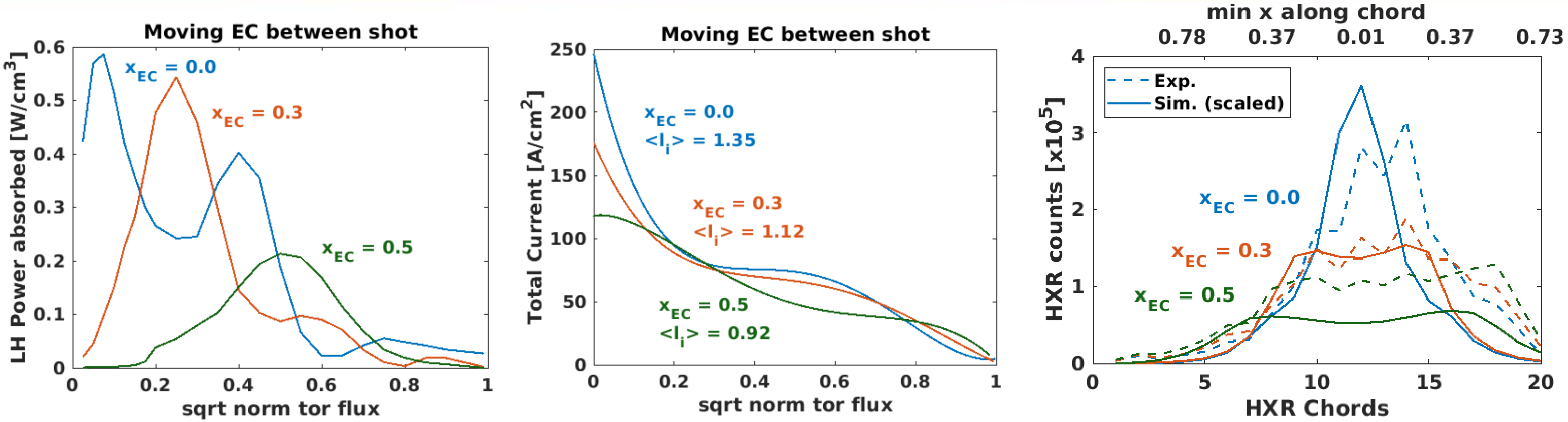
See **L. Liu**'s talk this meeting
X. Zhang, NF 2022

- **Higher heating efficiency**

$$\eta = \frac{P_{abs}}{\Delta P_{RF}}$$

IPP ASIPP

Moving EC Steers LH Absorption and Deposition



W. Choi, 66th APS, Invited talk, 2024

- **Scanned position of ~2 MW of ECCD from shot to shot**
  - x_{EC} = [0.0, 0.3, 0.5]
- **Finding supported by MSE-constrained equilibrium, l_i, and HXR**
  - HXR measures fast electrons, proxy for LH absorption
- **Resultant profile of LH absorption broaden, following EC location**
  - Simulation confirms steering effect using time-slice GENRAY/CQL3D analysis

Broad current profile required for advanced scenario

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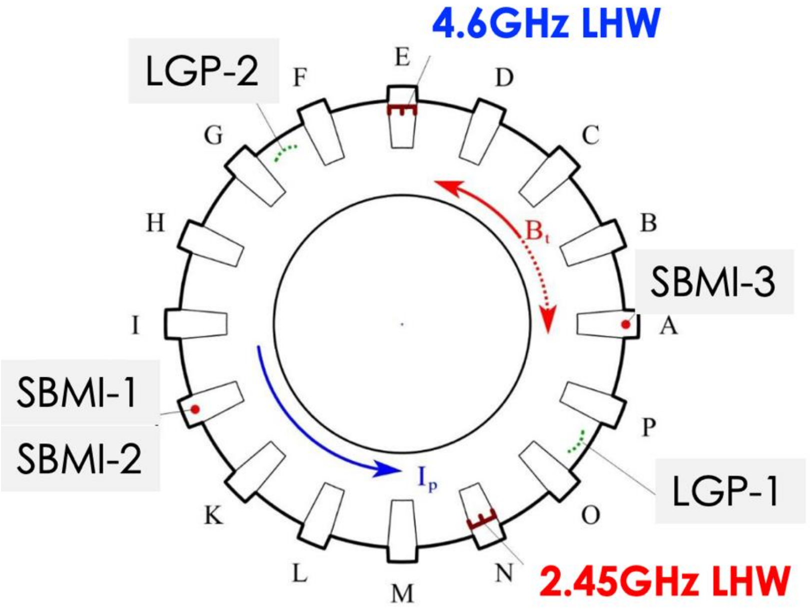
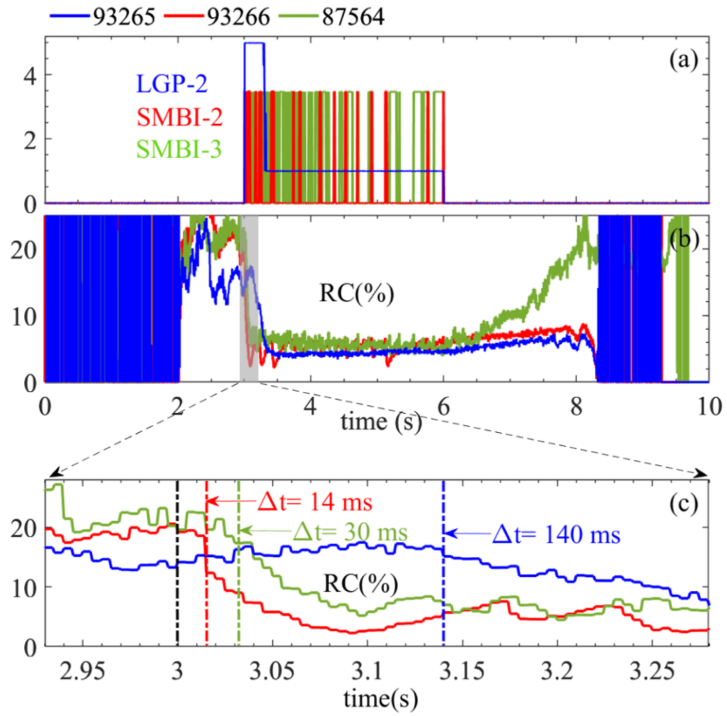
Sustain Good LHW-Plasma Coupling by Feedback Control using Gas Fueling for LPO





See **B. Ding**'s talk this meeting

- **Take RC of LH power as the reference for gas fueling feedback**
- **Study response time of various fueling methods (GP, SMI)**
  - SMBI on the electron-drift side has the fastest response time

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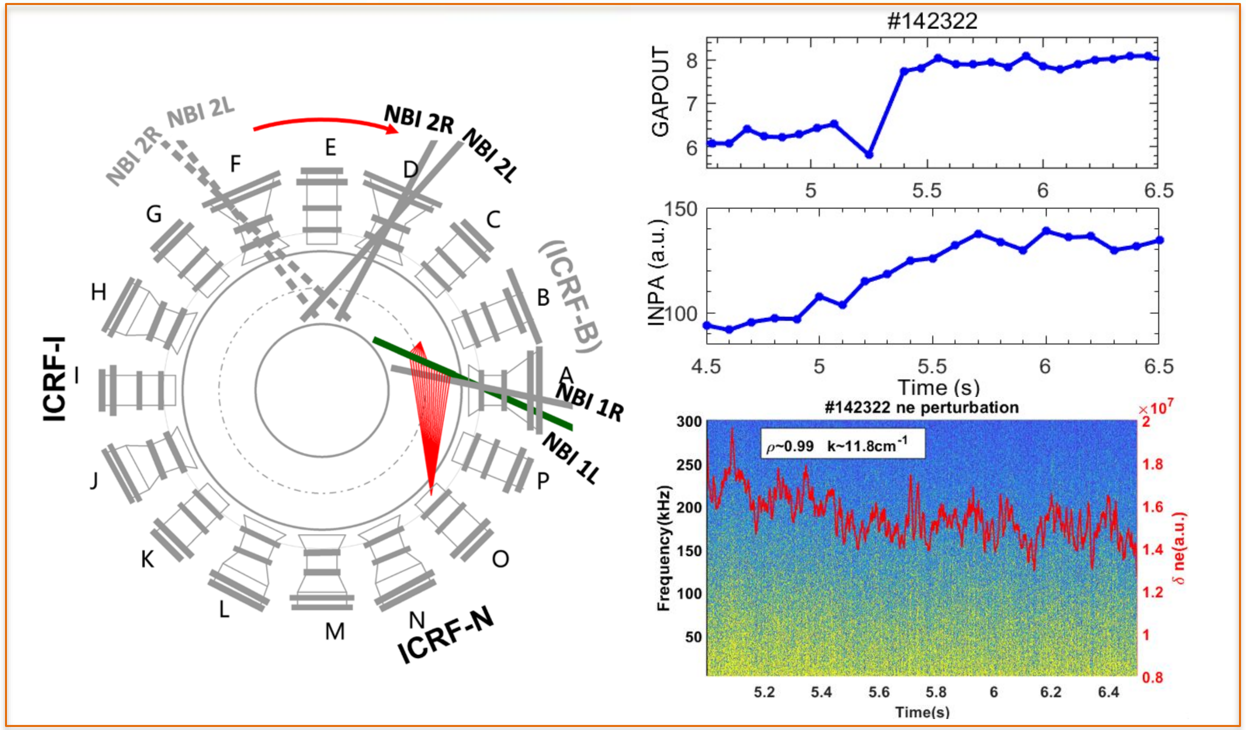
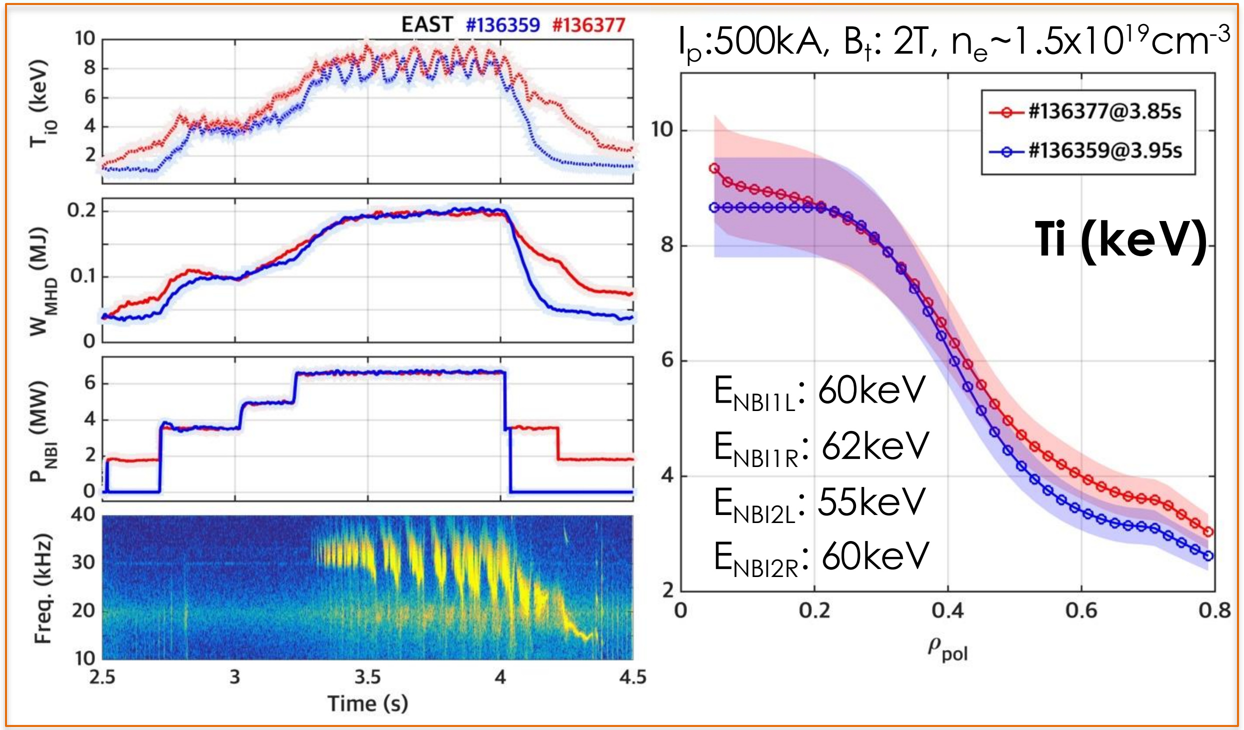
Improved Beam-ion Confinement to Enhance NBI Heating Efficiency





- **Enhance NBI heating capability by reducing beam-ion prompt loss**
  - Redirect NBI from ctr-I_p to co-I_p
  - Increased n_{fi} and reduced turbulence observed with increased gapout
- **Demonstrate high ion temperature (T_{i0}>9.0keV) plasma with impurity seeding**
  - Low density, high temperature in L-mode with full metal wall
  - Fishbone, Ti-ITB, Ar puffing

See **J. Wang**'s talk in this meeting

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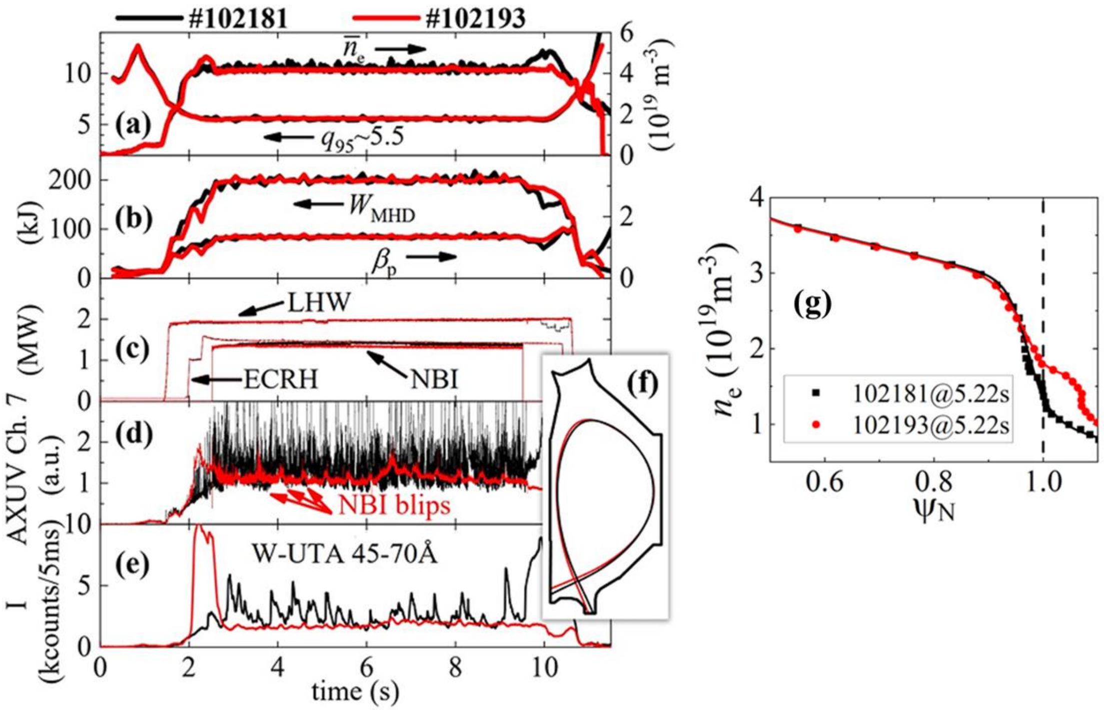
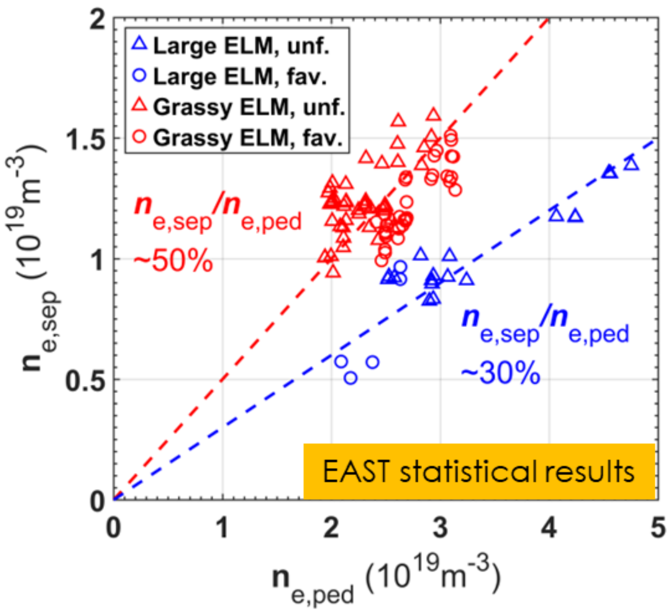
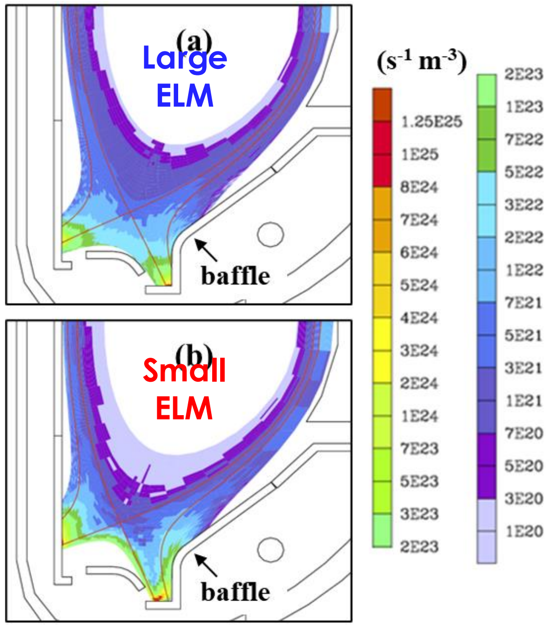
Natural Small ELMs Achieved by Changing Strike Point Location





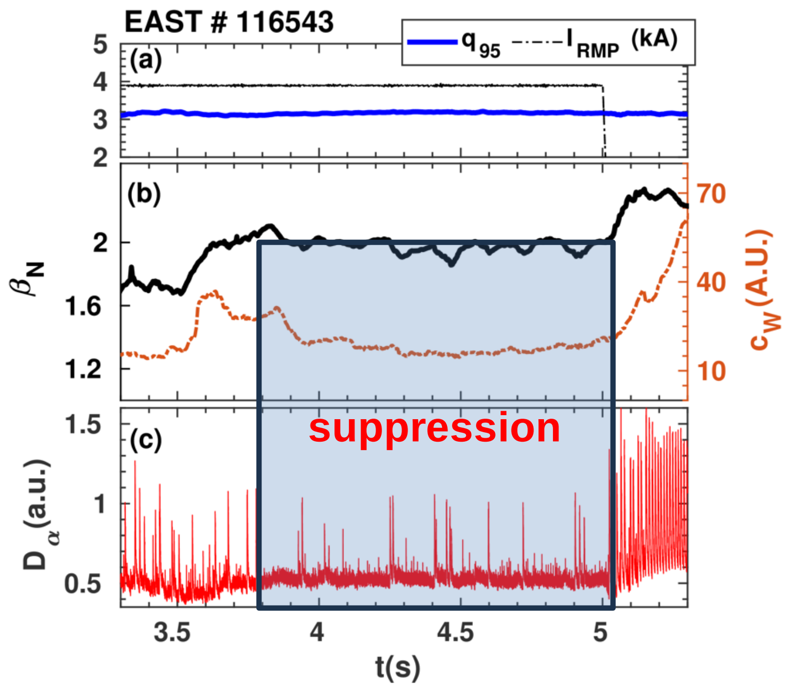
2D distribution of D^+ source

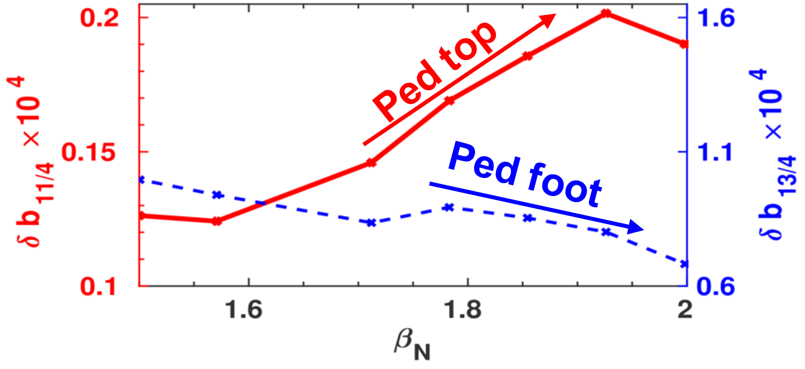


Y. Wang, NF 2024
X. Lin, PLA 2022

- **Small ELMs achieved by changing strike point location**
  - Significantly enhanced separatrix density $n_{e,sep}$
  - Consistent with previous study: lower n_e gradient and higher $n_{e,sep}/n_{e,ped}$
- **SOLPS-ITER simulation for different strike point locations determining $n_{e,sep}$**
  - Higher ionization source in the SOL region for the small ELM case
  - Providing a stronger fueling near the separatrix and thus enhancing $n_{e,sep}$

First Achieved ELM Mitigation/Suppression by n=4 RMPs in EAST with ITER Baseline Requirements





- Experimental condition is as close as possible to **ITER Q=10 scenario**
  - **q_{95} ~ 3.1, β_N~1.8-2.0**
  - **Low torque** T_{NBI} ~ 1.8 N·m (ITER 33MW NBI equivalent torque **1.1 N·m**)
  - **W concentration ↓**
  - T_i ~ T_e ~ 2.0keV
- ELM mitigation/suppression at **higher β_N >1.8**

  → well **validated MARS-F prediction** on enhancement plasma response (pedestal top harmonic) at higher β_N
- **ELM suppression *n*=4 RMP windows significantly extended**

P. Xie, NF 2023

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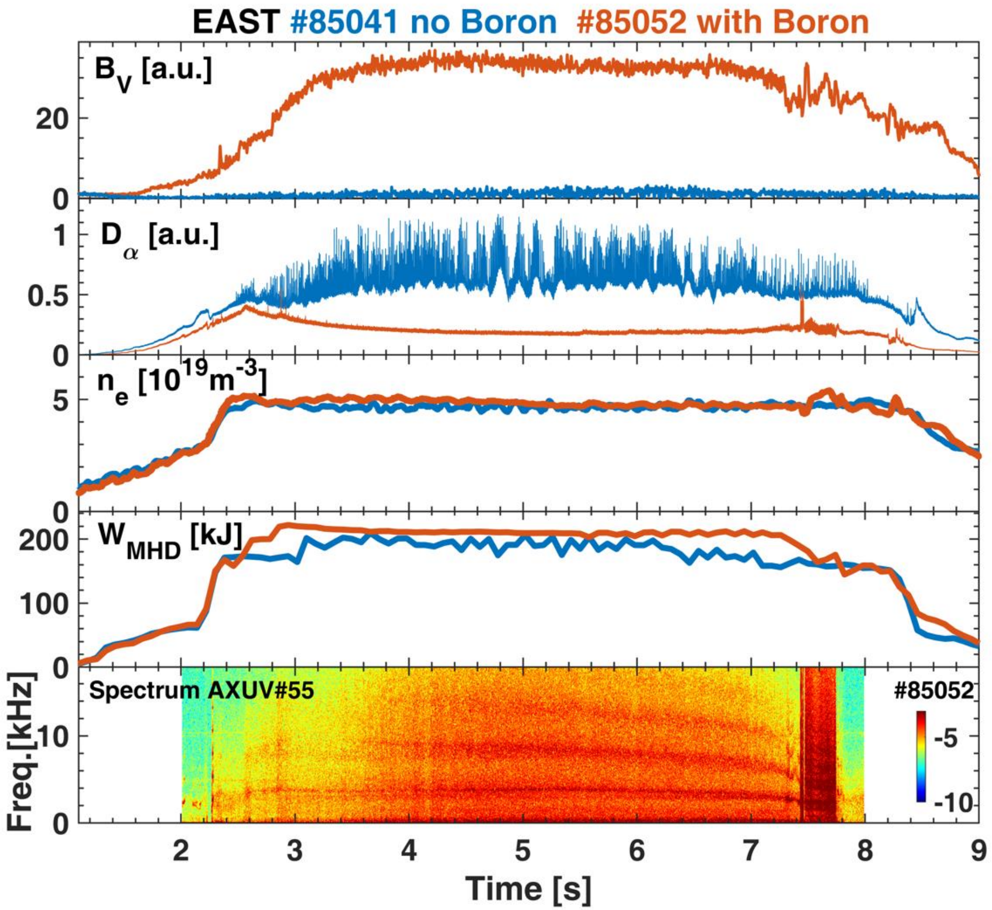
Robust ELM Suppression by Impurity Injection Compatible with Core Confinement



- Boron powder injection suppressed ELMs
- Fuel particle recycling reduced
- Stored energy increased slightly
- Harmonic mode destabilized with n=1 near separatrix

Z. Sun, 26th PSI, 2024

PPPL ASIPP

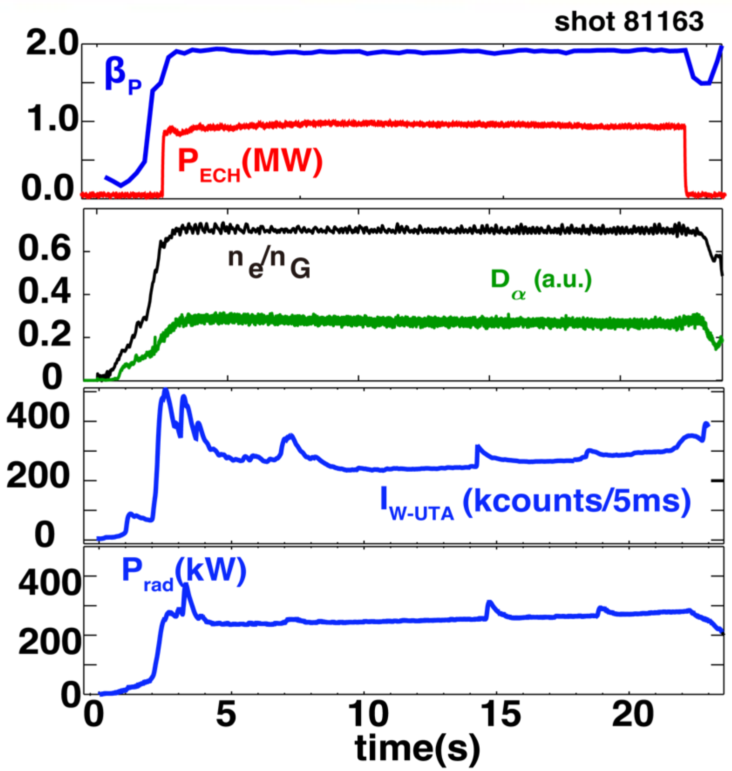
Outline

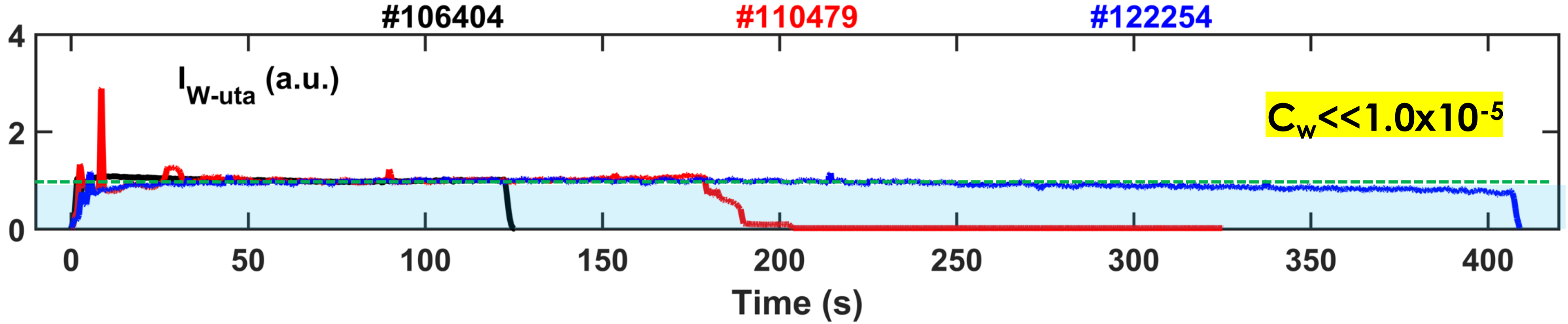
- **Progress of EAST in support of ITER and CFETR**
- **Key issues in high-performance and long-pulse regime**
  - Current status of EAST
  - Enhanced heating and current driven capabilities
  - Pedestal physics and ELM control
  - Particle and power exhaust handling
- **Recent results contributed to ITER new research plan**
- **Summary**

Well Controlled High-Z Impurity in High-β_P Plasmas

- **Small ELMs and high density** (n_{GW}~0.8) **reduced W-sputtering**
- **Avoid high-Z impurity accumulation by on-axis ECH**
  - W in good control within low level (C_W~0.3×10^{-5})
- **Modeling shows strong diffusion of TEM in the central region ρ<0.45**

X. Gong, NF 2024





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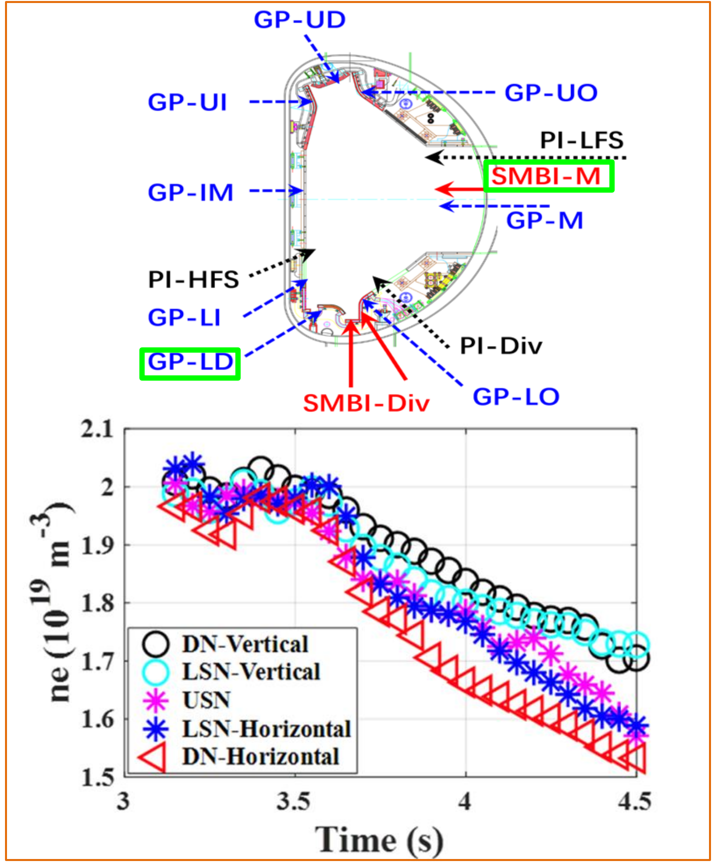
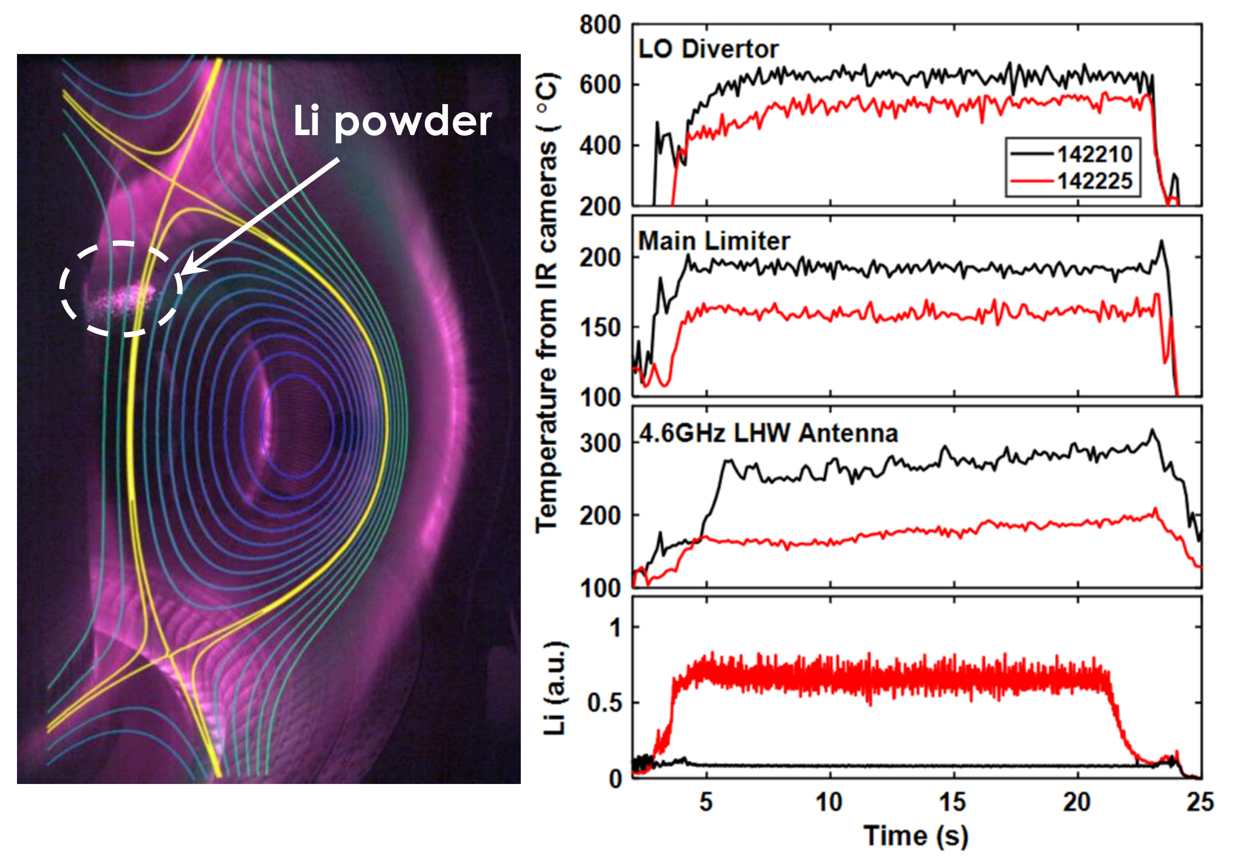
Particle Control and Heat Handling for Long Pulse H-mode





- Optimized configuration, high fueling efficiency by SMBI & DOME puffing
- Real time Lithium injection for particle control and heat handling

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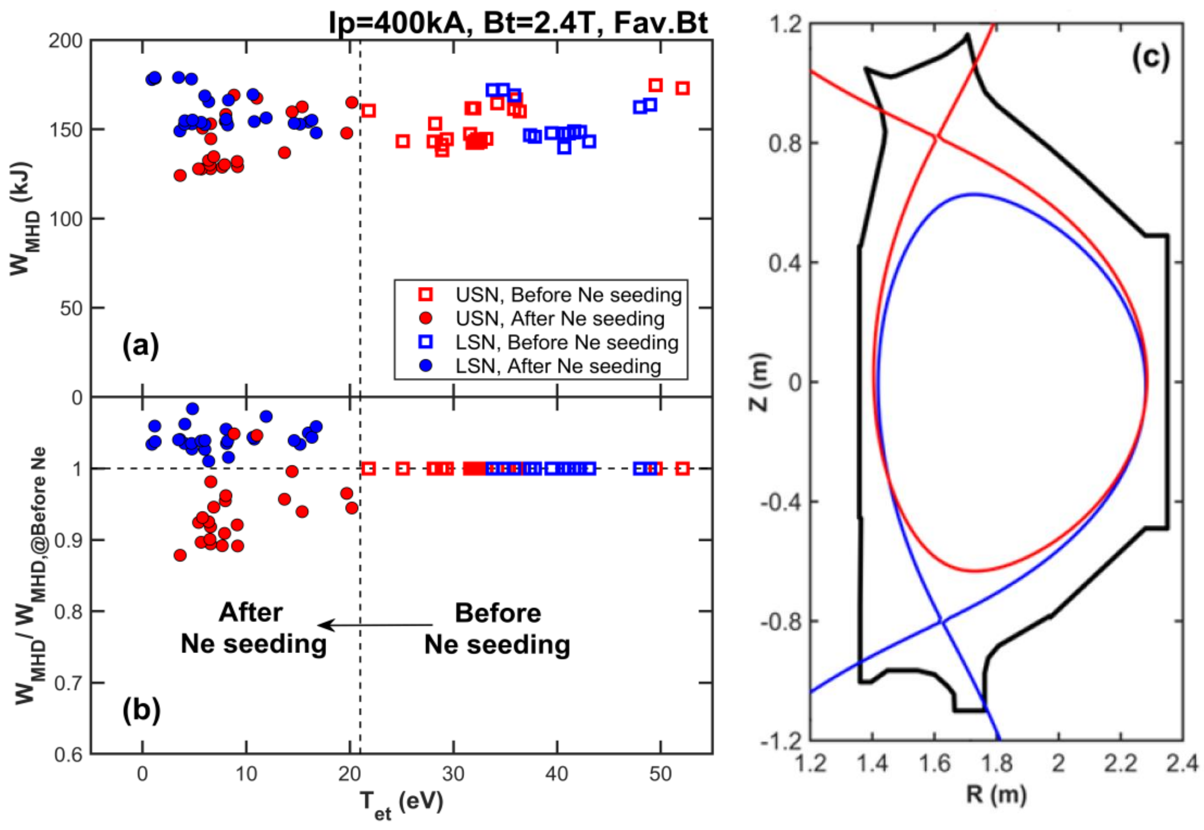
Compatibility of Core and Detachment with Impurity Seeding



- Apply impurity seeding (N_2/Ne/Ar) to reduce heat flux and detachment
- Position near SOL preferred for impurity seeding
- Impurity seeding with new lower corner-slot W divertor exhibits good core-edge integration than upper open divertor

K. Li, NF 2024
K. Li, NF 2023

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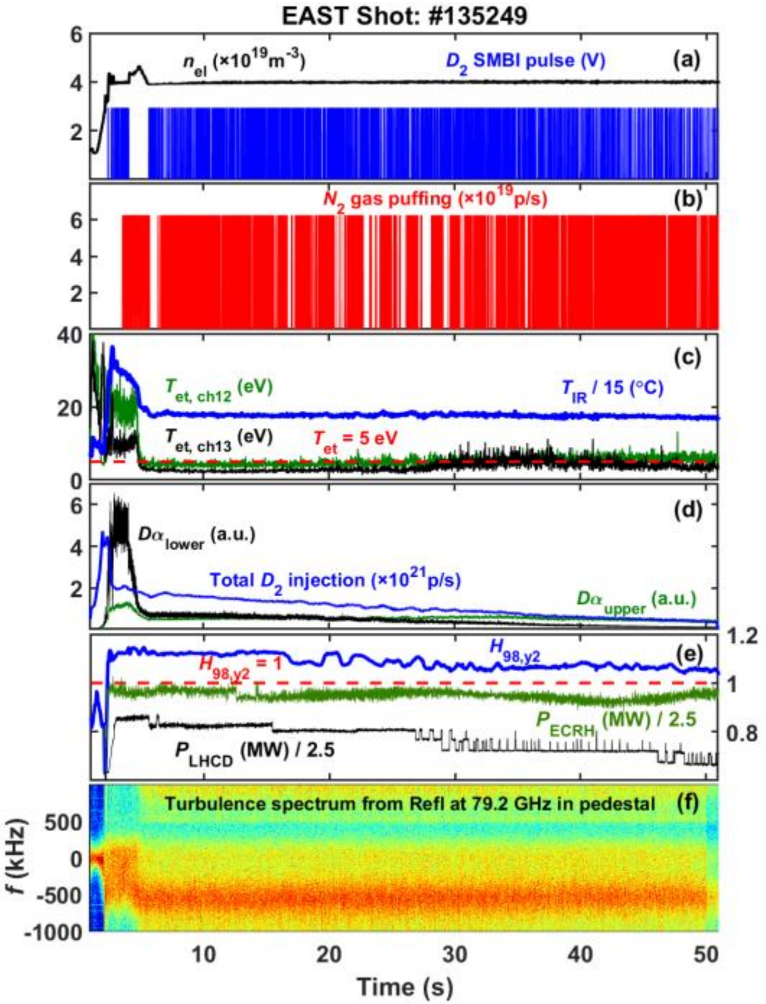
A Compatible Core and Edge Integration by Radiative Divertor Feedback Control

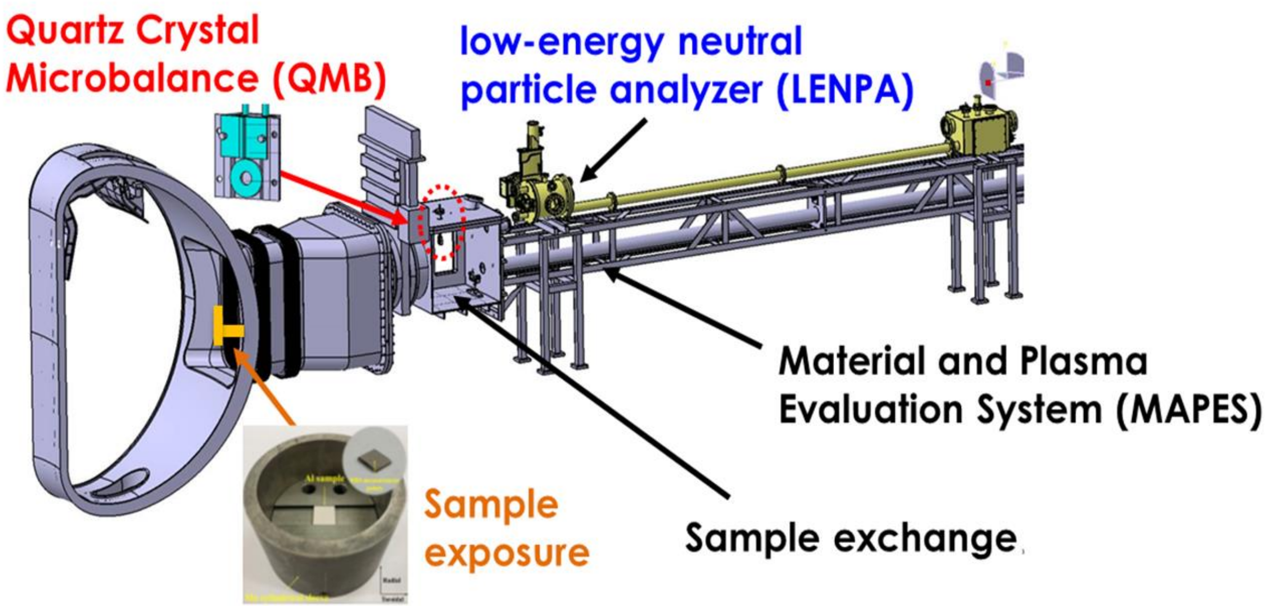
See **G. Xu**'s talk this meeting

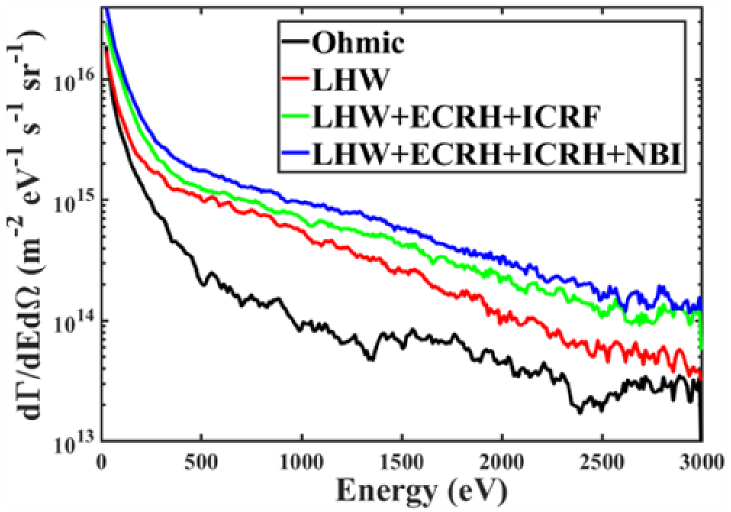
Control parameters	Actuator
Total radiation ($P_{rad,\ total}$)	LFS and divertor neon seeding
Divertor particle flux (j_{sat})	Divertor neon seeding LFS D2 fueling by SMBI
Div. electron temperature (T_{et})	Divertor neon/argon seeding
Div. target temperature ($T_{t,\ peak}$)	Divertor neon seeding
Div. electron temperature + X-point radiation (T_{et} + $P_{rad,\ X\text{-}point}$)	Divertor neon seeding



- **Achieved ~50s stationary detached ELM-free H-mode plasma using T_{et} feedback with N_2 seeding**
- **Pedestal turbulence replaces ELM might provide an exhaust channel for impurity accumulation**

Neutral-induced Wall Erosion Revealed in EAST





X. Shi, NF 2023

Leading the new ITPA DSOL task (DSOL- 46, R. Ding)

- **The Al erosion rates measured by QMB and sample exposure are consistent with the calculations and 3DGAPS modeling according to the neutral energy spectrum from the LENPA.**
- **Higher density and heating power can increase the flux and energy of neutral particles, which results in stronger material erosion.**

Outline

- ❑ Progress of EAST in support of ITER and CFETR
- ❑ Key issues in high-performance and long-pulse regime
- ❑ Recent results contributed to ITER new research plan
- ❑ Summary

The New ITER Baseline Brings New Challenges which Requires More R&D and Support from Current Experiments

"New Baseline Phases and Research Plan" —— A. Loarte, 2024, EPS, Invited

Now		~18 months	~26 months		~10 months
Engineering fabrication of system	Pre-SRO assembly	Integrated Commissioning I	Start of Research Operation (SRO)	Post SRO Assembly	Integrated Commissioning II

Install:
- Actively cooled W divertor
- Blanket shield blocks
- Inertial W First Wall panels
- 40 MW ECH
- 10 MW ICH

- Commission PCS and Protection Systems to reduce risks in DT-1
- Hydrogen L-mode to 15 MA/5.3T
- Demonstrate H-mode DD plasmas
- First assessment of boronization, fuel retention/recovery, ICWC

- Final, actively cooled W First Wall
- NBI: 33 MW
- ECH: 40 → 60-67 MW
- ICH: 10 → 20 MW
- Final diagnostics set

FPO-y	FPO-(…)	FPO-x
DT (Q=10), high duty ≥ 500 s Q ≥ 5, 1000, 3000 s		

FPO-5	FPO-4	FPO-3	FPO-2	FPO-1
D, DT (Q=10) ≥500 s High duty, 250 MW, ≥300 s	D, DT (Q=10) 500 MW, ≥300 s	D, DT (Q=10) 500 MW, ~50 s	D, DT, 100 MW, ~50 s	H, H+T, D

- **Key element of the new baseline: First Wall Material Beryllium → Tungsten**
- **Open issues with a W wall for ITER Q = 10 operation: Boronization, Limiter Operation, Impact of W on the H-mode Operational Space**

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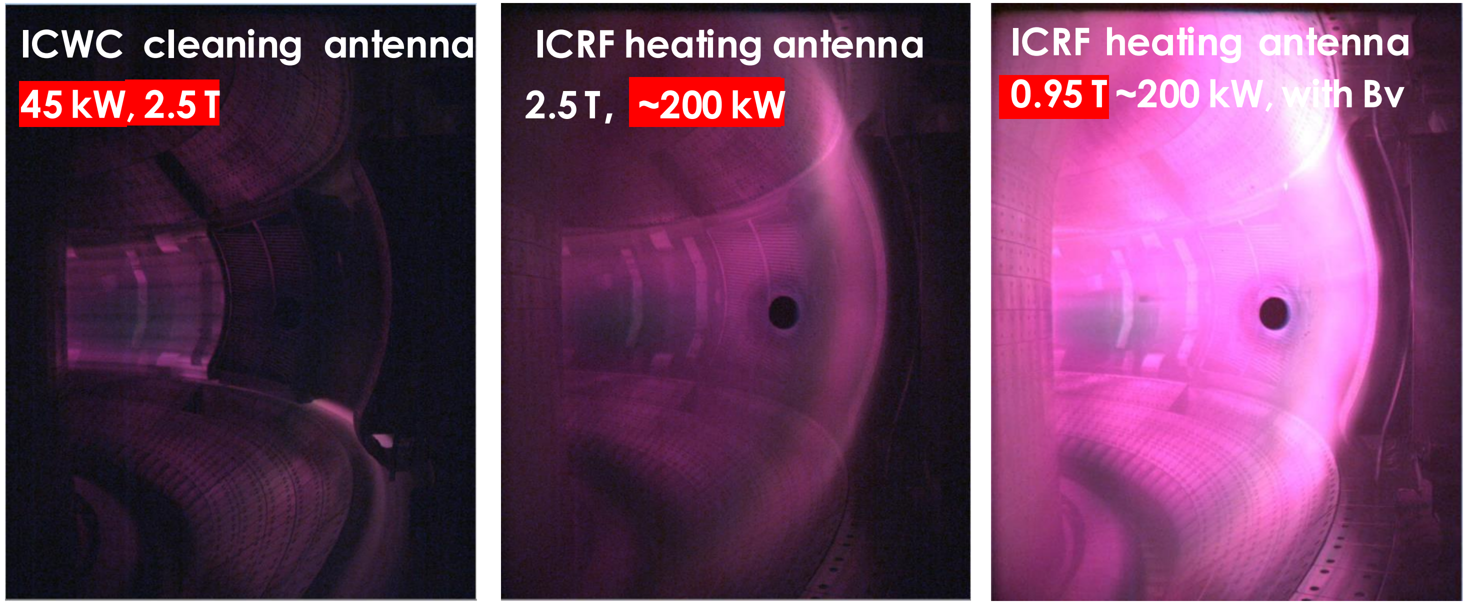
Outline

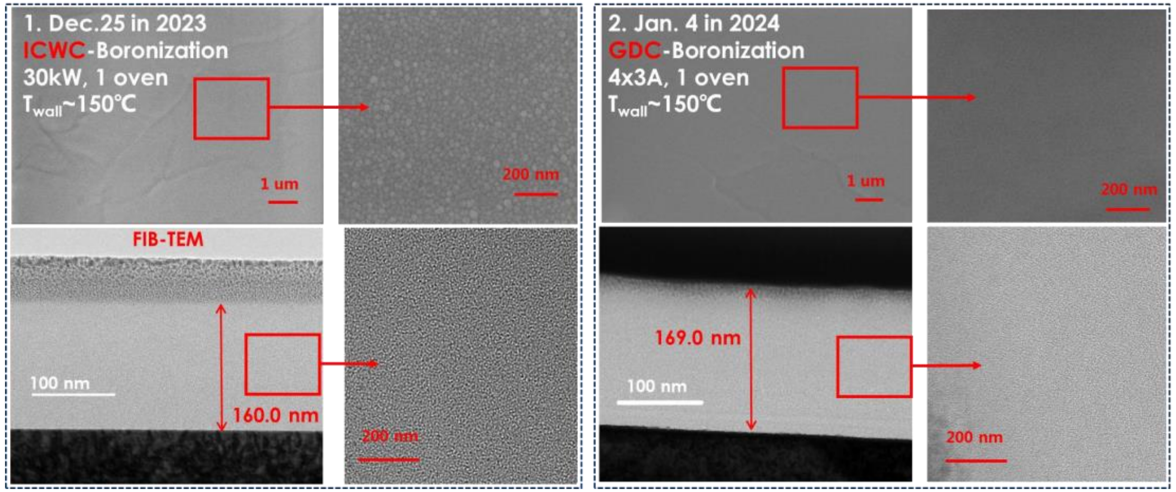
- **Progress of EAST in support of ITER and CFETR**
- **Key issues in high-performance and long-pulse regime**
- **Recent results contributed to ITER new research plan**
  - Boronization studies
  - Start-up experiments with ECH and W-limiter
  - H-mode operation with W wall
- **Summary**

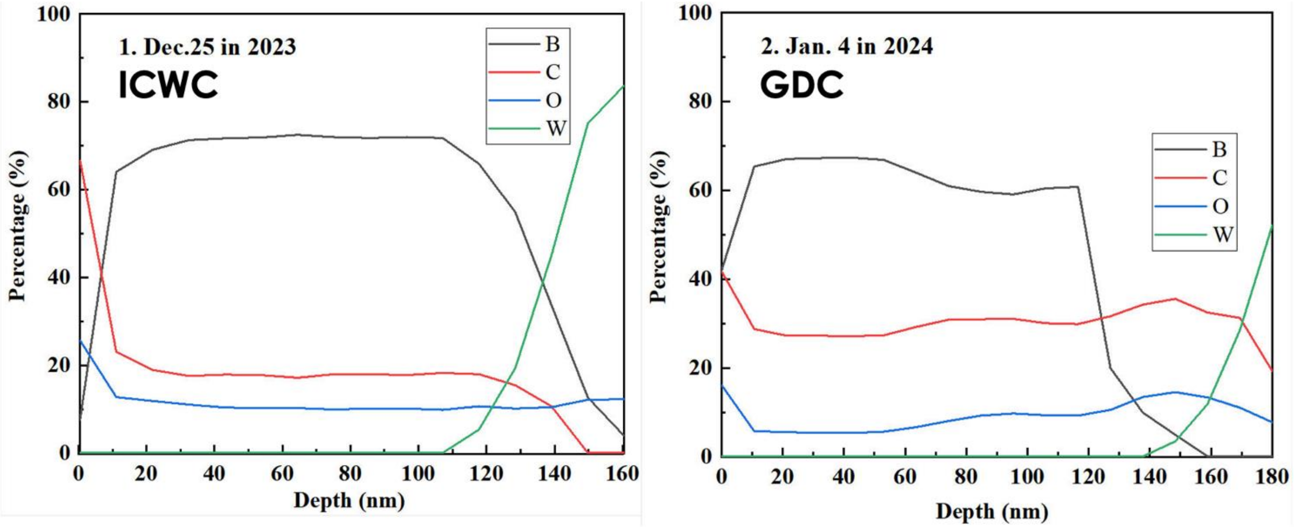
Improved Plasma Uniformity and Boron Deposition Rate were Obtained by Using ICRF Heating Antenna



- **ICRF heating antenna for He/D_2 plasma cleaning and boronization was performed**
  – Plasma was more bright and uniform with ICRF heating antenna than ICWC antenna
  – Plasma became more bright and uniform with increasing B_t and B_v
  – Boronization with ICRF heating antenna improved boron deposited rate

In-situ Boronized Samples with GDC and ICWC were Characterized and Compared





See **G. Zuo**'s talk this meeting

- **The surface of the sample via ICWC-boronization has clear granular**
- **The thickness of Boronization was similar, about ≧160nm**
- **The thickness measured by XPS is consistent with the result measured by FIB**
- **The composition is slightly different with ICWC and GDC**
  - B film with ICWC is **B:C:O=7:2:1**, higher ionization rate, B reacts with O and H/D
  - B film with GDC is **B:C:O=13:6:1**, lower ionization rate, more C deposition

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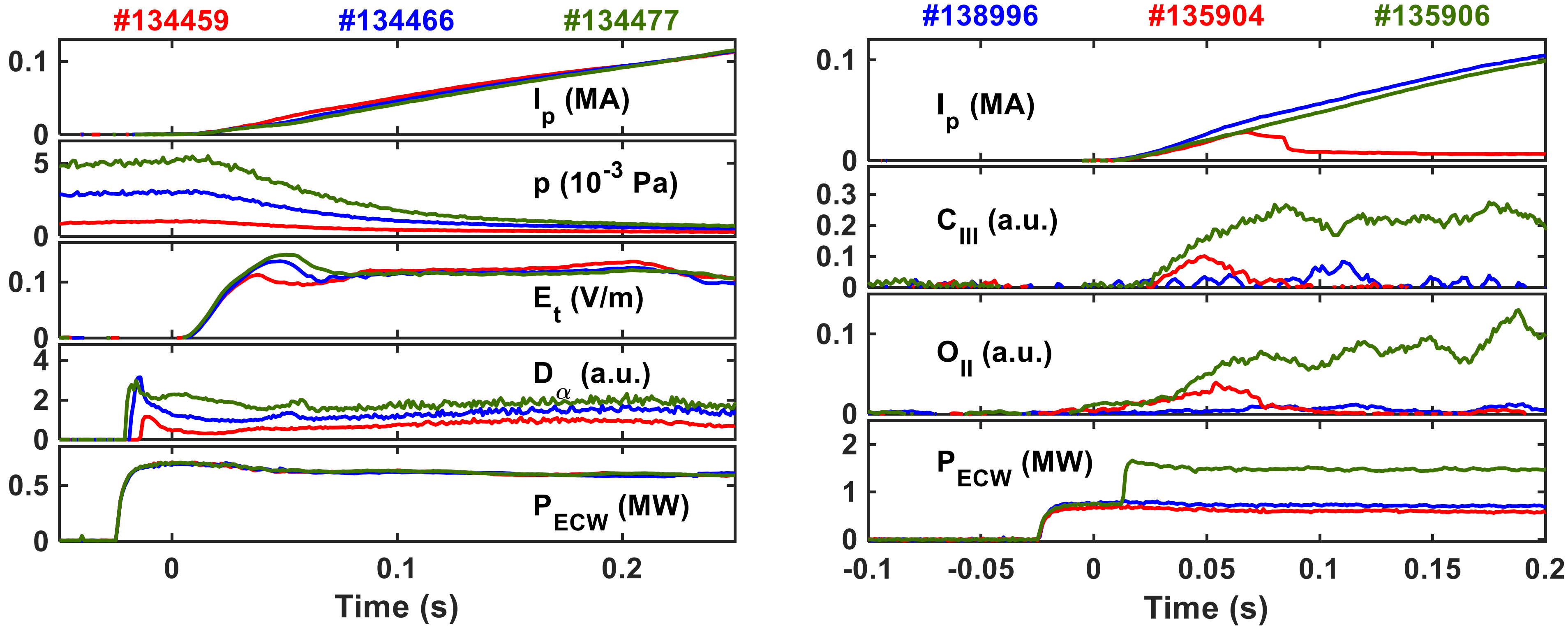
Robust Breakdown and Plasma Startup with ECW Assistance

- Non-inductive breakdown ($E_t = 0$) with optimized NFC and TPC
- Low-E_t (< 0.15 V/m) burn-through and Ip ramp up with ECW assistance (ECH & ECCD)
- Robust plasma startup in a large range of prefill gas pressure (P_{VV}~7.5e-4 Pa-5.1e-3 Pa)
- Tolerance to high impurity level

See **J. Qian**'s talk this meeting



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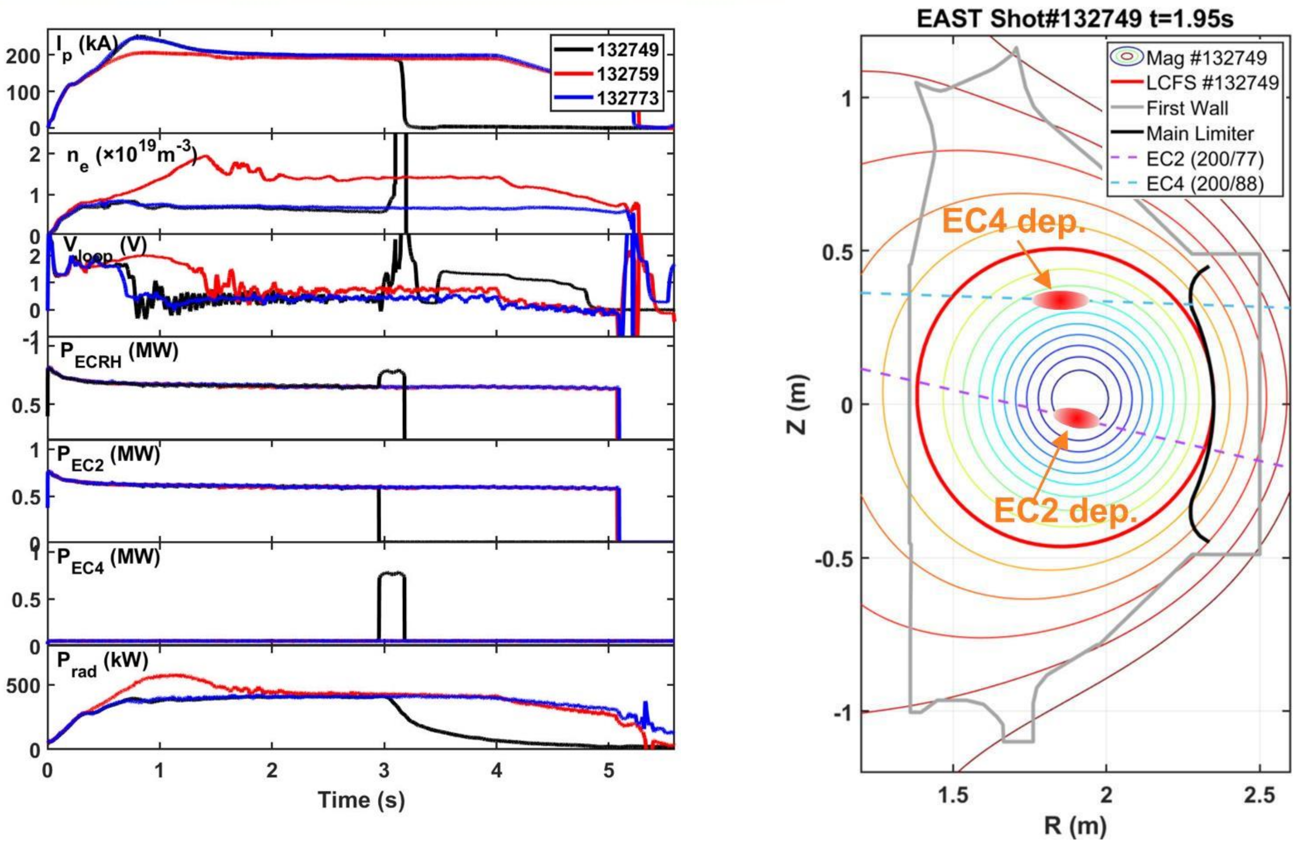
EC Assist was Mandatory for Success of the Discharges Starting on W Limiter

132749, n_e/n_{GW} ~0.15, EC off-axis
132773, n_e/n_{GW} ~0.15, EC on-axis
132759, n_e/n_{GW} ~ 0.35, EC on-axis



- **ECH breakdown assist used throughout for reproducibility**
- **Reliable Ip flattop at high current with 2 EC sources**
  - I_p~0.2MA is used
- **Switching EC from on-axis to off-axis leads to disruption**

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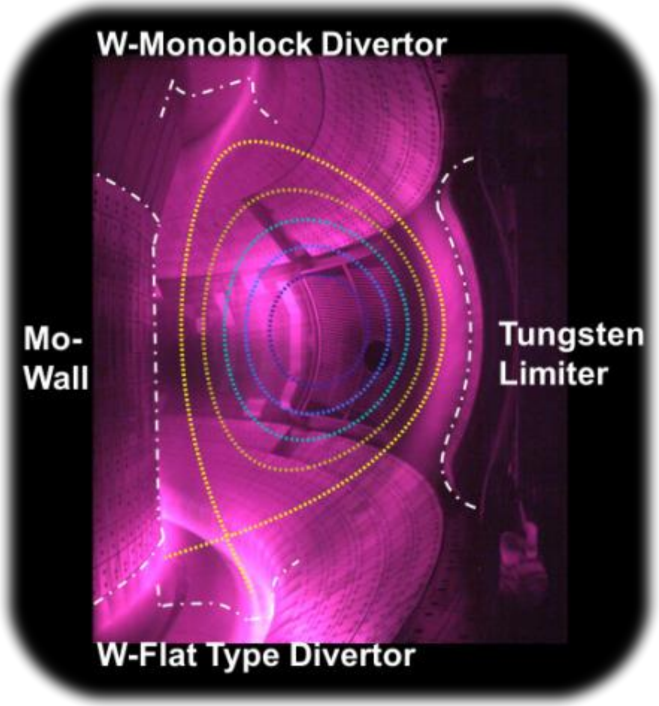
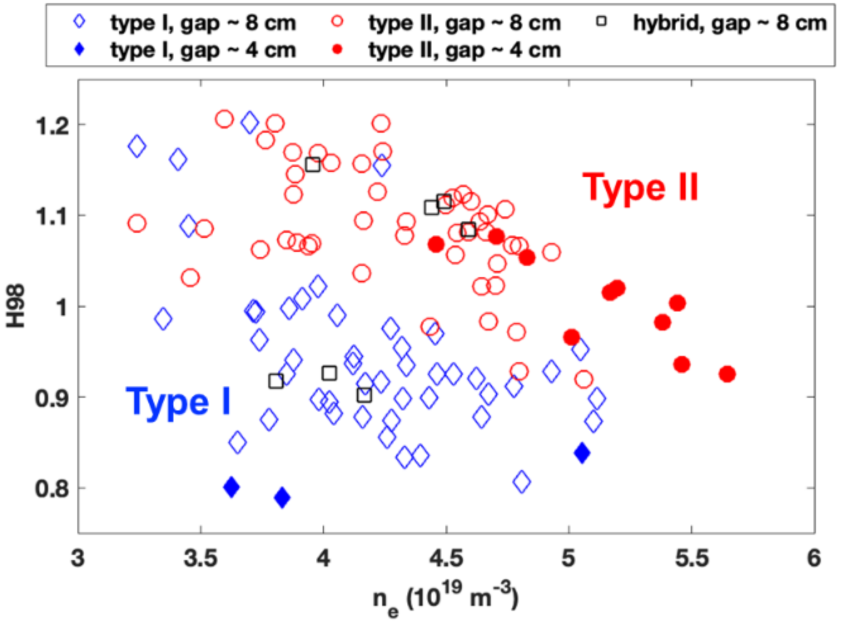
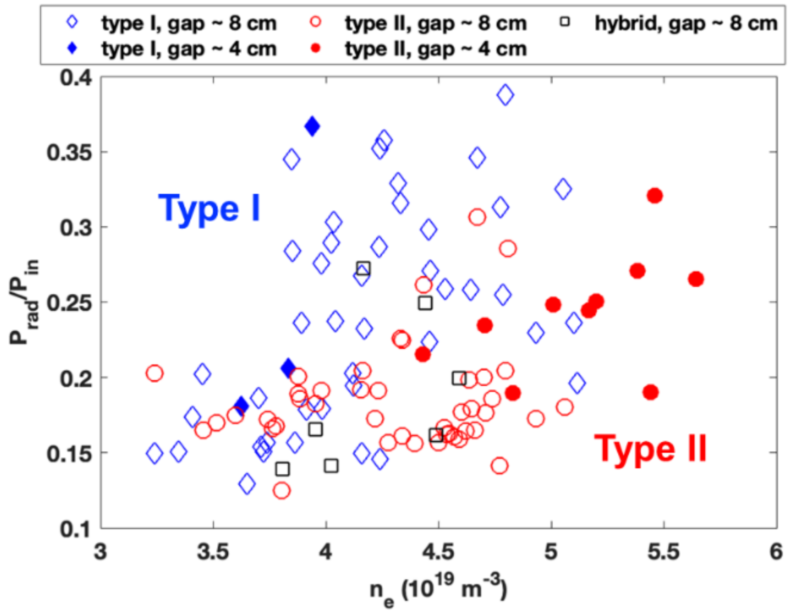
- **Summary**

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







- Assessed for low/no B coverage in high q_{95} ~ 6 DN plasmas with B_t ~ 2.45 T (central ECH)
- Type II ELMs provide higher confinement, lower impact of the separatrix-limiter gap and lower plasma radiation than Type I ELMs

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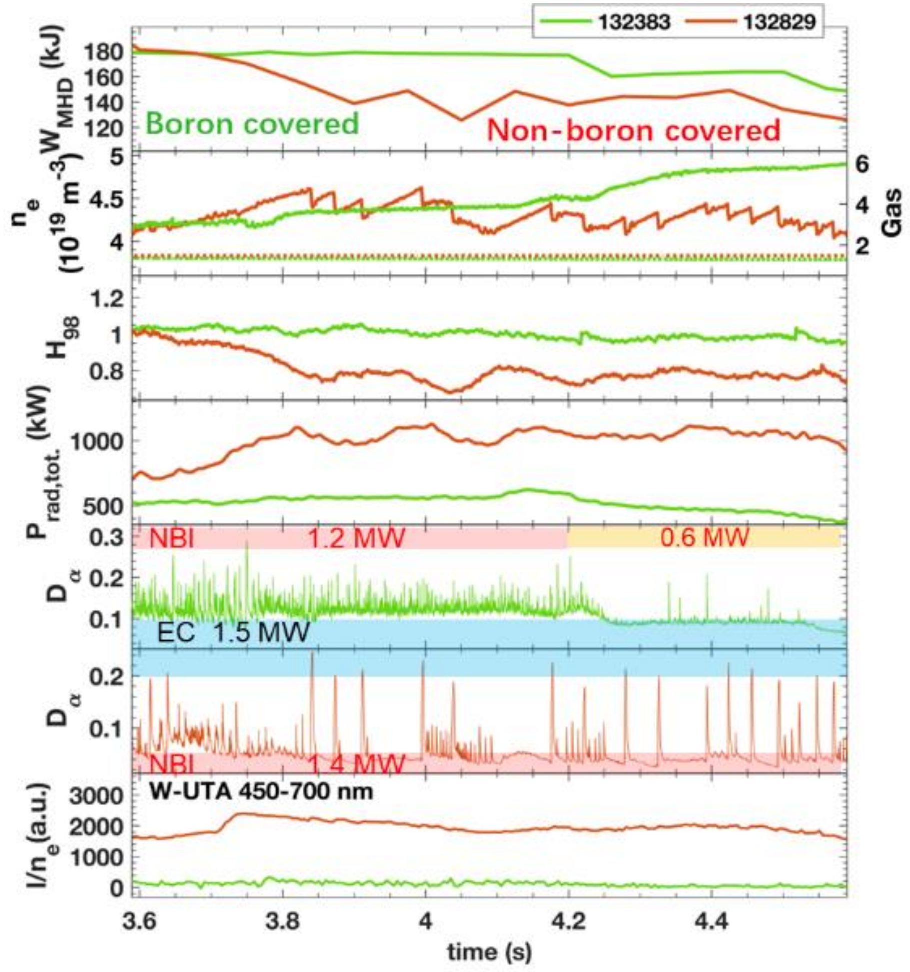
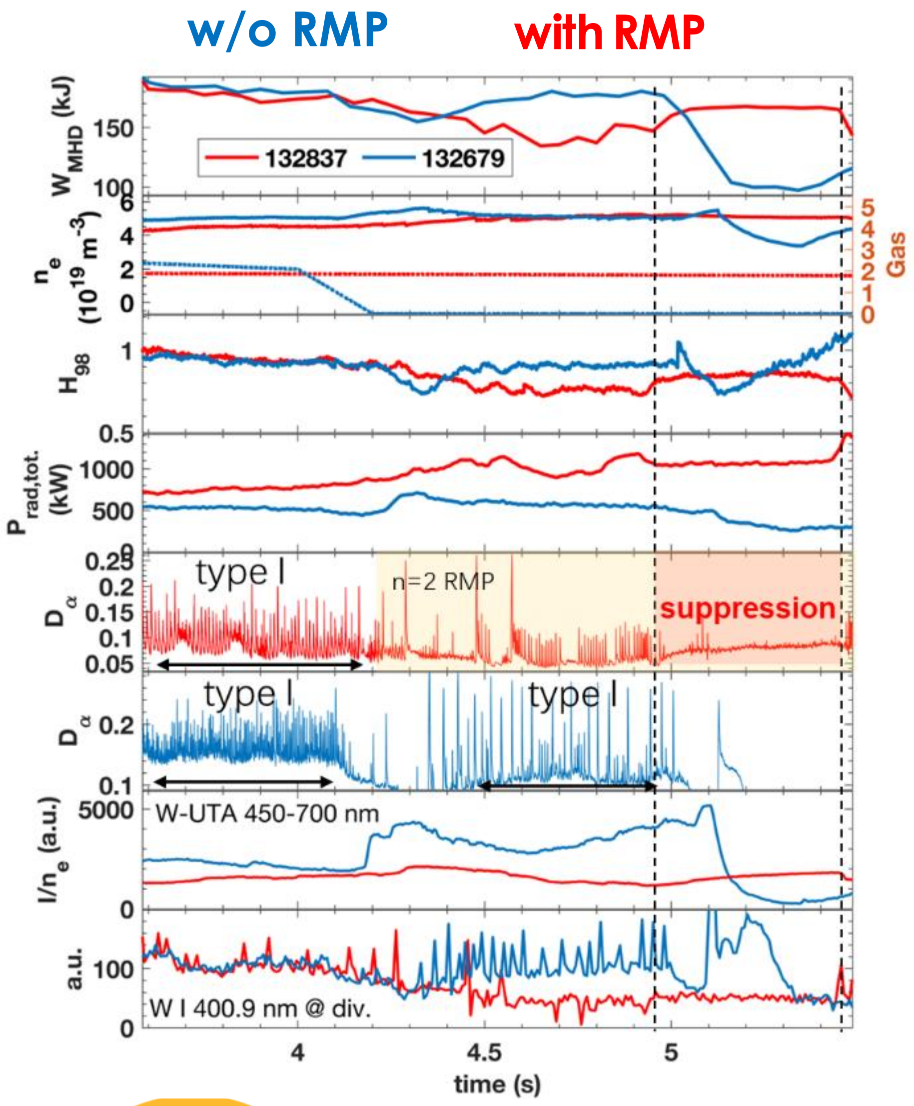
Impact of B Wall Coverage on H-mode Performance



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

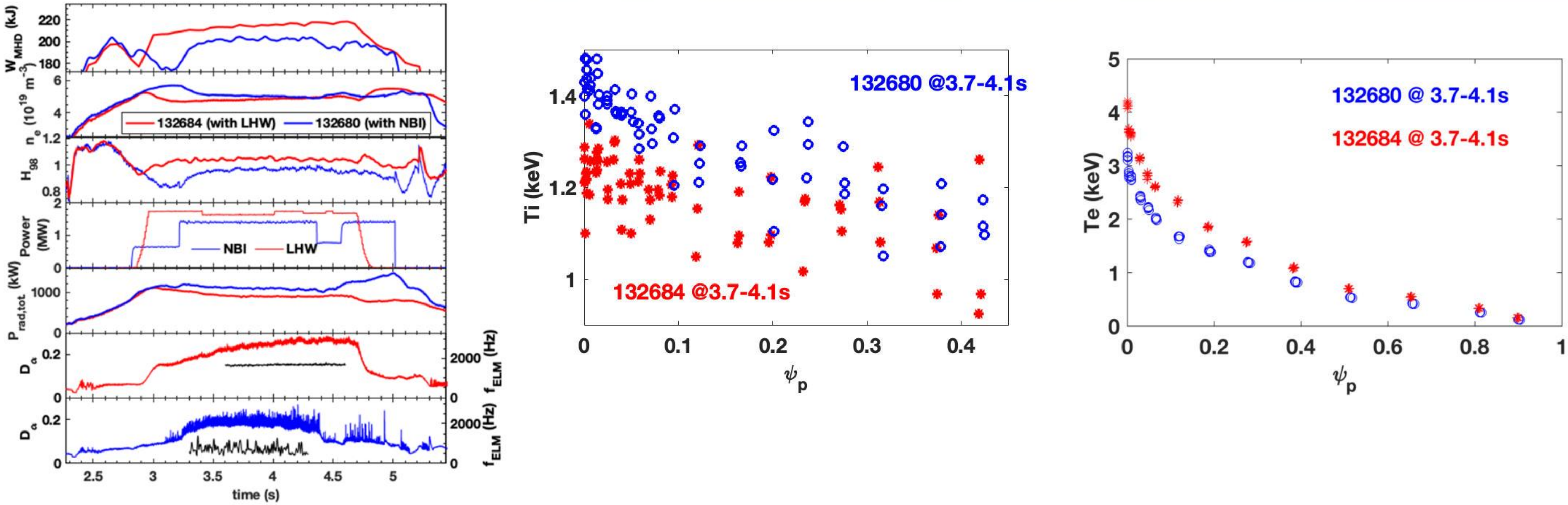
Impact of ELM Control on H-mode Performance



- **Compared to type I ELMs, impact of ELM mitigation/suppression with n=2 RMPs shows with**
  - reduction of W level in core
  - minor effects on plasma energy and particle confinement

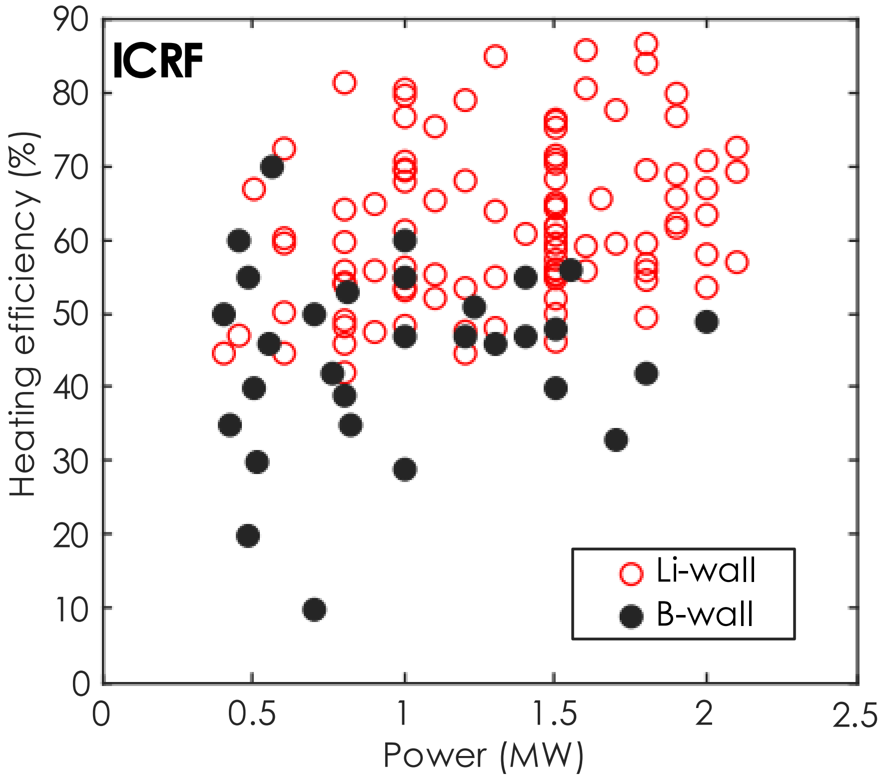
- ***Compatibility with nitrogen seeding in small ELM regime demonstrated***

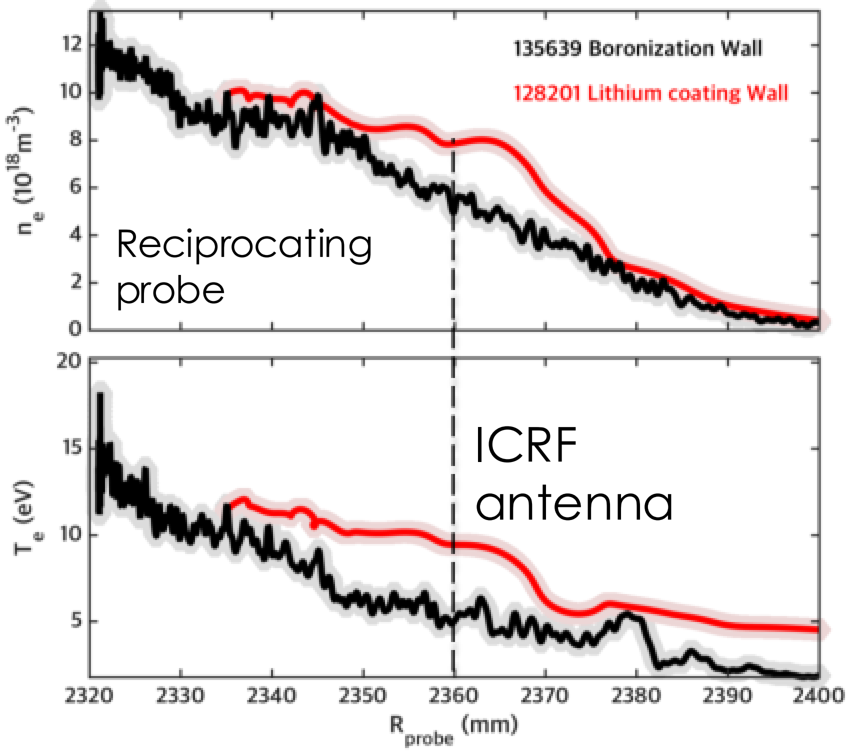
Impact of Heating and Current Drive Mix on H-mode Performance



- **Type II ELMs with 3MW ECH and similar levels of NBI or LHW**
- **An overall higher energy confinement for LHW heated plasma compared to NBI**
  - Higher Ti with NBI; higher Te with LHW
  - Similar ne and core plasma radiation

Impact of Wall Conditions on H&CD Efficiency





- **The reduced ICRF heating efficiency with Boron-coating compared with Li-coating**
- **Edge profiles changed with different wall conditions**

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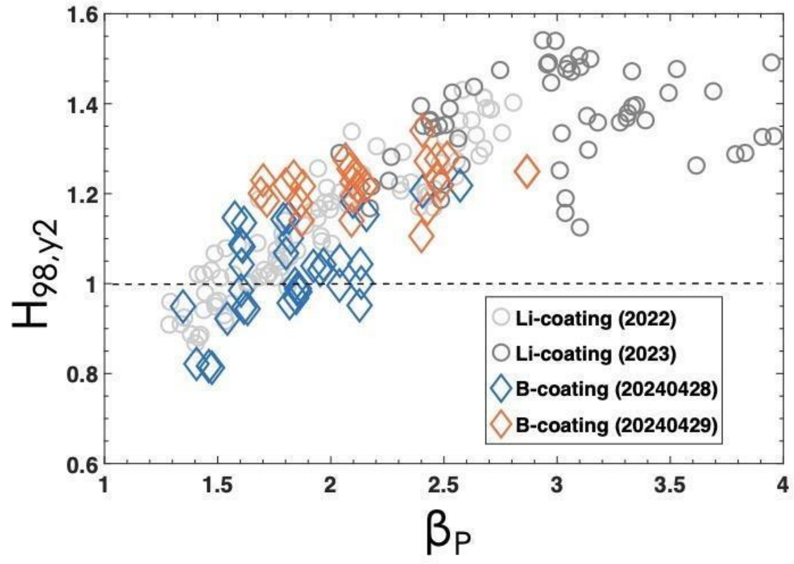
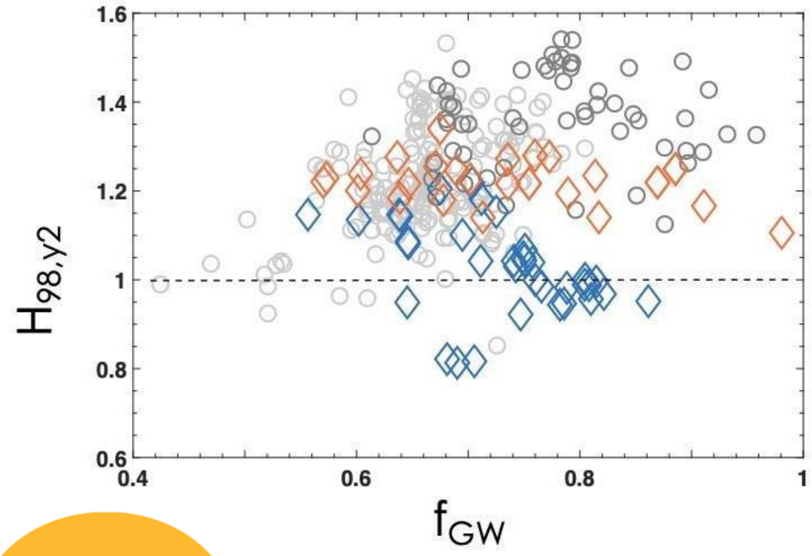
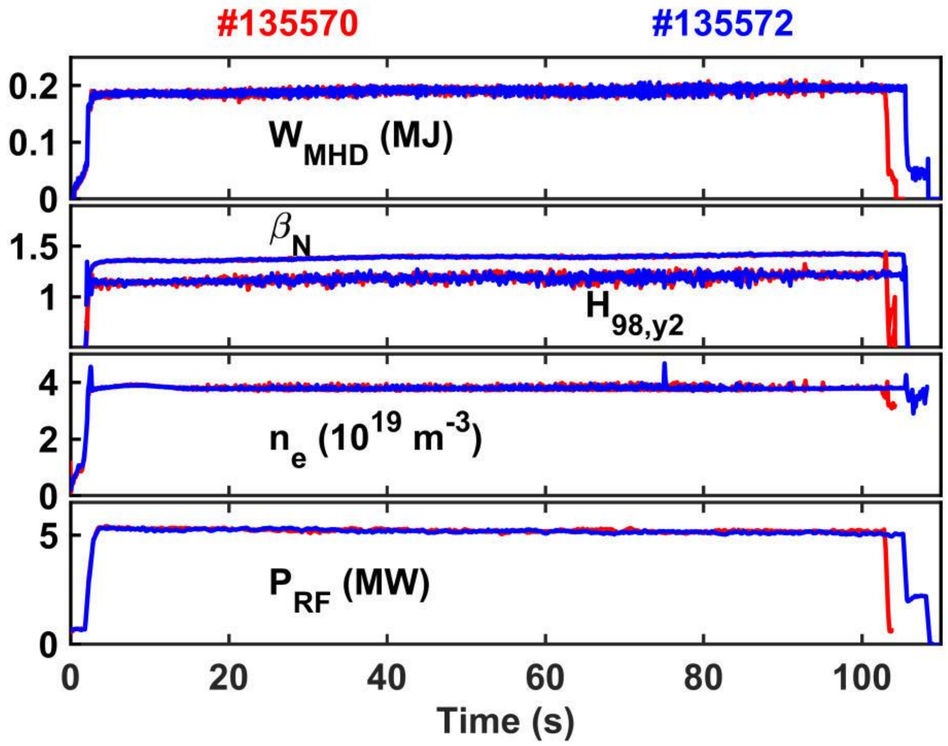
Demonstration Long Pulse H-mode Plasmas on Full Metal Wall

See **X. Gong's** talk in this meeting







- **Energy confinement with B-coating is reduced by ~10-15%, compared with Li-coating**
- **Stationary ~100s H-mode plasmas achieved**

Outline

- Progress of EAST in support of ITER and CFETR
- Key issues in high-performance and long-pulse regime
- Recent results contributed to ITER new research plan
- Summary

Summary

- **Significant progress has been made in long-pulse SSO on EAST**
  - Record of duration ~403s fully non-inductive H-mode plasma demonstrated
  - Development of state steady high-β_p scenarios up to 100s with zero torque injection (β_p~3.0/β_N~1.8, f_{BS}>50%, n_e/n_G~0.82, H_{98y2}~1.5)
- **Advances on key issues essential for long pulse SSO, support ITER and CFETR SSO**
  - Improved confinement with stability, broad j(r), Shafranov shift, e-ITB, high efficiency of H&CD at high density, active controls of radiative divertor, small ELM, plasma control, etc.
- **Dedicated joint ITER-EAST experiments have been performed in support of the ITER NRP.**
  - Long pulse type II H-mode plasmas up to 100 s were achieved on W wall without li coatings.
  - The impact of W limiter, heating schemes, boronizaiton on H-mode performance have been first evaluated in EAST.
- **Near-term plan with upgrade of inner components and augmented H&CD systems**
  - 1000s long-pulse H-mode operation with high bootstrap current fraction
  - Demonstrate SSO with **extended fusion performance** at 15-20 MW power injection

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

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