Progress on Long-pulse Steady-state High Performance Plasma on EAST

by

J. Huang[1]*

X. Gong[1], A. M. Garofalo[2], J. Qian[1], R. Ding[1], J. Chen[1], L. Xu[1], L. Zeng[1], B. Zhang[1], E. Li[1], Y. Huang[1], Y. Yu[1], X. Zhang[1], M. Li[1], A. Ekedah[3], R. Maingi[4], P. T. Bonoli[5], C. T. Holcomb[6], Y. Sun[1], L. Wang[1], Q. Zang[1], B. Lyu[1], H. Liu[1], Q. Ren[1], G. Li[1], D. Yao[1], P. Zi[1], G. Zuo[1], Y. Wang[1], H. Si[1], J. Wang[1], M. Wang[1], H. Xu[1], Q. Yuan[1], Q. Yang[1], L. Zhang[1], Y. Xie[1], Z. Huang[1], Y. Huang[1], G. Gao[1], G. Xu[1], J. Hu[1], K. Lu[1], Y. Song[1], B. Wan[1] , J. Li[1] and EAST team[1]

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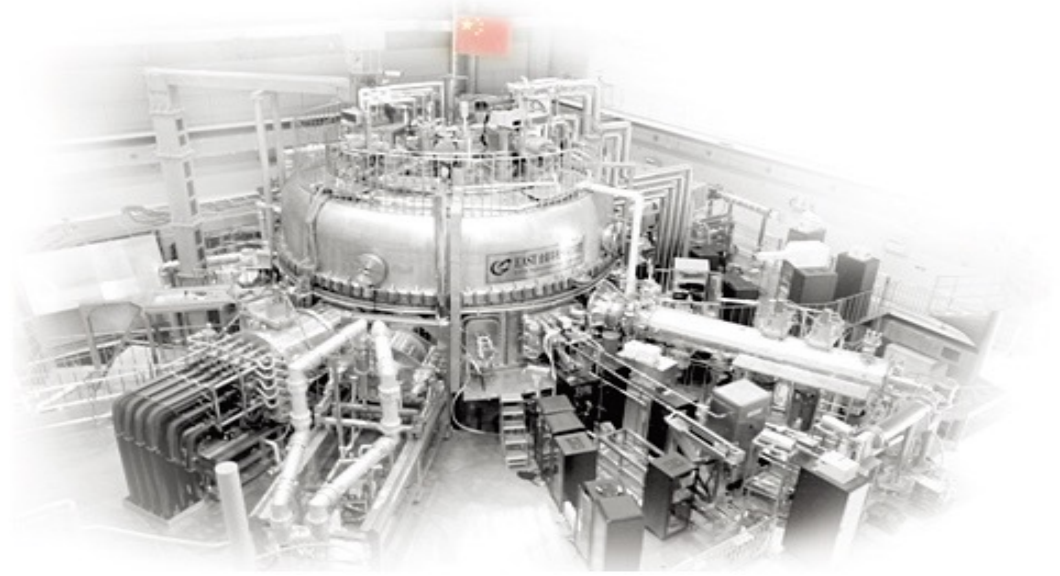

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Vienna, Austria, IAEA Headquarters

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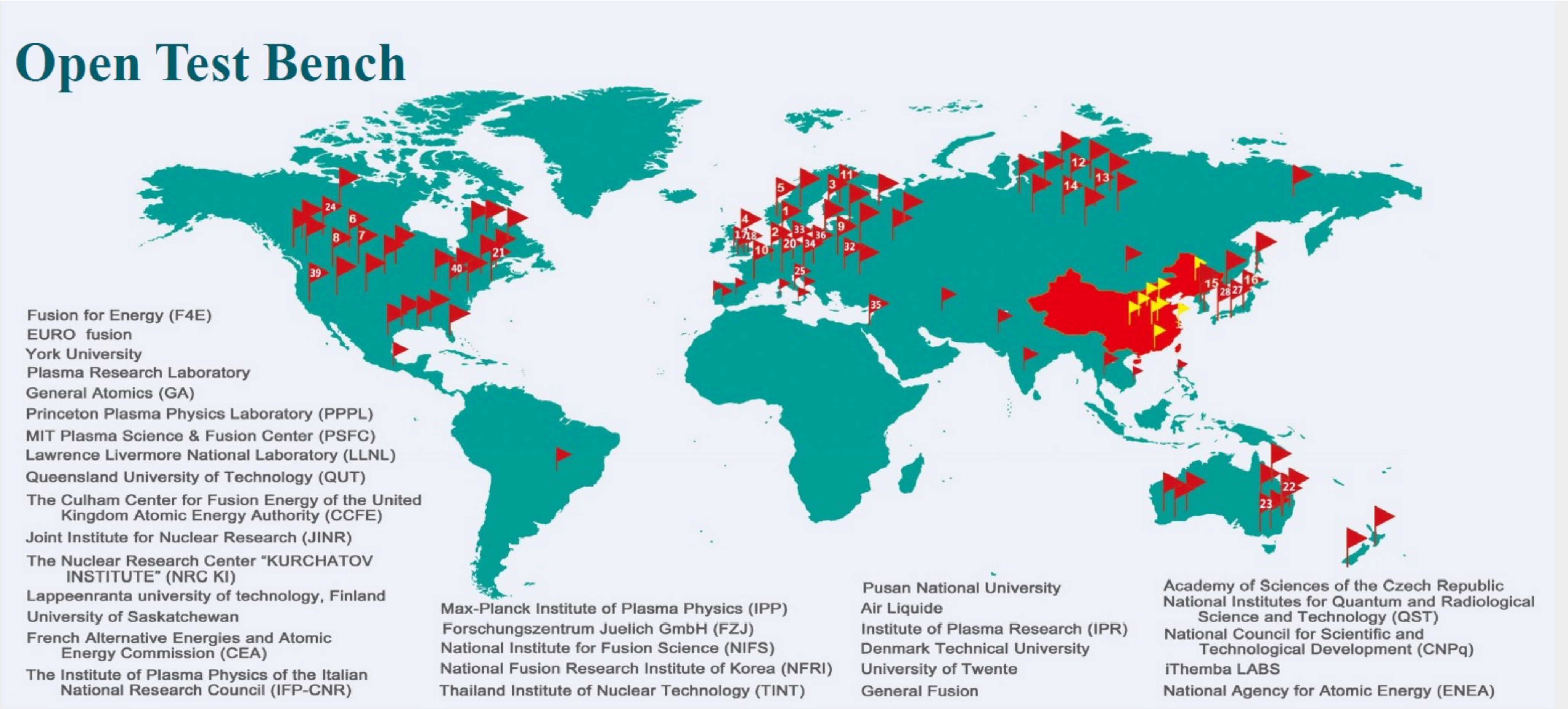
Acknowledgement



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

Outline

- Progress of EAST in support of ITER and CFETR
- Key issues in long-pulse and steady-state regime
- Future plans and summary

ASIPP

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- ❑ Progress of EAST in support of ITER and CFETR
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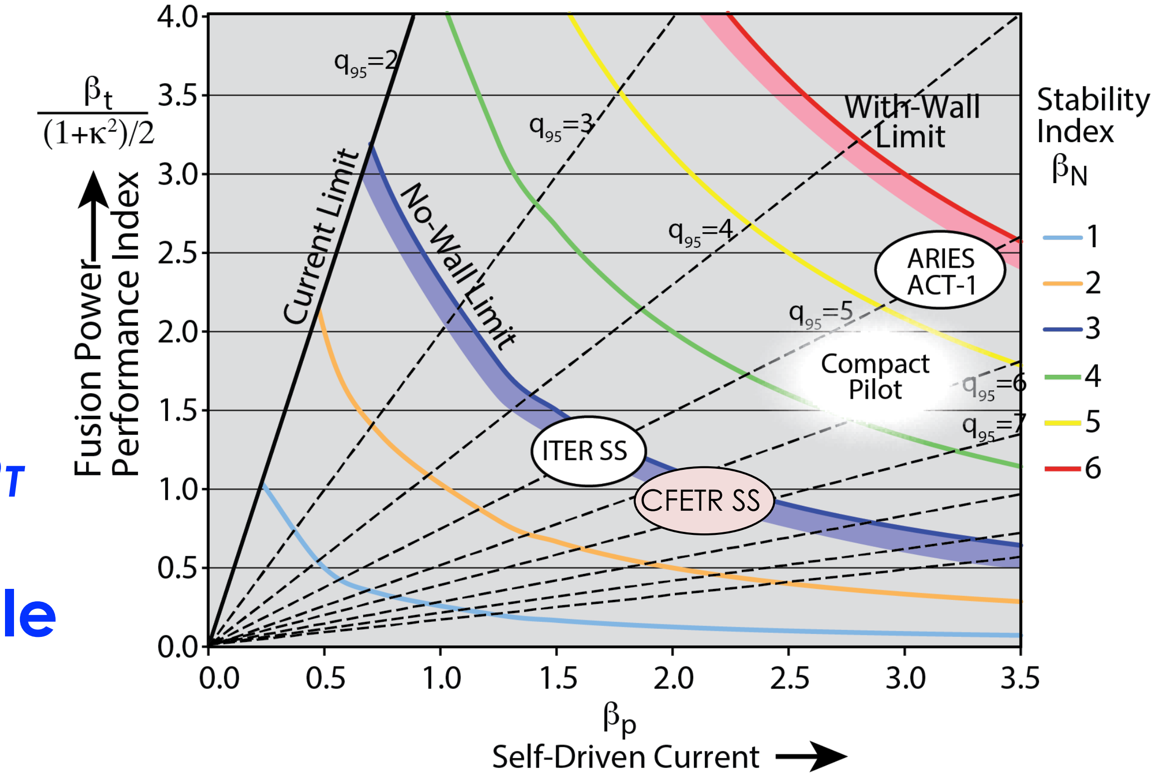
ASIPP

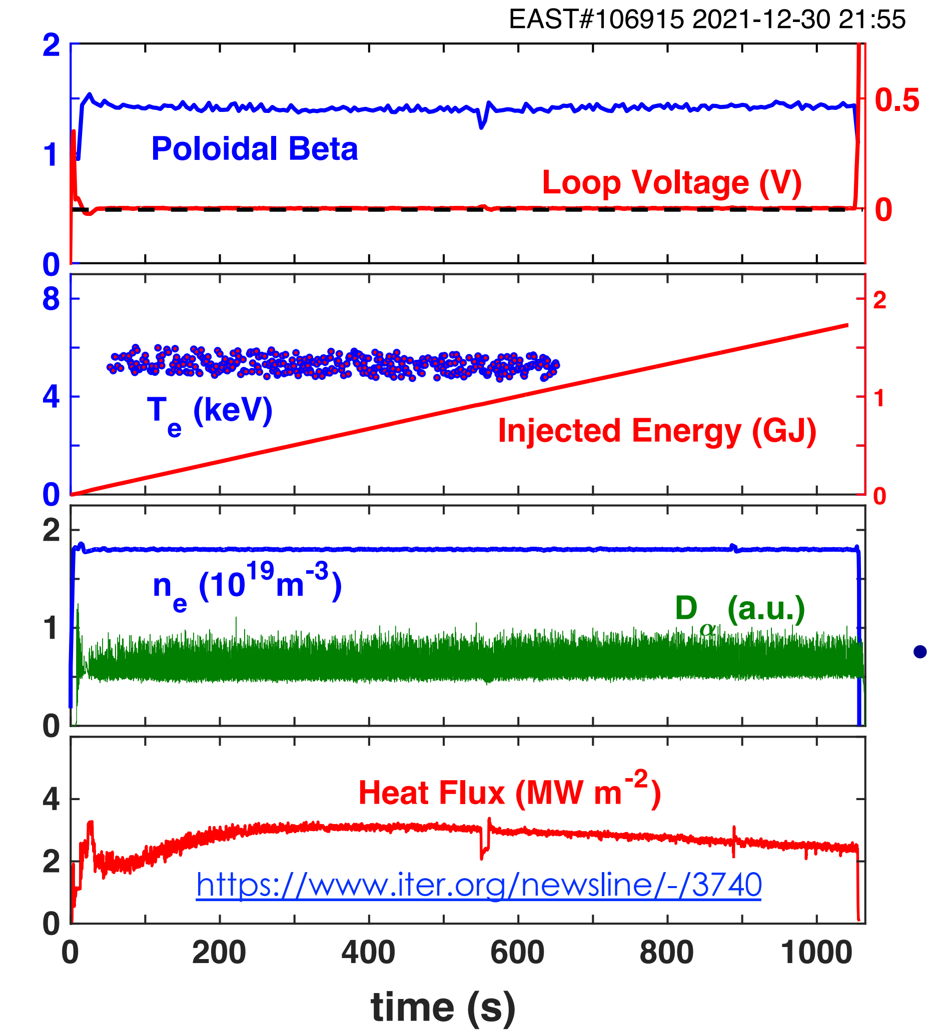
A Steady-state Tokamak Research Aims at Efficient Low Cost Fusion Reactors for a Sufficiently Long Duration

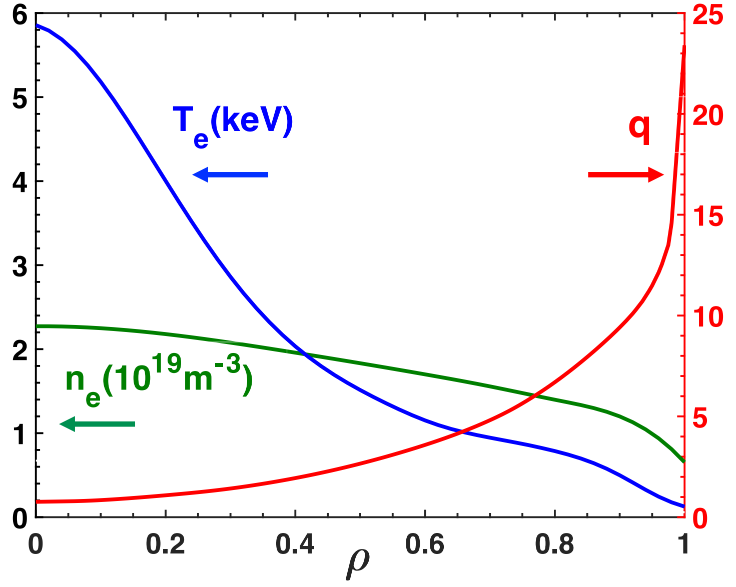
- **Steady state operation requires fully non-inductive current $I_P = I_{CS}\ (\rightarrow 0) + I_{BS} + I_{AUX}$**
- **High self-driven current requires high β_P**
- **High fusion power requires high pressure β_T**
- **Long pulse operation requires good particle control and heat flux exhaust**

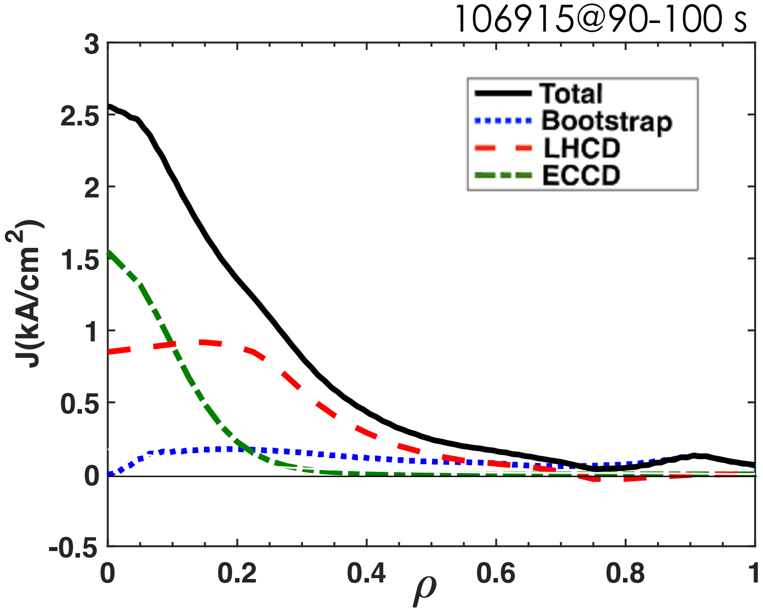


ITER aims at Q≥5 long-pulse (~3000s) and steady-state operation (SSO)

Demonstration of 1056-second Steady-state Plasma with Full Metal Wall on EAST



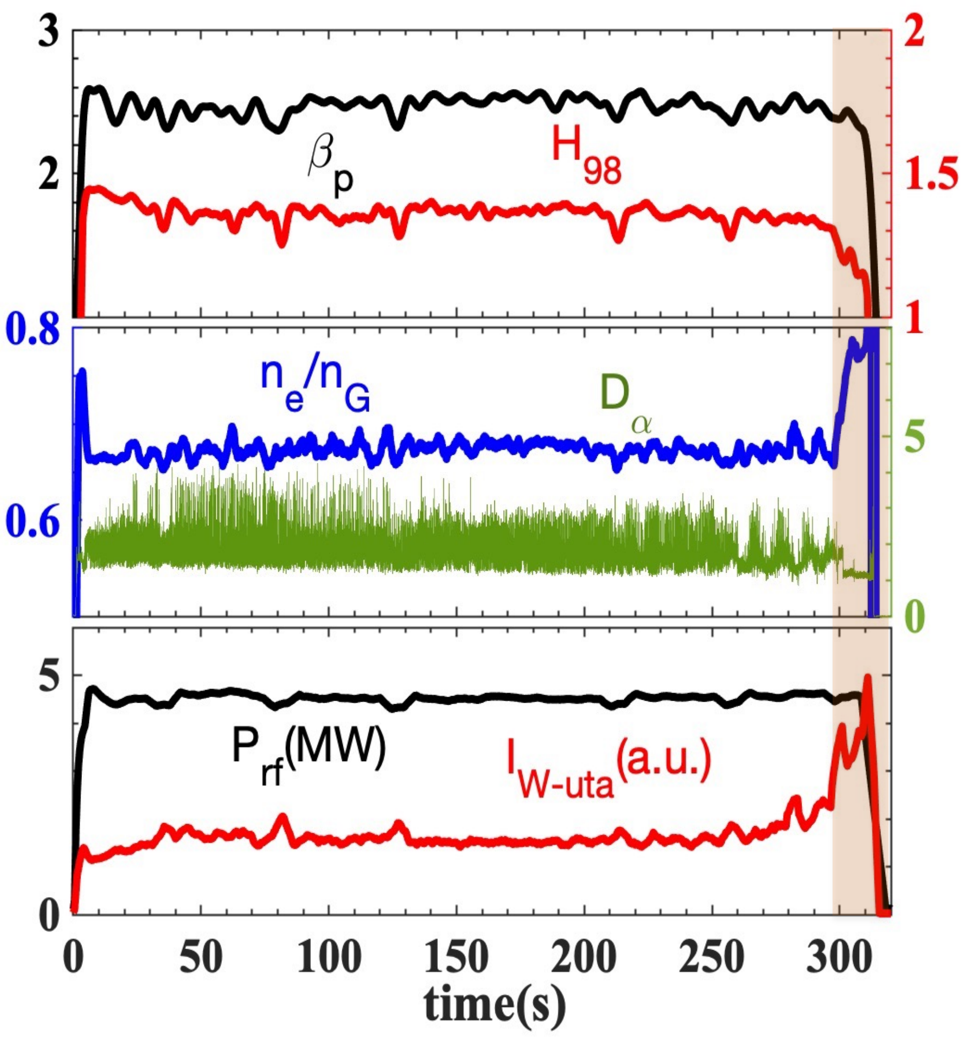


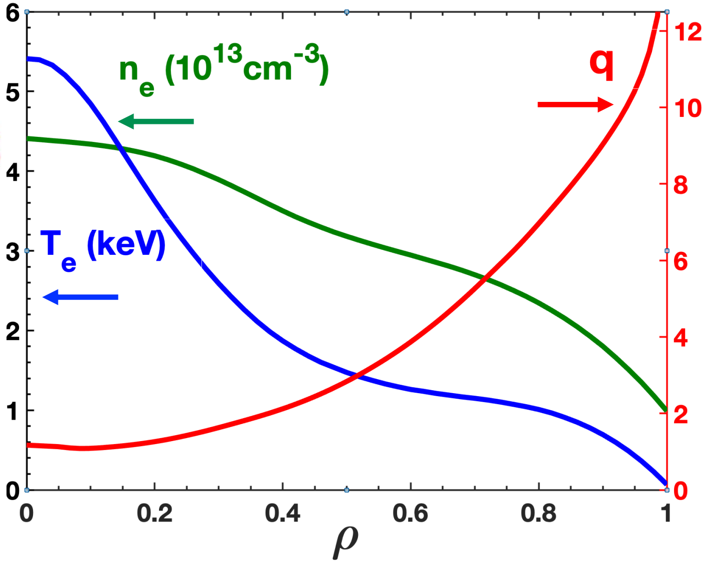


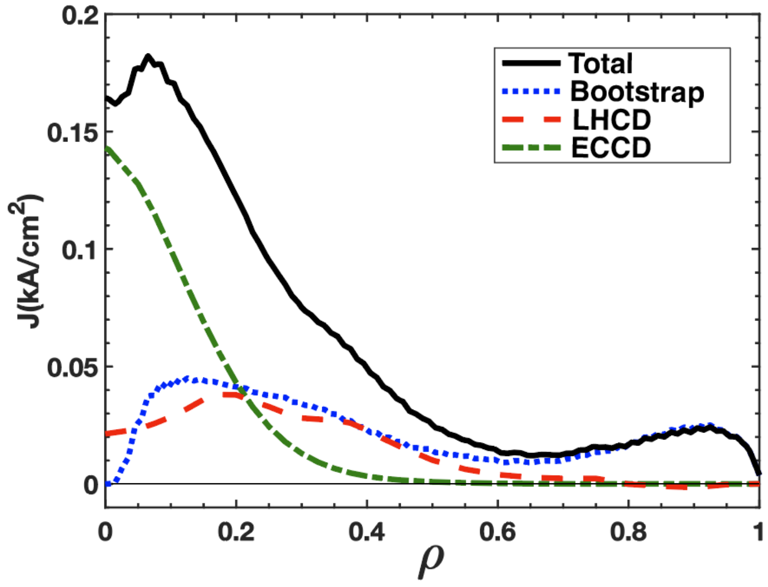
- **Fully non-inductive plasma with improved confinement**
  - H_{89} ~1.3, total injected energy ~ 1.73 GJ
  - f_{RFCD}~70%, f_{BS}~30%, V_{loop}~0 with feedback control by LHW
  - Enhanced power exhaust with new water-cooled W lower divertor
  - Lower recycling control with real-time wall conditioning
  - Good control of plasma equilibrium and position over long time scales

Y. Song, Sci. Adv., in press, 2022

Record Duration of 310-second H-mode Plasma Achieved with Tungsten Divertor on EAST







- **Steady-state high-performance plasma with dominant e-heating**
  - RF-only: P_{LHW}~2MW, P_{EC}~1.6MW, P_{IC}~1.2MW
  - H_{98y2} >1.3, f_{Gr}~0.7, zero injected torque
  - β_P~2.5, β_N ~1.6, f_{BS}>50%
  - Small ELM (f_{ELM} >2.5kHz) with negligible transient heat load
  - Robust iso-flux control with SP to W-divertor

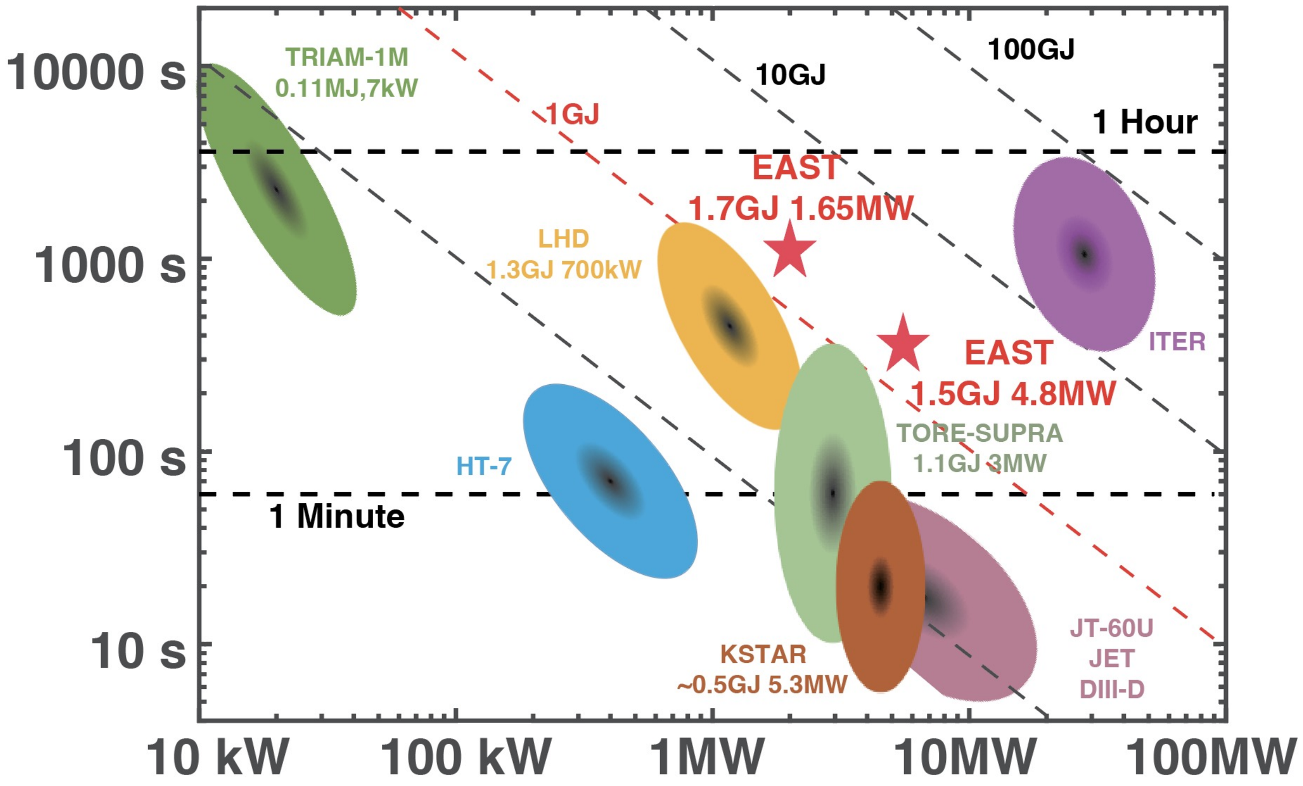
J. Huang, 64th APS, post-invited talk, 2022

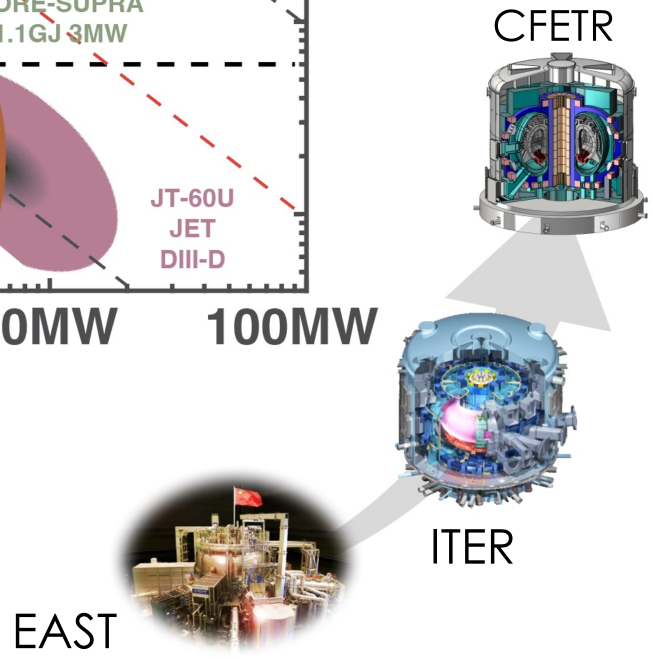
Strategies to Establish the Scientific Basis for Long-pulse Operation in Support of ITER and CFETR

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

S2: Demonstrate long-pulse (≥100s) H-mode plasmas and develop fully non-inductive high-β scenarios

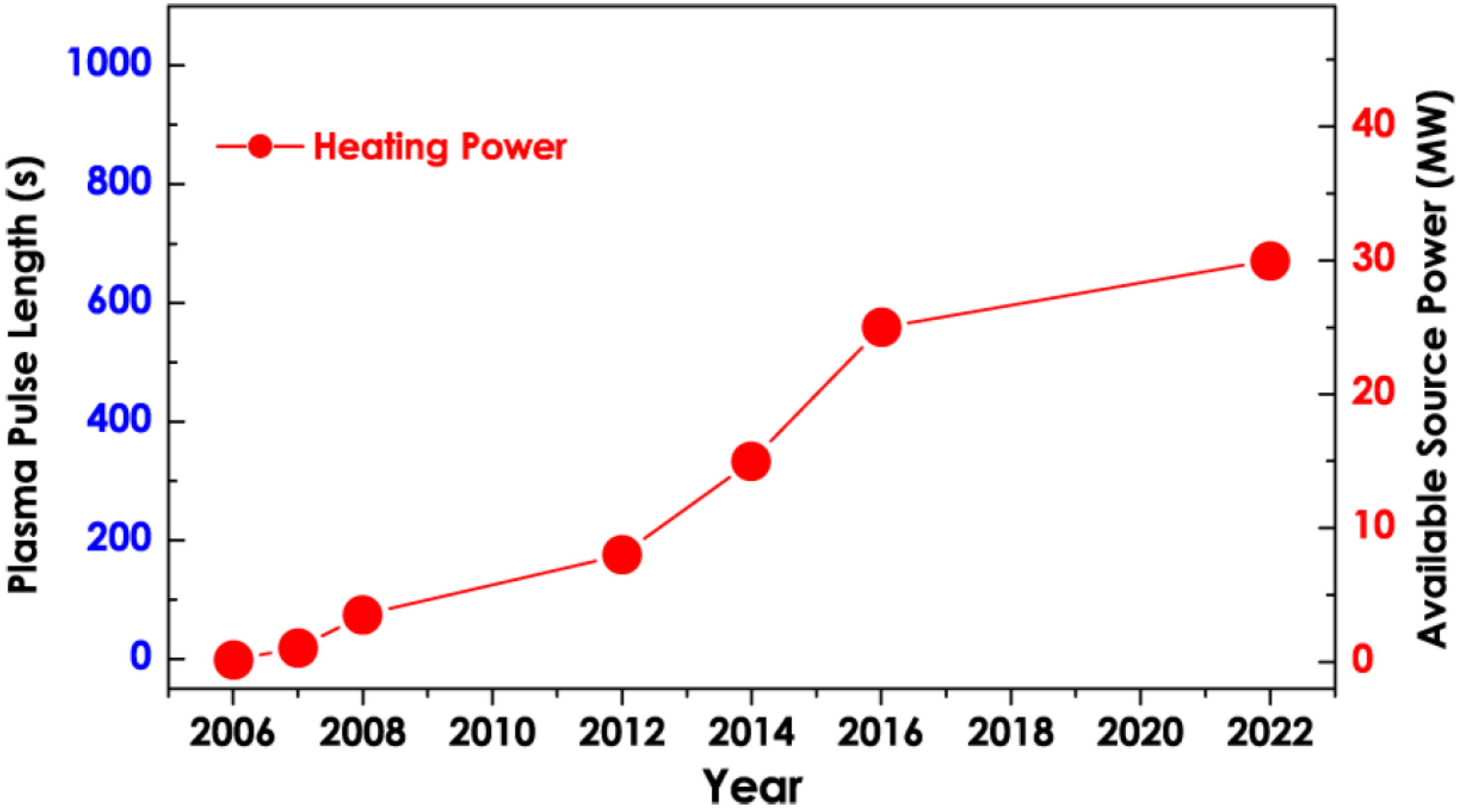
S3: Extend EAST operation regime to demonstrate steady-state high performance plasmas and deliver relevant physics for ITER and CFETR





Progress on Long-pulse Steady-state 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



Demonstrate capabilities of engineering and technical issues for LPO on EAST

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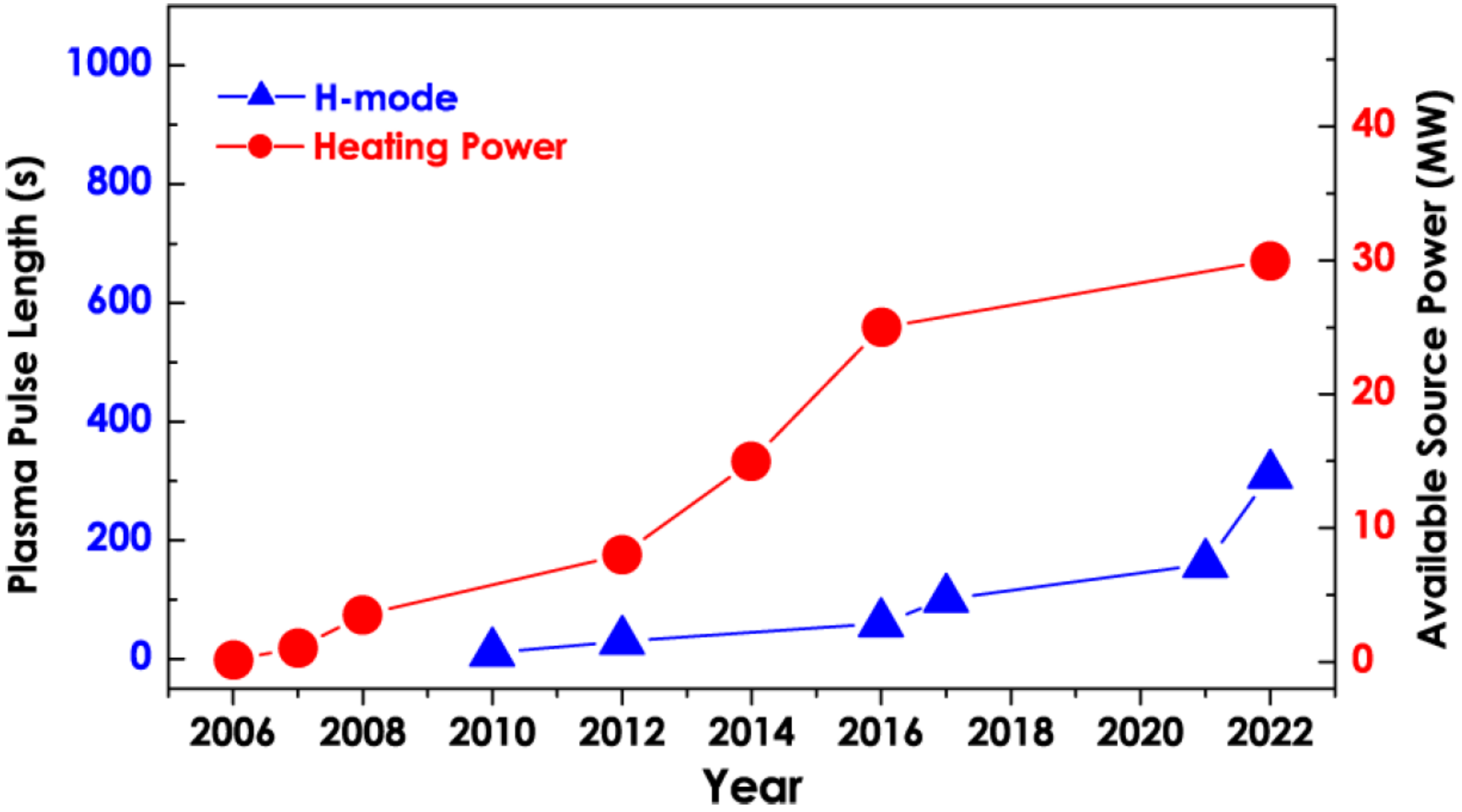

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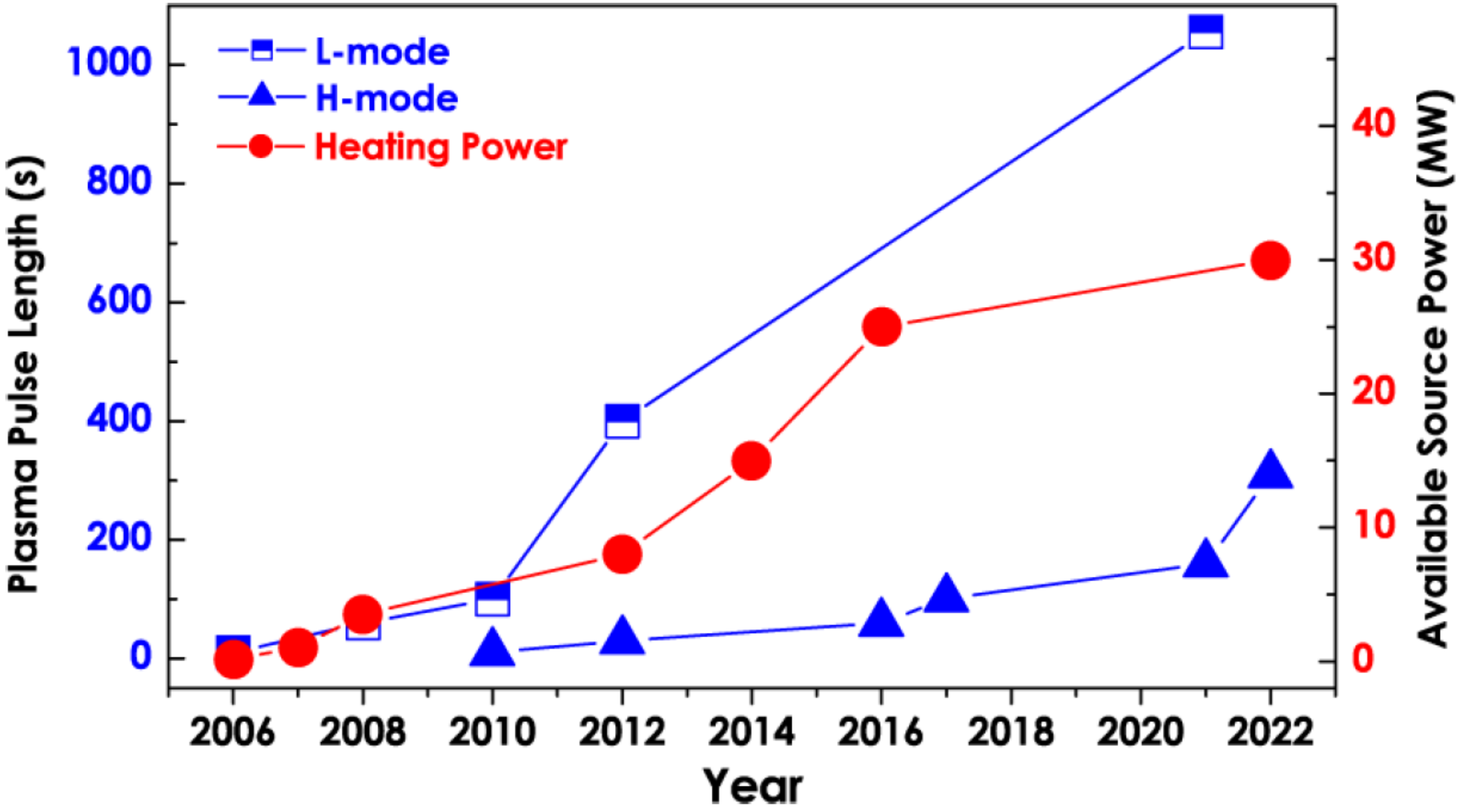

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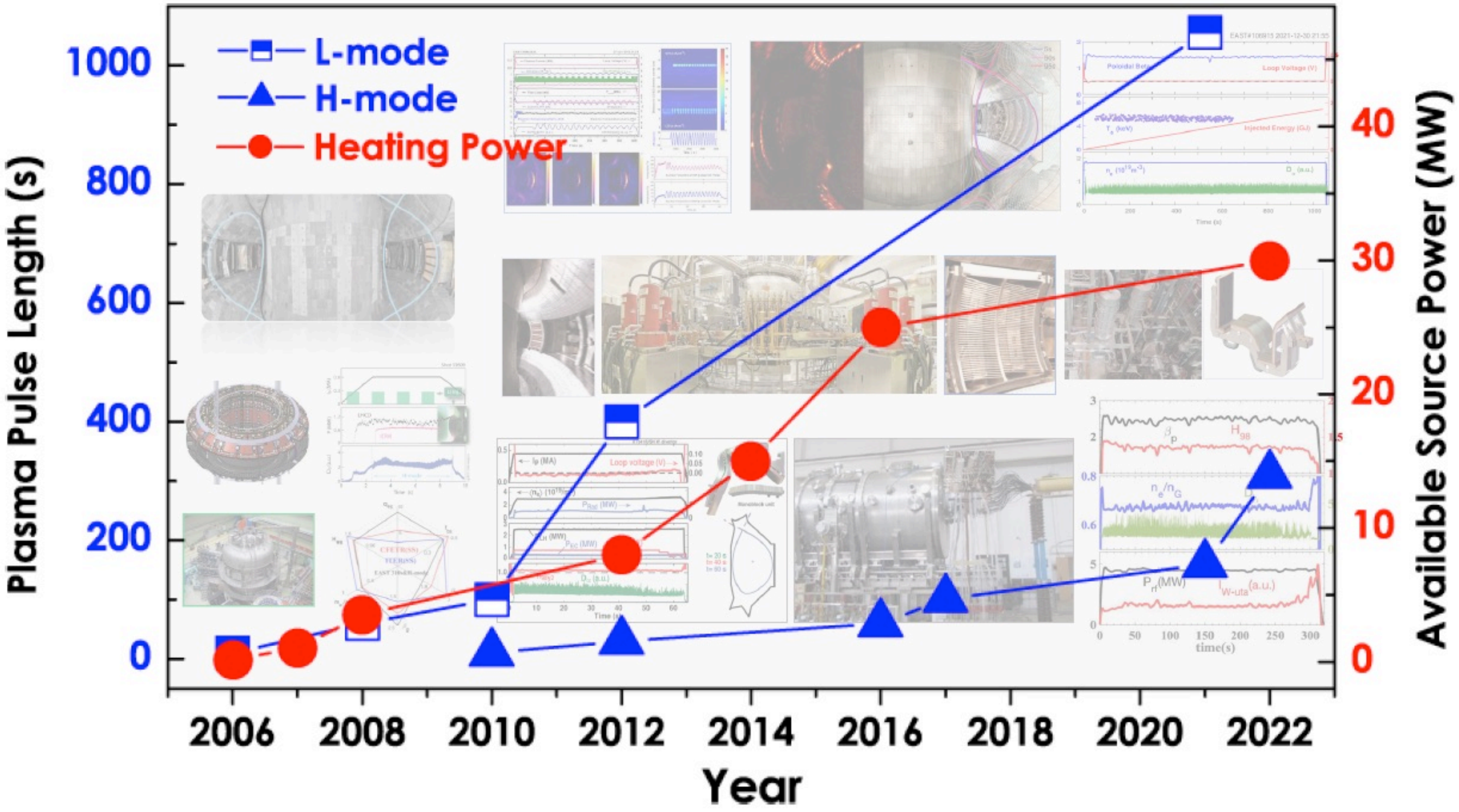

Demonstrate capabilities of engineering and technical issues for LPO on EAST

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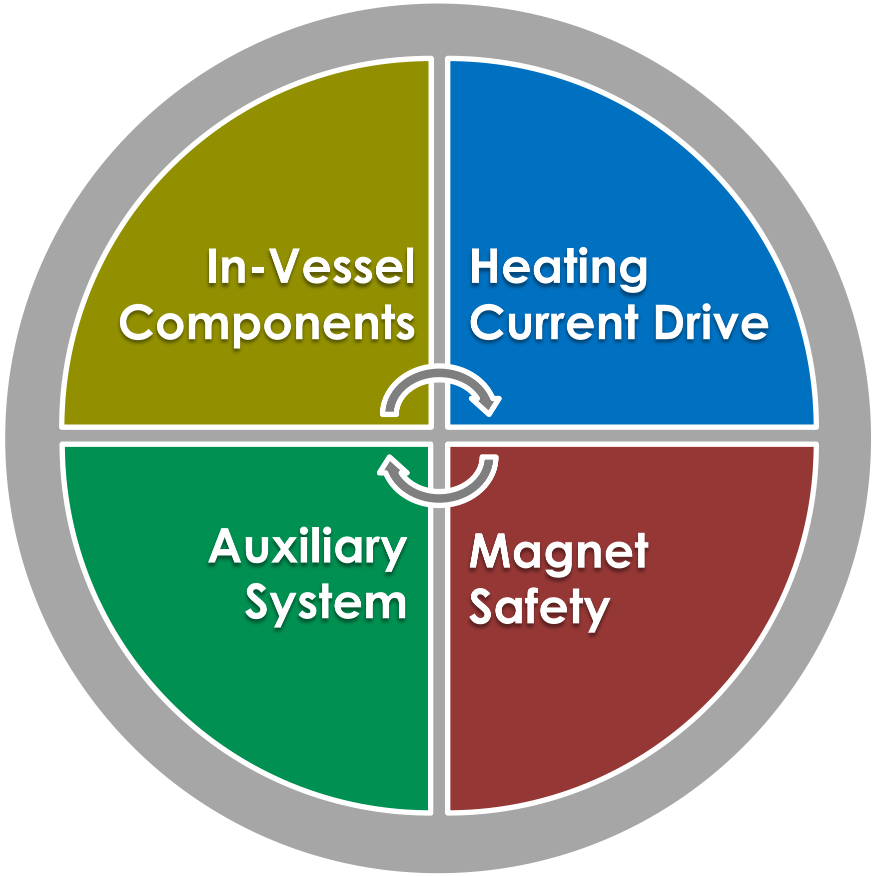
Outline

- **Progress of EAST in support of ITER and CFETR**
- **Key issues in long-pulse and steady-state regime**
  - Enhanced technical capabilities
  - Demonstrate1056s fully noninductive plasma
  - Achieve 310s steady-state high-performance plasma
- **Future plans and summary**

Hardware Upgrades Support Long-pulse SSO Research



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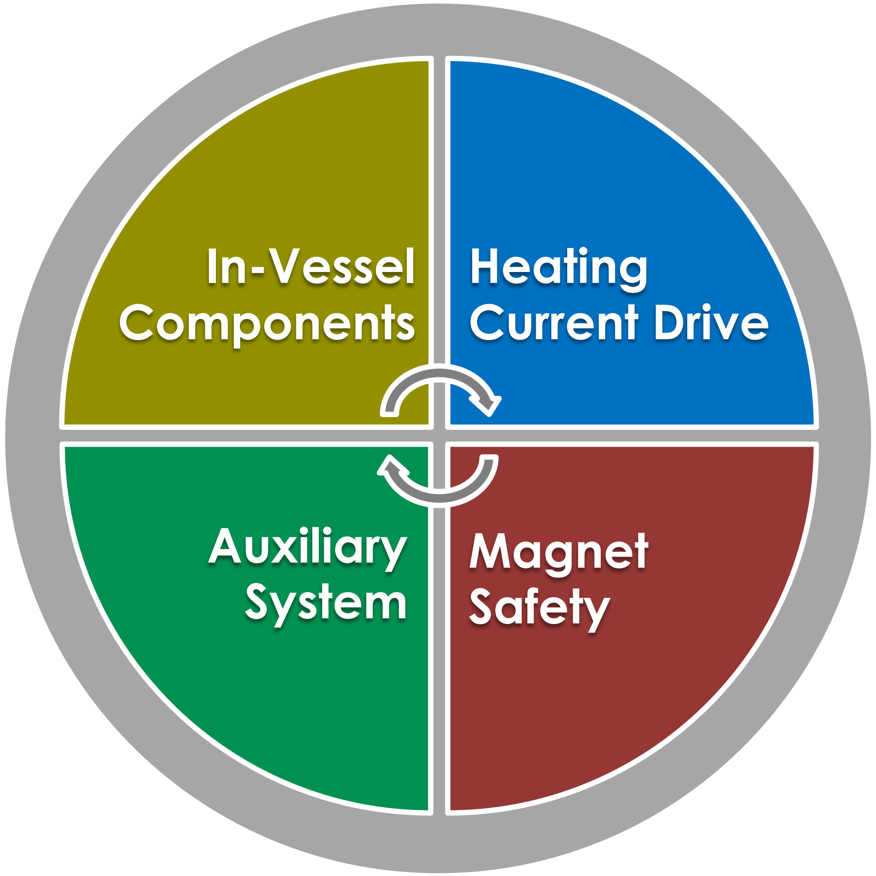

- Rearrangement of ports
- Improved coupling efficiency and injected power
- Guard limiter heat flux capability improvement

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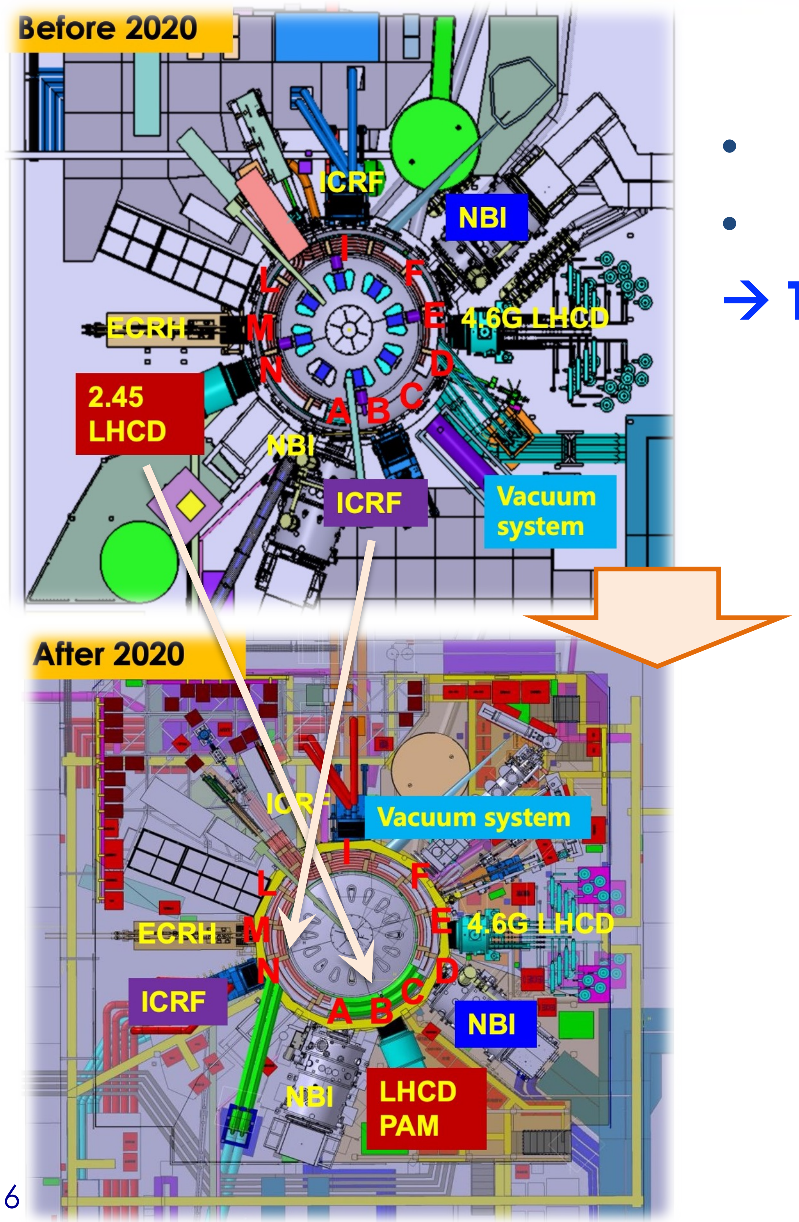
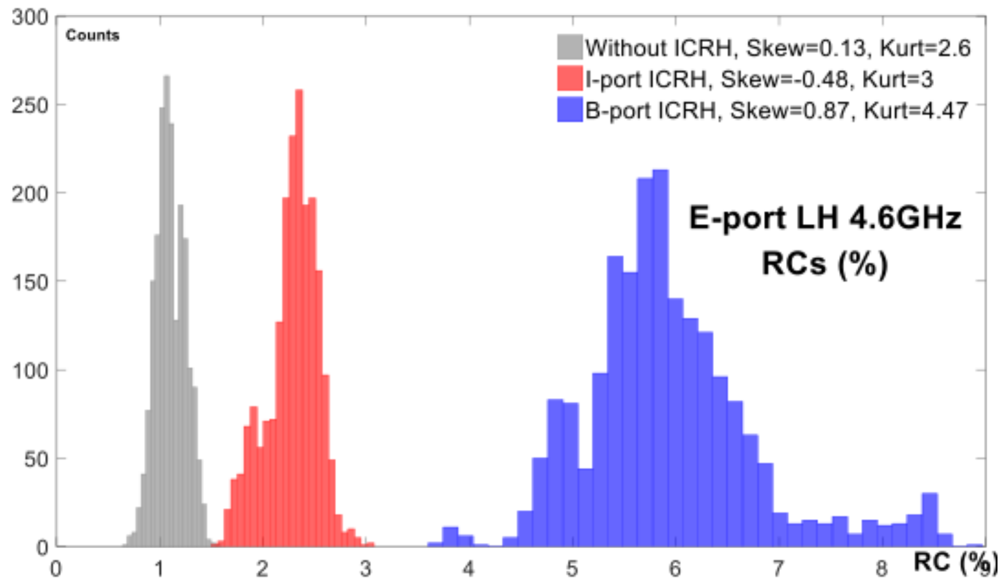
Rearrangements to Enhance H&CD Capability

See **M. Li**'s talk on Nov 16, this meeting

- **ICRF:** B port → **N port**
- **2.45GHz LHCD:** N Port → **B Port**

→ **To reduce interference of H&CD systems**





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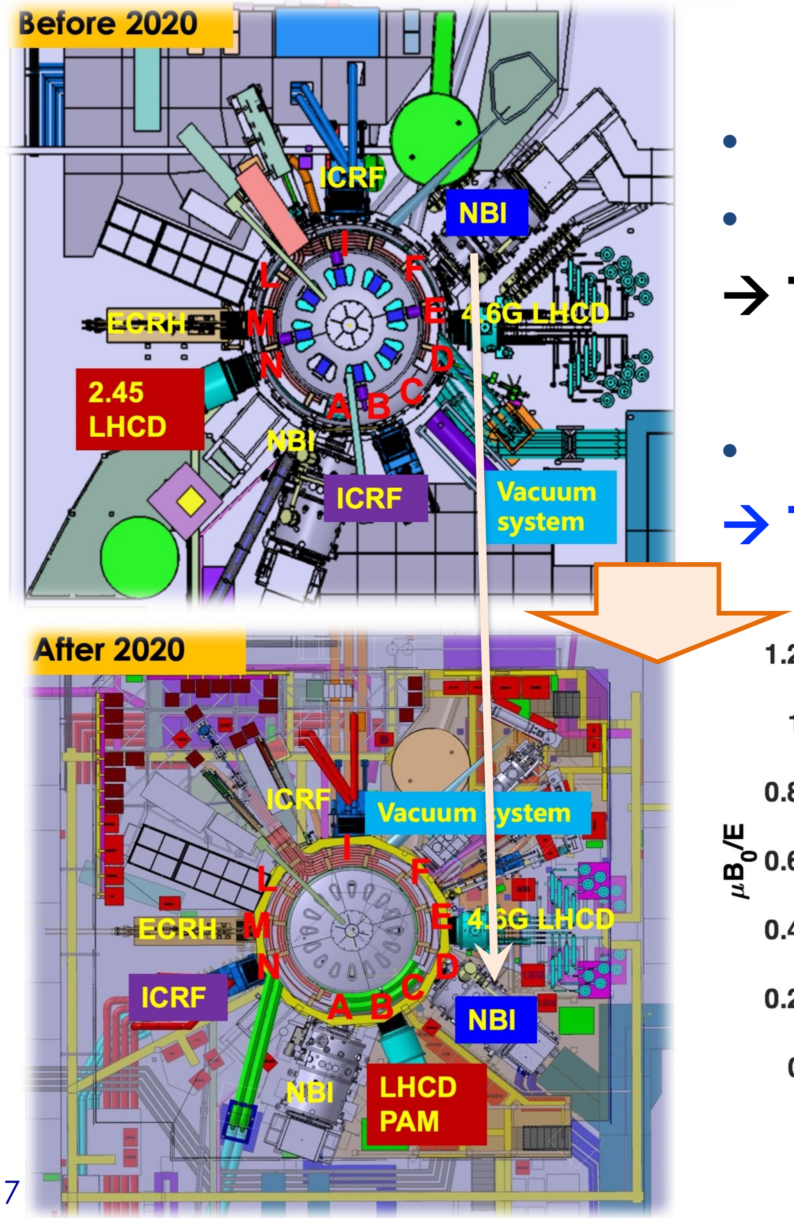
Rearrangements to Enhance H&CD Capability



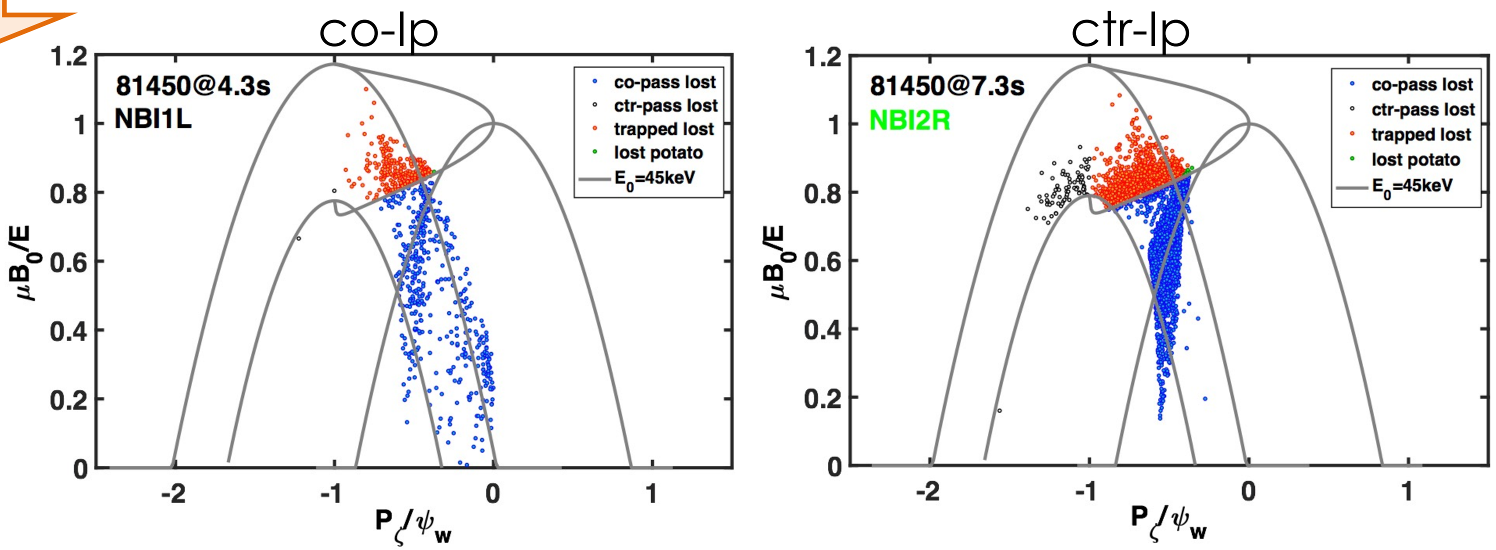
See **J. Wang**'s talk on Nov 16, this meeting

- **ICRF:** B port → **N port**
- **2.45GHz LHCD:** N Port → **B Port**

→ **To reduce interference of H&CD systems**

- **NBI:** F port (ctr-Ip) → **D port (co-Ip)**

→ **To reduce prompt loss for improve heating efficiency**



J. Huang, NF 2020

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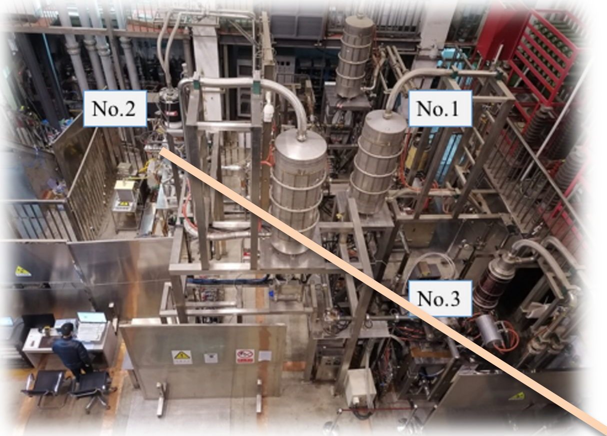
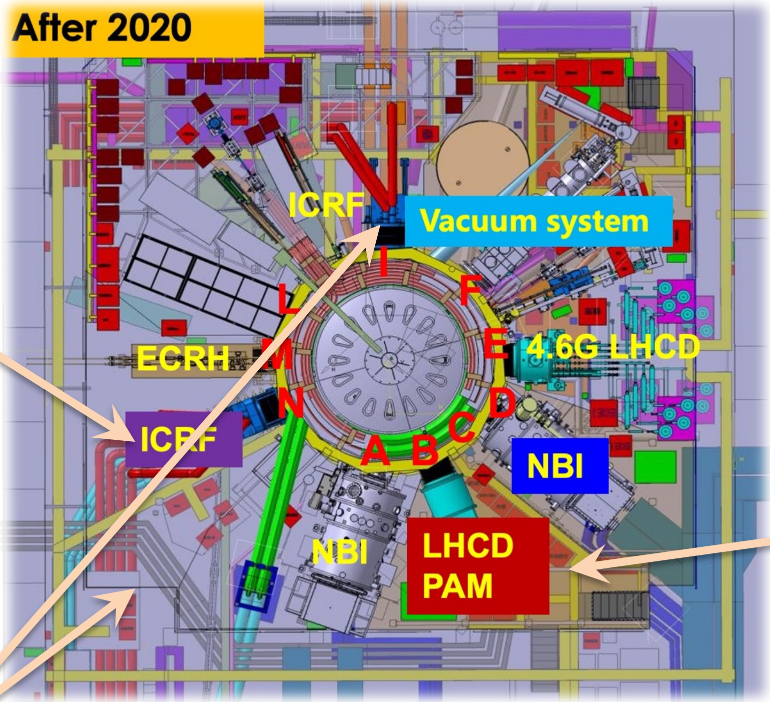
Improve Coupling and H&CD Efficiency

- **Available 4 Gyrotrons up to 4MW**

→ Flexible j(r) control and e-heating

See **M. Li**'s talk on Nov 16, this meeting



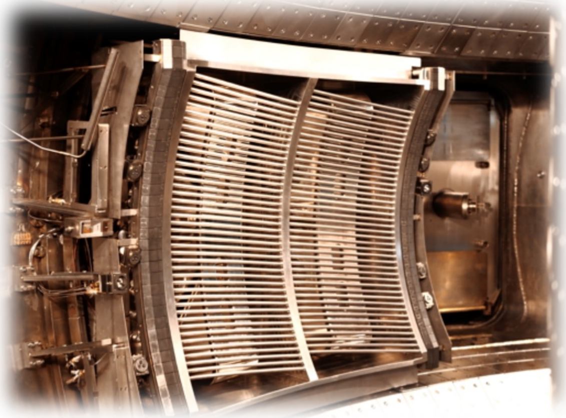


- **2.45GHz LHW: FAM→PAM antenna**

→ Improve long-distance coupling

- **ICRF with decreased $k_{||}$**

→ Improve coupling and heating efficiency



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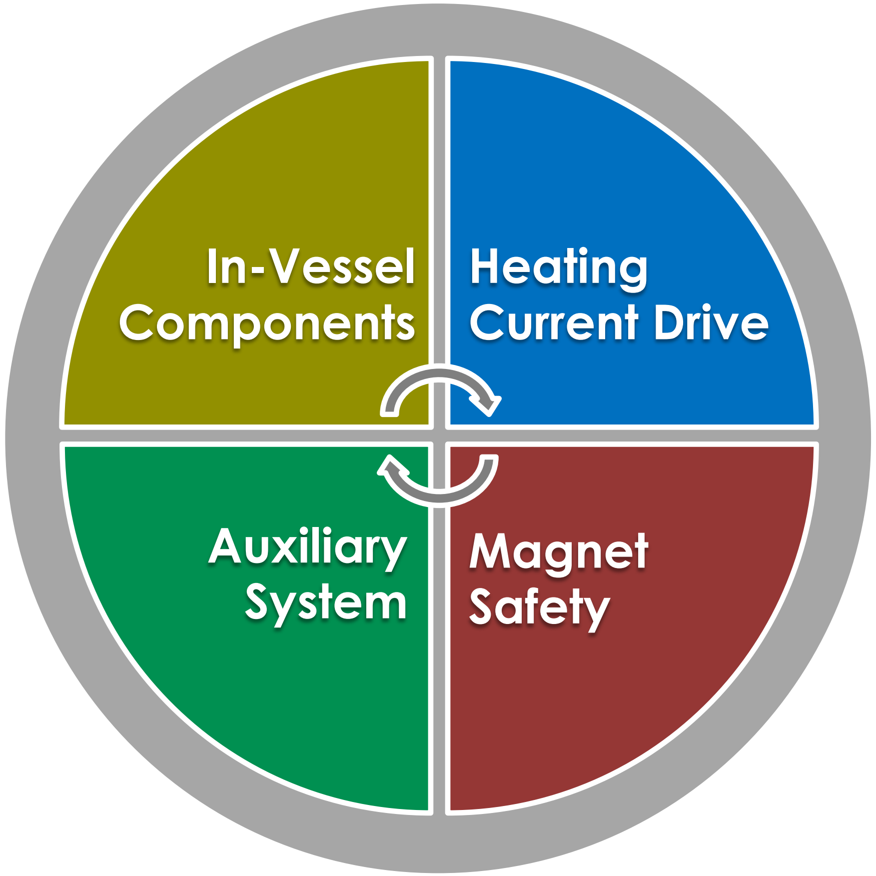
Hardware Upgrades Support Long-pulse SSO Research

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



- Rearrangement of ports
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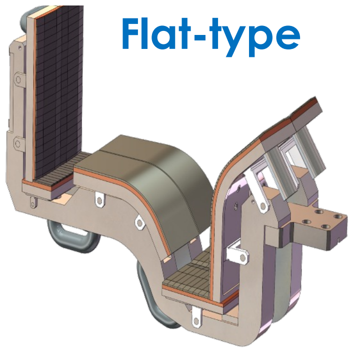
Full Metal Wall with Lower Divertor using W/Cu

Old graphite divertor

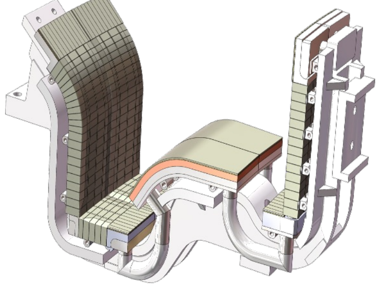
New lower tungsten divertor

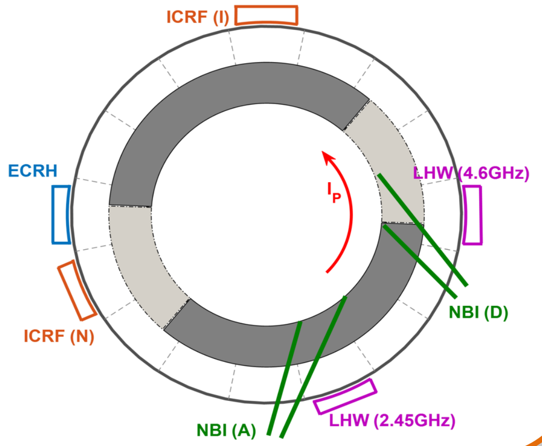
After 2020

Flat-type



Monoblock





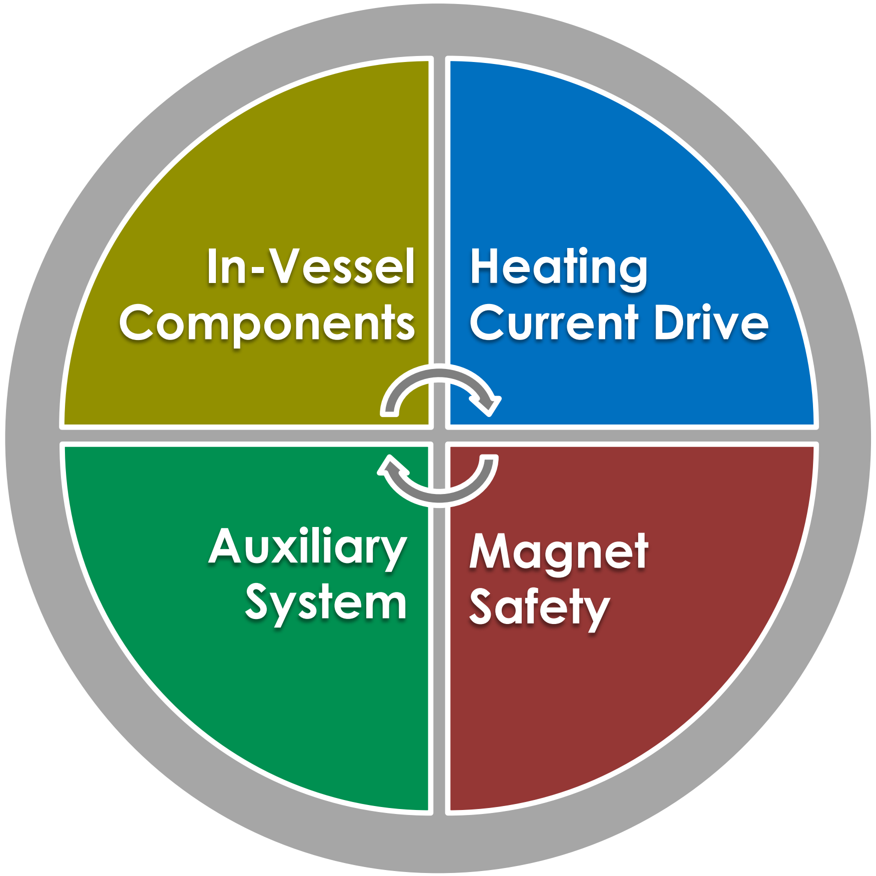
- **A new lower water-cooled tungsten divertor installed**
  - ¾ with the monoblock structure
  - ¼ with the flat-type structure
- **Enhanced particle/heat flux load and removal capability**
  - More closed geometry with larger slot to increase flow conductance ~36%
  - Increase steady-state heat exhaust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

See **H. Si**'s talk on Nov 16, this meeting

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
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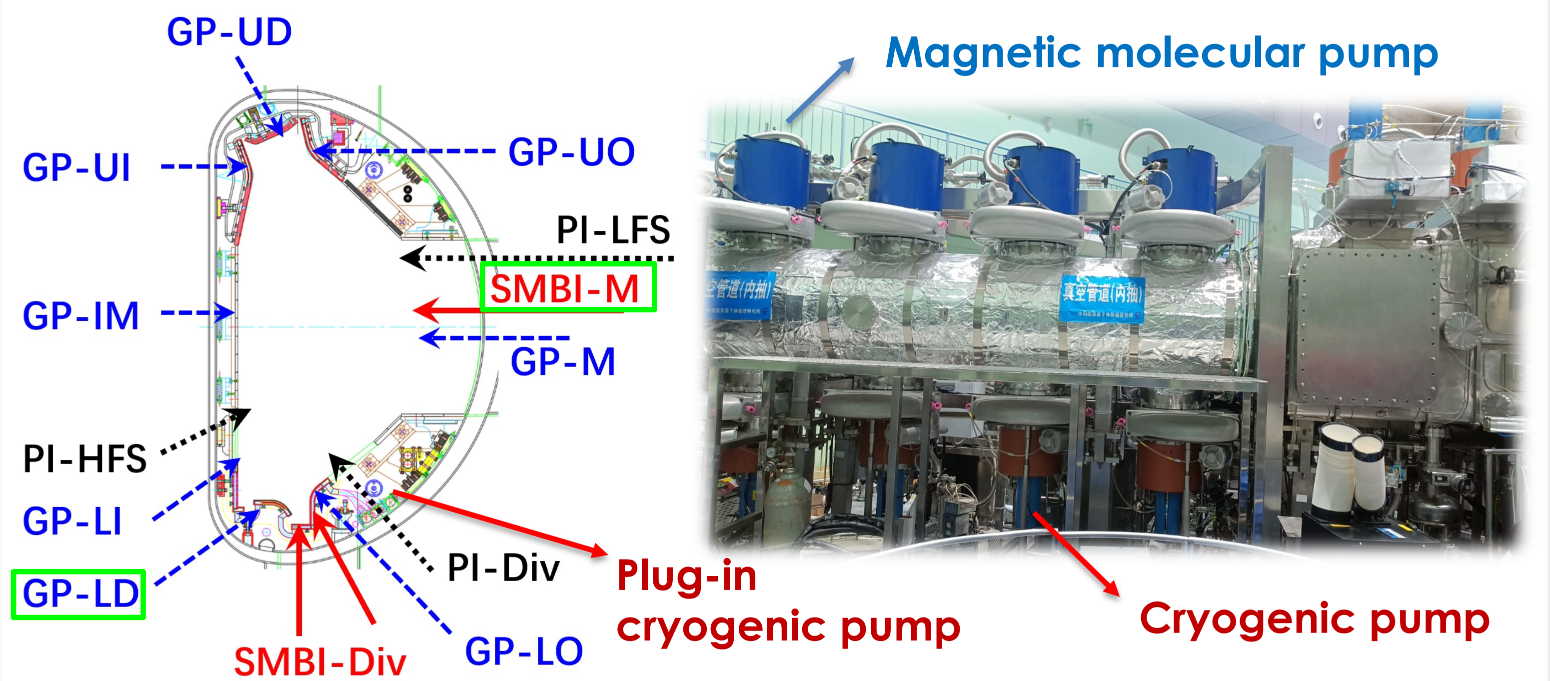
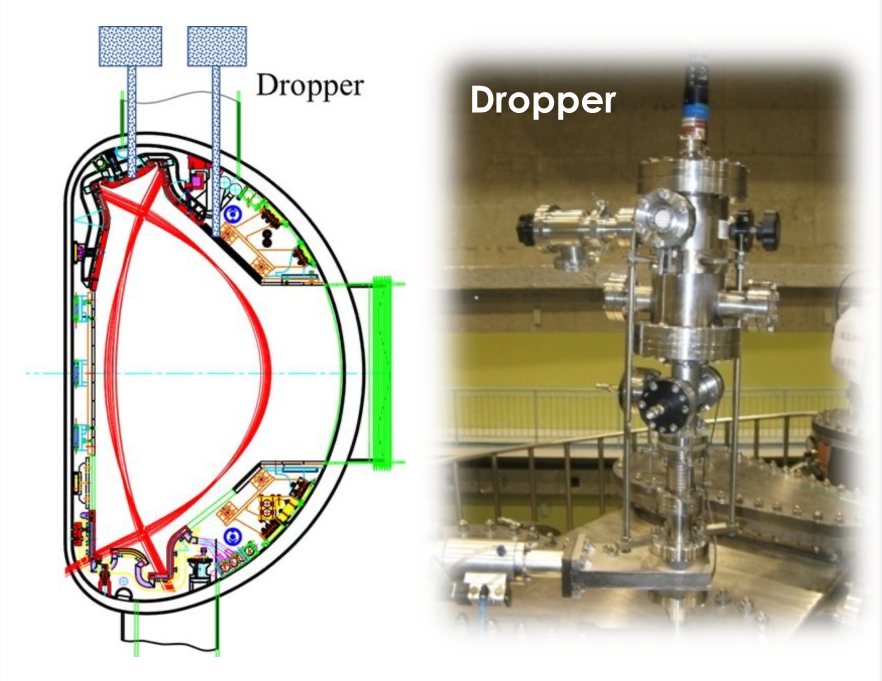
Advanced Pumping and Wall Conditioning Technologies

Pumping and fueling system on EAST



EAST impurity dropper from PPPL



- **Improved particle exhaust** with larger pumping speed and capacity
- **Enhanced fueling efficiency** using stable SMBI and DOME puffing
- **Effective wall conditioning** by intensive lithium coating and real-time control

See **W. Yu's** & **G. Zuo's** talk on Nov 14, this meeting

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Hardware Upgrades Support Long-pulse SSO Research

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- Higher spatial and temporal resolution for diagnostics

- Capability of cooling water system
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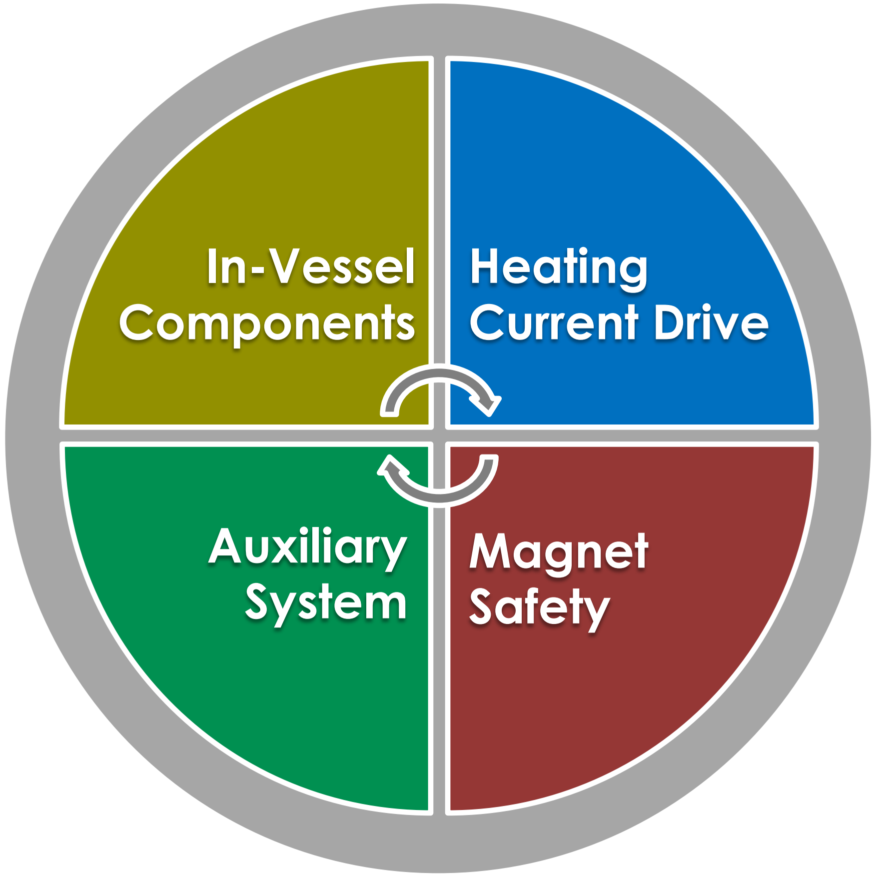

- Rearrangement of ports
- Improved coupling efficiency and injected power
- Guard limiter heat flux capability improvement

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

PF-coil Power Supply for EAST LPO and Contribution to ITER

15 kA quench protection

See **Z. Huang**'s & **Y. Huang**'s talks on Nov 16, this meeting

→ EAST

- **High availability for long pulse operation**
  - 15kA, 200 MVA/1800 s
  - Fault rate less than 0.1%
- **High reliability for system protection**
  - 100% fault protection
- **Fast respond/high stability for plasma control**
  - 100% fault protection0.1 ms for voltage source converter
  - 10 ms for current source 4-quadrant converter

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PF-coil Power Supply for EAST LPO and Contribution to ITER

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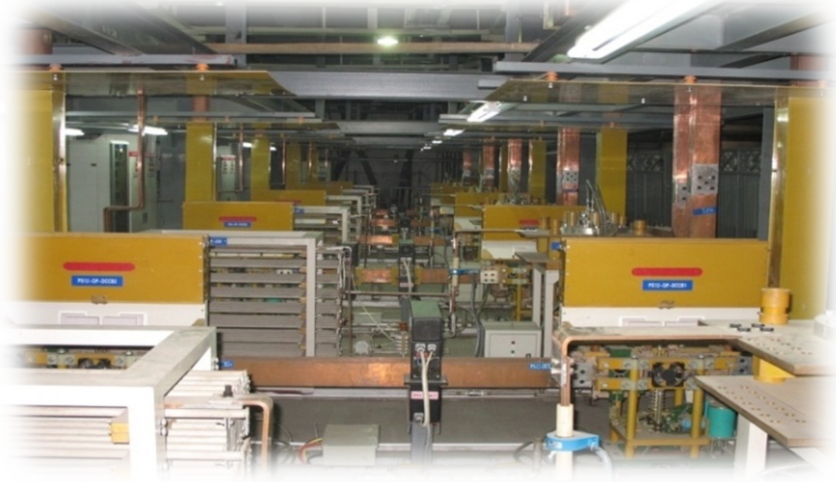

→ ITER

See **Z. Huang**'s & **Y. Huang**'s talks on Nov 16, this meeting

- **New design for coil power supply**
  - 55kA/160MVA converter module for more feasibility
  - Series connection to reduce reactive power for grid compatibility
  - External bypass for more reliability
- **R&D of ±55kA/160MVA converter system**
  - Integrated design for better current balance
  - Control and protection strategy for reliability and availability
- **120 kA steady-state and 450 kA pulse current test facility**

→ EAST

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  - 15kA, 200 MVA/1800 s
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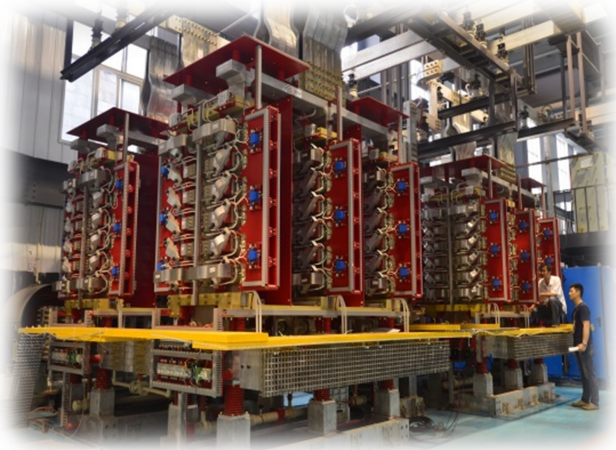

±55kA/160MVA converter

120 kA SS test facility

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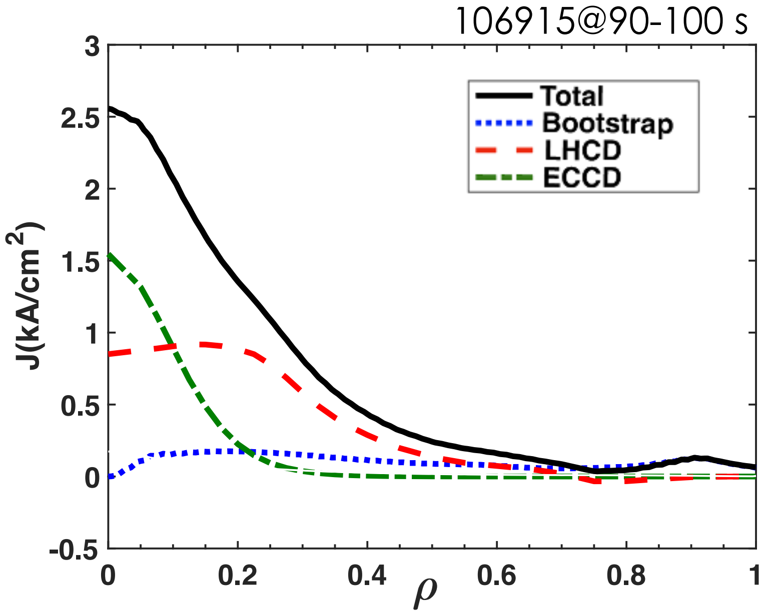
- **Key issues in long-pulse and steady-state regime**
  - Enhanced technical capabilities
  - Demonstrate1056s fully noninductive plasma
    1. Fully non-inductive current
    2. Power and particle handling
    3. Performance with plasma stability
    4. Stable plasma control
  - Achieve 310s steady-state high-performance plasma
- **Future plans and summary**

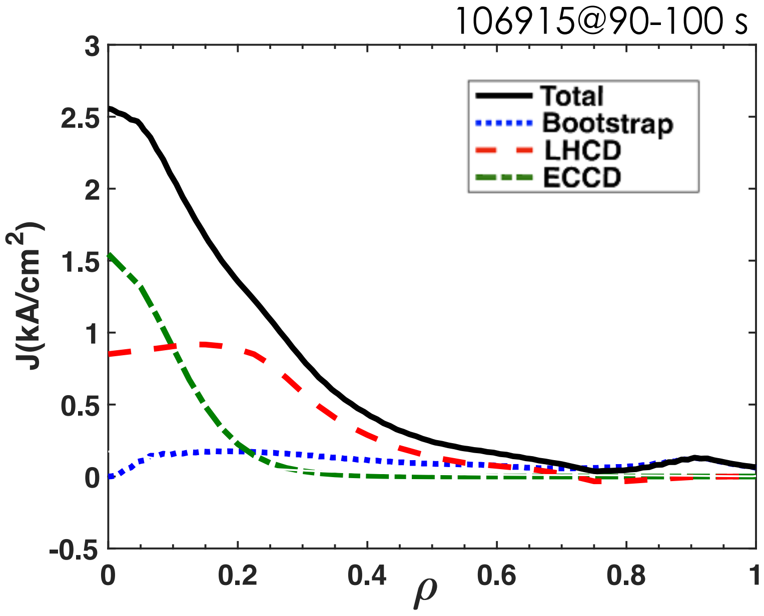
Improved CD Efficiency due to High T_e and Synergy Effect of ECCD and LHCD

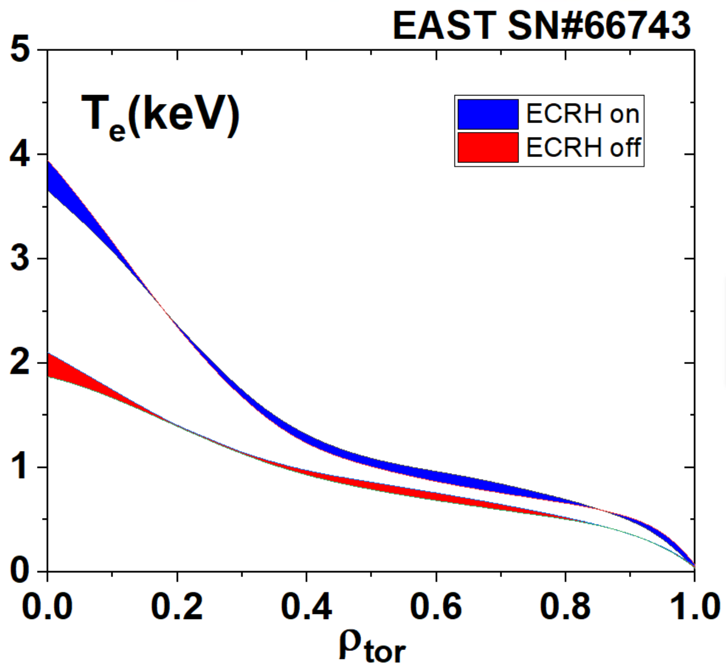


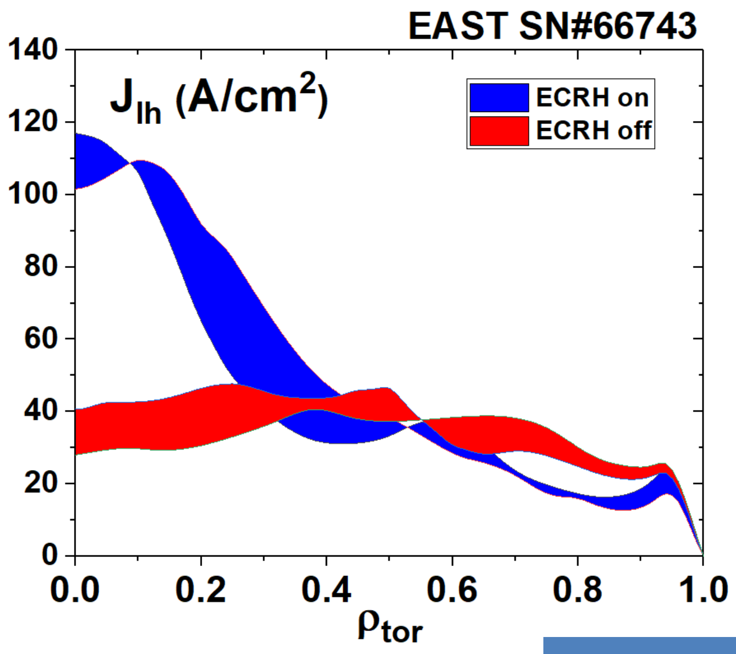
- **Fully non-inductive CD with f_{RF}~70% and f_{BS}~30% at β_P~1.5**
  - Monotonic current profile with q(0)>1
  - ECCD is on-axis and LHCD deposits at ρ <0.4 due to good accessibility

See **M. Li**'s talk on Nov 16, this meeting

Improved CD Efficiency due to High T_e and Synergy Effect of ECCD and LHCD







Du, NF 2018

- **Fully non-inductive CD with f_{RF}~70% and f_{BS}~30% at β_P~1.5**
  - Monotonic current profile with q(0)>1
  - ECCD is on-axis and LHCD deposits at ρ <0.4 due to good accessibility
- **Improved RF current efficiency ~0.87×10^{19}A/W/m²**
  - CD efficiency increases with <T_e>

See **M. Li**'s talk on Nov 16, this meeting

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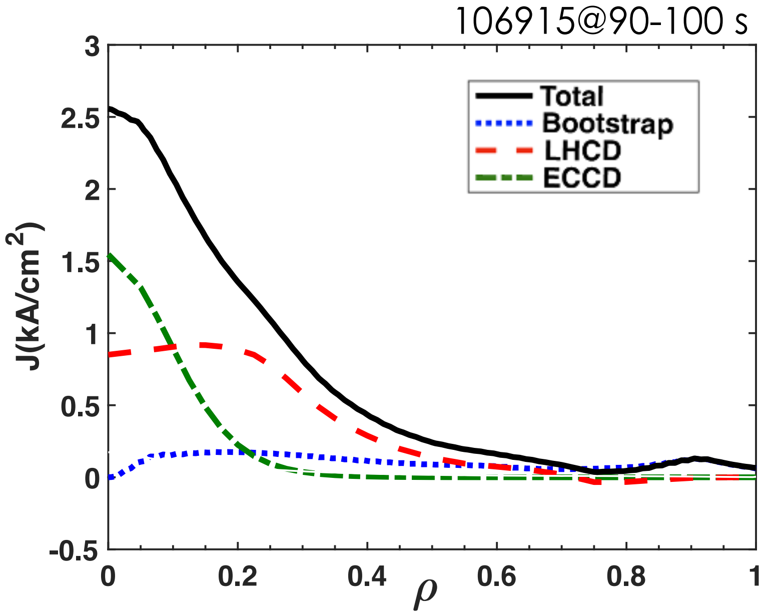
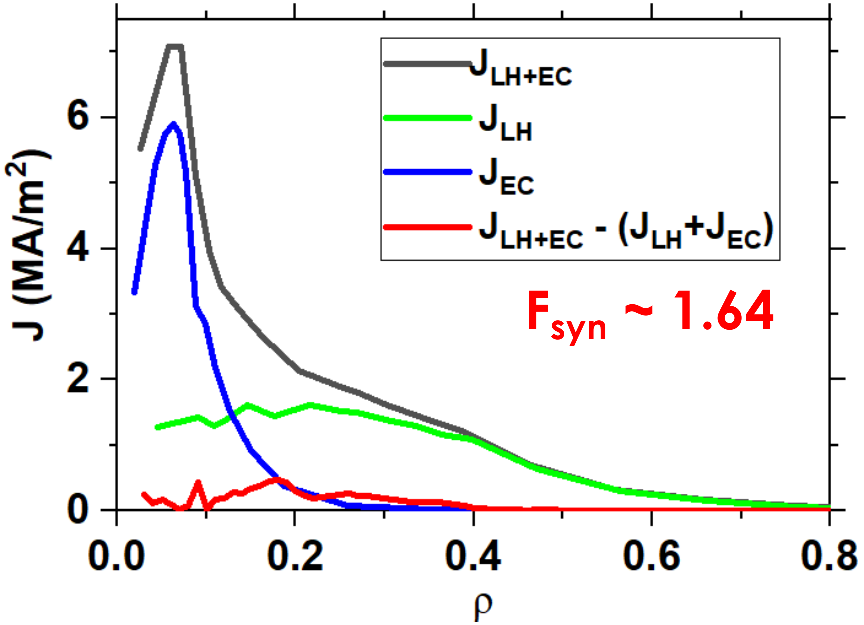
Improved CD Efficiency due to High T_e and Synergy Effect of ECCD and LHCD





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- **Improved RF current efficiency ~0.87×10^{19}A/W/m²**
  - CD efficiency increases with $\langle T_e \rangle$
  - Synergy factor as $F_{syn} = \Delta I / I_{EC}$ ~ 1.64 , due to velocity space diffusions between ECCD and LHCD

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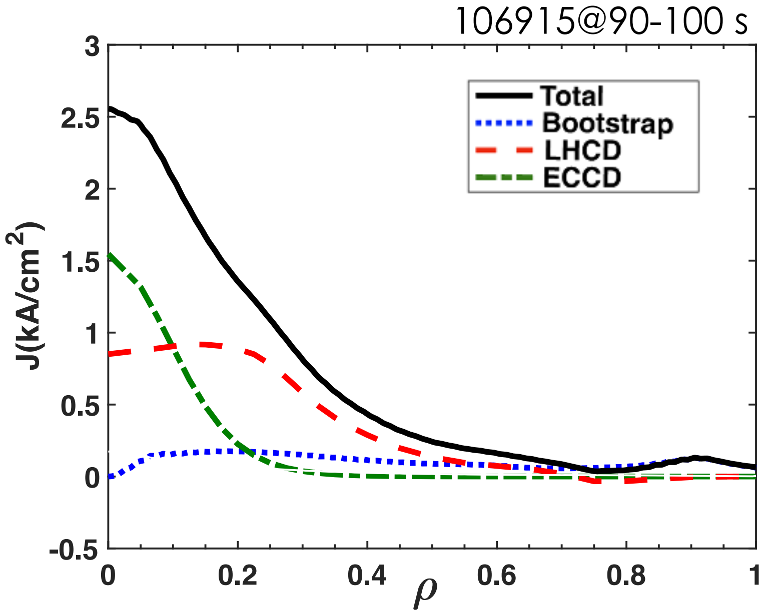
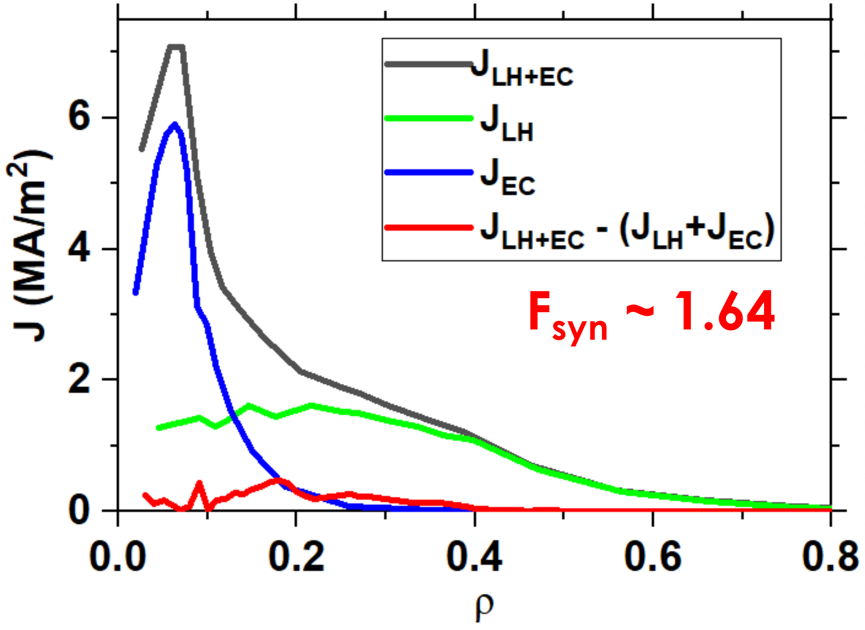
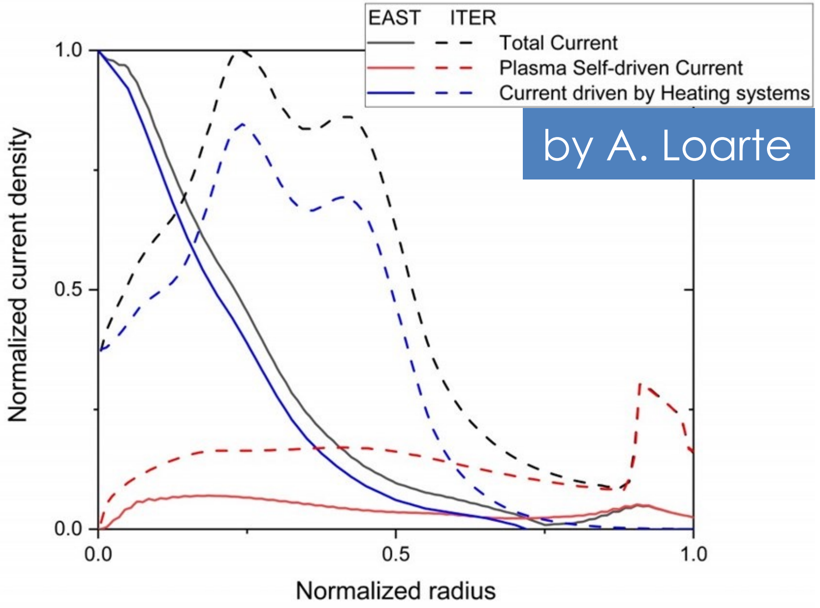
Improved CD Efficiency due to High T_e and Synergy Effect of ECCD and LHCD







https://www.iter.org/newsline/-/3740

- **Fully non-inductive CD with f_{RF}~70% and f_{BS}~30% at β_P~1.5**
  - Monotonic current profile with q(0)>1
  - ECCD is on-axis and LHCD deposits at ρ <0.4 due to good accessibility
- **Improved RF current efficiency ~0.87×10^{19}A/W/m^2**
  - CD efficiency increases with $\langle T_e \rangle$
  - Synergy factor as $F_{syn} = \Delta I / I_{EC}$ ~ 1.64 , due to velocity space diffusions between ECCD and LHCD
- **Similar CD proportion as shown in ITER 10MA Q≥5 SSO with f_{RF}~66%, f_{BS}~34% at β_P~1.0**

See **M. Li**'s talk on Nov 16, this meeting

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- **Progress of EAST in support of ITER and CFETR**
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  - Enhanced technical capabilities
  - Demonstrate1056s fully noninductive plasma
    1. Fully non-inductive current
    2. Power and particle handling
    3. Performance with plasma stability
    4. Stable plasma control
  - Achieve 310s steady-state high-performance plasma
- **Future plans and summary**

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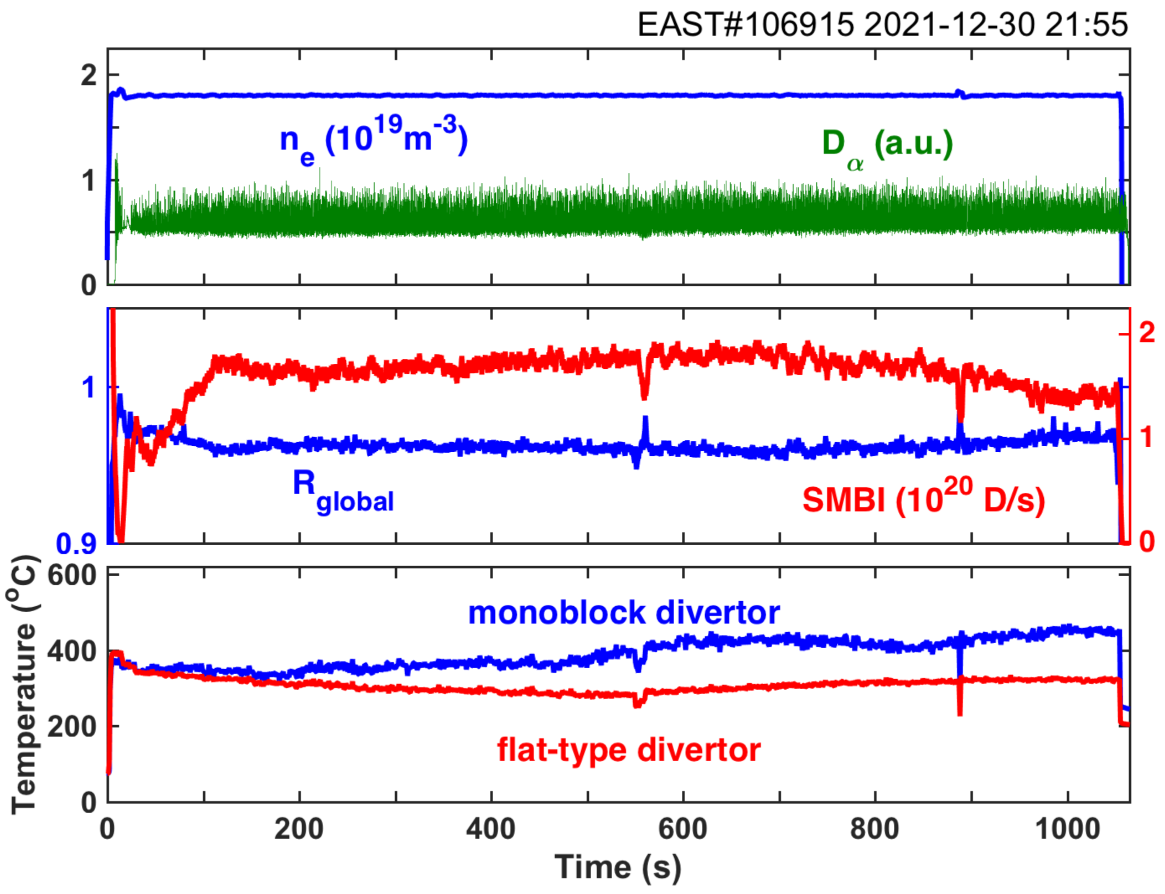
New Water-cooled W Lower Divertor Significantly Enhanced Particle and Power Exhaust



- Constant plasma density sustained by SMBI fueling
- Global recycling ~0.95-0.97 with real-time lithium injection
- Lower surface temperature on W-PFCs keeps 300-500°C
- Temperature on flat-type div. lower than that on monoblock div.

See **Y. Yu**'s talk on Nov 14, this meeting

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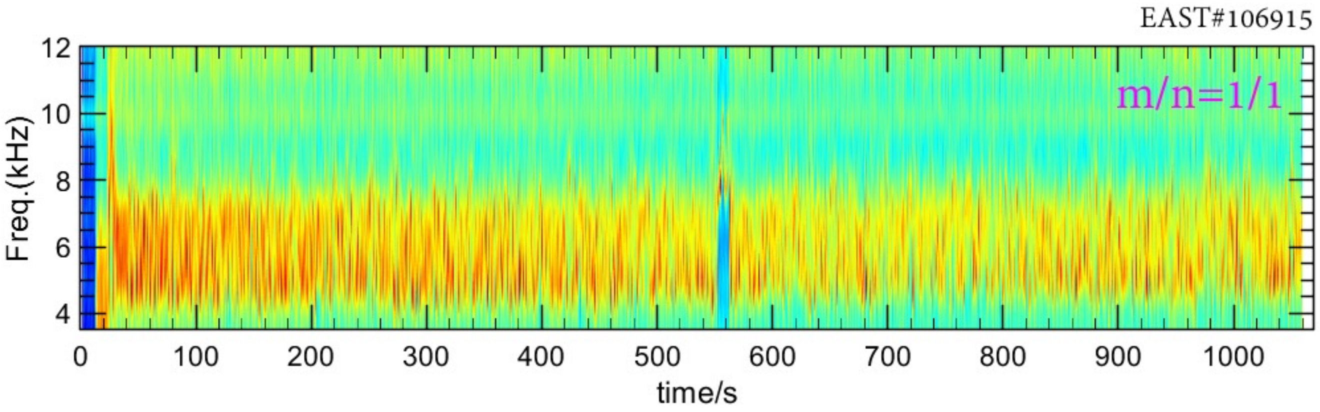
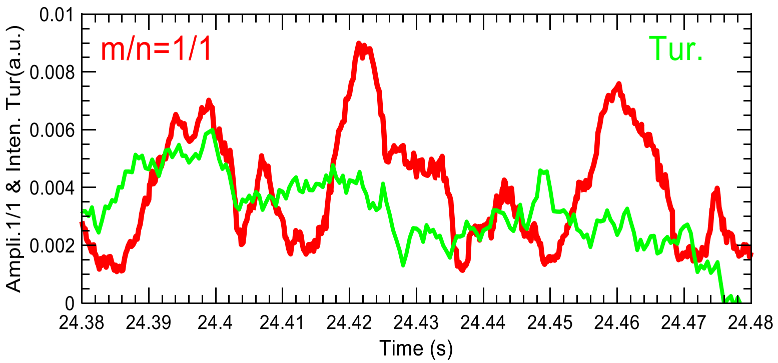
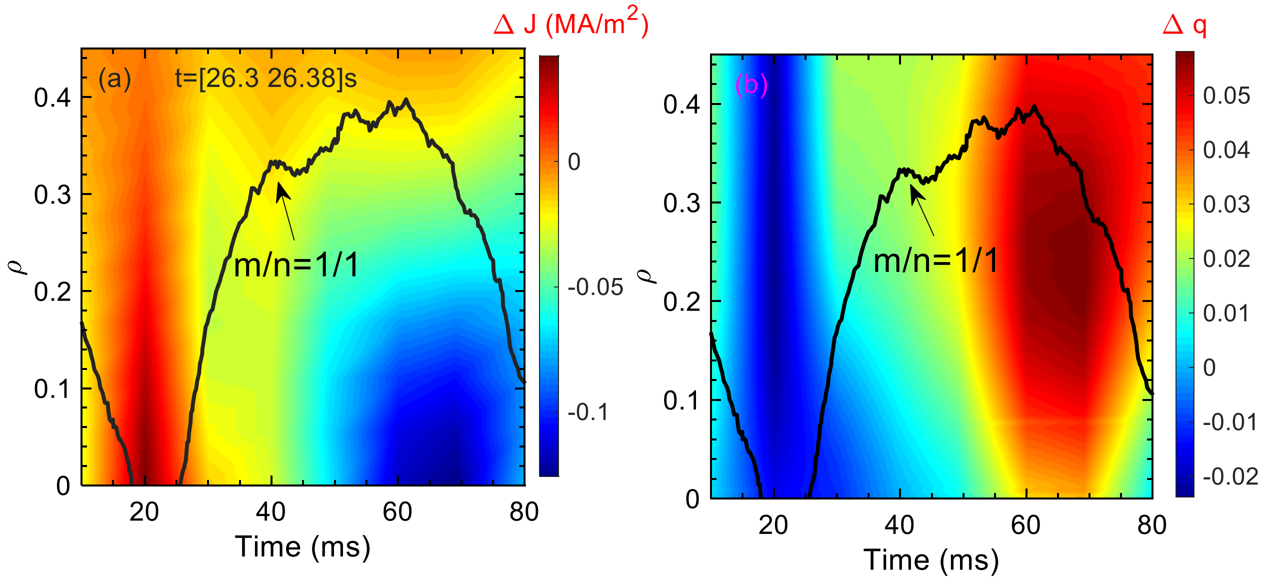
Saturated m/n=1/1 Mode Sustained High T_e Plasma with Improved Confinement







- **ETG turbulence can be reduced by m/n=1/1 mode**
  - 1/1 mode can generate negative current
  - Increase q(0)>1 with sawtooth free, helping to form weak magnetic shear
- **The self-regulation system to sustain SS LPO**
  - The interplay among negative current, kink mode, turbulence

Li, PRL 2022

See **L. Xu**'s talk on Nov 15, this meeting

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Key Issues in Plasma Control for EAST LPO

Magnetic measurements
- Magnetic probes and flux loop calibration
- PF and plasma current measurement

Integrator
- Integrator zero drift
- Linear voltage offset drift correction

Shape parameter estimation
- Equilibrium reconstruction for plasma shape control
- Fast Z estimator for vertical instability control

Plasma magnetic control
- Vloop control for fully non-inductive operation

It is necessary to control plasma equilibrium and position over long time scales

See **Y. Huang**'s talk on Nov 15, this meeting

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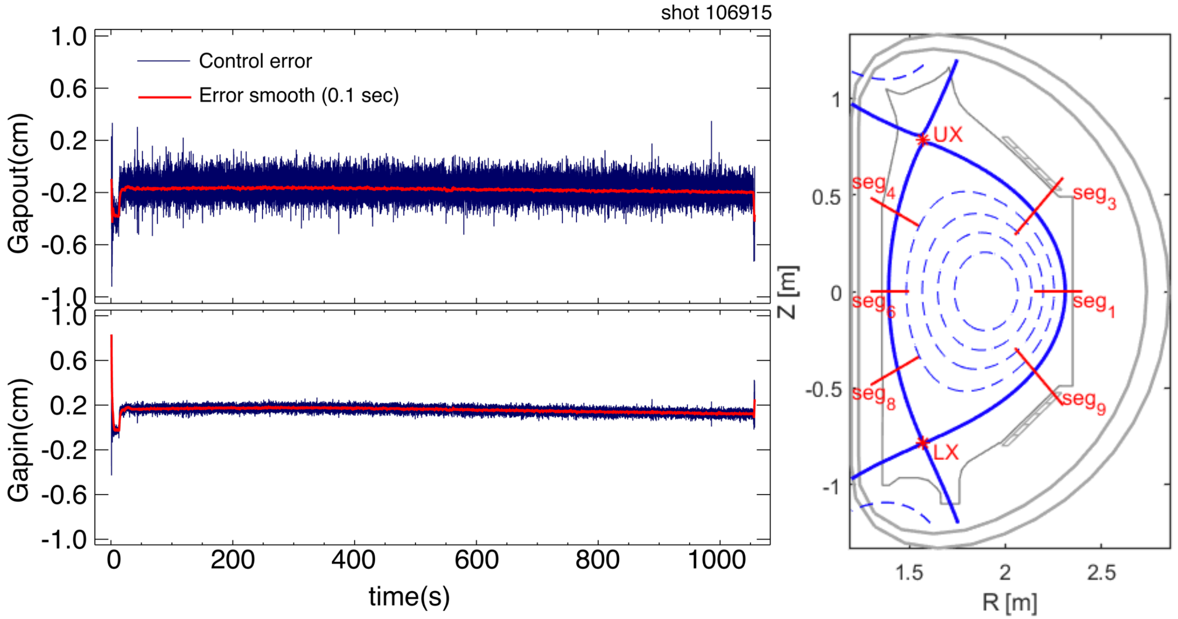
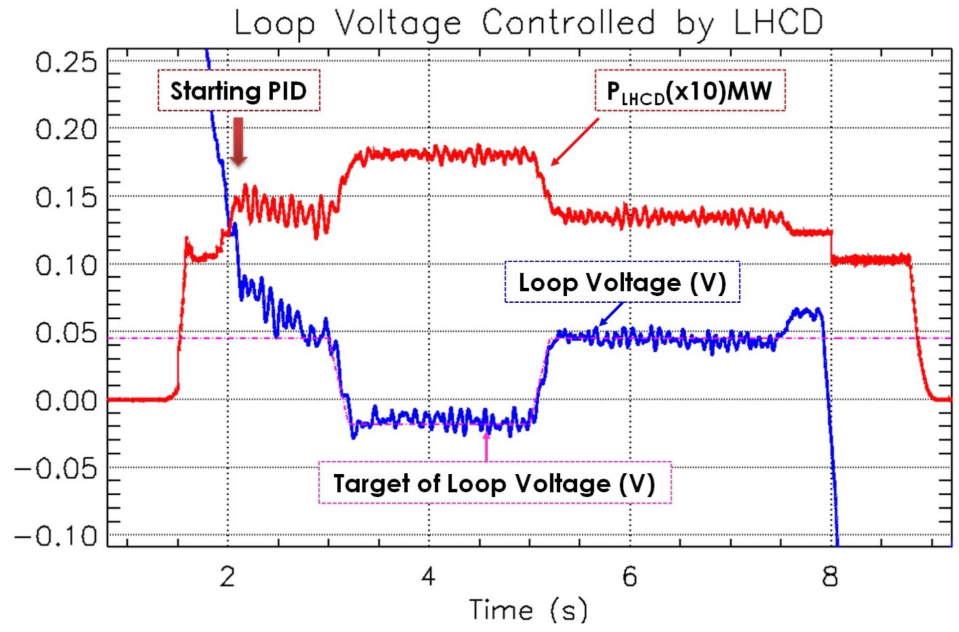
Roust Plasma Control Succeeded in Long Pulse Time Scale

Shape control



Vloop control



- **Good accuracy shape control with Gap <2mm, X-point(R,Z): <3/5mm**
  - PEFIT+ISO-FLUX control and new vertical control
  - Magnetic measurement using new fiber optic current sensors
  - Low zero drift integrator with linear drift deduction algorithm in PCS
- **Vloop control for fully non-inductive CD**
  - Using 4.6GHz LHW with optimized PID controller in PCS

See **Y. Huang**'s talk on Nov 15, this meeting

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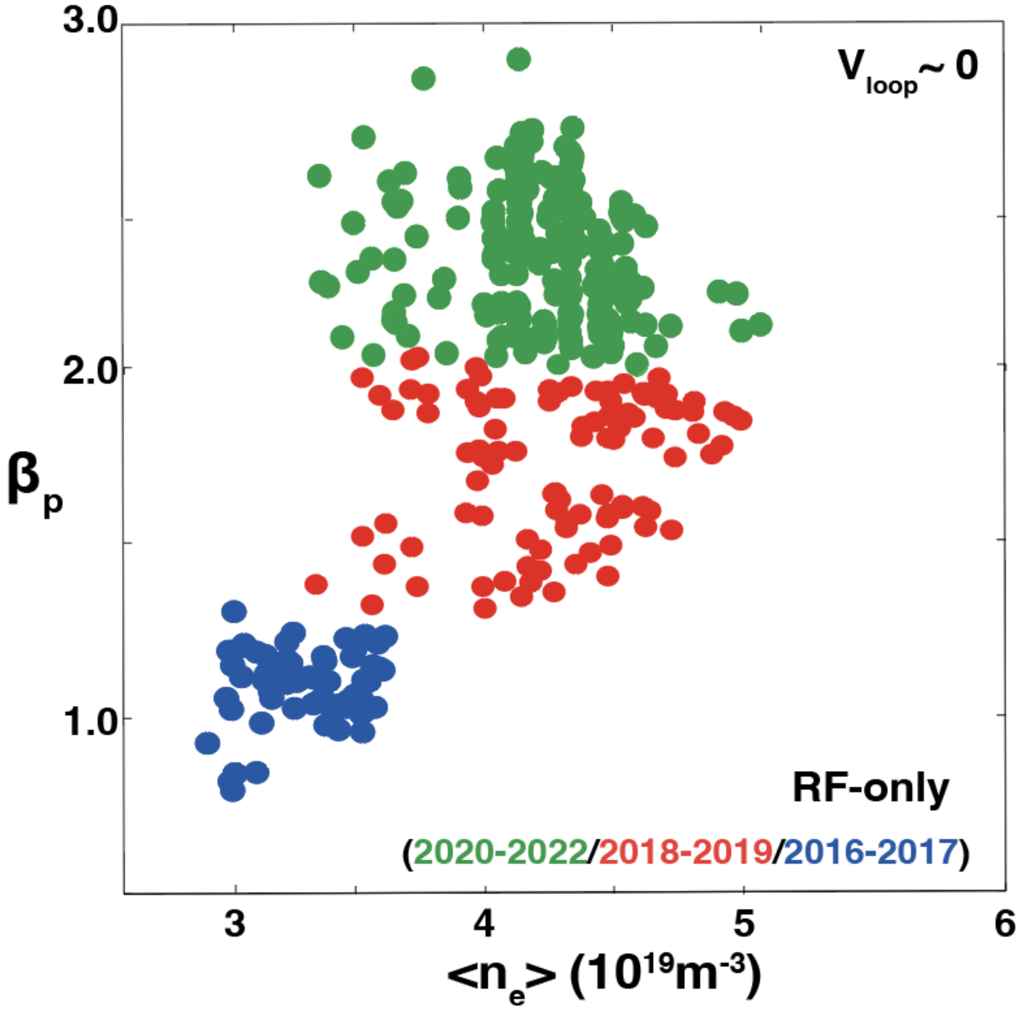
EAST/DIII-D Partnership: Sharing of Resources Accelerates Progress of Long-pulse High-performance Operation

Joint EAST/DIII-D Task Force
Development of High β_P Scenario
Leaded by A.M. Garofalo, X. Gong

Long-Pulse Initiative: **Extend Advancing Physics Understanding on DIII-D to True Steady-State on EAST**

See **A.M. Garofalo**'s talk on Nov 15, this meeting

Fully Non-inductive High-β_P Scenarios Extension to High Density Regime with Good Confinement



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DIII-D NATIONAL FUSION FACILITY SAN DIEGO
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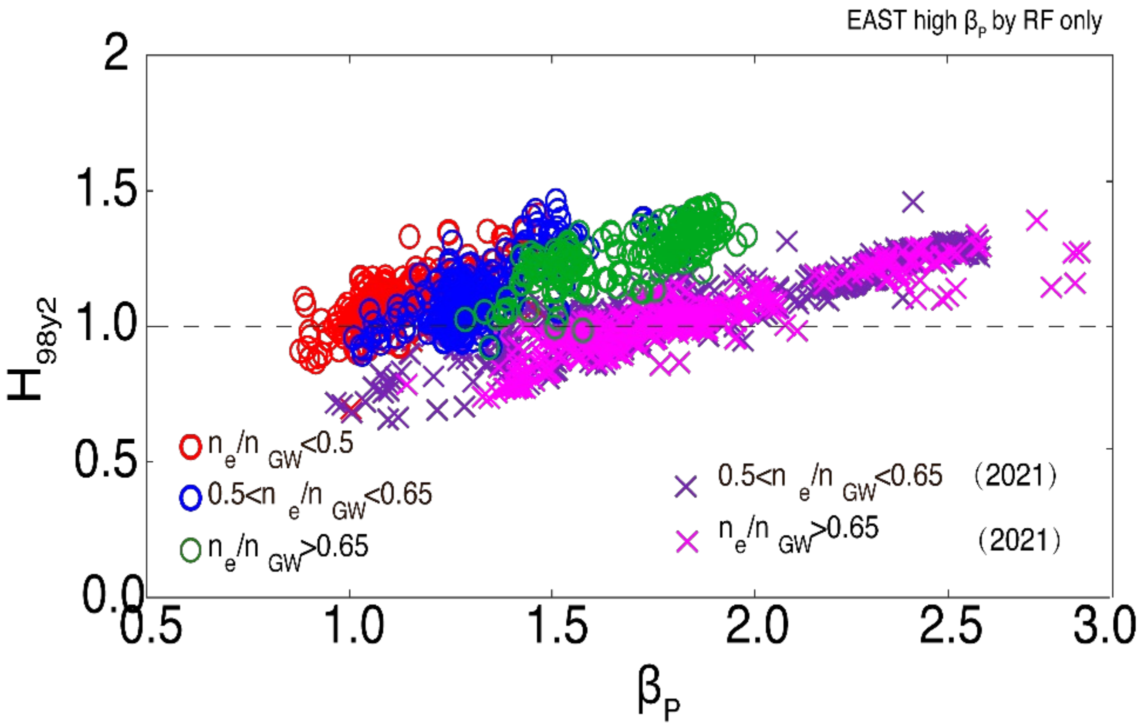
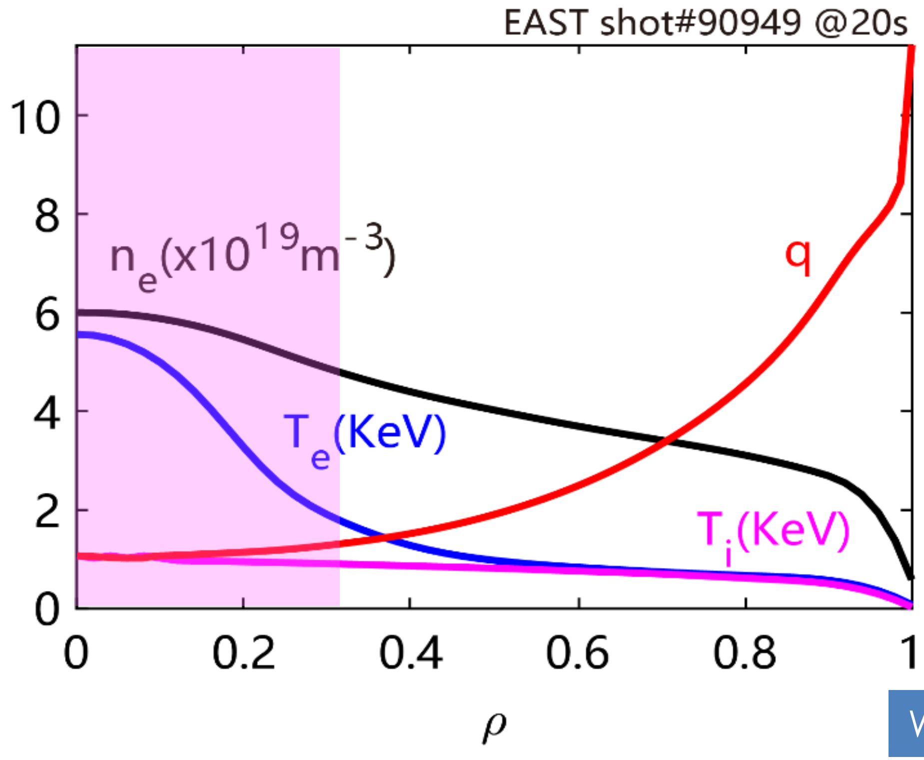
Experiments Show Improved Confinement when Extending to High β_P Regime



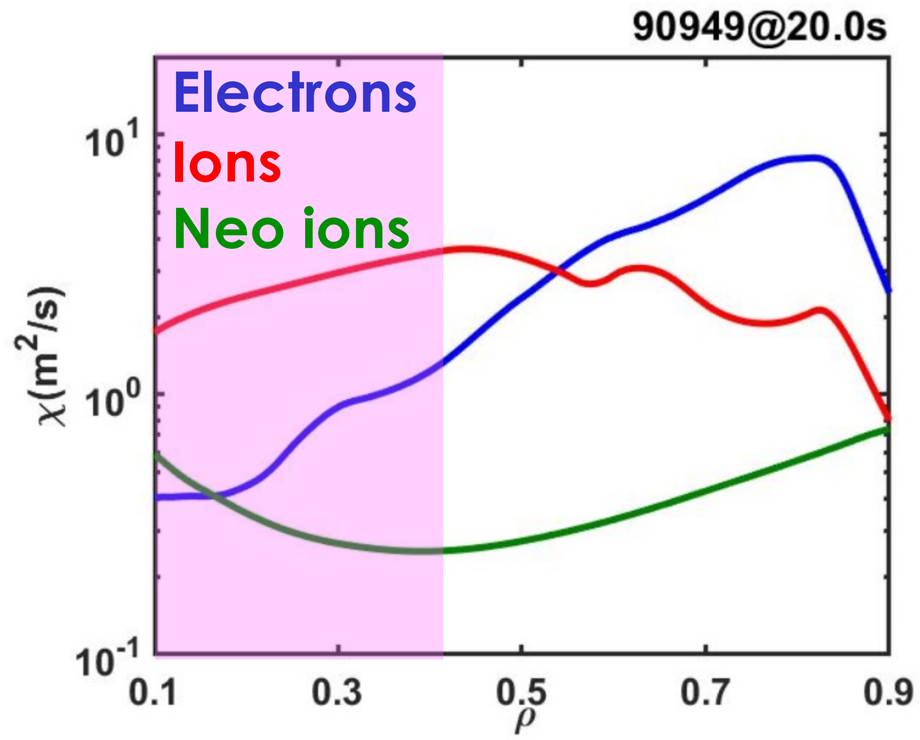


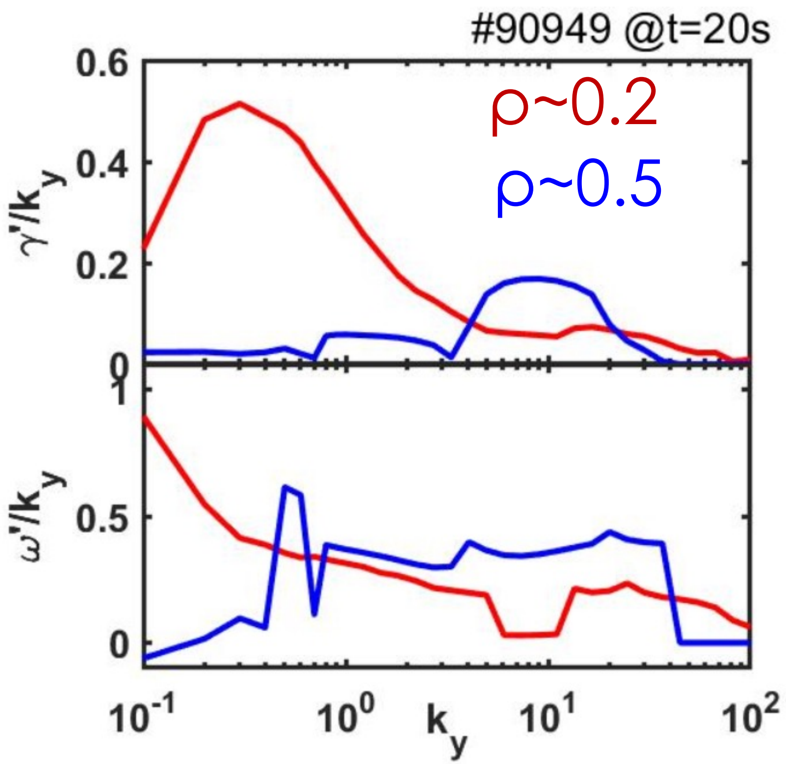
Wan, NF 2021

- **High energy confinement at high β_p and high density.**

- **Dominant electron heating**
  - T_e-ITB
  - Flat q-profile with q(0)>1.0
  - zero torque, low rotation

Reduced Transport in Electron Energy Channel Consistent with T_e-ITB Formation





Gong, NF 2021
Qian, POP 2021

- **Electron transport reduced in ρ<0.4**
  - Consistent with improved confinement
- **Linear analysis by TGLF**
  - TEM modes dominate at ITB
  - ETG modes dominate outside ITB

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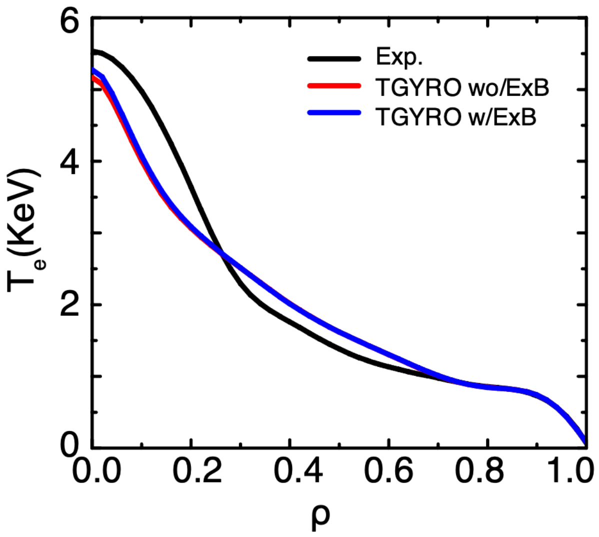
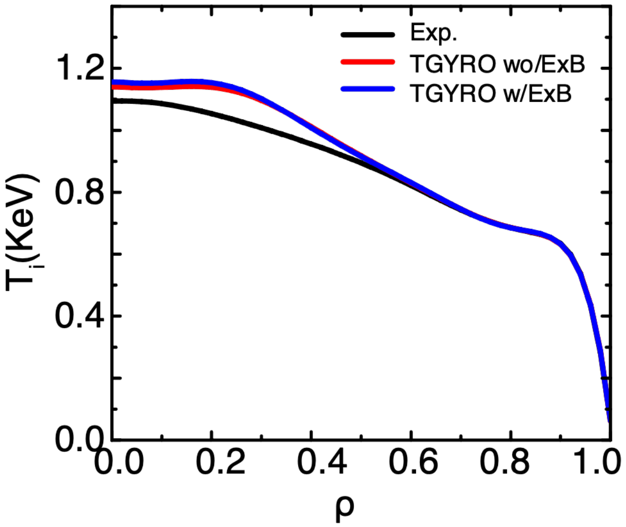
Transport Modeling Points to Strong Effect of Shafranov Shift

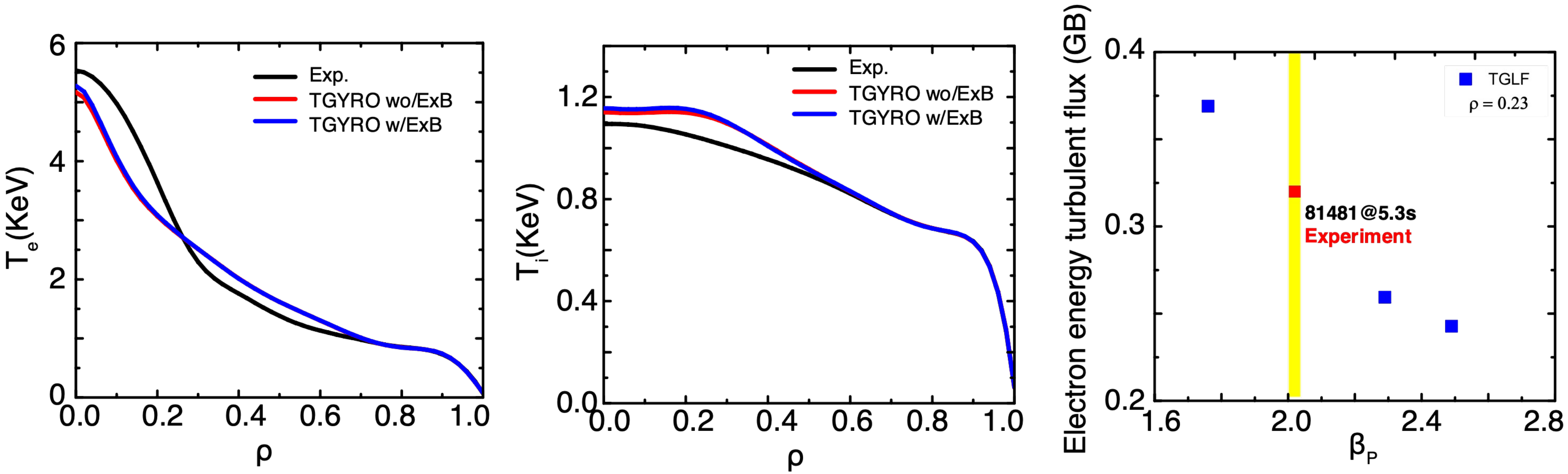




- **Energy transport insensitive to E×B shear flow**
  - Electrostatic TGLF-SAT0, with fixed experimental n_e

Qian, POP 2021
Kotschenreuther, IAEA 2020
Huang, PPCF 2020
Wu, NF 2019

Transport Modeling Points to Strong Effect of Shafranov Shift



- **Energy transport insensitive to E×B shear flow**
  – Electrostatic TGLF-SAT0, with fixed experimental n_e
- **Electron turbulent energy fluxes decreases with high β_p**
  – Consistent with turbulence measurements

Qian, POP 2021
Kotschenreuther, IAEA 2020
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Wu, NF 2019

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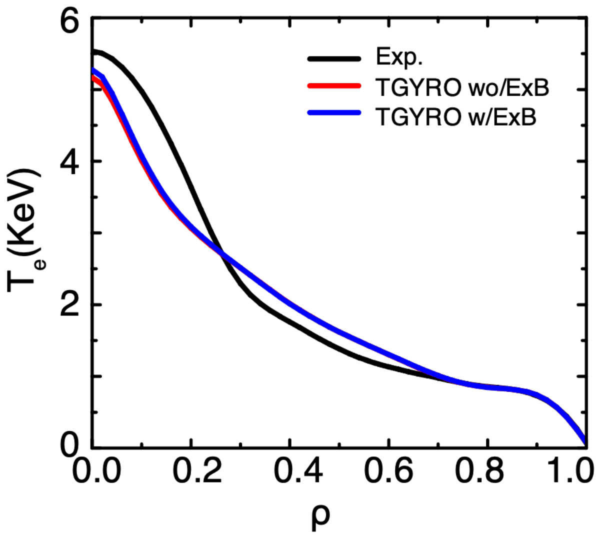
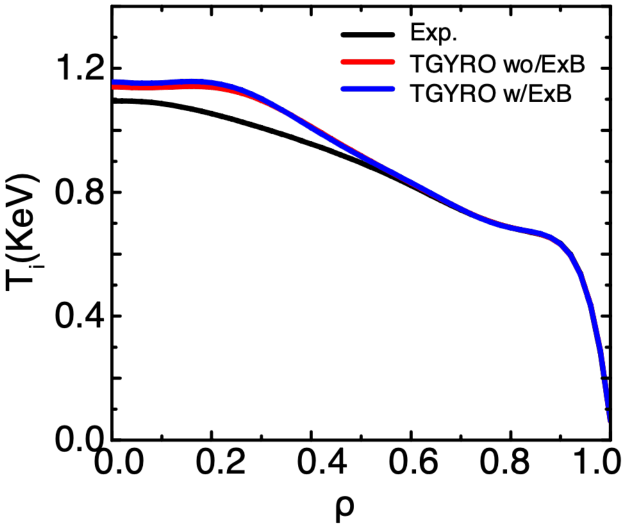
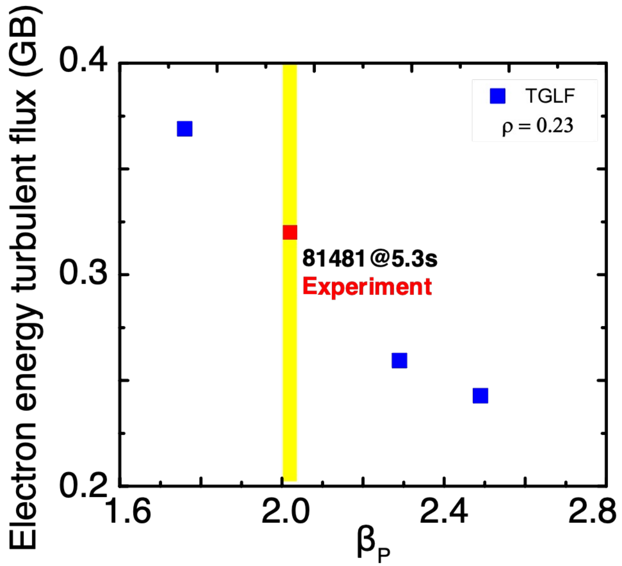
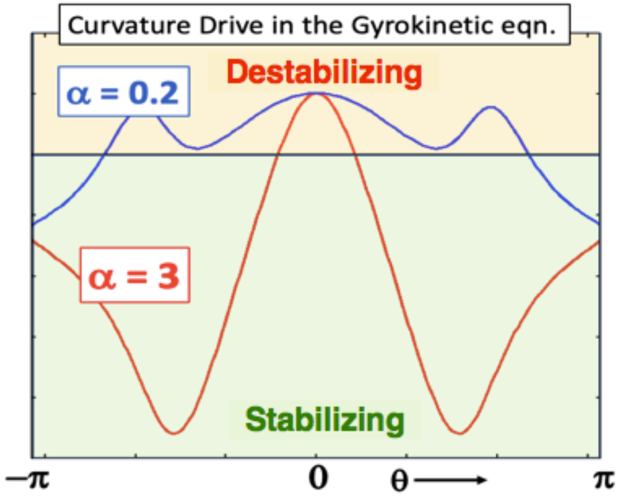
Transport Modeling Points to Strong Effect of Shafranov Shift









- **Energy transport insensitive to E×B shear flow**
  - Electrostatic TGLF-SAT0, with fixed experimental n_e
- **Electron turbulent energy fluxes decreases with high β_p**
  - Consistent with turbulence measurements
- **High Shafranov shift (α-stabilization) helps to improve energy confinement**
  - Shafranov shift ~ β_P ~ α ~ $d\beta_P/dr$
  - As α increases, unstable eigenfunction becomes narrower in θ

Qian, POP 2021
Kotschenreuther, IAEA 2020
Huang, PPCF 2020
Wu, NF 2019

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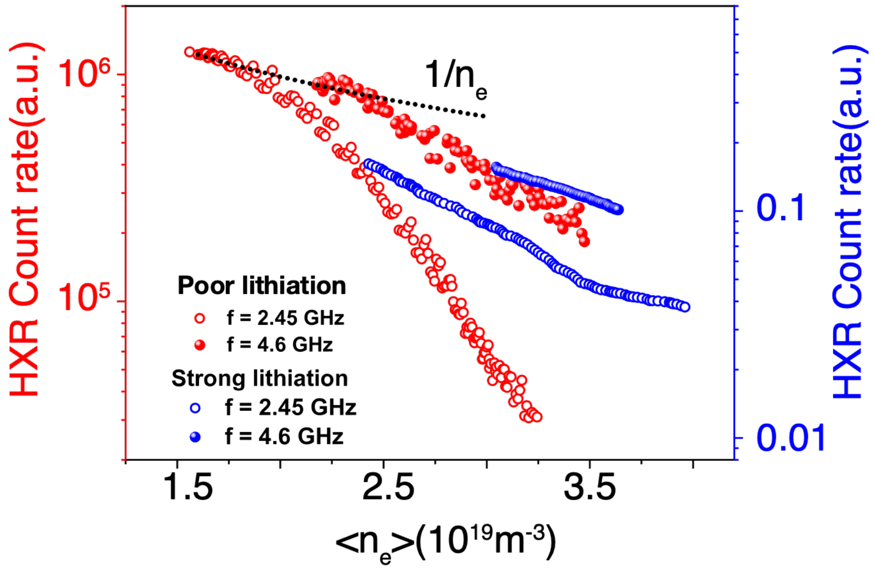
Higher LHW Frequency and Lower Recycling Wall Allowing High LHCD Efficiency at High Density

$I_{steady\text{-}state} = I_{BS} + \boxed{I_{AUX}}$



- **LHCD efficiency drops faster than $1/n_e$**

Li, NF 2022
Li, PPCF 2019
Ding, NF 2018

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Higher LHW Frequency and Lower Recycling Wall Allowing High LHCD Efficiency at High Density

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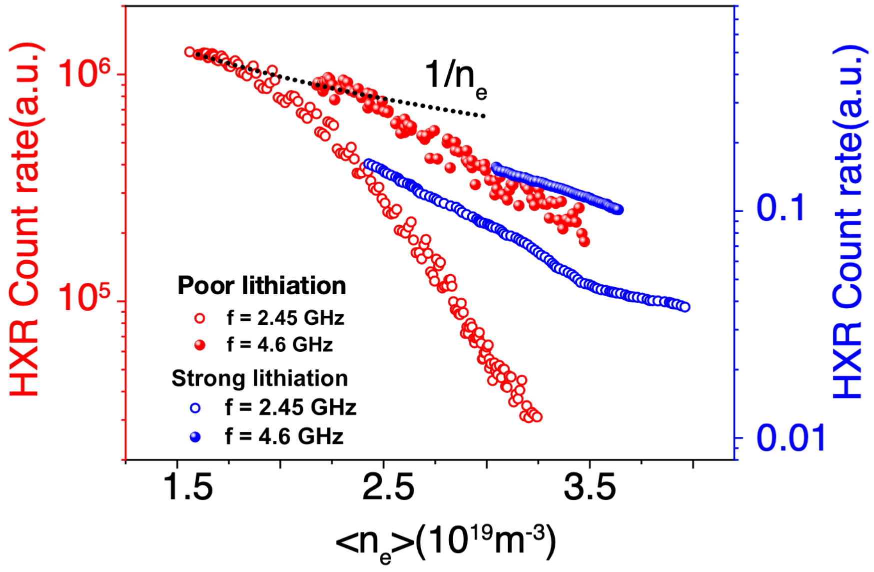

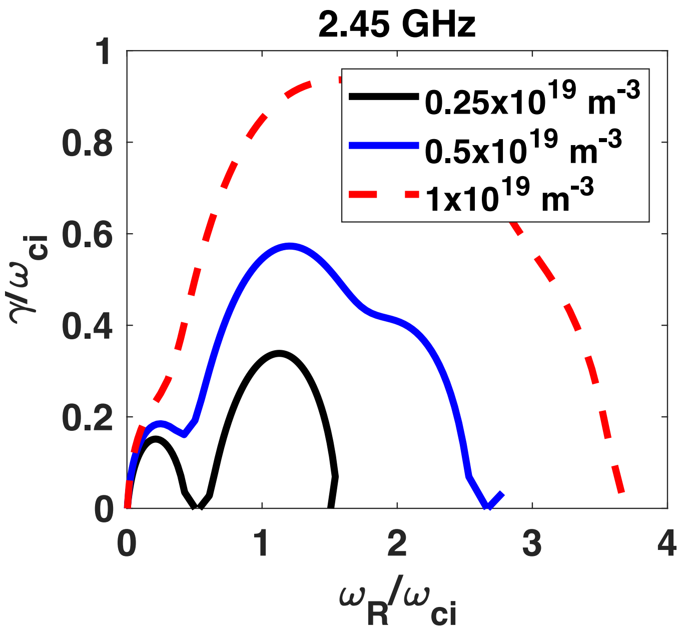

- **LHCD efficiency drops faster than $1/n_e$**
  - Parametric Instability (PI) growth rate increased with the density

Li, NF 2022
Li, PPCF 2019
Ding, NF 2018

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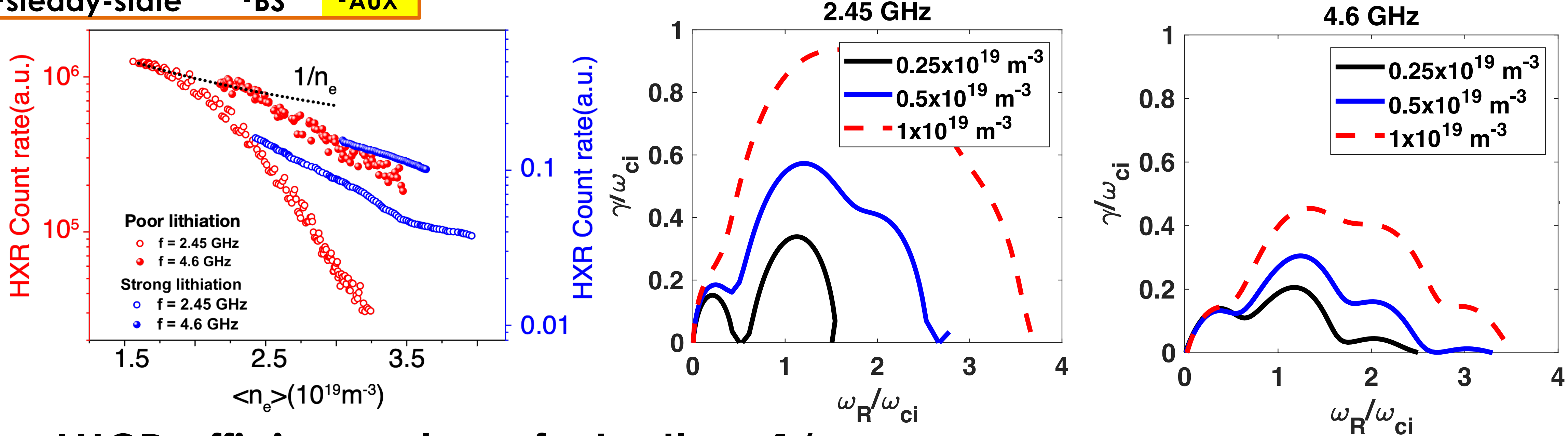
Higher LHW Frequency and Lower Recycling Wall Allowing High LHCD Efficiency at High Density

$I_{steady\text{-}state} = I_{BS} + I_{AUX}$



- **LHCD efficiency drops faster than $1/n_e$**
- **Higher LHW frequency has higher CD efficiency**
  - PI growth rate smaller with higher LH source frequency

Li, NF 2022
Li, PPCF 2019
Ding, NF 2018

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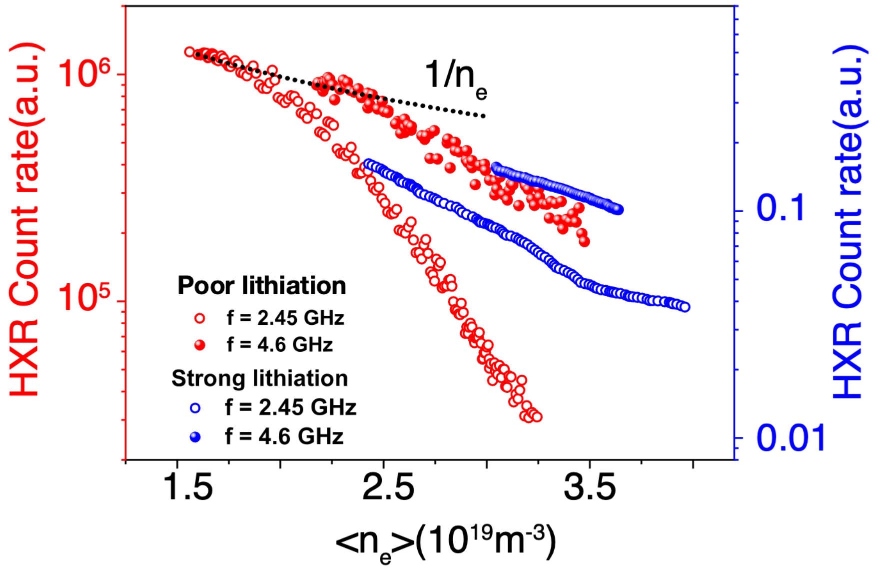
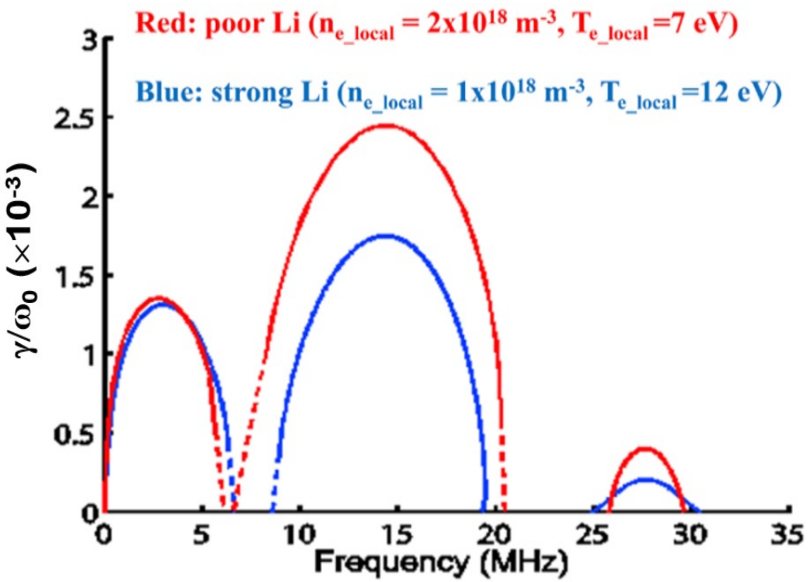
Higher LHW Frequency and Lower Recycling Wall Allowing High LHCD Efficiency at High Density

$I_{steady\text{-}state} = I_{BS} + I_{AUX}$





- **LHCD efficiency drops faster than $1/n_e$**
- **Higher LHW frequency has higher CD efficiency**
- **Lower recycling allows higher CD efficiency**
  - Lower edge neutral density improve accessibility
  - Higher temperature reduce PI intensity

Li, NF 2022
Li, PPCF 2019
Ding, NF 2018

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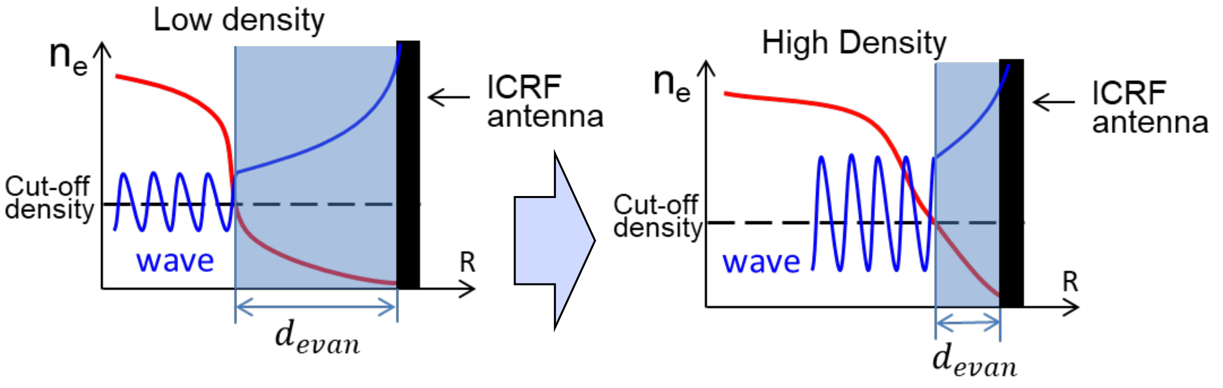
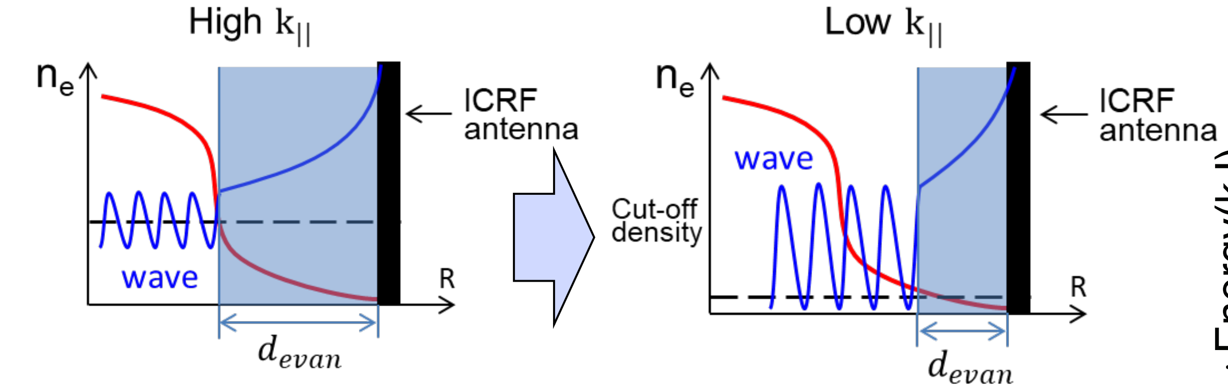
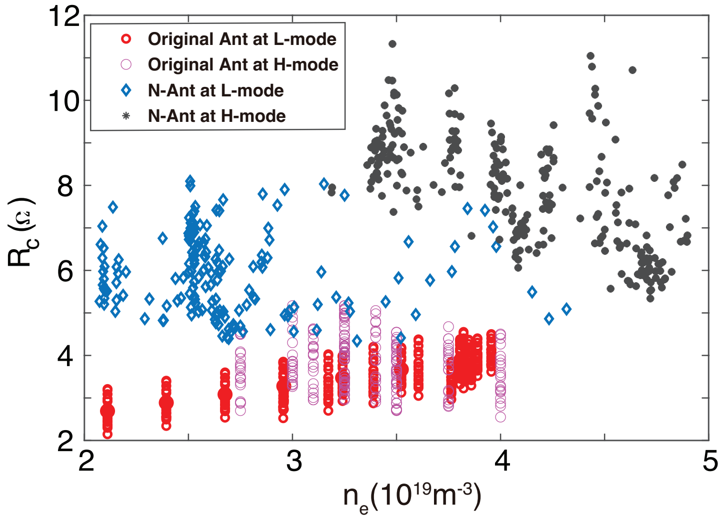
New Antenna with Decreased $k_{||}$ Improves ICRF Coupling and Heating Efficiency



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



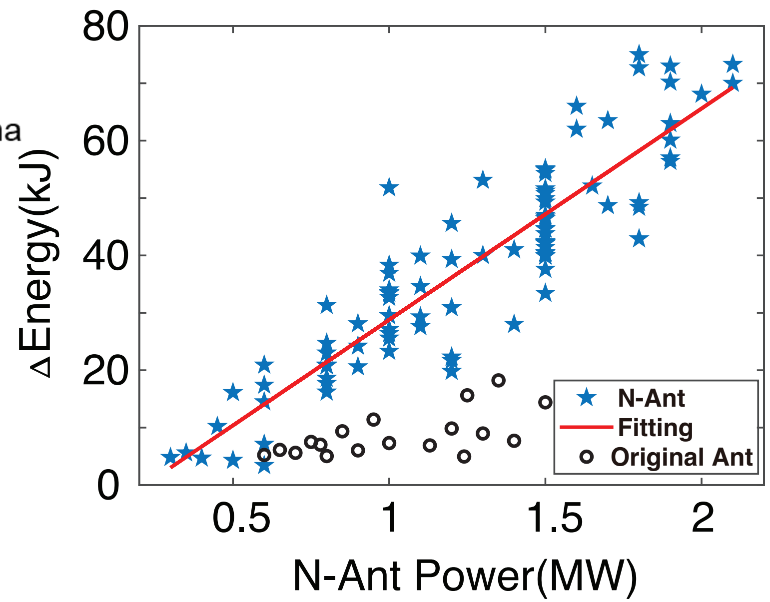
- $k_{||} \downarrow \rightarrow d_{evan} \downarrow \rightarrow \mathbf{R_c} \uparrow$



- **Enhanced coupled ICRF power**

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

Zhang, NF 2022



- **Higher heating efficiency**

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

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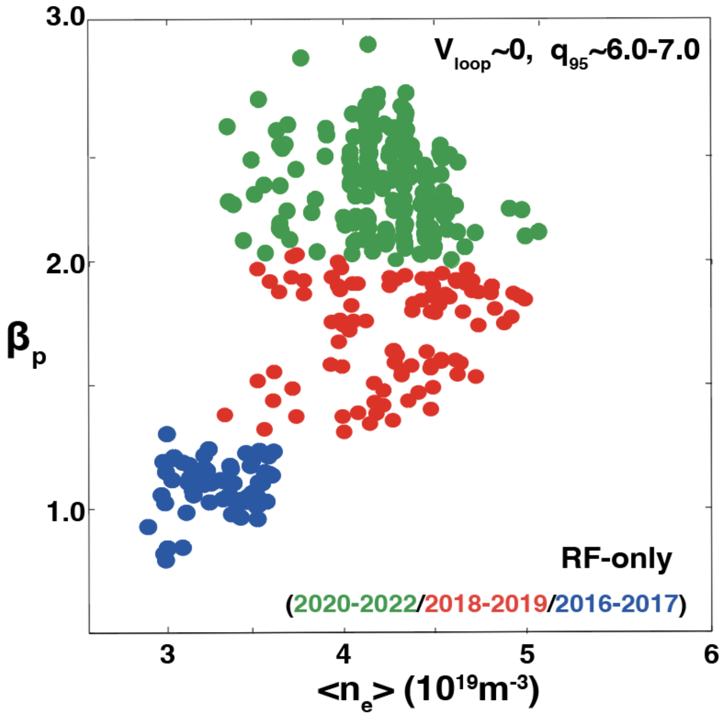
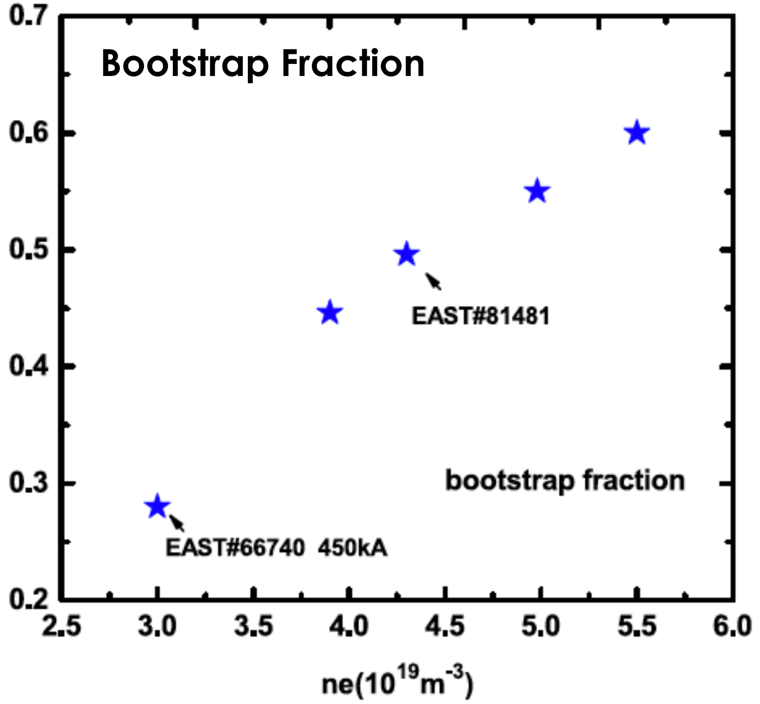
High Density Regime Helps to Improve Bootstrap Current Fraction

$I_{steady\text{-}state} = I_{BS} + I_{AUX}$





$$f_{BS} \propto \sqrt{\varepsilon}\frac{a\nabla p}{B_\theta^2}$$

Huang, NF 2020
Garofalo, NF 2017
Wu, NF 2018

- **Fully non-inductive high-β_P scenarios extension to high density regime**
  - High-β_P generates more f_{BS}

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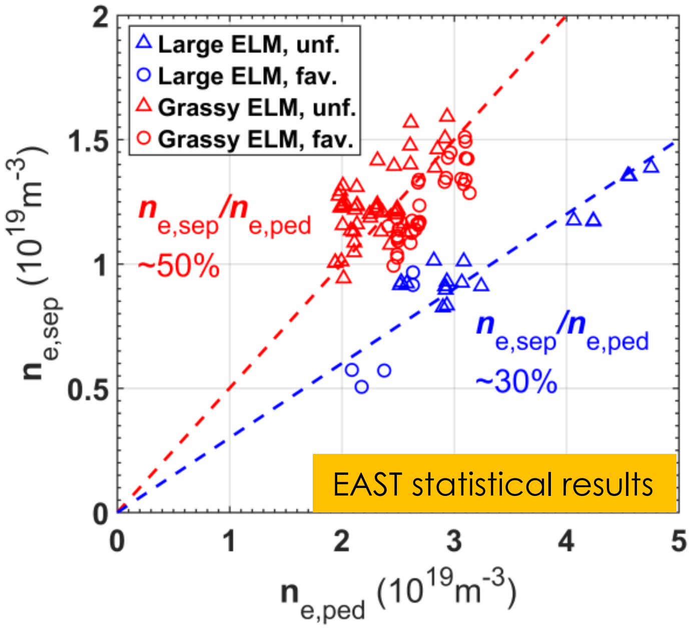
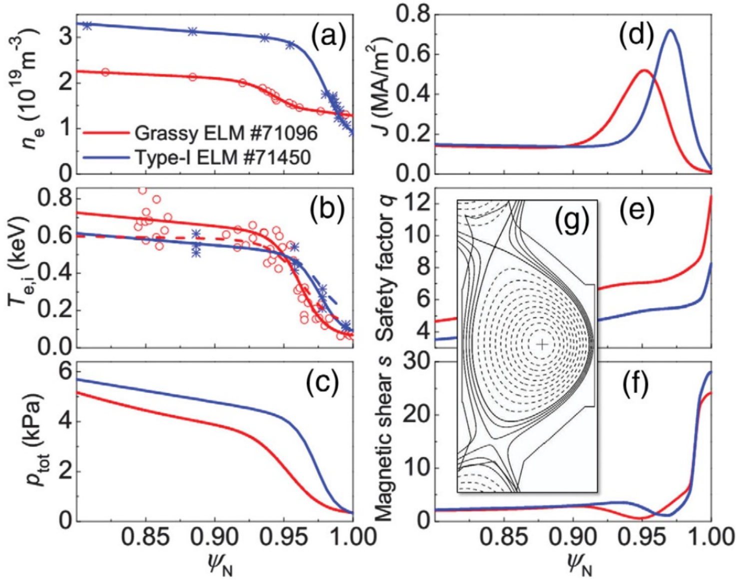
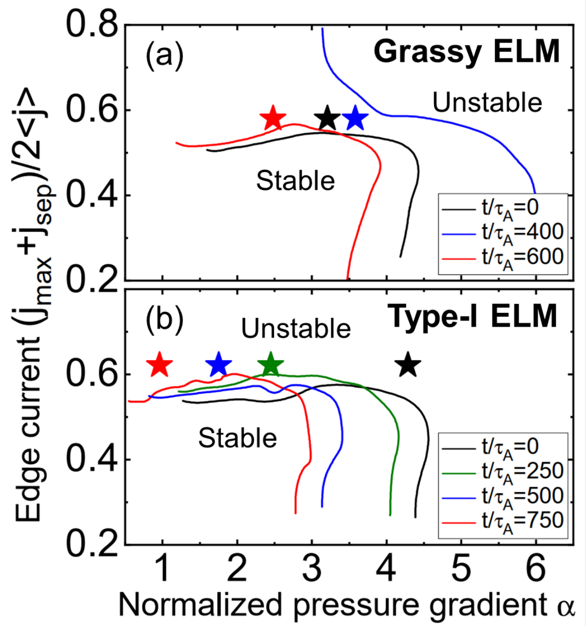
Lower Density Gradient for Small ELMs on EAST







- **Natural small ELMs in high β_P plasma**
  - Low n_e gradient and wide pedestal beneficial for small ELMs
- **Consistent with BOUT++ nonlinear simulations**
  - Expansion of PBM boundary → small ELMs
  - Pedestal staying in unstable region → large ELMs

Xu, PRL 2019
Yang, NF 2020
Lin, PLA 2022

See **Y. Wang**'s talk on Nov 16, this meeting

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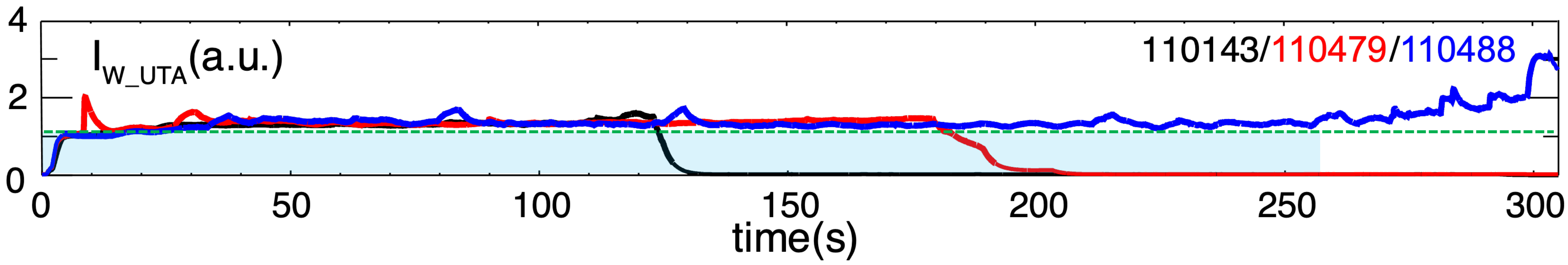
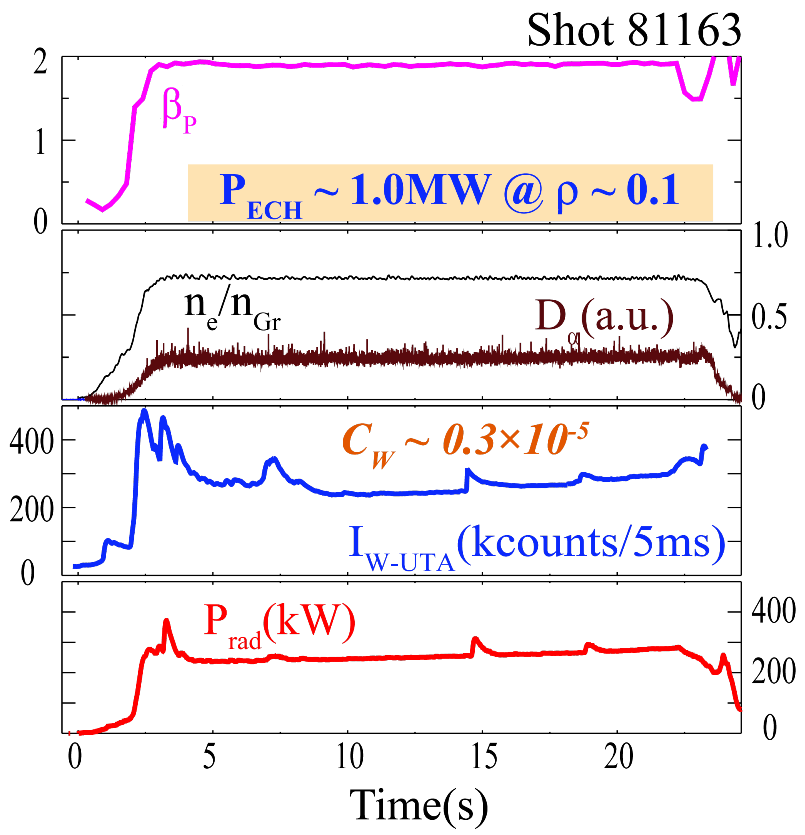
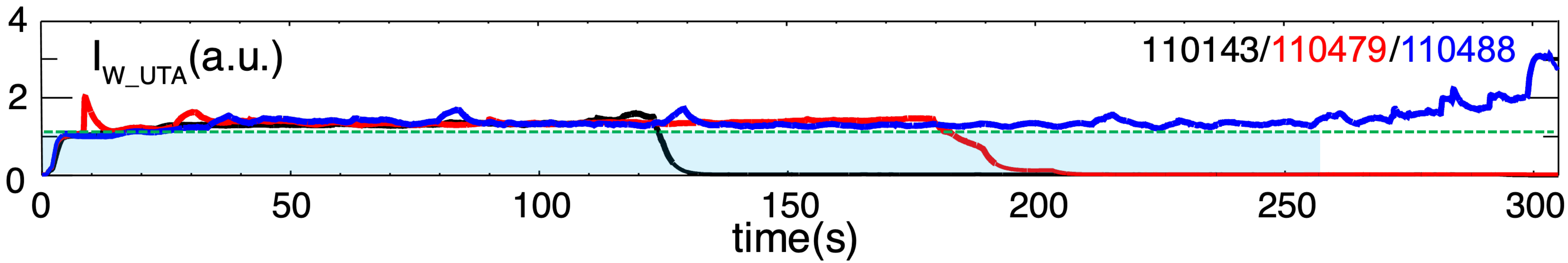
Well Controlled High Z Impurity in High β_P Plasma



Well Controlled High Z Impurity in High β_P Plasma

- **Small ELMs and high density (n_e/n_G~0.8) reduced W-sputtering**
- **Avoid high Z impurity accumulation by on-axis ECH**
  - W in good control within low level (C_W~0.3x10^{-5})





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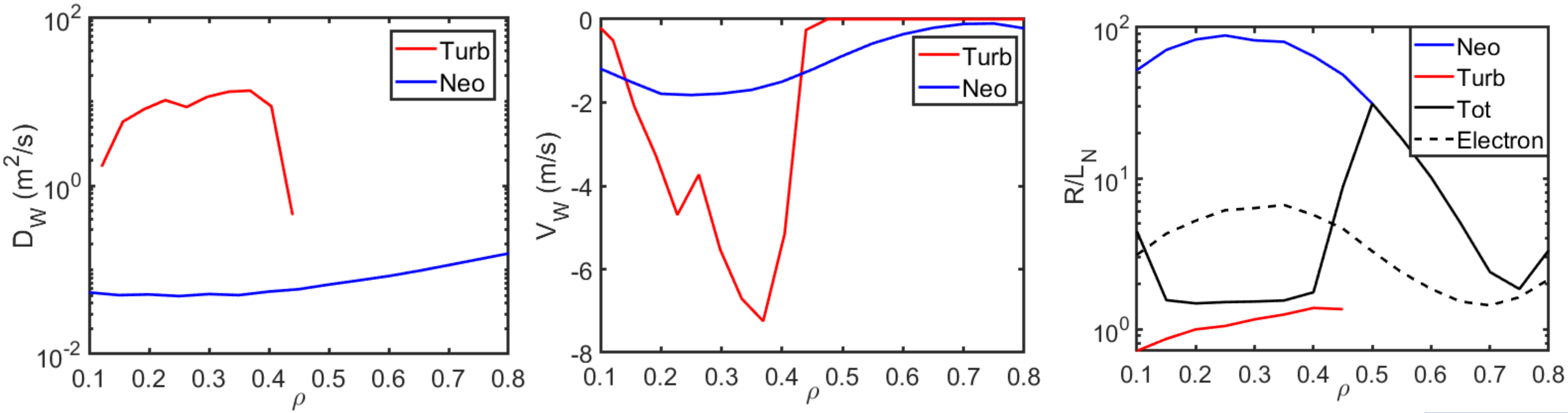
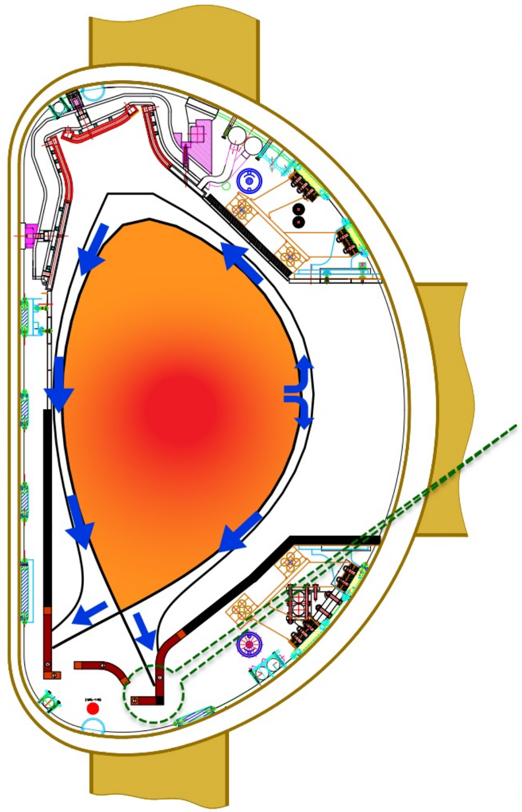
Modeling Shows Strong Diffusion of TEM in the Central Region Prevents W to Accumulate



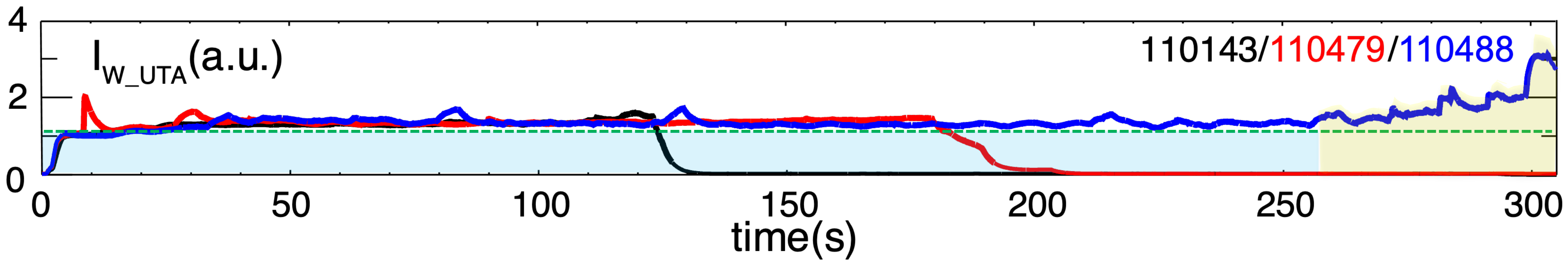
Gong, NF 2021

- **W modeling by QuaLiKiz and NEO**
- **TEM turbulence dominates**
- **W density peaking factor driven by the sum of neoclassical and turbulent transport lower than that of electron**
  - Strong turbulence diffusion inside $\rho<0.45$

Long-pulse Plasma Terminated with Increasing Tungsten



- **Hot spots at local regime of lower divertor, due to leading edge**



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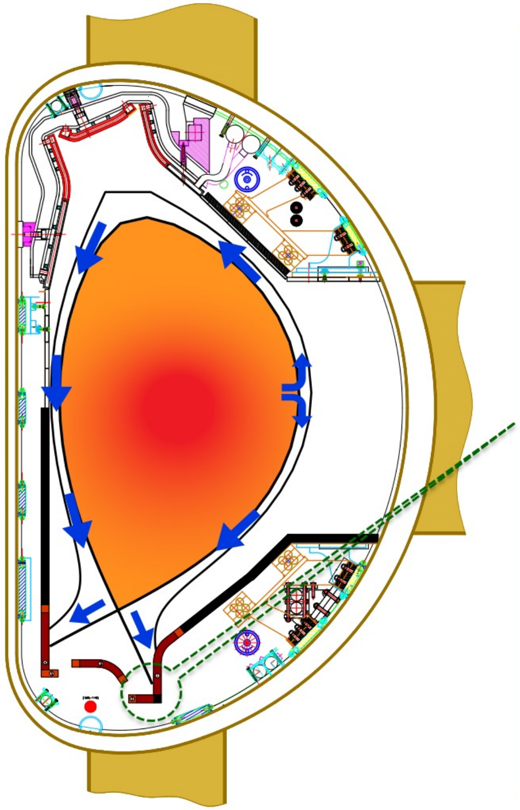
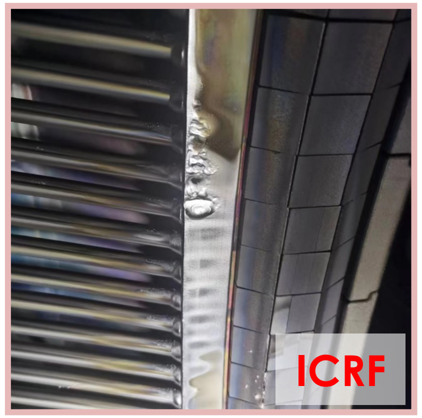
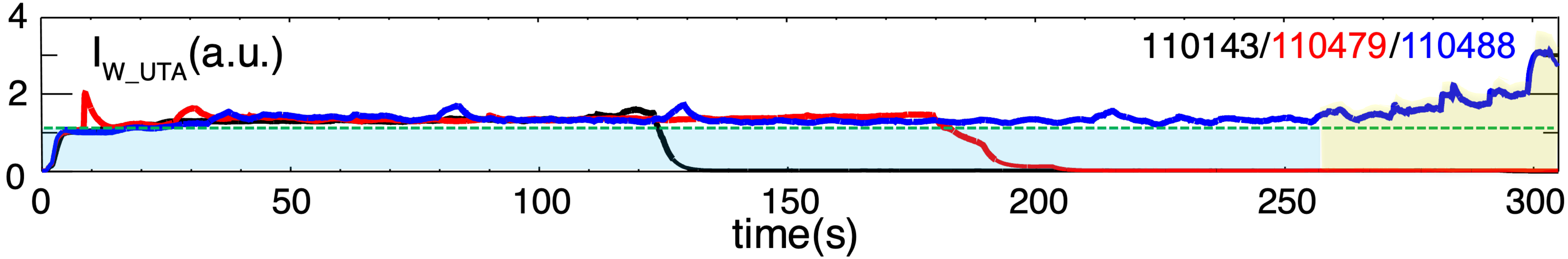
Long-pulse Plasma Terminated with Increasing Tungsten



- Hot spots at local regime of lower divertor, due to leading edge

- Sputtering and erosion from RF-antenna and guard limiter, also impact on plasma performance





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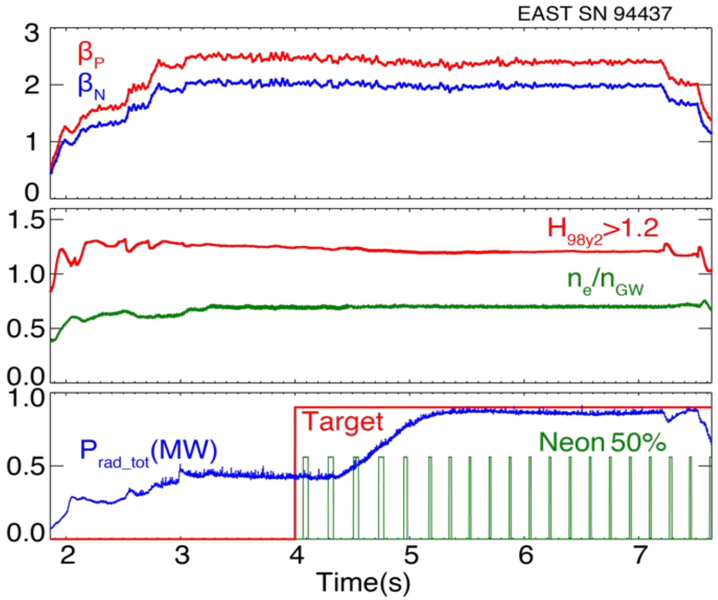
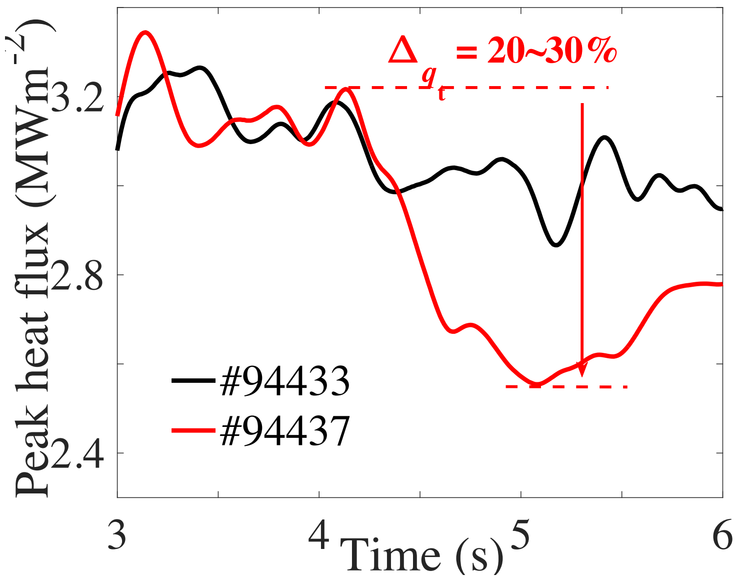
A Compatible Core and Edge Integration by Radiative Divertor Feedback Control

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





Gong, NF 2022

- **Radiative divertor feedback with a mixture of 50% neon and 50% D2 using $P_{rad,total}$**
- **Peak heat flux reduced by 20-30% (IR)**
- **Confinement maintained H_{98}>1.2**

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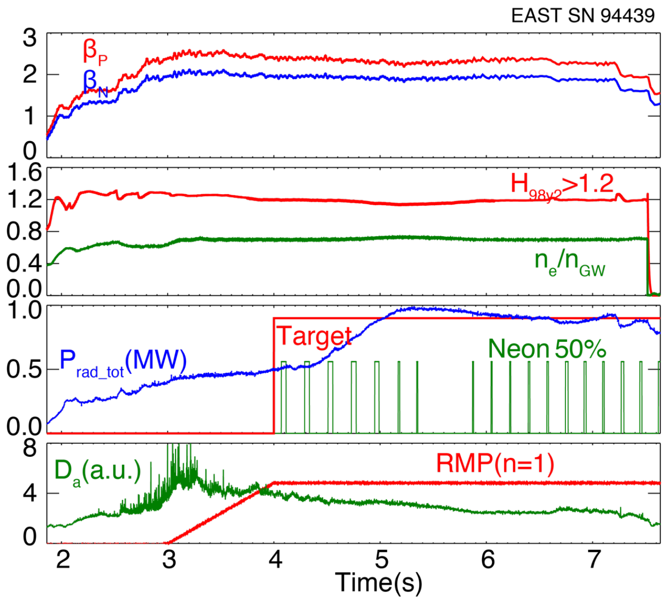

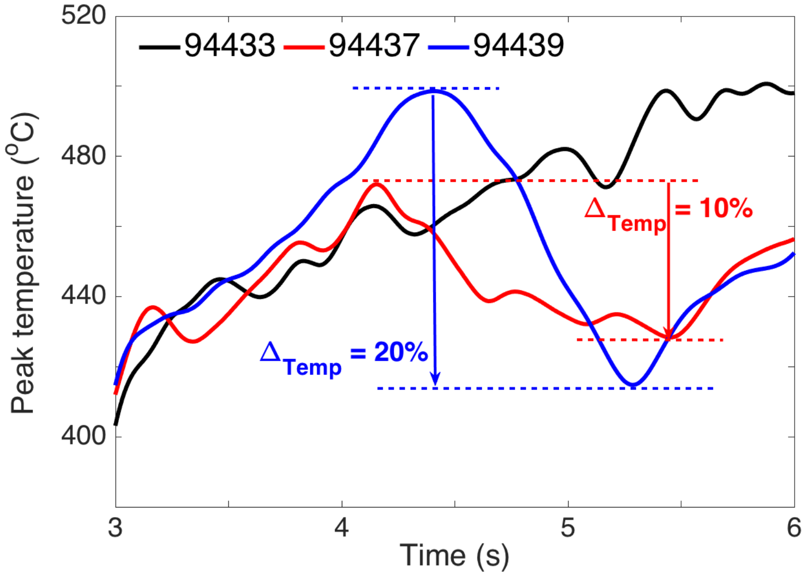

Gong, NF 2022

- **Core:** High β_P~2.5/β_N~2.0 with H_{98y2} >1.2, f_{Gr}~0.8, q_{95}~6.7
- **Pedestal:** ELM controlled by RMP n=1
- **Divertor:** Radiation and splitting

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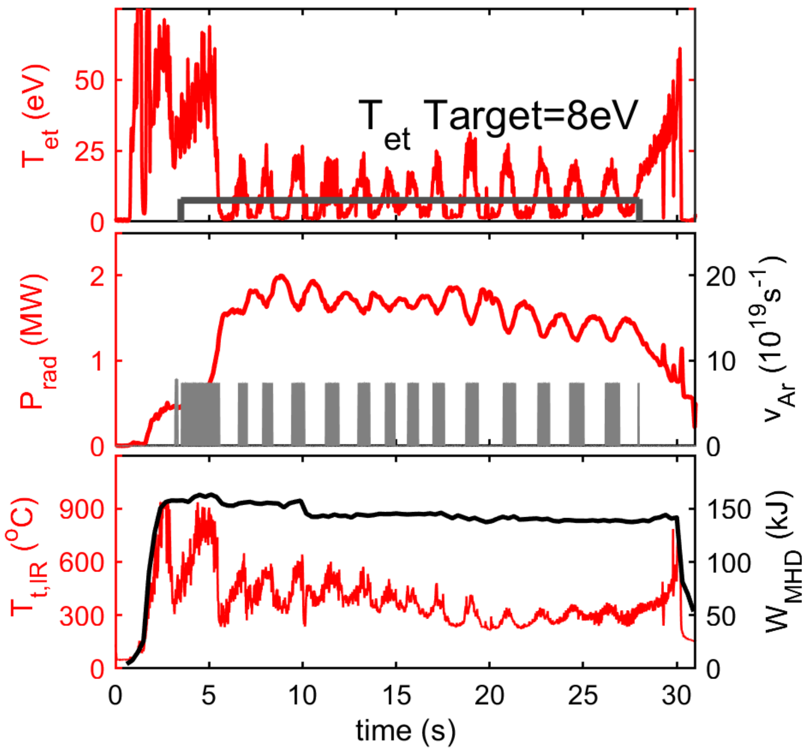

Wang, NF 2022

- **Active detachment control using divertor T_{et} feedback for long pulse**
- **H_{98y2}~1, good core-edge integration**

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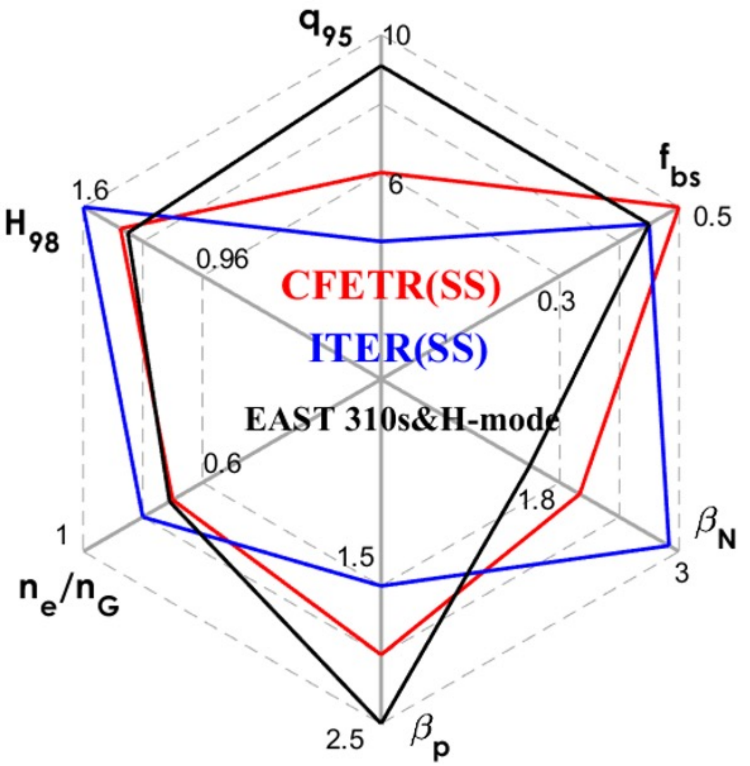
Outline

- ❑ Progress of EAST in support of ITER and CFETR
- ❑ Key issues in long-pulse and steady-state regime
- ❑ Future plans and summary

Challenges and Future Plans

- **Need to develop innovative physics understanding & approaches towards ITER&CFETR SS LPO:**
  - Handle particle and heat load, materials erosion, elimination of damaging with long pulse
  - Solve divertor/SOL, pedestal, confinement & transport and its trade-off with H&CD



Challenge/Goal	Approaches	Capabilities
Solve fully non-inductive high-β_p scenario with T_e~T_i at lower q_{95} and zero-torque, efficient H&CD at high density, β–limits,	• Discover high performance core solutions. Validate models in burning-plasma-relevant regimes • Major H&CD upgrade with shape, B-field • High current for ICRF ion heating and enable lower q_{95} • Transport for various Te/Ti , electromagnetic effects, magnetic shear and Shafranov shift, and ExB shear	• **6MW ICRF (2-antenna)** • **6MW EC (2-gyrotrons, dual Freq.)** • **4MW LHW PAM-4.6GHz** • **2MW NBI RF-sources** • **New modular limiters & Div.** • **New Control and DIAs upgrades**
Expand range of j(r) & P(r) to improve performance to find high confinement high-β_p regime with large radius ITB & high f_{BS}	• Develop integrated simulation tools to test fundamental physics of q_{min}>2 for ITB and f_{BS} • Increases in ECH&ICRH to access to ITER and CFETR relevant β_N & q_{95} • Focus on profile requirements for ideal MHD limits, good EP & global confinement	
Demonstrate long pulse with high power (P_{loss}/R) operation to extend fusion performance	• Improve particle and power handling, elimination of damaging from hot spots • Recycling and heat flux control etc. in real-time • Identify path to integration with divertor and core solutions	

Summary

- **Significant progress has been made in long-pulse SSO on EAST**
  - Demonstration of a 1056s time scale fully non-inductive plasma
  - Record of duration~310s H-mode plasma (β_P ~2.5, f_{bs}~50%, $H_{98(y2)}$>1.3) achieved
  - Extension of higher β_P at high density operation scenario with full metal wall

- **Advances on the key issues essential for long pulse SSO, providing supports to ITER and CFETR steady state operation**
  - 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.
  - W accumulation is prevented by TEM when using on-axis ECH

- **Near-term plan with upgrade of inner components and augmented H&CD systems**
  - 400-1000s long-pulse H-mode operation with >50% bootstrap current fraction
  - Demonstrate SSO with **extended fusion performance** at 15-20 MW power injection >100 s

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

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