Development of Long Pulse Fully Non-inductive High-confinement Plasma with Full Tungsten Limiter/Divertor on EAST

by

X. Gong[1*]

with **J. Huang[1], J. Qian[1], A. M. Garofalo[2], A. Loarte[3], R.A. Pitts[3], T. Wauters[3], R. Ding[1], X. Zhang[1], L. Zeng[1], B. Zhang[1], L. Xu[1], P. Li[1], W. Liu[1], K. Li[1], A. Ekedahl[4], R. Maingi[5], G. Zuo[1], Y. Yu[1], Q. Zang[1], L. Wang[1], H. Liu[1], Y. Zhang[1], L. Zhang[1], T. Zhang[1], D. Yao[1], Q. Yang[1], G. Li[1], Q. Ren[1], M. Li[1], B. Xiao[1], G. Xu[1], J. Hu[1], K. Lu[1], J. Chen[1], F. Liu[1], X, Wu[1],Y. Song[1], B. Wan[1], J. Li[1] and EAST team**

[1]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*

[2]*General Atomics, San Diego, CA, USA*

[3]*ITER Organization, CS 90 046, 13067, St. Paul Lez Durance Cedex, France*

[4]*CEA, IRFM, F-13108 Saint Paul-lez-Durance, France*

[5]*Princeton Plasma Physics Laboratory, Princeton, NJ, USA*

***E-mail: xz_gong@ipp.ac.cn**

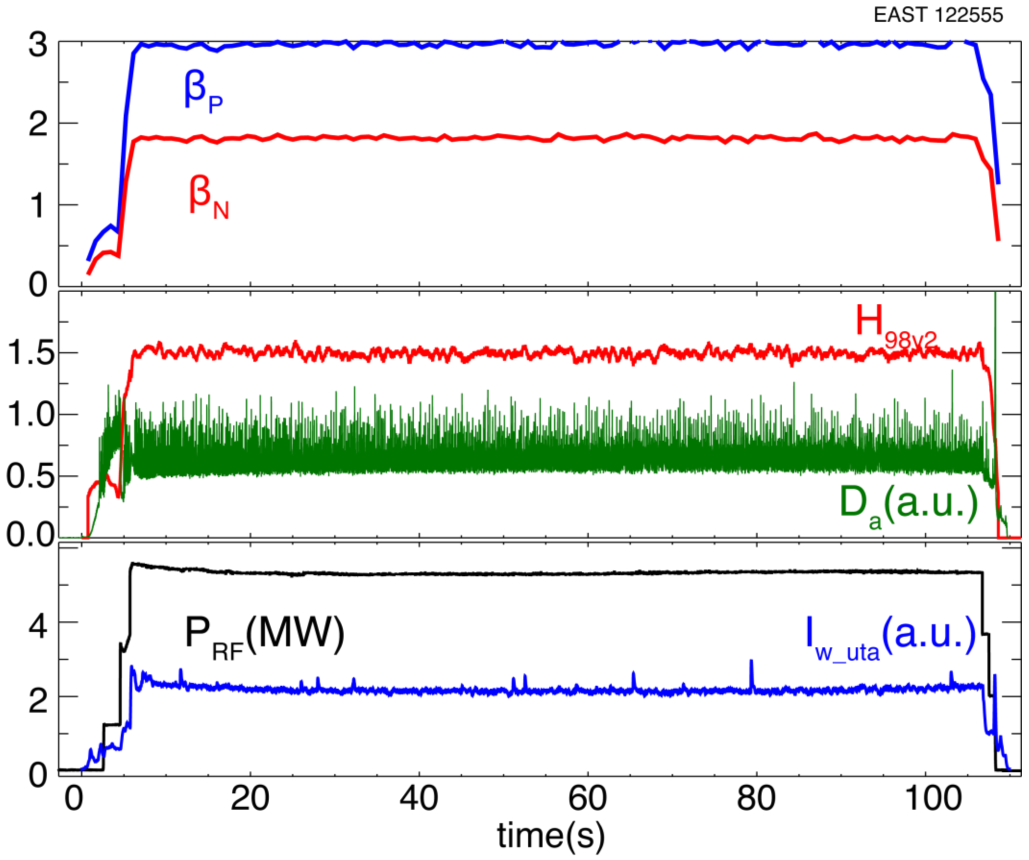
2nd Technical Meeting on Long-Pulse Operation of Fusion Devices
Oct. 17 2024, IAEA Headquarters Vienna

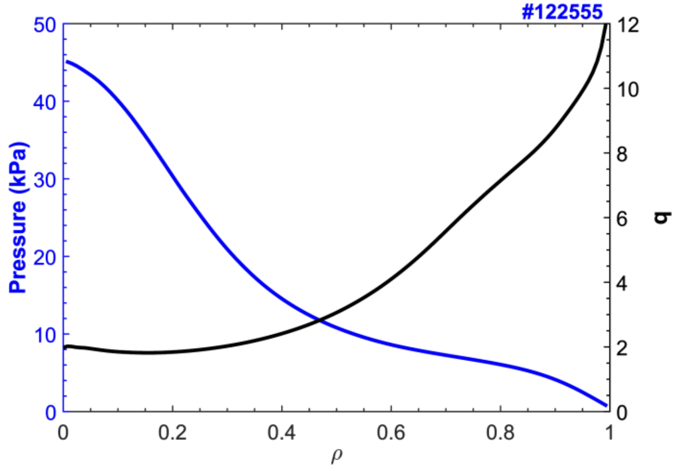
Outline

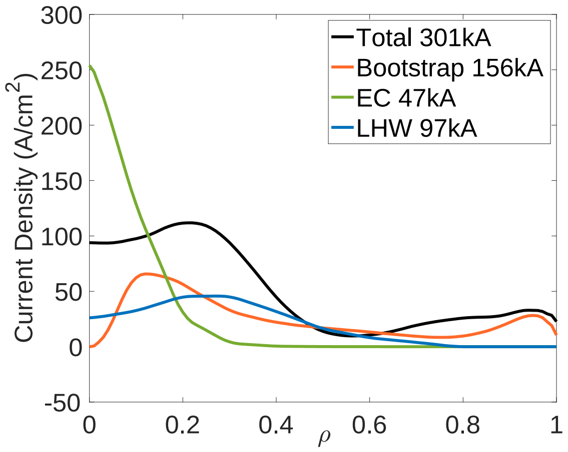
- **Extension of fusion performance towards SSO**
- **Physics understanding in high-β_p steady-state plasma**
  - Enhanced H&CD efficiency at high density
  - Improve confinement with zero torque injection
  - High-Z impurity and heat flux control
- **Long Pulse H-mode Plasmas on Full Metal Wall in Support of ITER NRP**
- **Future plan and summary**

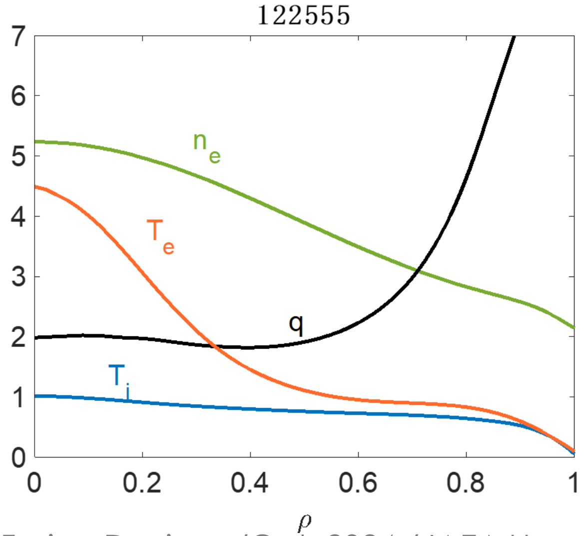
Fully Non-inductive High-β_P Scenarios Extension to High Density Regime with Good Confinement

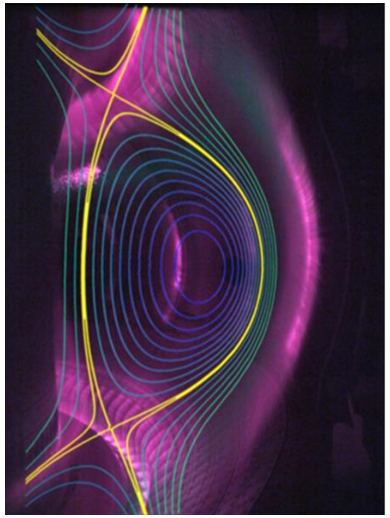
- **Long pulse operation with a duration of >100s in RF-heating: P_{EC}~1.75MW, P_{LH}~2.0MW, P_{IC}~1.6MW**
  – n_{GW}~0.82, flat q-profile with $q_{(0)}$>2.0
  – H_{98y2} ~1.5, β_P~3.0/β_N ~1.8, f_{BS}~56%





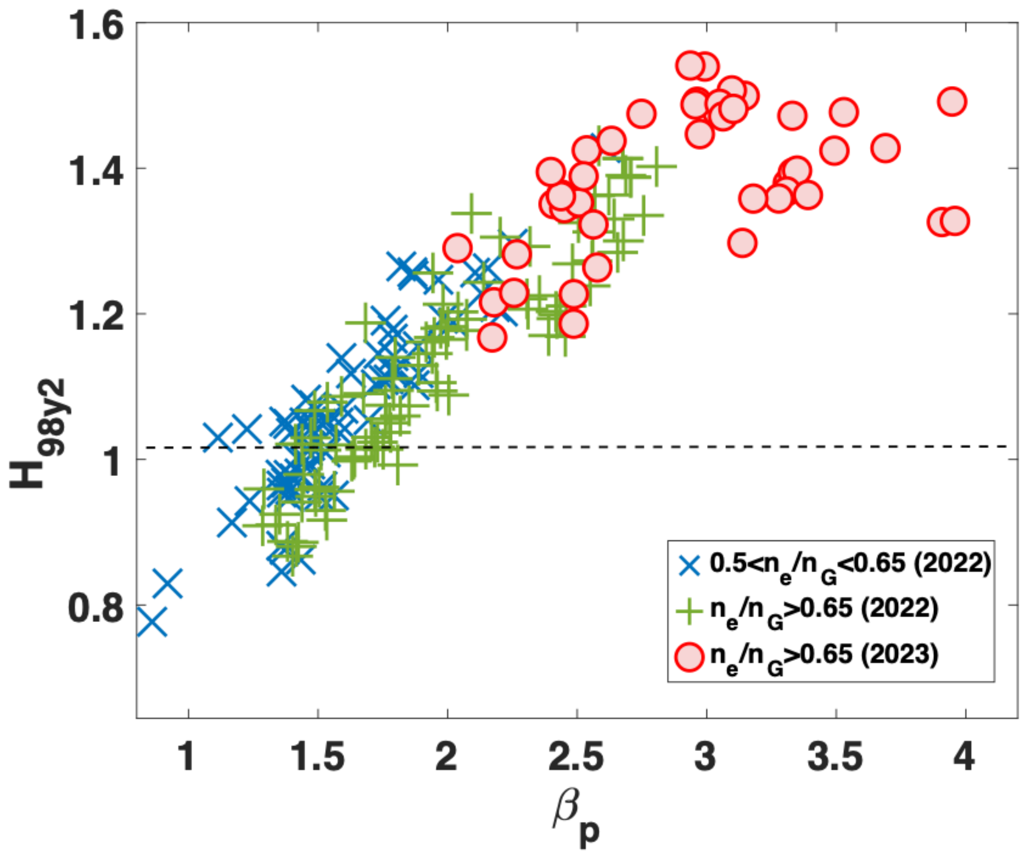






Experiments Show Improved Confinement when Extending to High-β_P Regime

- High energy confinement at high-β_p with high-n_e
- Zero torque with e-ITB
- Electron heating dominant
- Small ELMs (f_{ELM}~1kHz)
- Good high-Z impurity control



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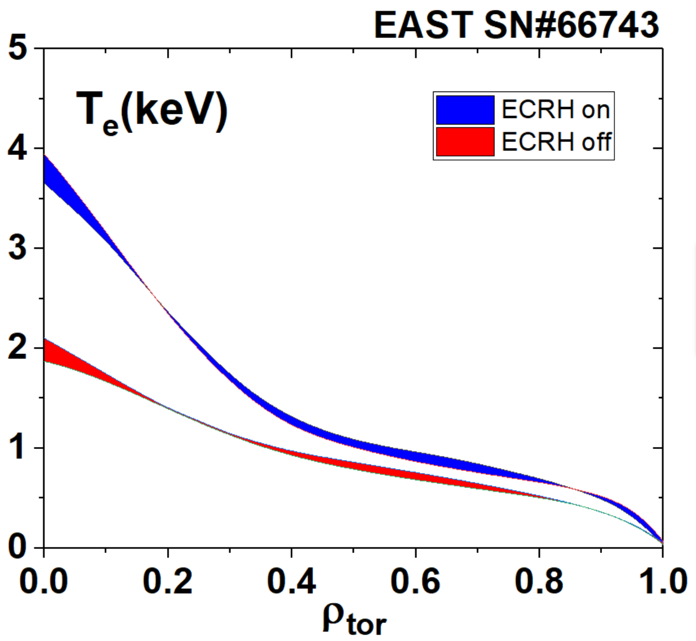
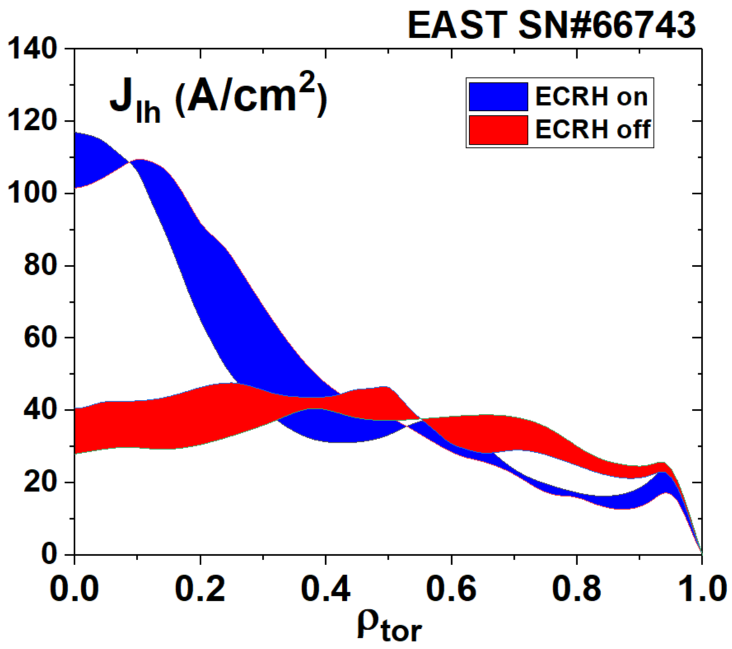
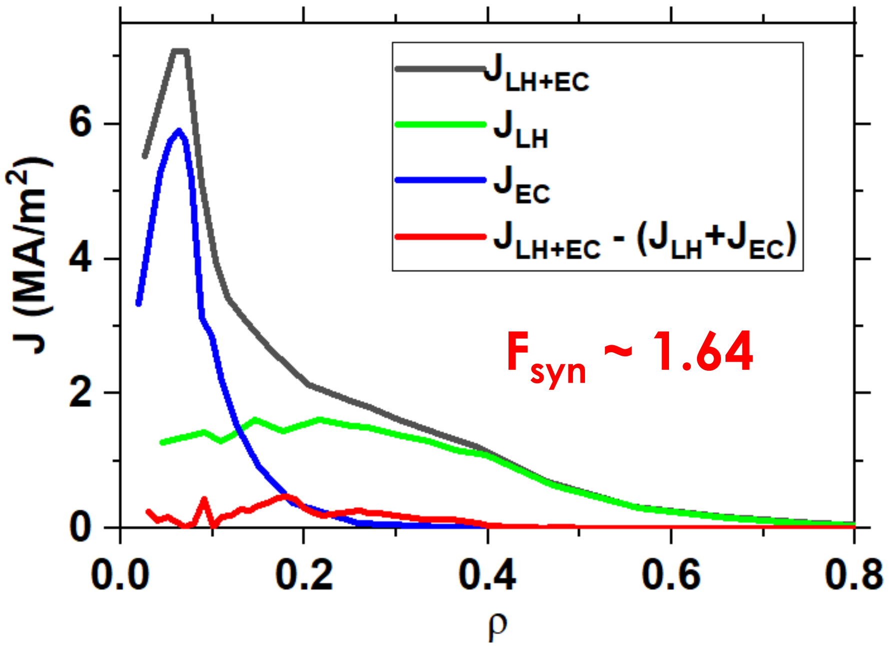
- ❑ **Future plan and summary**

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



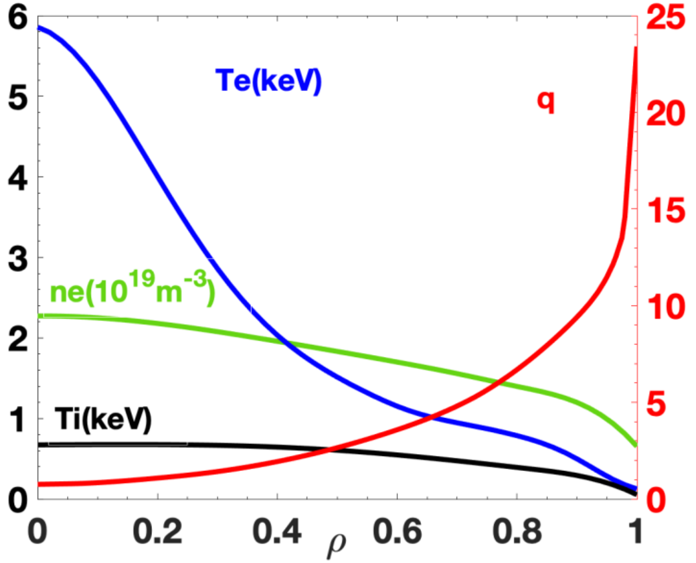


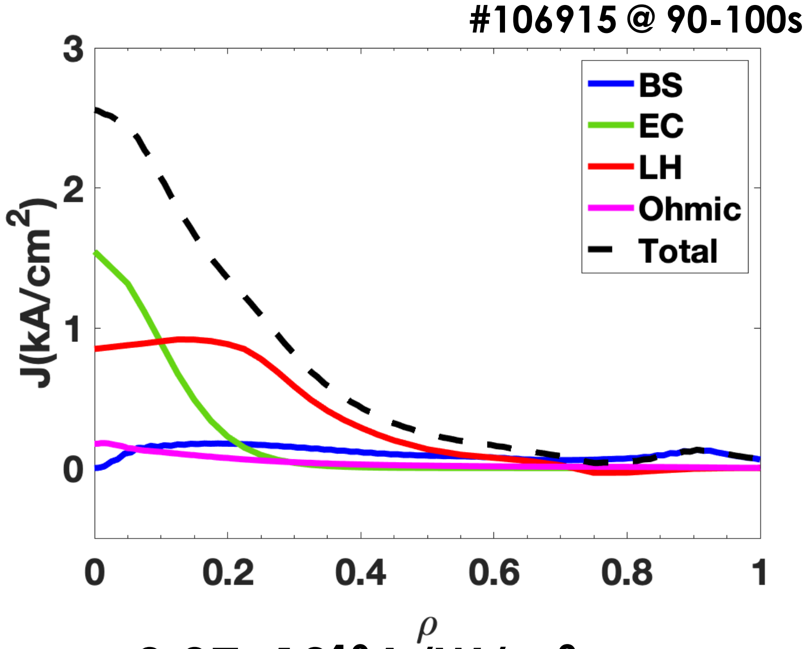


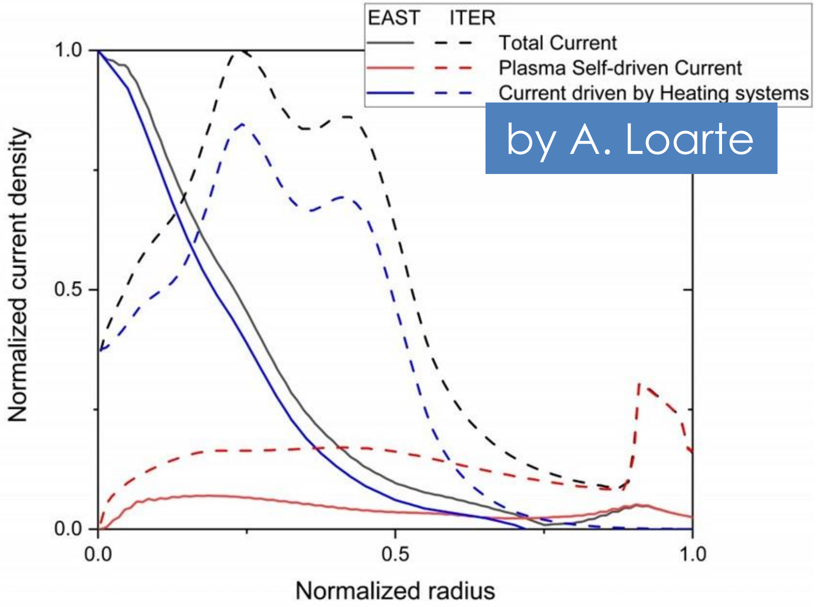
- **Improved RF current efficiency ~0.87×10^{19}A/W/m^2**
  - CD efficiency increases with $\langle T_e \rangle$
  - Synergy factor as $F_{syn} = \Delta I / I_{EC}$ ~ 1.64 , due to velocity space diffusions between ECCD and LHCD
- **Fully non-inductive CD with f_{RF}~70% and f_{BS}~30% at β_P~1.5**
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

ASIPP

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







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

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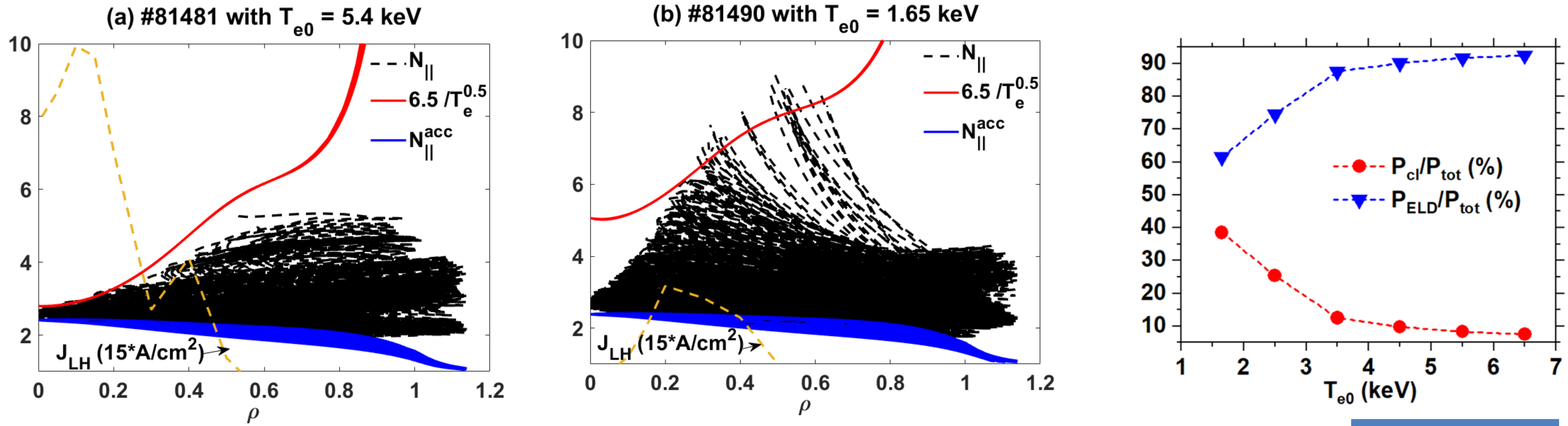
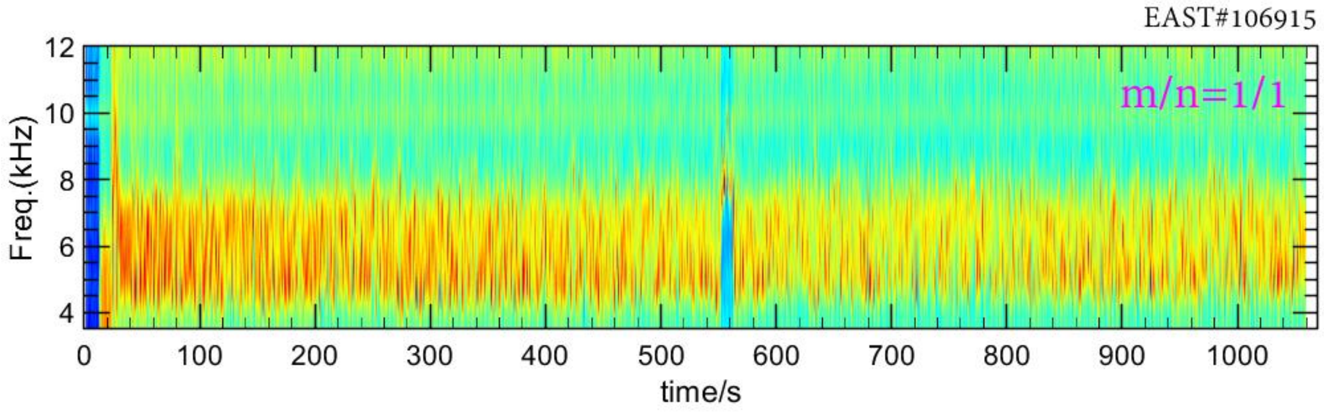
Higher Te can Reduce Power Loss of LH Waves in Edge

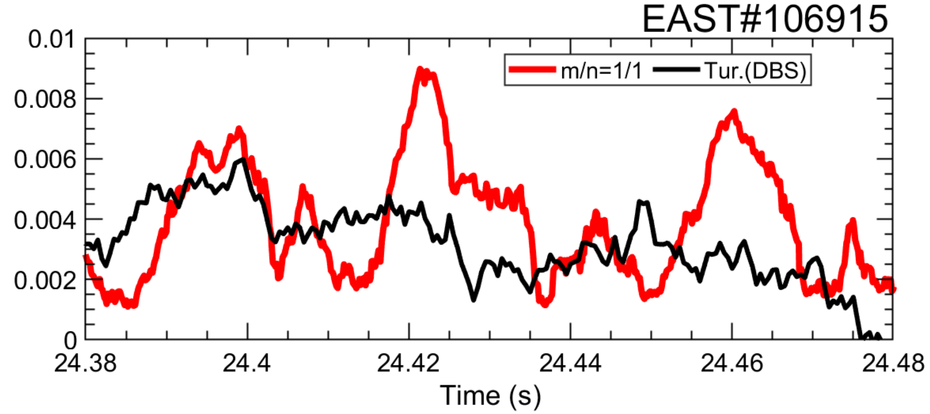


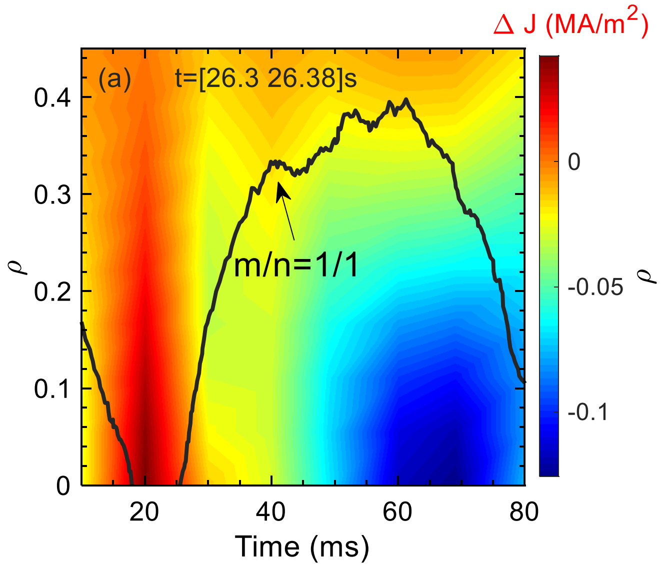
M. Li, NF 2023

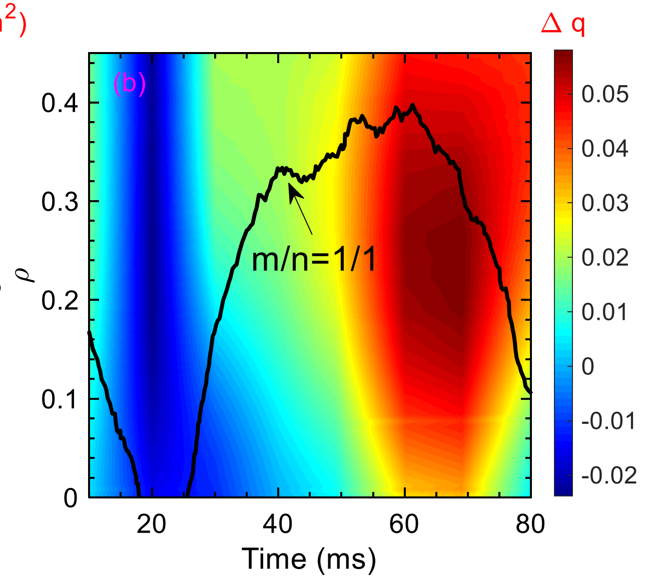
- **Higher electron temperature can shorten the $N_{||}$ spectral gap for Landau damping of LH waves**
- **Fewer passes between plasma edge and center are needed to bridge the spectral gap, leading to less LH power loss in the SOL by collisional damping**

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

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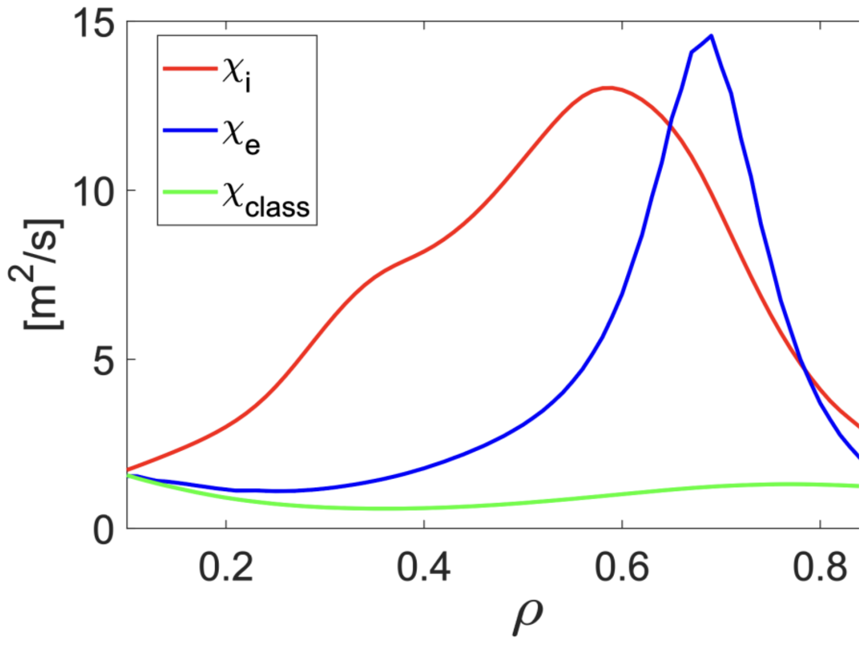
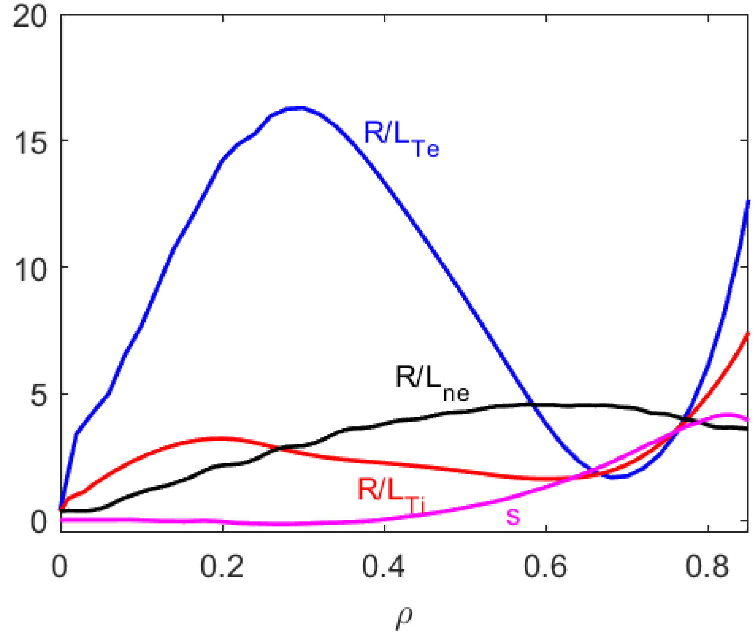
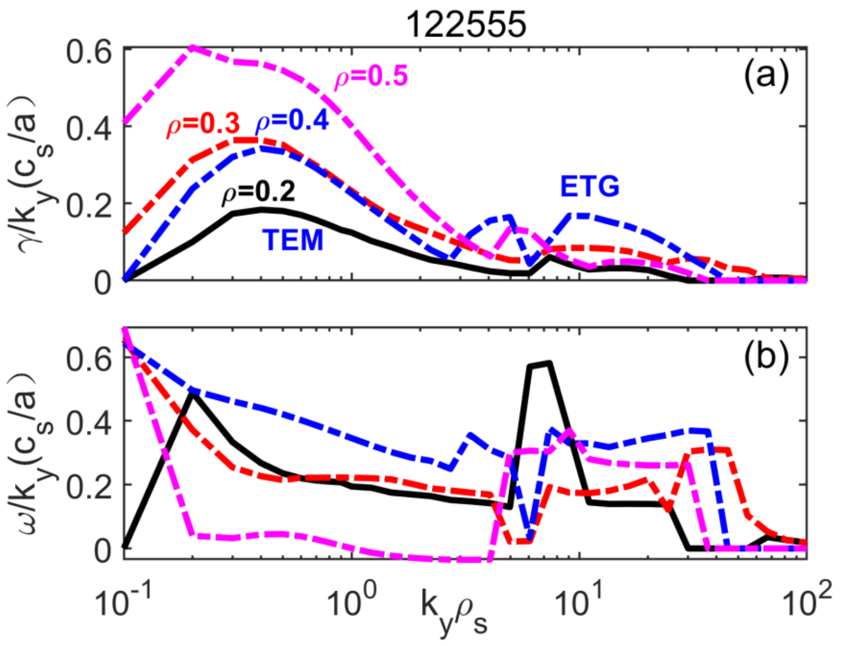
Reduced Transport in Electron Energy Channel Consistent with T_e-ITB Formation

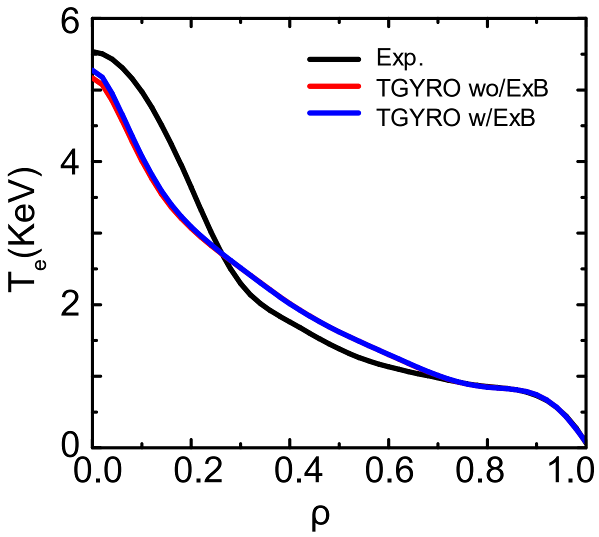


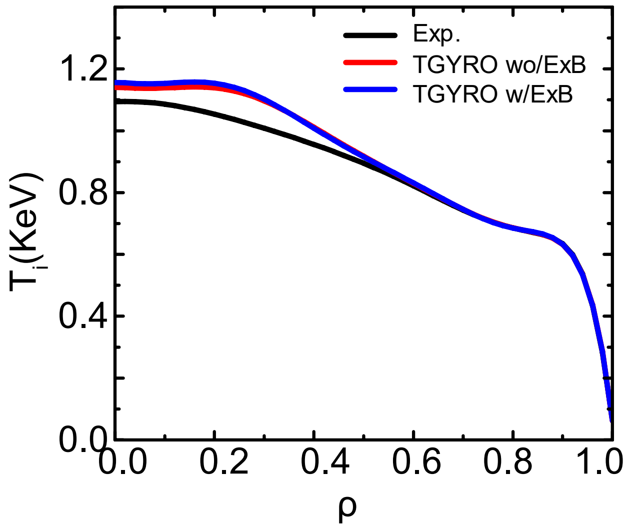


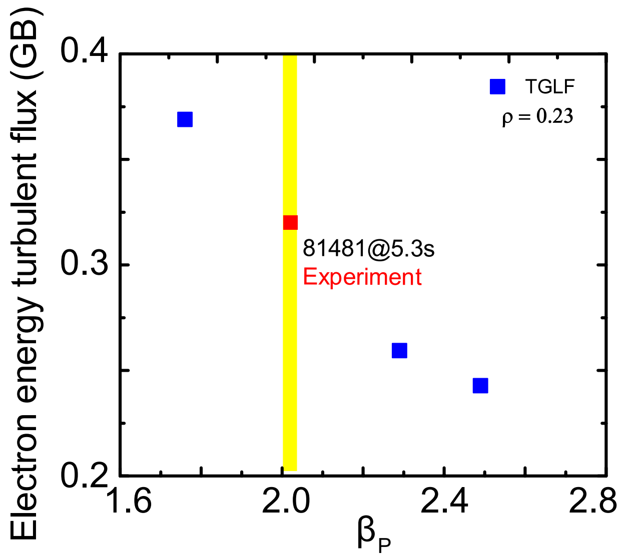


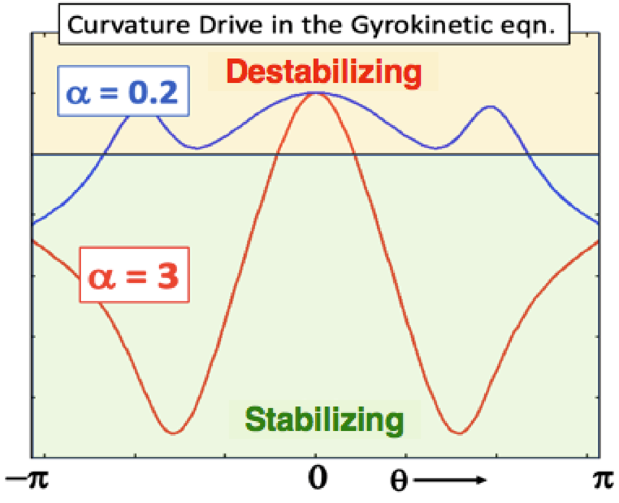
- **Electron transport reduced in ρ<0.4**
  - Consistent with improved confinement
- **Linear analysis by TGLF**
  - TEM modes dominate at ITB
  - ETG modes dominate outside ITB

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

Jinping Qian, POP 2021
Kotschenreuther, IAEA 2020
Juan Huang, PPCF 2020

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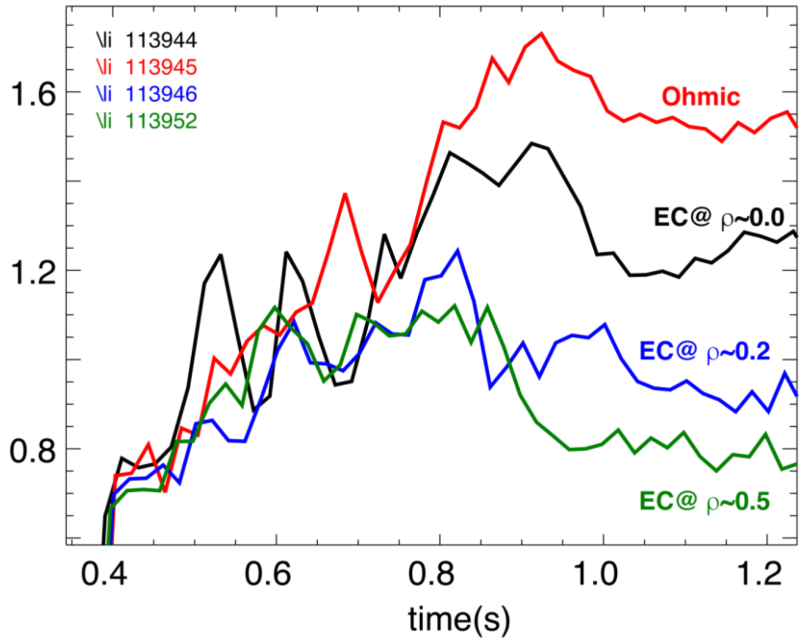
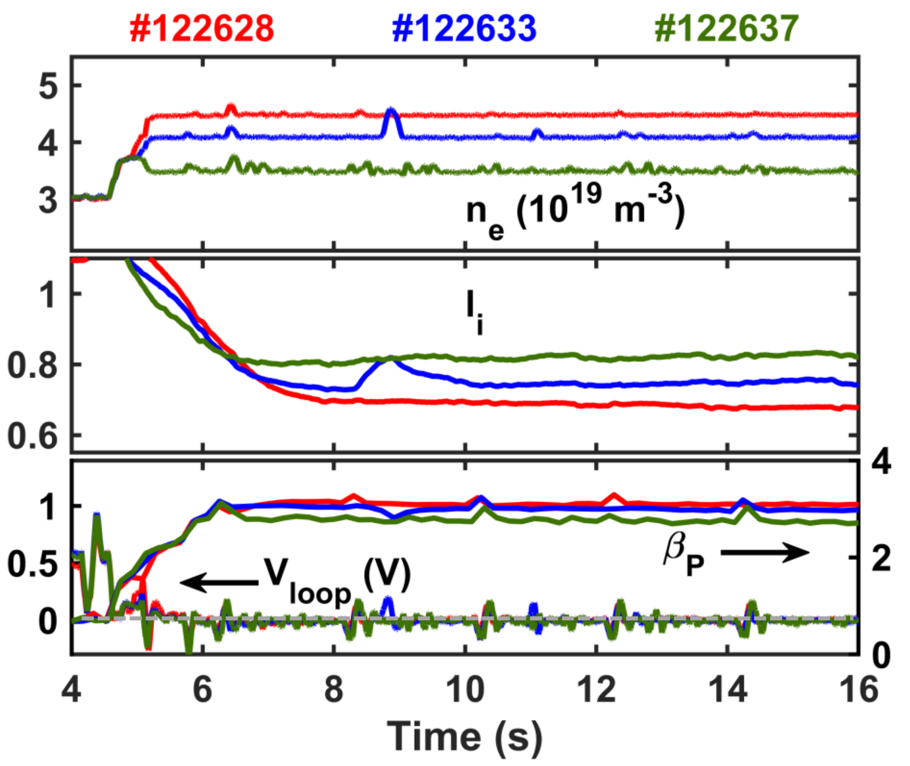
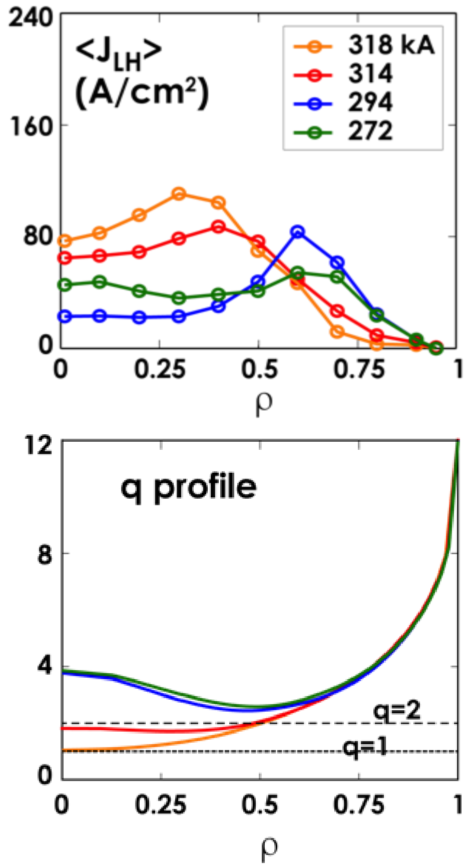
Broad Current Profile by Early EC Heating and off-axis LHCD at High Density Sustained Fully Non-inductive High-β_P Scenarios





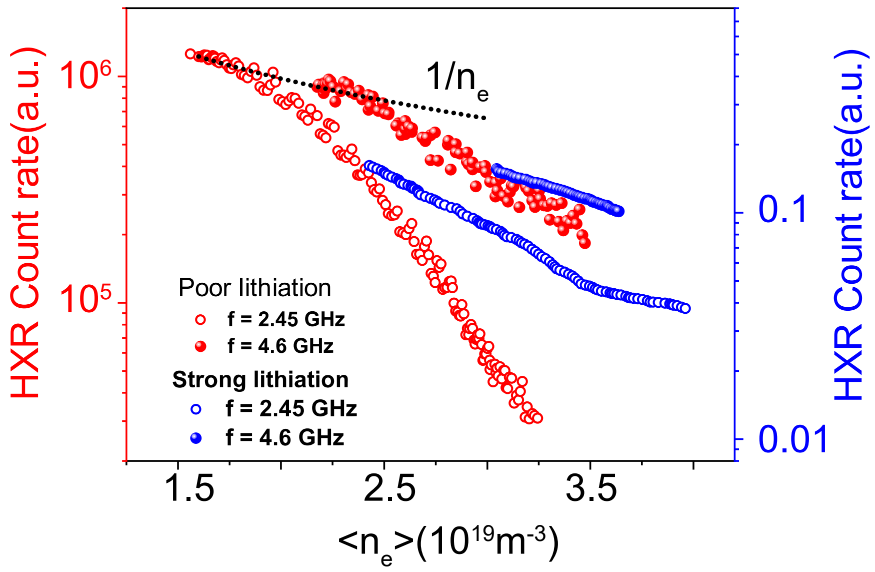


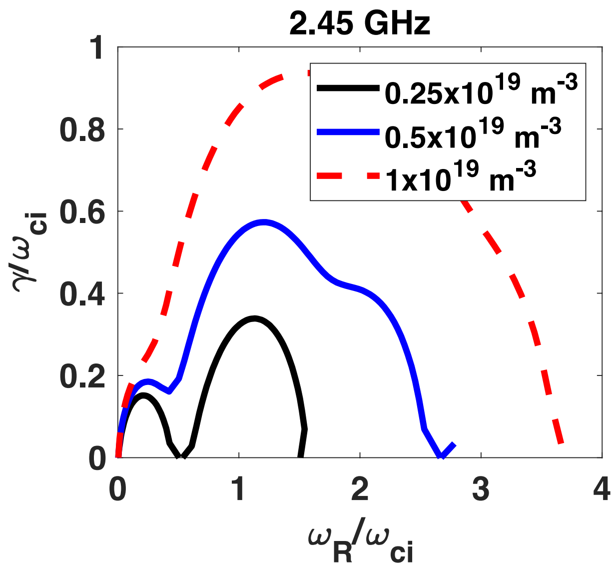
A. M. Garofalo NF 2017

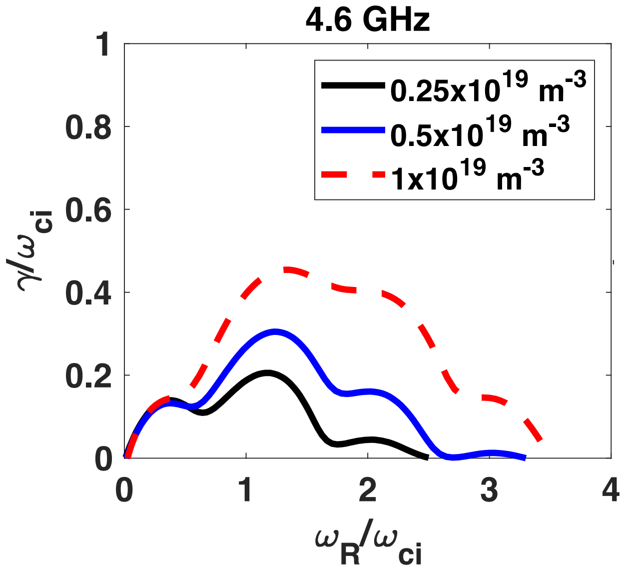
- Lower li obtained by early EC-heating during Ip ramp-up
- Current profile becomes broader with EC deposition more off-axis
- **Broader current profile obtained at high density with more off-axis LHCD**
  - $n_e \uparrow \Rightarrow \eta_{CD} \downarrow$; broad j(r)+weak shear → confinement ↑ + $\beta_P \uparrow$ ➔ $f_{bs} \uparrow$

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

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





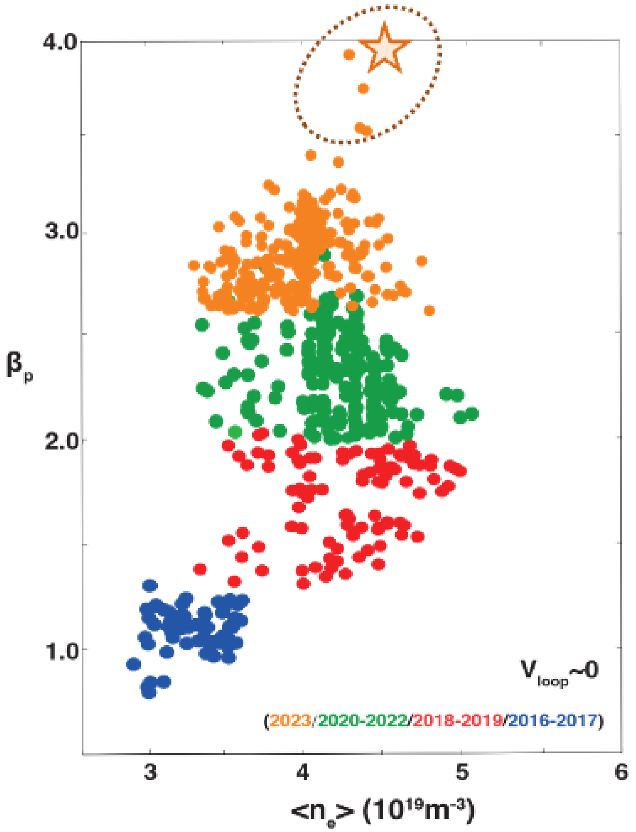


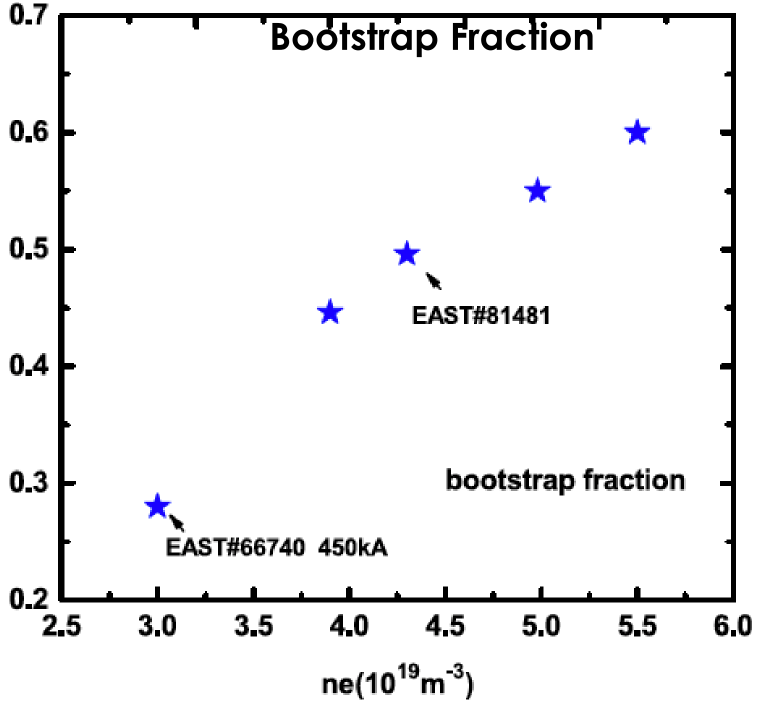
Miaohui Li, NF 2022

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

High Density Regime Helps to Improve Bootstrap Current Fraction in High-β_P Scenarios

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





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

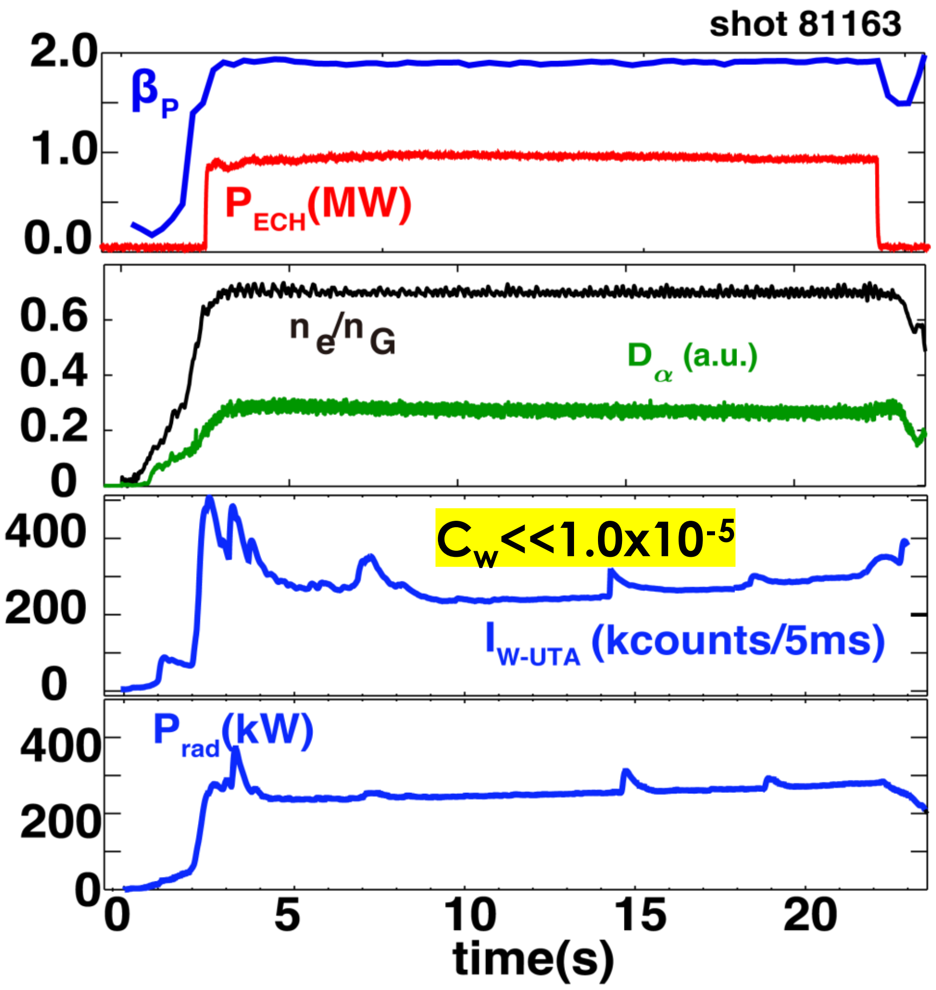
Juan Huang, NF 2020
A. M. Garofalo, NF 2017

- **Fully non-inductive high-β_P scenarios extension to high density regime**
  - High ∇n → turbulence transitions from ∇T driven to ∇n driven
  - High β_P → narrow eigenfuction, couples poorly to ∇n driven mode

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** $\rho<0.45$

X. Gong, NF, 2021 / X. Gong, NF 2024



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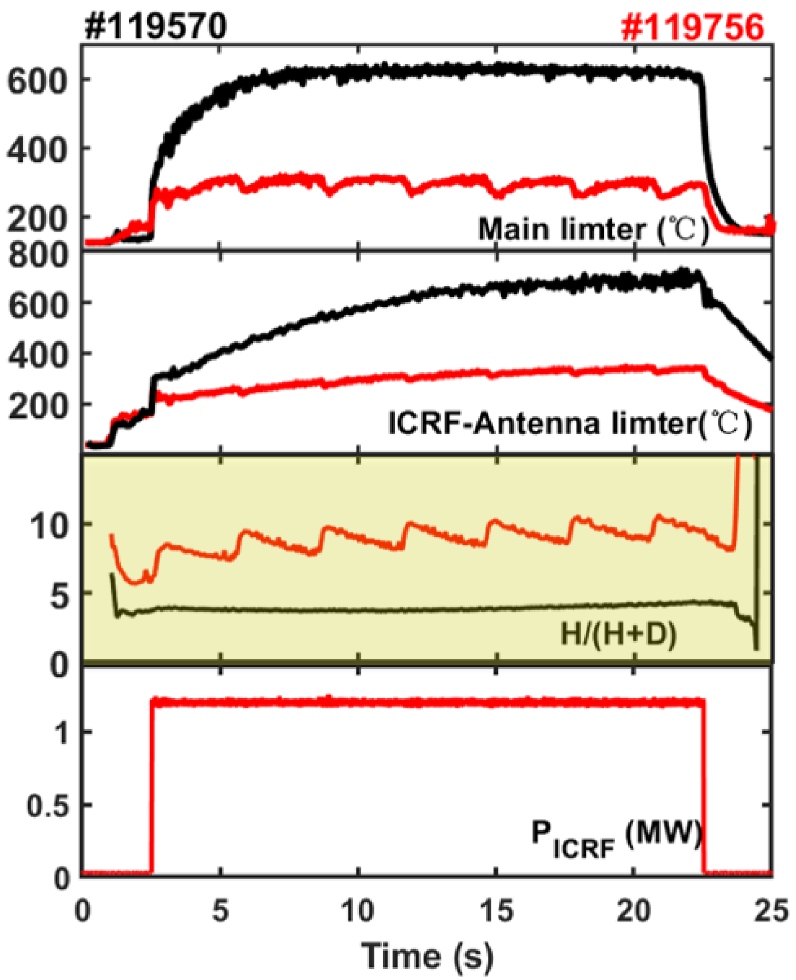
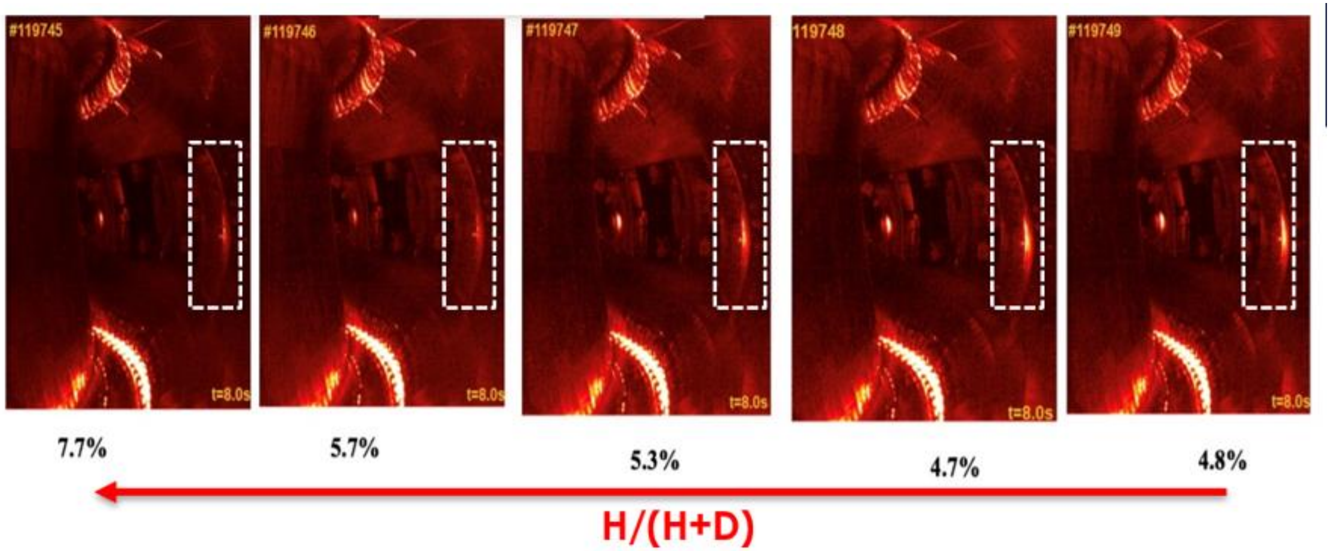
Mitigation of IC-Fast Ion Loading on PFCs by Optimizing H/D Ratio





ICRF H-monitory heating on EAST:

- IC ~ 1.5-2.5MW, $E_{fastions}$>150keV, E_{loss}>100keV
- Higher Density: $E_{fastions}\downarrow$~50keV-150keV
- Higher n_H/n_e : $E_{fastions}\downarrow$~50keV-100keV

Reduced temperature on main/guard limiters by active control of H/H+D (~8%)

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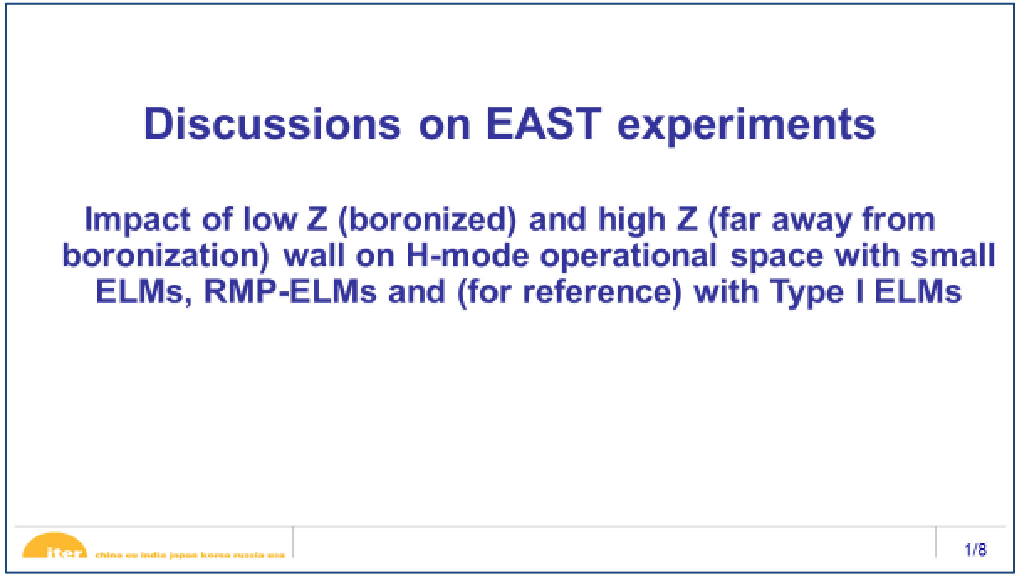
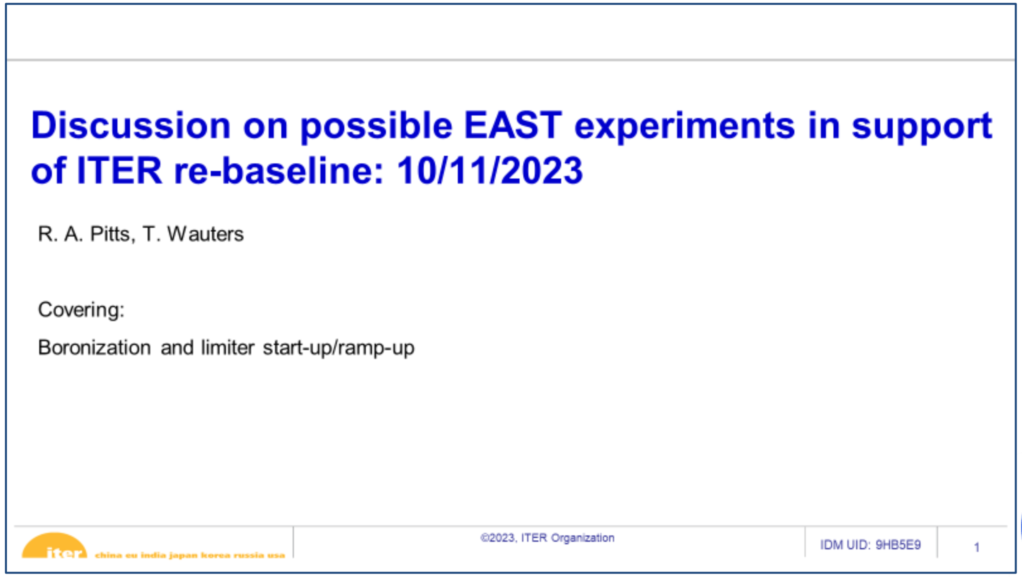
- **Long Pulse H-mode Plasmas on Full Metal Wall in Support of ITER NRP**
- **Future plan and summary**

Established a Joint EAST/ITER Team to Develop Detailed Experimental Plans on EAST to Address the ITER New Baseline Issues

1. Boronization studies on optimization, characterization of retained fuel and efficiency of removal
2. Limiter start up on W and L-mode ramp-up with low Z (boronized) and high-Z (far away from boronization) wall and mitigation of W accumulation related issues
3. Impact of low Z (boronized) and high Z (far away from boronization) wall on H-mode operational space with small ELMs, RMP-ELMs and (for reference) with Type I ELMs.

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





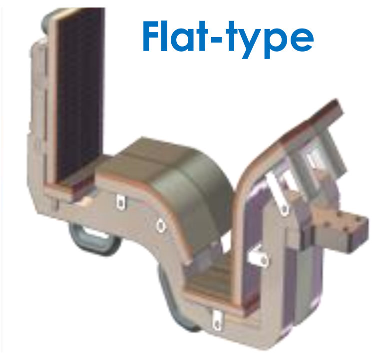
Dedicated EAST Mini-Campaign (Dec. 2023 – Jan 2024) was Performed in Support of New ITER Baseline

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

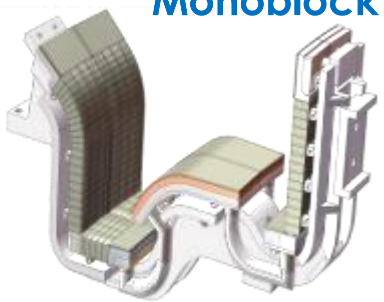
New Tungsten Lower Divertor

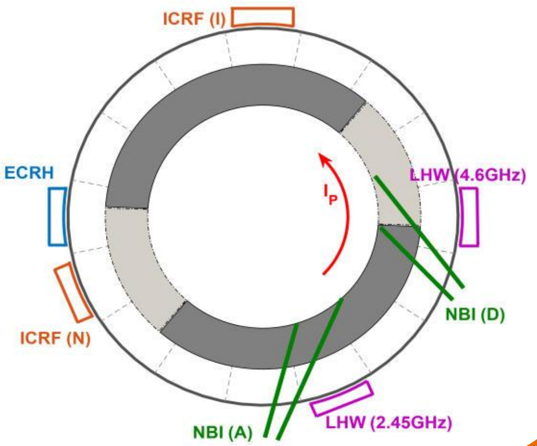
After 2021

Flat-type

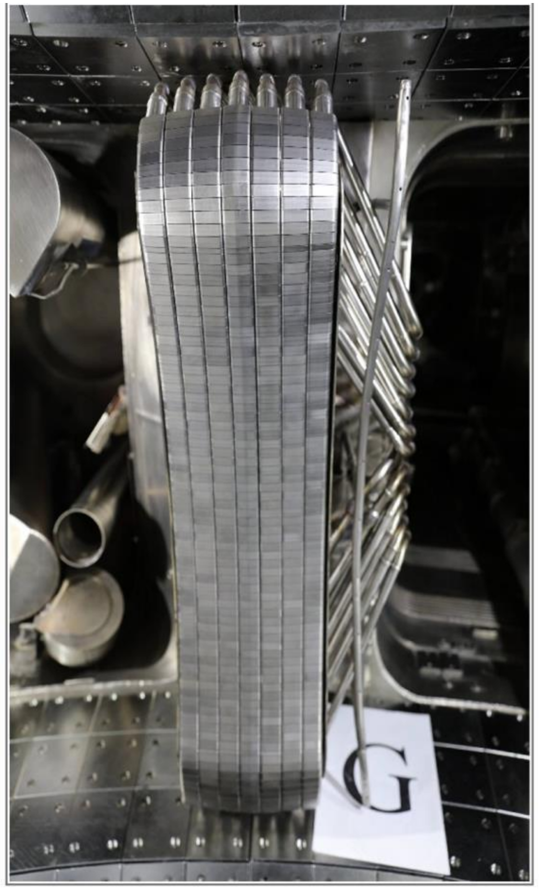


Monoblock

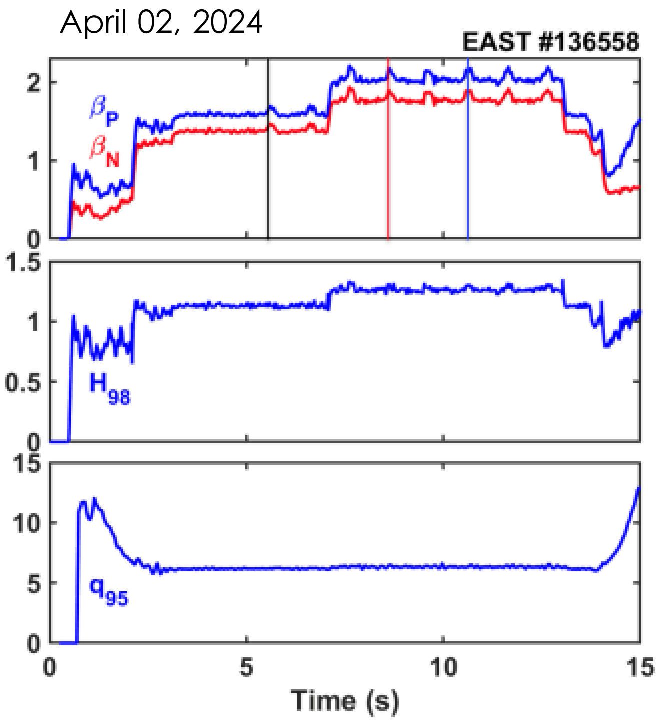


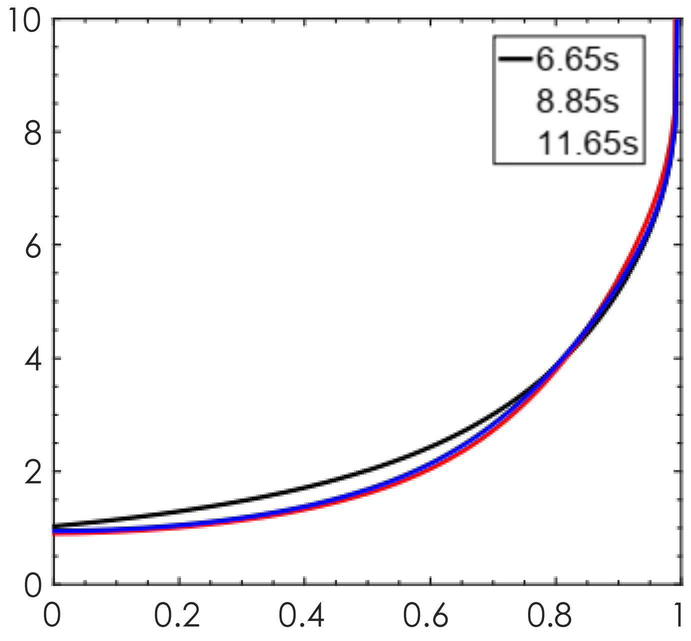


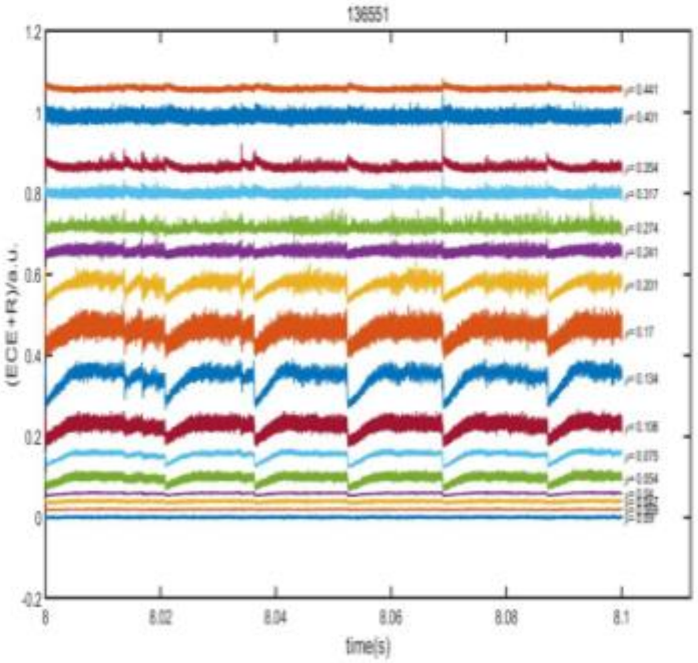
W-Limiter on EAST



Development of High-β Scenario by RF Heating with Boronization

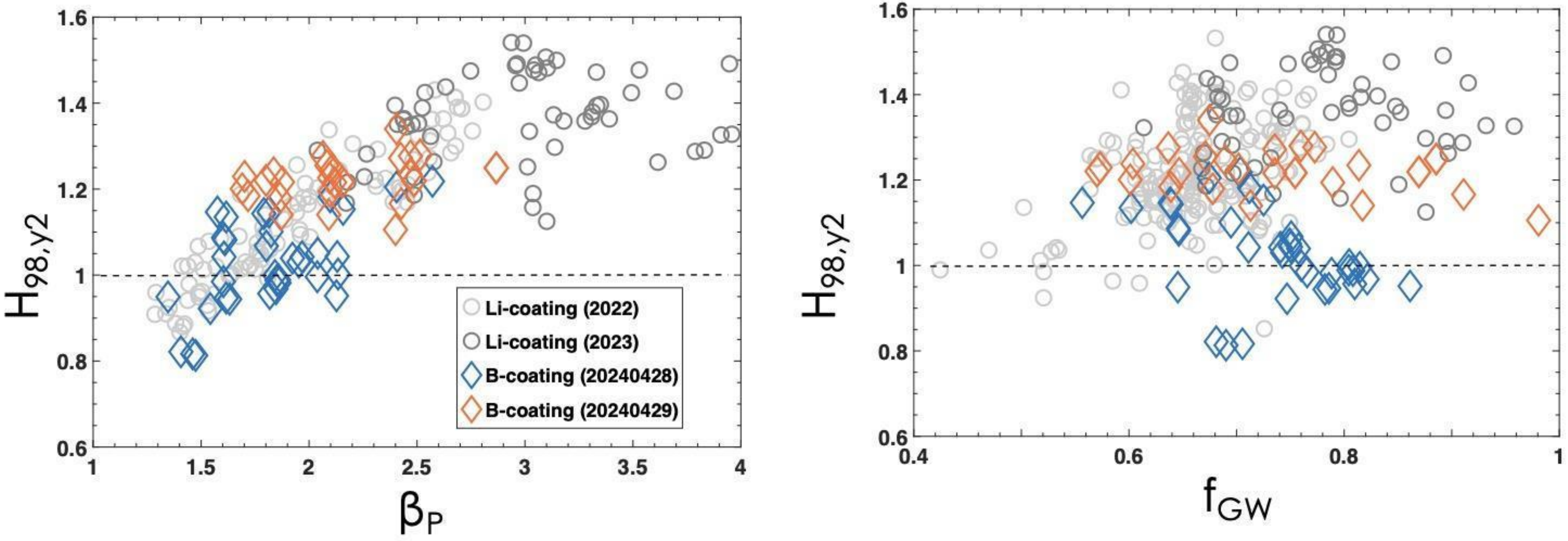






- **High-β plasmas by RF heating at high Bt~2.5T**
  - P_{LHW}~2.3MW, P_{EC}~2.4MW, P_{IC}~2.8MW
  - n_{Gr}~0.4-0.8, β_N~1.8, H_{98y2} ~ 1.2, q_{95}~6.0
- **Broader current profile during ICRF heating**
  - $q_{(0)}$ >1, sawtooth discharge

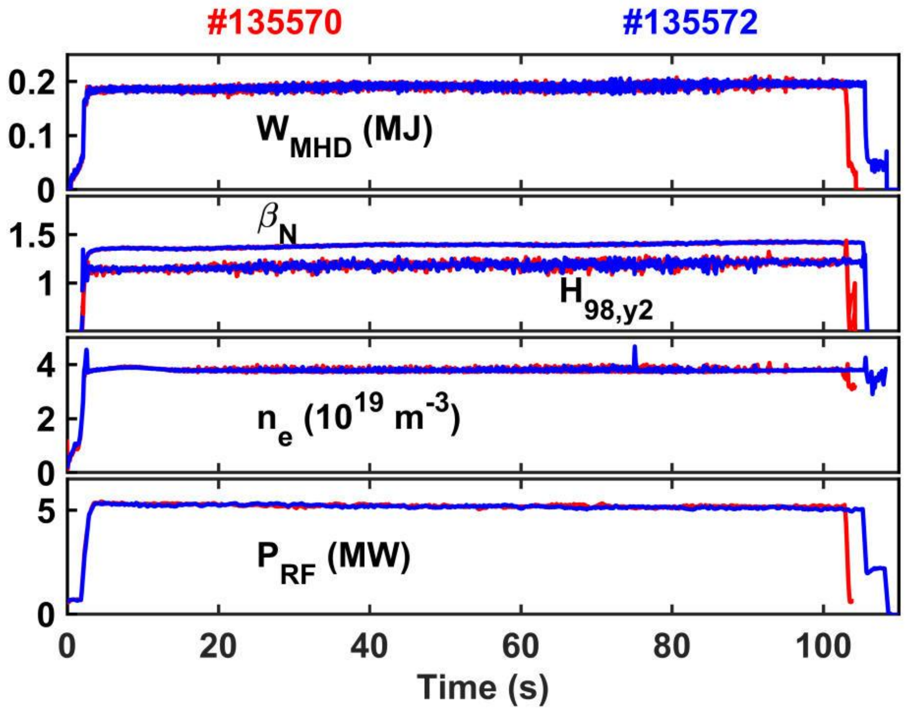
The Impact of Wall Conditions on Energy Confinement

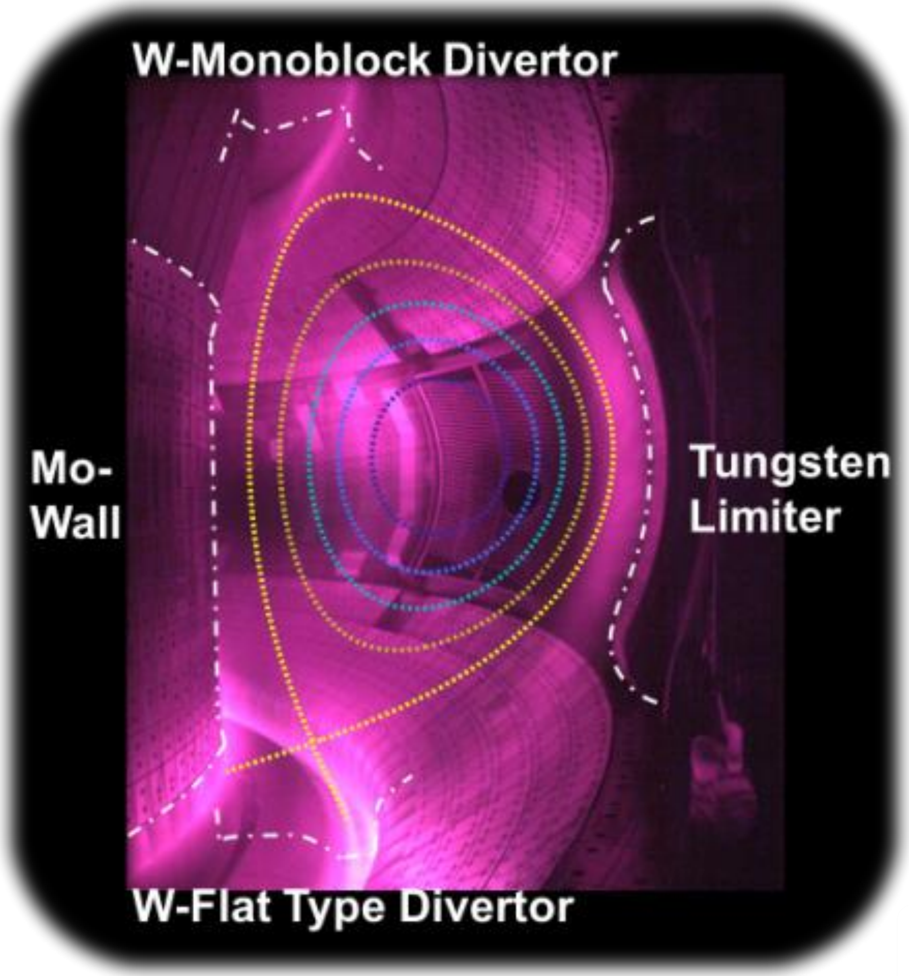


- **Energy confinement with Boron-wall is reduced by ~10-15%, compared with Li-coating**

Demonstration Long Pulse H-mode Plasmas on Full Metal Wall in Support of ITER New Research Plan

- **Stationary ~100s H-mode plasmas achieved**
  - n_e~4.3/ $H_{98y,2}$~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**
  - Small ELMs and high density reduced W-sputtering
  - Avoid impurity accumulation by on-axis ECH





Outline

- **Extension of fusion performance towards SSO**
- **Physics understanding in high-β_p steady-state plasma**
  - Enhanced H&CD efficiency at high density
  - Improve confinement with zero torque injection
  - High-Z impurity and heat flux control
- **Long Pulse H-mode Plasmas on Full Metal Wall in Support of ITER NRP**
- **Future plan and summary**

X. Gong / 2nd I

Summary

- **Significant progress ~100s SS high-β_p plasmas by RF-only achieved on EAST**
- **Near-term plan with upgrade of inner components/H&CD systems**
  - Develop high β_p scenario with ITER shaping (LSN) at moderate q_{95} ~5-6 in low aspect ratio
  - Develop high β_p scenario in ITER-like heating scheme by enhancing H&CD capabilities
  - Investigate the impact of wall condition on scenario development
  - 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

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