EAST Steady-state Long Pulse H-mode with Core-edge Integration for CFETR

by X. Gong[1]

With

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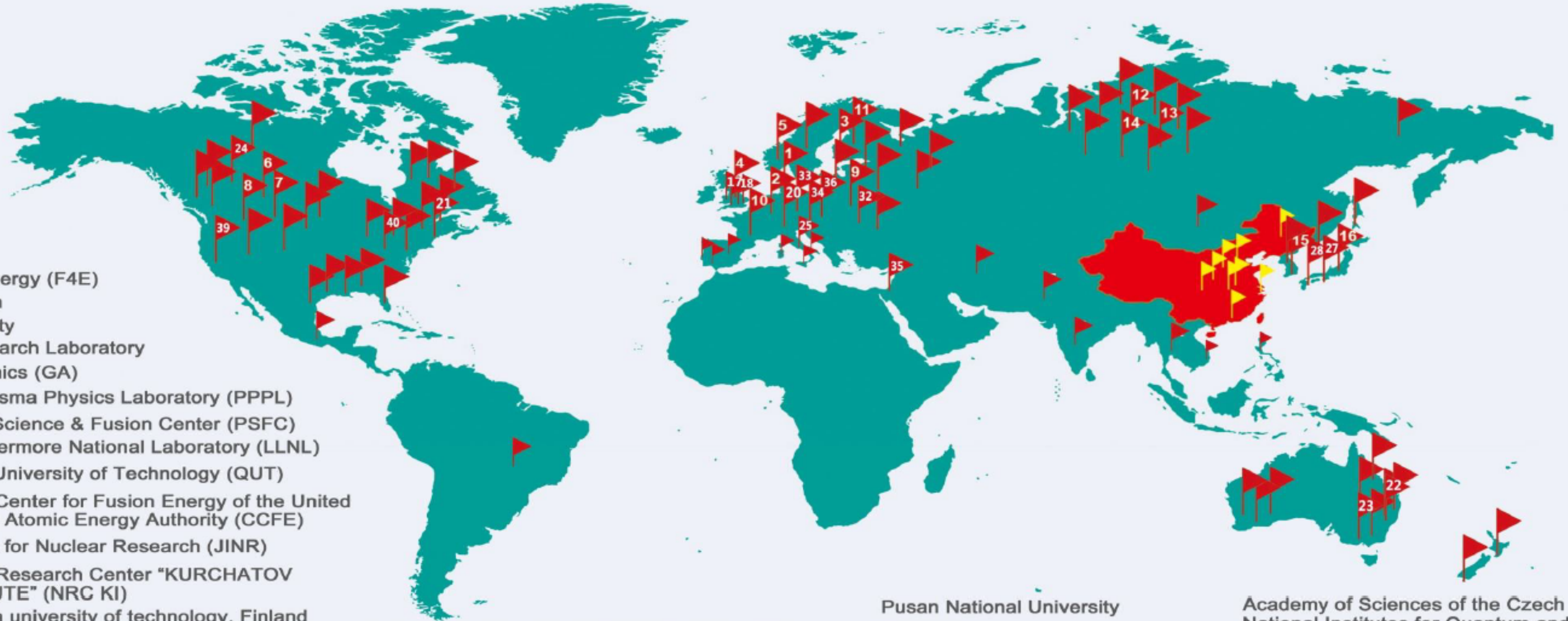
Acknowledgement

Open Test Bench



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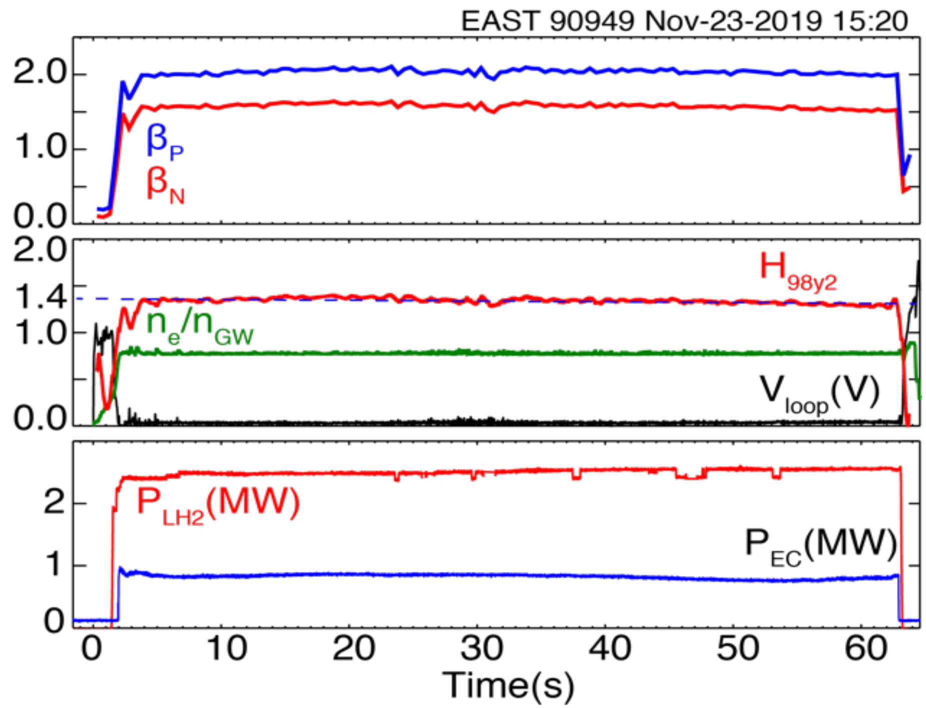
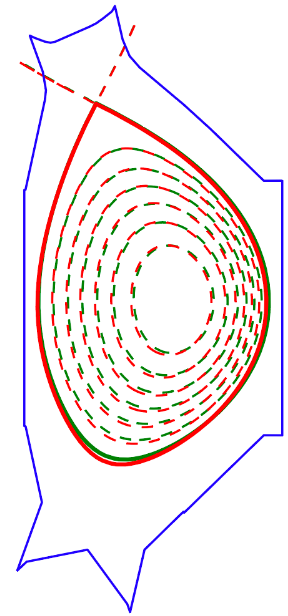
Great Progress on EAST Is Benefit from Broad Domestic and Wide International Collaboration!

ASIPP

A Minute Time Scale Steady-state High β_p Discharge was Achieved with Tungsten Divertor





@ 30/60s

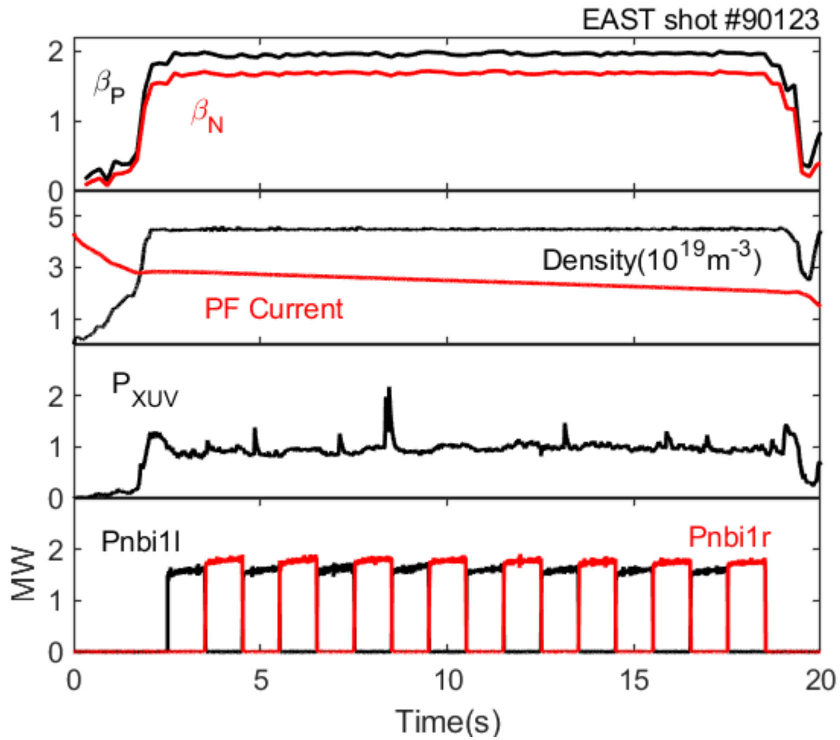
ITER-like Tungsten divertor

- **61.2s H-mode sustained with enhanced RF-heating**
  - **H_{98y2}~1.2, f_{Gr}~0.7, β_p~2.1, β_N~1.7, V_{loop}~0**
  - Robust iso-flux control with SP to W-divertor
- **101s H-mode achieved in 2017**
  - **H_{98y2}~1.1, f_{Gr}~0.6, β_p~1.2, β_N~1.0, V_{loop}~0**

X. Gong, Nucl. Fusion 59 (2019)

New Candidate of High β_P Long Pulse Operation with Low Torque at High Density

- **Long pulse operation with a duration of 20s by modulated neutral beam (~1.5MW) and RF (~4.0MW)**
  - β_p ~2.1, β_N ~1.8
  - H_{98y2} ~1.3
  - f_{Gr} ~ 0.8
  - T_{inj}~1.0Nm
  - f_{bs}~50%



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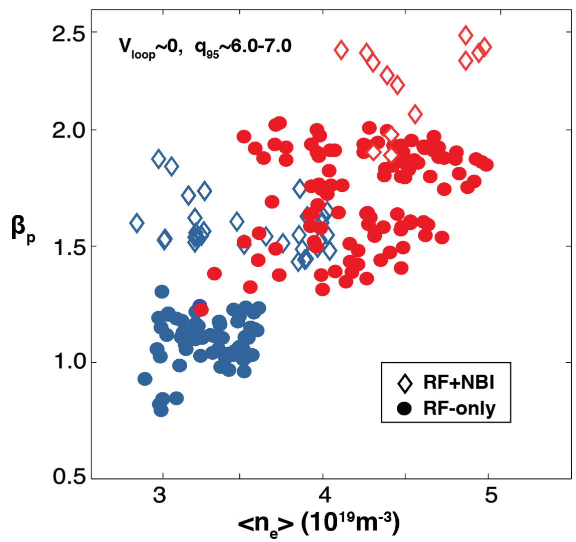
Experiments Demonstrated Steady-state Scenarios with Extension of Fusion Performance

- **β_P versus line-averaged density of zero loop voltage plasmas**
  - Fully non-inductive @ q_{95}~6.0-7.0
- **Extended operational regime**
  - High density f_{Gr}~0.8
  - f_{BS} ~ 50%
- **Dominant e-heating，~zero torque**
- **Small ELMs with well impurity control**
- **Improved confinement**
  - H_{98y2}~1.4
  - eITB inside r<0.4

J. Huang et al., Nucl. Fusion 60 (2020)
J. Huang, PPCF 62 (2020)

	CFETR A.3 SSO	EAST
P_Fusion	974	
β_N	2.0	2.0
f_{BS}	0.50	0.50
H factor	1.41	1.25
n_e/n_{GW}	0.57	0.8
q_{95} Iter	5.54	6.7



X. Gong 28th IAEA-FEC 2021

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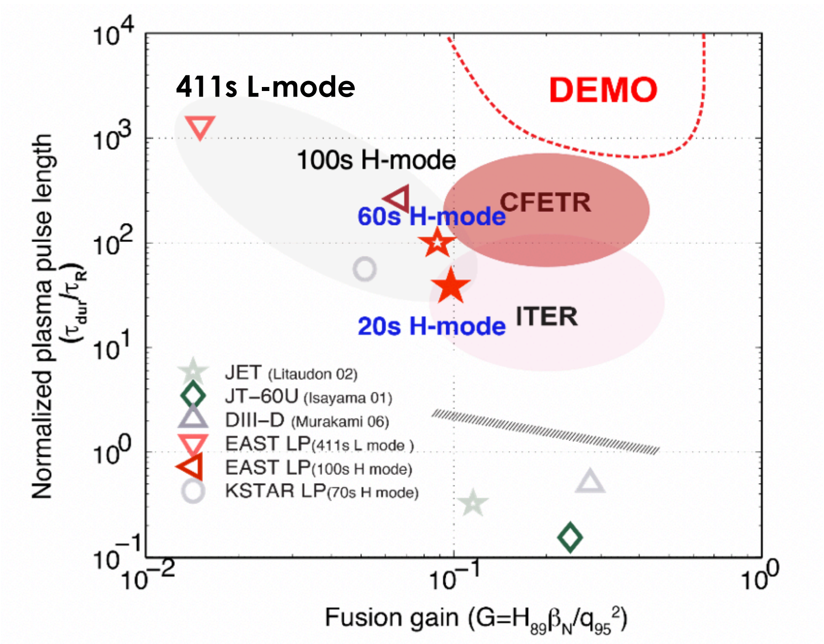
Strategies to Establish the Scientific Basis for Long Pulse Operation in Supporting ITER/CFETR

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



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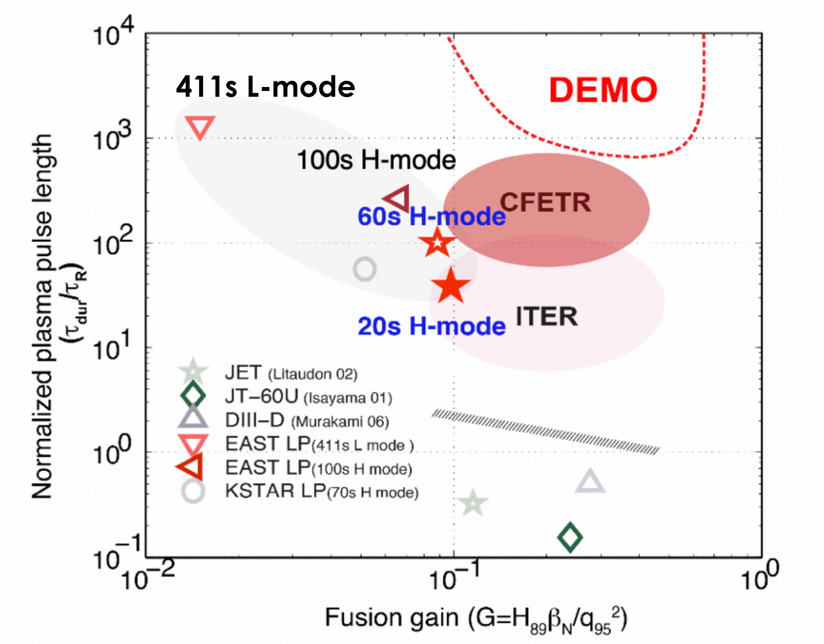
Strategies to Establish the Scientific Basis for Long Pulse Operation in Supporting ITER/CFETR

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



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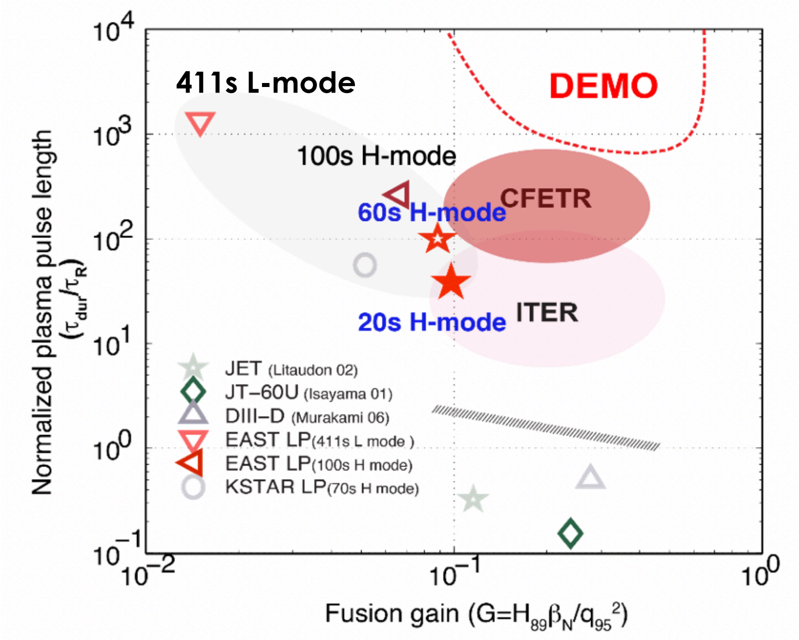
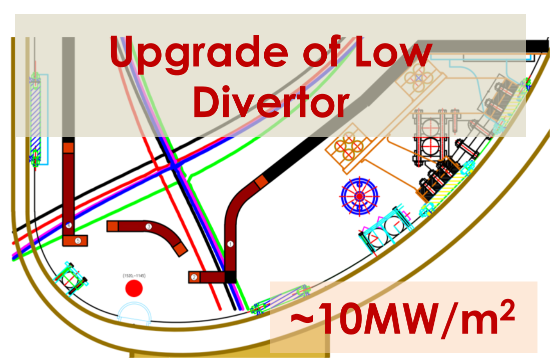
Strategies to Establish the Scientific Basis for Long Pulse Operation in Supporting ITER/CFETR

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





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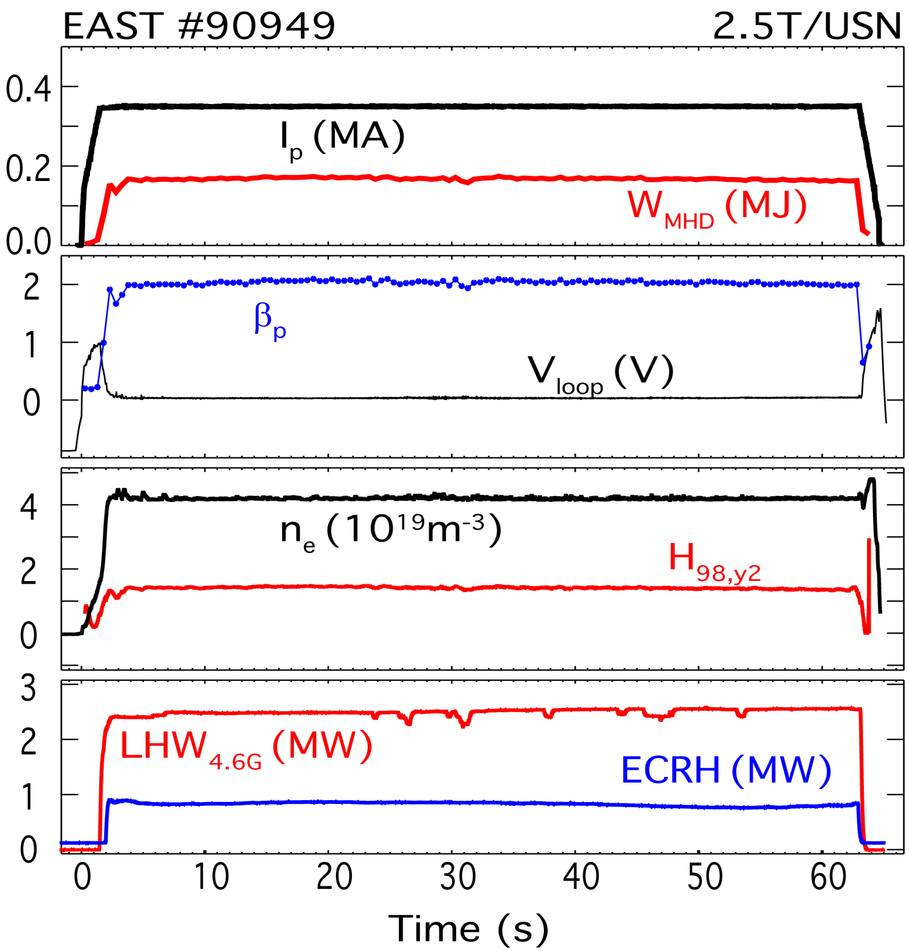
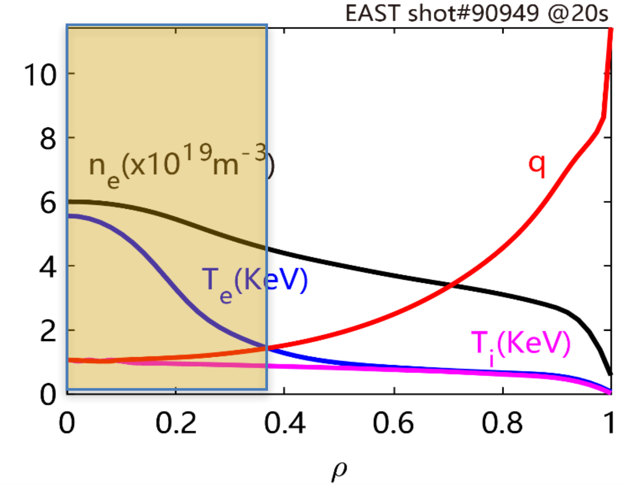
EAST Steady-state Long Pulse H-mode with Core-edge Integration



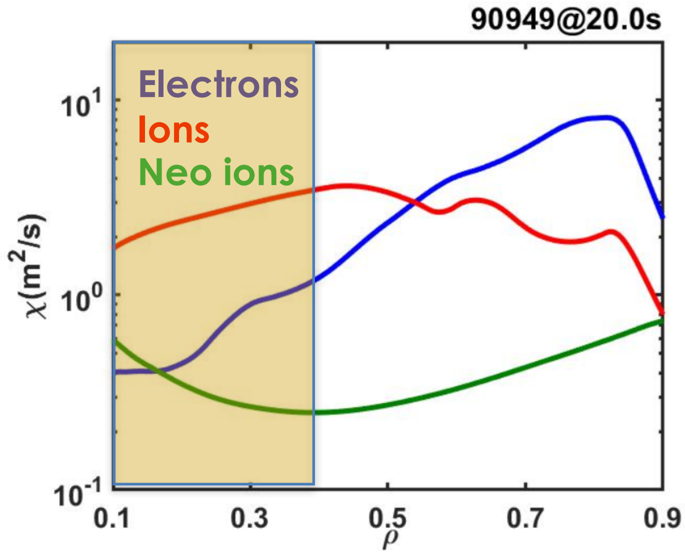
- **Improved confinement**
- **High LHCD efficiency at high density**
- **Broaden current profile**
- **Core-edge integration**

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

- **Dominant electron heating by ECH &LHW**
  - $T_e > T_i$
  - zero torque
  - low rotation
  - Flat q profile with q(0)>1.0



- **Electron transport is significantly reduced in the plasma core (rho<0.4)**
  - Consistent with improved confinement



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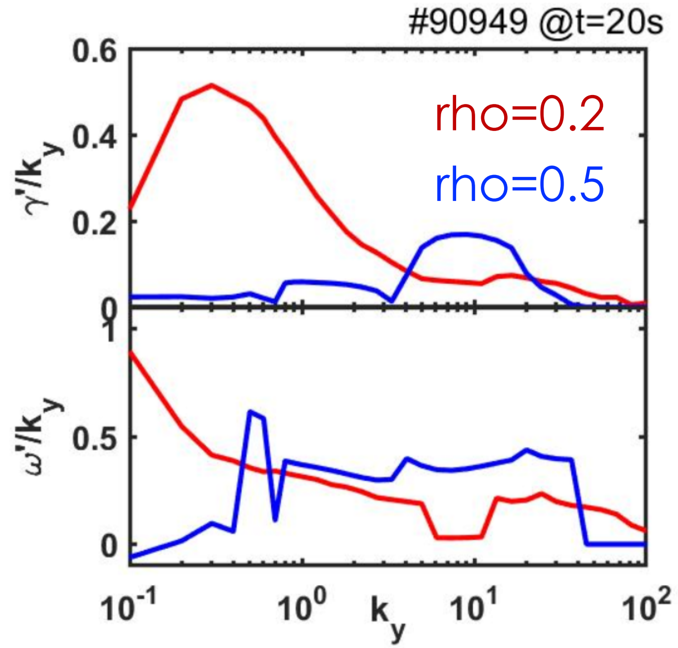
Reduced Transport in Electron Energy Channel Consistent with Te-ITB Formation



- **Linear analysis by TGLF**
  - TEM modes dominate in the low-k (ky<1) region, at ITB
  - ETG modes dominate in the high-k region, outside ITB
- **The decrease of the high-k turbulence (ETG)**
  - Causing the reduction of electron transport

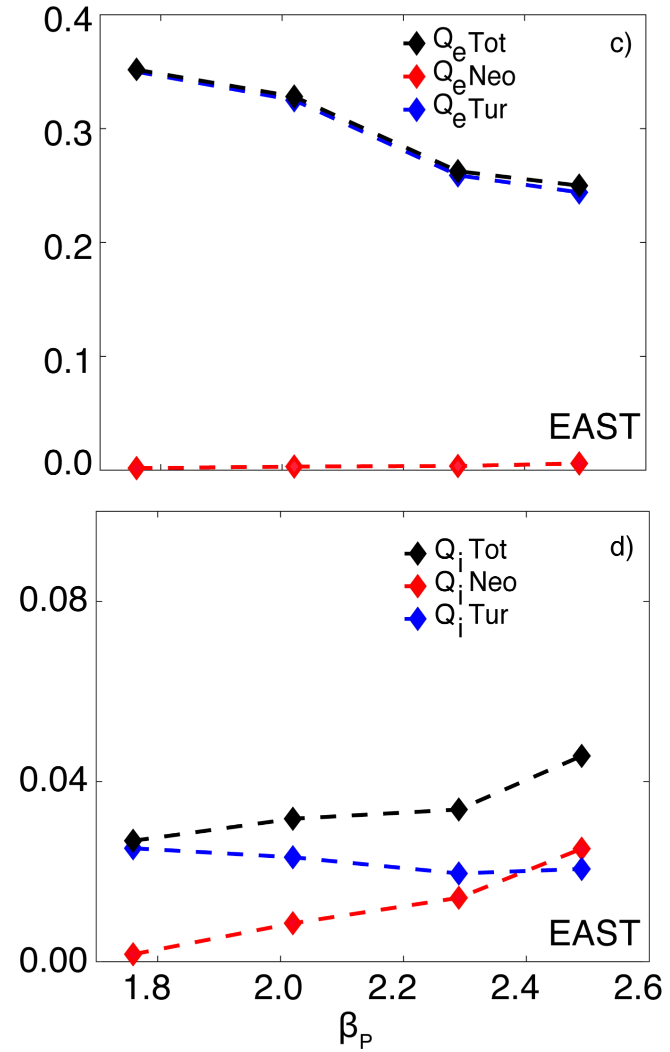
Modeling Shows β_P Stabilization Effect on Electron and Ion Turbulent Energy Fluxes

- **TGLF+NEO to predict transport**
  - Scaled pressure profiles at fixed q-profile generated from experimental reconstruction

- **Electron turbulent energy fluxes decreases with high β_p**

- **Ion turbulent energy fluxes decreases slowly with increase of β_p**

J. Qian, Phys. Plasmas 2021



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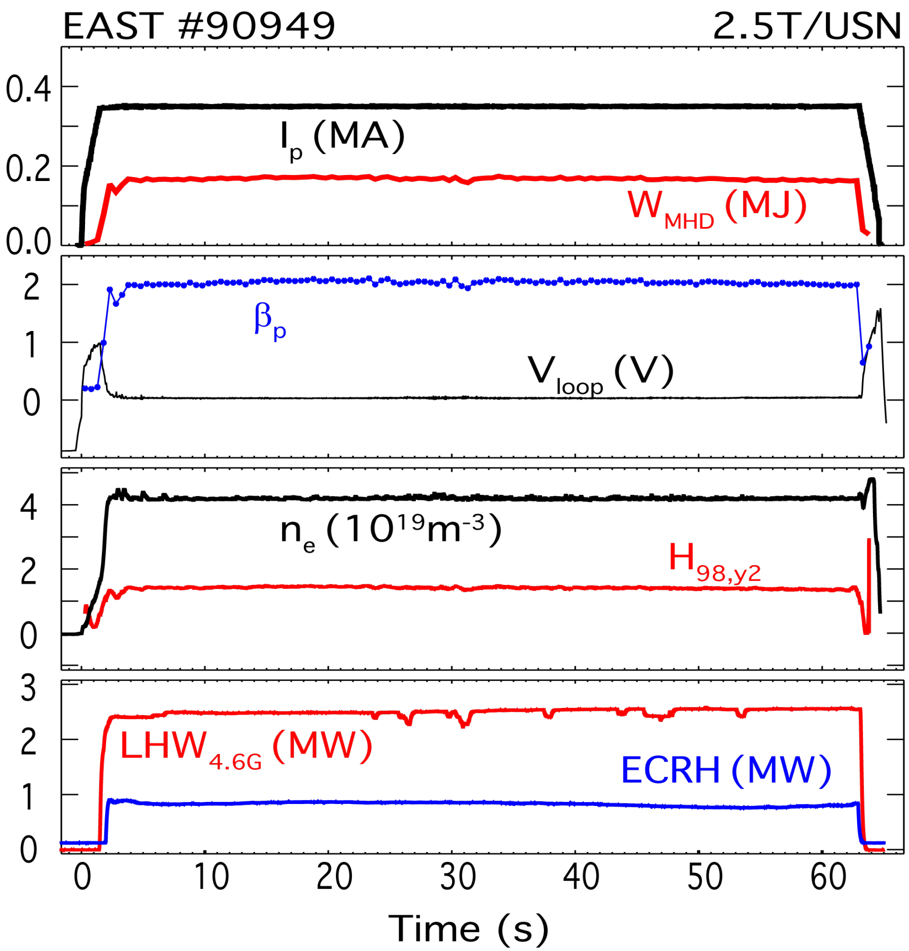
EAST Steady-state Long Pulse H-mode with Core-edge Integration



- Improved confinement
- High LHCD efficiency at high density
- Broaden current profile
- Core-edge integration

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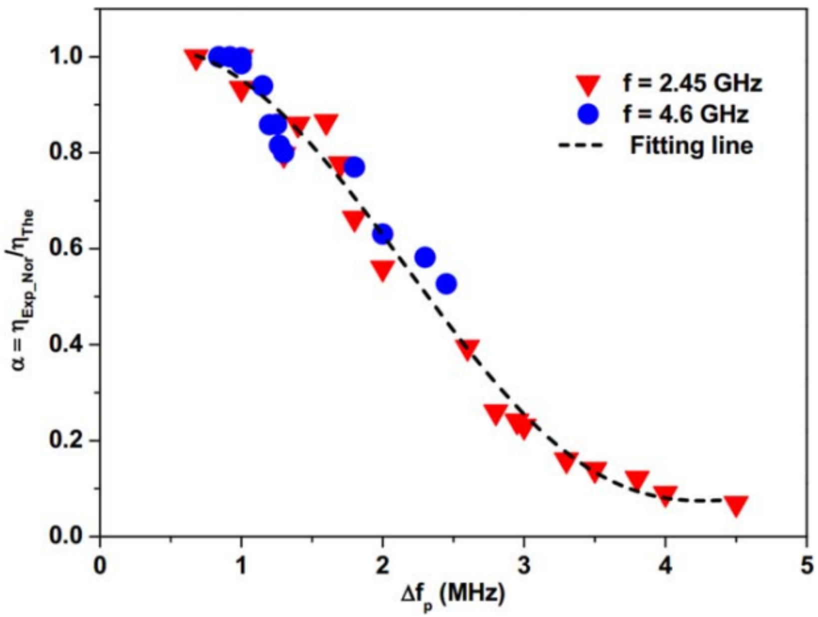
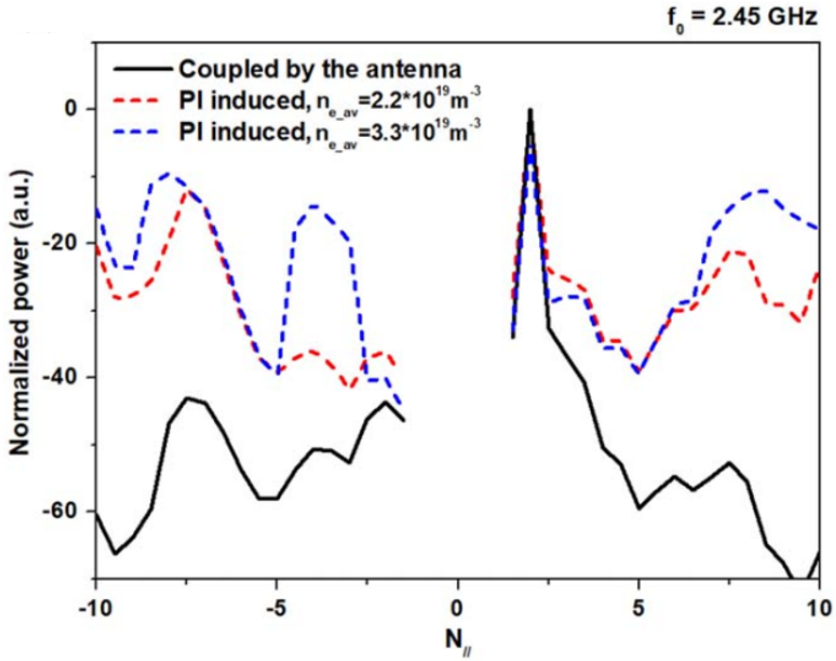
A Link Between the Degradation of Current Drive Efficiency and Spectral Broadening

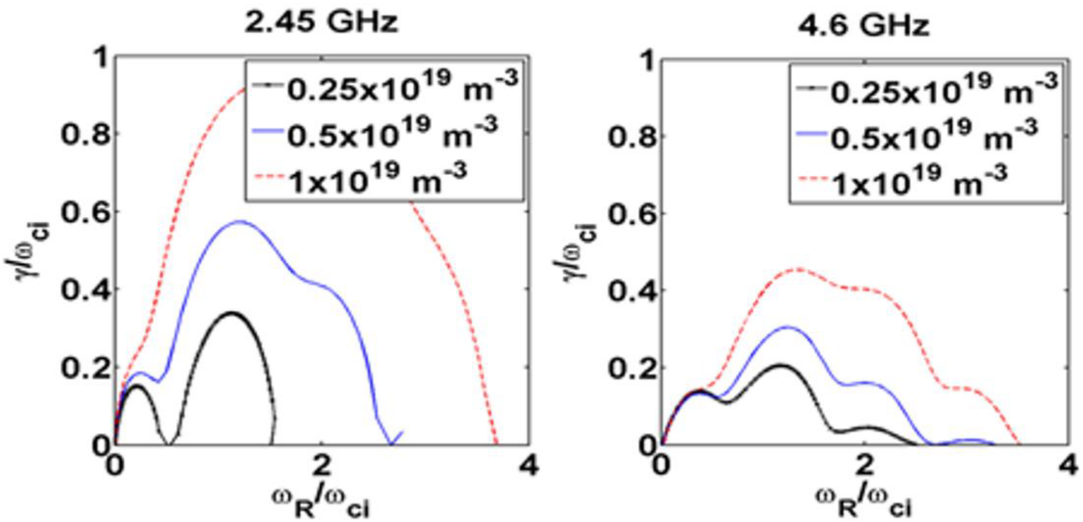


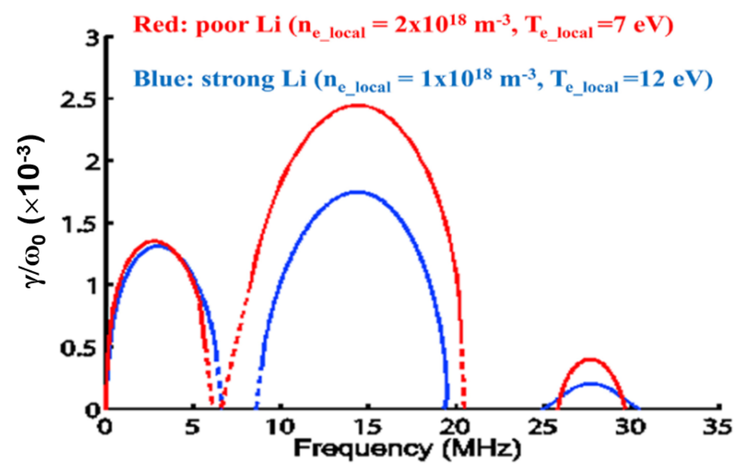


- **Spectral broadening is found to have a negative and significant effect on CD efficiency.**
- **The modeling results show that PI effect can redistribute the $N_{||}$ spectrum to some extent, thus leading to a pump power depletion.**

M. H. Li, et al., Plasma Phys. Control. Fusion 61 (2019)

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

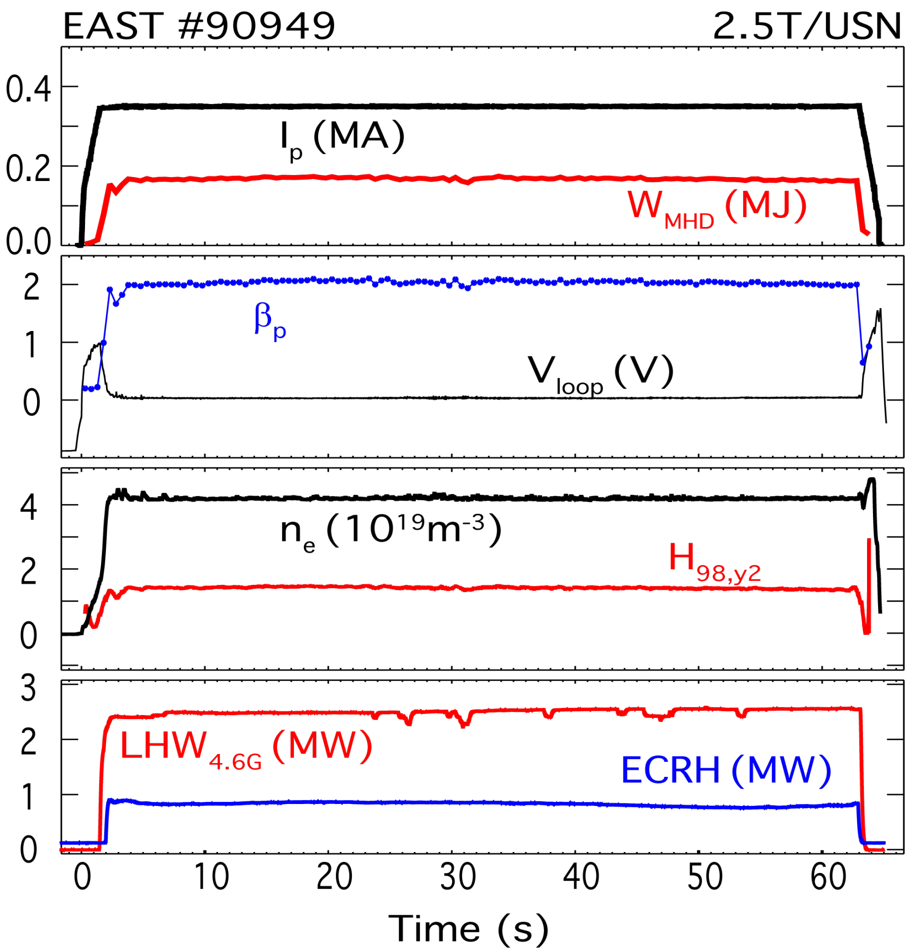




B J Ding Nucl. Fusion 58 (2018)

- **Consistent with Parametric Instability (PI) modeling:**
  - Growth rate is smaller with higher LH source frequency, thus to enhance CD efficiency;
  - Low recycling wall, producing higher temperature at the plasma edge, can reduce PI intensity.

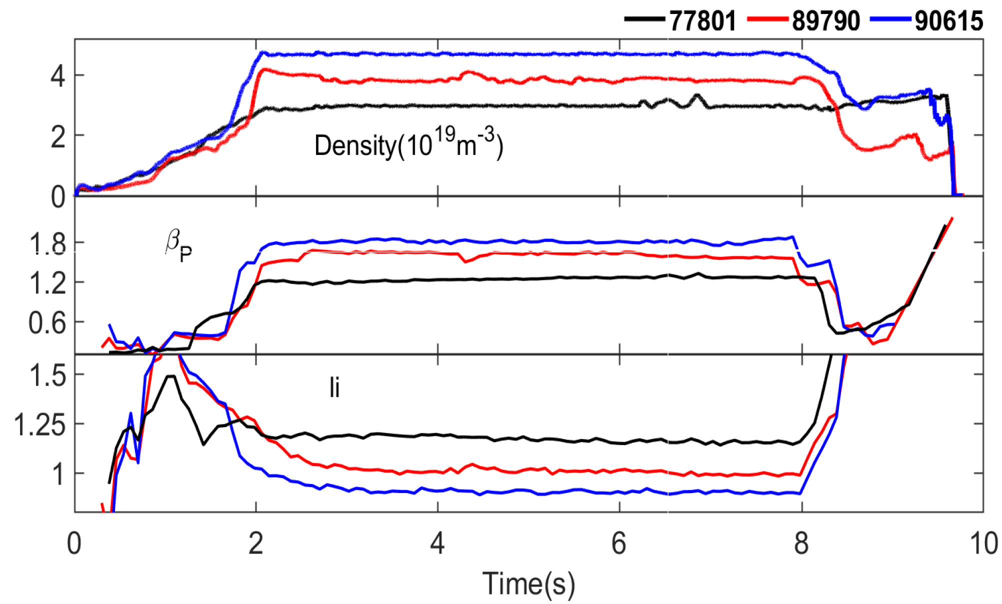
EAST Steady-state Long Pulse H-mode with Core-edge Integration



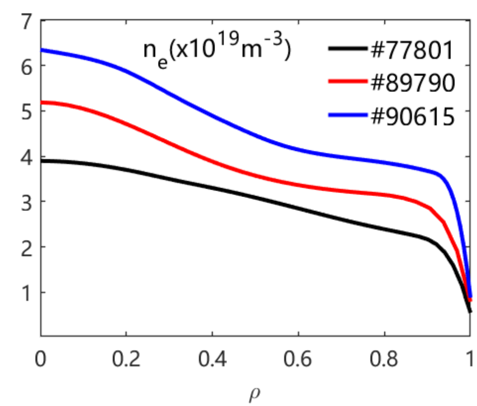
- **Improved confinement**
- **High LHCD efficiency at high density**
- **Broaden current profile**
- **Core-edge integration**

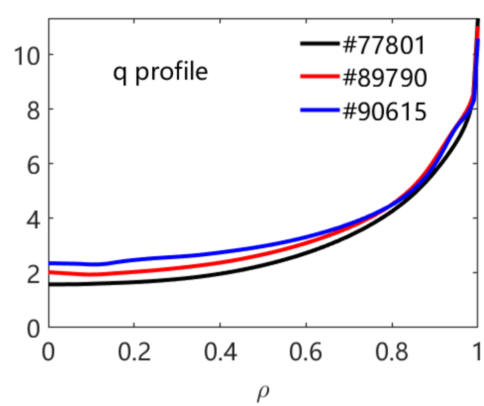
Broaden Current Profile Obtained with Off-axis LHCD and Bootstrap Current

- **Low l_i obtained at high density, high β_P**
  - Higher β_P generates more off-axis f_{BS}
  - High density operation allows LH off-axis deposition



- **Equilibrium analysis confirms a higher q0 for low l_i case**





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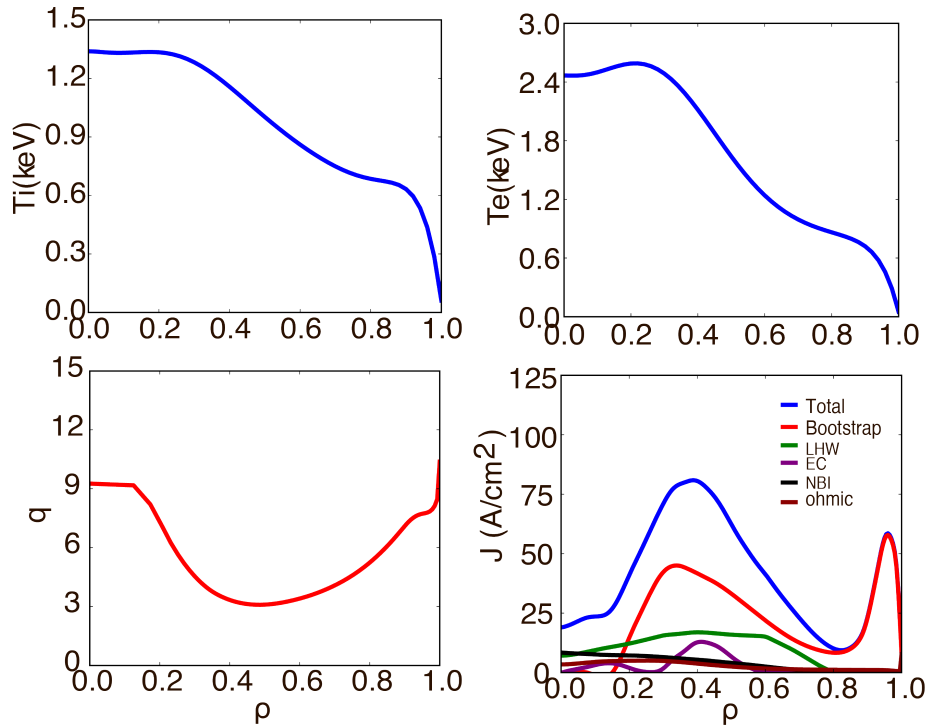
Modeling Shows that Larger ρ_{qmin} and ITB Radius on EAST can be Achieved at Higher β_p



J. Qian Phys. Plasmas 2021

- **Use integrated modeling with optimized H&CD scheme**
  - ECH+LHW, co-Ip NB & ICRF
- **Large ρ_{qmin} (~0.5) obtained with more off-axis f_{bs} CD**
  - f_{bs} from 43% to 63% with higher β_p

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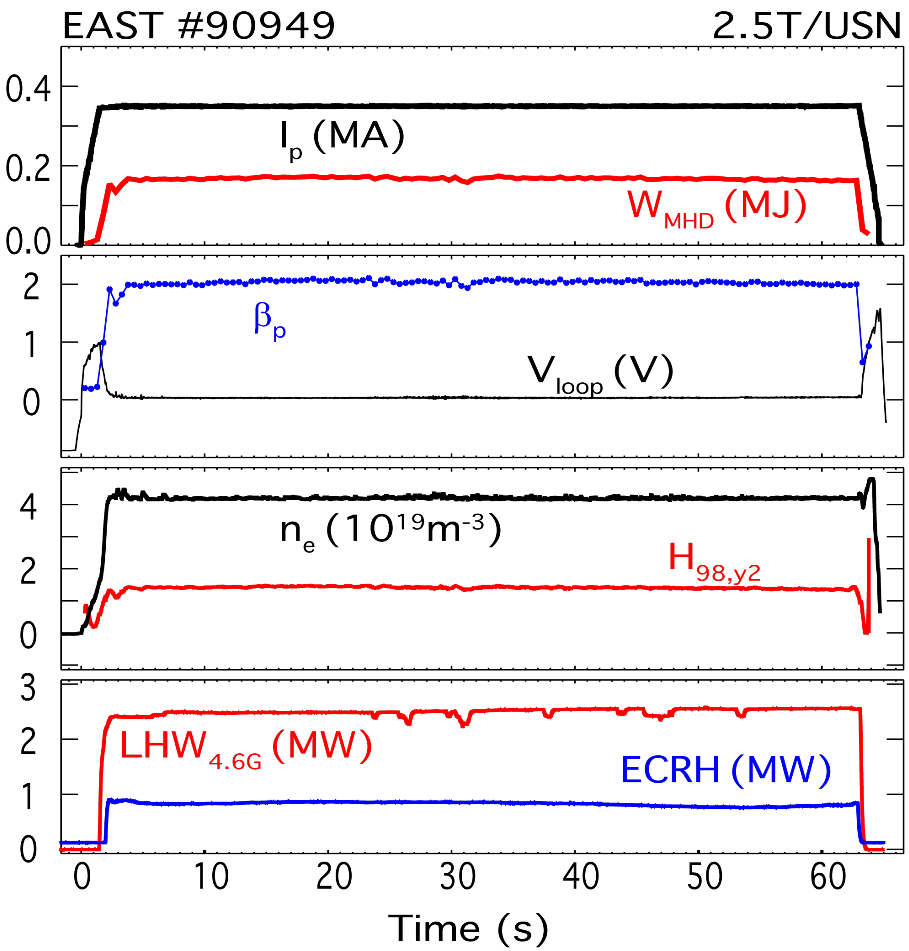
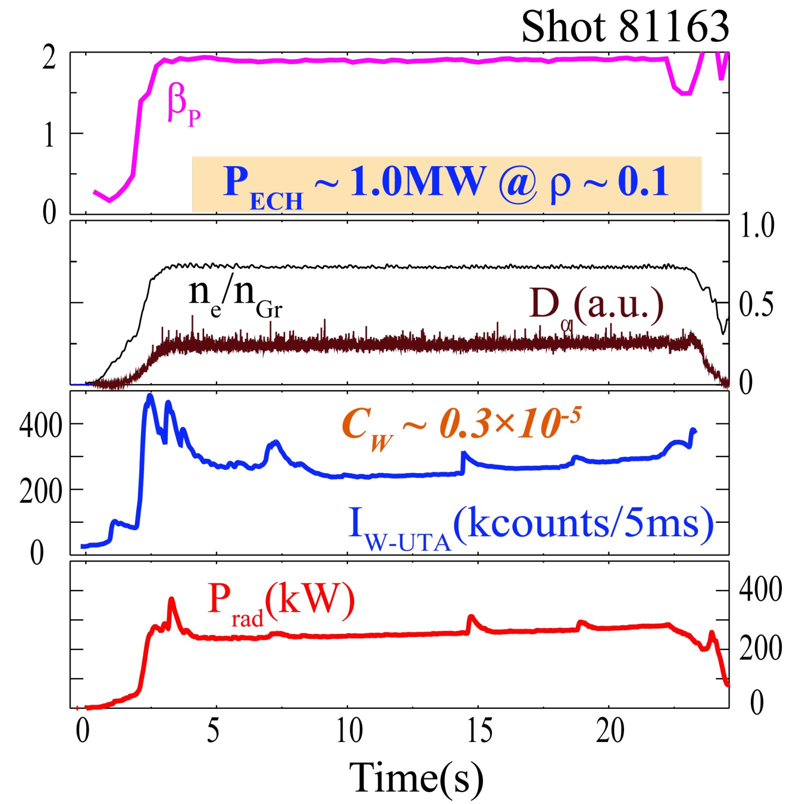
EAST Steady-state Long Pulse H-mode with Core-edge Integration



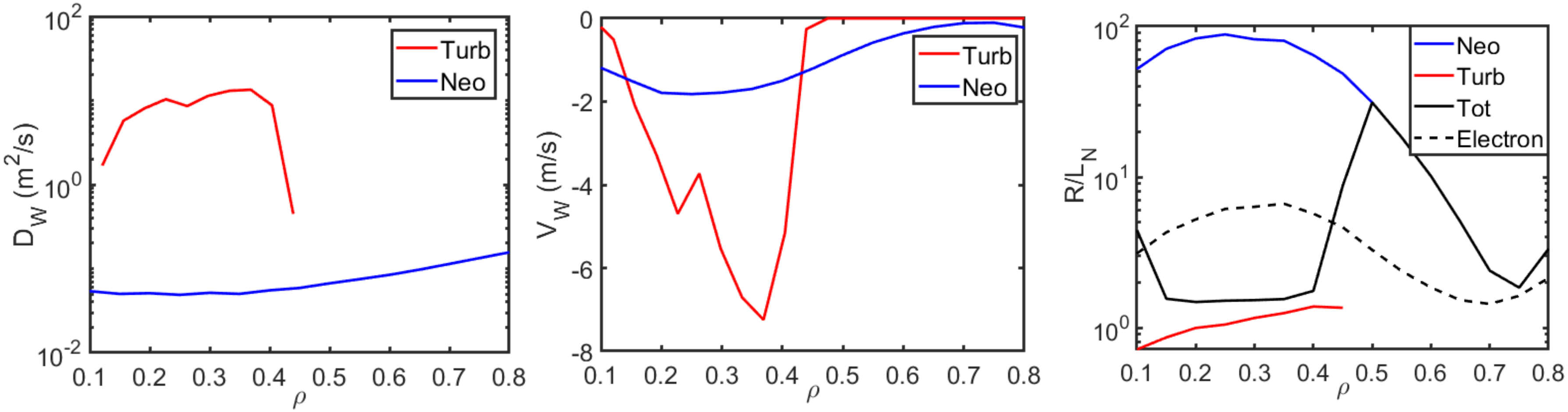
- Improved confinement
- High LHCD efficiency at high density
- Broaden current profile
- Core-edge integration

Well Controlled High Z Impurity in High β_p Plasmas

- **Small ELMs and high density(n_e/n_G~0.8) reduced tungsten sputtering**
- **On-axis ECH pump out high Z impurities from core plasma**
  - W in good control within a low level (Cw~0.3x10^{-5})

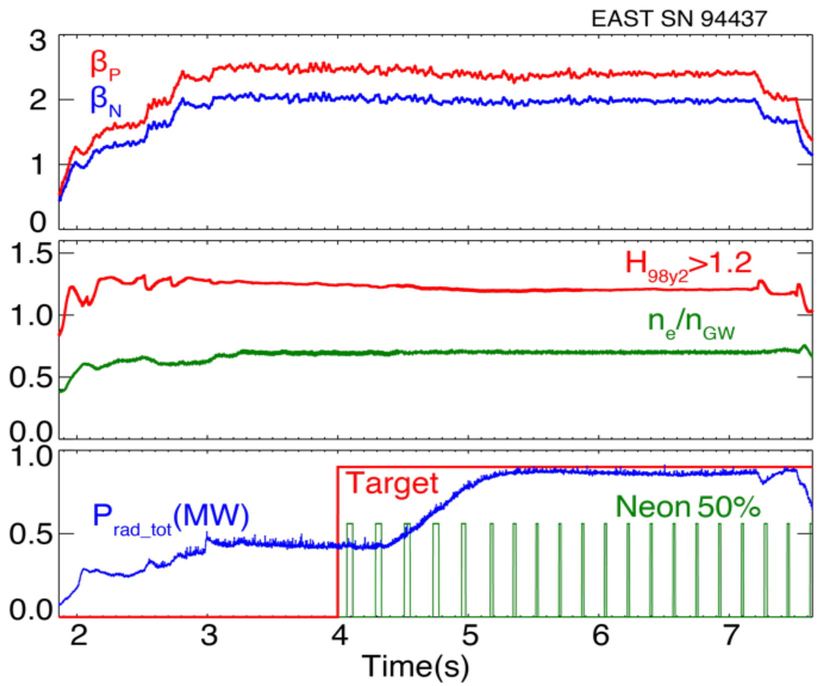


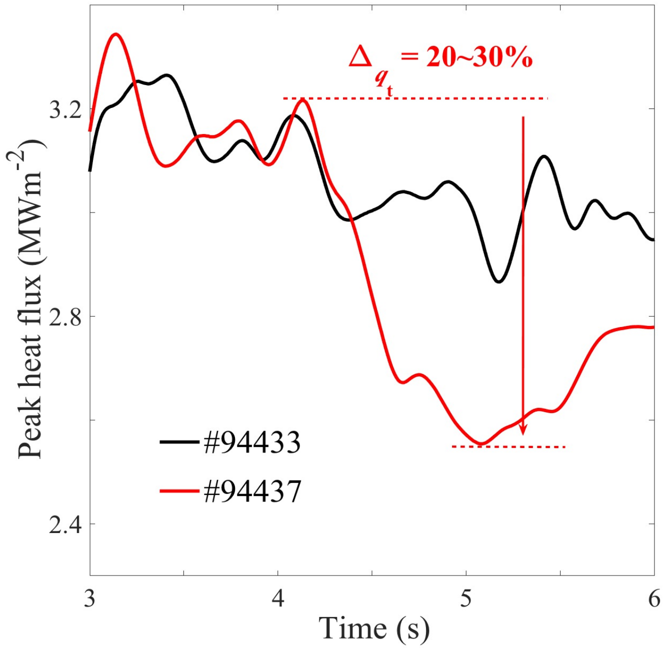
Modeling Shows that Strong Diffusion of TEM in the Central Region Prevents W to Accumulate



- **W modeling by QuaLiKiz and NEO**
- **TEM dominates and its strong diffusion prevents W to accumulate at r/a<0.4, including TEM and ITG**
- **The large modelled R/L_{Nw} at ρ~0.5 can be explained by the overestimation of stabilization effect on TEM by collisionality in QuaLiKiz.**

Demonstration of a Compatible Core and Edge Integration in High β_p Scenarios





- **Radiative divertor feedback with a mixture of 50% neon and 50% D_2**
- **Peak heat flux reduced by 20-30% (IR)**
- **Confinement maintained H_{98}>1.2**

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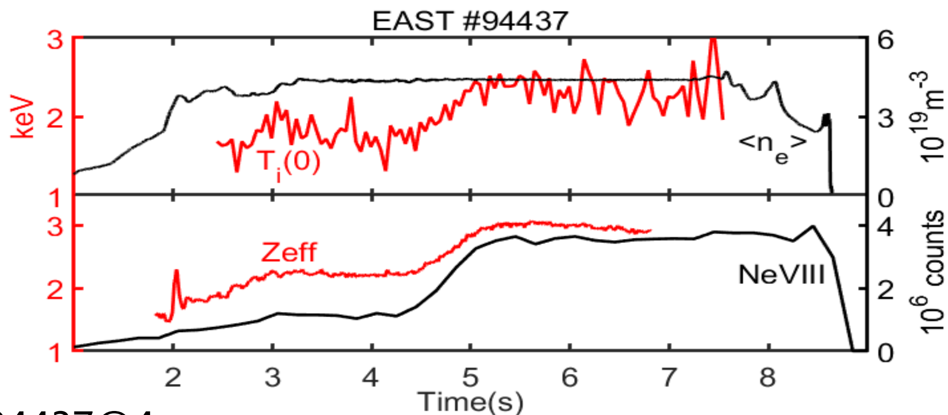
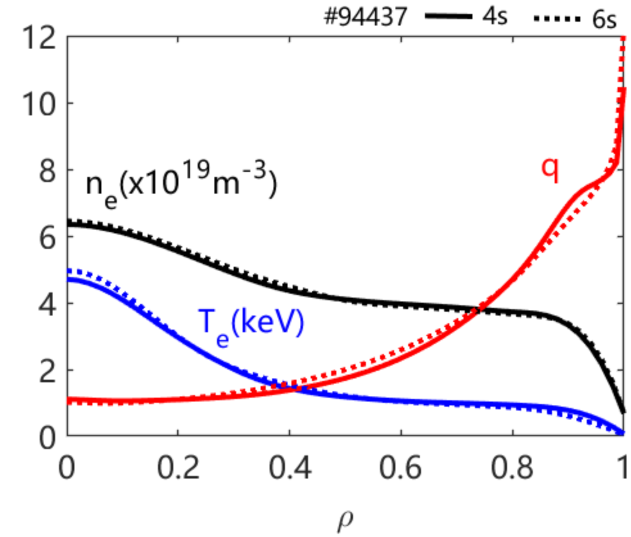
ITG is Stabilized During Neon Seeding, Leading to a Higher Ion Temperature

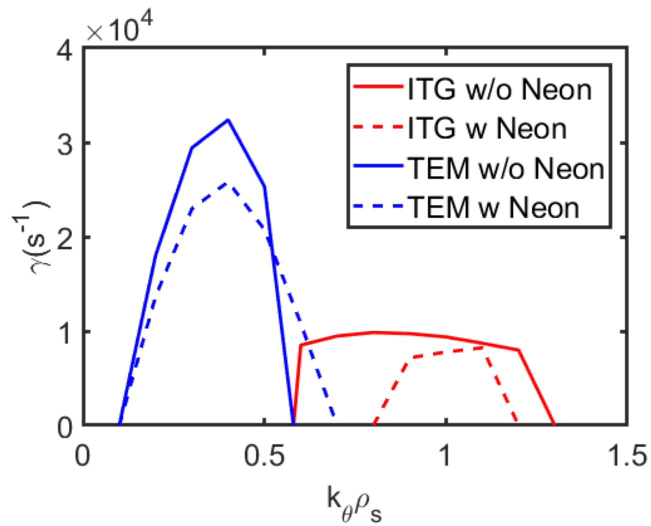


#94437@4s

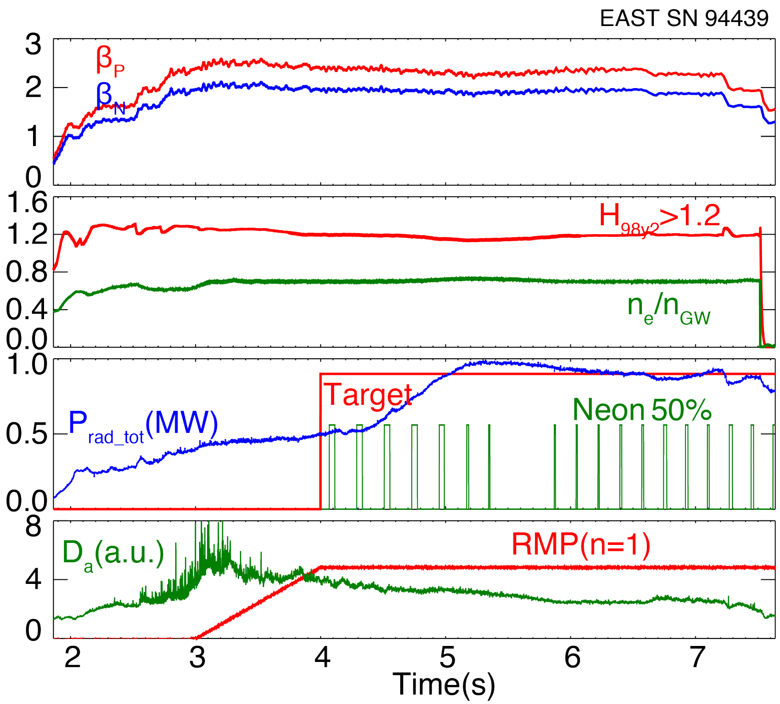
ρ	R/L_{Te}	R/L_{Ti}	T_e/T_i	ŝ	q	Z_{eff}	υ*
0.4	13.3	6.5	1.5	0.54	1.27	2.2	0.24

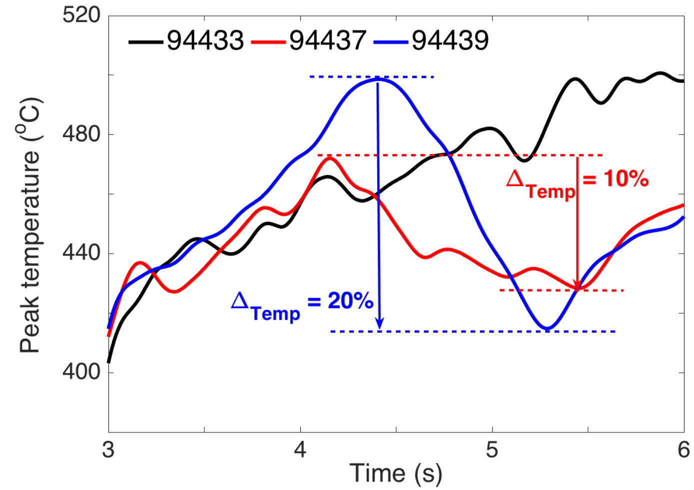


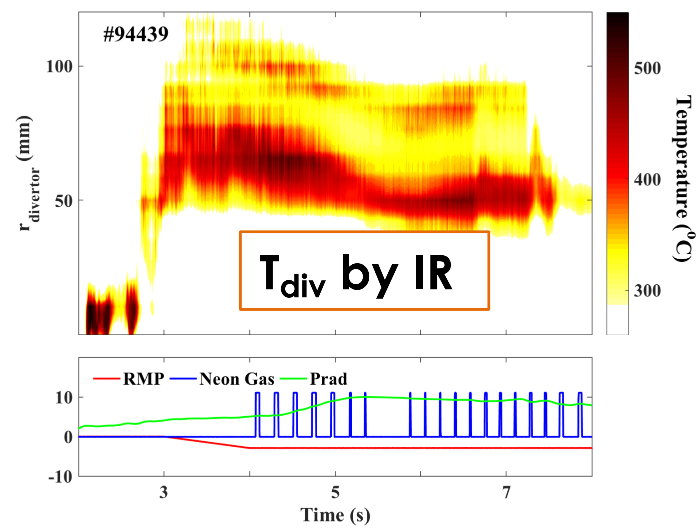
- **After Neon seeding, ITG is stabilized due to the dilution of main ions, which is consistent with the increase of T_i.**



Larger Reduced Divertor Temperature with Divertor Heat Flux Splitting







- **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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Summary

- **Steady-state long pulse (>60s) demonstrated with extension of fusion performance**
  - High f_{BS}~50% with improved energy confinement ($H_{98,y2}$ >1)
  - Improved confinement at higher β_P due to broader q-profile, Shafranov shift, e-ITB
  - W accumulation prevented by TEM with on-axis ECH
- **The Radiation feedback control is compatible with good core confinement in high βp discharges**
  - H_{98y2}>1.2
  - heat flux reduced by 20-30% with 50% neon
- **Further research on integration of core performance and edge-divertor plasma for scenarios will be addressed**

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