26th IAEA FEC, 17-22 October 2016, Kyoto, Japan

ASIPP

Overview of EAST Experiments on the Development of High-Performance Steady-State Scenario

B.N. Wan on behalf of
EAST team & collaborators

Email: bnwan@ipp.ac.cn

Institute of Plasma Physics, Chinese Academy of Sciences

Collaborators

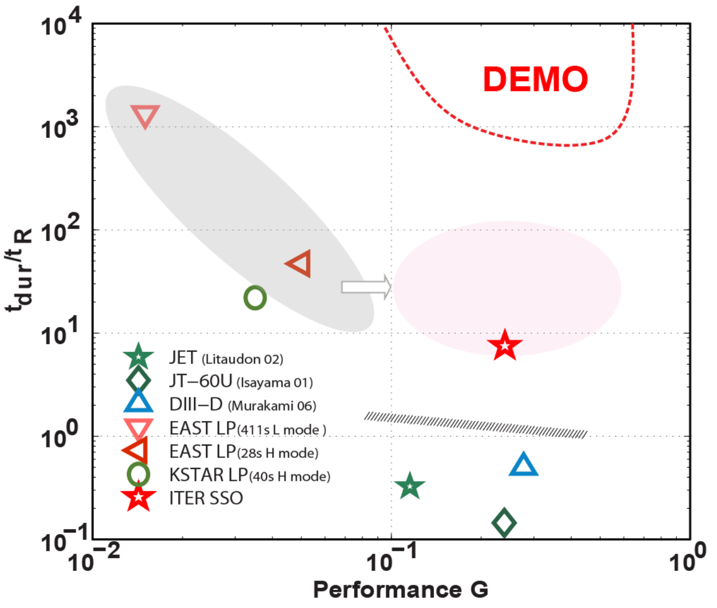
Scenario Developments on EAST

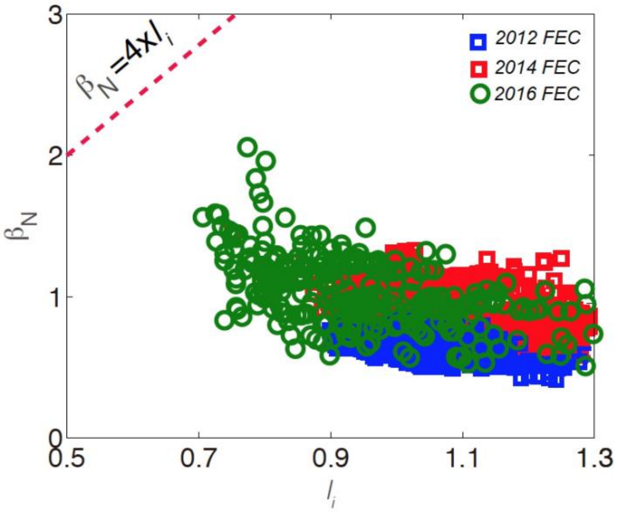
Step I

Improve heating efficiency and develop the SSO-relevant fundamental physics and key diagnostics;

Step II

Develop the SSO high performance plasma scenarios and demonstrate (≥100s) long-pulse H-mode plasmas;





Step III

Optimize the SSO plasma and extend the EAST operation domain towards long-pulse, high beta, high power, high performance regime.

Outline

- Introduction
  - *Facility upgrade in support of steady-state long-pulse scenarios*
- Exploration of Steady-State Plasma Operation with ITER-like Tungsten Divertor
  - *Scenario development with RF dominated heating*
  - *Hot spot issues*
- Progress of Key Physics Issues towards Steady-State Operation Regimes
  - *LHCD at high density*
  - *RMP ELM control*
  - *Particle/power exhaust control*
  - *MCM physics at low collisionality*
- Summary and Future Plans

Outline

- **Introduction**
  - ***Facility upgrade in support of steady-state long-pulse scenarios***
- **Exploration of Steady-State Plasma Operation with ITER-like Tungsten Divertor**
  - ***Scenario development with RF dominated heating***
  - ***Hot spot issues***
- **Progress of Key Physics Issues towards Steady-State Operation Regimes**
  - ***LHCD at high density***
  - ***RMP ELM control***
  - ***Particle/power exhaust control***
  - ***MCM physics at low collisionality***
- **Summary and Future Plans**

EAST SSO Capabilities

- ◆ LHCD 4+6 MW（2.45/4.6GHz）
  - Fast Electron Source
  - Edge Current Drive /Profile
- ◆ ICRH 6+6 MW（25-75MHz）
  - Ion and Electron Heating
  - Central Current Drive
- ◆ **ECRH 2(4) MW (140GHz)**
  - **Dominant electron heating**
  - **Steering mirror, j_ϕ tailoring**
- ◆ **NBI 4+4 MW（co/counter, 80kV）**
  - **Sufficient power to probe β limit**
  - **Variable rotation/ rot-shear**

- ☐ **Elevated capabilities in last two years allow EAST to play a key role for developing advanced SS scenarios**
  - **Fully non-inductive CD, high bootstrap current fraction (f_{bs}).**
  - **Active control of ELM and stationary heat load on divertors**

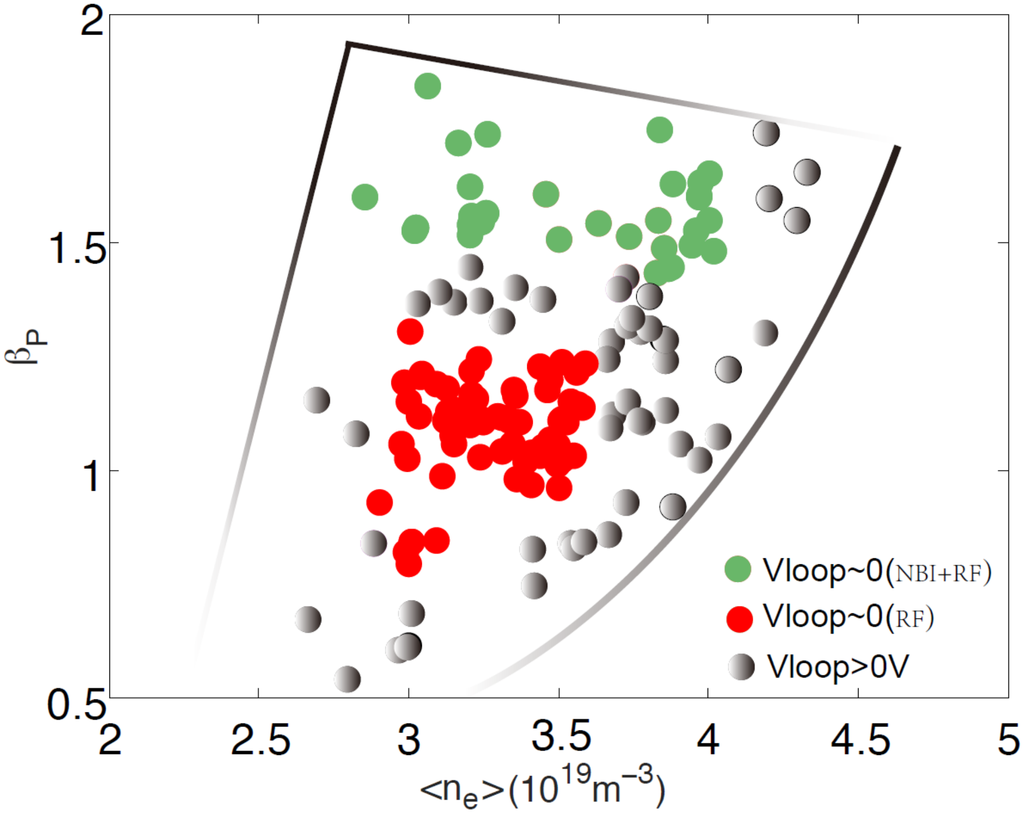
Outline

- Introduction
  - *Facility upgrade in support of steady-state long-pulse scenarios*
- **Exploration of Steady-State Plasma Operation with ITER-like Tungsten Divertor**
  - ***Scenario development with RF dominated heating***
  - ***Hot spot issues***
- Progress of Key Physics Issues towards Steady-State Operation Regimes
  - *LHCD at high density*
  - *RMP ELM control*
  - *Particle/power exhaust control*
  - *MCM physics at low collisionality*
- Summary and Future Plans

Fully non-inductive, high β_P long-pulse H-mode operations

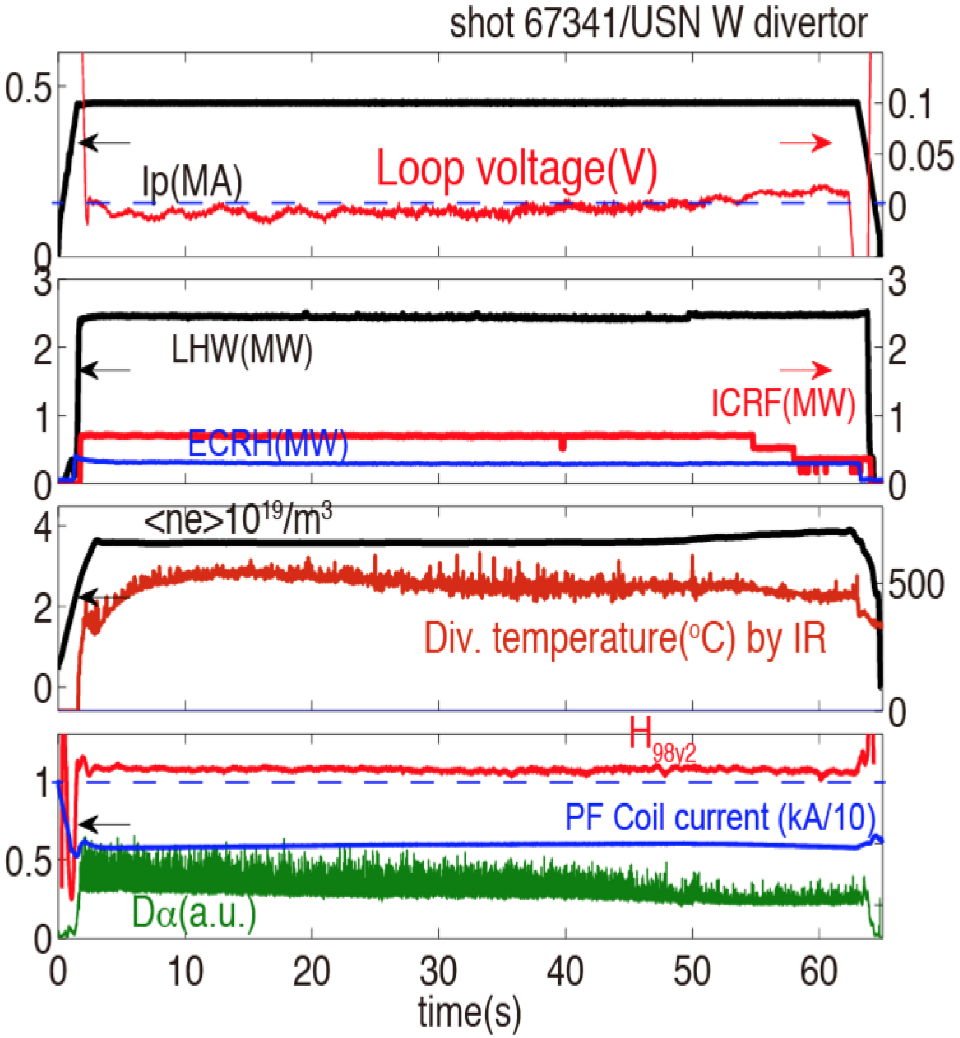
ASIPP

- The goal is to develop fully non-inductive scenarios
  - High LHCD with moderate f_{bs}
- Recent EAST results show that
  - Zero loop voltage is achieved at moderate density
  - Extension for ITER and CFTER
  - Optimization of P_{CD}, η_{CD} and f_{bs}



Scatter plot of EAST β_P versus line-averaged density of low loop voltage plasmas

Minute-scale H-mode operation (>60s)!



- **Pure RF heating:**

  $P_{LHW,\ 2.45GHz}$=0.4MW

  $P_{LHW,\ 4.6GHz}$=2.1MW

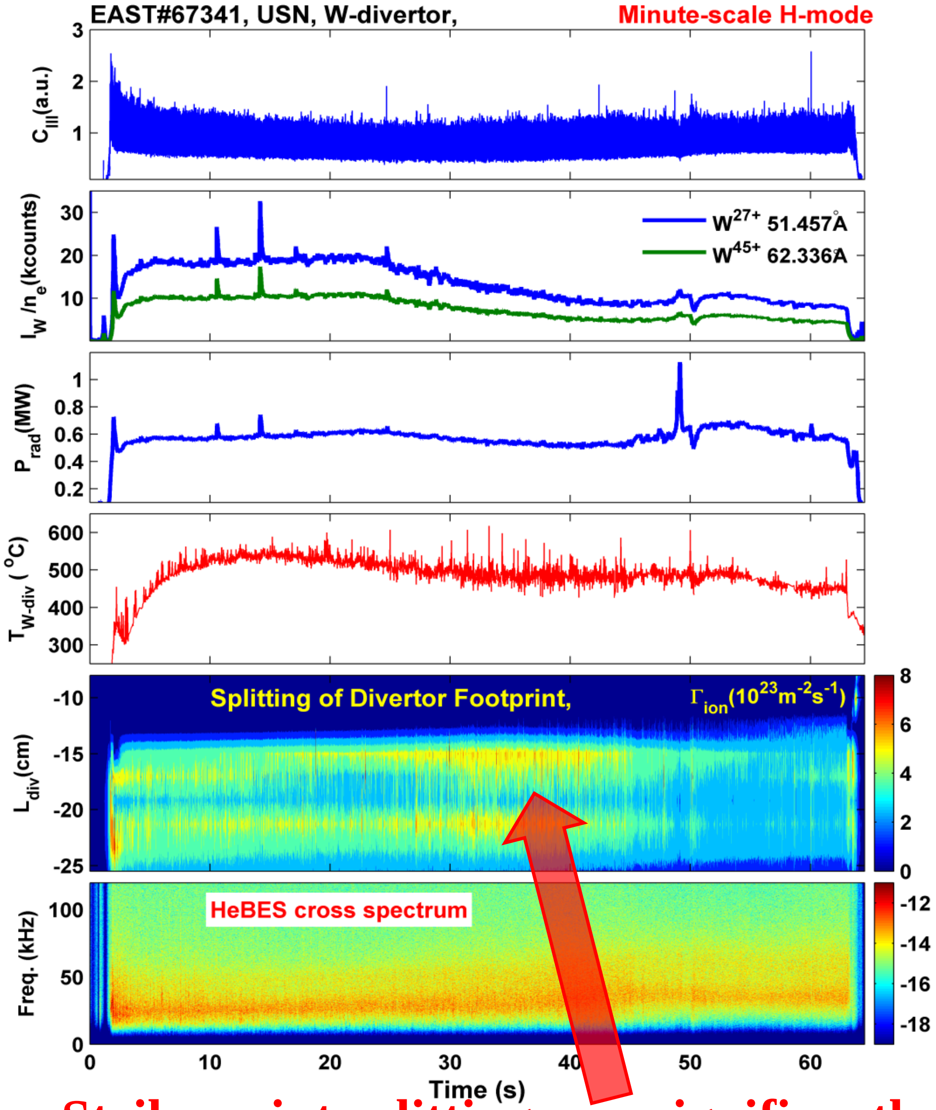
  P_{ICRF}=0.8MW,

  P_{ECRH}=0.3MW;

- **Good confinement with $H_{98(y2)}$~1.1;**
- **Good control of impurity level- assisted by ELMs and ECRH, and an edge coherent mode;**
- **Inter-ELM divertor heat flux ~3 MW/m^2**

Minute-scale H-mode operation (>60s)!

ASIPP



Strike point splitting can significantly reduce peak heat load!

- ➢ **Pure RF heating:**

  $P_{LHW,\ 2.45GHz}$=0.4MW

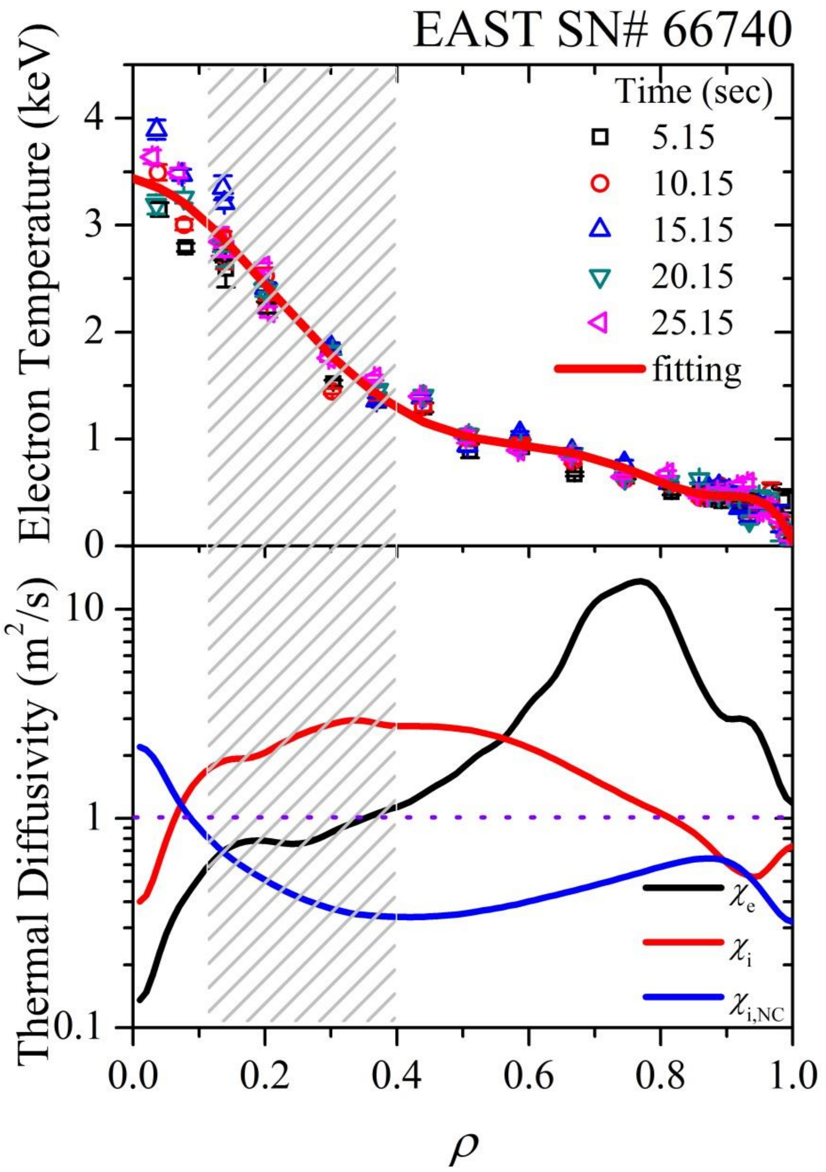
  $P_{LHW,\ 4.6GHz}$=2.1MW

  P_{ICRF}=0.8MW,

  P_{ECRH}=0.3MW;
- ➢ **Good confinement with $H_{98(y2)}$~1.1;**
- ➢ **Good control of impurity level- assisted by ELMs and ECRH, and an edge coherent mode;**
- ➢ **Inter-ELM divertor heat flux ~3 MW/m^2**

Core confinement for RF heated long-pulse fully non-inductive H-mode plasmas

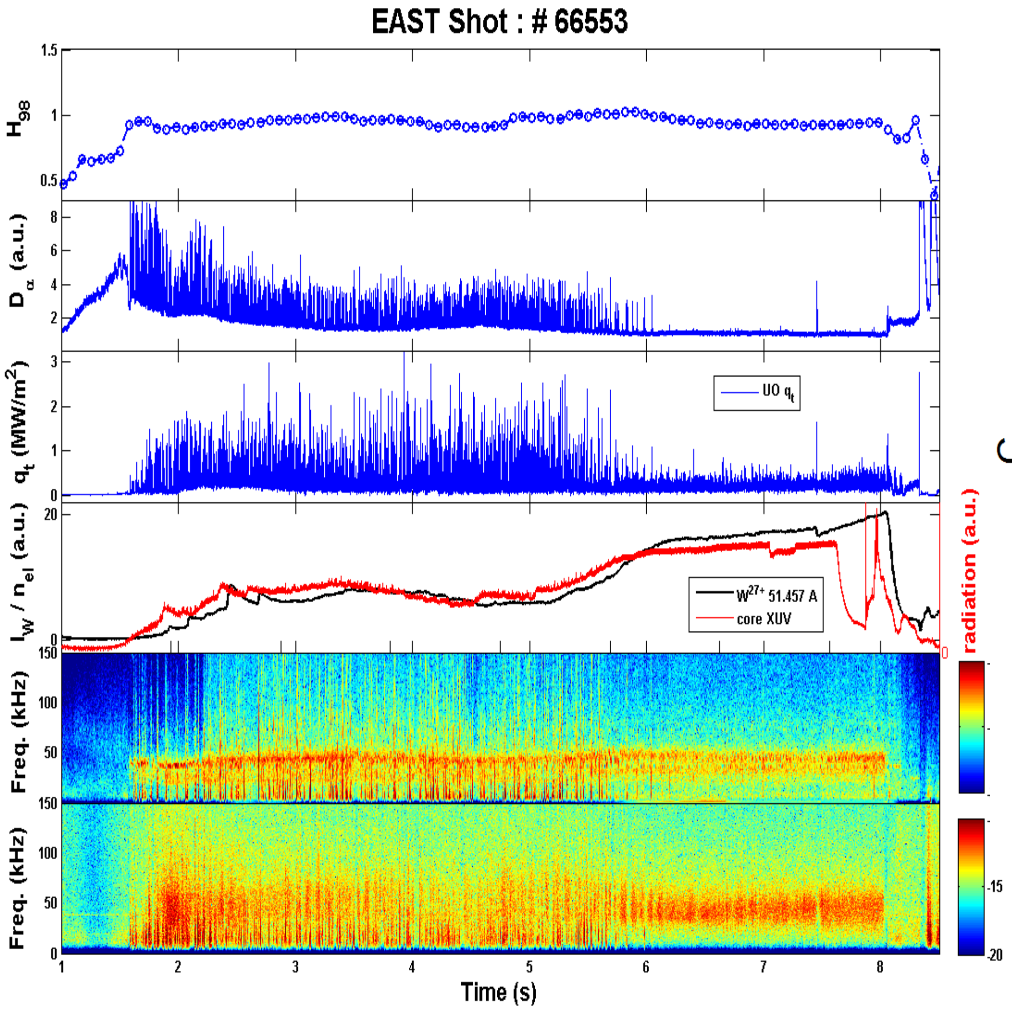
ASIPP

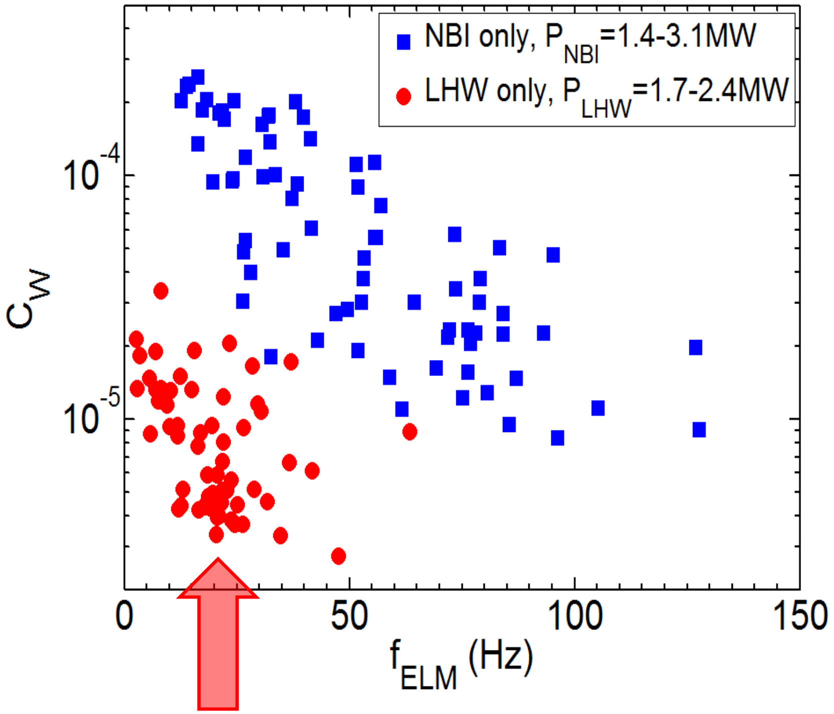


- **Stationary peaked T_e profile was typically maintained in the series of long pulse modes on EAST**
- **Power balance analysis shows the significantly reduced χ_e in plasma core**
- **The core T_e profile meets the ITB criterion [G. Gresset, NF 2002]**
  - **ρ_{Te}^*(max)=0.02>ρ_{ITB}^*~0.014**
- **The improved confinement was sustained very stably for tens of seconds!**

W transport in RF-dominated ELMy H-mode

RF heating plays a crucial role in regulating impurity exhaust

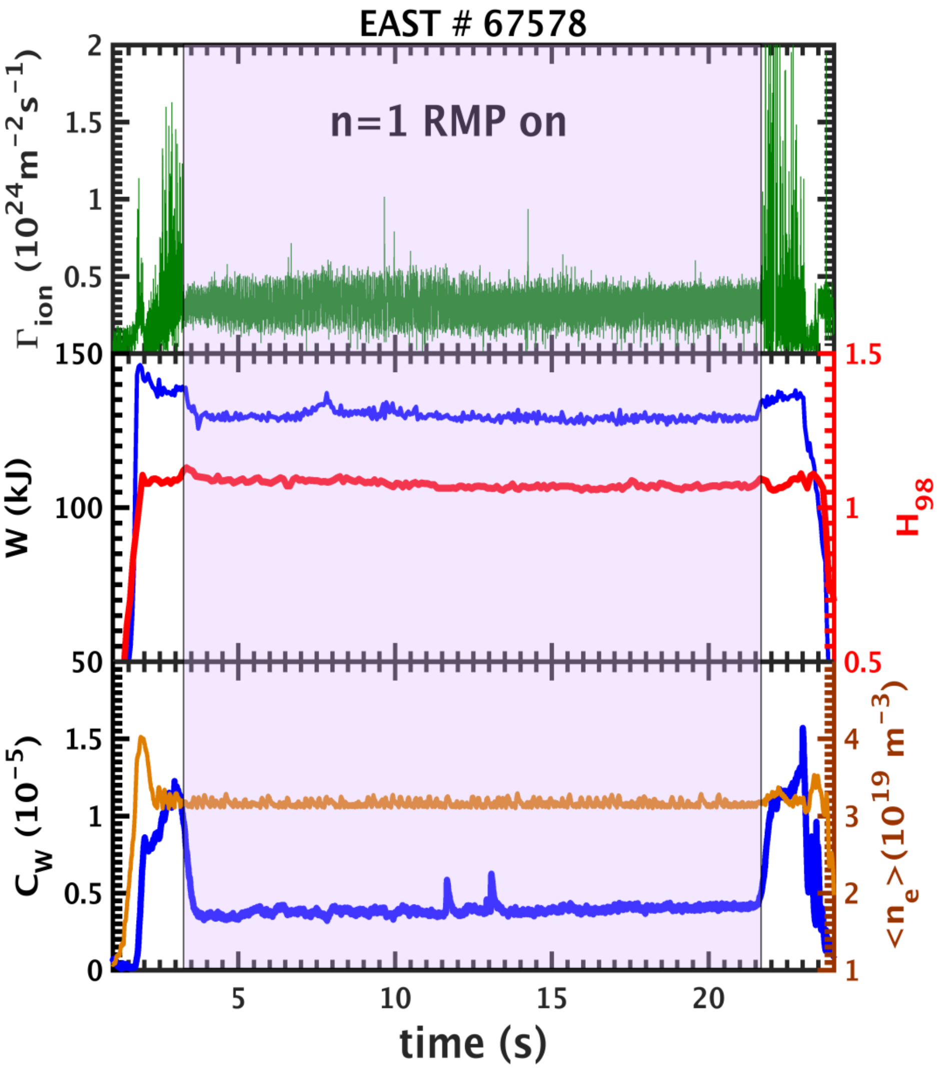




LHW

ELM suppression by RMP in long pulse H-mode with W divertor operation!

ASIPP

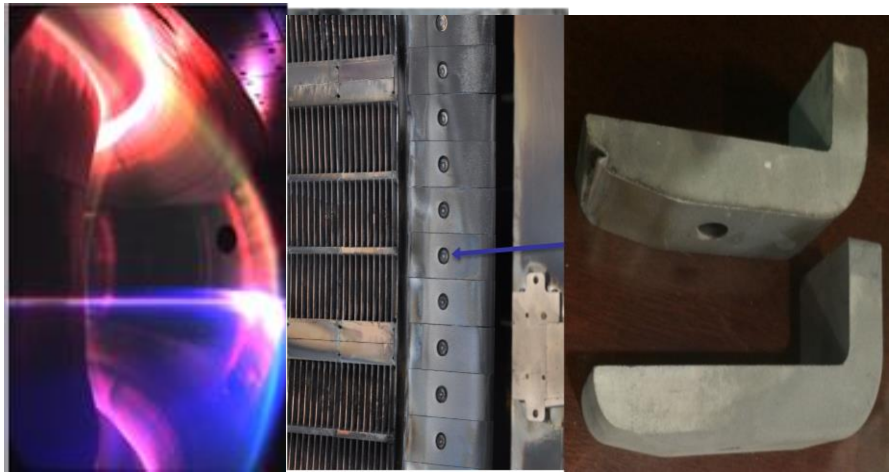


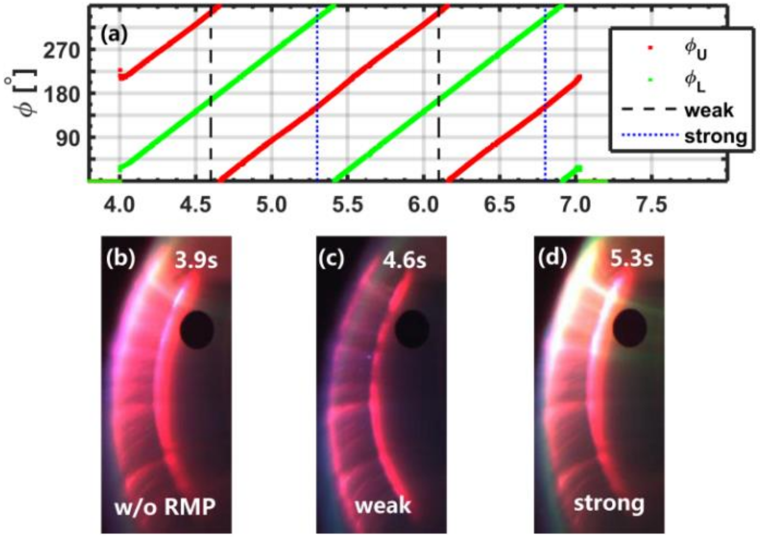
- ELM suppression in long-pulse (~ 20s) operational senario was realized with small effect on plasma performance (H_{98}>1)
- Using *n*=1 RMP with optimized spectrum
- Clear pump-out effect on W, which is helpful for sustaining long-pulse high-performance
- Compatible with long-pulse RF-heated H-mode plasmas

EX/P7-4；EX/P7-10

Hot spot issue and solutions

- Strong hot spots observed on the guard limiter of 4.6GHz LHCD antenna: limiting the pulse length due to strong impurity influx and damage to the limiter
- Global parameter scan identified a threshold LHCD power was around 2.5~3.0MW
- Possible mitigation from rotating RMP was observed by tuning the particle flux hitting on the guard limiter
- New guard limiter design was proposed with inclined surface to lessen direct particle deposition on the surface

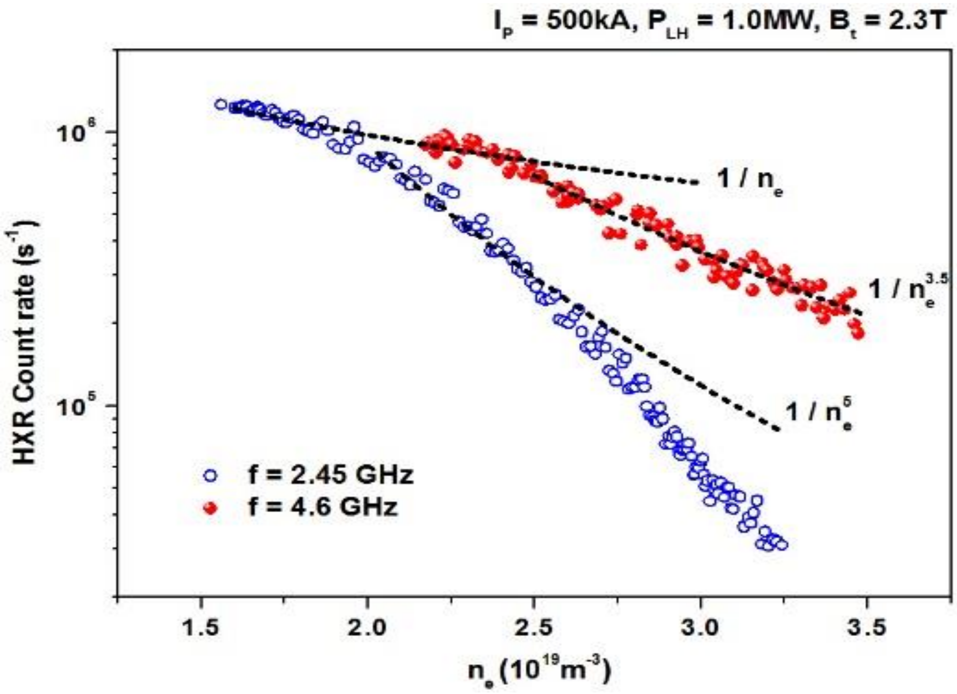


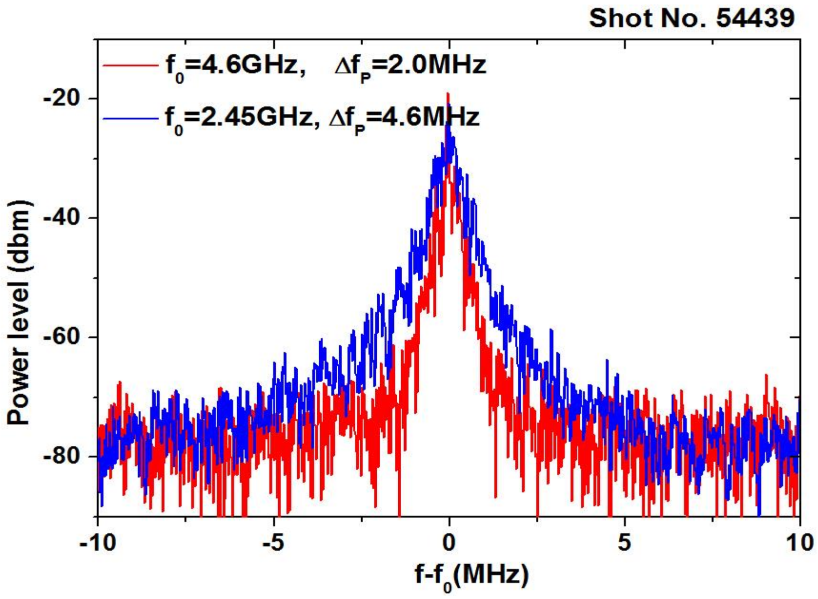


Outline

- Introduction
  - *Facility upgrade in support of steady-state long-pulse scenarios*
- Exploration of Steady-State Plasma Operation with ITER-like Tungsten Divertor
  - *Scenario development with RF dominated heating*
  - *Hot spot issues*
- **Progress of Key Physics Issues towards Steady-State Operation Regimes**
  - ***LHCD at high density***
  - ***RMP ELM control***
  - ***Particle/power exhaust control***
  - ***MCM physics at low collisionality***
- Summary and Future Plans

Higher CD driving at 4.6GHz

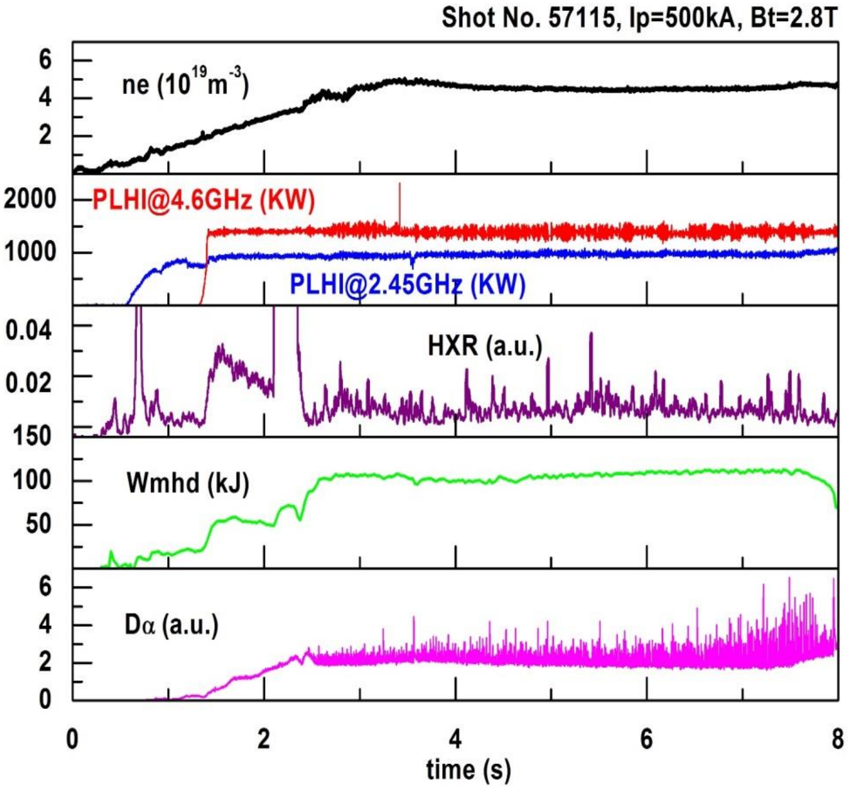


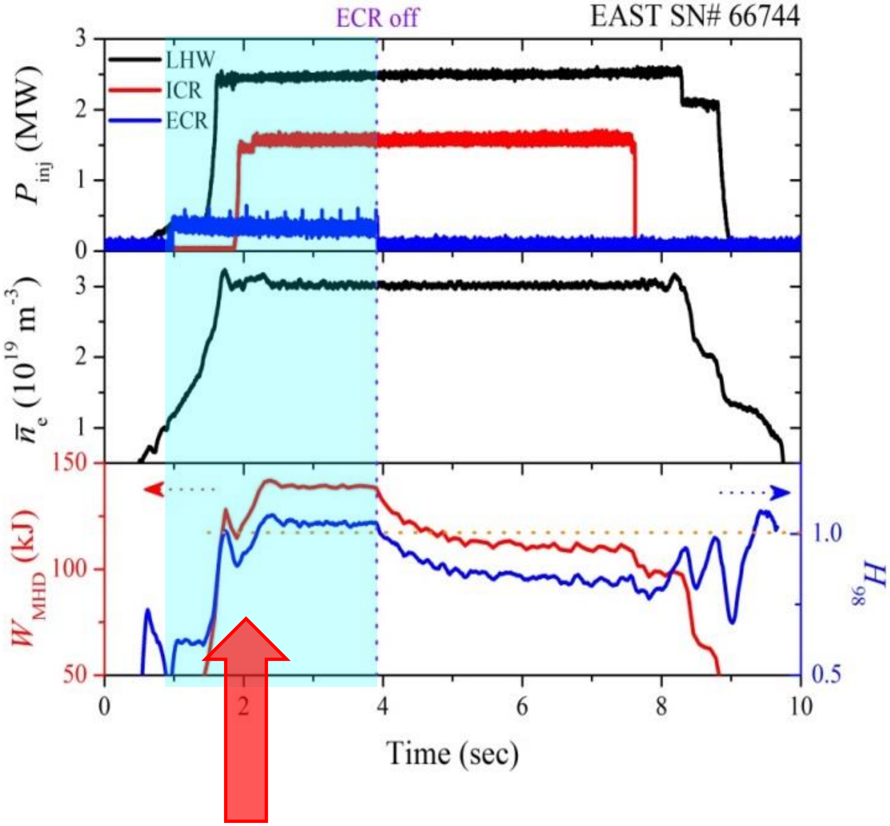


- ➢ **HXR measurement suggested higher current drive capability at 4.6GHz than 2.45GHz;**
- ➢ **Less parametric instability (PI) behavior with 4.6GHz wave**

EX/P7-5;EX/P7-7

LHCD still effective at high density in H-mode

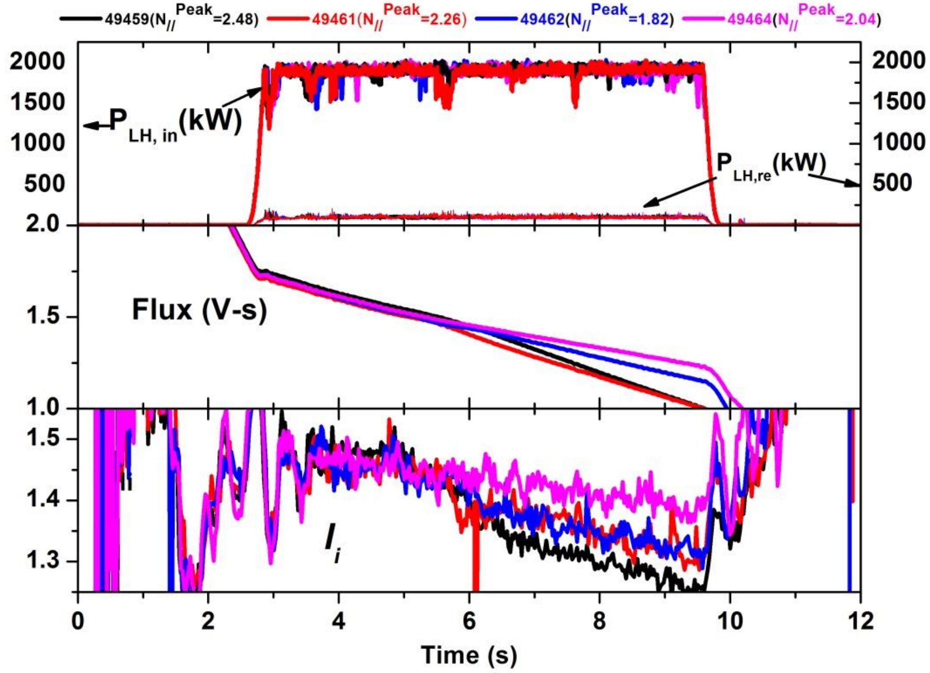


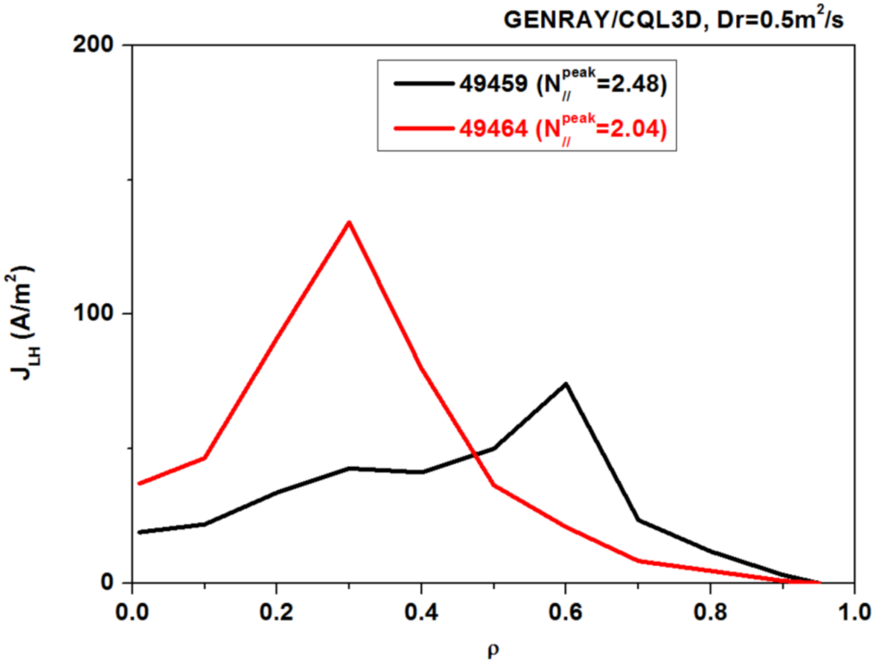


- ➢ **Even if at n_e~$4.5\times10^{19}m^{-3}$, part of current is still driven by LHW!**
- ➢ **Simulation show that N upshift improves accessibility of LHW at high density.**

ECRH plays a crucial role for achieving high-performance H-mode plasmas on EAST

Profile control with LH spectrum tuning



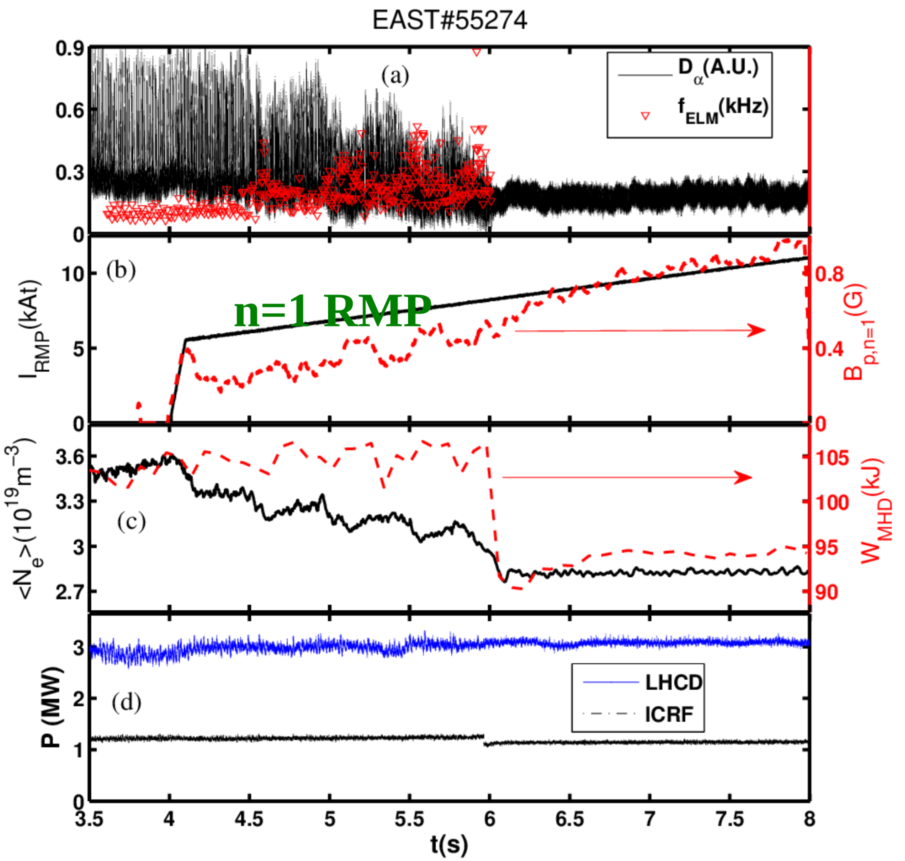


The best CD effect is obtained with $N_{//}^{peak}$=2.04

li in 49464 ($N_{//}^{peak}$=2.04) is the largest, indicating more current is driven in the core region compared to other cases.

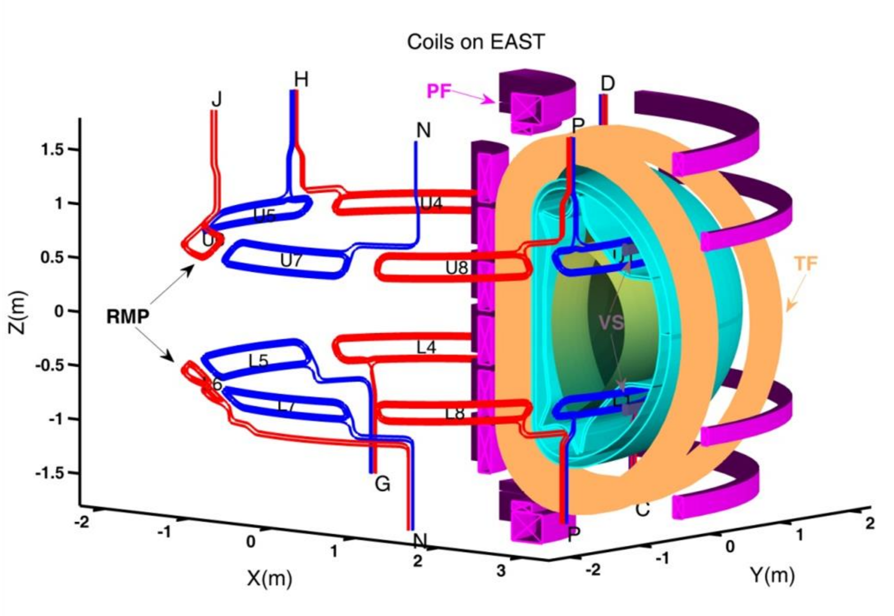
- **GENRAY/CQL3D simulation suggest different driven current profiles, qualitatively consistent with the experiments.**

ELM suppression with low *n* RMP



ELM suppression with *n*=1 RMP in slow-rotating RF heated plasmas

[Sun Y. *et al.*, Phys. Rev. Lett. 117, 115001 (2016)]

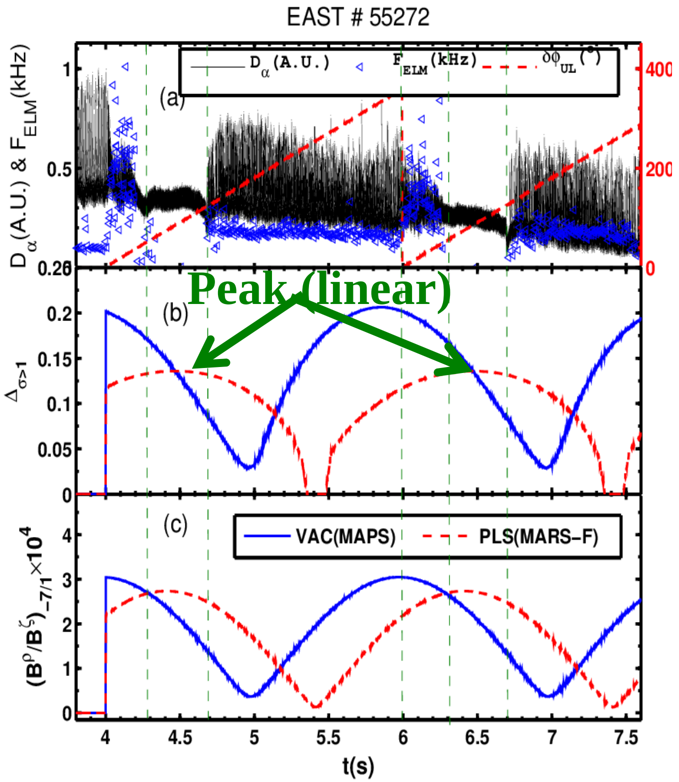


- Full ELM suppression was accessed using low *n* RMP in low rotating plasma with RF dominant heating in EAST
  - ✓ 3MW LHCD + 1MW ICRF
  - ✓ *n*=1, 2 RMP
  - ✓ $\Omega_\varphi \sim 0$

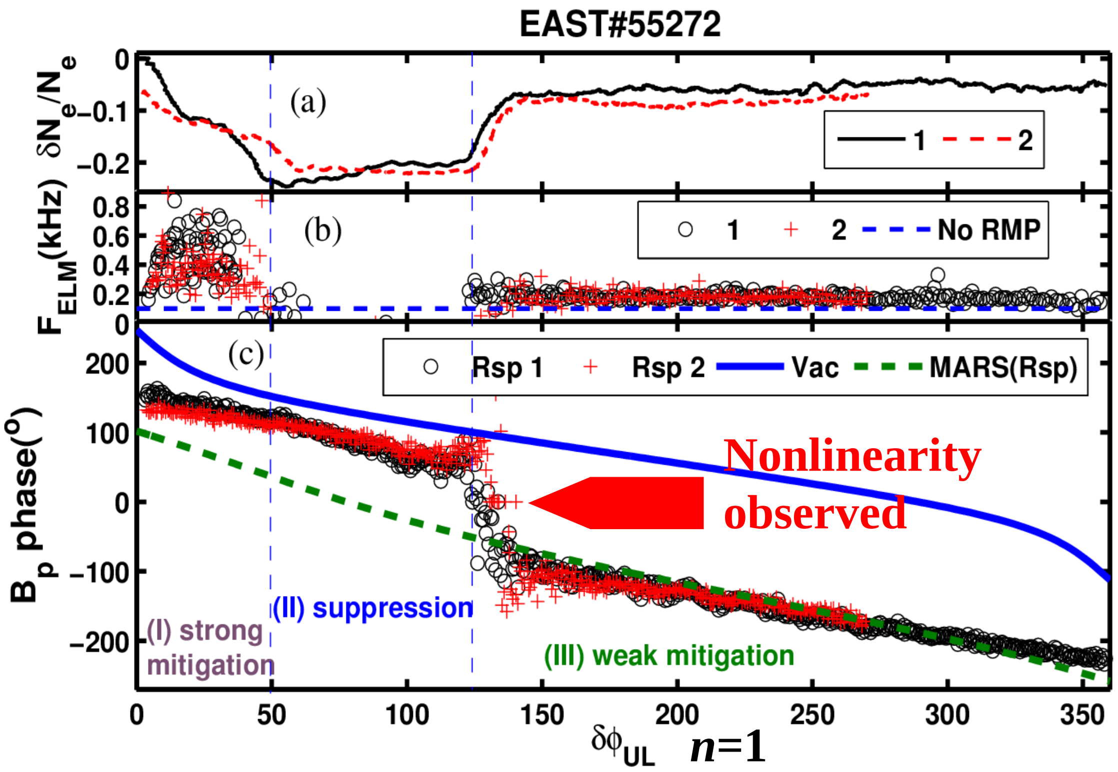
EX/P7-4

Nonlinear plasma response observed

ASIPP



Peak (linear)

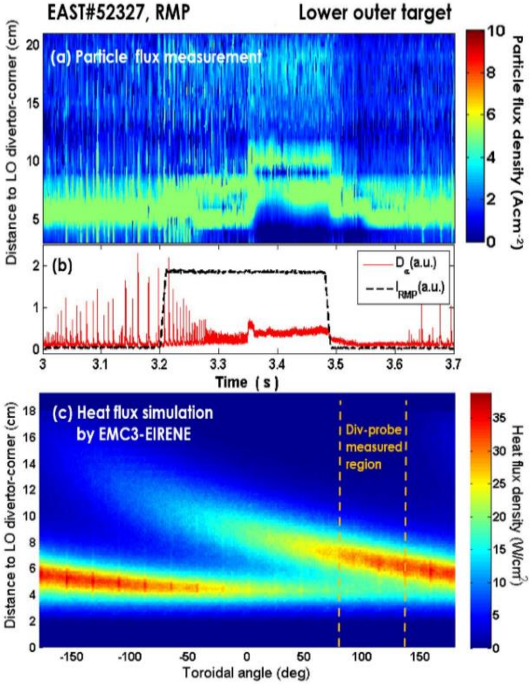


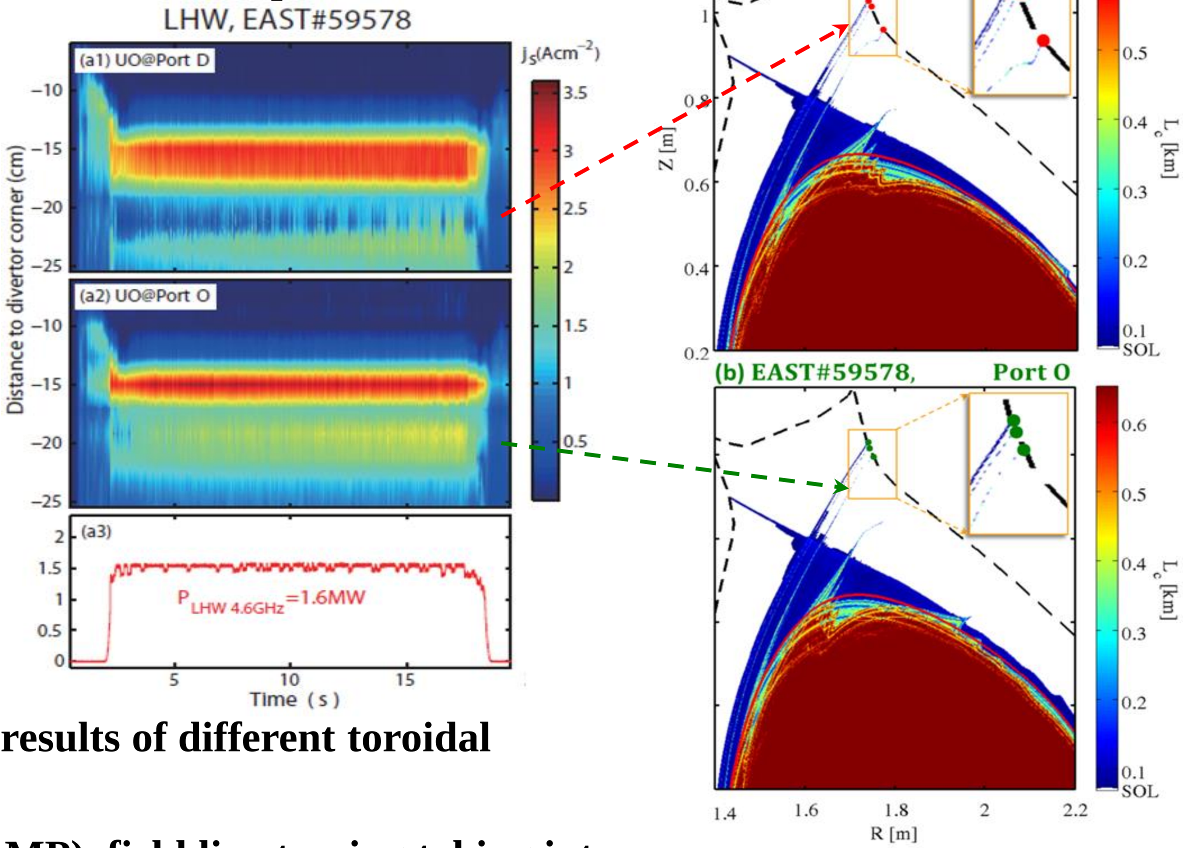
Nonlinearity observed

- **Linear plasma response determines the best spectrum for ELM suppression.**
- **Nonlinear plasma response suggests that a critical level of magnetic topological change taking into account plasma response plays a key role in accessing final ELM suppression**

Control of 3D divertor footprint

- Both LHW & RMP coils can induce edge topology change → striated magnetic flux lobes → 3D divertor footprints





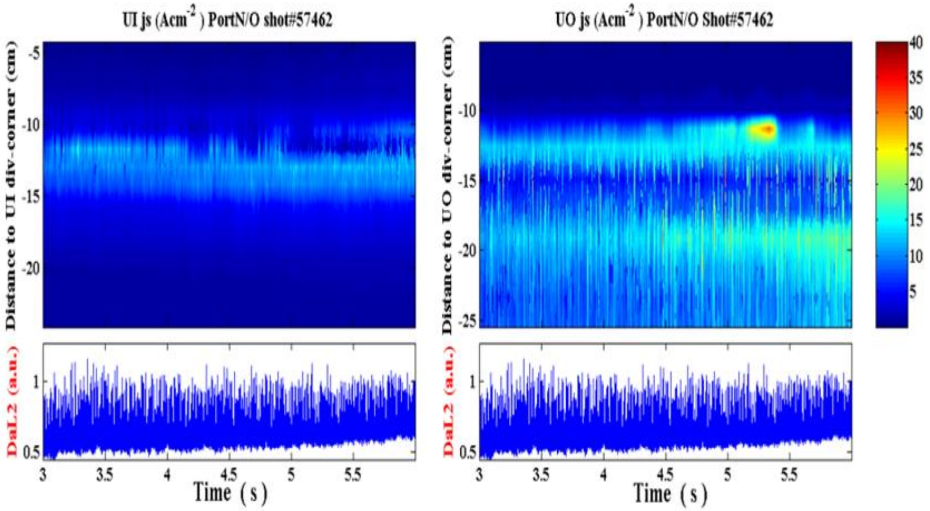
- The experimental and modeling results of different toroidal locations show good agreement.
- Simulations: EMC3-EIRENE (RMP), field line tracing taking into account helical current filaments in the SOL (LHW).

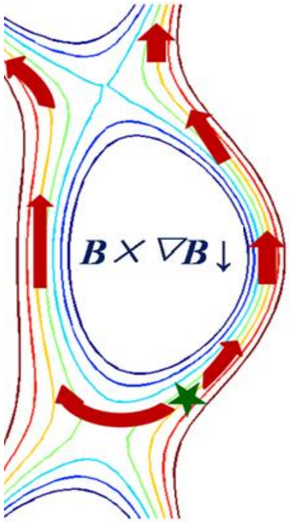
Allowing further heat flux control using 3D footprint with regulated divertor conditions.

EX/P7-10; TH/P6-20

Active control of particle exhaust

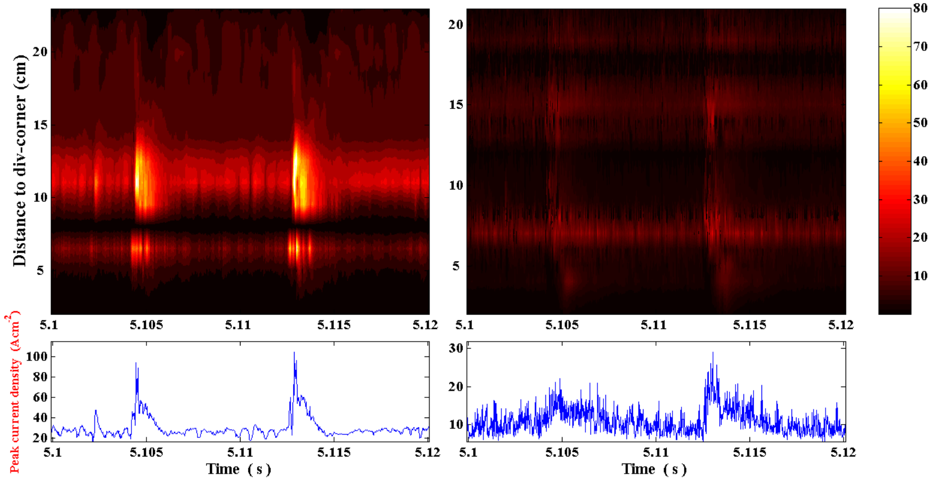
➢USN, W-divertor, Bx∇B↓

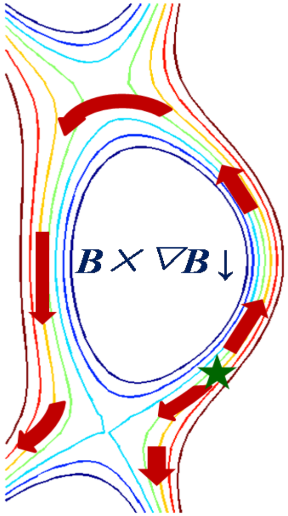


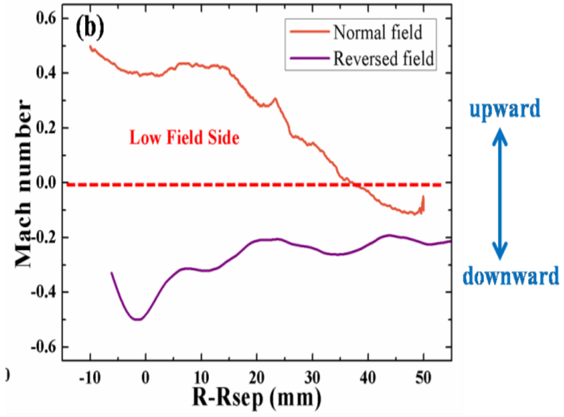


- ■ ELM particle flux favors outer divertor in USN, while favoring inner divertor in LSN.
- ■ A reference for particle exhaust during long-pulse H-mode operation, together with cryo-pumps.
- ■ Consistent with PS flow, as measured by LFS/HFS reciprocating Langmuir probes.
- ■ Compatible with ICRF heating

➢LSN, C-divertor, Bx∇B↓



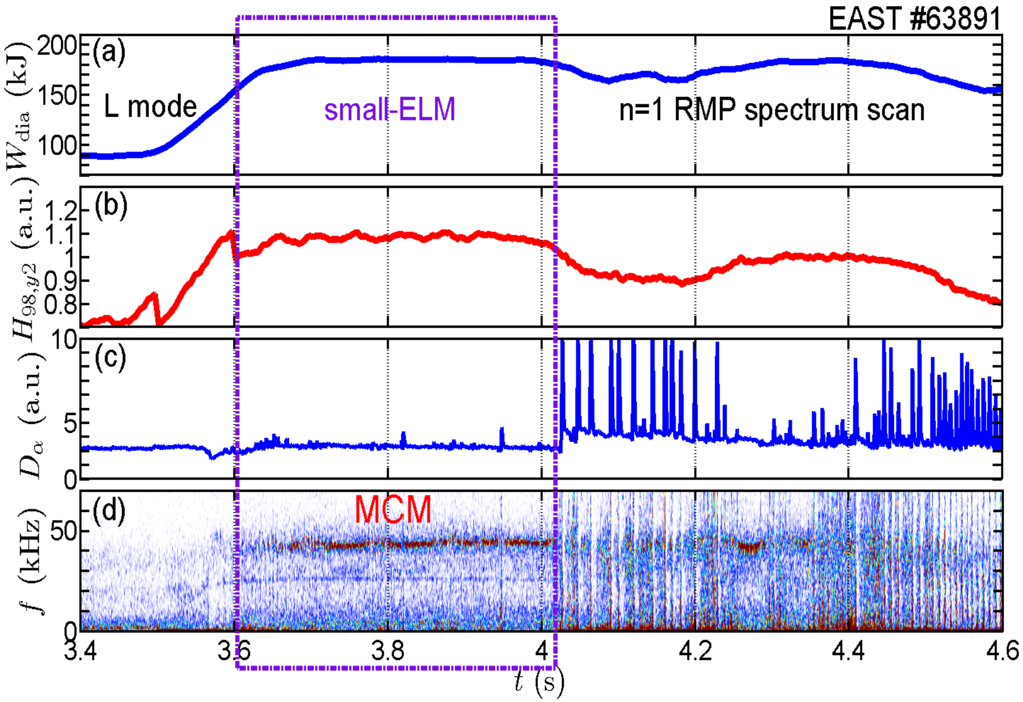


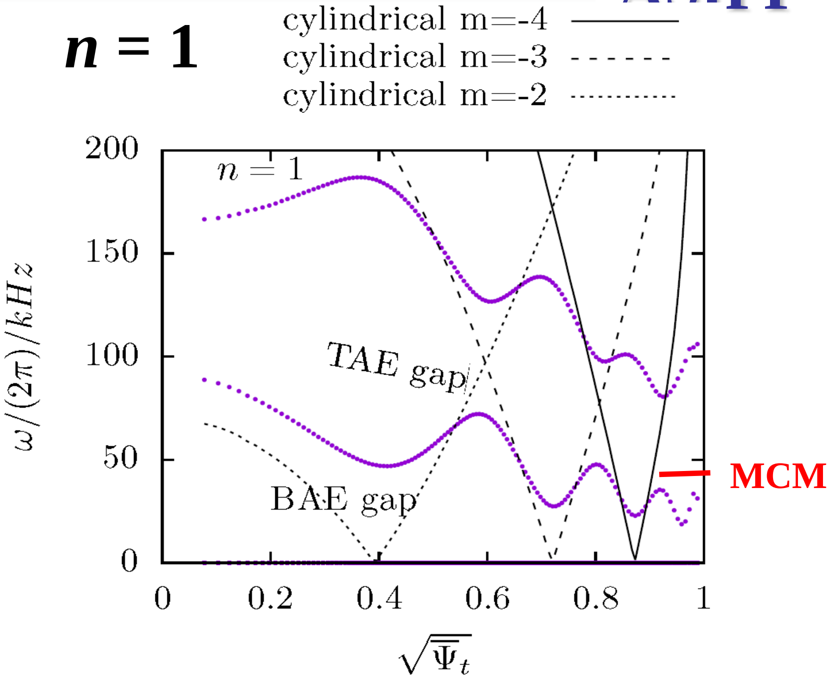


J. B. Liu et al., NF (2016)

New Stationary Small/No ELM H-Mode Regime at Low Collisionality

ASIPP



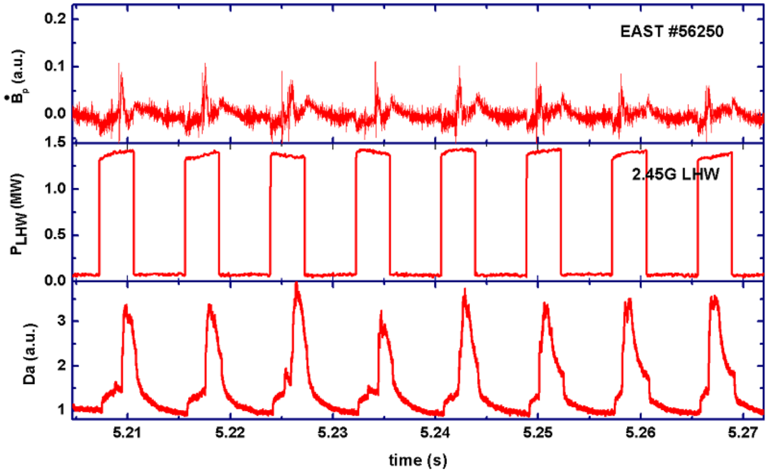


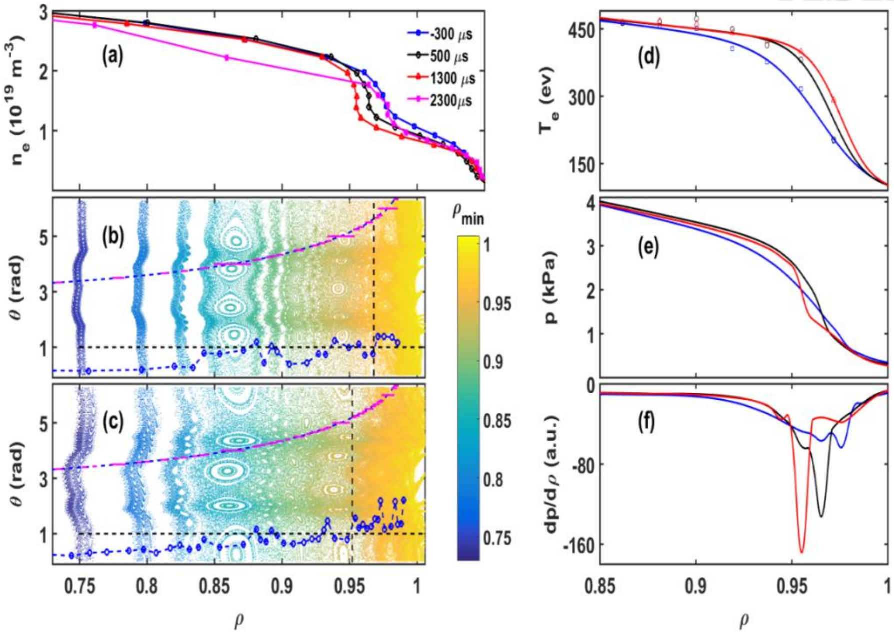
- **A new stationary small/no ELM H-mode at low collisionality ($\nu_e^* < 1$)**
- **Good energy confinement, $H_{98(y,2)} \gtrsim 1.1$,**
- **A low-*n* (mostly *n*=1 and sometimes *n*=2) electro-Magnetic Coherent Mode (MCM) at 30-60 kHz in the pedestal region.**

- **MCM frequency appears to be located in the TAE gap near the local trapped-thermal-electron bounce frequency**
- **Frequency scales linearly with the local Alfvén frequency, indicating the possibility of trapped-electron-driven TAE mode through bounce resonance with trapped thermal electrons.**

ELM pacing with LHCD modulation

120 Hz, 40% duty cycle





- ➢I_p~0.45MA, n_{el}=3.3~ 45%n_{GW}, B_t~2.33 T, $P_{LH\_4.6}$~1.3 MW, P_{NBI_1L}~2.8 MW
- ➢2.45G Modulation: $P_{LH\_2.45}$~1.4 MW, 120 Hz, 40% duty cycle

- ➢ **LHCD-induced flattening of density profile near the separatrix and pedestal density pump-out have been observed.**
- ➢ **Density gradient is steepened near the pedestal top, causing pedestal-pressure-gradient increase that may be responsible for the ELM triggering.**
- ➢ **Vacuum-field modeling of LHCD-induced 3D magnetic topology change indicates that the flat-density-profile region and its radial width expansion are largely consistent with those of the LHCD-induced edge stochastic magnetic field layer, which may explain the observed density profile change, similar to the effect of RMPs.**

Outline

- Introduction
  - *Facility upgrade in support of steady-state long-pulse scenarios*
- Exploration of Steady-State Plasma Operation with ITER-like Tungsten Divertor
  - *Scenario development with RF dominated heating;*
  - *Hot spot issues*
- Progress of Key Physics Issues towards Steady-State Operation Regimes
  - *LHCD at high density*
  - *RMP ELM control*
  - *Particle/power exhaust control*
  - *MCM physics at low collisionality*
- **Summary and Future Plans**

Summary

ASIPP

- Stationary RF-heated long-pulse H-mode operations (>60s !) were achieved on EAST with progress in the *relevant physics* in support of SSO on *tungsten divertor*
  - Extension of the *SSO towards high β_P regime (up to 1.8)*;
  - Achievement of *low-n (1, 2) RMP ELM suppression* in the RF dominant slow-rotating long-pulse H-mode plasma (~20s); Observation of the *first evidence of a nonlinear transition* from mitigation to suppression of the ELMs by using RMPs;
  - Extension of the *current drive in high-density domain* (up to $4.5 \times 10^{19} m^{-3}$) with 4.6 GHz and 2.45GHz LHCD systems together;
  - *Regulating heat deposition distribution* and *reducing transient peak heat fluxes* on the divertor and PFCs by applying *3D* magnetic perturbations at the plasma boundary.
  - Discovery of *a new stationary ELM-stable H-mode* ($H_{98(y,2)} \gtrsim 1.1$, $\upsilon_{e,ped}^{*} < 1$) *regime,* which exhibited a *low-n MCM* at the pedestal.

Future Plans

Step I

- Improve heating efficiency and develop the SSO-relevant fundamental physics and key diagnostics;

Step II

- Develop the SSO high performance plasma scenarios and demonstrate (≥100s) long-pulse H-mode plasmas;

Step III

- Optimize the SSO plasma and extend the EAST operational domain towards long-pulse, high β, high power, high performance regime.

List of EAST Contributions

ASIPP

- **OV/2-2 B.N. Wan:** Overview of EAST Experiments on the Development of High-Performance Steady-State Scenario
- **EX/4-3 A.M. Garofalo:** Development of High Poloidal β Steady-State Scenario with ITER-Like W Divertor on EAST
- **EX/10-2 G.S. Xu:** ELM Pace-Making and Long-Pulse ELM-Stable H-Mode Operation with LHCD in EAST
- **EX/P7-2 X. Gao:** Key Issues towards Long Pulse High Operation on EAST Tokamak
- **EX/P7-4 Y. Sun:** ELM Suppression Using Resonant Magnetic Perturbation in EAST
- **EX/P7-5 B. J. Ding:** Recent Experimental and Modelling Advances in the Understanding of Lower Hybrid Current Drive in ITER-Relevant Regimes
- **EX/P7-7 B. Lyu:** Experimental Study of Radio-Frequency Driven Spontaneous Rotation for High-Performance Plasmas on EAST
- **EX/P7-8 X.J. Zhang:** Heating and Confinements by the Waves in the Ion Cyclotron Range of Frequencies on EAST
- **EX/P7-10 L. Wang:** Evidence and Modelling of 3D Divertor Footprint Induced by Lower Hybrid Waves on EAST with Tungsten Divertor Operations
- **EX/P7-12 X.D. Zhang:** Fishtail Divertor: A New Divertor Concept on EAST for Active Control of Heat Load on Divertor Plate
- **EX/P7-15 G. Li:** Predictions of the Baseline Operation Scenario in Chinese Fusion Engineering Test Reactor
- **EX/P7-16 W. X. Ding:** Current Transport and Density Fluctuations at L-H Transition on EAST
- **TH/P6-19 T. Y. Xia:** Divertor Heat Flux Simulations in ELMy H-Mode Discharges of EAST and Other Tokamaks
- **TH/P6-20 J. Huang:** EMC3-EIRENE Simulations for the Impact of External Magnetic Perturbations on EAST Edge Plasma
- **FIP/1-1 P. Fu:** Recent Progress of ITER Package in ASIPP
- **FIP/P4-21 Z. Song**: Research and Development Progress of the ITER PF Converter System
- **MPT/1-2Ra G.-N. Luo:** Overview on Decade Development of Plasma-Facing Components at ASIPP

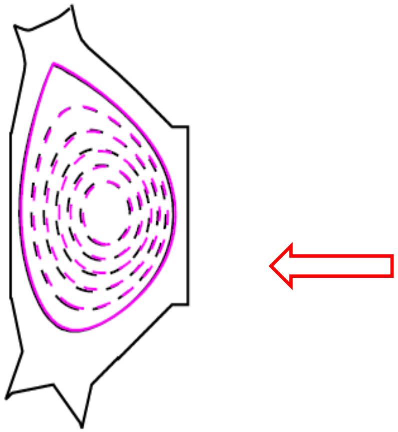
Welcome to the poster session for further discussions!

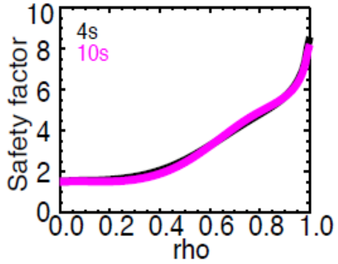
Thank you !

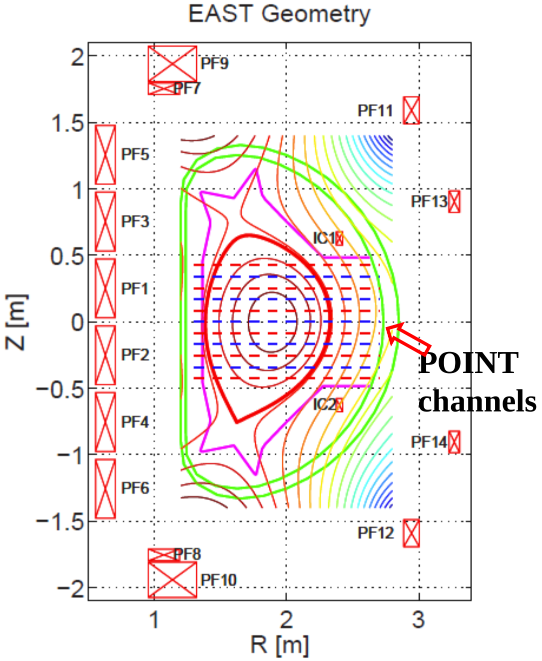
Backup slides

Diagnostics for key profiles

- ☐ Polarimeter Interferometer (POINT): n_e, j_ϕ, q, B_p profiles
- ☐ Core & edge TS: T_e, n_e
- ☐ AXUV & Bolometer: radiation
- ☐ CXRS & XCS: T_i, rotation
- ☐ SXPHA & ECE: T_e
- ☐ Reflectometry: pedestal n_e
- ☐ **He-BES:** edge n_e, T_e
- ☐ **Recip.-LPs:** SOL n_e, T_e, flow
- ☐ **Bremsstrahlung:** Z_{eff}
- ☐ FIDA: $V_{fast\text{-}particle}$
- ☐ High speed CCD
- ☐ **IR camera:** heat flux
- ☐ **Div-LPs:** div. particle/heat flux
- ☐ Total: >70 diagnostics



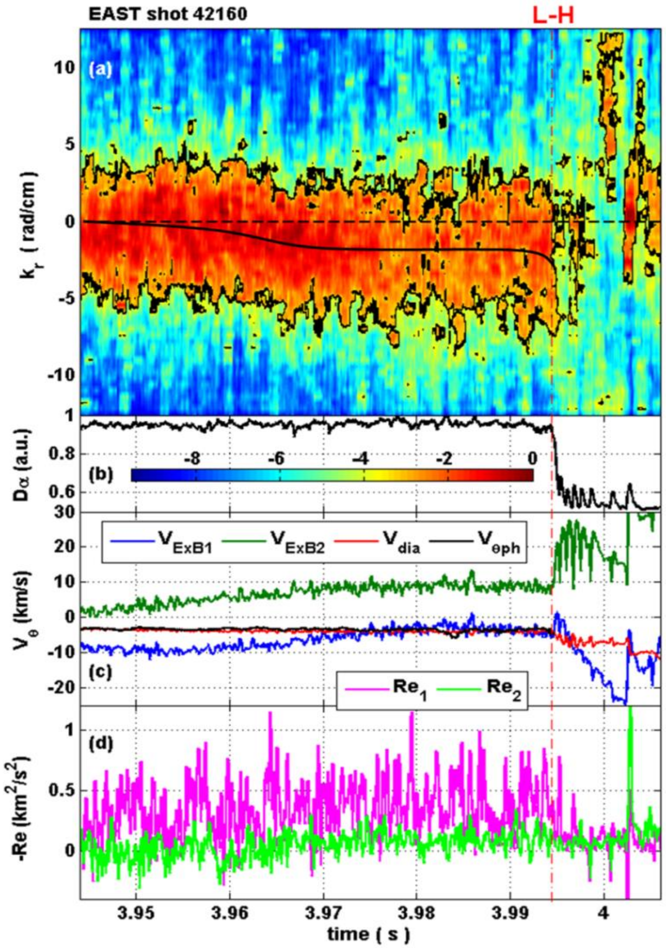


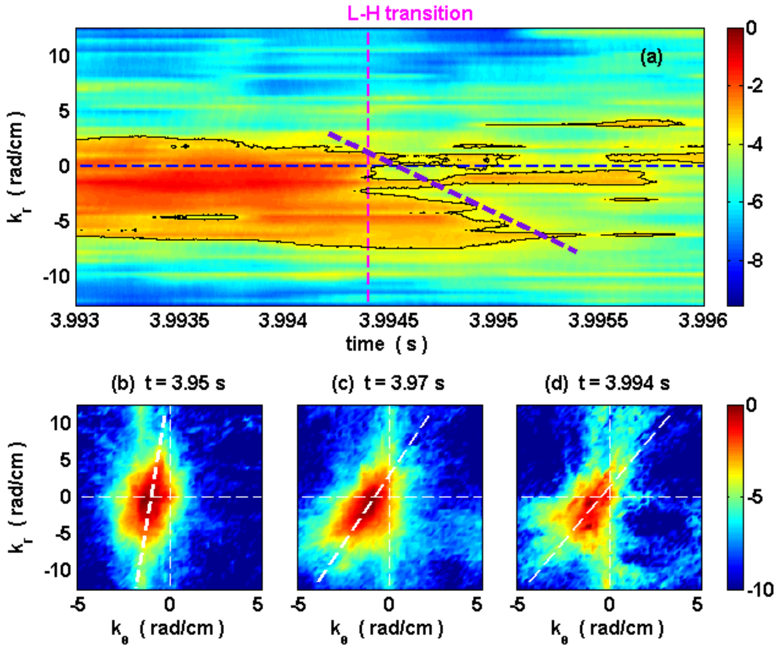


- ➢ Using POINT measurement as constraint, accurate *q* profile were derived
- ➢ Powerful tools for developing scenarios

EAST Experiment Shows New L-H Transition Mechanism

ASIPP

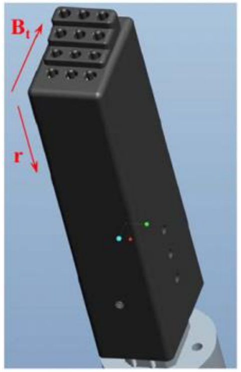




Shift accelerates at the transition, accompanied by turbulence suppression.

Eddy tilt increase as approaching the L-H transition.

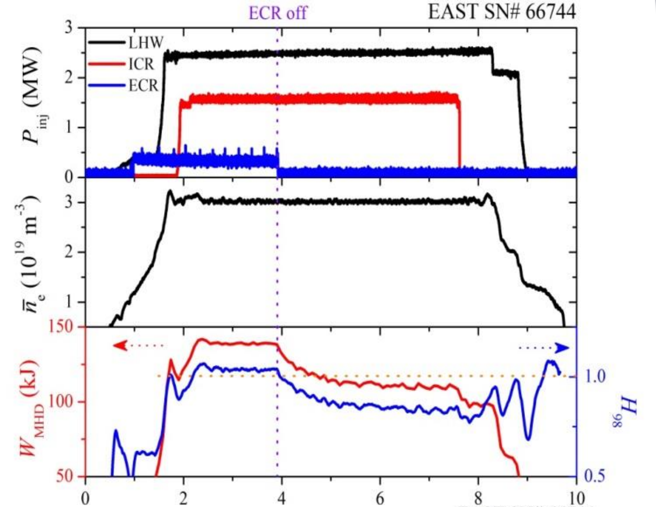
First direct observation of L-H transition mediated by turbulence k_r spectral shift and eddy tilting.

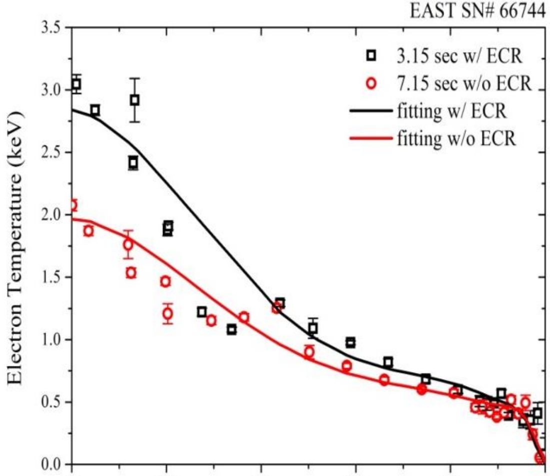


Reciprocating Langmuir probe array

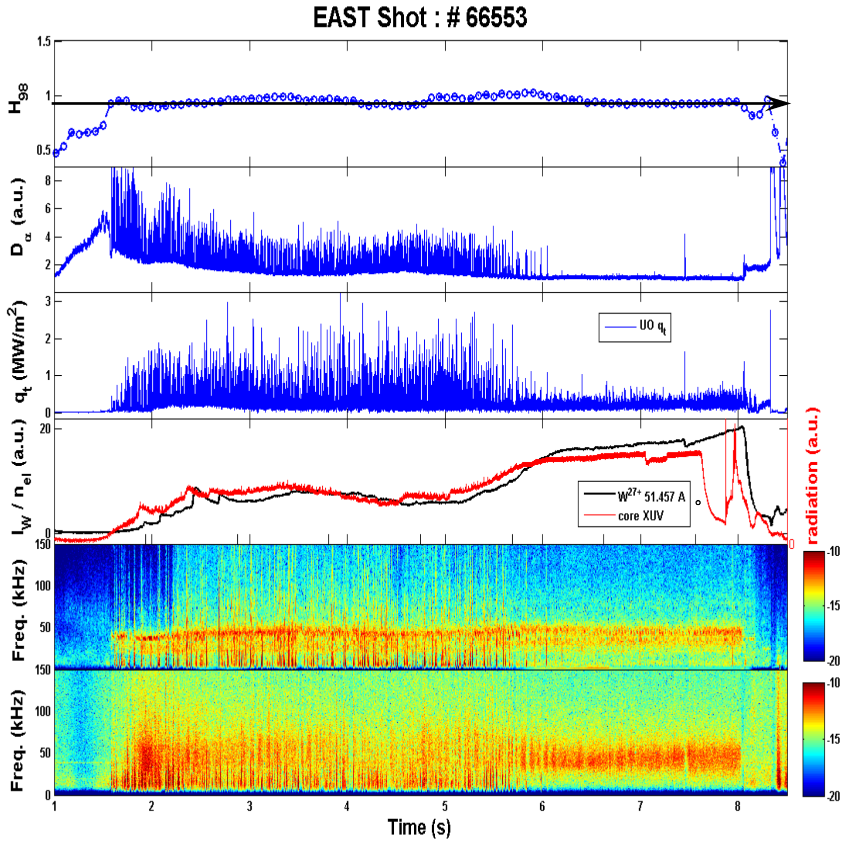
G.S. Xu, PRL 116, 095002 (2016)

Core confinement improvement and ELM effect for long pulse H-mode operation





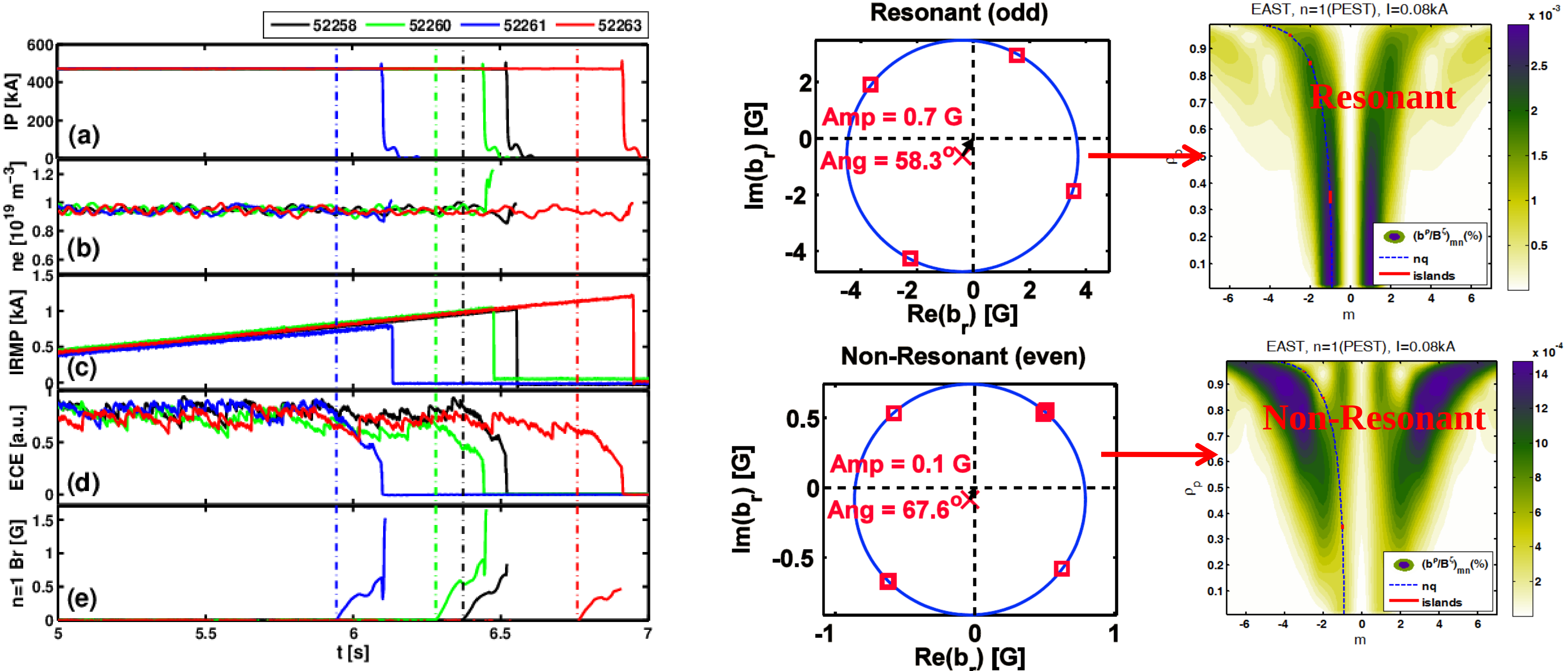
Adding additional central heating power i.e. ECR, is critical for keeping high performance



ELM-free H-mode (6.06-8s)
- **High confinement (H_{98} ~ 0.93)**
- **Impurity accumulation and high core radiation**

Small-ELM H-mode (1.6-6.06s)
- **High confinement (H_{98} ~ 0.98)**
- **Lower impurity/radiation level**
- **Suitable for long-pulse H-mode operation**

Low n=1 intrinsic error field measured in EAST



Compass scan [Wang H.H *et al*, Nucl. Fusion 56, 066011(2016)]

- ➢ **The measured n=1 intrinsic error field is of the order $B_{2/1}/B_0$ ~10^{-5}.**
- ➢ **The amplitude depends on the RMP configuration used, which agrees with linear plasma response modeling by MARS-F.**
  - ✓ **Non-Resonant: $B_{2/1}/B_0$ ~0.6x10-5 (better coupling)**
  - ✓ **Resonant: $B_{2/1}/B_0$ ~4.4x10-5**