IAEA

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Advances in H-mode Physics for Long Pulse Operation on EAST

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for EAST team & collaborators**

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Outline

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- **Introduction**
- **EAST upgraded capabilities**
- **Physics advances for long pulse H-mode operation**
- **Summary & future plans**

Introduction

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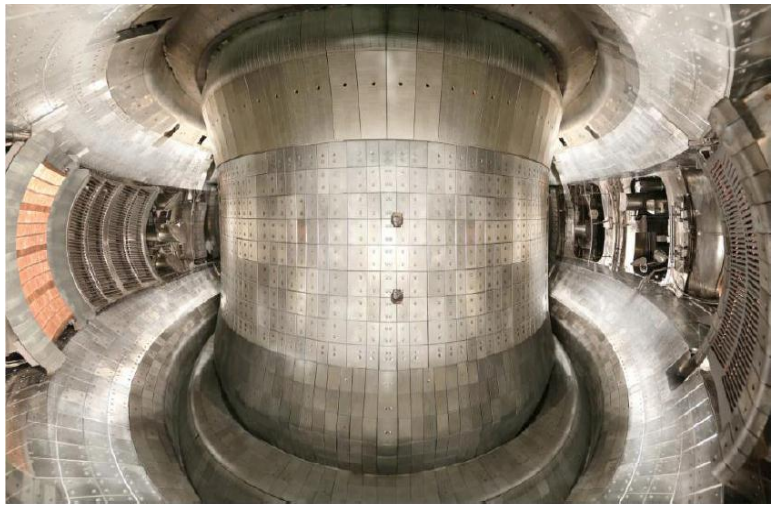
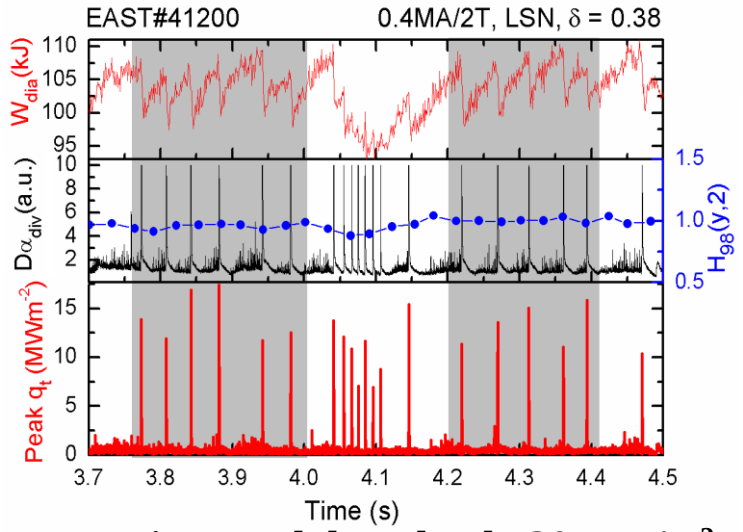
- **EAST as a SC machine aims at high performance long pulse operations.**
- **The enhanced capabilities since last IAEA-FEC allow EAST**
  - **Fully non-inductive operation with high f_{bs}.**
  - **Active control of transient and stationary heat load on divertors**
- **Significant progress in H-mode physics for long pulse operations**



EAST In-Vessel@2014



Transient peak heat load ~20MW/m^2 with P_{abs} ~2MW in type I ELMy H-mode

- **Significance for ITER & future reactors**

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H & CD capabilities allow truly advanced steady state plasma operations

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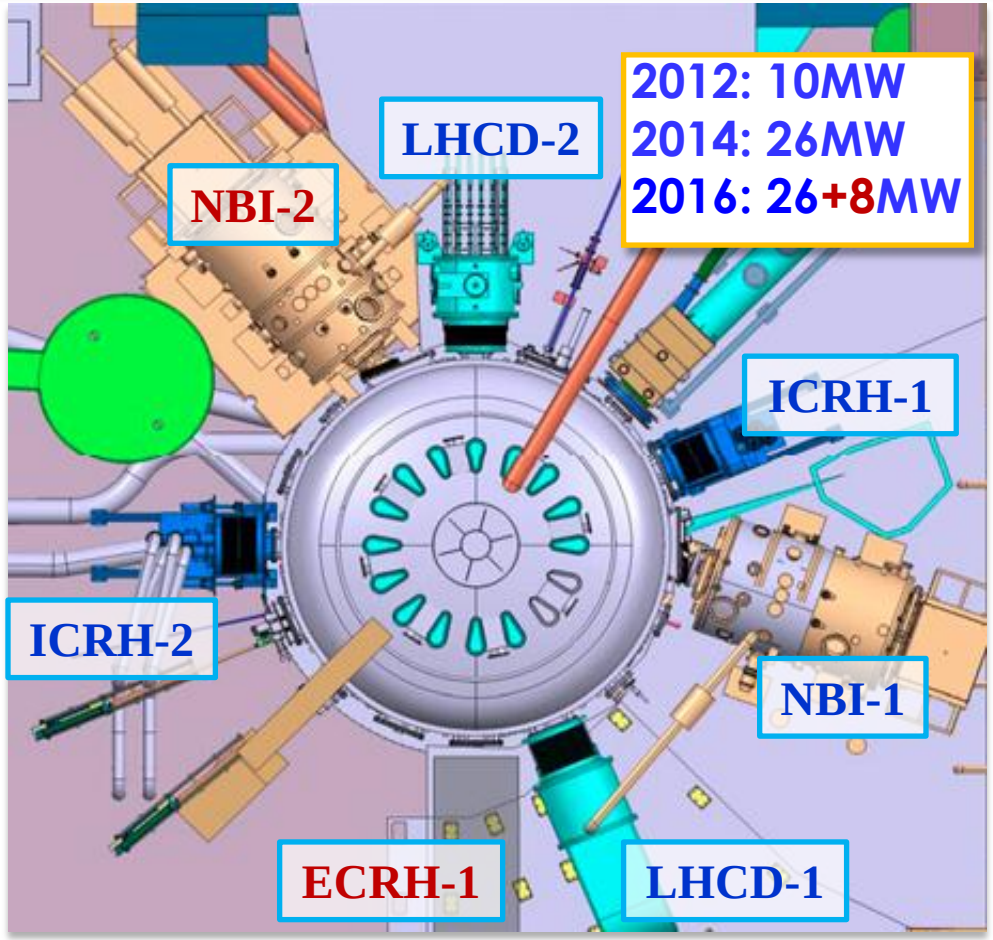
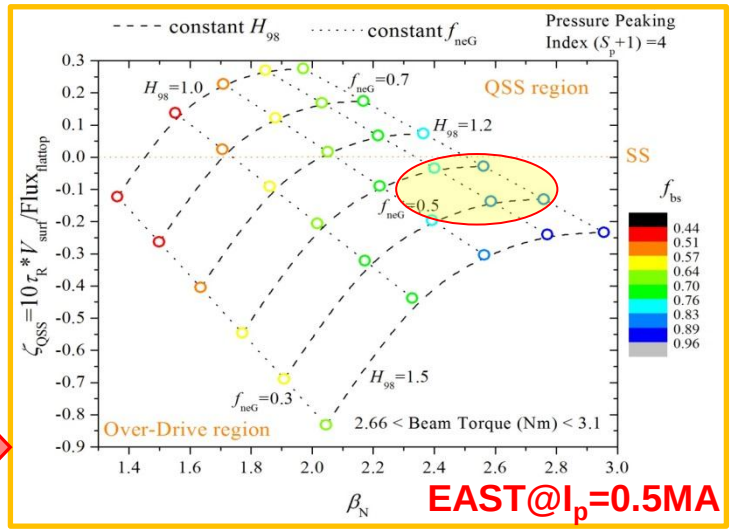


- **LHCD 4+6 MW (2.45/4.6GHz)**
  - Fast Electron Source
  - Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating
  - Central Current Drive
- **NBI 4+4 MW (co/counter, 80kV)**
  - Sufficient power to probe β limit
  - Variable rotation/ rot-shear
- **ECRH 4 MW (140GHz)**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

ITER-like RF-dominant H&CD, capable to address key issues of high performance SS operations



ITER-like PFC upgrade facilitate high power long pulse operations

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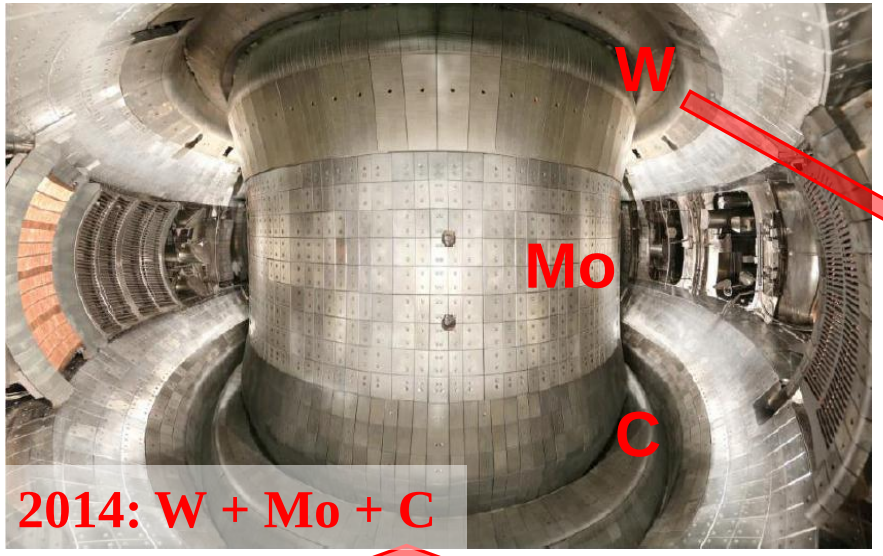
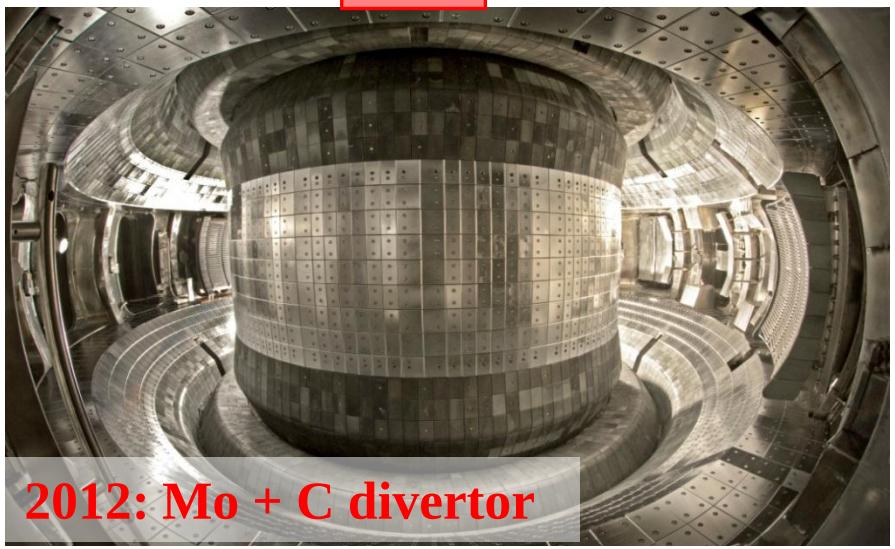
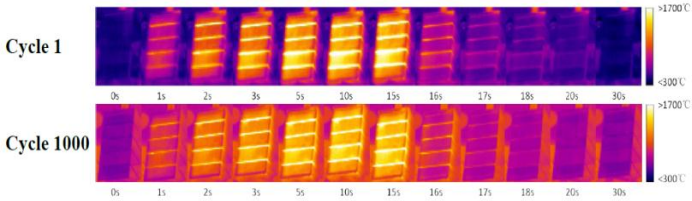




◆ITER-like, water-cooled, cassetted, W top divertor



- Heat load ~ 8.4 MWm^{-2}, cooling water of 20 °C, 15s/15s on/off cycles
- The mock up survived up to 1000 cycles, with surface temperature up to 1150 °C.

New or upgraded diagnostics for key profiles

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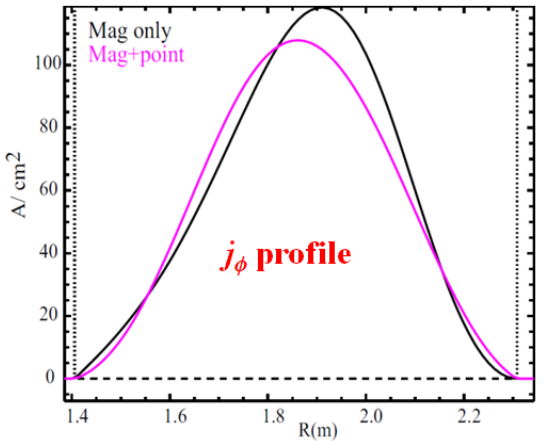
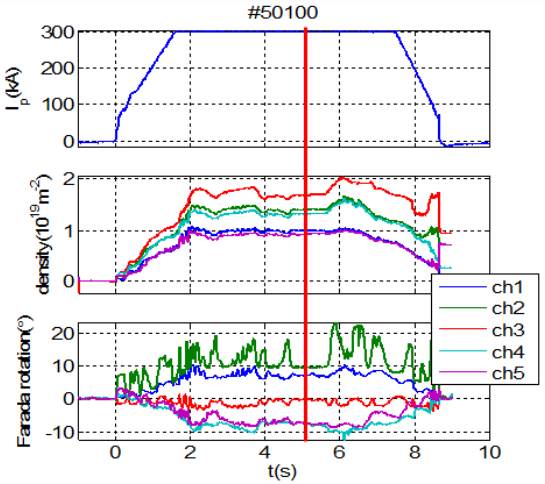
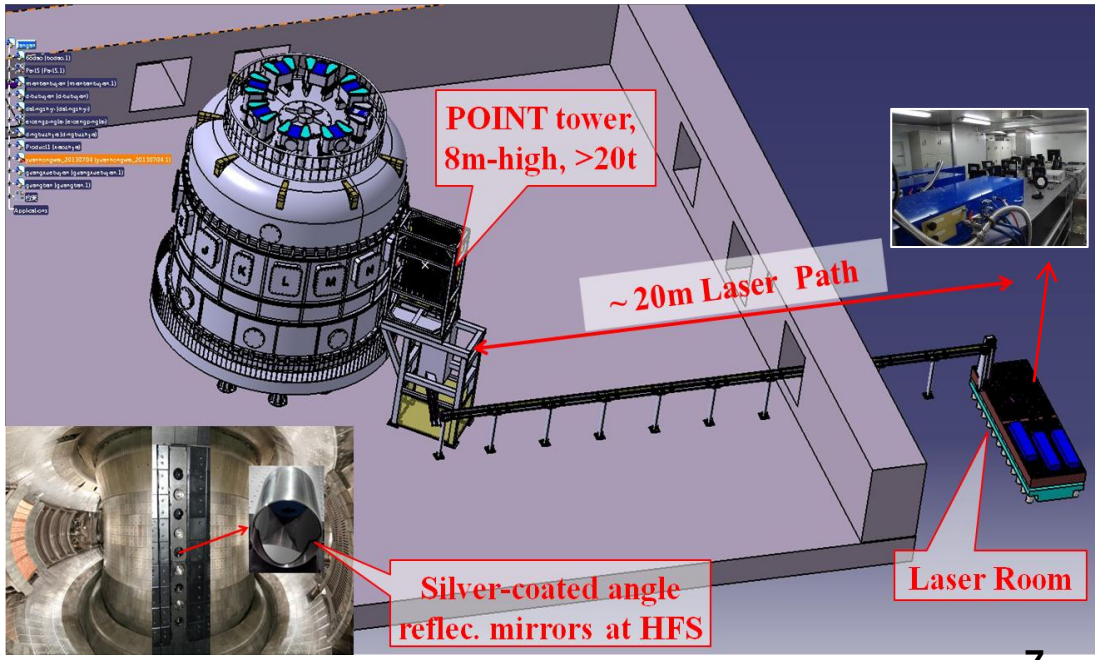
- **Polarimeter/ interferometer (POINT):** n_e, j_ϕ, q, B_p profiles
- **Core & edge TS:** T_e, n_e
- **AXUV & Bolometer:** radiation
- **CXRS & XCS:** T_i, rotation
- **SXPHA & ECE:** T_e
- **Reflectometry:** pedestal n_e
- **He-BES:** edge n_e, T_e
- **Recip.-LPs:** SOL n_e, T_e, flow
- **Filterscope:**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







New RMP coils commissioned successfully

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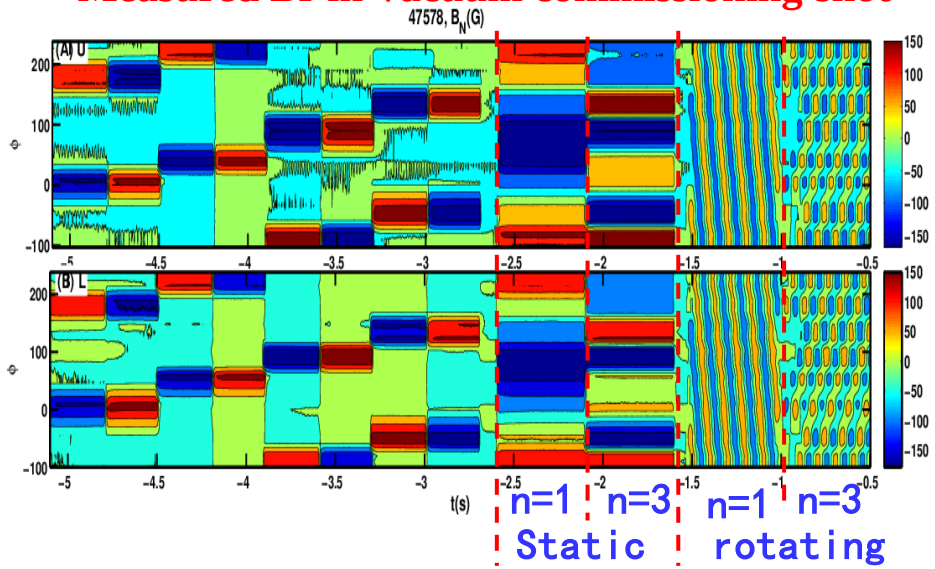
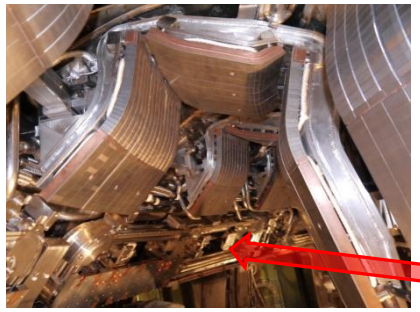
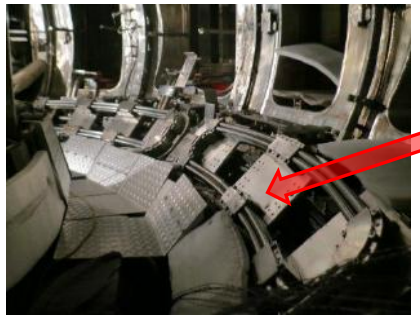
◆**RMP coil set-up: 8** (U) + **8** (L)=16 coils;
n = 1-3 rotating and **n=1-4 non-rotating**.

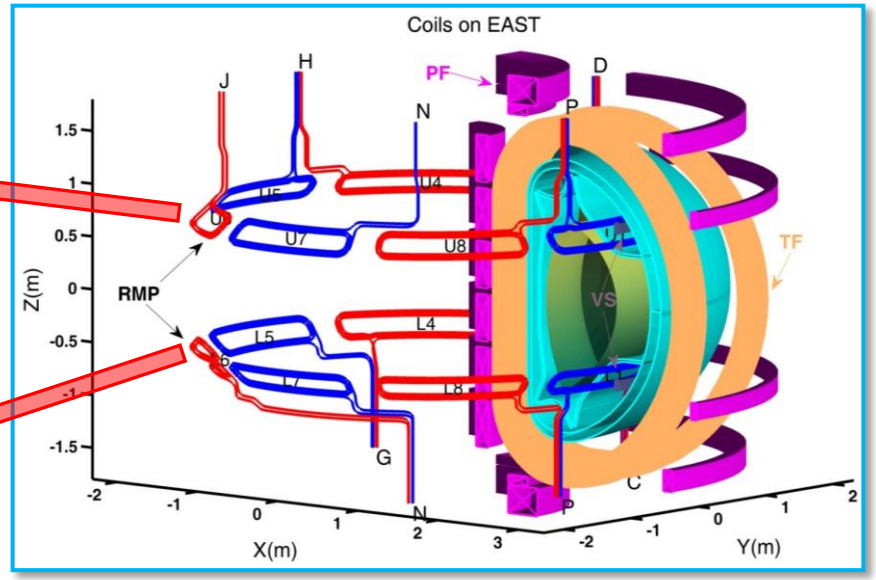
◆**Multi-Functions:**
- ➢Error Field correction (**EFC**)
- ➢Resistive Wall Mode (**RWM control**)
- ➢Edge Localized Mode (**ELM control**)
- ➢**3-D physics** studies

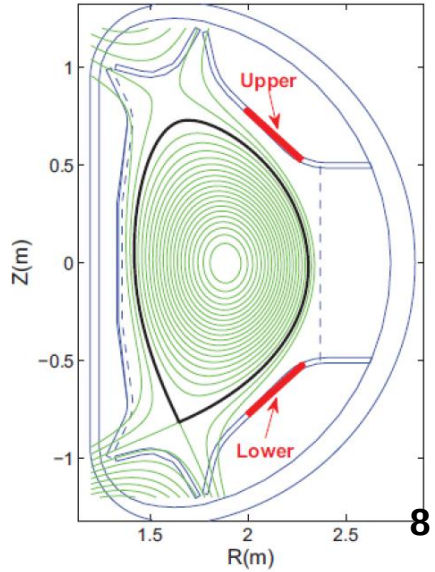
Measured Br in Vacuum commissioning shot











New RMP coils commissioned in ELM mitigation and error field measurements

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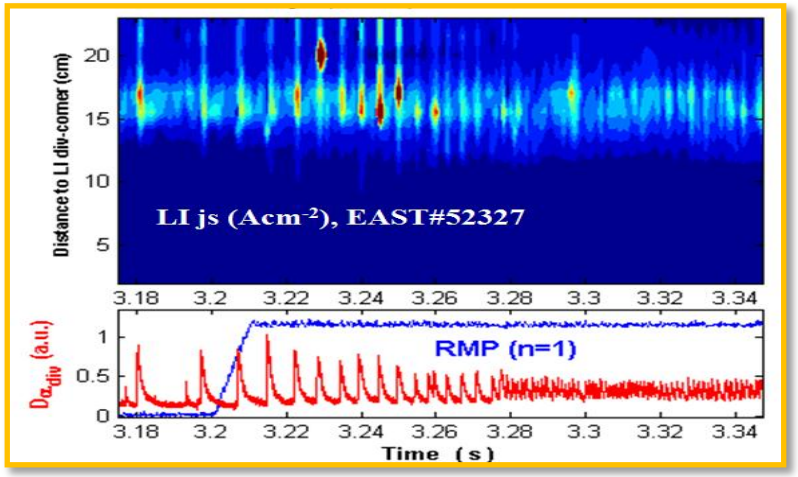

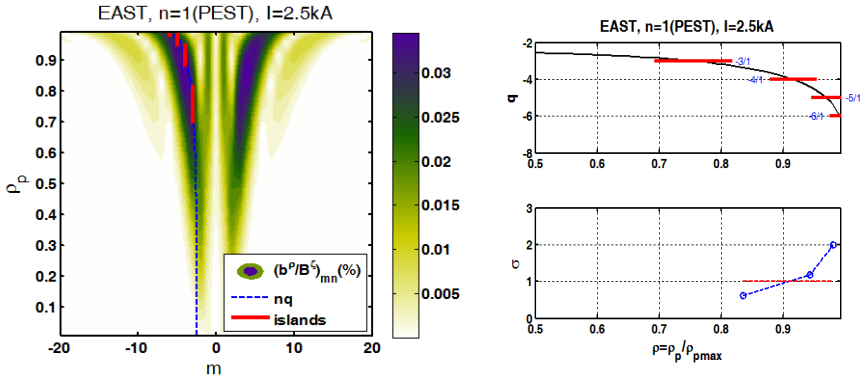

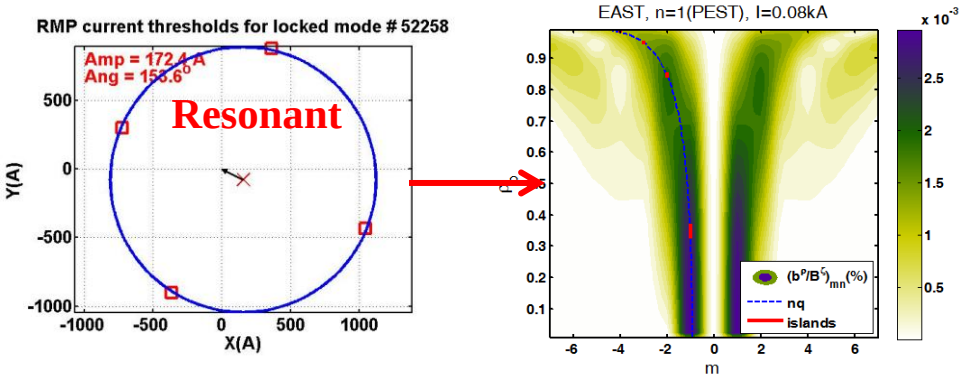

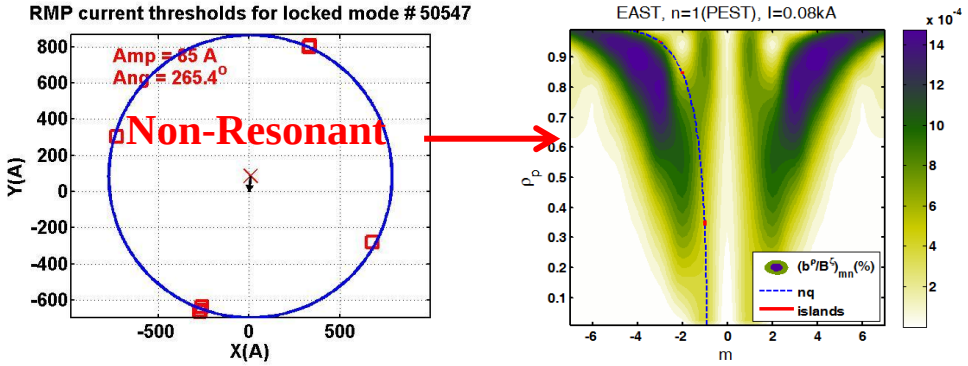

ELM Mitigation:

- ELM mitigation observed with strong n=1 field with good resonance.
- ELM frequency increased by a factor of 5.

Error field measurement:

- Both measured amplitude and phase of the intrinsic error field depends on the RMP configuration used.
- Resonant: $B_{2/1}/B_0$ ~ **4.5e-5**, ϕ ~ **154°**
- Non-Resonant: $B_{2/1}/B_0$ ~ **0.8e-5**, ϕ ~ **265°**

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Edge magnetic topology changed by LHCD, like RMPs

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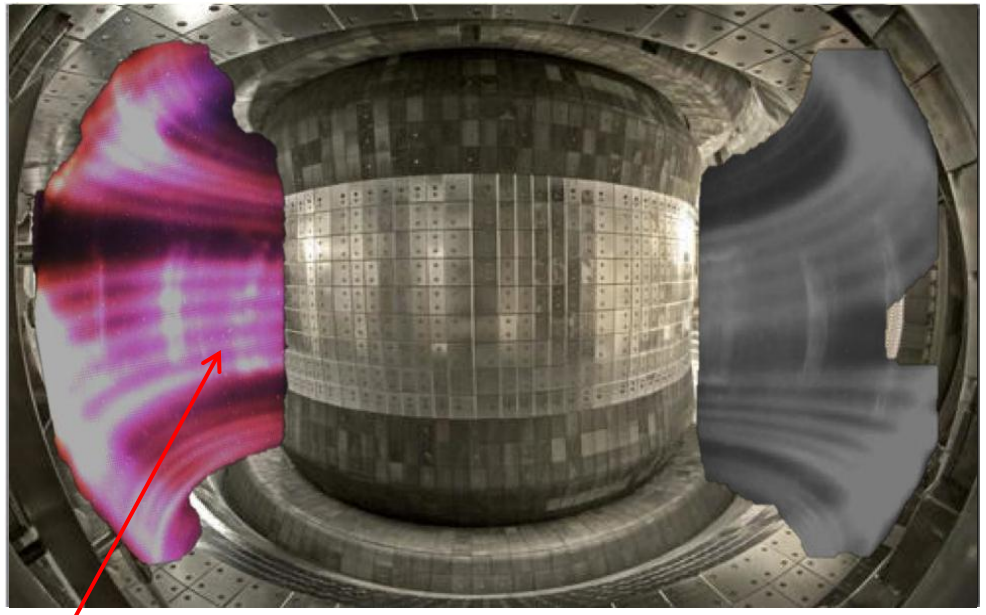
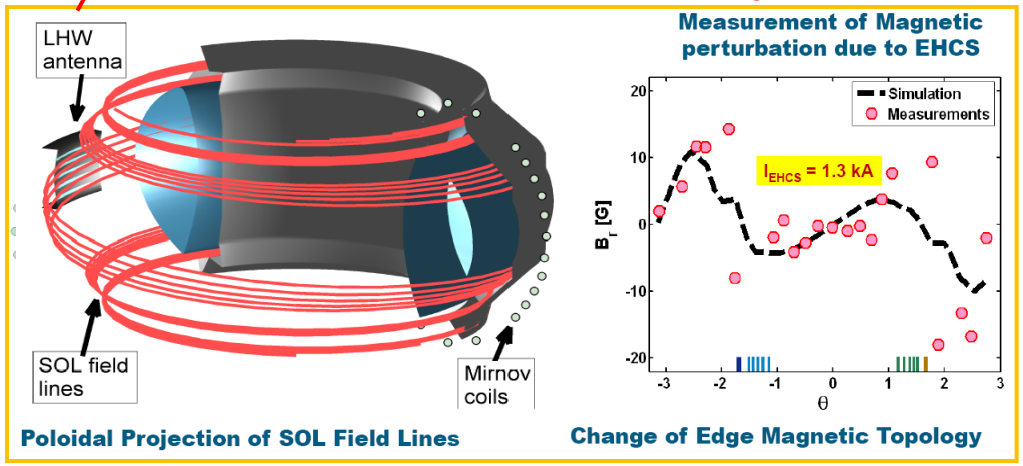
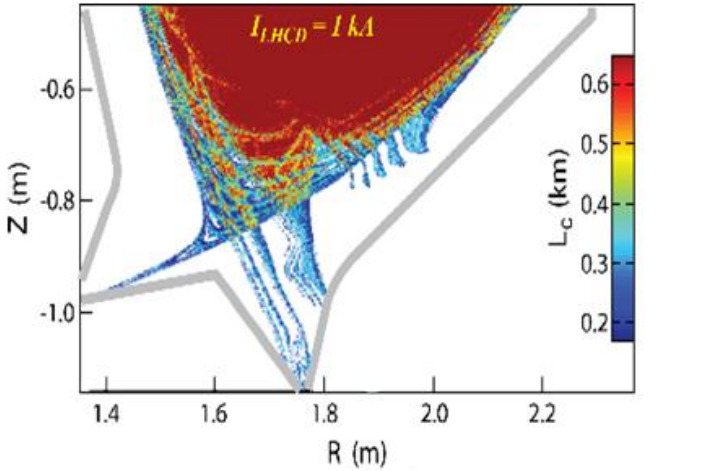
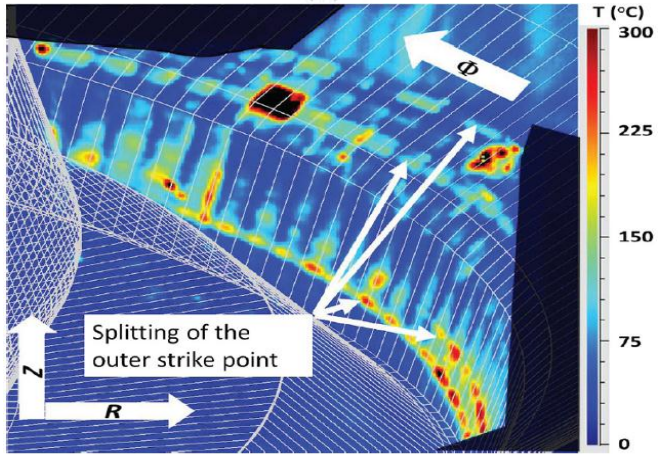


Helical Current Sheets induced by LHCD



➢Splitting of Strike Points





◆Exhibit n=1 helical structure

Y. Liang et al., PRL 110, 235002 (2013)

Flexible boundary control with LHCD

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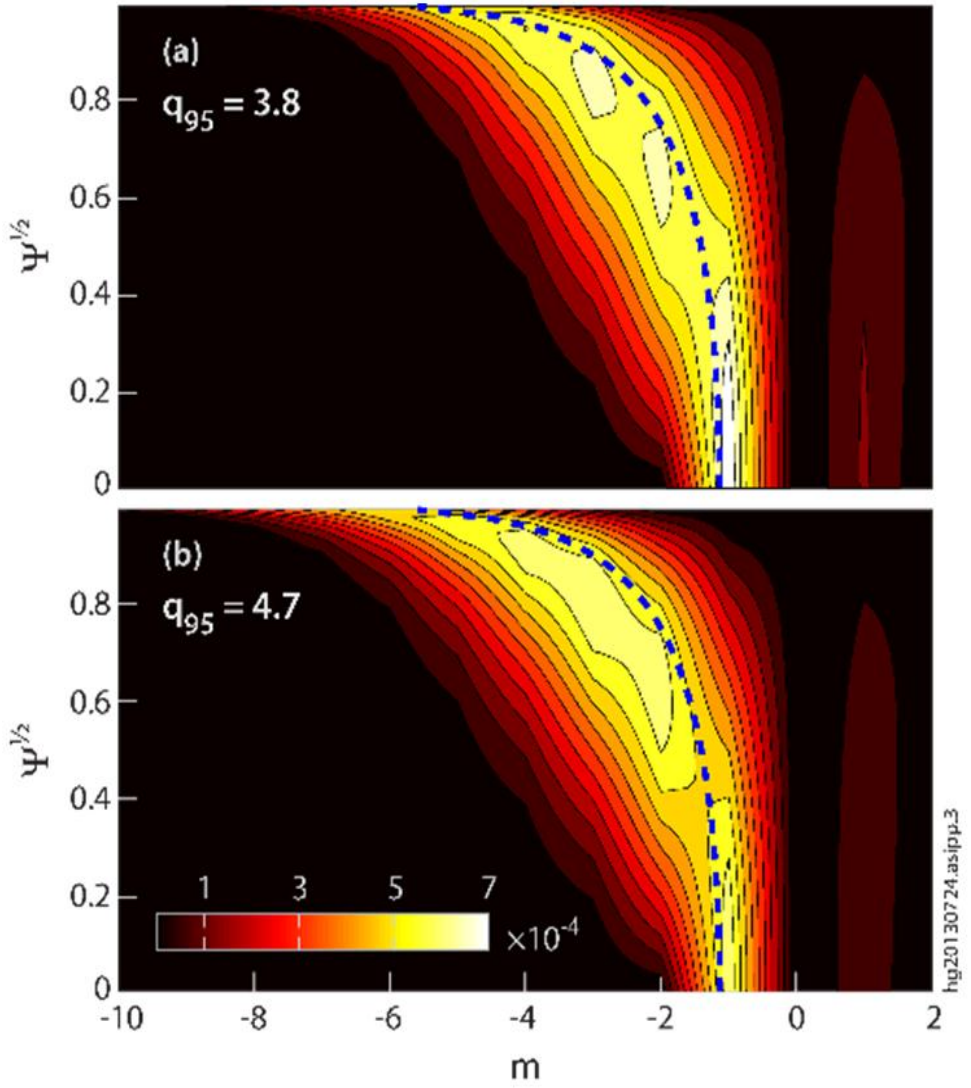

- **LHCD appears to be effective at controlling ELMs over a broad range q_{95}, in contrast to fixed RMP coils.**

- **Magnetic perturbations induced by LHCD are well aligned with the resonant magnetic surfaces at the edge.**
- **Closely matching the pitch of the edge field line for q_{95}.**
- **Highly localized at edge, without significantly affecting plasma core plasma.**

EX/P3-8 Liang Y.; J. Li, H.Y. Guo, B. N. Wan et al., Nature Phys. 9, 817 (2013)

ELM control by SMBI

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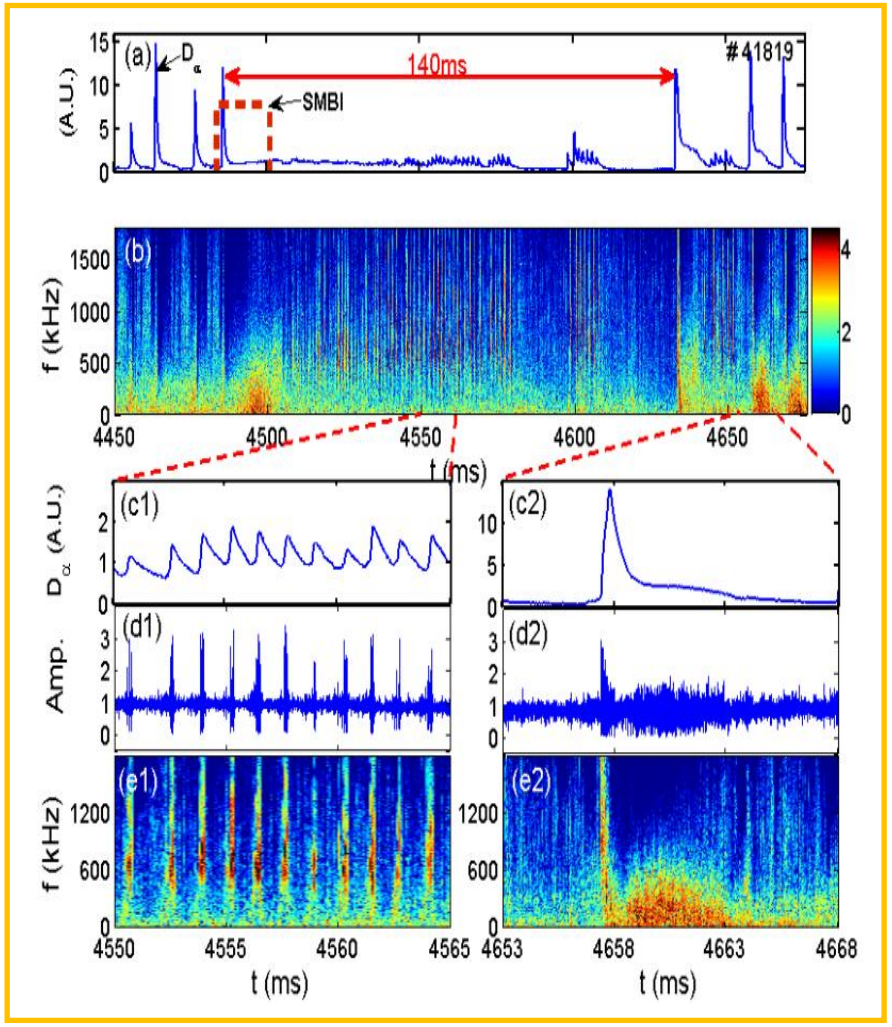
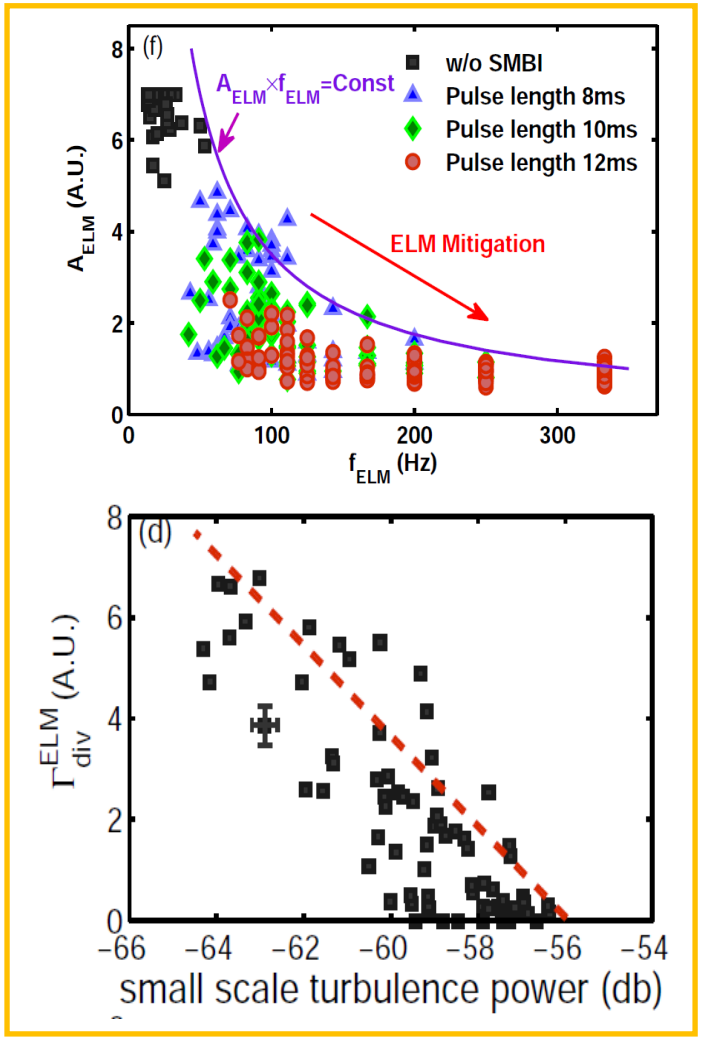
➢ **ELM suppression by intermittent small scale turbulence induced by SMBI**





X. L. Zou et al, submitted to PRL

Active control of divertor power deposition by regulating edge particle fluxes (LHCD+SMBI)

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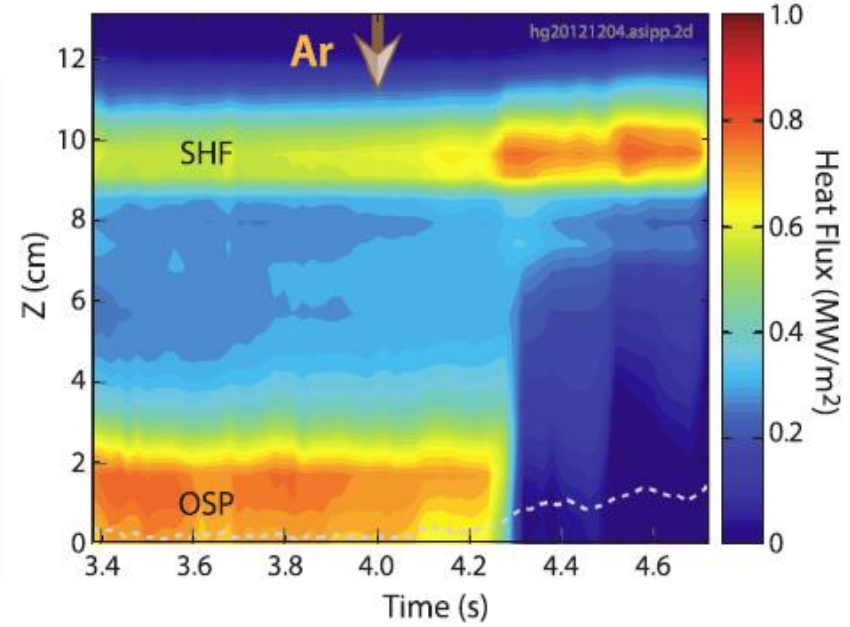
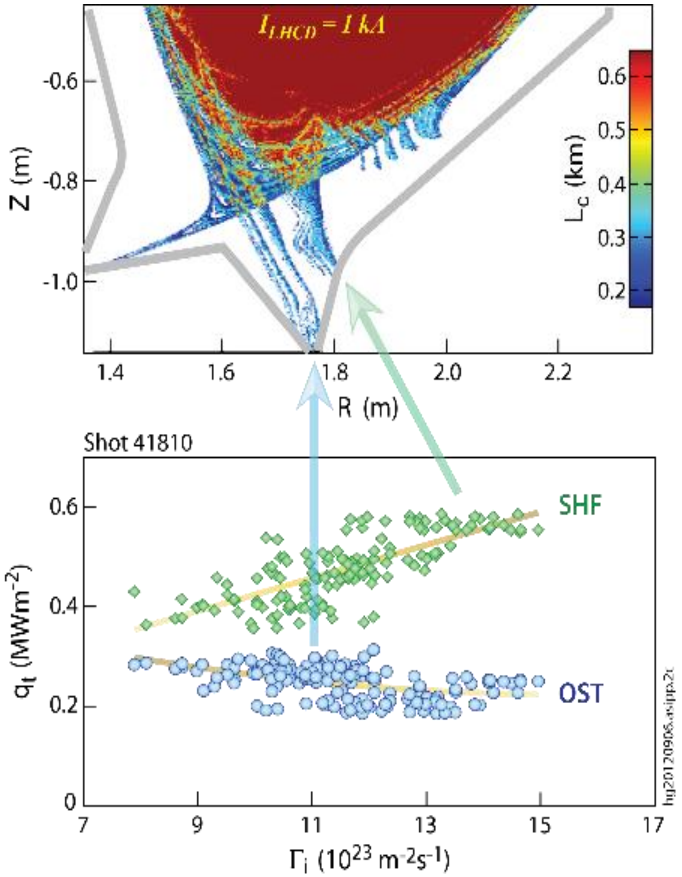
Regulating divertor conditions by

- **SMBI into pedestal**
- **Ar seeding into divertor region**
- **Normal gas puffing to control ne → Γ_i**



H.Y Guo, J. Li, B.N. Wan* et al 2014 PoP



◆ **Allowing active control of the ratio of q_{SHF}/q_{OST}, thus divertor power deposition pattern.**

EX/P3-10 Wang L.; J. Li, H. Y. Guo, B.N. Wan et al., Nature Phys. 9, 817 (2013)

Evidence of particle & heat exhaust by ECM in LHCD H-mode plasma

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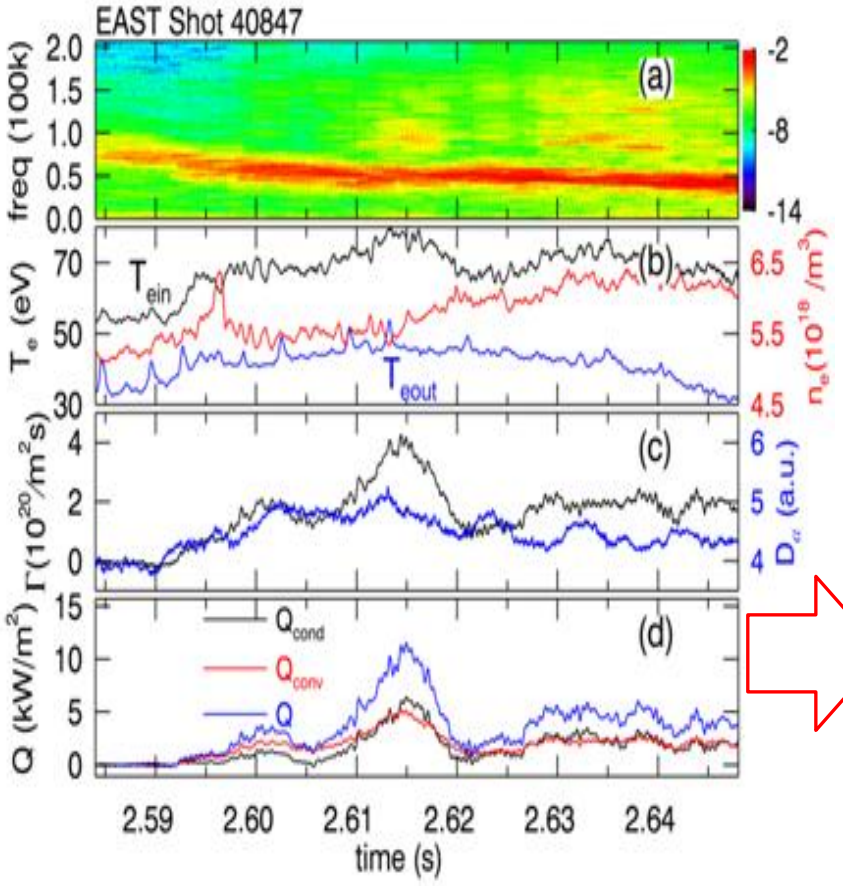
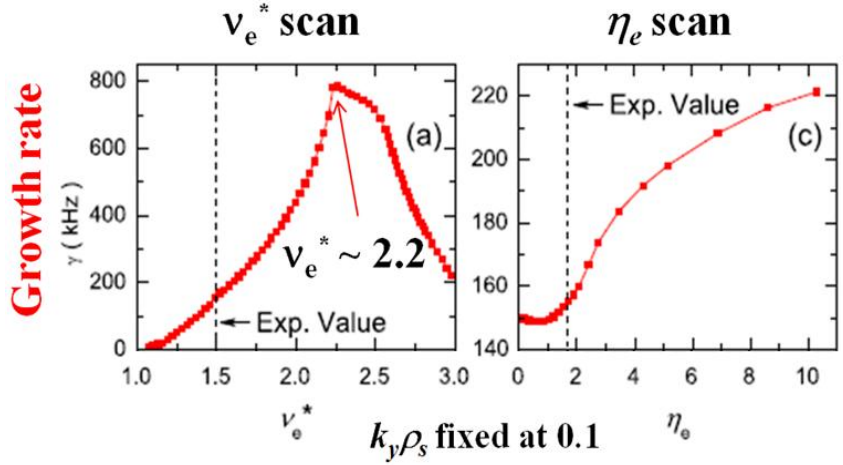
- Edge coherent mode (ECM) facilitates long pulse H-mode operations:
  f = 15-90 kHz ~ ω_{*e}, electron dia-direction, $n \sim 17$, $\lambda_\theta \sim 10$ cm, $m > 50$
- Locates in the steep-gradient pedestal region, with $\nu^*_{e,ped} \sim 0.5\text{-}5$
- q_{95}>3.7, $\bar{n}_e = 1.9\text{-}5\times10^{19}\, m^{-3}$





GYRO simulations show the nature of dissipative trapped electron mode (**DTEM**)

Reciprocating-LP measurements directly show the ECM-driven radial particle and power transport.

EX/9-5 Xu G.

H. Q. Wang et al., PRL 112, 185004 (2014)

Real-time Li aerosol injection → long pulse ELM-free H-mode

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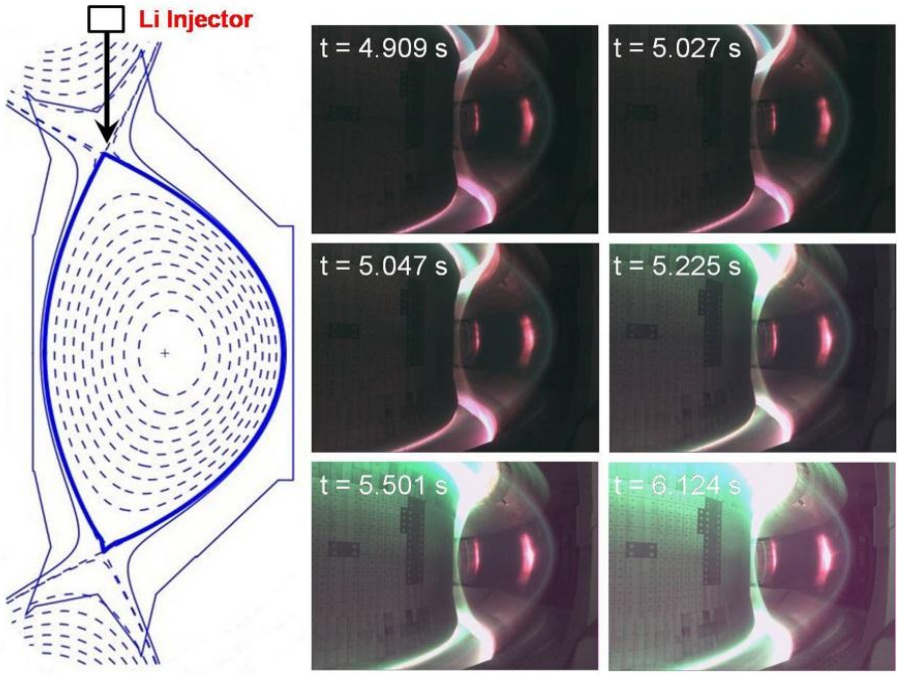

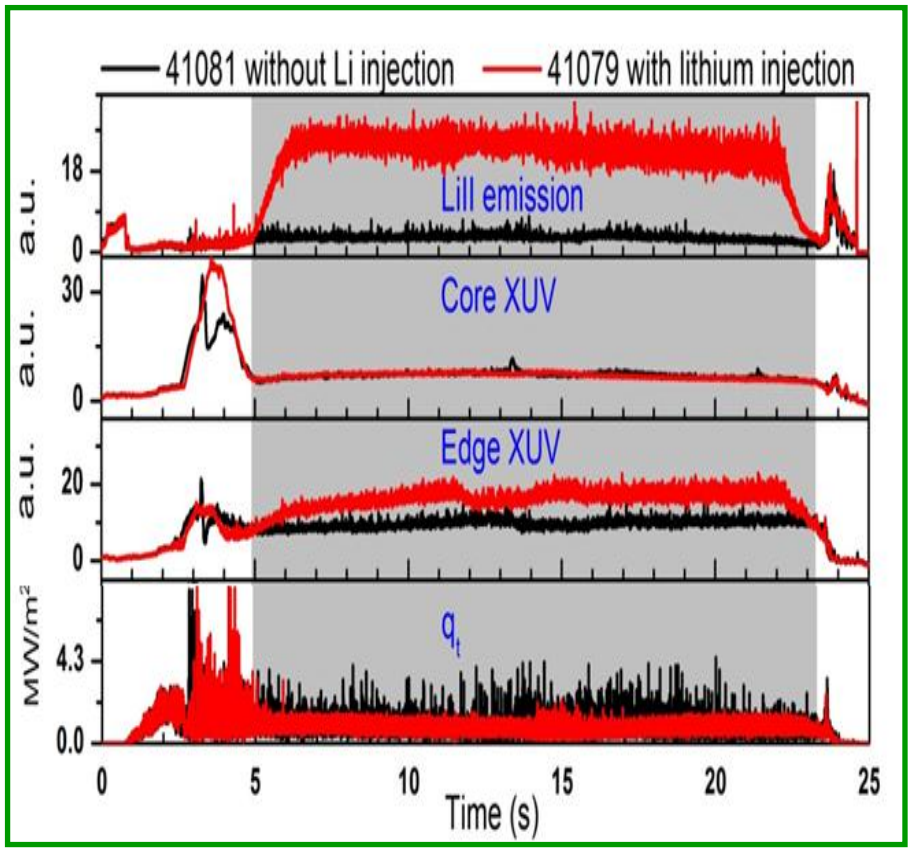

J. S. Hu et al., submitted to PRL

- Real-time Li aerosol injection can effectively suppress ELMs, then reduce heat load on divertor targets;
- Charged Li shield located at edge also provide a radiation heat exhaust;
- This provide a new method to achieve stationary H-mode;
- Li aerosol facilitates edge coherent mode (**ECM**) for particle/power exhaust.

Demonstrated for the 1st time ELM pacing by innovative Li-granule injection

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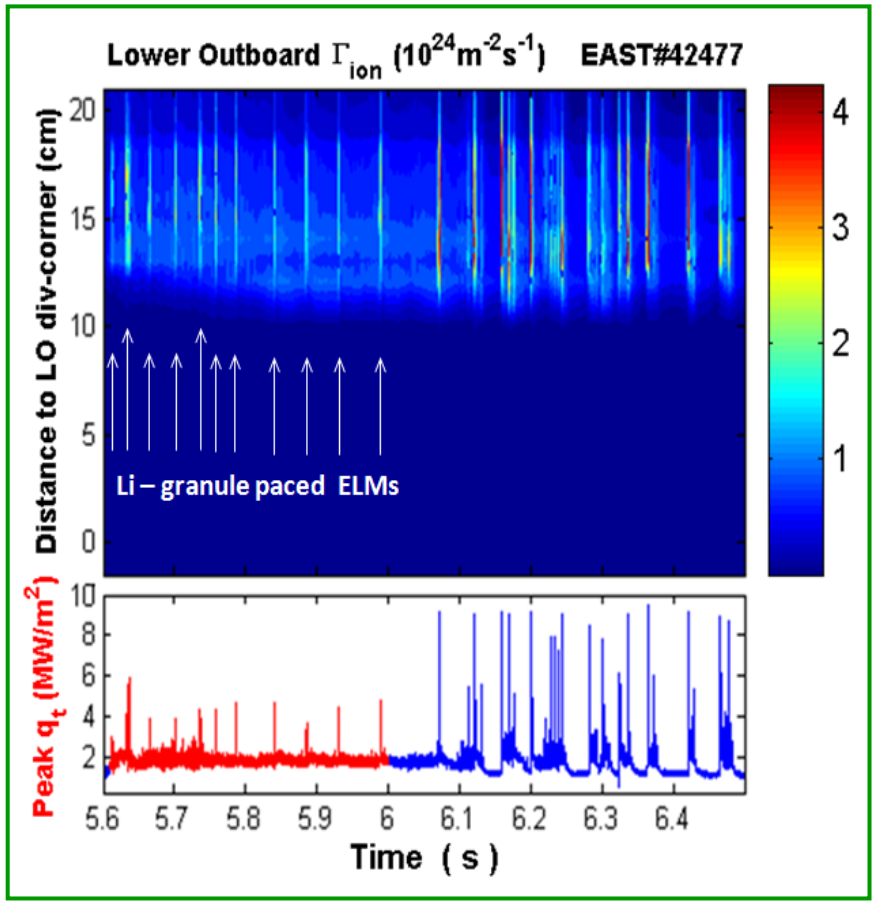
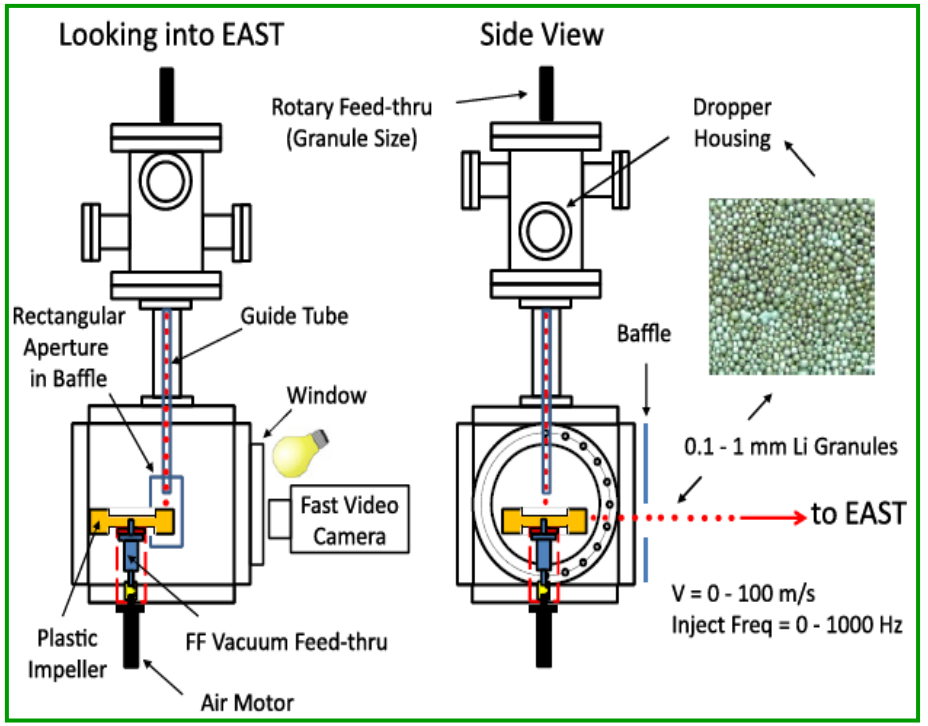


Collaborated with PPPL: D. Mansfield, 2013 NF



EX/P3-10 Wang L.

- **ELM trigger efficiency: ~100%.**
- **Triggering ELMs (~25 Hz) with ϕ0.7 mm Li granules @ ~45 m/s.**
- **Much lower divertor particle/heat loads than intrinsic type-I ELMs.**

Integration for long pulse H-mode operations (2.45GHz-LHCD & Li-coating)

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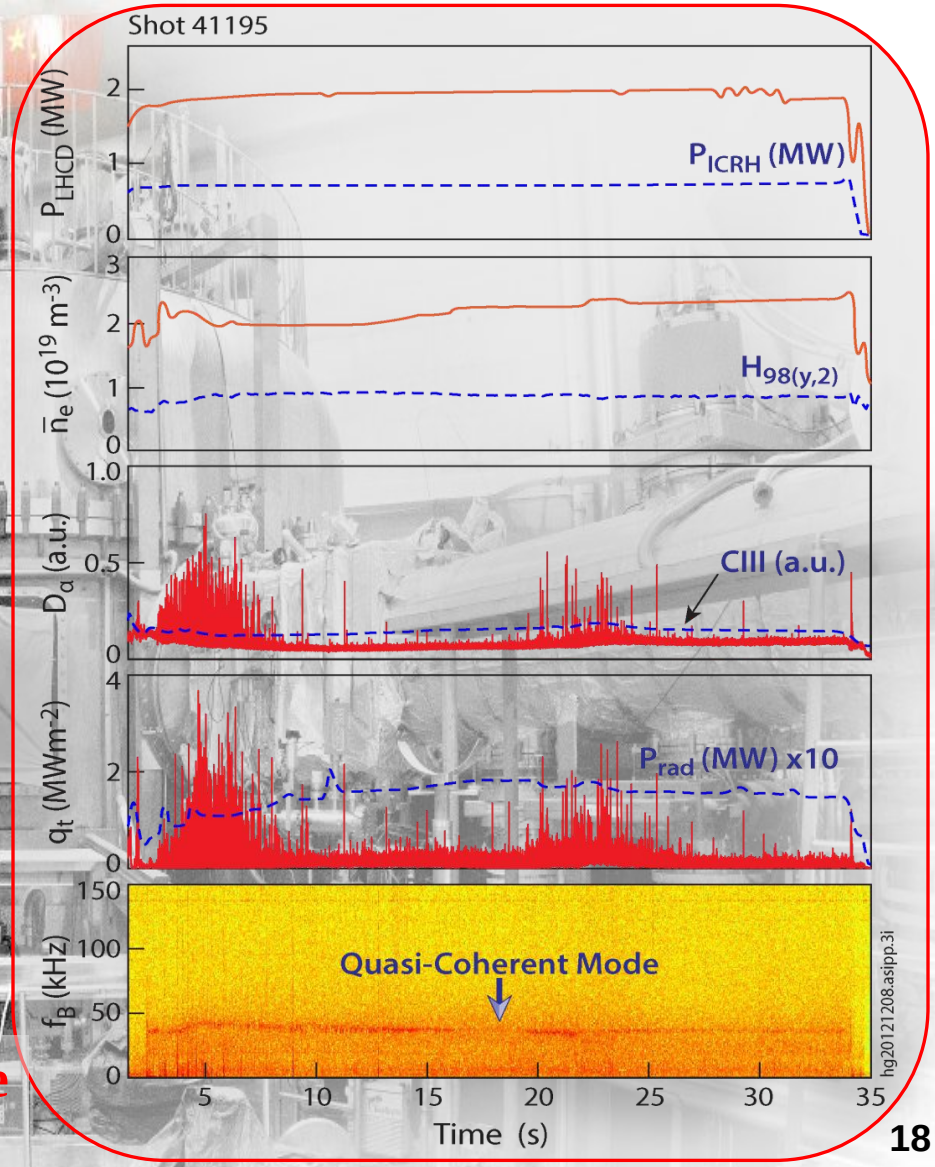
- Predominantly small ELMs with H_{98} ~ 0.9, between type-I and -III ELMy H-modes, DN.
- Target heat flux is largely below 2 MW/m^2, with T_{target} < 250 ^{o}C.
- Accompanied by an ECM, continuously removing heat & particles.



J. Li, H.Y. Guo, B.N. Wan et al., Nature Phys. 9, 817 (2013)

Long pulse H-mode operation with Newly installed 4.6GHz-LHCD& Li-coating

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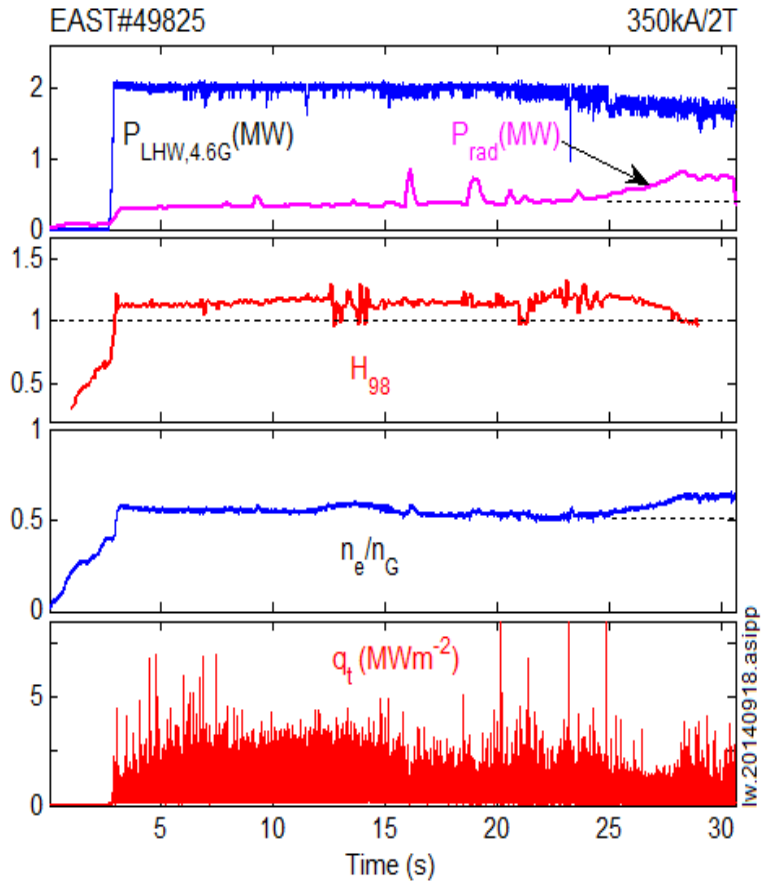
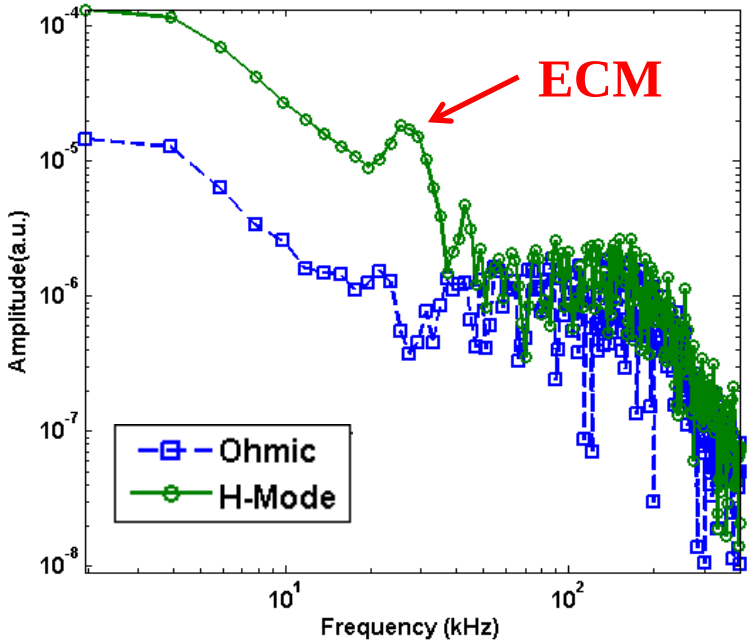
➢**Long-pulse H-mode up to 28 s with H_{98} ~1.2**



Small ELMs with better confinement than the record 32 s H-mode.



- **LHCD & Li**
- High δ ~ 0.6, q_{95} ~ 6.5, n_e/n_G ~ 0.55
- Presence of an **ECM ~ 30kHz**
- Peak heat flux: **< 3MW/m^2 largely**
- Disrupted due to the raise of radia. power and n_e

Newly installed Co-Ip NBI system commissioned successfully → H-mode with NBI alone or modulation

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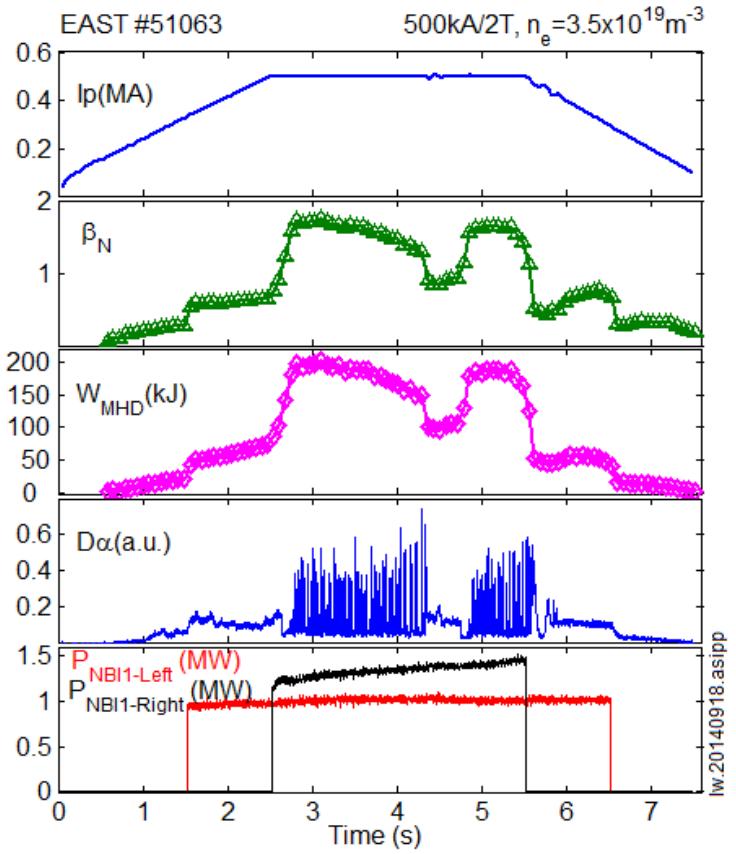
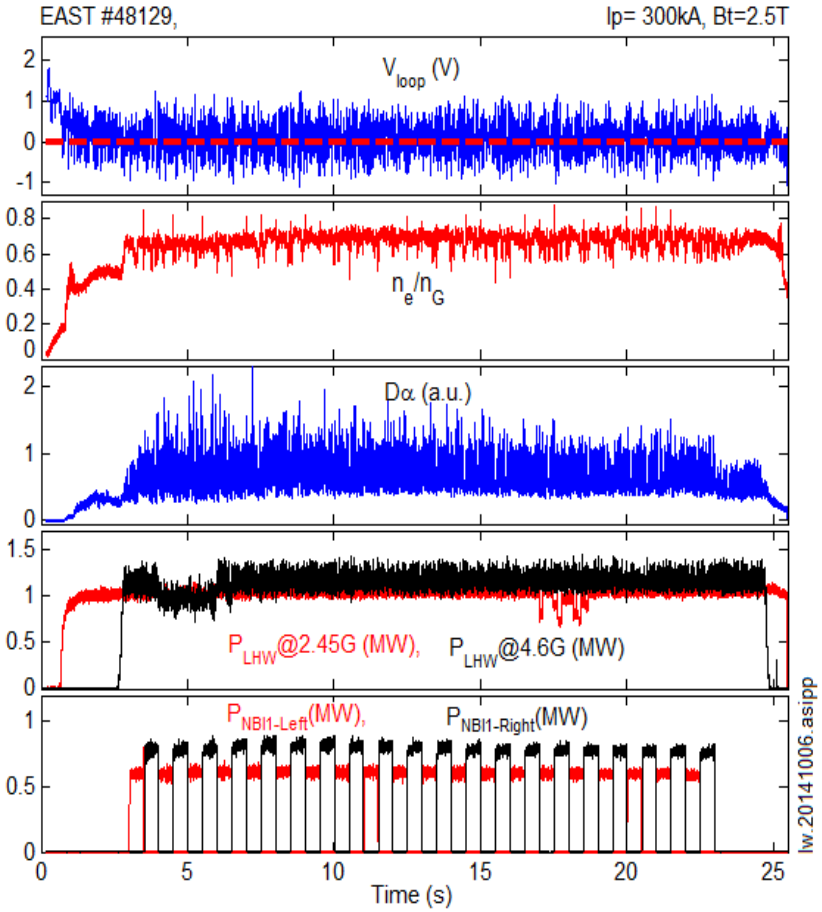


A H-mode plasma heated by NBI alone in EAST with P_{NBI} ~ 2.3 MW, β_N = **1.8** and W_{MHD} ~ 200kJ.



Nearly fully non-inductive long pulse H-mode by LHCD+NBI modulation with small ELMs, P_{NBI}=1.2 MW, $P_{LHW,2.45G}$=1MW, $P_{LHW,\ 4.6G}$=1.2MW, n_e/n_G ~0.7, V_{loop}<0.1V.

EX/P3-12 Xu Y.; EX/P3-5 Lu B.

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Summary & Future Plans

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- **Most of the upgraded EAST systems have been successfully commissioned.**
- **Significant advances have been made in H-mode physics, especially at ELM control and divertor heat flux handling.**
- **The new EAST capabilities will provide possibilities to address some of key issues for long pulse high performance operations.**

✓**Sufficient H&CD allow long pulse operation with ITER-like scheme:**

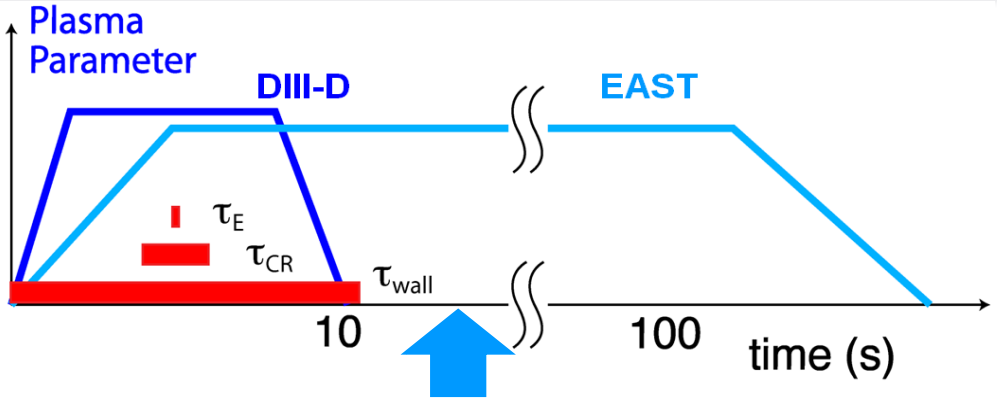
low torque, off-axis, dominated Te heating, low Ip ramping rate

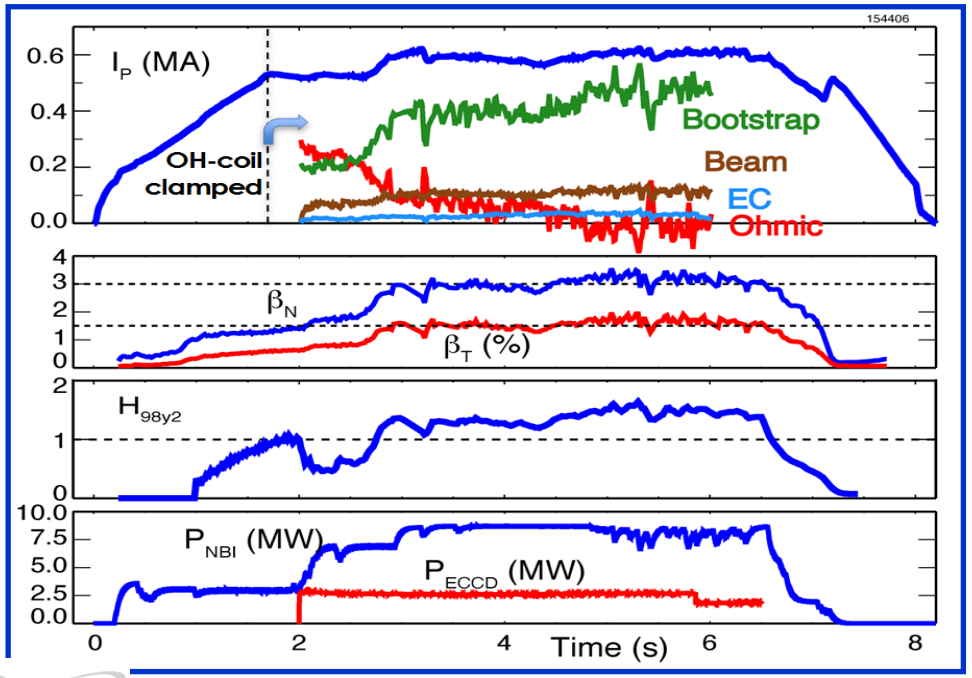
✓**Multi-tools allow flexible heat flux control:**

➢**Transient (ELMs): LHCD, SMBI, Li-aerosol, Li/D_2 granule, RMP, …**

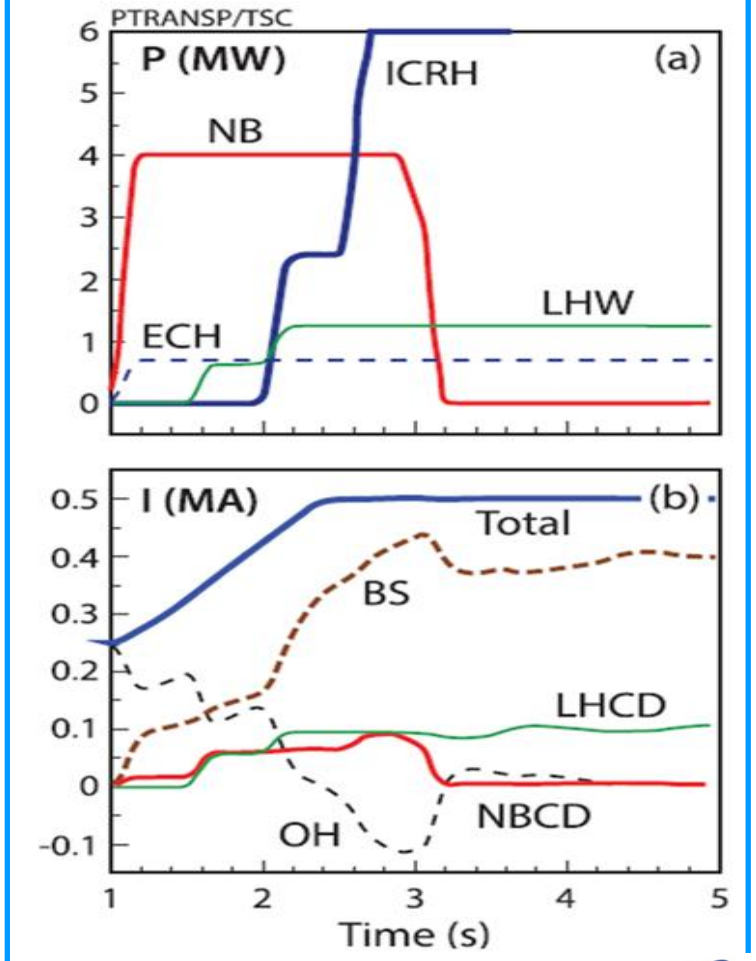
➢**Stationary: rad.-divertor/SMBI + edge topology change (LHCD/RMP)**

Joint DIII-D/EAST Experiment Developed Fully Non-inductive Scenarios for Steady-State H-mode Operations on EAST





Prediction for EAST



PPC/P2-31 Garofalo A.; EX/P2-39 Gong X.

List of EAST contributions

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- **EX/P2-39 X. Gong: Development of Fully Non-inductive Scenario at High Bootstrap Current Fraction for Steady State Tokamak Operation on DIII-D and EAST**
- **EX/9-5 G. Xu: A Long-Pulse H-Mode Regime with a New Coherent Mode Providing Continuous Transport across Pedestal in EAST**
- **EX/P3-3 X. Zhang: High Power ICRF Systems and Heating Experiments in EAST**
- **EX/P3-4 G. Calabro: EAST Snowflake Experiment: Scenario Development and Edge Simulations**
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- **EX/P3-6 L. Xiang: Investigation of Argon Seeding in Different Divertor Configurations in EAST and Corresponding SOLPS 5.0 Modeling**
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- **EX/P3-9 X. Gao: Study of Pedestal Turbulence on EAST Tokamak**
- **EX/P3-10 L. Wang: Progress in Active Control of Divertor Power Load in the EAST Tokamak**
- **EX/P3-11 B. Ding: Investigation of LHW-Plasma Coupling and CD Related to H-Mode Experiments in EAST**
- **EX/P3-12 Y. Xu: The Latest Development of EAST Neutral Beam Injector**
- **FIP/P4-2 L. Hu: Progress on the ITER Diagnostic-Radial X-Ray Camera**
- **TH/P2-1 C. Pan: The Combining Effect of the Inductive Electric Field and the Lower HybridWaves on the Impurity Ions Toroidal Rotation in the Lower Hybrid Current Drive Tokamak Plasmas**
- **TH/P2-45 T. Xia: Fluid Simulation of Particle and Heat Fluxes during Burst of ELMs on EAST and DIII-D**
- **TH/P3-13 X. Gong: Theoretical Analysis of ICRH Antenna's Impedance Matching for ELMy Plasmas on EAST**
- **EX/P6-54 G. Xu: The Role of Lithium Conditioning in Achieving High Performance Long Pulse H-Mode in the NSTX and EAST Devices**
- **MPT/P8-14 G. Luo: Overview on Design and Development of EAST Tungsten/Copper Divertor and Tungsten-Related Plasma-Wall Interaction Experiments**

Thank you!

EAST – Test Bed for ITER & CFETR