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ASIPP

Advances in the long-pulse steady-state high beta H-mode scenario with active controls of divertor heat and particle fluxes on EAST

by
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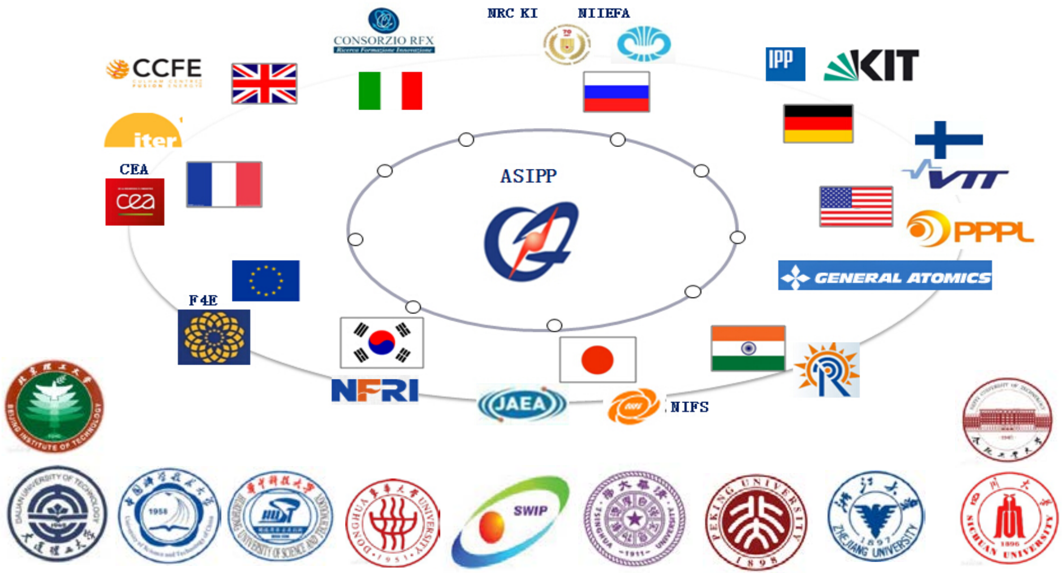
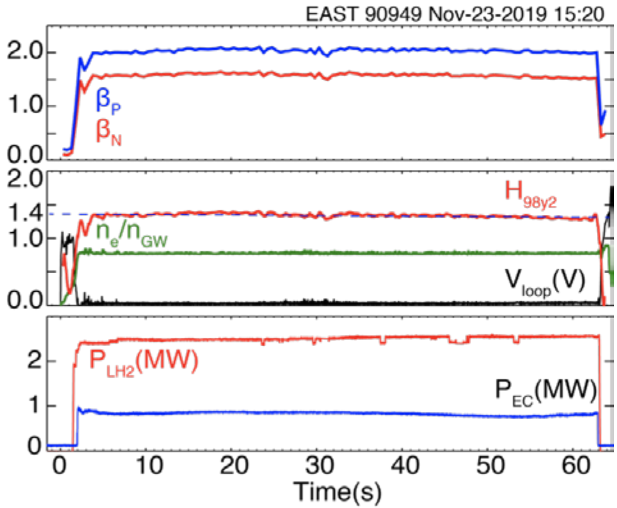
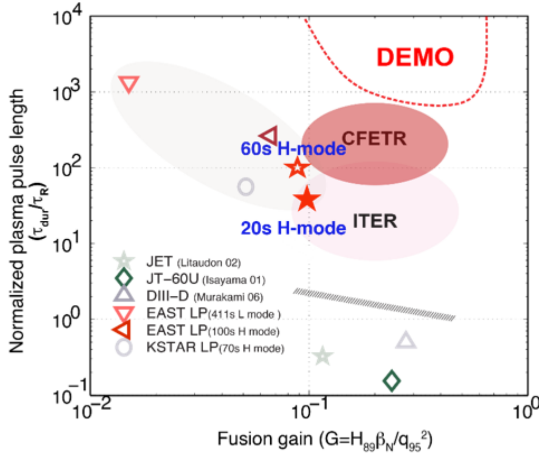
We acknowledge contributions from domestic and international partners to EAST research program



EAST demonstrated high β_P long pulse H-mode operation with high f_{bs}





- **A 60s time scale long-pulse steady-state high β_P H-mode discharge achieved by pure RF heating with the ITER-like tungsten divertor.**

Overview of the parameter space of obtained and prospective long pulse high β_p H-mode plasmas

Outline

- **Extension of steady-state operational regime**
- **Physics studies to resolve key issues for steady state operation**
- **Progress in supporting of ITER**
- **Summary and future Plan**

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- **Extension of steady-state operational regime**
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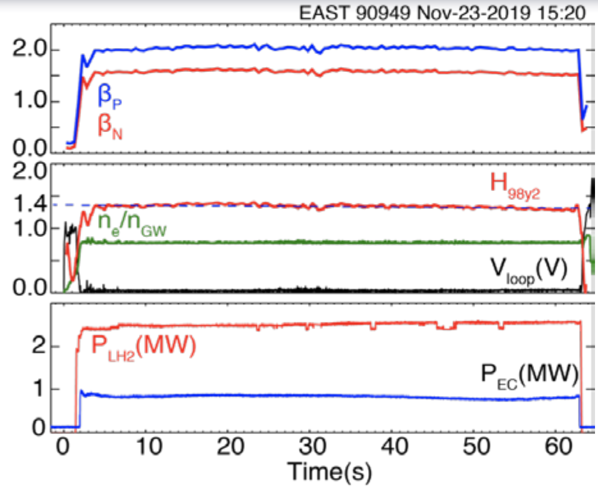
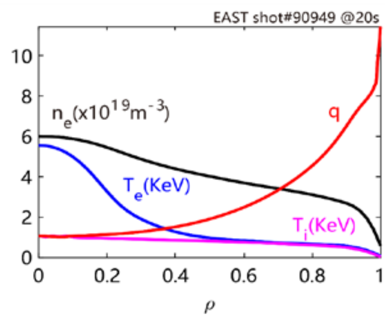
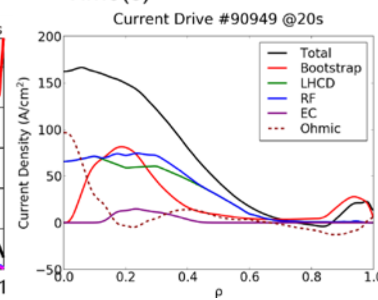
A 60s scale steady-state discharge was achieved

- **Dominant electron heating by ECH &LHW**
  - β_p~2.1, β_N~1.7,H_{98}>1.3
  - eITB (T_e>T_i), zero torque, low rotation
  - Flat q profile with q(0)>1.0, f_{bs}~f_{LHCD}

- **Good control of impurity**
  - Small ELMy, on-axis ECH



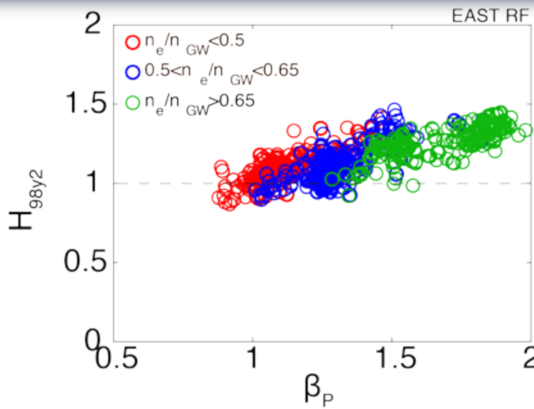




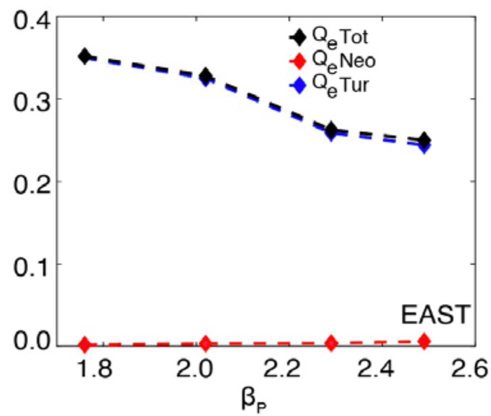
Gong - EX/1-TH/1

Experiments show improved confinement and reduced turbulence when extending to higher β_p

- **The higher β_p with high energy confinement at high density.**



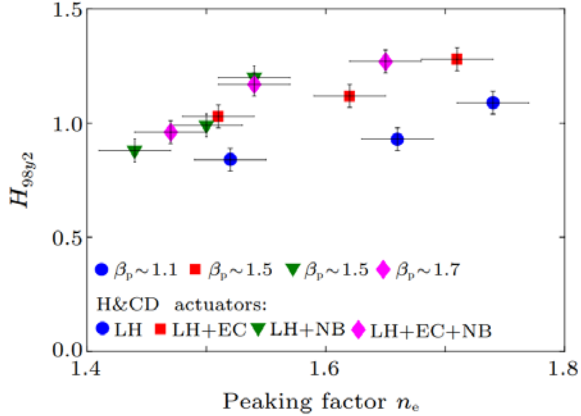
- **The electron turbulent energy fluxes decrease with β_p increase.**
  - The transport dominated by the trapped electron mode (TEM) due to the electron heating by RF power (Te >>Ti).



Gong - EX/1-TH/1

Density gradient is a control knob to improve energy confinement

- **A clear dependence of H_{98y2} on the density peaking factor was observed.**
  - High density gradient can enhance the Shafranov shift stabilizing effect significantly in high β_p regime.



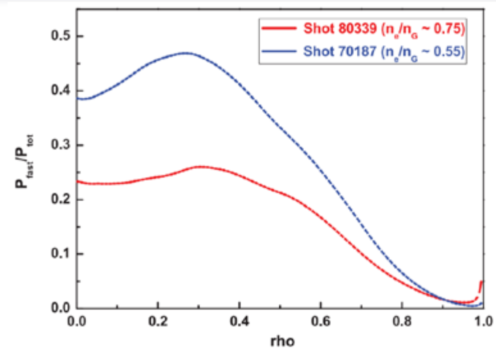
The same trends in various Heating/CD mixtures

---A new pass for Steady-State Tokamak Fusion Reactor

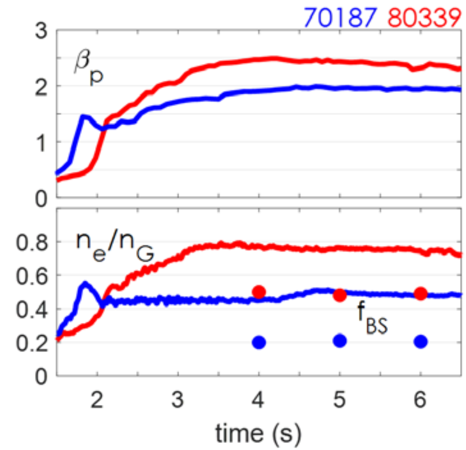
Wan, CPL 37 (2020) 045202

Optimization of fast ion confinement

- **Fast-ion pressure decreased at high-density/low beam.**
  - Increase density from 4.4×10^{19} m^{-3} to 5×10^{19} m^{-3} and decrease the beam voltage from 60 to 50 kV

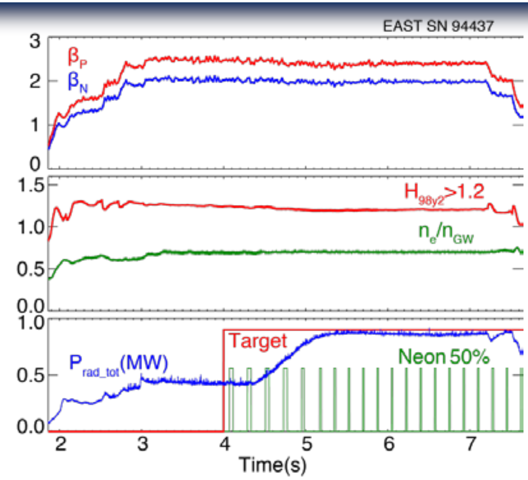


- **Improved plasma performance (β_P~2.5 and H_{98y2}>1.1) with reduced fast-ion loss**
  - A bootstrap current fraction (f_{BS}) up to 50% with balanced NB injection.



Huang, NF 60 (2020) 016002

Demonstration of a compatible core and edge integration in high β_p scenarios



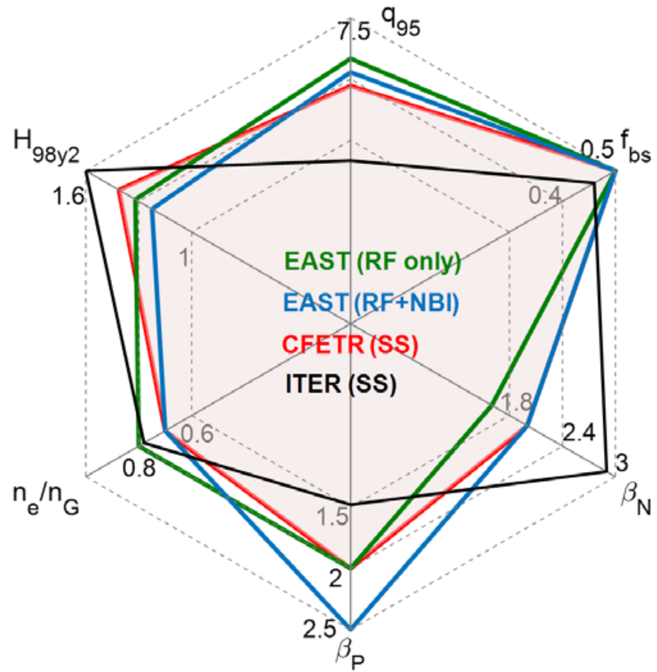
- **A compatible core and edge integration in high β_p scenarios**
  - high confinement H_{98y2} >1.2
  - β_P~2.5/β_N~2.0, f_{bs}~50%
  - n_e/n_{GW}~0.7, q_{95}~6.7
- **The peak heat flux is reduced by ~30% on the tungsten divertor**
  - Active impurity seeding through radiative divertor feedback control via radiated power.
  - A mixture of 50% neon and 50% D_2 is applied.

Gong - EX/1-TH/1

Long-pulse Fully Non Inductive with RF only Close to 1GW CFETR Performance Achieved

- **Improved confinement (H_{98y2}~1.3)**
- **~zero torque with eITB**
- **Electron heating dominant**
- **Small ELMs (f_{ELM}~1kHz)**
- **Good impurity control**

Close to 1GW CFETR Performance



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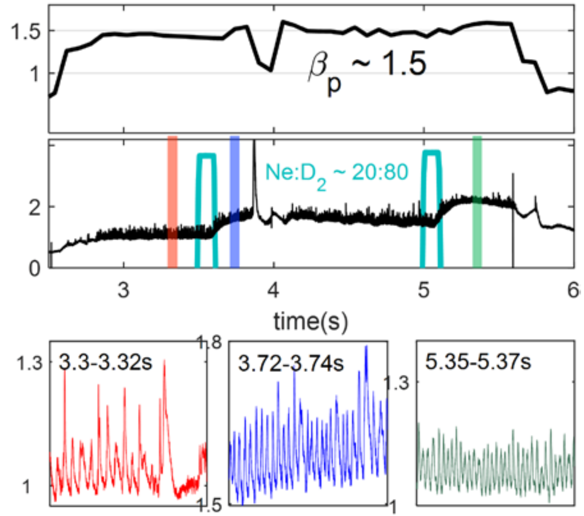
Divertor impurity seeding extends the grassy-ELM regime to lower q95

- **Stationary grassy ELM regime**
  - Low heat flux
  - Strong particle exhaust capability
- **Divertor impurity seeding leads to a transition from mixed ELMs to grassy ELMs**
  - 20% Neon injected near the outer strike point of the upper divertor.



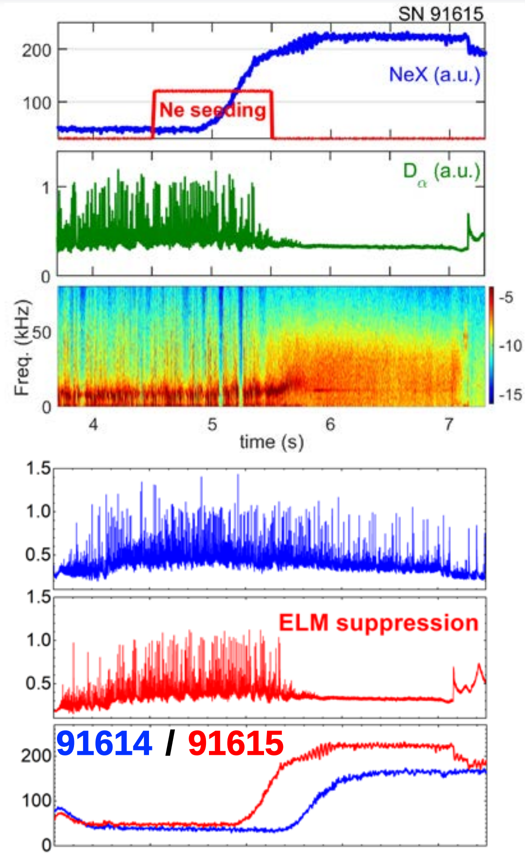
Extension of the grassy-ELM regime to lower q95→5

Li, PPCF 62 (2020) 095025

ELM suppression by Neon seeding

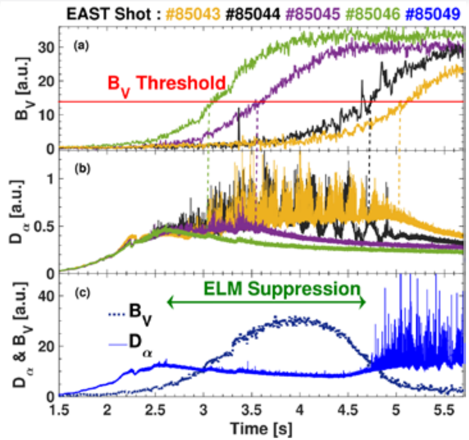
- **ELM suppression achieved with neon seeding.**
  - Edge Coherent Mode (ECM) disappears and replaced by a **Broad-Band fluctuation** in the pedestal gradient region.

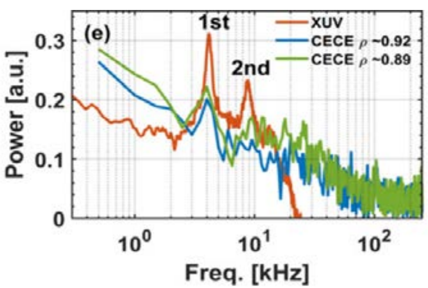
- **Existence of a threshold of neon seeding observed for ELM suppression.**



ELM suppression by boron injection

- **Suppression of edge localized modes with real-time boron injection using the tungsten divertor is obtained.**



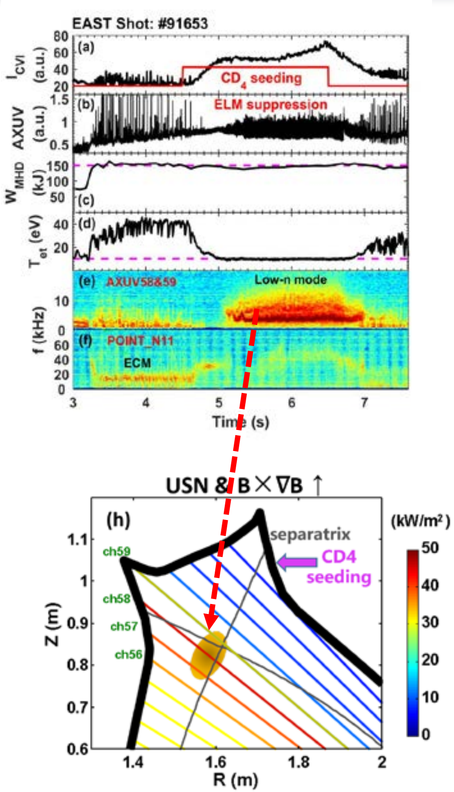


- **Edge harmonic oscillations appear during B powder injection.**
  - Sufficient particle transport to maintain constant density and avoid impurity accumulation in ELM-stable plasmas.

Diallo – EX/4-6
Sun, NF 61 (2021) 014002

ELM suppression by divertor CD4 seeding

- **With divertor CD4 seeding, sustained ELM suppression and divertor detachment achieved**
  - An n=1 low-frequency mode (<10kHz) near the upper X point.

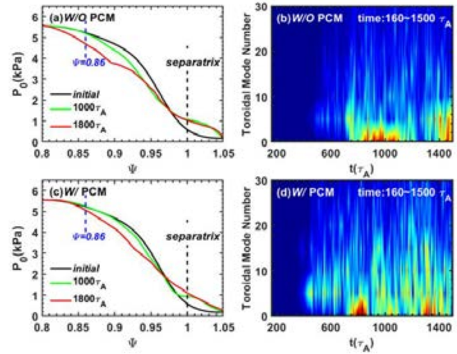


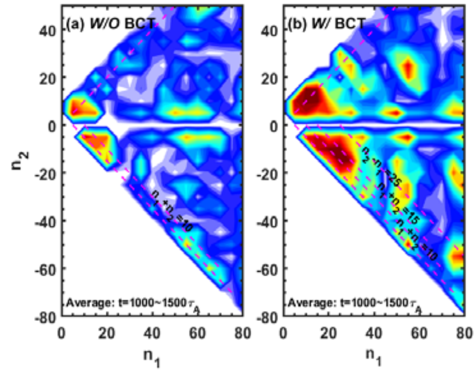
- **Tungsten impurity concentration is significantly reduced when the mode appears, suggesting that the low-frequency mode enhances the impurity exhaust.**

Xu -EX/P2-872

Simulation suggests ELMs can be mitigated by pedestal coherent mode

- **The pedestal coherent modes (PCM) is always accompanied with the ELM mitigation and suppression on EAST.**
- **Simulation by BOUT++ shows pedestal coherent mode (PCM) decreases the ELM size by ~45%.**
  - ELM mitigation by PCM is related with the three-wave nonlinear interactions
- **PCM leads to the wider mode spectrum →stronger mode coupling →lower energy loss of ELMs**

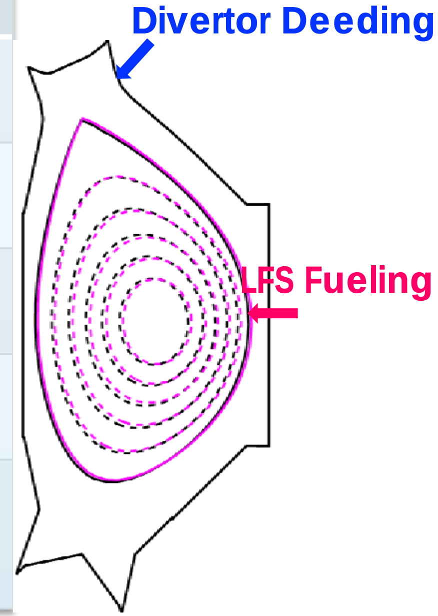




Xia -TH/2-3

EAST successfully develop active detachment controllers

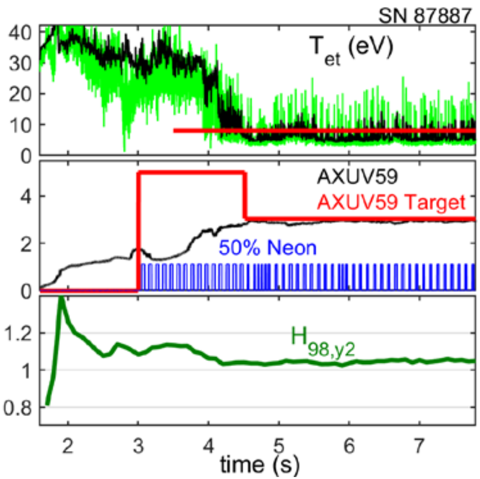
Control parameters	Actuator
Total radiation ($P_{rad, total}$)	LFS and divertor neon seeding
Divertor particle flux (j_{sat})	Divertor neon seeding LFS D2 fueling by SMBI
Div. electron temperature (T_{et})	Divertor neon/argon seeding
Div. target temperature ($T_{t, peak}$)	Divertor neon seeding
Div. electron temperature + X-point radiation (T_{et} + $P_{rad, X\text{-}point}$)	Divertor neon seeding

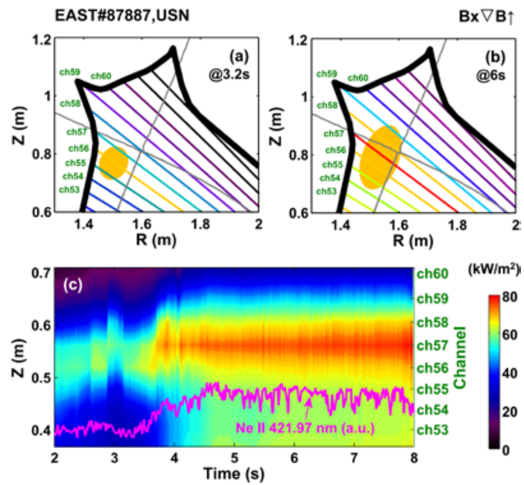


Wang -EX/7-1

Feedback detachment control via $T_{e,div}$ + P_{rad} in grassy ELM H-mode

- **A new detachment feedback control scheme, combining divertor radiation near the X point and target plate Te signals, is demonstrated.**
  - Divertor target T_{et} near strike point maintained at 5-8 eV.

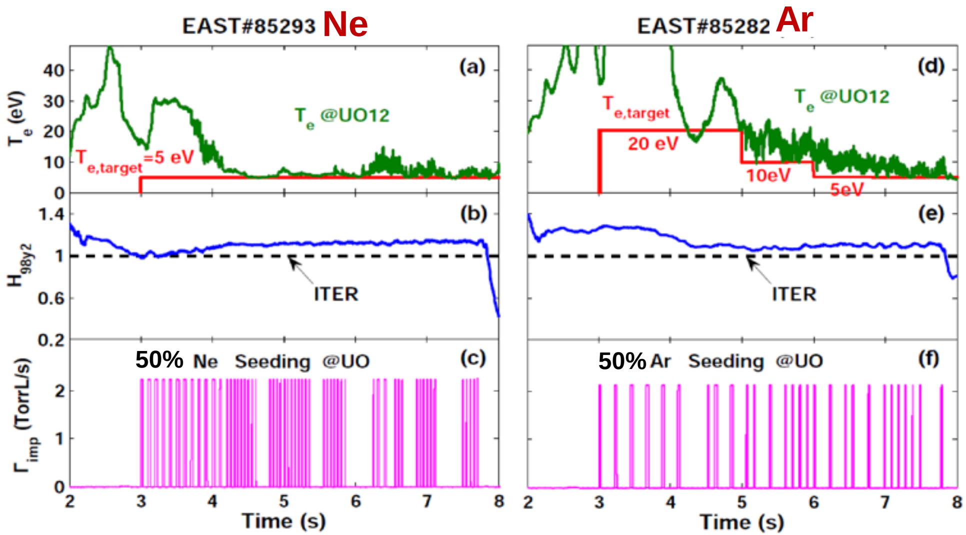




Xu, NF 60 (2020) 086001

Feedback control of H-mode detachment via Divertor-Te

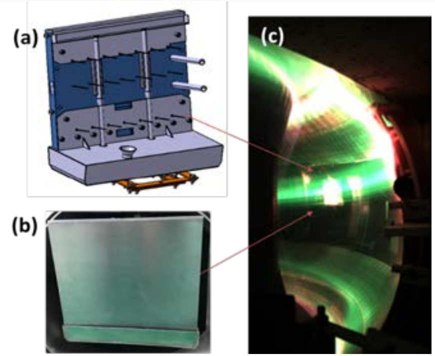
- $T_{e,div}$ control is important for sputtering reduction
- Neon is more compatible with core plasma for $T_{e,div}$ = 5eV.
  - Argon seeded detachment reduces confinement slightly.



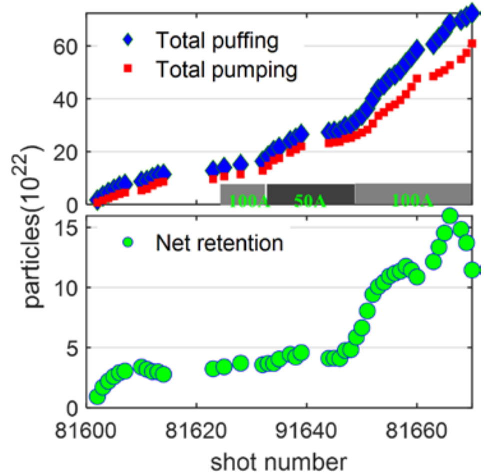
Wang -EX/7-1

Development of flowing liquid Li limiters (FLiLis)

- **Liquid Li is being studied as an alternative PFM for better handling of particle and heat flux.**
  - Four generations of FLiLi have been successfully in EAST.



- **D retention increases gradually during FLiLi operation.**
  - FLiLi can well solve the problem of the saturation of Li coated wall.



Zuo, Nucl. Fusion 59 (2019) 016009

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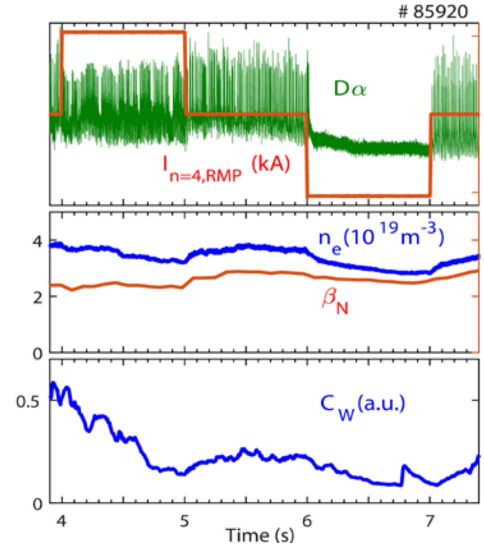
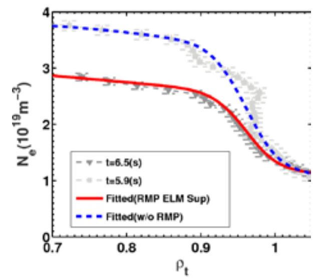
ELM suppression by n=4 RMP in low torque plasmas

- **Type-I ELMs are suppressed by n=4 RMP with upper-lower odd coil phasing, but not for the even one.**
  - W concentration decreased with RMP
  - Significant density pump-out (20%) happens during ELM suppression, but less drop (5%) in stored energy

- **The target plasma is close to ITER type-I ELMy H-mode operational window**
  - T_{NBI} = 1.1 N· m (0.9 N·m ITER equivalent torque in EAST)
  - $q_{95} \sim 3.65$, $\nu^*_{e,ped} \sim 0.5$, $\beta_N \sim 1.4$

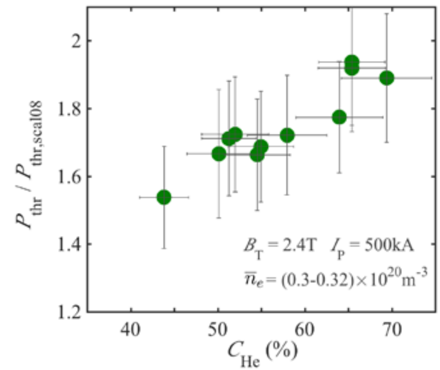




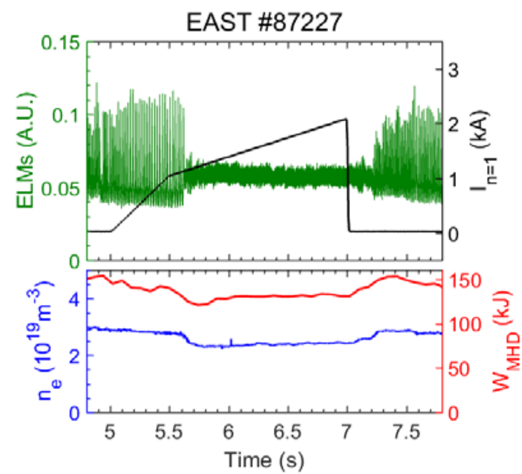
Sun -EX/4-4

Helium plasmas demonstrated under pure RF-heating and ITER-like tungsten divertor

- **Concentration of helium (C_{He}) in the plasma is confirmed to play a critical role in H-mode operation.**
  - higher concentration raises the H-mode threshold power and deteriorates the energy confinement in H-mode.



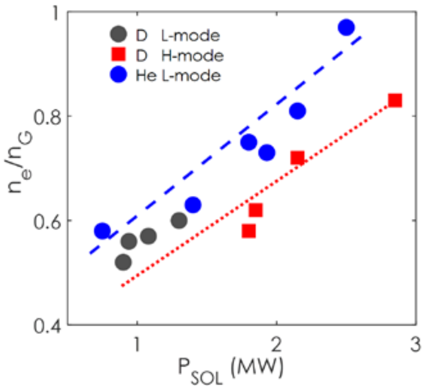
- **ELMs suppression by n=1 RMP is achieved in helium plasma.**
  - Strong density pump-out effect during ELMs suppression, but less drop in plasma confinement.

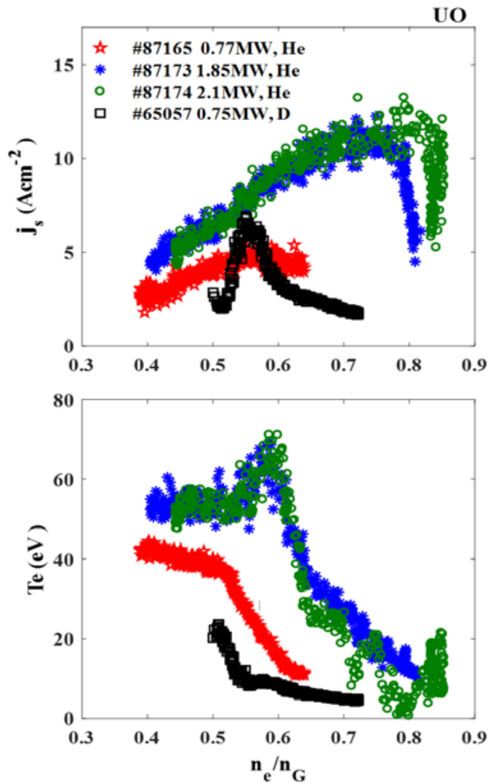


Zhang -EX/P2-927

Divertor Detachment Achieved with Density Ramp-Up in He Plasmas

- **A clear particle flux rollover occurs with favorable B_T ($B\times\nabla B\uparrow$), similar as the D plasmas.**
- **Te at strike point decreases with the density ramping up.**
- **Higher detachment threshold density in He than D.**

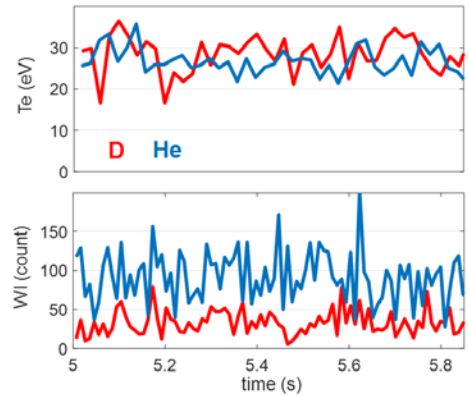




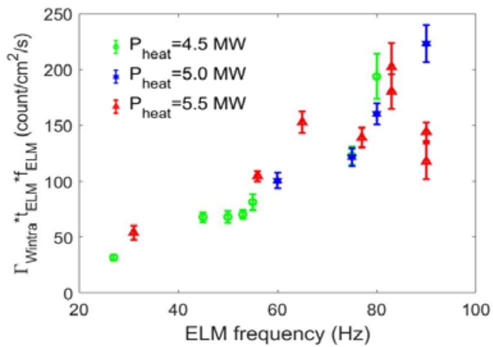
Ding -EX/P2-1068

W Erosion is more serious in He plasmas

- **W erosion rate in He plasmas is more than 3 times that in D plasmas.**



- **The intra-ELM W sputtering source increases linearly with the ELM frequency.**
  - similar to the deuterium plasmas from DIII-D and JET.



Ding -EX/P2-1068

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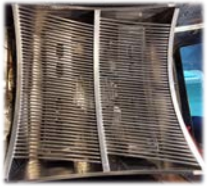
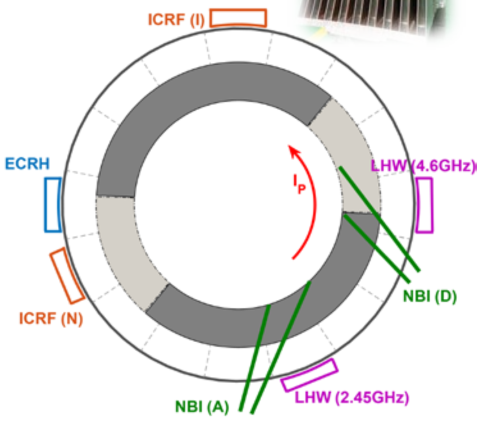
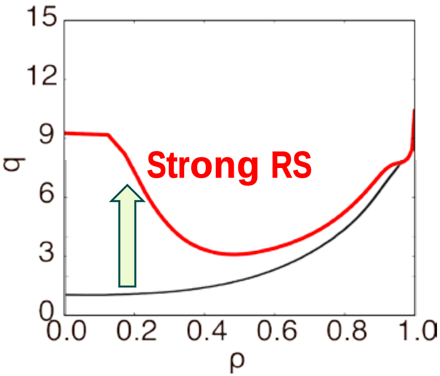
EAST augmented capabilities provide flexibility to continue long-pulse H-mode scenario development

- **Heating/CD systems upgraded**
  - PAM launcher for LHW(2.45GHz)
  - Lower K spectrum for ICRF(N)
  - A new gyrotron for ECRH (1MW)
  - Two co-current NBI systems





To optimize profiles for scenario development and instability control



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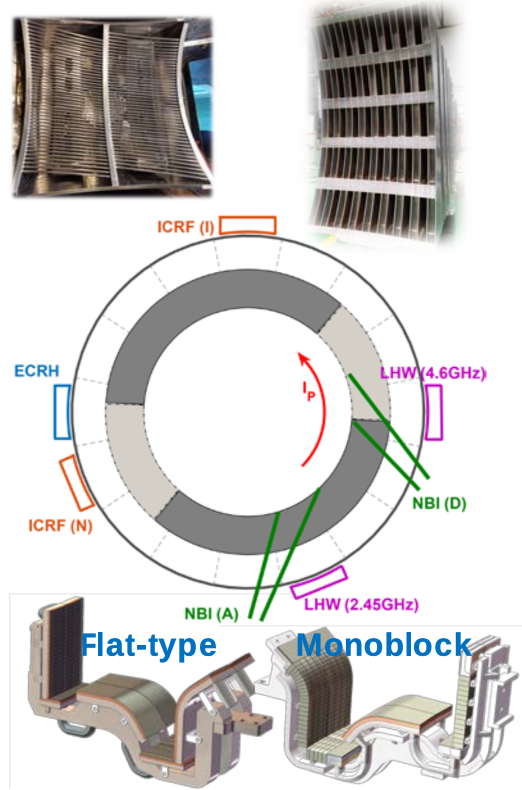
To increase the steady-state heat exhaust to 10MW/m²

- **A new lower water-cooled tungsten divertor installed**
  - ¾ with the monoblock structure
  - ¼ with the flat-type structure



Summary

- **Significant progress has been made in the long-pulse steady-state high β_P H-mode scenario**
  - A minute time scale H-mode discharge(β_P ~2.0, f_{bs}~50%, $H_{98(y2)}$>1.3)
  - A compatible core and edge integration in high β_p scenarios

- **Key advances on the developments of long pulse operation, delivering steady state operation in ITER and CFETR**
  - Active controls of radiative divertor, ELM suppression, He plasmas etc.

- **A new lower tungsten divertor is installed and the H/CD systems are upgraded for achieving**
  - >400s long-pulse H-mode operation with ~50% bootstrap current fraction;
  - Demonstration of power exhaust at ~10 MW power injection for >100s.

Thank you !