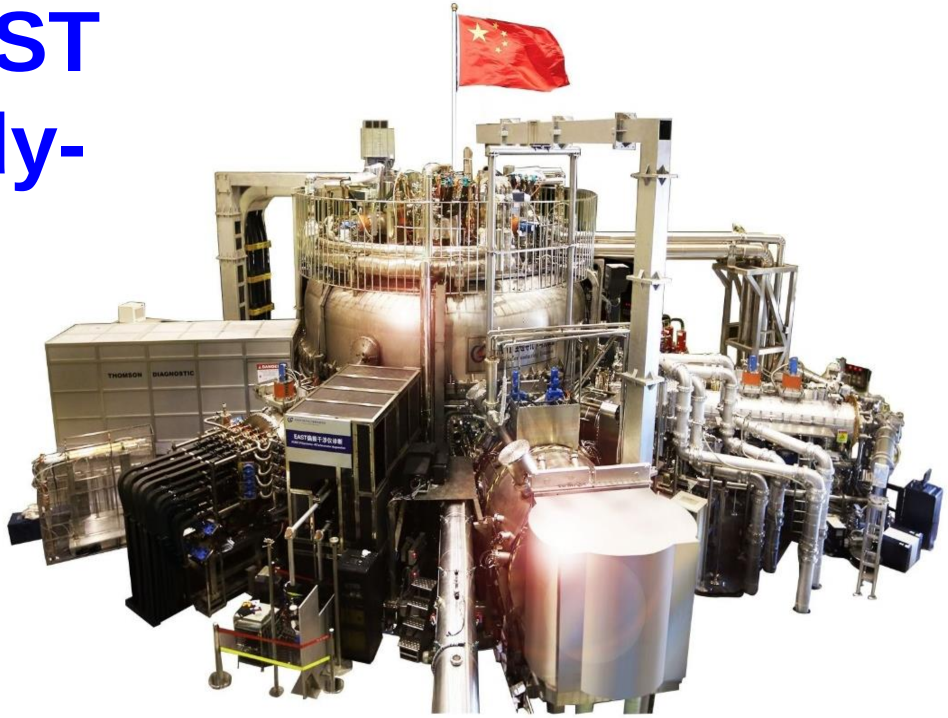
Particle & power exhaust of new EAST lower W divertor for advanced steady-state operations



L. Wang, G. S. Xu, J. B. Liu, L. Meng, K. Li, K. Wu, Q. Yuan, B. Cao, L. Yu, Y. Yu, F. Ding, R. Ding, G. Z. Jia (**ASIPP**)

D. Eldon, H. Q. Wang (**General Atomics**)

C. F. Sang (**DLUT**)

Institute of Plasma Physics, Chinese Academy of Sciences

Outline

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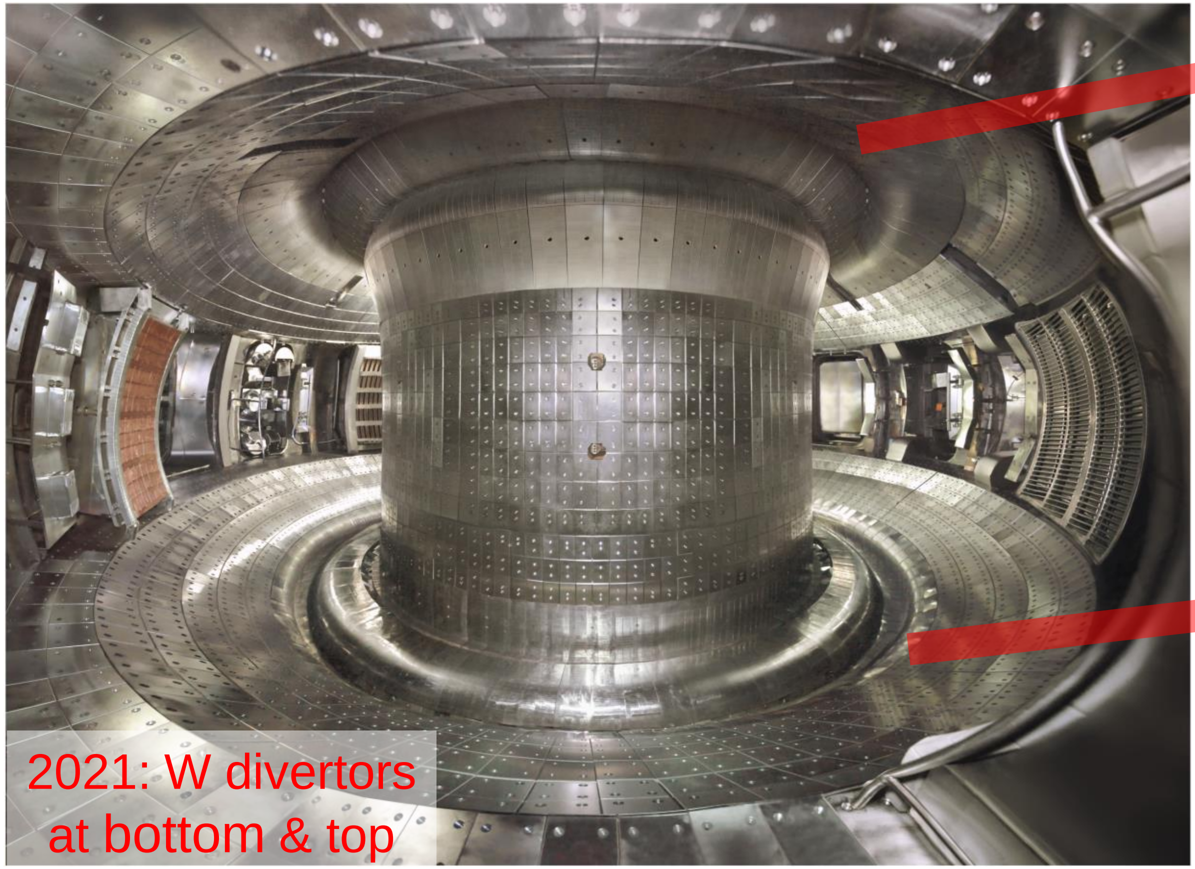
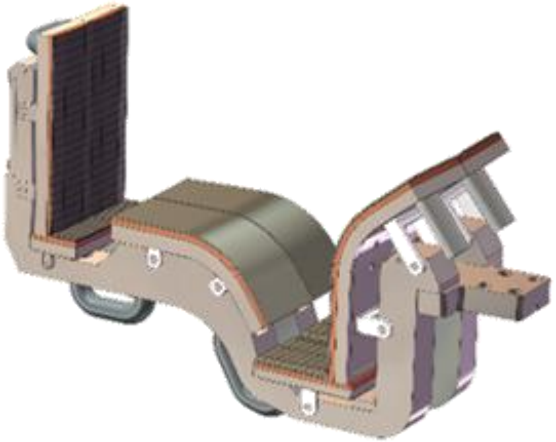
New lower W divertor for enhanced power & particle exhaust

- **Mission**
  - **H-mode ≥ 400s; 10 MW*100s; 1000s SSO**
  - **Divertor & PWI Physics**
  - **→ Core-edge integration for ITER/CFETR**



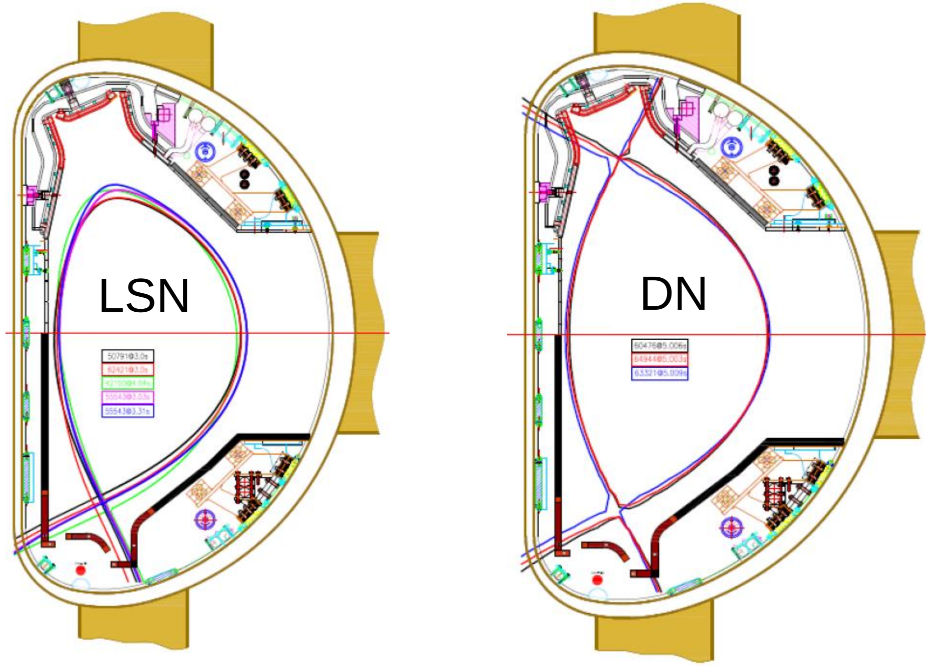
ITER-like upper W-divertor (2014)

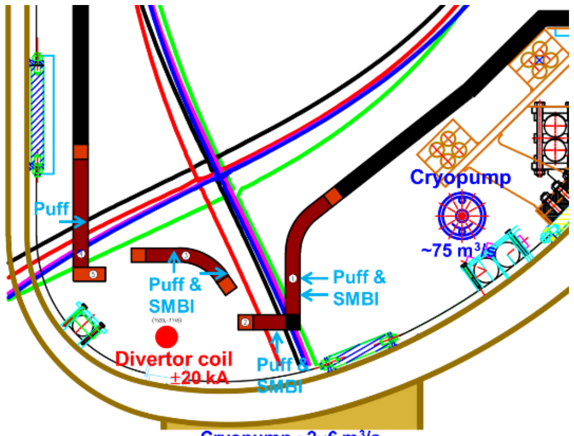


Upgraded lower W-divertor (2021)

New lower W divertor for enhanced power & particle exhaust

- **W/Cu divertor with water-cooling**
  - **SS power exhaust over 10MW/m²**
- **Enhanced particle exhaust capability**
- **Closed outer divertor and open inner divertor for balanced detachment**
- **Facilitate both LSN and DN, flexible strike point**
- **A new divertor coil for X-divertor operation**
- **Plasma configuration with δ_L =0.4-0.6**



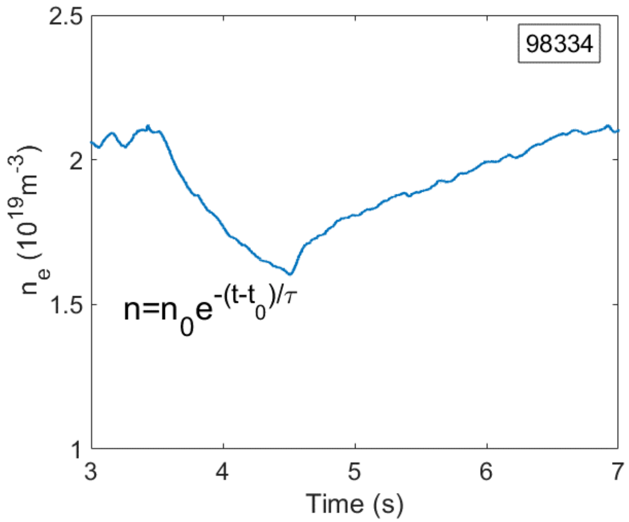


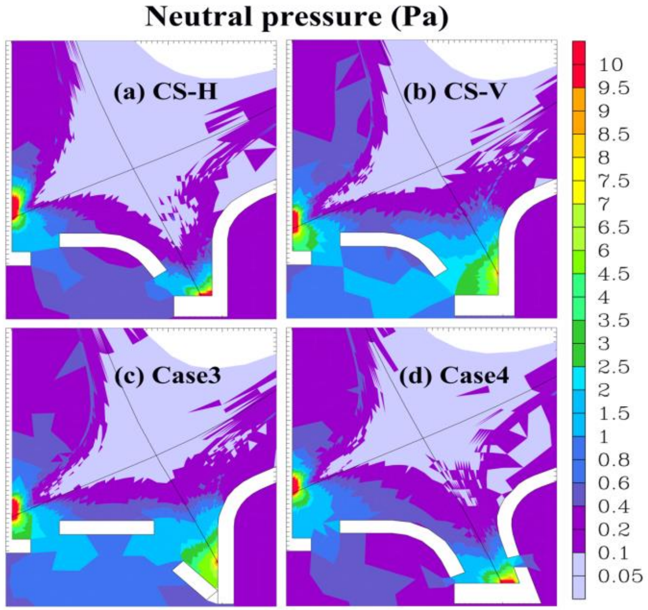
G. S. Xu et al., Nucl. Fusion (2021)

Effect of divertor closure on particle exhaust

- **New lower divertor has stronger particle exhaust than upper W divertor**
- **Stronger particle exhaust capability with LOSP on horizontal target in both LSN and DN**
  - Consistent with SOLPS simulation [G. S. Xu 2021 NF]
- **Switch off all gas puff to examine the particle exhaust capability**
  - Characterization of density decay time
- **Enhanced particle exhaust after strong lithiation**

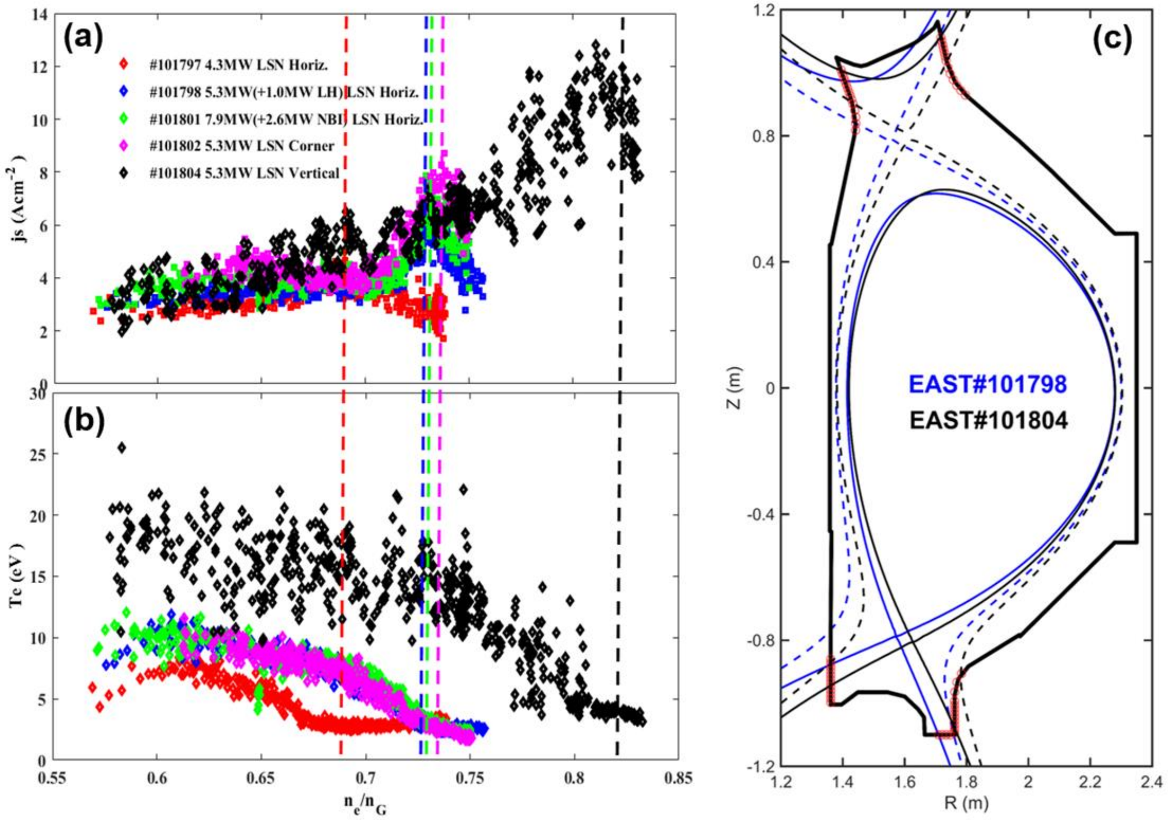
New Lower divertor operation with Bx∇B↓					
shot	98326	98318	98334	98336	98341
Config.	LSN-H	LSN-V	DN-H	DN-V	USN
τ (s)	3.57s	6.86s	3.81s	5.55s	6.26s

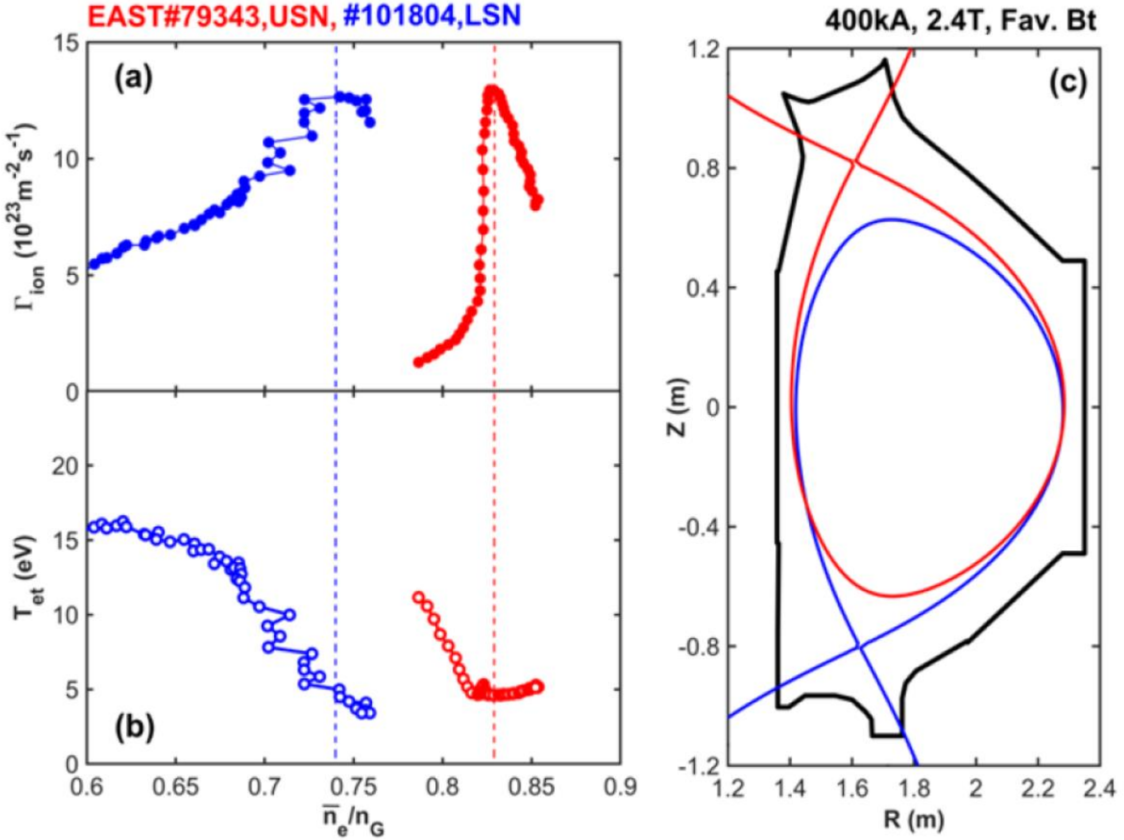




Effect of divertor closure on H-mode detachment access

- **Plasma density ramping-up for detachment access**
  - A clearly lower n_e threshold with strike point on the horizontal target, higher neutral density
  - Change of divertor closure in LSN with B×∇B↓





- **A lower n_e threshold with closed new divertor than upper open divertor at similar P_{heat}**

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Outline

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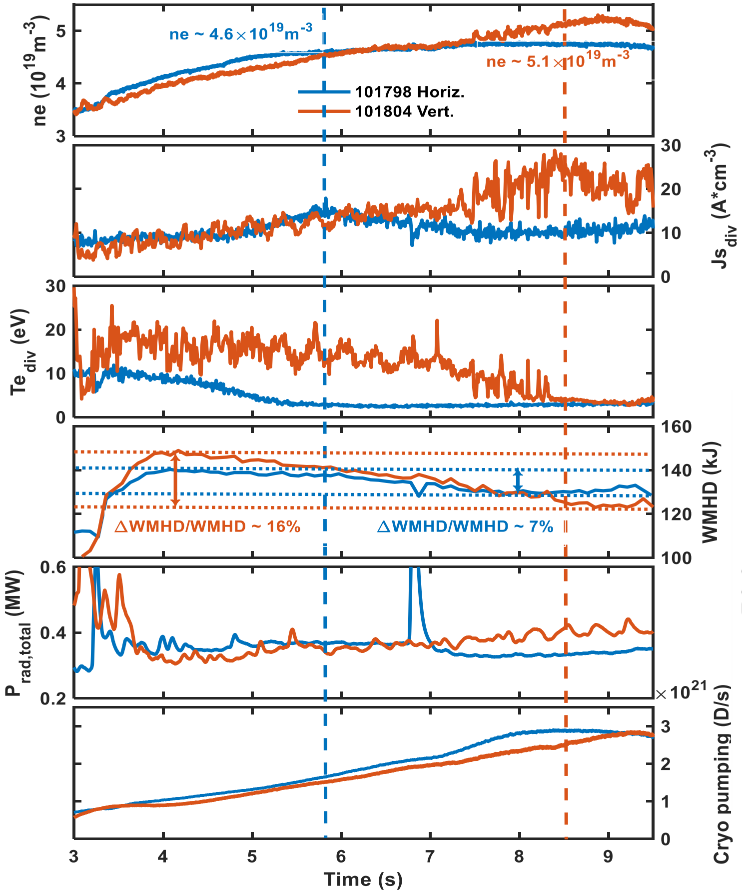
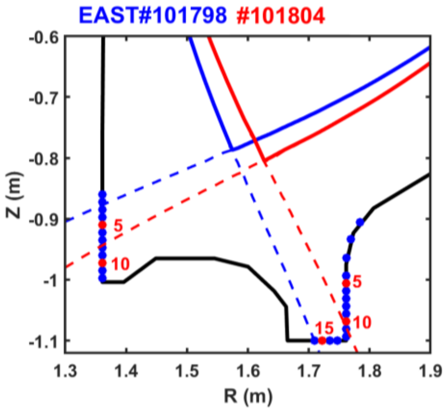
Effect of divertor closure on detachment-core compatibility

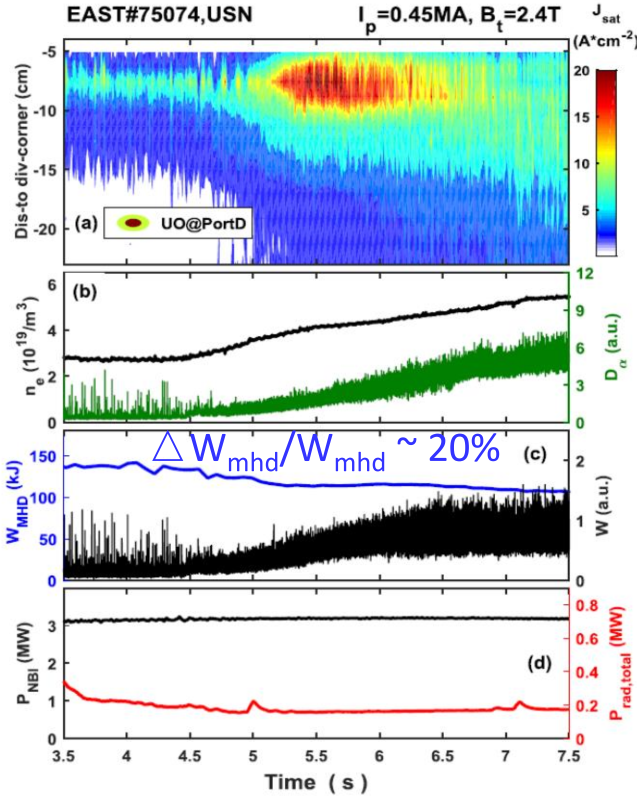
- **The plasma performance loss at H-mode detachment is much lower than upper open W divertor**
  - **Lower closed divertor: $\triangle W_{mhd}$ ~ 7% (Horizontal); ~ 15% (vertical)**
  - **Upper open divertor: $\triangle W_{mhd}$ ~ 20%**

LSN with new divertor





USN with upper divertor



J. B. Liu et al., Nucl. Fusion (2019)

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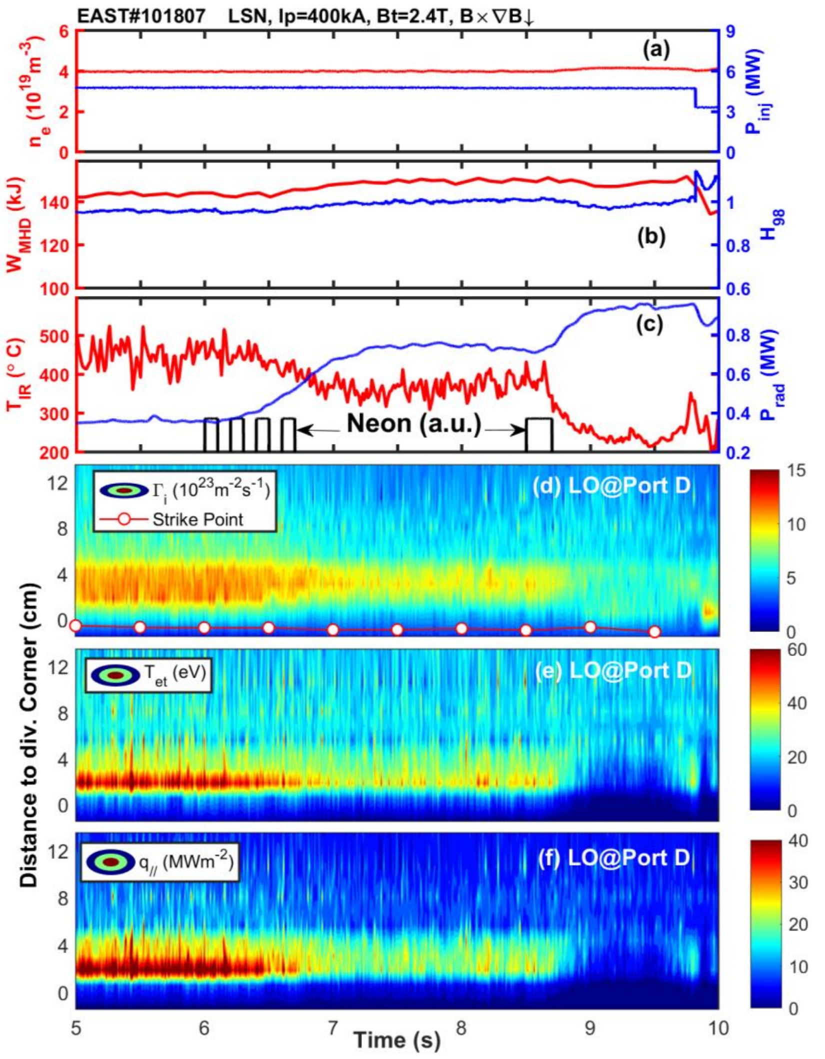
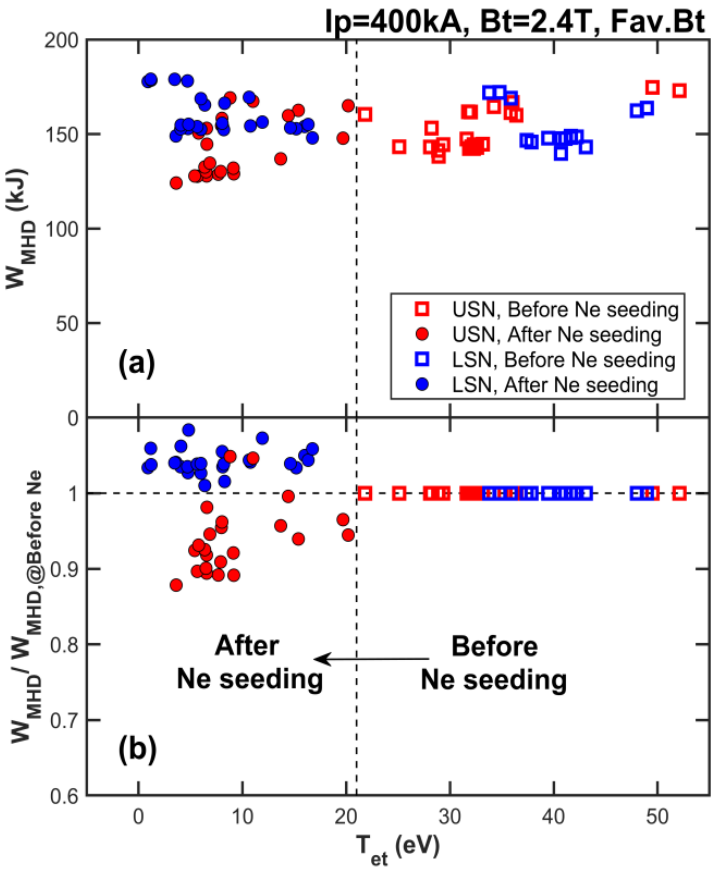
Compatibility of radiative divertor detachment and core performance

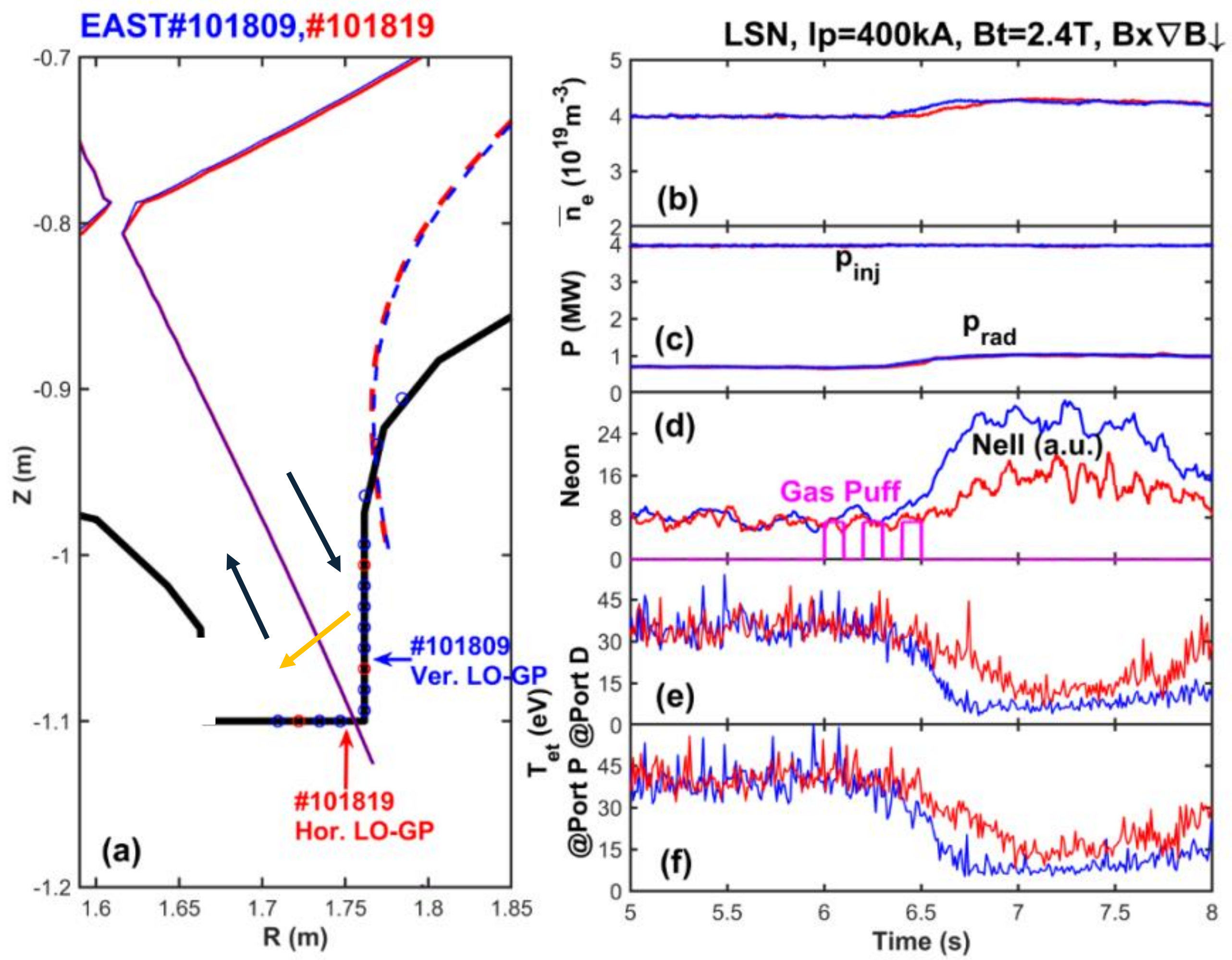




- **Impurity seeding to reduce heat load has been performed in new lower W divertor**
- **Impurity seeding with new lower W divertor exhibits good core-edge integration than upper W divertor**

Effect of impurity seeding location on detachment

- **Stronger Te decrease with Neon seeding @ SOL on vertical target**
  - More particles around the strike point
  - The effect of $E_\theta \times B$
- **Stronger particle exhaust with Neon seeding @ PFR on horizontal target**



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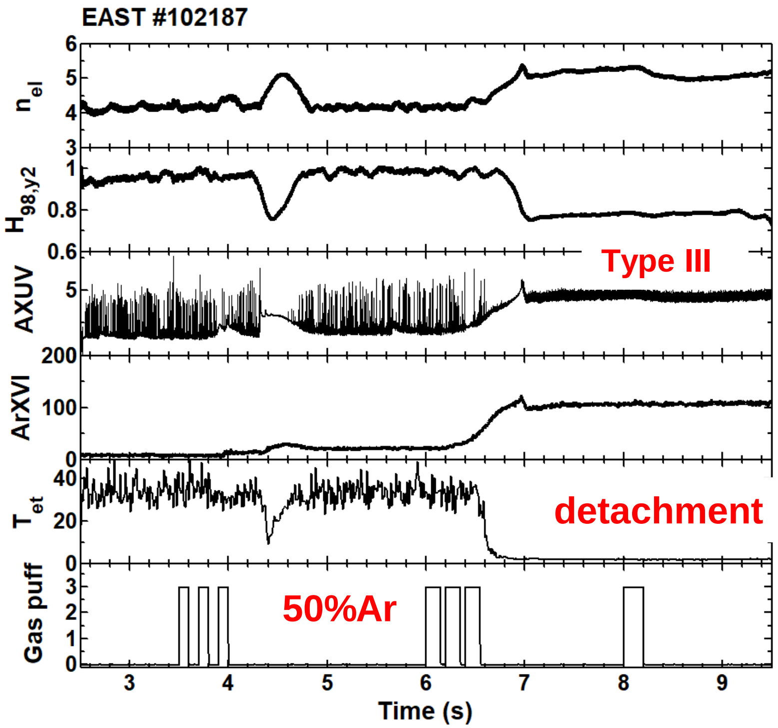
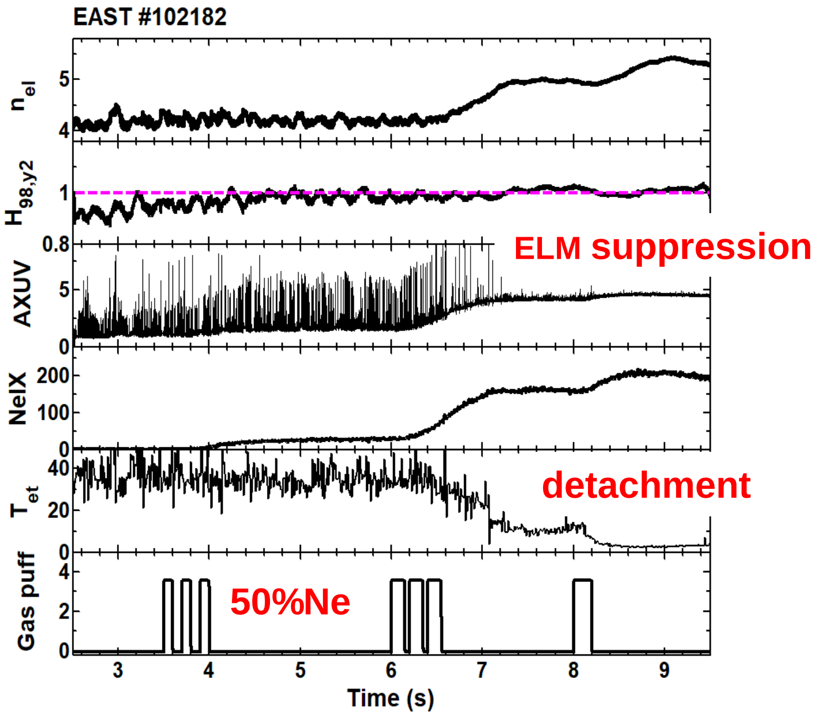
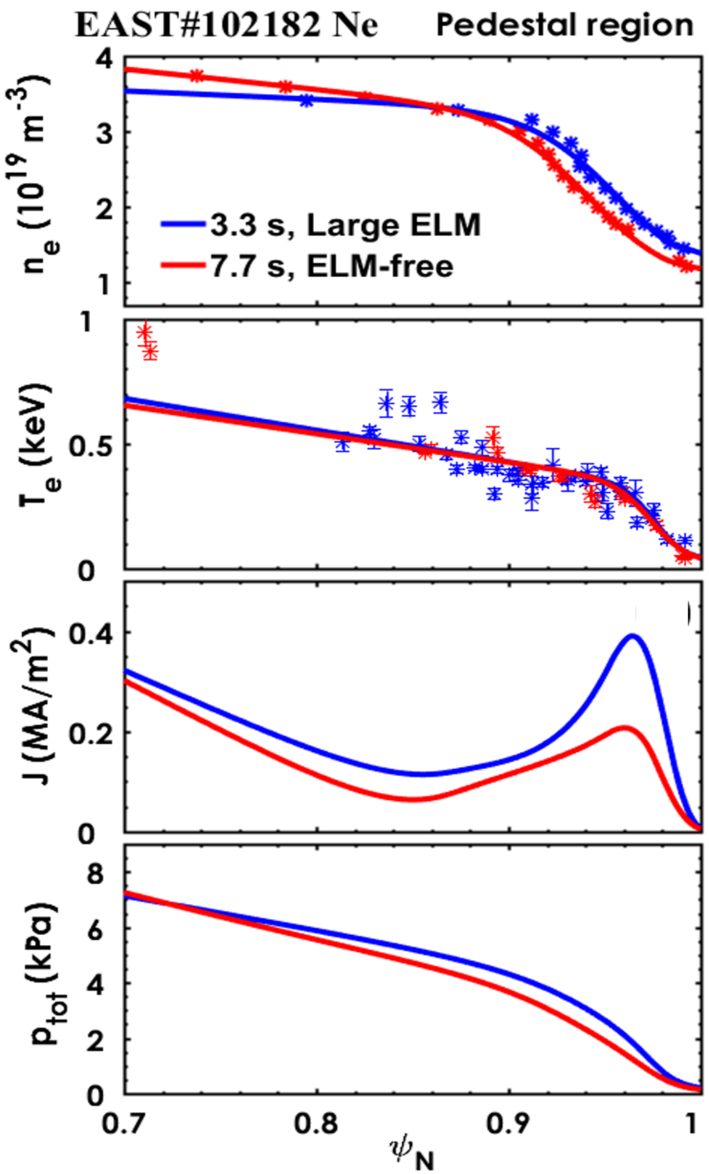
Integrated detachment & ELM control with new closed lower divertor



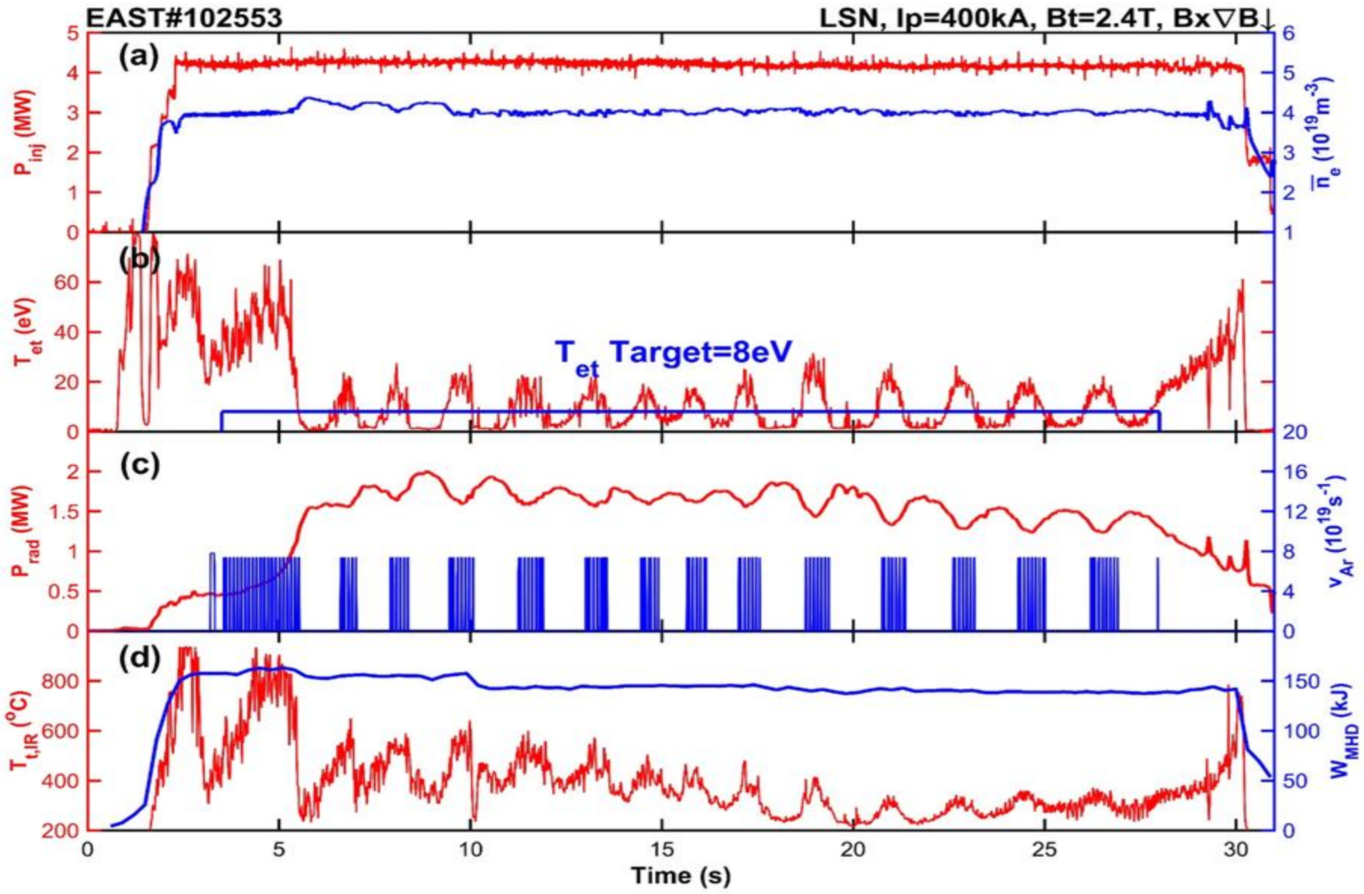




- Ar seeding: transition to small ELMs (f_{ELM}~1kHz) and confinement degrades (H_{98}: 1→0.8)
- Ne seeding: simultaneous ELM suppression and detachment with new lower divertor: (q_{95}~5.5, Δn_{el}>5%, f_{ELM}~100Hz) with H_{98}~1
  - Z_{eff} ↗after neon → edge j_{bs} and ∇P_{ped} ↘ → stabilization of ELMs
  - No ELM suppression in USN configuration with neon

Long pulse H-mode detachment feedback control ~ 25 s

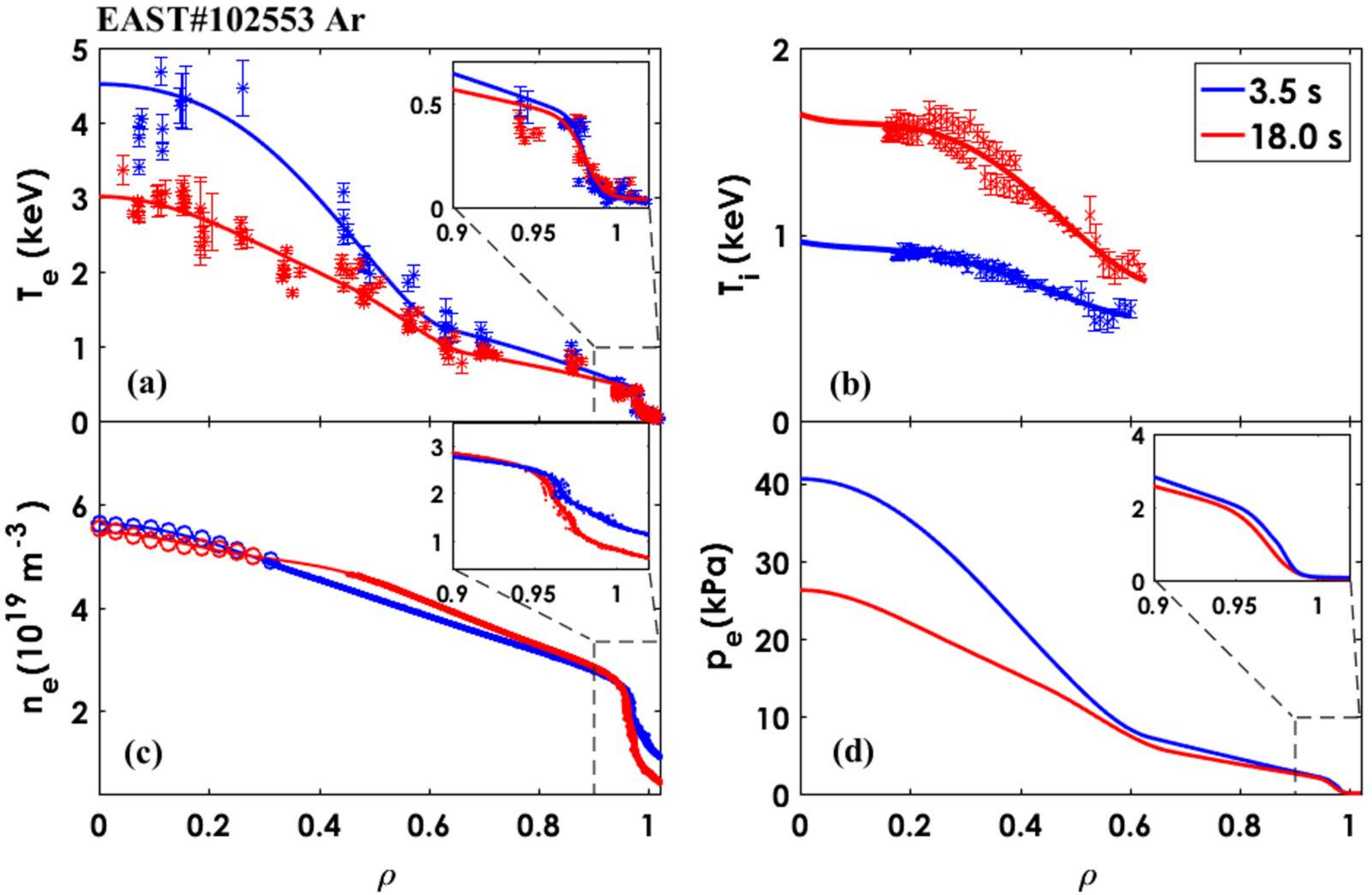
- T_{et} FB control via Ar seeding
- Slight W_{mhd} loss (8%), H_{98}~ 1, good core-divertor integration
- Dive-LP & IR-camera data show good consistence
- Further optimization of FB to maintain stable detachment



L. Wang et al Nucl. Fusion (2022)

A significant progress on PWI control for long pulse core-edge integration

Core plasma characteristics comparison between attachment and detachment with Ar seeding



*Profiles during **attachment (3.5 s)** and **detachment (18.0 s)** with Ar seeding.*

- **The increase of T_i compensates the core confinement loss with Te reduction in detachment.**
- **Ar seeding → destabilization of ITG → reduce Ti thermal transport**

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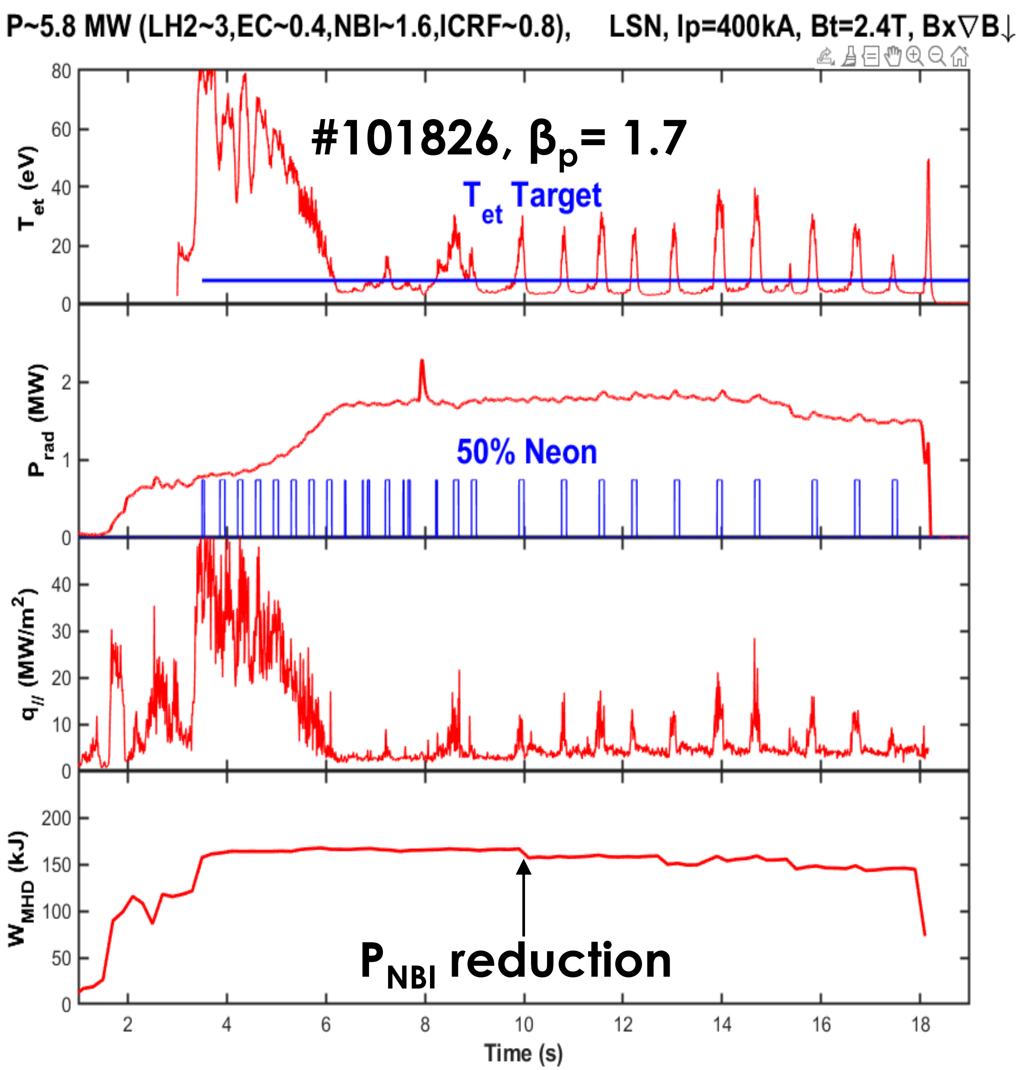
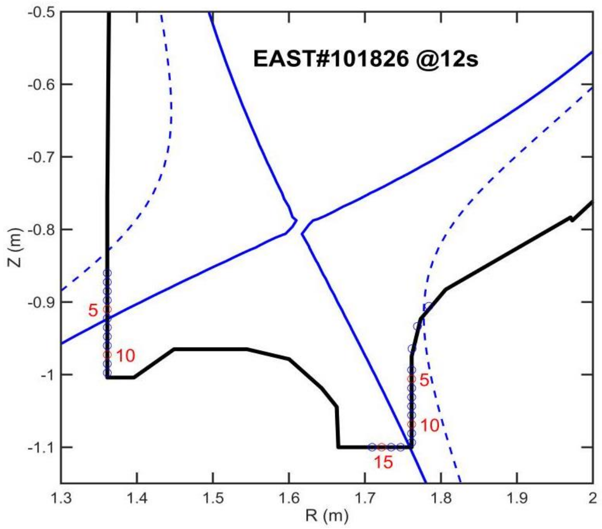
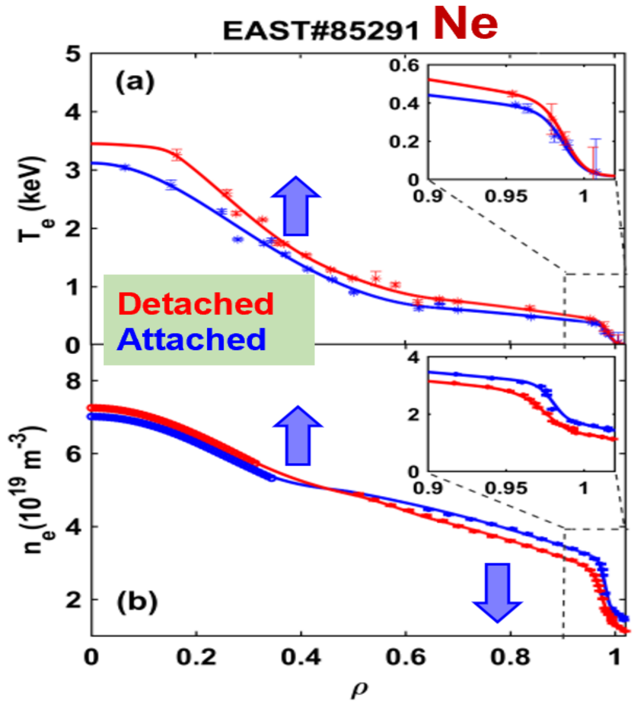
Long pulse detachment feedback control via $T_{e,div}$ with Neon



- T_{et} more directly & easily, absolute measurement, still needs optimization
- Neon exhibits good core-edge integration than Argon
- The energy loss at 10s was due to P_{NBI} reduction.





K. D. Li et al., Nucl. Fusion (2021)

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Outline

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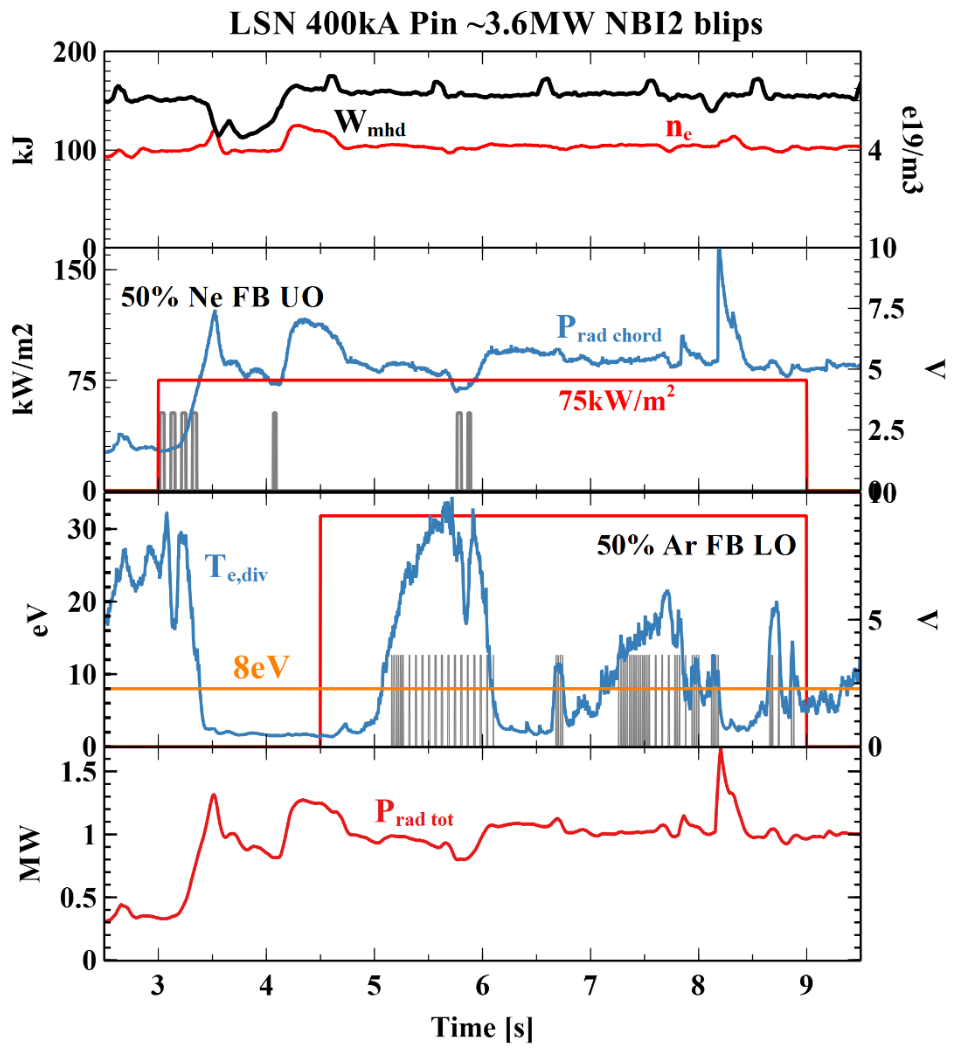
Double feedback control of $T_{e,div}$ & $P_{rad, core chord}$ achieved in EAST

- $P_{rad, chord}$ FB control : UO 50% Ne
- $T_{e,div}$ FB control: LO 50% Ar
- Slight impact on W_{mhd}
- Both local and main plasma radiation Increase
- $T_{e, div}$ reduced for both FB control phases



GENERAL ATOMICS

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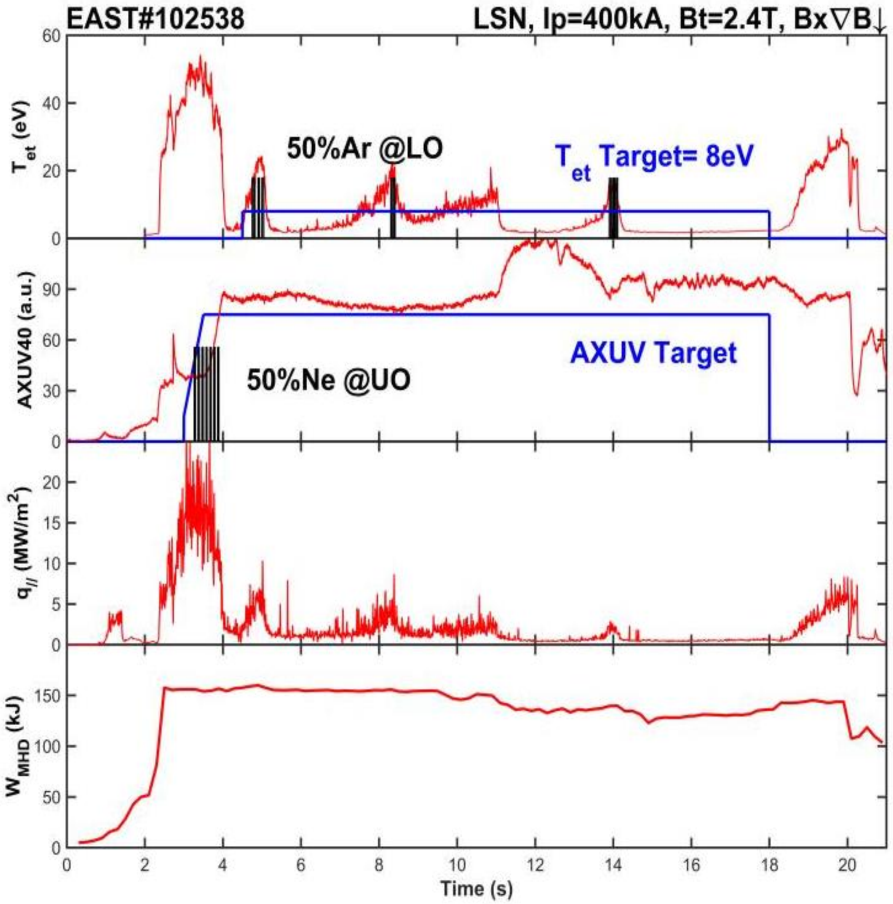
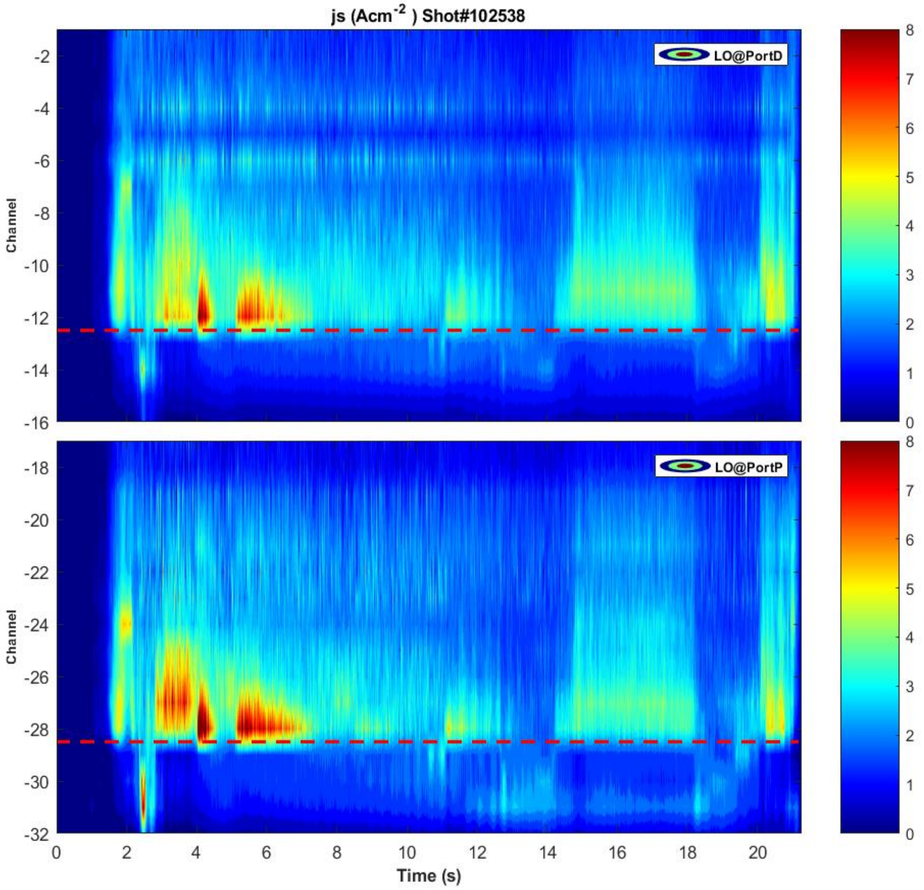
Double feedback control of $T_{e,div}$ & $P_{rad,\ core\ chord}$ → 20s long pulse





- More control optimization needed in future
- Core-edge integration problem with two impurities simultaneously

GENERAL ATOMICS

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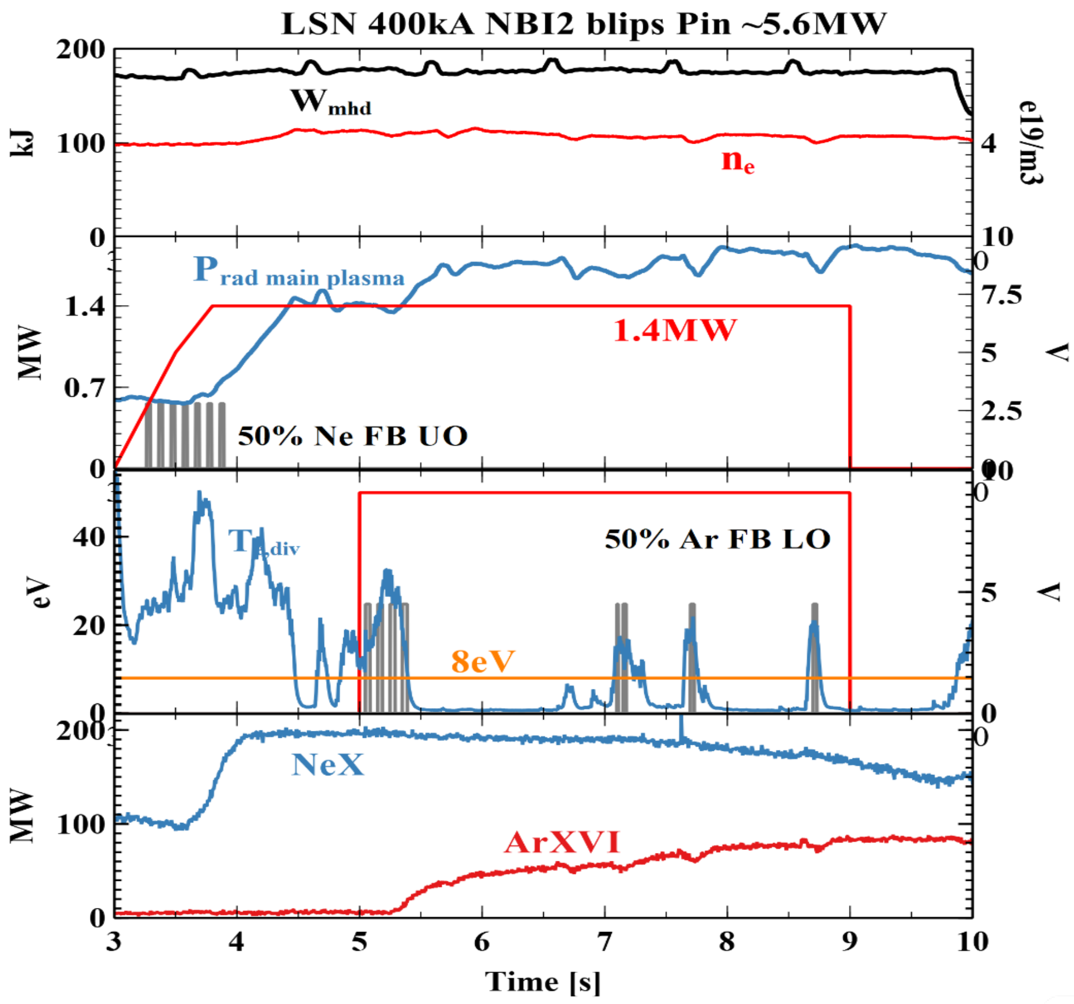
Double feedback control via $T_{e,div}$ & $P_{rad,\ main\ plasma}$

- $P_{rad,main}$ FB control: UO 50% Ne
- $T_{e,div}$ FB control: LO 50% Ar
- No degradation of W_{mhd} within 10s
- The Ar injection for $T_{e,div}$ control influences control accuracy of $P_{rad,\ main}$



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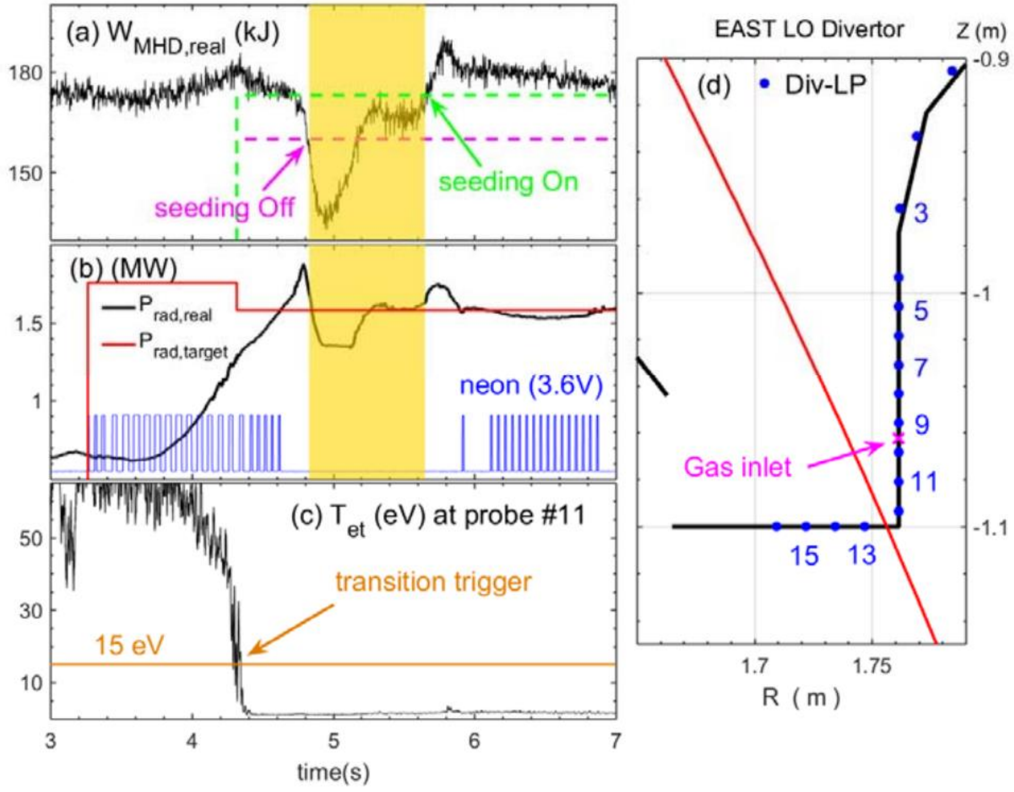
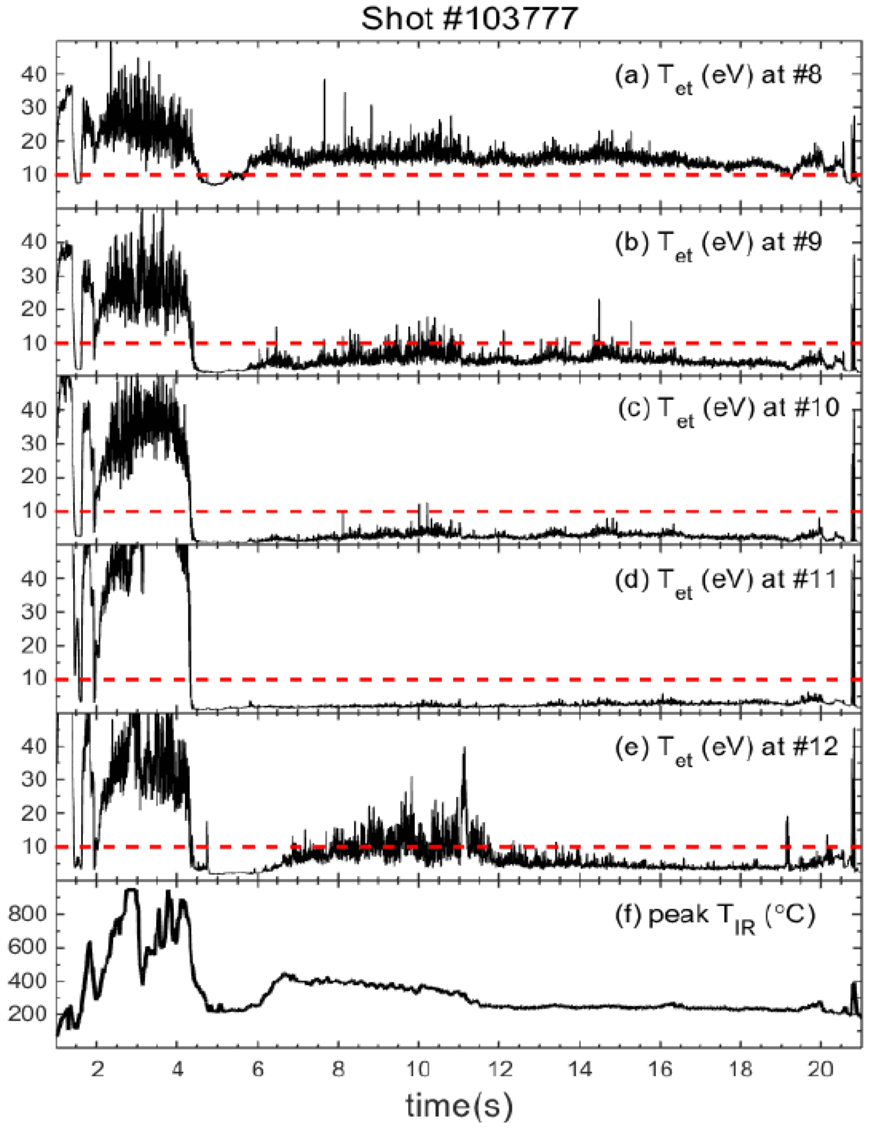
Double feedback control of $P_{rad, total}$ & plasma stored energy

- **Stored energy monitor during detachment with neon**
- **Impurity seeding off when W_{mhd} is lower than the target**
- **Use of a single impurity seeding valve**





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Outline

01 Lower divertor upgrade & Physics validation

02 Detachment compatible with high-confinement core

03 Progress in double feedback control

04 Summary & near-term Plans

Summary & near-term plans

- **Physics design of new lower W divertor experimentally demonstrated**
  - Divertor closure, particle exhaust, impurity screening, detachment access
- **Achievement of detachment sustained with core in H-mode over 25s**
  - Alternative controller needs to be developed for reactors
- **Simultaneous detachment and ELM control with new lower W divertor**
  - Ne seeding: H_{98}~1, ELM suppression
  - Ar seeding: H_{98} (1→ 0.8), strong ELM mitigation
- **Double FB control of T_{et} & P_{rad}, P_{rad} &W_{mhd} for core-edge integration carried out**

Next step → In support of ITER & CFETR

- **Demonstration of H-mode detachment >100s, associated with particle balance for long pulse operation**
- **Integrated Div&PWI control compatible with core plasma at high P_{heat}**
  - Bridge the gap between moderate and high power input for reactors

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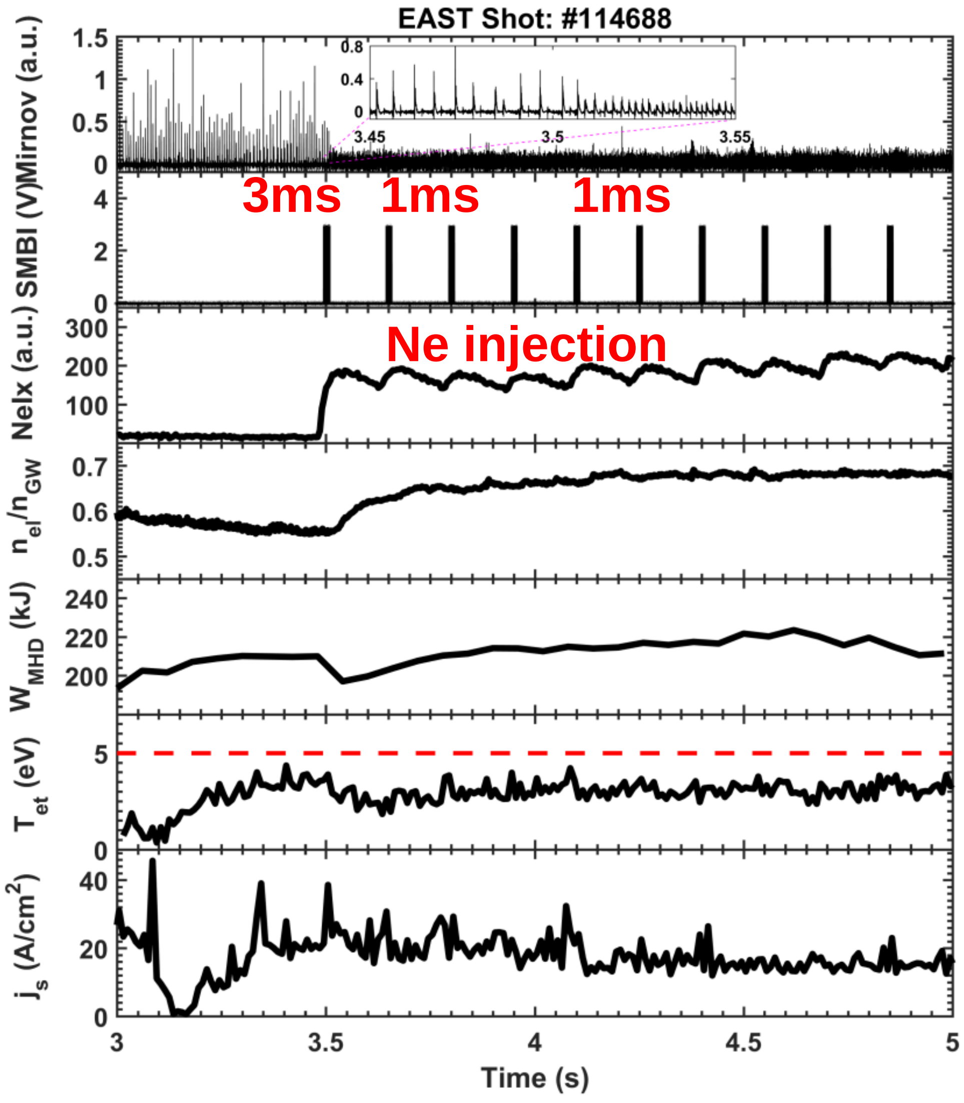
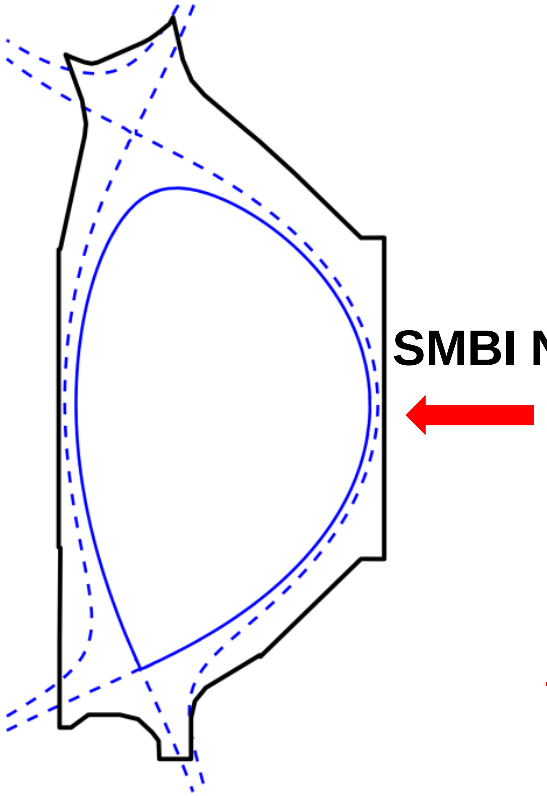
Thank you !

ELM mitigation & detachment by LFS Ne injection





q_{95} = 4.0

I_p = 550kA

B_t = 2.1T

LSN, unfavorable B_t

Strike point on horizontal target

f_{ELM}=200→500Hz

T_{et} < 5eV, **divertor detachment**

SMBI pulse: first 3ms + multiple 1ms (interval 0.15s)

P_{LHW} =0.7MW, P_{ECH} =1.1MW, P_{NBI} =2.2MW