Latest advances in joint EAST/DIII-D divertor detachment expts. for fusion reactors

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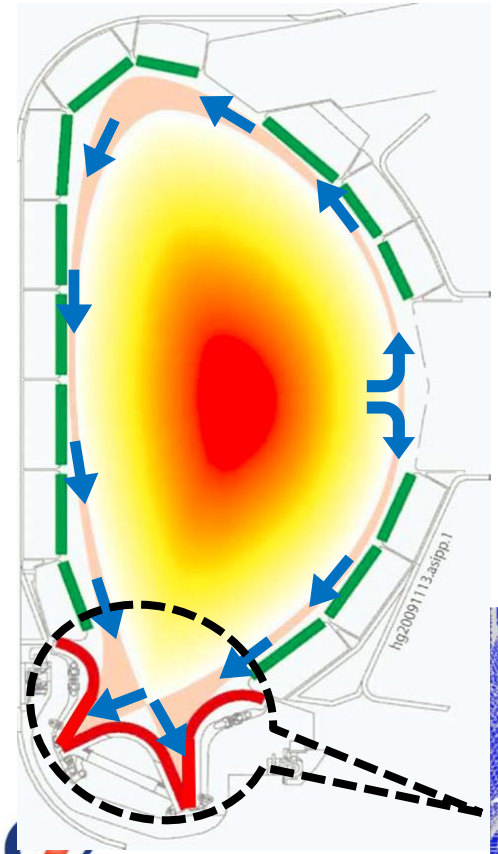
10th US-PRC MFC Virtual Workshop,
US: March 22-26 / PRC: March 23-27, 2021 LLNL, US

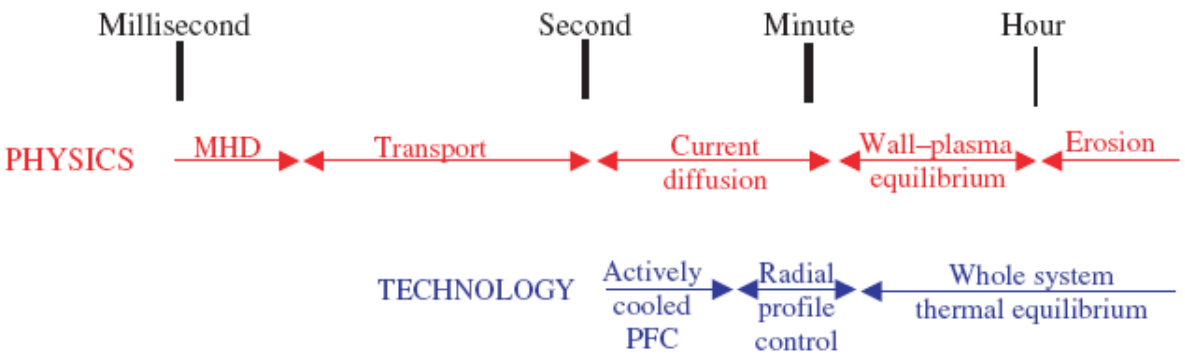
Outline

- **Motivation & Key issues**
- **Active detachment control compatible with core**
  - EAST H-mode plasmas
  - DIII-D high β_p scenario
- **Summary & Near-term Plans**

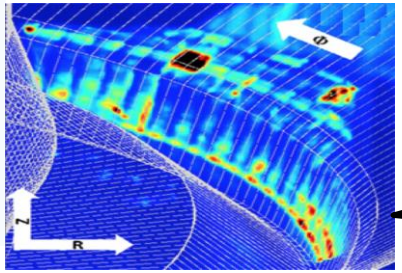
Divertor & PWI Challenges in fusion devices

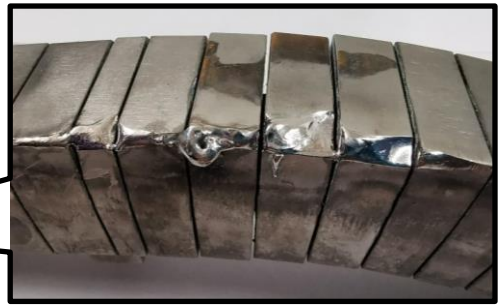
- **Divertor & Plasma wall interaction**
  - Particle/power exhaust and PMI effect in divertor volumes
  - Integration of core performance & edge issues





- **EAST:** ITER-like W divertor, RF heating, long pulse
- **DIII-D:** High performance plasma, full diags., Physics





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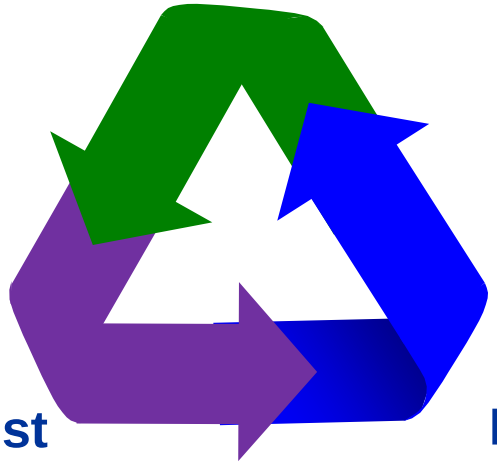
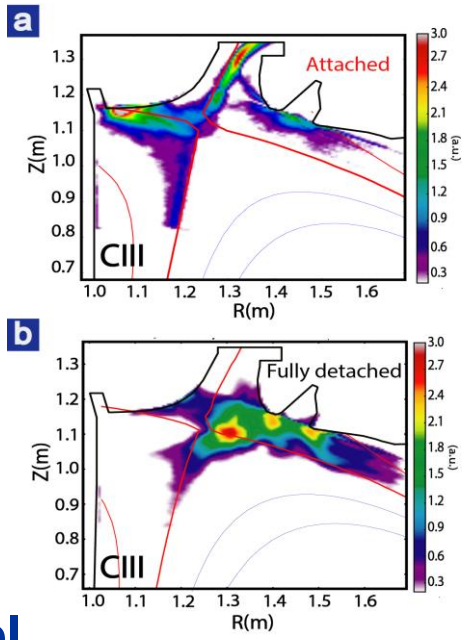
Key PWI Issues for Long-Pulse High Performance Operations

Heat Load on Target Plates



Particle Exhaust & Neutral Recycling

Edge & Core Impurity Control



- Critical challenges for EAST long-pulse operation, especially with heating power > 10 MW.
- Detachment is acknowledged as the most promising means for steady-state PWI control.

→ Joint research to provide a solution on integrated Div&PWI control, compatible with core plasma for ITER & CFETR.

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Active detachment controller development on EAST

- **The detachment FB control on EAST has been demonstrated in**
  - **Normal ELMy H-mode**
  - **Grassy ELMy H-mode**
  - **High β_p scenario**
- **A series of detachment/radiation controller developed successfully**

Table 1 The developed control methods of radiation and divertor detachment on EAST. FB – feedback.

FB Control methods	FB parameters	Diagnostics
Total Radiation FB[Wu18NF]	$P_{rad,total}$	AXUV
Particle flux FB[Wang19NF,Yuan20FED]	j_{sat}	Divertor - LPs
Electron temperature FB[Eldon21NME]	T_{et}	Divertor - LPs
Synergy FB of electron temperature and X-point radiation[Xu20NF]	$T_{et} + P_{rad,\ X\text{-}point}$	Divertor - LPs & AXUV
Target temperature FB[Chen20NF]	$T_{t,\ peak}$	IR thermography

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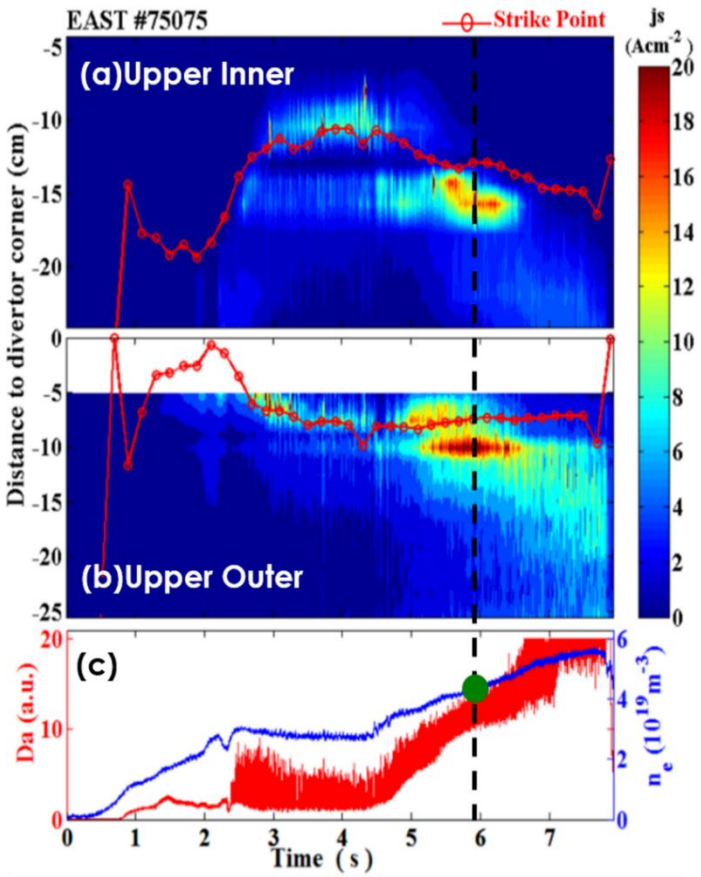
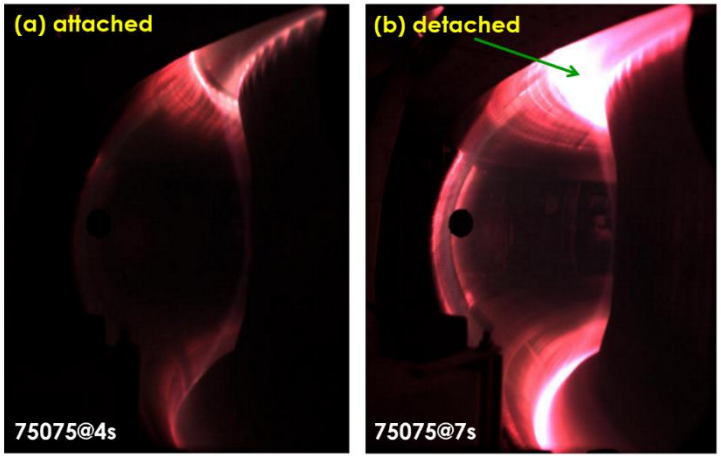
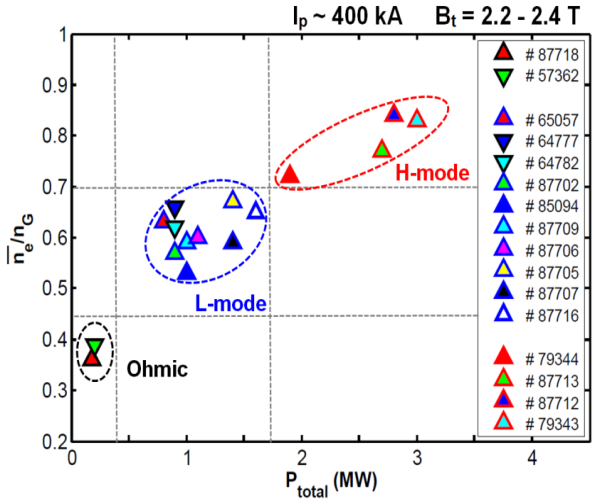
Achievement of H-mode detachment with W divertor in EAST

- Particle flux rollover observed w/ Bx∇B↑





- Neutral density increase during detachment



J. B. Liu, L. Wang* et al., Nucl. Fusion 2019

L. Y. Meng, L. Wang* et al., PPCF 2019

- Detachment n_e threshold is higher in H- than L-mode on EAST

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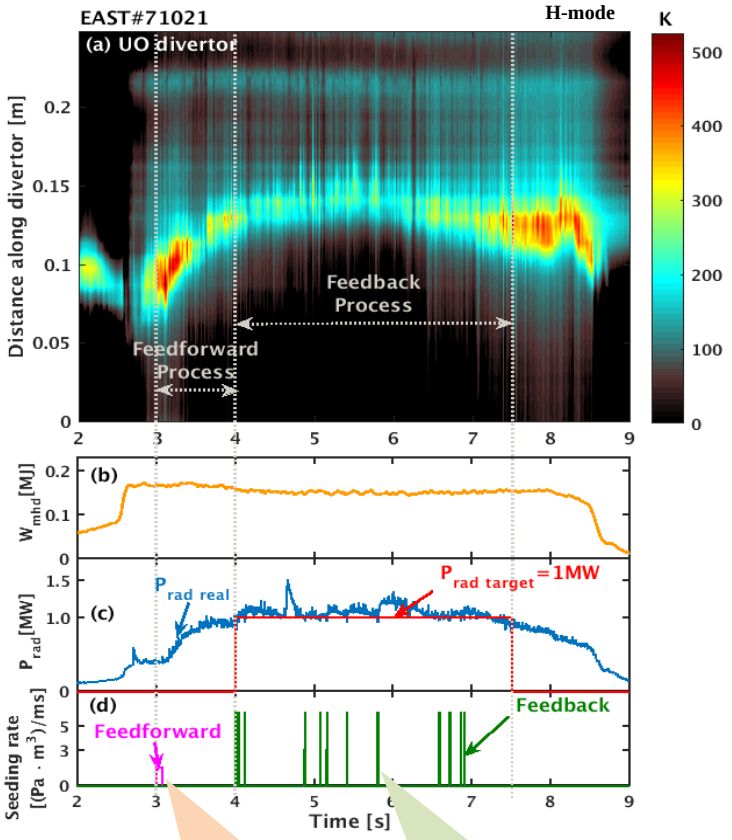
Active feedback control of P_{rad} to reduce heat flux

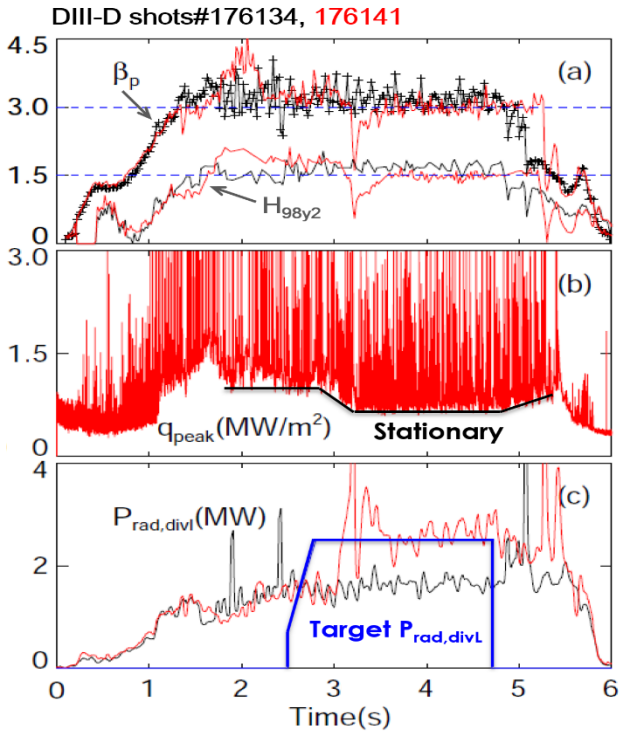


Neon puffing from top divertor

Neon-SMBI from LFS mid-plane

K. Wu et al., Nucl. Fusion (2018)

- **Radiation power was actively controlled by feedback of LFS neon-SMBI seeding.**
  - slight loss of plasma stored energy: 7 - 11%
  - f_{rad} extended to 41% in 2018.
- **Divertor seeding exhibits much better in ctd. Expts**
  - ✓ Demonstration in DIII-D high β_p scenario with ITB+ETB



L. Wang, 27th IAEA-FEC (2018) & NF (2019)

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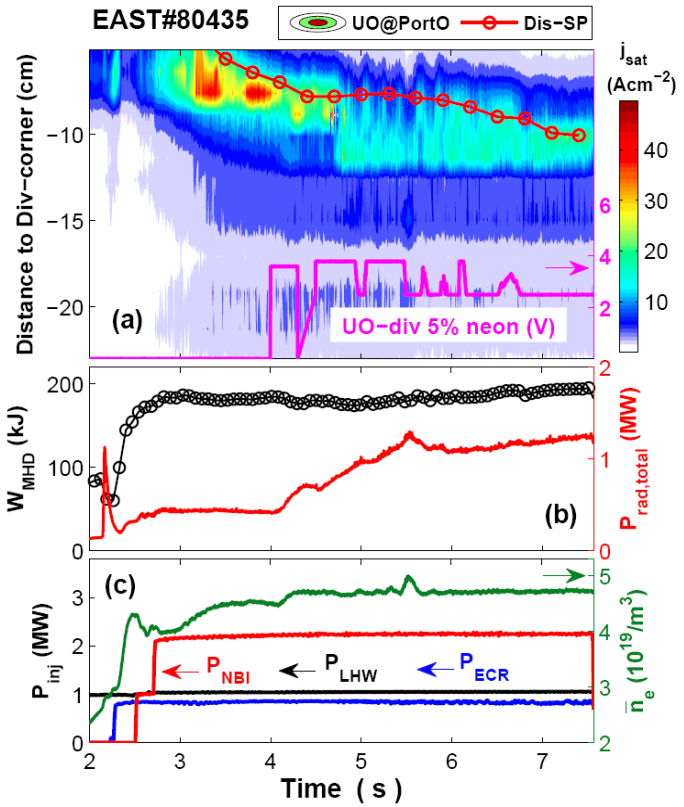
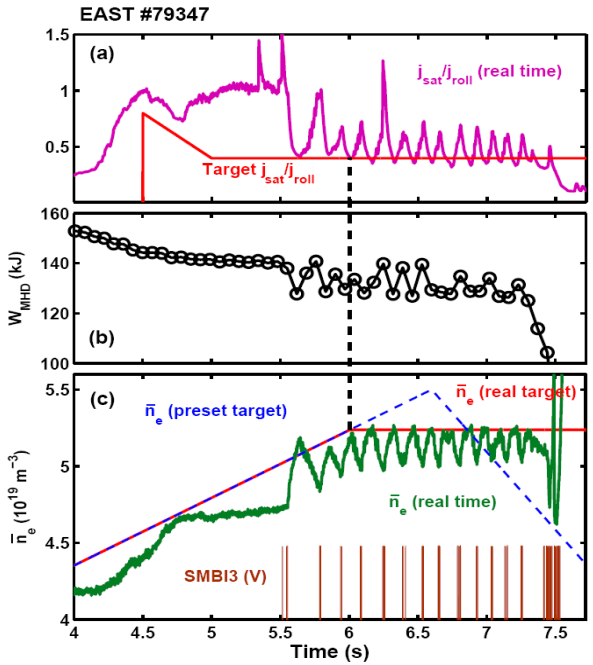
Feedback control of H-mode detachment degree via j_{sat}

- **The feedback was achieved with two separate means, $T_{e,div}$ < 5eV**
  - ✓ Divertor neon seeding
  - ✓ LFS SMBI D_2 fueling
- **Excellent compatibility with core plasma performance, $\Delta W_{mhd} < 10\%$**





Control: L. Wang et al., Nucl. Fusion (2019)
Q. Yuan et al., Fusion Eng. Design (2020)
Physics: J. B. Liu et al., Nucl. Fusion (2019)
Modeling: X. J. Liu et al., PoP (2019)

- **Demonstrated in DIII-D high β_p scenario with H_{98} ~ 1.5, 2019**

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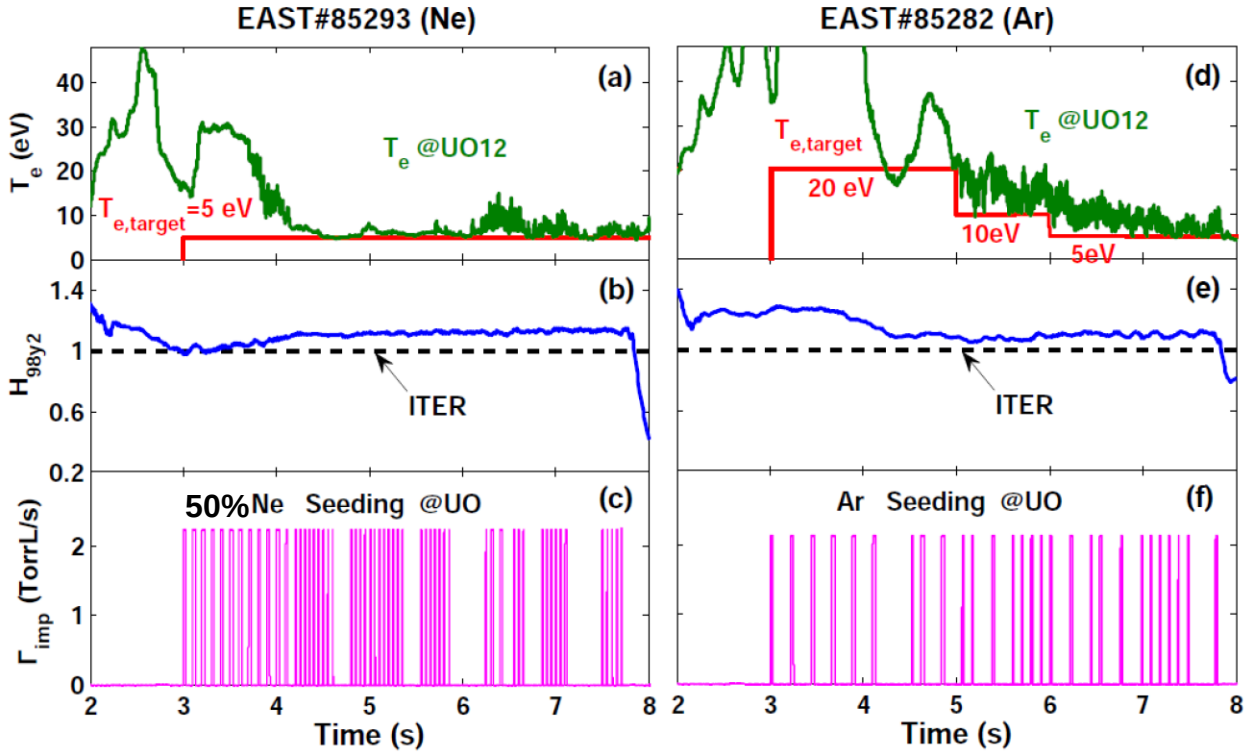
Demonstration of detachment control via Divertor-Te feedback

- **Argon accesses detach. more easily than Neon, while slight performance loss**
  - Neon case needs much more particles than Ar for cooling Te
- **For $T_{e,div}$ =5eV, neon is more compatible with core plasma, H_{98} ~ 1.1**



D. Eldon et al., Nucl. Mater. Energy (2021)
D. Eldon, 24th PSI Conference (invited talk), 2021 Korea
L. Wang, 28th IAEA-FEC (Oral talk), 2021 France

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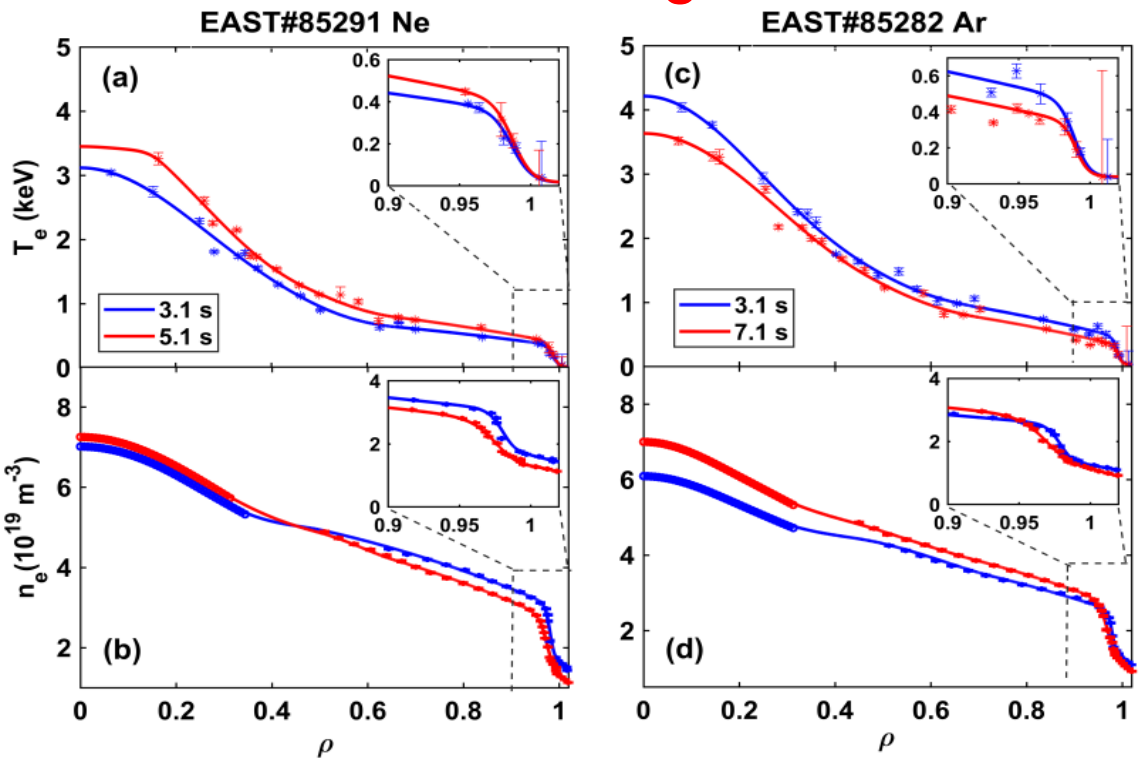
Neon vs Argon



D. Eldon, 24th PSI Conference (invited talk), 2021 Korea

L. Wang, 28th IAEA-FEC (Oral talk), 2021 France

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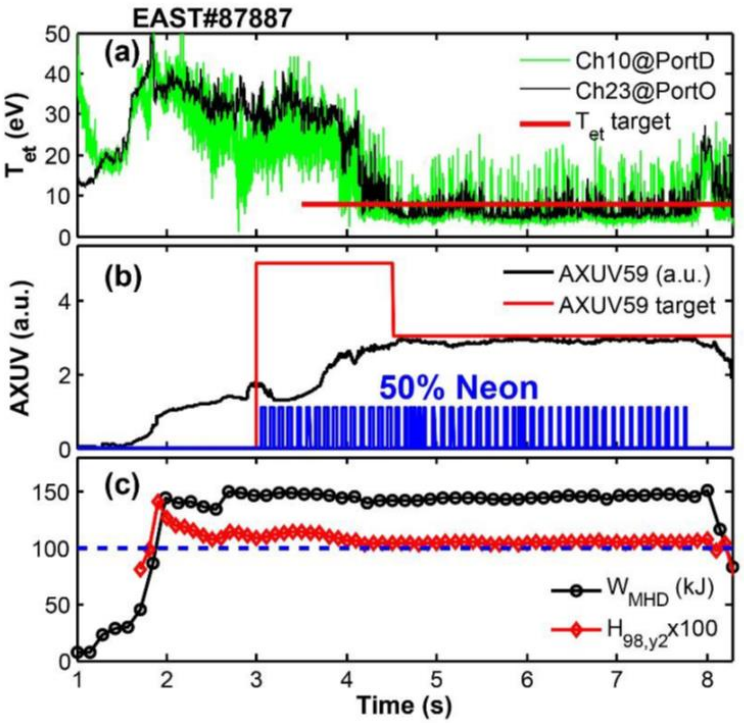
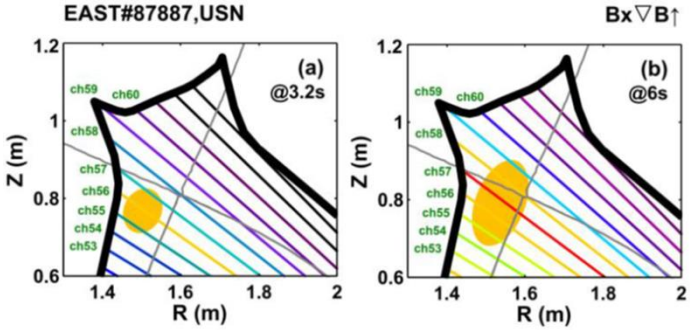
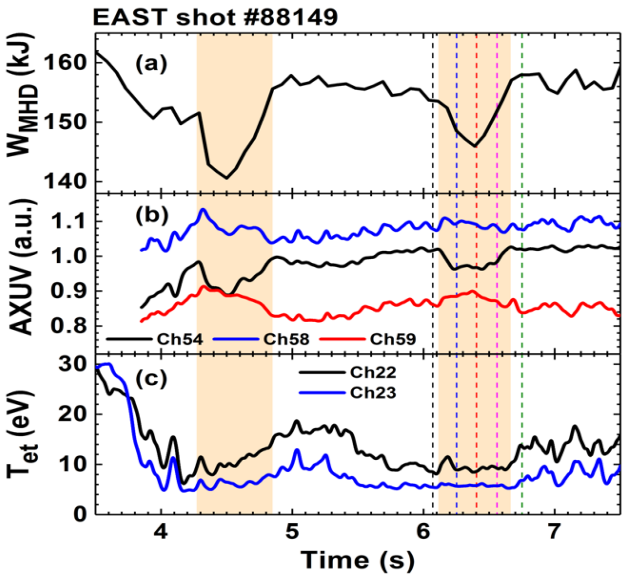
Detachment feedback control via $T_{e,div}$ + P_{rad}

- **A new combined feedback control module using real-time divertor LP measurement and X-point radiation**







G.S. Xu et al., Nucl. Fusion (2020)
G.S. Xu, 24th PSI Conference (invited talk), 2021 Korea

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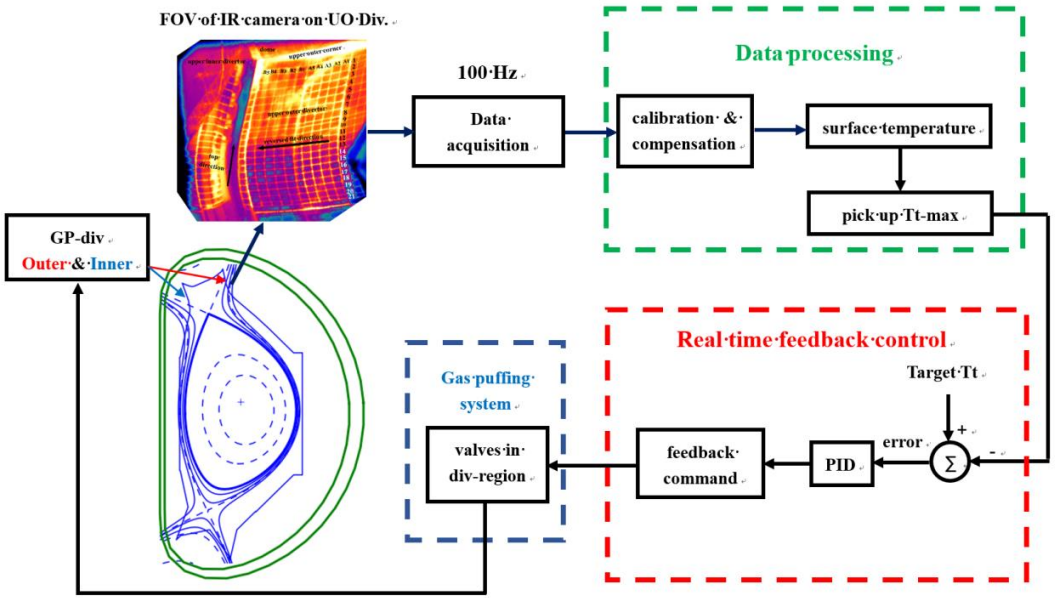
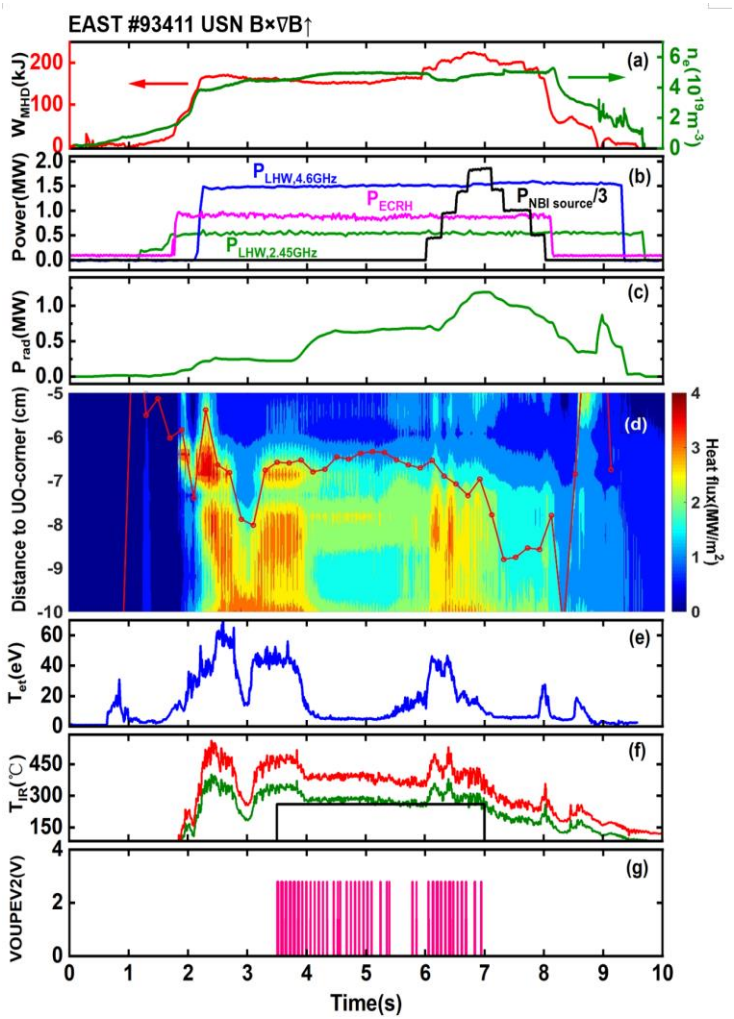
EAST demonstrated IR surface temperature control

- IR surface temp. more directly addresses hardware limit
- Requires real-time processing of IR camera data by PCS
- RT signal used to modulate gas puff





M. W. Chen et al., Nucl. Fusion (2020)

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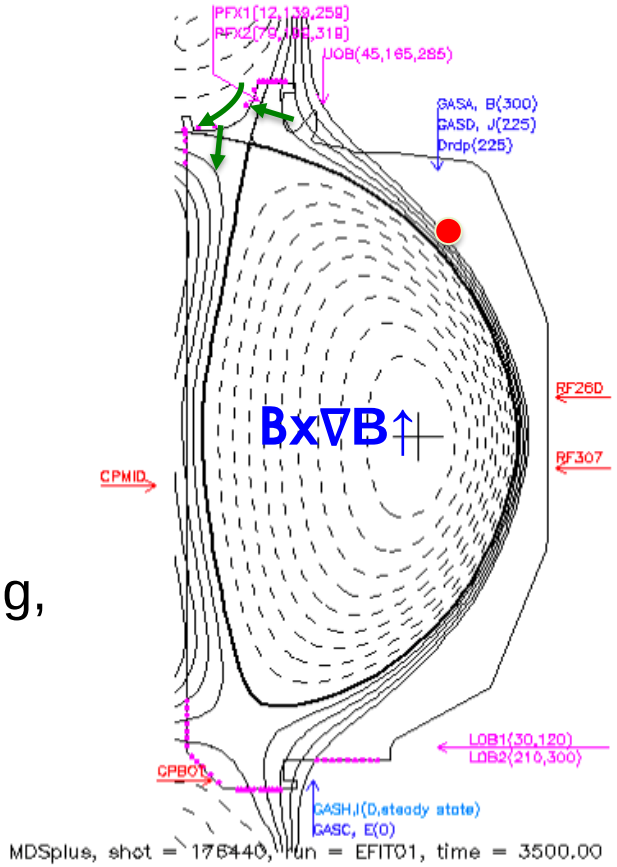
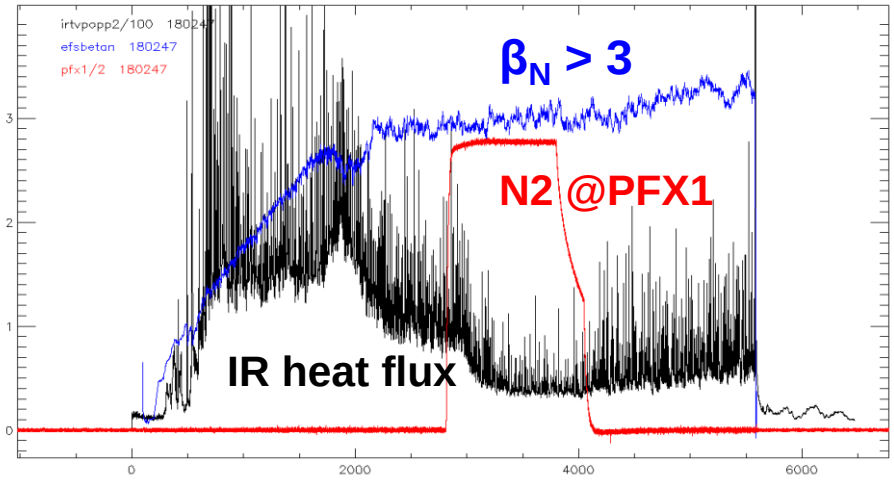
Latest experimental progress in USN (September, 2019)

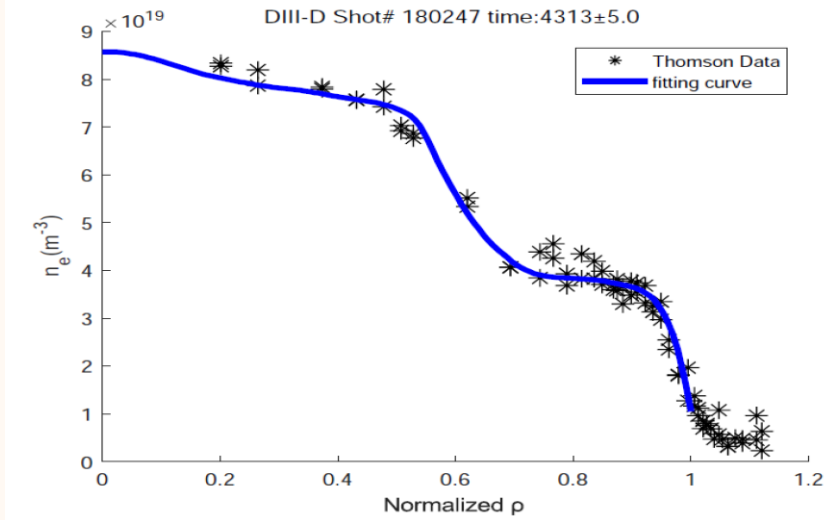
- Detachment feedback control algorithm
- More closed USN configuration
  - Constant Ip~0.72 MA & Bt w/o ramping
  - Increase β_N ~ 3 & dRsep to > 5mm
- Feedforward N2 seeding → $T_{e,div}$ < 5eV
  - N2 seeding through PFX1
- Feedback detachment control with N2 seeding, GASB/PFX1
  - Target j_sat/j_roll =0.3 (T_et < = 5eV)
  - Target j_sat/j_roll = 0.6, 0.3 in one shot
- Neon seeding for USN detachment access, & feedforward control

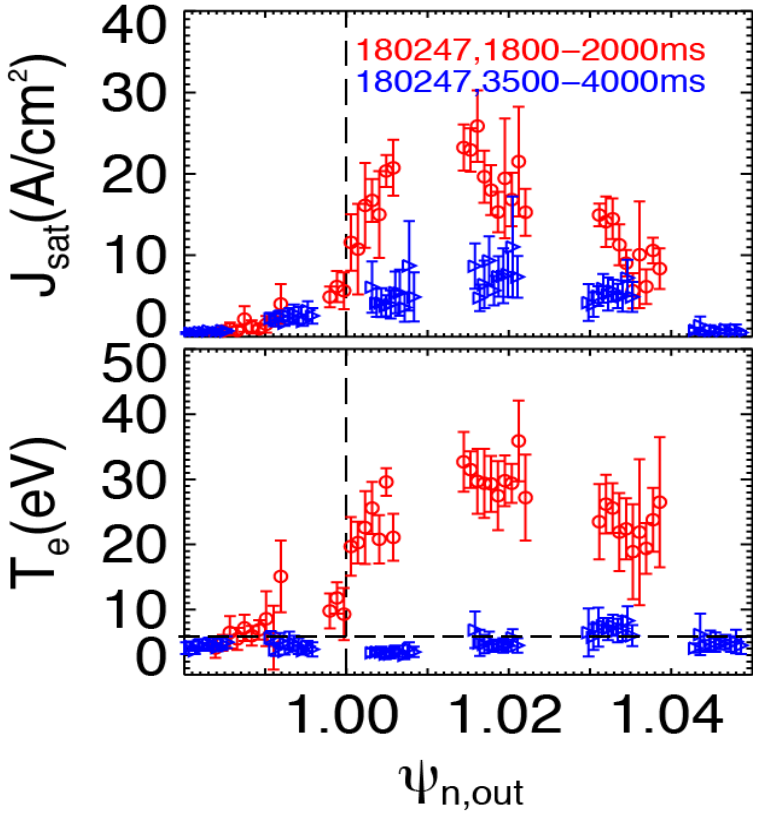


Demonstrated the excellent compatibility of complete detachment with high β_p scenario with sustained ITB+ETB

➢ **Excellent core-edge-divertor integration: ITB+ETB+detachment**







H. Q. Wang et al., Invited talk, 62nd APS-DPP, 2020
D. Eldon et al., Invited talk, 24th PSI, 2021
H. Q. Wang et al., this US-PRC MFC Workshop
L. Wang et al., Oral, 28th IAEA-FEC, 2021

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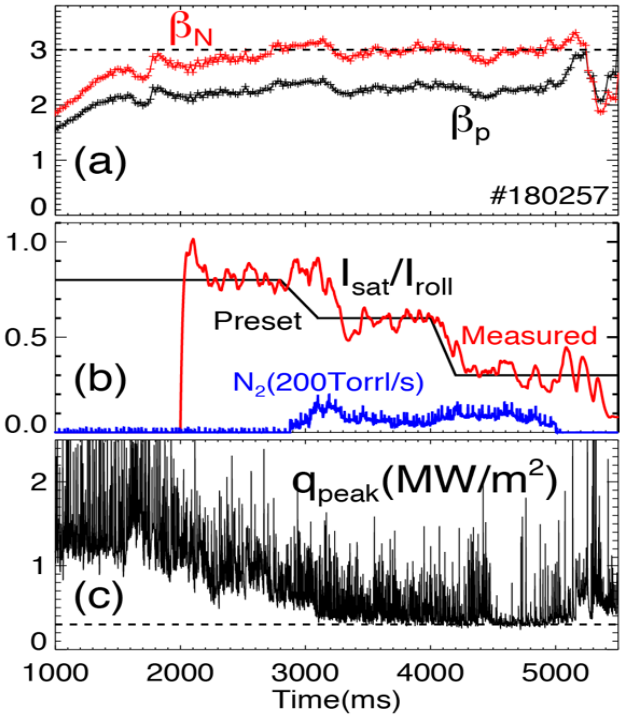
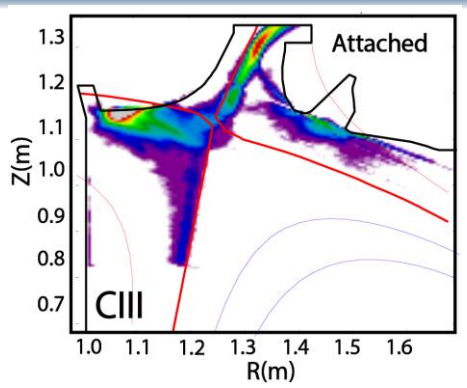
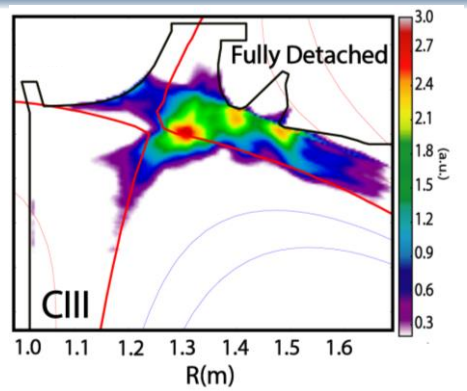
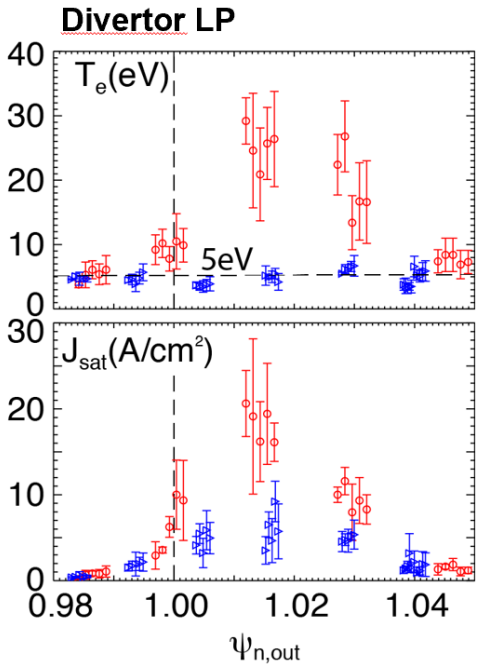
Achieved feedback control of detachment in high β_p scenario successfully, excellent core-edge integration

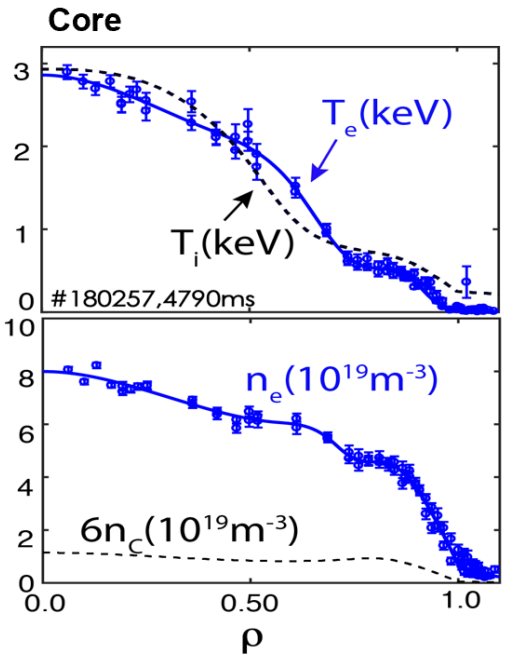
- β_N~3, β_p>2, H_{98}~1.5, q_{95}~8, V_{loop}< 100mV: ITER-SS relevant scenario
- DoD>3, Div-LP $T_{e,\,div} \leq$ 5eV across the entire target











L. Wang, H. Wang*, S. Ding, A. Garofalo, X. Gong et al.,

Nature Commun. 12, 1365 (2021)

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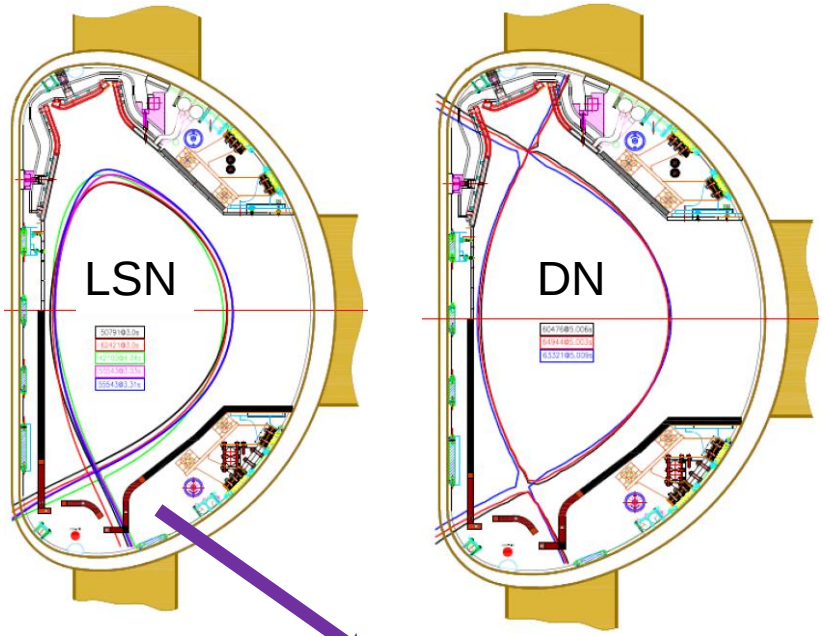
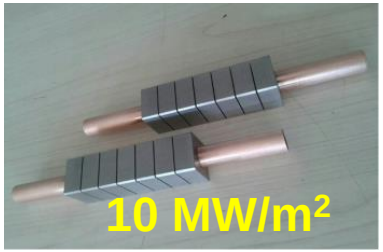
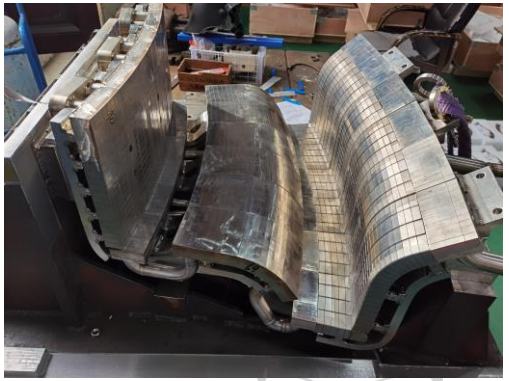
Bottom divertor upgrade (C → W, assembly ongoing)

- **Mission**
  - H-mode ≥ 400s; 10 MW*100s
  - Divertor & PWI control Physics
  - → Core-edge integration for ITER/CFETR
- **W/Cu divertor with water-cooling**
  - Monoblock in the strike point region (10MW/m²)
  - Flat-type structure for the dome plates (5MW/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**
- **SMBI for impurity seeding feedback control**







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Joint DIII-D/EAST research demonstrated active feedback control of detachment compatible with core plasma

- **EAST: Active feedback control of H-mode detachment/radiation**
  - P_{rad} (2017), J_{sat} (2018), $T_{e,div}$ (2019), $T_{e,div}$+P_{rad} (2019), T_{IR} (2019)
  - Good compatibility with core performance: $H_{98} > 1$, $T_{e,div} \sim 5$eV
- **DIII-D: Integration of full detachment+ITB+ETB in high β_p scenario**
  - $T_{et,div} \sim 5$eV, $\beta_N \sim 3$, $\beta_p > 2$, $H_{98} \sim 1.5$: excellent core-edge-divertor integration
  - Degree of detachment (DoD) controlled actively

Next step → In support of ITER & CFETR

- **Demonstration of stable H-mode detachment control > 100s**
  → Integrated Div&PWI control means compatible with core plasma
- **EAST's new lower W divertor for enhanced heat/particle exhaust compatible with high-performance SSO**
  ✓ More advanced & reliable divertor diagnostics
  → Long pulse H-mode ≥ 400 s with $H_{98} > 1$, $f_{bs} > 50\%$

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Joint Detach. Exp. Main objectives (Apr. 2021, DIII-D)

- **Can we approach to $q_{95} < 7$ & $G>0.2$ in high β_p scenario?**
  - Higher core performance with sufficient NB
  - Can we maintain full detachment simultaneously?
  - How → Better integration of ITB + ETB + (full) detach. + ELM supp./mitig.? Propose N_2&Neon mixed seeding.

- **Can we achieve detachment+ITB-ETB with more ITER-like single null shape?**

- **Validate self-consistent simulations of integrated core-edge-divertor solution.**

Thank you for your attention!

Group photo in EAST control room

Group photo in DIII-D control room

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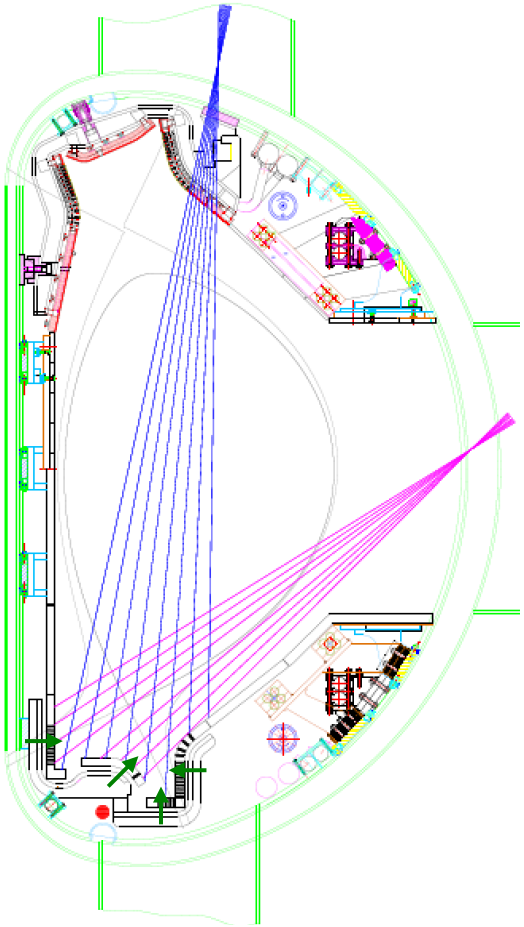
Upgrade of div.-diagnostics & gas puff systems



- **Div-gas puff locations**
  - **Normal fast valves**
  - **New div-SMBI**
  - **Impurity, Fueling**

- **1st Priority: safety & operation oriented**
- **2nd Priority: physics oriented**

Categories	Div-diagnostics	Plasma parameters
Heat & Particle Fluxes	IR camera	Heat Flux, T_{target}
	Divertor probes	ne/Te/Particle & Heat fluxes/3D
	Thermal Couplers	Temperature
	Neutral pressure	Neutral pressure
Impurities	Visible spectroscopy	Visible spectroscopy
	Bolometer	Absolute measurements of total radiation losses
	EUV/VUV	High-Z impurity emission
	Divertor LIBS/LIAS	Retention & wall analysis
Phys. & PMI	Reflectometry	ne profile & turbulence
	Edge Current Actuator	SOL current filaments

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