Achievements of actively controlled divertor detachment compatible with sustained high confinement core in DIII-D & EAST

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28th IAEA FEC, May 10-15, 2021 online

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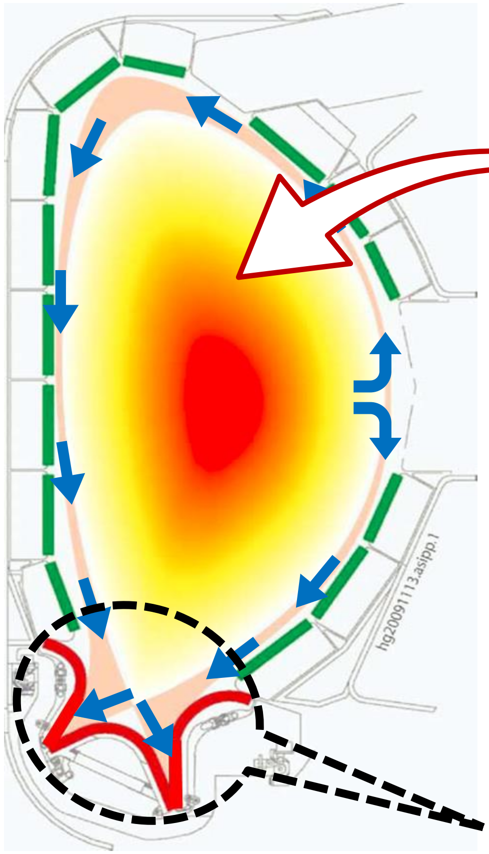
Outline

- **Motivation & Major Progresses**
- **Active detachment control compatible with core**
  - DIII-D: fully detached high-β_p plasmas
  - EAST H-mode plasmas
- **Summary & Near-term Plans**

Divertor heat load control & Core-Edge integration are critical issues for fusion reactors

- **A steady-state tokamak fusion reactor: sustain fusion energy output for sufficiently long operation**
  - Detachment: most promising means for SS PWI control



SS Fusion Core

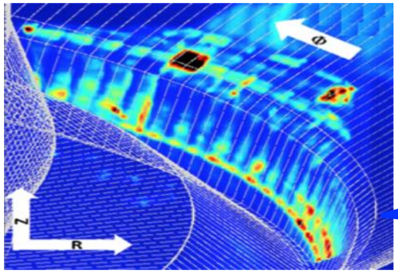
- ○ Ignition
- ○ High fusion gain
- ○ Non-inductive CD
- ○ Controlled Stability
- ○ …

High heat flux
Long duration

Boundary condition

Boundary/PWI

- ○ Materials life cycle
- ○ Pumping & He removal
- ○ Fueling/Recycling
- ○ T Retention
- ○ …



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

EAST

- ITER-like W divertor
- RF heating
- Long pulse
- …

DIII-D

- High performance
- Control & Phys.
- Full diagnostics
- …

High β_P scenario: **a promising candidate for ITER's steady-state operation**

- **DIII-D: Integration of full detachment + ITB + ETB in high β_p scenario**
  - $T_{et,div} \leq 5$eV, $H_{98} \sim 1.5$, $\beta_N \sim 3$, $\beta_p > 2$ and very low divertor particle flux
  - Excellent core-edge-divertor integration [L. Wang et al., Nature Commun. 12, 1365 (2021)]

- **EAST: A series of active detach. controllers compatible with H-mode**
  - P_{rad} (2017), J_{sat} (2018), $T_{e,div}$ (2019), $T_{e,div}+P_{rad,\ X\text{-}point}$ (2019), T_{IR} (2019)
  - $T_{e,div} \sim 5$eV & $H_{98} > 1$ in standard H-mode, grassy ELMy H-mode, high β_P scenario

Both EAST & DIII-D successfully developed active detachment controllers compatible with high-H_{98} core plasmas

- **EAST: 5 detachment/radiation controllers achieved with core $H_{98} > 1$**

Control methods	Control parameters
Total radiation [Wu18NF]	$P_{\mathrm{rad,total}}$
Div. particle flux[Wang19NF,Yuan20FED]	j_{sat}
Div. electron temperature[Eldon21NME]	T_{et}
Combination of div. electron temperature and X-point radiation[Xu20NF]	$T_{\mathrm{et}} + P_{\mathrm{rad,\ X\text{-}point}}$
Div. target temperature[Chen20NF]	$T_{\mathrm{t,\ peak}}$

- **DIII-D: DoD controller via J_{sat} achieved with core H_{98} ~1.5 in high β_p scenario**

Control methods	Control parameters
Div. electron temperature [Eldon17NF]	$T_{\mathrm{et,\ DivTS}}$
Div. radiation [Eldon17NF]	$T_{\mathrm{et}} + P_{\mathrm{rad,\ div}}$
Div. particle flux [Eldon21NME]	j_{sat}

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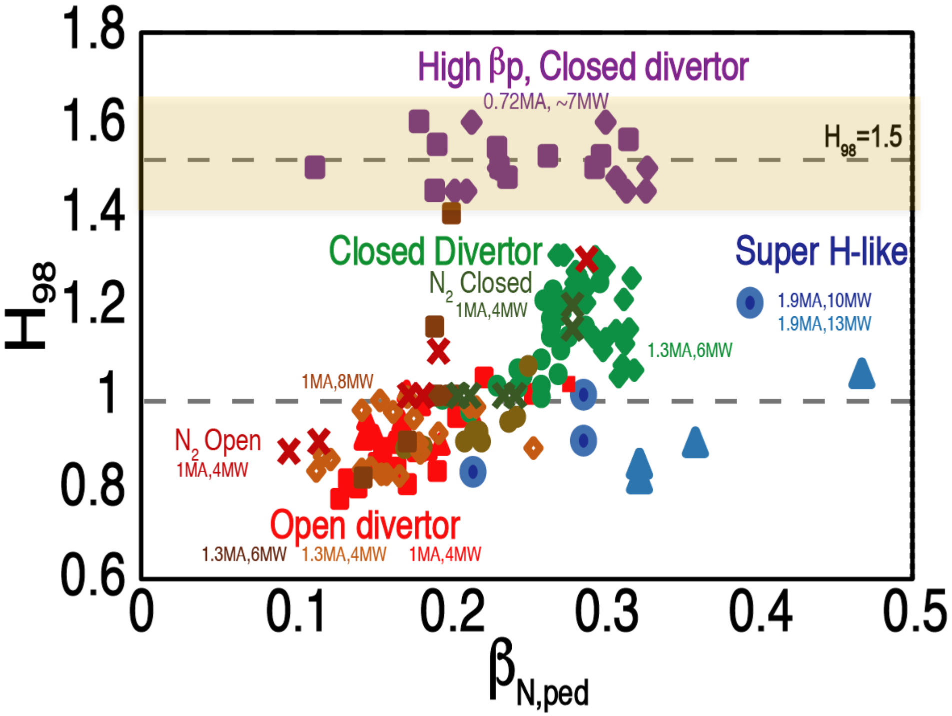
High β_p is a promising candidate scenario for steady-state fusion core, facilitating core-edge-divertor integration

- **High β_p → Strong Shafranov shift → High confinement quality → high fusion gain → reduce reactor cost**
  - Large-radius ITB + ETB → isolate hot core vs cold boundary

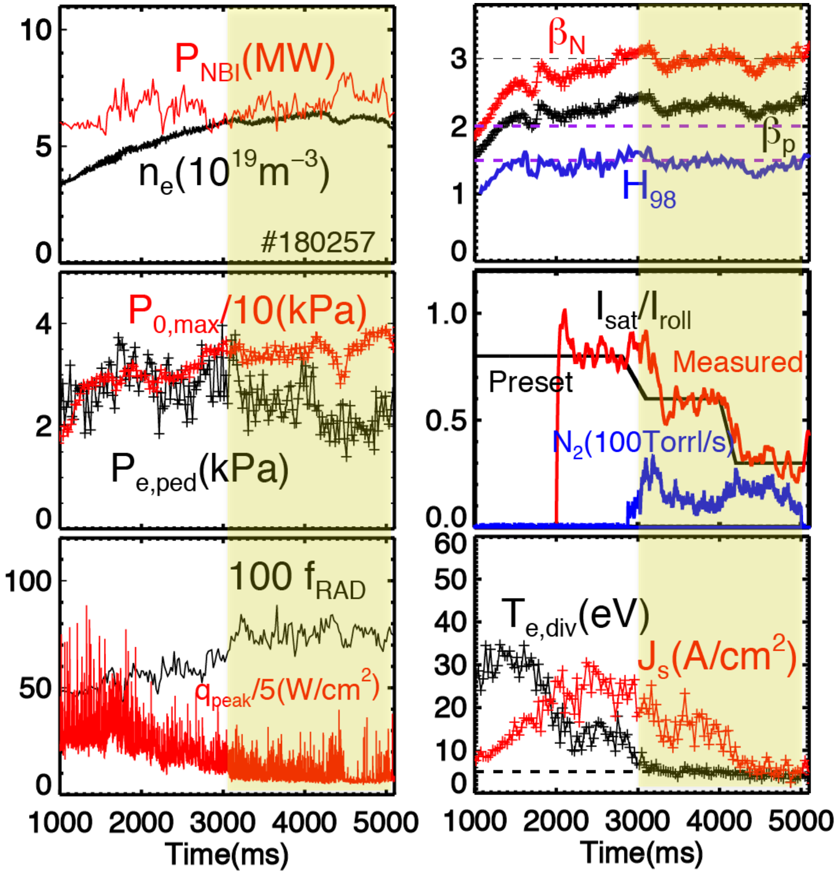
- **High β_p: high confinement at lower pedestal Te → benefit heat exhaust**
  - Full detachment with $T_{e,div} \leq 5$ eV across the entire target
  - ITB breaks core stiffness and improves core-edge integration

- **Recent experiments & simulations support the possibility of high β_p scenario for ITER reaching Q=10 at low Ip** [S. Ding, this Conf., EX/1-TH/1-3, Tue AM]



X. Gong, this conference, EX/1-TH/1-5, Tue AM
A. Garofalo, AAPPS-DPP 2019; J. Qian, APS-DPP 2019;
J. McClenaghan, IAEA-FEC 2018; J. Huang, EPS-DPP 2019

DIII-D: Excellent compatibility of detachment and high global performance has been achieved in N_2 seeded high β_p plasmas



- $\beta_N \sim 3$, $\beta_p \sim 2.4$, $H_{98} \sim 1.5$, $f_{GW} > 0.9$, $f_{NI} \sim 0.7$

- **Degree of Detachment feedback control**
  - Adjust impurity puff rates[D. Eldon, this conference, EX/P1-934]
  - DoD ~ I_{roll}/I_{sat}, follows the control preset

- **Radiation dominates the power dissipation**
  - $P_{rad,tot}/P_{nbi} \sim 0.75$; $P_{rad,core}/P_{nbi} \sim 0.3$

- **IR peak heat flux from 2MW/m^2 to ~0.3MW/m^2**

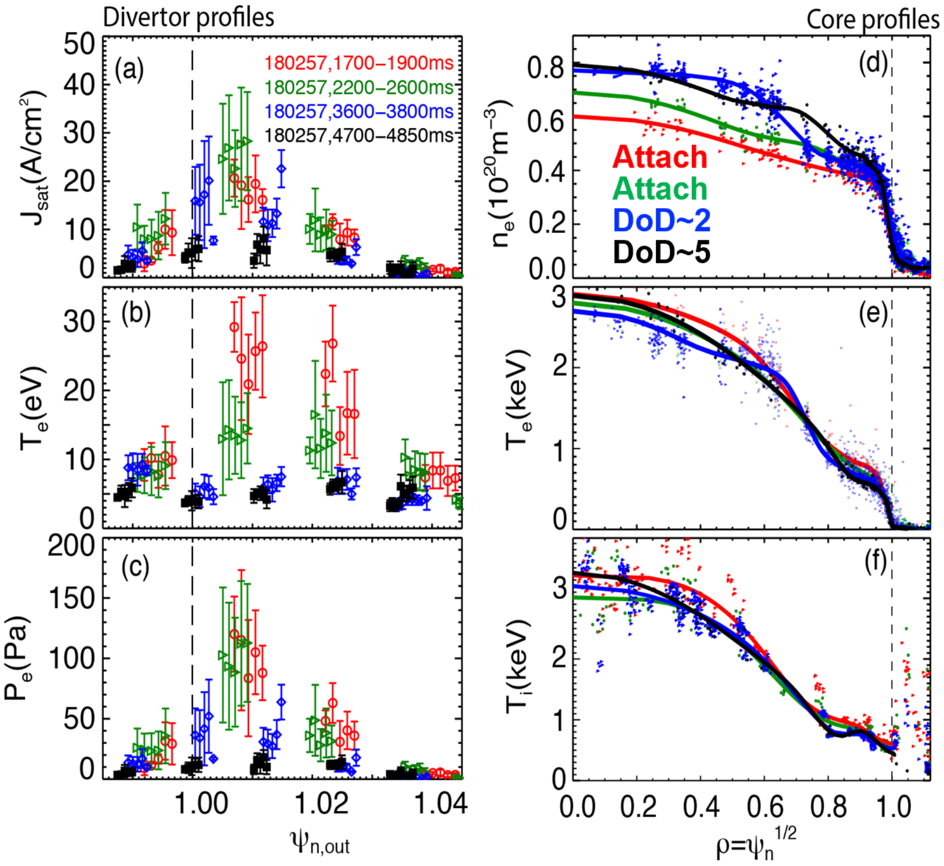
H. Wang, 62nd APS-DPP, 2020; H. Wang, 29th ITPA-DSOL, 2020
L. Wang, H. Wang*, S. Ding, A. Garofalo, X. Gong et al., Nature Commun. 12, 1365 (2021)

DIII-D: Full detachment and sustained large-radius ITB + ETB are simultaneously demonstrated in high β_p plasmas

- **$T_{e,div} \leq$ 5eV across entire target plates**
  - > 90% divertor pressure loss
  - DoD >5 with strong J_{sat} reduction
  - High neutral pressure → exhaust

- **ITB grows during detachment**
  - ITB at a large radius
  - n_e and T_e ITB grows and expand

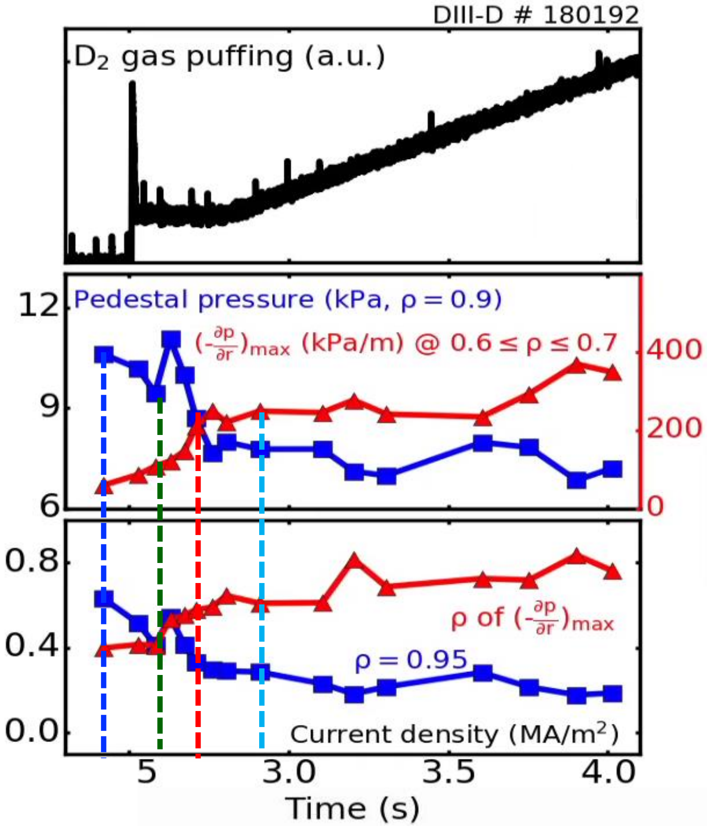
- **P_{ped} reduces due to detachment**
  - T_e pedestal reduced by 50%
  - n_e pedestal increases slightly

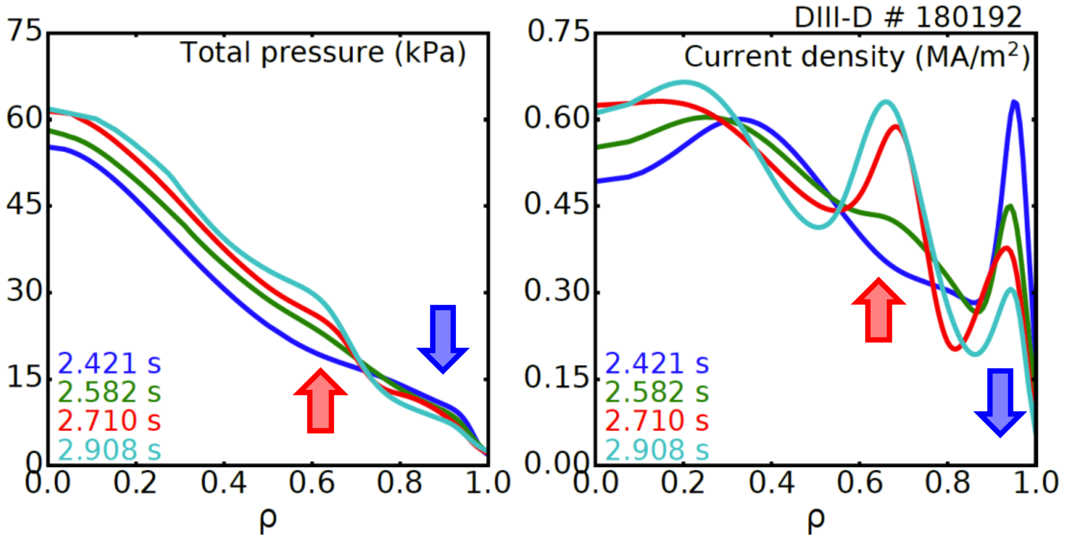


H. Wang, 62nd APS-DPP, 2020; H. Wang, 29th ITPA-DSOL, 2020
L. Wang, H. Wang*, S. Ding, A. Garofalo, X. Gong et al., Nature Commun. 12, 1365 (2021)

DIII-D: Current density increases at large radius (ρ =0.6-0.7) due to reduced P_{ped} during detachment access

- **D_2 fueling detachment lowers P_{ped} height, which promotes strong ITB**
  - Further evidenced by neon seeding
- **Edge current density decreases → current density increases at large radius**
  - Decrease of magnetic shear around ρ = 0.6-0.7 triggers ITB





DIII-D: Formation of Strong Large-Radius (ρ =0.6-0.7) ITB due to Reduced P_{ped} Height, induced by divertor detachment

- **s-α contour plot is produced by CGYRO scan based on experimental data**
  - Large radius ρ=0.6, $k_\theta\rho_s$=0.3, EM

Reduction of pedestal & its current density

↓

Current density at ρ ~ 0.6 increases

↓

Magnetic shear at ρ ~ 0.6 decreases

↓

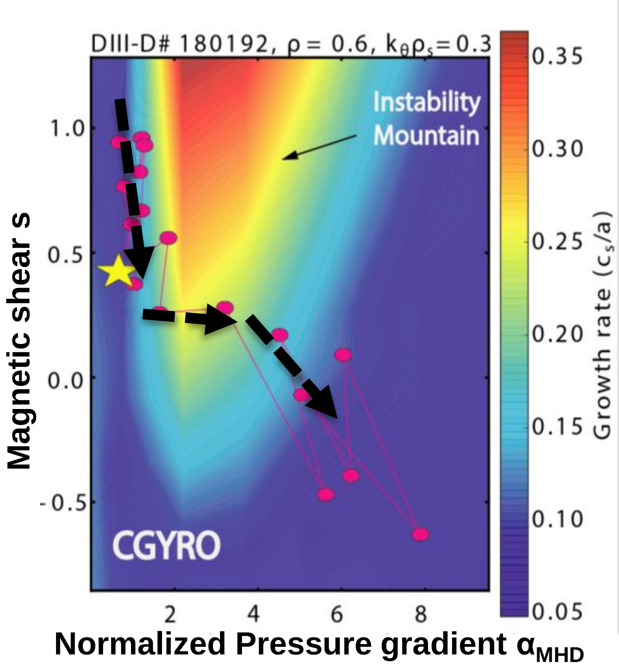
Plasma leaves high growth rate region

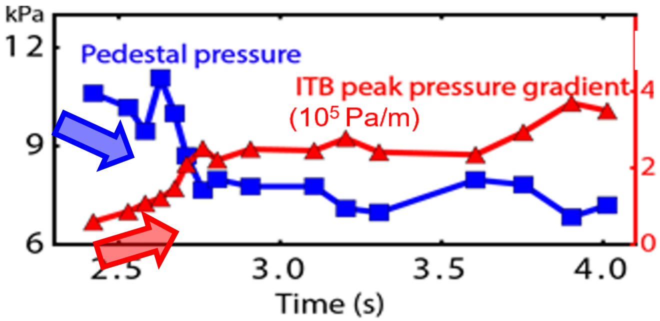
↓

Pressure gradient build up

↓

Plasma moves into second stability regime





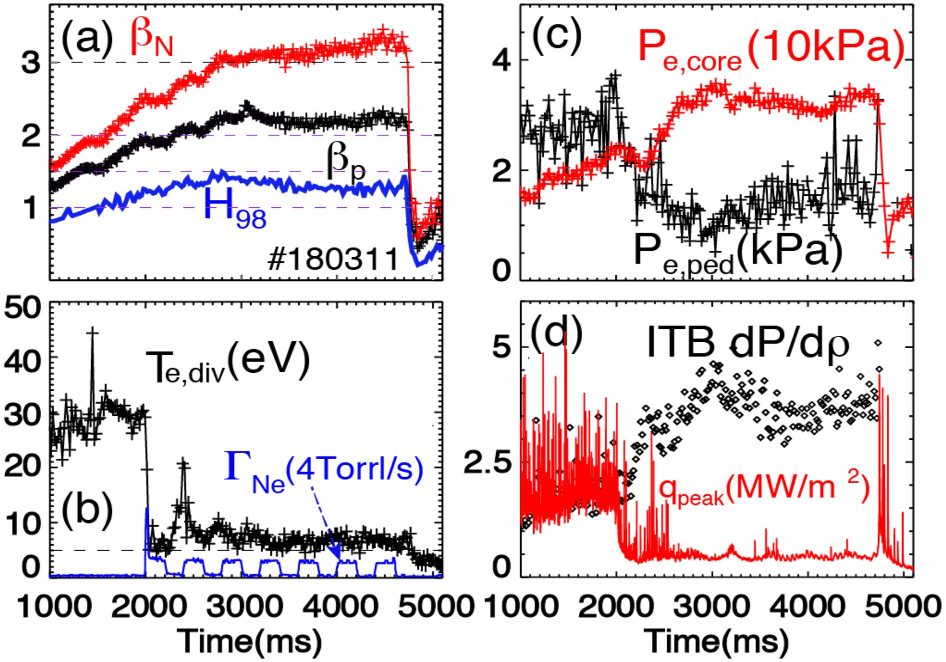
S. Ding, 10th US-PRC MFC Workshop, March 2021
L. Wang, H. Wang*, S. Ding, A. Garofalo, X. Gong et al., Nature Commun. 12, 1365 (2021)

DIII-D: Neon seeding detachment leads to more effective P_{ped} reduction and strong large-radius ITB formation

- **β_N>3, β_p~2.3, H_{98}~1.4, f_{GW}>1.1, q_{95}~7**

- **Neon reduces pedestal even more compared to N2 cases**
  - **Lower pedestal, higher ITB**

- **Partially detached w/ $T_{e,div}$= 5-10eV**



- **Steady ELM suppression + divertor detachment + high performance core**
  - Reproducible ELM suppression by neon seeding

L. Wang, H. Wang*, S. Ding, A. Garofalo, X. Gong et al., Nature Commun. 12, 1365 (2021)

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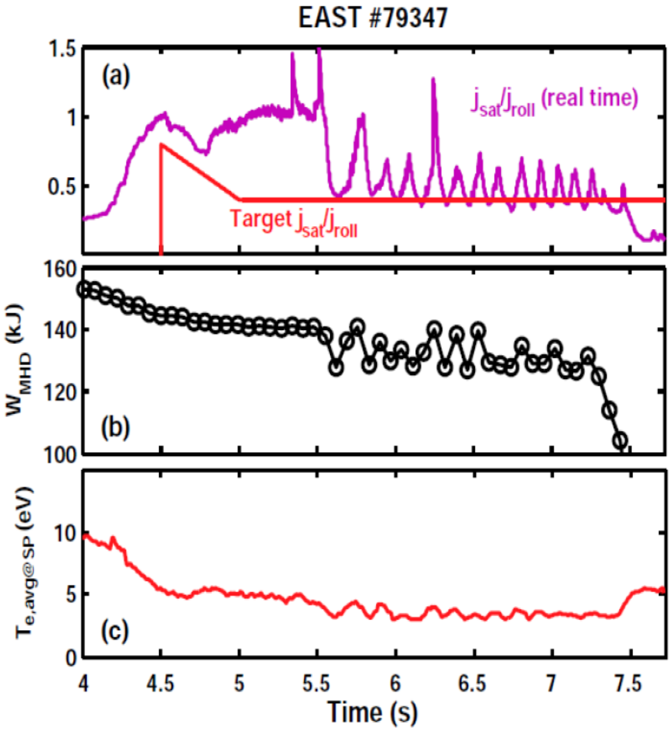
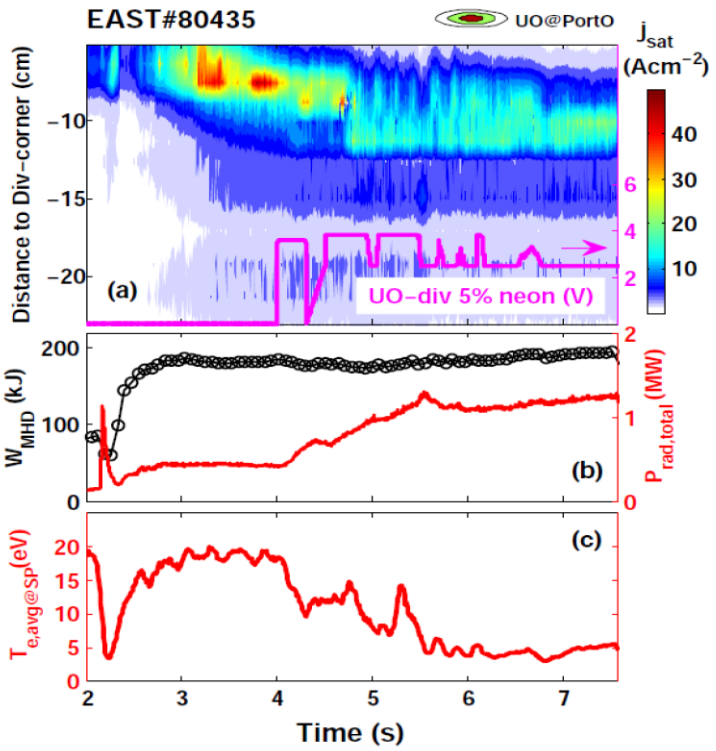
EAST: Achieved feedback control on degree of detachment (DoD) via j_{sat} in standard H-mode

- **The feedback was achieved with two separate means, $T_{e,div}$ < 5eV**
  - ①LFS D2 fueling using SMBI, ②Divertor neon seeding



Q. Yuan et al., Fusion Eng. Des. (2020)

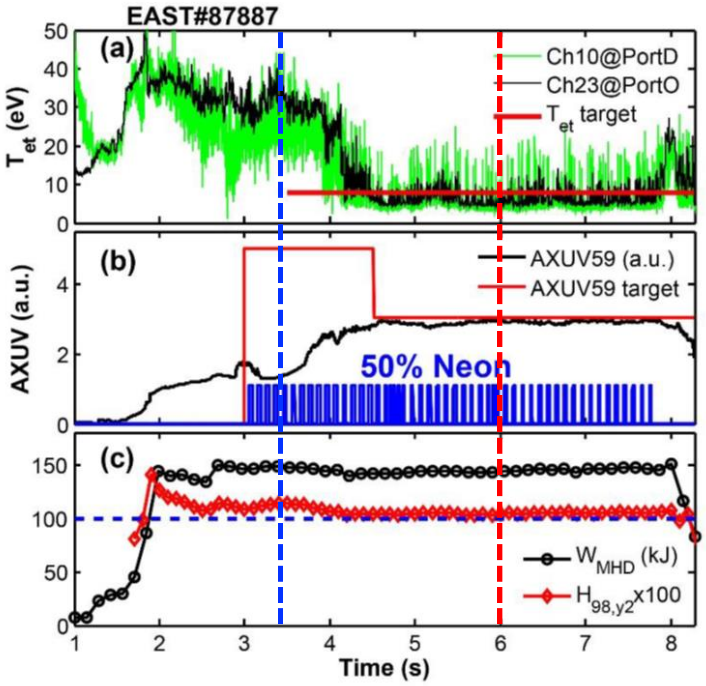


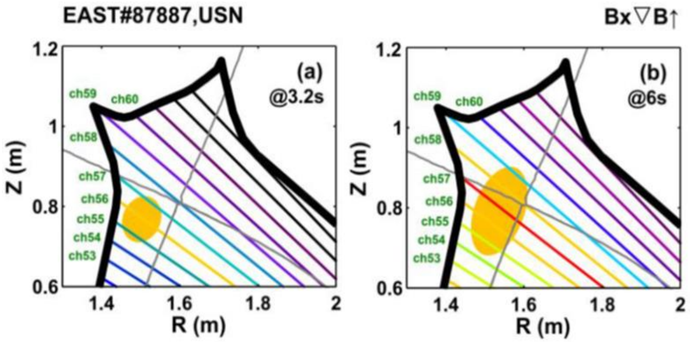
L. Wang et al., Nucl. Fusion (2019)

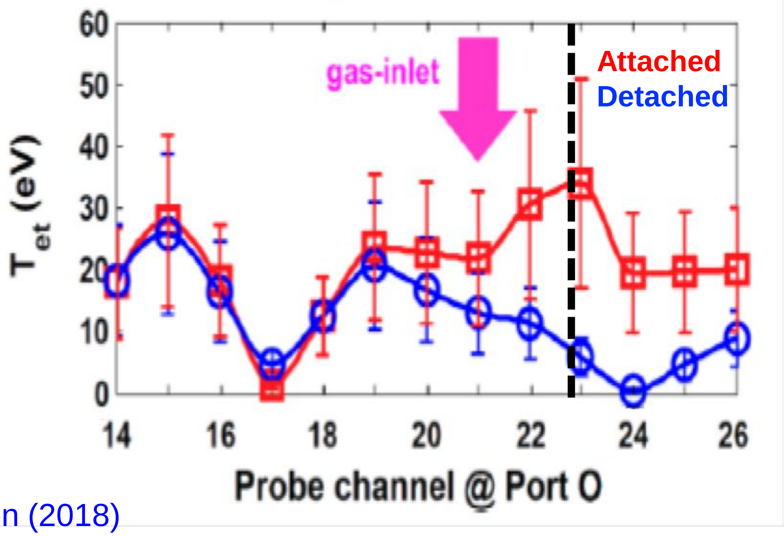
- **Excellent compatibility with core plasma, △W_{MHD} < 10%**
  - **Neon seeding compatible with core → no confinement loss**

EAST: Achieved feedback detachment control via $T_{e,div}$ + P_{rad} in grassy ELMy H-mode

- **A new combined control module using Div.-LP $T_{e,div}$ & X-point radiation**
  - Divertor target Te near strike point maintained at 5-8 eV
  - **H_{98} >1 & plasma stored energy remains constant**





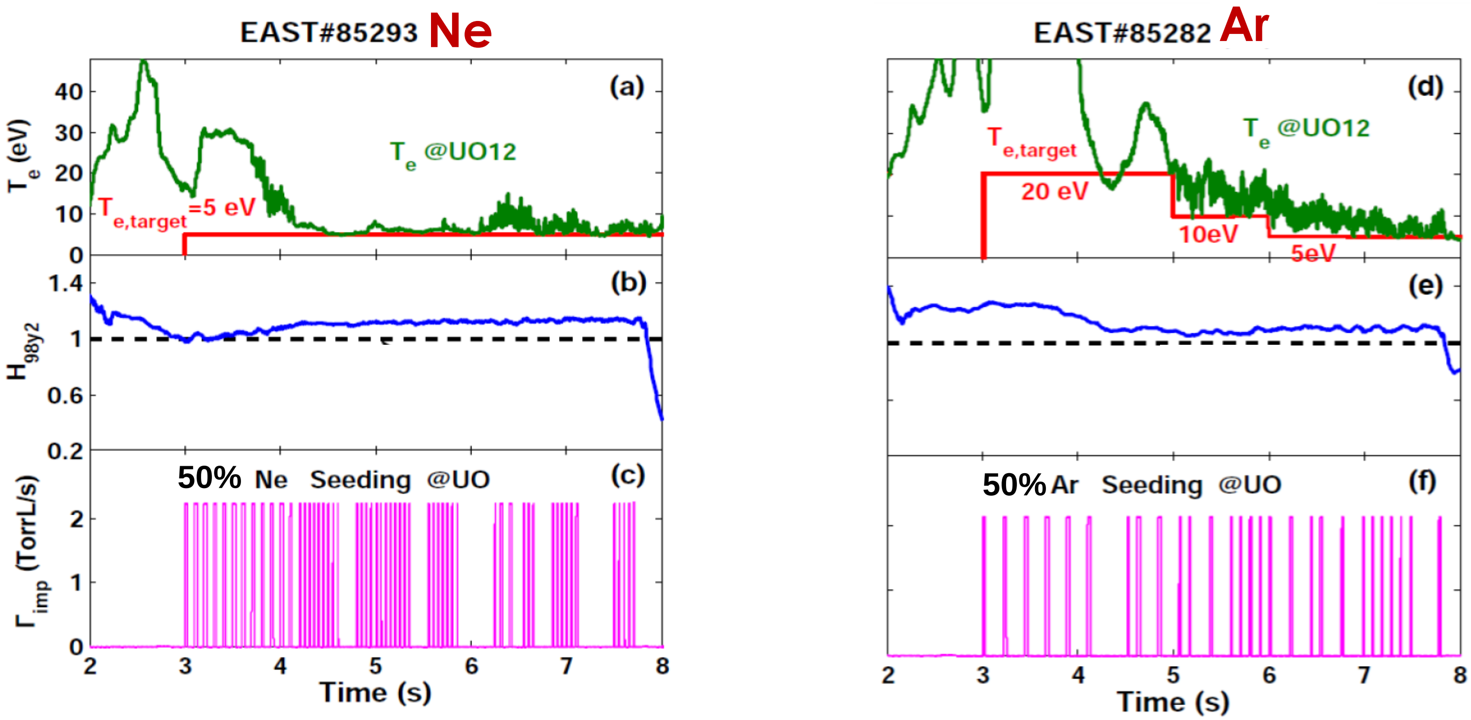


G. Xu, this conference, EX/P2-872, Tue PM

G. Xu et al., Nucl. Fusion (2020) ; K. Wu et al., Nucl. Fusion (2018)

EAST: Achieved feedback control of H-mode detachment via **Divertor-Te**

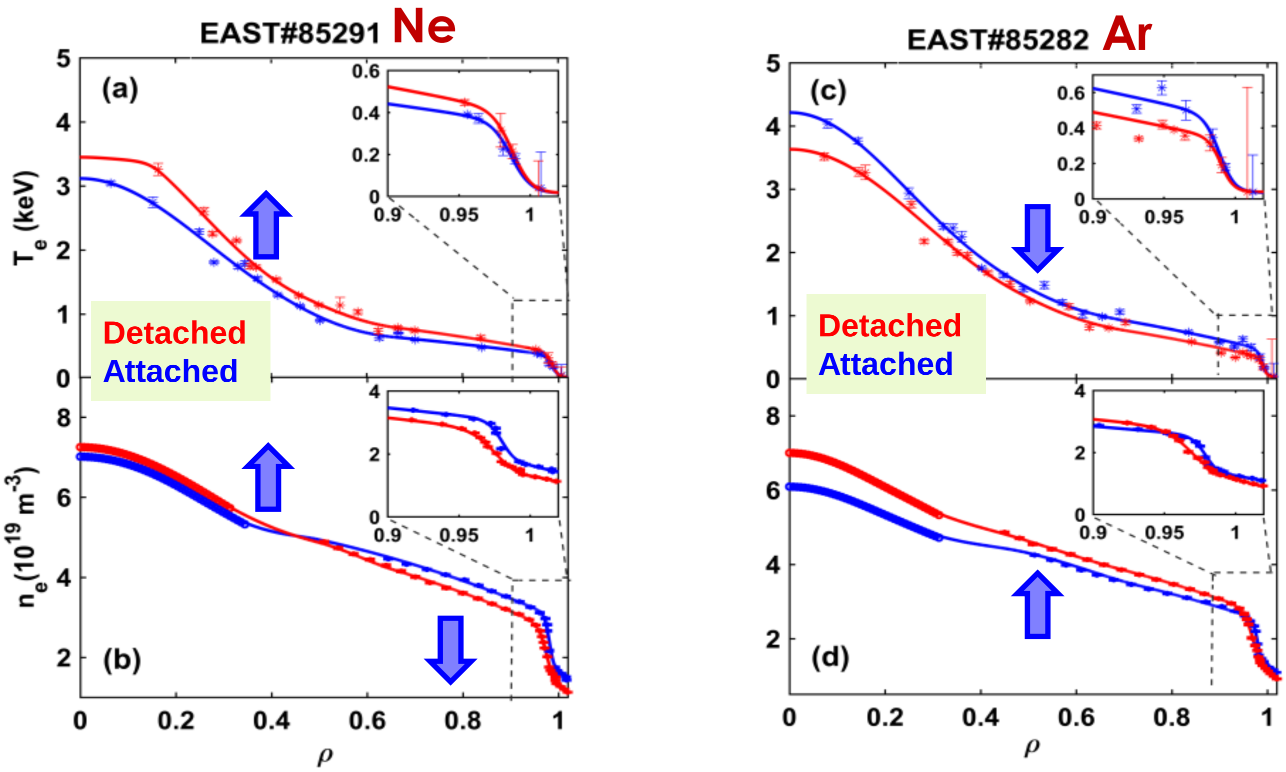
- **$T_{e,div}$ control is important for sputtering reduction**
- **For $T_{e,div}$ =5eV, neon is more compatible with core plasma, H_{98} ~ 1.1**
- **Argon seeded detachment induces slight confinement loss**



D. Eldon, this conference, EX/P1-934, Tue AM
D. Eldon et al., Nucl. Mater. Energy (2021); D. Eldon, 24th PSI Conference, 2021

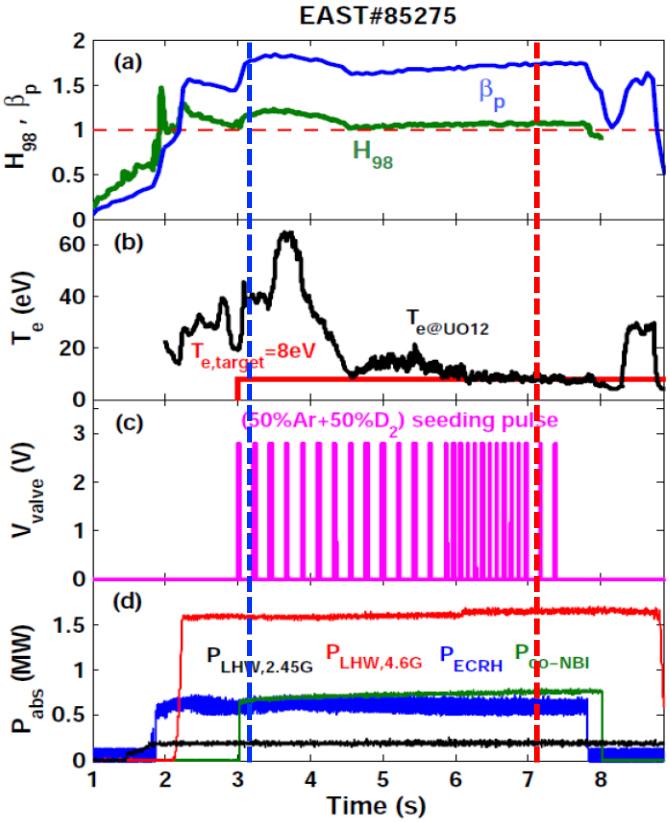
EAST: Ne improves confinement facilitating steep-gradient core while Ar degrades core T_e in standard H-mode

- **$T_{e,div}$ control is important for sputtering reduction**
- **For $T_{e,div}$ =5eV, neon is more compatible with core plasma, H_{98} ~ 1.1**
- **Argon seeded detachment induces slight confinement loss**

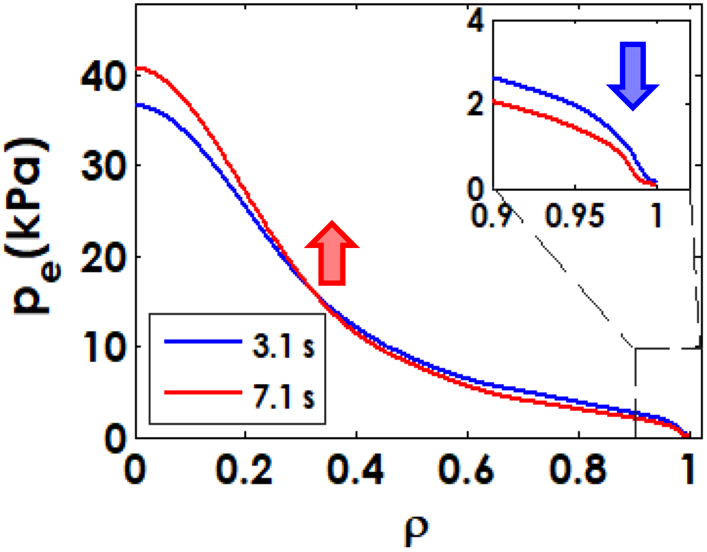


K. D. Li et al., Nucl. Fusion (2021, in press)
D. Eldon, this conference, EX/P1-934, Tue AM

EAST: Active detachment control is used to improve core-edge integration in **high β_p scenario**



- **T_{et} ~ 8 eV, β_p ~ 1.8 and H_{98} ~ 1.1 using Ar**
  - Ar facilitates steep-gradient core and lower pedestal, different from standard H-mode in EAST
- **Detachment → weaker ETB & higher core, similar to detached high β_p scenario in DIII-D**



- **β_P ~2.5, β_N~2.0, H_{98} >1.2 and q_{95}~6.7 achieved using neon seeding with more heating power** [X. Gong, this conference, EX/1-TH/1-5, Tue AM]

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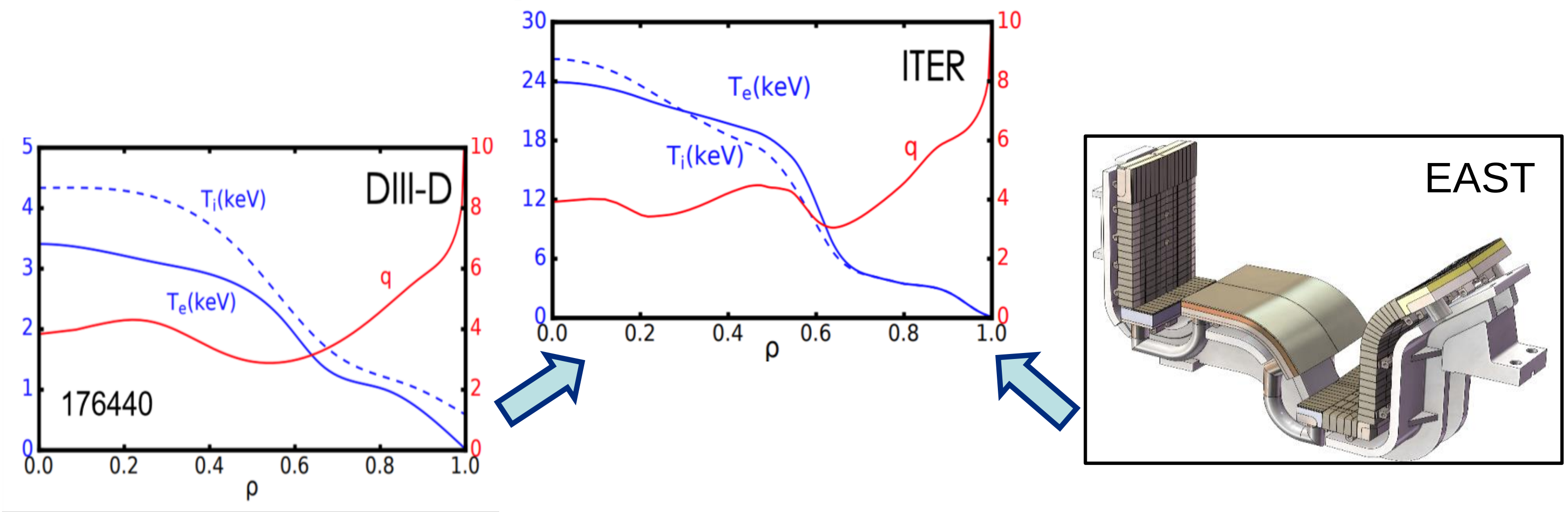
Joint DIII-D/EAST research demonstrated active control of detachment compatible with improved core plasma

- **A series of detachment control techniques for core-edge integration**
  - DIII-D&EAST: divertor J_{sat}, $T_{e,div}$, P_{rad}
  - EAST: divertor T_{IR}, $T_{e,div}$+ $P_{rad, x\text{-}point}$

- **DIII-D: Excellent integration of full divertor detachment with high β_p high confinement core, benefits from large-radius ITB + ETB**
  - H_{98} ~ 1.5, $T_{e,div} \leq$ 5eV across the entire target plates
  - The synergy btw. ITB+ETB improves core-edge integration

- **EAST: Partial detachment & improved core confinement in standard H-mode, grassy ELMy H-mode, high β_p scenario**
  - $H_{98} > 1$, $T_{e, div}$ ~ 5 eV around the strike point
  - Neon seeding is more compatible with core plasma, at present

Near-term Plans → In support of ITER & CFETR



- **DIII-D: Detached high-β_p plasmas with $q_{95} < 7$ & G>0.2**
  - Full detachment + ITB + ETB **+ ELM suppression**
  - **More ITER-like single null shape**

- **EAST: Stable H-mode detachment control > 100s**
  - New lower W divertor for enhanced heat and particle exhaust
  - **Provide PWI solution for H-mode ≥ 400s**

Thank you for your attention!

Group photo in **EAST control room**

Group photo in **DIII-D control room**

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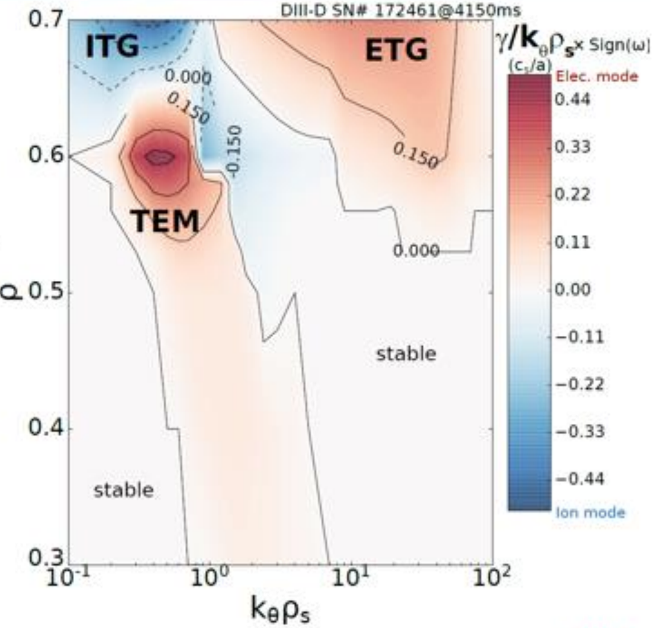
L. Wang / 28th IAEA-FEC, May 2021

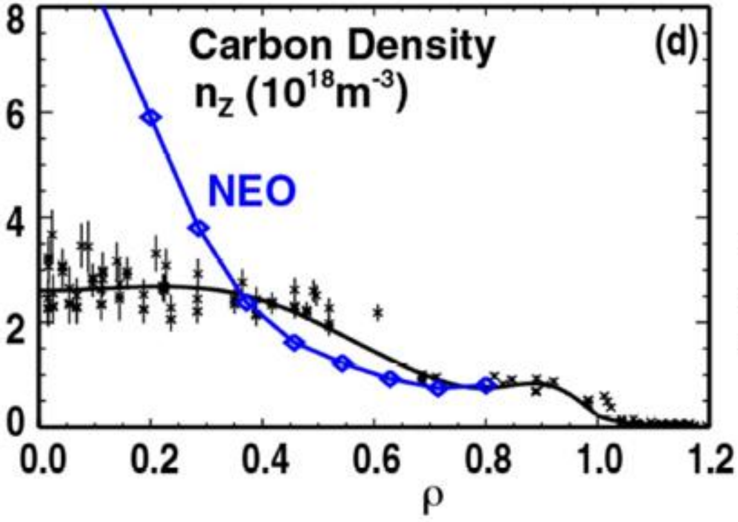
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

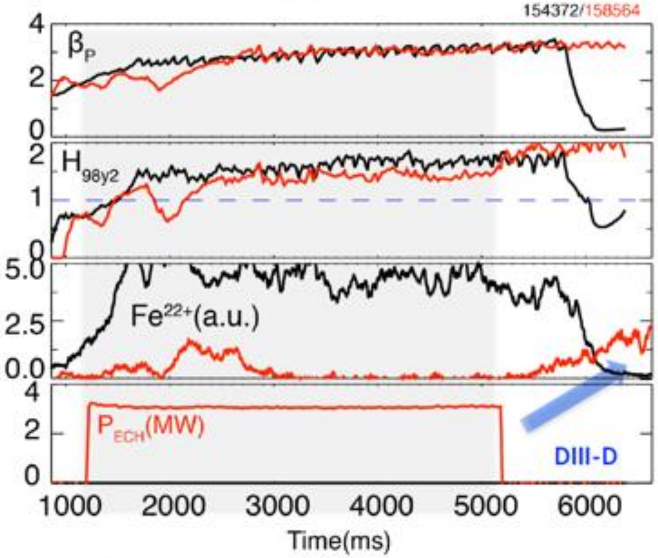
Backup slides

Less Peaked Impurity Profile is Observed in High β_P Plasma Without ECH

- **A stationary, flat carbon density profile inside the ITB**
- **NEO predicts peaked impurity profiles**
- **Experiments show no metal impurity accumulation**
- **GK simulation shows TEM dominant inside ITB at lower q_{95}**
  - Working hypothesis: Impurity control by self-generated TEM
- **ECH can further help control impurity**

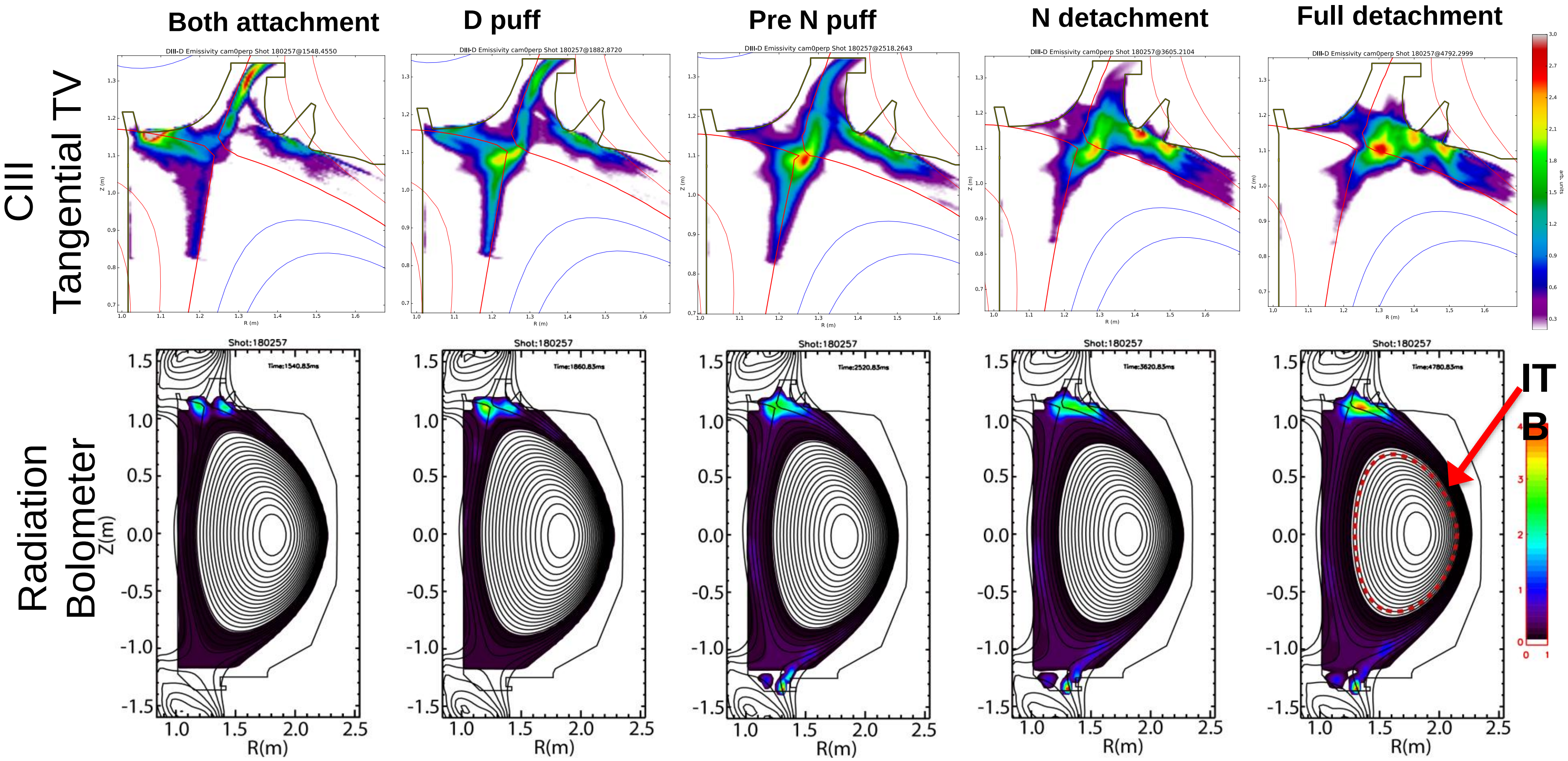






Garofalo, PPCF 2018
Ding, NF 2020
Qian, APS invited 2019

2D images show the peak radiation near X-point during detachment



Both attachment

D puff

Pre N puff

N detachment

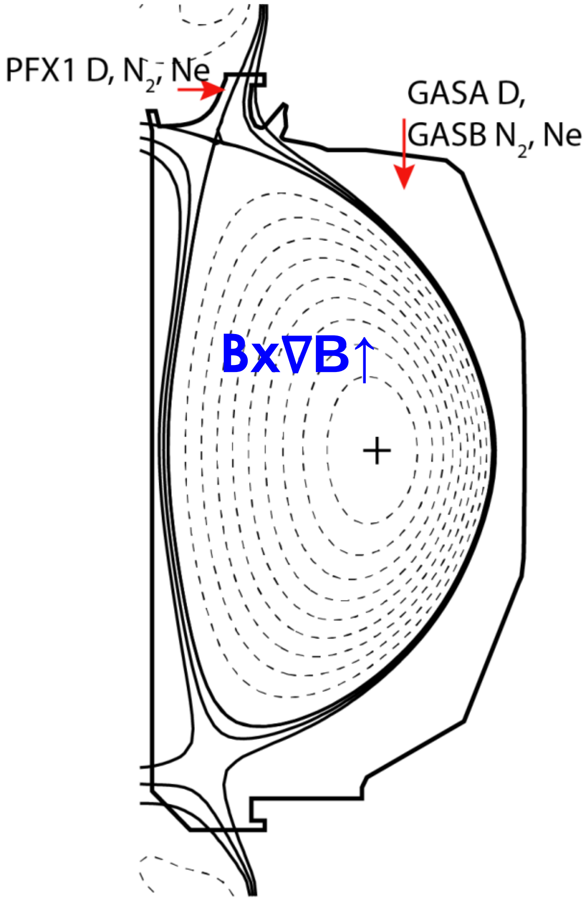
Full detachment

CIII Tangential TV

Radiation Bolometer

ITB

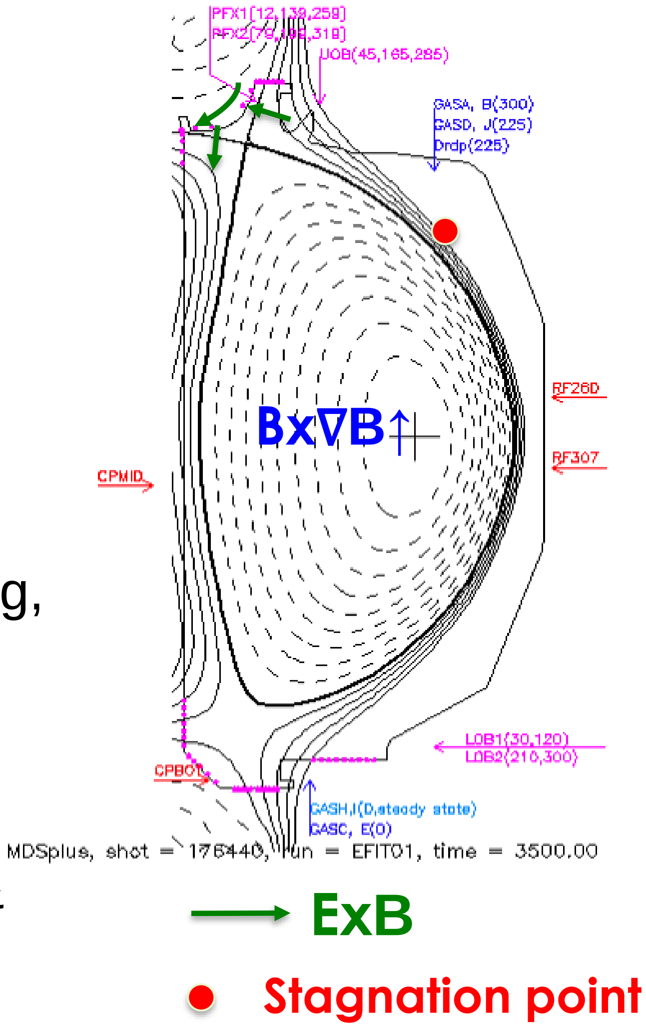
DIII-D experiment was performed under favorable B_T to study the compatibility of high performance core and divertor detachment



- Upwardly Biased Quasi-Double Null with dRsep ~+7mm > $2\lambda_q$
  - Ip~0.72MA
- **Ion B-gradB drift towards divertor → favorable B_T**
  - Beneficial for full detachment
- **Impurity: Nitrogen, Neon; from divertor or main-chamber**
- **NBI only, No ECH**
- **Several actively feedback controls**
  - ✓ β_N feedback control → adjust the P_{NBI}
  - ✓ n_{eped} feedback control →D gas puffing
- **Diagnostics:**
  - Divertor: Langmuir probes, Bolometer, IR camera, pressure gauge, Tangential TV, Filterscope, …
  - Core: TS, CER, SPRED, VB, …

Latest experimental progress in USN (September, 2019)

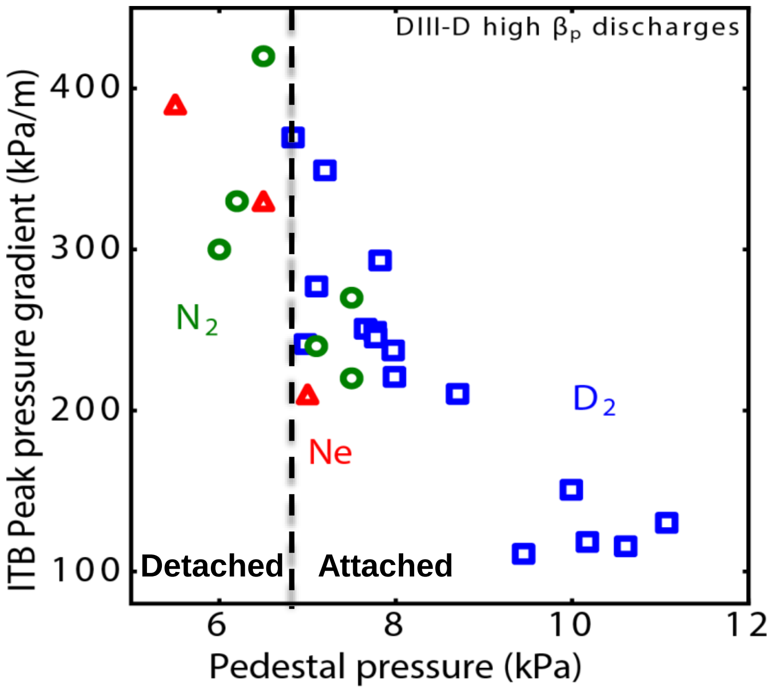
- ✓ Detachment feedback control algorithm
- ✓ More closed USN configuration
  - Constant Ip~0.72 MA & Bt w/o ramping
  - Increase β_N ~ 3 & dRsep to > 5mm
- ✓ Feedforward N2 seeding → $T_{e,div} < 5$eV
  - N2 seeding through PFX1
- ✓ Feedback detachment control with N2 seeding, GASB/PFX1
  - Target j_sat/j_roll =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



Special Core-edge integration in high β_p plasmas: synergy between ITB and ETB

- **Both impurity and D_2 fueling show the synergy between ITB and ETB**

ITB ∇P v.s. Pedestal top pressure



➢ **Extra bonus for core-edge integration**

- Weaker ETB → benefits small ELMs → less intermittent events
- Strong ITB → high confinement → reduced P_{heat} for feedback control
- High β_p → wide pedestal → larger space between radiation cooling and pedestal top

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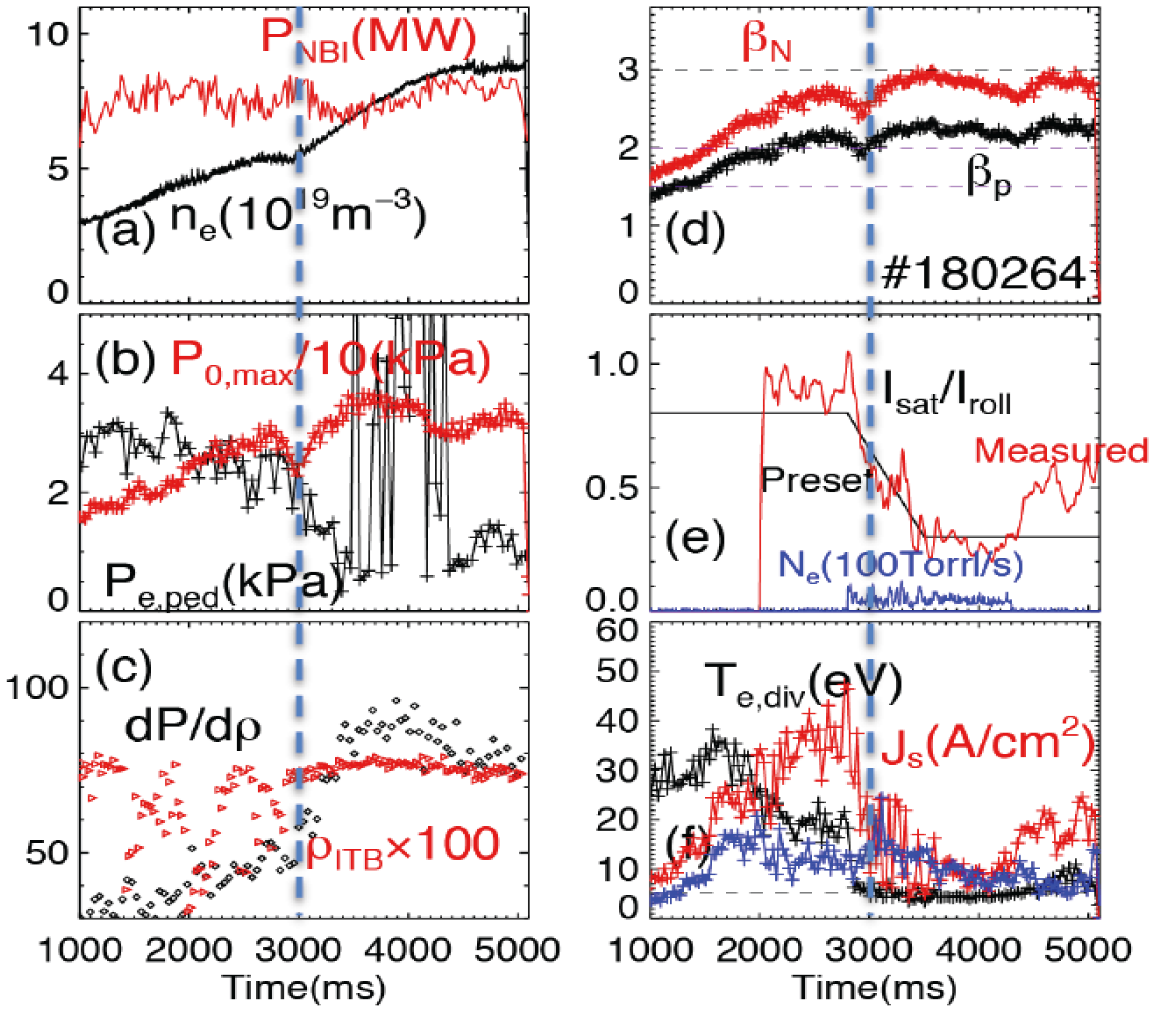
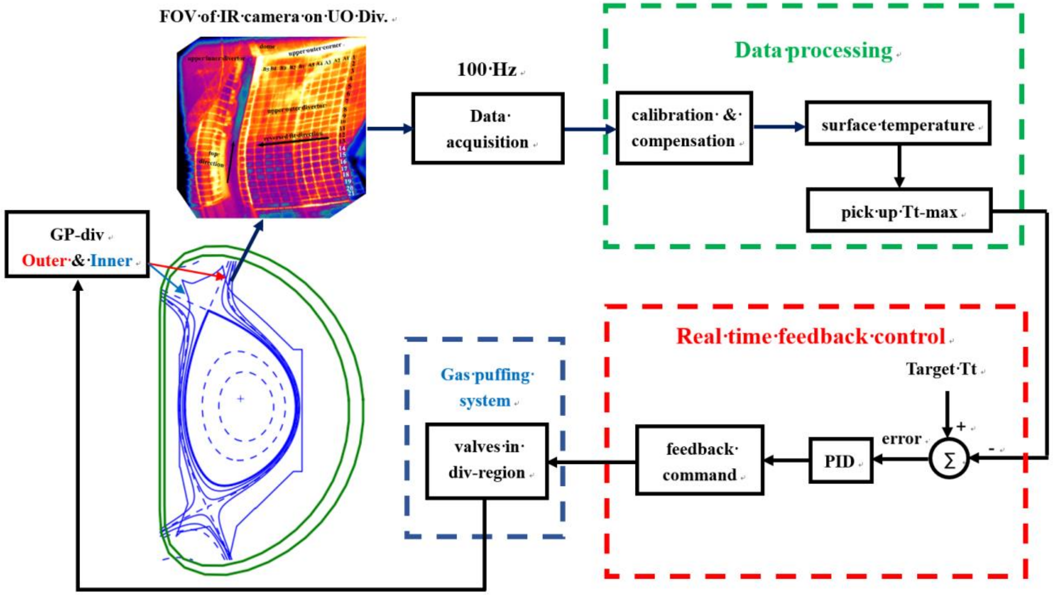
D2+Neon puff, feedback control



EAST demonstrated IR surface temperature control for detachment

- **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**



FOV of IR camera on UO Div.

100 Hz

Data acquisition

Data processing

calibration & compensation

surface temperature

pick-up Tt-max

Real-time feedback control

Target Tt

error

+

-

Σ

PID

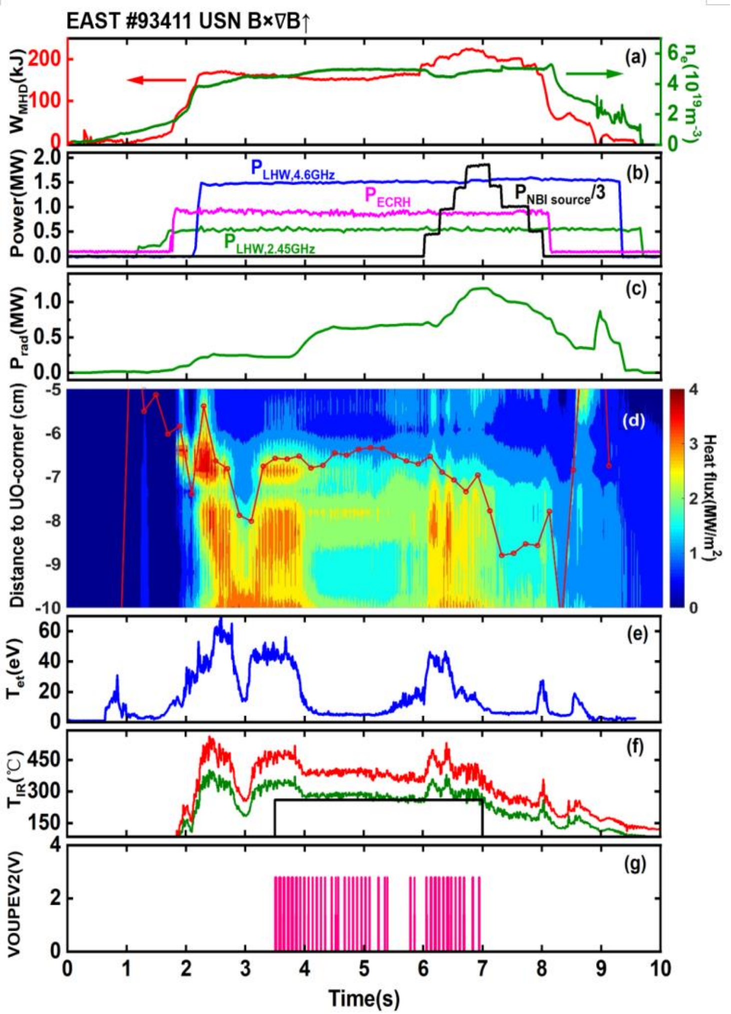
feedback command

Gas puffing system

valves in div-region

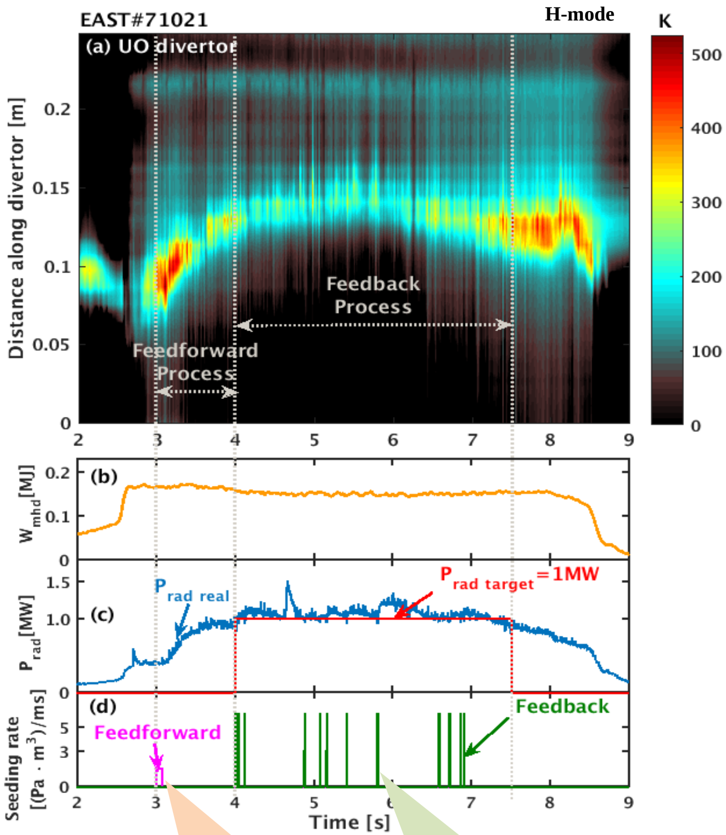
GP-div

Outer & Inner



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

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

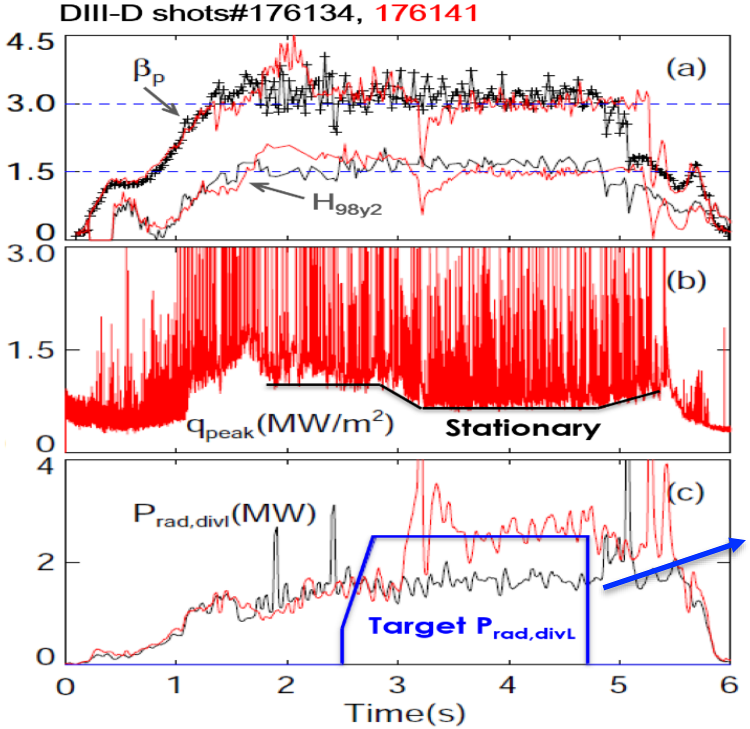


Neon puffing from top divertor

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

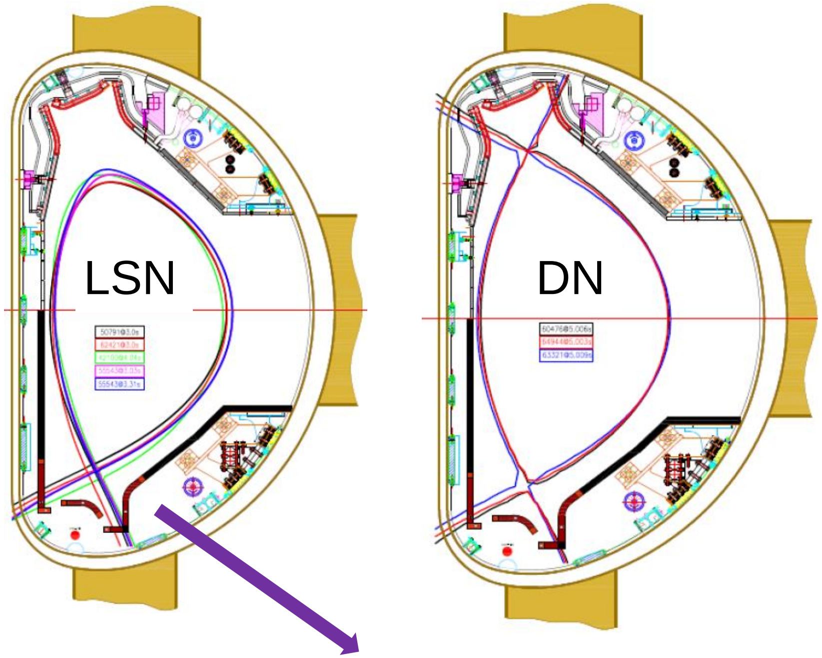


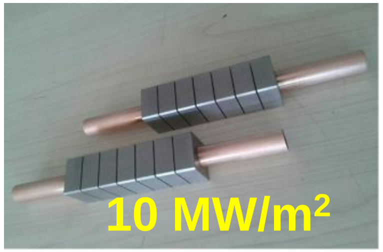
FB control:
D. Eldon

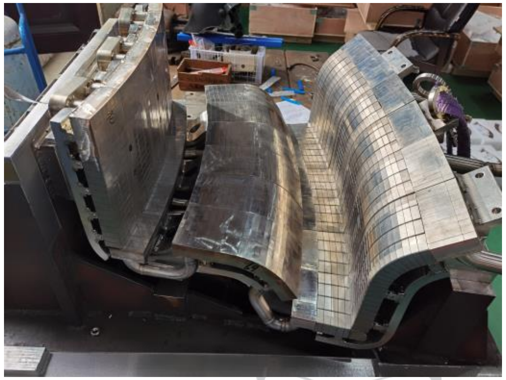
L. Wang, 27th IAEA-FEC (2018) & NF (2019)

Bottom divertor upgrade (C → W, finished)

- **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**



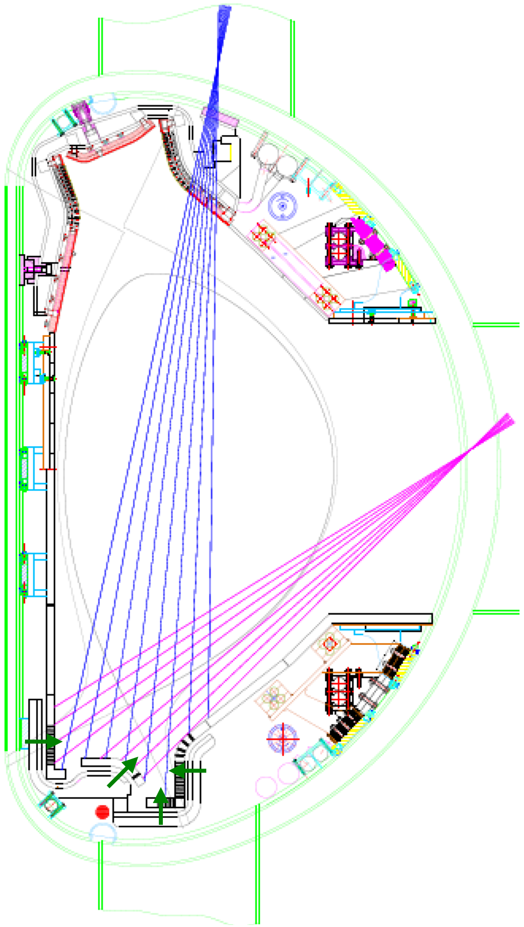




Upgrade of div.-diagnostics & gas puff systems

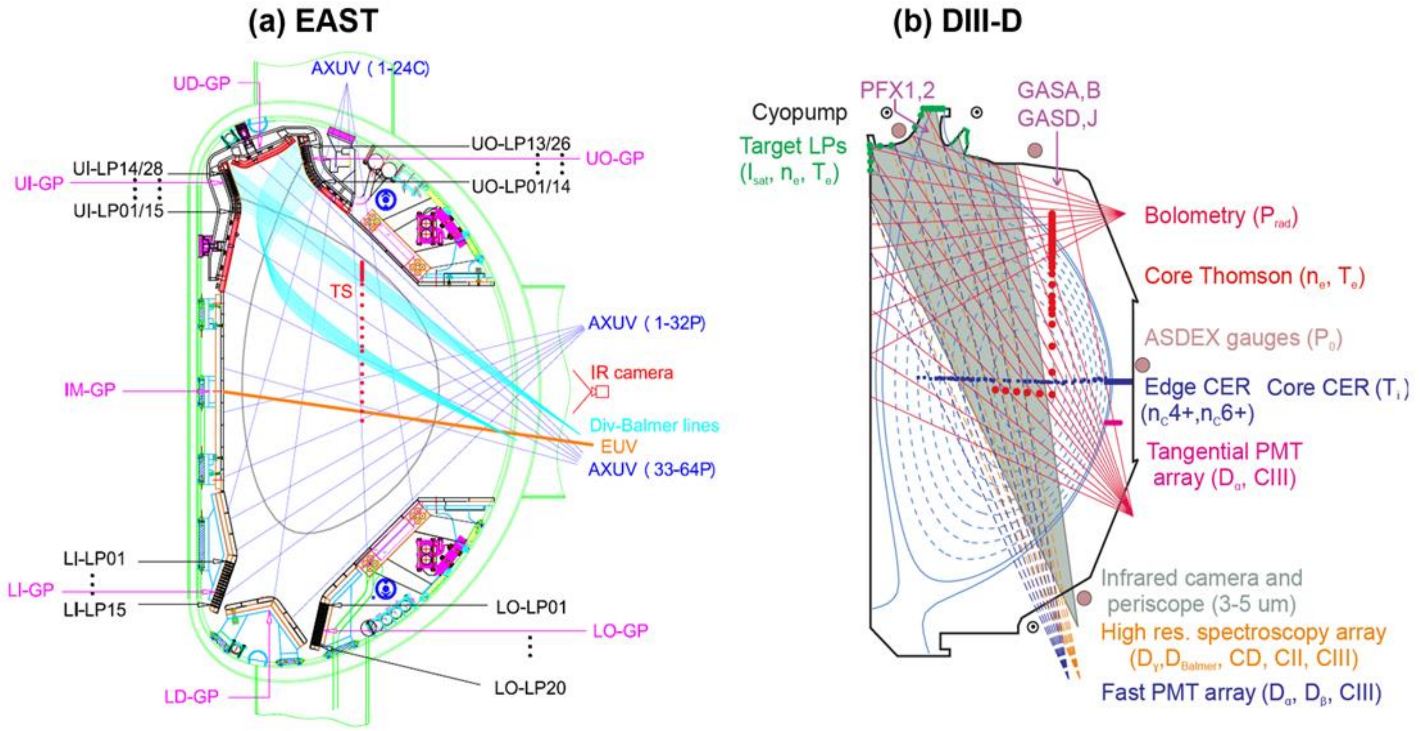
- **1st Priority: safety & operation oriented**
- **2nd Priority: physics oriented**

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



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

Joint DIII-D/EAST research on core-edge-divertor integration



- **EAST:** **ITER-like tungsten divertor for long pulse operation, RF heating, FB**
- **DIII-D:** **High performance plasma, bottom open & top closed divertors**