Divertor detachment and radiated power control developments on DIII-D and EAST

EX/P1-934

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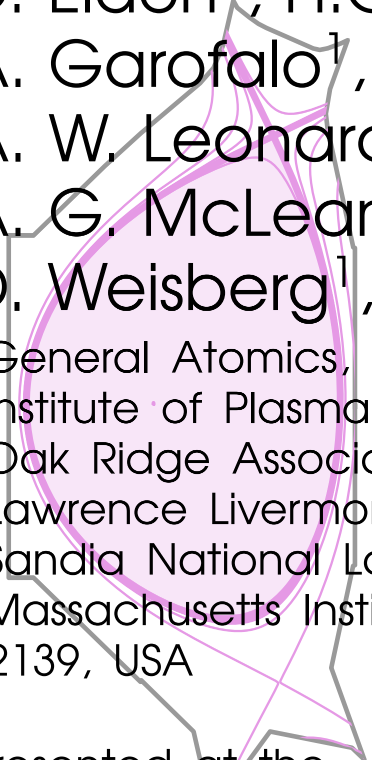

EAST
80613
5000 ms

DIII-D
180257
3000 ms

presented at the

28th IAEA Fusion Energy Conference

2021-05-11

Divertor detachment and radiated power control developments on DIII-D and EAST

- Detachment control systems using Langmuir probe (LP) feedback added at DIII-D and EAST
- Stable divertor T_e (new, using EAST's triple LPs) or J_{sat} (based on JET[1]) and can follow dynamic targets (new, aggressive demonstration of control capability)
- Integrated with core scenario to allow up to $H_{98,Y2} \approx 1.5$ (DIII-D), 1.1 (EAST); $\beta_p \approx 2.3$ (DIII-D), 1.5 (EAST) while detached[A]
- Similar outcomes despite differences in divertor material, geometry, impurity species (first successful use of Ar for control at EAST), and heating method
- Radiated power control deployed in super-H mode

[1] C Guillemaut et al. In: Plasma Phys. Control. Fusion 59 (2017), p. 045001

[A] Based on DIII-D#180257, EAST#85293

Related presentations

- **Liang Wang, High β_p, talk #892 May 14**
  - Poster #1497 May 11
- **Theresa Wilks, Super H-mode, talk #863 May 12**
  - Poster #1443 May 11

Introduction and motivation

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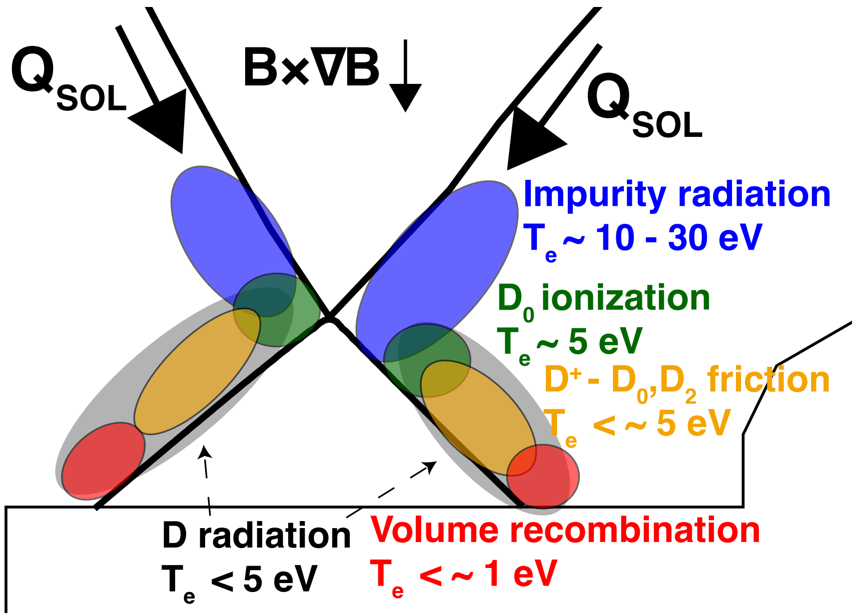
Detachment control system

High β_p scenario core performance with detachment control

Radiated power control near super H-mode

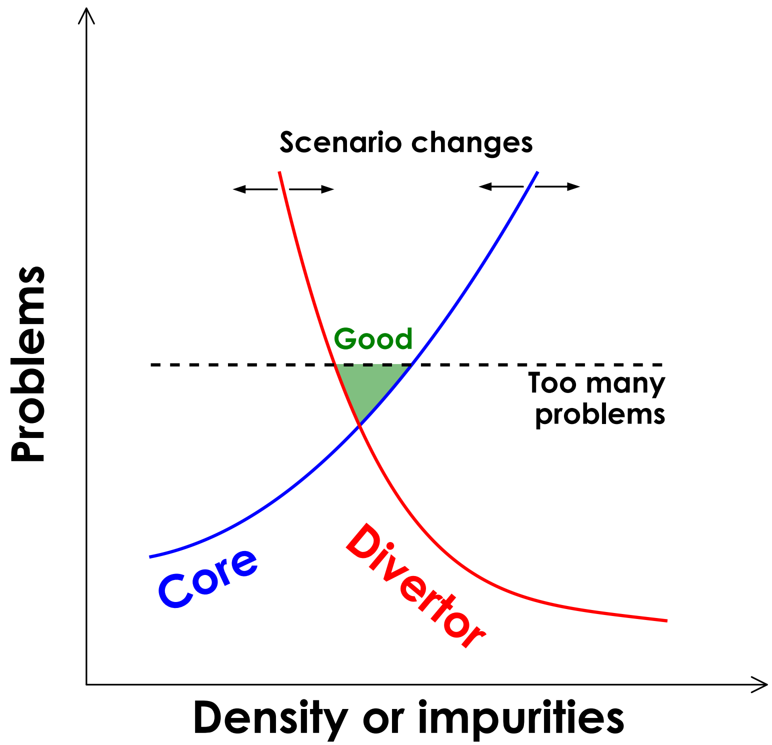
Conclusions

ITER requires heat exhaust mitigation such as divertor detachment to protect plasma facing components[3, 2]



- **Detach = dissipate energy and momentum along the open field lines**
- $T_e(R, Z)$ **sets where dissipation processes turn on**[2]
- **Reduce** Q_{SOL} **until tolerable by PFCs (**$\lesssim$**10–15 MW** m^{-2}**)**[3, 4]
- **Reduce** T_e **at the plate to avoid sputtering**

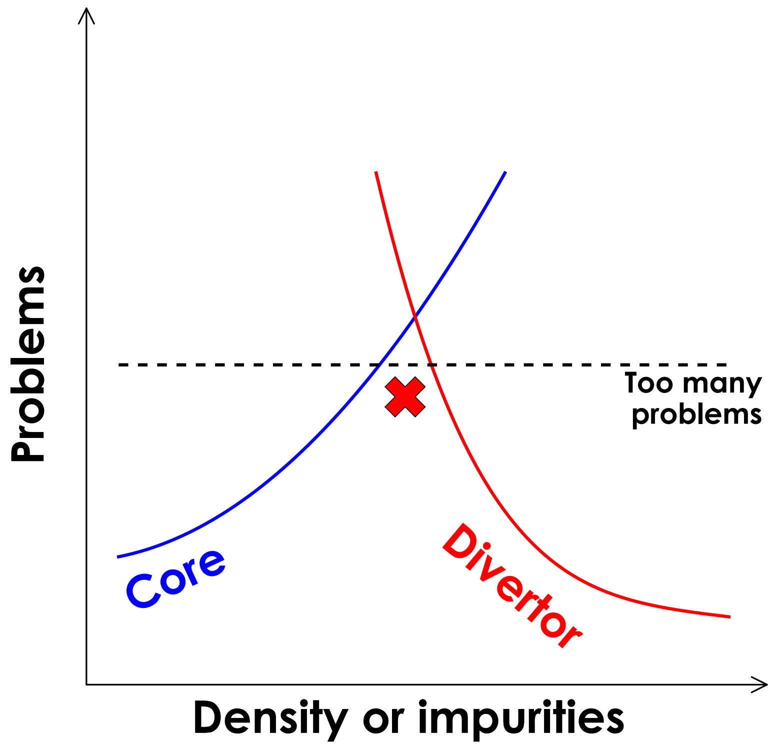
Divertor control is an optimization problem



- **Detach by increasing n_e or P_{rad}**
  - Prevent divertor melting & sputtering
- **Can cause problems for core**
  - Lower confinement
  - MARFE
  - H-L transition[5]
  - Radiative collapse
  - Density limit
- **Optimum set point is not static**
  - Control must adapt

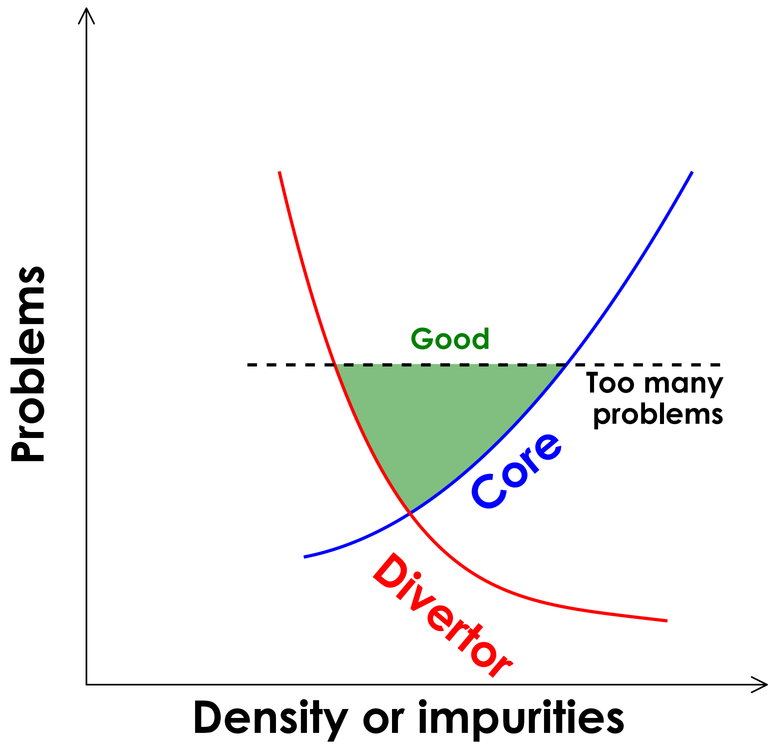
(5) A. W. Leonard et al. In: Nucl. Fusion 57 (2017), p. 086033

Not all scenarios allow successful integration studies on present devices



- Open divertor: higher n_e required for detachment
- RMP or ECH in DIII-D: low n_e required
- High performance DIII-D scenarios typically do not tolerate detachment
- Detachment studied in low performance scenarios

The high β_p scenario was able to maintain confinement in detachment



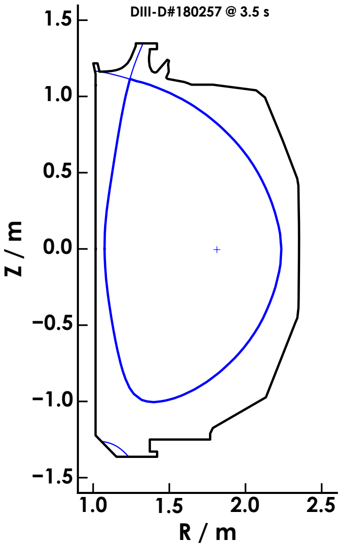
- **Motivation:** $\beta_p \propto I_{bs}/I_p$
  - Steady-state relevant
- **First development on JT-60U**[(6)]
- **Pedestal is degraded by detachment**
- **ITB maintains confinement**
- **Supports core-edge integration studies on DIII-D and EAST**

- $\beta_p = 2\mu_0 \frac{\langle p \rangle_A}{\langle B_{pol} \rangle^2}$

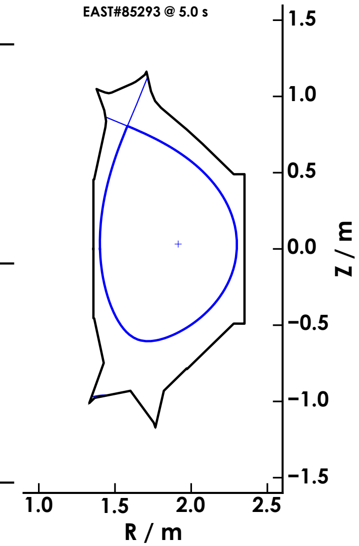
$\langle p \rangle_A$ = pressure averaged over poloidal cross section
$\langle B_{pol} \rangle$ = average poloidal magnetic field on the boundary

(6) M. Kikuchi. In: Nucl. Fusion 30.2 (1990), pp. 265–276

Similar high β_p scenarios developed in DIII-D and EAST



		DIII-D	EAST
Target material		C	W
Target geometry		horiz	vert
PF coils		Cu	SC
P_{beam}	/ MW	6.8	0.0
P_{RF}	/ MW	0.0	2.9
P_{total}	/ MW	6.9	3.0
q_{95}		7.9	6.5
β_p		2.3	1.5
β_N		3.0	1.2
$H_{98,y2}$		1.8	1.1
$\langle n_e \rangle$	/ 10^{19} m^{-3}	6.2	5.3
I_p	MA	0.7	0.4
Impurity species		N_2	Ne
		#180257	#85293



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ASIPP

Detachment control system

Introduction and motivation

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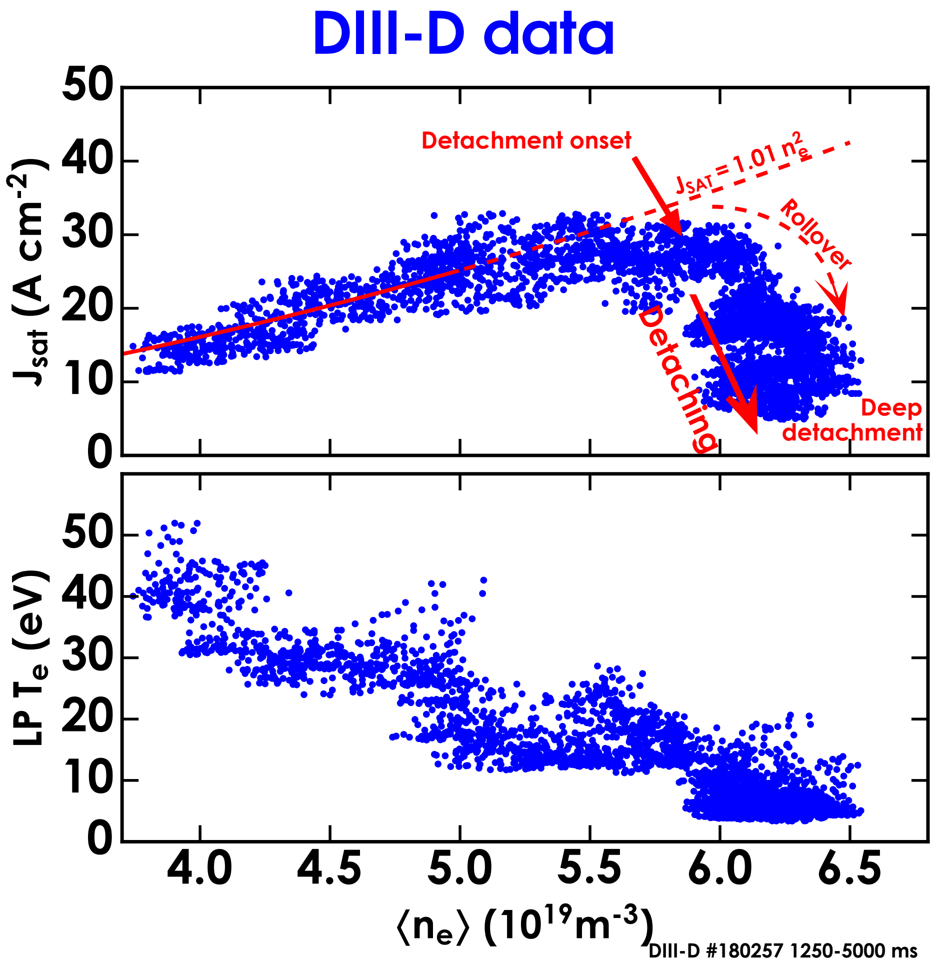
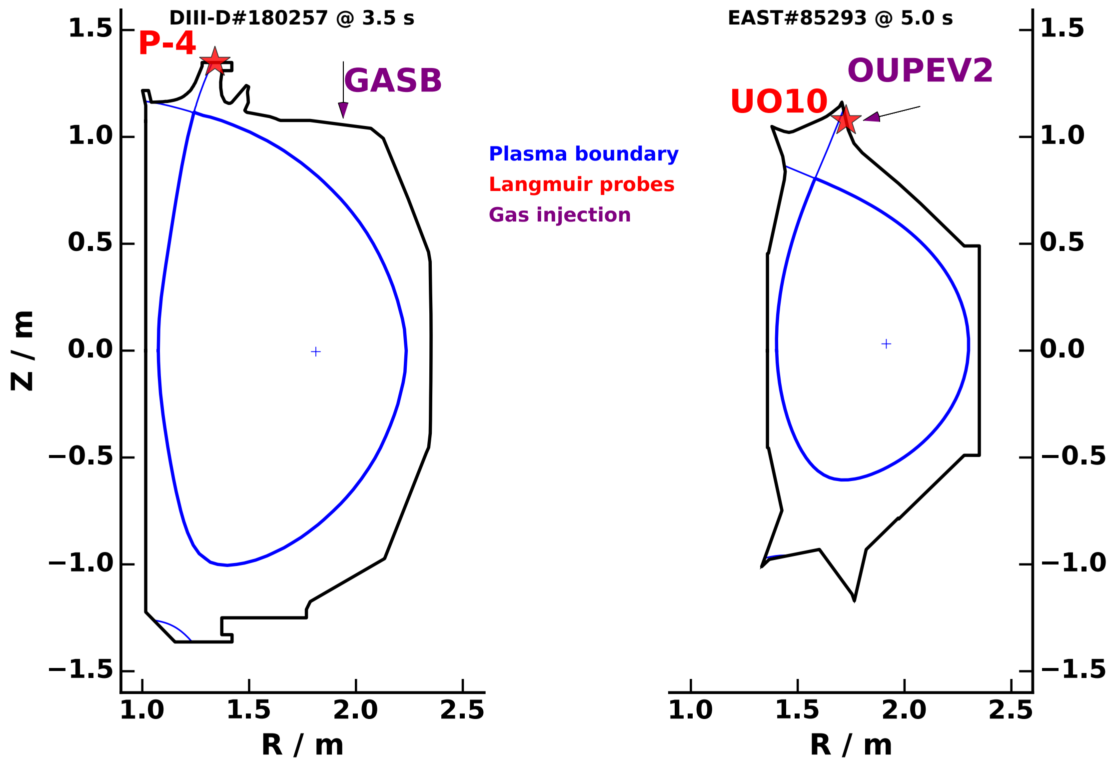
Detachment is characterized by low T_e & J_{sat} rollover



- **Attached:** $J_{sat} \propto \langle n_e \rangle^2$ **(more particles hit divertor)**
- **Detached: momentum loss reduces** J_{sat}
- J_{sat} **"rolls over" as density increases**
- **Degree of detachment** $\propto \langle n_e \rangle^2 / J_{sat}$

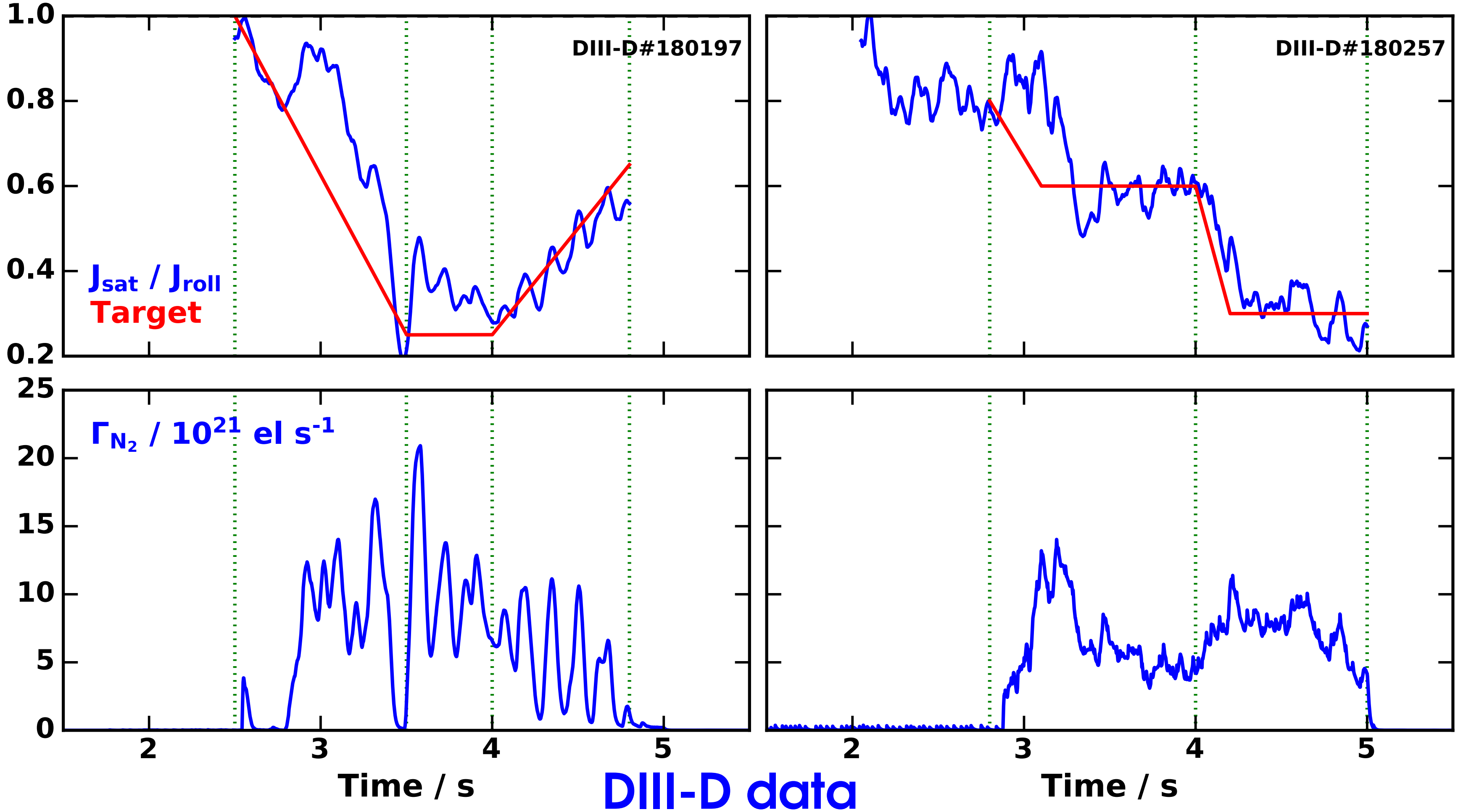
DIII-D & EAST studies in similar scenarios using sensors in the divertor and nearby gas inlets

DIII-D probes: (7) J. G. Watkins et al. In: Rev. Sci. Instrum. 79 (2008), 10F125



EAST probes: (8) J. C. Xu et al. In: Rev. Sci. Instrum. 87.8 (2016), p. 083504

DIII-D demonstrates ability to follow dynamic J_{sat} targets with PID loop between LP & N_2 puff



DIII-D data

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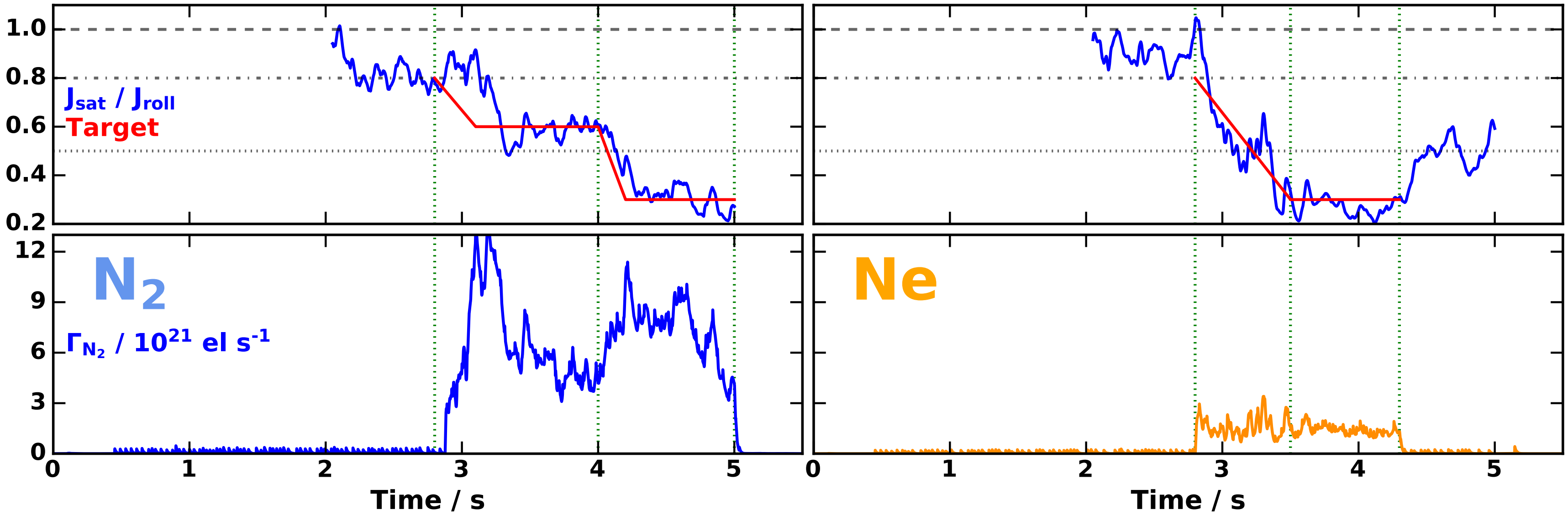
DIII-D control was demonstrated with N_2 and Ne puffing

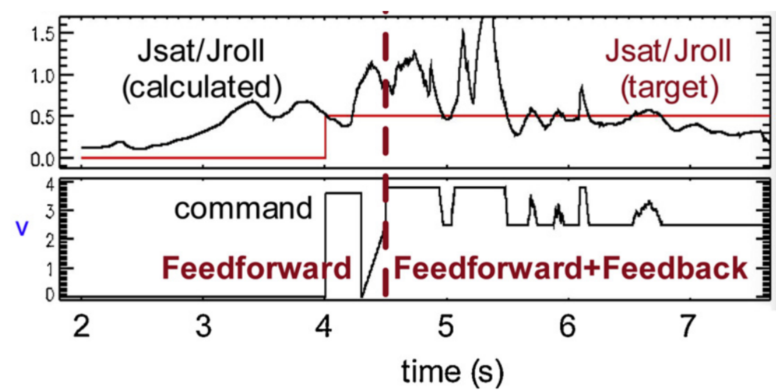


- Dynamic target following performance is probably not overly sensitive to scenario details
- Neon control on DIII-D can be challenging; may be easier in this scenario

DIII-D data

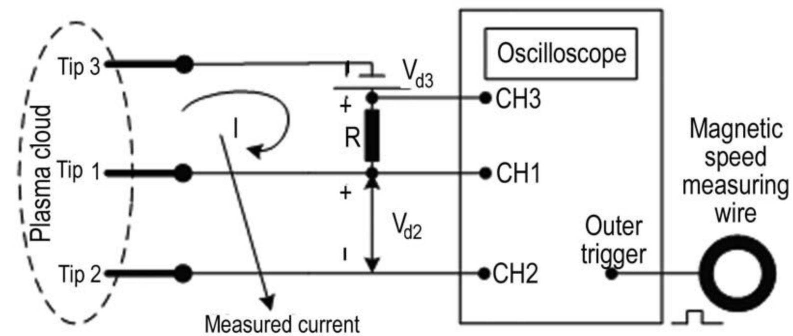
First use of triple-tip Langmuir probes for $T_{e,div}$ control

- **EAST J_{sat} control has been documented previously**



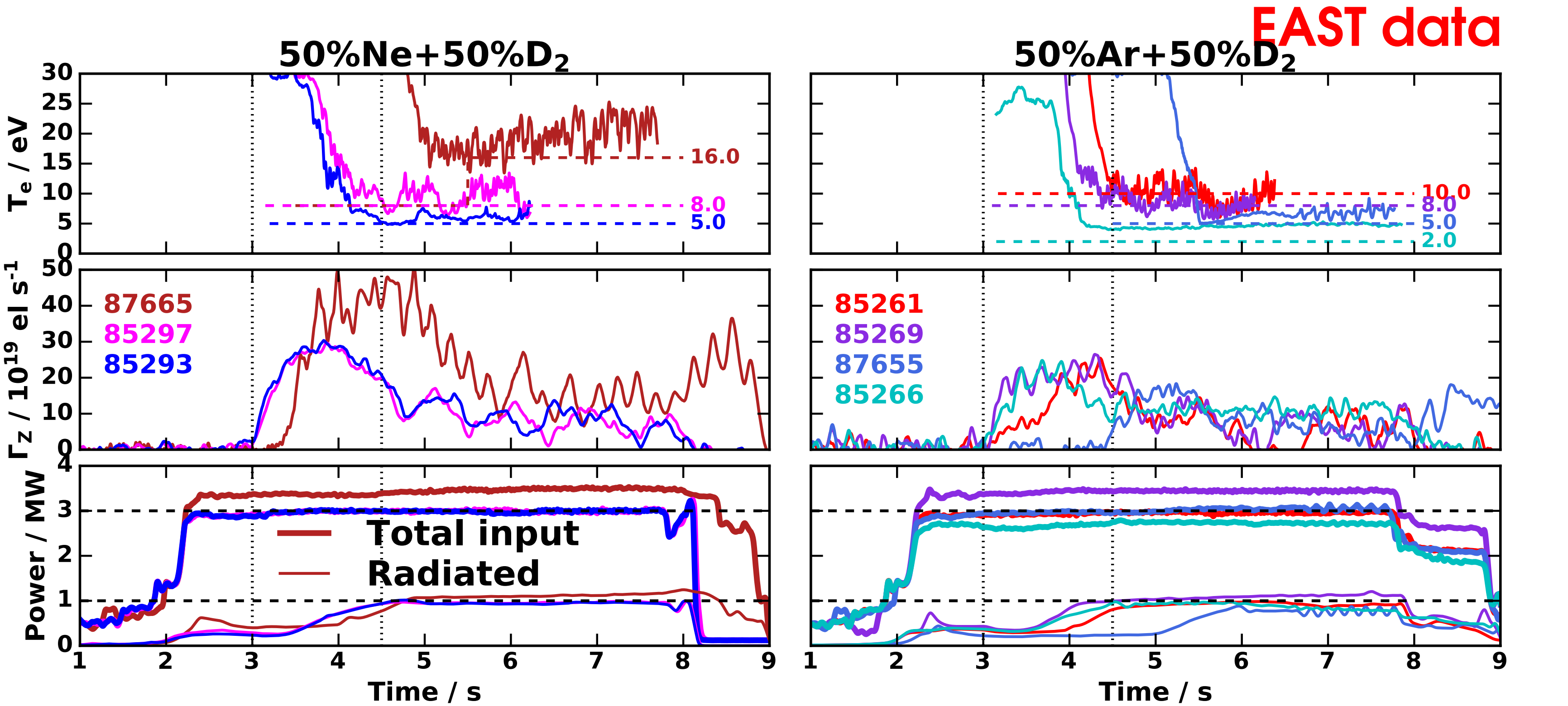
(9) Q. Yuan et al. In: Fusion Eng. Des. 154 (2020), p. 111557

- **Fast & simple T_e from triple probes**



(10) E. Tang et al. In: Plasma Sci. Technol. 14 (2012), p. 747

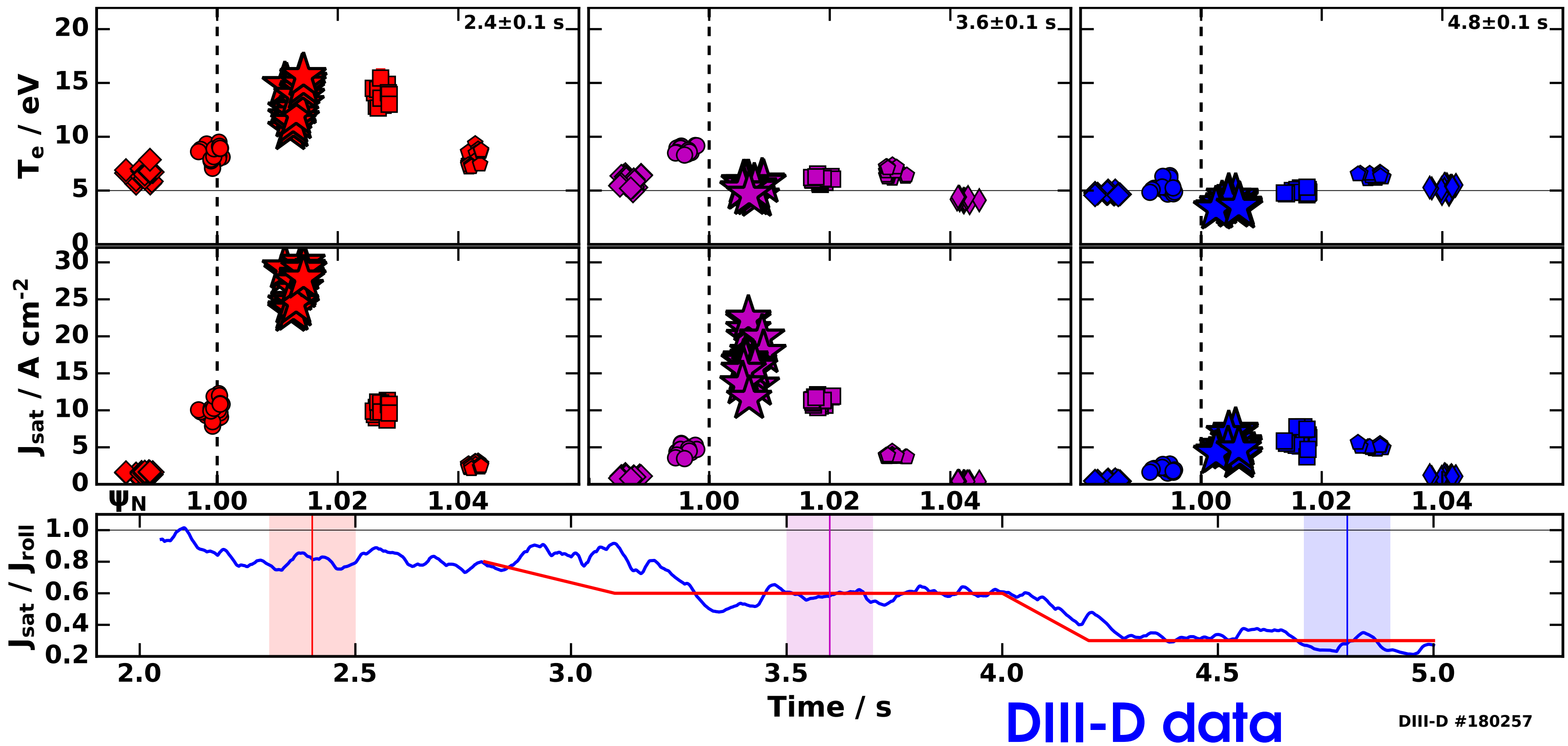
EAST demonstrated ability to meet a range of targets using feedback of T_e from 3LP



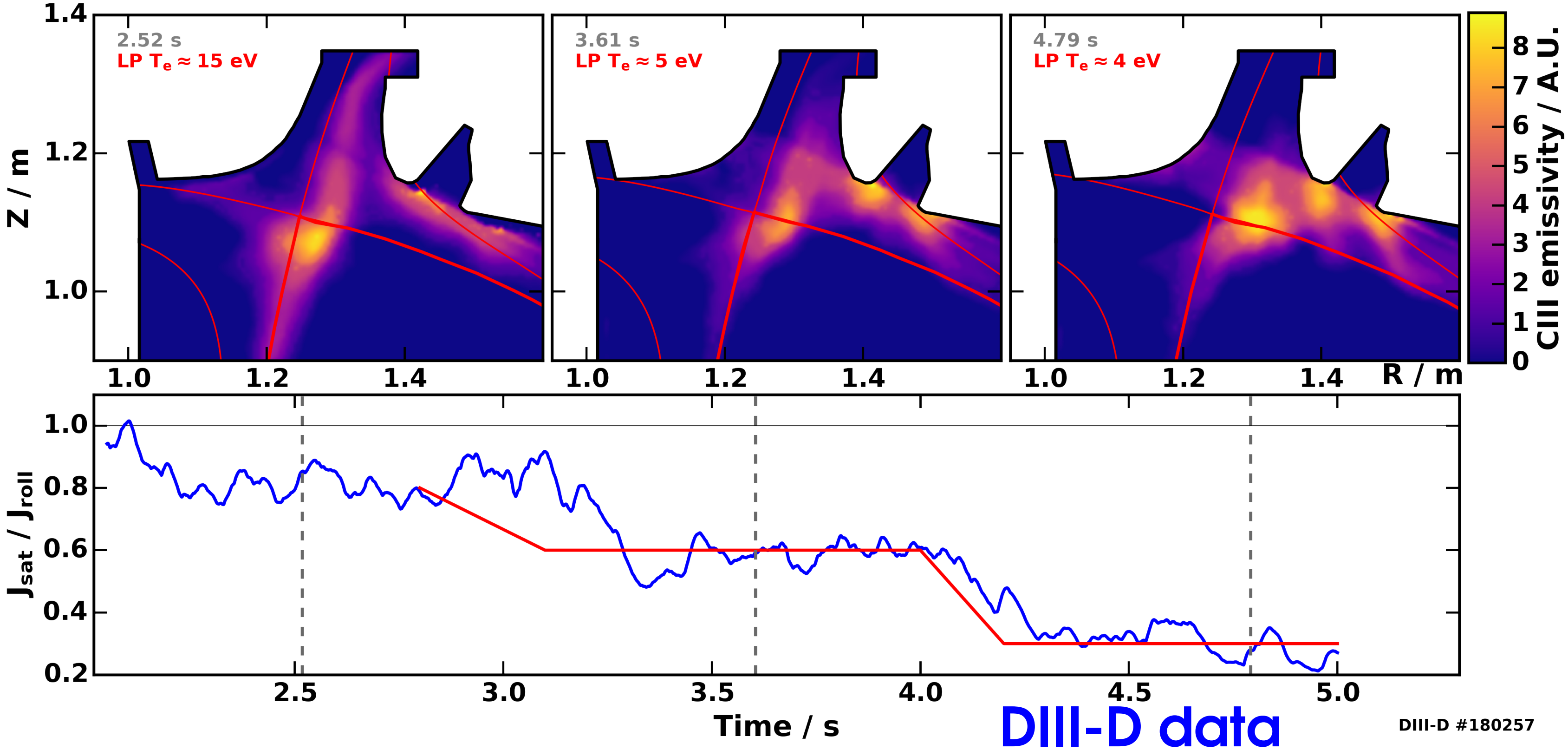
* Γ_Z is the flow of impurity gas out of the tank

ASIPP

T_e and J_{sat} are reduced across the whole divertor target plate



Tangential TV[11] shows CIII emission moving from target to X-point, consistent with detachment



(11) M. E. Fenstermacher et al. In: Phys. Plasmas 4 (1997), p. 1761

Control limitations and considerations

- **So far: rely on fixed strike point instead of RT analysis of profiles from multiple LPs → vulnerable to strike point drift**
  - Some EAST data thrown out after strike point drifted
  - Longer EAST pulse → more drift → improvement needed
- **LPs might have trouble measuring low T_e**
  - EAST: 200 V external voltage makes calculations easy, but reduces sensitivity to low T_e
  - Probes might overestimate T_e at low T_e [12]
- **T_e sensitivity decreases with further progress into detachment; for example:**
  - Detachment onset: $\gtrsim$ 10 eV to $\approx$ 5 eV
  - DOD=2 to DOD=4: $\approx$ 5 eV to $\approx$ 4 eV

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(12) P. C. Stangeby. In: Plasma Phys. Control. Fusion 37.9 (1995), pp. 1031–1037

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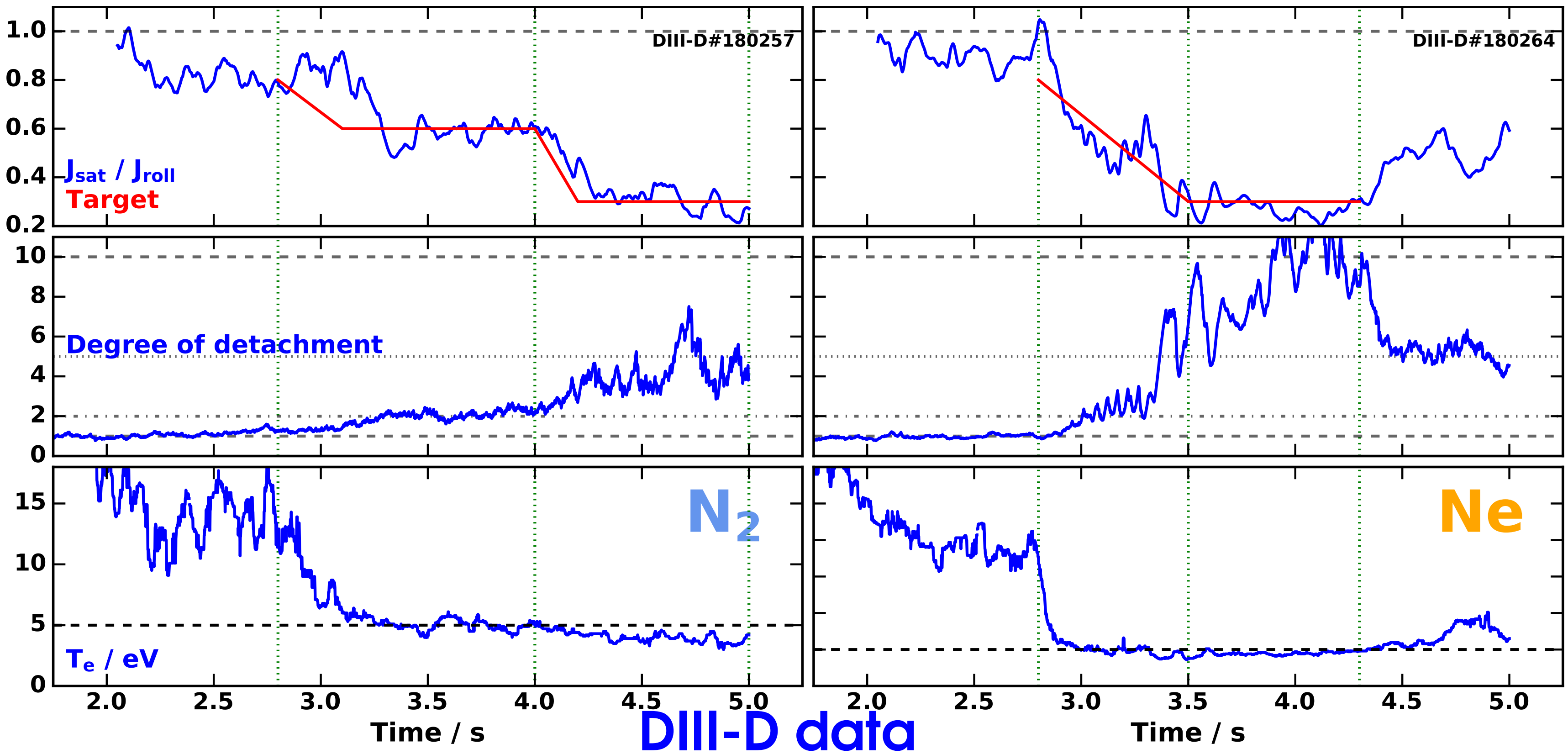
ASIPP

J_{sat} can be a more sensitive indicator of progress deeper into detachment than T_e



DIII-D data

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High β_p scenario core performance with detachment control

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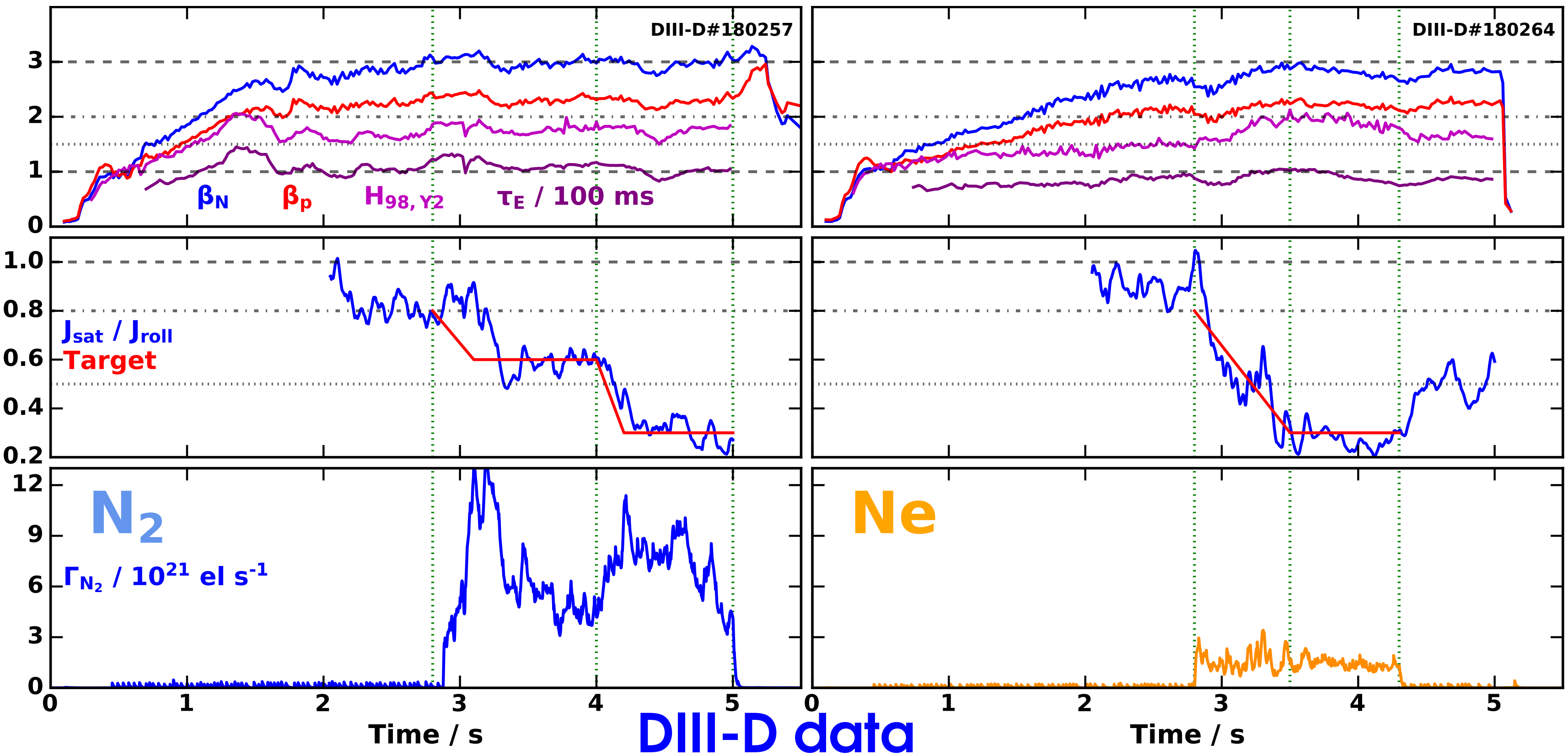
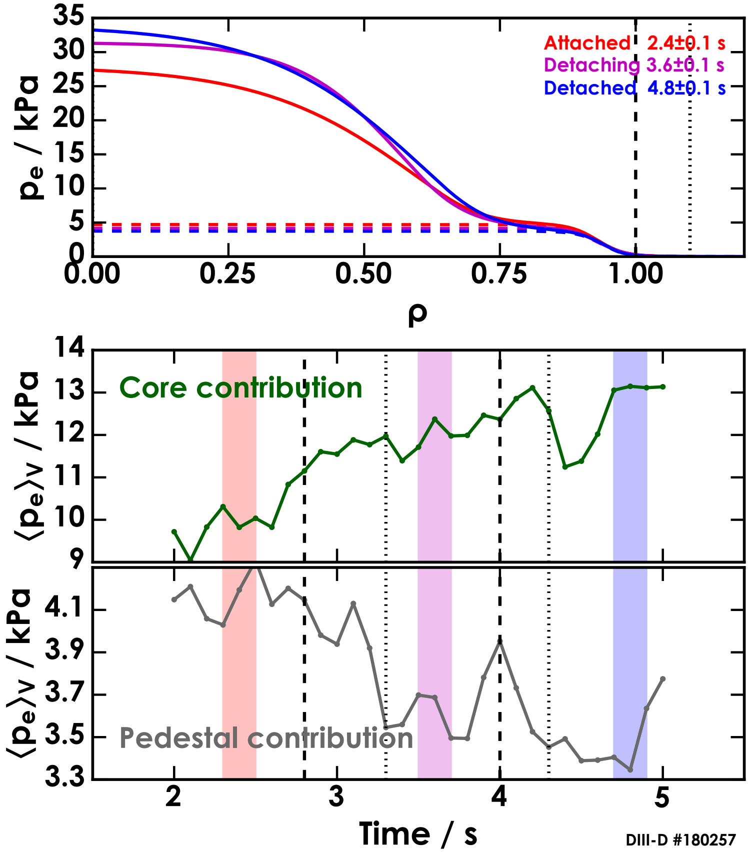
Maintained H_{98} and β during detachment in DIII-D high β_p scenario



DIII-D data

ITB retains confinement even as the pedestal degrades due to heavy puffing



DIII-D data[13]

- **High fuel or impurity puffing can degrade pedestal**
  - By ≈ 20% in this case
- **ITB growth compensates for pedestal degradation**[14, 15]
  - By ≈ 30%

(13) D Eldon et al. In: Rev. Sci. Instrum. 83 (2012), 10E343
(14) T. Fujita et al. In: Nucl. Fusion 42.2 (2002), pp. 180–186
(15) J. McClenaghan et al. In: Nuclear Fusion 59.12 (2019), p. 124002

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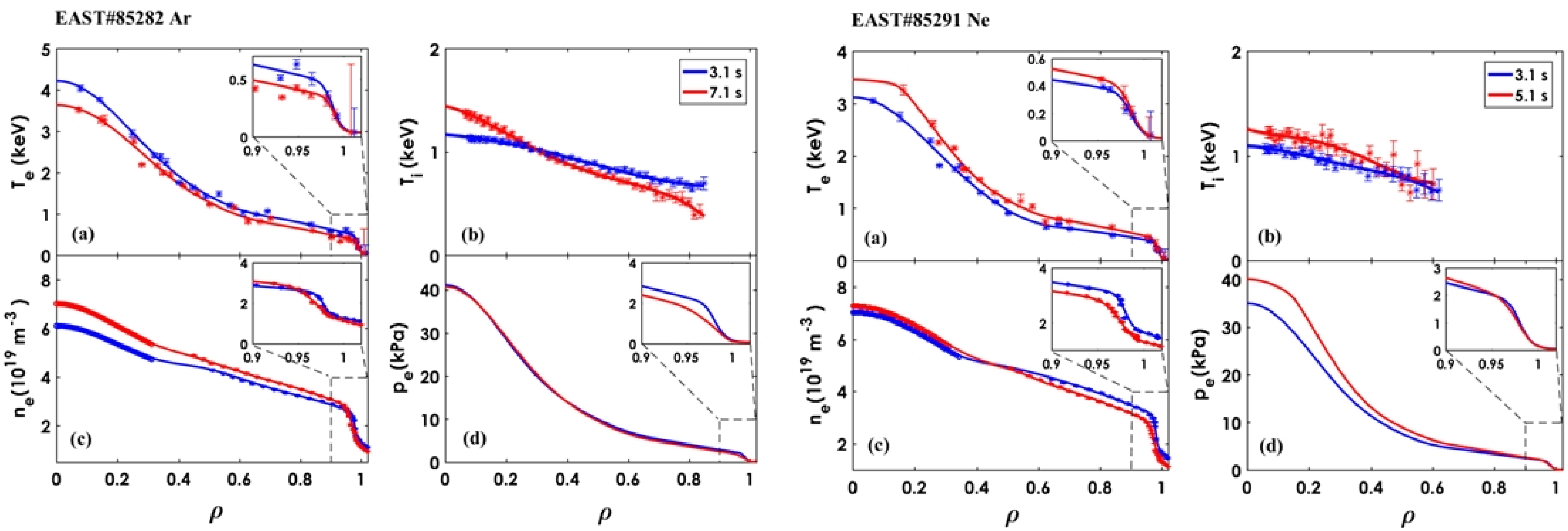
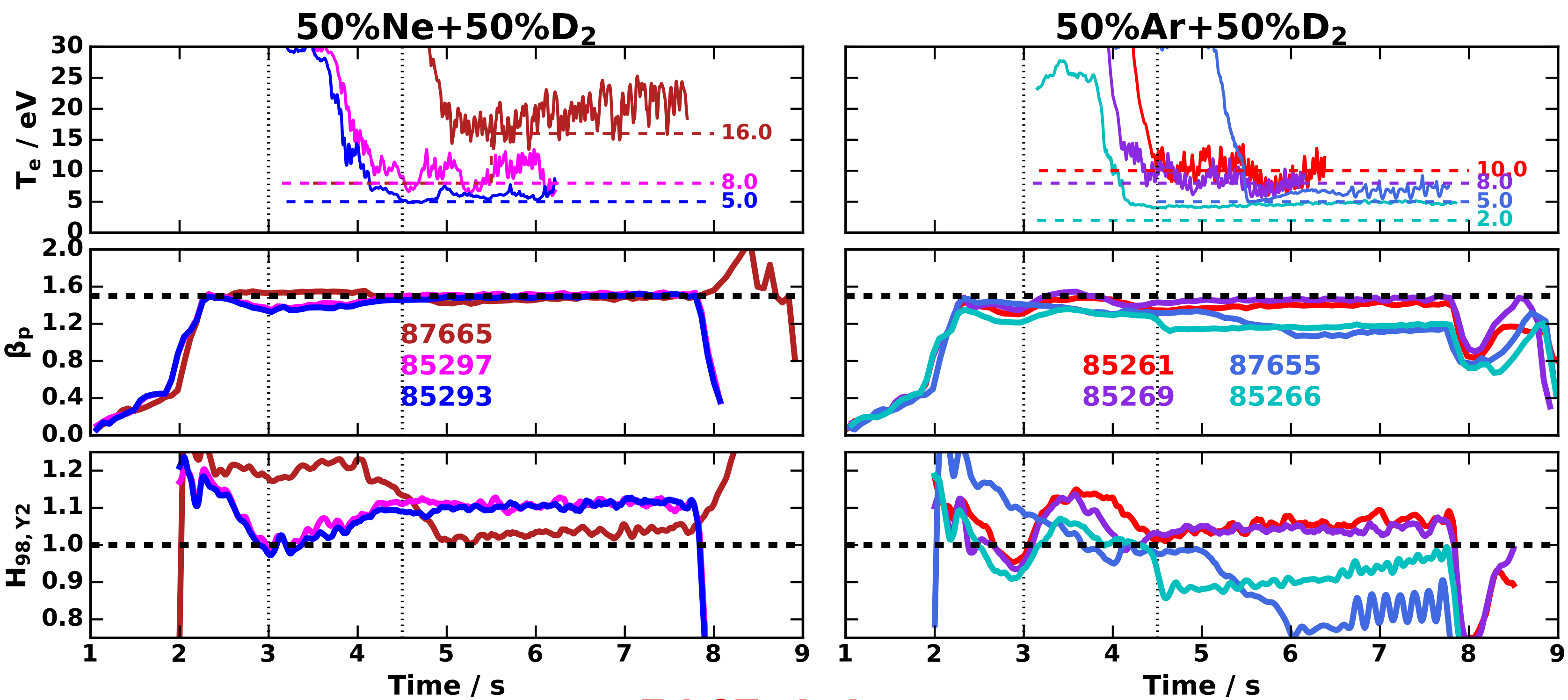
EAST high β_p scenario has significant core gradients that could compensate for weakened pedestal



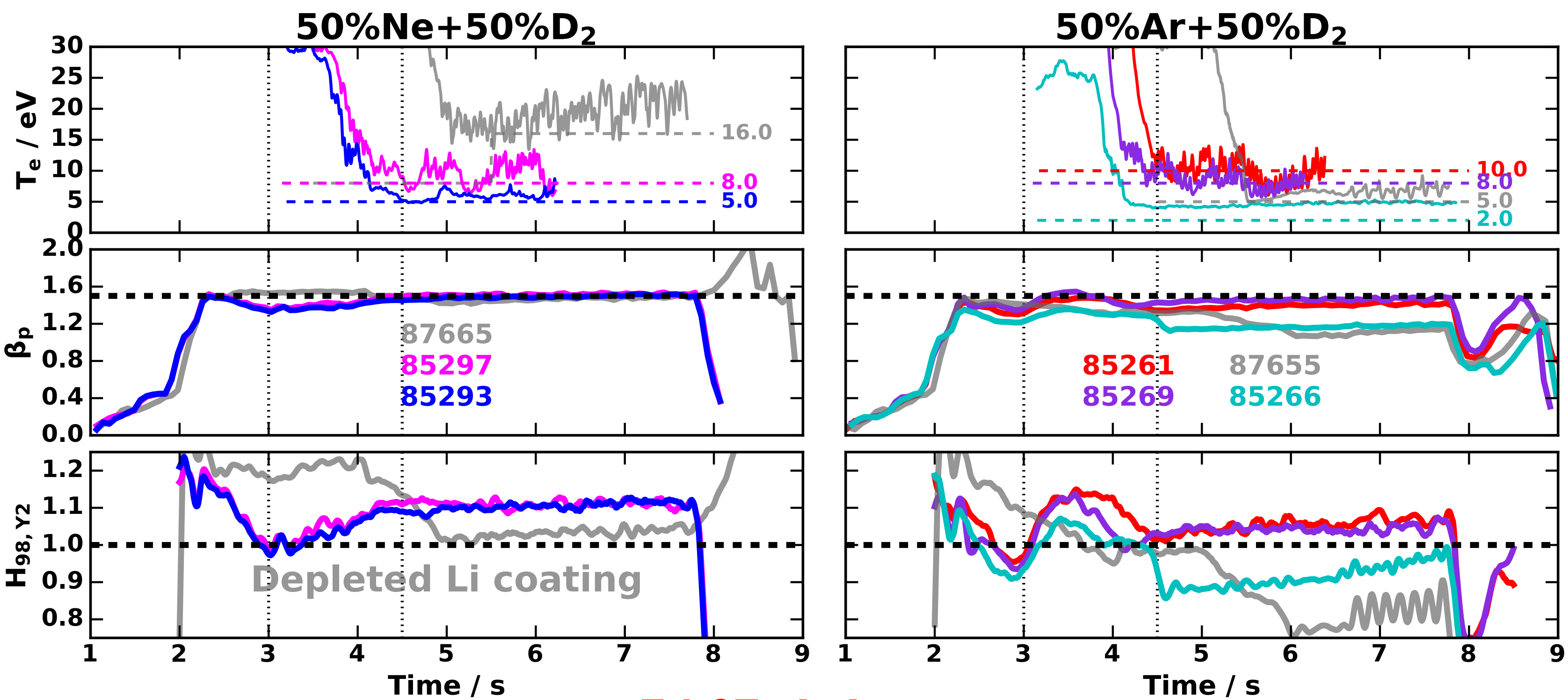
EAST data

EAST retains $H_{98} \geq 1$ unless heavy argon puff (≈10% loss) or depleted Li coating (≈20% loss)



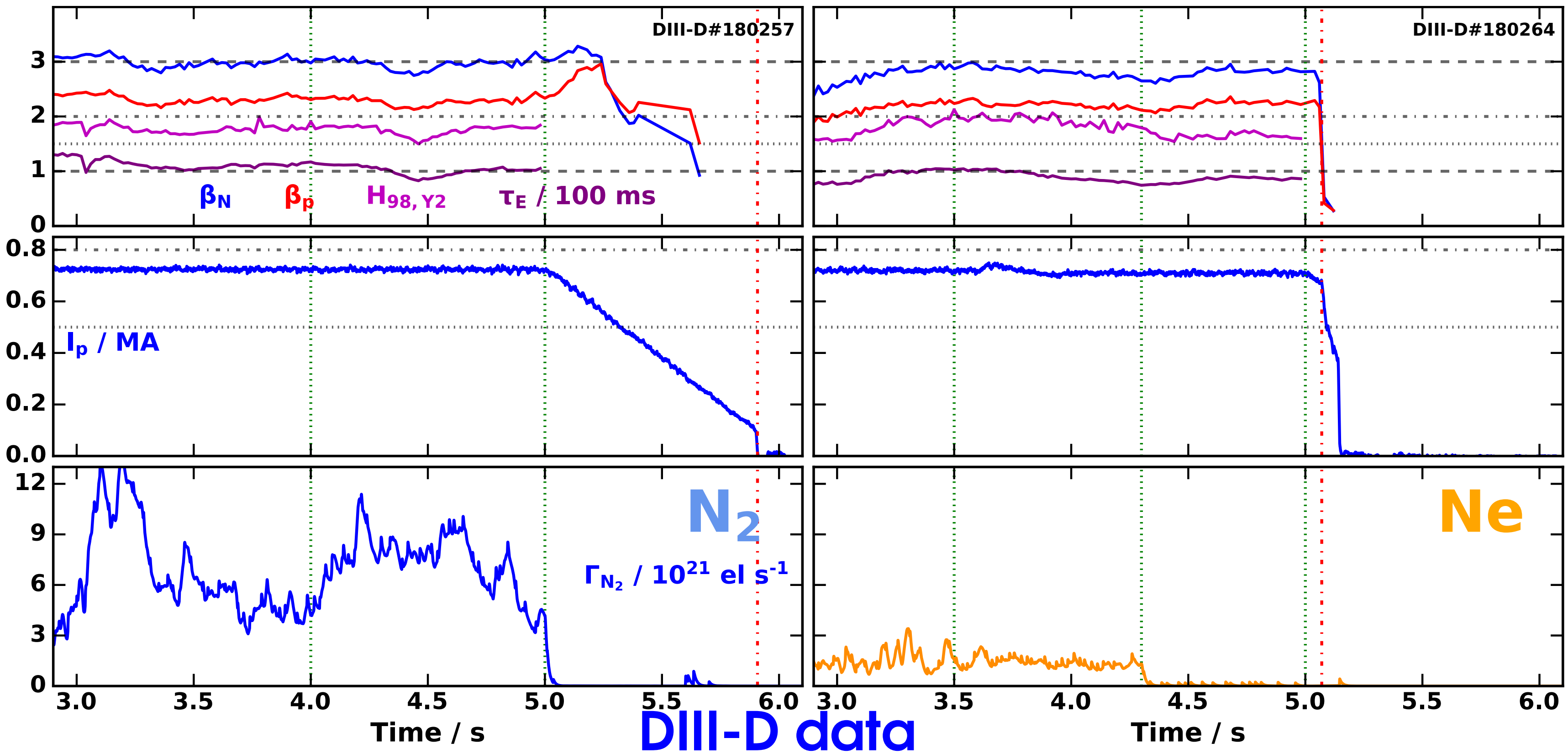
EAST data

EAST retains $H_{98} \geq 1$ unless heavy argon puff ($\approx$10% loss) or depleted Li coating ($\approx$20% loss)



EAST data

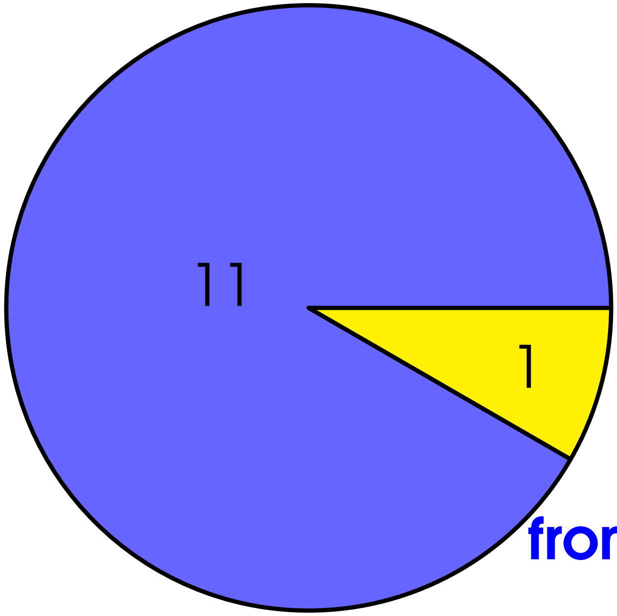
Although confinement quality remained good, disruption risk increased during neon seeding in DIII-D high β_p



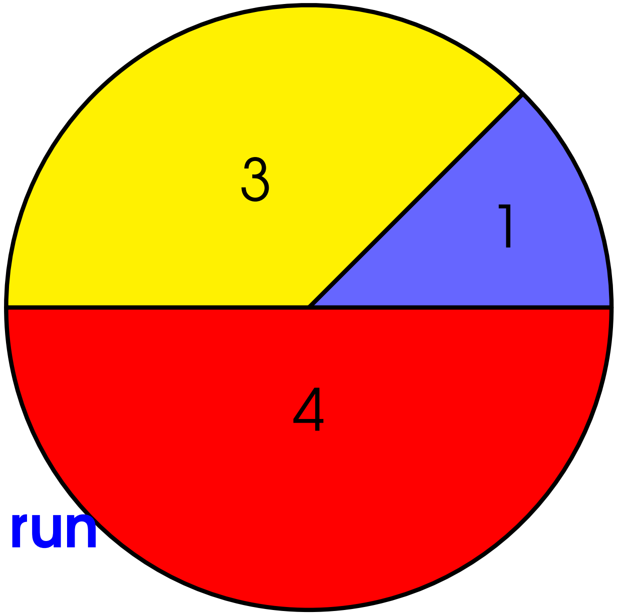
In DIII-D, neon was associated with more disruptions than nitrogen when used for detachment control in high β_p

Safe rampdown	Disruption in rampdown	Disruption in I_p flattop

Nitrogen
180246 – 180257



Neon
180259 – 180266



DIII-D data, from the same run as #180257

Radiated power control near super H-mode

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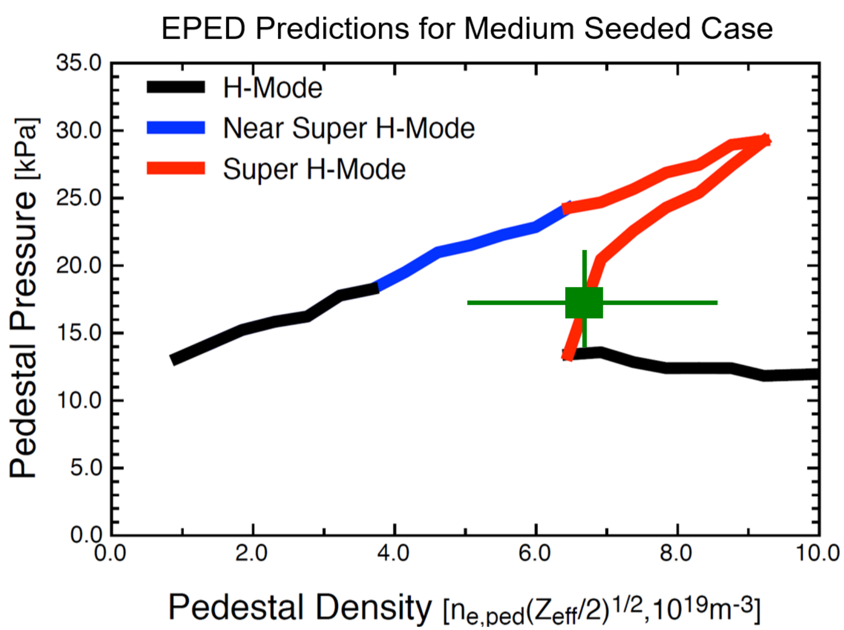
Super H-mode enables higher pedestal height and fusion performance than for H-mode



See Talk #863 by T. Wilks, May 12

DIII-D DATA

- **Super H-mode exists in narrow region of parameter space, first predicted by EPED**(16)
- **Performance boost is all from pedestal**
  - In contrast to high β_p, where performance depends more on ITB & pedestal can be sacrificed

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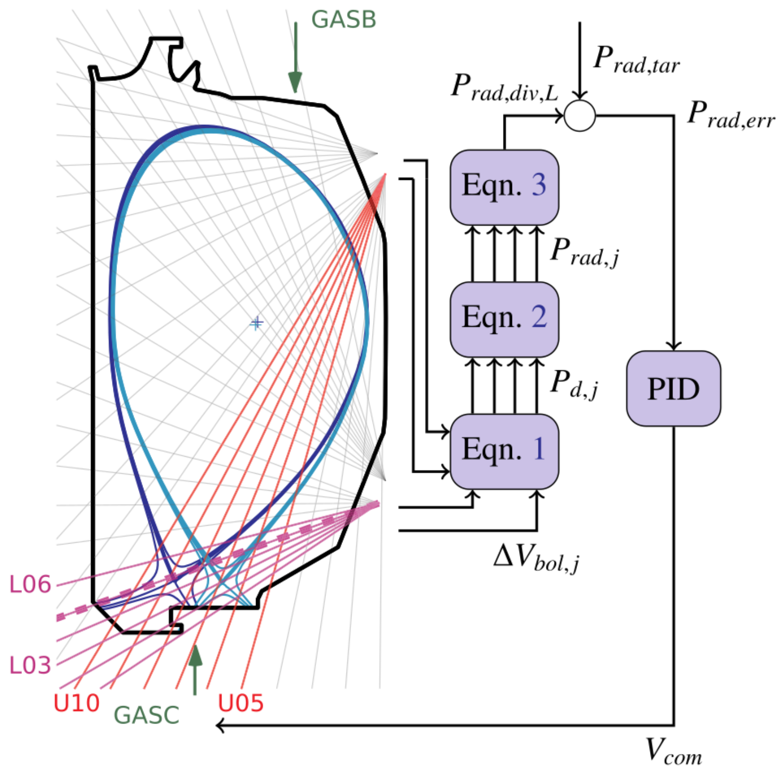
DIII-D's radiated power control system(17) uses foil bolometers(18)



- Voltage on the foils ($\Delta V_{bol,j}$) converted into estimate for radiated power from lower divertor ($P_{rad,div,L}$)
- Plasma region can be changed ($P_{rad,core}$, $P_{rad,div,U}$, $P_{rad,\Sigma}$) by selecting different bolometer channels

$$P_{d,j} = \left(A_j \cdot \Delta V_{bol,j} + B_j \cdot \frac{d}{dt} \Delta V_{bol,j} \right) \quad (1)$$

$$P_{rad,j} = 2\pi R_j r_j \Delta\theta_j K_j P_{d,j} \quad (2)$$

$$P_{rad,div,L} = \sum_j C_j P_{rad,j} \quad (3)$$

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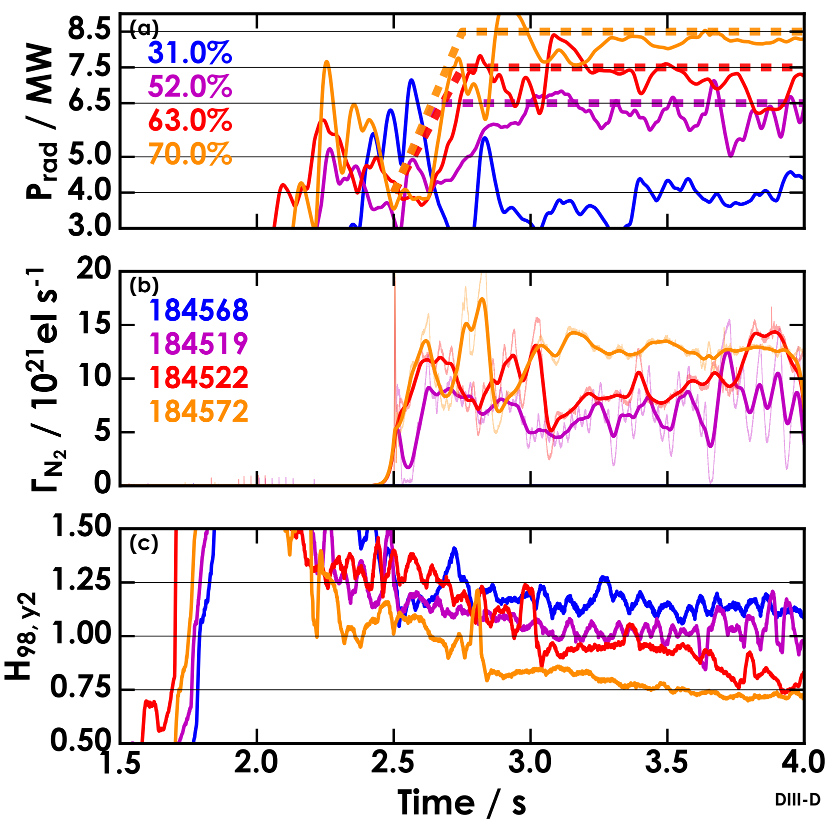
Radiated power control works in super-H mode, but degrades confinement quality



- **Nitrogen injection → up to 70% P_{rad}**
- **ITER needs** ≈ 70%P_{rad} (19, 20, 21)
- **Confinement (H_{98}) degraded by 25% at highest P_{rad}**
- **Super H is lost at higher P_{rad}**
  - 60% P_{rad}: super H lost partway through (marginal)
  - 70% P_{rad}: not super H

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Summary: LP detachment control integrated with core scenario while maintaining confinement

- DIII-D[22] & EAST[9] added J_{sat} control similar to JET[1]
- EAST added triple Langmuir probe T_e control
- Control avoids excess puffing, while high β_p scenario tolerates detachment w/ high confinement (ITB ...)
- Achieved $H_{98} \approx 1.5$ and $\beta_p \approx 2.3$ in controlled detachment in DIII-D
- Achieved $H_{98} \approx 1.1$ and $\beta_p \approx 1.5$ in controlled detachment in EAST
- Radiated power control added to super-H mode for up to 70% P_{rad}

References I

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